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Seismic dispersion and attenuation in fluid-saturated rocks: theory and experiment

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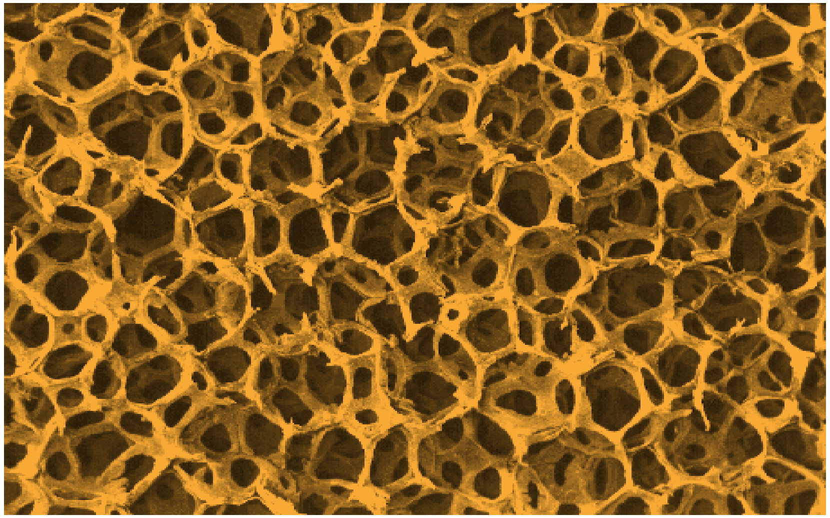
Curtin University and CSIRO, Perth, Western Australia

BalticPetroModel, Петергоф, 17-19 Сентября 2014

What are the mechanisms of wave attenuation/dispersion in a fluid-saturated rocks?



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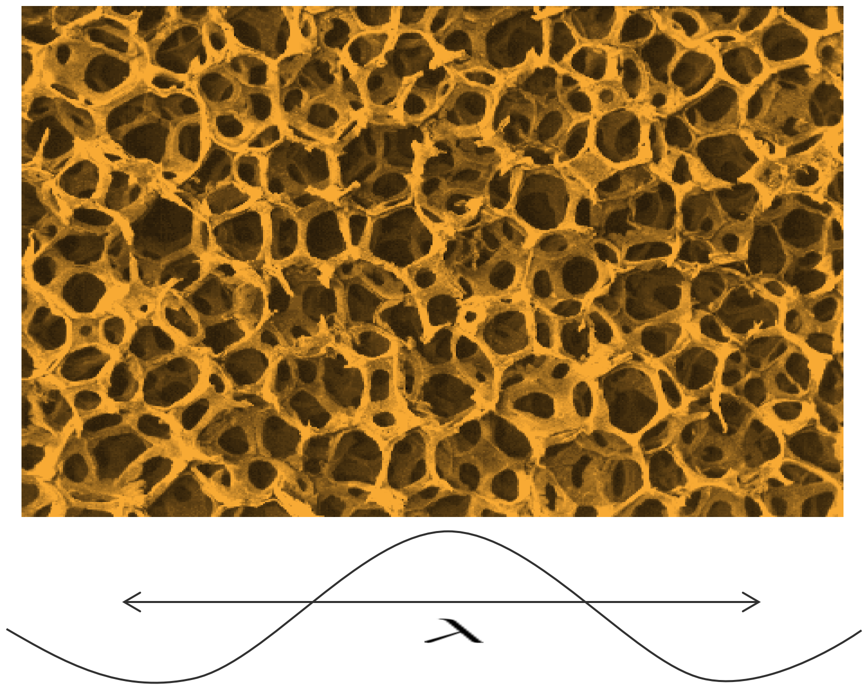
1. Biot’s global flow

- Dispersion/attenuation caused by fluid pressure relaxation between peaks and troughs in the wave



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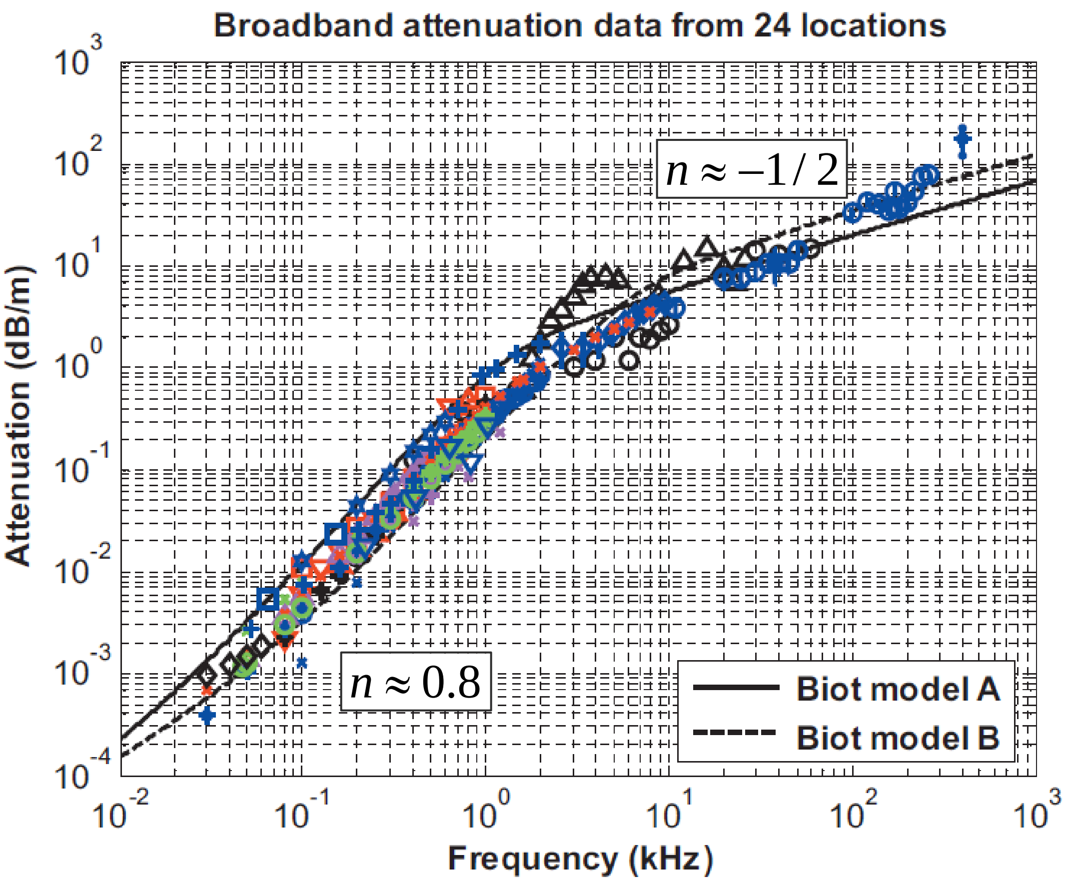
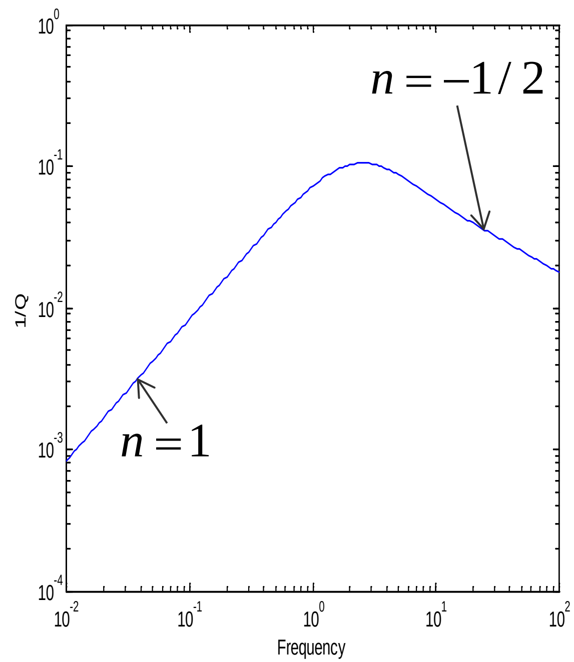
Acoustic attenuation in ocean sediments



Zhou, J.-X., Zhang, X.-Z. and Knobles, D. P., JASA, **125**, 2847-2866 (2009)

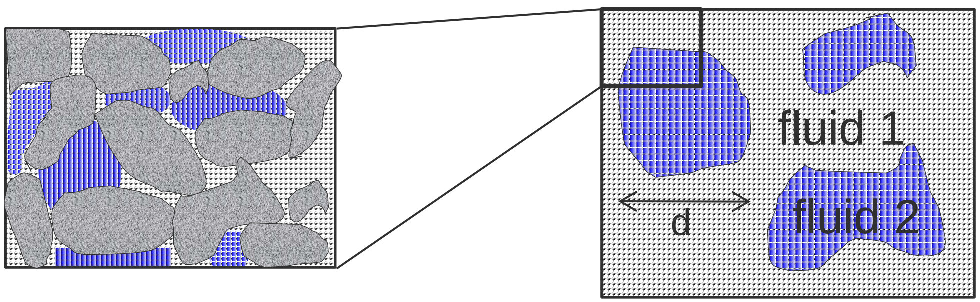


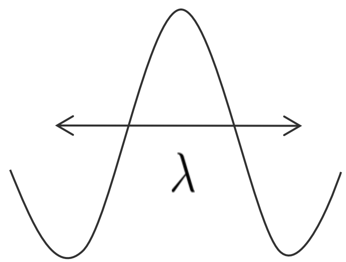
Biot, MA, JASA, **28,** 168-191(1956)

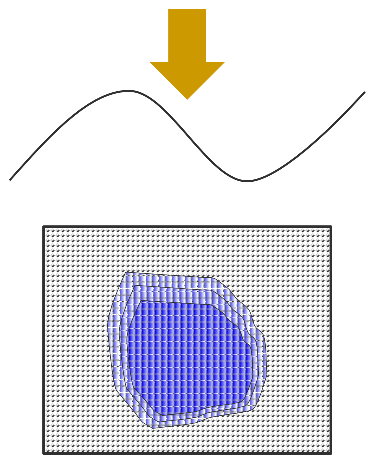
$$\alpha = A\frac{k}{2Q} = A\frac{\omega}{2cQ} = A\frac{\pi f}{cQ} \qquad A = 20\log_{10} e = 8.69$$

2. Mesoscopic flow

- fluid pressure relaxation caused by the presence of mesoscopic heterogeneities (fluid patches; macro-fractures)



