IMPACT OF EXPERIMENTAL METHODS IN THE DIFFERENCES OBSERVED BETWEEN STATIC AND DYNAMIC MODULI

E. BEMER, N. DUBOS-SALLÉE, V. POITRINEAU

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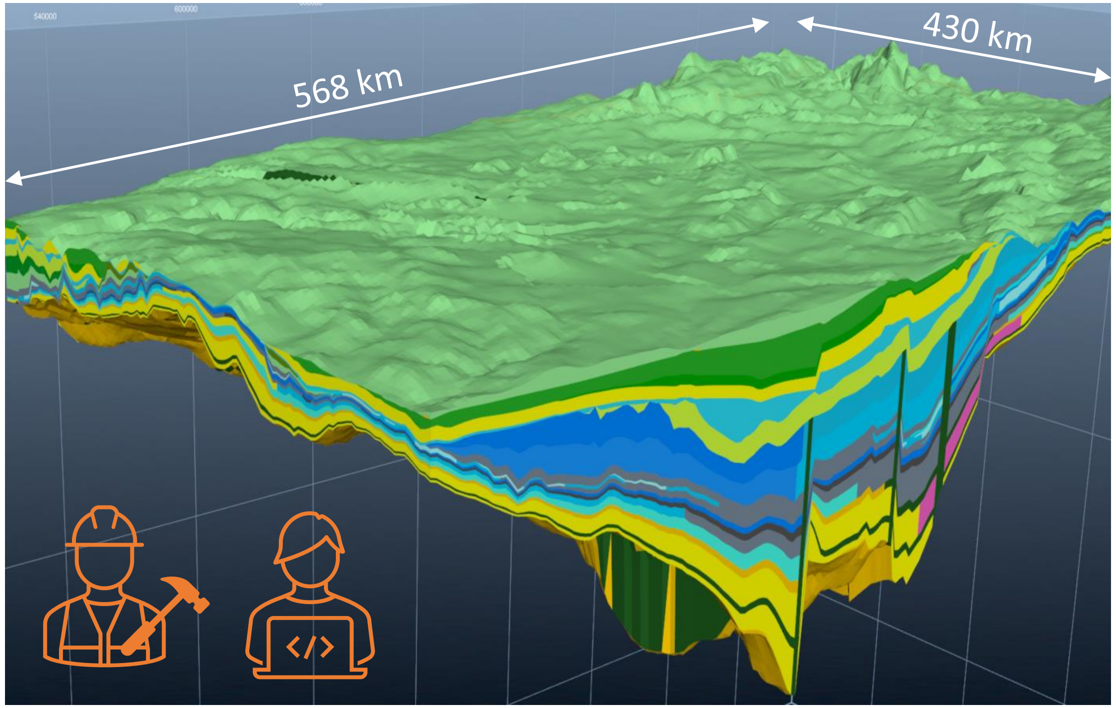
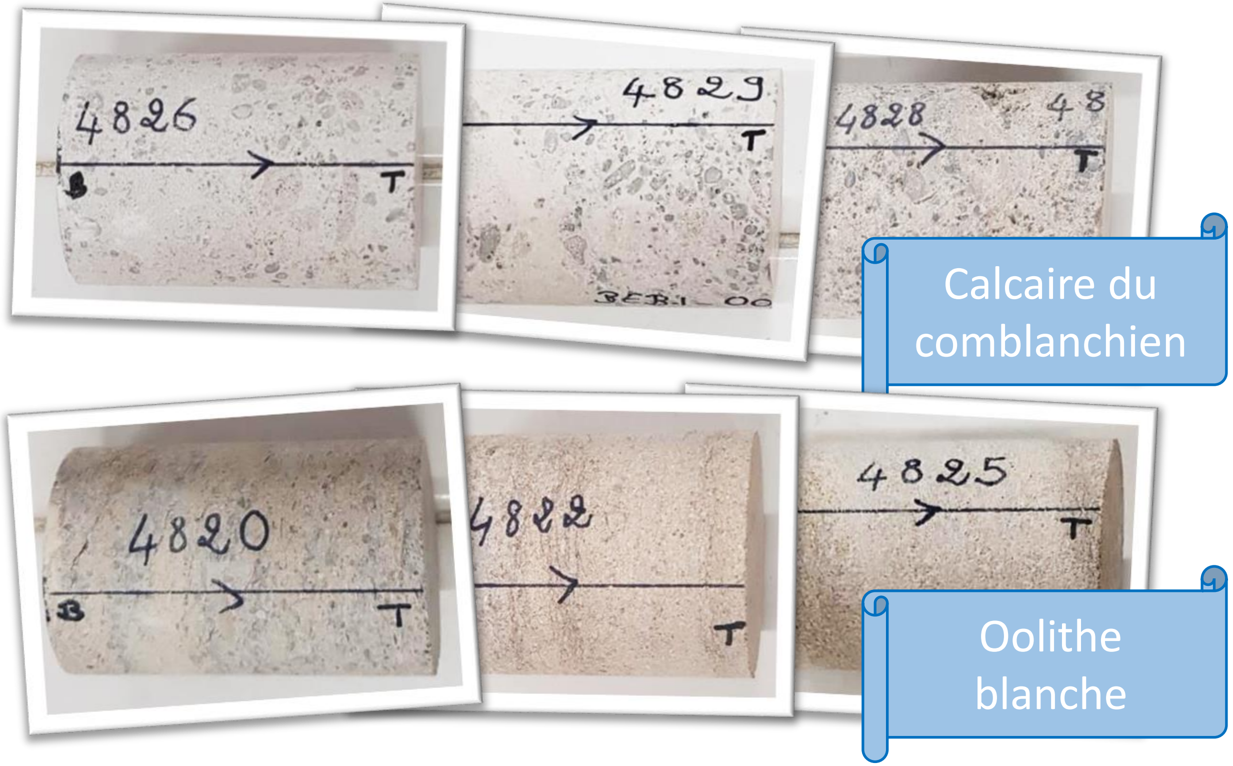
THE AGE-OLD PROBLEM

