Coupled and multiphysics phenomena
24th ALERT School, Aussois, 1-3 October 2015

Thermo-hydro-mechanical issues in geomaterials Physical mechanisms and experimental determination

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ParisTech

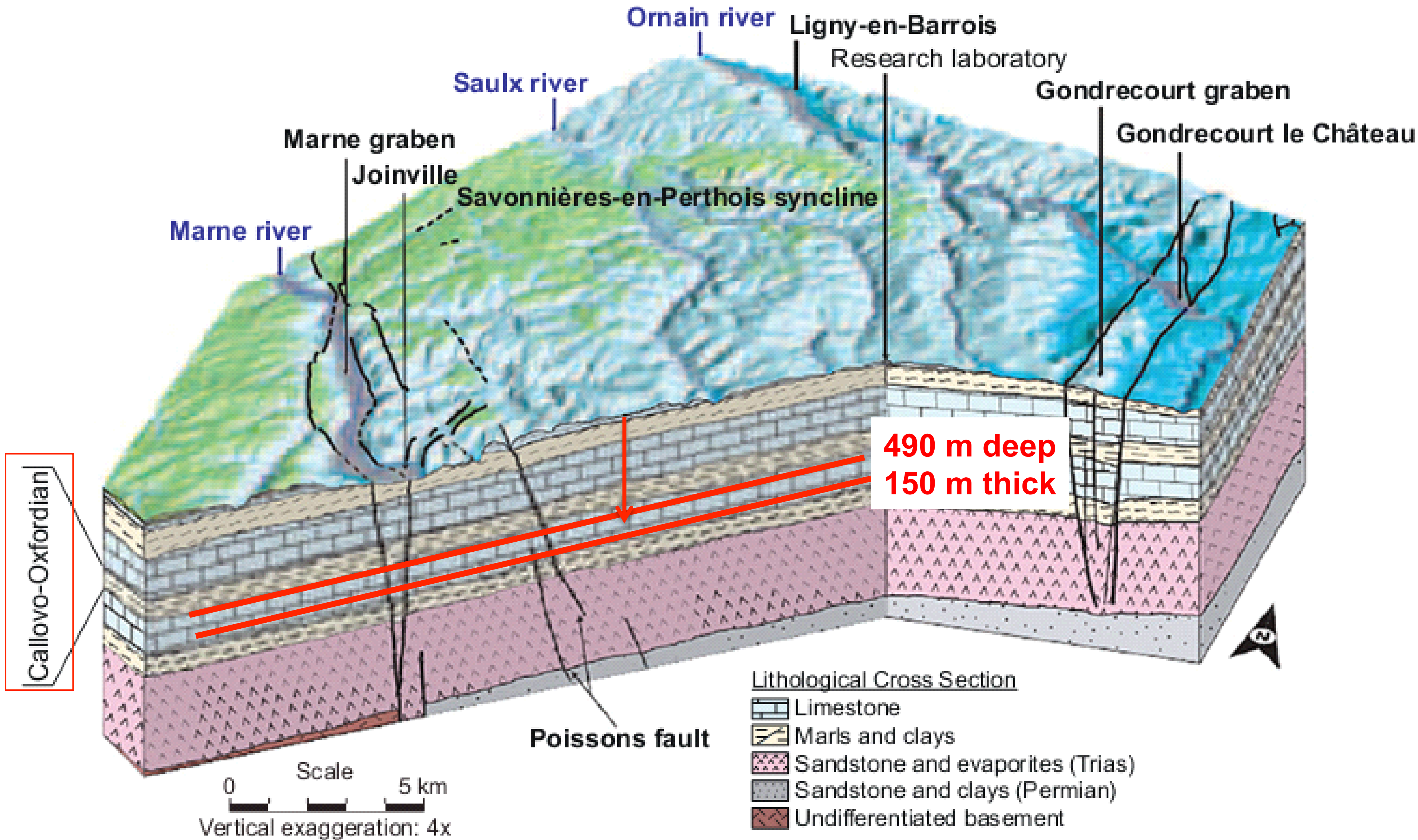
Sinkhole in unsaturated collapsible loess (Northern France)

Unsaturated soil : water + air

Loess: small clay fraction

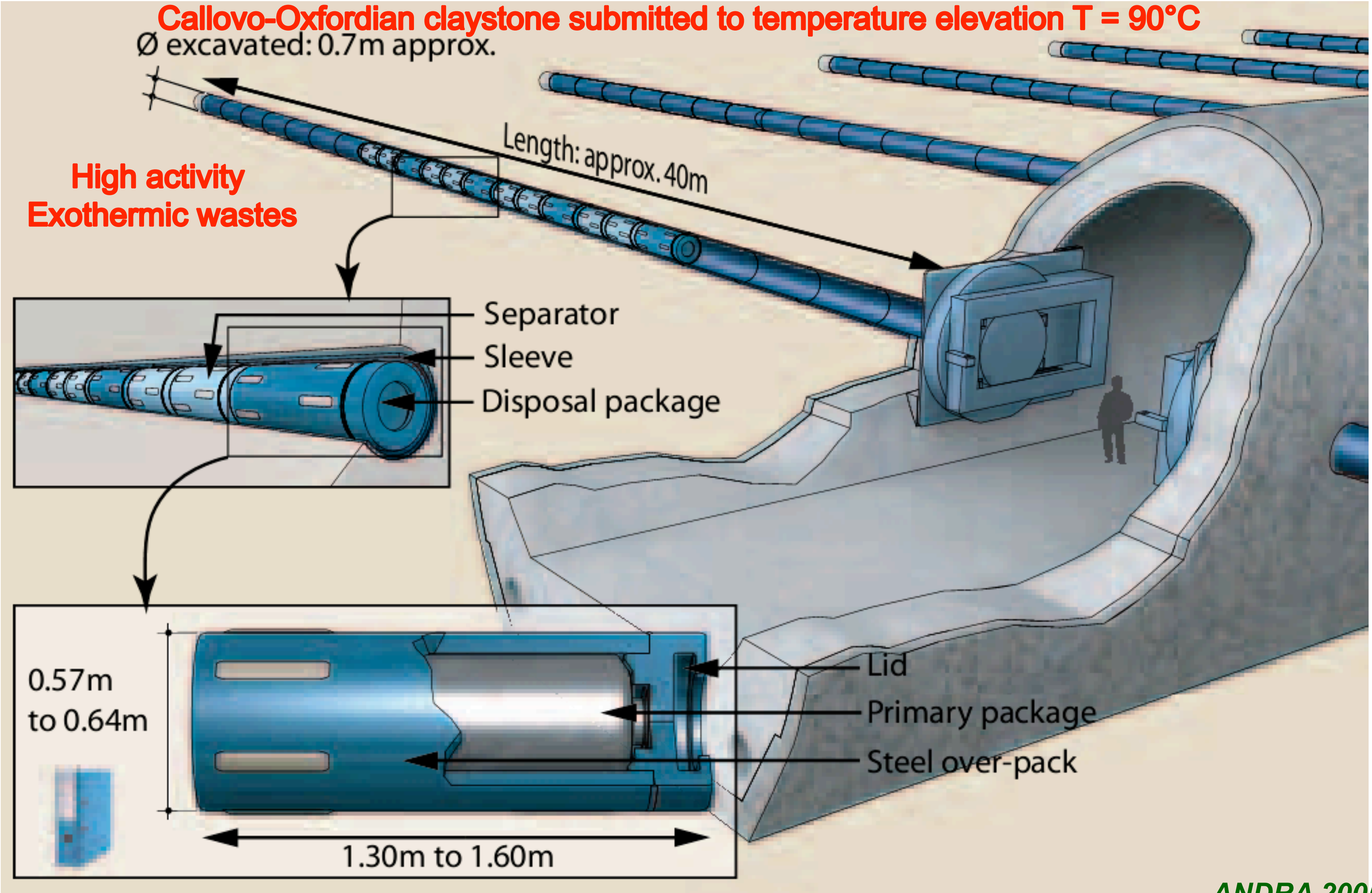
Hydro-mechanical coupling

Deep radioactive geological disposal in claystone in France, - 490m



ANDRA 2005

Deep radioactive geological disposal
French concept in claystone, - 490m



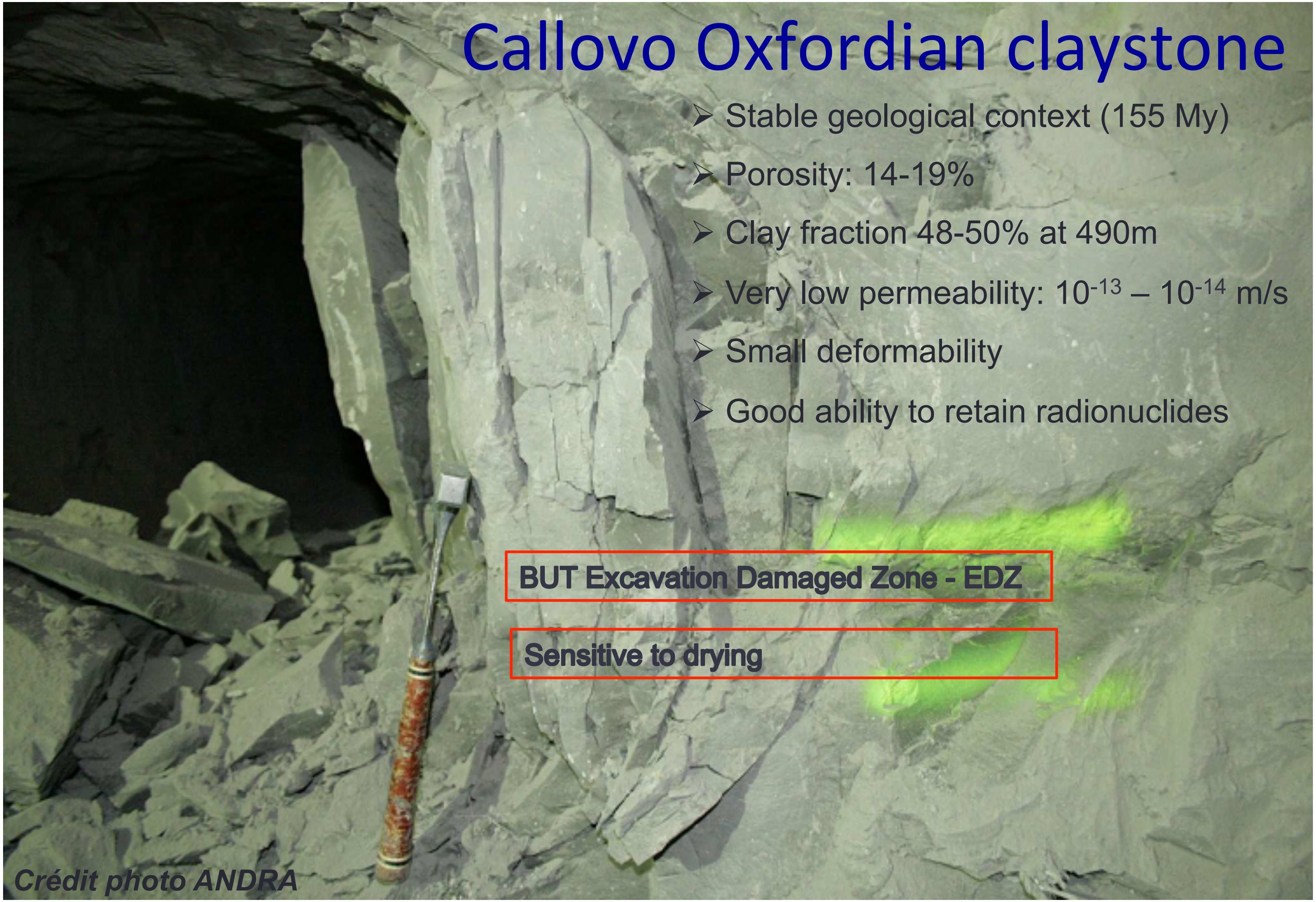
ANDRA 2005

Callovo Oxfordian claystone

- Stable geological context (155 My)
- Porosity: 14-19%
- Clay fraction 48-50% at 490m
- Very low permeability: 10^{-13} – 10^{-14} m/s
- Small deformability
- Good ability to retain radionuclides

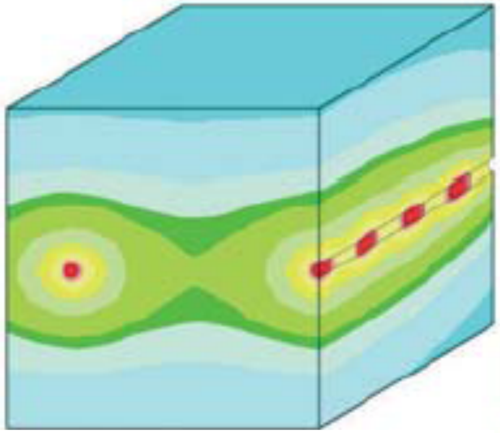
BUT Excavation Damaged Zone - EDZ

Sensitive to drying

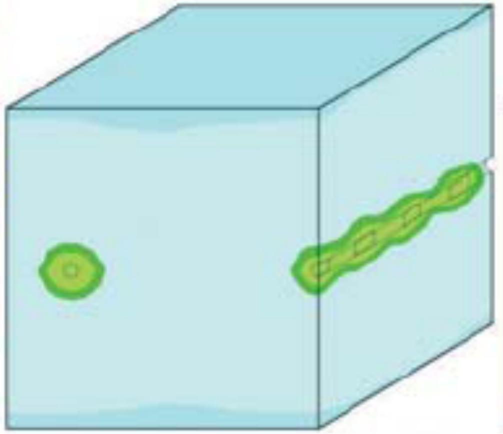


Crédit photo ANDRA

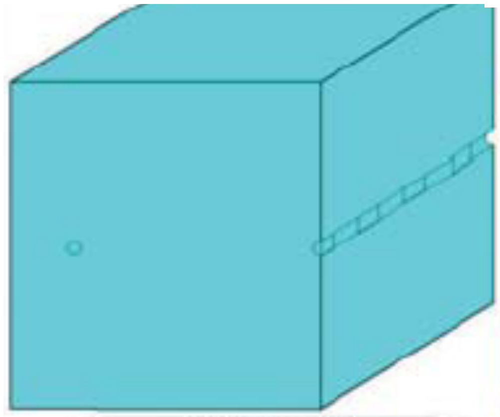
Thermal transient phase, France



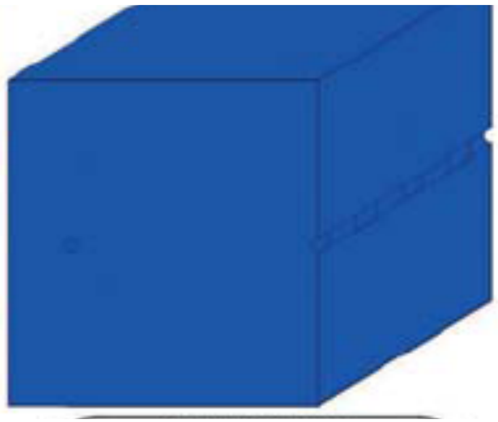
10 - 15 y: Thermal peak at 90°C



1000 y: Local uniformity at 40-46°C



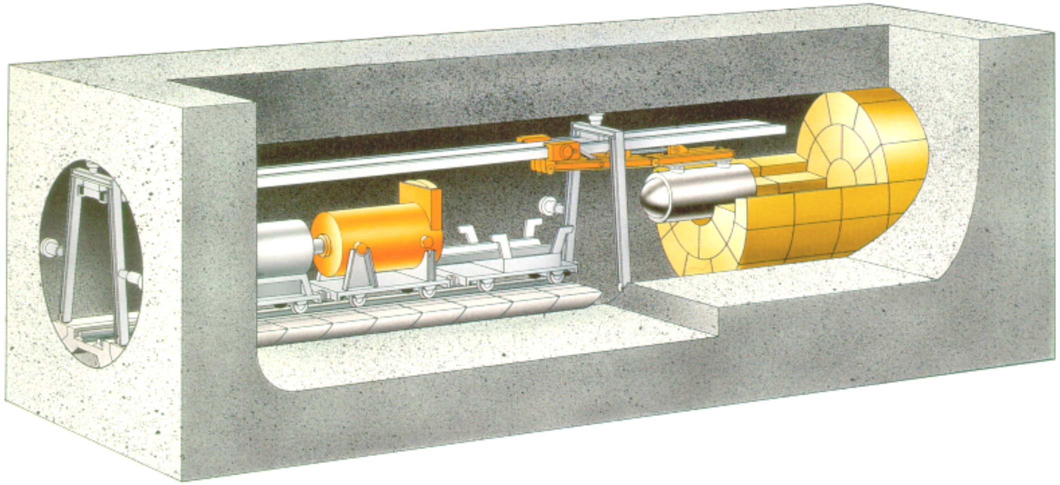
3000 y: Global uniformity at 30-35°C

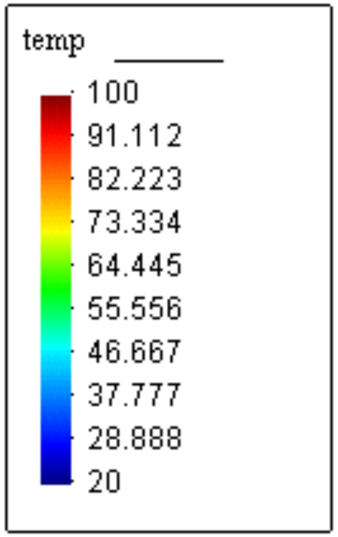


50 000 y: Back to initial T at 5°C

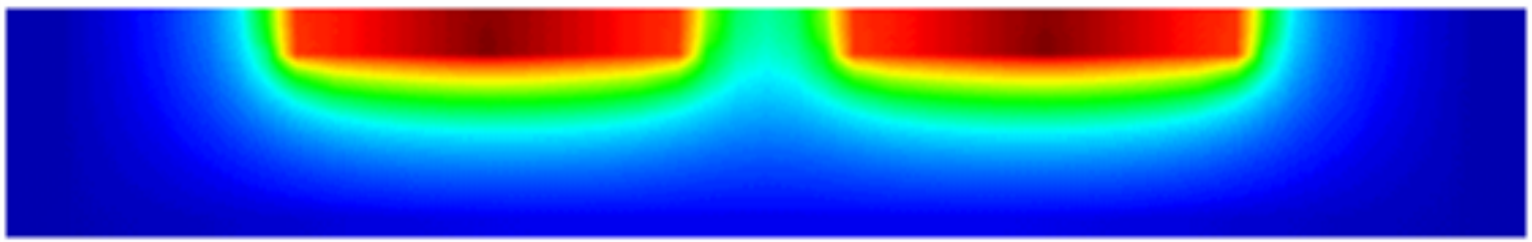
ANDRA 2005

Radioactive waste concept in granite highly compacted bentonite (Sweden)





Temperature elevation

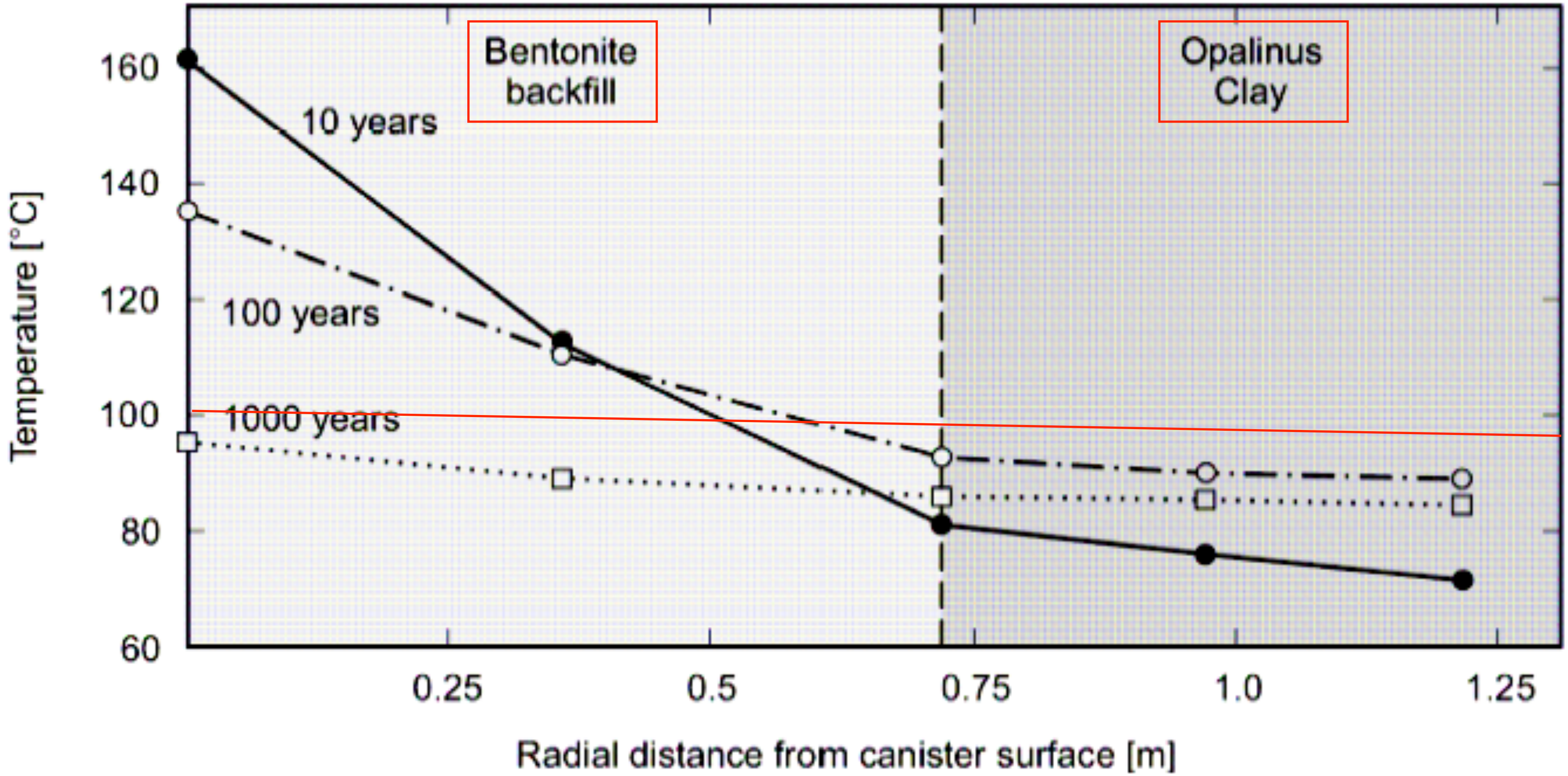


Gens, Romero et al.

Thermal transient phase, Switzerland

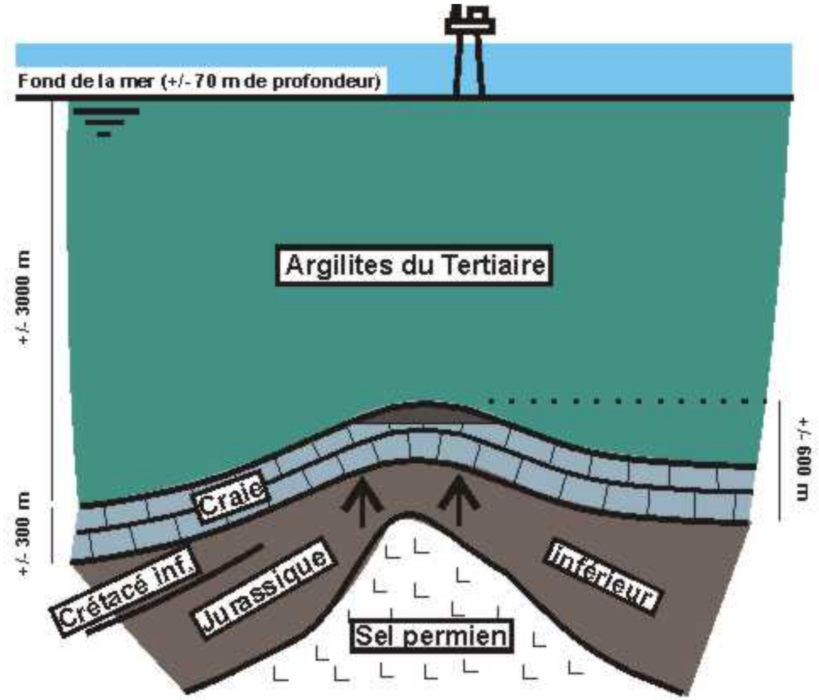
Higher temperatures thanks to buffer

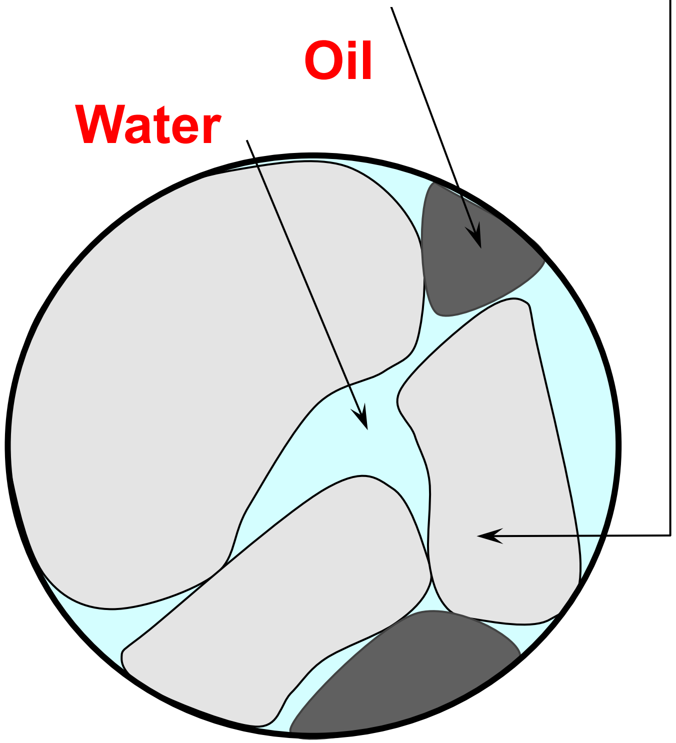
Temperatures smaller than 100°C in host clay



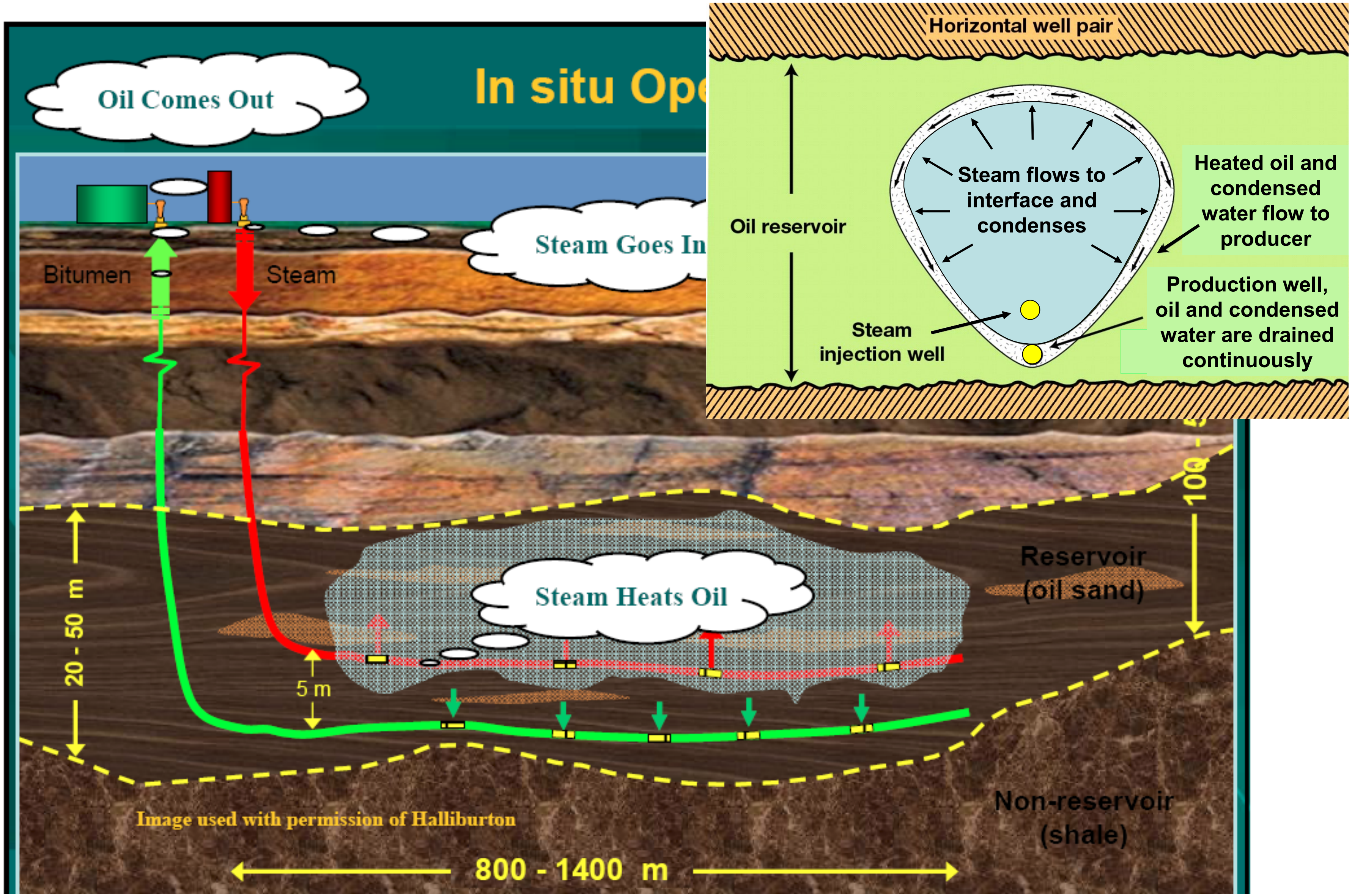
Ekofisk oilfield subsidence (North sea)