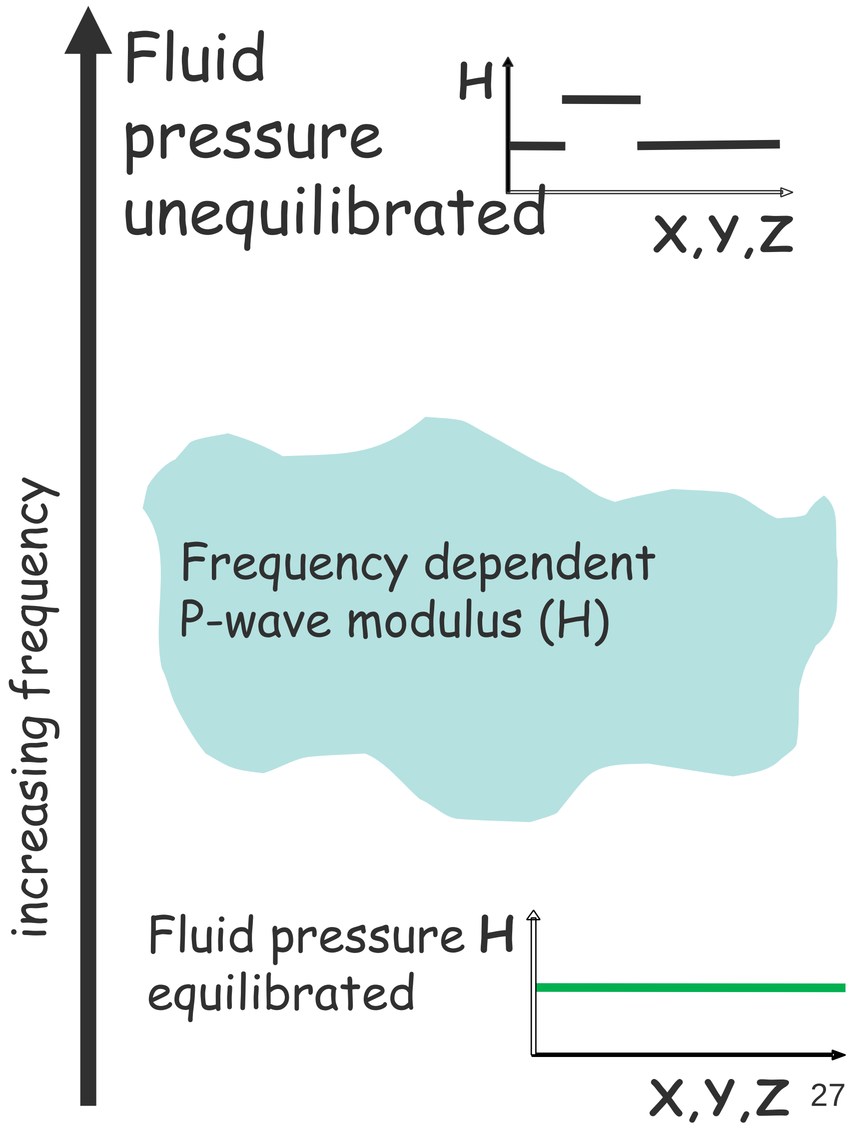


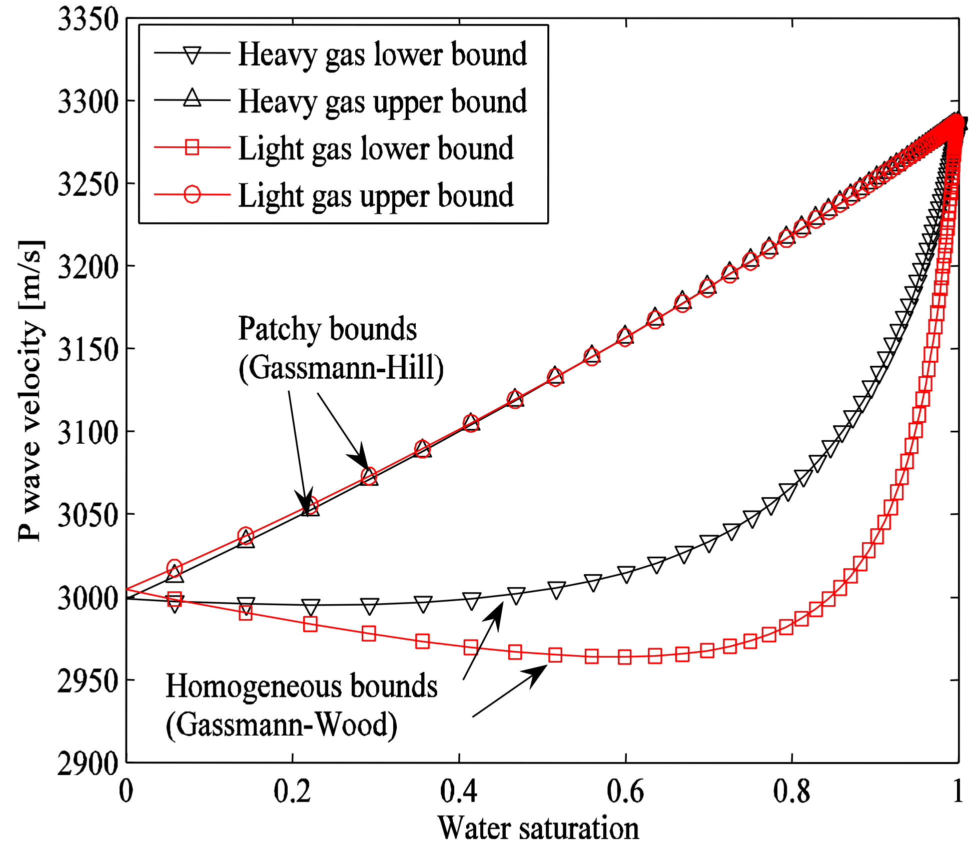


pressure gradients between patches of different fluids

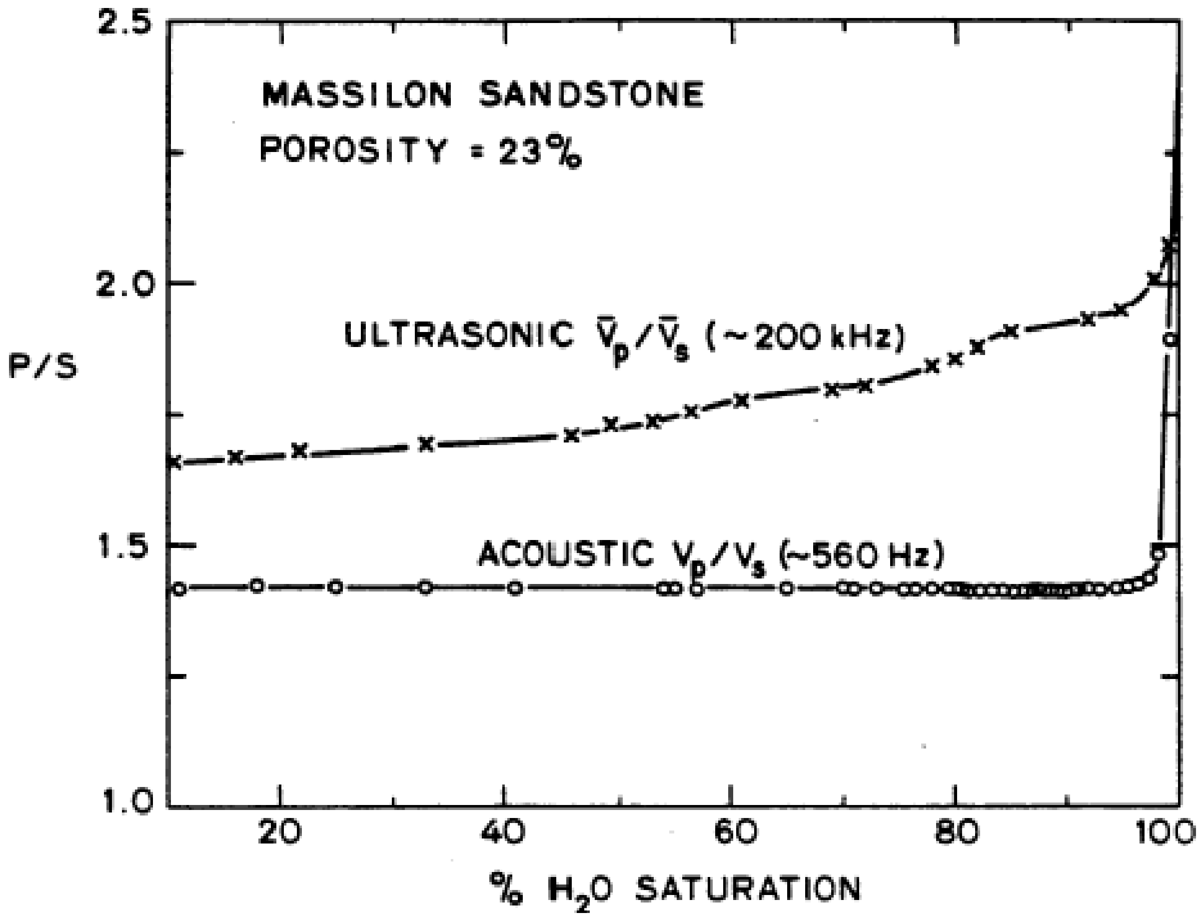
Wave induced fluid flow at mesoscopic heterogeneities

