From hydraulic and mechanical properties to hydro-mechanical coupling in porous rocks:

The hidden role of the microstructure

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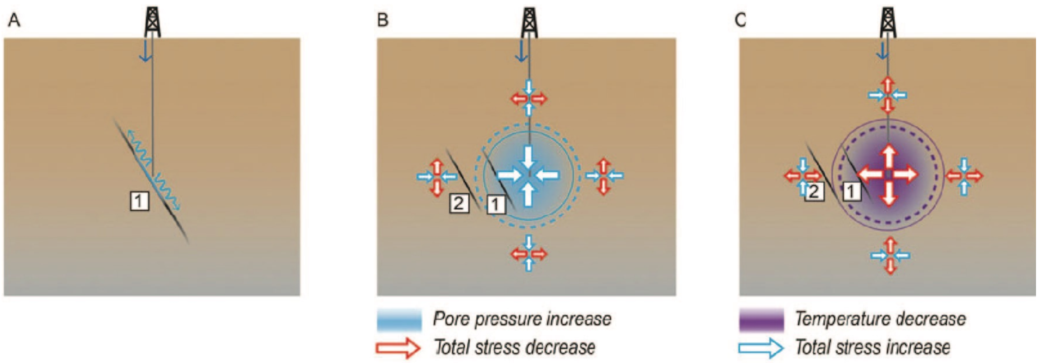
[3]*Ecole Polytechnique Fédérale Lausanne (EPFL), Switzerland*
[4]*Geophysics institute, University of Leoben, Austria*

Légende :
- *Quand le travail a été commencé.*
- *Quand le travail a été fini.*
- *Où je travaille maintenant.*

Problem: *Geomechanics of Fluids injections @ depth*



Proof of caution

My expertise is exclusively in the elastic realm

⇔ Some layman concepts/terms might be used when in the brittle realm

Sample dilation and fracture in response to high pore fluid pressure and strain rate in quartz-rich sandstone and siltstone

M. E. French,[1] D. F. Boutt,[2] and L. B. Goodwin[3]

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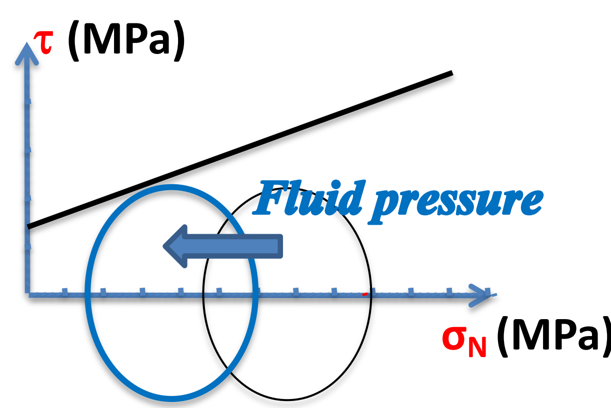
JGR Solid Earth

RESEARCH ARTICLE
10.1029/2018JB016546

Special Section:
Physical Properties of Rocks, Friction and Fracturing: the Walsh Volume

Time-Dependent Deformations of Sandstone During Pore Fluid Pressure Oscillations: Implications for Natural and Induced Seismicity

C. Noël[1], L. Pimienta[1], and M. Violay[1]



Problem: *Inconsistencies from brittle & creep experiments on role of pore fluid ?*

Typical procedure ⇔ Before experiment : ***Darcy permeability => Characteristic time*** or ***flow rate*** *for fully drained conditions*
In French et al. (2012) & Noel et al. (2019) ⇔ *Sample should be **largely** drained*

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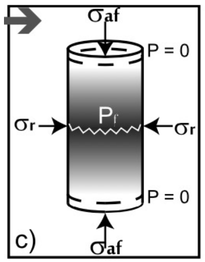

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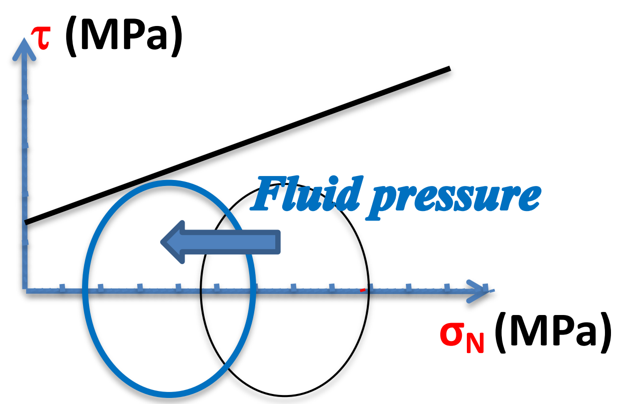

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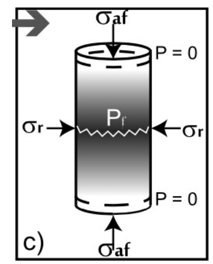

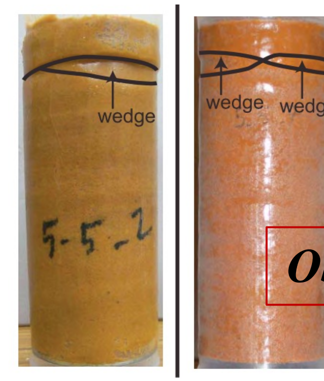

Observed

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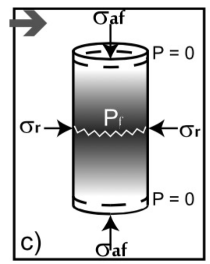

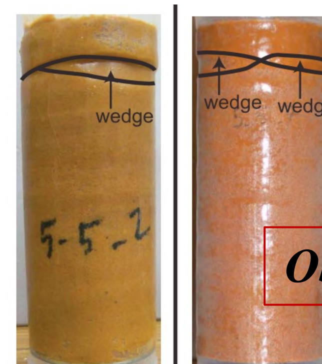

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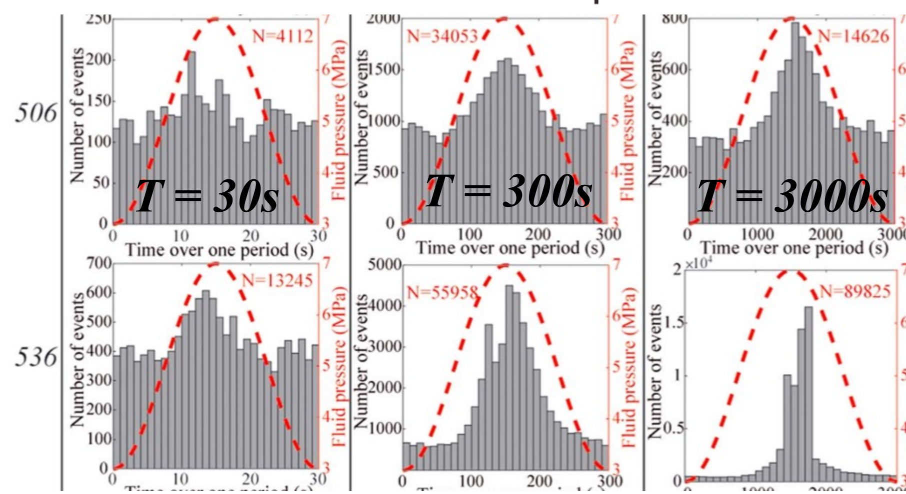

Creep/Brittle behaviours in porous sandstones
as if *fluid pressure* ***did not have time to equilibrate*** *across the sample ?*

Problem: *Anomalously low skeleton bulk moduli ?*

Typical procedure ⇔ Before experiment : Typical procedure ⇔ Before experiment : ***Darcy permeability* => *Characteristic time*** or ***flow rate*** *for full fluid pressure equilibration*

Skeleton compressibility C_s [GPa^{-1}]	$\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{P_d}$	$\left(\frac{\Delta \epsilon_b}{\Delta P_c}\right)_{P_d}$
Skeleton compressibility C_ϕ [GPa^{-1}]	$\frac{1}{V_p}\left(\frac{\partial V_p}{\partial P_c}\right)_{P_d}$	$\frac{1}{V_f}\left(\frac{\Delta V_f}{\Delta P_c}\right)_{P_d}$

e.g. in quartz-rich :
$K_s \sim K_{quartz}$

To get the skeleton bulk modulus $K_s = 1/C_s$ ***experimentally*** :
=> "Unjacketed test" $K_{unj} = K_s$: "outer" confining Pressure P_c = "inner" pore pressure P_p

Problem: *Anomalously low skeleton bulk moduli ?*

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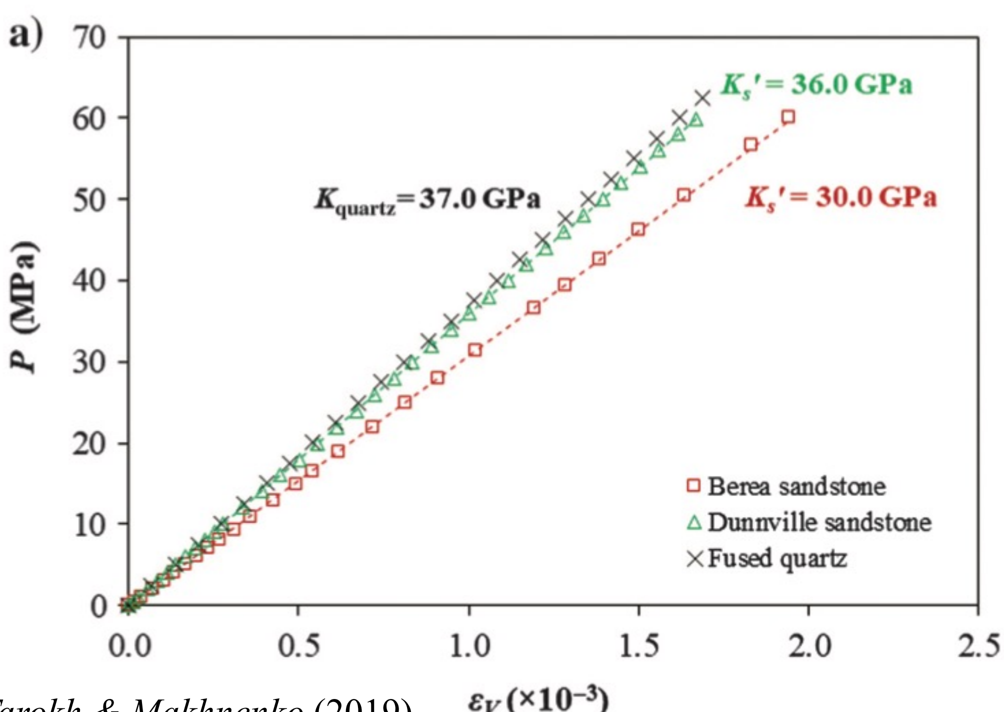

Tarokh & Makhnenko (2019)

Berea sandstone interpreted as with isolated porosity & micro-heterogeneous

Values down to $K_\text{s} \sim 15$ GPa have been reported for sandstones (Fabre & Gustkiewicz, 1997; Tarokh & Makhnenko, 2019) !?

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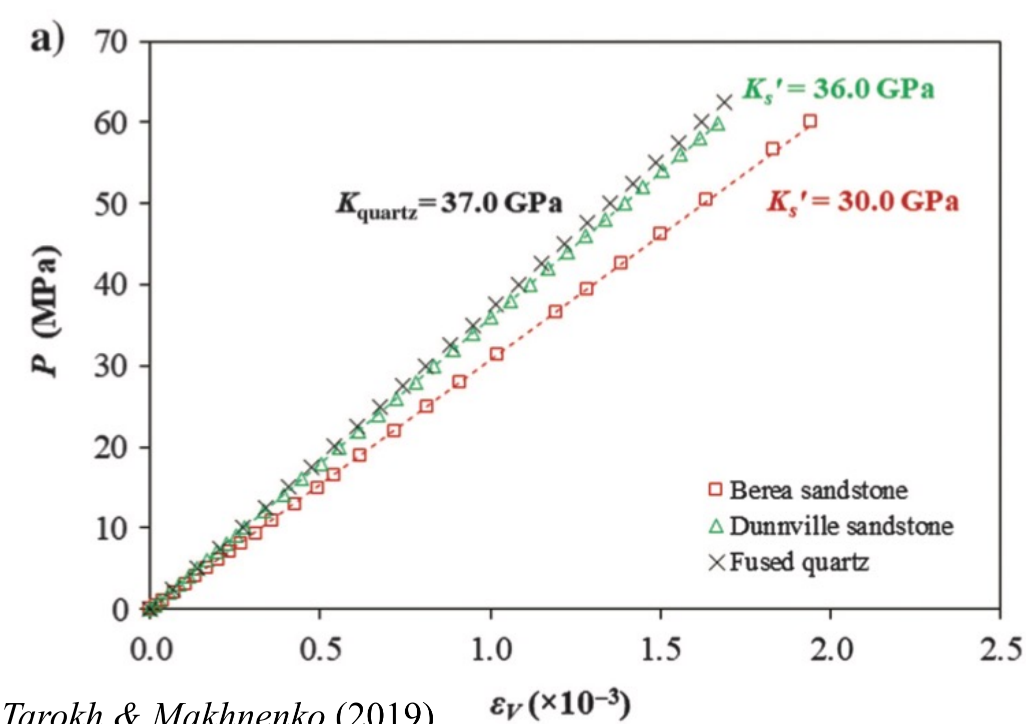

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~~as~~ what if
…
fluid pressure ***did not have time to equilibrate*** *across the sample ?*

Background

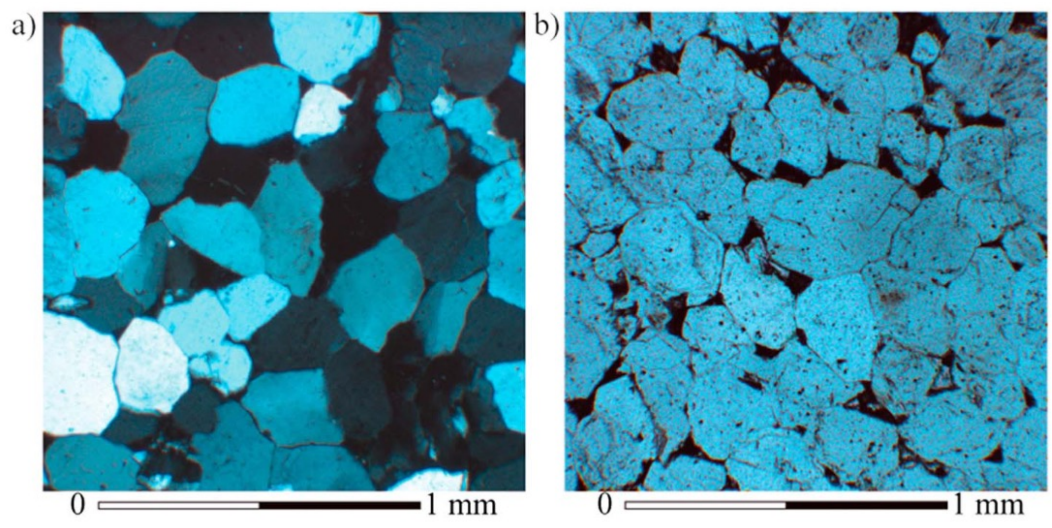
Do we fully know how porous rocks respond to fluid pressure variation ?

i.e. What dictates :

- **Magnitude** of effect experienced by the rock ?
- **Characteristic time** at which effect takes place ?

Medium considered :

- *Quartz-rich clean sandstone*
- *Well-cemented*
- *Homogeneous & Isotropic*
- *Pressure-dependent properties*
- *Water full saturation*



SEM example for Fontainebleau sandstone

Outline

0 _ **Background** for Hydro-Mechanics
i.e. What we know (or expect) in poroelasticity
(a view from experimental RP)

I _ Hydraulic & Mechanical properties, *if two pore families*
i.e. Recalling & using the simplest theoretical models.
(a view from experimental RP)

II _ If so, How to combine Hydraulic & Mechanical in such rocks ?
(a view from experimental RP)

III _ Implications for ***measured*** *rock properties* (K_S, K_ϕ , *etc.*)

Background : *Poroelastic & Compressibility coefficients*

Biot's theory	Theoretical definition
Drained compressibility C_d [GPa^{-1}]	$-\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{p_f}$
Biot's coefficient α []	$-\left(\frac{\partial V_p}{\partial V_b}\right)_{p_f}$
Undrained compressibility C_u [GPa^{-1}]	$-\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{m_f}$
Skempton's coefficient B []	$\left(\frac{\partial p_f}{\partial P_c}\right)_{m_f}$
Zimmerman's theory	**Theoretical definition**
Bulk compressibility C_{bc} [GPa^{-1}]	$-\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{p_f}$
Pore compressibility C_{pc} [GPa^{-1}]	$-\frac{1}{V_p}\left(\frac{\partial V_p}{\partial P_c}\right)_{p_f}$
Bulk compressibility C_{bp} [GPa^{-1}]	$\frac{1}{V_b}\left(\frac{\partial V_b}{\partial p_f}\right)_{P_c}$
Pore compressibility C_{pp} [GPa^{-1}]	$\frac{1}{V_p}\left(\frac{\partial V_p}{\partial p_f}\right)_{P_c}$
Skeleton compressibility C_s [GPa^{-1}]	$\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{P_d}$
Skeleton compressibility C_ϕ [GPa^{-1}]	$\frac{1}{V_p}\left(\frac{\partial V_p}{\partial P_c}\right)_{P_d}$

Drained
Boundary Conditions

Undrained
Boundary Conditions

ΔP_c
solicitation

Δp_f
solicitation

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$\Delta \boldsymbol{P}_c$ *solicitation*

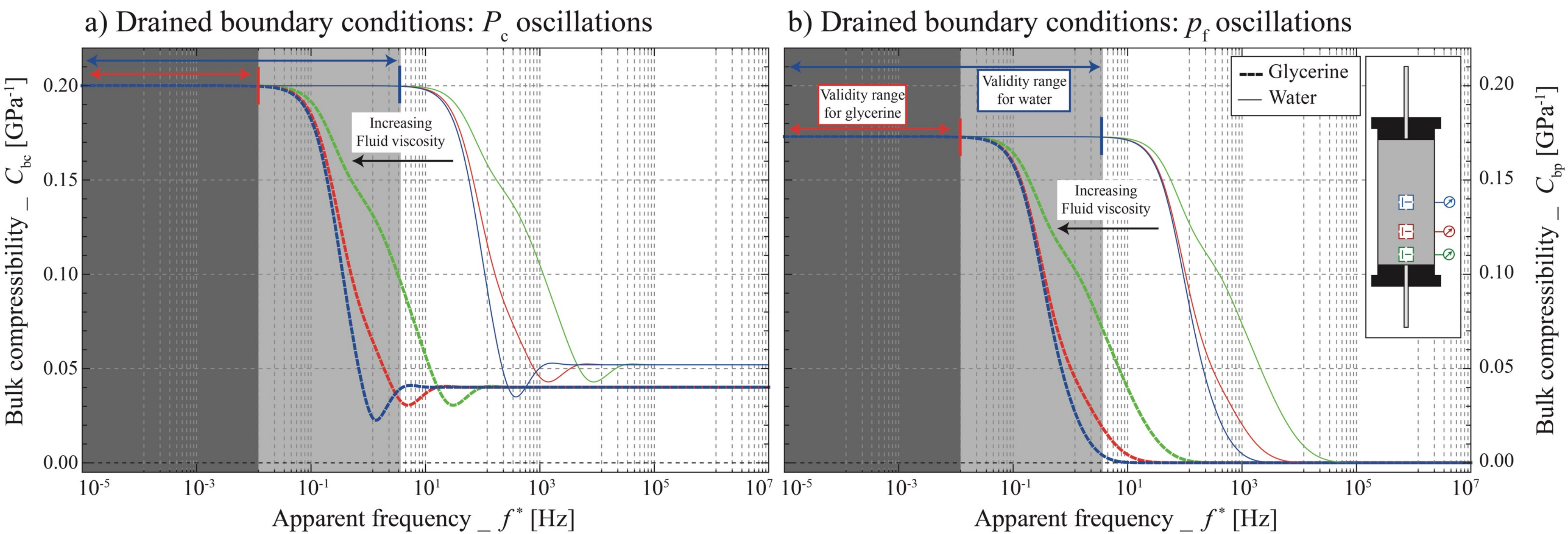
$\Delta \boldsymbol{p}_f$ *solicitation*

EXPERIMENTALLY : Role of **strain rates** or **oscillating frequency**

Differential equation for fluid pressure diffusion (or strain):

$$\frac{\partial p_f}{\partial t} - \frac{\kappa}{\eta S_s}\frac{\partial^2 p_f}{\partial z^2} = B\frac{\partial P}{\partial t},$$

(Darcy) Permeability => dictates the time for the effect.



