# Seismic Velocity Dispersion and Attenuation

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- Introduction
- Dispersion/attenuation mechanisms
- How to measure dispersion/attenuation
- Conclusions and outlook



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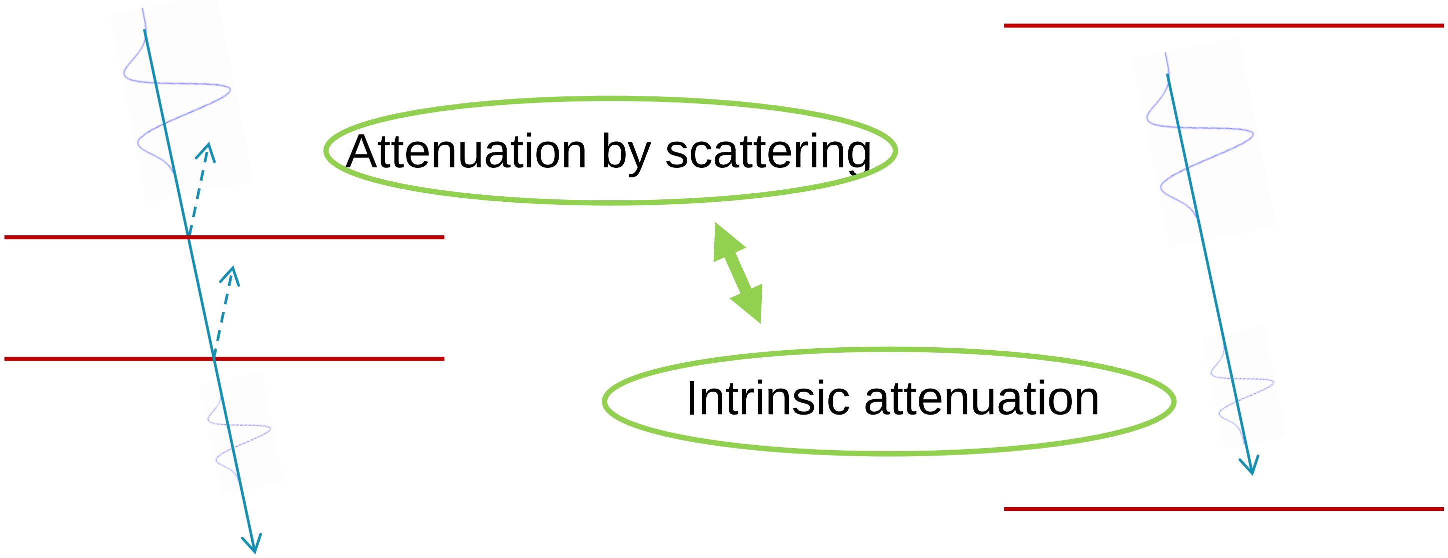
# Seismic Dispersion and Attenuation - Introduction




- Intrinsic attenuation in the subsurface is primarily due to rock-fluid interaction (viscous flow within the rock matrix)
- Intrinsic attenuation depends on permeability
- "Holy grail": Permeability from seismic
  Problem: - How to differentiate between scattering and local-flow induced attenuation
  - Several intrinsic attenuation mechanisms

# Seismic Dispersion and Attenuation - Introduction

## Relation between attenuation and velocity dispersion ($v = v(f)$)

Seismic wave $\quad \boldsymbol{A_0}\, e^{-ikx}\, e^{-\alpha x}\, e^{-i\omega t}$ $\quad$ with $\omega = 2\pi f$

$$\underbrace{e^{-ikx}\, e^{-\alpha x}}_{e^{i(k+i\alpha)x}}$$

$e^{i(k+i\alpha)x}$ complex wavenumber with real and imaginary part

Phase velocity $\quad v = \dfrac{\omega}{k}$ $\quad$ (real part)

Attenuation $\quad \alpha = \dfrac{\omega}{2\,v}\, Q^{-1}$ $\quad$ (imaginary part)

$f$: frequency
k: wavenumber
α: attenuation coefficient
Q: Quality factor

k, v, α, Q are functions of frequency



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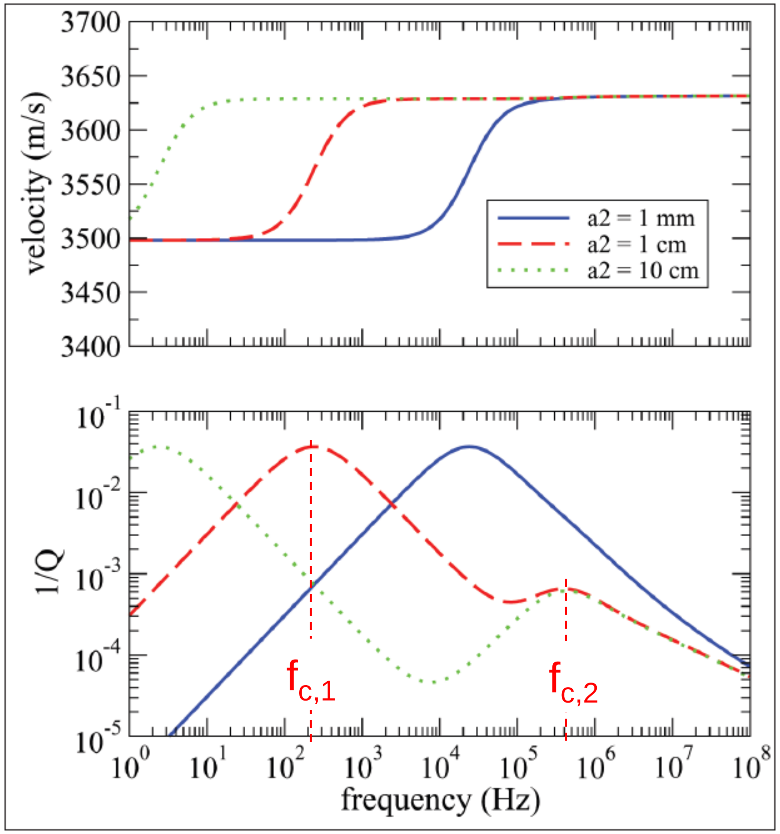
# Seismic Dispersion and Attenuation - Introduction

Frequency dependencies of real and imaginary parts of a response function of a physical system (v and Q in our case) are related by the

**Kramers-Kronig relation:** $\chi_2(\omega) = -\frac{1}{\pi}\mathcal{P}\int_{-\infty}^{\infty} \frac{\chi_1(\omega')}{\omega' - \omega}\,d\omega', \quad \chi_1(\omega) = \frac{1}{\pi}\mathcal{P}\int_{-\infty}^{\infty} \frac{\chi_2(\omega')}{\omega' - \omega}\,d\omega'$

Velocity dispersion and attenuation in rocks




General features:

- Velocity increases with frequency
- Velocity increases around characteristic frequencies, $f_c$
- Attenuation, 1/Q, is highest at $f_c$



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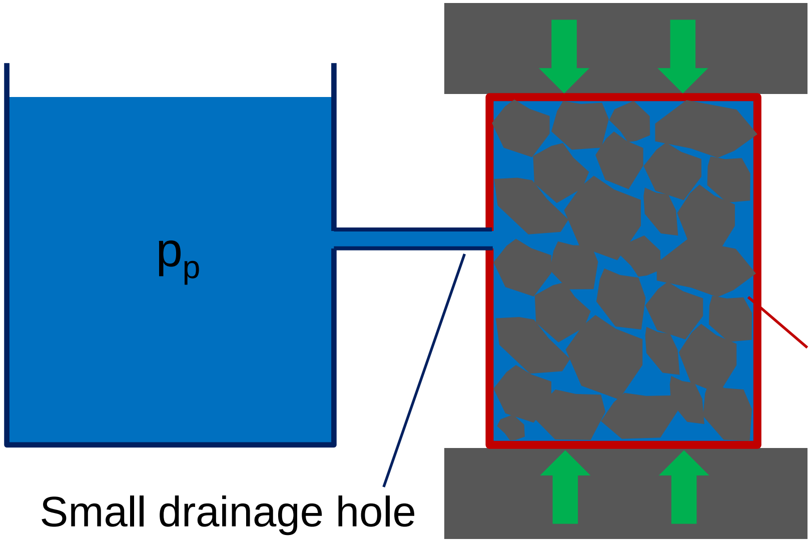
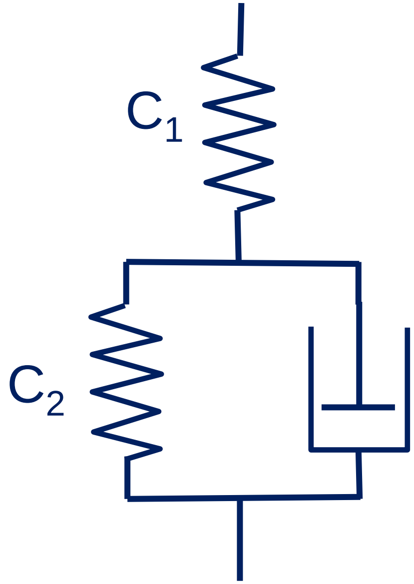
## Easy example: Dynamic stiffness of a rock

Sinusoidal loading of sample

Equivalent description (visco-elastic model)