Enhanced recovery by sea-water injection: 10 m subsidence

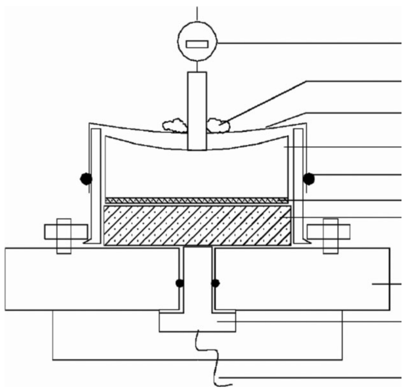




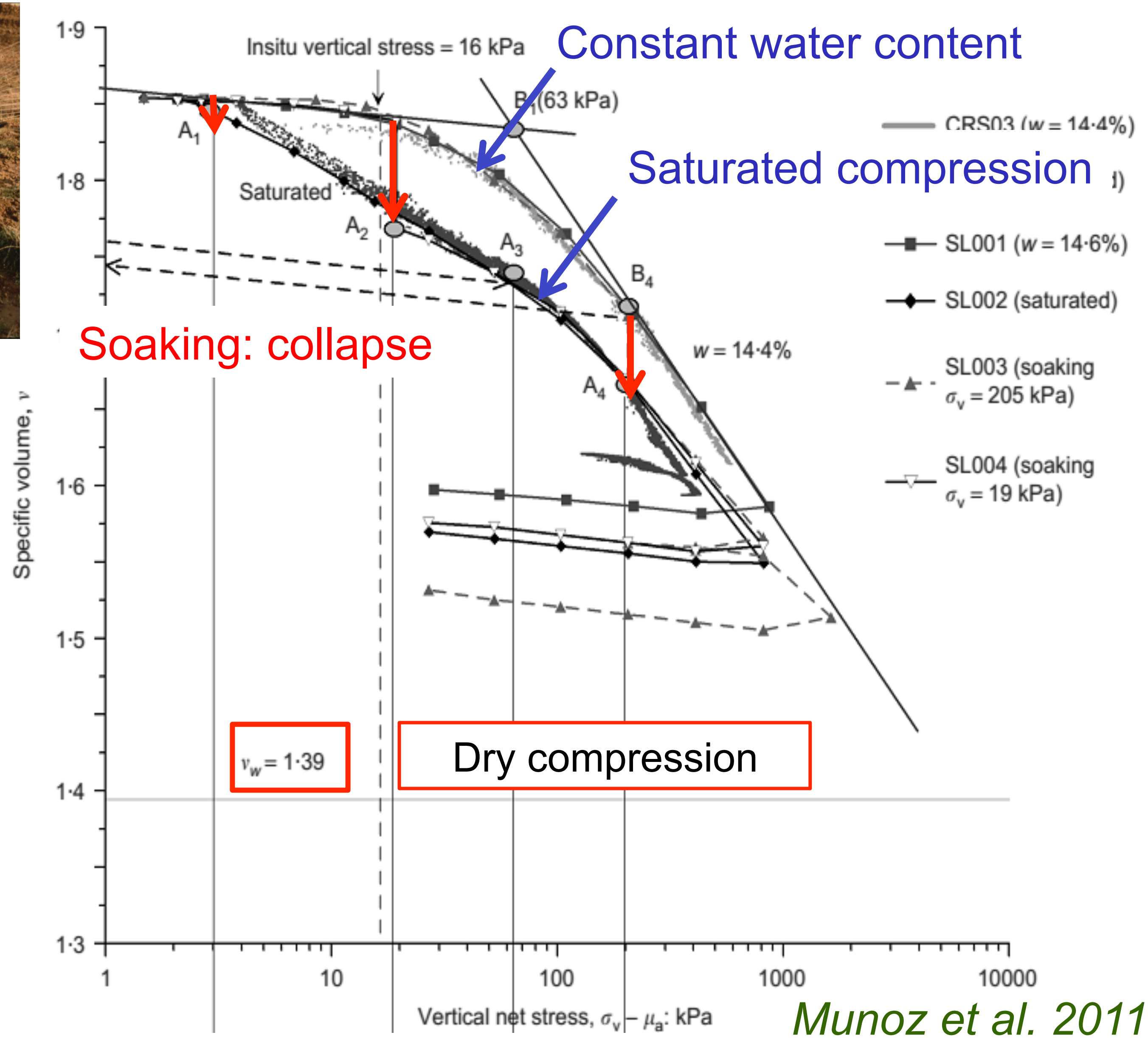
Non conventional oil recovery – oil sands
Steam assisted gravity drainage (SAGD)



Collapse behaviour of loess (Northern France)

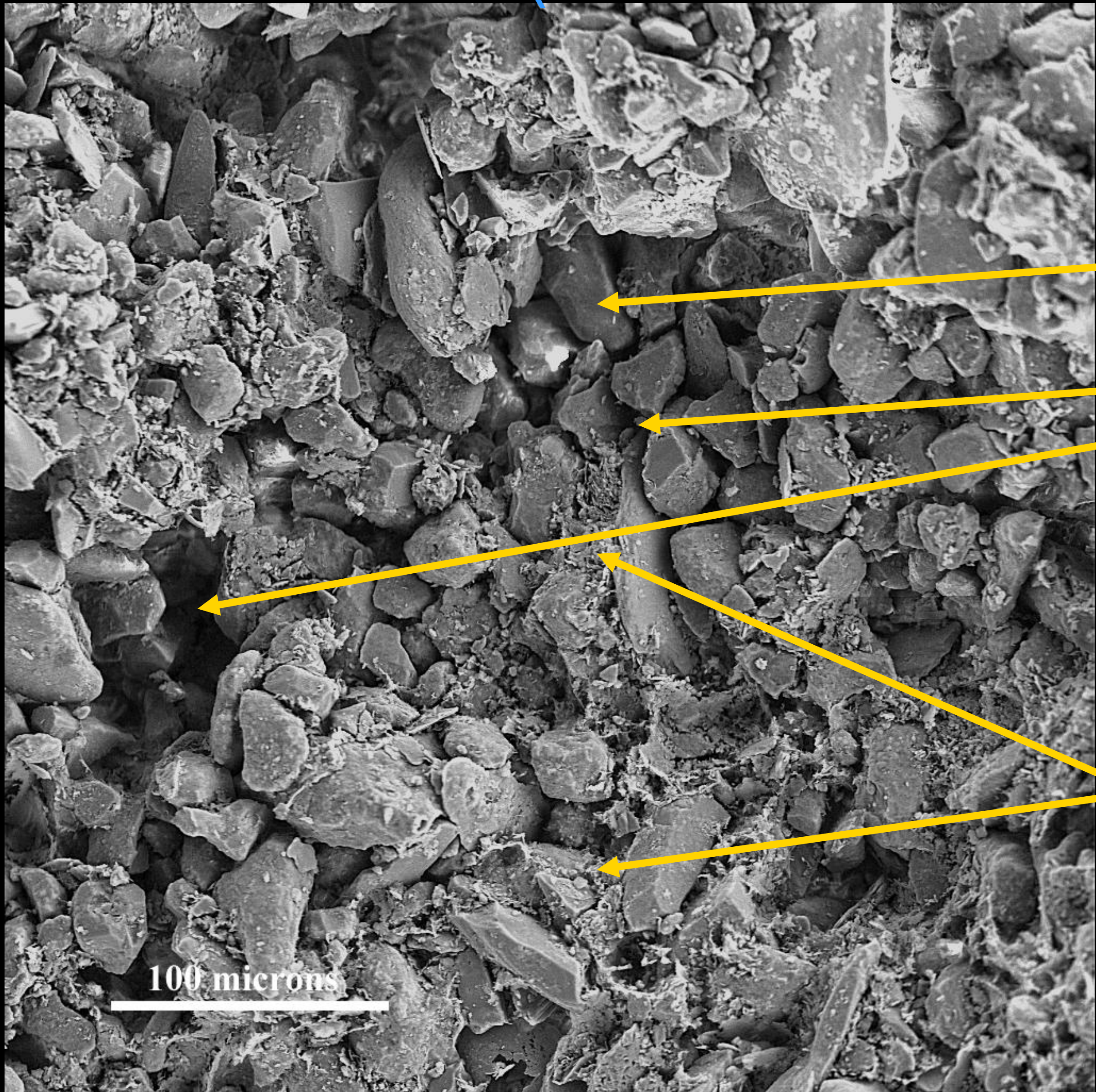


Oedometer compression



Munoz et al. 2011

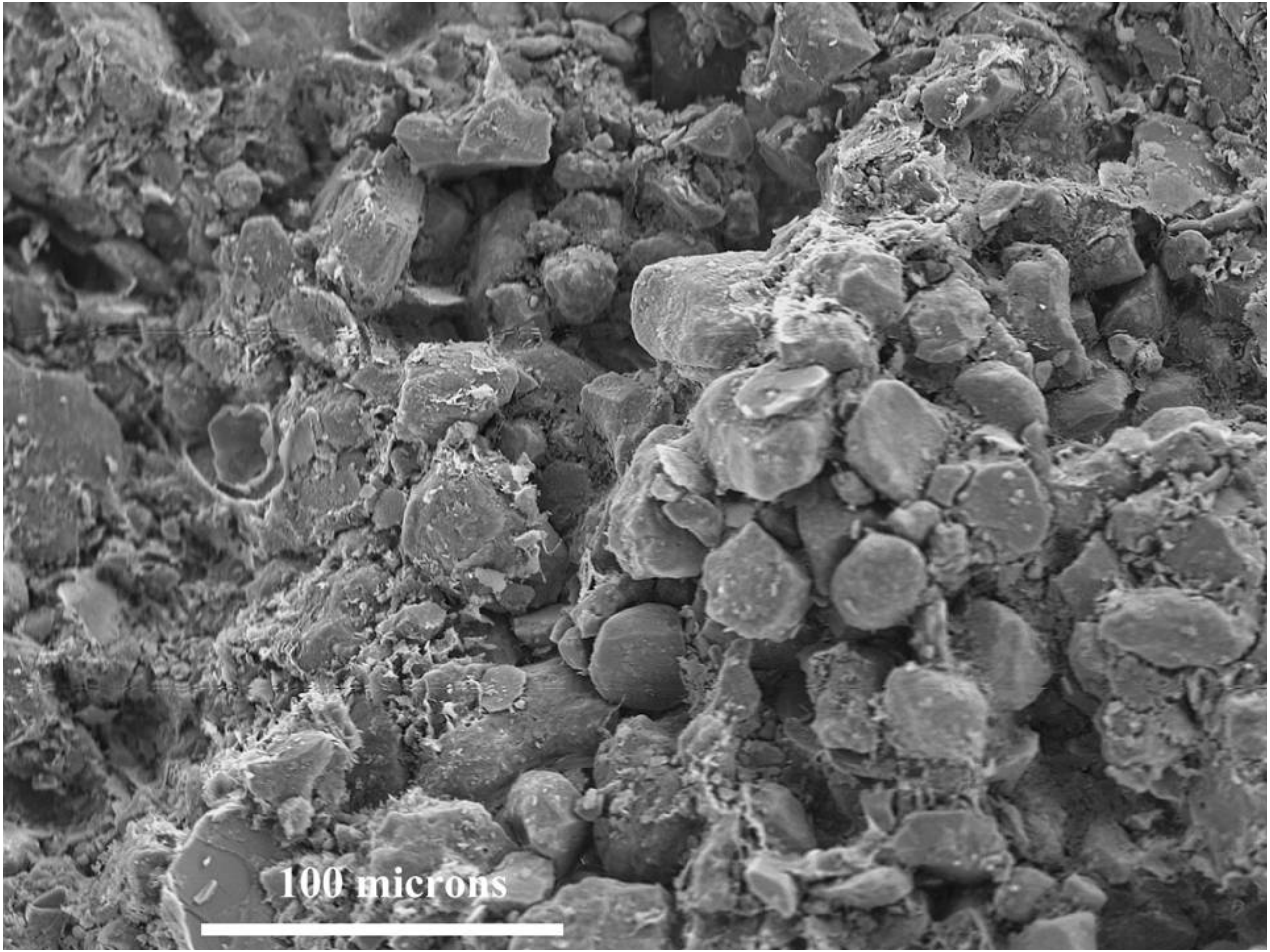
Natural collapsible unsaturated loess (Northern France)



silt grain (20-30 µm)

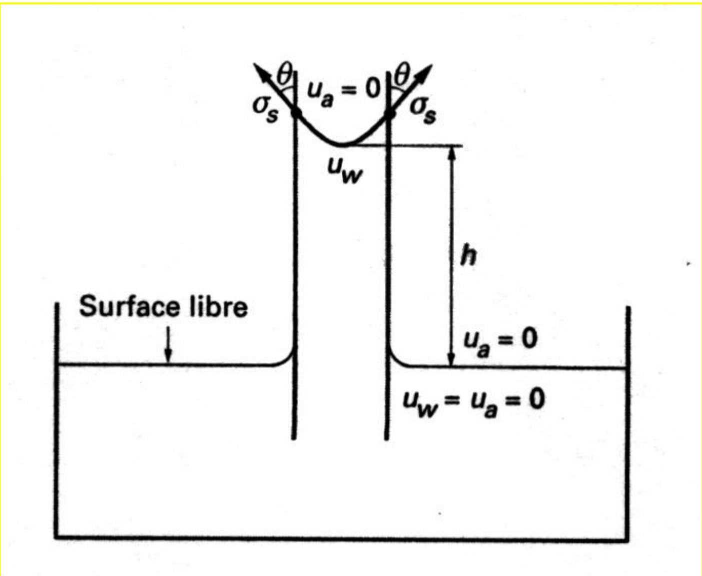
Dry inter-grain pores (20-30 µm)
- *Compressed*
- *Collapsed*

Clay aggregate (saturated)

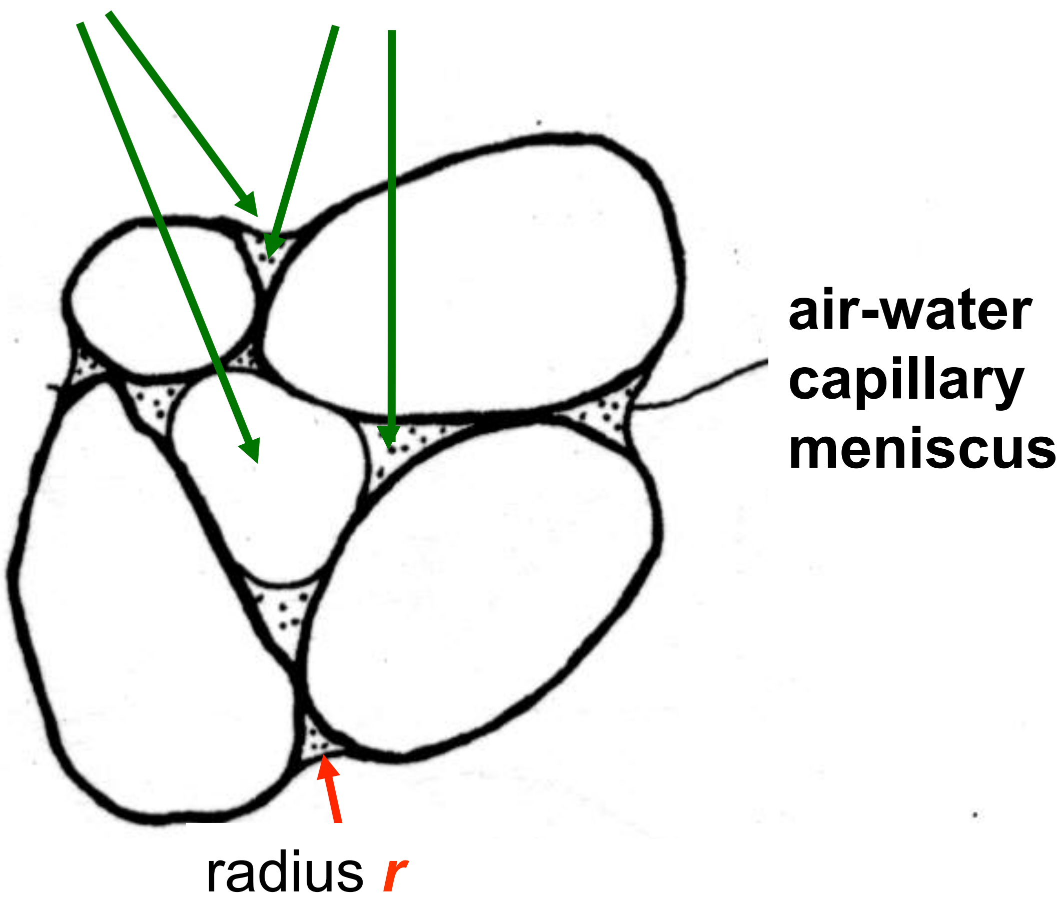

100 microns

Unsaturated granular soil

suction $s = u_a - u_w$

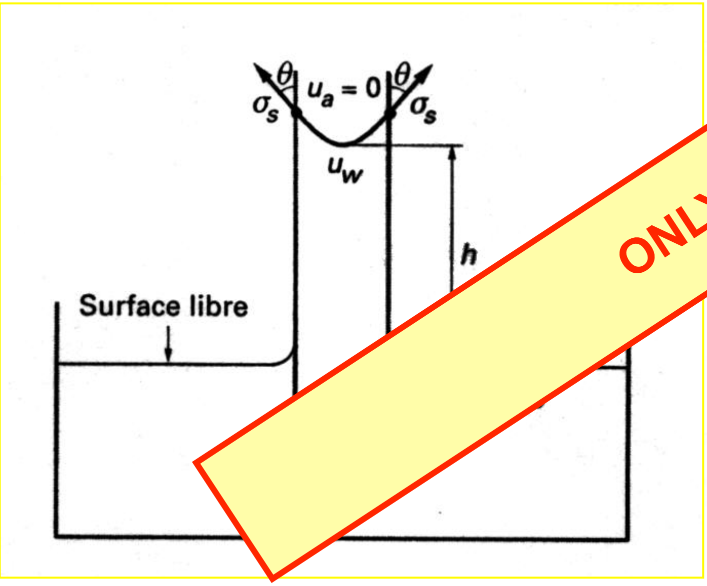


$$u_a - u_w = \frac{2\sigma_s \cos\theta}{r}$$

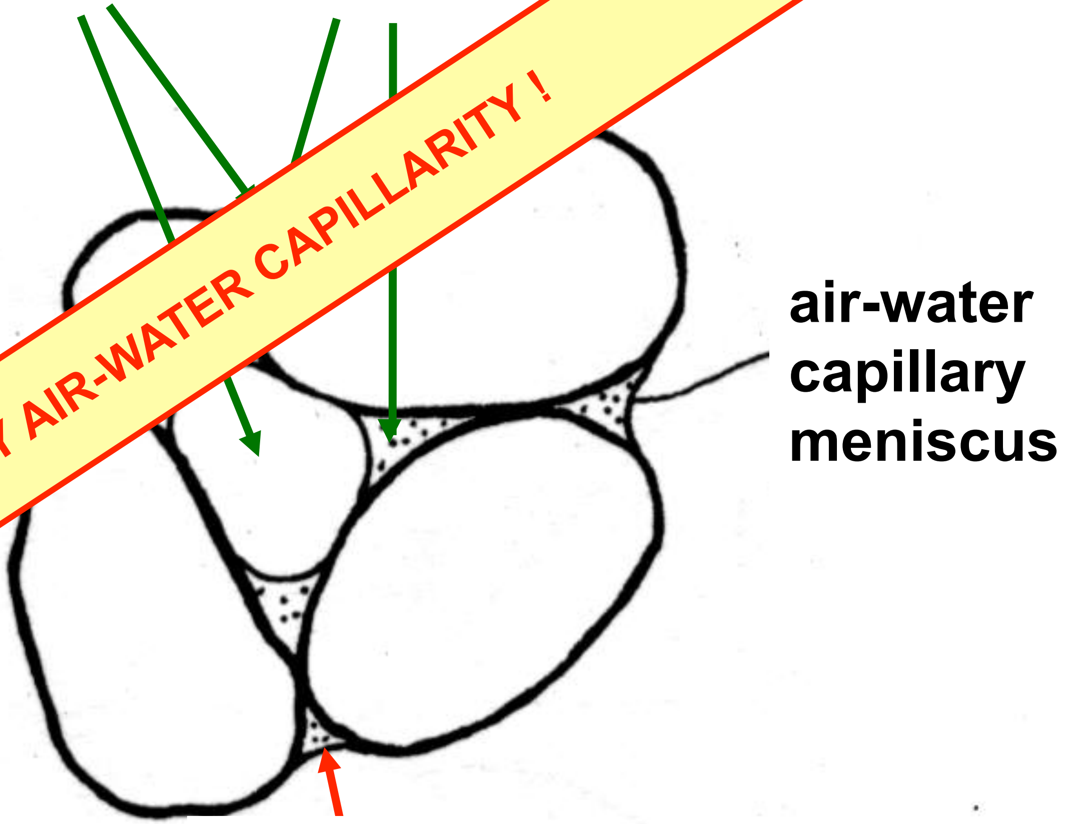


Unsaturated granular soil

suction $s = u_a - u_w$

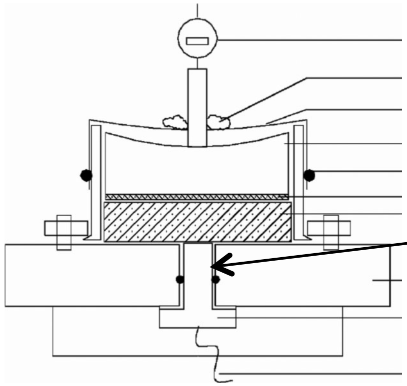


$$u_a - u_w = \frac{2\sigma_s \cos\theta}{r}$$

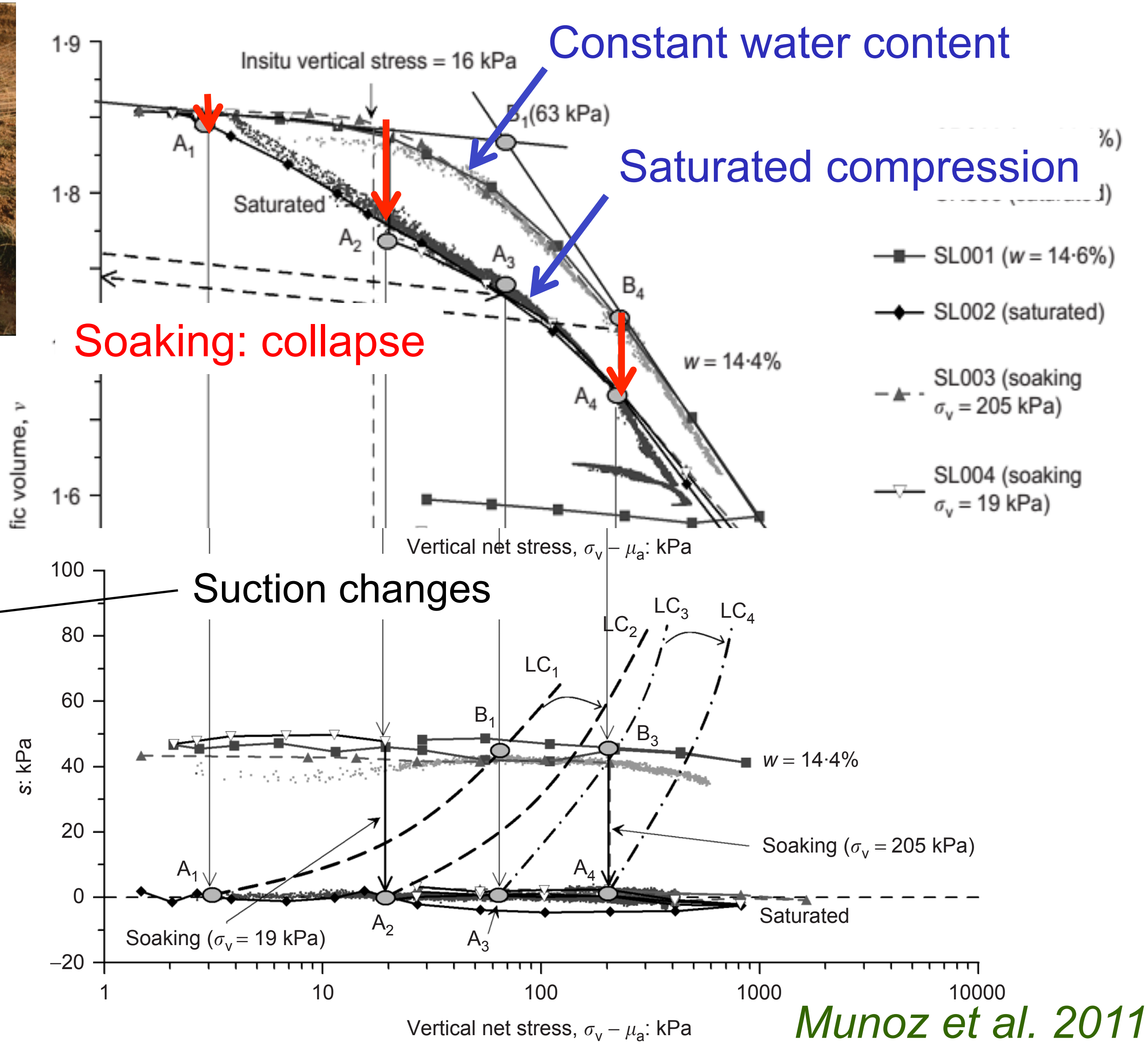


ONLY AIR-WATER CAPILLARITY !