GEOLOGICAL MODEL
(FROM SURFACE TO BASEMENT)



Outcome of the geologists' and modelers' hard work: 3D numerical model with **multiple facies** to be populated with **geomechanical properties**

MATERIAL AVAILABLE TO THE EXPERIMENTER: **A FEW SAMPLES**



No choice but to link **static** elastic moduli to **dynamic** elastic moduli available at different scales

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THE AGE-OLD PROBLEM

CAUSES FOR DIFFERENCES BETWEEN **DYNAMIC** (∿) AND **STATIC** (⇕) MODULI OF ROCKS
(Fjær, 2019)

Experimental conditions

1. Strain rate
   ∿ squirt flow, scattering…
2. Drainage conditions
   ⇕ usually drained
   ∿ undrained
5. Strain amplitude
   ⇕ non-elastic processes

Studied rock

Cracks, heterogeneities

Permeability

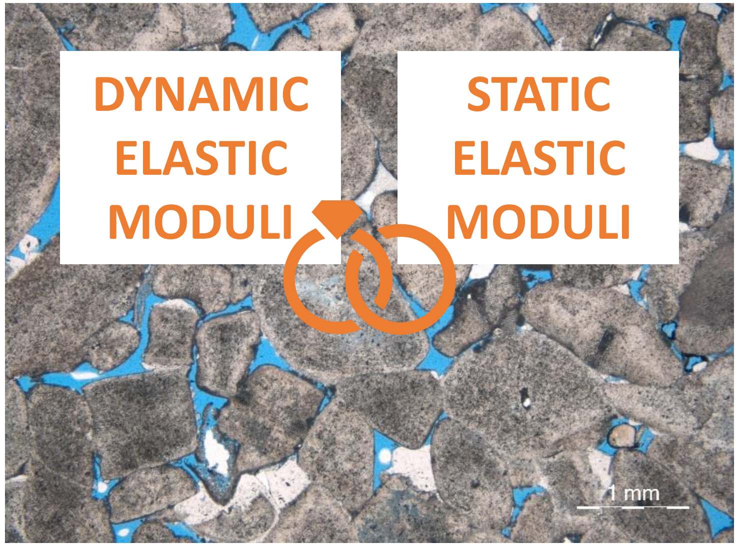
3. Heterogeneities
   (probed rock volume)
4. Anisotropy

Cracks/grain contacts

6 Measurement methods

- Focus on laboratory scale
- Study of outcrop limestones

Euville limestone



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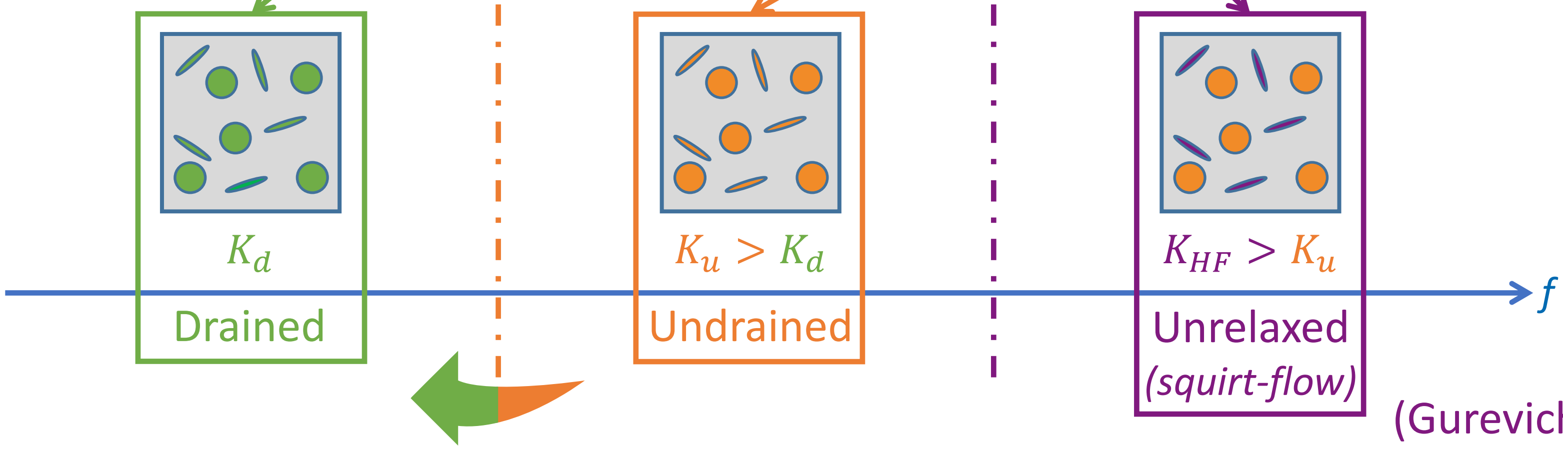
MEASUREMENT OF **DYNAMIC ELASTIC MODULI**
FLUID FLOW REGIME DURING WAVE PROPAGATION

- Measurement conditions in the laboratory (for isotropic rocks)
  - Ultrasonic velocity measurements (500 kHz)
  - Saturation state: dry sample or sample saturated by a liquid
  - Computation of $K_{Lab} = \rho\left({V_p}^2 - \frac{4}{3}{V_s}^2\right)$ and $G_{Lab} = \rho {V_s}^2$
- Fluid flow regime?