Partial fluid saturation





Patchy saturation



Murphy, W.F. III, 1984, J. Geophys. Res. **89,** B13, 2156-2202

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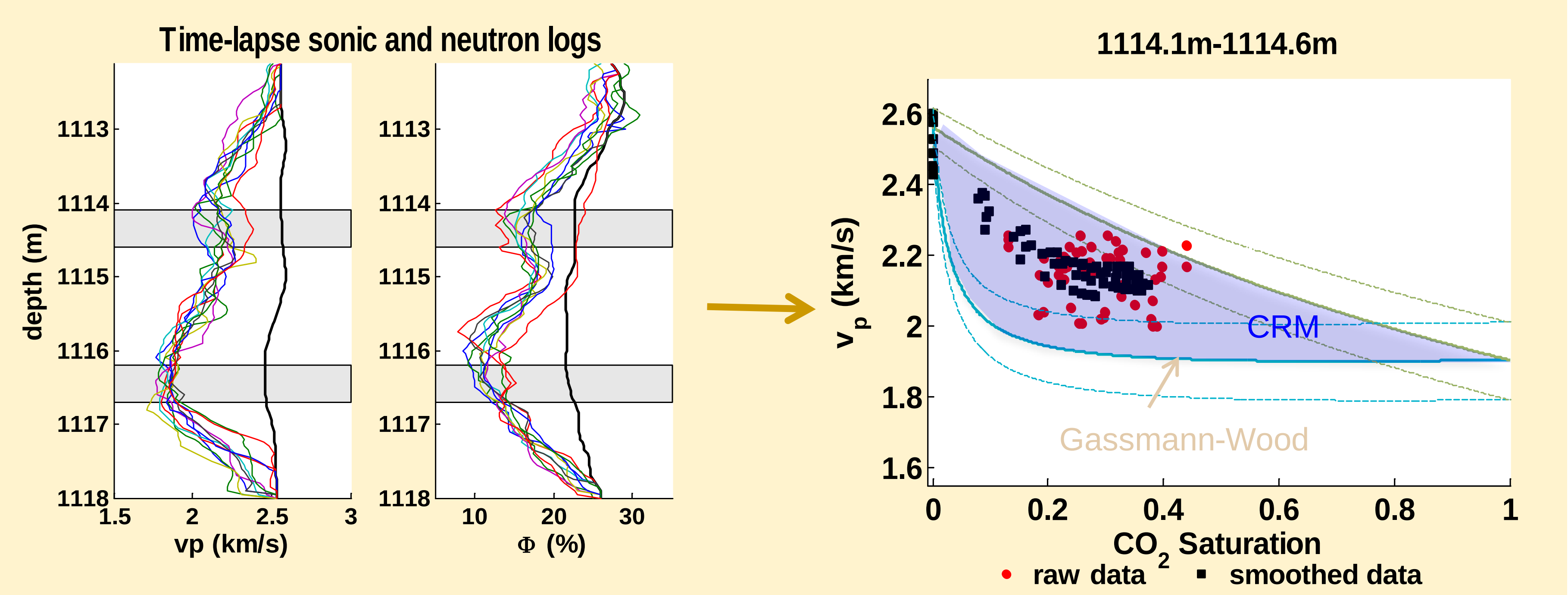
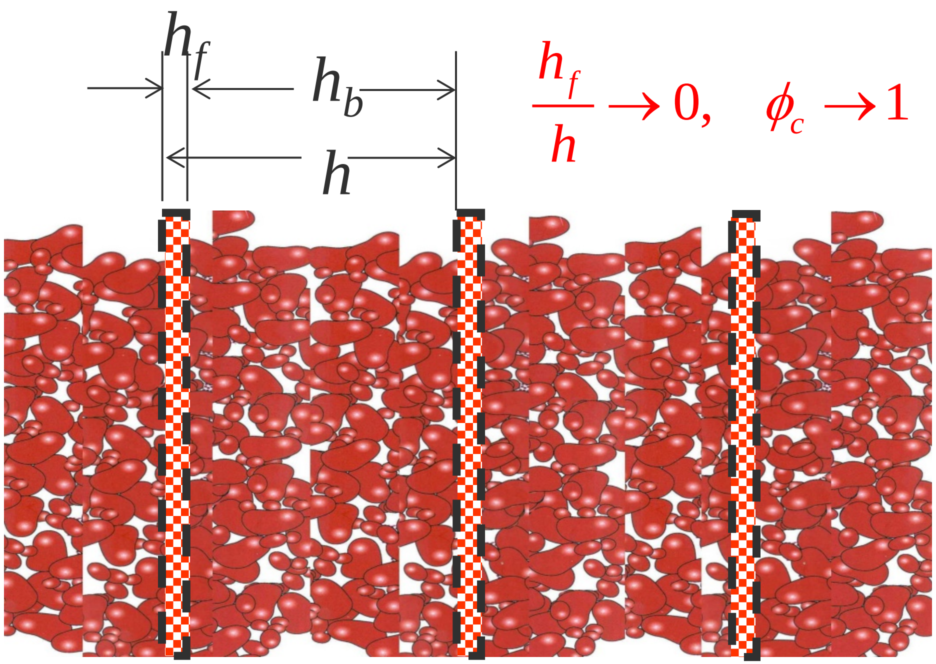
Velocity-saturation relations based on unique time-lapse logs: Nagaoka CO_2 experiment

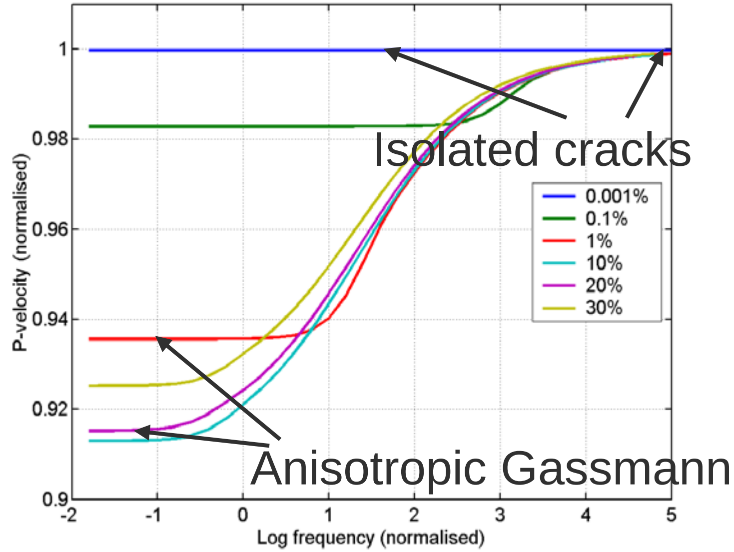


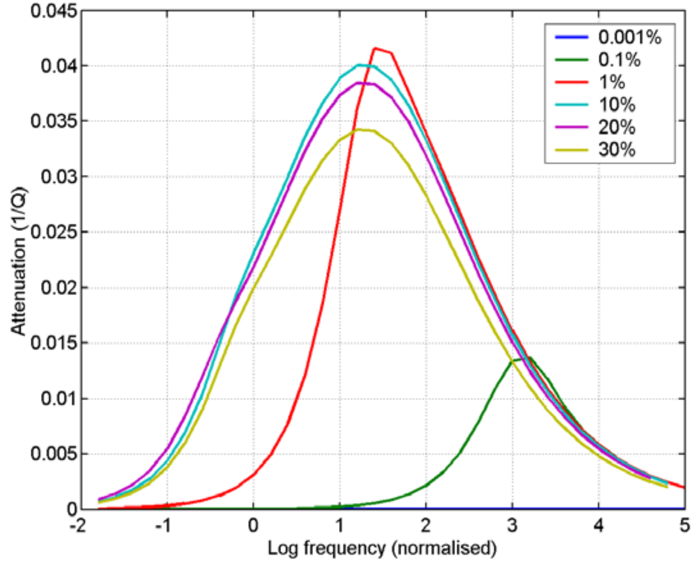
- CO_2 saturation from Neutron logs
- Smoothing variations between subsequent time-lapse logs
- Velocity-saturation relations: Gassmann-Wood, Gassmann-Hill, continuous random media model

Caspari et al., Geophys. Res. Lett., **38**, L13301

Attenuation and dispersion in a porous rock with aligned planar fractures







Brajanovski, Gurevich & Schoenberg, *Geophys. J. Int.*, 2005.

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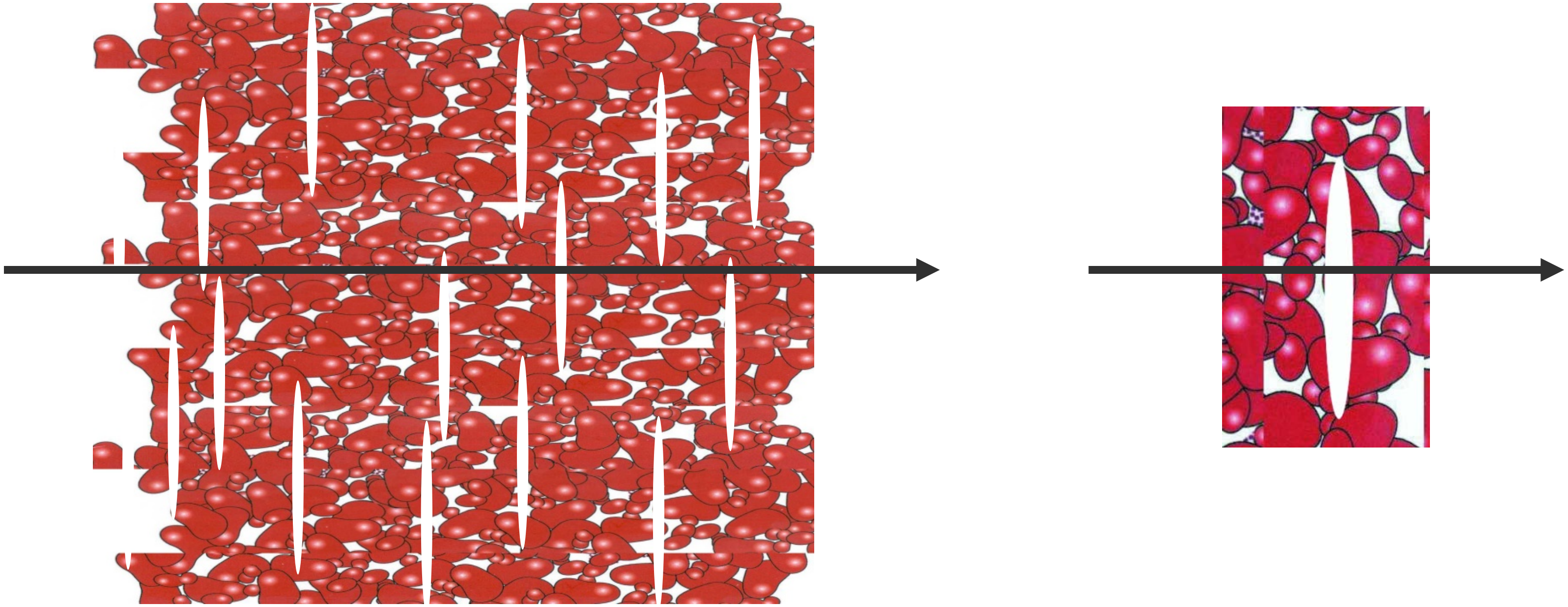
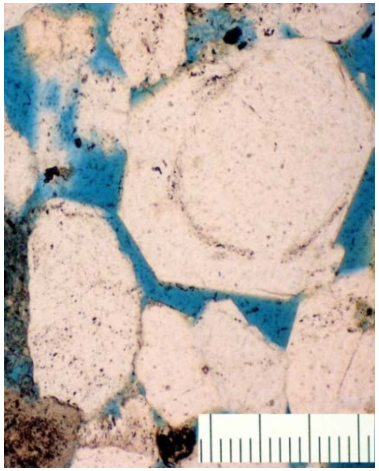
Circular cracks in a porous medium

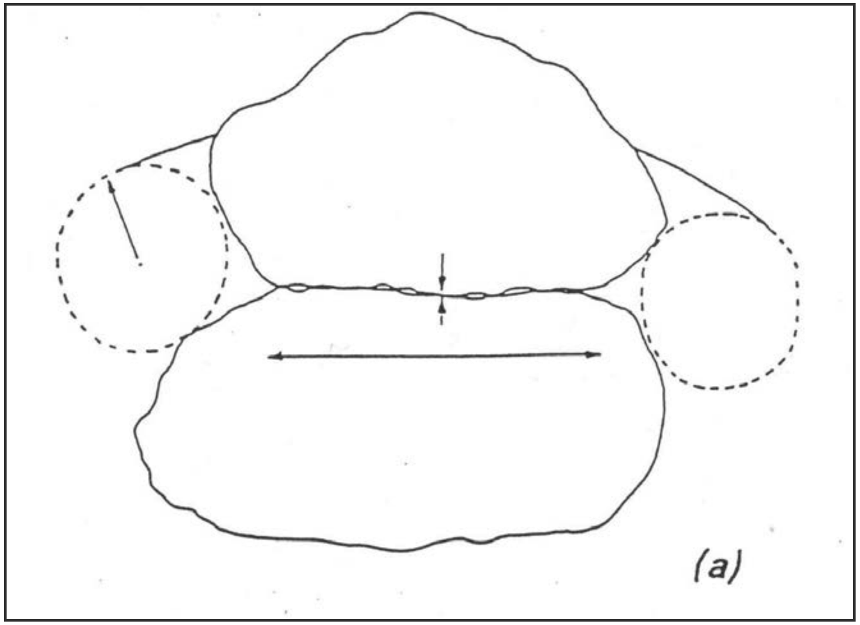


- Galvin and Gurevich, Appl. Phys. Lett., 2006;
- Galvin and Gurevich, IJSS 2008
- Galvin and Gurevich, JGR 2009

