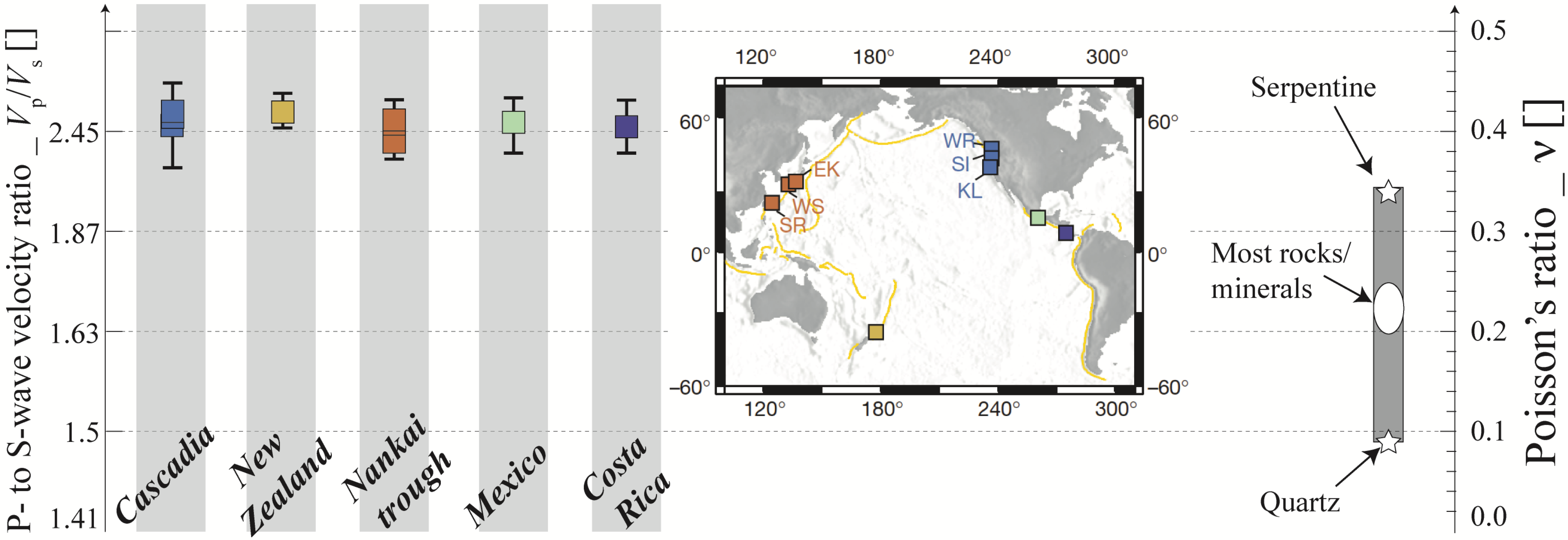
EGU General Assembly 2020

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

L. Pimienta[1], A. Schubnel[2], J. Fortin[2], Y. Guéguen[2], H. Lyon-Caen[2] & M. Violay[1]

[1]*Lab. of Exp. Rock Mechanics (LEMR),* EPFL, *Switzerland*
[2]*Lab. of Geology, Ecole Normale Superieure (*ENS), *France*

Context *Anomalously 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) ⇔ 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 $(V_p/V_s)_{lab} << (V_p/V_s)_{field}$ measurements.
- ⇒ Typically ultrasonic measurements *(e.g. Christensen, 1984; Christensen, 1996; Wang et al., 2012; etc.)*

⇨ **High** $(V_p/V_s)_{field}$ ⇔ Insights for ***mafic*** and/or ***anisotropic*** zones ?

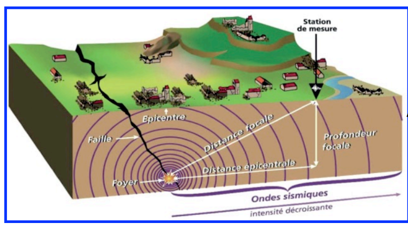
⇨ *Are **anisotropy** or **mafic** composition **necessary conditions** for* high (V_p/V_s) ?

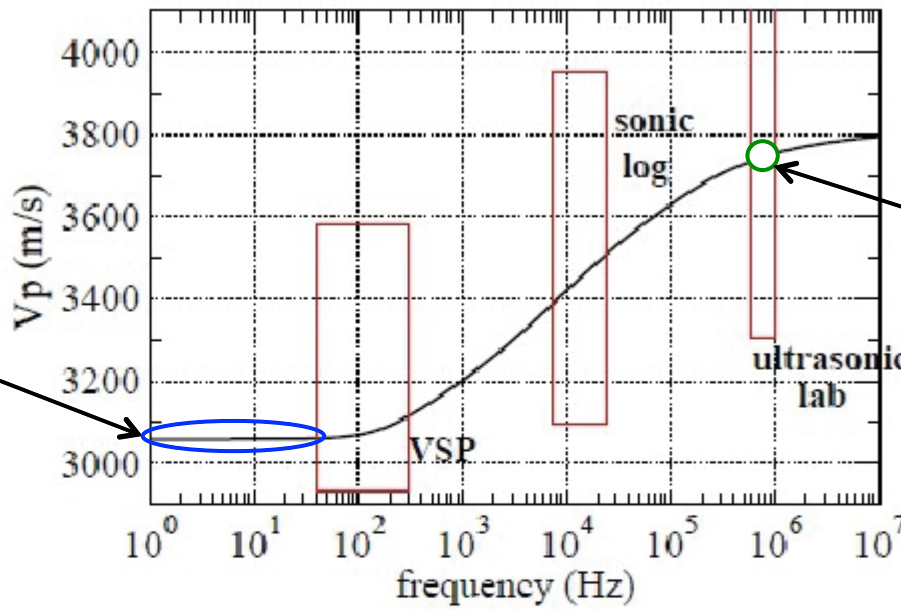
Main questions:

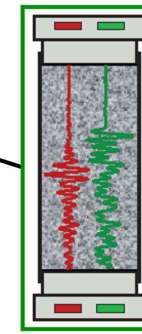
1. Can we directly compare $(\mathbf{V_p/V_s})_{field}$ and $(\mathbf{V_p/V_s})_{lab}$?
2. Do anomalous V_p/V_s (i.e. $\nu > 0.4$) exist in ***isotropic*** rocks ?
3. Is there a control of rock ***mineral composition*** on $\mathbf{V_p/V_s}$?