(Borgomano, Pimienta, Fortin, Guéguen, 2019)

(Gurevich et al., 2009)

Biot-Gassmann's equation

$$K_u = K_d\left[1 + \frac{\left(1 - \frac{K_d}{K_s}\right)^2}{(1-\phi)\frac{K_d}{K_s} - \left(\frac{K_d}{K_s}\right)^2 + \phi\frac{K_d}{K_{fl}}}\right] \qquad G_u = G_d = G$$

K_s = solid matrix bulk modulus

K_{fl} = fluid bulk modulus

ϕ = effective porosity

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MEASUREMENT OF **DYNAMIC ELASTIC MODULI**
SPECIFICITIES OF THE FOLLOWED APPROACH

- Two types of velocity measurements
  - First break picking (FB)

$$V = \frac{L}{\Delta t}$$

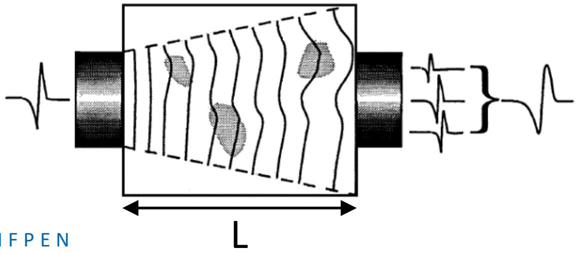
  - Phase spectral ratio method (PH): comparison of the sample signal with a reference signal recorded in an aluminum sample

$$\Delta\varphi = 2\pi f\left(\frac{L}{V(f)} - \frac{L_o}{V_o}\right)$$

(Rasolofosaon et al., 2008) *(Bemer et al., 2019)*

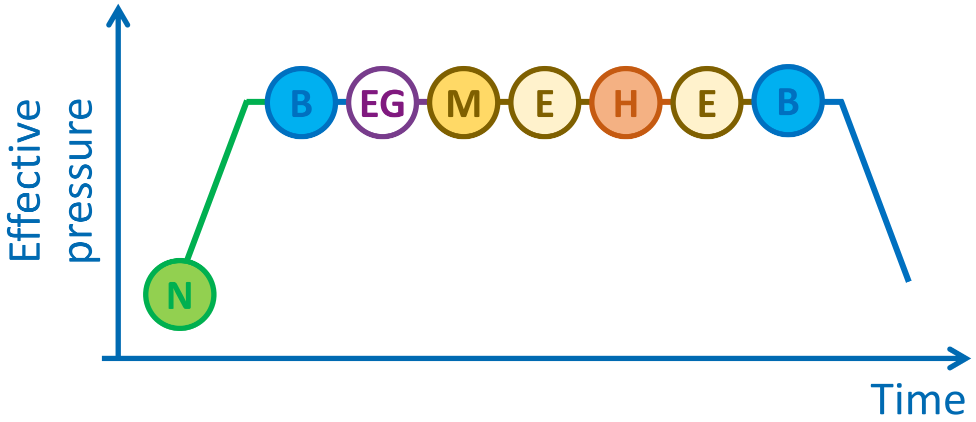
Homogenized velocities provided by phase velocity measurement more representative of the sample macroscopic behavior

(Dubos-Sallée et al., 2016)



Path dispersion
(Cadoret, 1993)

- Fluid substitution technique
  - Measurement of velocities for various saturating fluids of different bulk moduli



N	Nitrogen	Gas
B	Brine	Liquids (miscible fluid replacement)
EG	Ethylene-Glycol	
M	Methanol	
E	Ethanol	
H	Heptane	

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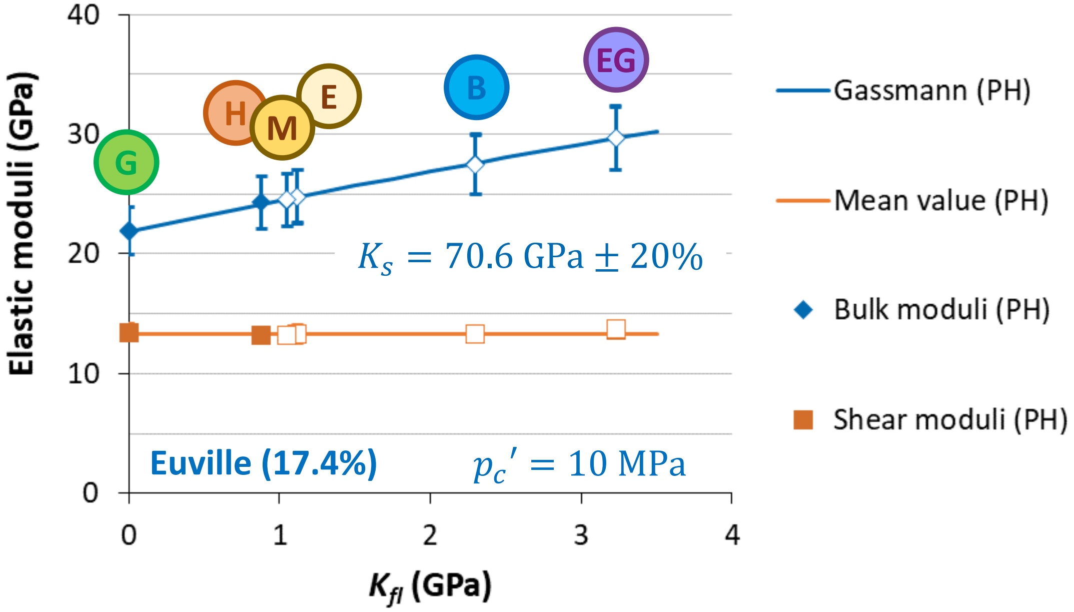
MEASUREMENT OF DYNAMIC ELASTIC MODULI
INTERPRETATION OF THE EXPERIMENTAL DATA



BIOT-GASSMANN'S EQUATION

$$K_u = K_d \left[1 + \frac{\left(1 - \frac{K_d}{K_s}\right)^2}{(1-\phi)\frac{K_d}{K_s} - \left(\frac{K_d}{K_s}\right)^2 + \phi \frac{K_d}{K_{fl}}} \right]$$

$$G_u = G_d = G$$

- Interpretation
  - K_d and K_s estimated from inverse analysis
  - G = mean value for the 5 liquids