Collapse behaviour of loess (Northern France)



Oedometer compression



Munoz et al. 2011

Bishop's "effective" stress

$$\boxed{\sigma' = \sigma - u_a + \chi\,(u_a - u_w)}$$

dry : $0 < \chi < 1$ *: saturated*

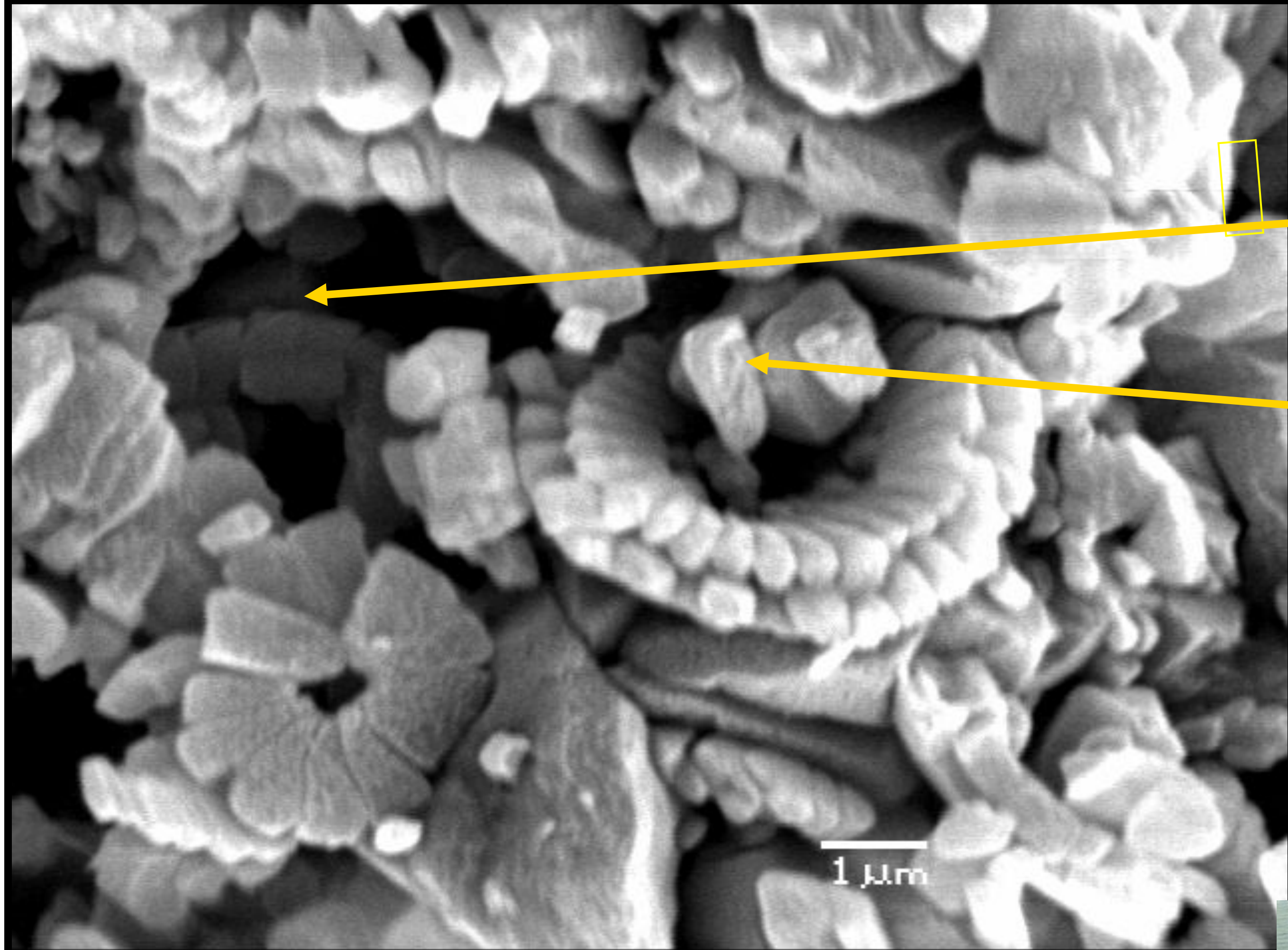
- *collapse under wetting : suction decrease down to zero*
- $\sigma - u_a$ *constant*
- $\chi > 0$

σ' *decreases so volume should increase due to stress release*
BUT volume decrease ! NOT VALID

2 INDEPENDENT STRESS VARIABLES NECESSARY

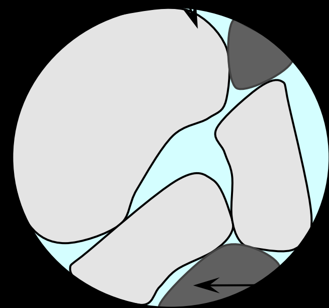
Net stress : $\sigma - u_a$ Suction : $u_a - u_w$

Oil reservoir chalk

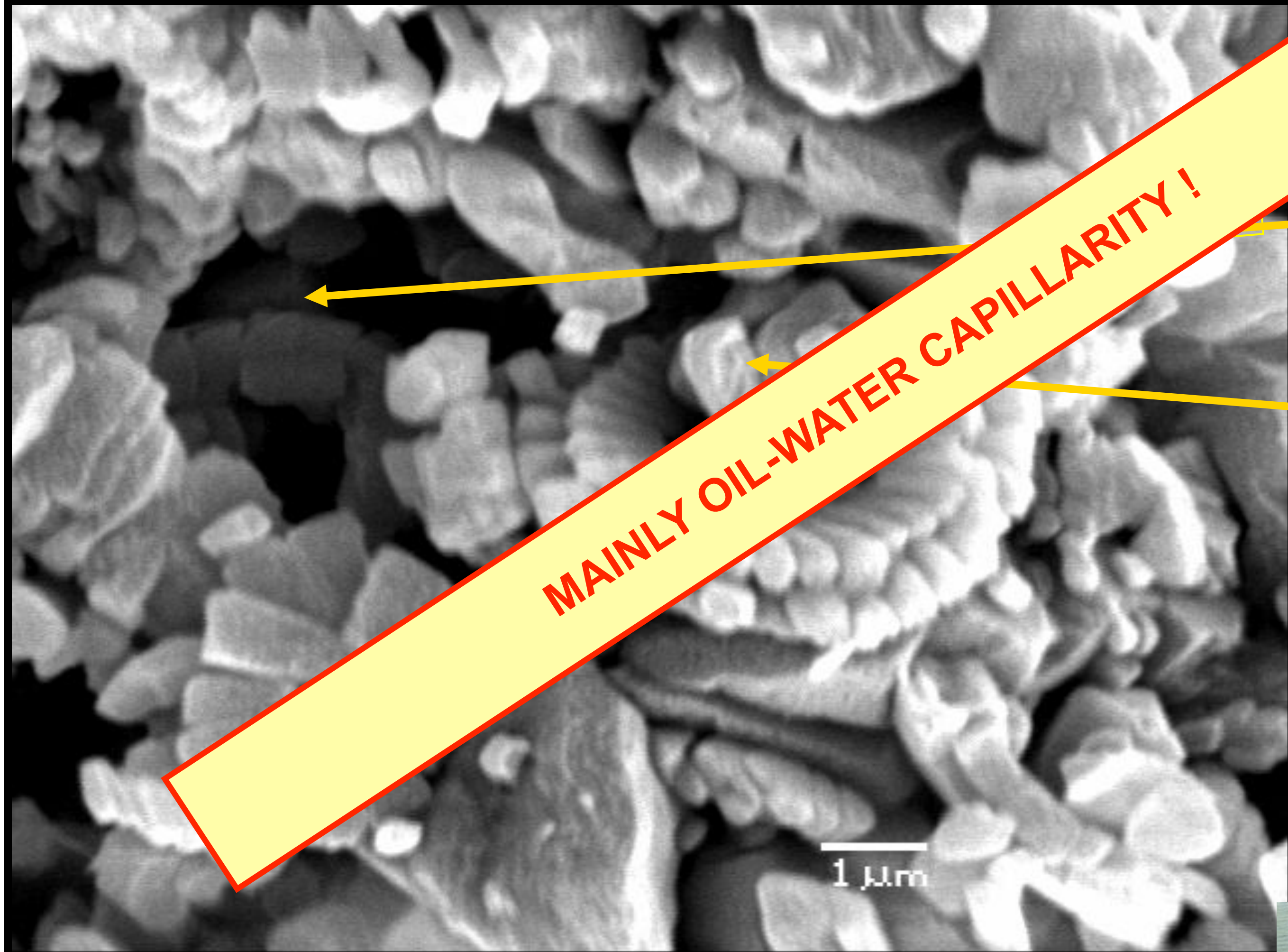


pore (ϕ 2µm)

coccolith (ϕ 1-10 µm)
pure calcite : $CaCO_3$
n = 38-41%



Oil reservoir chalk



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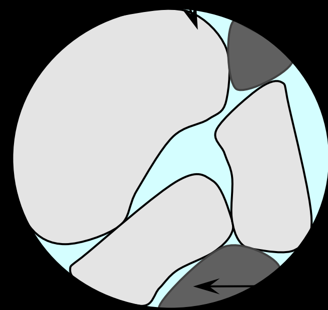
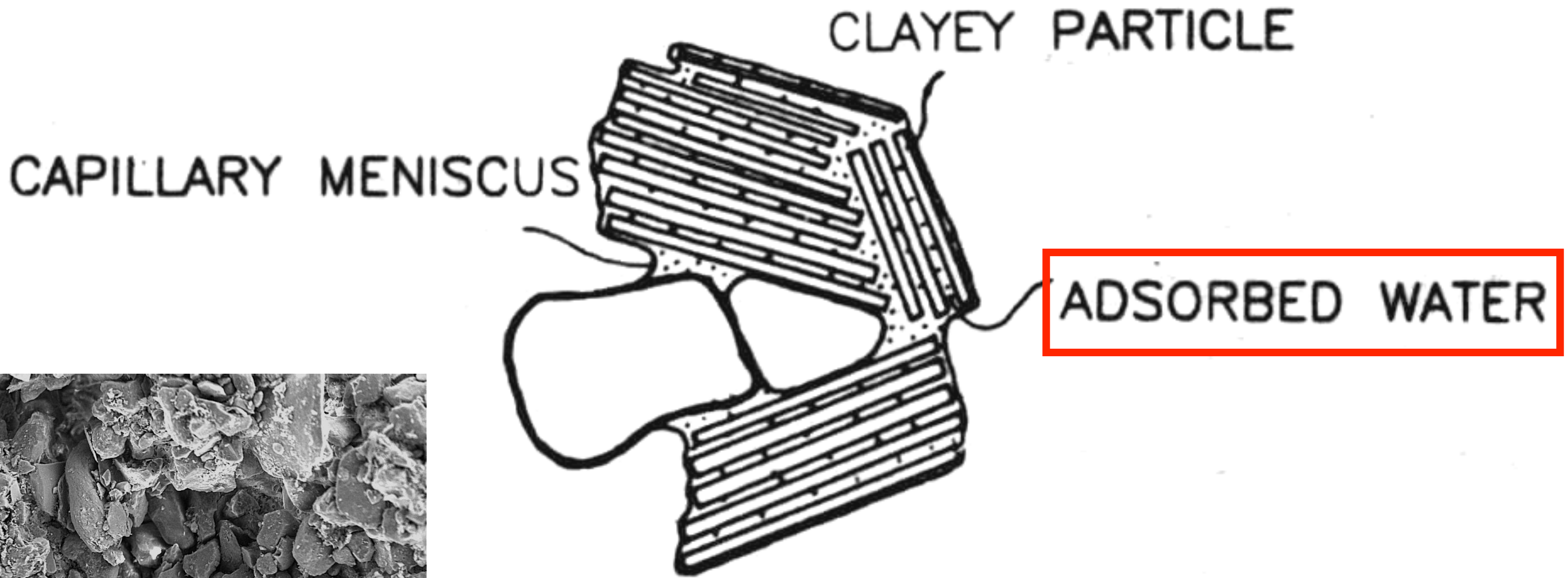
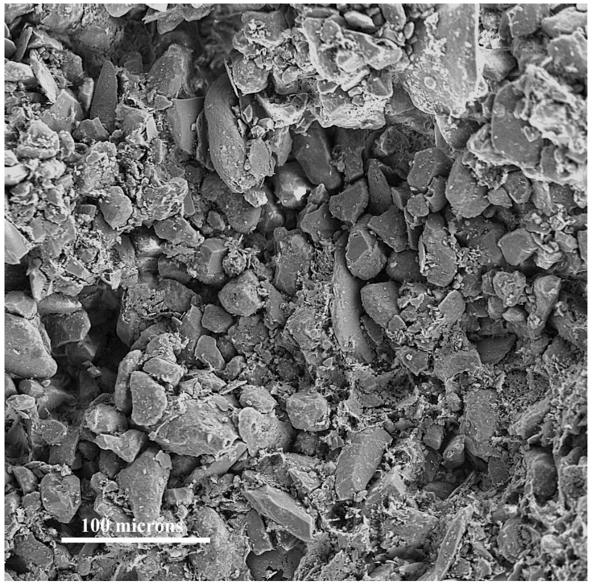


Unsaturated fine grained soils
Schematic view





Clay mineralogy
Clay water interaction

)

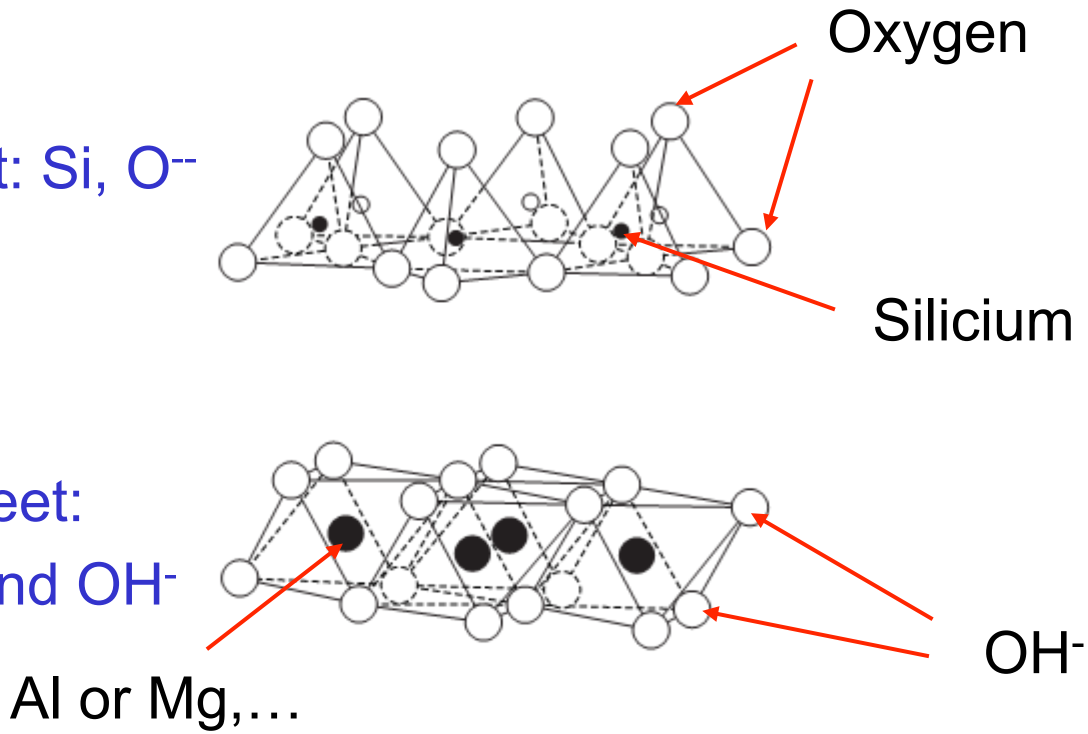
Clay minerals have a paramount role
in THM coupling
(sand or sandstone are not sensitive to water;
they only dilate when heated)

Clay mineralogy
Elementary sheets

Tetraedral sheet: Si, O^{--}

Octaedral sheet:

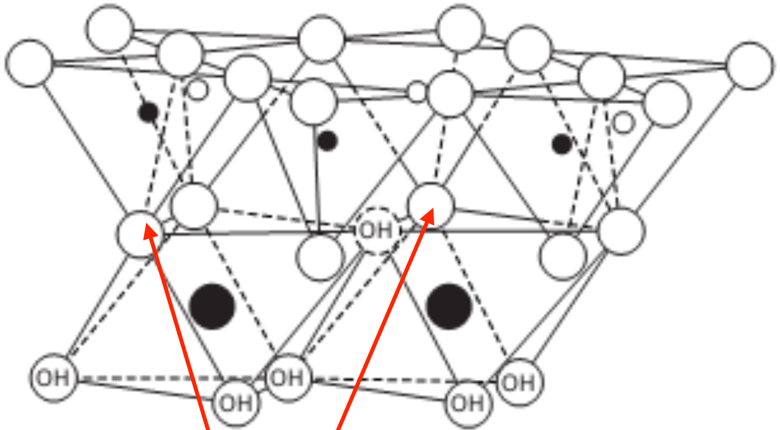
Mg or Al etc… and OH^{-}



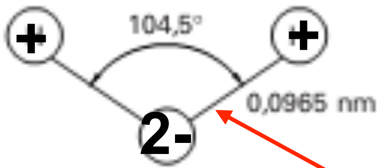
After Grim 1968, Mitchell 1976

Kaolinite: 1 tetra + 1 octa

7 Å= 0,7 nm



OH^- substituted by O^{--}



~1 Å

Water molecule

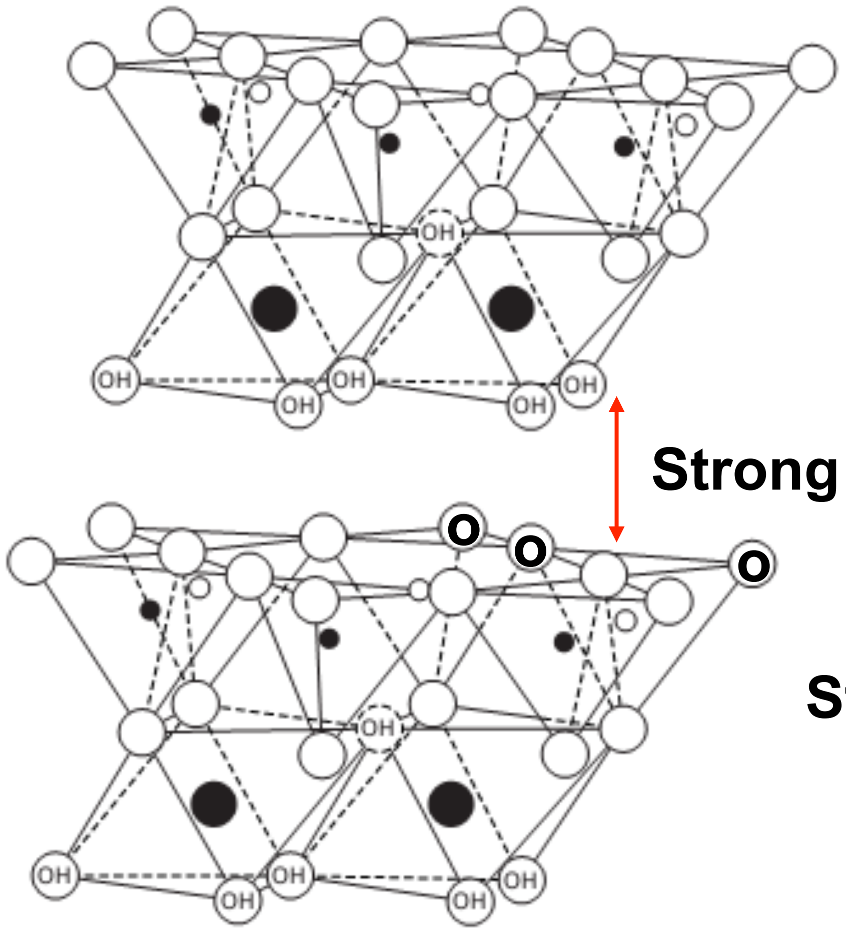
Negatively charged platelets

INTERACTION

Electrical dipole

Mitchell 1976

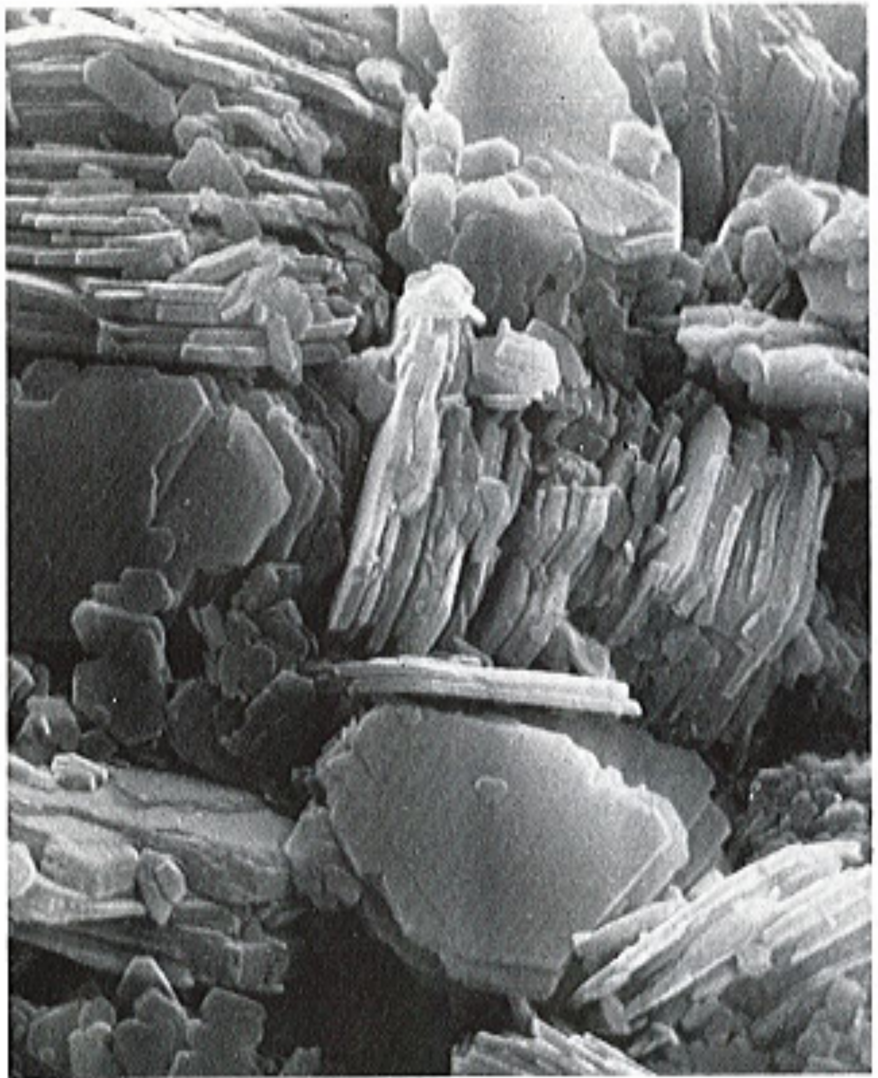
Kaolinite layer



Strong hydrogen bond
O-HO

Stable platelets

Kaolinite

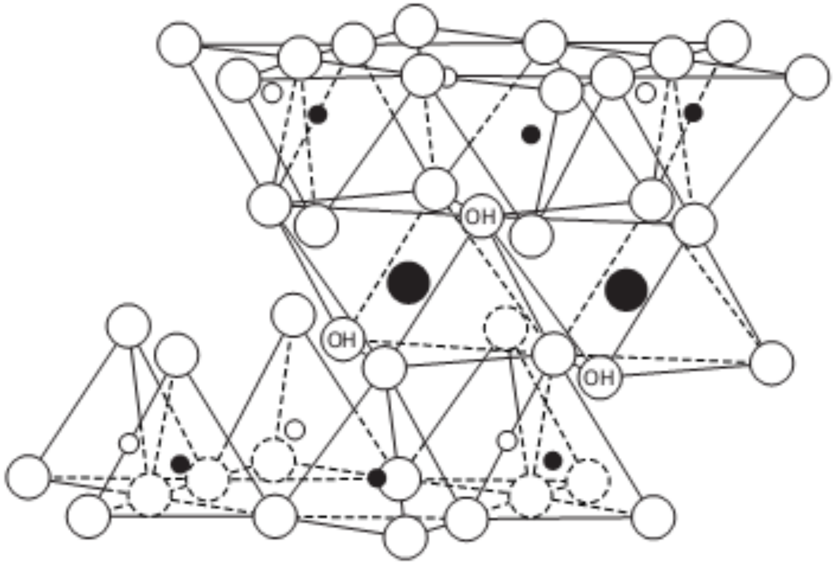


7,5 µm

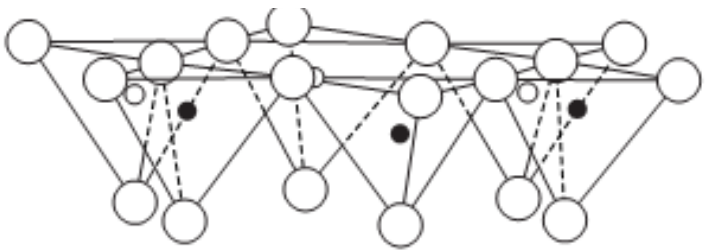
Tovey 1971 in Mitchell 1976

Montmorillonite: 1 octa + 2 tetra

9.6 Å= 0.96 nm



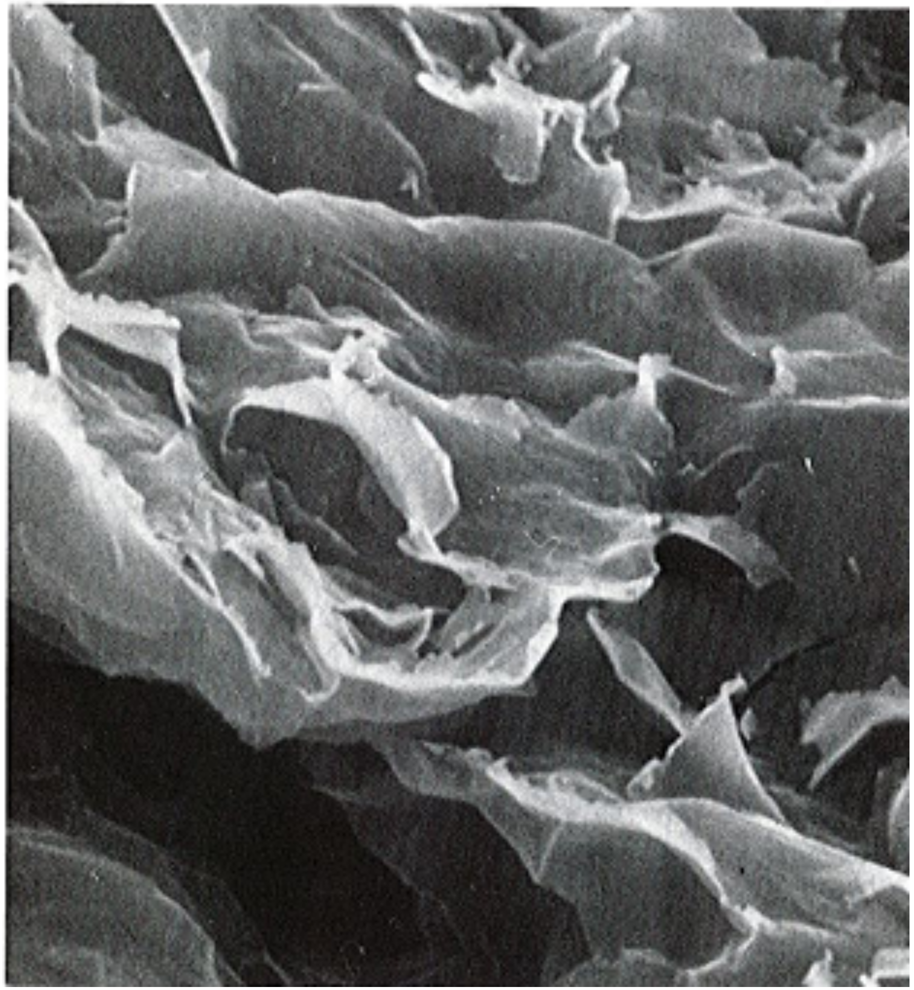
Exchangeable cations (Ca^{++}, Na^{+} to compensate electrical deficiency)



Water molecules stuck around cations: hydration

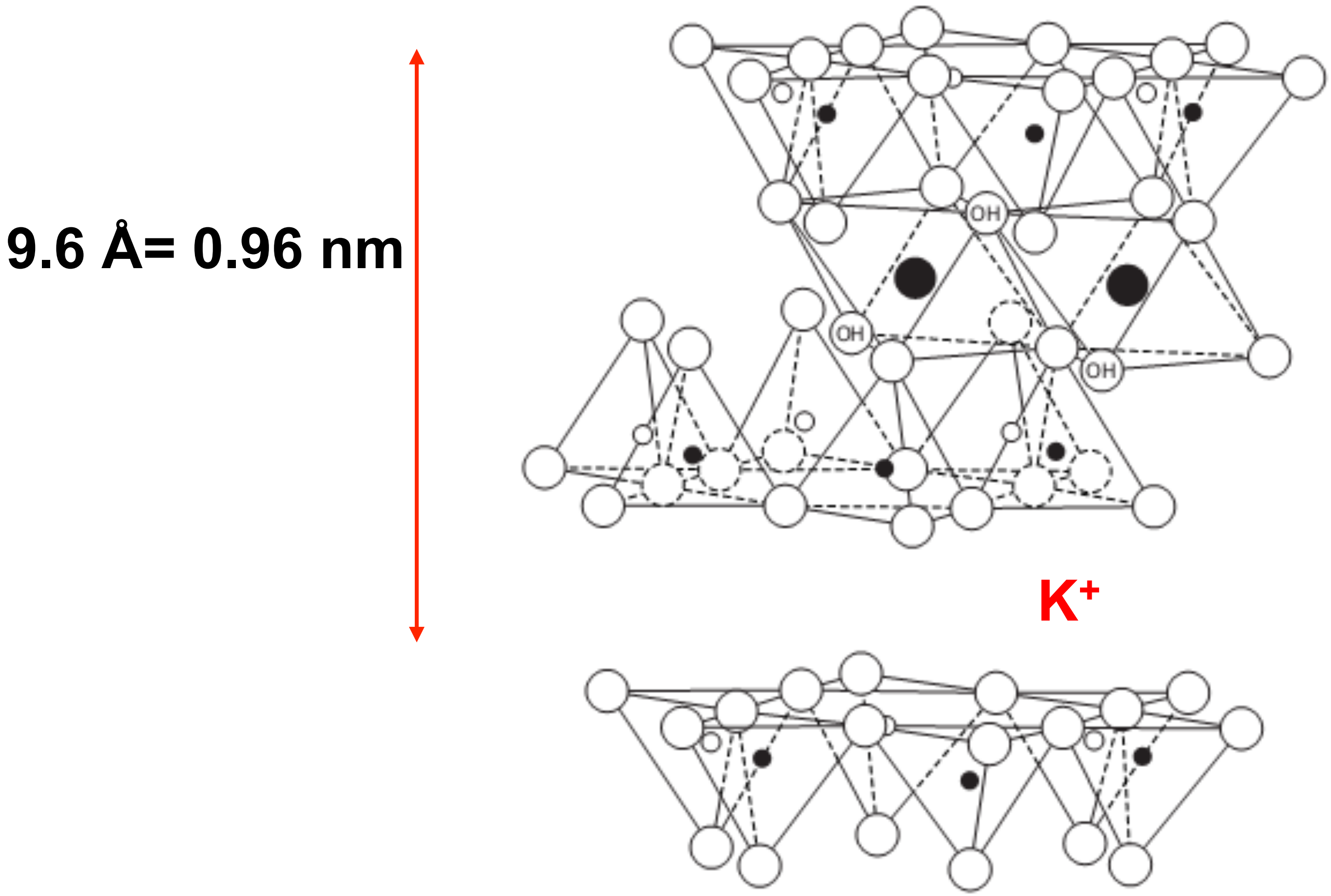
INSTABLE PLATELETS : INTERLAYER SWELLING

Montmorillonite suspension (gel)



7,5 µm

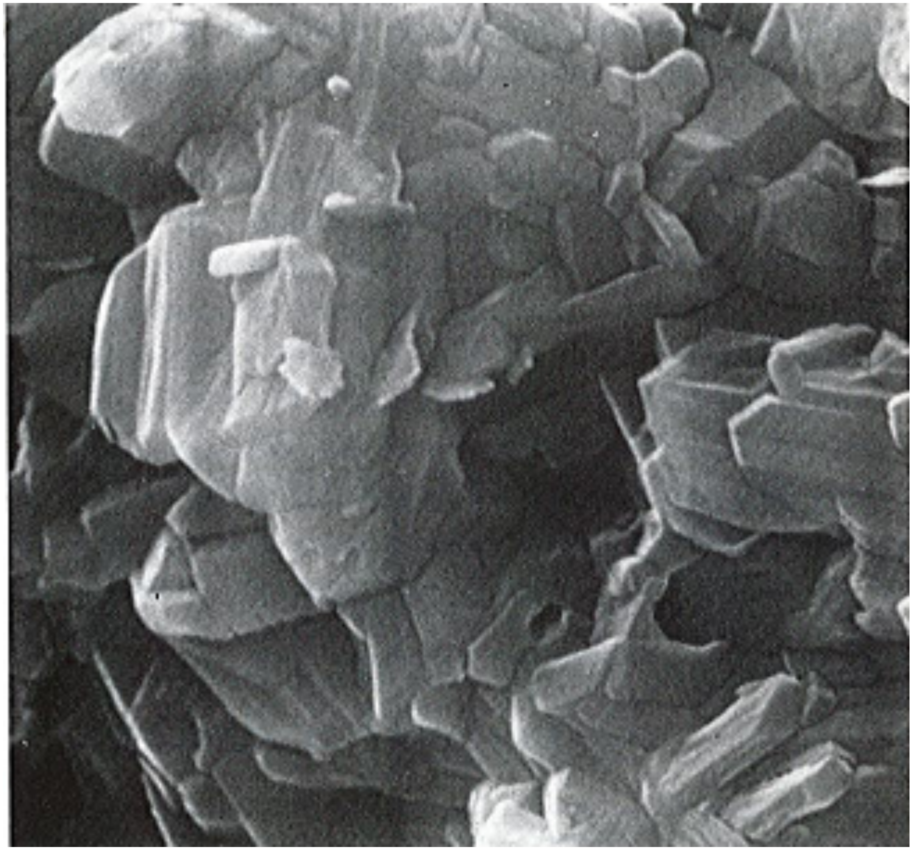
Illite: 1 octa + 2 tetra, K^+ bonding



Stable structure, same as mica (muscovite)