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)







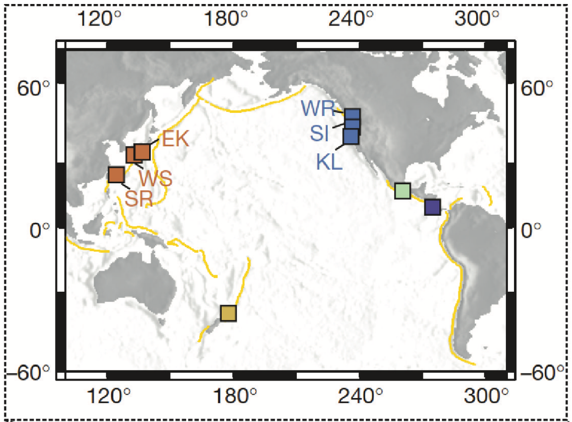
Modified from Pride et al. (2004)

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

Main questions:

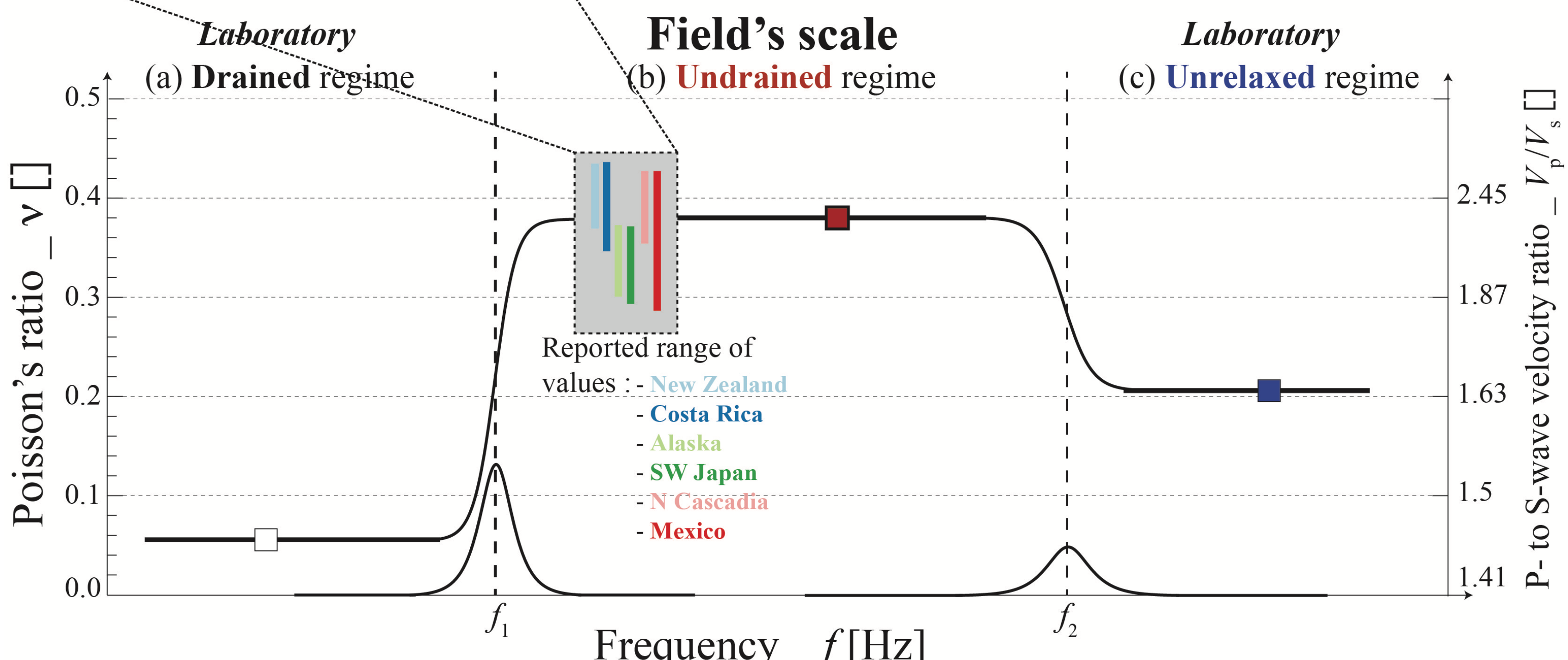
1. Can we directly compare $(\mathbf{V_p/V_s})_{field}$ and $(\mathbf{V_p/V_s})_{lab}$?
NO: One needs to account for the **frequency dependence**

Q.1 *Effect of frequency on* $\mathbf{V_p/V_s}$ *?* *=> Very large*



Laboratory: Poisson's ratio a **quartz-pure isotropic** Fontainebleau sandstone ranges from ~ 0.1 (dry) to ~ **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.

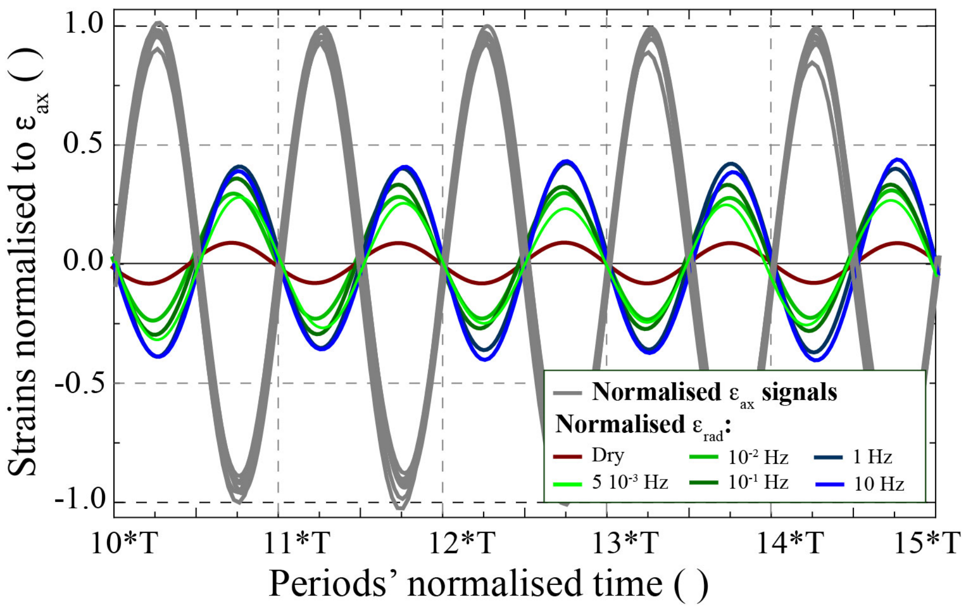


Audet & Kim (2016)
Pimienta et al. (2016)

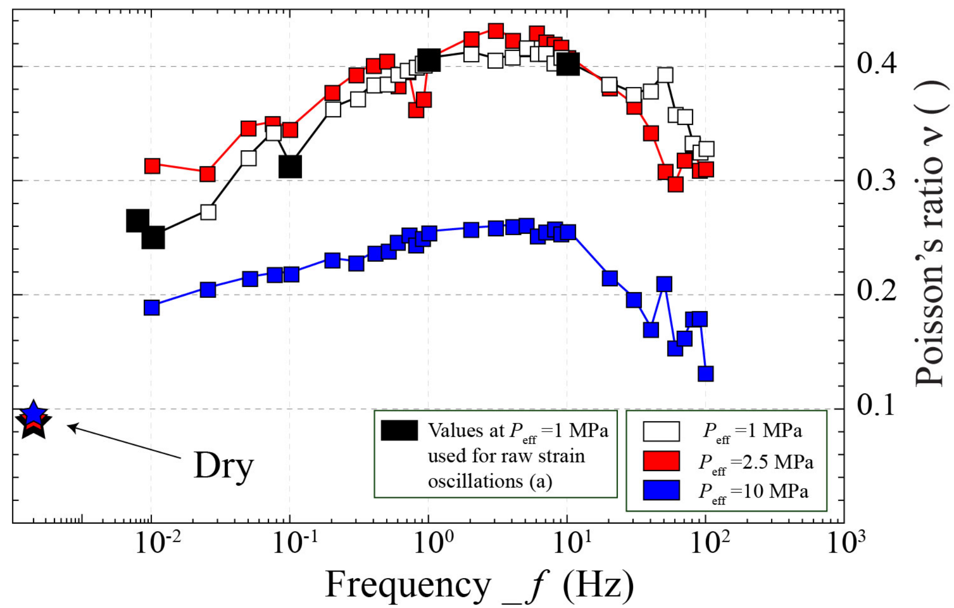
Method *Stress-strain oscillations*

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.

