Our research & What we do

PHYSICS OF ROCKS

BRITTLE
PLASTIC

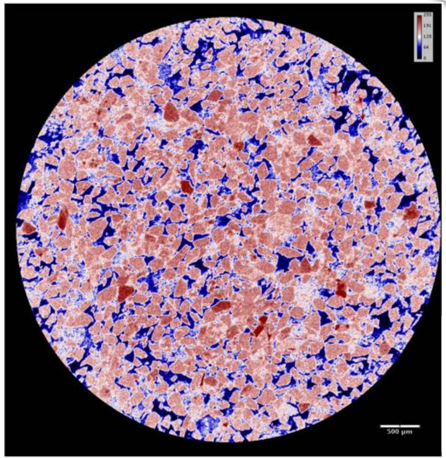
HYDRAULIC

THERMAL

ELASTICITY
Poroelasticity
viscoelasticity

FRICTIONAL

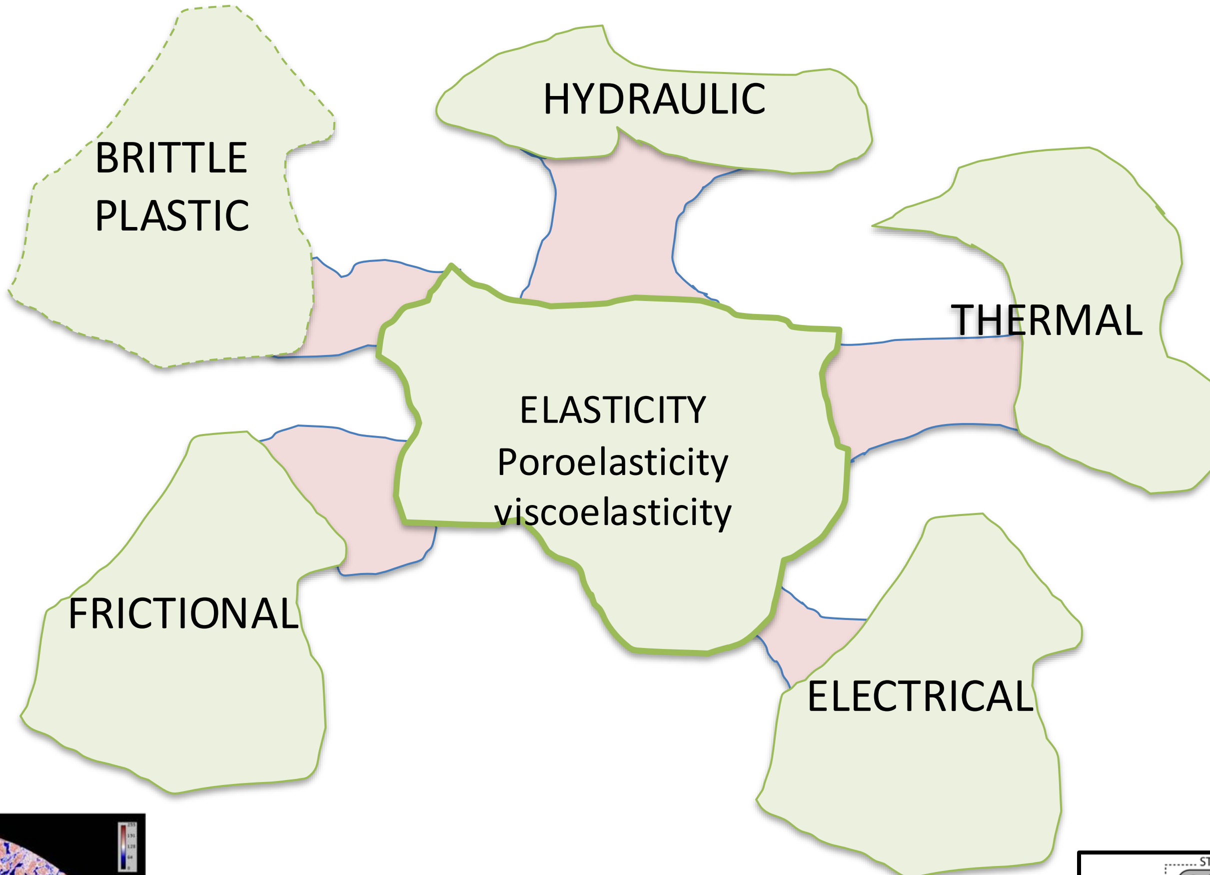
ELECTRICAL

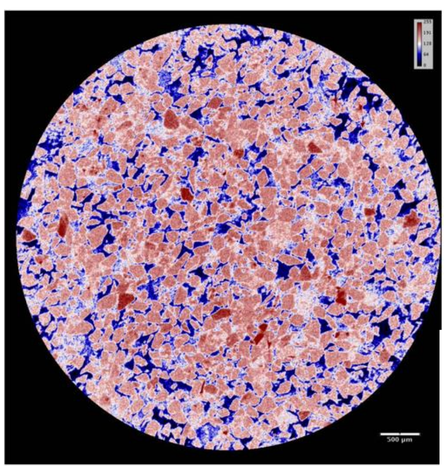


CT scan image of Berea sandstone (Rocketh repository)

Our research & What we do

PHYSICS OF ROCKS





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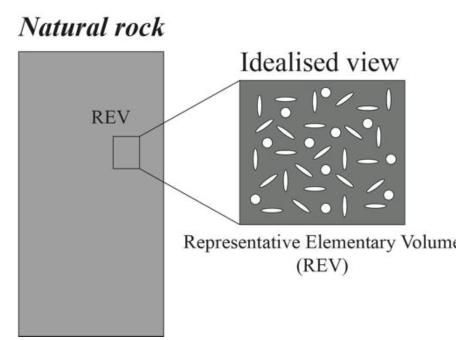
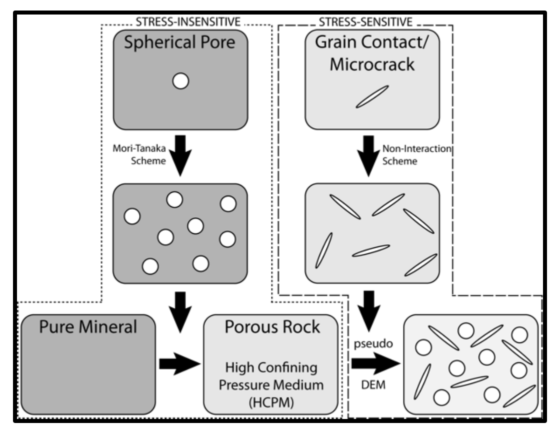
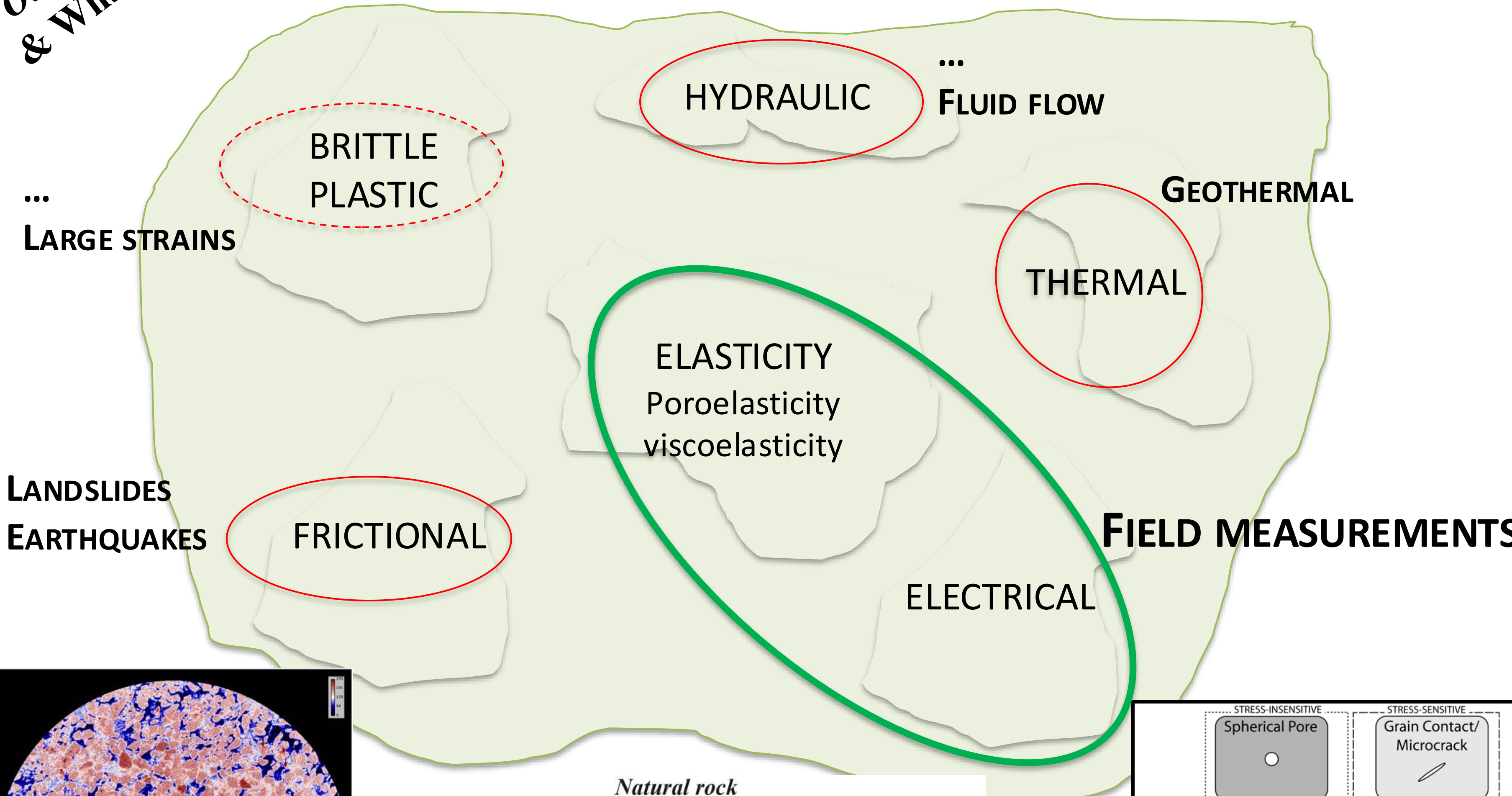
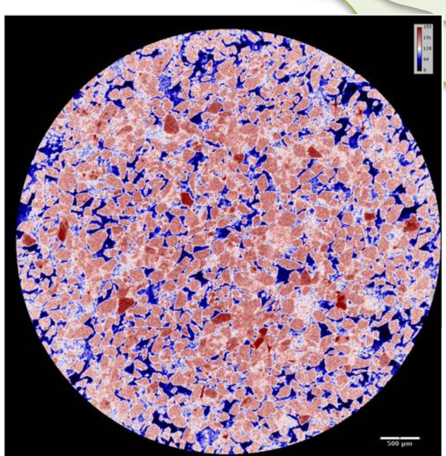




Our research & What we do

Physics of Rocks





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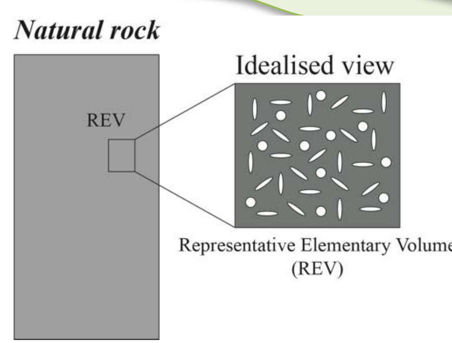
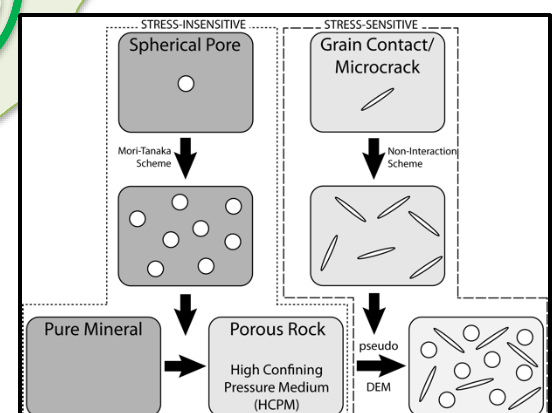
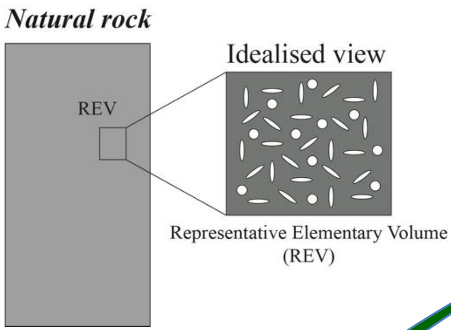




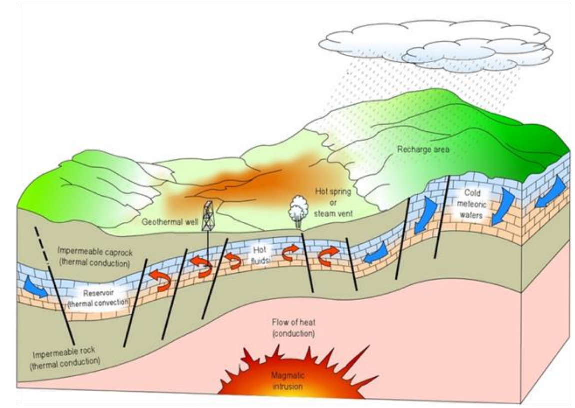
Poroelastic; Hydraulic; Electrical;
Thermal; Frictional; Dissipative

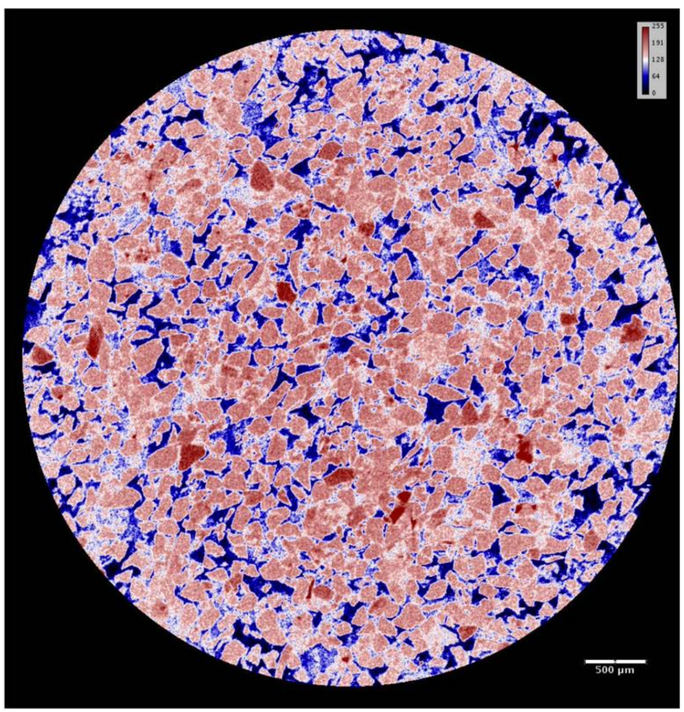


Laboratory Experiments

cm --> nm-μm --> km

... **the scales** !?





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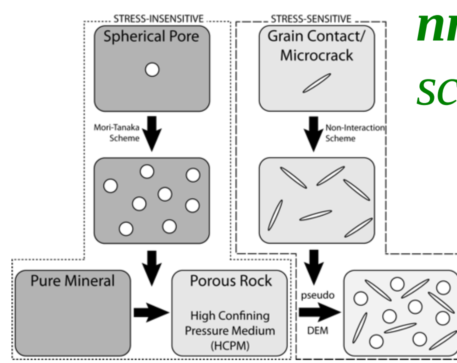
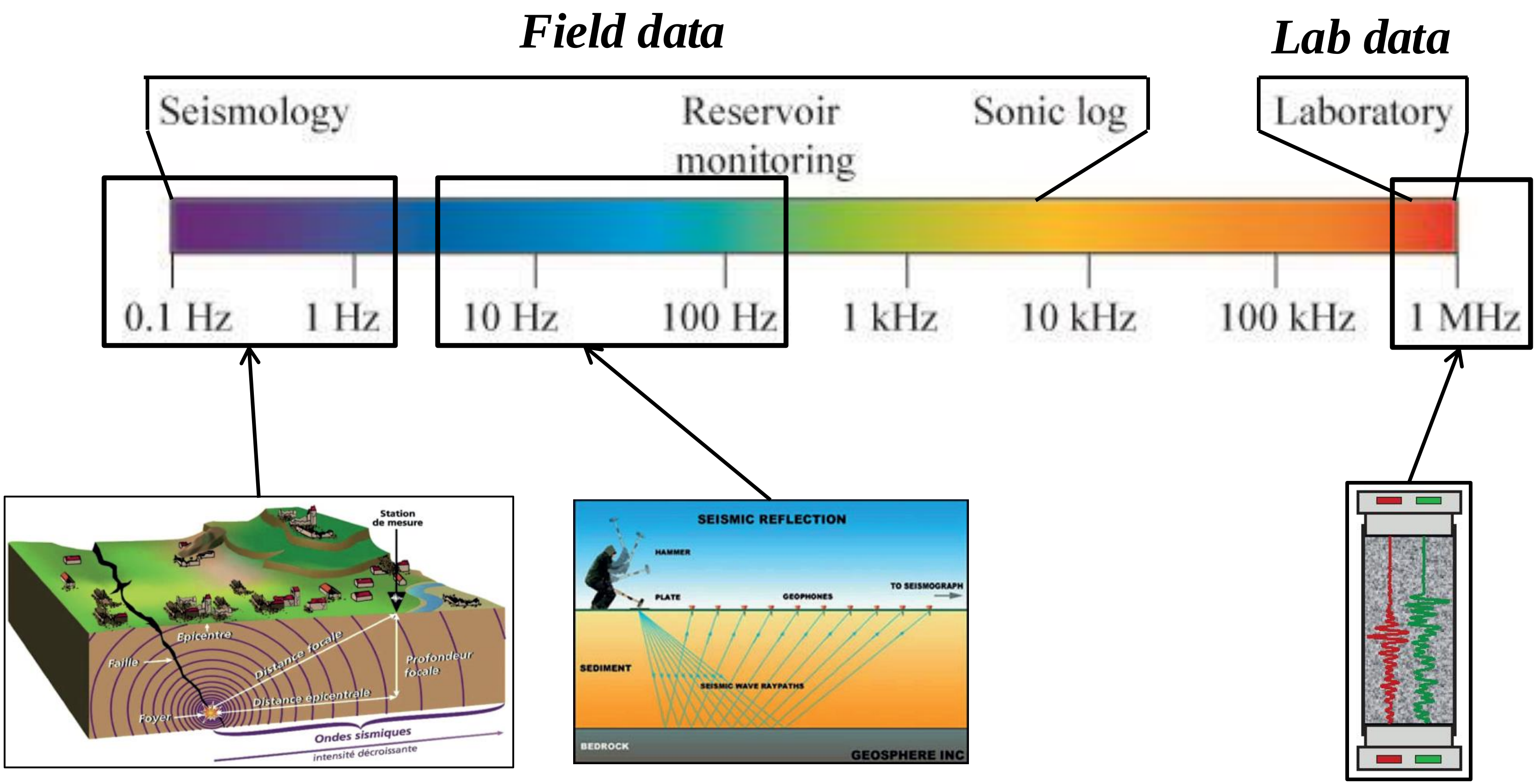