3. Squirt flow

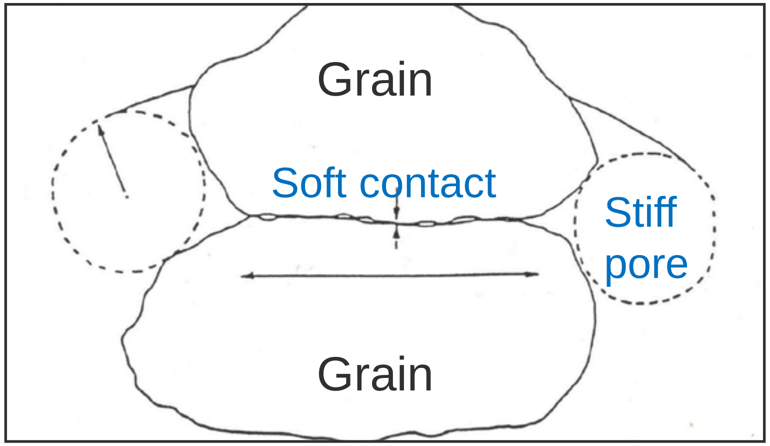
- Dispersion/attenuation due to fluid pressure relaxation at finite frequencies

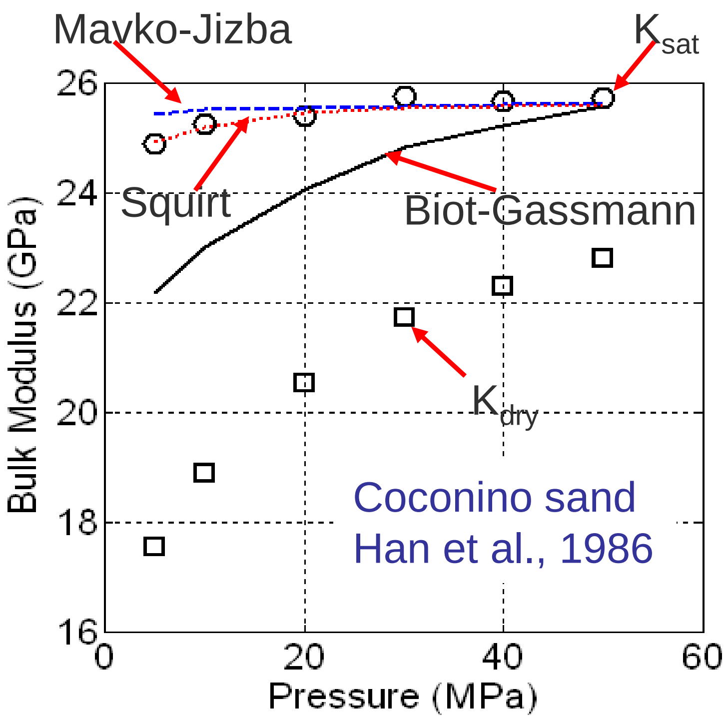




Murphy, Winkler and Kleinberg, Geophysics 51, 757, 1986

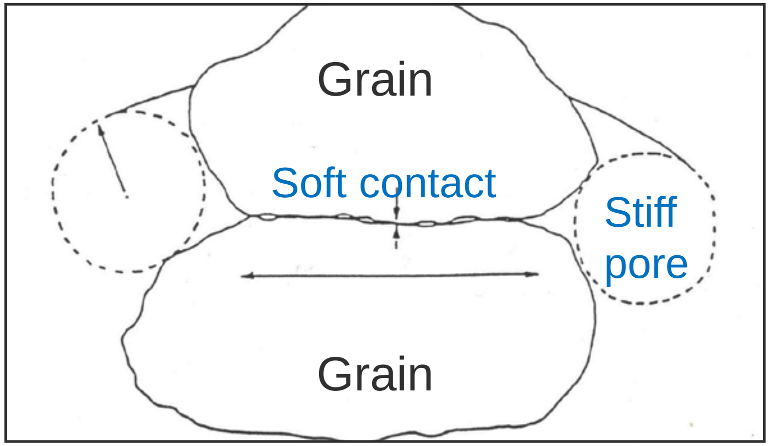
Squirt flow: Effect of stress, fluid and frequency:

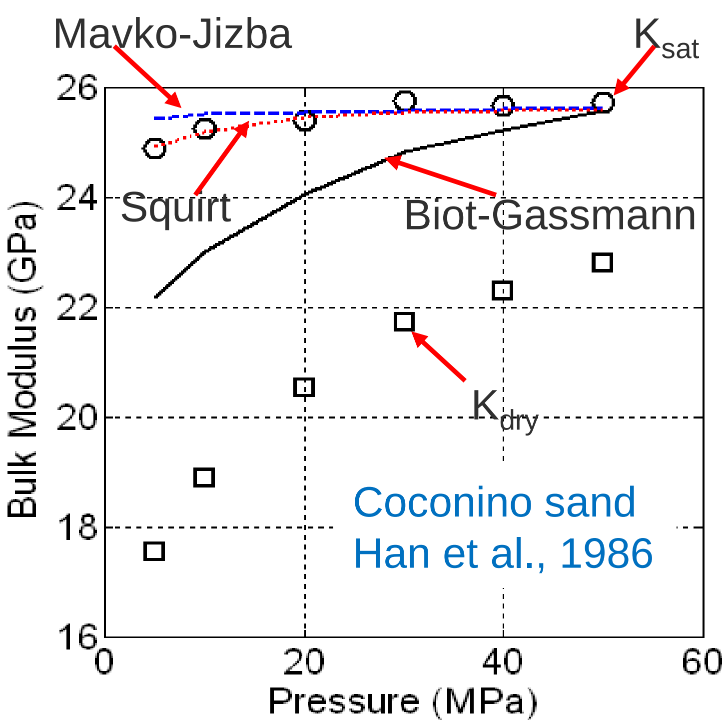


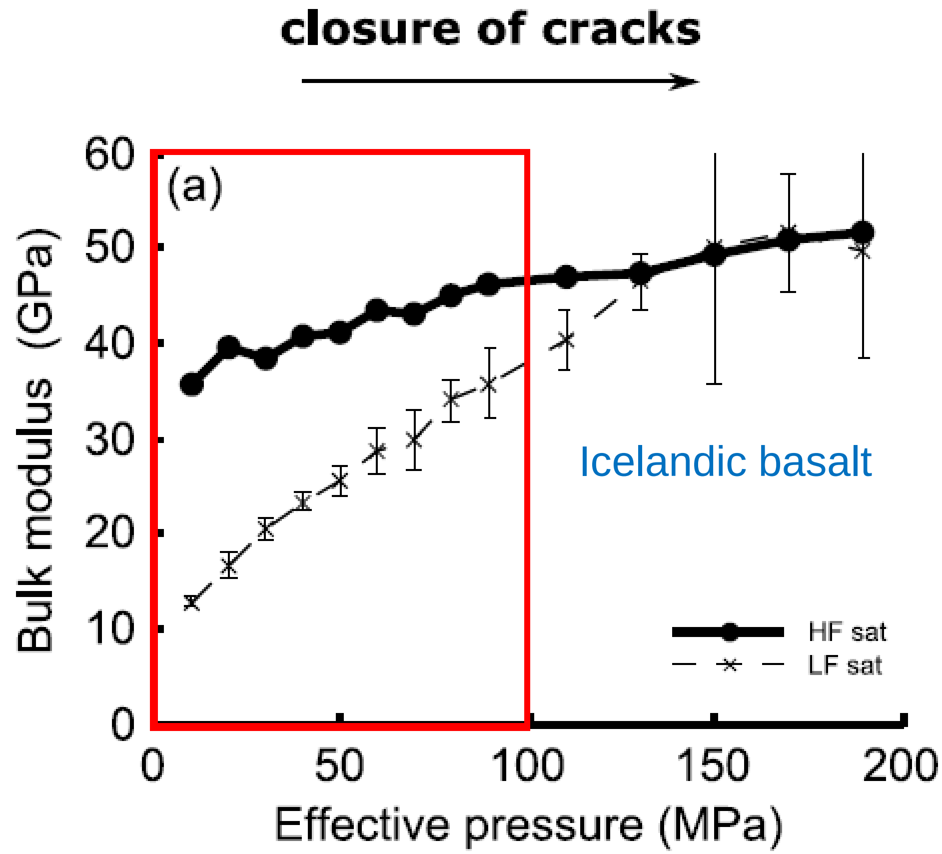


- In a dry rock at low confining stress, grain contacts are soft
- In a liquid-saturated rock, at low frequencies the fluid pressure can equilibrate, and contacts are still soft (Gassmann)
- At high frequencies, the pressure has no time to equilibrate, thus contacts are stiff -> dispersion.
- Confining pressure closes soft pores (reduces dispersion)
- **Squirt flow!**

Squirt flow: Effect of stress, fluid and frequency







Fortin, J., Gueguen, Y., David, E., Adelinet, M., Piementa, L., and Schubnel, A., 2013, Poromechanics V. 235-238.

Mechanisms of attenuation/dispersion

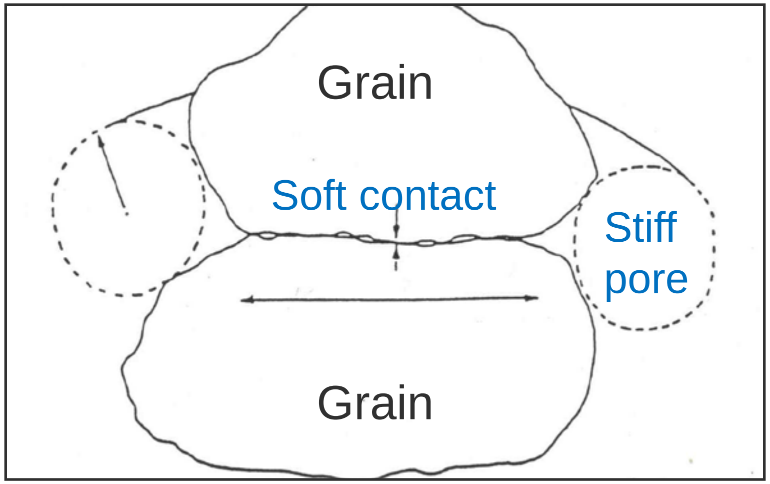
Wave-induced flow:

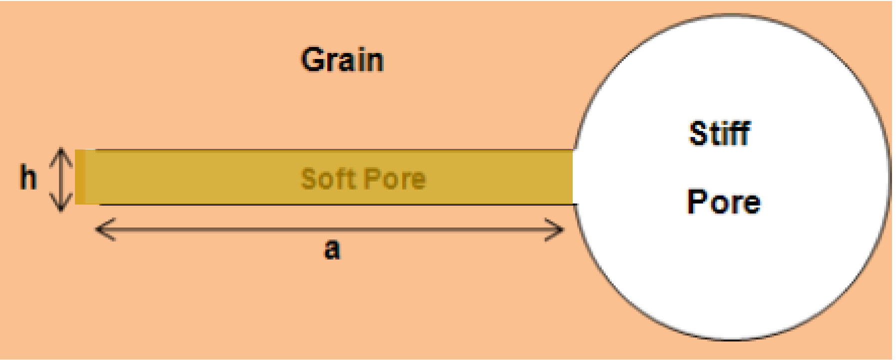
- Global flow: Biot theory
- mesoscopic flow: Biot theory (inhomogeneous)
- squirt flow: **No universally accepted unified model**