a) Normalised raw strain oscillations



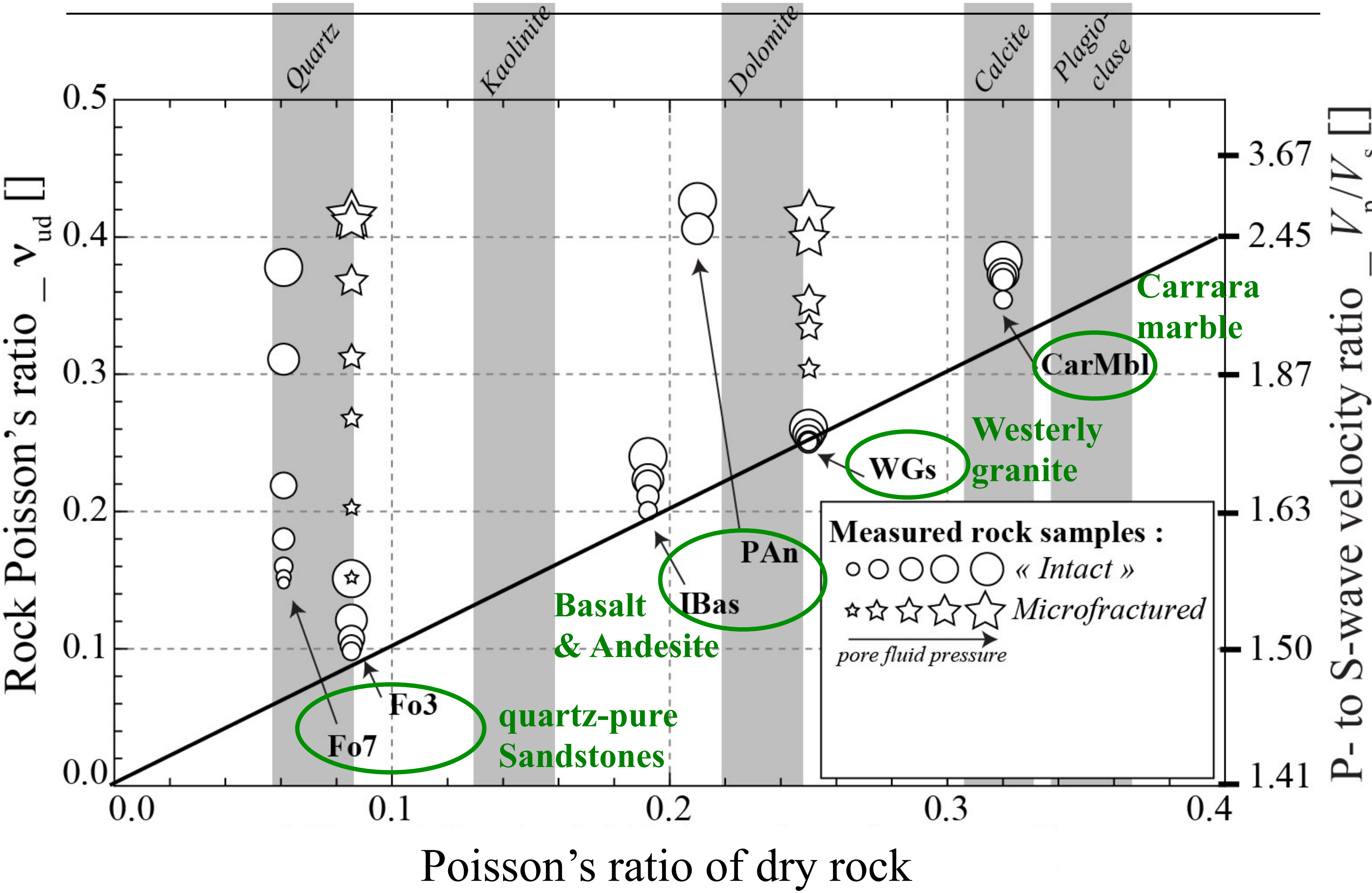
b) Poisson's ratio



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)