- Quality check
  - Comparison of G and $G_{Lab/N} \approx G_{dry}$ and of K_d and $K_{Lab/N} \approx K_{dry}$ ➔ dispersion?
  - Consistency of K_s with sample mineralogy: $K_{calcite} = 76.8$ GPa (Mavko *et al.*, 2009)

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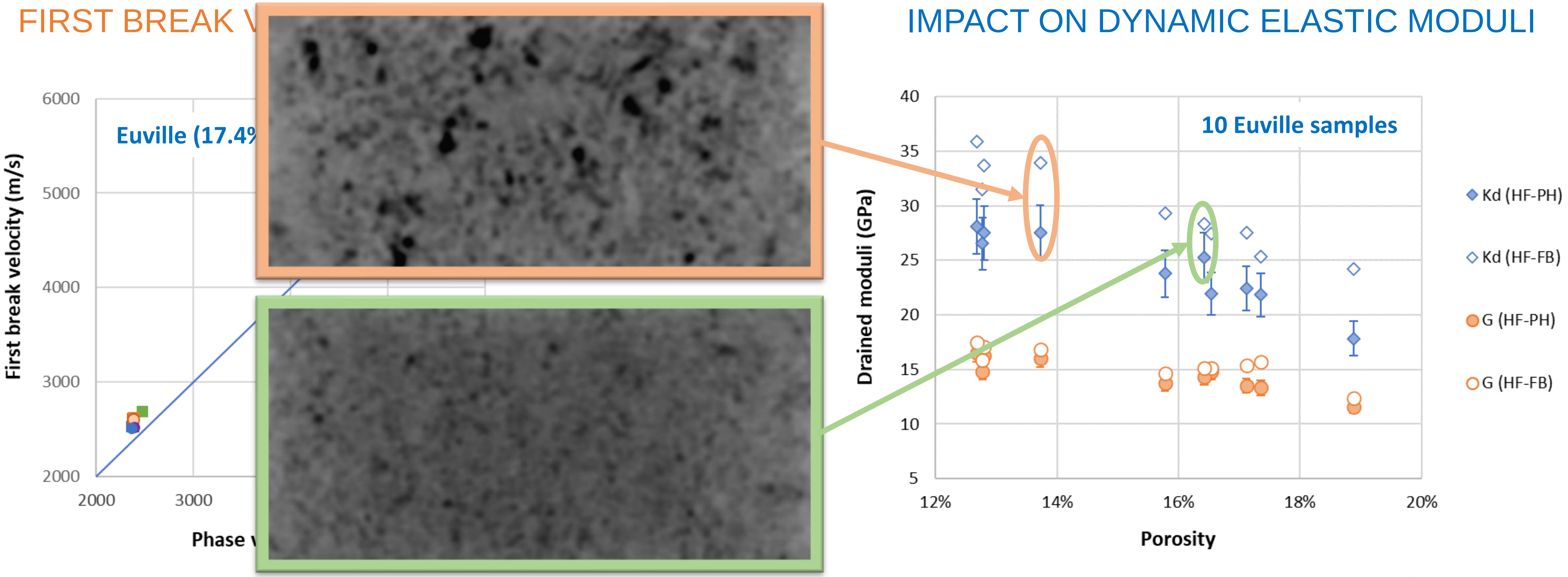
MEASUREMENT OF DYNAMIC ELASTIC MODULI
INTERPRETATION OF THE EXPERIMENTAL DATA

FIRST BREAK V

IMPACT ON DYNAMIC ELASTIC MODULI



First break velocities around 10% higher than phase velocities **for this sample**

Dynamic elastic moduli derived from first break velocities significantly higher (around 20% for K_d and 10% for G **for Euville limestone**)

Deviation between first break and phase velocities representative of the **rock intrinsic heterogeneity**

(Dubos-Sallée et al., 2016)

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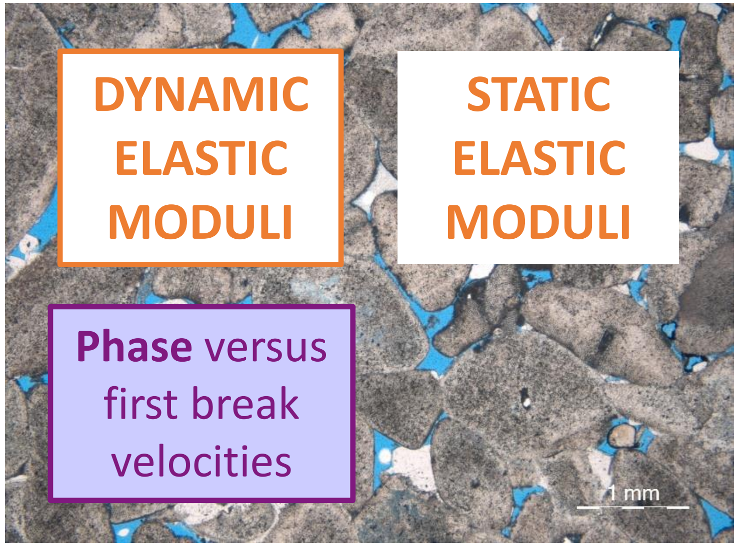
Experimental conditions	Studied rock	Measurement methods

1. Strain rate
   ∿ squirt flow, scattering…
   — *Cracks, heterogeneities*
2. Drainage conditions
   ⇕ usually drained
   ∿ undrained
   — *Permeability*
3. Heterogeneities
   (probed rock volume)
4. Anisotropy
5. Strain amplitude
   ⇕ non-elastic processes
   — *Cracks/grain contacts*