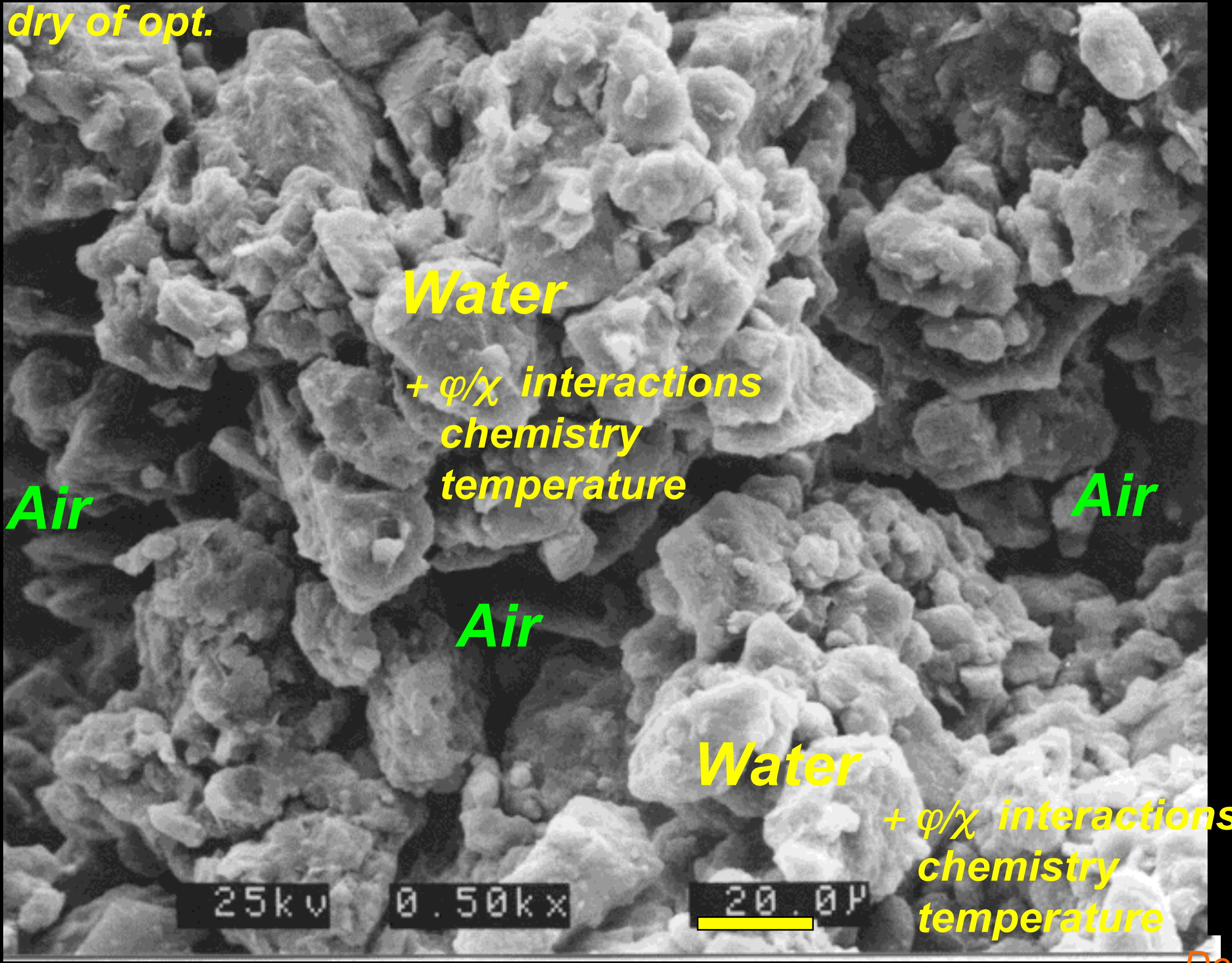
Tovey 1971 in Mitchell 1976

Illite



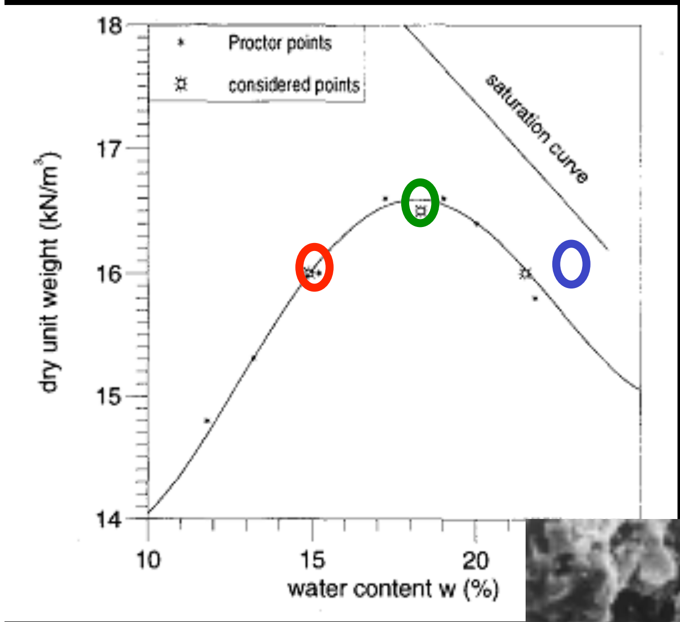
7,5 µm

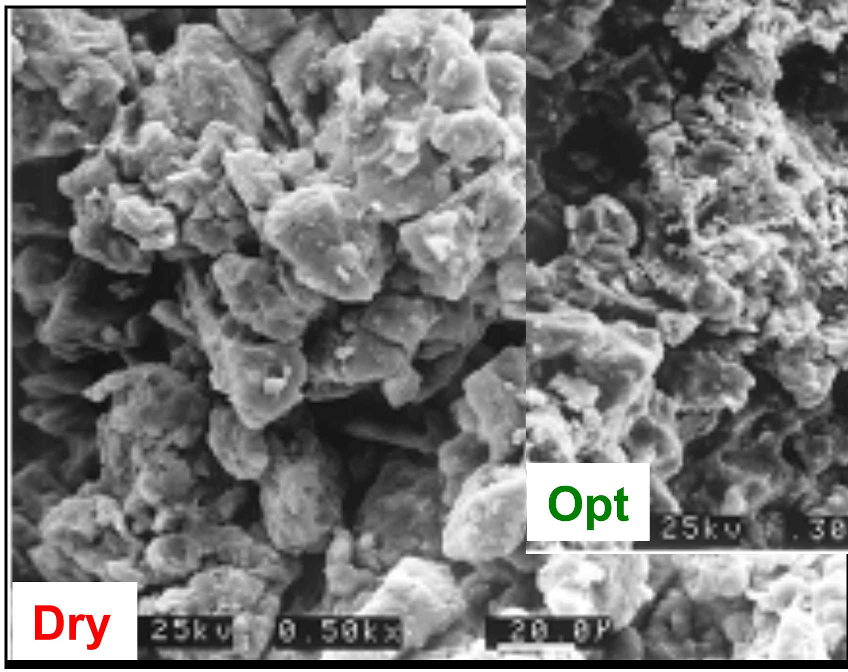
Compacted silt

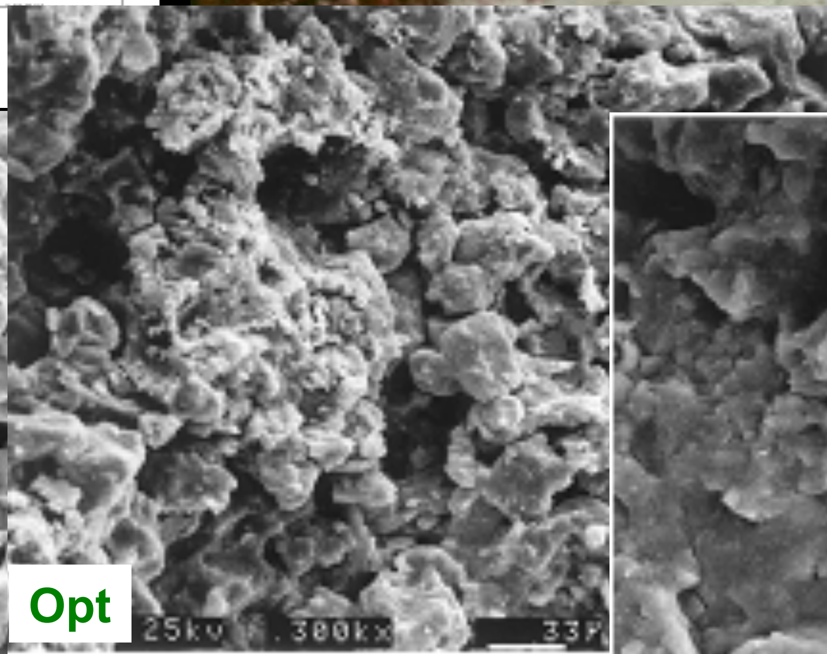


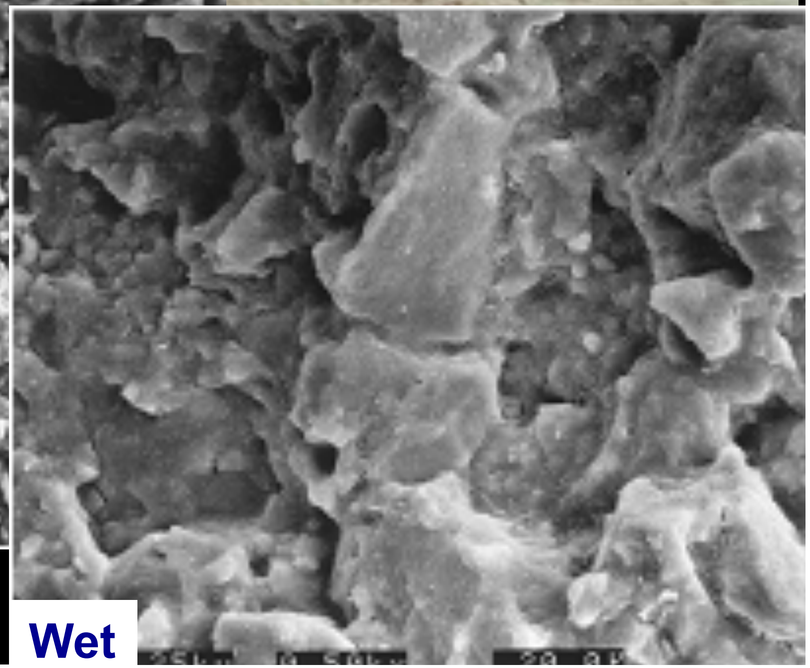
Delage et al. 96

Compacted silt

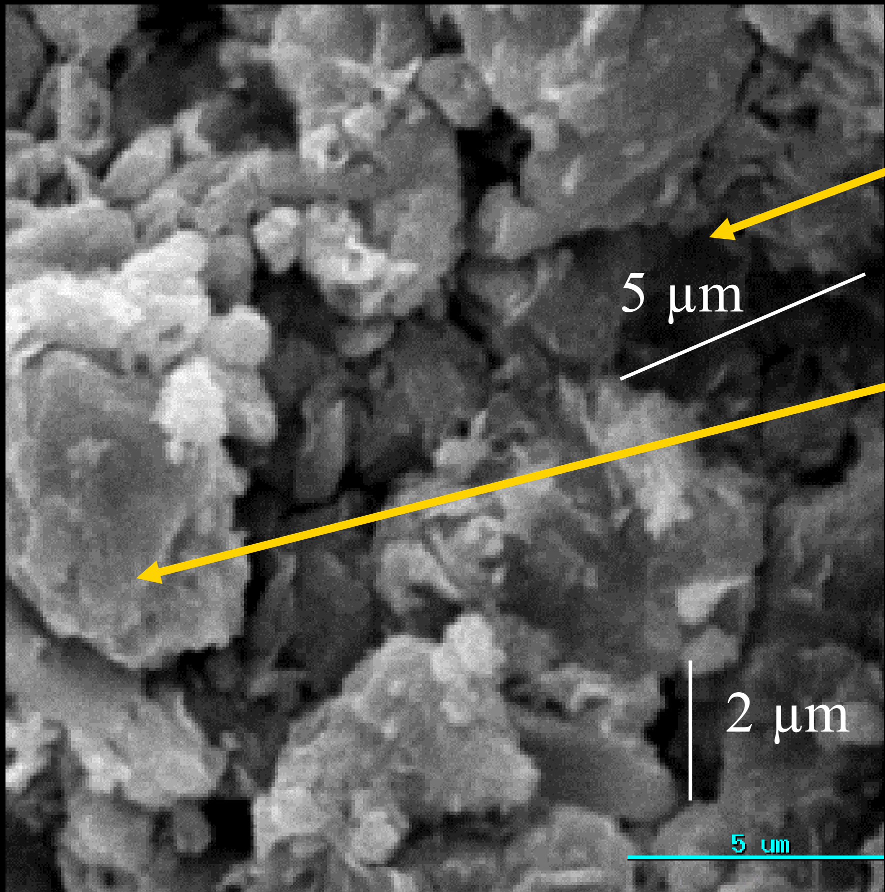






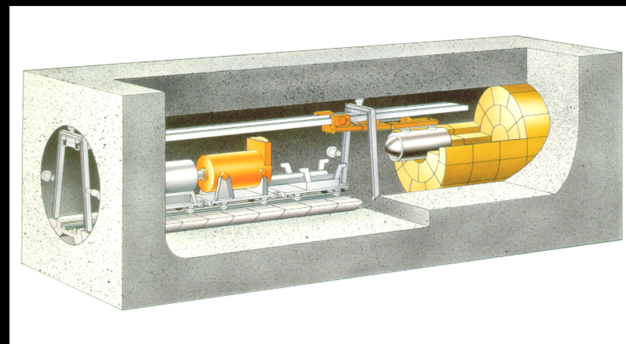


HEAVILY COMPACTED SMECTITE



inter-aggregate pore

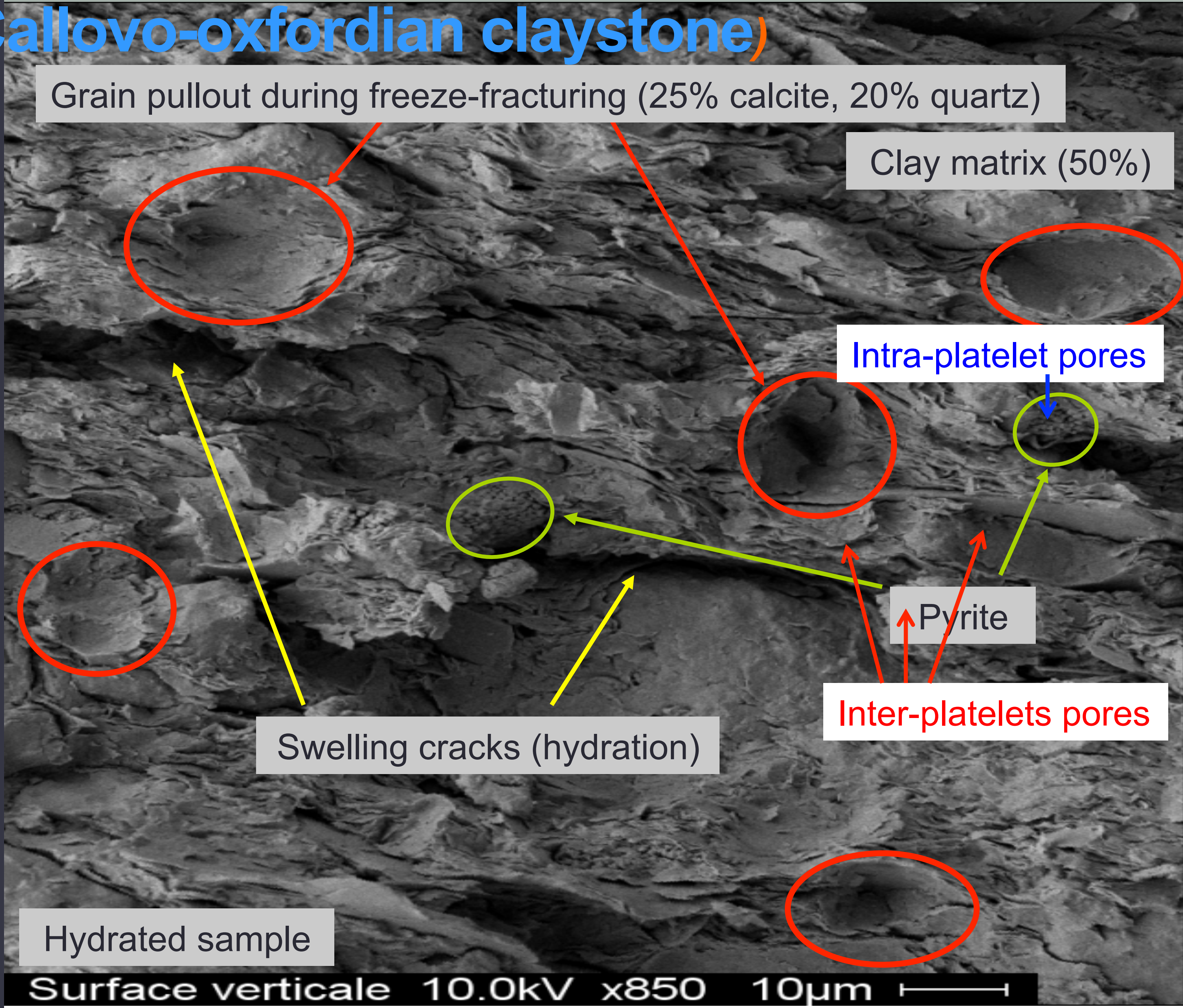
aggregate (ϕ 2-3 mm)



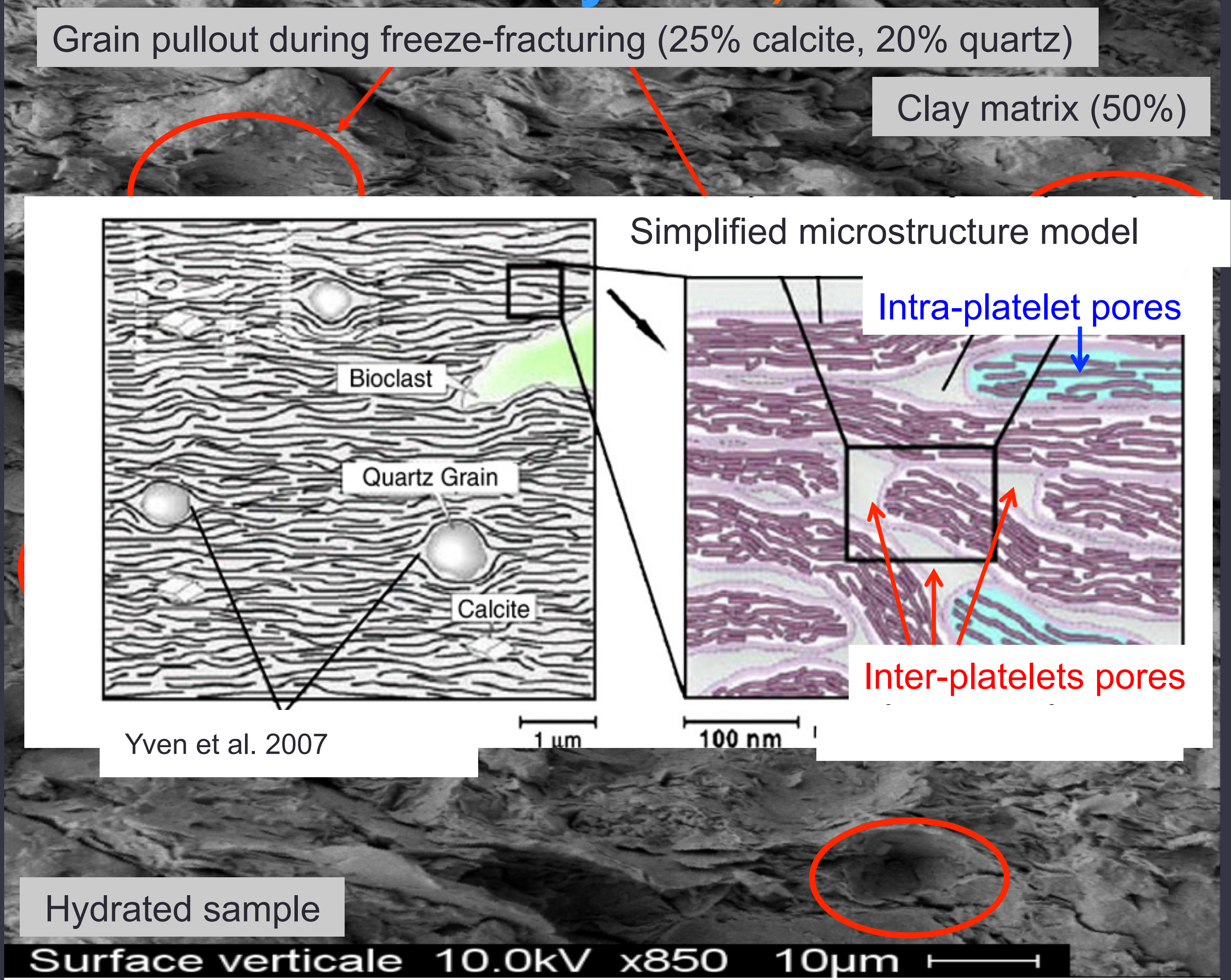
Compacted Kunigel clay (Japan), r = 2 Mg/m^3, w = 8%

Cui et al. 2002

Callovo-oxfordian claystone)

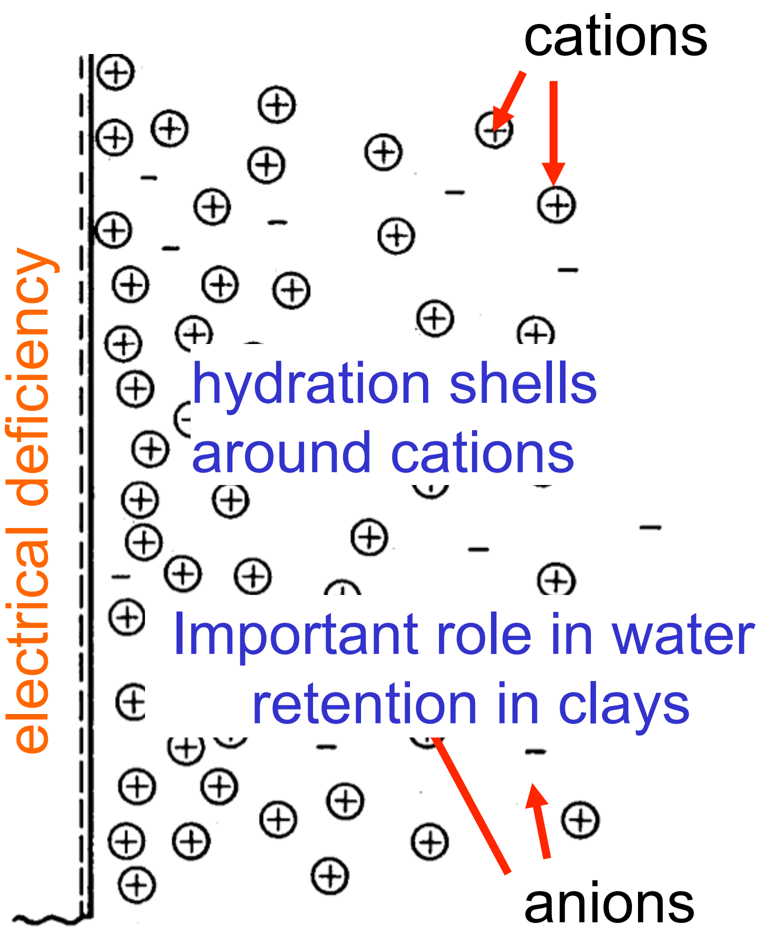


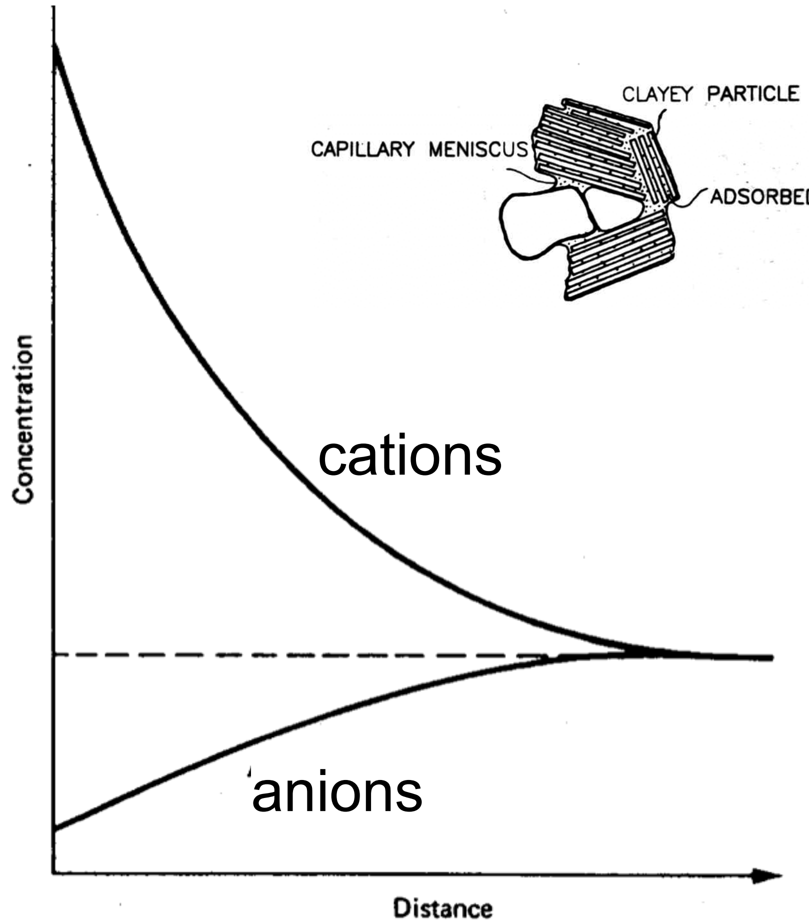
Callovo-oxfordian claystone)



Clay water interaction : double layer theory

from Mitchell (1993)