- **Let's try to develop something simple**

Pressure relaxation

Modified from Murphy et al. (Geophysics, 1986)





Stiff pores are dry; soft pores filled with fluid

Boundary conditions → $p|_{r=a} = 0$

$$K^* = \frac{\Delta F}{-\Delta h} \qquad \Delta F = \int_{S_g} p(r)dS \qquad \frac{d^2 p}{dr^2} + \frac{1}{r}\frac{dp}{dr} + k^2 p = C$$

$$\frac{1}{K_{mf}(P,\omega)} = \frac{1}{K_h} + \frac{1}{\dfrac{1}{\dfrac{1}{K_{dry}(P)} - \dfrac{1}{K_h}} + \dfrac{1}{\left(\dfrac{8\alpha^2}{3i\omega\eta} - \dfrac{1}{K_g}\right)\phi_c(P)}}$$

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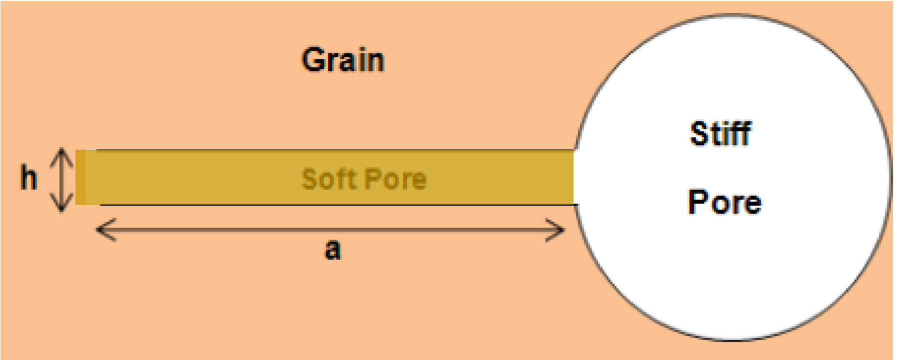
Partially relaxed modulus- simplified

$$\frac{1}{K_{mf}(P,\omega)} = \frac{1}{K_h} + \frac{1}{\dfrac{1}{\dfrac{1}{K_{dry}(P)} - \dfrac{1}{K_h}} + \dfrac{1}{\left(\dfrac{8\alpha^2}{3i\omega\eta} - \dfrac{1}{K_g}\right)\phi_c(P)}}$$



$$\omega_t = \frac{8\alpha^3 K_h}{3\eta}\left[\frac{K_h}{K_{dry}(P)}\right]^{1/2}$$

Then Gassmann or Biot for stiff pores

Unknown parameters: α, ϕ_c

Gurevich, Makarynska, de Paula, Pervukhina, 2010, Geophysics, 75, N109–N120.

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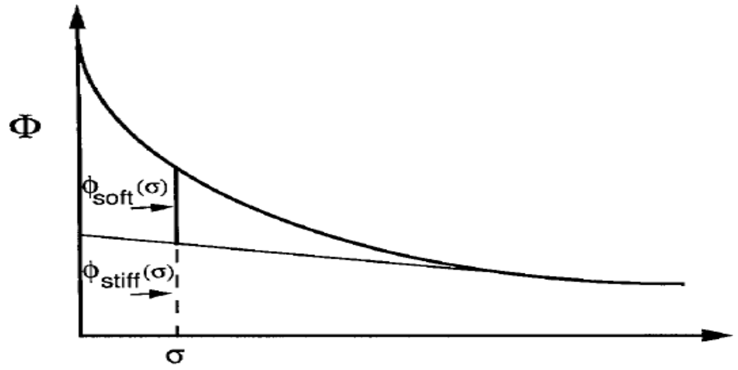
How to estimate soft porosity ϕ_c

Measured from strains (Walsh 1965)



Estimated using stress sensitivity approach (Shapiro, Geophysics 2003)

$$K_{dry}(P) = K_h\left[1 + \theta_s P + \theta_c \phi_c\right]$$

$$\phi_c = \phi_{c0} \exp\left(-\theta_c P / K_h\right)$$

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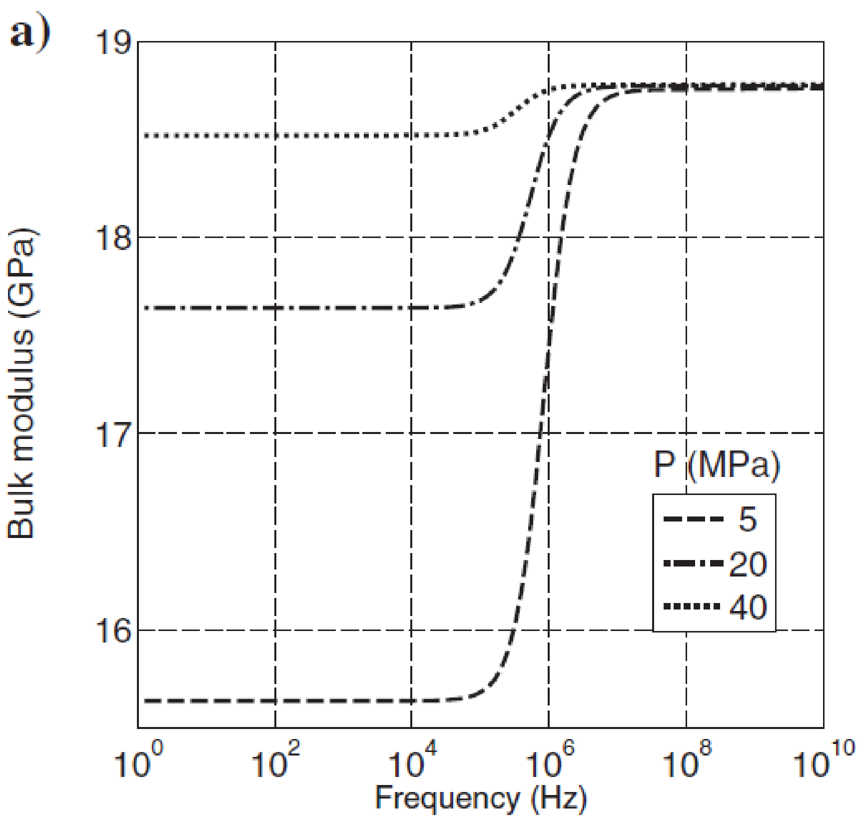
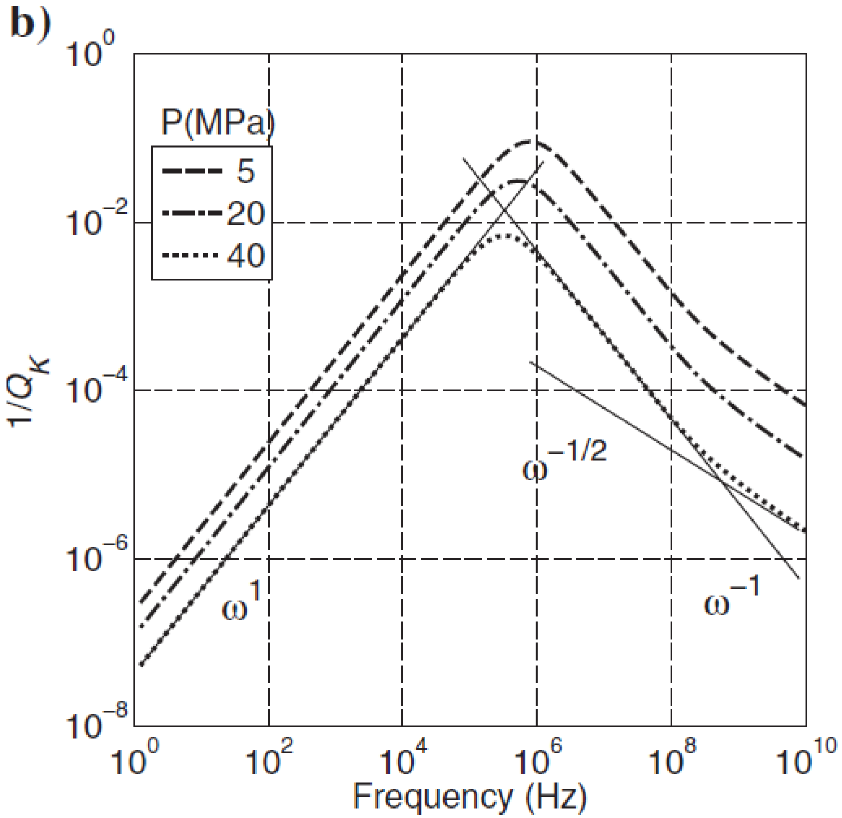
Dispersion and attenuation **vary with pressure**