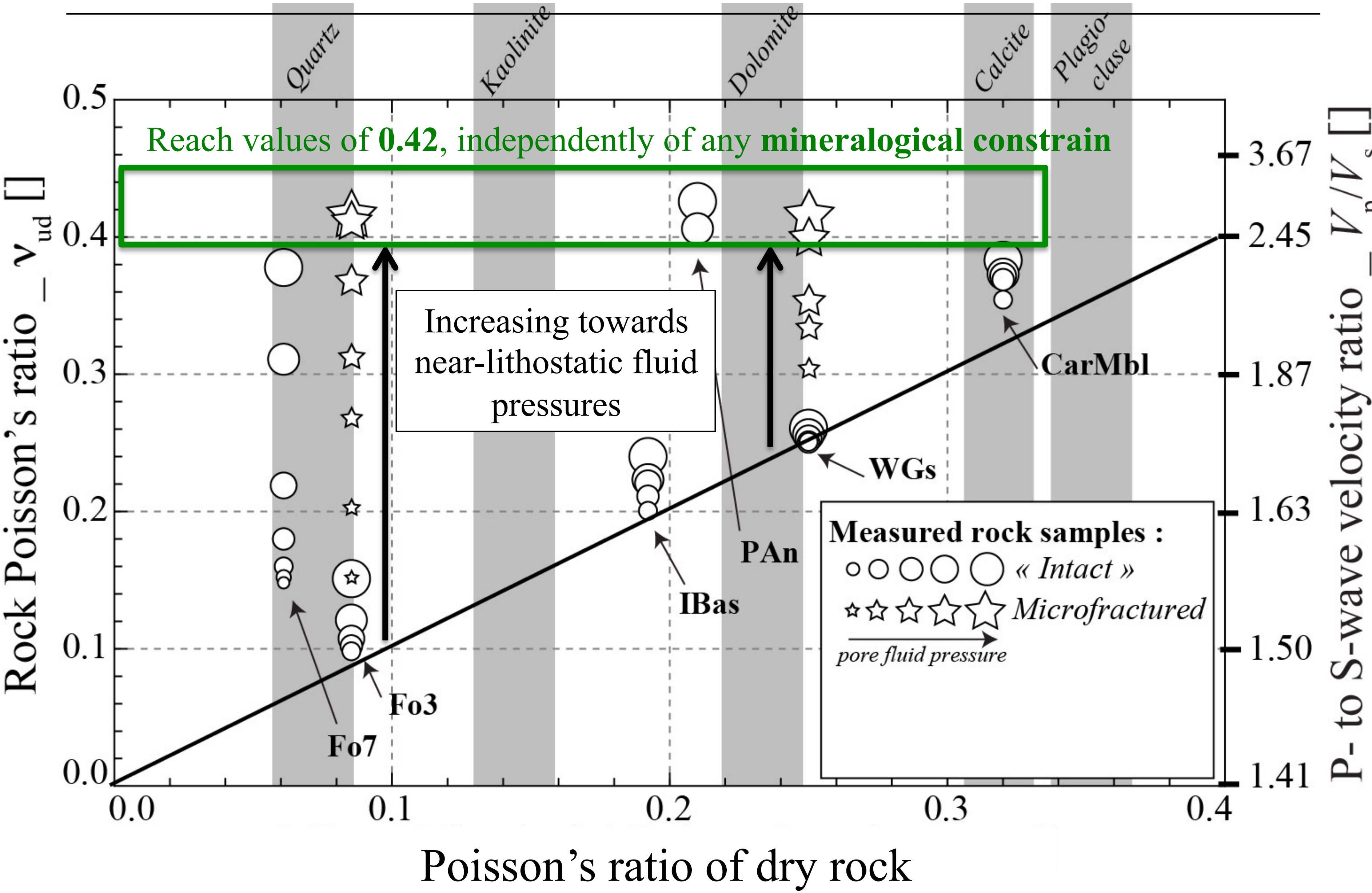
Pimienta et al. (2018), ***GRL***

Results *Measurements of undrained Poisson's ratio*



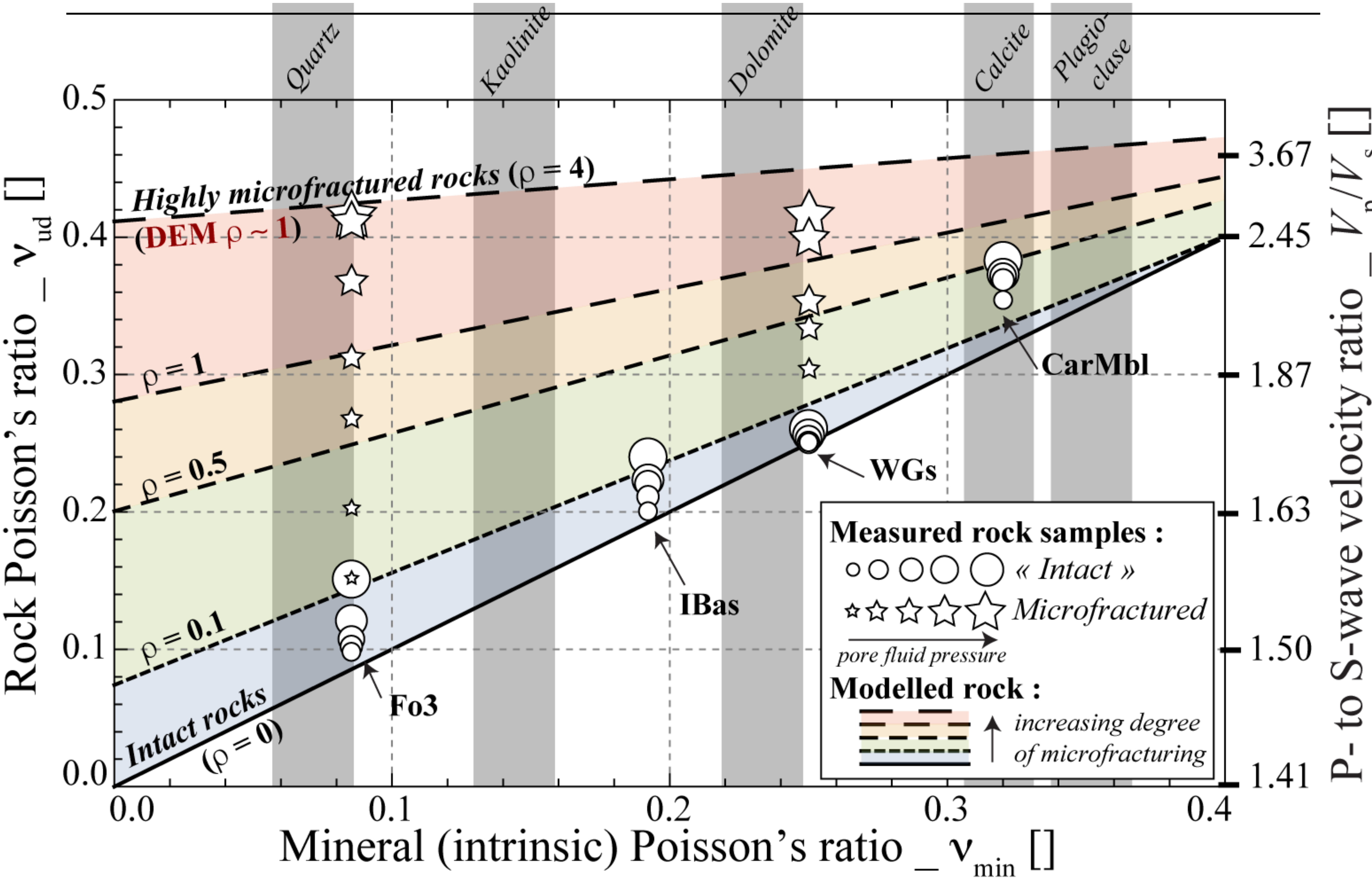
Measurements at varying fluid pressures in various isotropic crustal rocks ranging in mineralogy