# Seismic Dispersion and Attenuation - Introduction

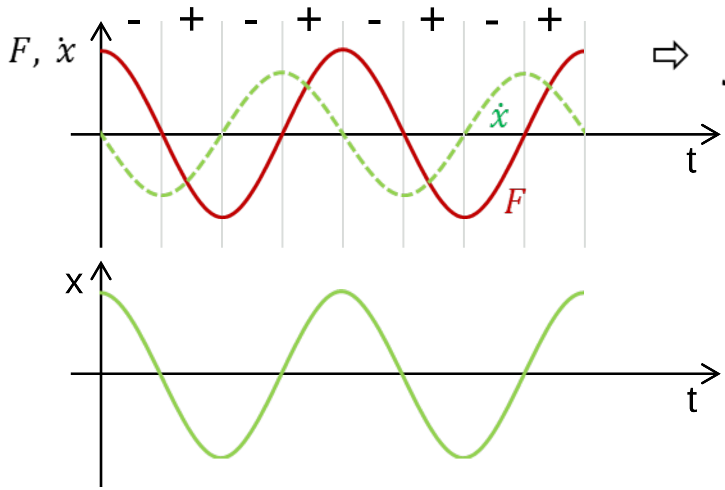
## (A) Low-frequency limit

- Fluid flows in and out of sample
- Pore pressure is constant
- Rock stiffness is given by matrix stiffness (drained stiffness), $M = M_{dry} = \frac{1}{C_1+C_2}$
- No energy dissipation (1/Q = 0)

## (B) High-frequency limit

- Excitation too fast for drainage ⇨ no flow
- Pressure build-up in pore fluid during loading
- Enhanced rock stiffness, $M = \frac{1}{C_1}$
- No energy dissipation (1/Q = 0)

Dissipated energy is given by: $\int F\,dx = \int F\,\frac{dx}{dt}\,dt = \int F\,\dot{x}\,dt$




⇨ $\int F\,\dot{x}\,dt = 0$



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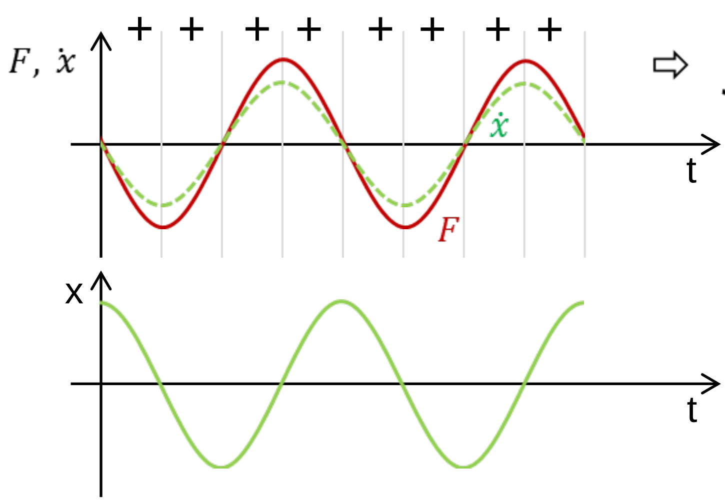
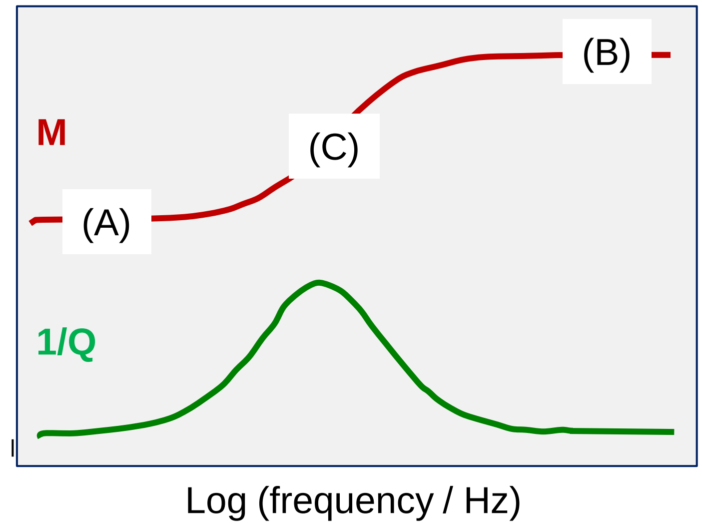
## (C) Intermediate frequencies

- Force and displacement not in phase (phase shift δ)
  ⇨ finite energy dissipation (1/Q > 0)
- Maximum attenuation at $f = f_c = \frac{1}{\tau_c}$ with $\tau_c$ the characteristic drainage time

Extreme case: $\delta = \frac{\pi}{2}$ $(Q = \frac{1}{\tan\delta} = 0)$




⇨ $\int F\,\dot{x}\,dt \neq 0$



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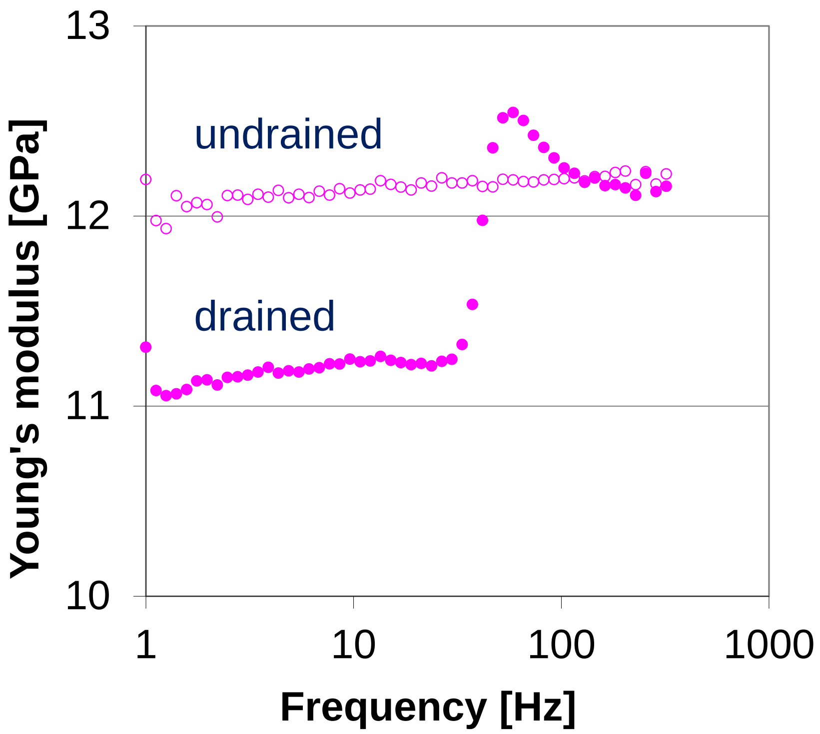
Measurement with water-saturated sandstone



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# Relationship between acoustic wave velocities and rock properties

Acoustic p and s-wave velocities depend on rock stiffness and density

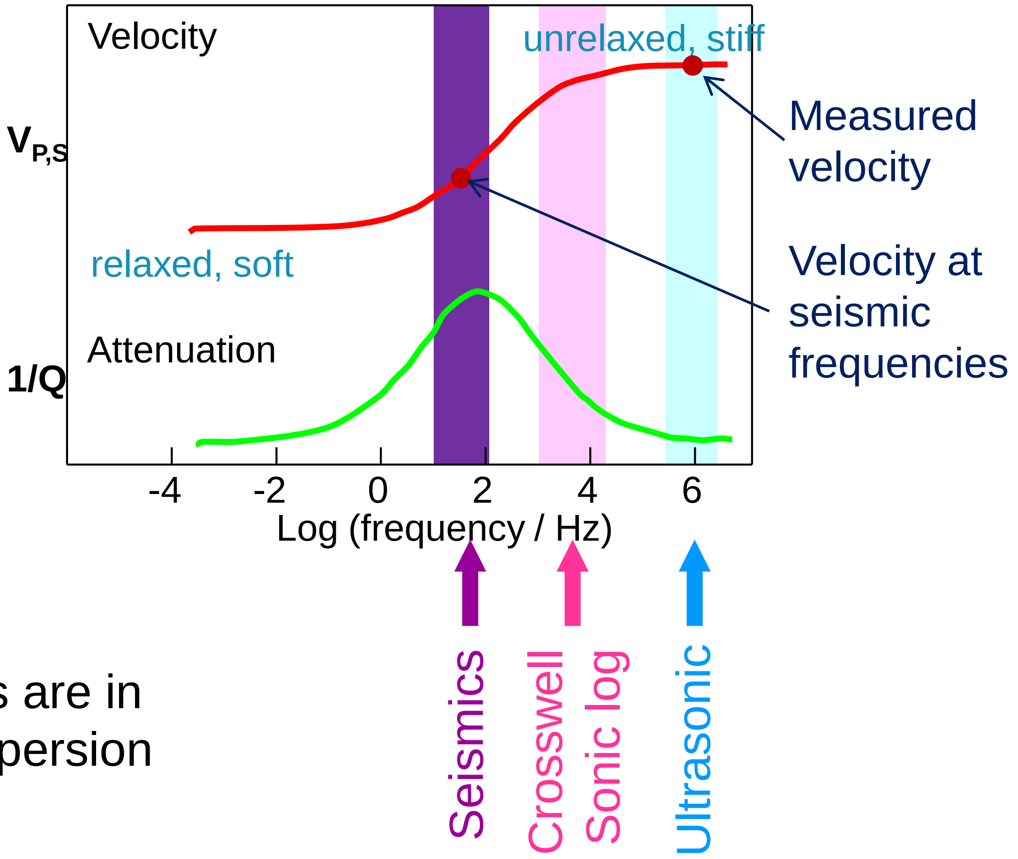
$$V_p = \sqrt{\frac{M}{\rho}} = \sqrt{\frac{K + \frac{4}{3}\mu}{\rho}}$$

$$V_s = \sqrt{\frac{\mu}{\rho}}$$

M: p-wave modulus
K: bulk modulus
μ: Shear modulus
ρ: Density

# Where is it important to consider seismic dispersion and attenuation?

⇨ Velocity models based on laboratory measurements with core material at ultrasonic frequencies