Dispersion



Attenuation



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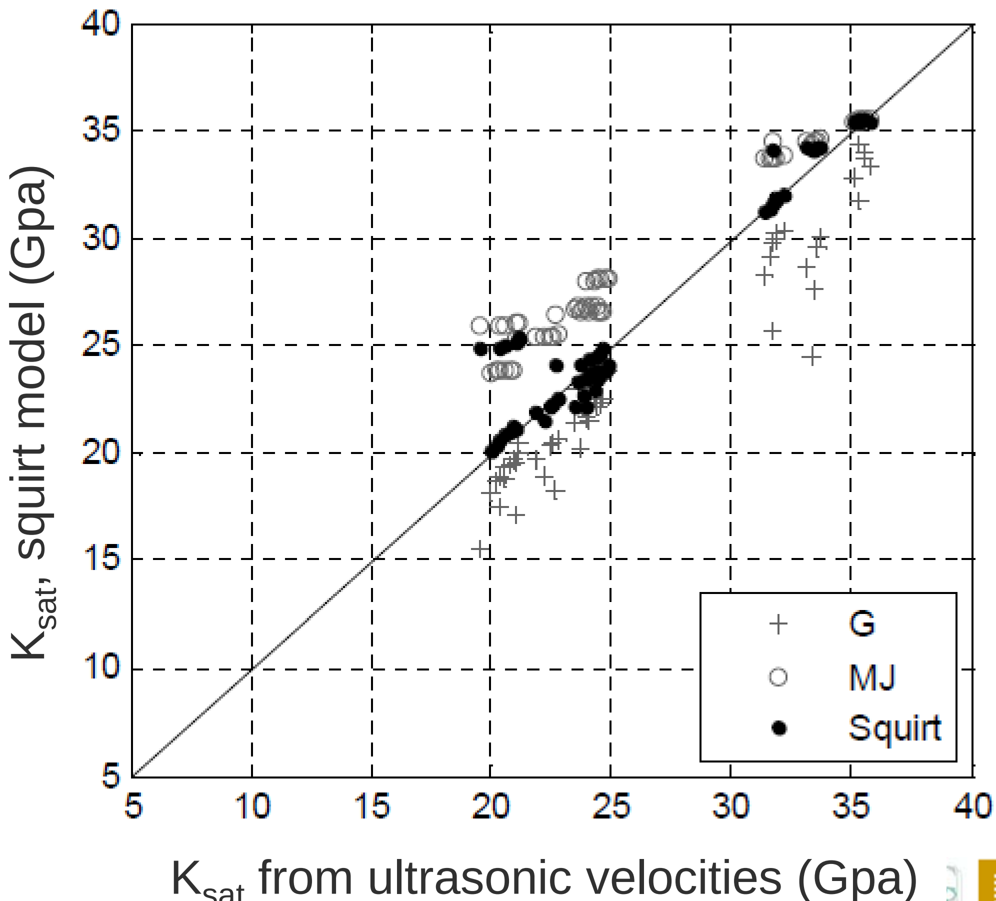
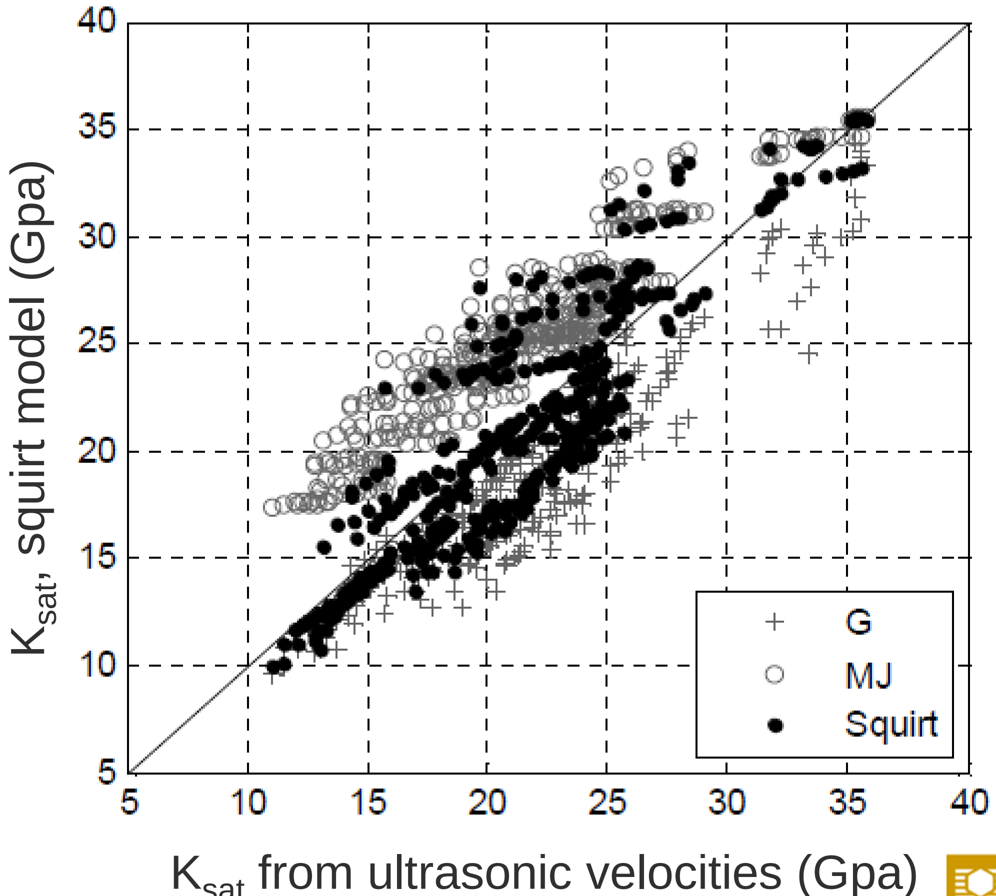
Predictions by new squirt model of moduli: effect of intermediate porosity

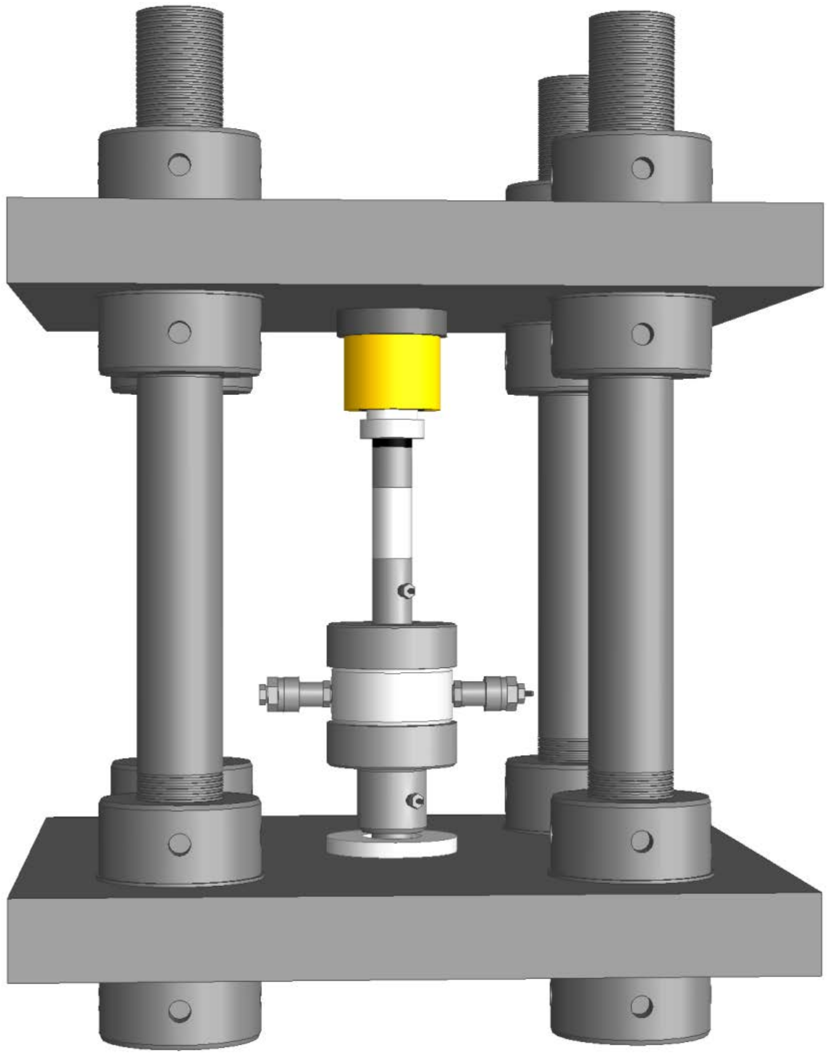


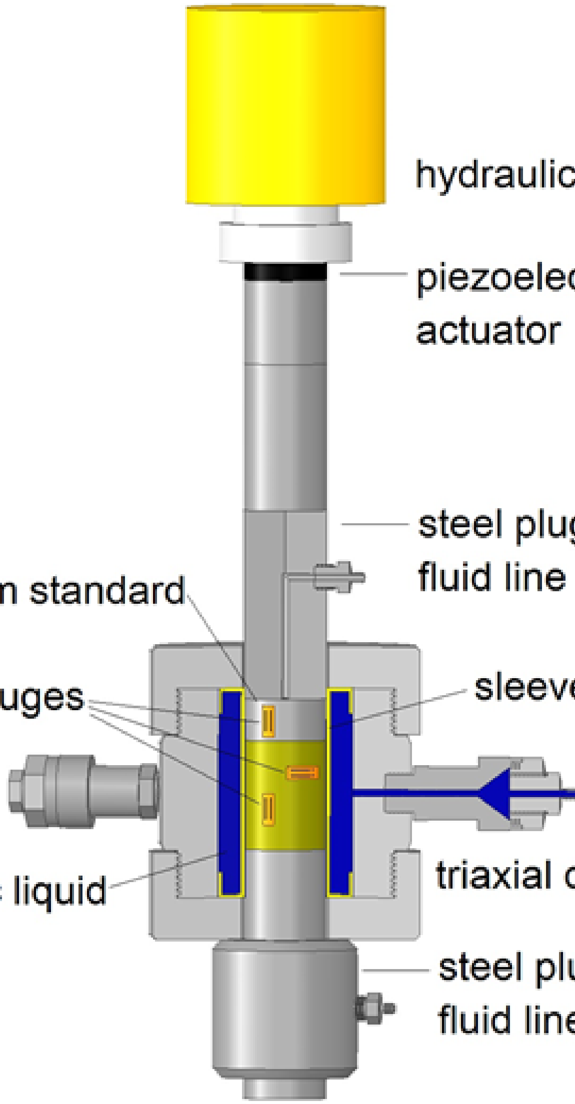
de Paula, Pervukhina, Makarynska, Gurevich, 2010, Geophysics, 75, N109–N120.

Predictions by new squirt model of moduli: effect of intermediate porosity



APPARATUS





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Confining pressure: 0 – 70 MPa

Pore pressure : 0 – 20 MPa

Frequency range: 0 – 120 Hz

Strain: 10^{-8} – 10^{-6}

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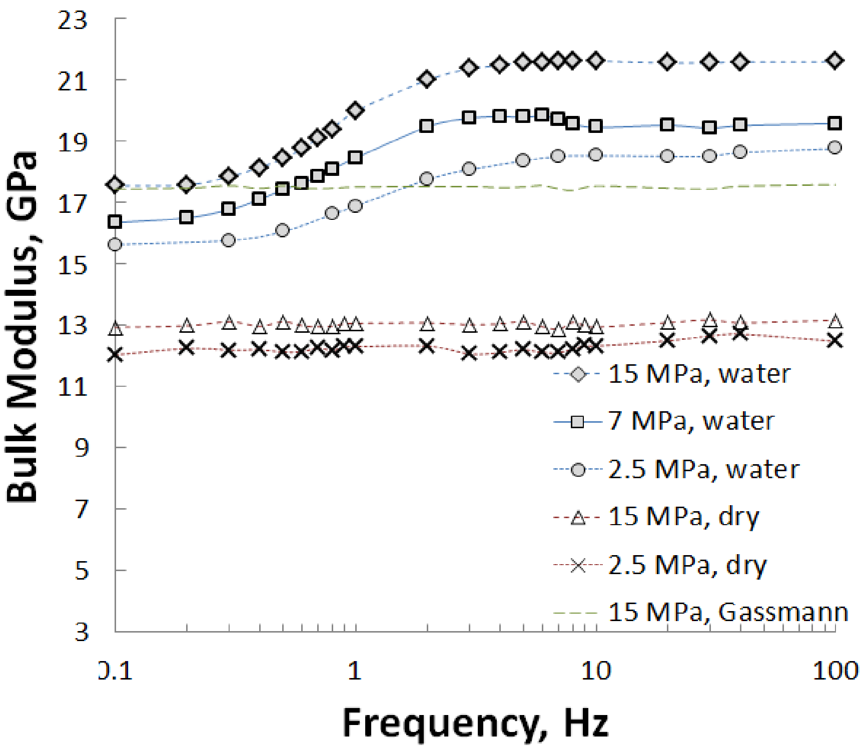
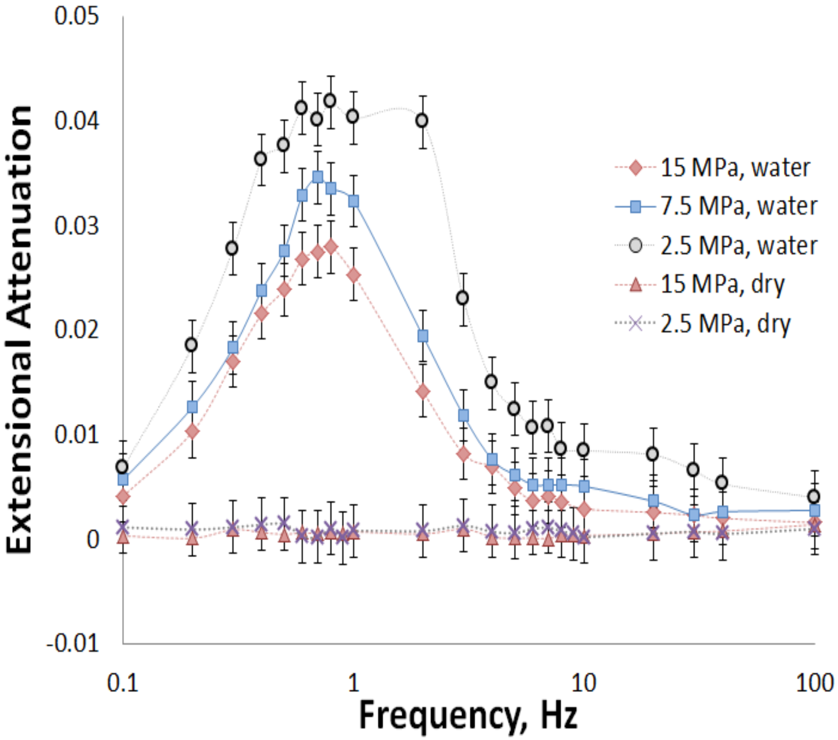
SAMPLE A