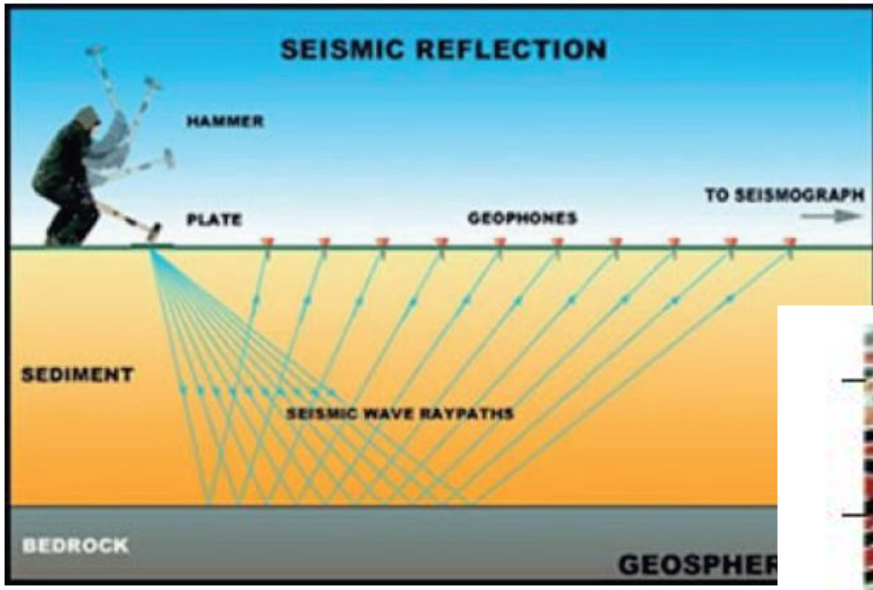
nm-μm
scale

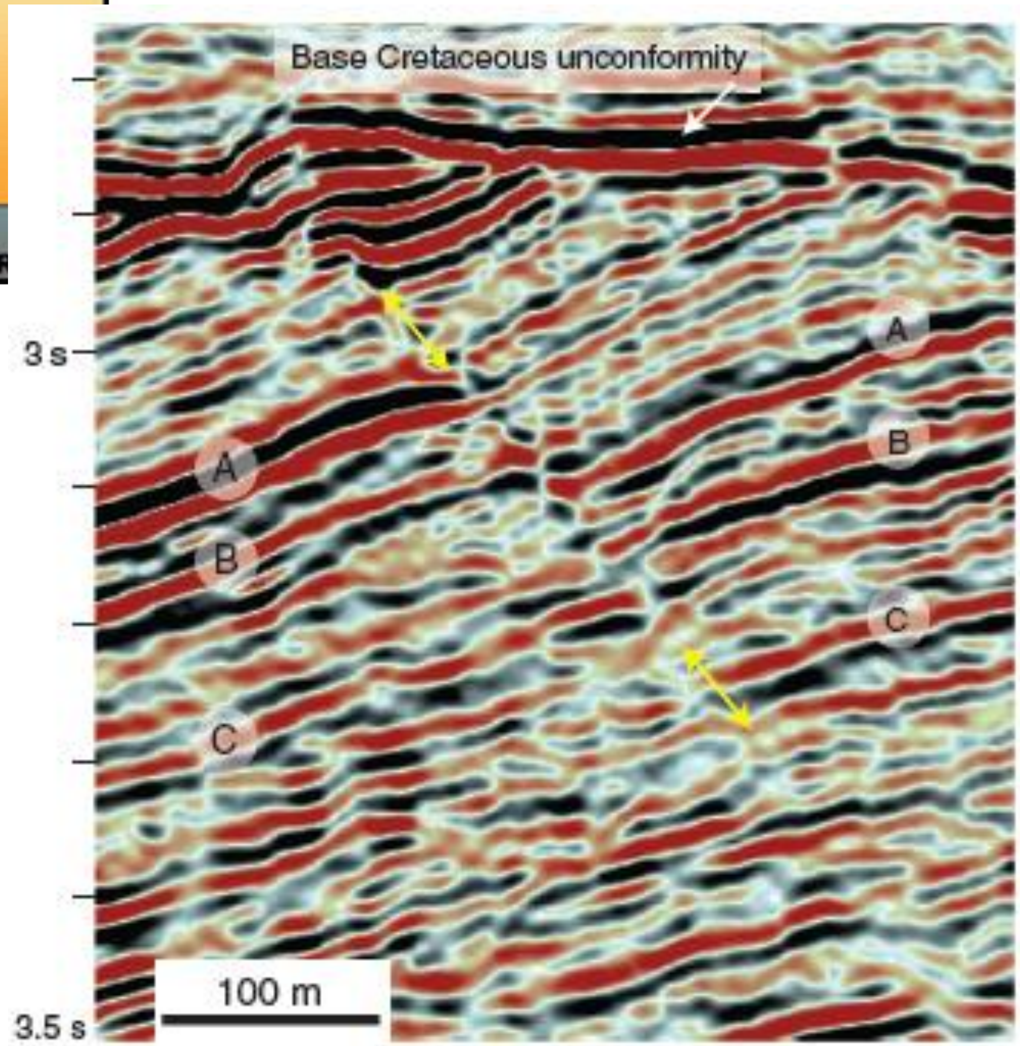
μm-mm
scale

Seismic **Attenuations** in rocks
⇔ Rocks elastic & **dissipative** properties



Seismics


SEISMIC REFLECTION
HAMMER
PLATE
GEOPHONES
TO SEISMOGRAPH
SEDIMENT
SEISMIC WAVE RAYPATHS
BEDROCK
GEOSPHER

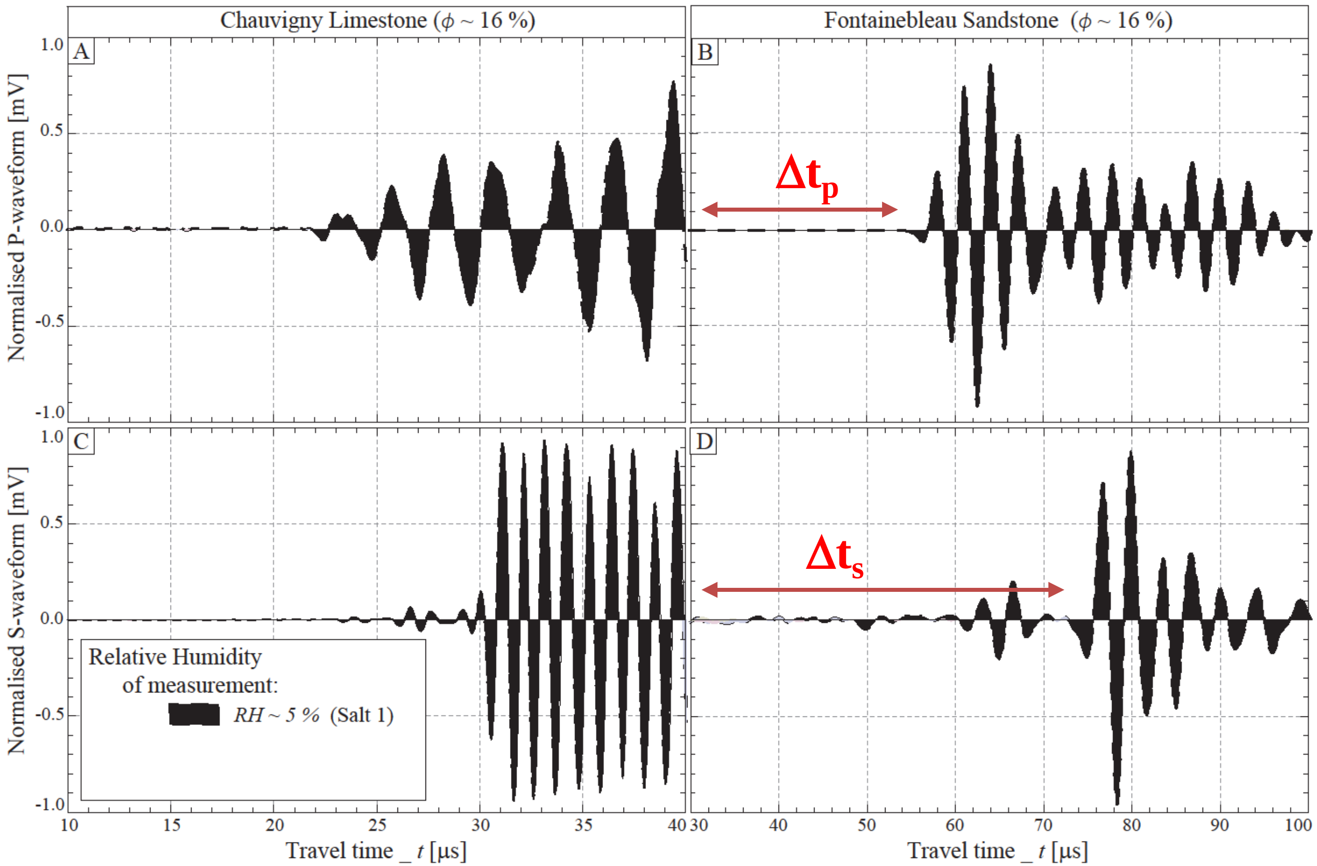

Base Cretaceous unconformity
3 s
3.5 s
A
B
C
A
B
C
100 m

Velocity of waves :

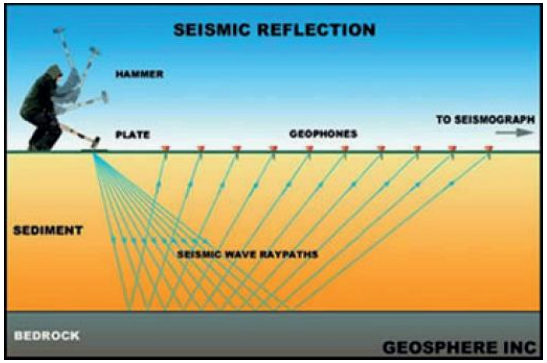
Δt <=> Travelled distance (hence travel time)

(1-D) Wave equation

$$\rho \frac{\partial^2 u}{\partial t^2} = M(\omega) \frac{\partial^2 u}{\partial x^2}$$

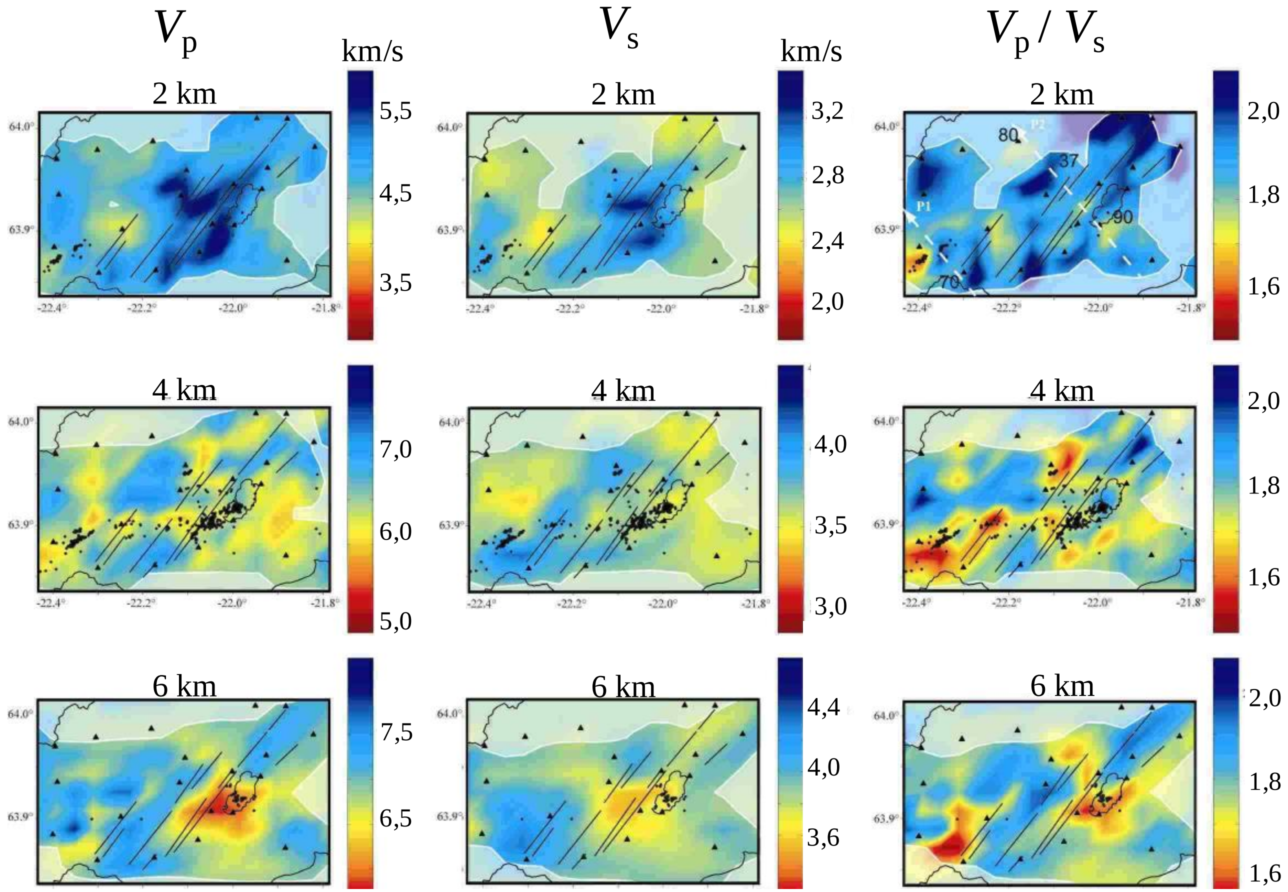


Seismics



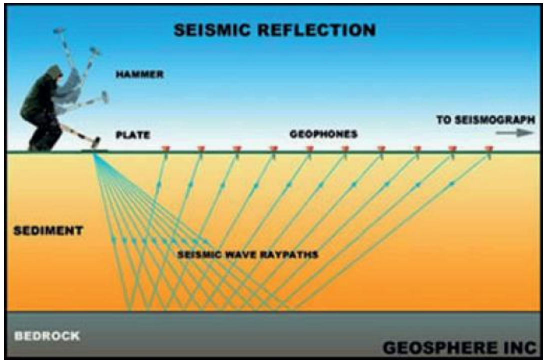
Inverse problem

=> Rocks, fluids, P-T from mechanical properties



Geoffroy and Dorbath (2008), ***GRL***

Seismics

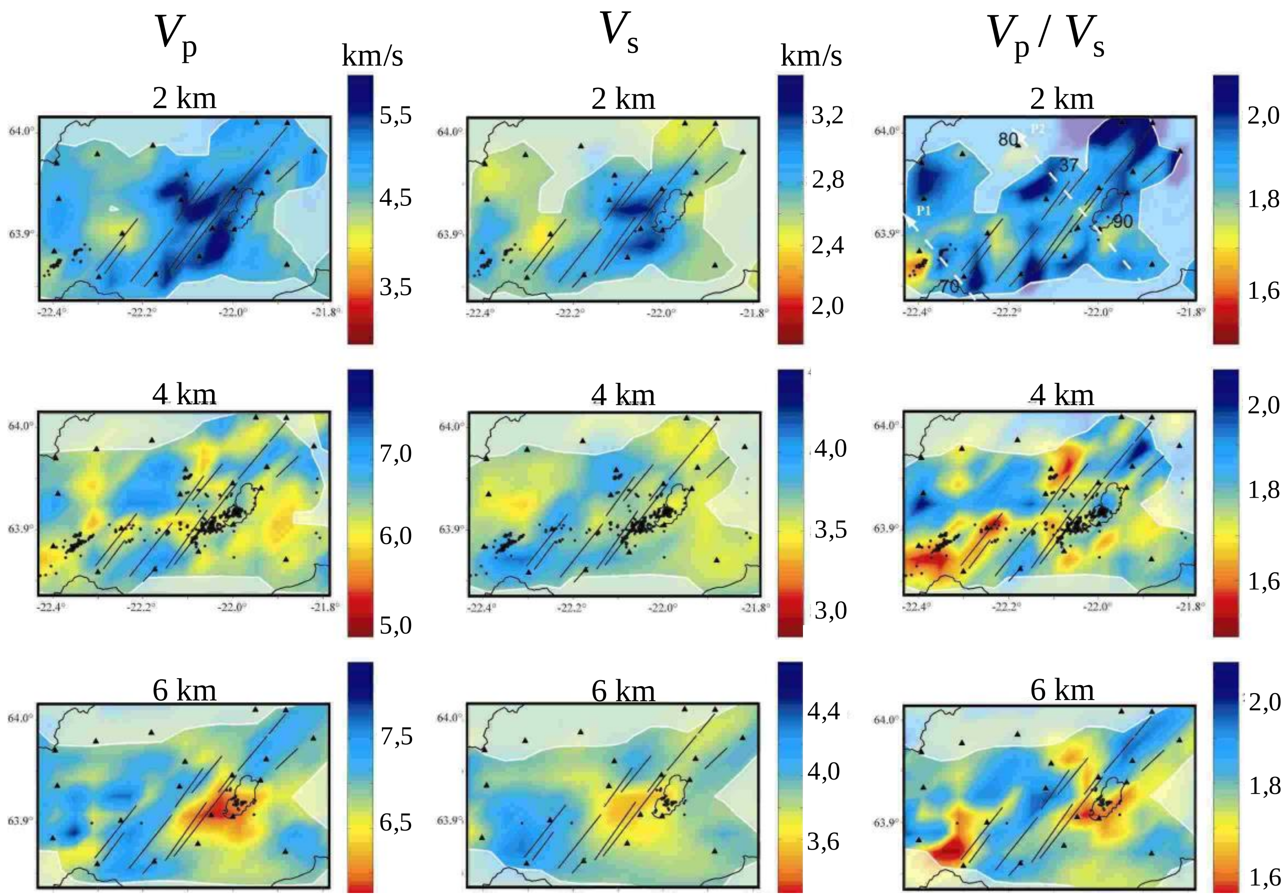


Inverse problem

=> Rocks, fluids, P-T from mechanical properties

V_p & V_s

⇔ 2 independent informations



<u>**IF**</u> *isotropic medium*
⇔ *Only 2 elastic constants to characterise the rock*

$$V_p = \sqrt{\frac{K + 4/3G}{\rho}} \qquad V_s = \sqrt{\frac{G}{\rho}}$$

linear reversible elasticity

Velocity of waves :

Δt <=> Travelled distance (hence travel time)

Attenuation of waves :

α <=> Decay over travelled distance (& travel time) ⇔ *Sesimology*

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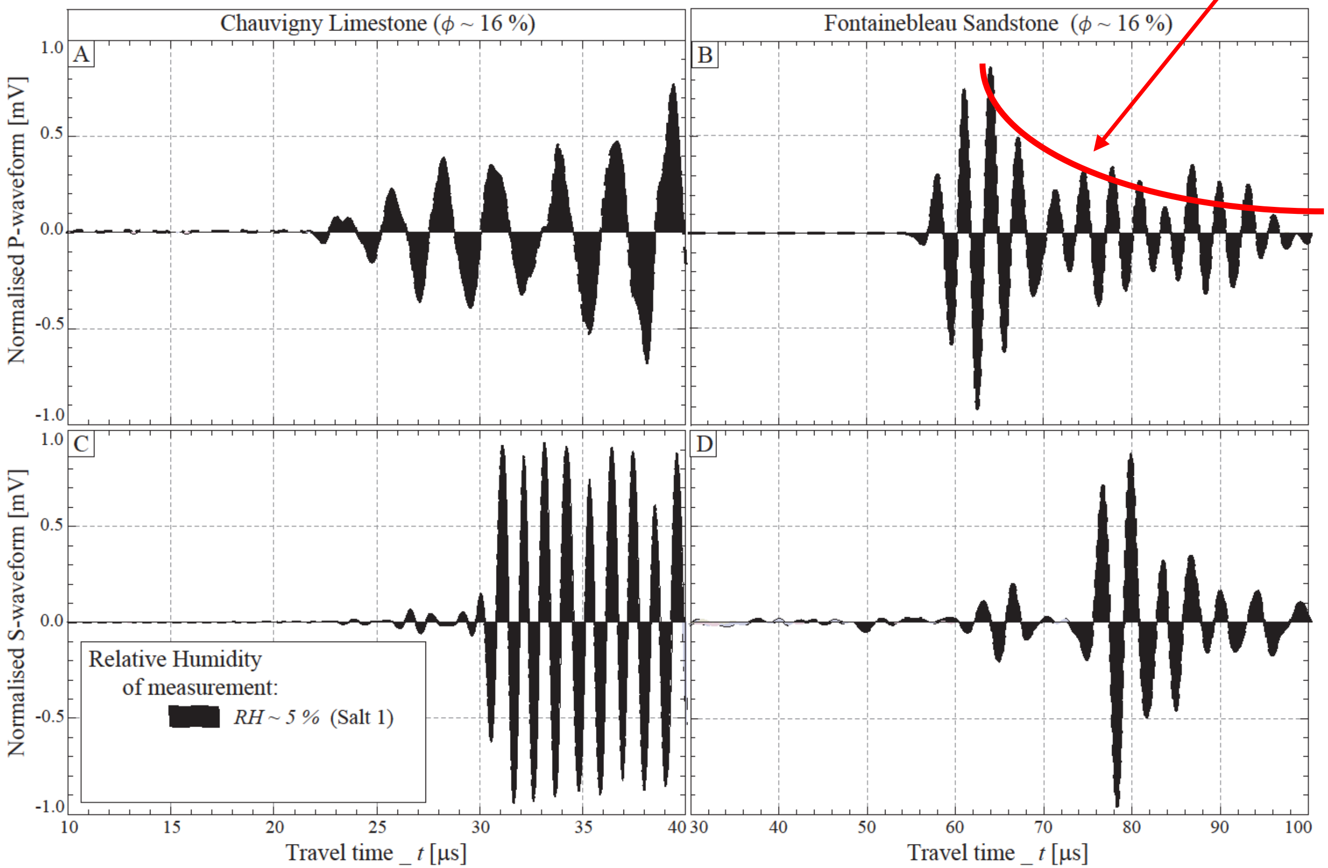
$$u = e^{-\alpha x} e^{i\omega(t-x/c)}$$



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Attenuation of waves :

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<=> Wave energy loss (e.g. from adsorption) ⇔ *4D seismic*

Caracterised as Q_p & Q_s

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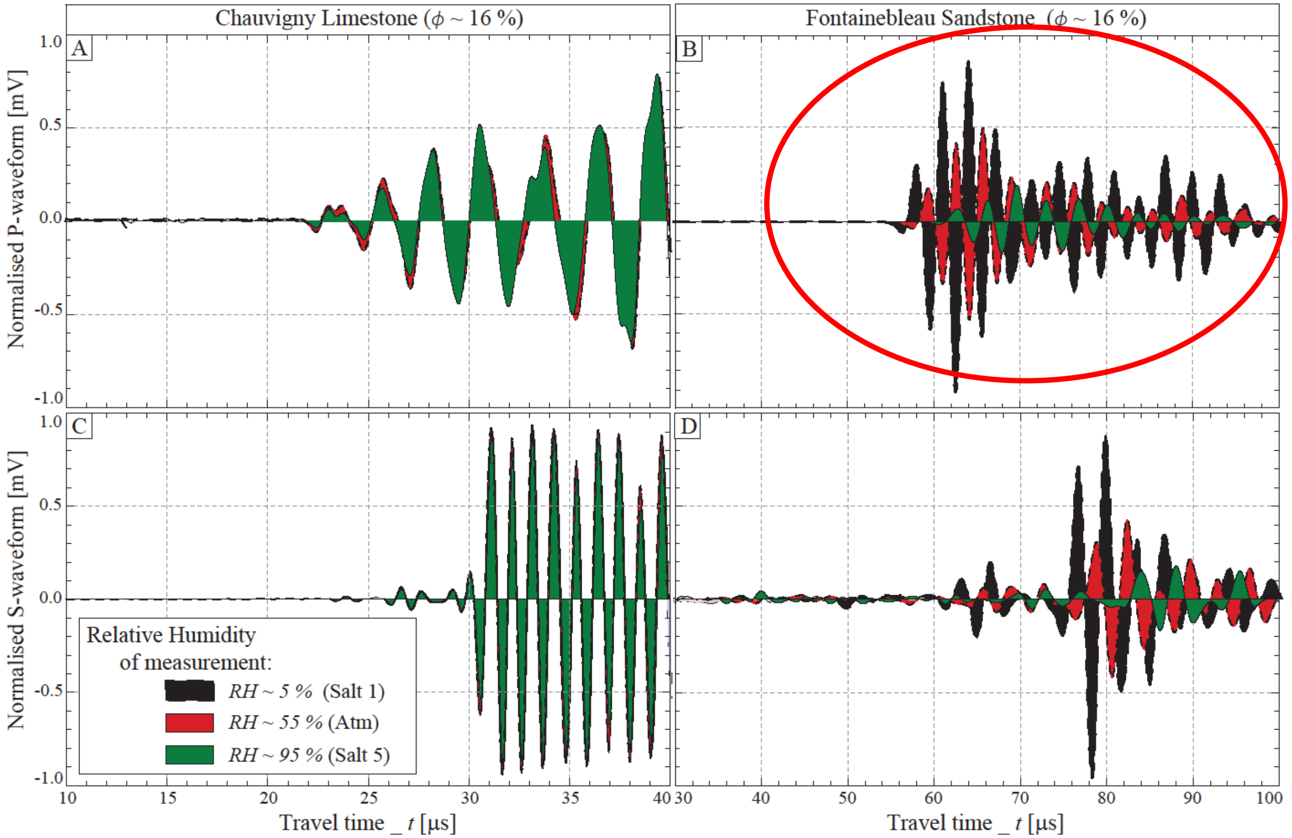

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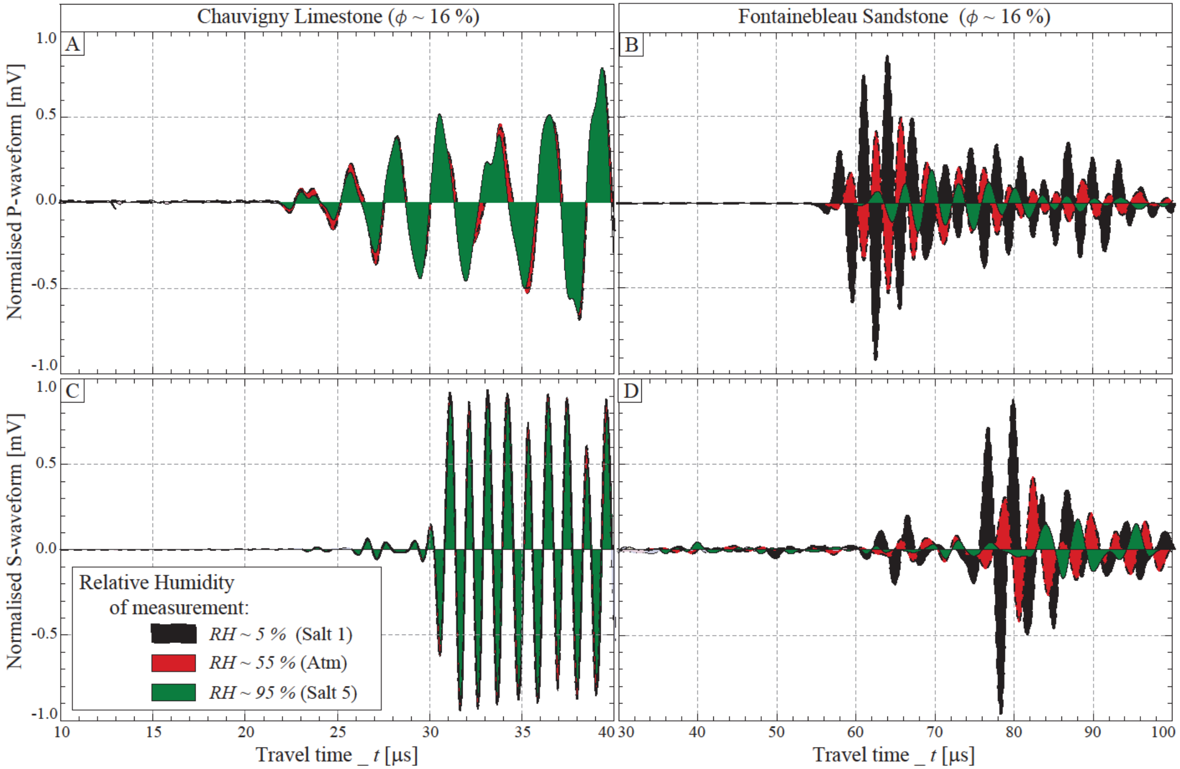
$$\alpha = \omega v_I / (v_R^2 + v_I^2) \quad , \quad c = (v_R^2 + v_I^2)/v_R$$