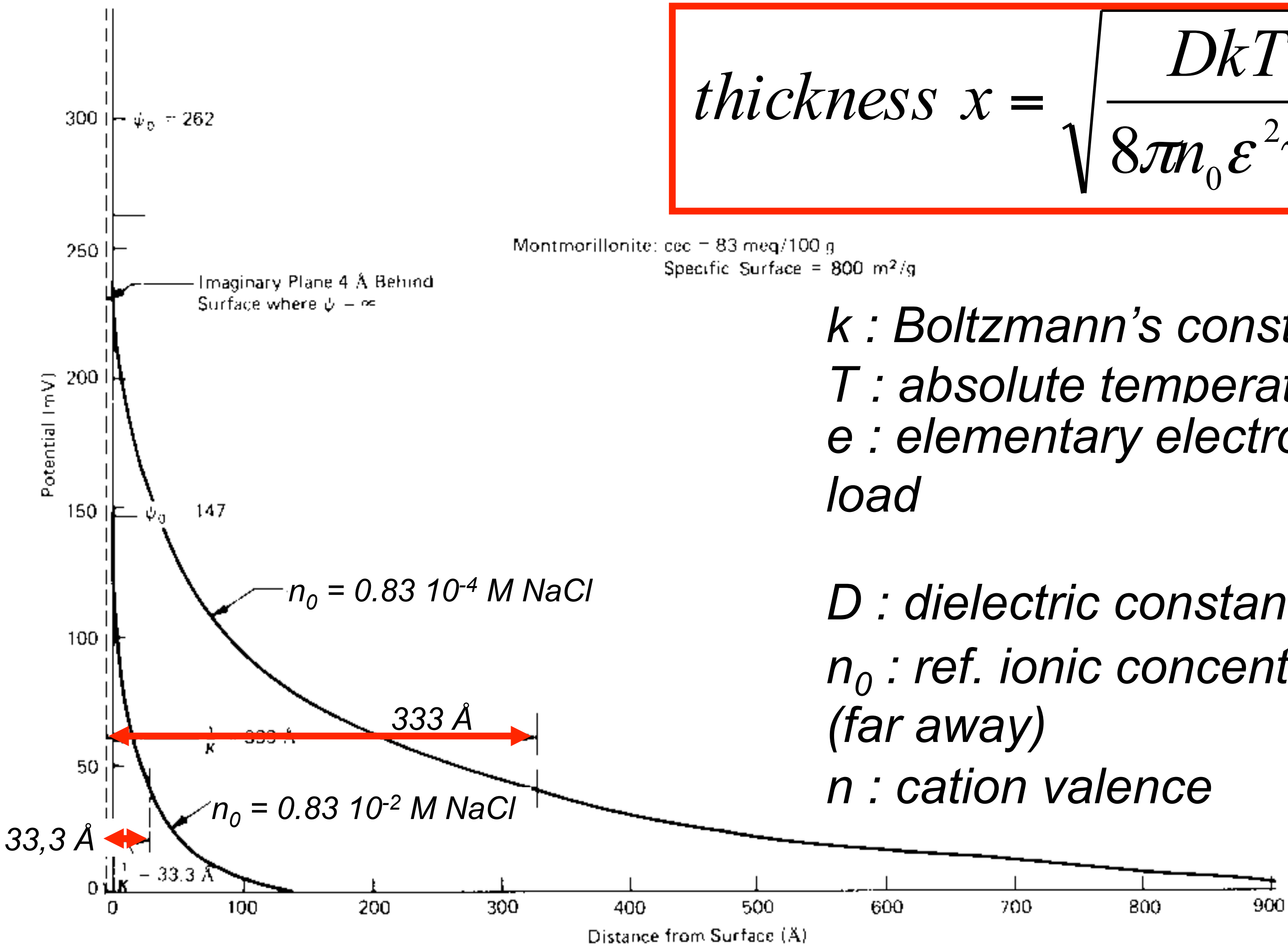




Double layer theory

Mitchell (1993)

$$thickness\ x = \sqrt{\frac{DkT}{8\pi n_0 \varepsilon^2 \nu^2}}$$



k : Boltzmann's constant

T : absolute temperature

e : elementary electronic load

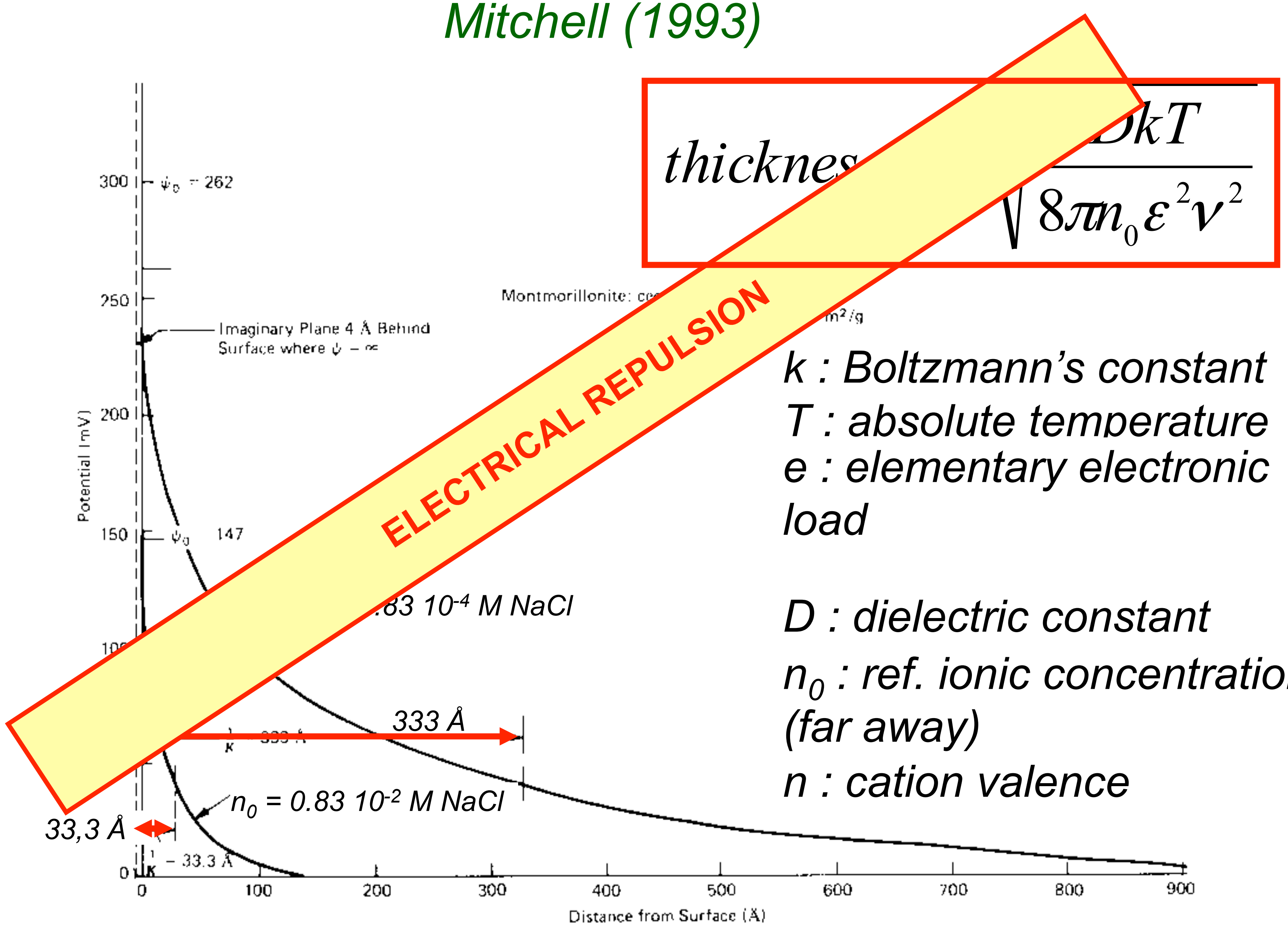
D : dielectric constant

n_0 : ref. ionic concentration (far away)

n : cation valence

Double layer theory

Mitchell (1993)



k : Boltzmann's constant

T : absolute temperature

e : elementary electronic load

D : dielectric constant

n_0 : ref. ionic concentration (far away)

n : cation valence

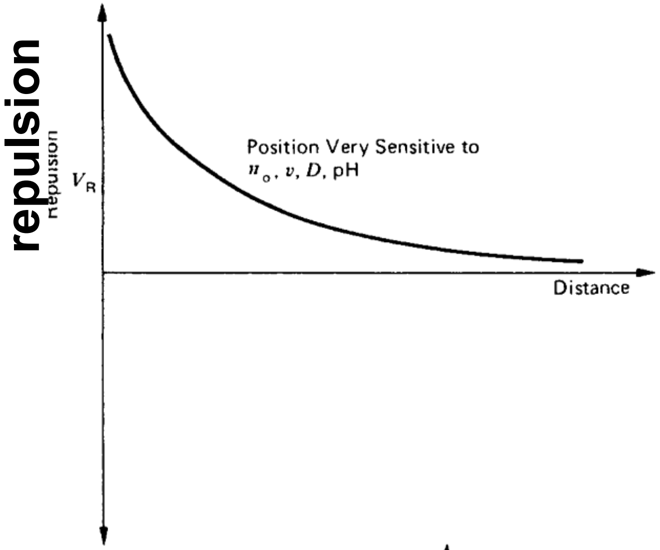
Interparticle interaction

Mitchell (1993)

D : dielectric constant

n_0 : ref. ionic concentration (far away)

n : cation valence



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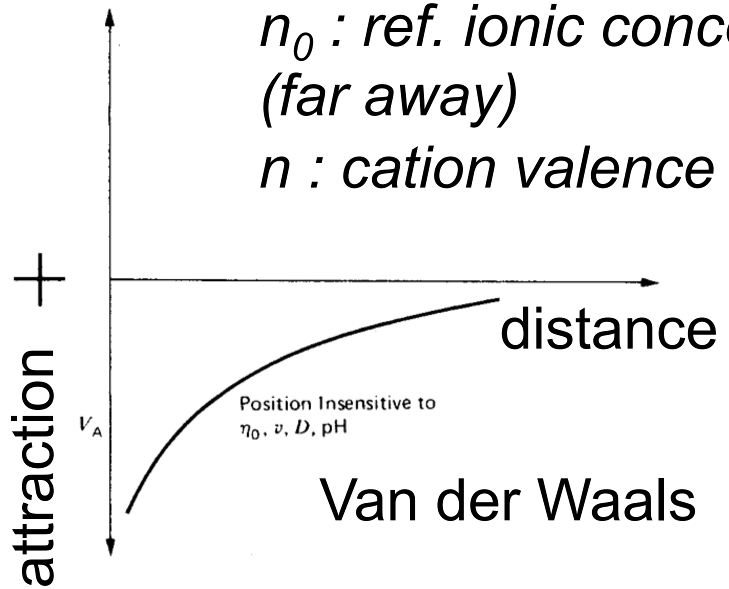

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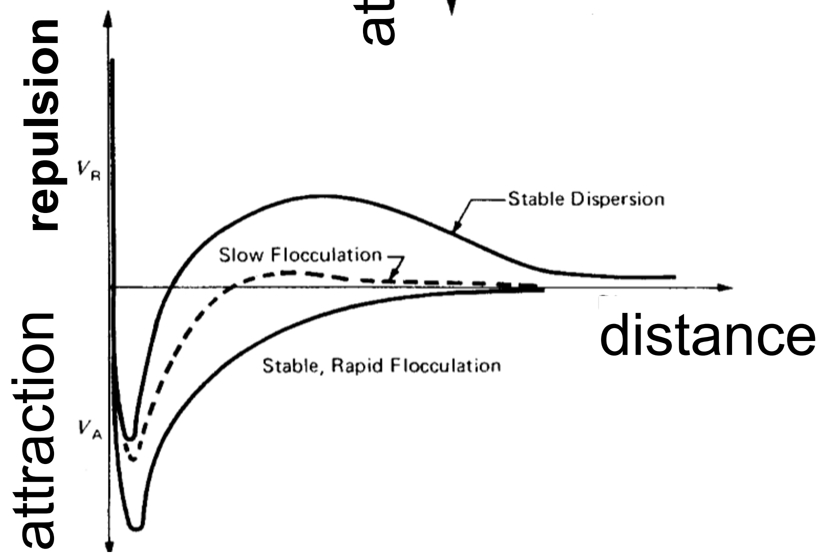


HYDRATION OF SMECTITES

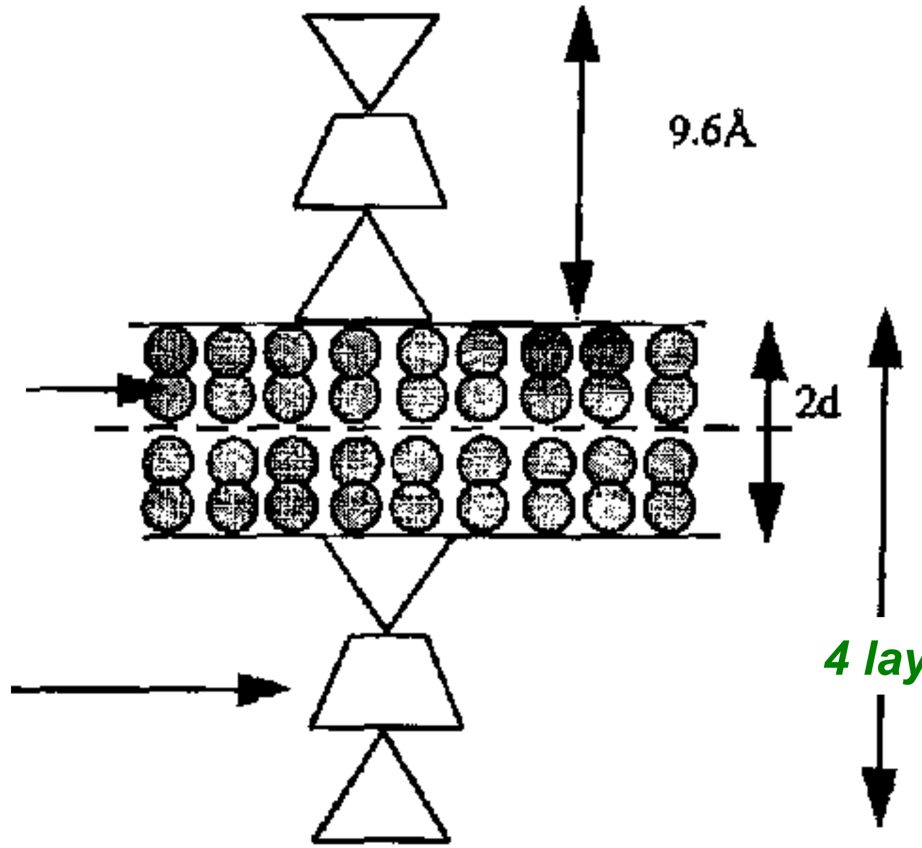
Saturated intra-aggregates swelling mechanisms

Saiyouri, Hicher & Tessier (2000), using Pons et al. (1981)

- X ray scattering at low angles
- Probabilistic analysis

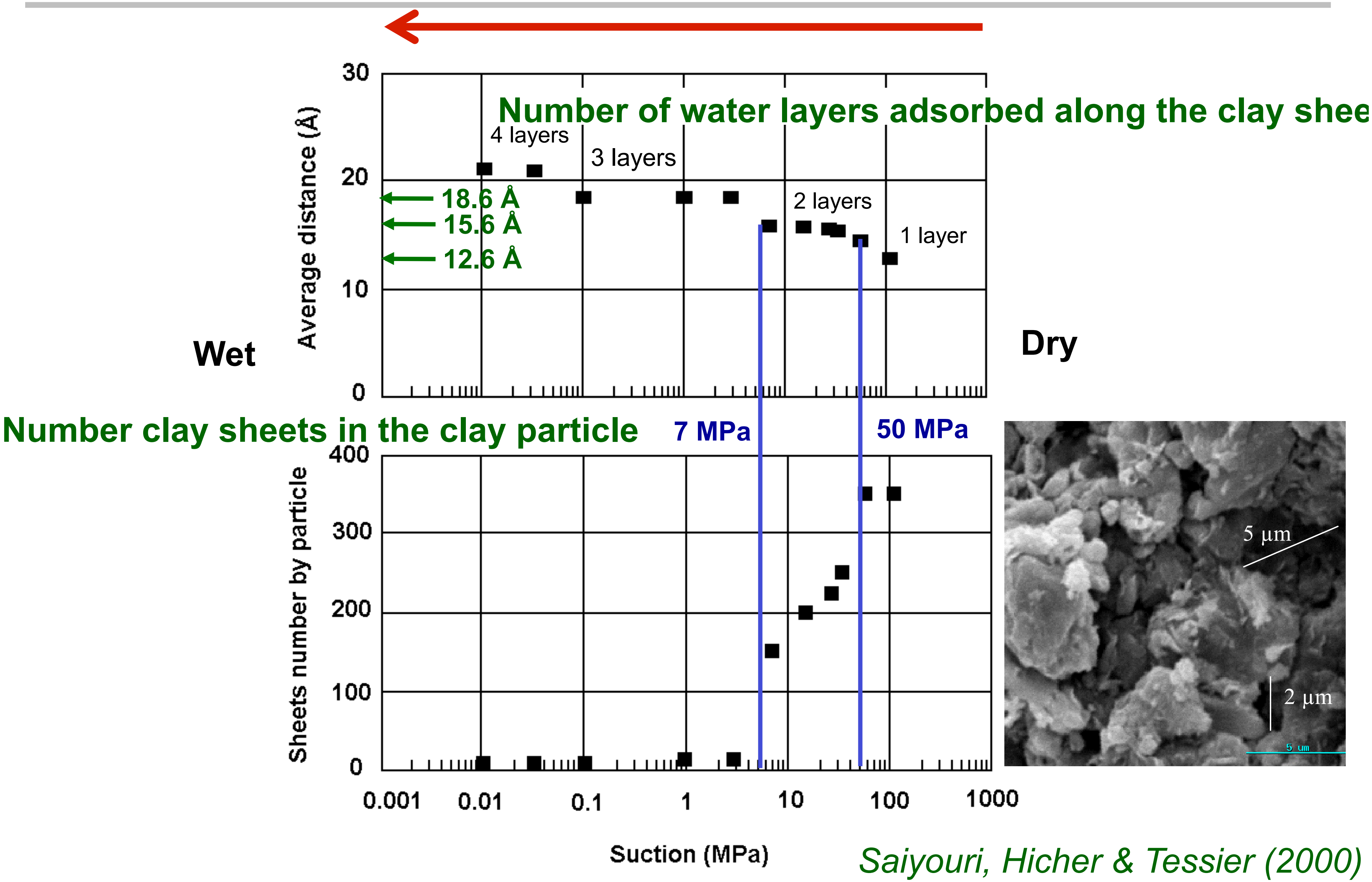
→ *- Interlayer distances inside a particle*
- Number of clay layer in a particle

Saturated intra-aggregates swelling mechanisms



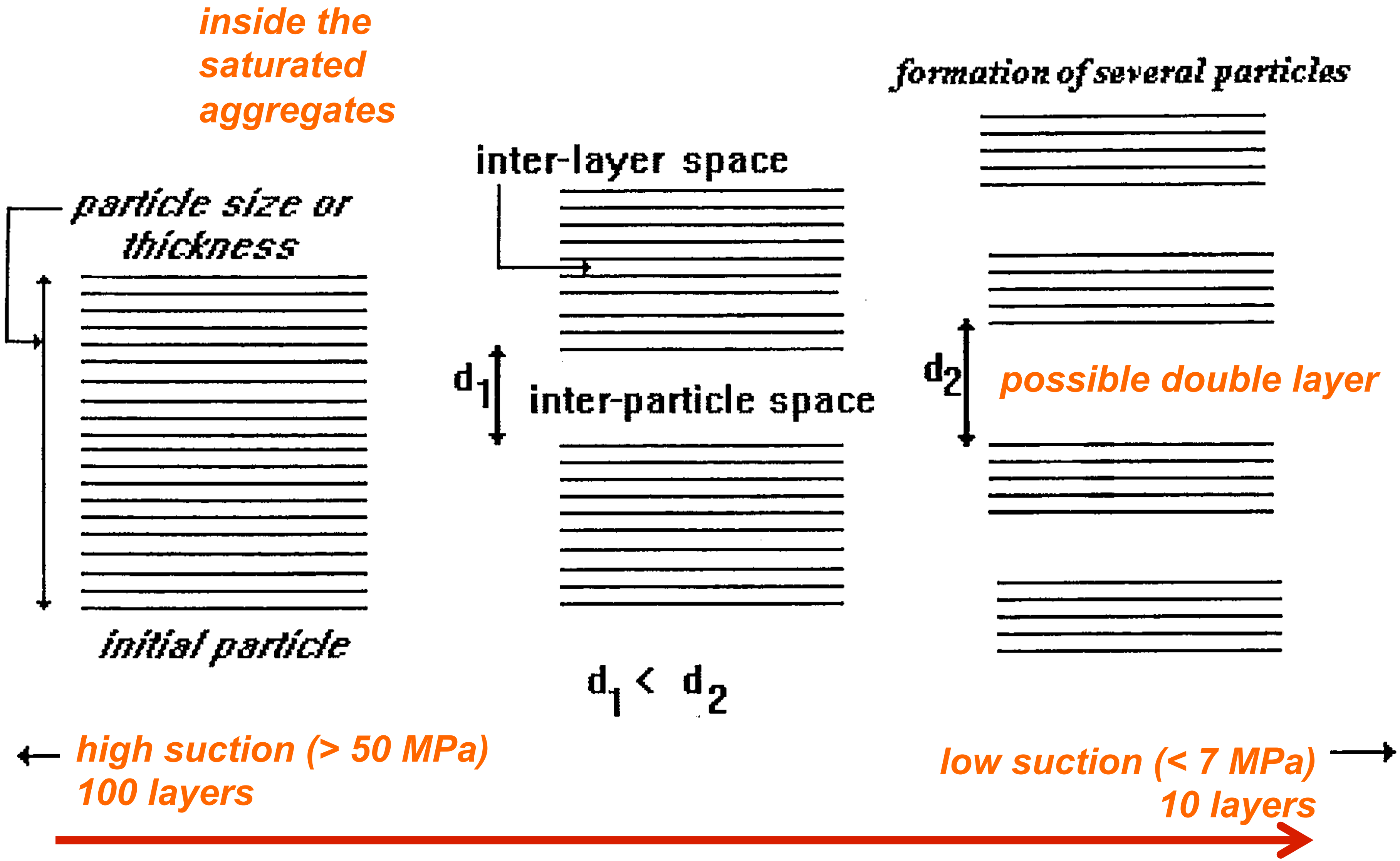
Sayiouri, Hicher & Tessier (2000)

Hydration from a dry state, FoCa



Saiyouri, Hicher & Tessier (2000)

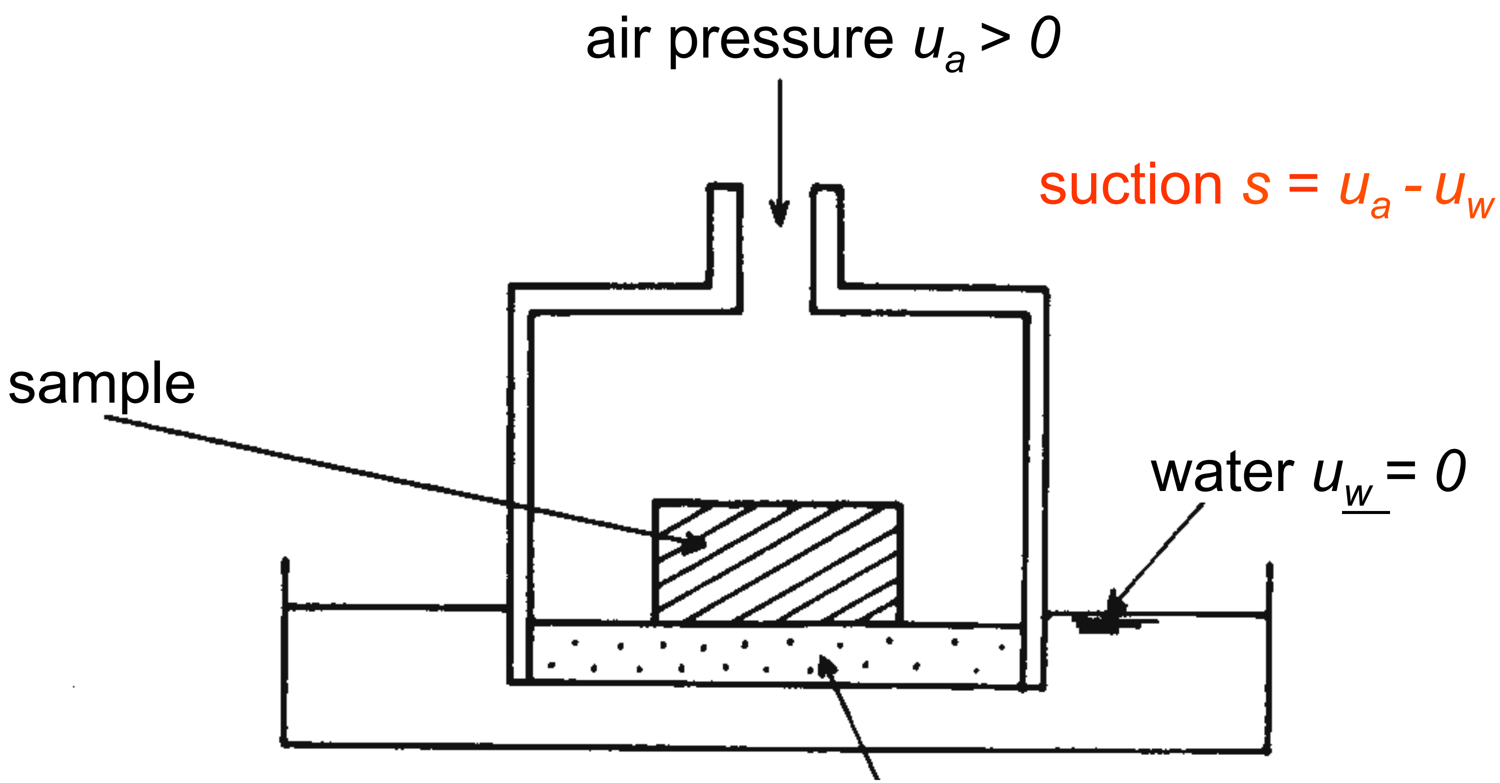
Hydration from a dry state, FoCa



Sayiouri, Hicher & Tessier (2000)

WATER RETENTION PROPERTIES

Air overpressure technique of controlling suction *(axis translation)*

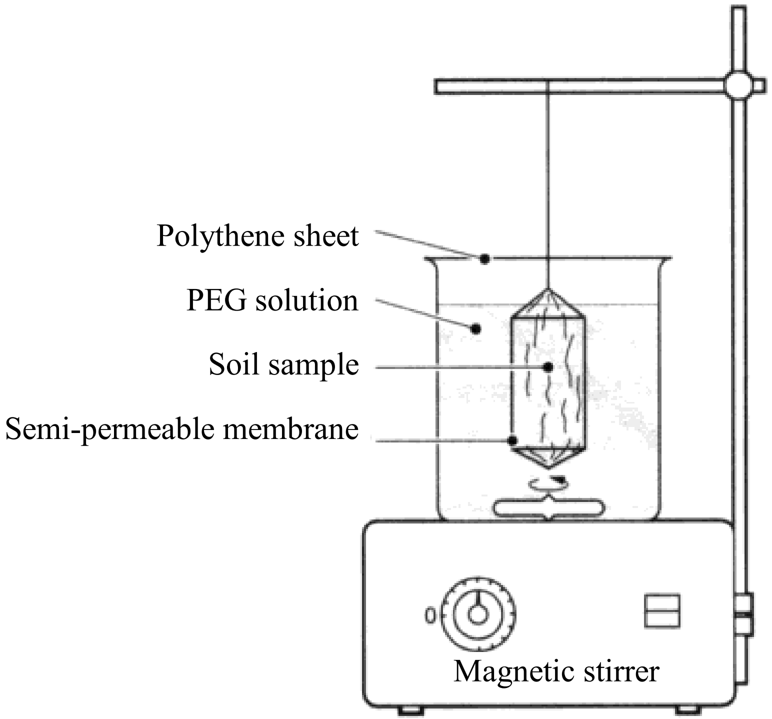


Ceramic porous stone (thin porosity)
High Air Entry Value (HAEV) : *remains saturated*

Other techniques (see paper)

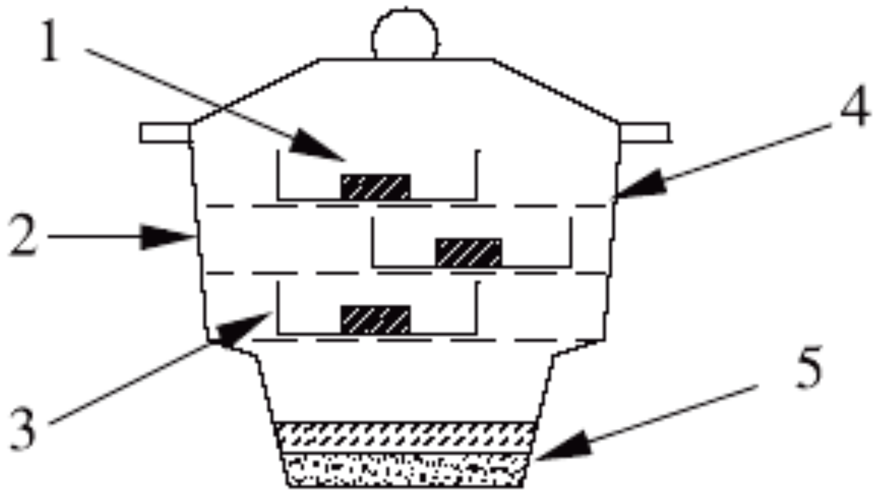
Osmotic method

(semi-permeable membrane + large moleculesPEG salt)



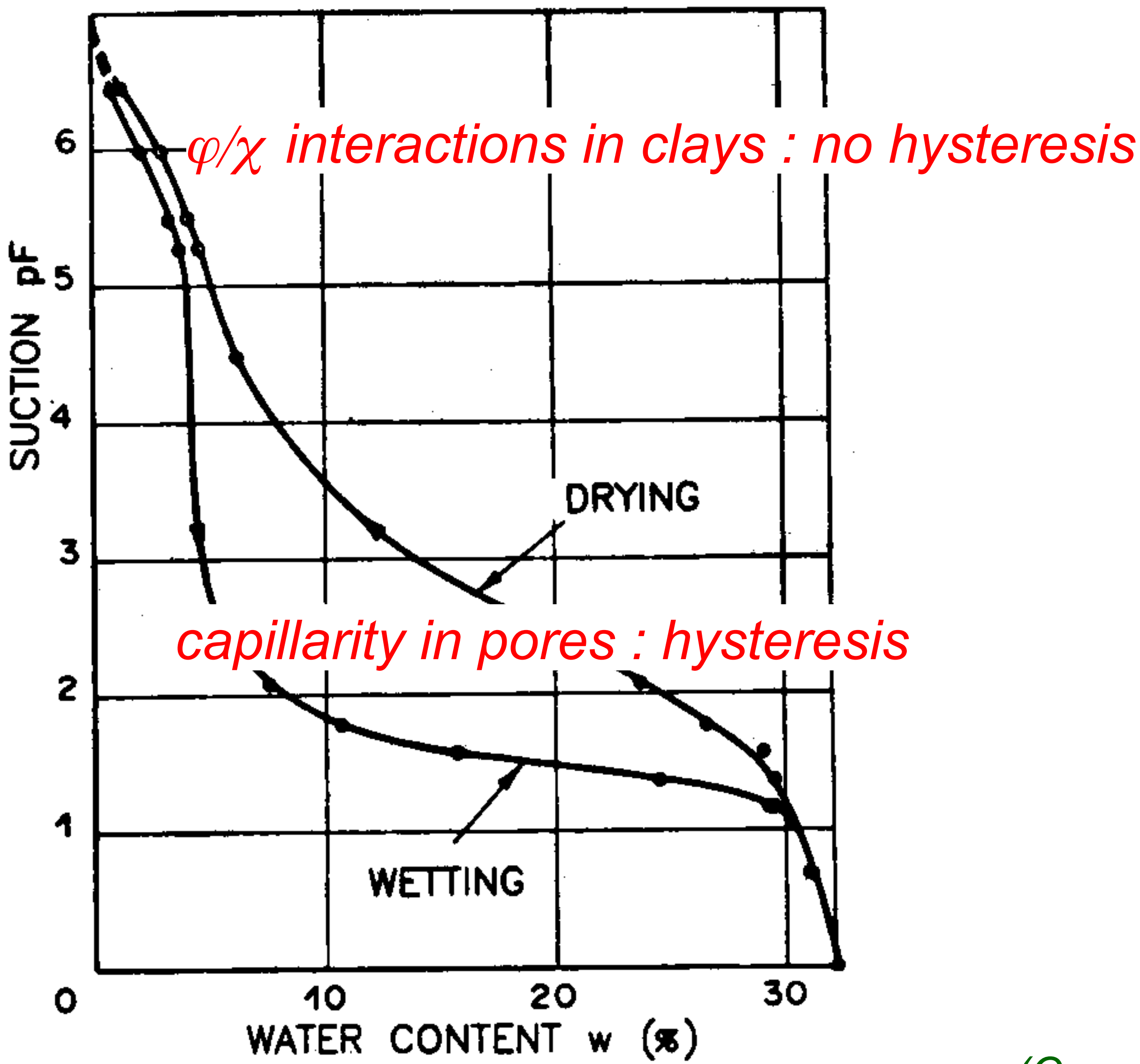
Controlled relative humidity

(saturated salt solutions)