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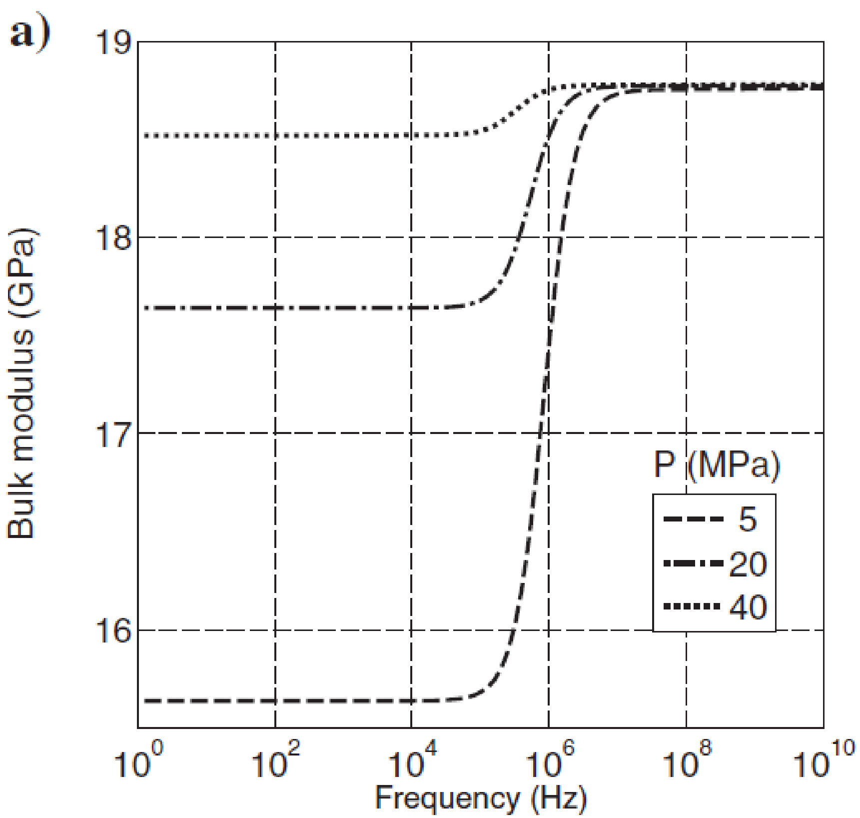
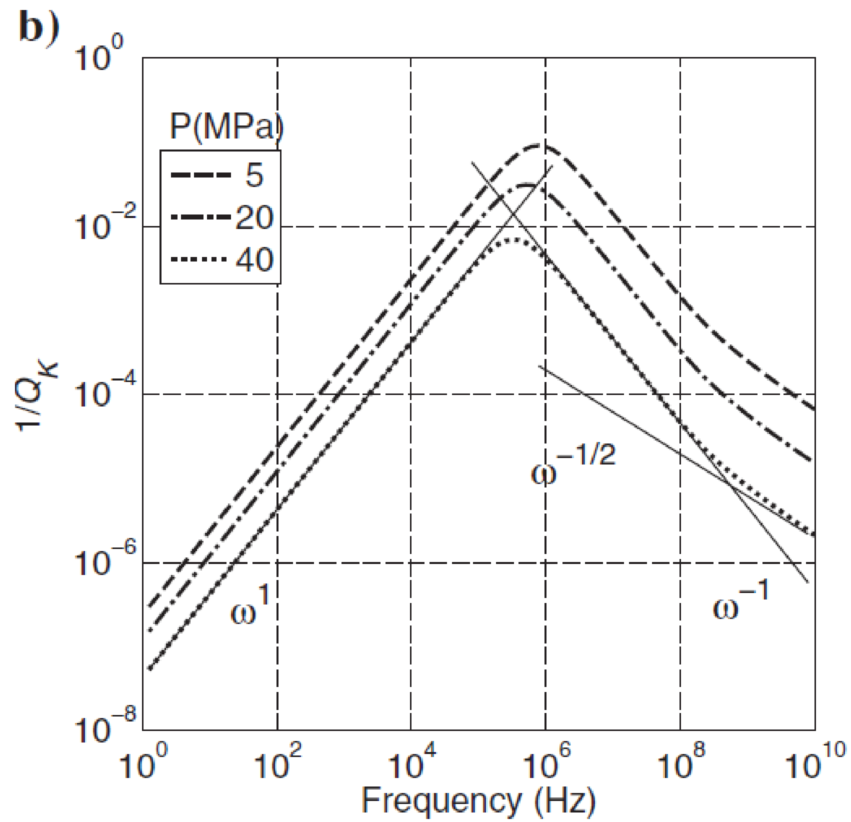
Dispersion and attenuation **vary with pressure**

Dispersion



Attenuation



Mechanisms of attenuation/dispersion

Wave-induced flow:

- Biot's global flow
- mesoscopic flow
- squirt flow

All these phenomena caused by fluid viscosity

No universally accepted unified model

To investigate validity of different models, let's consider rigorous bounds (for mixture of solid and viscous fluid)

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A mixture of two elastic solids

- For given volume fractions, Hashin-Shtrikman bounds define a range of possible moduli (static)
  - Bulk: $K_{HS}^{-} < K < K_{HS}^{+}$
  - Shear: $G_{HS}^{-} < G < G_{HS}^{+}$

A mixture of an elastic solid and a viscous fluid

- For a given frequency ω, can be considered as a particular case of a mixture of two viscoelastic materials

o Solid: K and G real

o Fluid: K_f real and $G_f = i\omega\eta$ fluid viscosity

- Moduli are complex!
- Thus bounds must be regions in complex plane (for each frequency!)

Bulk modulus

On the effective viscoelastic moduli of two-phase media. I. Rigorous bounds on the complex bulk modulus

By L. V. Gibiansky and G. W. Milton

Courant Institute, 251 Mercer Street, New York, New York 10012, U.S.A.

Proc. R. Soc. Lond. A (1993) **440**, 163–188

Printed in Great Britain

6-2

Shear modulus

On the effective viscoelastic moduli of two-phase media. II. Rigorous bounds on the complex shear modulus in three dimensions

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and

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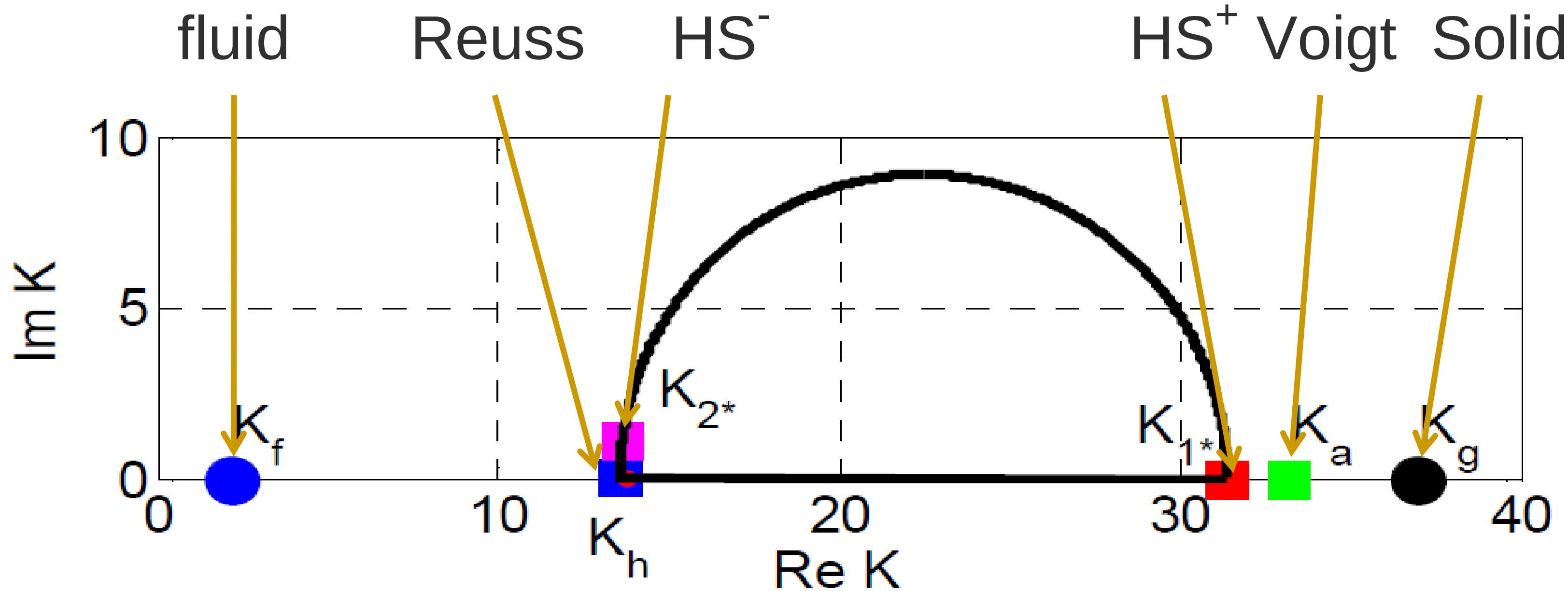
Lawrence Livermore National Laboratory
P. O. Box 808 L-202
Livermore, CA 94551-9900