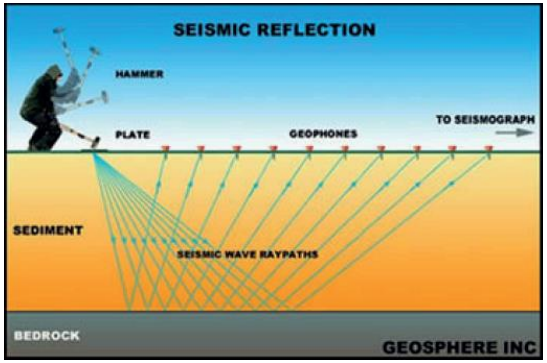
$$v_R + i v_I = \sqrt{M(\omega)/\rho}$$



- Imaginary = 0 ⇔ α = 0

- Imaginary > 0 ⇔ *wave energy absorbed*

Seismics

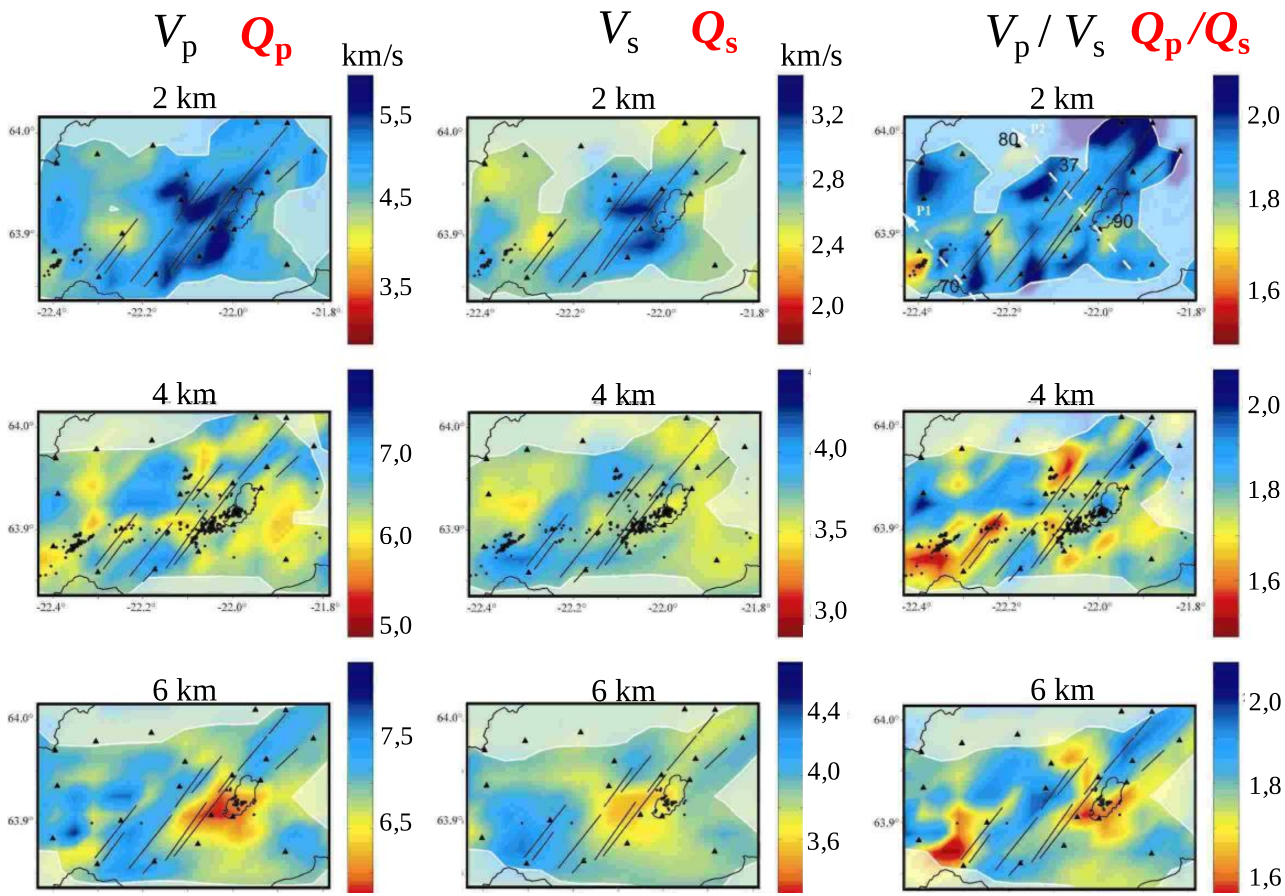


Inverse problem

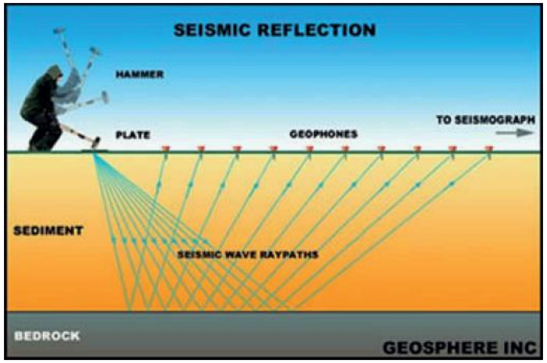
=> Rocks, fluids, P-T from mechanical properties

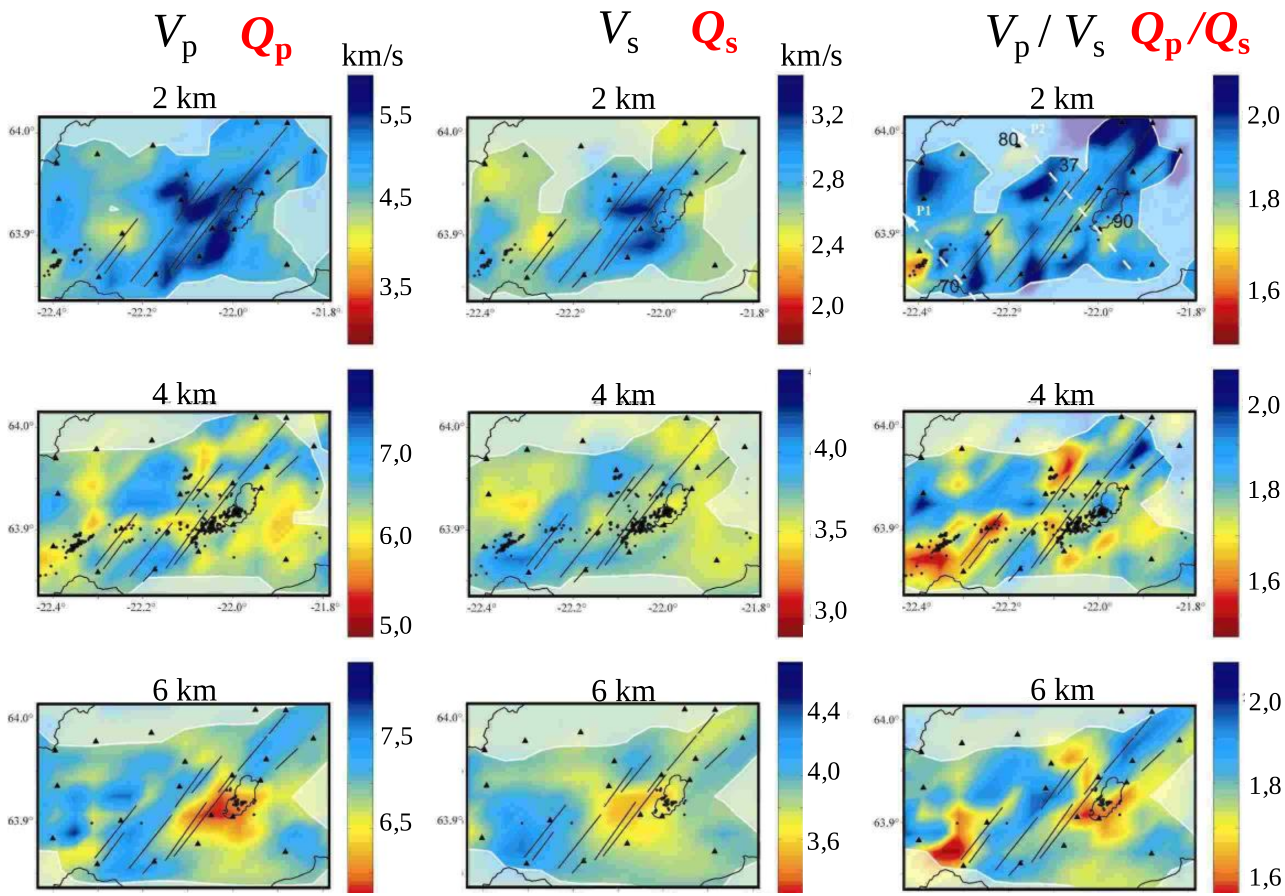
V_p & V_s & Q_p & Q_s

⇔ **4** independent informations !?



Seismics





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=> Rocks, fluids, P-T from mechanical properties

V_p & V_s & Q_p & Q_s

⇔ 4 independent informations !?

IF *isotropic medium*

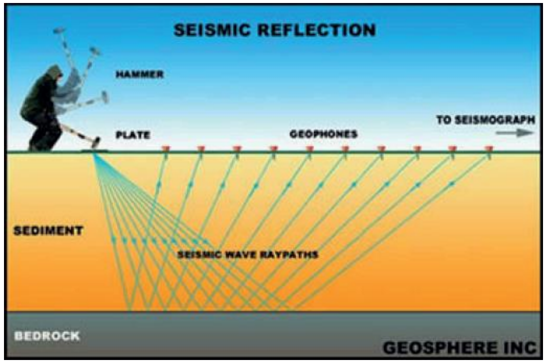
⇔ *Only 2 viscoelastic constants to characterise the rock*

$$\frac{(1-\nu)(1-2\nu)}{Q_P} = \frac{1+\nu}{Q_E} - \frac{2\nu(2-\nu)}{Q_S}$$

$$\frac{1+\nu}{Q_K} = \frac{3(1-\nu)}{Q_P} - \frac{2(1-2\nu)}{Q_S}$$

linear reversible viscoelasticity

Seismics



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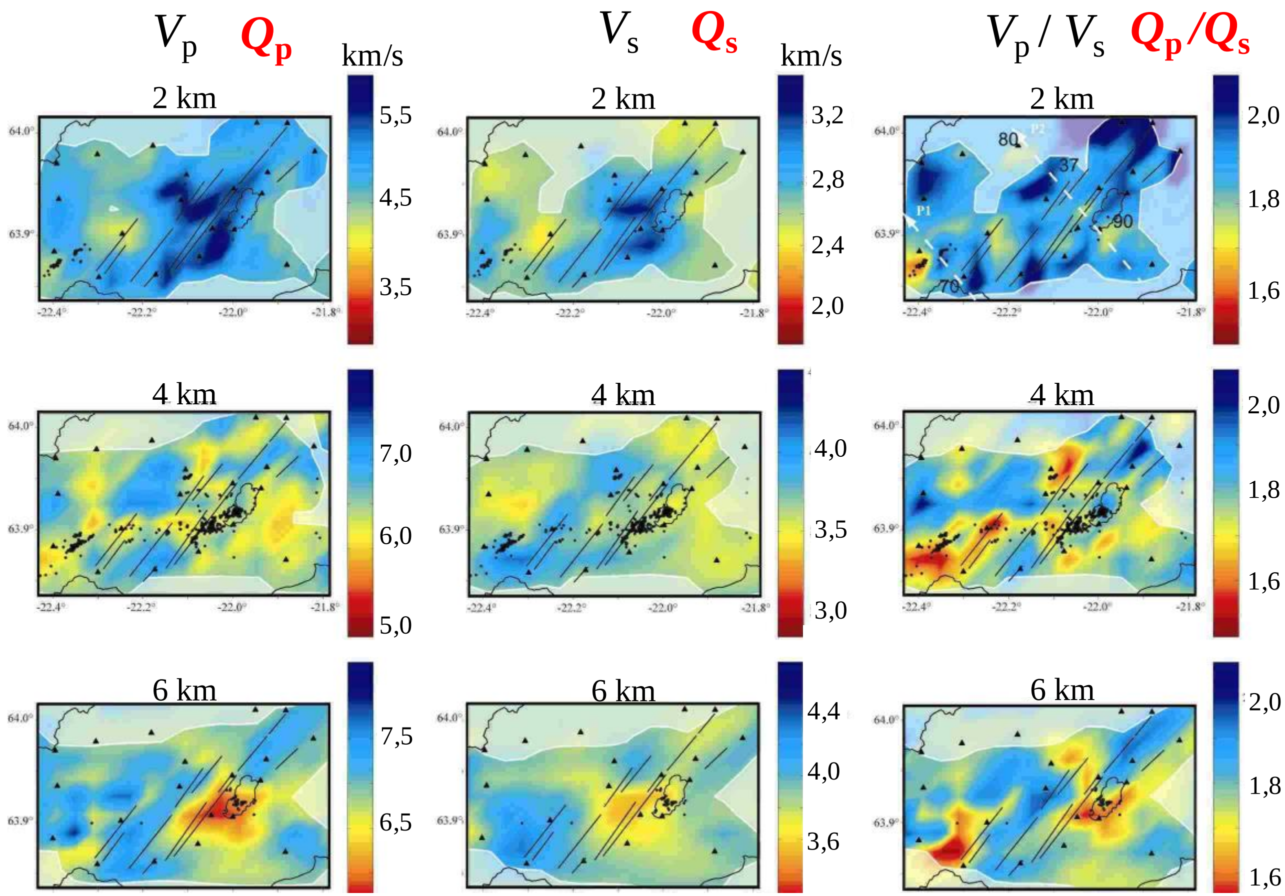

$$\frac{1+\nu}{Q_K} = \frac{3(1-\nu)}{Q_P} - \frac{2(1-2\nu)}{Q_S}$$

__IF__ *isotropic medium*

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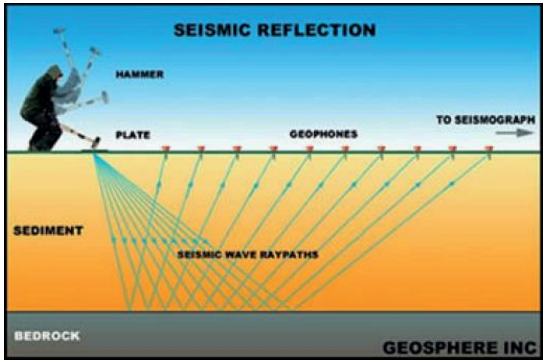
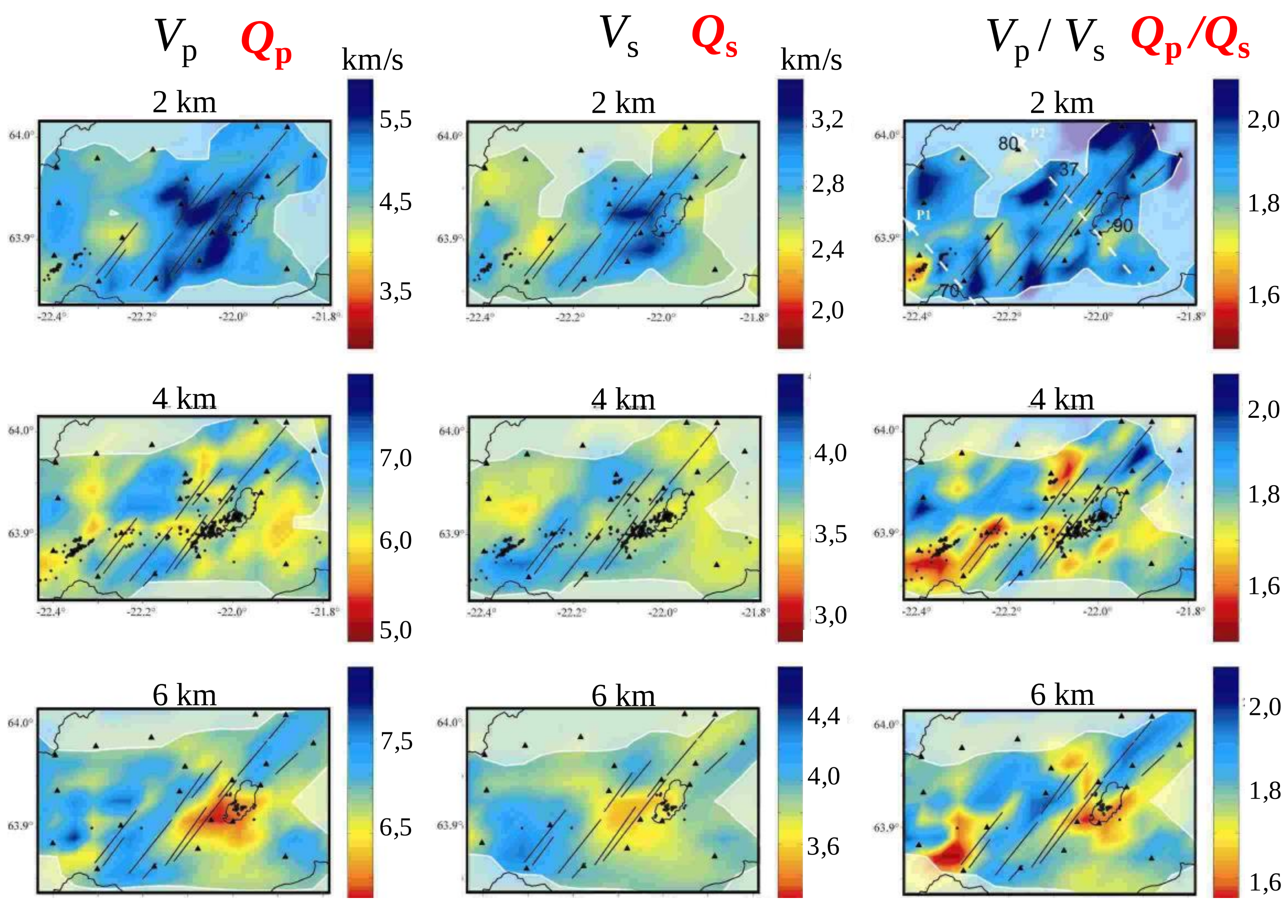
linear reversible viscoelasticity

$$V_p = \sqrt{\frac{K + 4/3G}{\rho}} \qquad V_s = \sqrt{\frac{G}{\rho}}$$

Complex quantities

Seismics





Inverse problem

=> Rocks, fluids, P-T from mechanical properties

V_p & V_s & Q_p & Q_s

⇔ **4** independent informations !?

Limit:

Precise knowledge of ***elastic &*** ***dissipative properties*** in fluid-saturated crustal rock/reservoirs

Seismic **Attenuations** in rocks
⇔ Rocks elastic & **dissipative** properties

Attenuation is an intrinsic rock property

$$\rho \frac{\partial^2 u}{\partial t^2} = M(\omega) \frac{\partial^2 u}{\partial x^2}$$

$$u = e^{-\alpha x} e^{i\omega(t-x/c)}$$

$$\alpha = \omega v_I / (v_R^2 + v_I^2) \quad , \quad c = (v_R^2 + v_I^2)/v_R$$

$$v_R + i v_I = \sqrt{M(\omega)/\rho}$$

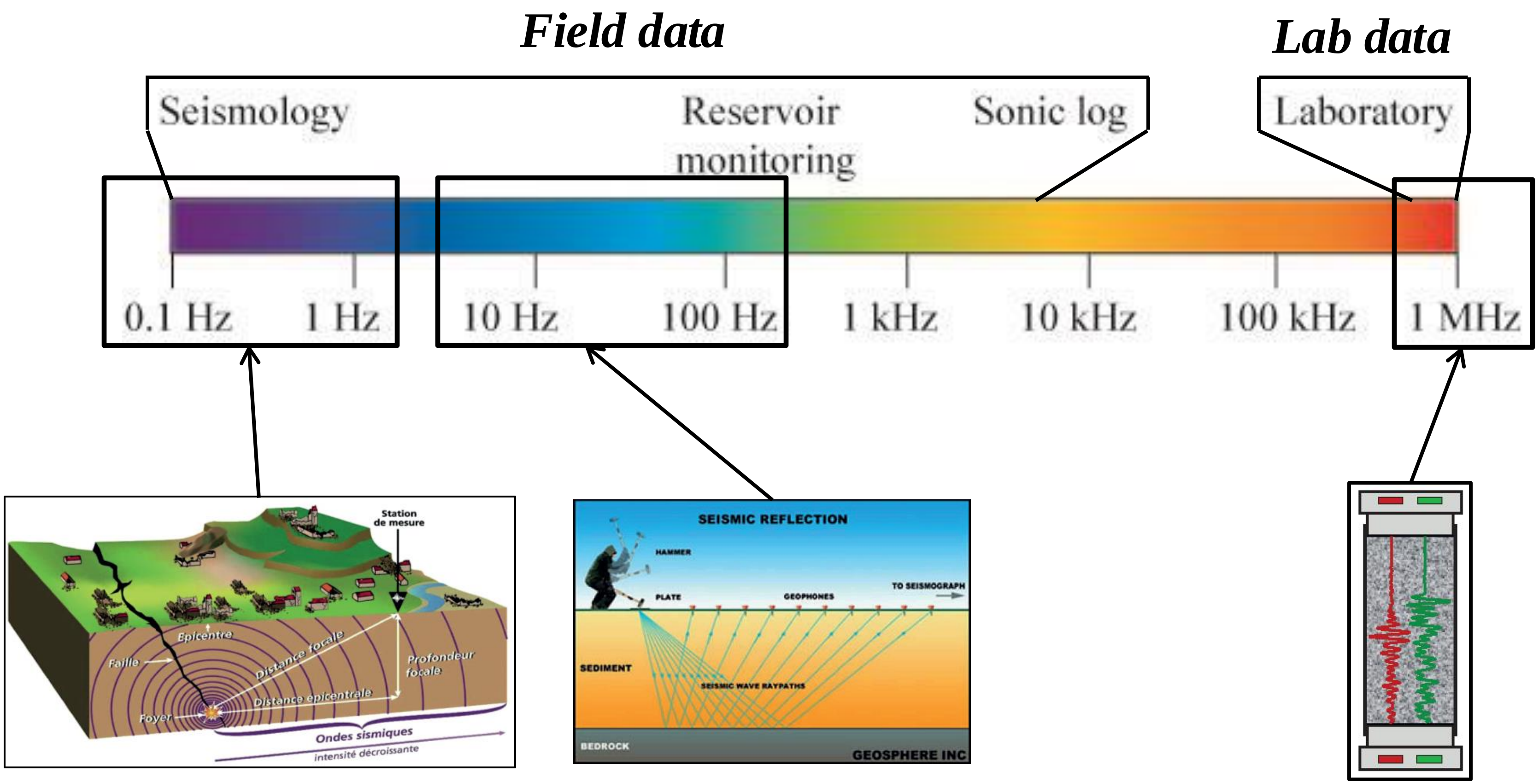
Realm of linear rev. viscoelasticity

Why do we care ?

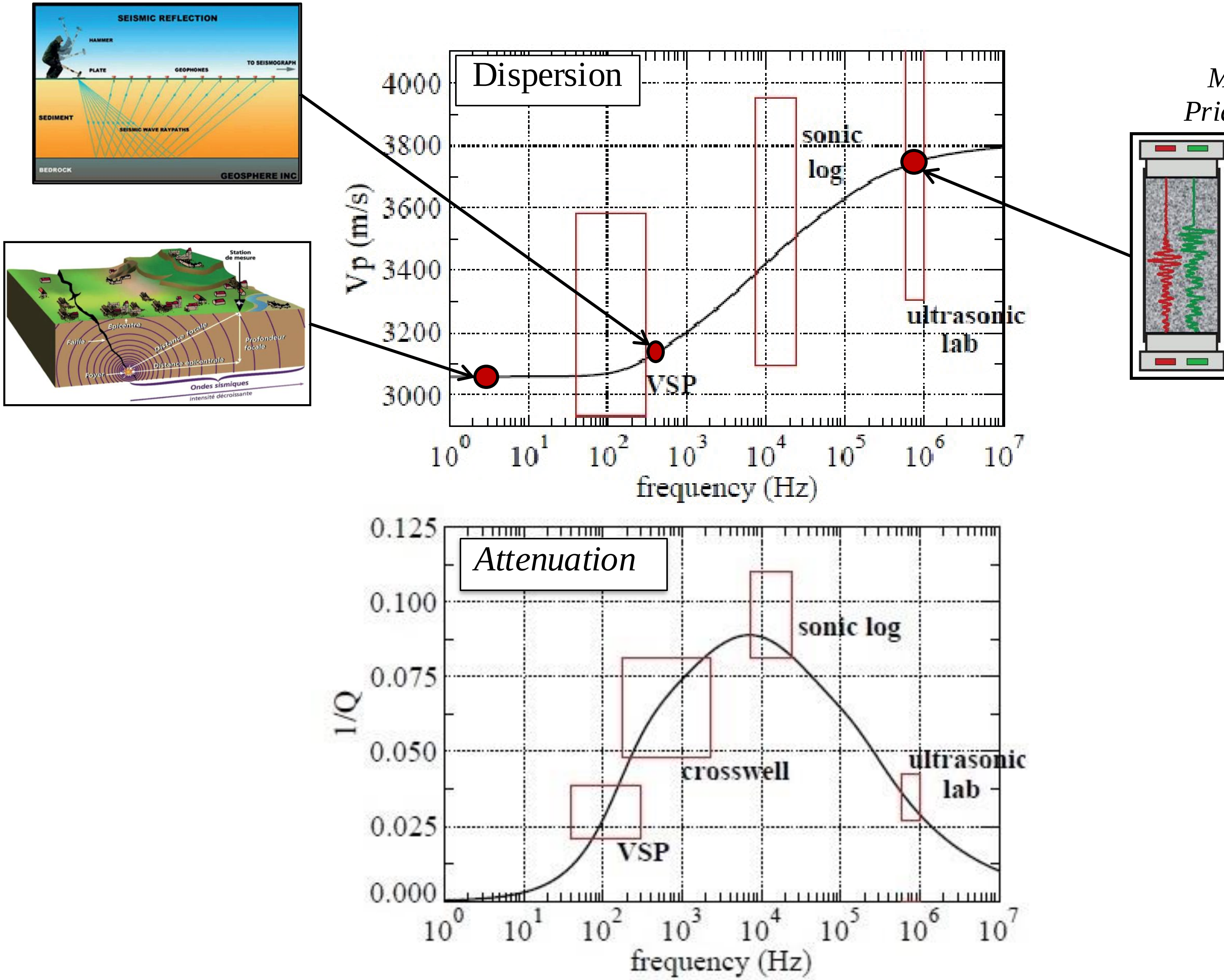
Elasticity & dissipation
⇔ *2 faces of the same coin ?*

Causes ??