- Focus on laboratory scale
- Study of outcrop limestones

Euville limestone



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MEASUREMENT OF STATIC ELASTIC MODULI
TRIAXIAL CELL EQUIPMENT

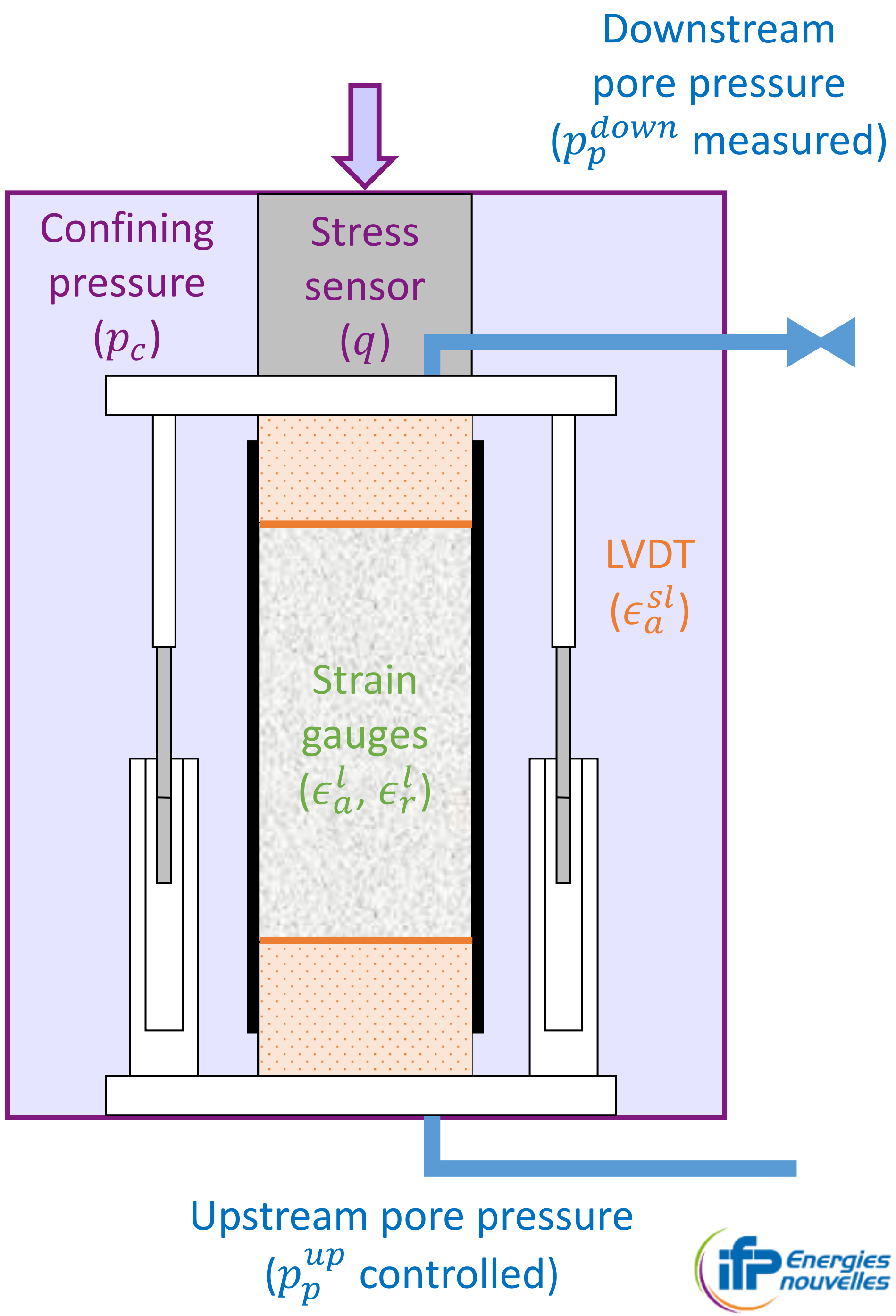
- Standard approach
  - Static elastic moduli measured in controlled drained conditions during an unloading phase carried out at constant confining pressure

$$E_d = \frac{\Delta\sigma_a}{\Delta\epsilon_a} \qquad \frac{E_d}{\nu_d} = -\frac{\Delta\sigma_a}{\Delta\epsilon_r}$$

- Measurement system
  - Internal stress sensor (full Wheatstone bridge) ➔ deviatoric stress ($q = \sigma_a - p_c$)
  - 3 pressure transducers ➔ confining pressure (p_c), upstream (p_p^{up}) and downstream (p_p^{down}) pore pressure
  - 3 axial and 3 radial strain gauges ➔ local axial strain (ϵ_a^l) and local radial strain (ϵ_r^l)
  - 4 axial LVDT ➔ semi-local axial strain (ϵ_a^{sl})