Results ***Measurements** of undrained Poisson's ratio*



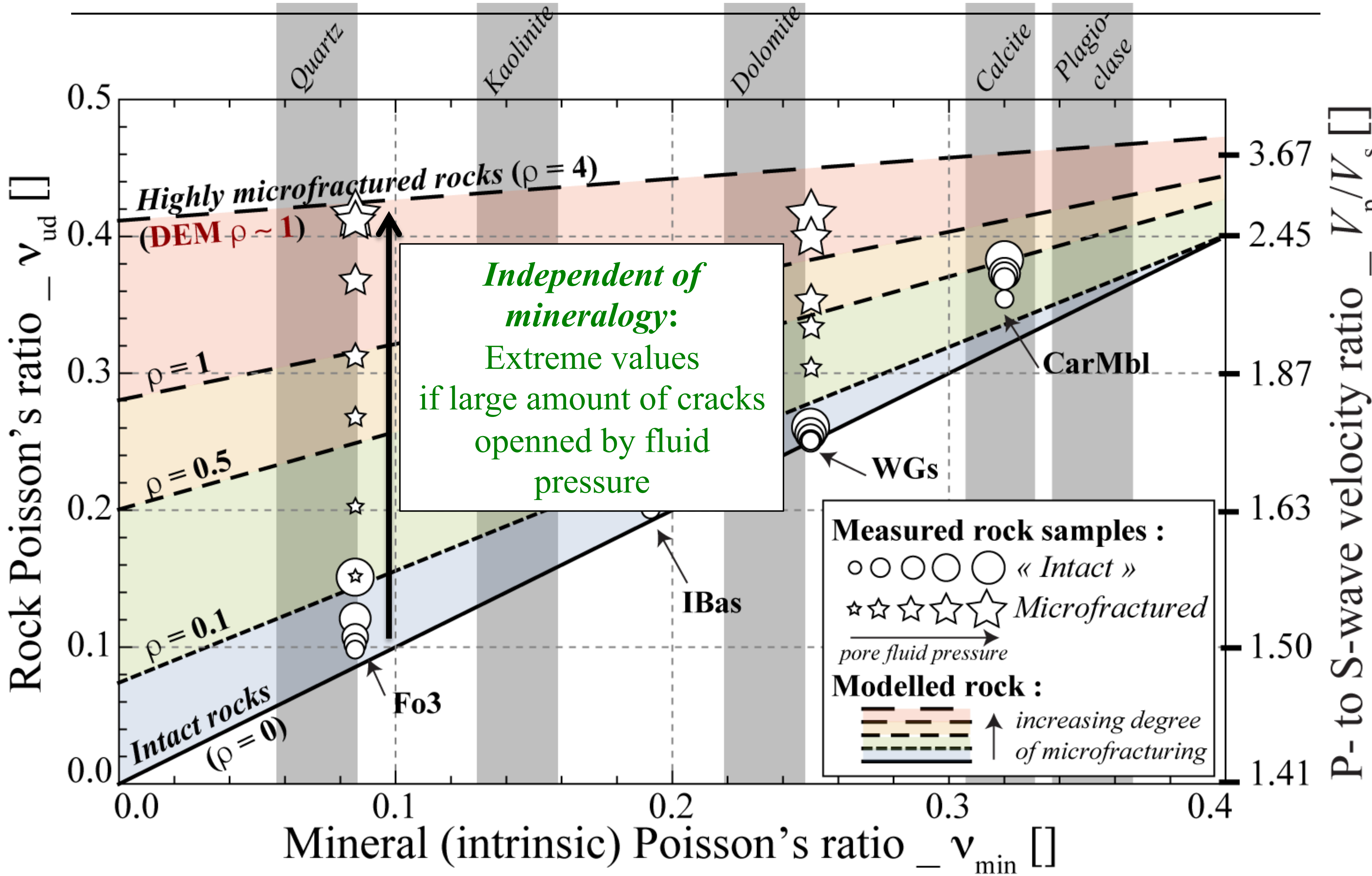
Measurements at varying fluid pressures in various isotropic crustal rocks ranging in mineralogy

Results *Simple model for undrained Poisson's ratio*



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

Results *Simple model for undrained Poisson's ratio*



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

CONCLUSION

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

1. Directly infer $(V_p/V_s)_{field}$ **from** $(V_p/V_s)_{lab}$?
=> **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 openned 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* $(V_p/V_s)_{field}$ *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} m^2.

For further information, please refer to

Pimienta, L., Schubnel, A., Violay, M., Fortin, J., Guéguen, Y. & Lyon Caen, H., (**2018**): Anomalous Vp/Vs ratios at seismic frequencies might evidence highly damaged rocks in subduction zones, *Geophysical Research Letters*, **45**. (doi: 10.1029/2018GL080132)

