Seismic wave attenuation at low frequencies: measurements and mechanisms

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Why

- The study of fluid saturation of crustal rocks can be conducted with seismic wave attenuation at low frequency (Goloshubin et al., 2006).
- **Oil reservoirs** seem to exhibit **high-attenuation** (low Quality factor, $Q$) at low frequencies (Chapman et al. 2006).
Theory

• **Attenuation** of seismic waves describes the **loss of energy** of the “elastic” perturbation.

• **Patchy Saturation** (White, 1975) and **Squirt Flow** (Mavko and Jizba, 1991) quantify the loss of energy due to fluid flow (ΔP -> ΔV) in porous media.

• Study of **Pore Pressure** is a key to get valuable information about these mechanisms.
Method

Sub-resonance experiments (e.g. Peselnik and Liu, 1987).

• Application of a “low” frequency (e.g. 0.1 - 100 Hz) sinusoidal stress.

• Measurements of the sinusoidal and “delayed” \( \Phi \) shortening across the sample.

\[
Q^{-1} = \tan(\Phi)
\]
At ETH Zurich

2 machines for measuring Q

Broad Band Attenuation Vessel (BBAV)
Will be presented now

150 mm

100 mm

SWAM – Today poster session 3 (10:50-12:00)
- 76 x 250 mm cylindrical sample
- Measure of **local pore pressure**
- **Bulk** values of force and **strain** ($10^{-6}$)
- 25 MPa confining pressure in oil medium
- Full **pore fluids** circuit
- Fully automatic **400 points/day** in frequency range (0.1-100Hz)
BBAV

Big sample (250 mm long, 76 mm diameter) → 5 pore pressure sensors
Calibration obtained testing materials with "known elasticity"

- Aluminum, Q -> Inf  
  (Nowik and Berry, 1972)
- PMMA (Plexiglas), Q~12  
  (Lakes, 2009)
Rock data

**Berea** sandstone 200-500 mD, 20 % porosity

**Water** saturated at 0 and 90%, 0 MPa pore pressure

Madonna et al. JGI sub.

Berea sandstone ~90% water sat.

Berea sandstone 0% water sat.
Berea sandstone: 500-1000 mD, 20% porosity
Water content 0 - 90%, confining pressure 0-15 Mpa, 0 MPa pore pressure

BS002, Dry, 0MPa confining pressure (Pc)
BS002, 90% sat., <2MPa Pc
BS002, 90% sat., 15MPa Pc

Berea sandstone 60% or 90% water saturation <2 MPa Pc
Understanding

Mavko et al. 2003

\[ f_{\text{squirt}} \approx \frac{K_0 \alpha^3}{\eta} \]

\[ f_{\text{patchy}} \approx \frac{k \cdot K_s}{\pi L^2 \eta} \]

Questions:

- Introduction
- Methods – BBAV
- Q measurements
- Q mechanisms
- Conclusions
Understanding

**Squirt flow** (Mavko and Jizba 1998) exchange of fluids between cracks and pores

$$7 \text{ Hz} < f_{\text{squirt}} < 7000 \text{ Hz}$$

- Typical frequency of squirt (Hz)
- Bulk module of Berea sandstone (7 GPa) (Hart and Wang 1995)
- Crack's aspect ratio ($10^{-3}$-$10^{-4}$) (Mavko et al. 2003)
- Viscosity of water ($10^{-3}$ Pa s)

$$1/C_{pc} = 5 \text{ MPa}$$

- $1/C_{pc}$ = cracks closure pressure (Jaeger et al. 2007)
- Berea sandstone: $\alpha = 10^{-4}$
- $E_m$ (matrix Young module): 97 GPa (Zimmermann 1991)

Cracks are closed at $15 \text{ MPa } P_c$
Berea sandstone

500-1000 mD
20 % porosity

60% Water content

Pc 0 - 15 MPa

We need more calibrations and rock experiments

First approximation K₀ constant

BS002, κ: 0.5-1D, Φ: 20%, 60% water sat.

\[ f_{\text{squirt}} \approx \frac{K_0 \alpha^3}{\eta} \]
Uncovering of mechanisms

- The dimensions of the sample allow us to **insert in small holes** some pressure sensors
- **Verify patchy and/or squirt** flow theories

Quintal et al. 2011
Uncovering of mechanisms
Pore pressure evolution vs stress field change

Introduction
Methods – BBAV
Q measurements
Q mechanisms
Conclusions
Conclusions

- The B.B.A.V. has been designed, built and successfully tested

**Q measurements** from rock seem to indicate attenuation driven by saturation

**Pore pressure measures** suggest transfer of energy from elastic perturbation to fluid within the pores

- **Outlook:** measure Q values for different types of rocks at different Confining Pressure and Saturation

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