Include end platen deformation and **interface effects**

Euville sample



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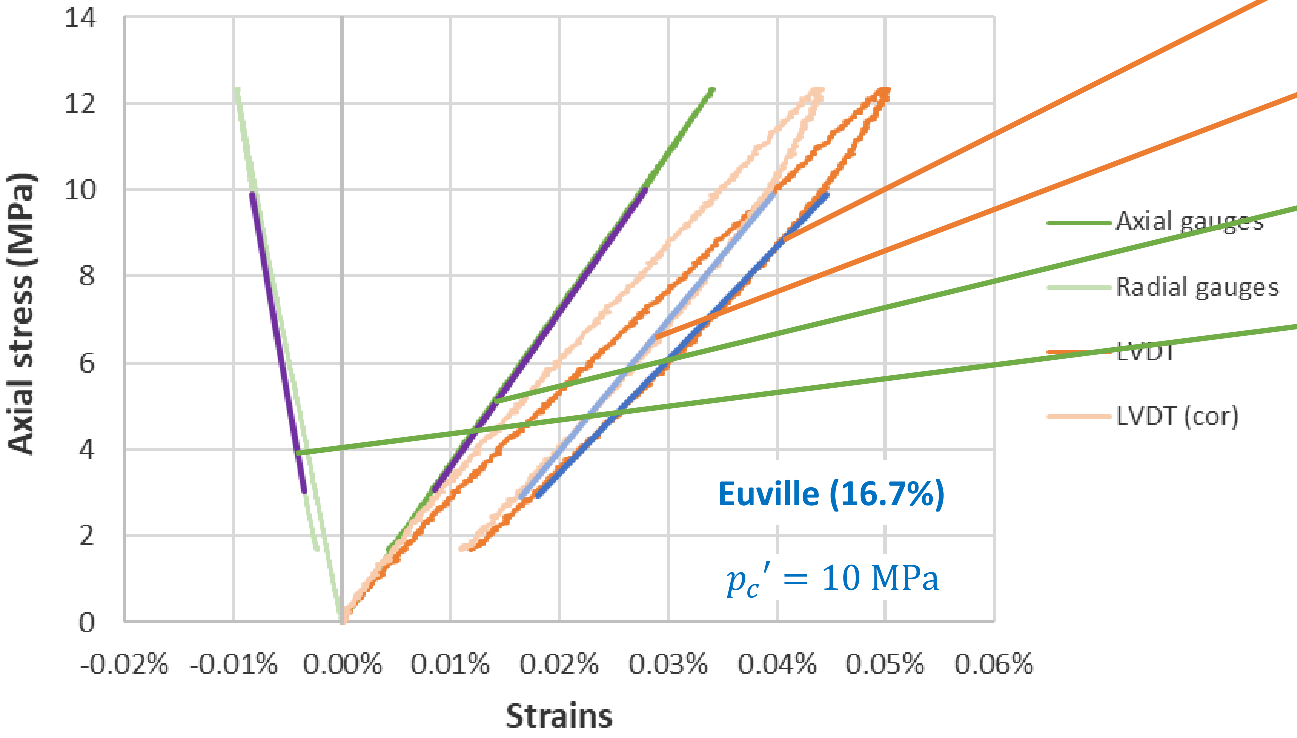
MEASUREMENT OF STATIC ELASTIC MODULI
FOCUS ON THE INTERFACE EFFECTS



$E_d^{LVDT} = 26.2$ GPa

$E_d^{LVDT}(cor) = 30.2$ GPa

$E_d^{SG} = 35.9$ GPa

$\left(\frac{E_d}{\nu_d}\right)^{SG} = 144$ GPa

$\nu_d^{SG} = 0.25$

Drained Young's modulus derived from LVDT significantly lower than the one derived from strain gauges even after correction of end platen deformation

Can interface effects be calibrated to some degree?

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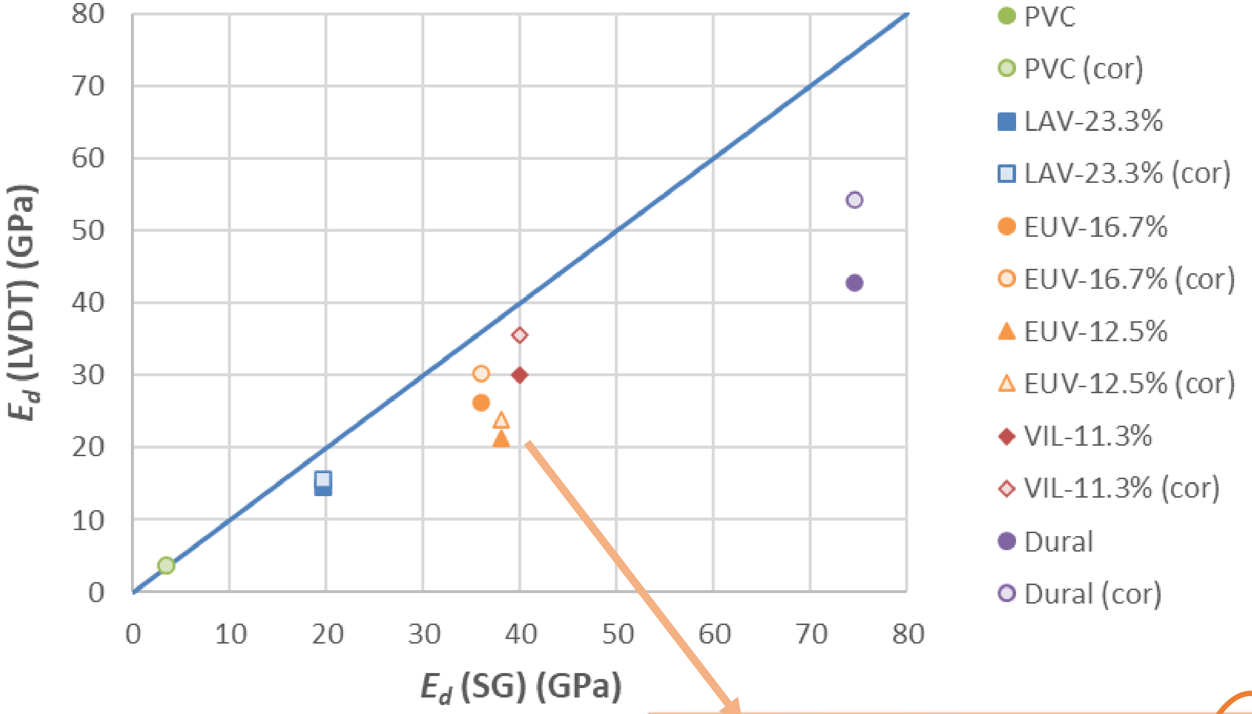
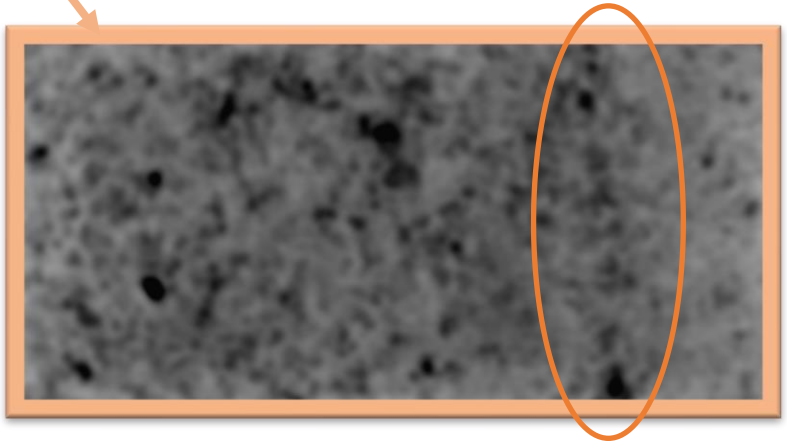
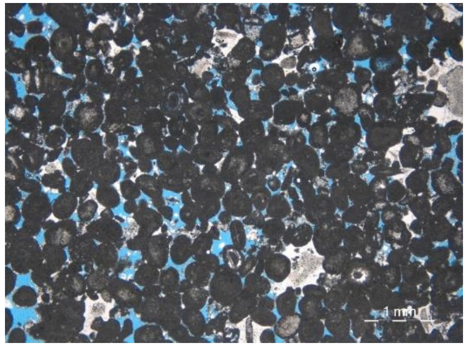