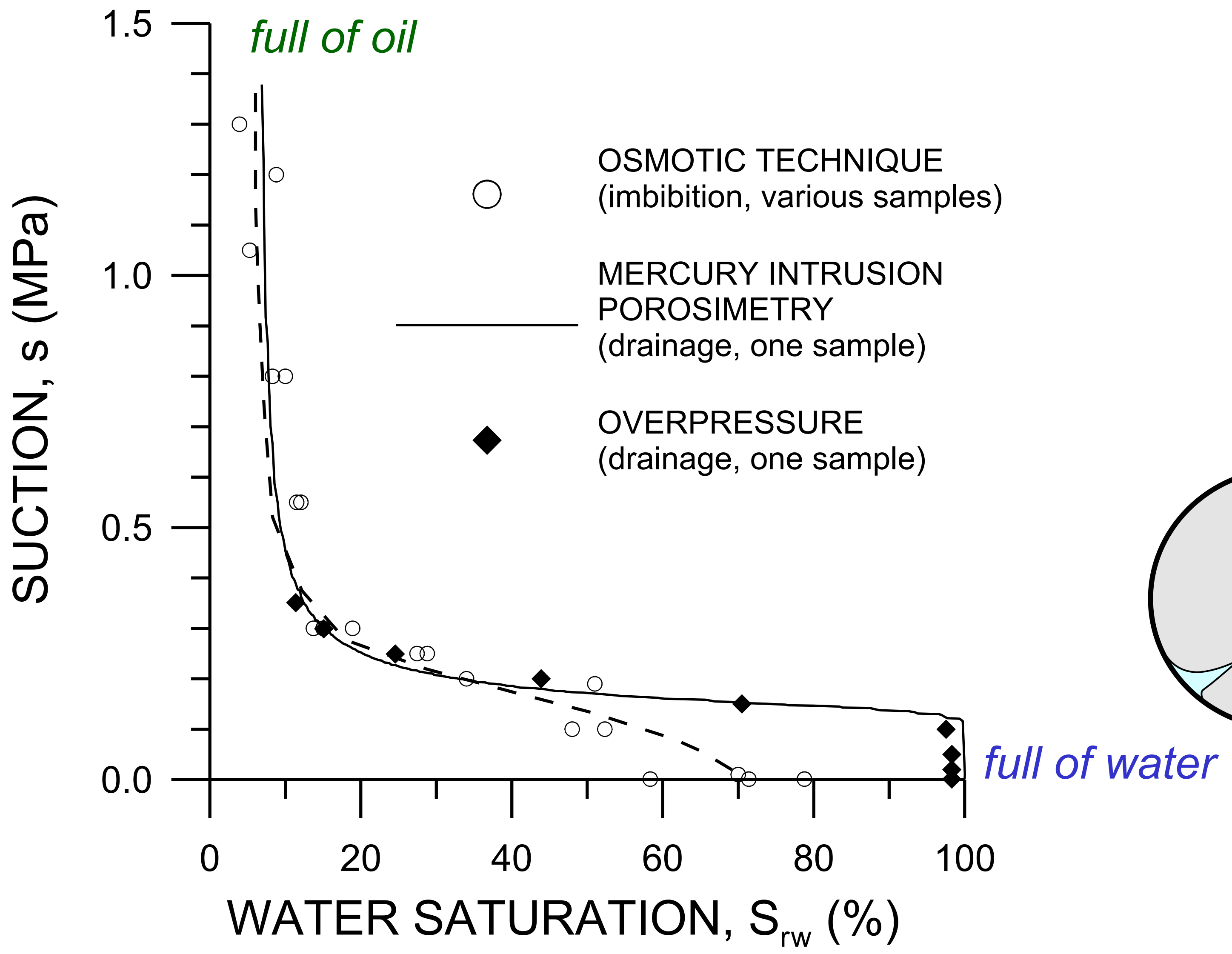
$$u_a - u_w = \frac{RT}{Mg} \log RH$$

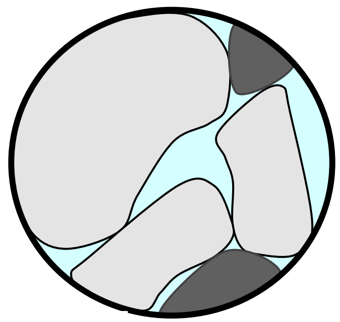
Water retention curve, clayey sand



(Croney et al. 1952)

Oil-water retention curve, lixhe chalk

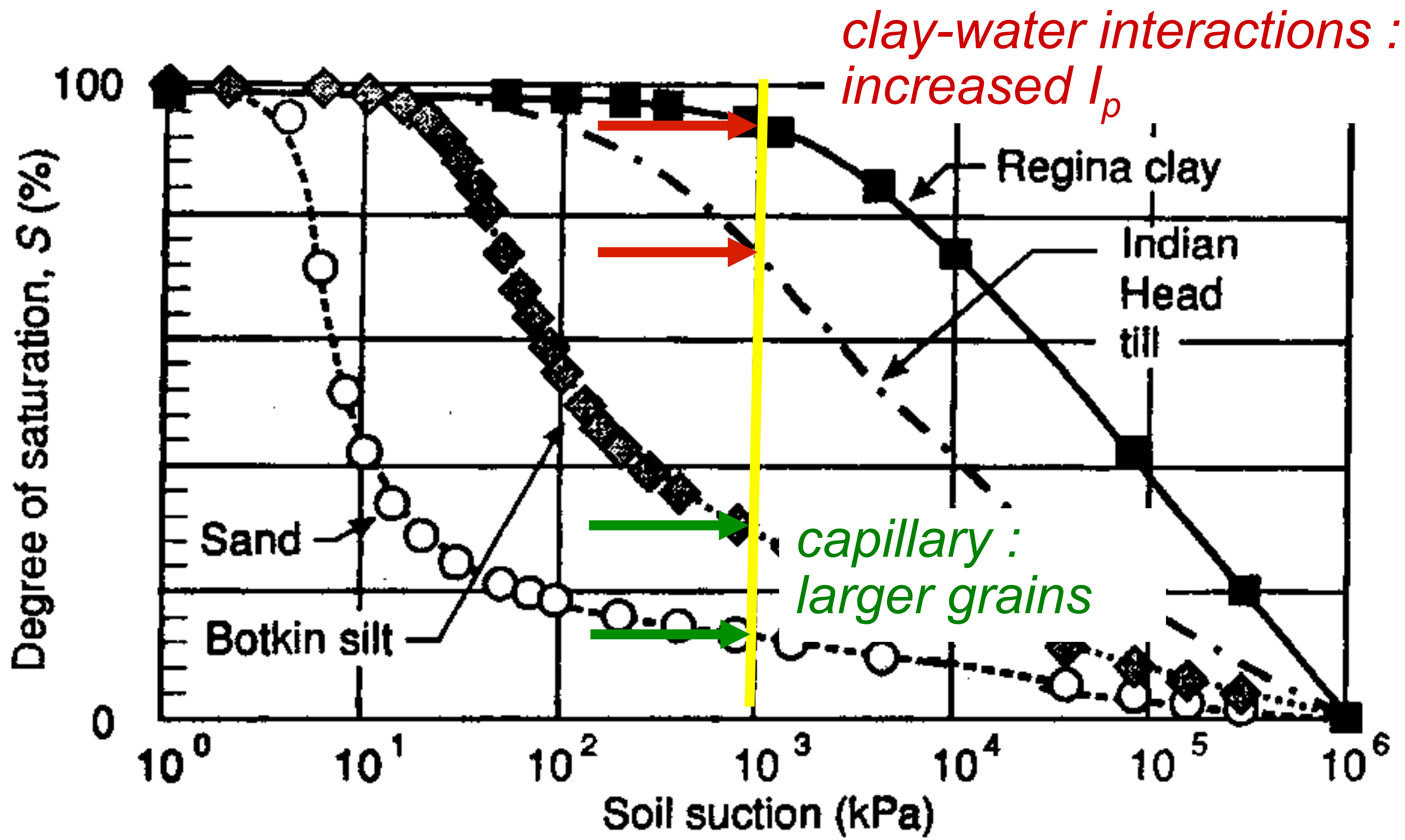




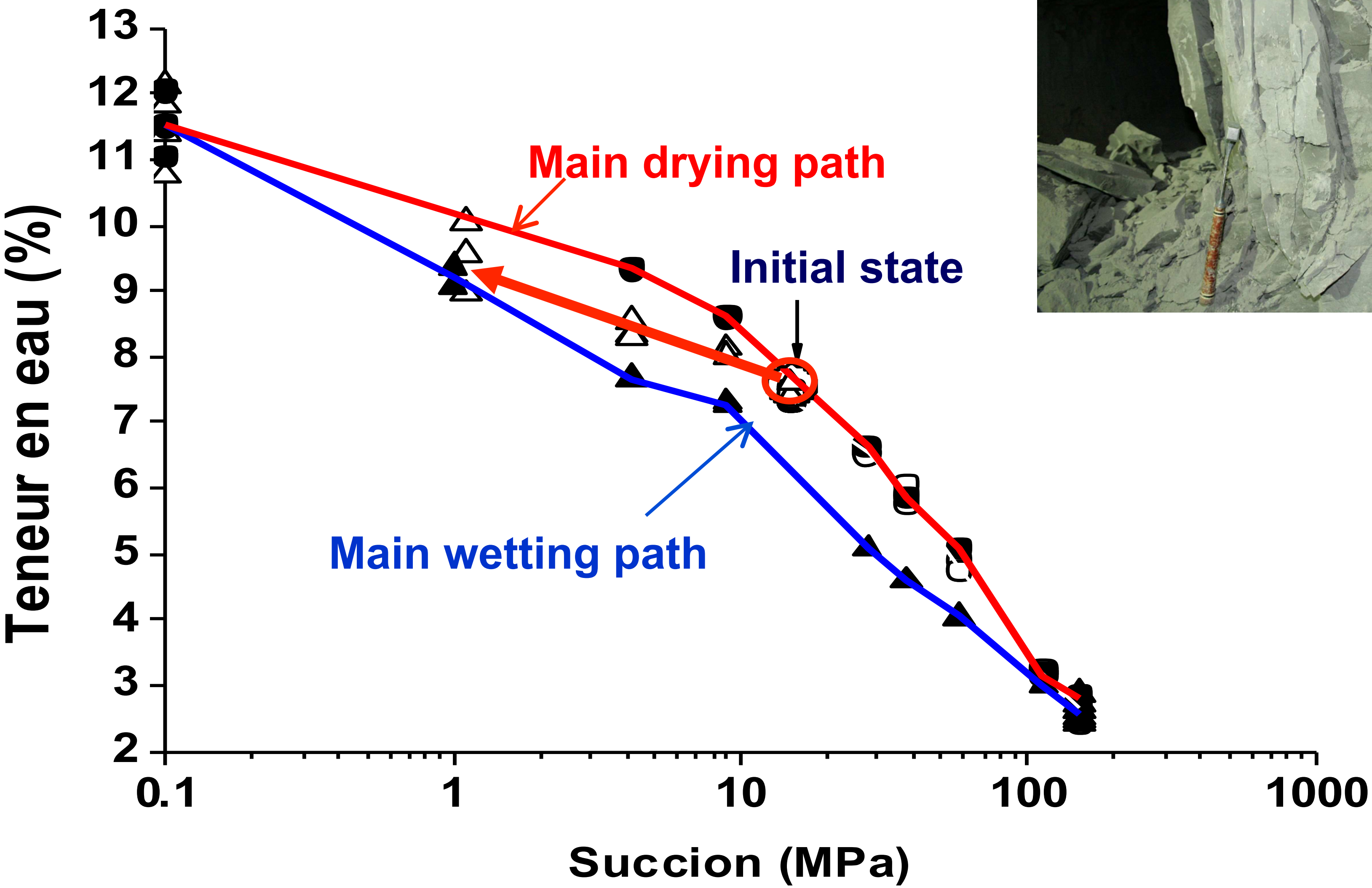
Priol et al. 2005

TYPICAL WATER RETENTION CURVES

(Barbour 98, Vanapalli, et al. 99)