Pimienta et al. (2017)

Outline

0 _ Background for Hydro-Mechanics :

i.e. What we expect in poroelasticity & some unconsistencies

(a view from experimental RP)

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II _ If so, How to combine Hydraulic & Mechanical in such rocks ?

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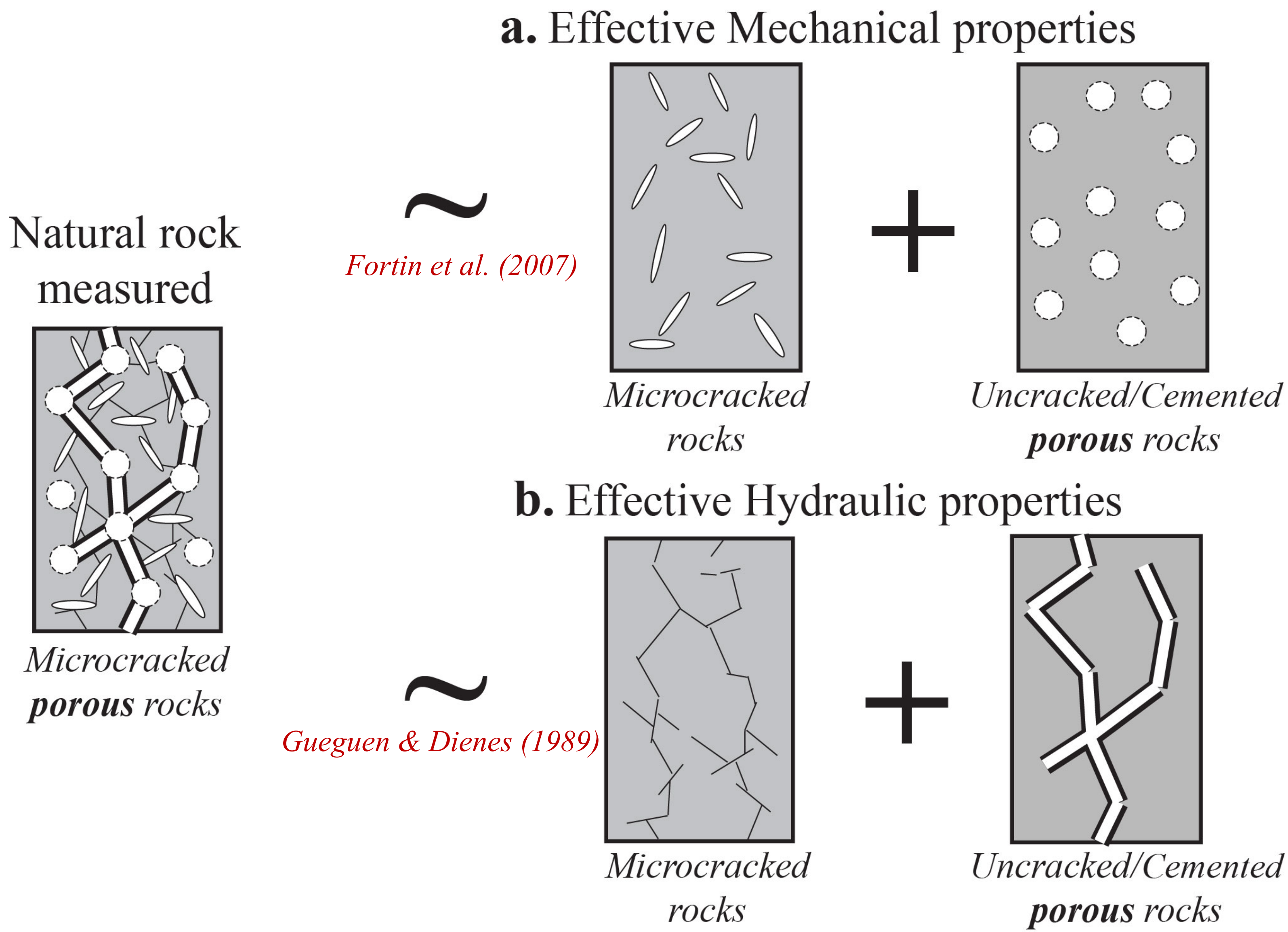
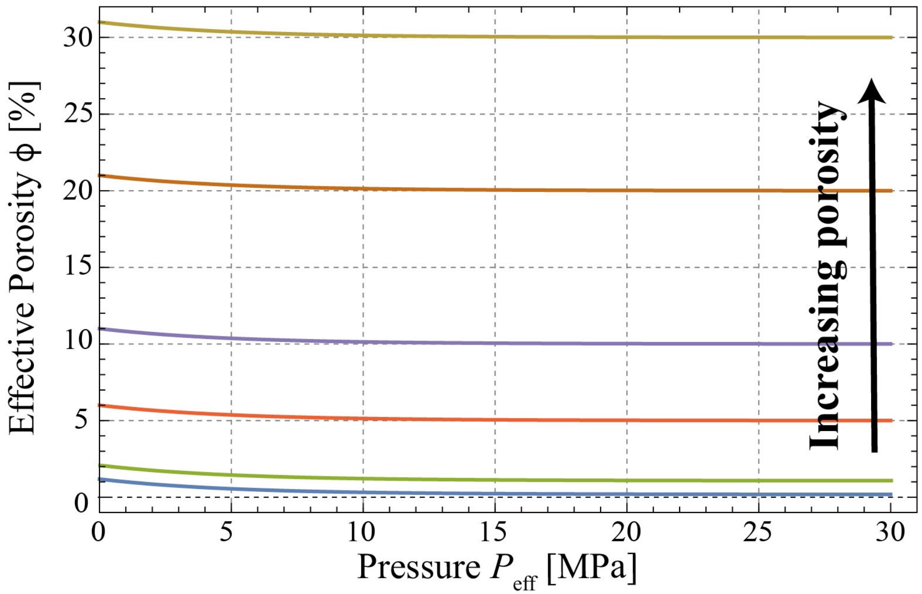
(a view from experimental Rock Physicist)

I_ Hydraulic & Mechanical properties



I_ Hydraulic & Mechanical properties

a. Porosity variation



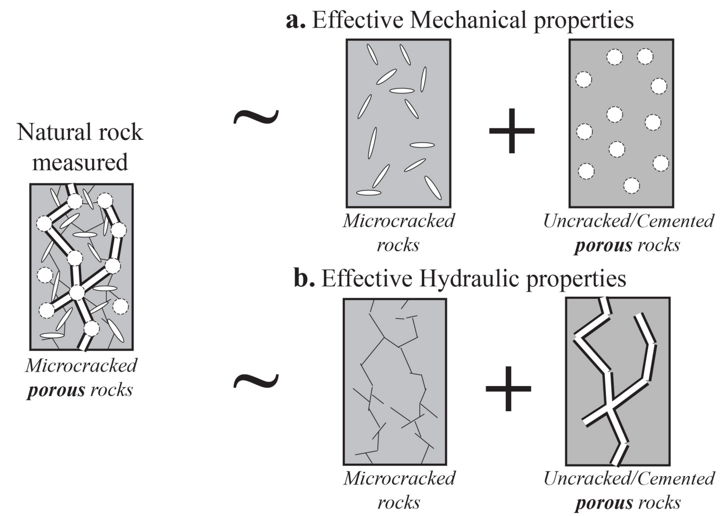
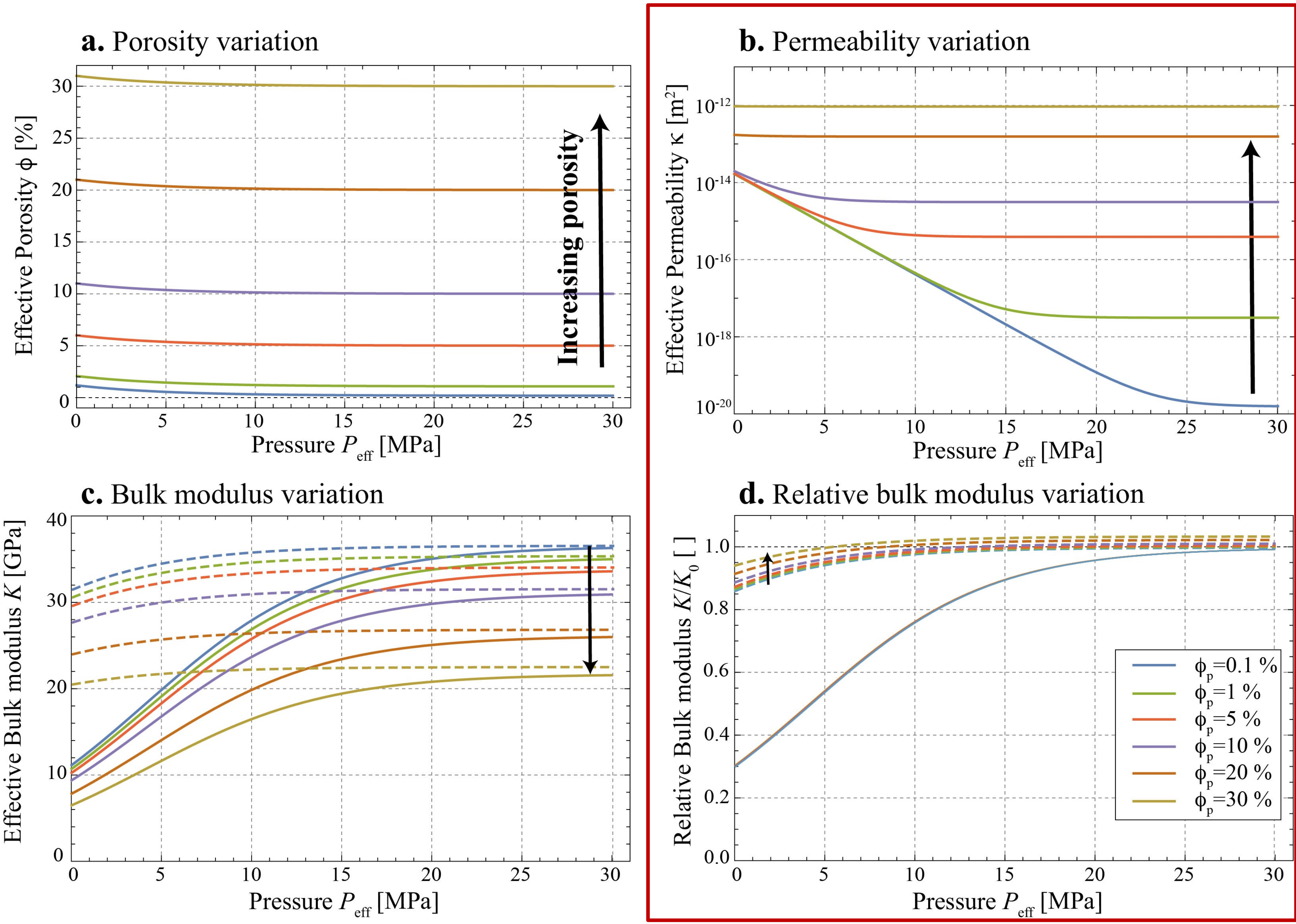
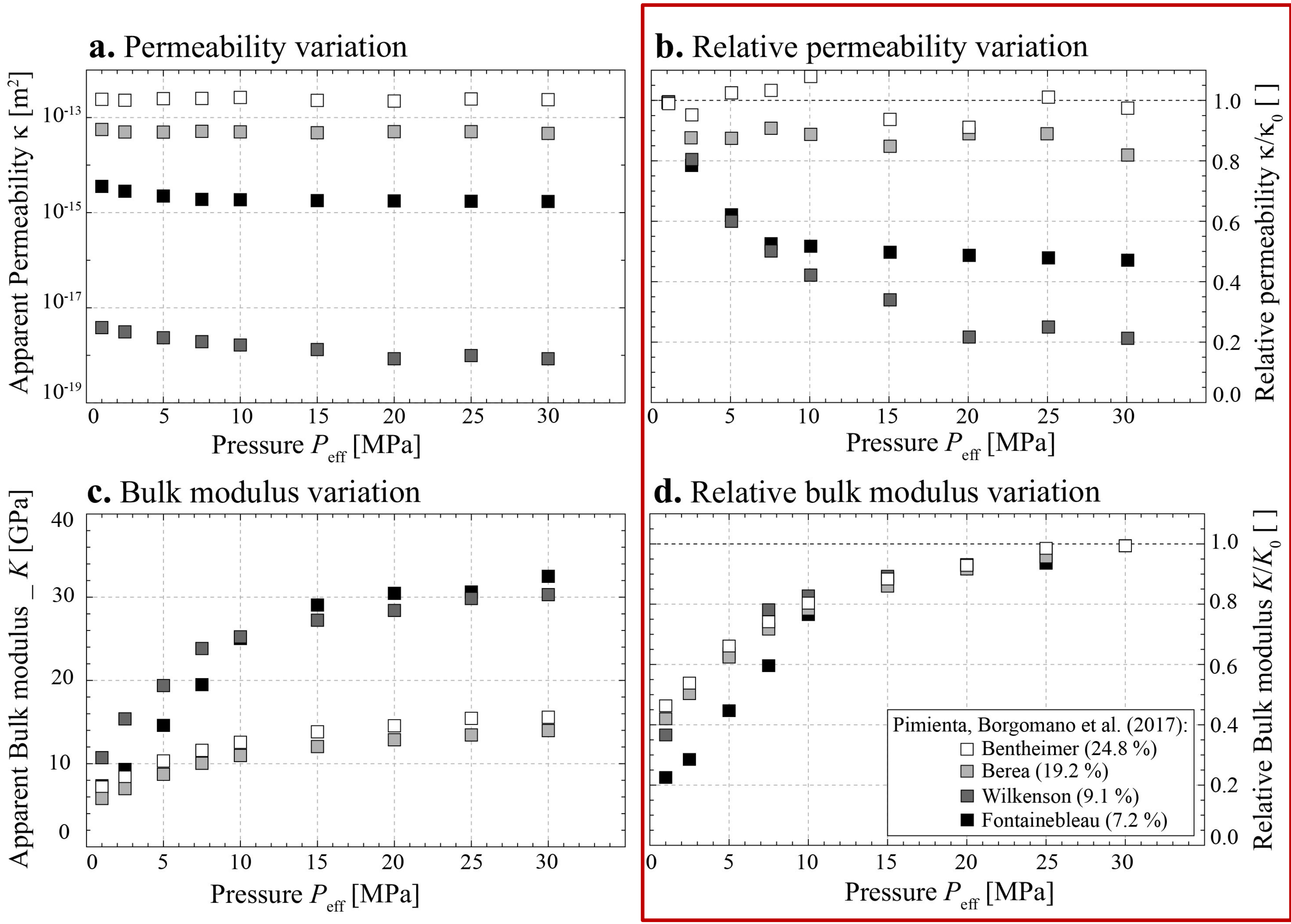


Table 1. Microstructural parameters used for the prediction of the synthetic curves of mechanical (i.e. bulk modulus) and hydraulic (i.e. permeability) properties as a function of Terzaghi effective pressure. Cracks porosity, opening and aspect ratio are assumed to be the same in all synthetic rocks.