Hoping for your interest and questions,

Thank you

L. Pimienta[1], A. Schubnel[2], J. Fortin[2], Y. Guéguen[2], H. Lyon-Caen[2] & M. Violay[1]

[1]*Lab. of Exp. Rock Mechanics (LEMR),* EPFL, *Switzerland*

[2]*Lab. of Geology, Ecole Normale Superieure (*ENS), *France*

dépasser les frontières

LETTRES SCIENCES ÉCOLE NORMALE SUPÉRIEURE

EPFL

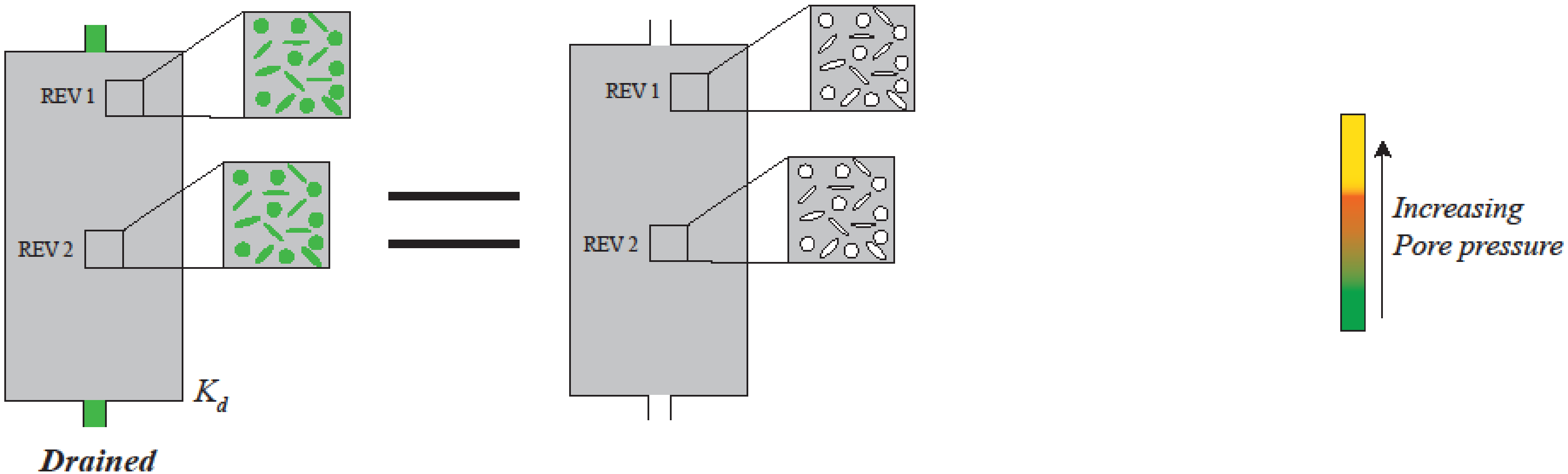
REFERENCES

- ✓ Audet, P., Bostock, M. G., Christensen, N. I., & Peacock, S. M. (2009). Seismic evidence for overpressured subducted oceanic crust and megathrust fault sealing. Nature, 457(7225), 76–78.
- ✓ Audet, P., & Bürgmann, R. (2014). Possible control of subduction zone slow-earthquake periodicity by silica enrichment. Nature, 510(7505), 389–392.
- ✓ Audet, P., & Kim, Y. H. (2016). Teleseismic constraints on the geological environment of deep episodic slow earthquakes in subduction zone forearcs: A review. Tectonophysics, 670, 1–15.
- ✓ Christensen, N. I. (1984). Pore pressure and oceanic crustal seismic structure. Geophysical Journal of the Royal Astronomical Society, 79(2), 411–423.
- ✓ Christensen, N. I. (1996). Poisson's ratio and crustal seismology. Journal of Geophysical Research, 101(B2), 3139–3156.
- ✓ Kodaira, S. (2004). High Pore Fluid Pressure May Cause Silent Slip in the Nankai Trough. 318 Science, 304(5675), 319 1295–1298.
- ✓ Peacock, S. M., Christensen, N. I., Bostock, M. G., & Audet, P. (2011). High pore pressures and porosity at 35 km depth in the Cascadia subduction zone. Geology, 39(5), 471–474.
- ✓ Pimienta, L., Borgomano, J. V. M., Fortin, J., & Guéguen, Y. (2017). Elastic dispersion and attenuation in fully saturated sandstones: Role of mineral content, porosity, and pressures. Journal of Geophysical Research, 122, 9950–9965.
- ✓ Pimienta, L., Fortin, J., & Guéguen, Y. (2016). Effect of fluids and frequencies on Poisson's ratio of sandstone samples. Geophysics, 81(2), D183–D195.
- ✓ Pride, S. R., Berryman, J. G., & Harris, J. M. (2004). Seismic attenuation due to wave-induced flow. *Journal of Geophysical Research: Solid Earth*, *109*(B1).
- ✓ Wang, X. Q., Schubnel, A., Fortin, J., David, E. C., Gueguen, Y., & Ge, H.-K. (2012). High Vp/Vs ratio: Saturated cracks or anisotropy effects? Geophysical Research Letters, 39, L11307.
- ✓ Winkler, K., & Nur, A. (1979) Pore fluids and seismic attenuation in rocks. Geophysical Research Letters, **6**, 1–4.

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



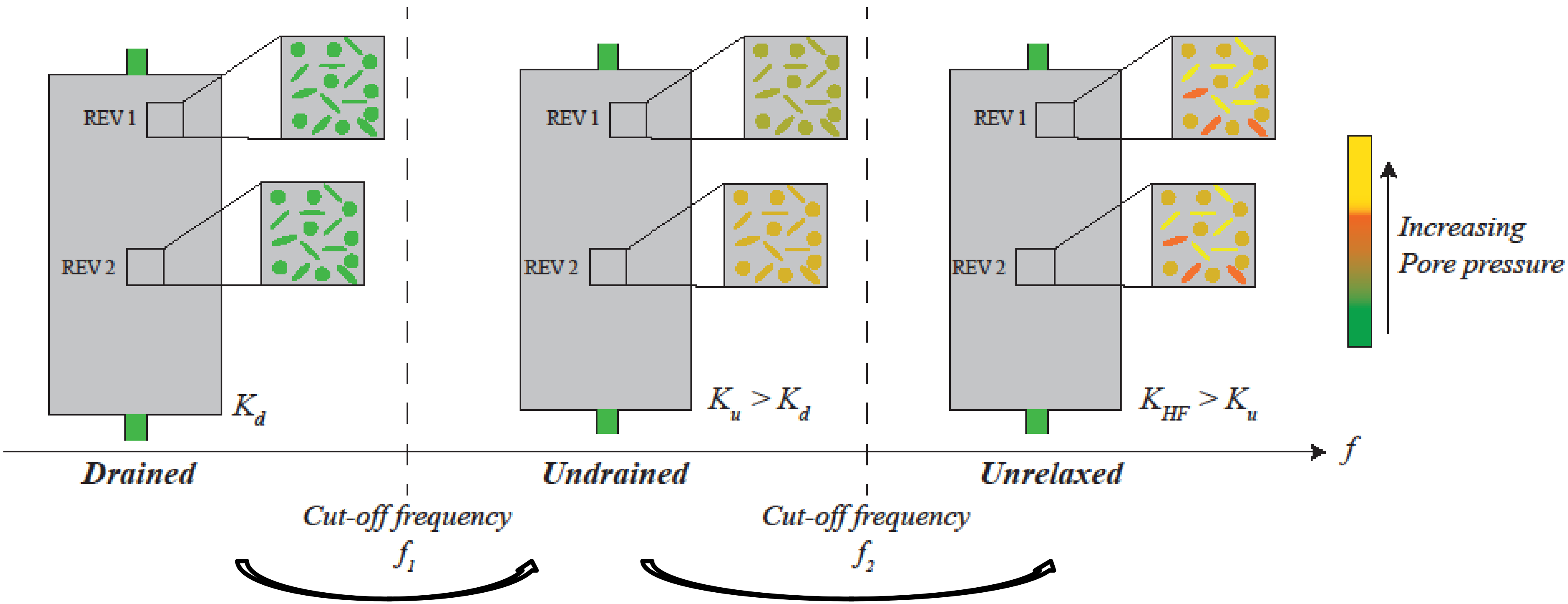
Elastic constants **independent** of the fluid

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

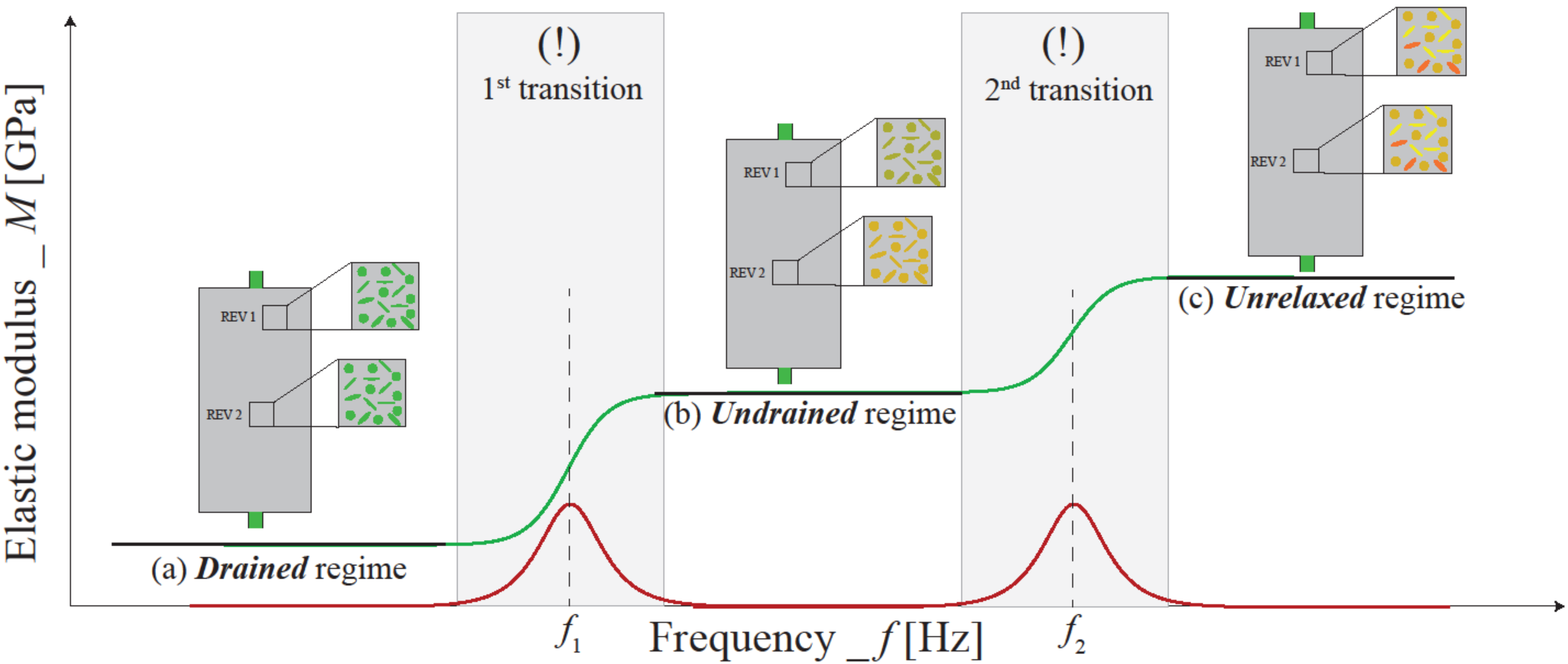
Isolated inclusions: 3rd ***mechanical*** regime
→ ***Unrelaxed*** ⇔ Fluid overpressure dependent on the **geometry** of the inclusion