Personal opinion: Upscaling effects are in most cases larger than velocity-dispersion effects (at least for sandstones)



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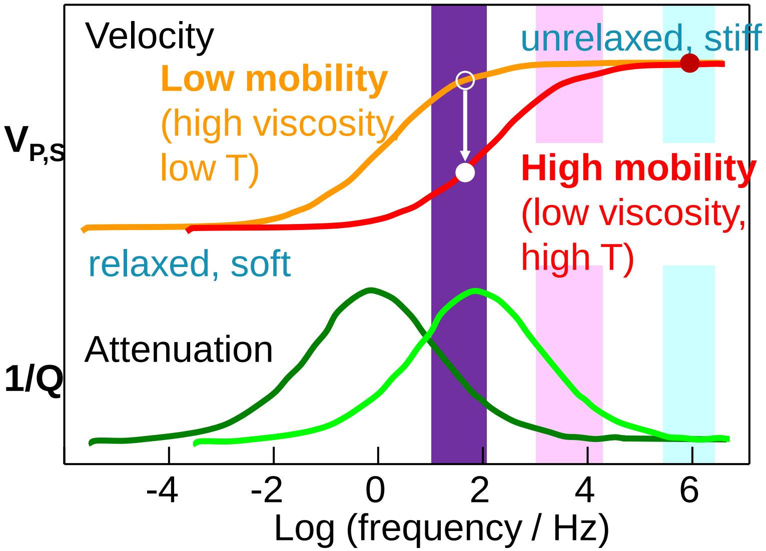
# Where is it important to consider seismic dispersion and attenuation?

## Reservoir surveillance, time-lapse seismic

Stress, temperature, and saturation can have significant impact on velocity dispersion, which needs to be accounted for in **rock-physics models** for quantitative interpretation of seismic data (inversion for temperature, pressure and stauration changes)

## Areas of application

- Thermal EOR
- CCS



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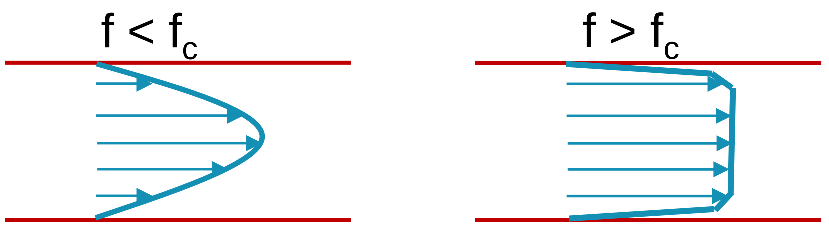
# Dispersion/Attenuation Mechanisms

- "Biot" flow

Biot (1956)

Transition between viscous and inertial flow in pore space




$$f_c \approx \frac{\phi H}{\rho K_f} \cdot \frac{\eta}{k}$$

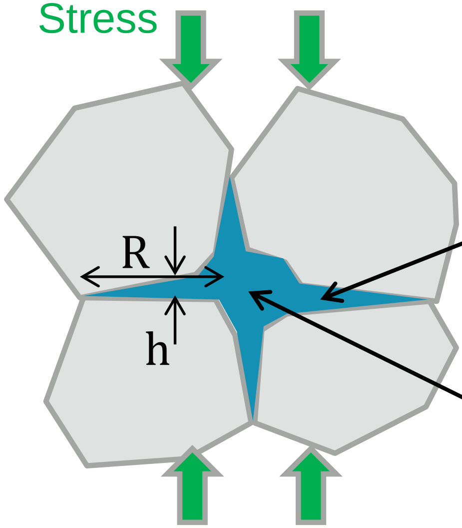
- Relatively small effect in most cases (~ 2%)
- Characteristic frequencies usually in the ultrasonic range

- Squirt flow

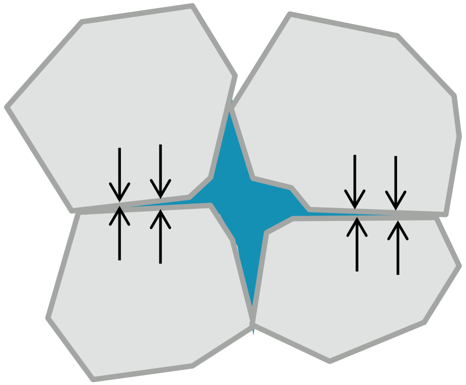
Dvorkin, Mavko, Nur (1995)

$$f_c = \left(\frac{h}{R}\right)^2 \frac{K_f}{\eta} \propto \frac{1}{\eta}$$

$f_c$ is typically in the ultrasonic range

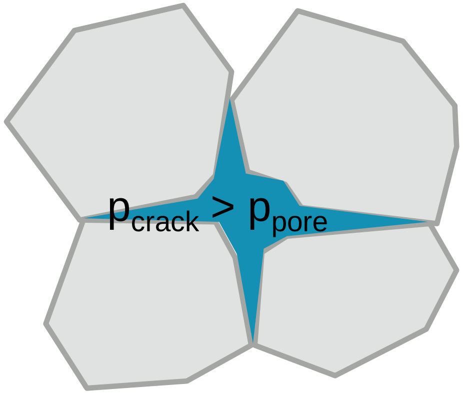



(A) Slow loading



- Flow from cracks into pores
- Soft response of rock

(B) Fast loading




- Reduced local flow
- Stiff response of rock



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# Dispersion/Attenuation Mechanisms

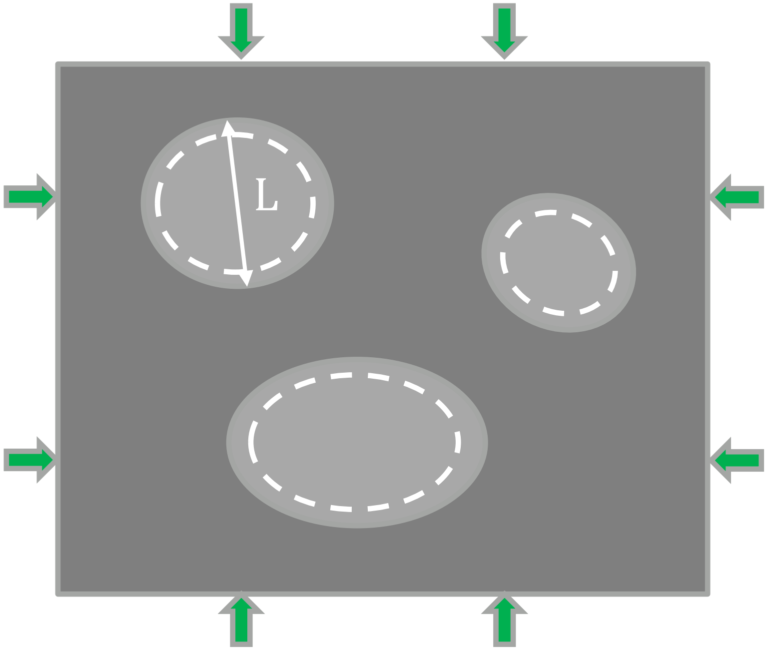
- Double porosity — Pride and Berryman (2003)
- Patchy saturation — White (1975), Johnson (2001)

Both models are conceptually similar

$$f_c \approx \frac{K_f}{\phi\, L^2} \cdot \frac{\eta}{k}$$

Inclusions of different porosity (i.e. stiffness) or fluid saturation (e.g. compressible gas bubbles), with $L \ll$ wavelength of seismic wave