Synthetic sample	Porosity ϕ_p (%)	Tubes radius r (μm)	Cracks porosity ϕ_c (%)	Cracks opening w (μm)	Cracks aspect ratio ξ
1	0.1	0.01	$\exp(-P_c/5)$	$0.2\exp(-P_c/5)$	2×10^{-3}
2	1	0.1			
3	5	0.5			
3	10	1			
4	20	5			
5	30	10			



a. Porosity variation
Effective Porosity ϕ [%]
Increasing porosity
Pressure P_{eff} [MPa]
b. Permeability variation
Effective Permeability κ [m²]
Pressure P_{eff} [MPa]
c. Bulk modulus variation
Effective Bulk modulus K [GPa]
Pressure P_{eff} [MPa]
d. Relative bulk modulus variation
Relative Bulk modulus K/K_0 [ ]
Pressure P_{eff} [MPa]
ϕ_p=0.1 %
ϕ_p=1 %
ϕ_p=5 %
ϕ_p=10 %
ϕ_p=20 %
ϕ_p=30 %



a. Permeability variation
Apparent Permeability κ [m²]
10-13
10-15
10-17
10-19
Pressure Peff [MPa]
b. Relative permeability variation
Relative permeability κ/κ0 [ ]
c. Bulk modulus variation
Apparent Bulk modulus _ K [GPa]
d. Relative bulk modulus variation
Relative Bulk modulus K/K0 [ ]
Pimienta, Borgomano et al. (2017):
Bentheimer (24.8 %)
Berea (19.2 %)
Wilkenson (9.1 %)
Fontainebleau (7.2 %)

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=> Hydraulic & Mechanical pp depend ***in opposite manner*** to microstructure

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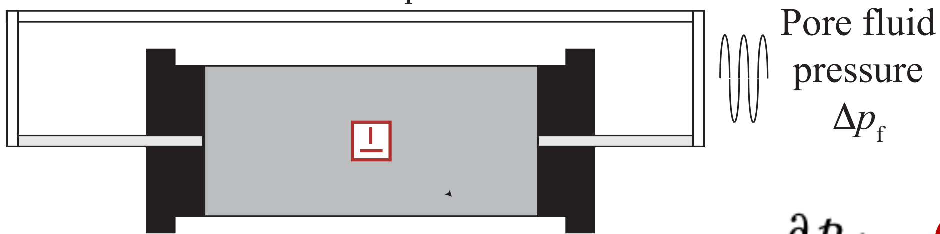
(a view from experimental Rock Physicist)

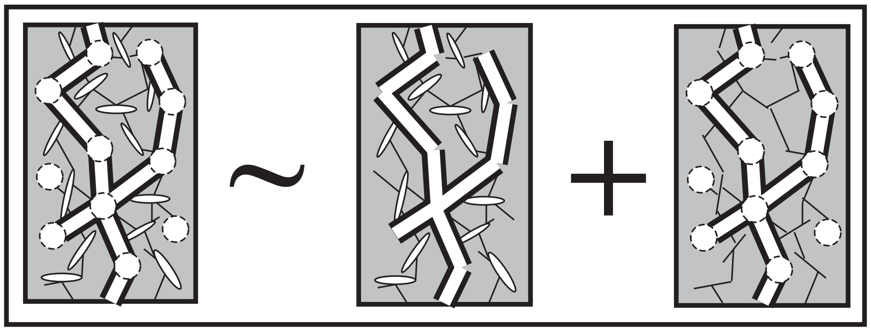
a. Schematics for C_{bp}



$$\frac{\partial p_f}{\partial t} - \frac{\kappa}{\eta S_s}\frac{\partial^2 p_f}{\partial z^2} = B\frac{\partial P}{\partial t},$$

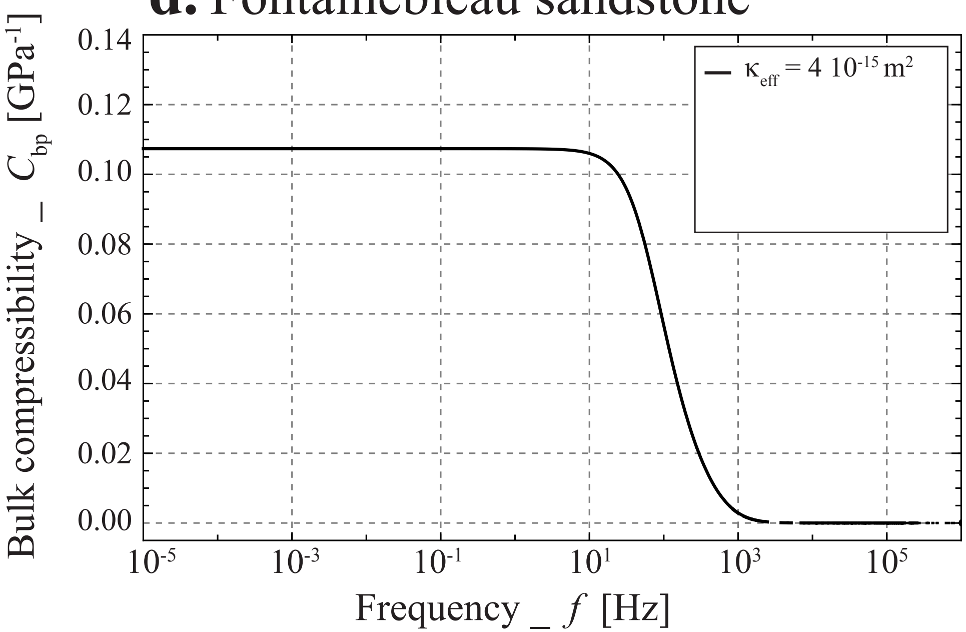
(Darcy) Permeability

b. Typical approach

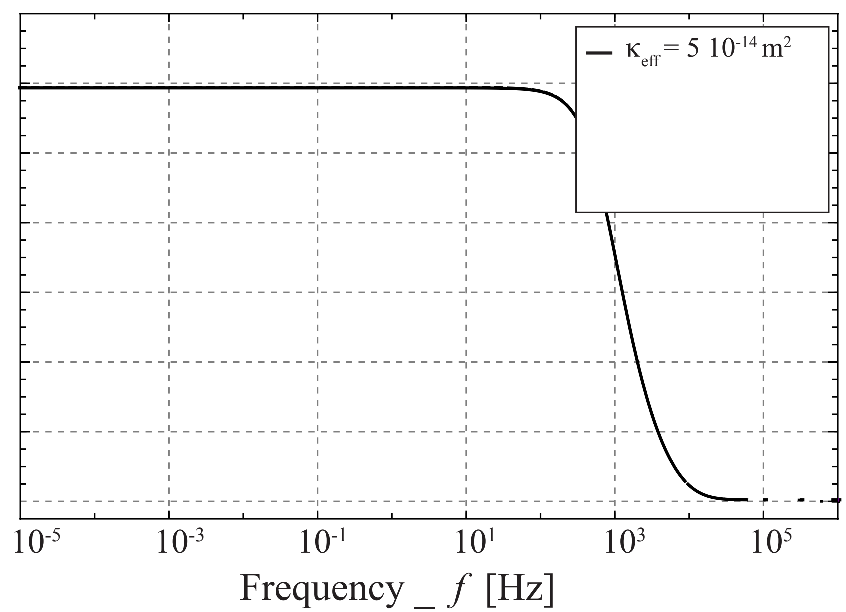


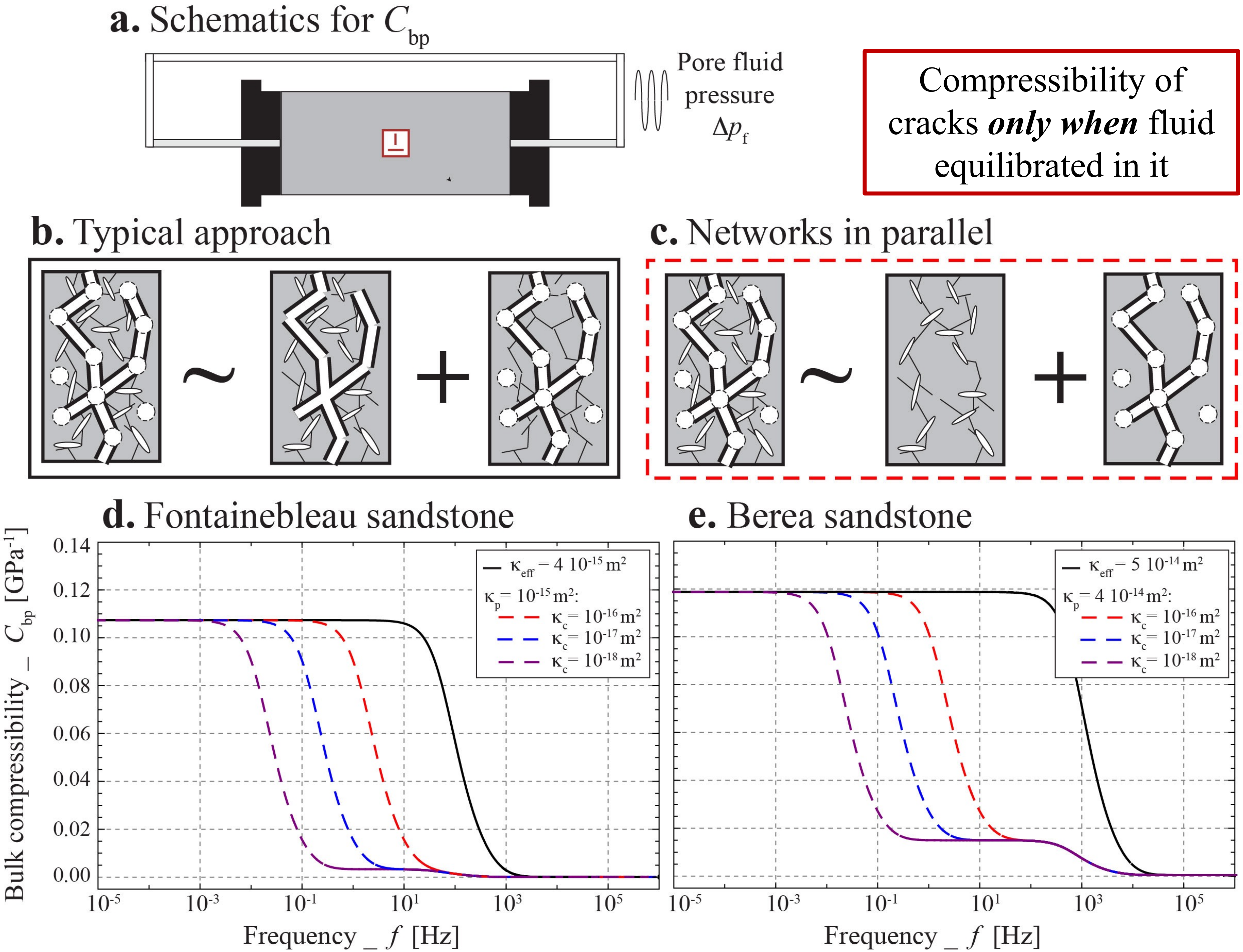
Pressurisation of fluid at the exact same time in ***cracks*** & ***pores***

d. Fontainebleau sandstone

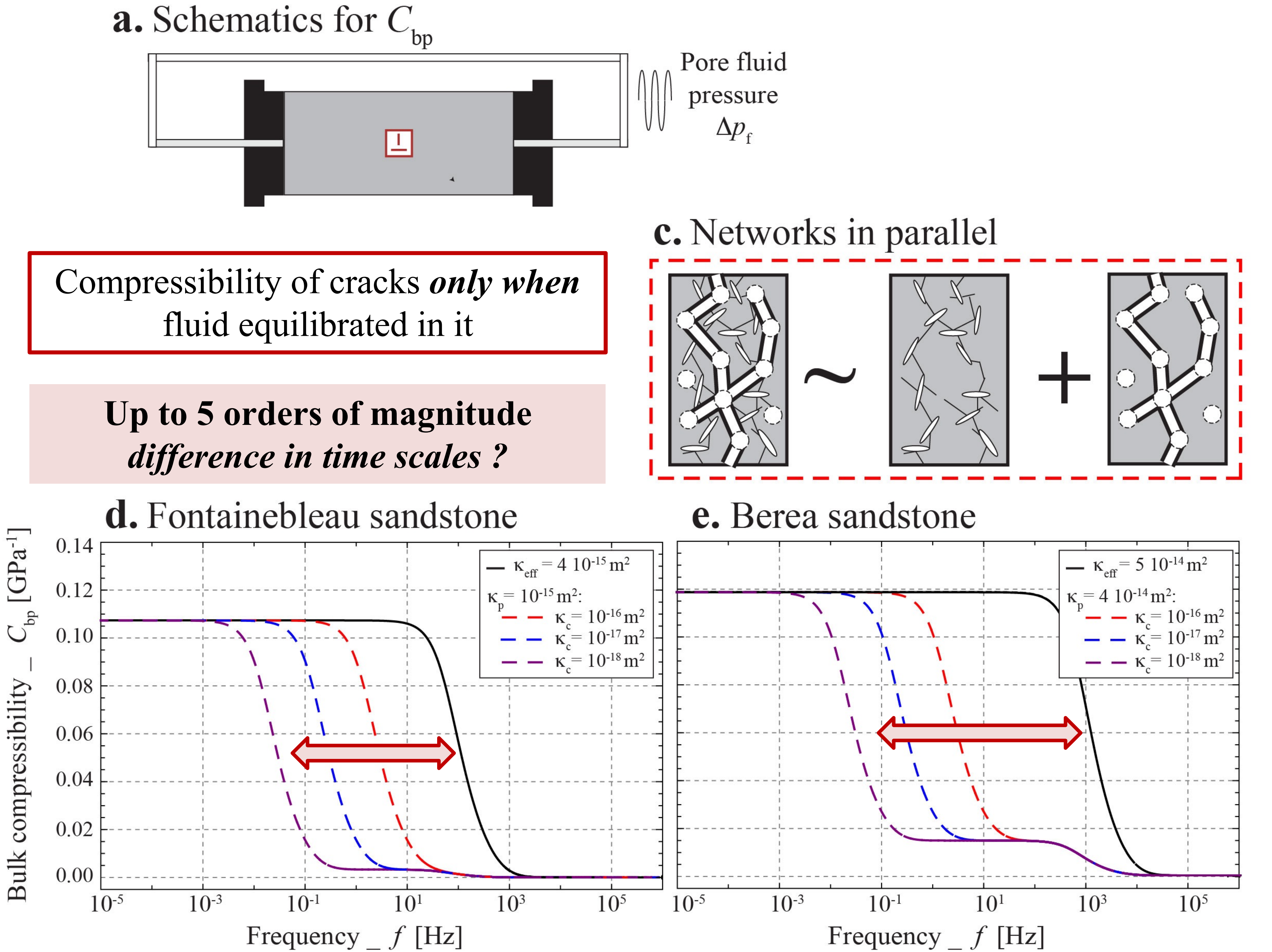


e. Berea sandstone





a. Schematics for C_{bp}
Pore fluid pressure Δp_f
Compressibility of cracks ***only when*** fluid equilibrated in it
b. Typical approach
c. Networks in parallel
d. Fontainebleau sandstone
e. Berea sandstone
Bulk compressibility _ C_{bp} [GPa^{-1}]
Frequency _ f [Hz]
κ_{eff} = 4 10^{-15} m^2
κ_p = 10^{-15} m^2:
κ_c = 10^{-16} m^2
κ_c = 10^{-17} m^2
κ_c = 10^{-18} m^2
κ_{eff} = 5 10^{-14} m^2
κ_p = 4 10^{-14} m^2:



a. Schematics for C_{bp}
Pore fluid pressure Δp_f
Compressibility of cracks ***only when*** fluid equilibrated in it
Up to 5 orders of magnitude *difference in time scales ?*
c. Networks in parallel
d. Fontainebleau sandstone
$\kappa_{eff} = 4\ 10^{-15}\ m^2$
$\kappa_p = 10^{-15}\ m^2$:
$\kappa_c = 10^{-16}\ m^2$
$\kappa_c = 10^{-17}\ m^2$
$\kappa_c = 10^{-18}\ m^2$
e. Berea sandstone
$\kappa_{eff} = 5\ 10^{-14}\ m^2$
$\kappa_p = 4\ 10^{-14}\ m^2$:
$\kappa_c = 10^{-16}\ m^2$
$\kappa_c = 10^{-17}\ m^2$
$\kappa_c = 10^{-18}\ m^2$
Bulk compressibility _ C_{bp} [GPa^{-1}]
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
10^{-5}
10^{-3}
10^{-1}
10^{1}
10^{3}
10^{5}
Frequency _ f [Hz]

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In rocks with double porosity
=> Hydraulic & Mechanical pp depend ***in opposite manner*** to microstructure

II _ If so, How to combine Hydraulic & Mechanical in such rocks ?

If C_{cracks} when P_f equilibrated in cracks => ***Very different from expected*** !

III _ If so, Effect on measured properties & some brittle effects ?

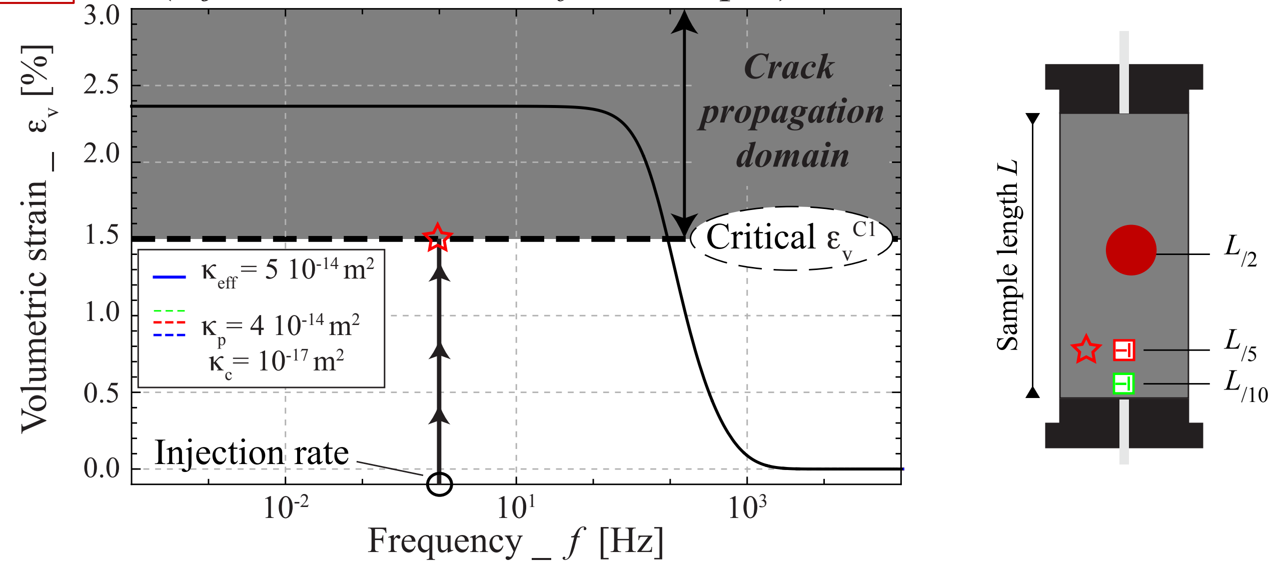
(a view from experimental Rock Physicist)

Fitting to French et al. (2012)

"Proof of caution"

a. Testing concept for Hydraulic fracturing:

(*Injection at one side of the sample*)



Failure occurs if $\varepsilon_V >$ critical ε_V^{CL}

If fluid pressurisation rate below that predicted, it should fail at the center (red dot)

Fitting to French et al. (2012)

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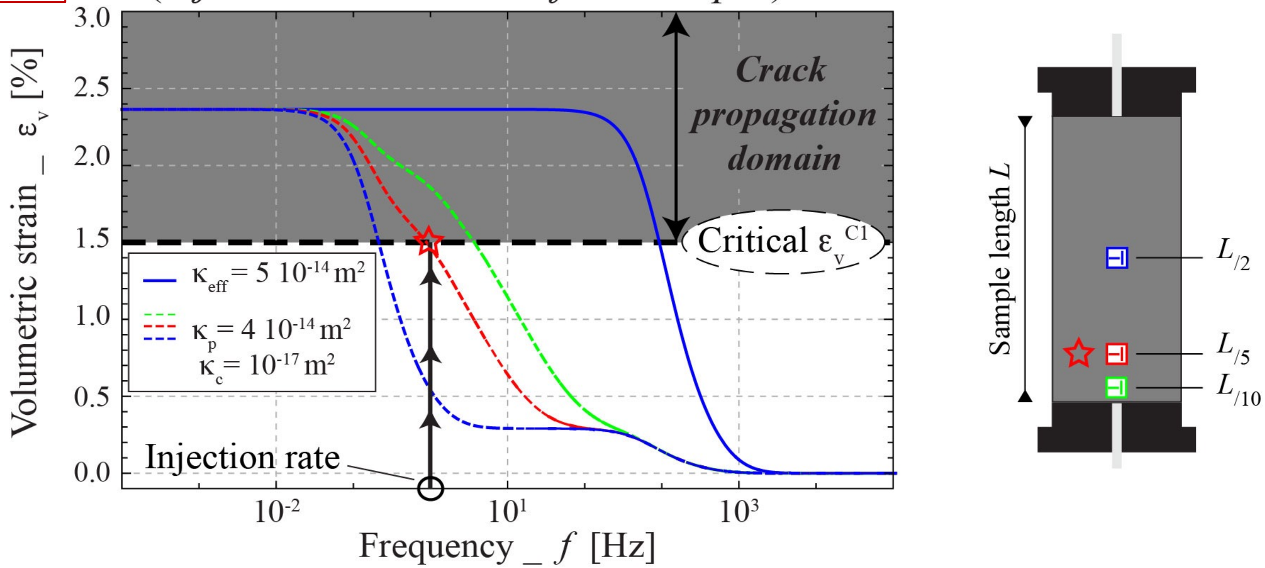

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If fluid pressurisation rate below that predicted, it should fail at the center (red dot)

→

Can be explained if much longer diffusion time inside

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i.e. What we expect in poroelasticity & some unconsistencies

(a view from experimental RP)

I _ Hydraulic & Mechanical properties ***if two pore families***:

i.e. Recalling & using the simplest theoretical models.