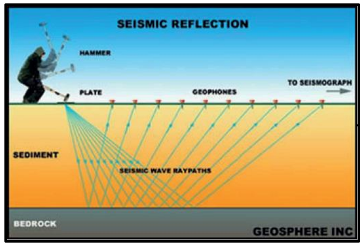
Investigation in the laboratory ?

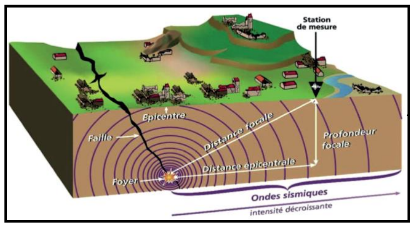


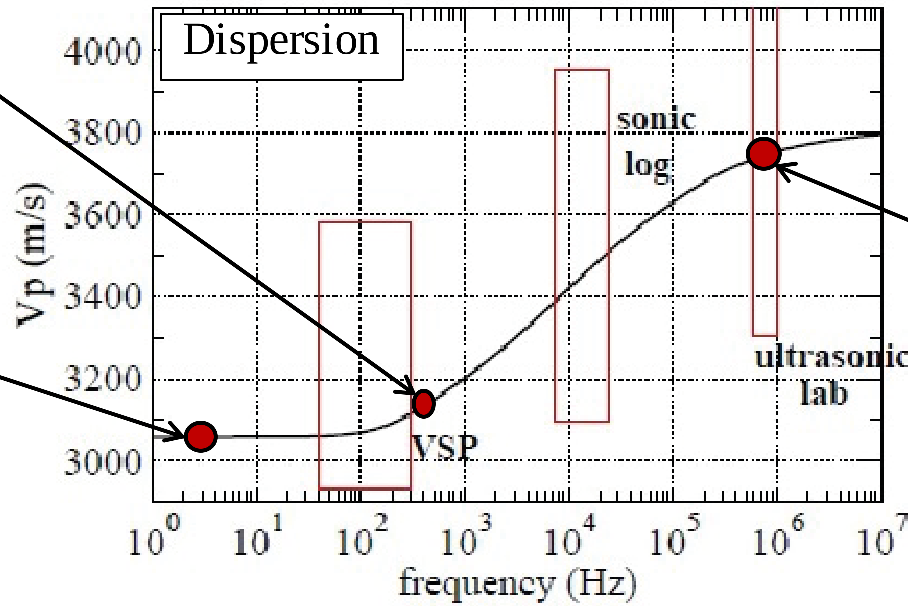
Can we compare between measurements ?



Modified from Pride et al. (2004)







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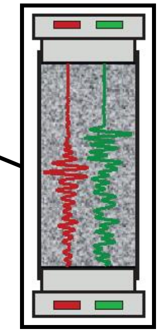


Cause ?

Viscoelasticity ?

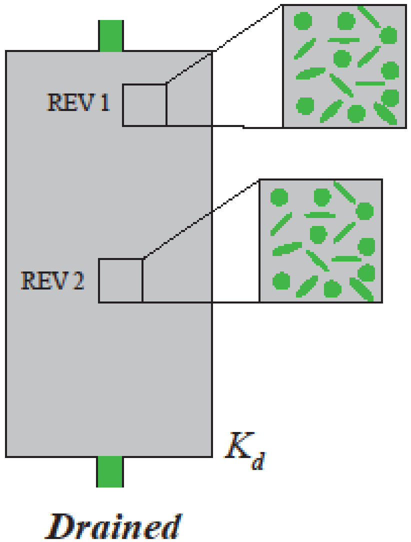
High T-P conditions

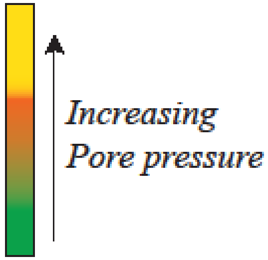
Fluid mobility

Low T-P conditions

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

→ ***Drained*** ⇔ Fluid allowed to flow out of the REV





REV = R*epresentative* E*lementary* V*olume*

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

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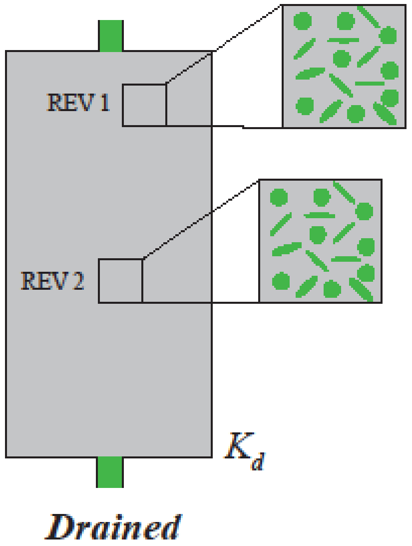

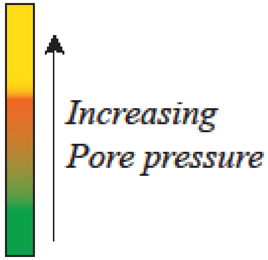

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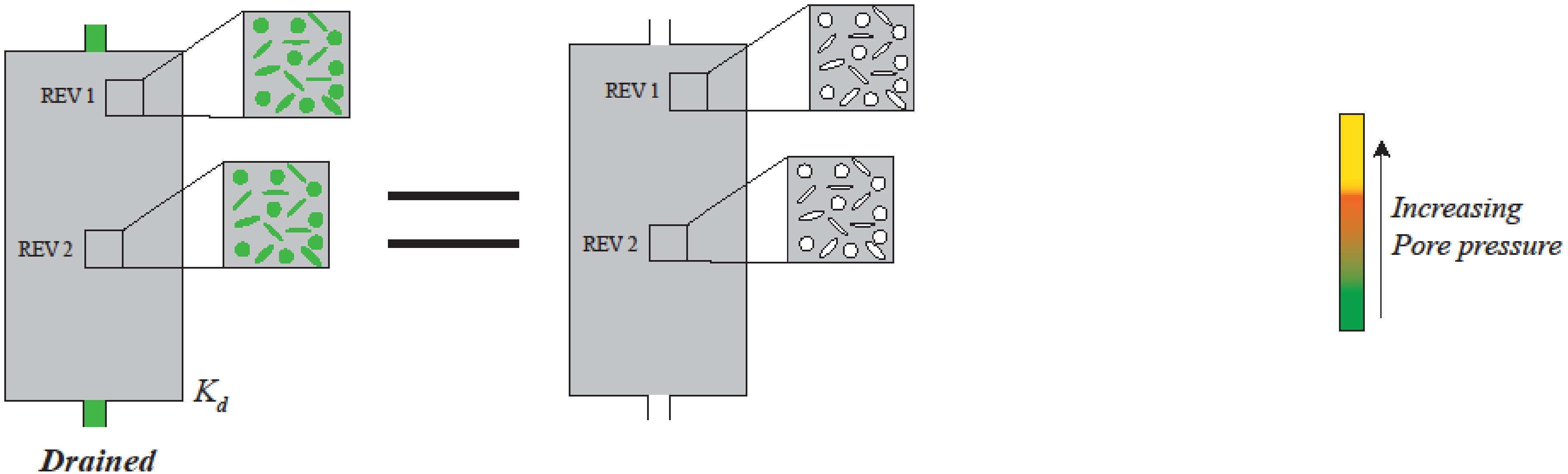


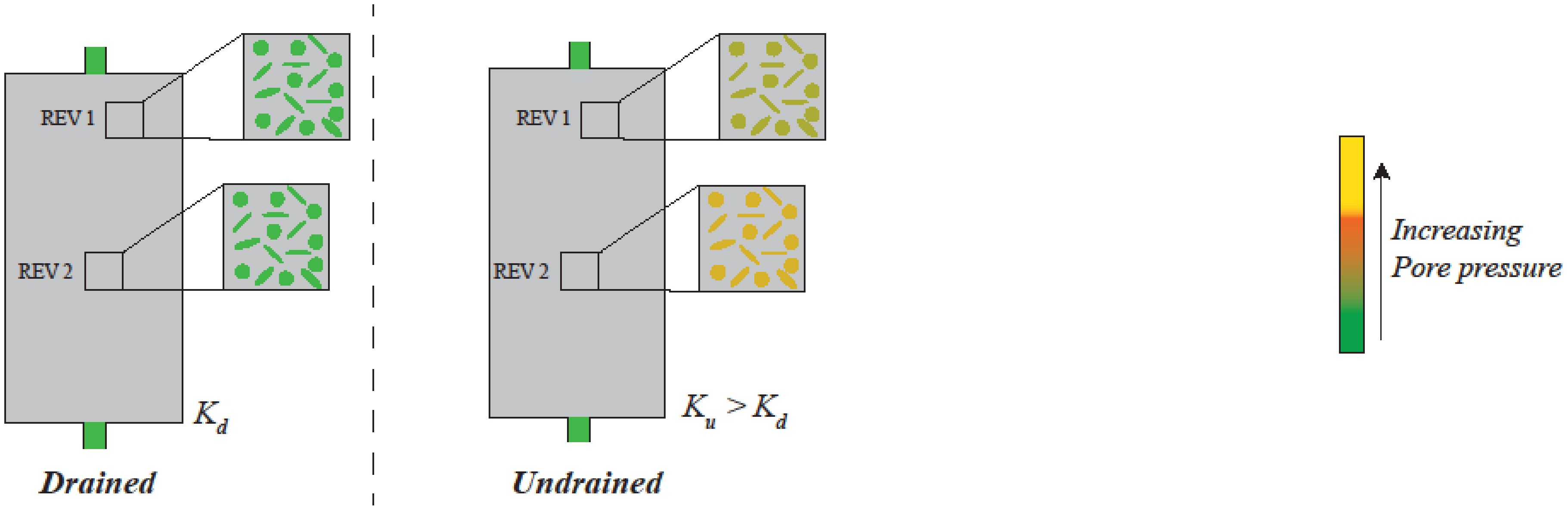
Elastic constants
independent of the fluid

REV = R*epresentative* E*lementary* V*olume*

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



Bulk modulus K

dependent of the fluid

REV = *Representative Elementary Volume*

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

→ ***Drained*** ⇔ Fluid allowed to flow out of the REV

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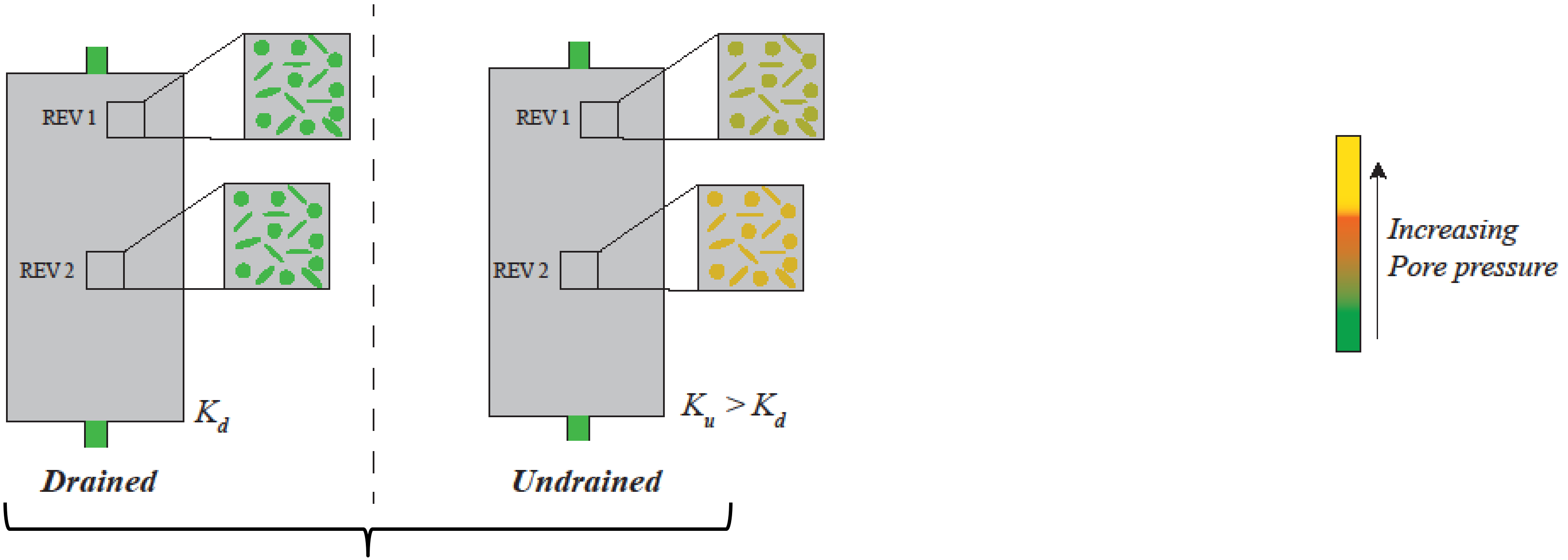


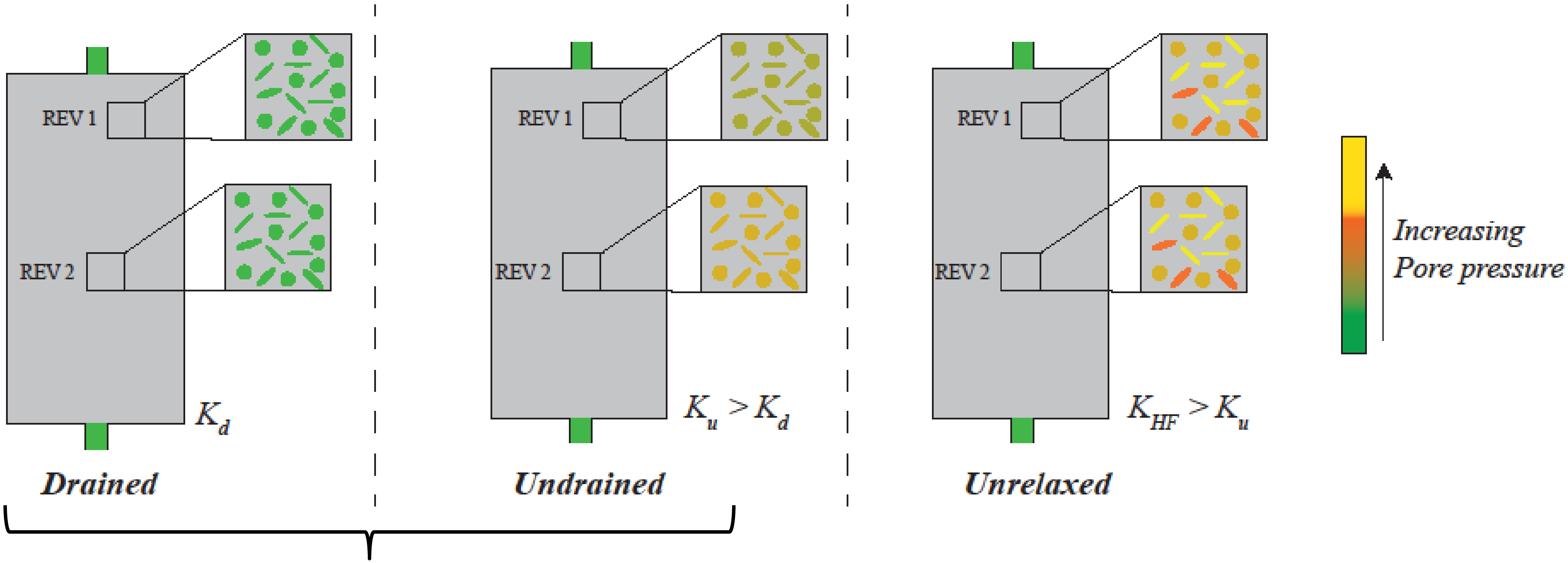
Relaxed regimes

↔ **Isobaric** at the scale of the REV

REV = *Representative Elementary Volume*

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

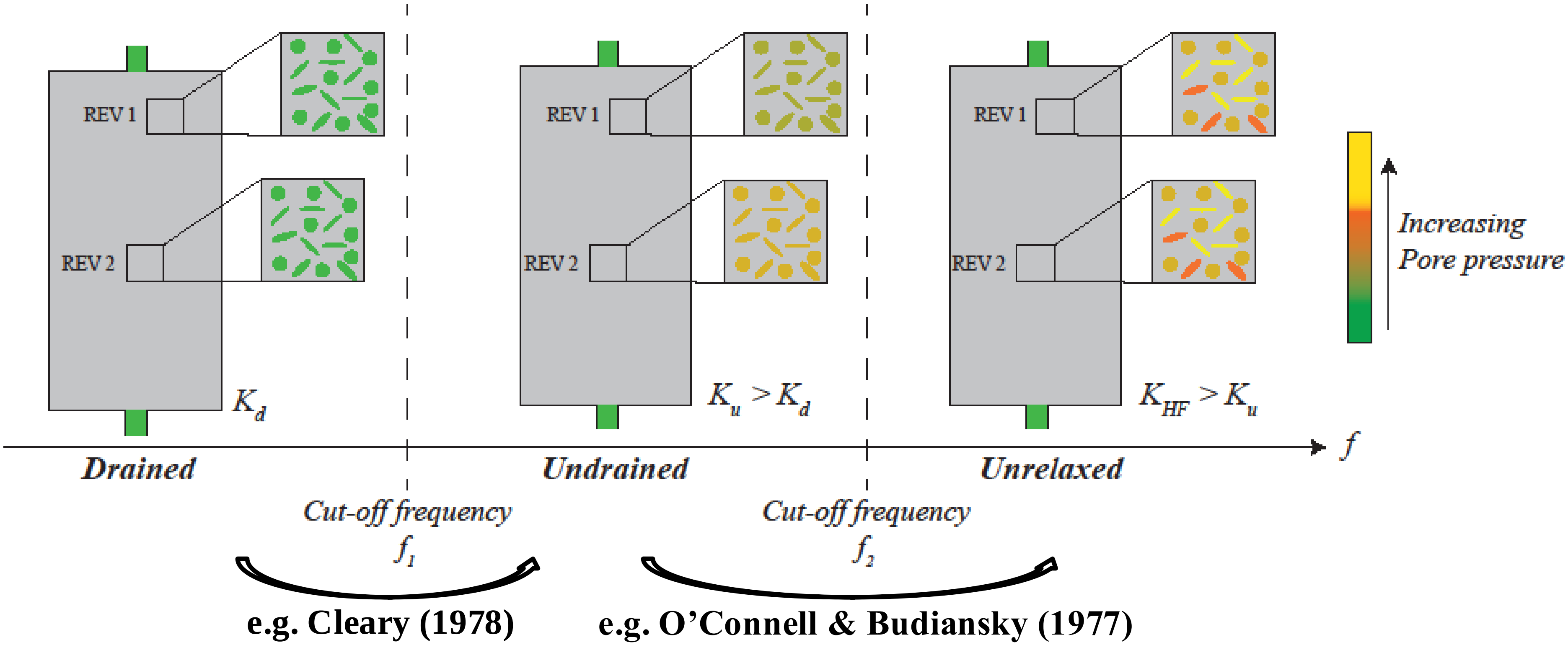
Isolated inclusions: 3rd ***mechanical*** regime
→ ***Unrelaxed*** ⇔ Fluid overpressure dependent on the **geometry** of the inclusion



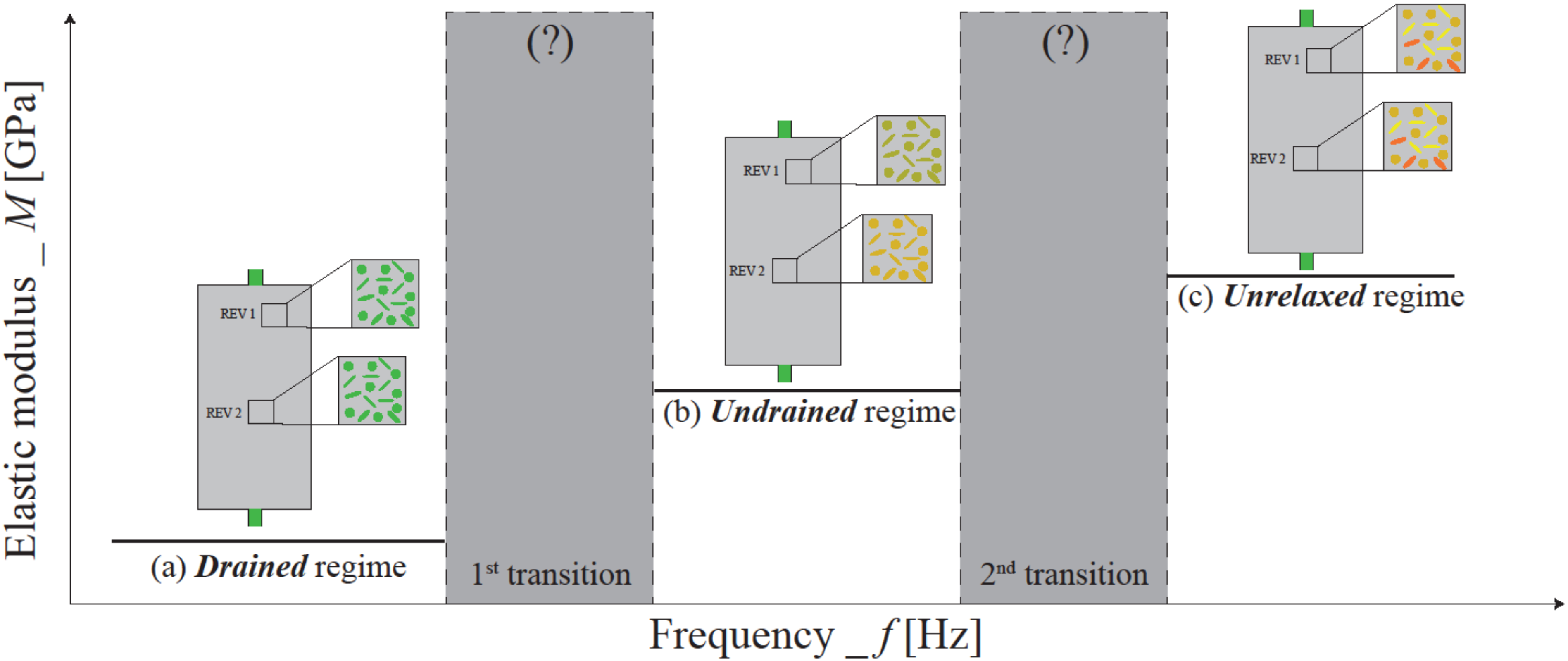
Relaxed regimes
↔ **Isobaric** at the scale of the REV