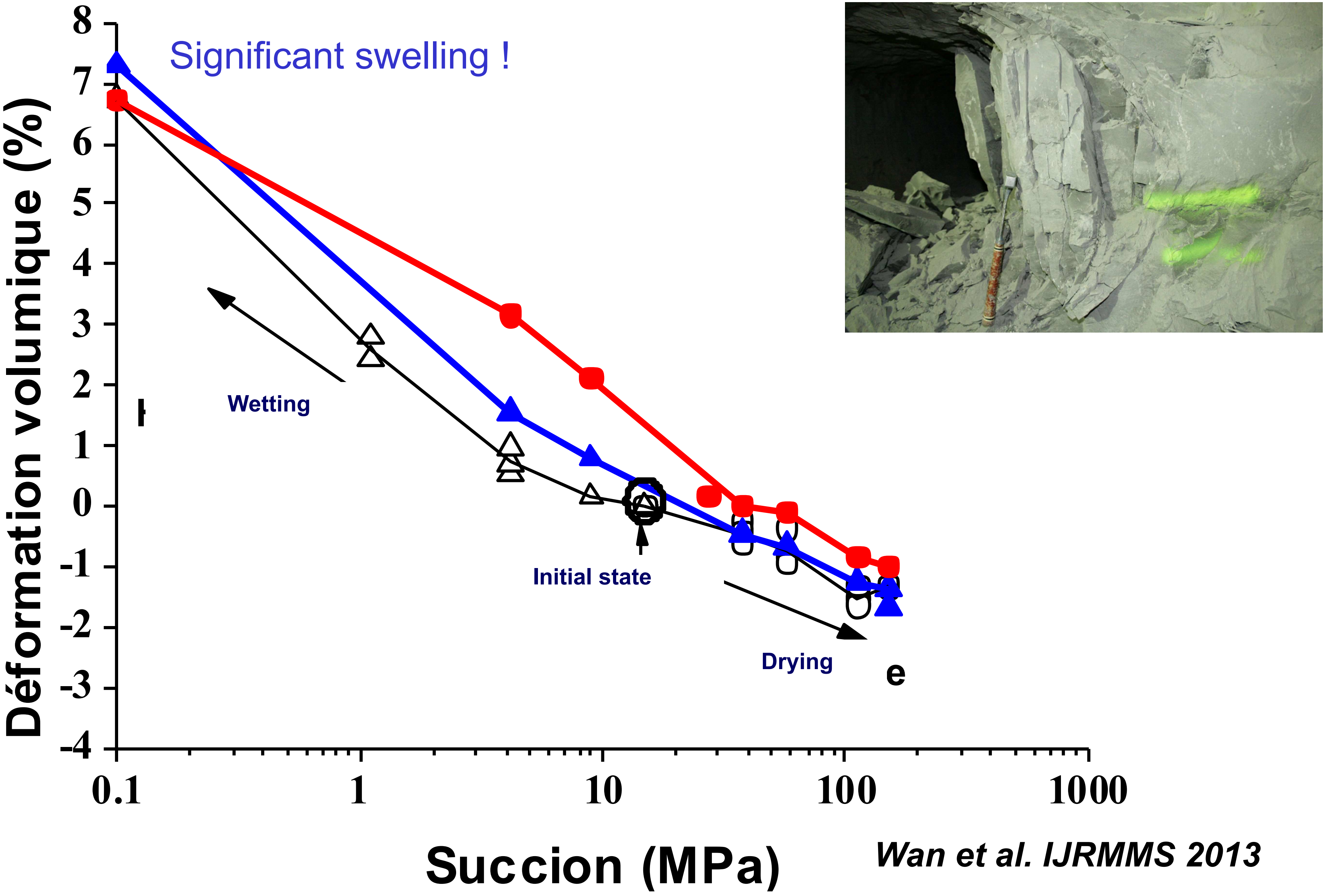


Water retention properties, COx



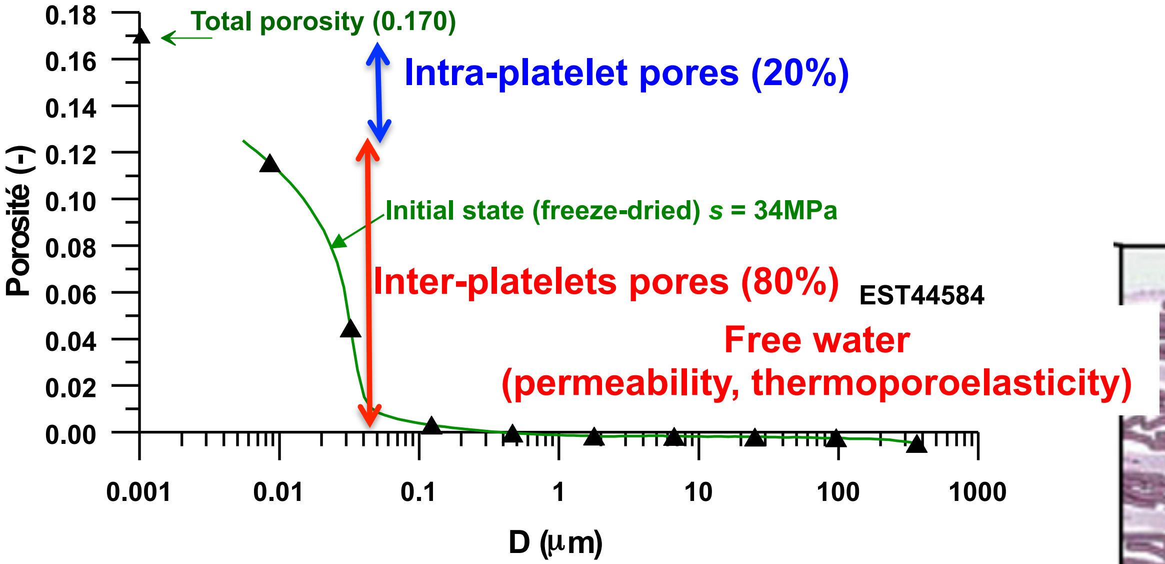
Wan et al. IJRMMS 2013

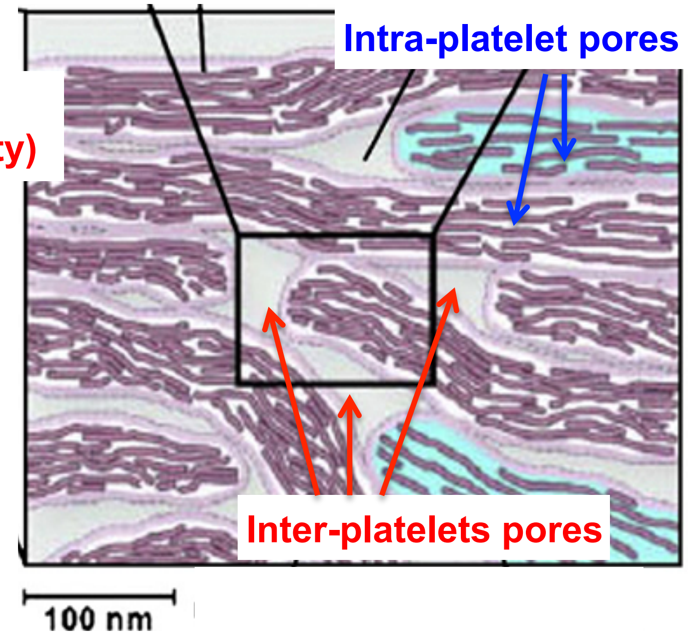
Water retention properties, COx

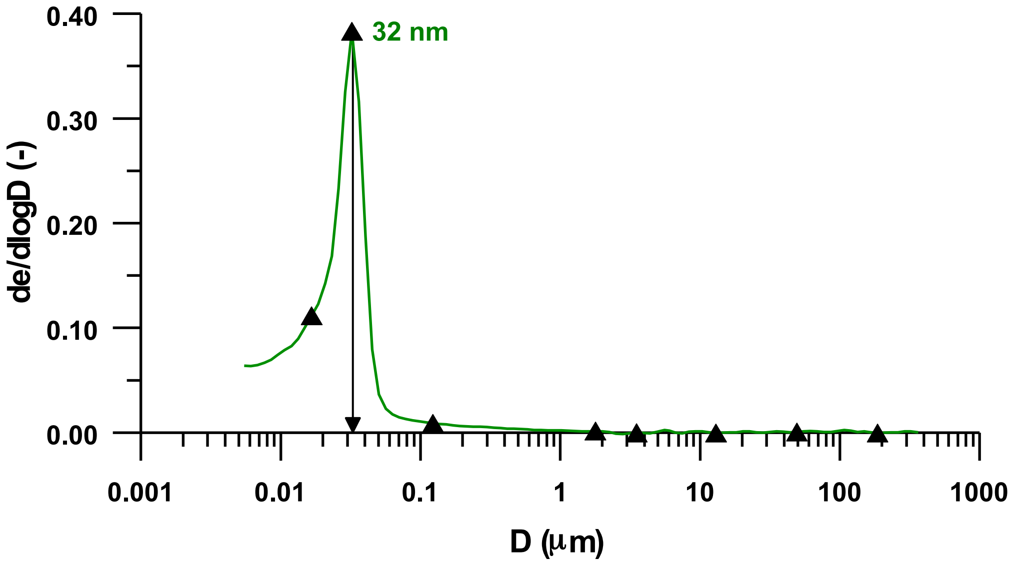


Wan et al. IJRMMS 2013

Mercury intrusion porosimetry, COx claystone



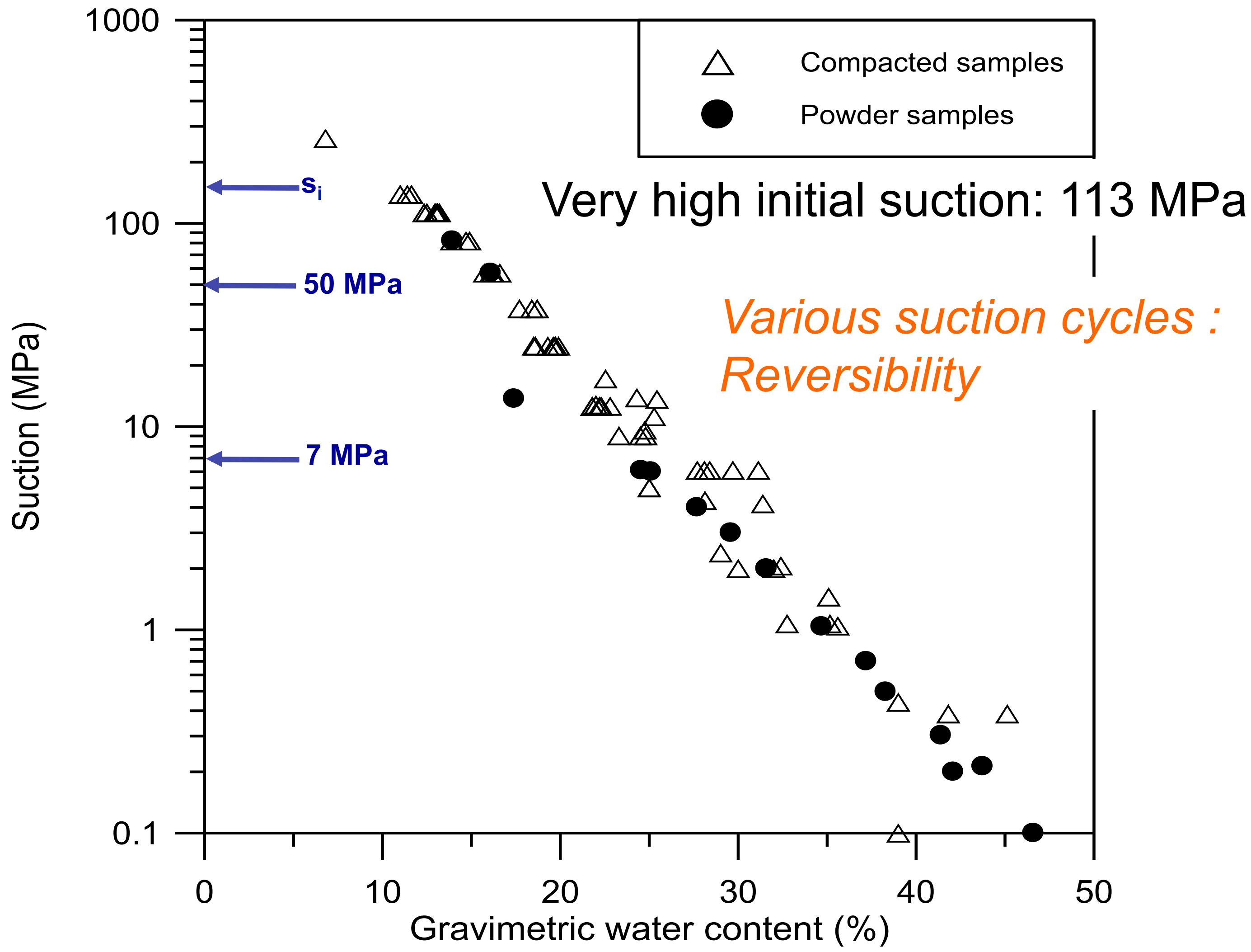




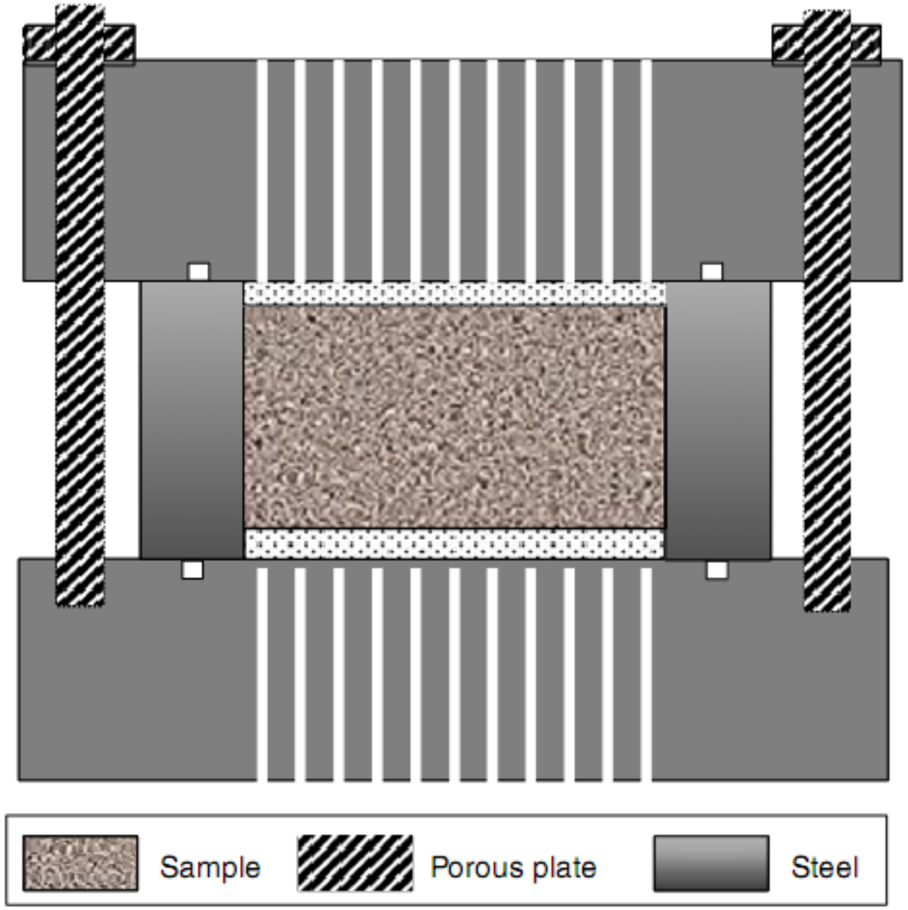
Initial state, s = 17 MPa

Menaceur 2014

Compacted bentonite

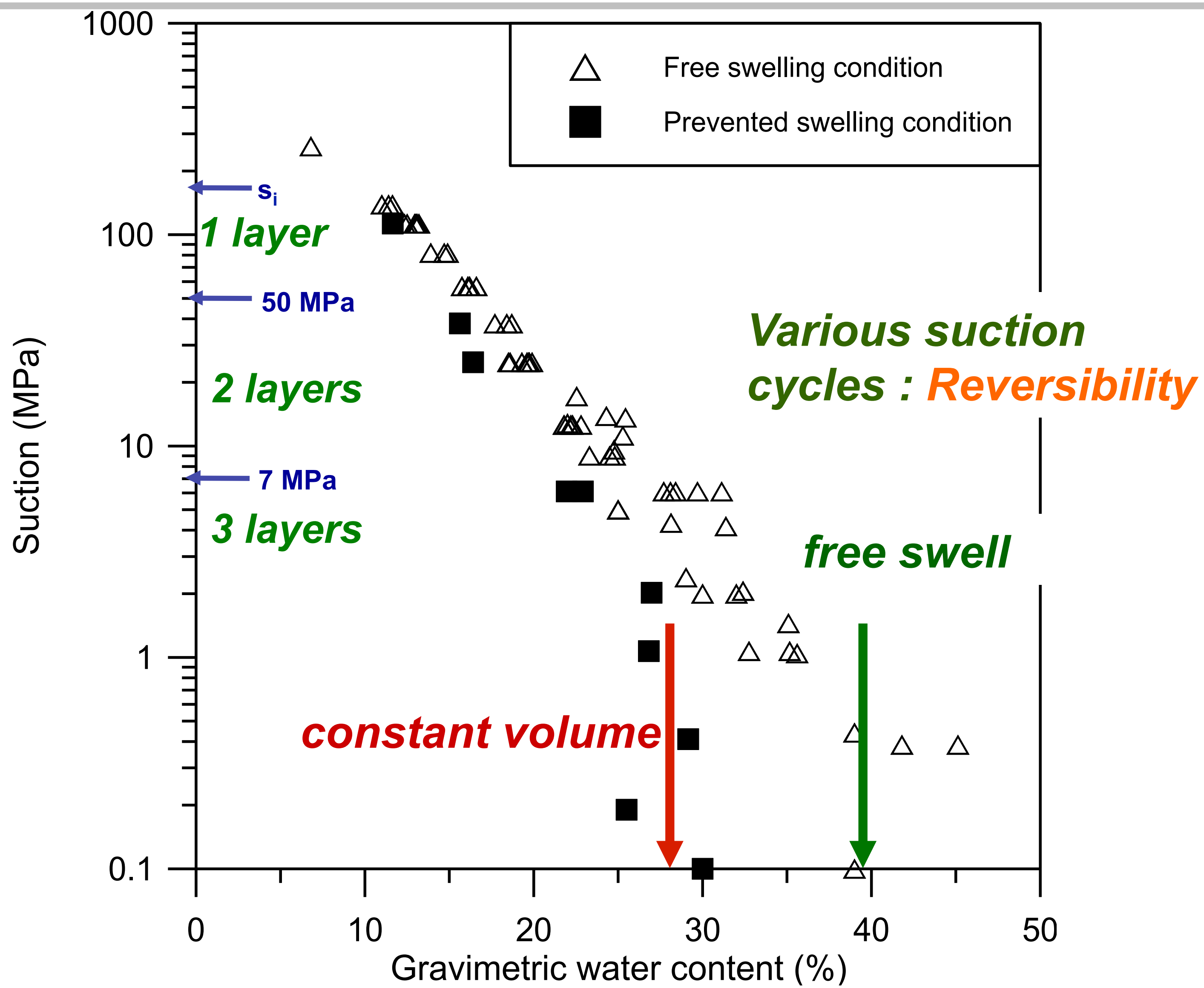


Water retention properties, constant volume



Yahia-Aissa et al. 2002, Villar et al. 2005

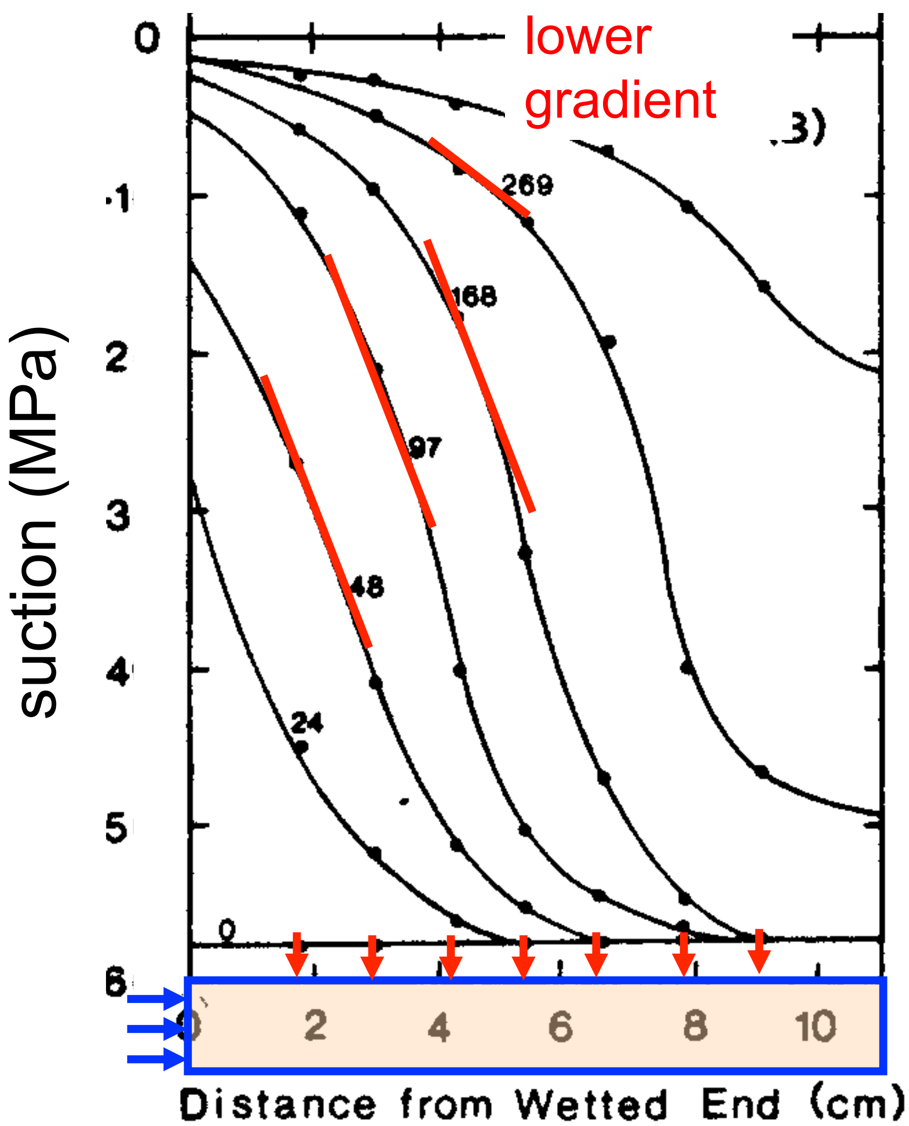
Water retention properties, bentonites



Yahia-Aissa et al. 2002

FLUID TRANSFERS

Unsaturated permeability

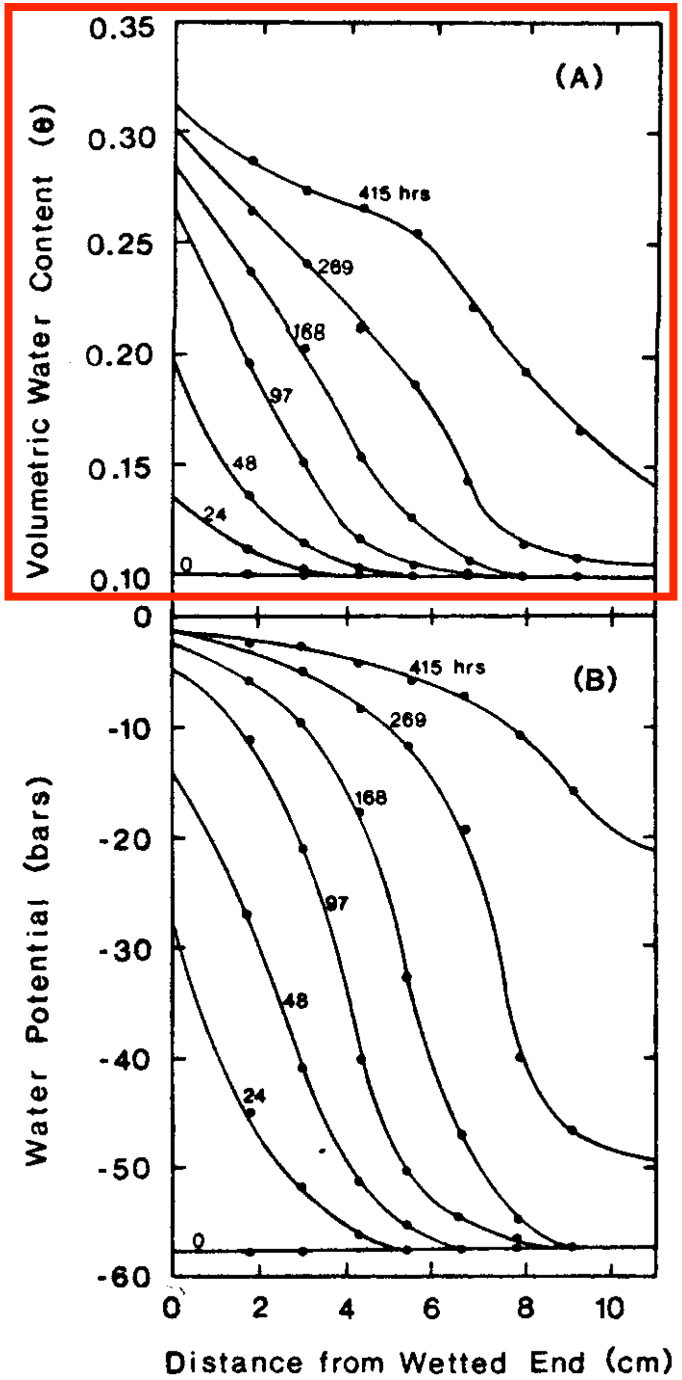


<u>Instantaneous profile method</u>

- water infiltration in a column with suction monitoring along column
- water retention curve determined (psychrometer)

curve slopes give hydraulic gradient *i* at various suctions

Daniel 1984



- the water retention curve provides the corresponding water contents

- changes in water content with time provide water unit flow

$$q = A \frac{\int_{x_i}^{L} \theta_{t+\Delta t}\, dx - \int_{x_i}^{L} \theta_t\, dx}{\Delta t}$$

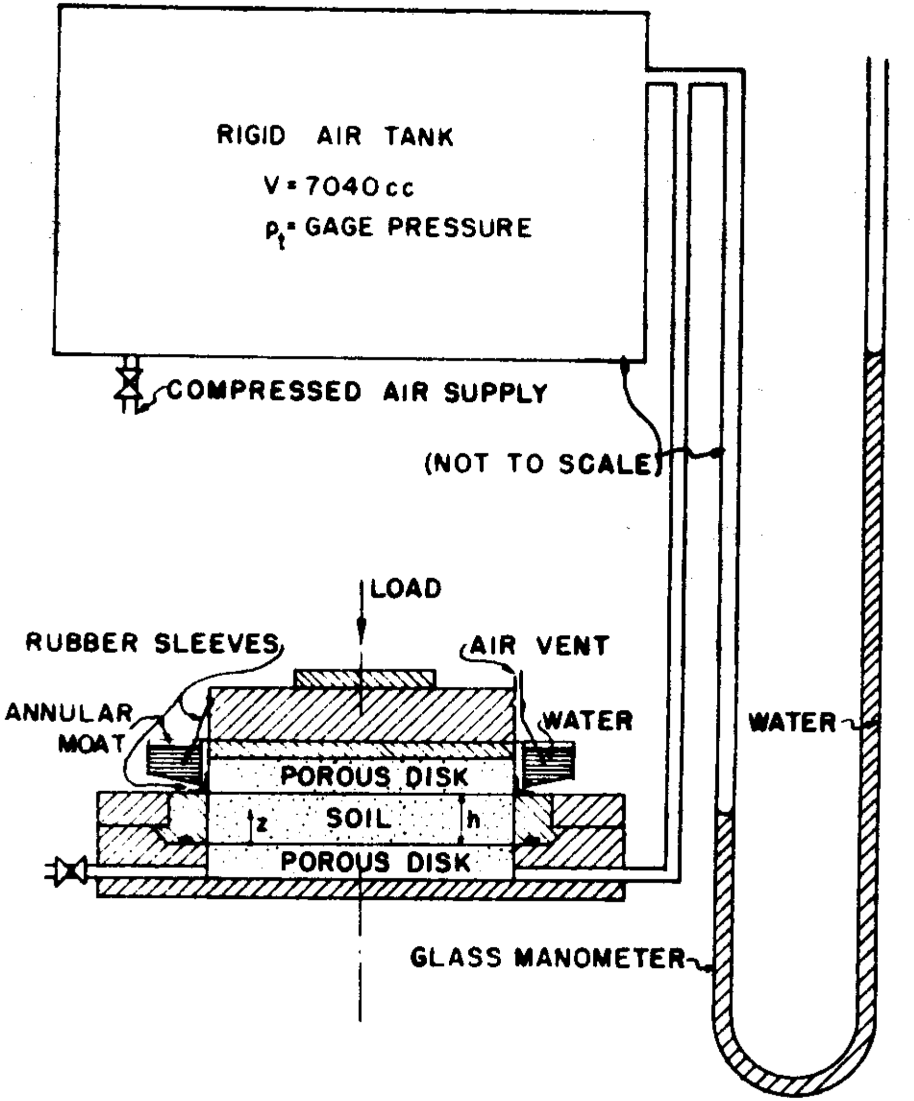
- unsaturated permeability is given by :

$$K = -\frac{1}{A} \frac{q}{0,5\left(i_t + i_{t+\Delta t}\right)}$$

A is the sectional area

Air permeability measurement

Yoshimi and Osterberg (1963)

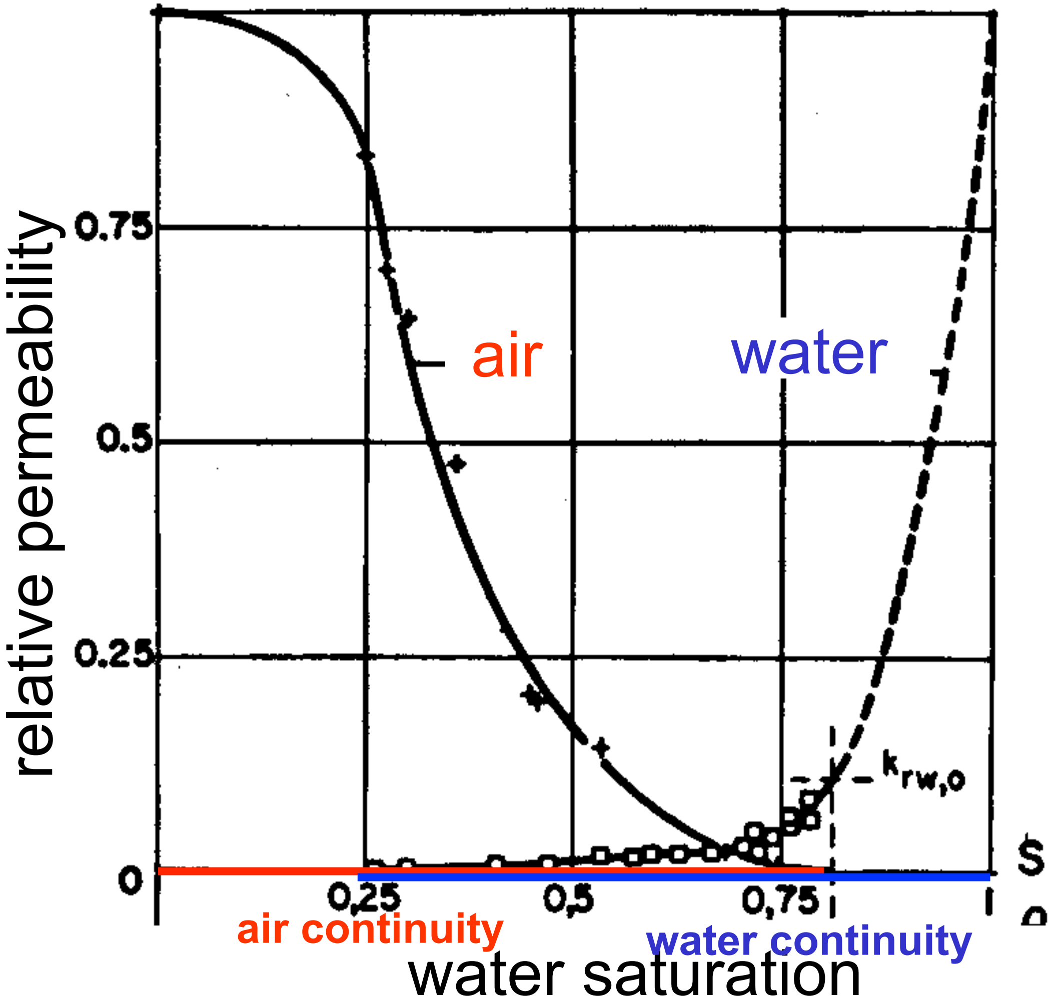


like variable head permeameter

$$K_a = -\frac{2{,}3Vh\mu_a}{t}\frac{lg\frac{p(t)}{p(0)}}{S\left[p_a + \frac{p(0)}{4}\right]}$$

$$K_a = a\left[e(1 - S_r)\right]^n$$

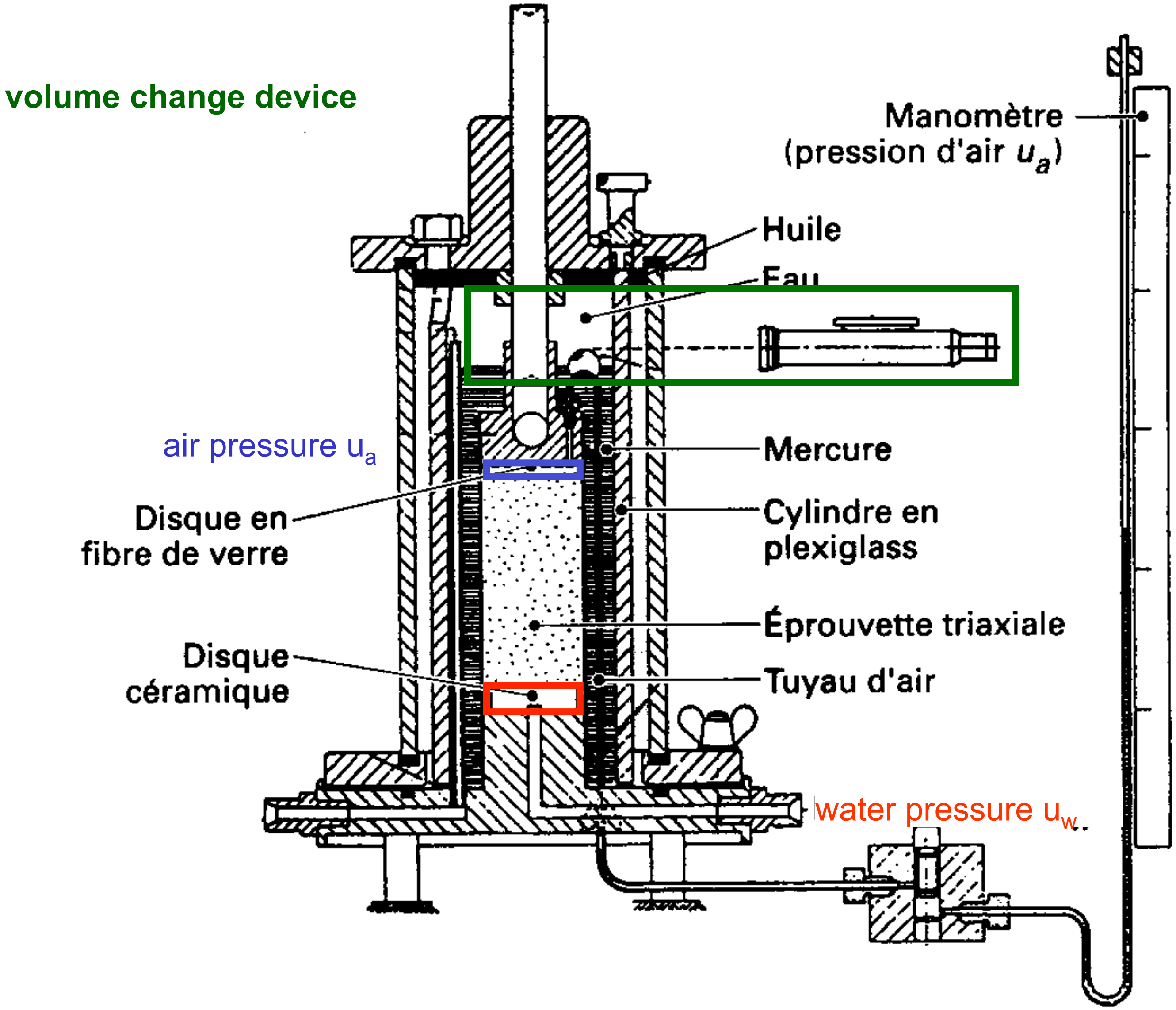
Air and water permeability



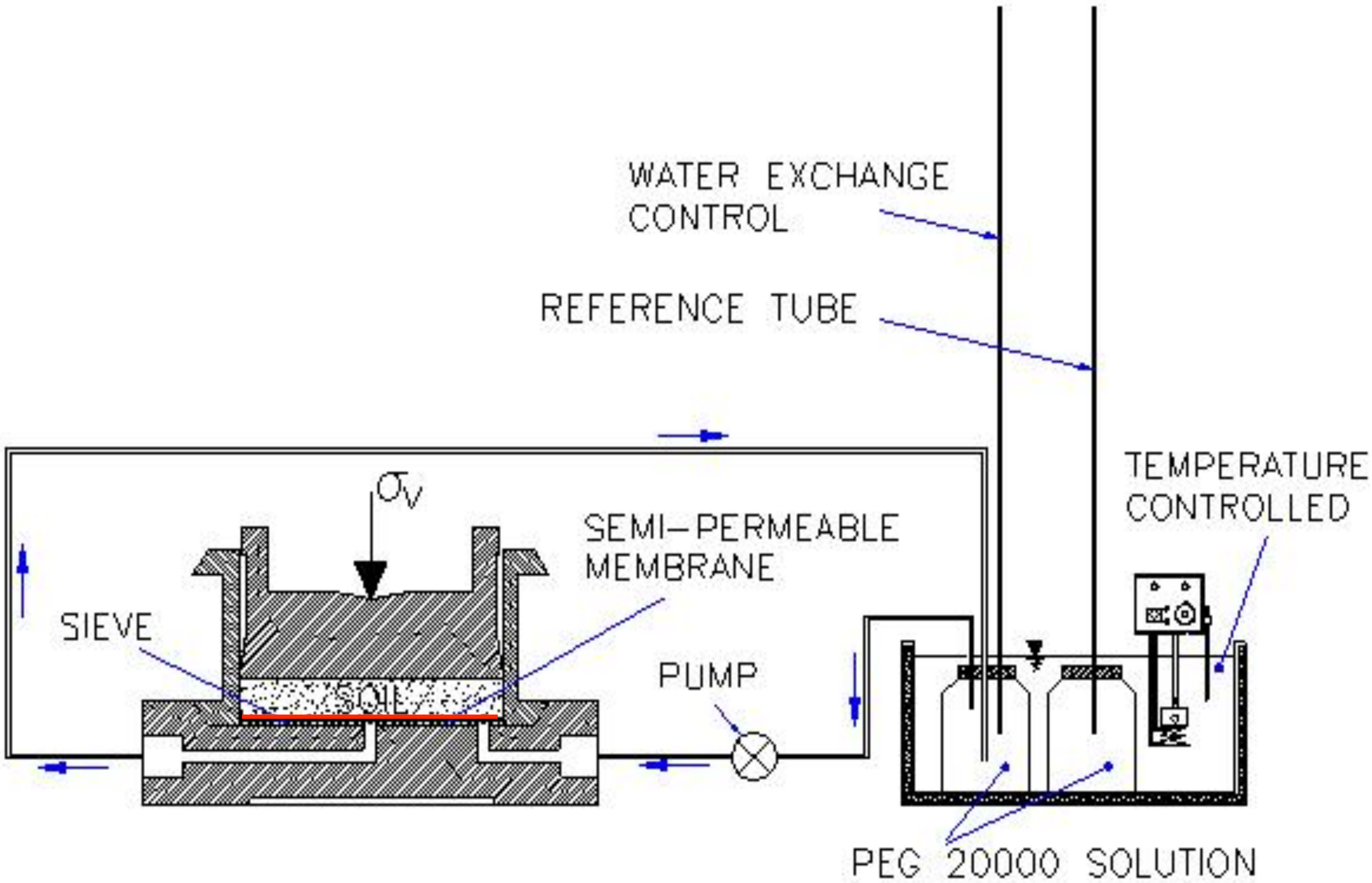
MECHANICAL TESTING

Bishop & Donald's suction controlled triaxial cell

(1962) axis translation method



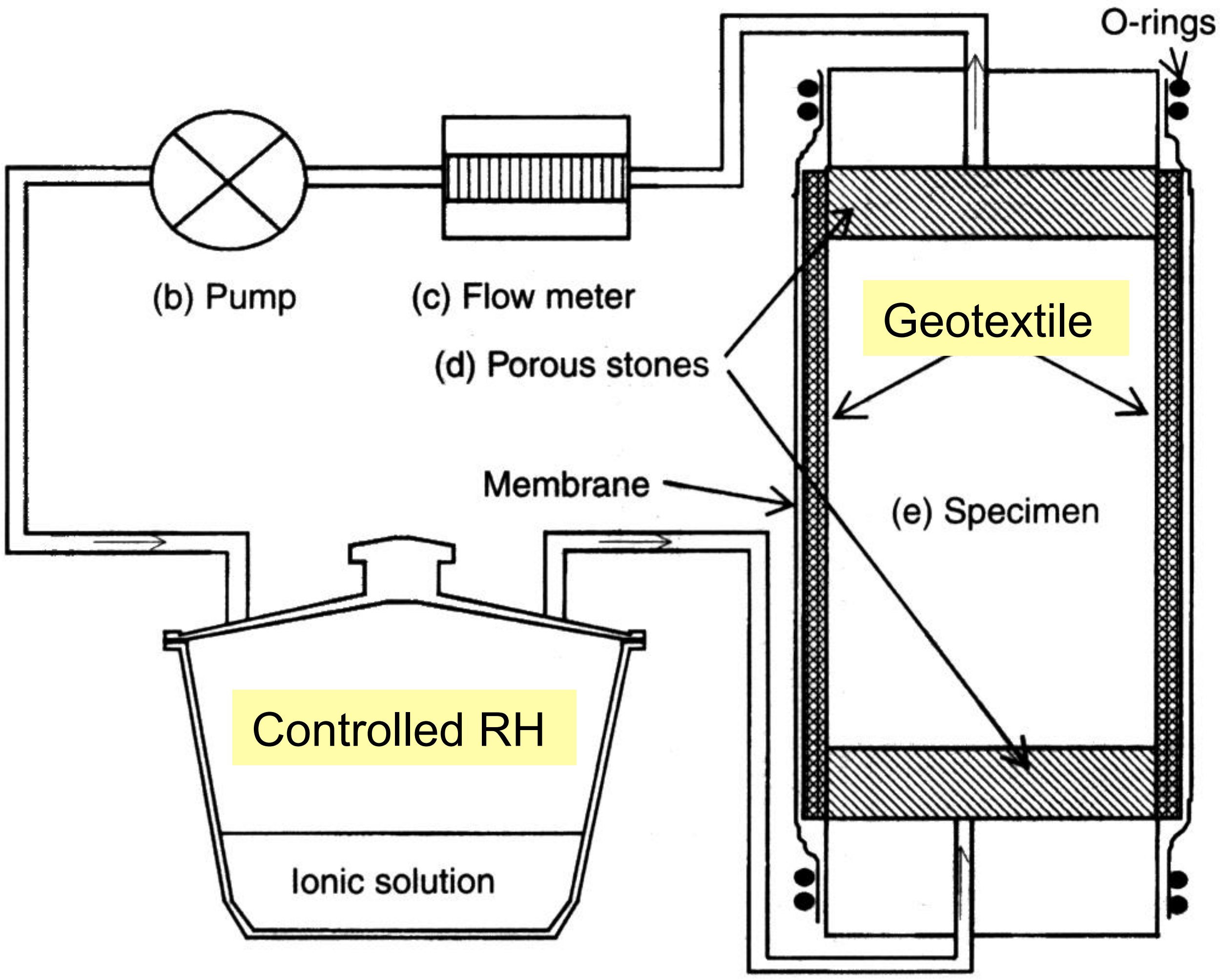
Osmotic suction controlled oedometer



Kassiff & Benshalom (1974), Delage et al. (1992)