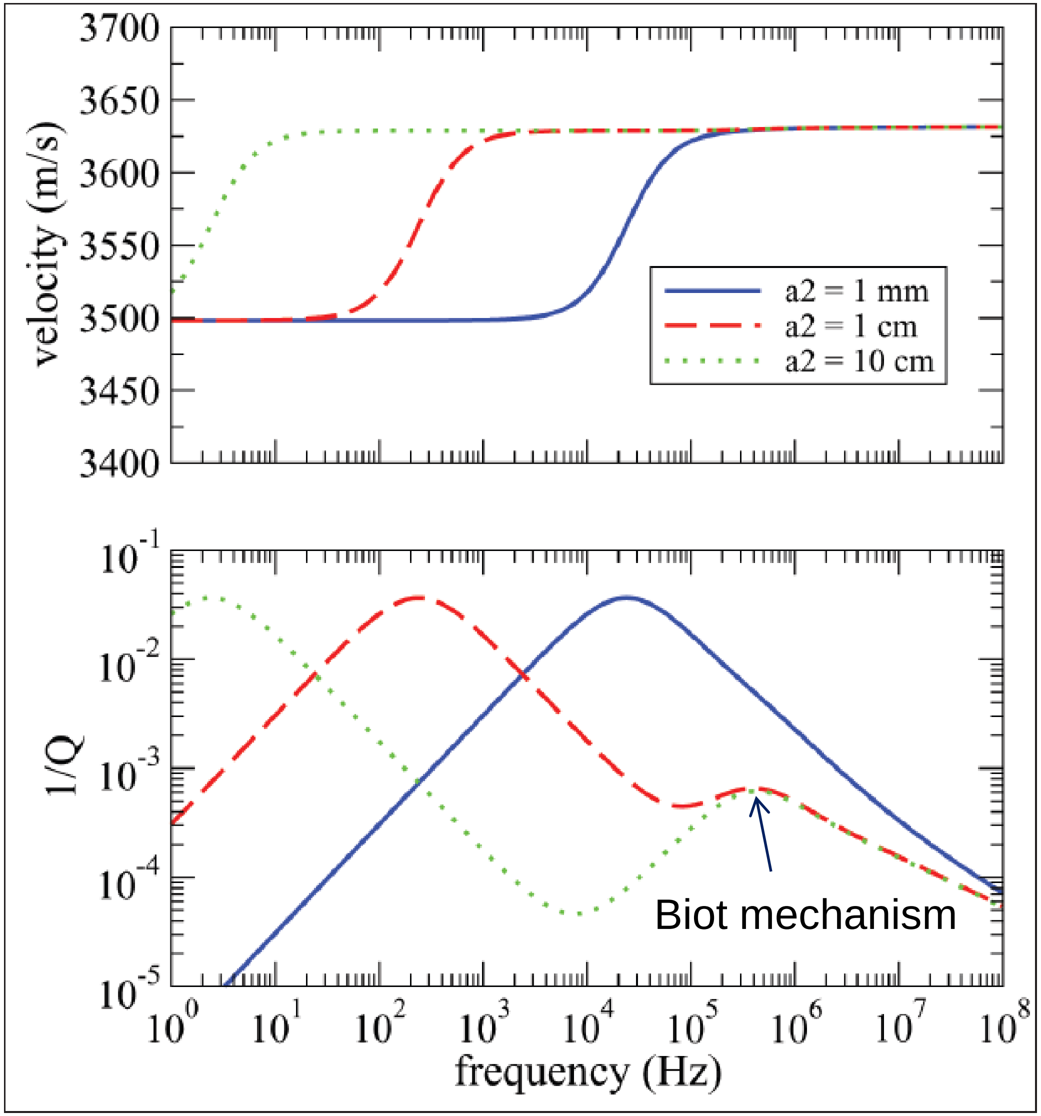
⇨ **local flow on meso scale**



# Unified double-porosity model

Pride, Berryman, Harris (2004)

Characteristic frequency can vary over several orders of magnitude, including the seismic range



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# Dispersion/Attenuation Mechanisms

## Several other mechanisms, including:

- Grain-to-grain movement  (important at teleseismic frequencies)
  Jackson and Paterson (1986)
- Visco-elasticity of pore fluids (e.g. heavy oil or kerogen)
  Das and Batzle (2008); Kato, Onozuka, Nakayama (2008)
- Viscous shear relaxation (typically at ultrasonic frequencies)
  O'Connell and Budiansky (1977); Vo-Thanh (1990)
- Fractures (related to double-porosity model)
  Maultzsch, Chapman, Liu, Li (2003)
- Rheology of bound water in shales (not understood yet)

# Measuring seismic dispersion/attenuation

## Direct measurements

Only field measurements possible because of large wavelength at seismic frequencies

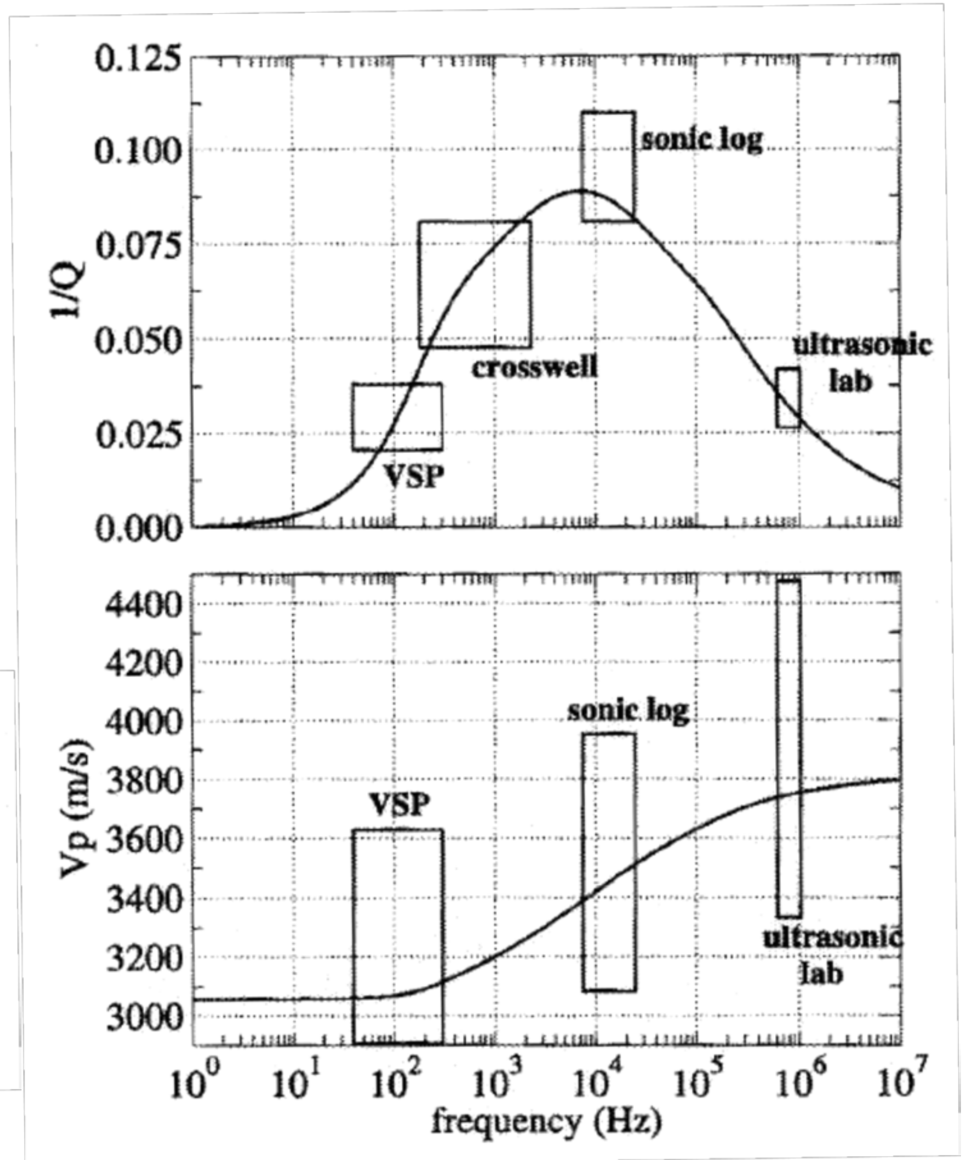



**Figure 3.** Attenuation and dispersion predicted by the double-porosity model of *Pride and Berryman* [2003a] (the solid curves) as compared to the data of *Sams et al.* [1997] (rectangular boxes). The number of $Q^{-1}$ estimates determined by *Sams et al.* [1997] falling within each rectangular box are 40 VSP, 69 cross-well, 854 sonic log, and 46 ultrasonic core measurements. A similar number of velocity measurements were made. These various measurements come from different depth ranges at their test site.

from Pride, Berryman, Harris (2004)

# Indirect measurements

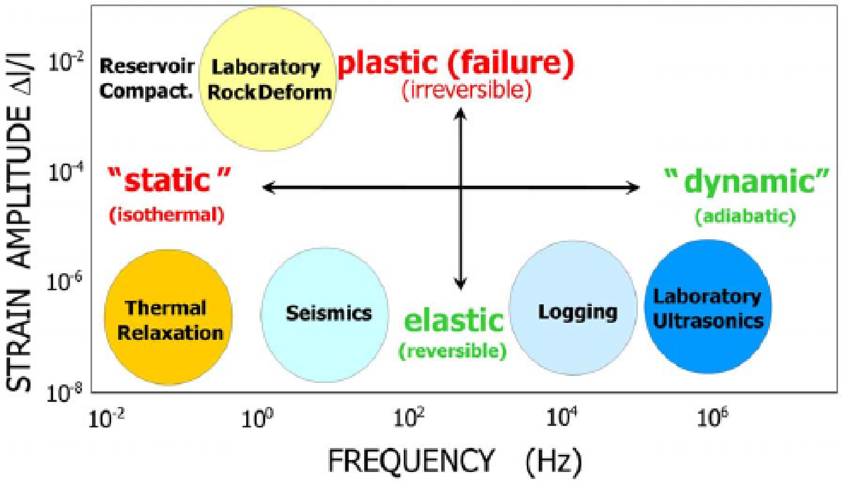
Determine velocities from dynamic rock stiffness

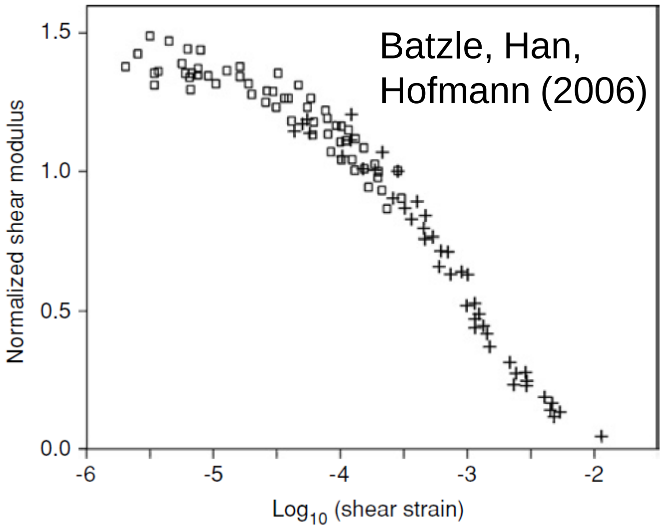
$$V_p = \sqrt{\frac{M}{\rho}} \quad \text{with} \quad M(f) = \frac{E(1-\nu)}{(1+\nu)(1-2\nu)}$$

$$V_s = \sqrt{\frac{\mu}{\rho}} \quad \text{with} \quad \mu(f) = \frac{E}{2+2\nu}$$