REV = *Representative Elementary Volume*

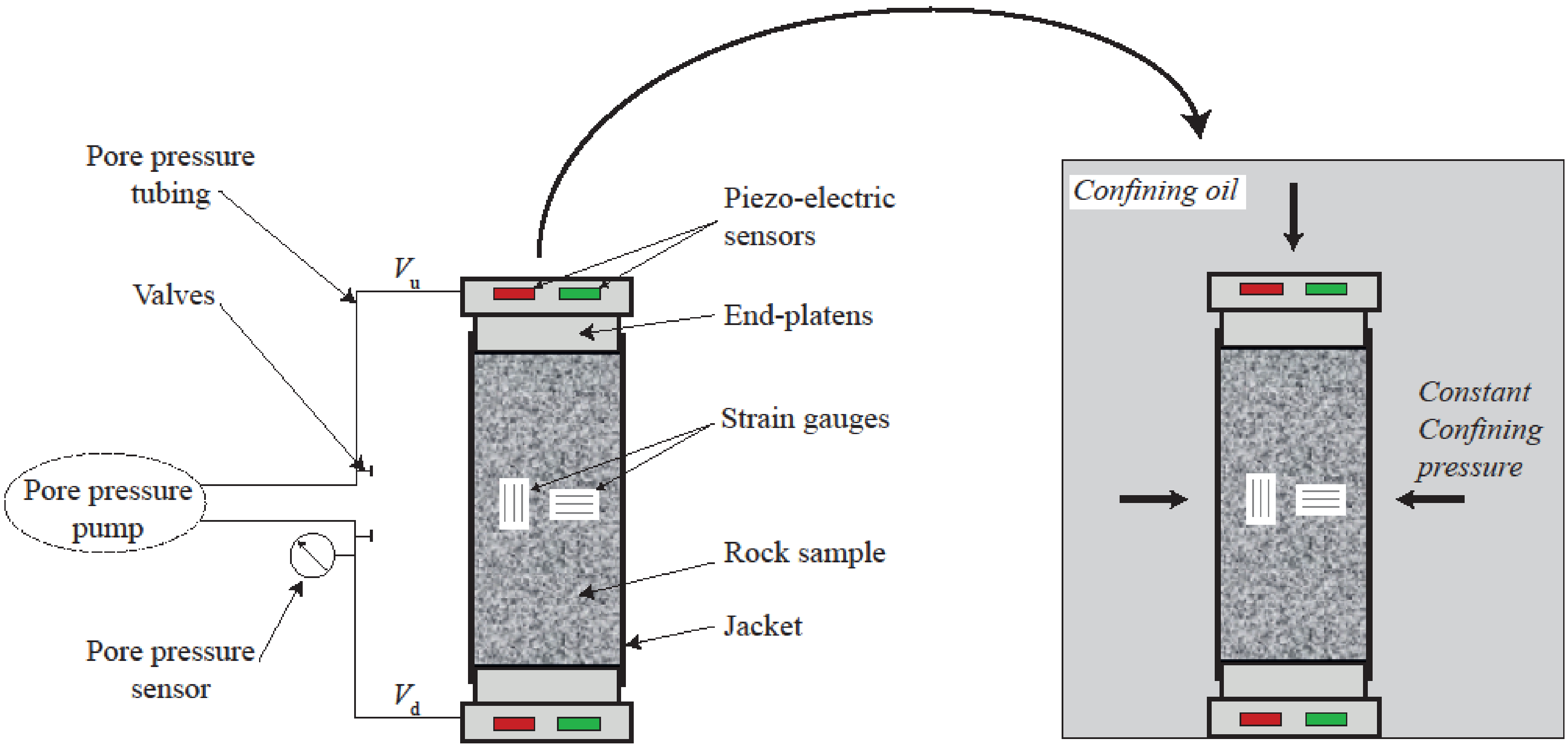
Fluid movement
→ Frequency dependence

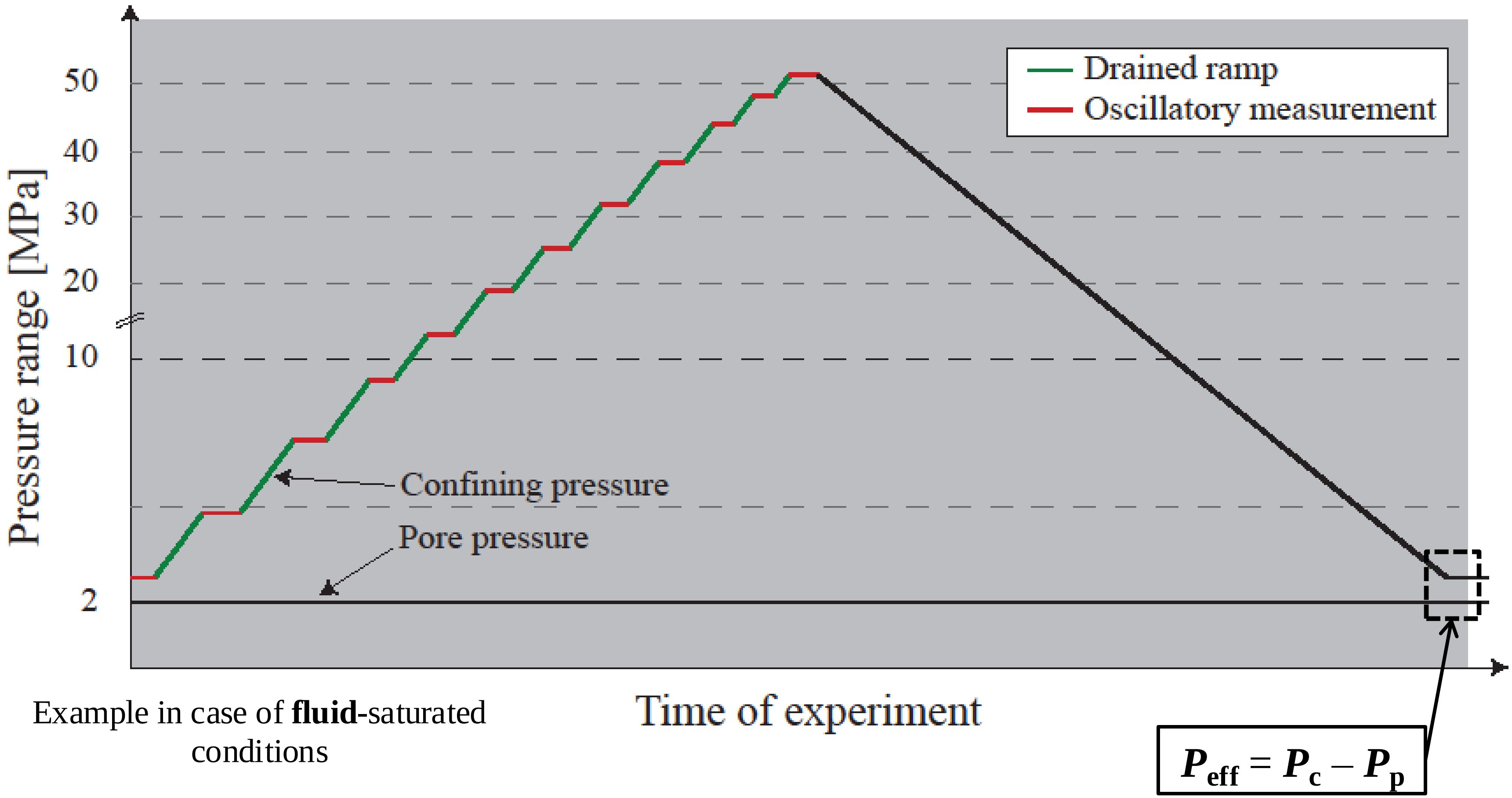


Higher **Viscosity** ↔ Lower fluid **velocity**
Higher **Frequency** ↔ Shorter **time** for flow



Dispersion/Attenuation between regimes?


Pore pressure tubing
Valves
Pore pressure pump
Pore pressure sensor
V_u
V_d
Piezo-electric sensors
End-platens
Strain gauges
Rock sample
Jacket
Confining oil
Constant Confining pressure



Example in case of **fluid**-saturated conditions

Sample measured at different confining pressures

⇒ Sample's behaviours **at depth**

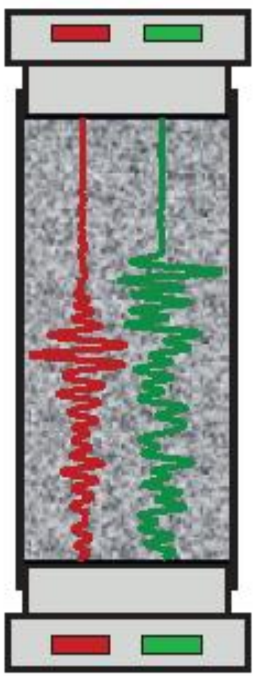
Elastic behaviour of a rock

⇔ **Strain** response to an applied **Stress**: Small, Instantaneous & Reversible

⇔ Characterised by different elastic constants: ***K***, ***G***, ***E***, ***ν***

Isotropic rock

↔ 2 independent constants



↔ ***Quasi-static*** stress-strain measurements

K ↔ Bulk modulus

G ↔ Shear modulus

or

E ↔ Young modulus

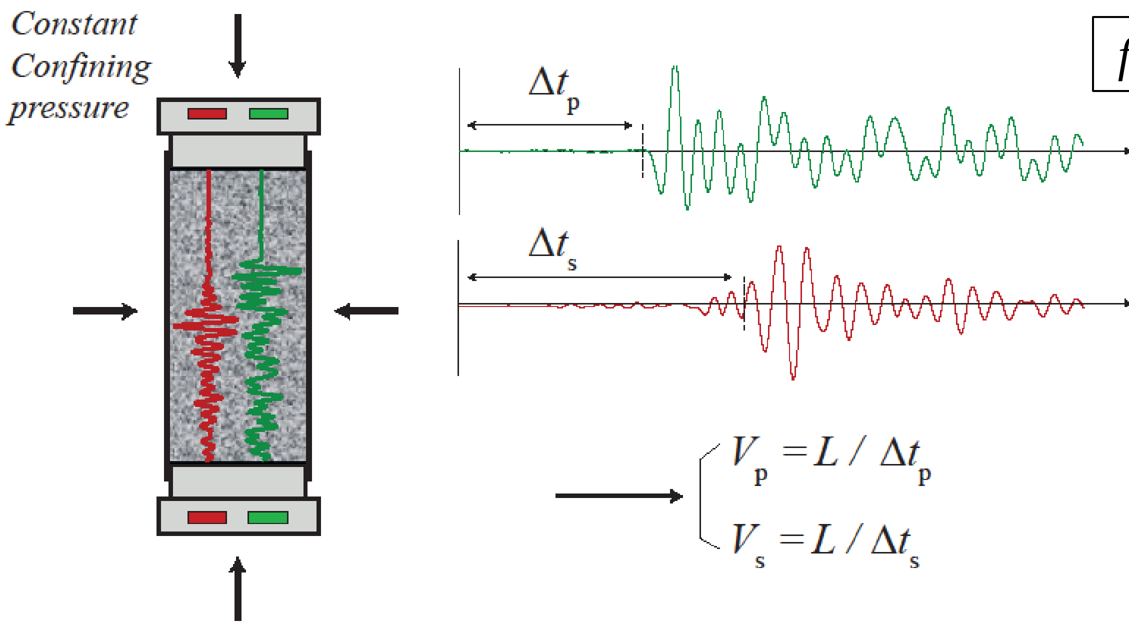
ν ↔ Poisson ratio

or

↔ ***Ultrasonic*** wave velocity measurements

V_p ↔ P-wave velocity

V_s ↔ S-wave velocity

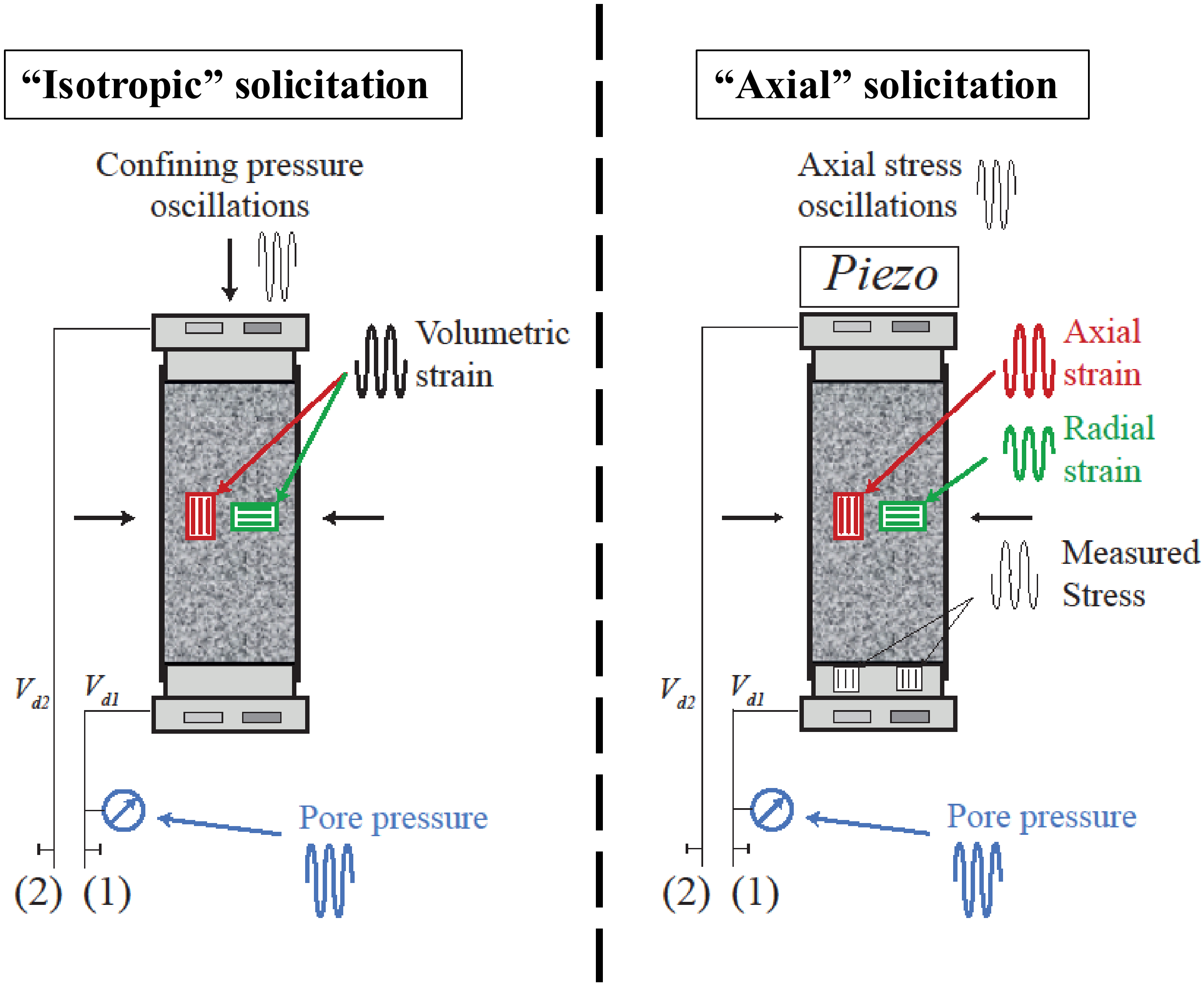


$f \sim 1$ MHz

$$\begin{cases} V_p = L / \Delta t_p \\ V_s = L / \Delta t_s \end{cases}$$

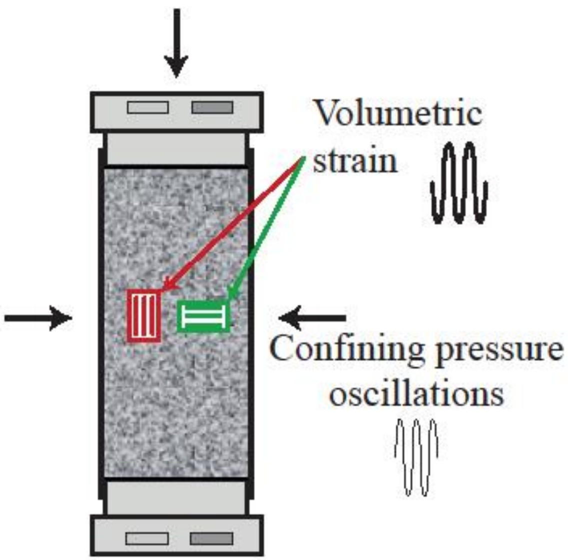
Assume rock **Isotropic** ⇨ $V_p = \sqrt{\dfrac{K + 4/3G}{\rho}}$ $\quad V_s = \sqrt{\dfrac{G}{\rho}}$

➡ $\boldsymbol{K_{HF}}$ **&** $\mathbf{G_{HF}}$

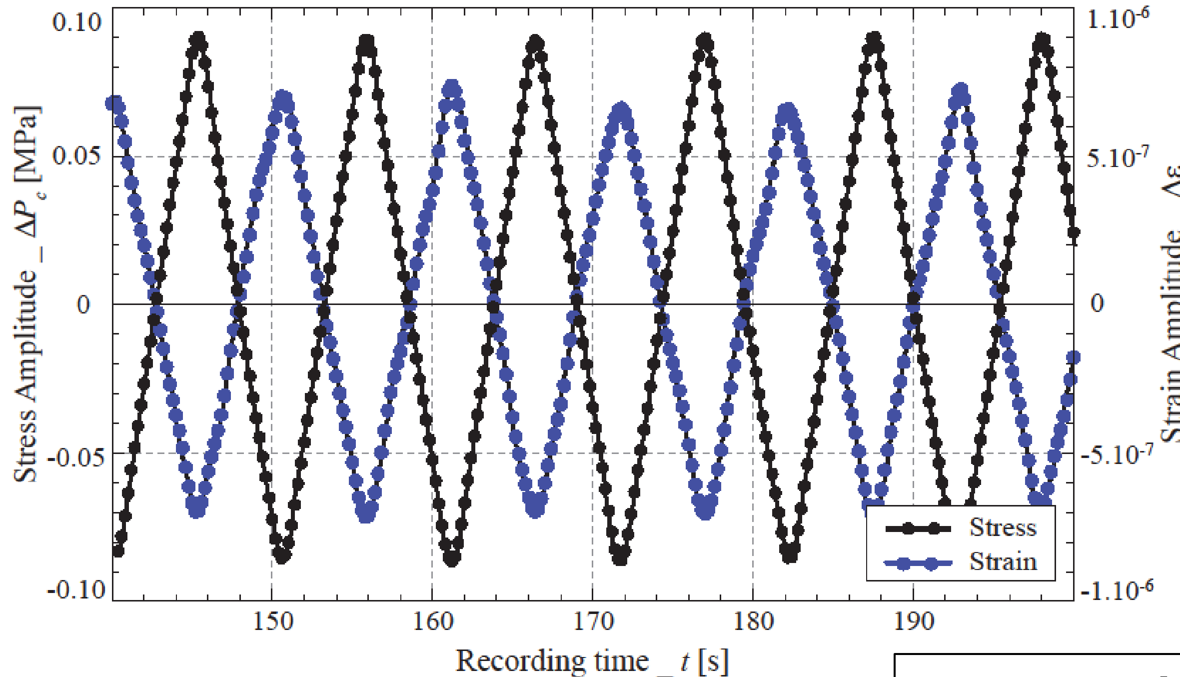


"Isotropic" solicitation
Confining pressure oscillations
Volumetric strain
V_{d2}
V_{d1}
Pore pressure
(2) (1)
"Axial" solicitation
Axial stress oscillations
Piezo
Axial strain
Radial strain
Measured Stress
V_{d2}
V_{d1}
Pore pressure
(2) (1)

“Isotropic” solicitation



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

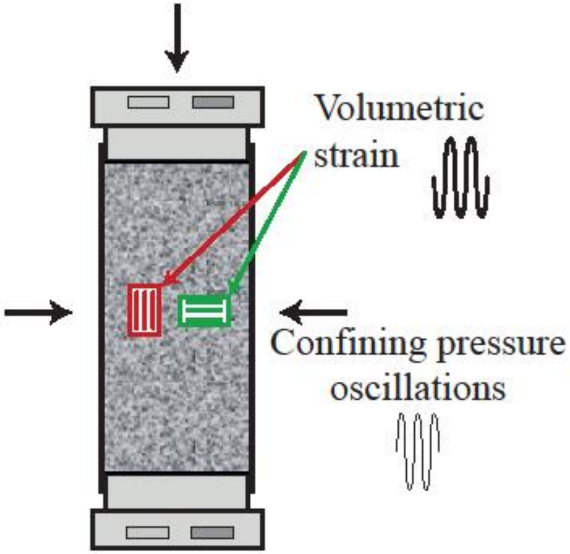


Gypsum sample

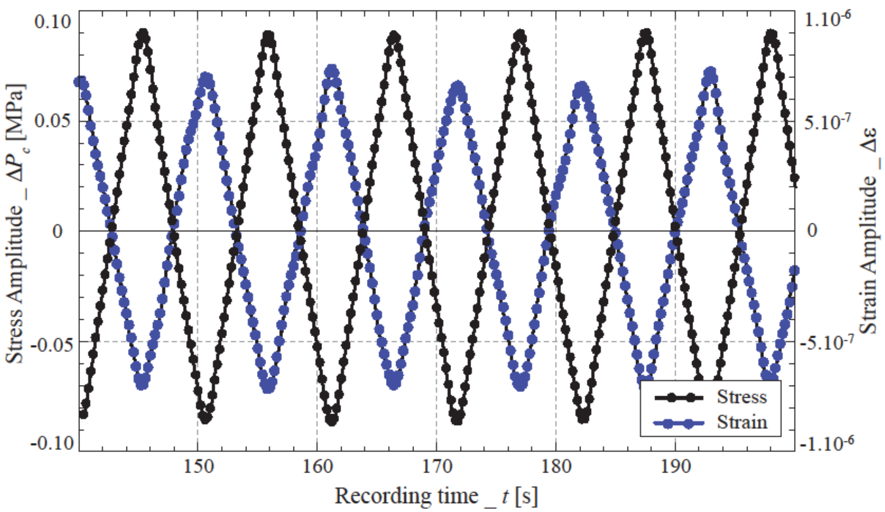
→ P_c ~ 1 MPa
→ f ~ 0,1 Hz

⇨ **Elastic** response:

→ Amplitude ratio => $\boldsymbol{K_{LF}}$
→ Phase shift => $\boldsymbol{Q_K^{-1}}$



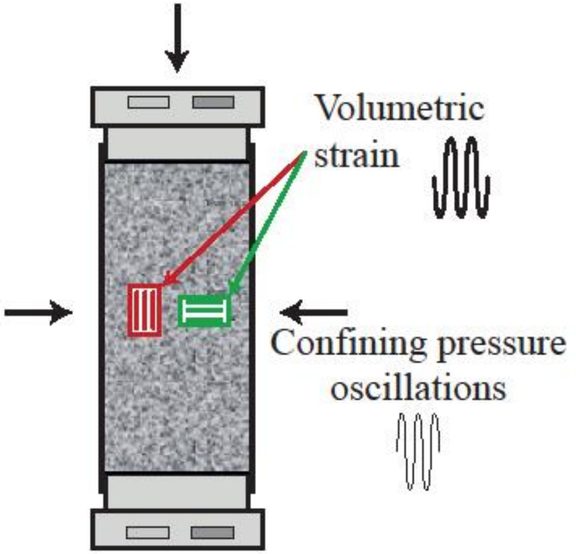
Rock can be described by ***complex elastic properties***

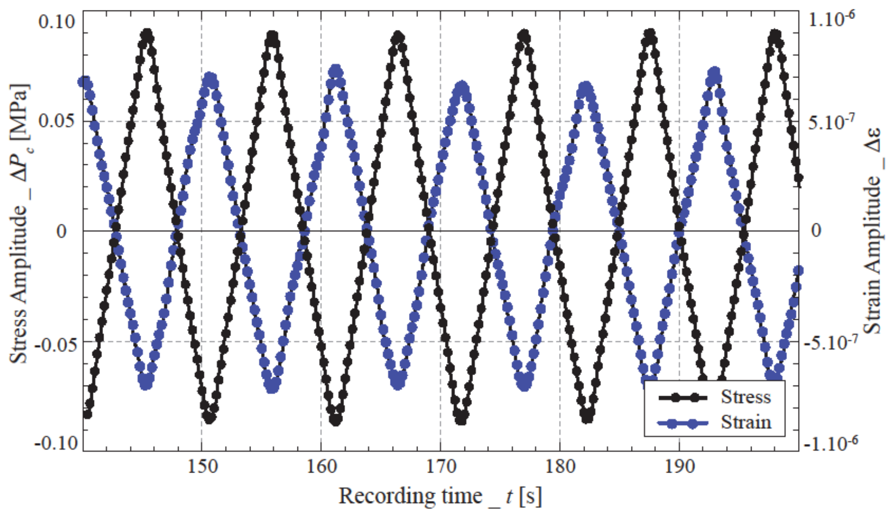


Elastic response:

→ Amplitude ratio => $\boldsymbol{K_{LF}}$

→ Phase shift => $\boldsymbol{Q_K^{-1}}$





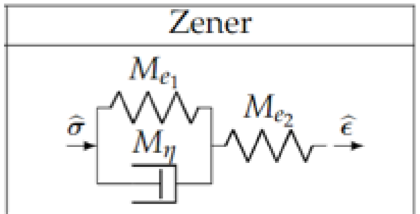
Rock can be described by ***complex elastic properties***