(a view from experimental RP)

In rocks with double porosity
=> Hydraulic & Mechanical pp depend ***in opposite manner*** to microstructure

II _ If so, How to combine Hydraulic & Mechanical in such rocks ?

If C_{cracks} when P_f equilibrated in cracks => ***Very different from expected*** !

III _ If so, Effect on measured properties & some brittle effects ?

(a view from experimental Rock Physicist)

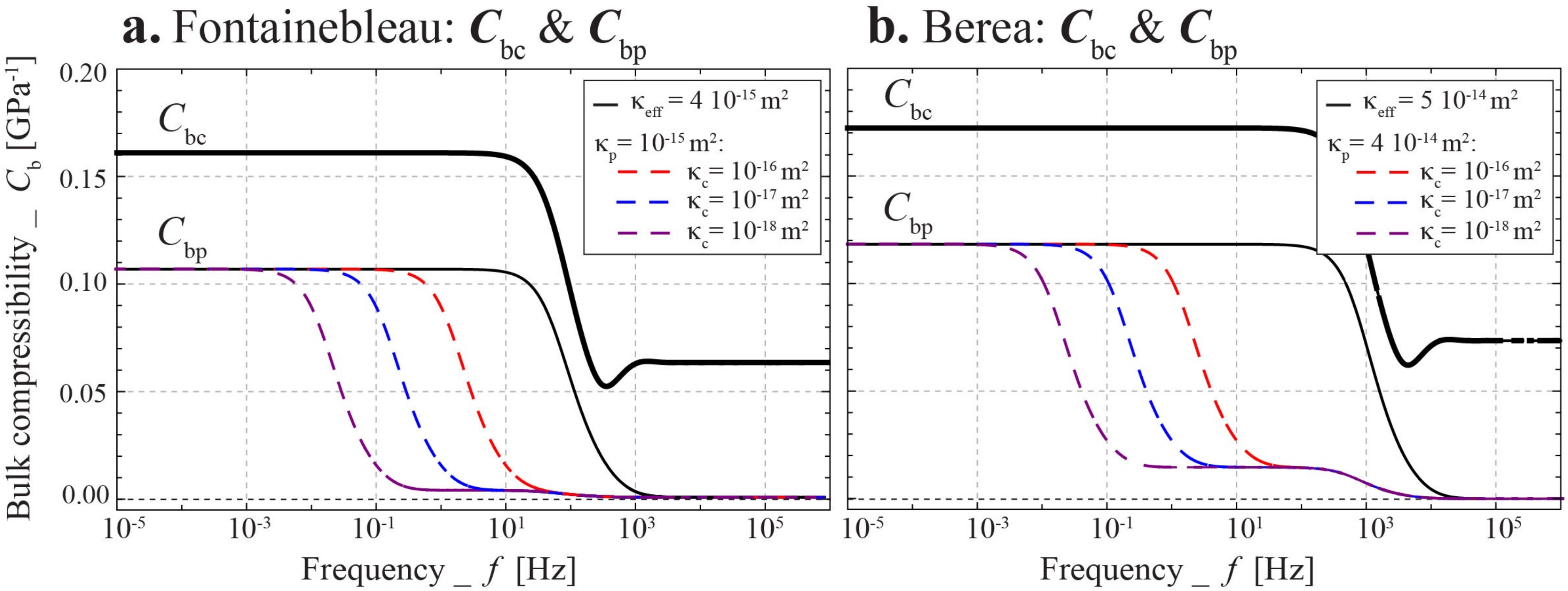
Could explain unexpected failures

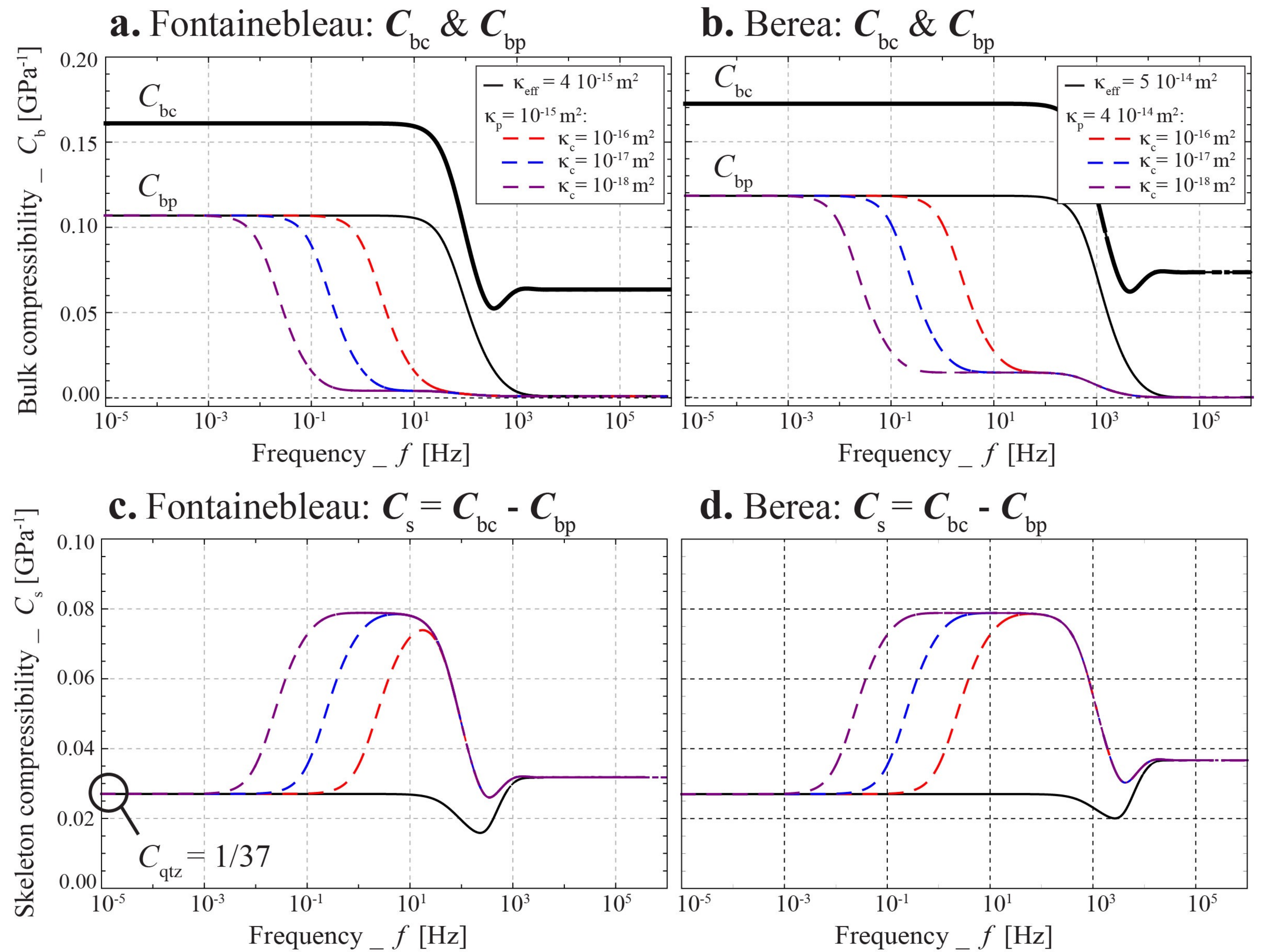
BUT …. Bulk modulus showed fully consistent frequency-dependent dispersion for Drained – to – Undrained transition !

Stress is uniformly applied to the rock sample

versus

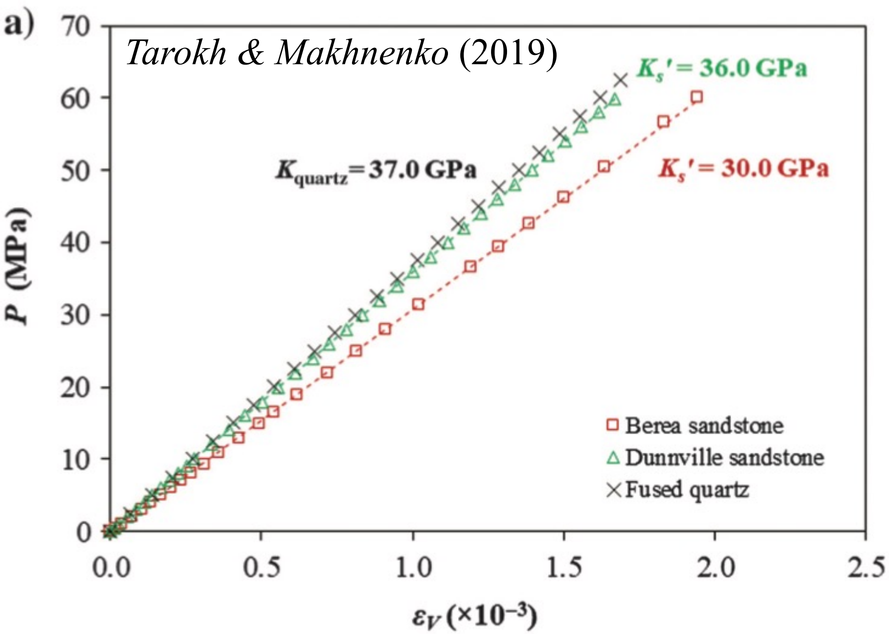
Fluid pressure needs to diffuse from the injection point



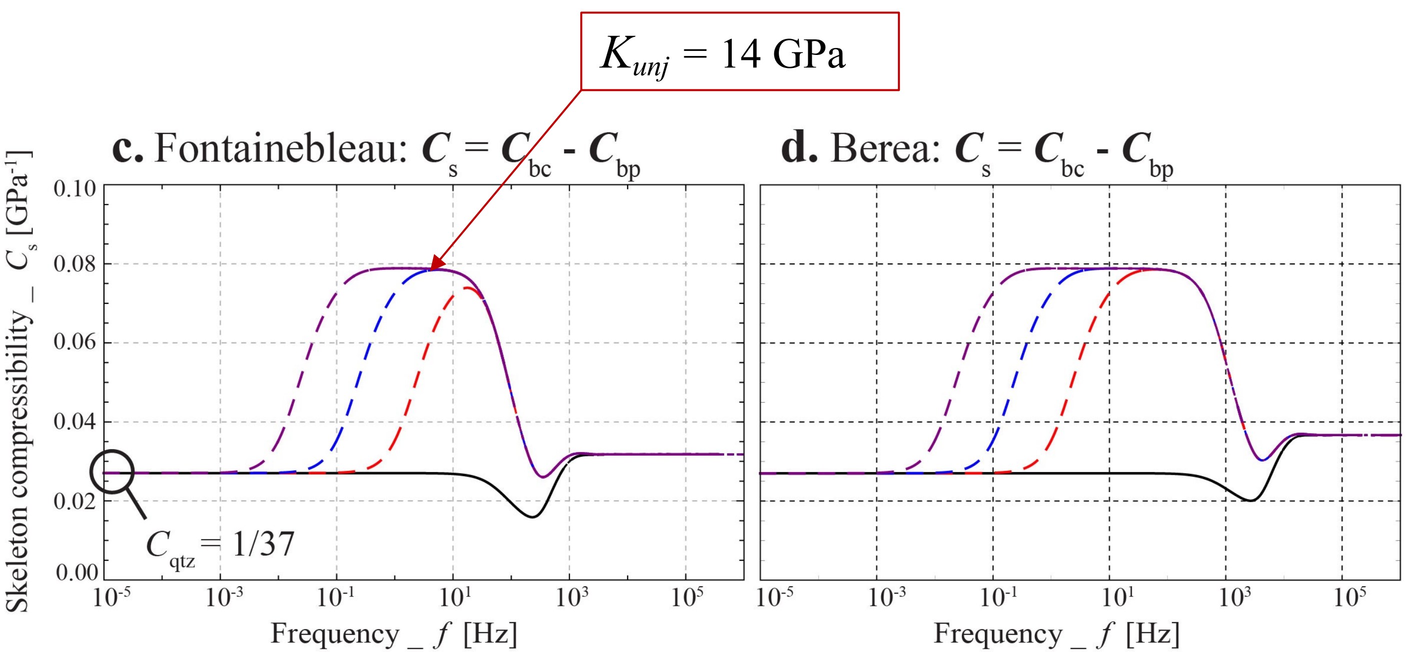


a. Fontainebleau: C_bc & C_bp
b. Berea: C_bc & C_bp
c. Fontainebleau: C_s = C_bc - C_bp
d. Berea: C_s = C_bc - C_bp
Bulk compressibility _ C_b [GPa^-1]
Skeleton compressibility _ C_s [GPa^-1]
Frequency _ f [Hz]
C_bc
C_bp
κ_eff = 4 10^-15 m^2
κ_p = 10^-15 m^2:
κ_eff = 5 10^-14 m^2
κ_p = 4 10^-14 m^2:
κ_c = 10^-16 m^2
κ_c = 10^-17 m^2
κ_c = 10^-18 m^2
C_qtz = 1/37

III_ Hydraulic & Mechanical properties



Values ranging down to 15 GPa have been reported for sandstones (Fabre & Gustkiewicz, 1997; Tarokh & Makhnenko, 2019)



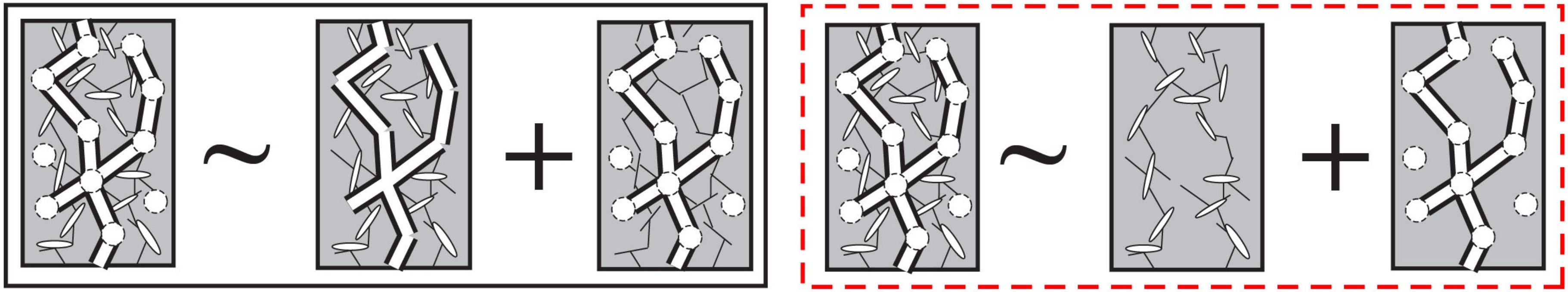
Conclusion

Rocks, in particular sandstones, often bear two pores famillies (cracks-pores or soft-stiff).

- Hydraulic & Mechanical properties depend in an exact opposite manner to these pore families.

- If accounting for such existence, Hydro-Mechanical response of porous rocks might behave in an exotic manner.

- Could explain the (1) delayed mechanical response to fluid injections; (2) low K_s retrieved in some permeable samples; etc.



MERCI

***& Beware** the hidden microstructure*

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Hydro-mechanical coupling in porous rocks: hidden dependences to the microstructure?

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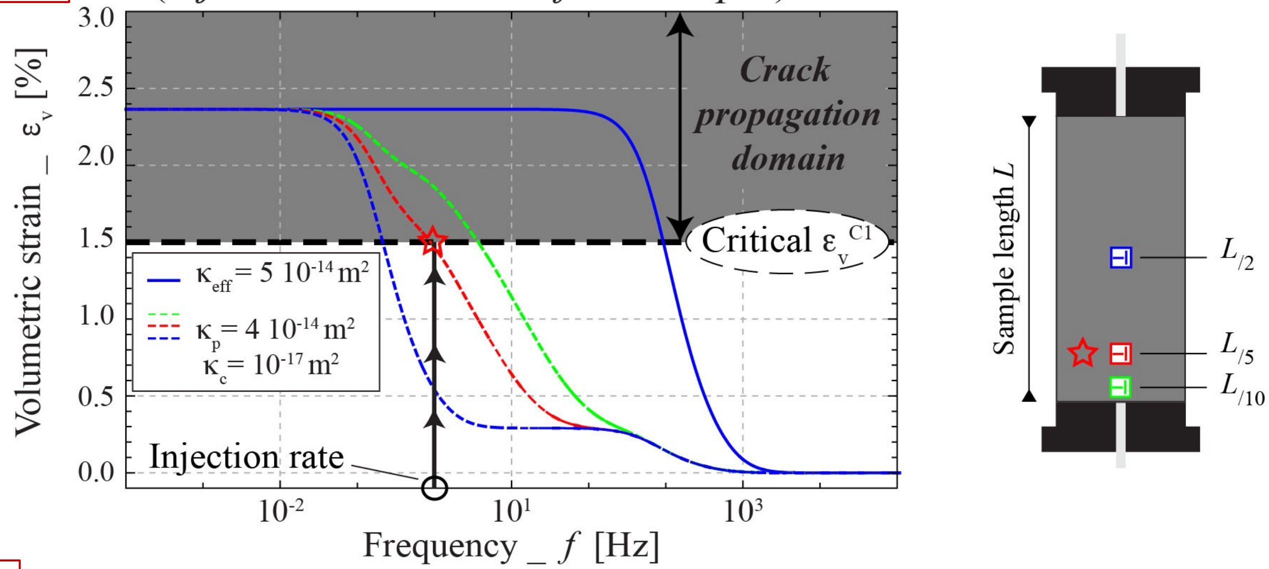
Fitting to French et al. (2012)