M: p-wave modulus
μ: Shear modulus
E: Young's modulus
ν: Poisson's ratio
ρ: Density

Small strain amplitudes (< $10^{-6}$) are required



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# Measuring seismic dispersion/attenuation

**Indirect measurements**

Techniques:

(A) Excitation of eigenfrequencies (resonances)

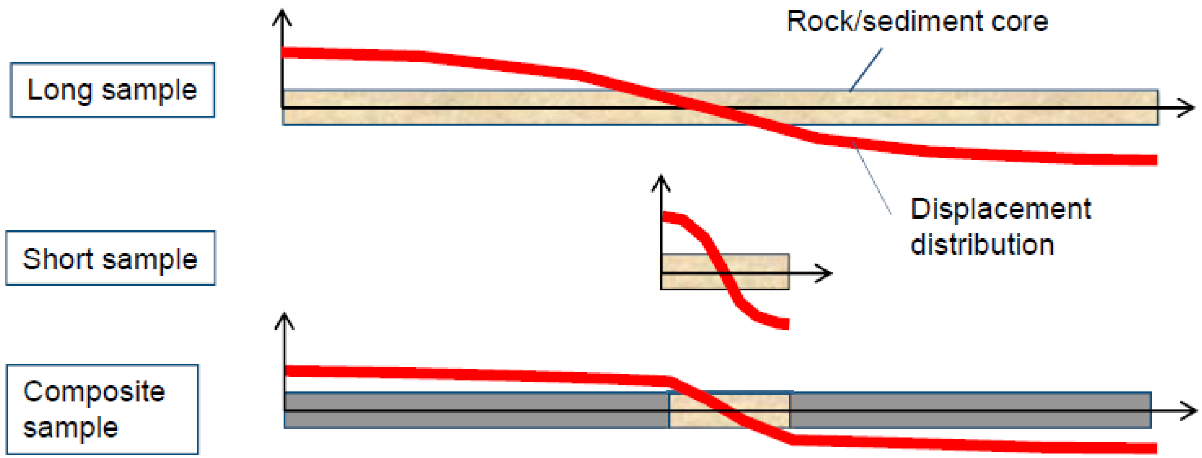
- Resonant-bar technique
- Differential Acoustical Resonance Spectroscopy (DARS)

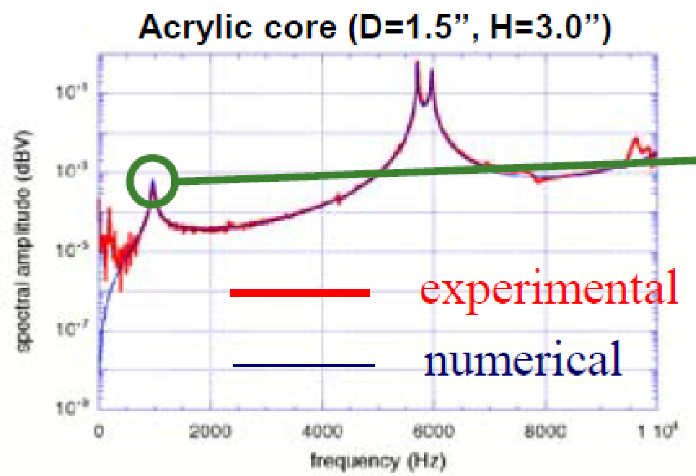
(B) Ecitation of forced oscillations

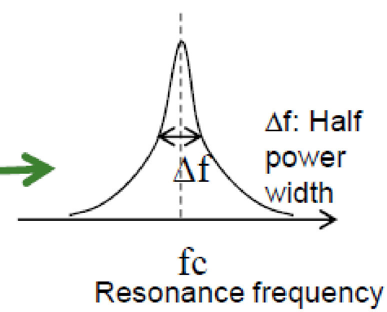
- Torsional excitation
- Axial excitation

# Split Hopkinson Resonant Bar (SHRB) Test

Nakagawa,
Rev. Sci. Instr. (2011)




Apparent attenuation $\xi = \frac{1}{2}\frac{\Delta f}{f_c}\left(=\frac{1}{2Q}\right)$ — Seismic Q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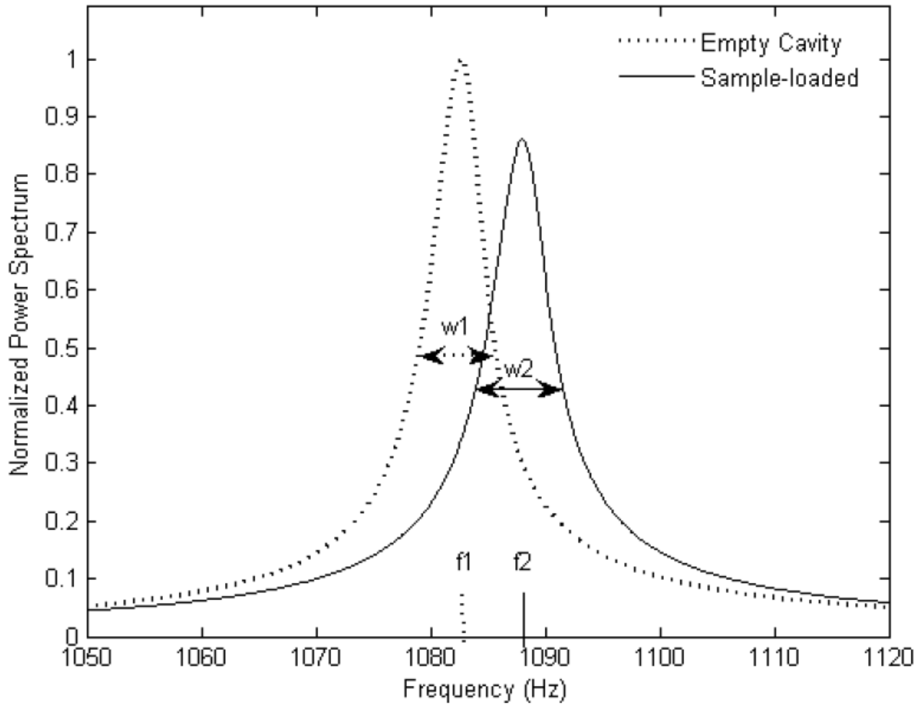
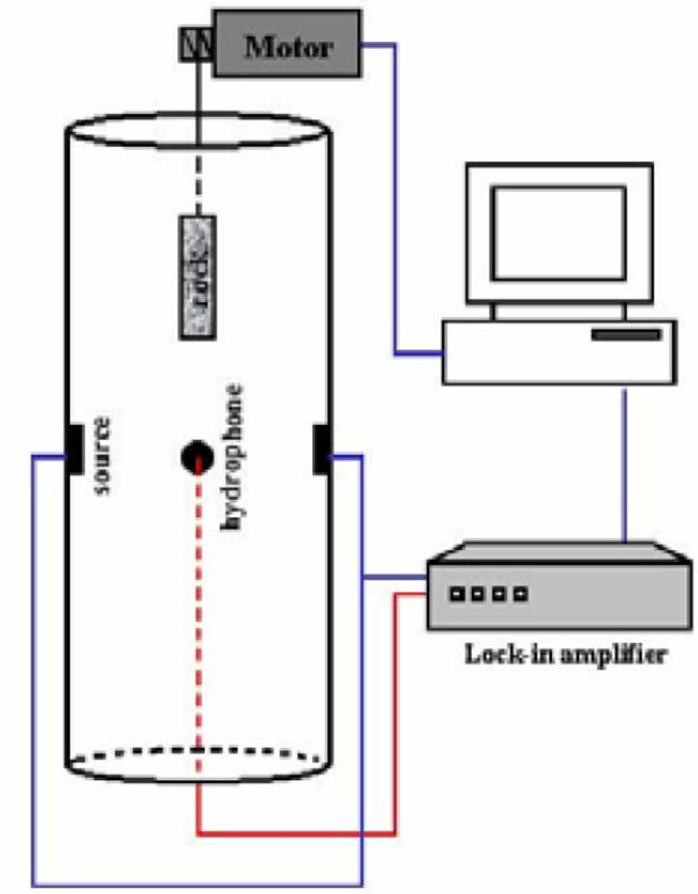
# Seismic-frequency techniques – Resonator techniques

- Introduce small rock sample in a fluid (gas) filled resonator
- Measure perturbed resonance curve as a function of sample position
- Invert data for dynamic stiffness of rock (real and imaginary part)