Elastic response:

→ Amplitude ratio => $\boldsymbol{K_{LF}}$

→ Phase shift => $\boldsymbol{Q_K^{-1}}$

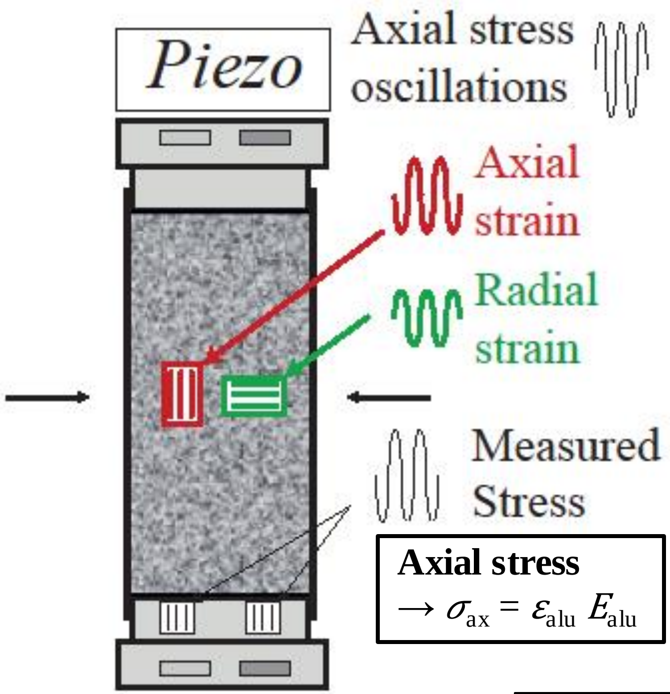
An ***example*** *?*
Rheological viscoelastic models



$$\hat{\sigma} = \frac{M_{e_1}M_{e_2} + i\omega M_\eta M_{e_1}}{M_{e_1} + M_{e_2} + i\omega M_\eta}\hat{\epsilon}$$

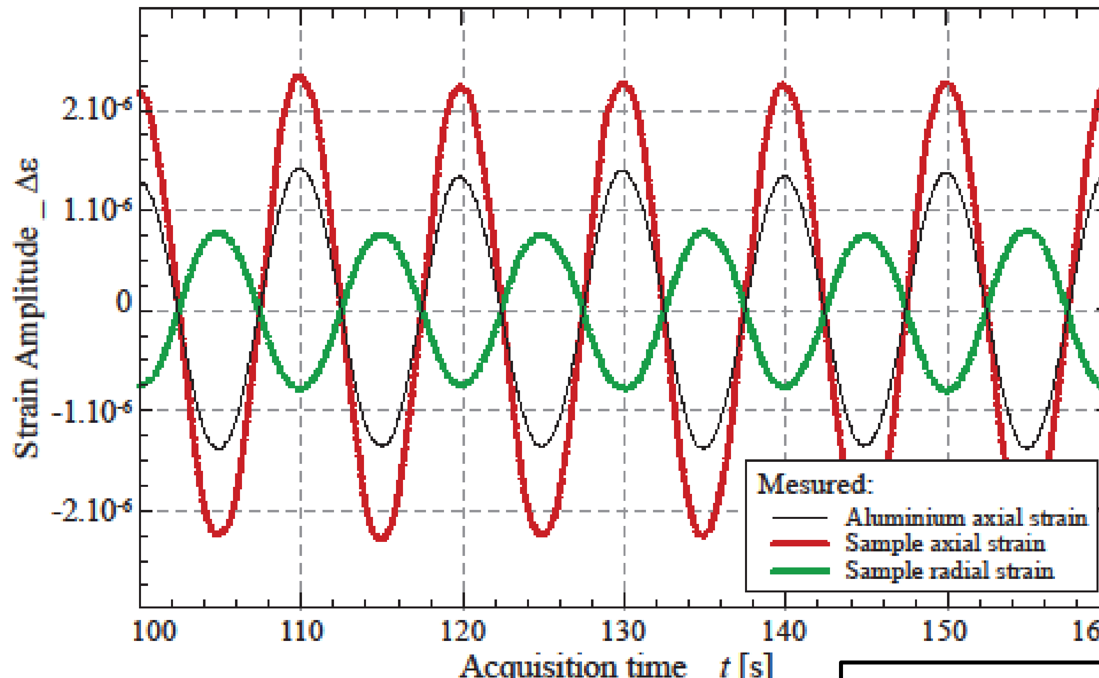
$$Q_{Zen}(\omega) = \frac{1 + \omega^2\tau_\epsilon\tau_\sigma}{\omega(\tau_\epsilon - \tau_\sigma)}$$

"Axial" solicitation



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

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



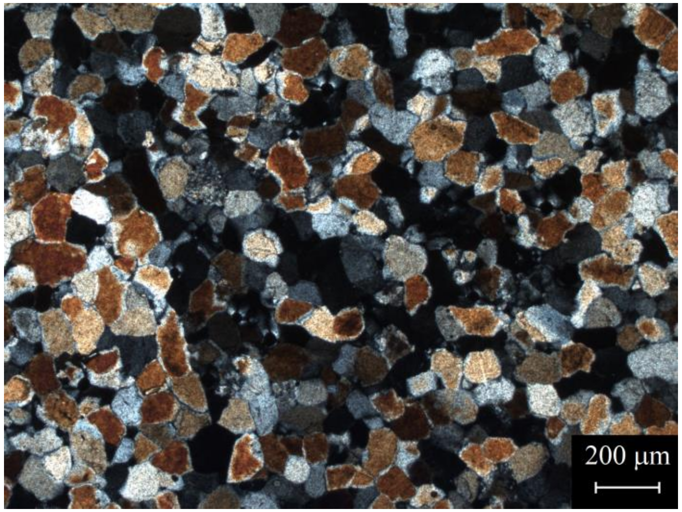
Gypsum sample

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

⇨ **Elastic** response:

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

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



Thin section of Fontainebleau sandstone using polarising microscope. Example of a 7 % porosity sample

- Clean sandstone (≈ 100 % quartz)
- Well sorted, constant grain size (≈ 100 µm)

→ **Homogeneous** medium

- Random crystal/grain orientations

↔ Spatial averaging of quartz anisotropy

→ **Isotropic** medium

→ **Fo7:**

↔ 7.2 % porosity

↔ 4 10^{-15} m^2 permeability

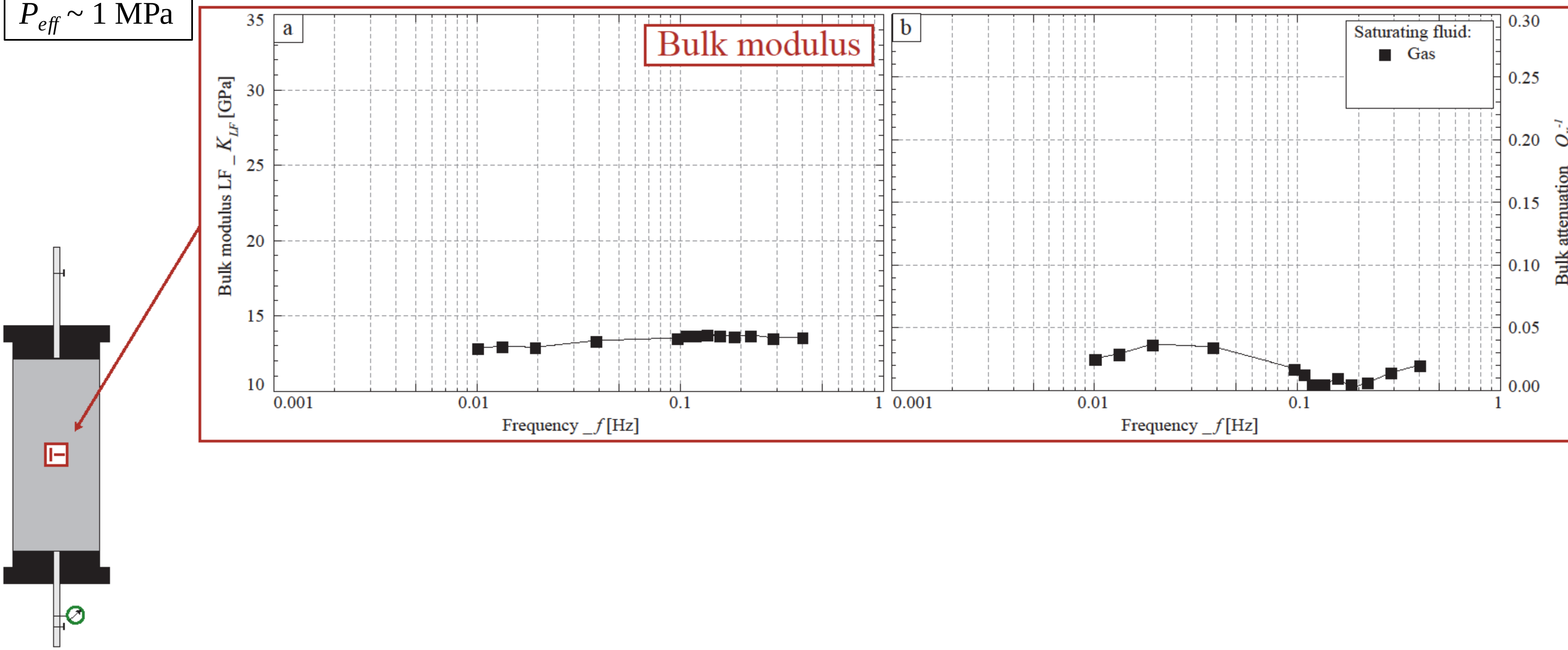
⇨ Measurements under:

(1) Dry

(2) **Glycerine** saturation

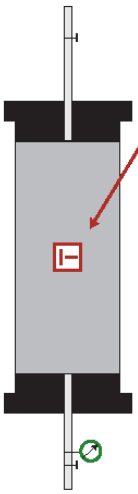
(3) **Water** saturation

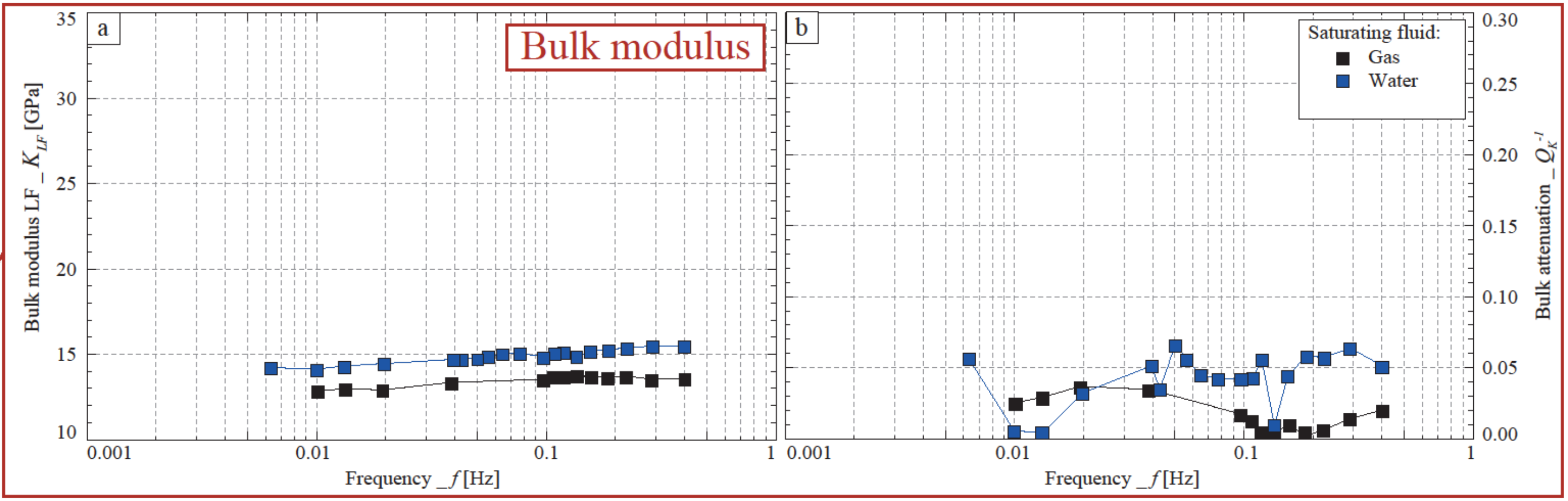
P_{eff} ~ 1 MPa



Bulk modulus
a
Bulk modulus LF _ K_LF [GPa]
35
30
25
20
15
10
0.001
0.01
0.1
1
Frequency _ f [Hz]
b
Saturating fluid:
Gas
Bulk attenuation _ Q_K^-1
0.30
0.25
0.20
0.15
0.10
0.05
0.00
0.001
0.01
0.1
1
Frequency _ f [Hz]

$P_{eff} \sim 1$ MPa



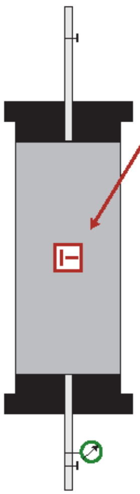


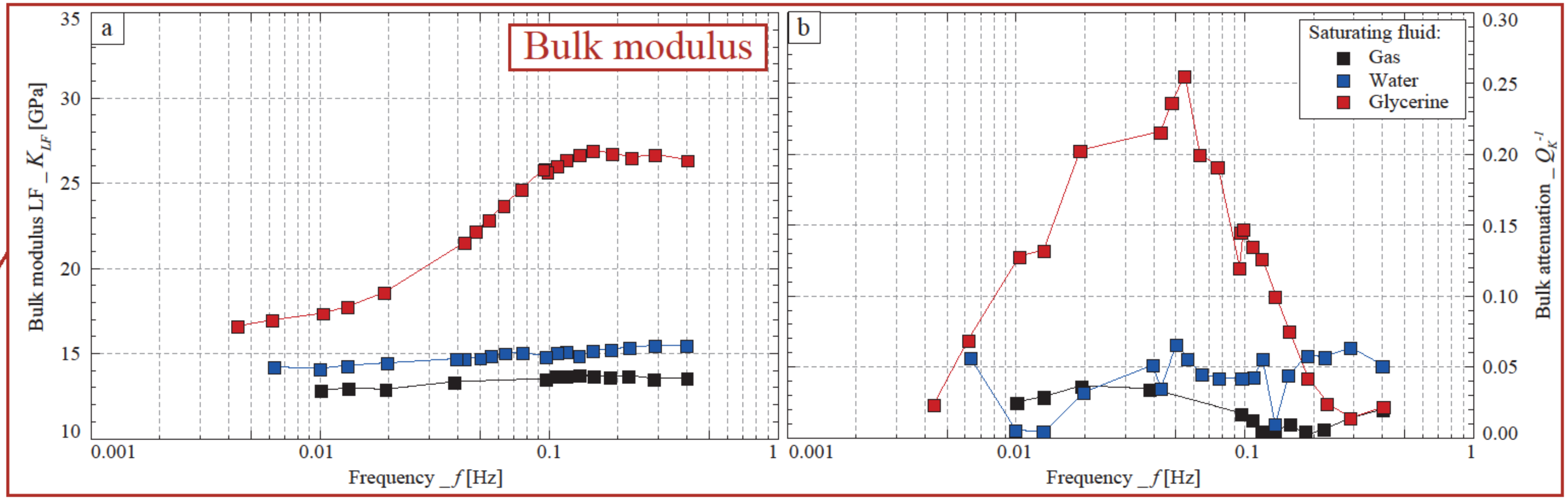
→ Water saturation:

↔ $K^{dry} \sim K^{wat}$

↔ No frequency dependence of K & Q_K^{-1}

$P_{eff} \sim 1$ MPa





→ Water saturation:

↔ $\boldsymbol{K^{dry}} \sim \boldsymbol{K^{wat}}$

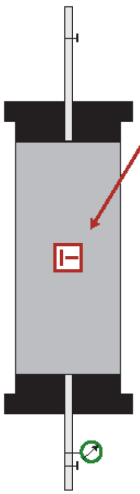
↔ No frequency dependence of $\boldsymbol{K}$ & $\boldsymbol{Q_K^{-1}}$

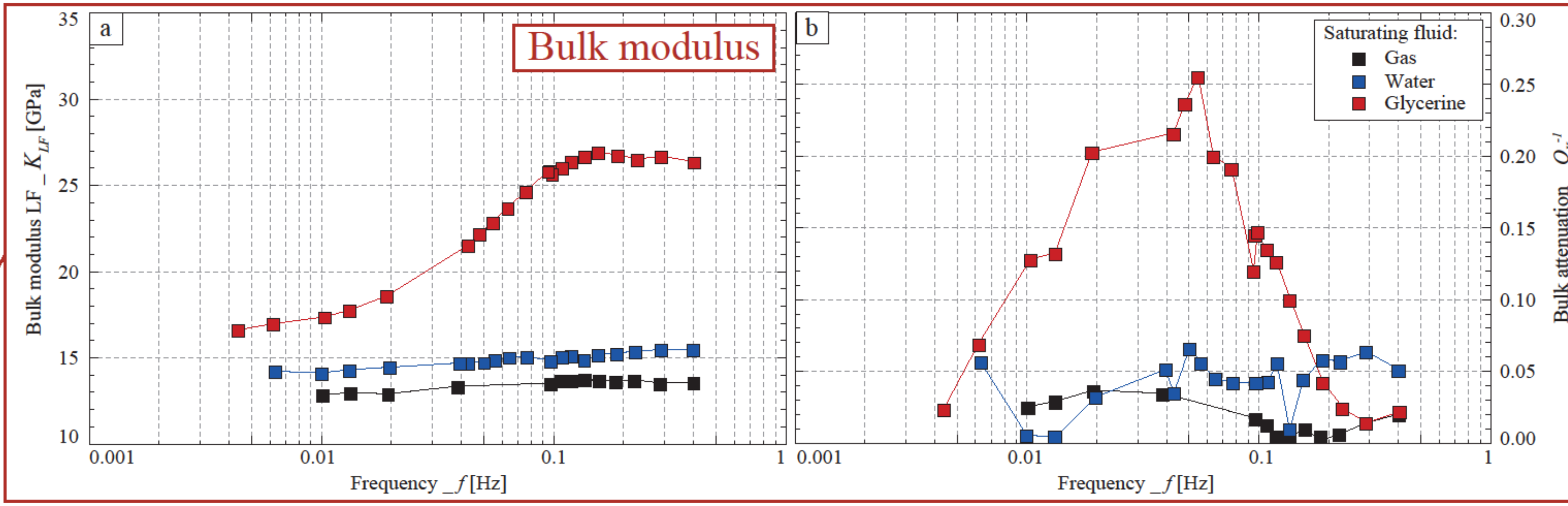
→ Glycerine saturation:

↔ Large frequency dependence of $\boldsymbol{K}$ & $\boldsymbol{Q_K^{-1}}$

↔ Direct correlation between $\boldsymbol{K}$ & $\boldsymbol{Q_K^{-1}}$

$P_{eff} \sim 1$ MPa





→ Water saturation:

↔ $K^{dry} \sim K^{wat}$

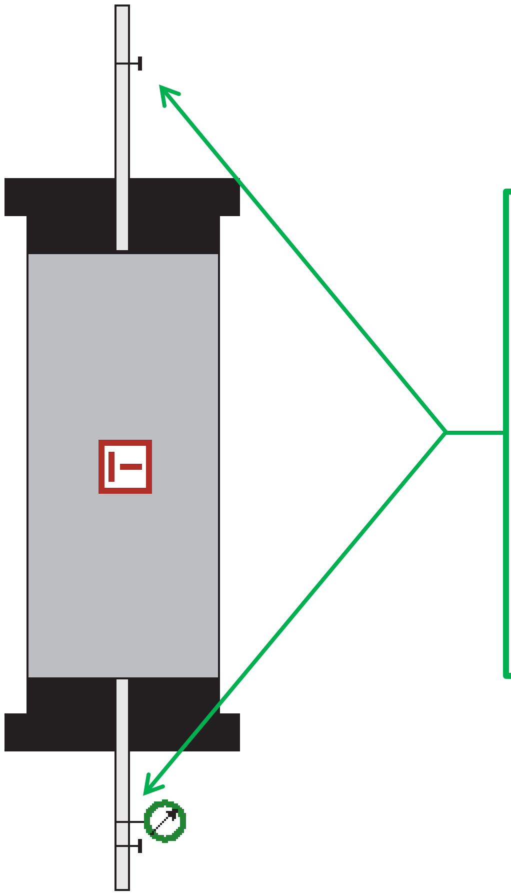
↔ No frequency dependence of K & Q_K^{-1}

→ Glycerine saturation:

↔ Large frequency dependence of K & Q_K^{-1}

↔ Direct correlation between K & Q_K^{-1}

Cause of Dispersion/Attenuation effect ?



2nd information in porous rocks:

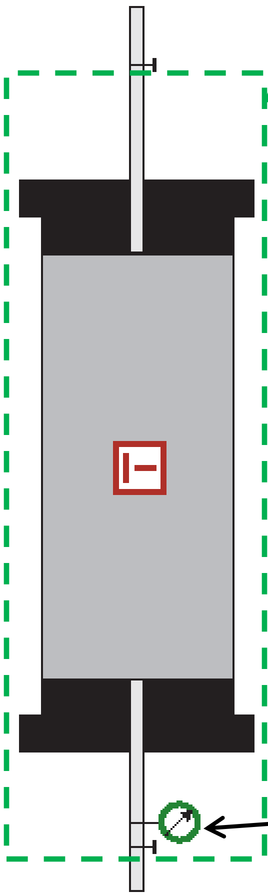
→ **Pore fluid pressure** out of the sample

⇔ Sample's « **Hydraulic** » response

→ Obtained by

(1) Closing the pore fluid line & Creating a dead volume at both sample's ends.

(2) Measuring the **build-up pressure** in the **dead volume**.



System **experimentally undrained**
⇔ fluid not allowed to flow out of the system
(**sample + dead volume**).