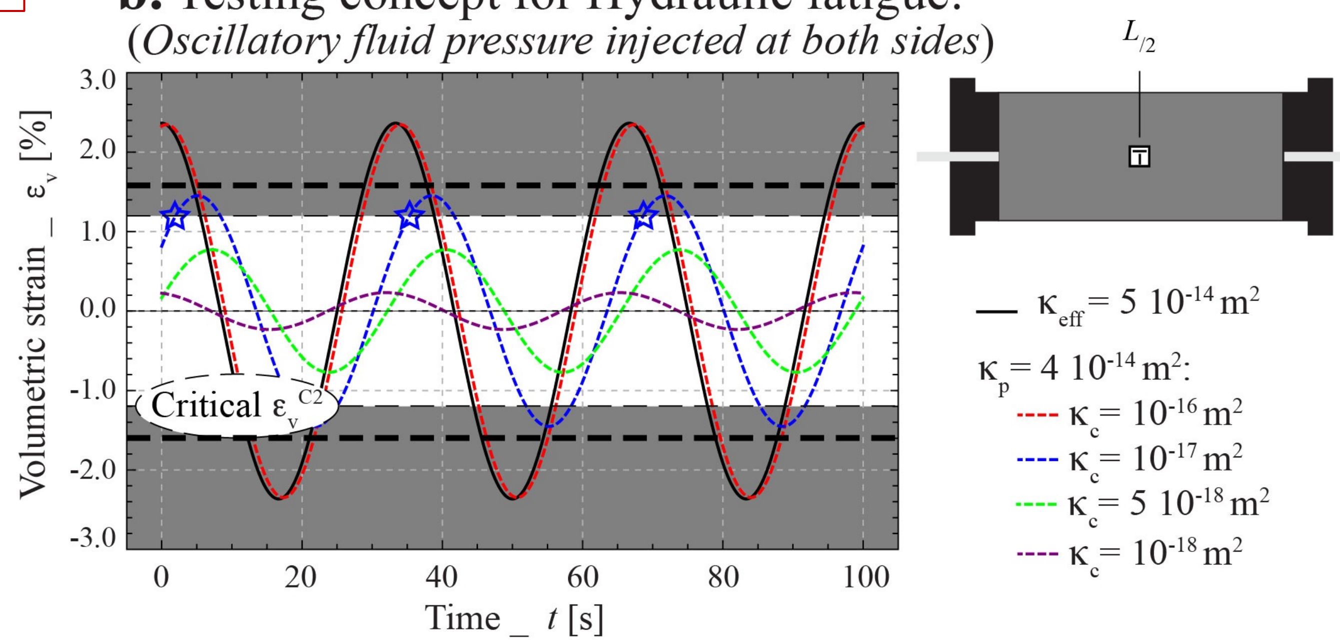
a view from experimental Rock Physicist ***specialising in the elastic regime*** *...*

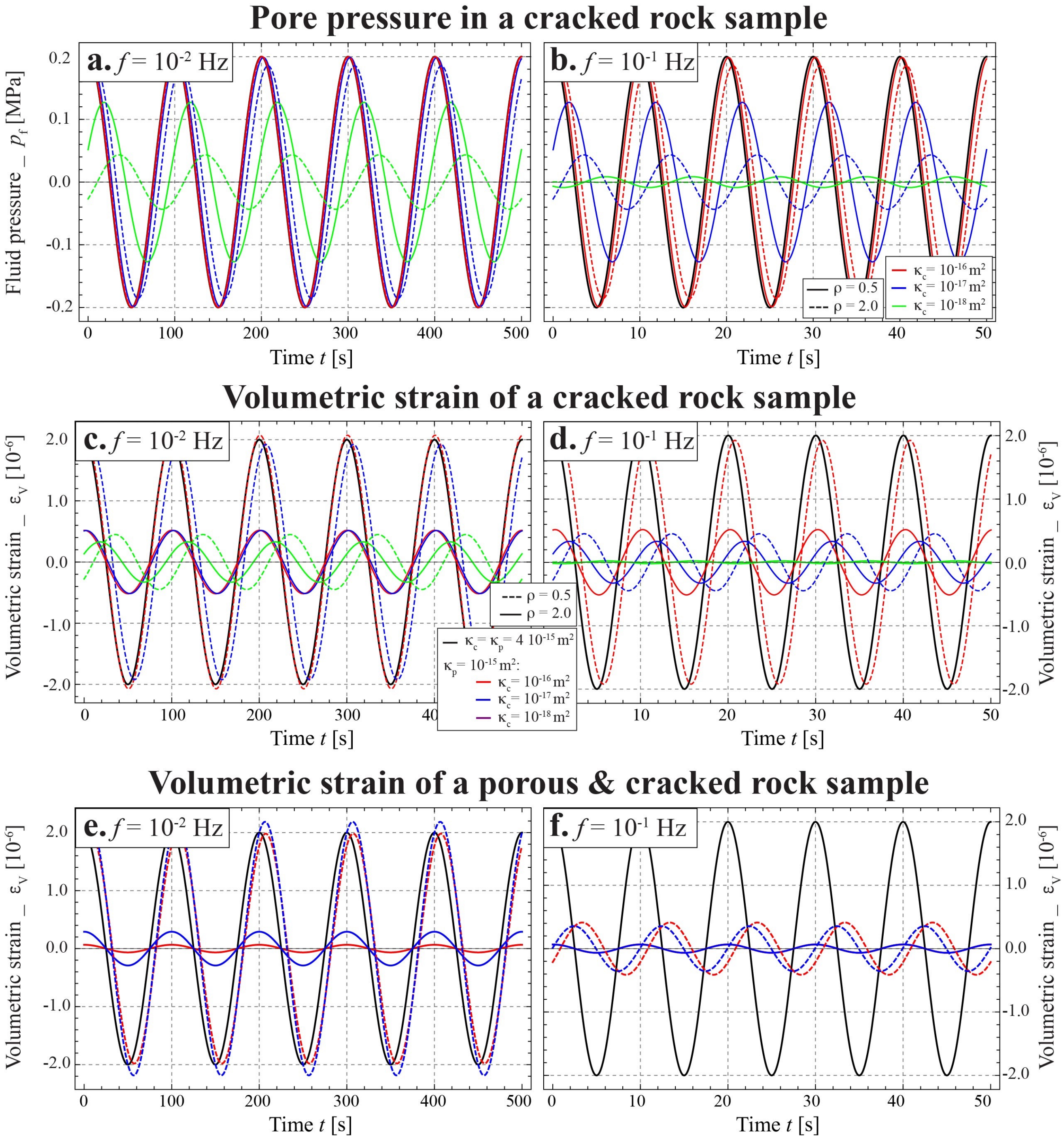
Fitting to Noel et al. (2019)

a. Testing concept for Hydraulic fracturing:
(*Injection at one side of the sample*)



b. Testing concept for Hydraulic fatigue:
(*Oscillatory fluid pressure injected at both sides*)





Pore pressure in a cracked rock sample
a. f = 10^-2 Hz
b. f = 10^-1 Hz
Fluid pressure _ p_f [MPa]
Time t [s]
ρ = 0.5
ρ = 2.0
κ_c = 10^-16 m²
κ_c = 10^-17 m²
κ_c = 10^-18 m²
Volumetric strain of a cracked rock sample
c. f = 10^-2 Hz
d. f = 10^-1 Hz
Volumetric strain _ ε_V [10^-6]
ρ = 0.5
ρ = 2.0
κ_c = κ_p = 4 10^-15 m²
κ_p = 10^-15 m²:
κ_c = 10^-16 m²
κ_c = 10^-17 m²
κ_c = 10^-18 m²
Volumetric strain of a porous & cracked rock sample
e. f = 10^-2 Hz
f. f = 10^-1 Hz

Outline

*I*_ Experimental Complexities

- Role of the ***fluid volumes***
- Role of ***strain amplitudes*** and ***rates***
- Theory versus Experiment

*II*_ Experimental method

- Apparatus & Protocols
- Principle

*III*_ Bentheim sandstone sample

- Results
- Interpretation & Discussion

*IV*_ Conclusions

I_Experimental complexities: *Principle*

Biot's theory	Theoretical definition
Drained compressibility C_d [GPa^{-1}]	$-\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{p_f}$
Biot's coefficient α []	$-\left(\frac{\partial V_p}{\partial V_b}\right)_{p_f}$
Undrained compressibility C_u [GPa^{-1}]	$-\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{m_f}$
Skempton's coefficient B []	$\left(\frac{\partial p_f}{\partial P_c}\right)_{m_f}$

Drained
Boundary Conditions

Undrained
Boundary Conditions

I_Experimental complexities: *Principle*

Biot's theory	Theoretical definition
Drained compressibility C_d [GPa^{-1}]	$-\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{p_f}$
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Zimmerman's theory	Theoretical definition
Bulk compressibility C_{bc} [GPa^{-1}]	$-\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{p_f}$
Pore compressibility C_{pc} [GPa^{-1}]	$-\frac{1}{V_p}\left(\frac{\partial V_p}{\partial P_c}\right)_{p_f}$
Bulk compressibility C_{bp} [GPa^{-1}]	$\frac{1}{V_b}\left(\frac{\partial V_b}{\partial p_f}\right)_{P_c}$
Pore compressibility C_{pp} [GPa^{-1}]	$\frac{1}{V_p}\left(\frac{\partial V_p}{\partial p_f}\right)_{P_c}$

Drained
Boundary Conditions

Undrained
Boundary Conditions

ΔP_c
solicitation

Δp_f
solicitation

I_Experimental complexities: *Principle*

Biot's theory	Theoretical definition	Conditions
Drained compressibility C_d [GPa^{-1}]	$-\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{p_f}$	**Drained** ***Boundary Conditions***
Biot's coefficient α []	$-\left(\frac{\partial V_p}{\partial V_b}\right)_{p_f}$	**Drained** ***Boundary Conditions***
Undrained compressibility C_u [GPa^{-1}]	$-\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{m_f}$	**Undrained** ***Boundary Conditions***
Skempton's coefficient B []	$\left(\frac{\partial p_f}{\partial P_c}\right)_{m_f}$	**Undrained** ***Boundary Conditions***
Zimmerman's theory	**Theoretical definition**	
Bulk compressibility C_{bc} [GPa^{-1}]	$-\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{p_f}$	ΔP_c ***solicitation***
Pore compressibility C_{pc} [GPa^{-1}]	$-\frac{1}{V_p}\left(\frac{\partial V_p}{\partial P_c}\right)_{p_f}$	ΔP_c ***solicitation***
Bulk compressibility C_{bp} [GPa^{-1}]	$\frac{1}{V_b}\left(\frac{\partial V_b}{\partial p_f}\right)_{P_c}$	Δp_f ***solicitation***
Pore compressibility C_{pp} [GPa^{-1}]	$\frac{1}{V_p}\left(\frac{\partial V_p}{\partial p_f}\right)_{P_c}$	Δp_f ***solicitation***
Skeleton compressibility C_s [GPa^{-1}]	$\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{P_d}$	**Unjacketed** ***Boundary Conditions***
Skeleton compressibility C_ϕ [GPa^{-1}]	$\frac{1}{V_p}\left(\frac{\partial V_p}{\partial P_c}\right)_{P_d}$	**Unjacketed** ***Boundary Conditions***

I_Experimental complexities: *Principle*

Biot's theory	Theoretical definition
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Pore compressibility C_{pp} [GPa^{-1}]	$\frac{1}{V_p}\left(\frac{\partial V_p}{\partial p_f}\right)_{P_c}$
Skeleton compressibility C_s [GPa^{-1}]	$\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{P_d}$
Skeleton compressibility C_ϕ [GPa^{-1}]	$\frac{1}{V_p}\left(\frac{\partial V_p}{\partial P_c}\right)_{P_d}$

Considered easier to get experimentally **BUT** need precise knowledge of:

V_p ⇔ *Pore fluid volume*

$m_f = \rho\, V_p$ ⇔ *Pore fluid mass*

In practice, measured properties are

1a) $V_{tot} = V_p + V_f$ ⇔ Tubing total fluid vol.

2) $m^*_f = \rho\,(V_p + \boldsymbol{V_d})$ ⇔ "Dead vol."

In practice, measured properties are

1b) $V_{tot} = V_p + V_f$ ⇔ Tubing total fluid vol.

I_Experimental complexities: *Principle*

Biot's theory	Theoretical definition	Measurement
Drained compressibility C_d [GPa^{-1}]	$-\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{p_f}$	$-\left(\frac{\Delta\epsilon_b}{\Delta P_c}\right)_{p_f}$
Biot's coefficient α []	$-\left(\frac{\partial V_p}{\partial V_b}\right)_{p_f}$	
Undrained compressibility C_u [GPa^{-1}]	$-\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{m_f}$	
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Skeleton compressibility C_ϕ [GPa^{-1}]	$\frac{1}{V_p}\left(\frac{\partial V_p}{\partial P_c}\right)_{P_d}$

All properties defined

- as ***Partial derivatives*** => Only in case of ***small*** stress/strain ***amplitudes***
- under ***steady-state conditions*** => Only in case of ***low*** stress/strain ***rates***

Considered easier to get experimentally BUT need precise knowledge of:

V_p ⇔ *Pore fluid volume*

$m_f = \rho\, V_p$ ⇔ *Pore fluid mass*

In practice, measured properties are

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1b) $V_{tot} = V_p + V_f$ ⇔ Tubing total fluid vol.

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Biot's coefficient α []	$-\left(\frac{\partial V_p}{\partial V_b}\right)_{p_f}$	$-\frac{1}{V_b}\left(\frac{\Delta V_f}{\Delta \epsilon_b}\right)_{p_f}$
Undrained compressibility C_u [GPa^{-1}]	$-\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{m_f}$	$-\left(\frac{\Delta \epsilon_b}{\Delta P_c}\right)_{m_f^*}$
Skempton's coefficient B []	$\left(\frac{\partial p_f}{\partial P_c}\right)_{m_f}$	$\left(\frac{\Delta p_f}{\Delta P_c}\right)_{m_f^*}$
Zimmerman's theory	**Theoretical definition**	**Measurement**
Bulk compressibility C_{bc} [GPa^{-1}]	$-\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{p_f}$	$-\left(\frac{\Delta \epsilon_b}{\Delta P_c}\right)_{p_f}$
Pore compressibility C_{pc} [GPa^{-1}]	$-\frac{1}{V_p}\left(\frac{\partial V_p}{\partial P_c}\right)_{p_f}$	$-\frac{1}{V_f}\left(\frac{\Delta V_f}{\Delta P_c}\right)_{p_f}$
Bulk compressibility C_{bp} [GPa^{-1}]	$\frac{1}{V_b}\left(\frac{\partial V_b}{\partial p_f}\right)_{P_c}$	$\left(\frac{\Delta \epsilon_b}{\Delta p_f}\right)_{P_c}$
Pore compressibility C_{pp} [GPa^{-1}]	$\frac{1}{V_p}\left(\frac{\partial V_p}{\partial p_f}\right)_{P_c}$	$\frac{1}{V_f}\left(\frac{\Delta V_f}{\Delta p_f}\right)_{P_c}$
Skeleton compressibility C_s [GPa^{-1}]	$\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{P_d}$	$\left(\frac{\Delta \epsilon_b}{\Delta P_c}\right)_{P_d}$
Skeleton compressibility C_ϕ [GPa^{-1}]	$\frac{1}{V_p}\left(\frac{\partial V_p}{\partial P_c}\right)_{P_d}$	$\frac{1}{V_f}\left(\frac{\Delta V_f}{\Delta P_c}\right)_{P_d}$

No Problem !
No pressurization of fluid ⇔ No effect of the fluid compressibility

No Problem !
Can be accounted for by measuring properties for 2 distinct dead volumes (V_1 & V_2)

Problem !!
Fluid pressurizes so that C_f plays a role
=> Properties can hardly be obtained

I_Experimental complexities: *Principle*

Biot's theory	Theoretical definition	Measurement
Drained compressibility C_d [GPa^{-1}]	$-\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{p_f}$	$-\left(\frac{\Delta \epsilon_b}{\Delta P_c}\right)_{p_f}$
Biot's coefficient α []	$-\left(\frac{\partial V_p}{\partial V_b}\right)_{p_f}$	$-\frac{1}{V_b}\left(\frac{\Delta V_f}{\Delta \epsilon_b}\right)_{p_f}$
Undrained compressibility C_u [GPa^{-1}]	$-\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{m_f}$	$-\left(\frac{\Delta \epsilon_b}{\Delta P_c}\right)_{m_f^*}$
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Zimmerman's theory	**Theoretical definition**	**Measurement**
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Pore compressibility C_{pc} [GPa^{-1}]	$-\frac{1}{V_p}\left(\frac{\partial V_p}{\partial P_c}\right)_{p_f}$	$-\frac{1}{V_f}\left(\frac{\Delta V_f}{\Delta P_c}\right)_{p_f}$
Bulk compressibility C_{bp} [GPa^{-1}]	$\frac{1}{V_b}\left(\frac{\partial V_b}{\partial p_f}\right)_{P_c}$	$\left(\frac{\Delta \epsilon_b}{\Delta p_f}\right)_{P_c}$
Pore compressibility C_{pp} [GPa^{-1}]	$\frac{1}{V_p}\left(\frac{\partial V_p}{\partial p_f}\right)_{P_c}$	$\frac{1}{V_f}\left(\frac{\Delta V_f}{\Delta p_f}\right)_{P_c}$
Skeleton compressibility C_s [GPa^{-1}]	$\frac{1}{V_b}\left(\frac{\partial V_b}{\partial P_c}\right)_{P_d}$	$\left(\frac{\Delta \epsilon_b}{\Delta P_c}\right)_{P_d}$
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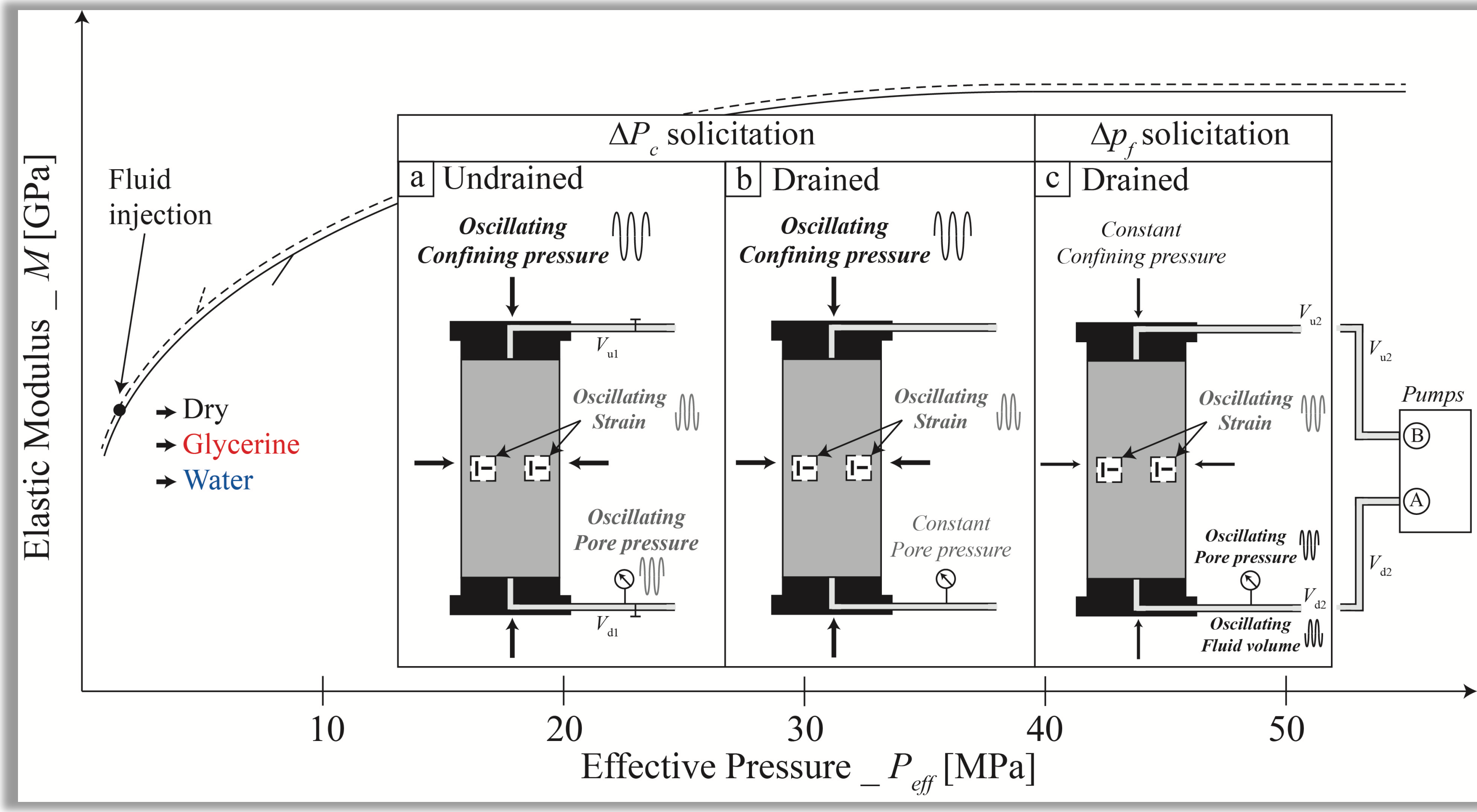
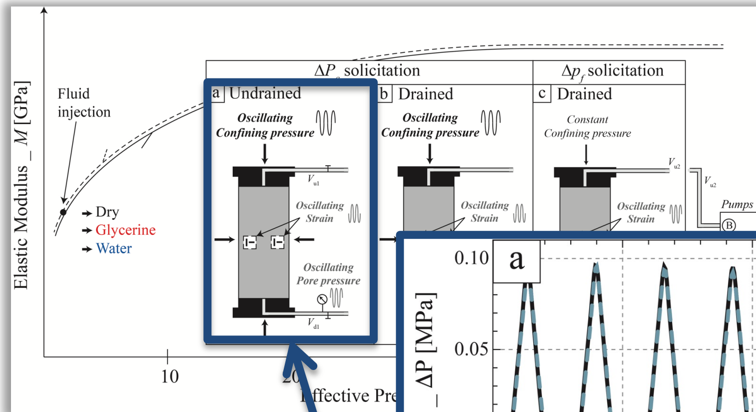
II_Experimental method : *Apparatus & Principle*