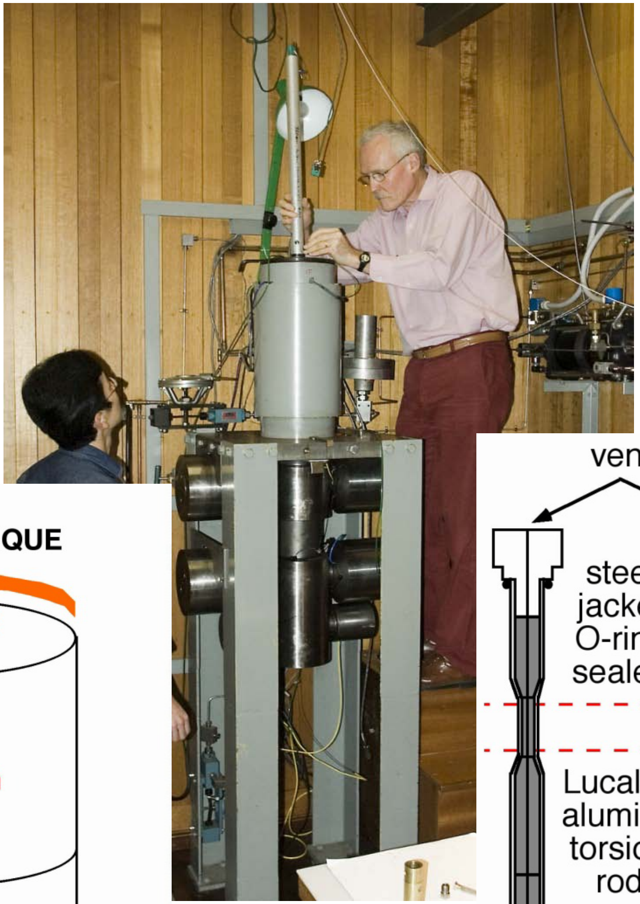



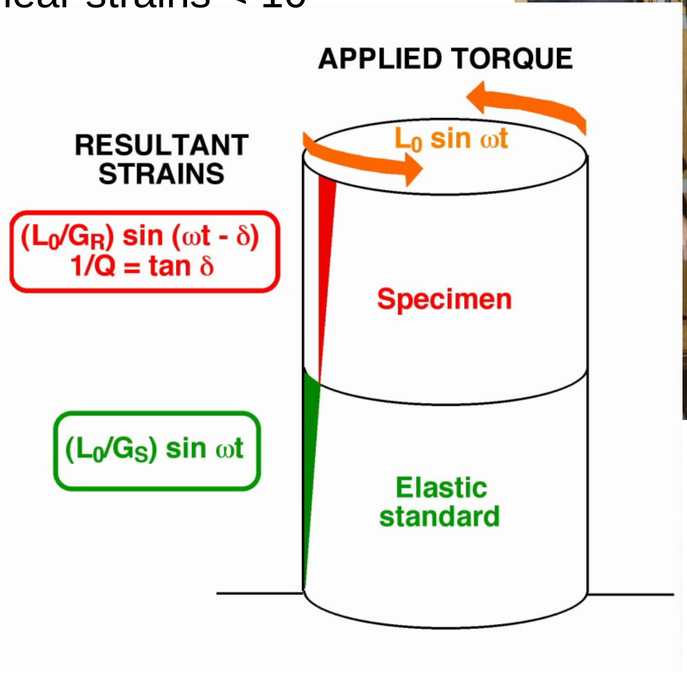

Harris, Quan, Xu (2005)

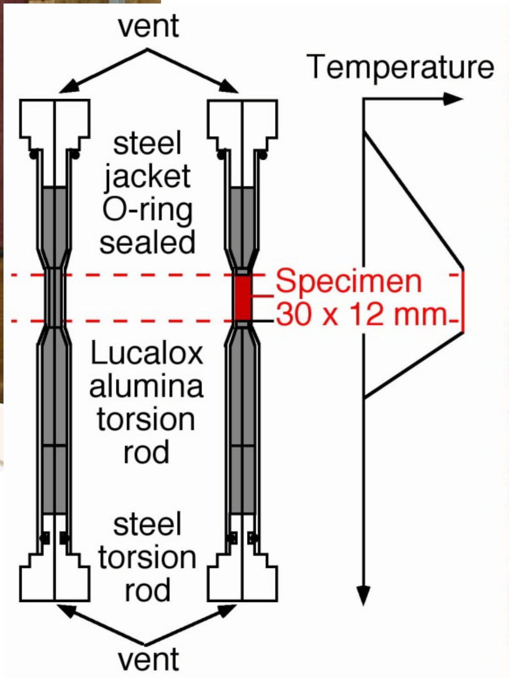
# Seismic-frequency techniques – Forced Oscillator Techniques

Torsional forced oscillation method
Jackson and Paterson (1986)

Implementation within internally heated gas apparatus: P = 200 MPa
T to 1300 C
oscill'n periods 1-1000 s
shear strains < $10^{-5}$





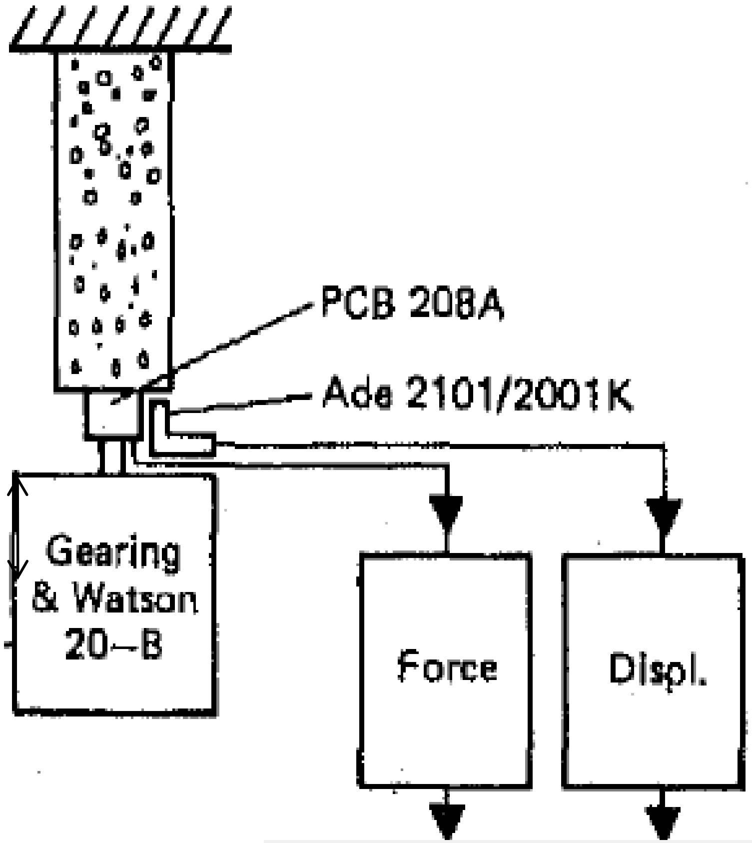



# Seismic-frequency techniques – Forced Oscillator Techniques

Spencer (1981)