⇓

Build up pore pressure (Δp_f) induced by confining pressure (ΔP_c) for different frequencies
→ Characterised as a **pseudo-Skempton coefficient**:

$$B^* = \Delta p_f / \Delta P_c.$$

Dynamic response

$\Delta p_f \sim 0 \rightarrow B^* \sim 0 \rightarrow$ **No fluid flow** out of the sample

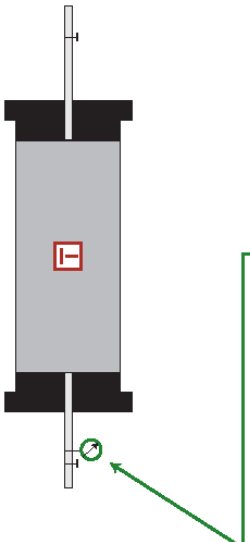
$\Delta p_f > 0 \rightarrow B^* > 0 \rightarrow$ **Fluid flow** out of the sample

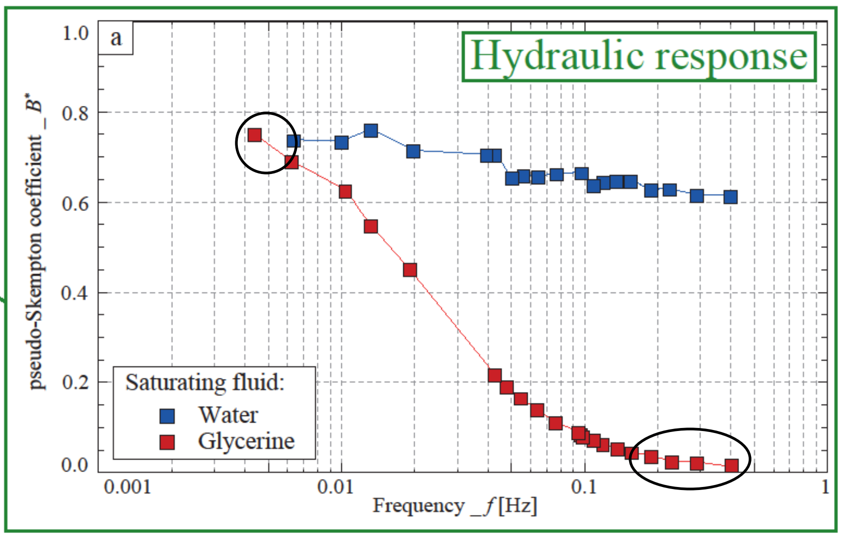
P_{eff} ~ 1 MPa

→ Water saturation:
↔ **No** frequency dependence of $\boldsymbol{B^*}$
→ Glycerine saturation:
↔ **Large** frequency dependence of $\boldsymbol{B^*}$

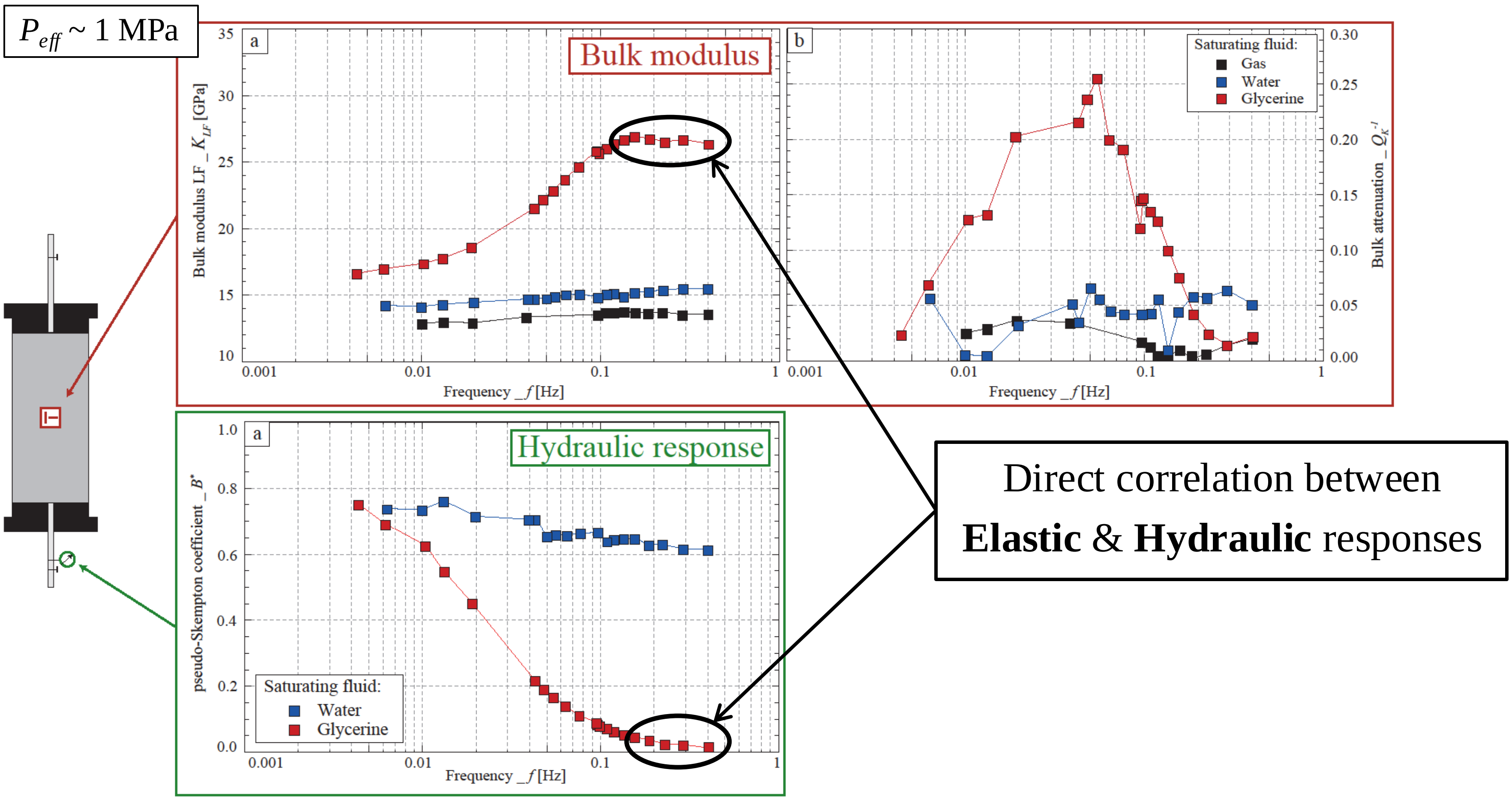
Very low frequency → **Large** $\boldsymbol{B^*}$
→ **Large** fluid flow out of the sample

Higher frequency → $\boldsymbol{B^* \sim 0}$
→ **No** fluid flow out of the sample



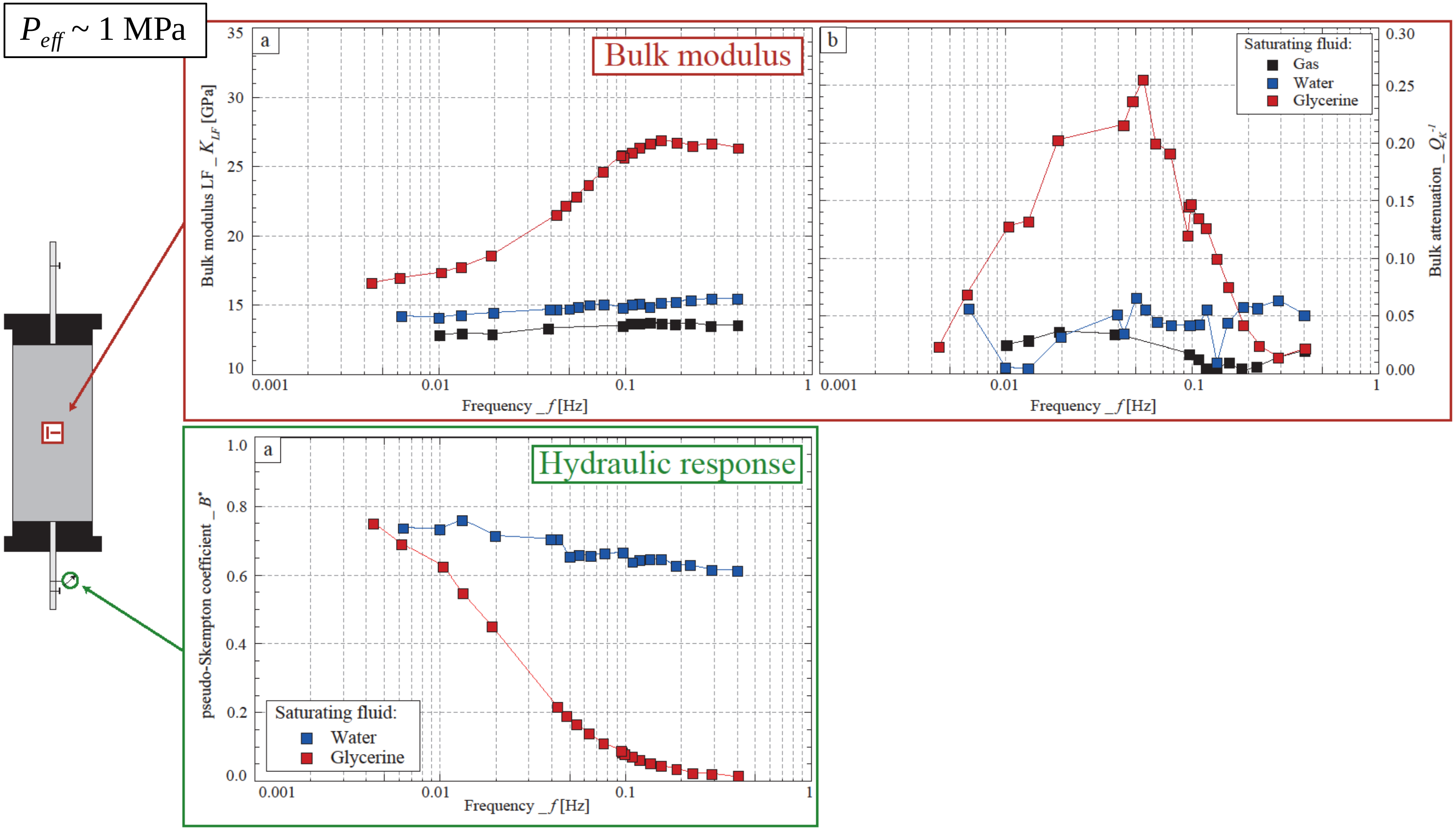


Frequency-dependent fluid-flow out of the sample !



Dispersion/Attenuation ⇔ Macroscopic fluid-flow

⇔ **Drained/Undrained** transition **!**



Why **Water** and **Glycerine** differ ?

Assuming a typical microstructure with: ↔ Compliant spheroidal microcracks

↔ Equant pores

⟹ Theoretical cut-off frequencies:

Drained/Undrained: $f_1 = (4.\kappa.K_d)/(L^2.\eta)$ ↔ (Cleary, 1978)

Undrained/Unrelaxed: $f_2 = (\xi^3.K_d)/\eta$ ↔ (e.g. O'Connell & Budiansky, 1977)

L ↔ Characteristic length for fluid diffusion

κ ↔ Permeability

K_d ↔ Drained bulk modulus

η ↔ Fluid's viscosity

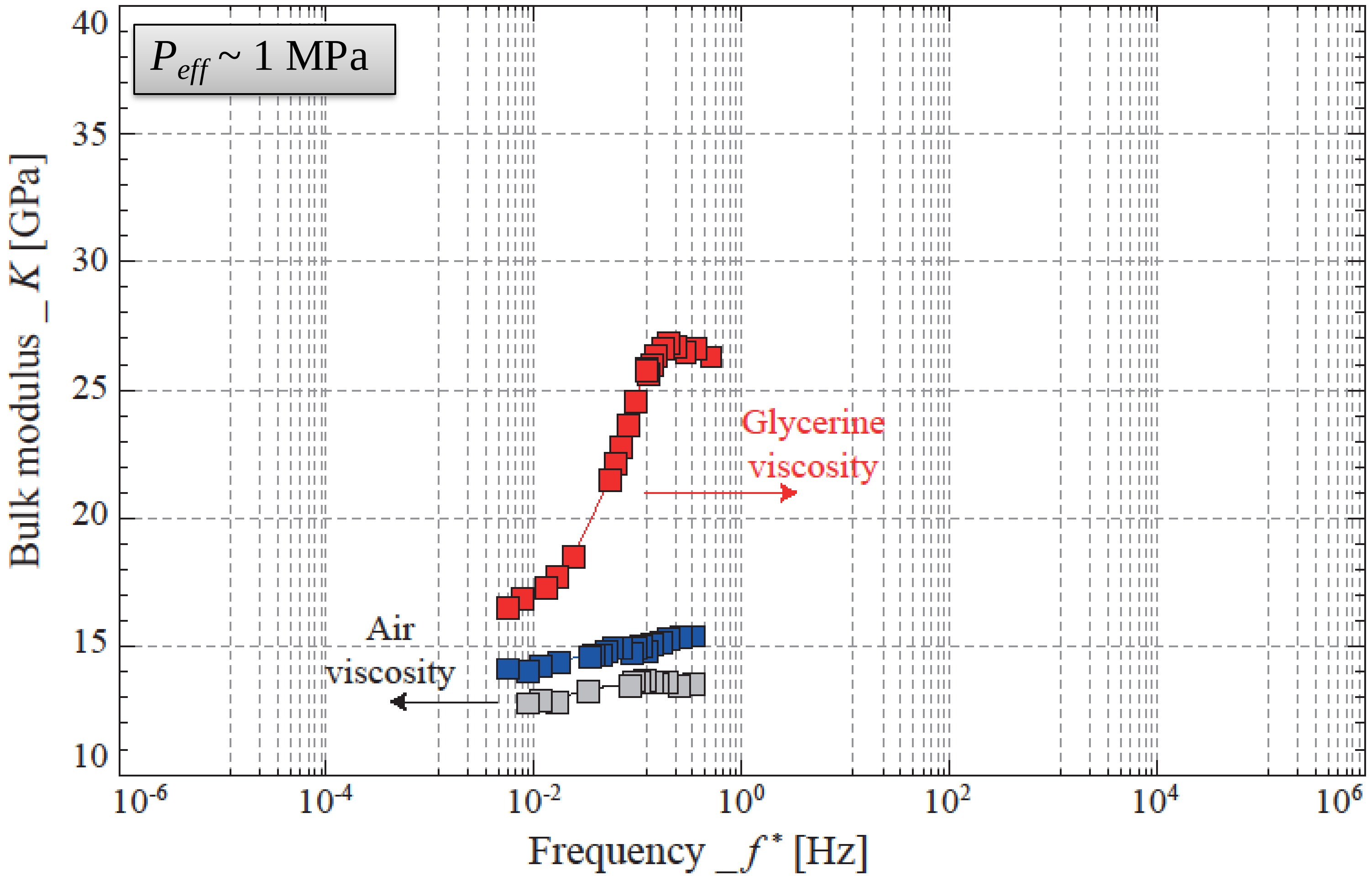
ξ ↔ Aspect ratio of the microcracks

➡

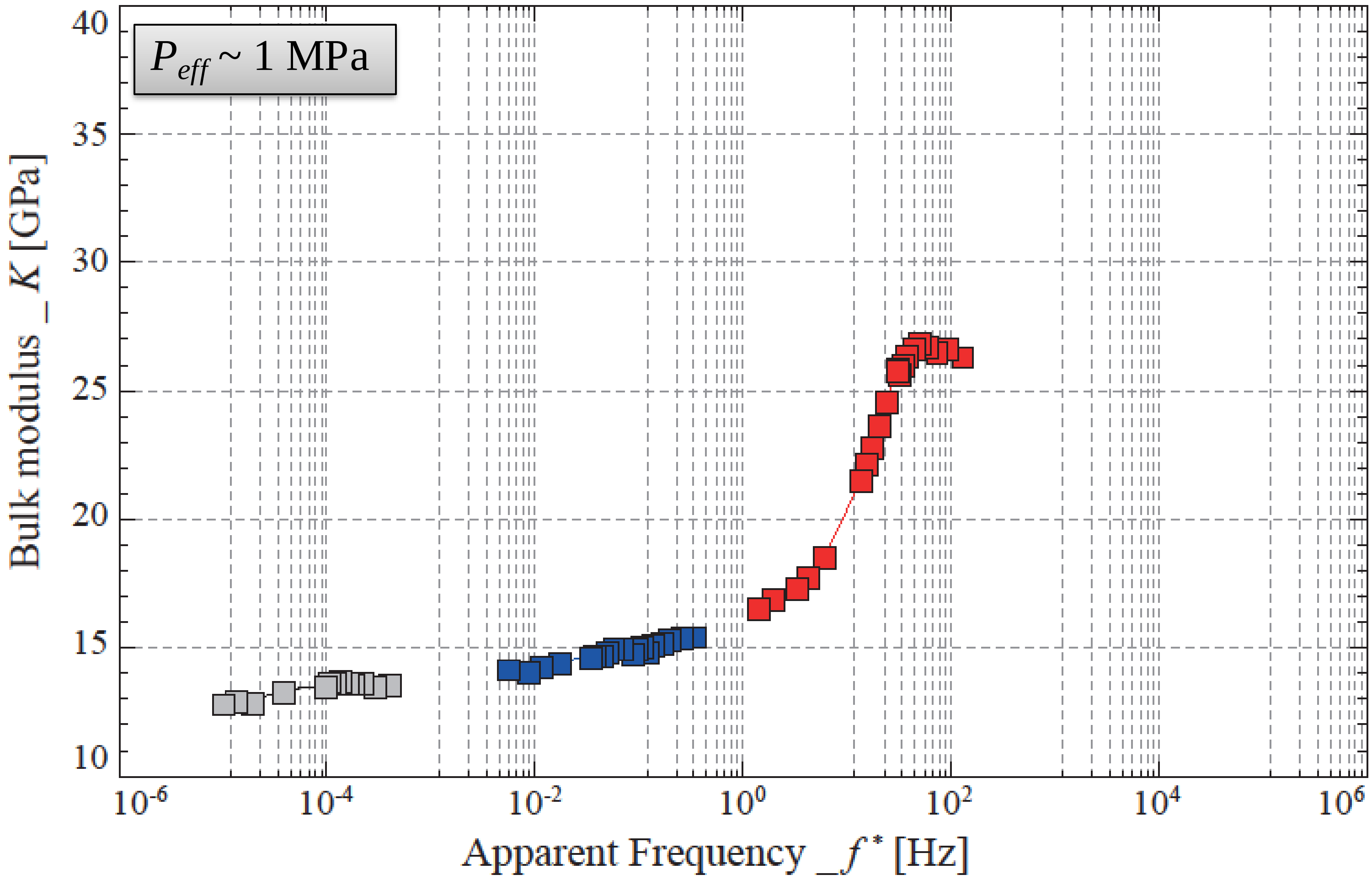
Apparent frequency

$$f^* = f\,.\,(\eta/\eta_0)$$

With $\eta_0 = 10^{-3}$ Pa.s^{-1}



P_{eff} ~ 1 MPa
Bulk modulus _K [GPa]
40
35
30
25
20
15
10
Glycerine viscosity
Air viscosity
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
Frequency _f^* [Hz]



P_{eff} ~ 1 MPa
Bulk modulus _K [GPa]
Apparent Frequency _f* [Hz]
40
35
30
25
20
15
10
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}

Assuming a typical microstructure with: ↔ Compliant spheroidal microcracks

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⇨ Biot-Gassmann theory:

$$\begin{cases} K_u = f\,(K_d, K_s, K_f, \phi) \\ G_u = G_d \end{cases}$$

K_u ↔ Undrained bulk modulus

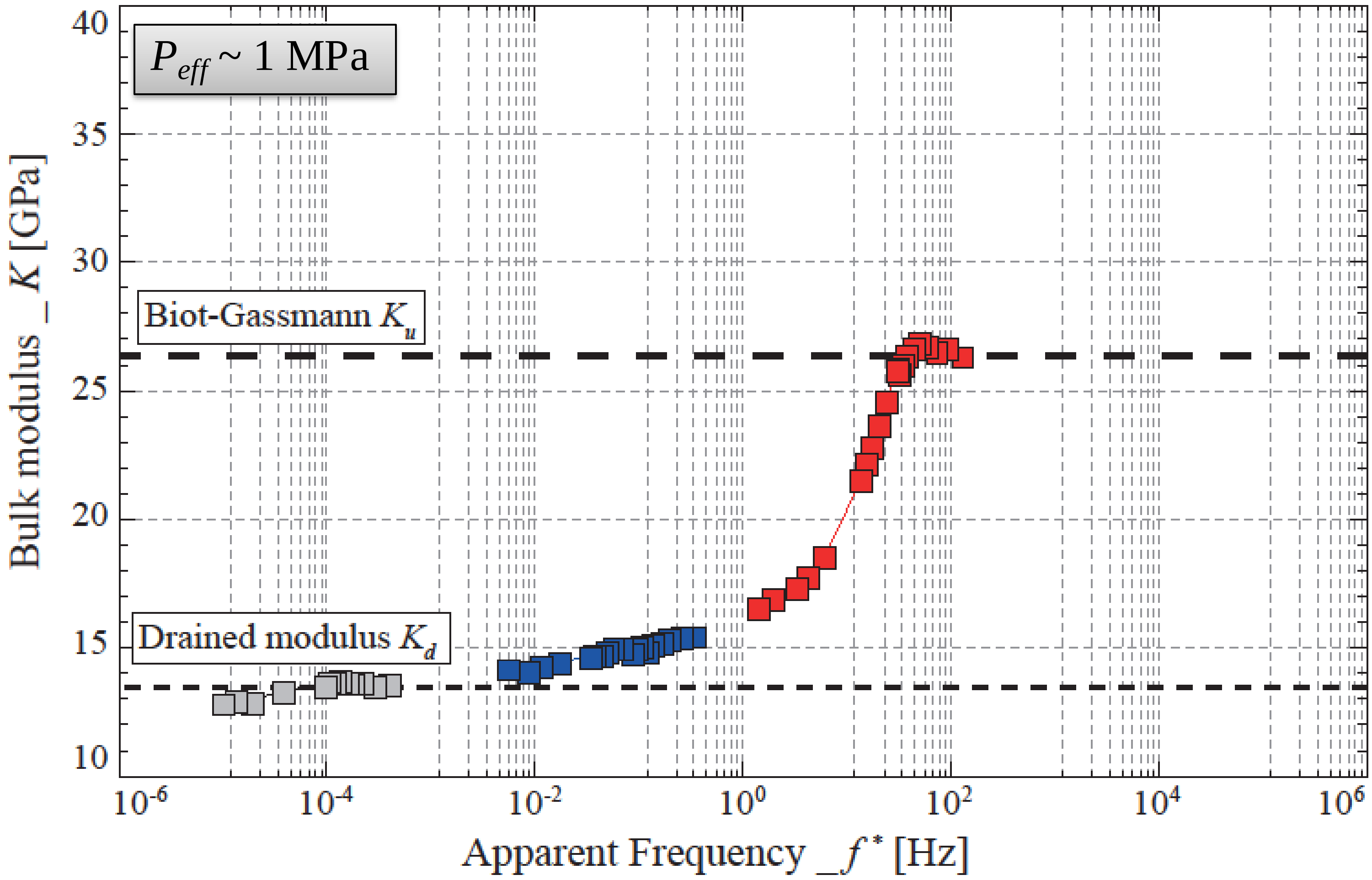
K_d ↔ Drained bulk modulus

K_s ↔ Squeleton bulk modulus

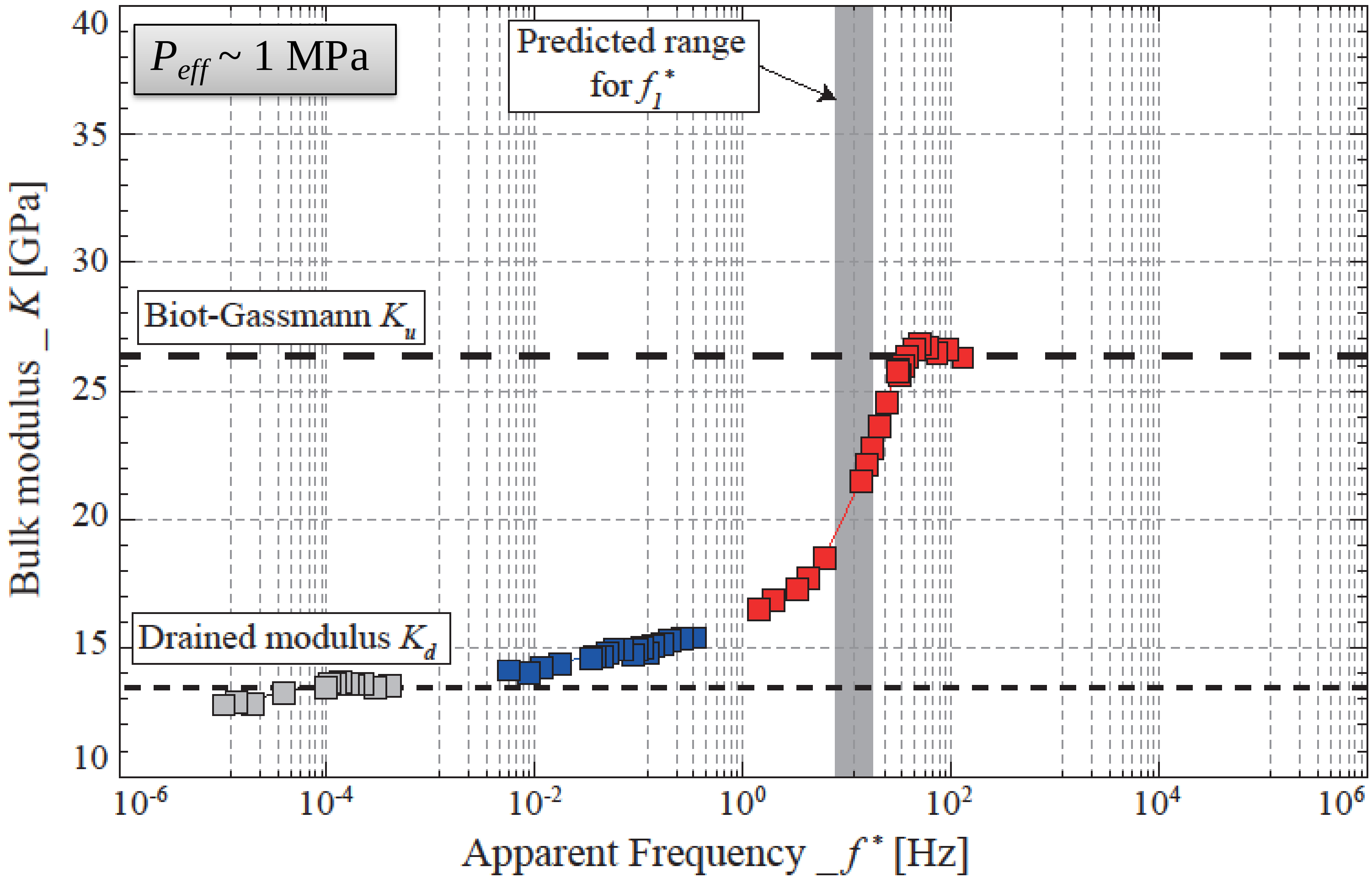
K_f ↔ Fluid bulk modulus

G_u ↔ Undrained shear modulus

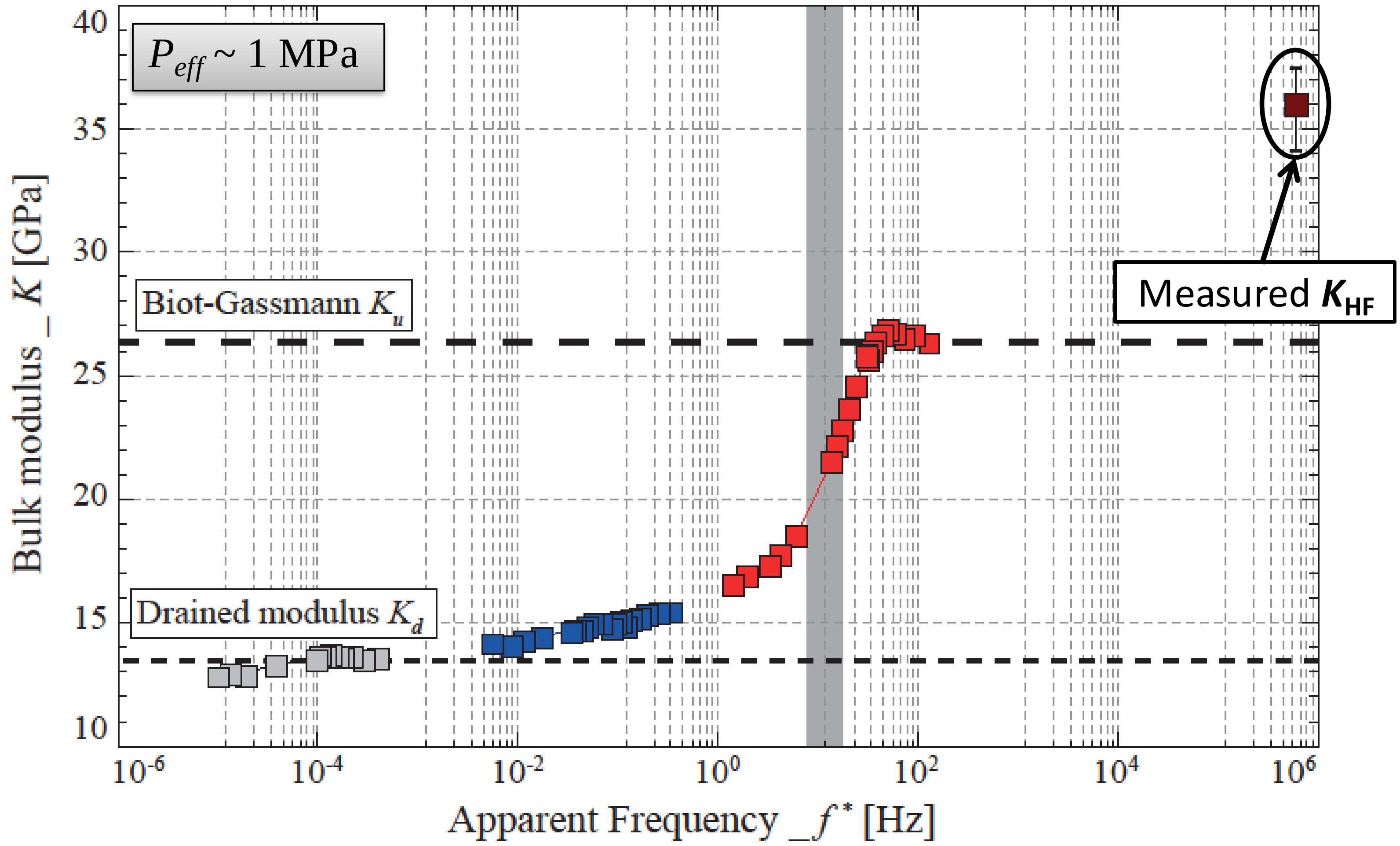
G_d ↔ Drained shear modulus



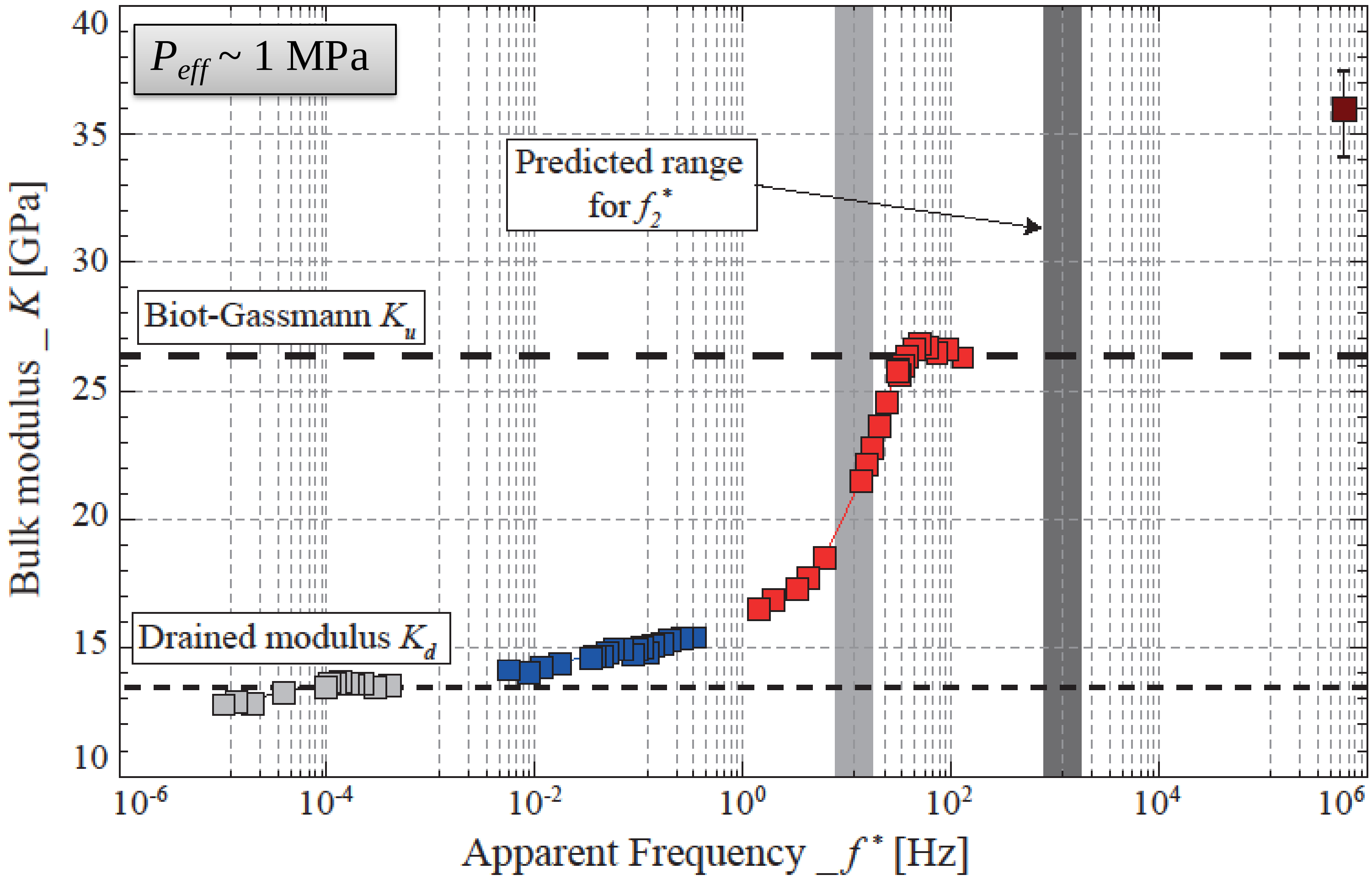
P_{eff} ~ 1 MPa
Biot-Gassmann K_u
Drained modulus K_d
Bulk modulus _K [GPa]
Apparent Frequency _f^* [Hz]
40
35
30
25
20
15
10
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}



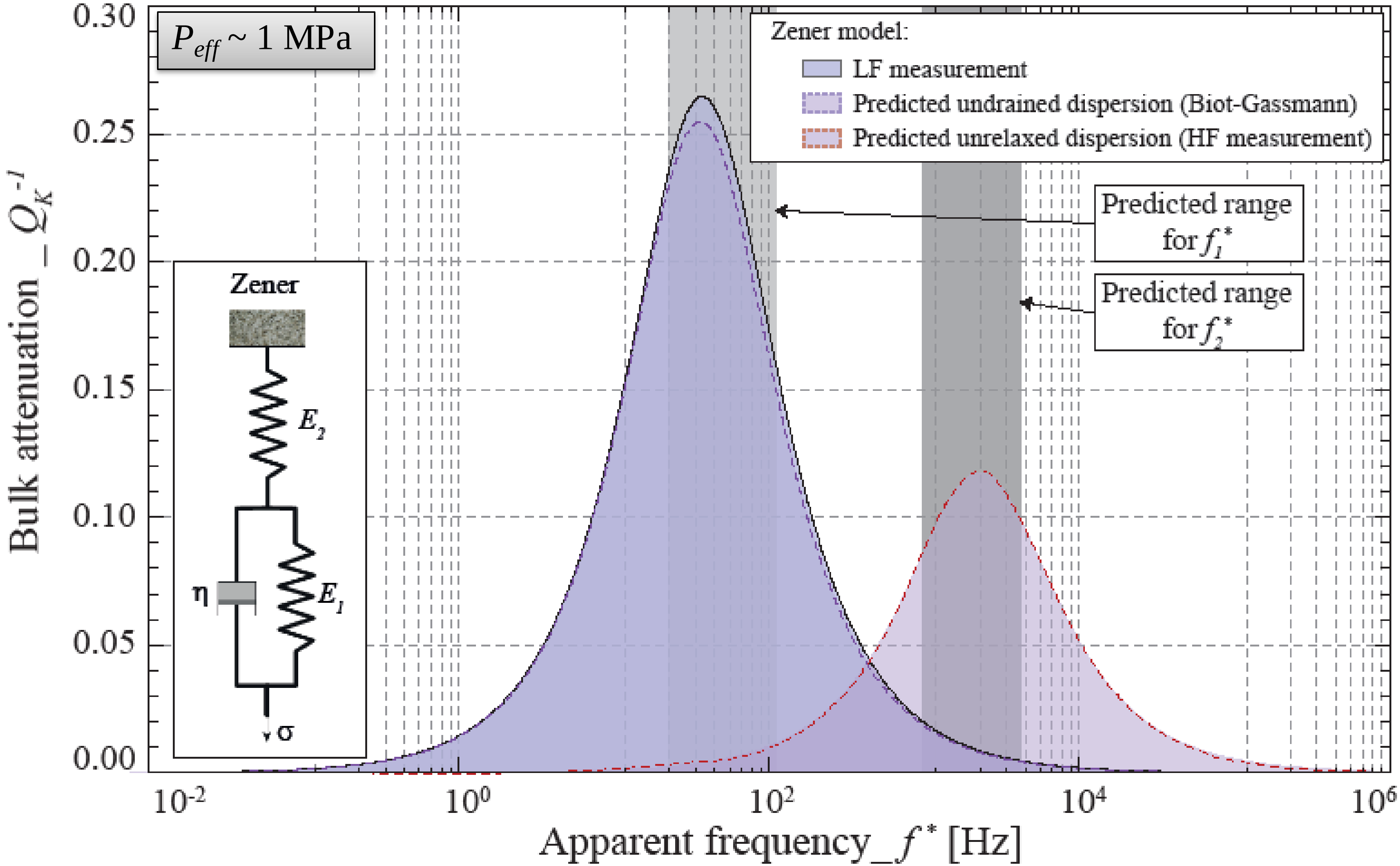
P_{eff} ~ 1 MPa
Predicted range for f_1^*
Biot-Gassmann K_u
Drained modulus K_d
Bulk modulus _ K [GPa]
Apparent Frequency _f * [Hz]
40
35
30
25
20
15
10
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}

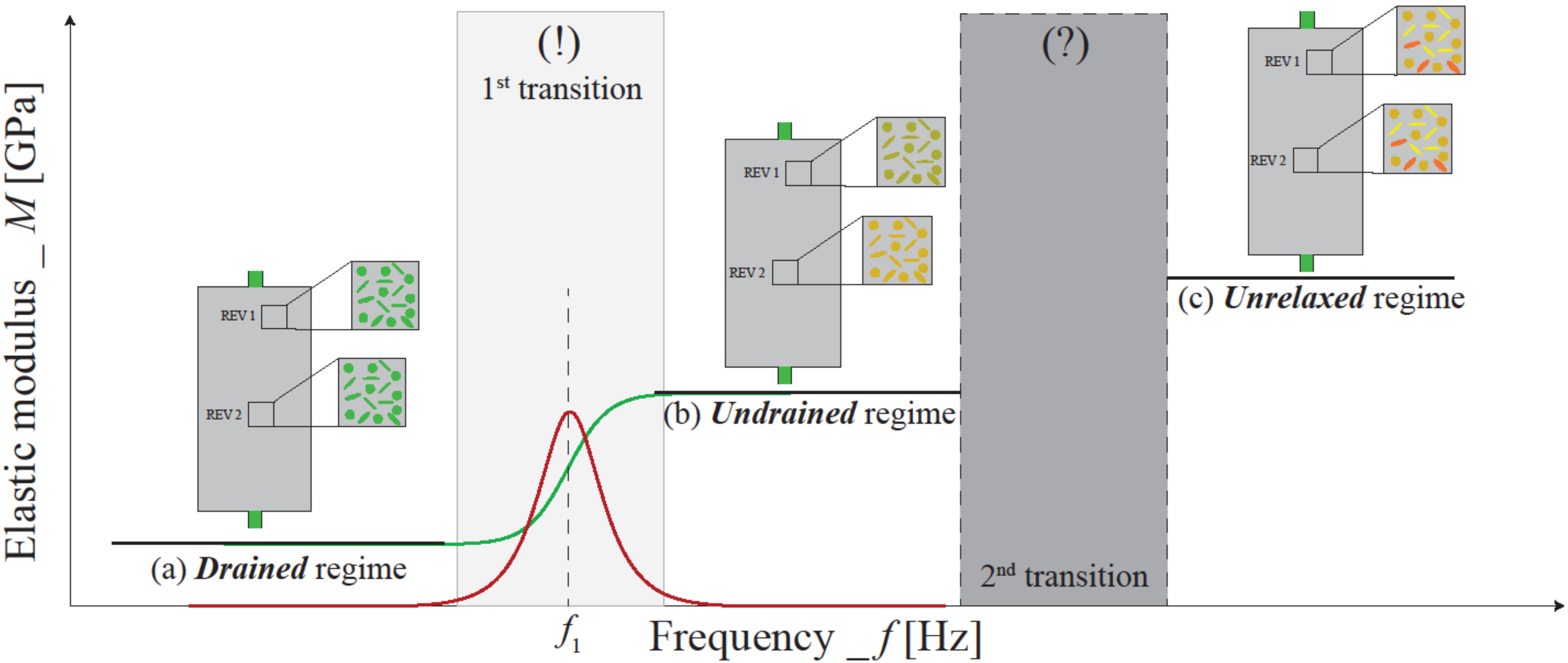


P_{eff} ~ 1 MPa
Biot-Gassmann K_u
Drained modulus K_d
Measured K_{HF}
Bulk modulus _ K [GPa]
40
35
30
25
20
15
10
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
Apparent Frequency _ f^* [Hz]



P_{eff} ~ 1 MPa
Predicted range for f_2^*
Biot-Gassmann K_u
Drained modulus K_d
Bulk modulus _ K [GPa]
Apparent Frequency _ f^* [Hz]
40
35
30
25
20
15
10
10^{-6}
10^{-4}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}


P_{eff} ~ 1 MPa
Zener model:
LF measurement
Predicted undrained dispersion (Biot-Gassmann)
Predicted unrelaxed dispersion (HF measurement)
Predicted range for f_1^*
Predicted range for f_2^*
Zener
E_2
E_1
η
σ
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Bulk attenuation_ Q_K^{-1}
10^{-2}
10^{0}
10^{2}
10^{4}
10^{6}
Apparent frequency_ f^* [Hz]



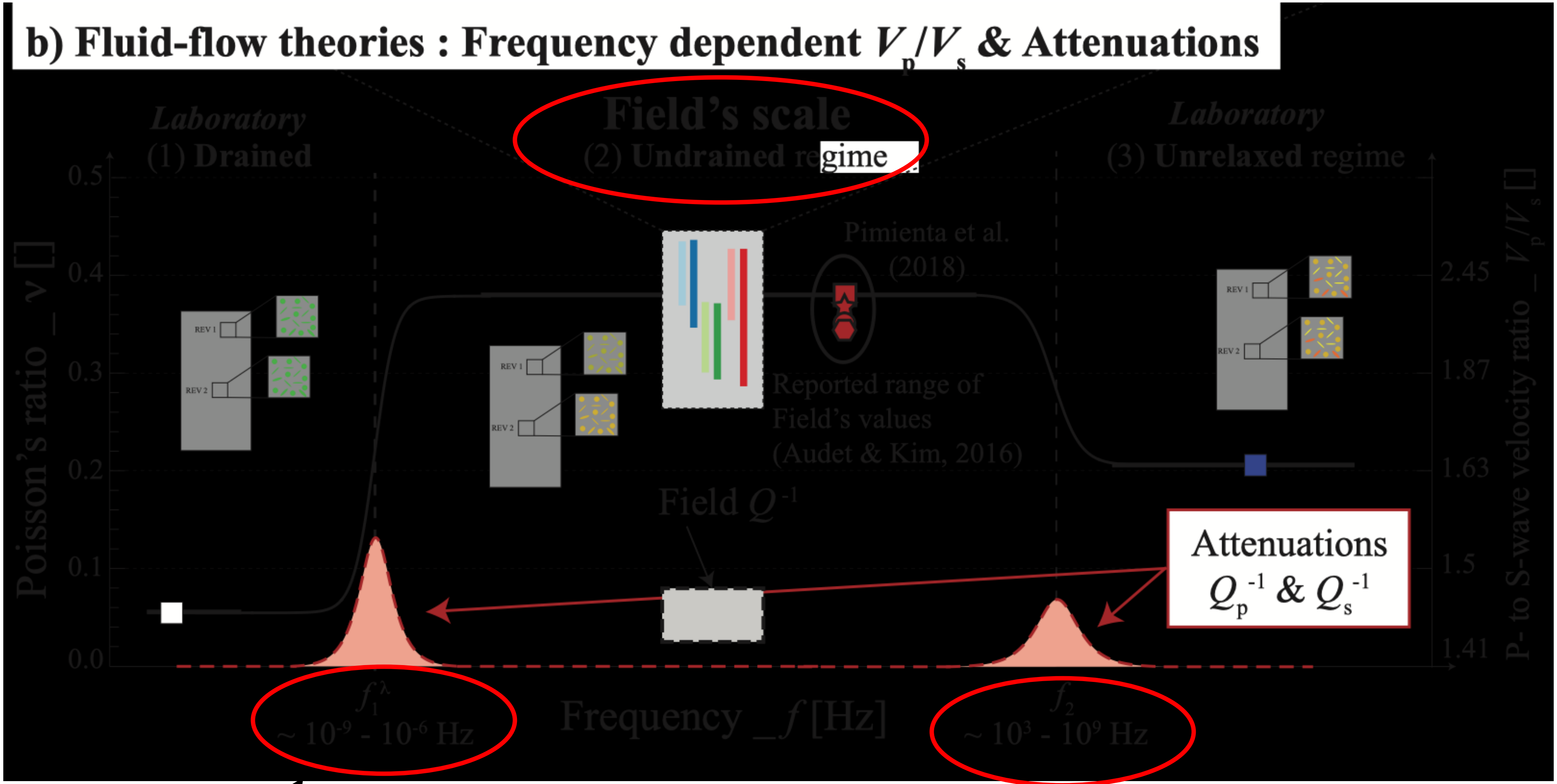
Dispersion/Attenuation

From Drained to Undrained transition

Pimienta et al. (2015a), ***Geophysics***

Why does it matter ?

Application to Low Velocity (subduction) Zones *(e.g. Audet & Kim, 2016)*

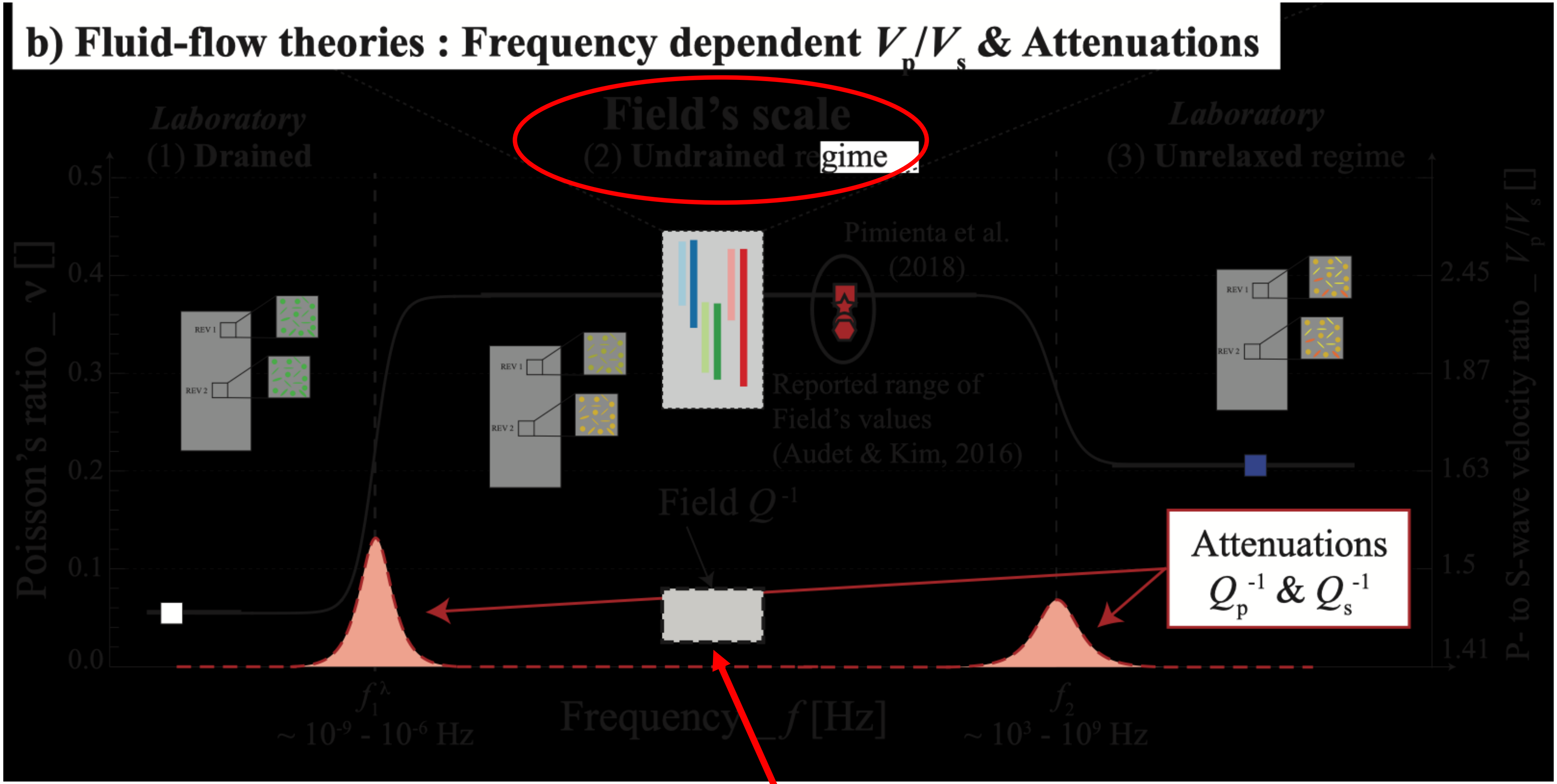


~ ***permeability*** *&* ***wave-length***

~ microcracks ***aspect ratio***

Why does it matter ?

Application to Low Velocity (subduction) Zones *(e.g. Audet & Kim, 2016)*



Frequency-dependent Fluid flow or viscoelasticity

Cannot explain both V_p/V_s & attenuations @ field scale !?