- Truly homogeneous samples
  - PVC
  - Dural
- Another Euville sample with lower porosity
- Two other limestone samples to extend the porosity range
  - Lavoux limestone
  - Vilhonneur limestone



Elastic moduli derived from strain gauges preferentially considered

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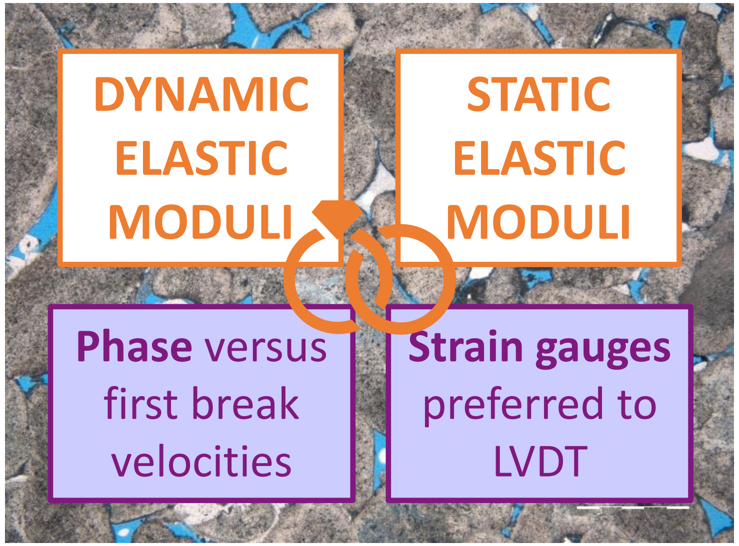

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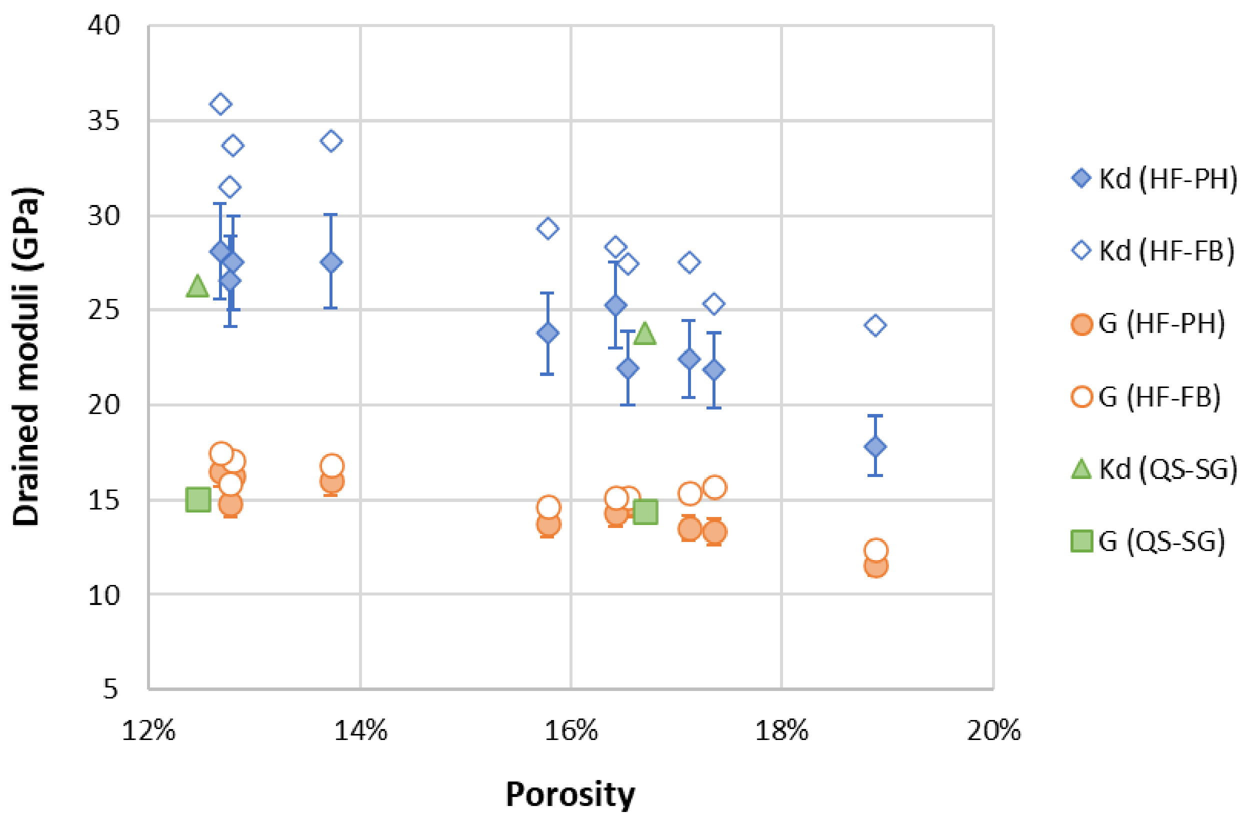
RECONCILIATION?



