Anomalous Vp/Vs in highly pressurized rocks: 
Evidence for anisotropy or mafic composition?

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Anomally high $V_p/V_s$ in subduction zones

Extreme $V_p/V_s$ ↔ Low Velocity Zones (LVZ), where slips & earthquakes occur

(mostly) Interpreted as zones with near-lithostatic fluid pressures

e.g.
Kodaira (2004)
Audet et al. (2009)
Peacock et al. (2011)
Audet & Bürgmann (2014)
Audet & Kim (2016), review
Motivation  
*Insights from the laboratory to the field?*

\( V_p/V_s \) (i.e. Poisson’s ratio in isotropic rocks) \( \Leftrightarrow \) Increases at **High fluid pressures**

\( e.g. \) Christensen (1984); Wang et al. (2012)

But, in the **laboratory**:

⇒ Large \((V_p/V_s)_{lab}\) only in rocks rich in minerals of high Poisson’s ratio; e.g. Basalts (\( e.g. \) Christensen, 1984), Marbles (\( e.g. \) Wang et al., 2012), etc.

⇒ NO Poisson’s ratio reported reach 0.4; hence \((V_p/V_s)_{lab} \ll (V_p/V_s)_{field}\) measurements.

⇒ Typically ultrasonic measurements (\( e.g. \) Christensen, 1984; Christensen, 1996; Wang et al., 2012; etc.)

⇒ **High \((V_p/V_s)_{field}\) \Leftrightarrow Insights for mafic and/or anisotropic zones?**

⇒ **Are anisotropy or mafic composition necessary conditions for high \((V_p/V_s)\)?**

**Main questions:**

1. Can we directly compare \((V_p/V_s)_{field}\) and \((V_p/V_s)_{lab}\)?

2. Do anomalous \(V_p/V_s\) (i.e. \( \nu > 0.4\)) exist in isotropic rocks?

3. Is there a control of rock mineral composition on \(V_p/V_s\)?
**Q.1 Field vs Laboratory measurements**

*Laboratory* ultrasonic ($f \sim 1$ MHz) P- and S-waves velocity across the sample. ⇒ Approximately 6 orders of magnitude higher than *field* frequencies ($f \sim 1$ Hz) & Fluid-saturated rocks are *dissipative* (e.g. Winkler & Nur, 1979)

Assuming an ideal homogeneous rock (at *any* length scales) ⇒ Very different wave velocities will be measured depending on the frequency of measurement

**Main questions:**

1. Can we directly compare ($V_p/V_s$)$_{\text{field}}$ and ($V_p/V_s$)$_{\text{lab}}$?

**NO:** One needs to account for the *frequency dependence*
Laboratory: Poisson’s ratio a **quartz-pure isotropic** Fontainebleau sandstone ranges from \( \sim 0.1 \) (dry) to \( \sim 0.38 \) in the undrained regime, i.e. range reported in LVZ YET, typical **ultrasonic** measurements would yield values of about 0.2 at near-lithostatic fluid pressures.
**Method**

*Stress-strain oscillations*

**Axial stress oscillations**, at various frequency, on dry and water-saturated samples.
Fig. (a): With normalised axial strain oscillations (grey curves), large variations in radial strains from dry (red) to water-saturated and large frequency dependence (green to blue curves).
Fig. (b): Poisson’s ratio, ratio of radial-to-axial strain, consequently highlight strong increase with frequency. Effect decreases as effective pressure increases (or as fluid pressure decreases).
⇒ Undrained regime corresponds to maximum in Poisson’s ratio.

**Exemple** for a isotropic 100% quartz Fontainebleau sandstone, with large degree of cracking:
Poisson’s ratio of up to 0.42 in undrained regime at lowest effective pressure (i.e. near lithostatic pressure)

*Pimienta et al. (2018), GRL*
Results

Measurements of undrained Poisson’s ratio

Measurements at varying fluid pressures in various isotropic crustal rocks ranging in mineralogy
Results

Measurements of undrained Poisson’s ratio

Reach values of 0.42, independently of any mineralogical constrain.

Increasing towards near-lithostatic fluid pressures.