e.g. Cleary (1978) **e.g. O'Connell & Budiansky (1977)**

Higher **Viscosity** ↔ Lower fluid **velocity**
Higher **Frequency** ↔ Shorter **time** for flow

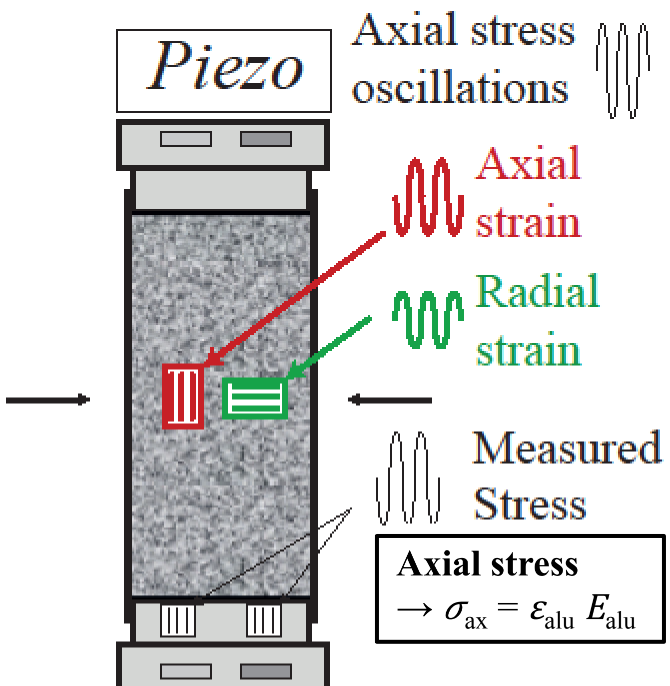
SuppMat.: *Frequency dependence in a fluid-saturated rock ?*



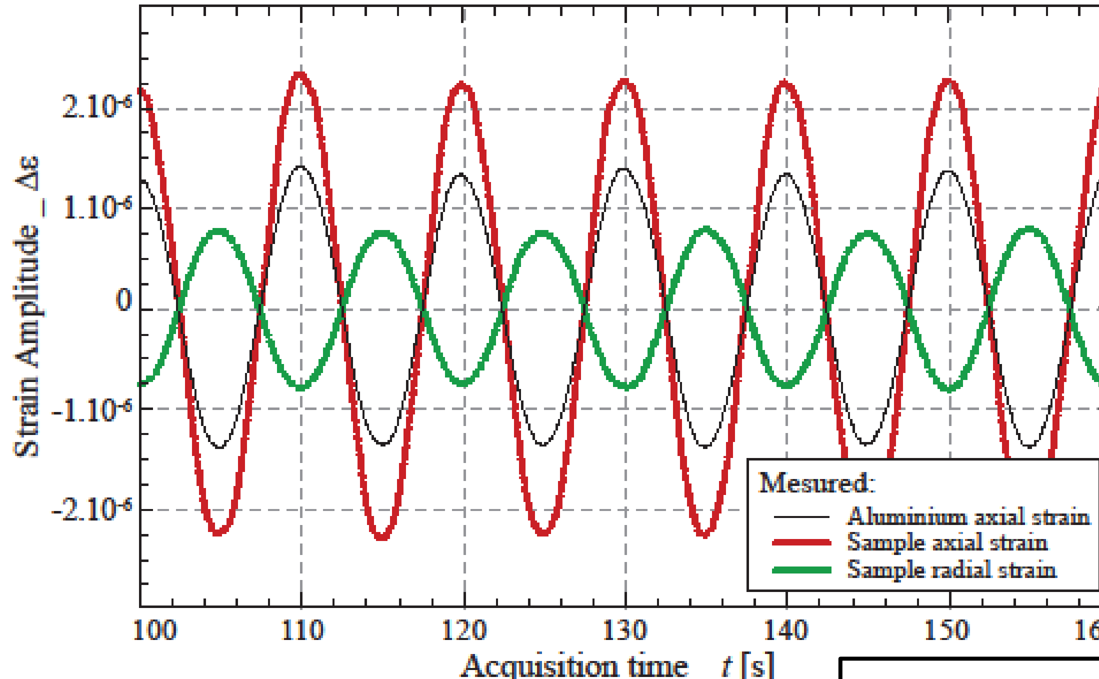
Experimental validation in e.g.
Pimienta et al. (2015a; 2015b)