Homogenized dynamic elastic moduli derived from **phase velocities** consistent with static elastic moduli derived from **strain gauges**

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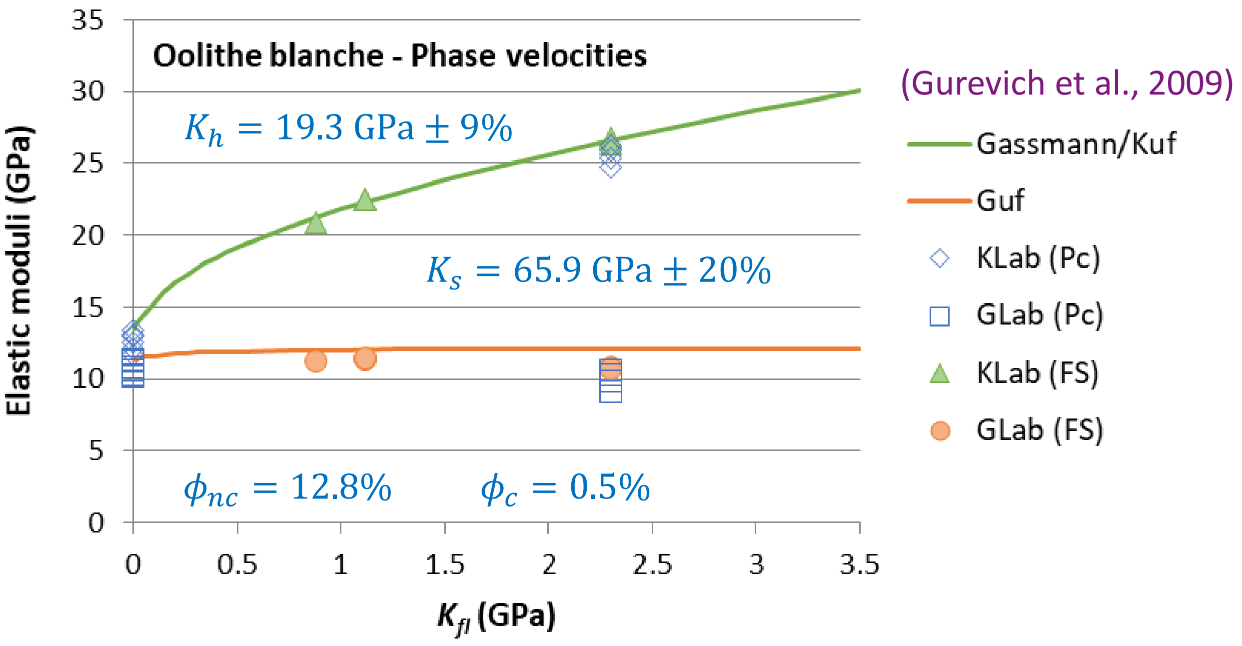
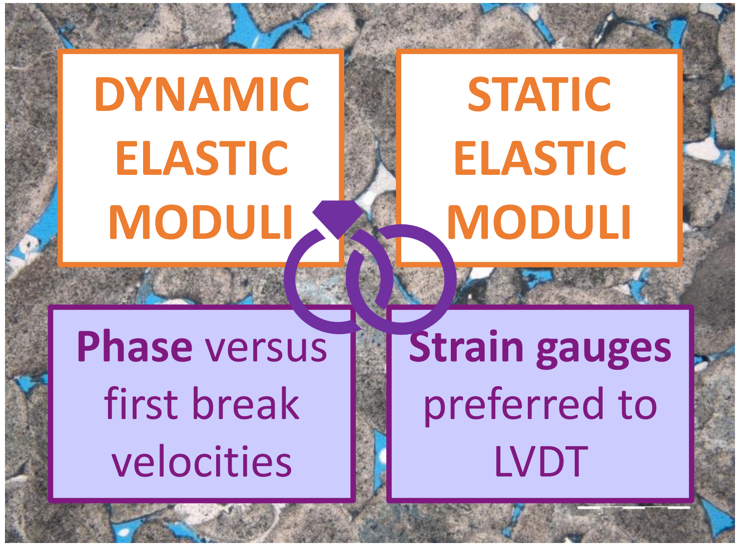
CONCLUSIONS AND PROSPECTS

- Phase velocity measurements and fluid substitution technique provide equivalent static elastic moduli when there is no dispersion effect…
- What about carbonate rocks with cracks?





⇨ Prospects: Measurements of static elastic moduli

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EXTENSION OF BIOT-GASSMANN'S EQUATION TO CONSIDER THE UNRELAXED REGIME

Unrelaxed response *(Mavko and Jizba, 1991)*

$$K_{Lab} = K_{uf}\left[1 + \frac{\left(1 - \frac{K_{uf}}{K_s}\right)^2}{(1 - \phi_{nc})\frac{K_{uf}}{K_s} - \left(\frac{K_{uf}}{K_s}\right)^2 + \phi_{nc}\frac{K_{uf}}{K_{fl}}}\right] \qquad \mu_{Lab} = \mu_{uf}$$

K_{uf} = unrelaxed frame bulk modulus

μ_{uf} = unrelaxed frame shear modulus

K_s = solid matrix bulk modulus

K_{fl} = fluid bulk modulus

ϕ_{nc} = non-compliant porosity

K_h = frame bulk modulus without ϕ_c

ϕ_c = compliant porosity

$$\frac{1}{K_{uf}(p'_c)} = \frac{1}{K_h} + \frac{1}{\frac{1}{\frac{1}{K_{dry}(p'_c)} - \frac{1}{K_h}} + \frac{1}{\left(\frac{1}{K_{fl}} - \frac{1}{K_s}\right)\phi_c(p'_c)}}$$

$$\frac{1}{\mu_{uf}(p'_c)} - \frac{1}{\mu_{dry}(p'_c)} = \frac{4}{15}\left(\frac{1}{K_{uf}(p'_c)} - \frac{1}{K_{dry}(p'_c)}\right)$$

(Gurevich et al., 2009)

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