Three sets of Boundary Conditions & Two types of solicitations:

- Undrained (Jacket ***on*** or ***off***) + ΔP_c solicitation
- Drained + ΔP_c solicitation
- Drained + Δp_f solicitation

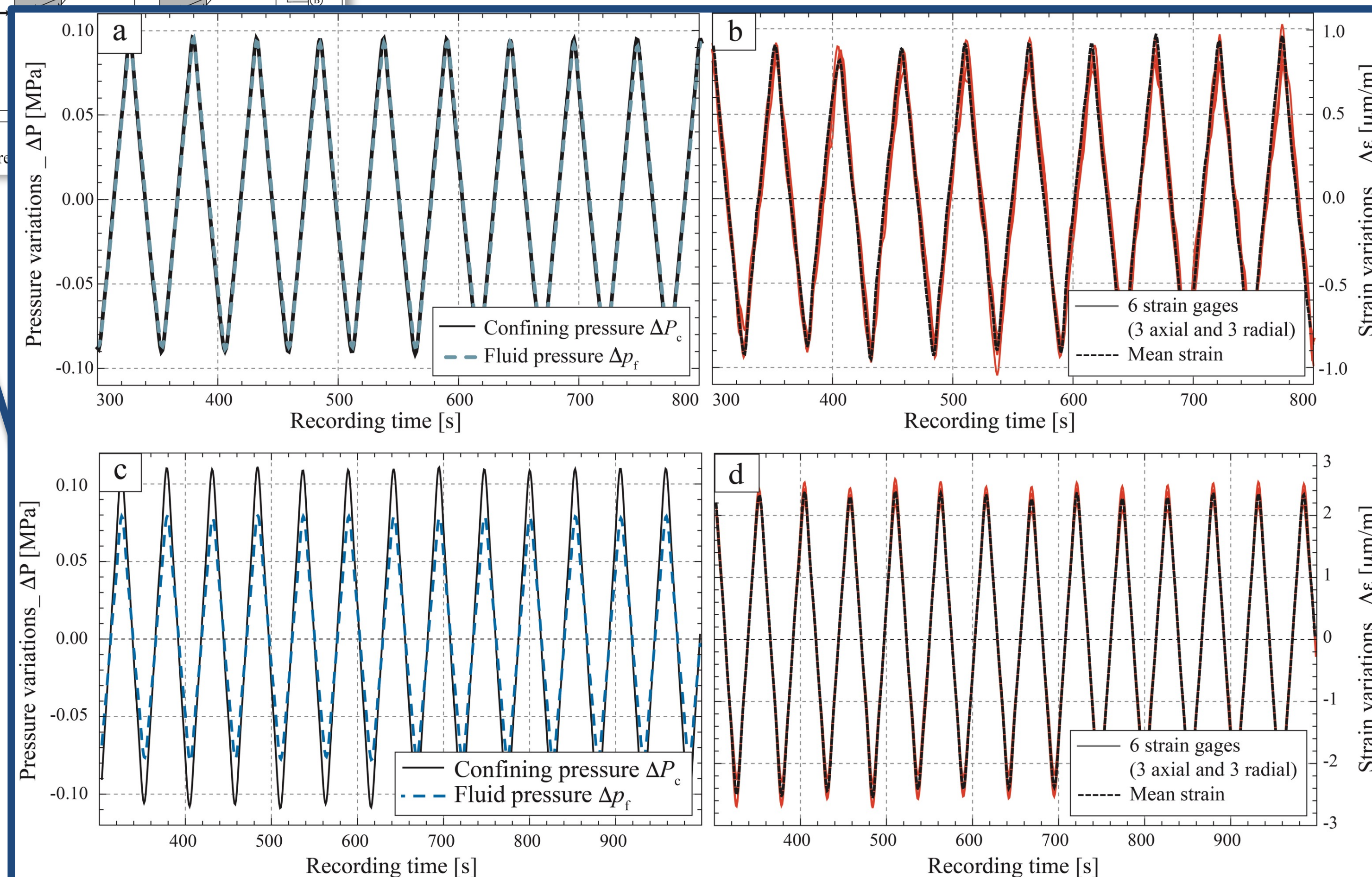
II_Experimental method : *Exemple*



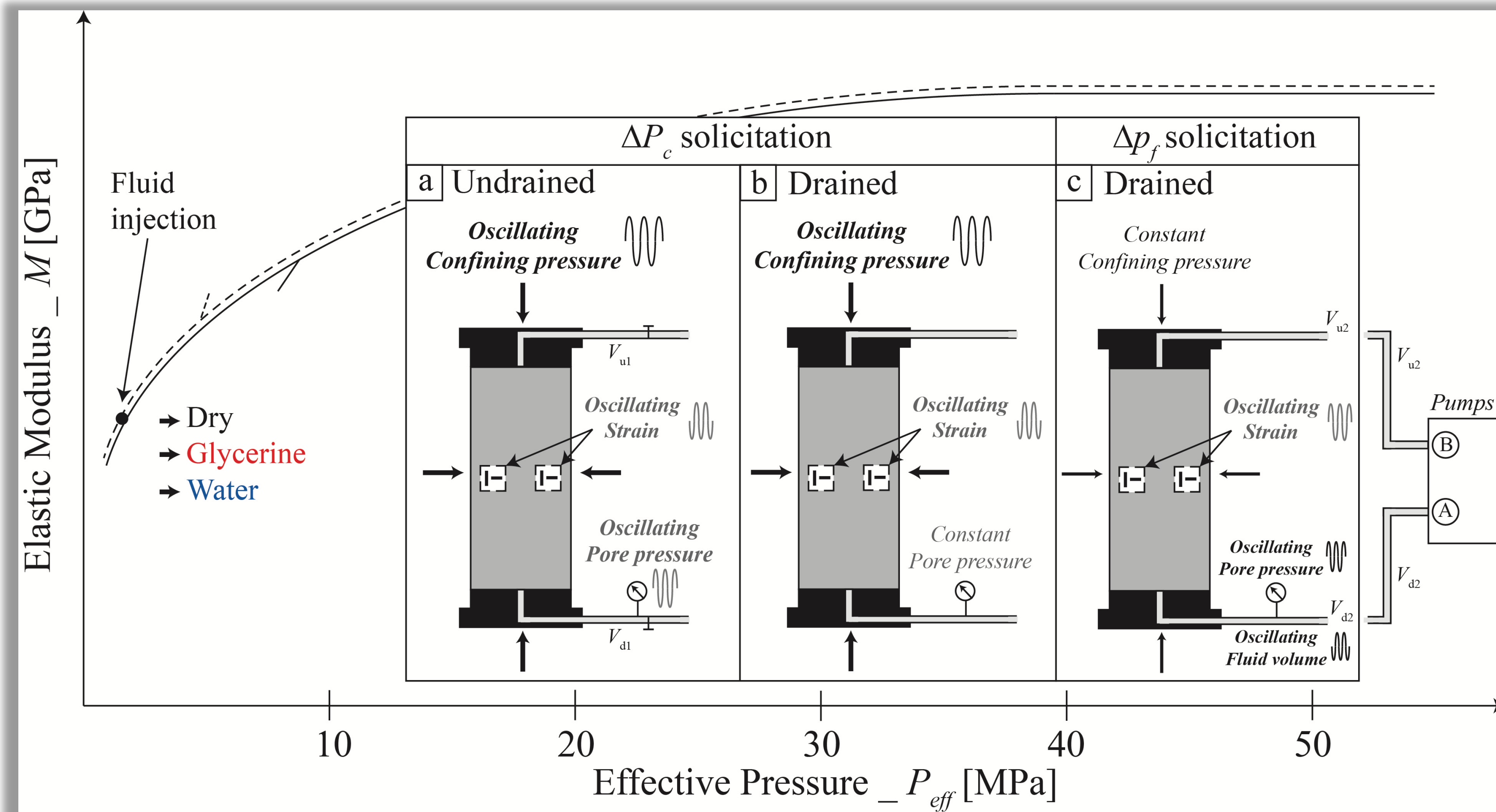
Unjacketed test (a & b)

Quality check from Δp_f measured in dead volume

$\Delta P_c = \Delta p_f \Leftrightarrow$ pore fluid equilibrated in sample !



II_Experimental method : *Apparatus & Principle*

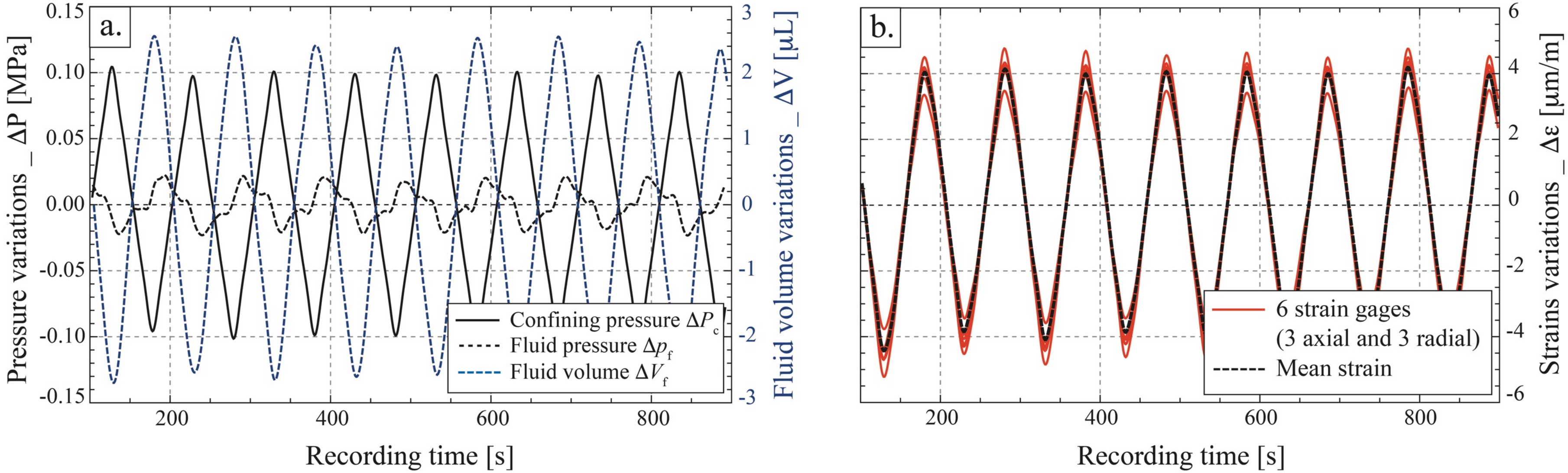


Three sets of Boundary Conditions & Two types of solicitations:

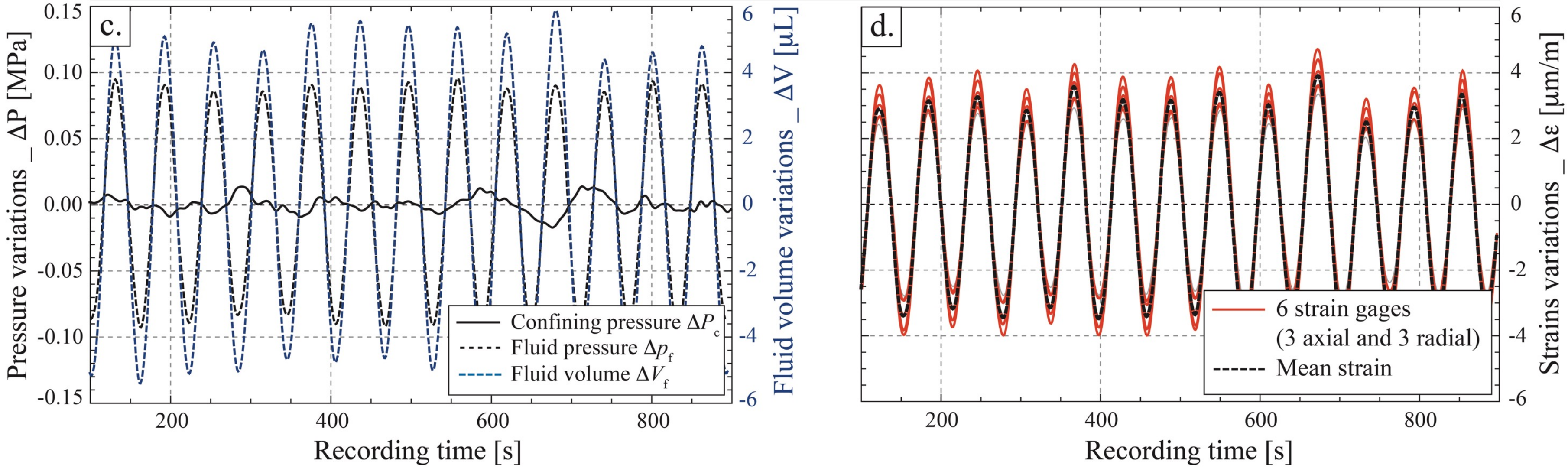
- Undrained (Jacket ***on*** or ***off***) + ΔP_c solicitation => C_{ud} & B or C_s
- Drained + ΔP_c solicitation => $C_{bc}=C_d$ & C_{pc} (or α)
- Drained + Δp_f solicitation => C_{bp} & C_{pp}