Bounds for a poroelastic material

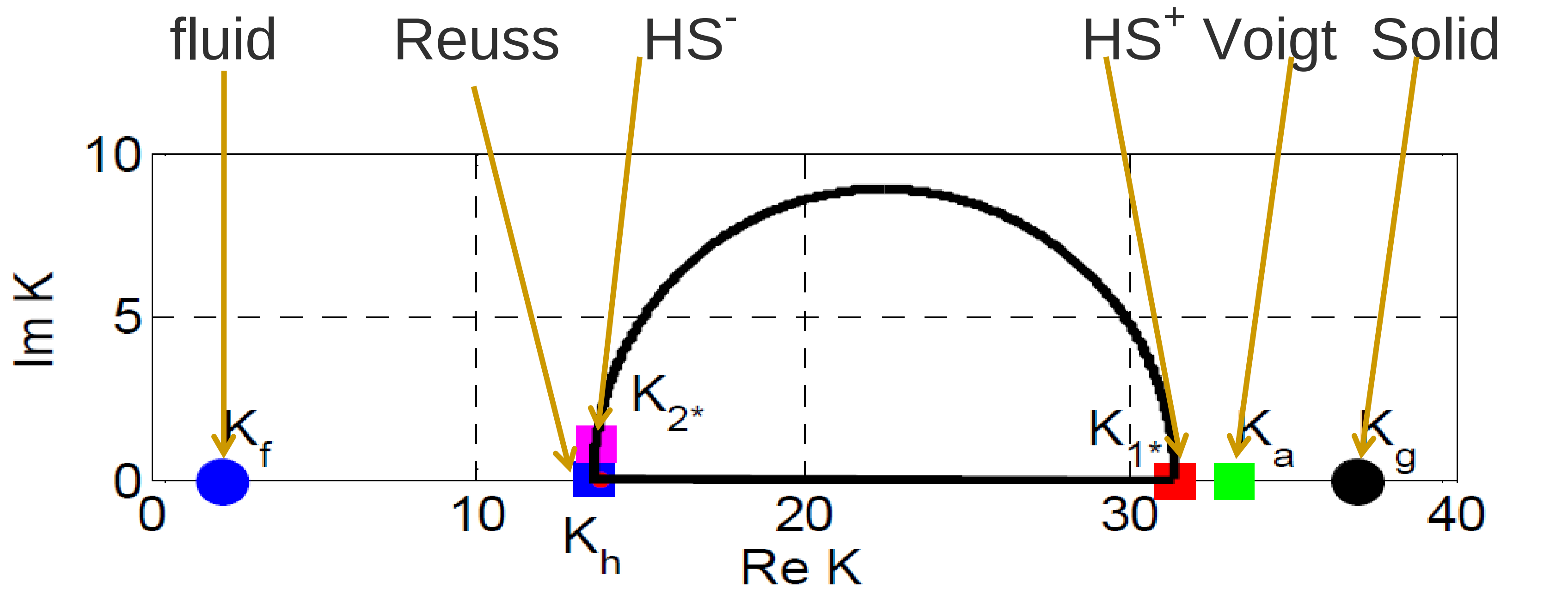
K_g, G_g, K_f real, $G_f = i\omega\eta_f$



- All bulk moduli are real except for HS$^-$, which has a tiny imaginary part ~ $|i\omega\eta_f| = \omega\eta_f \ll K_f$. We used frequency $4\cdot 10^{10}$ Hz to see it!
- Bounds are semi-circle connecting formal HS bounds (computed for inviscid fluid).
- Are independent of frequency.

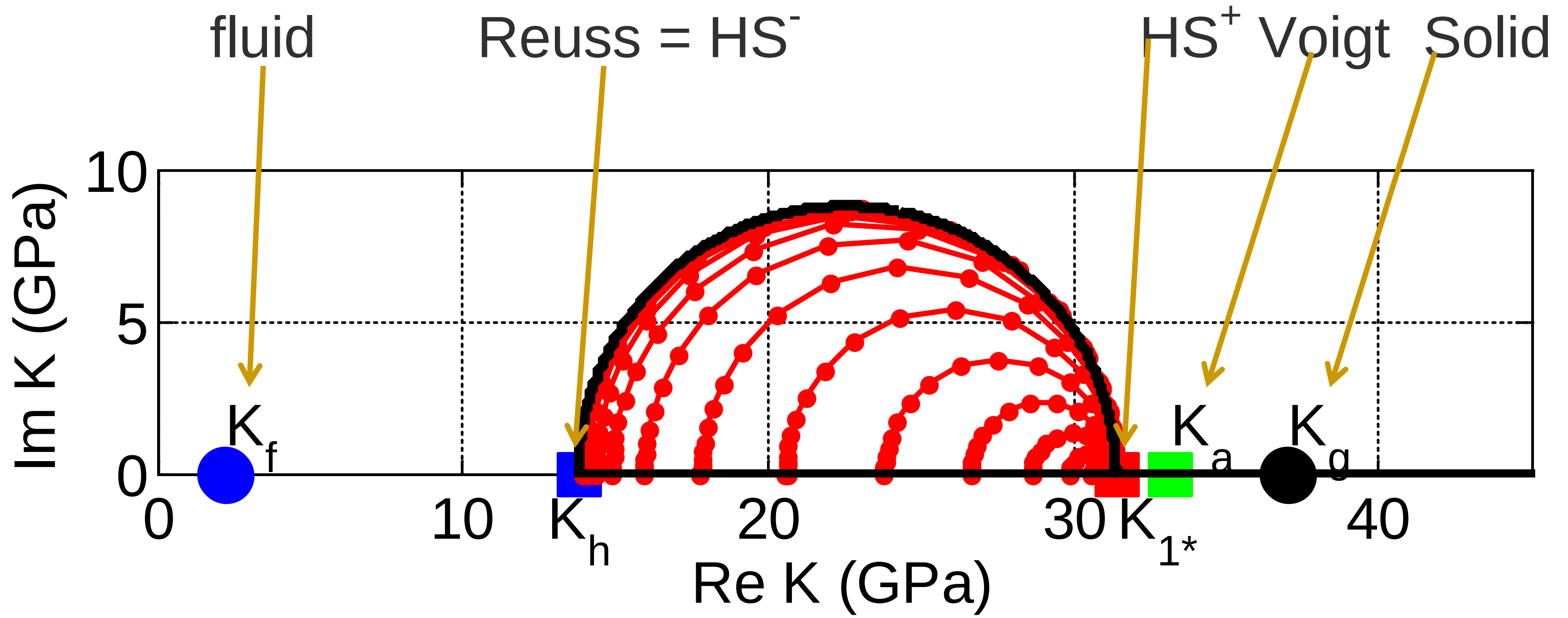
Bounds for a poroelastic material

K_s, μ_s, K_f real, $G_f = i\omega\eta_f$ $f = 4\cdot 10^{10}$ Hz



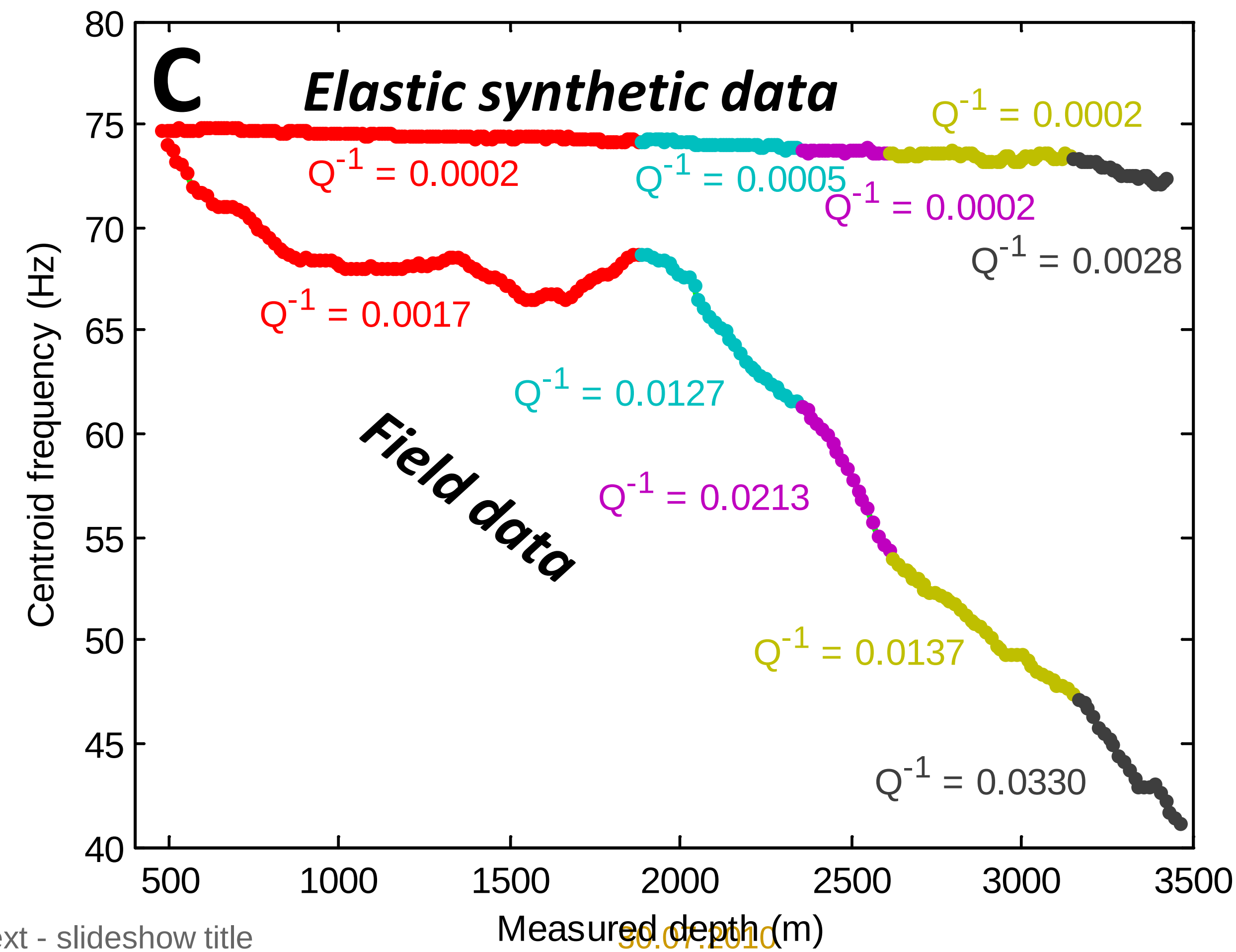
- A tiny imaginary fluid shear modulus $\boxed{\left|i\omega\eta_f\right| = \omega\eta_f \ll K_f}$ can cause huge attenuation. Is this realistic?

Estimates and bounds for the complex bulk modulus



- Different red curves: different aspect ratios of cracks
- Points on curves: different frequencies

Q estimation from borehole sesmic data



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Summary

- Mesoscopic flow is significant when there is large spatial variation in properties (partial saturation; fractures etc.)
- Squirt is significant when there is strong stress dependency
- Now possible to observe in lab in a broad frequency range
- Rigorous bounds for attenuation and dispersion

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2nd Meeting

Acknowledgements

- Sponsors of Curtin Reservoir Geophysics Consortium (CRGC)
- CSIRO