SuppMat.: *Principle for measurements*

“Axial” solicitation



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



Gypsum sample

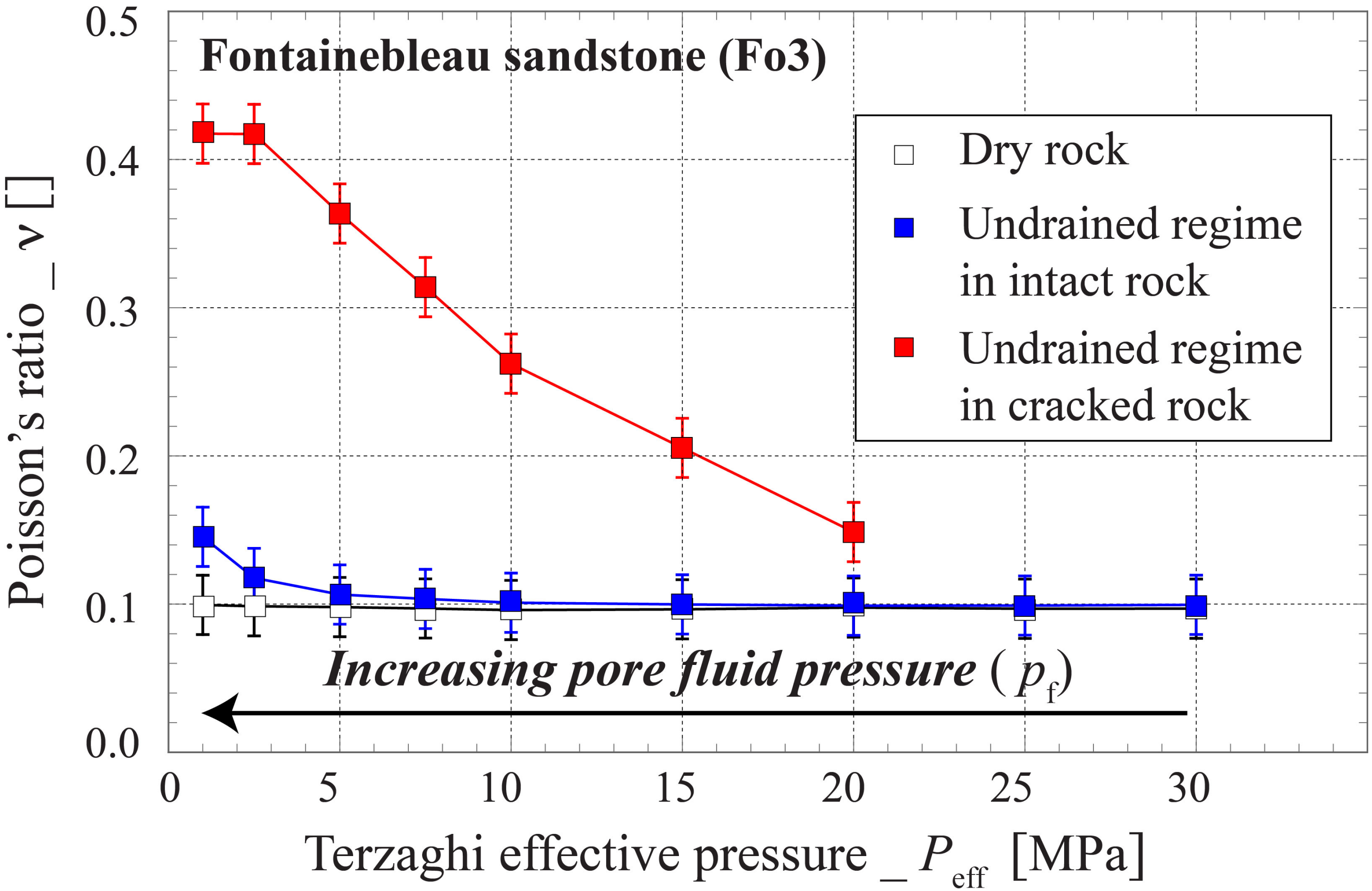
$\rightarrow P_c \sim 1$ MPa
$\rightarrow f \sim 0{,}1$ Hz

⇨ **Elastic** response:

→ Amplitude ratio => $\boldsymbol{E_{LF}}$ **&** $\boldsymbol{\nu_{LF}}$

→ Phase shift => $\boldsymbol{Q_E^{-1}}$ **&** $\boldsymbol{Q_\nu^{-1}}$

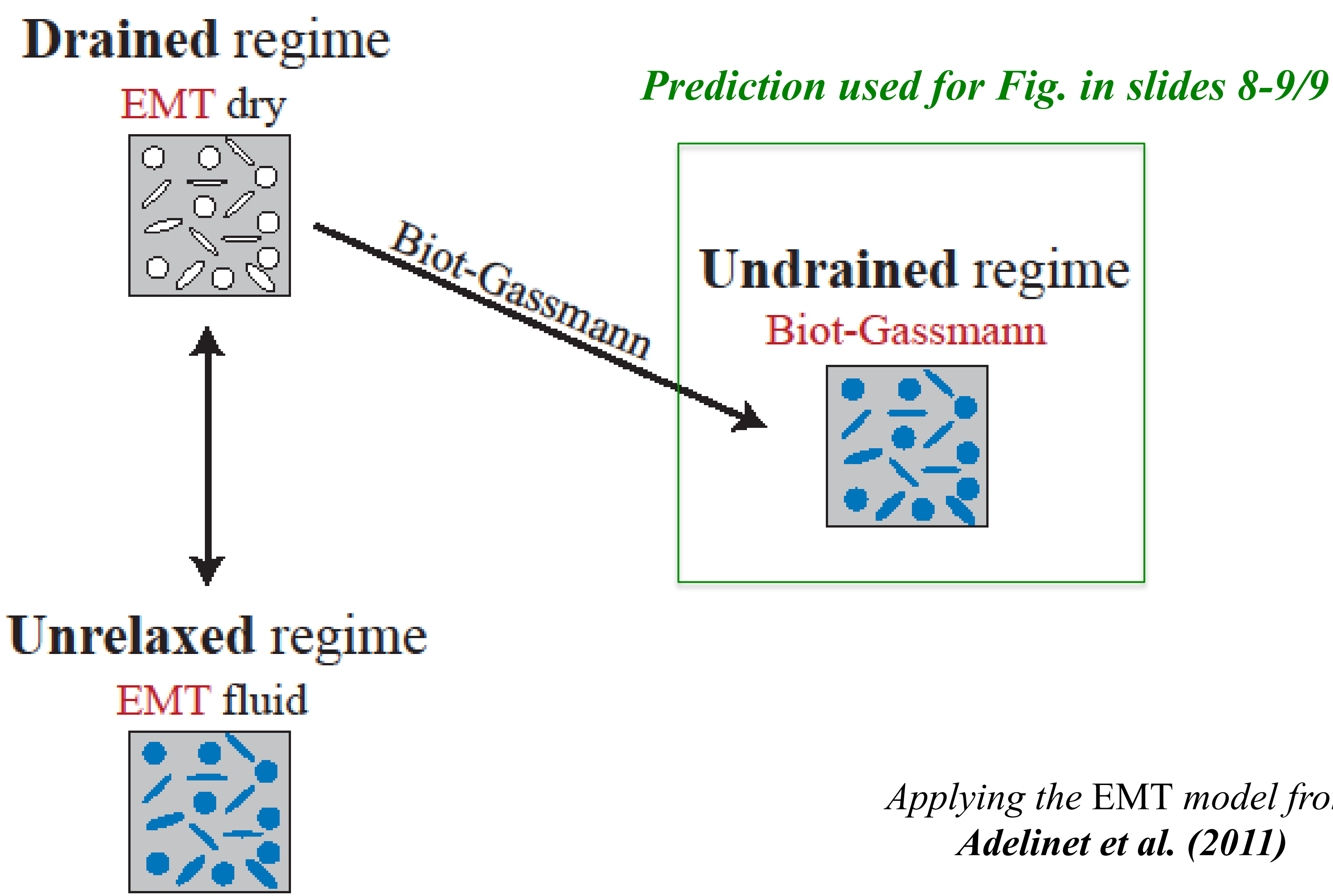
SuppMat.: *Drained & Undrained vs effective pressure*



Datasets used for Fig. in slides 6-9/9

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)***