Measurements at varying fluid pressures in various isotropic crustal rocks ranging in mineralogy.
Results

**Simple model for undrained Poisson’s ratio**

![Graph showing results](graph.png)

*Highly microfractured rocks (ρ = 4)*

*(DEM ρ ~ 1)*

*ρ = 1*

*ρ = 0.5*

*ρ = 0.1*

*Intact rocks (ρ = 0)*

*WGs*

*CarMbl*

*Fo3*

*IBas*

*P - to S-wave velocity ratio V_p/V_s [ ]*

*Mineral (intrinsic) Poisson’s ratio ν_min [ ]*

*Measured rock samples:*

- ○ ○ ○ ○ « Intact »
- ★ ★ ★ ★ Microfractured

*Modelled rock:*

- increasing degree of microfracturing

Pimienta et al. (2018), GRL
Independent of mineralogy: Extreme values if large amount of cracks opened by fluid pressure.
CONCLUSION

Extreme $V_p/V_s \Leftrightarrow$ Low Velocity Zones (LVZ), where slips & earthquakes occur

1. Directly infer $(V_p/V_s)_{\text{field}}$ from $(V_p/V_s)_{\text{lab}}$ ?
   => NO: need to account for the frequency dependence!

2. Extreme $V_p/V_s$ (i.e. $\nu > 0.4$) in isotropic rocks ?
   => YES: if microcracks opened by high fluid pressure

3. Control of rock mineral composition on $V_p/V_s$ ?
   => NO: Extreme $V_p/V_s$ even in quartzite, if cracked & high $p_f$

At the lab. scale: The only necessary conditions are (i) high degree of microfracturing, and (ii) near lithostatic fluid pressure.

At the field scale: Anomalous $(V_p/V_s)_{\text{field}}$ might not necessarily yield constrains on mineralogy or degree of anisotropy.

Permeability of heavily cracked rocks, corresponding to high $V_p/V_s$, could be as high as about $10^{-16} \text{ m}^2$. 
For further information, please refer to


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**Hoping for your interest and questions,**

**Thank you**

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SuppMat.: Frequency dependence in a fluid-saturated rock?

Poroelasticity: 2 mechanical regimes (e.g. Biot, 1941; 1956)
→ Drained ⇔ Fluid allowed to flow out of the REV

Elastic constants independent of the fluid

REV = Representative Elementary Volume
SuppMat.: Frequency dependence in a fluid-saturated rock?

**Poroelasticity:** 2 *mechanical* regimes (e.g. Biot, 1941; 1956)

→ **Drained** ⇔ Fluid allowed to flow out of the REV
→ **Undrained** ⇔ Fluid not allowed to flow out of the REV

**Isolated inclusions:** 3rd *mechanical* regime

→ **Unrelaxed** ⇔ Fluid overpressure dependent on the geometry of the inclusion

*Higher Viscosity* ⇔ *Lower fluid velocity*

*Higher Frequency* ⇔ *Shorter time* for flow
SuppMat.: Frequency dependence in a fluid-saturated rock?

Experimental validation in e.g. Pimienta et al. (2015a; 2015b)
“Axial” solicitation

Axial stress oscillations
Axial stress
Radial strain
Measured Stress

Axial stress
→ $\sigma_{ax} = \varepsilon_{alu} E_{alu}$

Elastic response:
→ Amplitude ratio
→ Phase shift

$\Rightarrow E_{LF}$ & $\nu_{LF}$
$\Rightarrow Q_E^{-1}$ & $Q_v^{-1}$

SuppMat.: Principle for measurements

Strain amplitudes $\Delta \varepsilon \sim 10^{-6}$

Gypsum sample

→ $P_c \sim 1$ MPa
→ $f \sim 0.1$ Hz
Exemple for a isotropic 100% quartz Fontainebleau sandstone, with large degree of cracking: Extreme Poisson’s ratio in undrained regime at lowest effective pressure (i.e. near lithostatic pressure)
SuppMat.: Principle for the inclusion model

Applying the EMT model from Adelinet et al. (2011)

i.e. based on modelling approaches by Kachanov (1993)

Prediction used for Fig. in slides 8-9/9