Method: Drained boundary conditions

Confining pressure oscillations

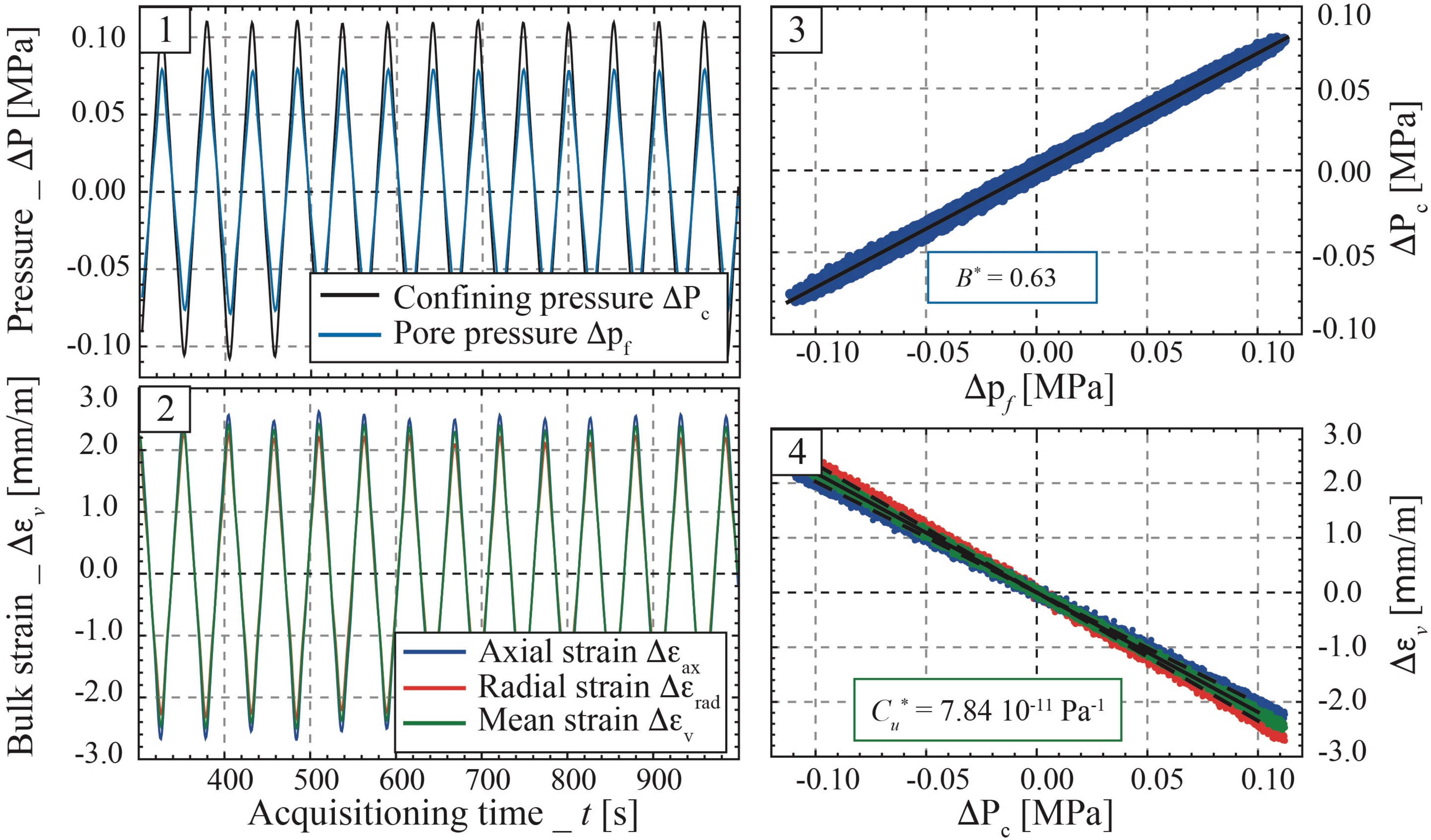


Pore pressure oscillations

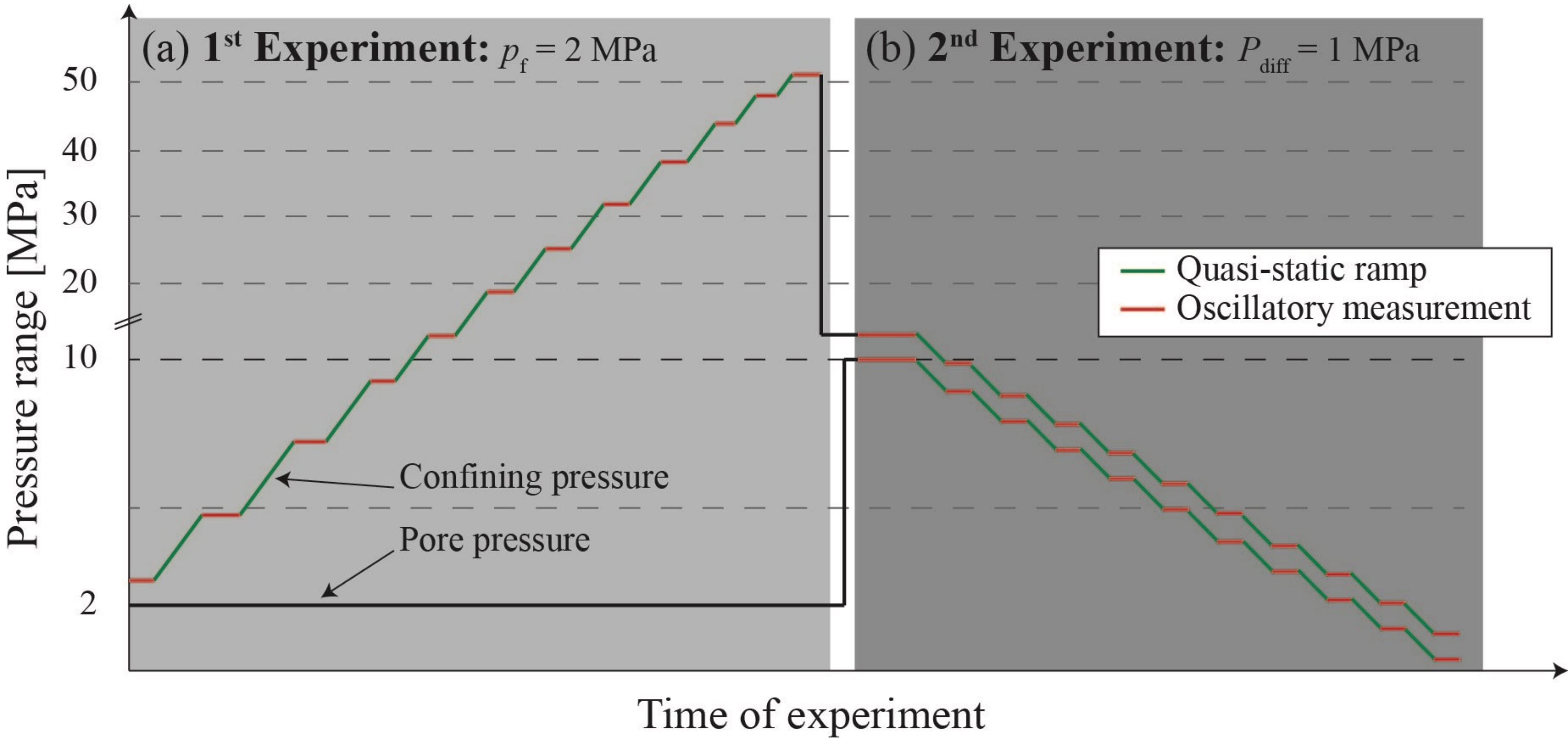


Method: Undrained properties

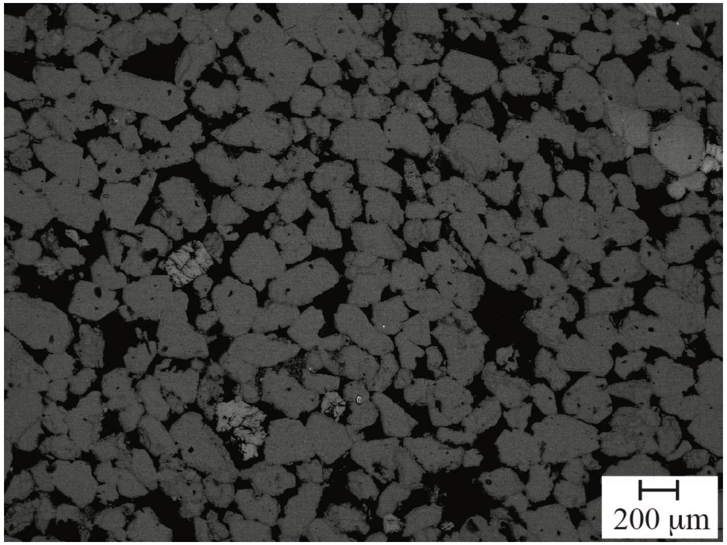
(c) Exemple of measurement: *Undrained conditions*



Method: Undrained properties

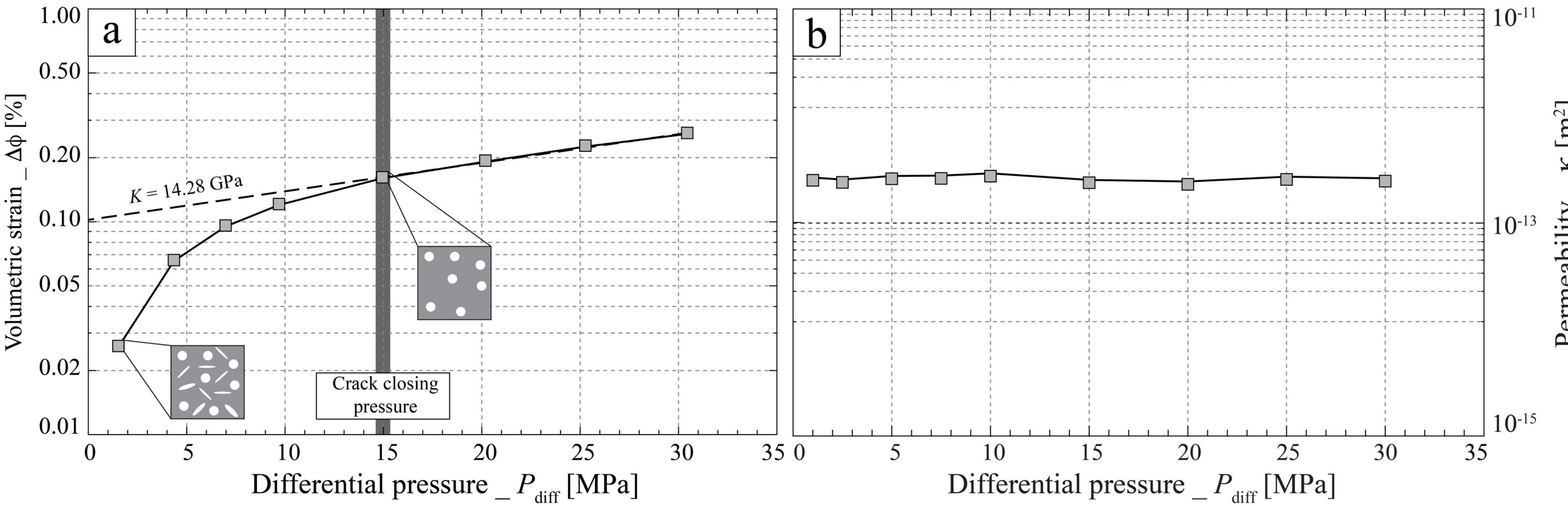


III_Bentheim sandstone : *the rock sample*

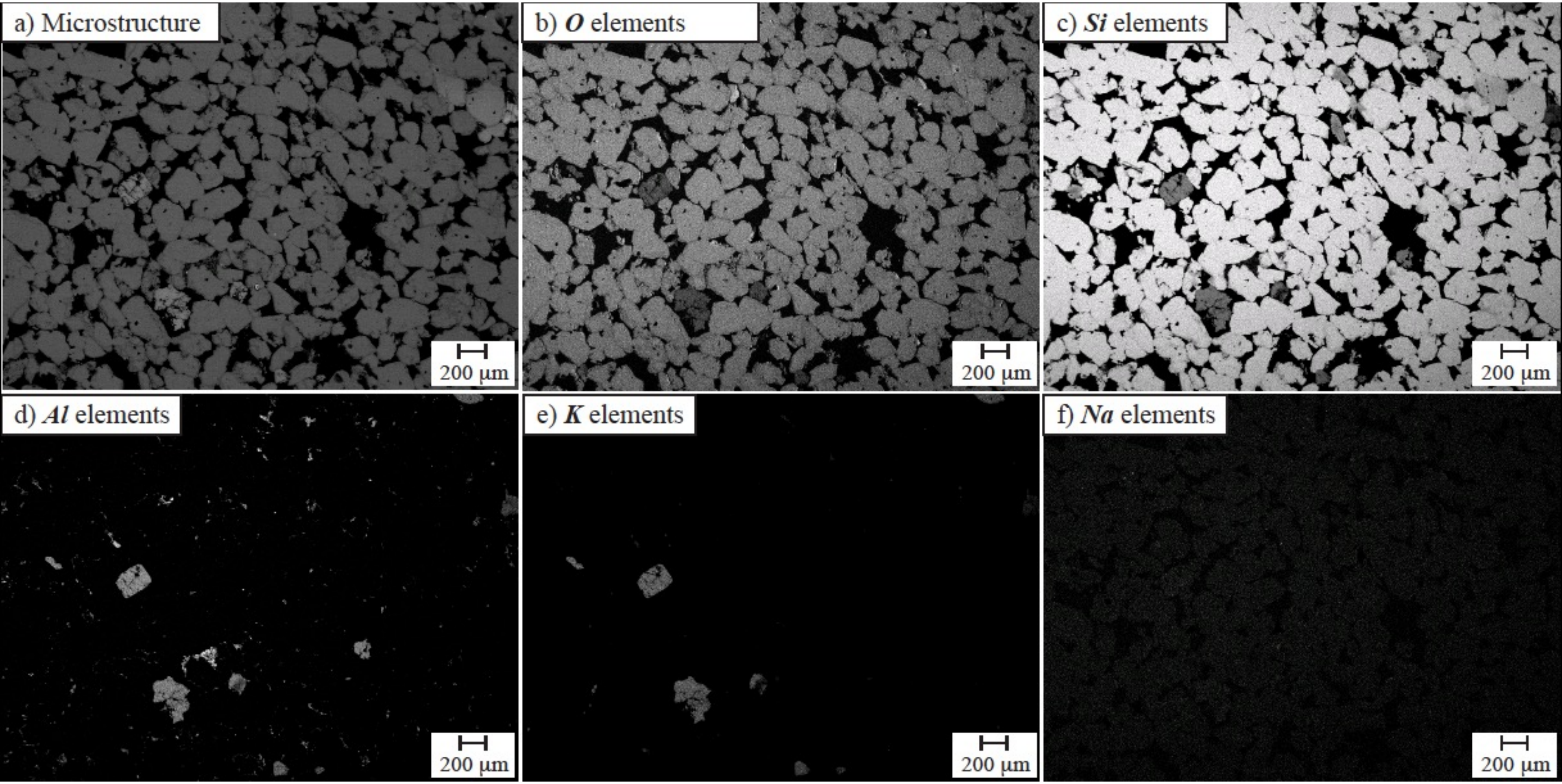


Bentheim sandstone

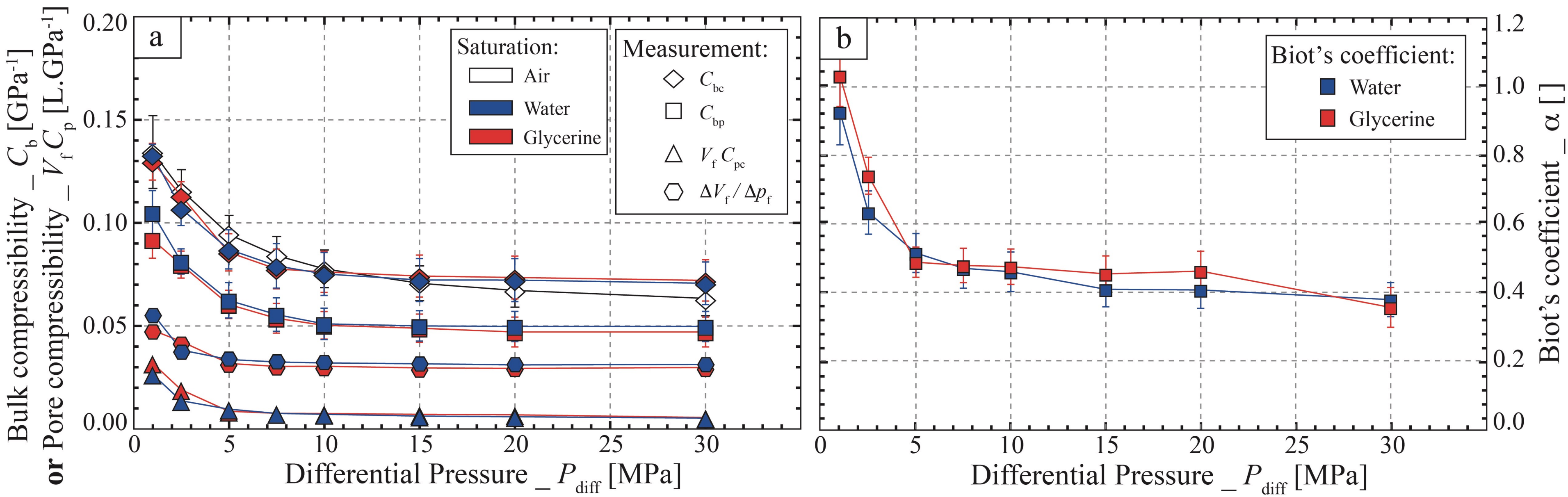
- Clean (> 95% quartz) sandstone.
- Homogeneous and isotropic at sample scale.
- Porosity of 24.3%
- Permeability of about 2 10^{-13} m^2 (200 mD).
- Crack closing pressure of about 15 MPa.
- No pressure dependence of permeability.
- ➢ Under Dry, Water & Glycerine saturation



III_Bentheim sandstone : *the rock sample*



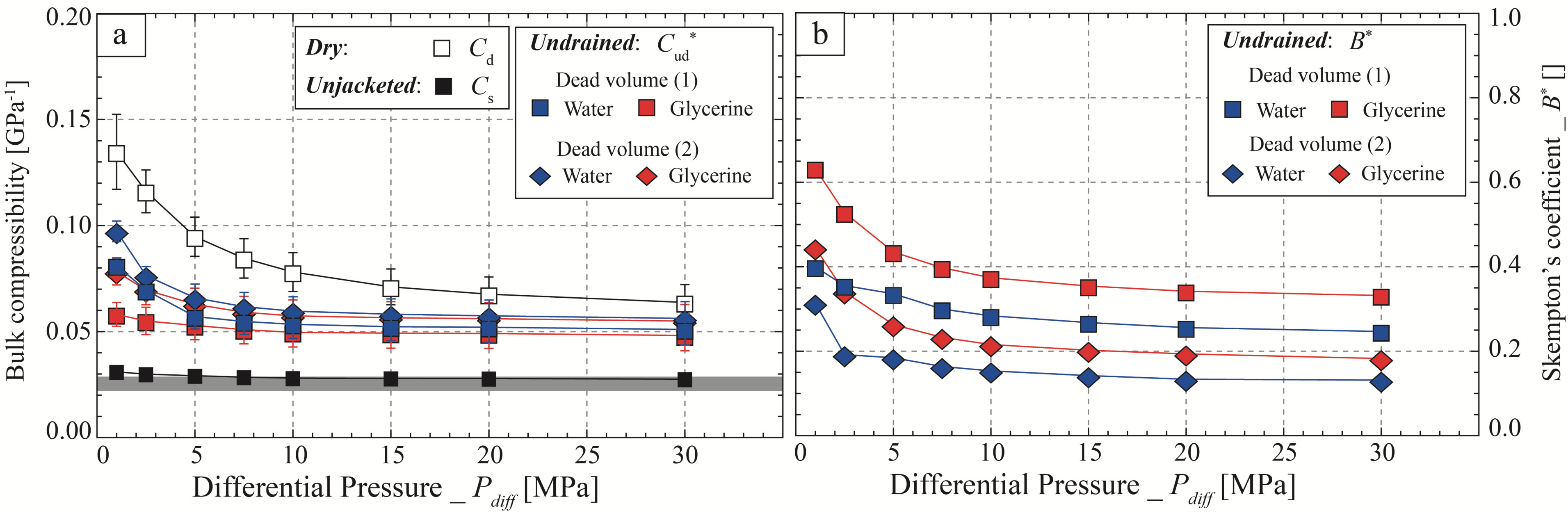
III_Bentheim sandstone : *Results*



Drained

- Dependence to P_{diff} of all coefficients.
- Drained properties independent of the saturating fluid
- $C_{bc} > C_{bp}$ ⇔ Consistent !
- $C_{pc} > C_{bp}$ ⇔ Consistent !
- α reaches 1 at lowest P_{diff}

III_Bentheim sandstone : *Results*



Drained

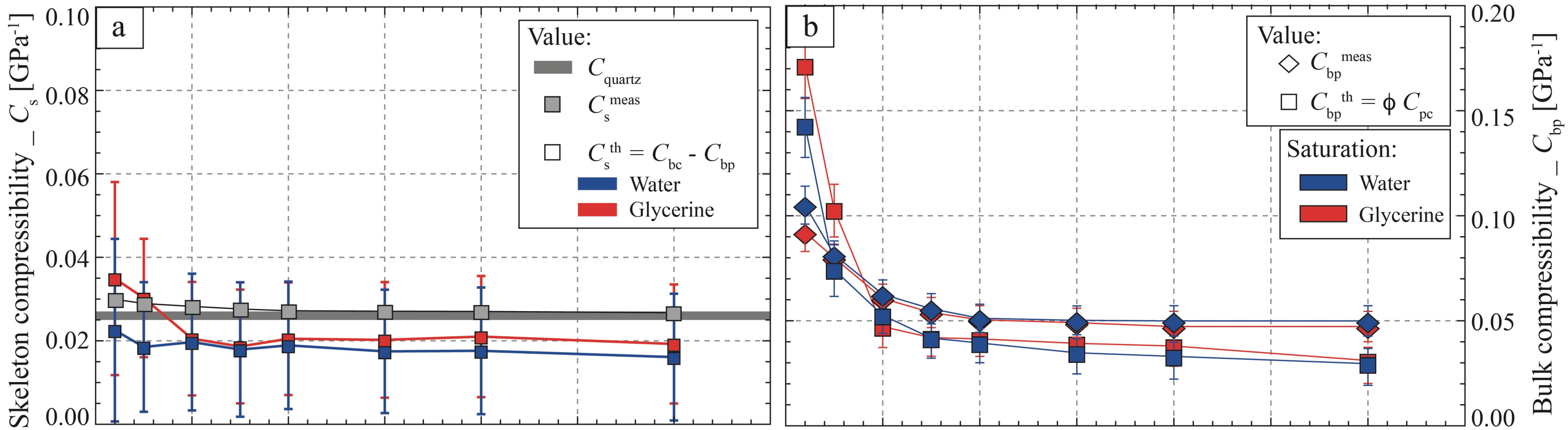
- Dependence to P_{diff} of all coefficients.
- Drained properties independent of the saturating fluid
- $C_{bc} > C_{bp}$ ⇔ Consistent !
- $C_{pc} > C_{bp}$ ⇔ Consistent !
- α reaches 1 at lowest P_{diff}

Undrained & Unjacketed

- Lower dependence to P_{diff}
- C_s fits with C_{quartz}
- Undrained properties dependent to
  - C_f ⇔ Consistent !
  - V_d ⇔ Consistent !