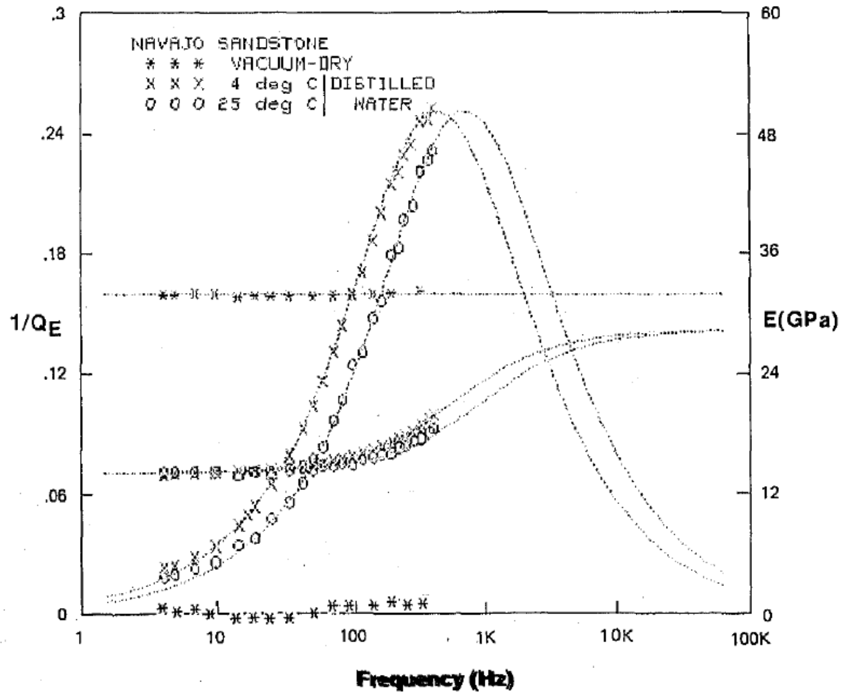
Actuator

1-1000 Hz




E = Stress, σ / strain, ε

Dispersion and attenuation of dry and saturated sandstone




Experimental data are fitted by Cole-Cole model



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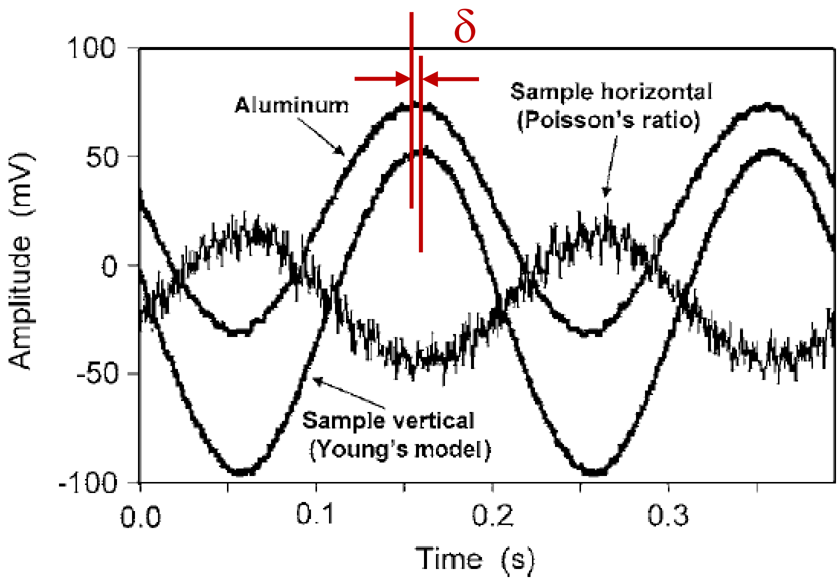
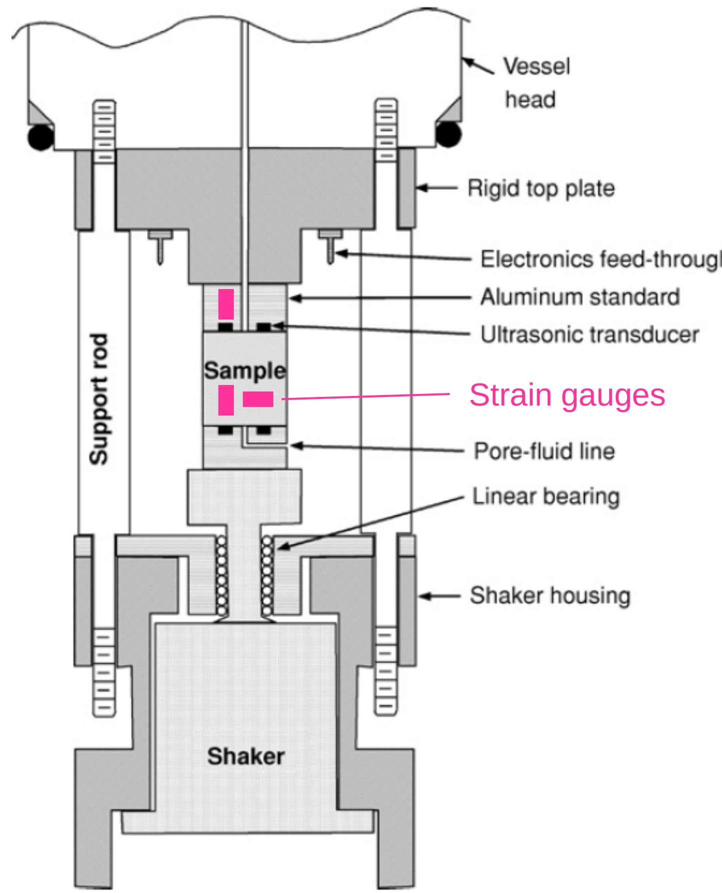
# Seismic-frequency techniques – Forced Oscillator Techniques

**Batzle, Han, Hofmann (2006):**

Use **strain gauges** to measure strains in axial and radial direction in a core plug and a reference sample (Al) both excited by a sinusoidal force in axial direction




$$E^{rx} = E^{al}\frac{\varepsilon_{33}^{al}}{\varepsilon_{33}^{rx}}$$

$$1/Q = \tan\delta$$



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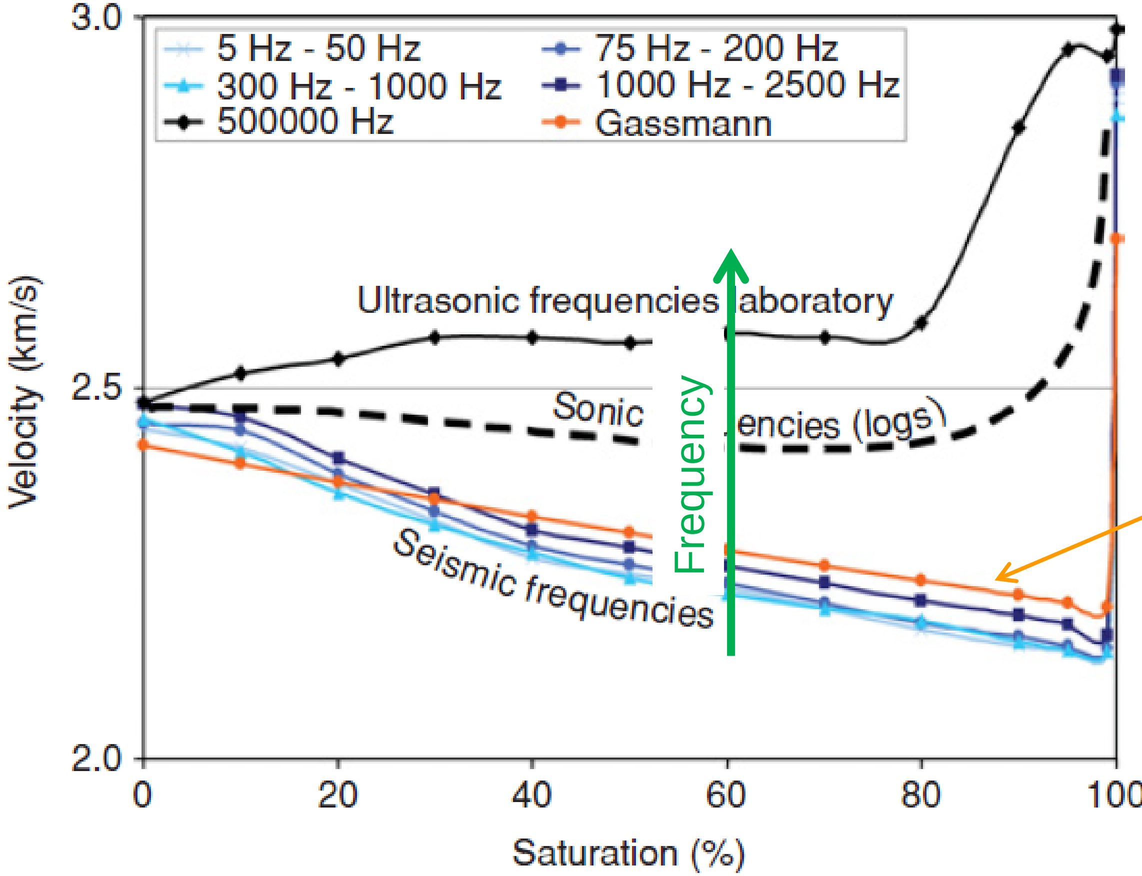
# Saturation dependence of dispersion/attenuation

Saturation effects in sandstones




Ignoring dispersion effects can result in wrong estimates of saturation changes based on sonic logs

Gassmann model (low-frequency limit)

Batzle, Han, Hofmann (2006)



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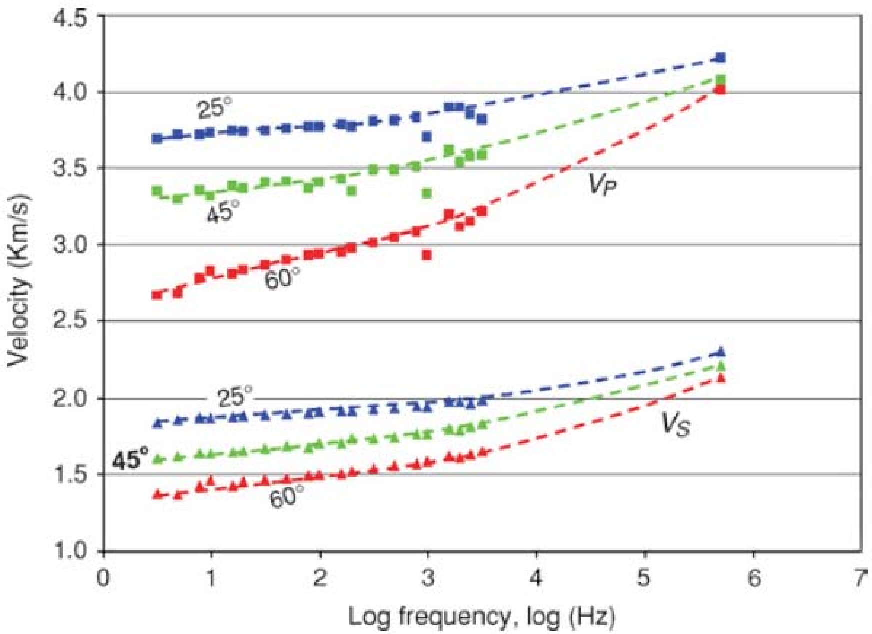
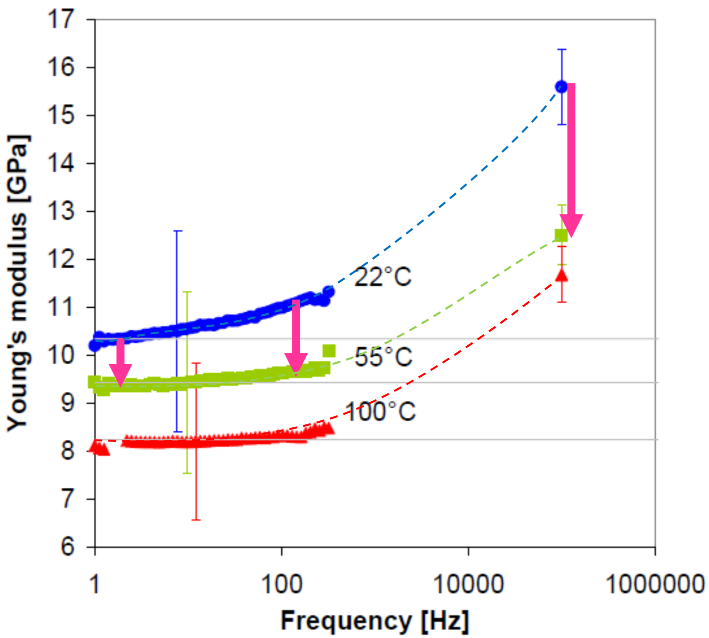
# Temperature dependence of dispersion/attenuation

Heavy-oil saturated Uvalde carbonate




Batzle, Han, Hofmann (2006)

Athabasca heavy-oil sands




Bauer, Korndorffer, van der Linden (2011)

$$f_c(T) \propto \frac{k}{\eta(T)}$$

Oil viscosity decreases with temperature (by several orders of magnitude)