III_Bentheim sandstone : *Interpretation & Discussion*

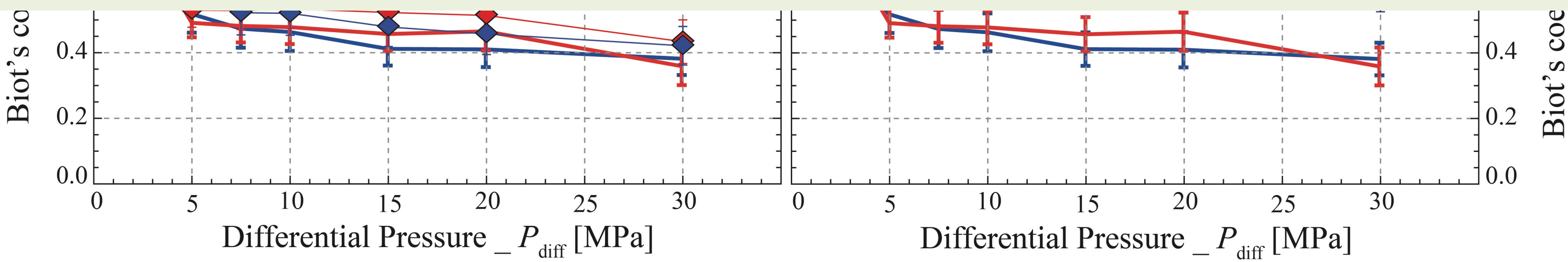
Measured vs Inferred Zimmerman's coefficients



Checking Zimmerman's coefficients

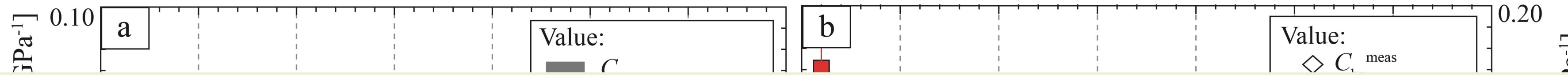
For this sandstone sample:

- $C_{bc} - C_{bp} = C_s = C_{quartz}$
- $C_{bp} = \phi\, C_{pc}$, with small deviation at low $P_{diff} < 5$ MPa.



III_Bentheim sandstone : *Interpretation & Discussion*

Measured vs Inferred Zimmerman's coefficients



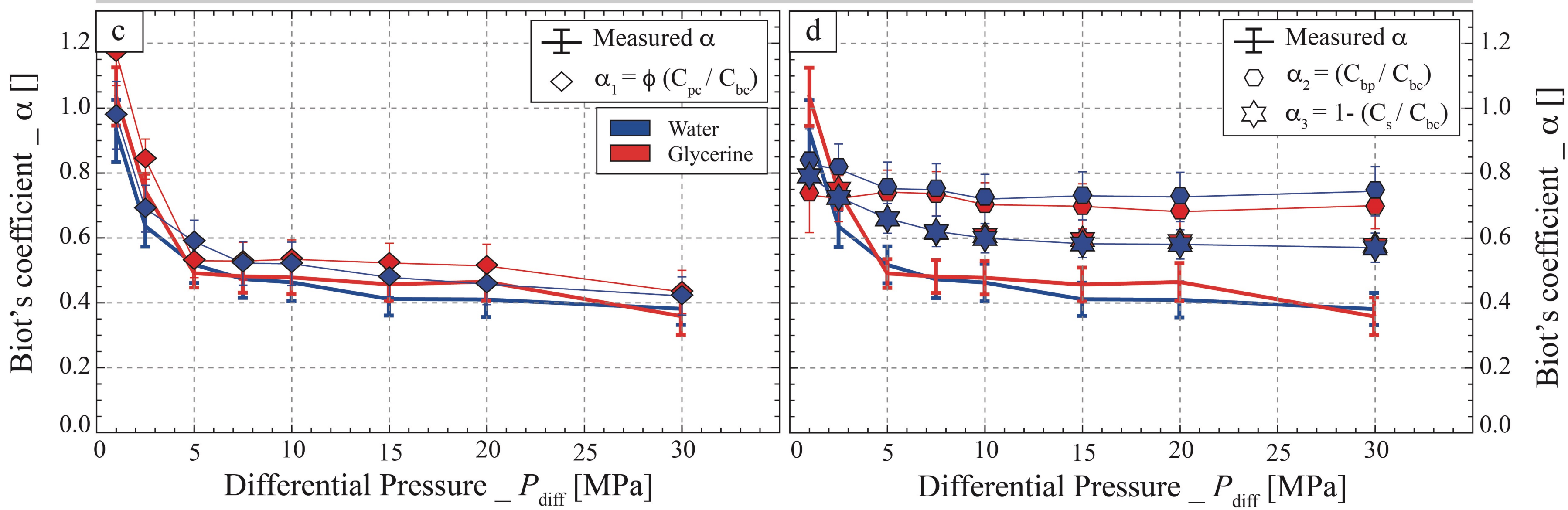
Zimmerman's vs Biot's coefficients

For this sandstone sample:

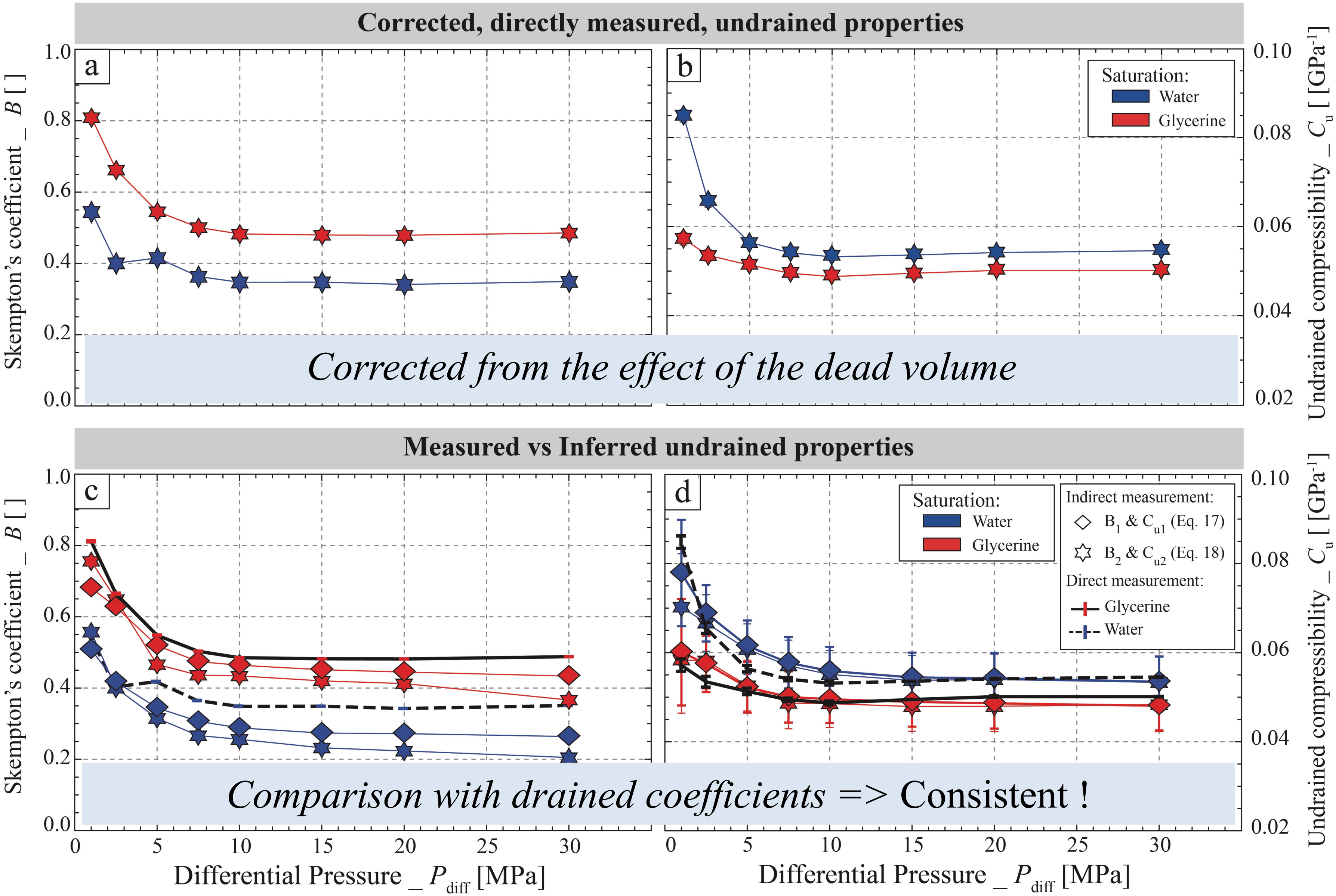
- ➢ α obtained fits only with α_1
- ➢ α_1 & α_2 not same pressure dependence.

NB: α_1 & α_2 at high P_{diff} probably fit α (i.e. shift from corrections).

Measured vs Inferred Biot's coefficient



III_Bentheim sandstone : *Interpretation & Discussion*



III_Bentheim sandstone : *Interpretation & Discussion*

What of the pore compressibility coefficients $\mathbf{C_{pp}}$ **&** $\mathbf{C_{\phi}}$?

From Zimmerman (2000)

&

$C_{\phi} = C_{pc} - C_{pp}$

Measured coefficients	Relation
$C_{bc}, C_{bp}, C_{pc}, C_u$	$C_{pp} = \frac{C_{bp}C_{pc}}{C_{bc} - C_u} - C_f$
C_{pc}, B	$C_{pp} = \frac{C_{pc}}{B} - C_f$
C_{bc}, C_{bp}, C_u	$C_{pp} = \frac{C_{bp}^2}{\phi(C_{bc} - C_u)} - C_f$
C_{bp}, B	$C_{pp} = \frac{C_{bp}}{\phi B} - C_f$
C_{bc}, C_u	$C_{pp} = \frac{(C_{bc} - C_{qtz})^2}{\phi(C_{bc} - C_u)} - C_f$
C_{bc}, B	$C_{pp} = \frac{(C_{bc} - C_{qtz})}{\phi B} - C_f$
C_{bc}	$C_{pp} = \frac{(C_{bc} - C_{qtz})^2}{\phi(C_{bc} - C_{u1})} - C_f$
C_{bc}	$C_{pp} = \frac{(C_{bc} - C_{qtz})}{\phi B_1} - C_f$

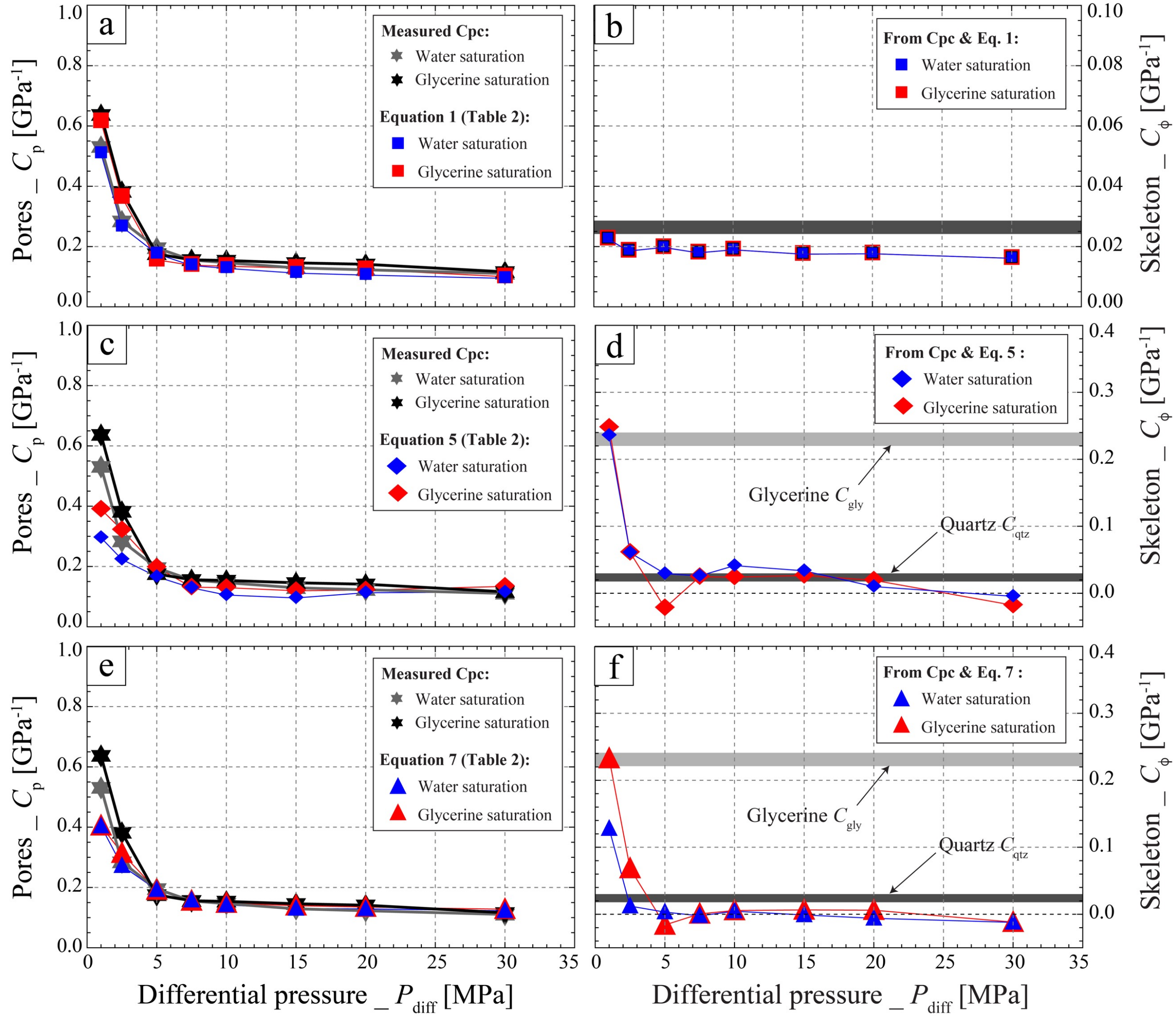
Increase in theoretical combinations

⇩

Decrease number of unknowns

III_Bentheim sandstone : *Interpretation & Discussion*

What of the pore compressibility coefficients $\mathbf{C_{pp}}$ **&** $\mathbf{C_{\phi}}$?



Conclusion

Method

→ New method from ***low amplitude*** and ***low frequency*** pressure oscillations

→ Use Three boundary Conditions & Two solicitation methods

- Up to 7 constants measurable independently.

Case of Bentheim sandstone

→ Pressure dependence of all compressibility/poroelasticity coefficients

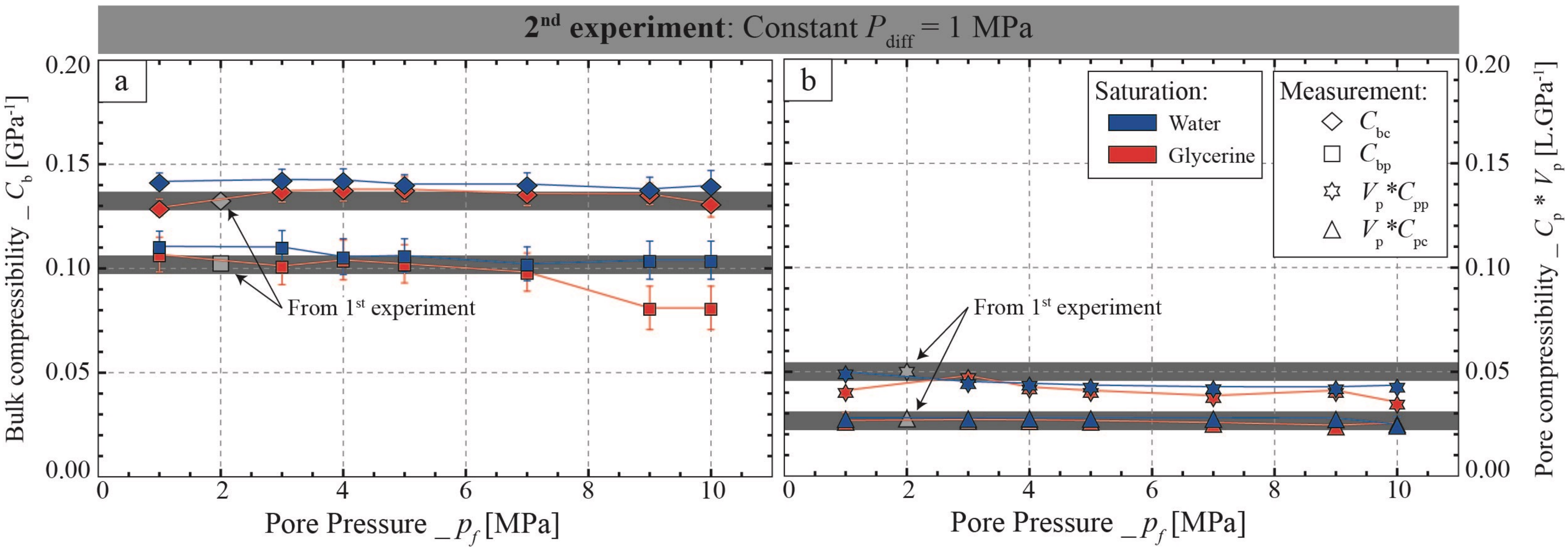
→ Overall fit with poroelastic theories:

- No effect of fluids under drained conditions
- Effect of fluid compressibility under undrained conditions
- Good comparison between the different coefficients:
  - Zimmerman's coefficients
  - Biot versus Zimmerman's theories

→ It is inferred that : $C_\phi = C_s = C_{quartz}$ (i.e. rock micro-homogeneous)

III_Bentheim sandstone : *Interpretation & Discussion*

Role of the pore fluid pressure @ constant Pdiff ?



What has been done…
And what might remain !?

Thank you for your attention

Pimienta, L., Fortin, J., & Guéguen, Y. (**2017**): New method for Compressibility & Poroelasticity coefficients in porous and permeable rocks, *Journal of Geophysical Research*