⇨ $f_c$ shifts to higher frequencies



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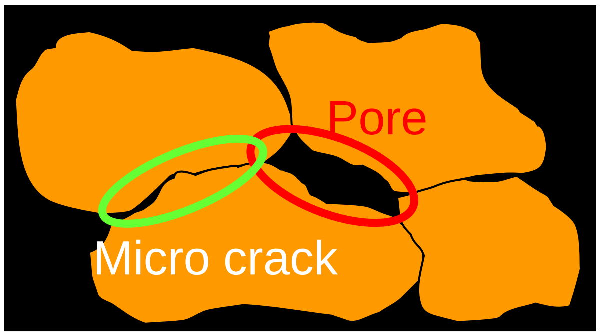
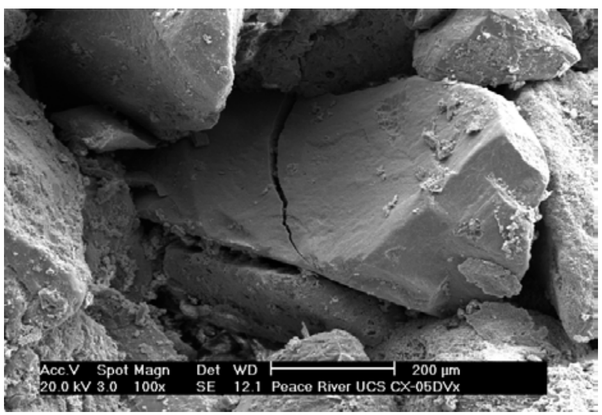
# Temperature dependence of dispersion/attenuation

Velocity dispersion in heavy-oil sands caused by micro cracks?

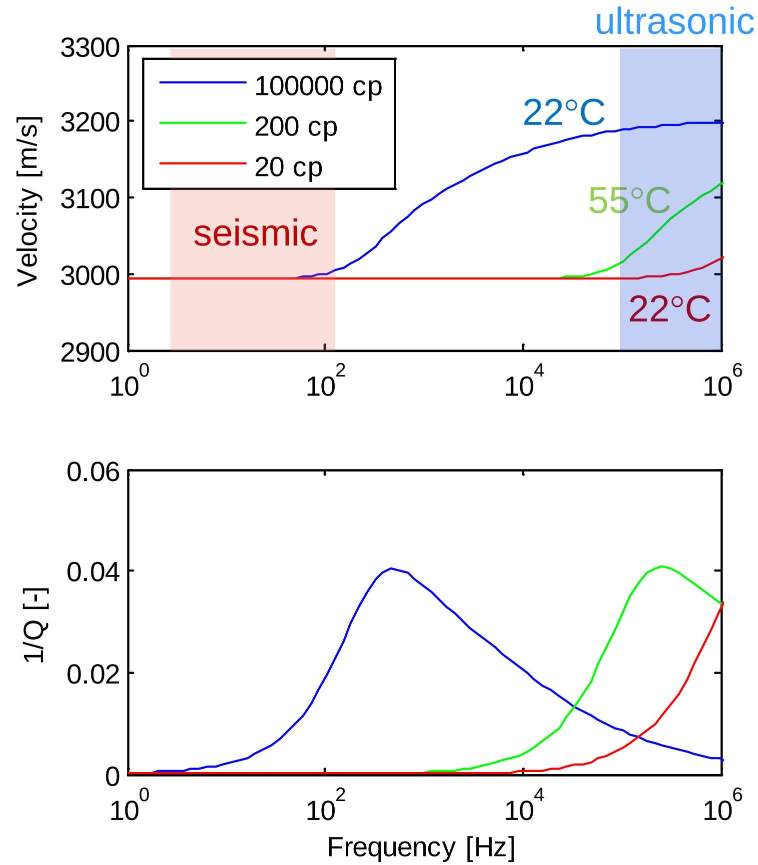
Locked sand: large contact areas




## Double-porosity model

Pride, Berryman, Harris (2004)




Input parameters: Radius of penny-shaped inclusion = 0.9 mm; aspect ratio = $3 \cdot 10^{-4}$; volume fraction of inclusions = 0.03%



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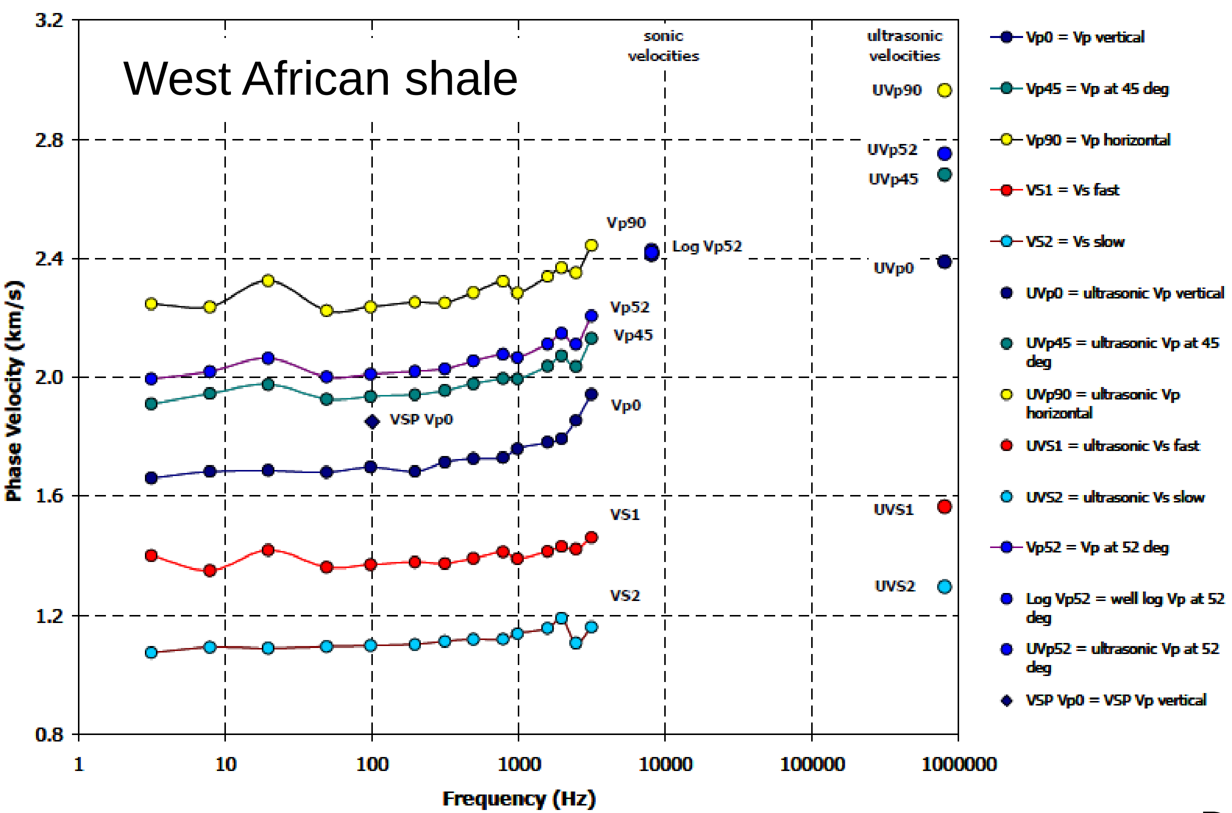
# Dispersion in Shales

- Indications (few studies only!) for strong dispersion in shales
- Dispersion mechanisms in shales not understood yet – related to bound water?




Integration of different techniques:

- Seismic/VSP
- Sonic logs
- Ultrasonics
- Dynamic stiffness
- microindendation

Duranti, Ewy, Hofmann (2006)



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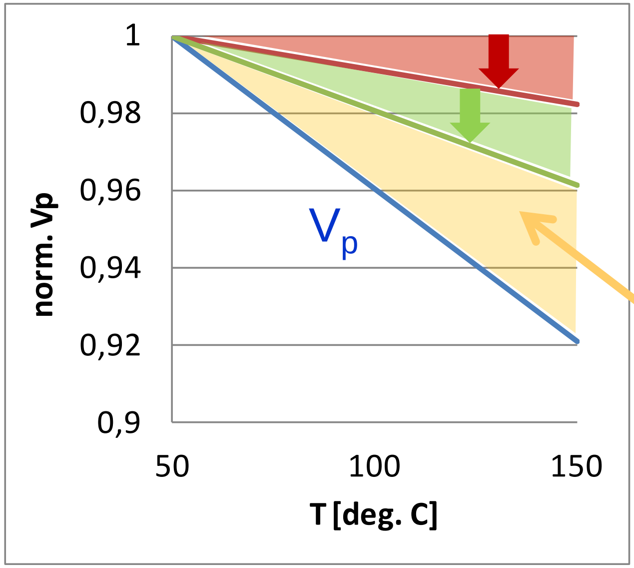
# Dispersion in Shales – Temperature dependence

Typical temperature dependence of ultrasonic velocities in shales (schematic)




Decrease due to pore-pressure increase

Decrease due to fluid-compressibility changes

Thermally-induced reduction of frame stiffness?

Triaxial compaction tests:

Nearly temperature-independent frame stiffness

Temperature dependence of velocity dispersion

Temperature changes in shale formations (e.g. caprock of heated reservoir) could be greatly overestimated by ignoring dispersion effects and their temperature dependence

# Conclusion

- Several mechanisms for velocity dispersion and attenuation have been identified and theoretically described
- Importance for seismic is still under debate
- Few reliable experimental studies
- Detection of velocity dispersion/attenuation in seismic surveys has in principle huge potential (permeability from seismic, fracture sizes, etc.). However, there is no deployable tool yet.