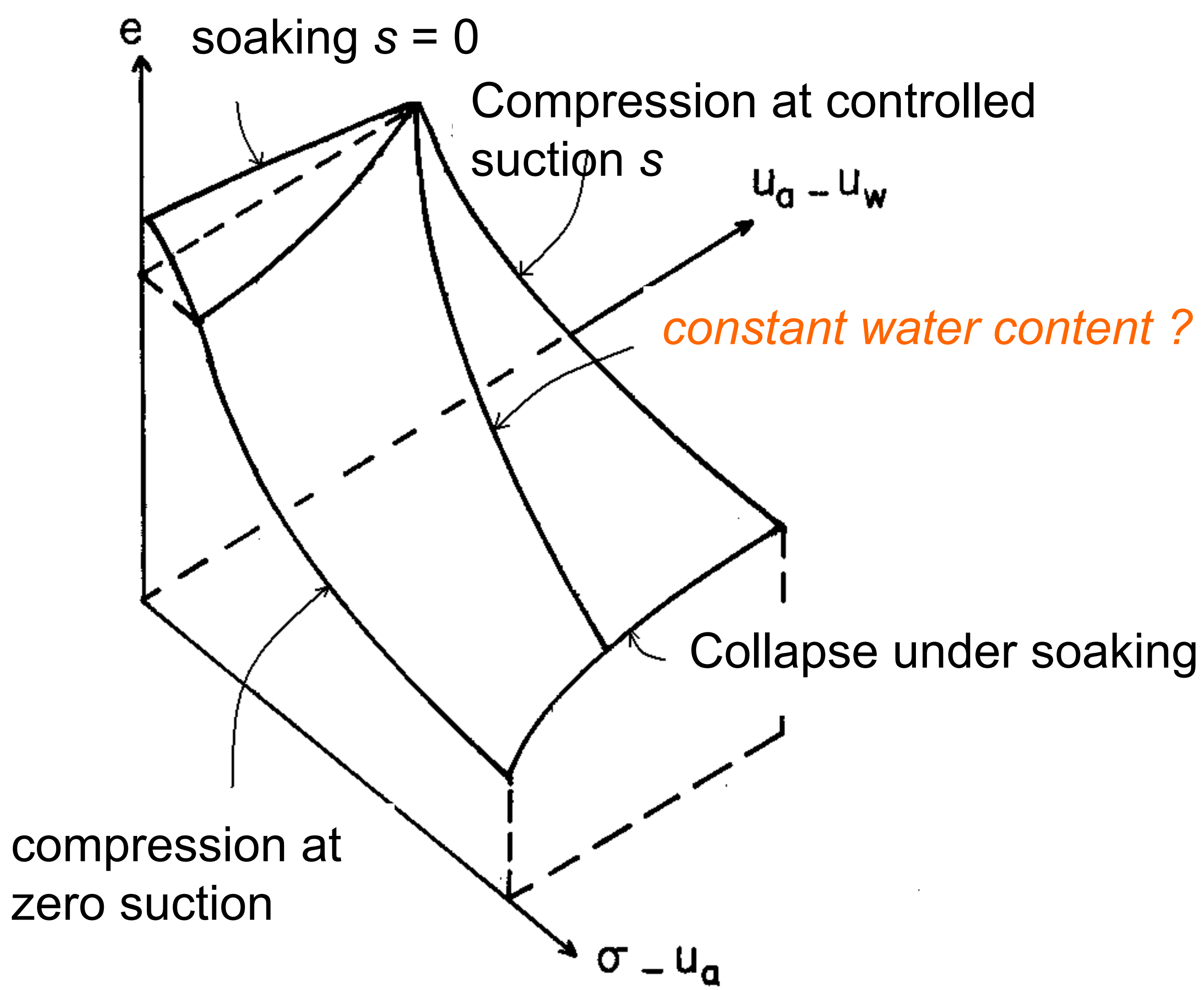
Vapour equilibrium triaxial

(Blatz & Graham 2000)



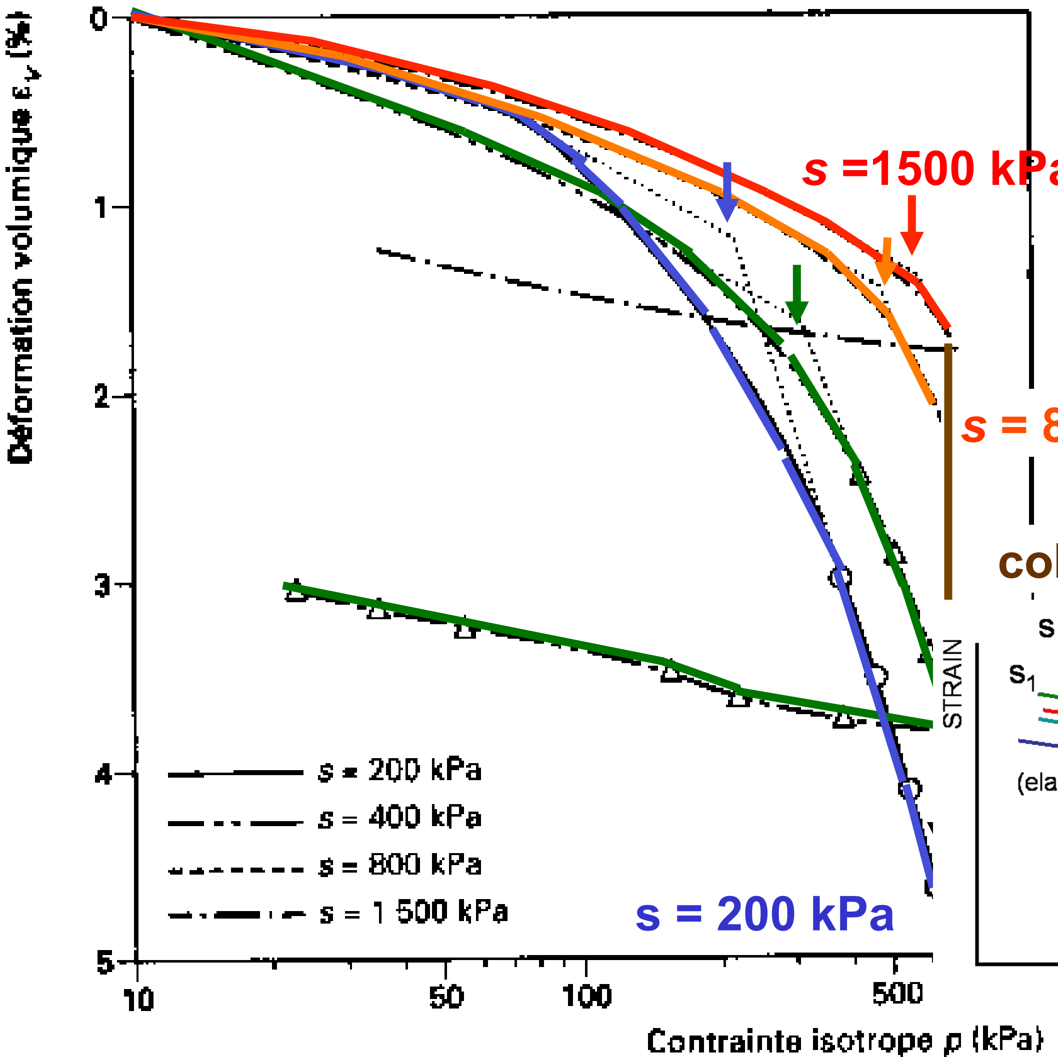
TYPICAL FEATURES

The state surface concept
(Matyas & Radhakrishna 1968)



Isotropic compression

(cui & delage 1996, osmotic triaxial)



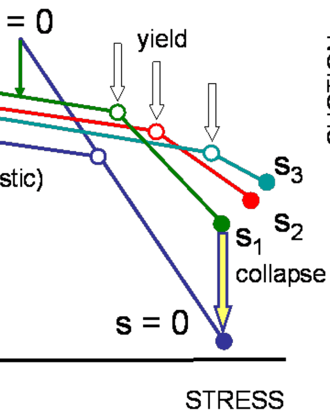
drier sample :

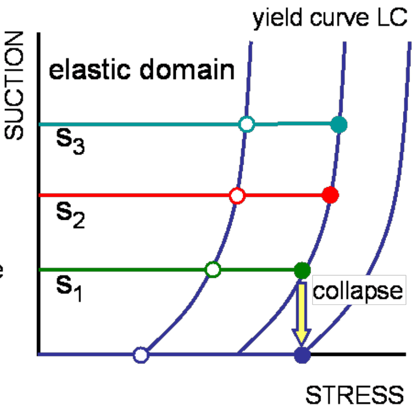
- stiffer

-higher yield stress

LC curve

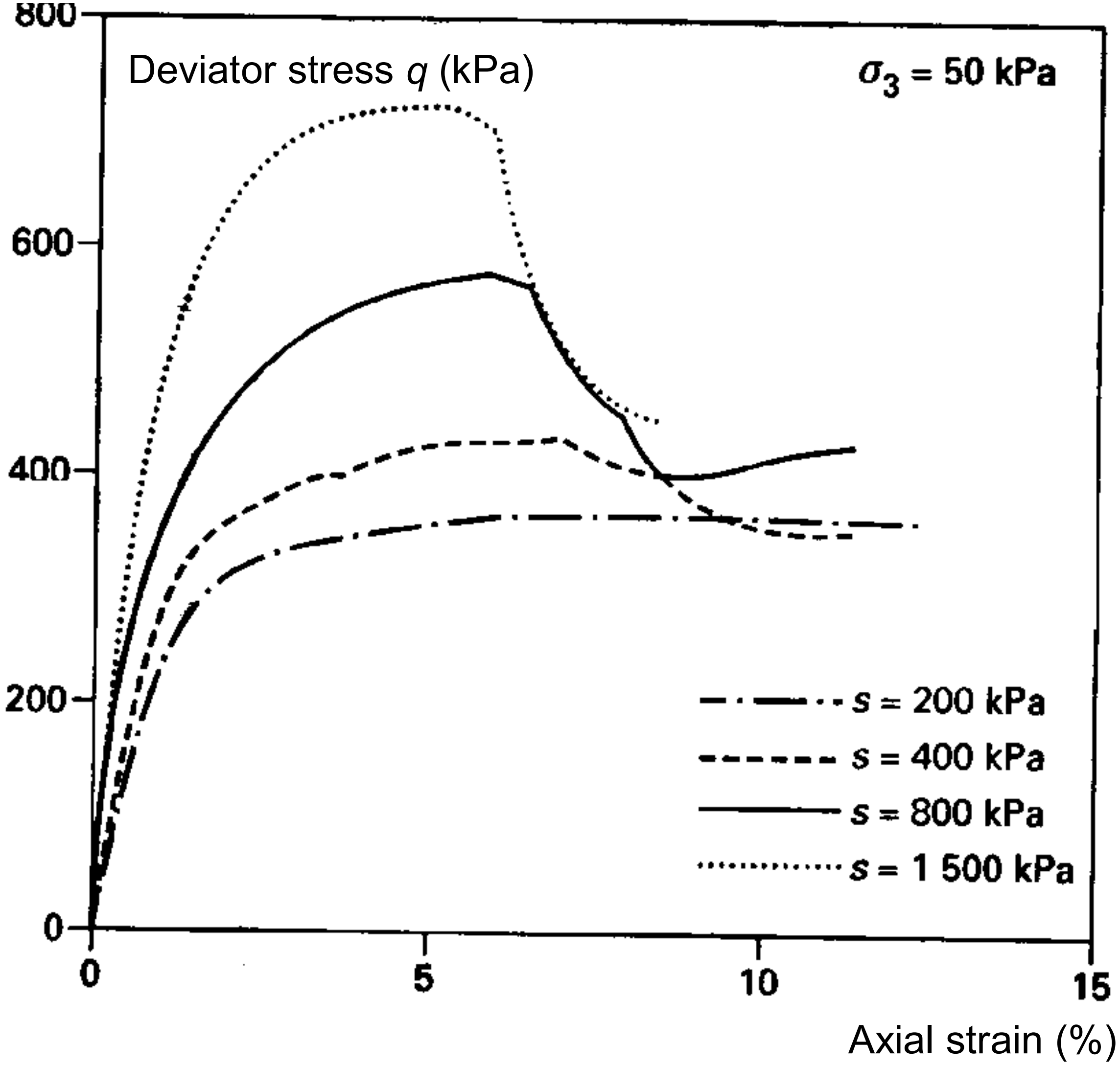
Barcelona basic model





Constant σ_3 triaxial compression

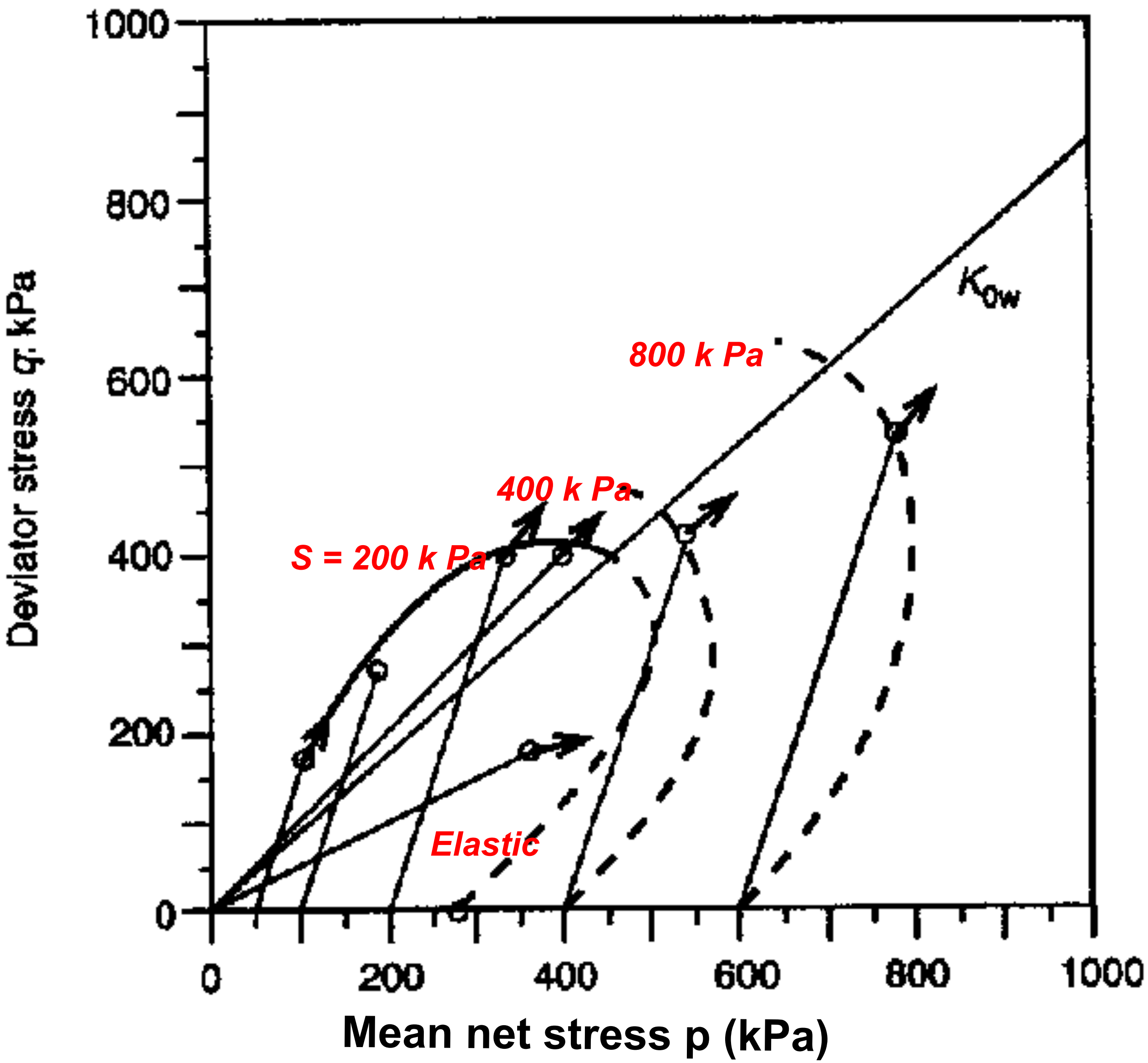
(Cui & Delage 1996)



drier sample is :

- stiffer
- more resistant
- more fragile

Elasto-plastic behaviour

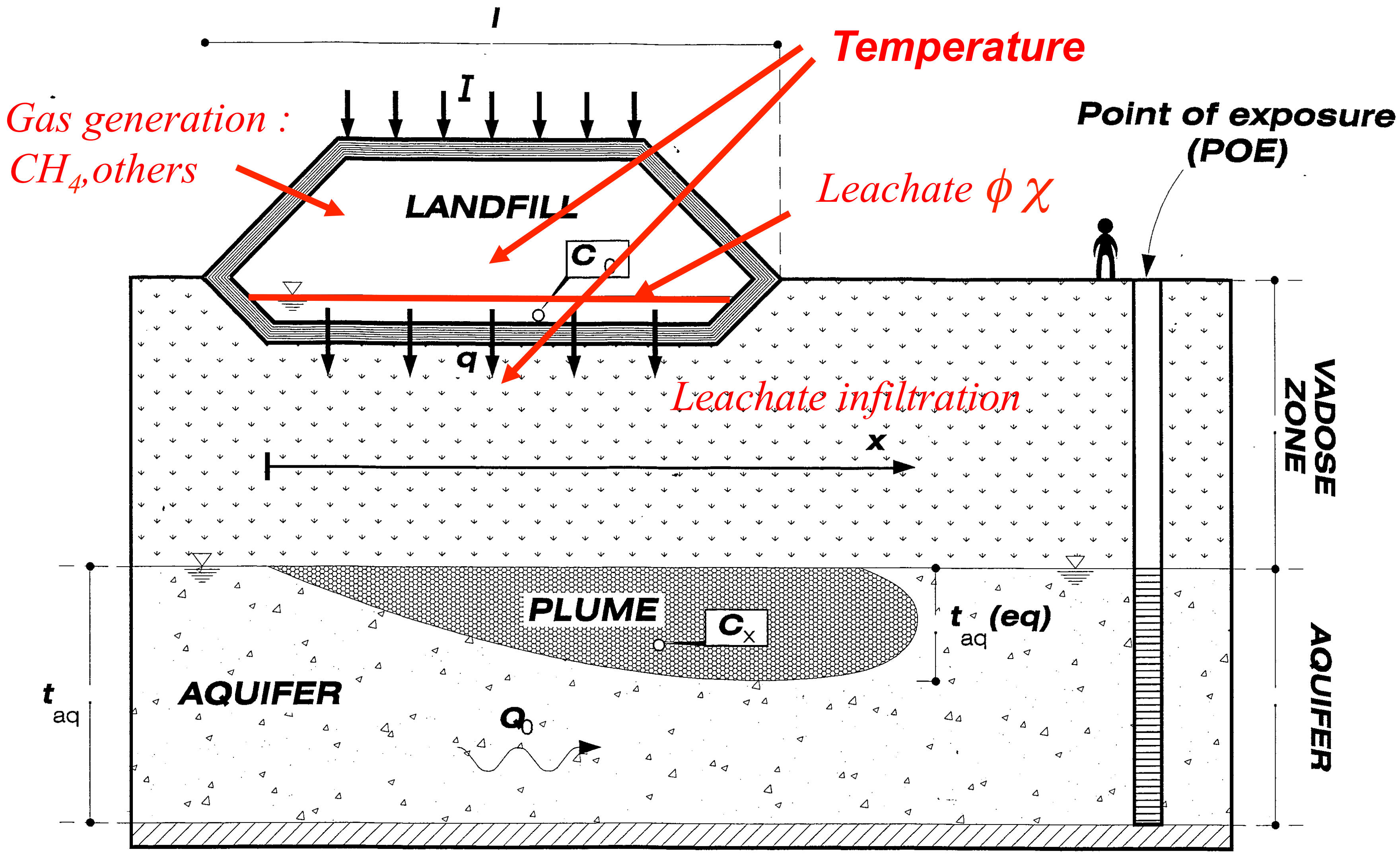


- *suction hardening*
- *stress hardening*
- *plastic flow*

Cui & Delage 96, anisotropically compacted

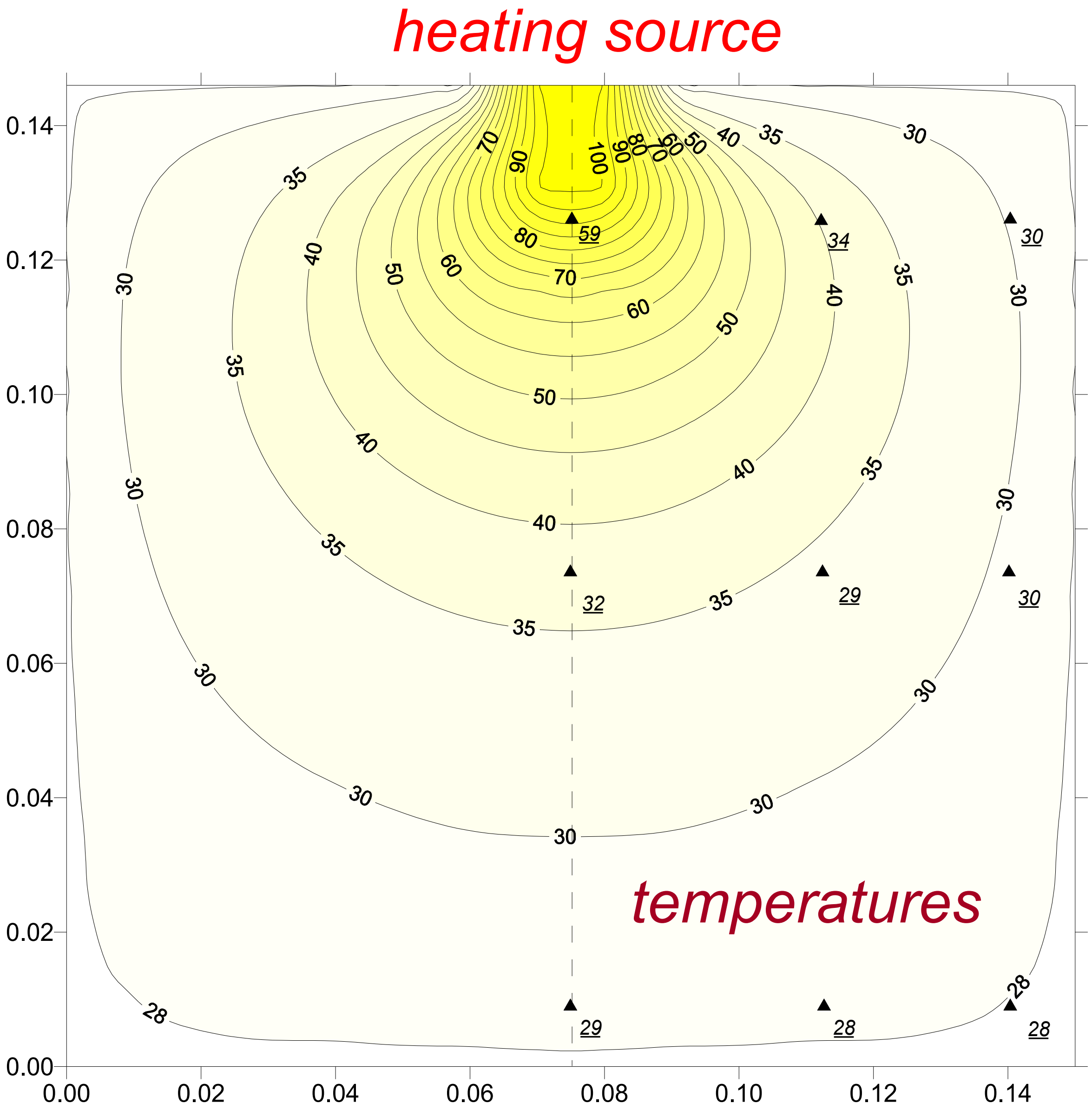
THERMAL ISSUES

Surface waste disposal



Di Molfietta and Aglietto 1999

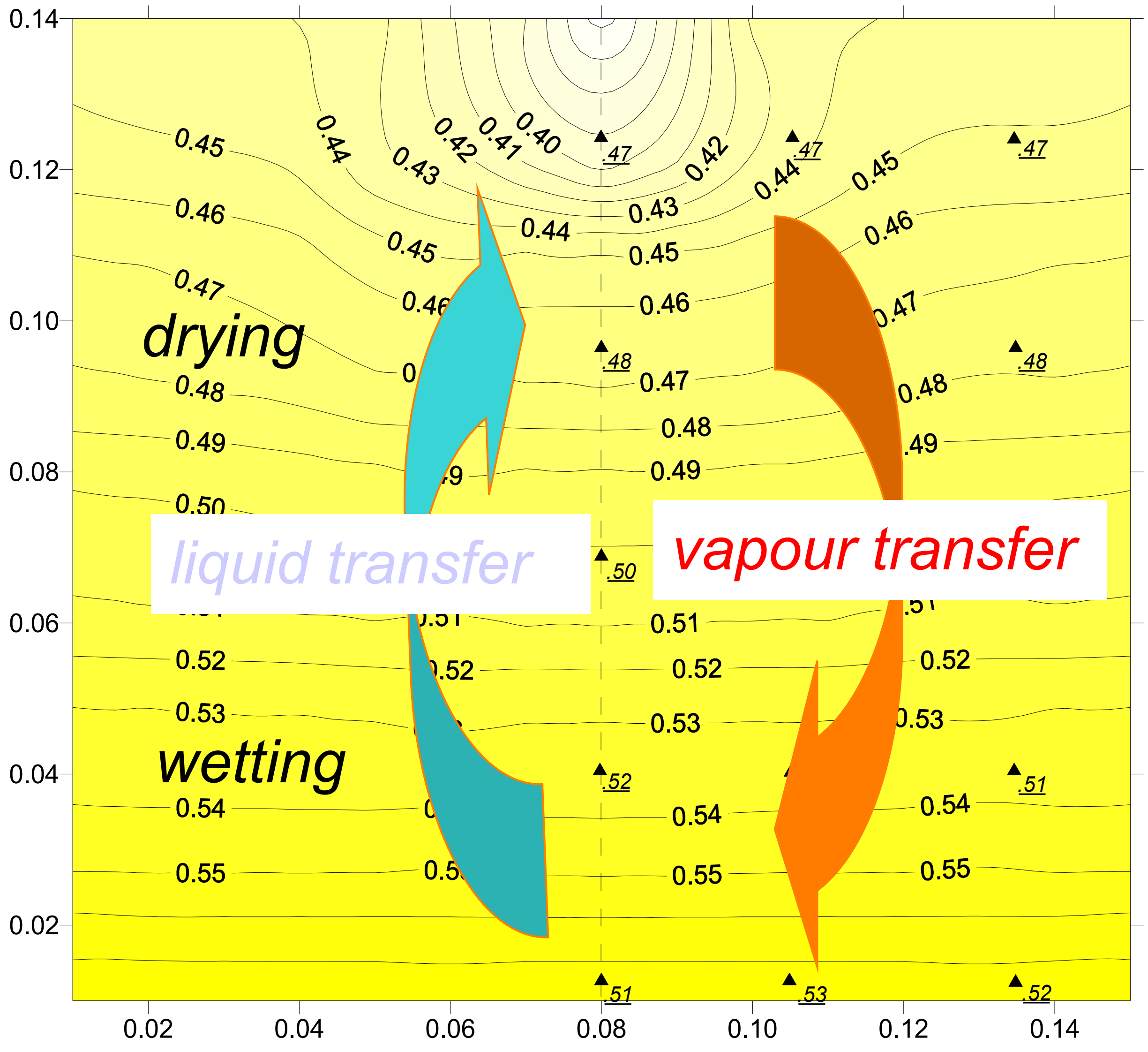
Heat effects: lab experiments



Compacted bentonite, S_{ri} = 50%

Villar 1994

Coupled THM transfers

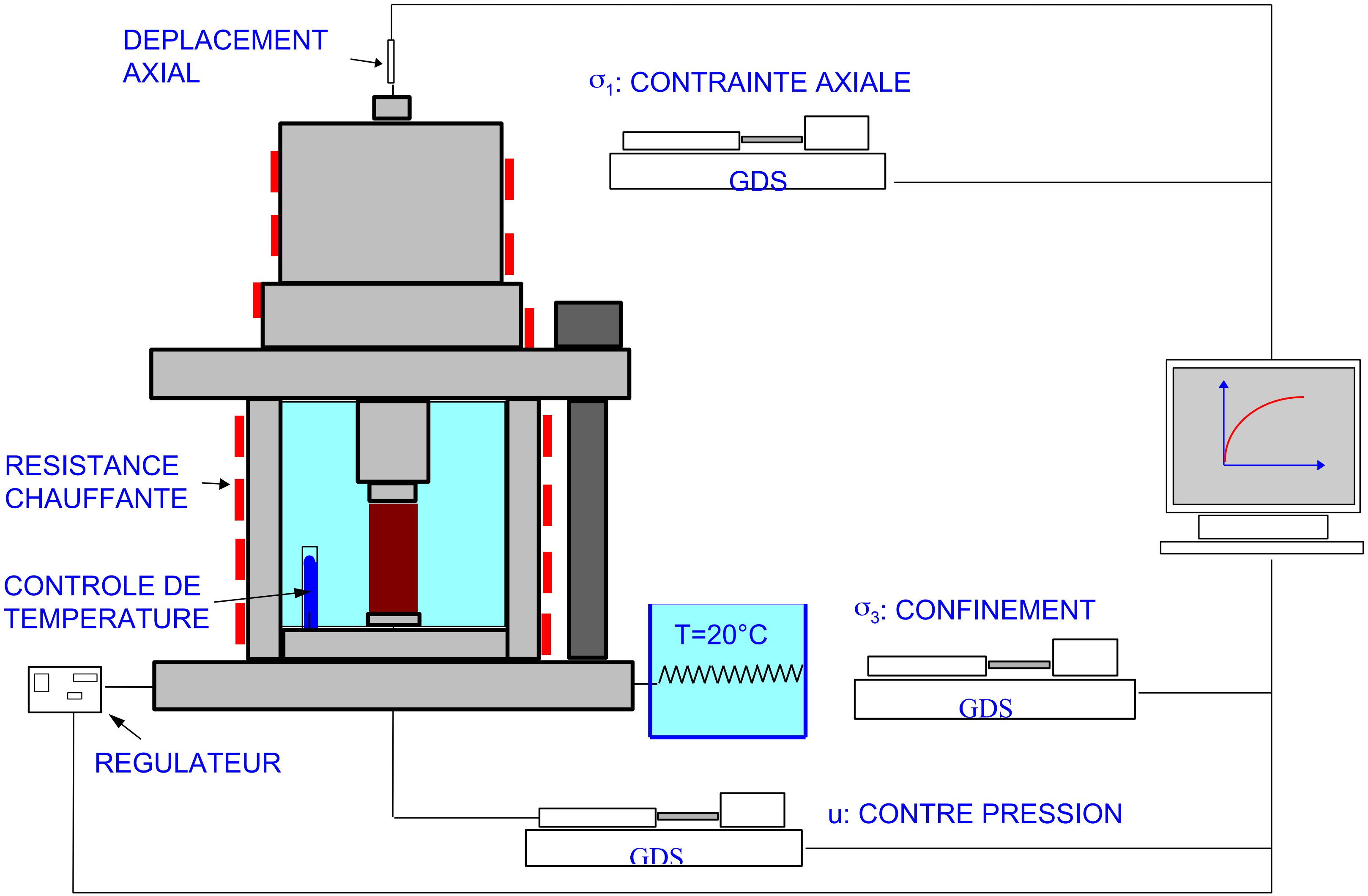


degree of saturation

Compacted bentonite, S_{ri} = 50%

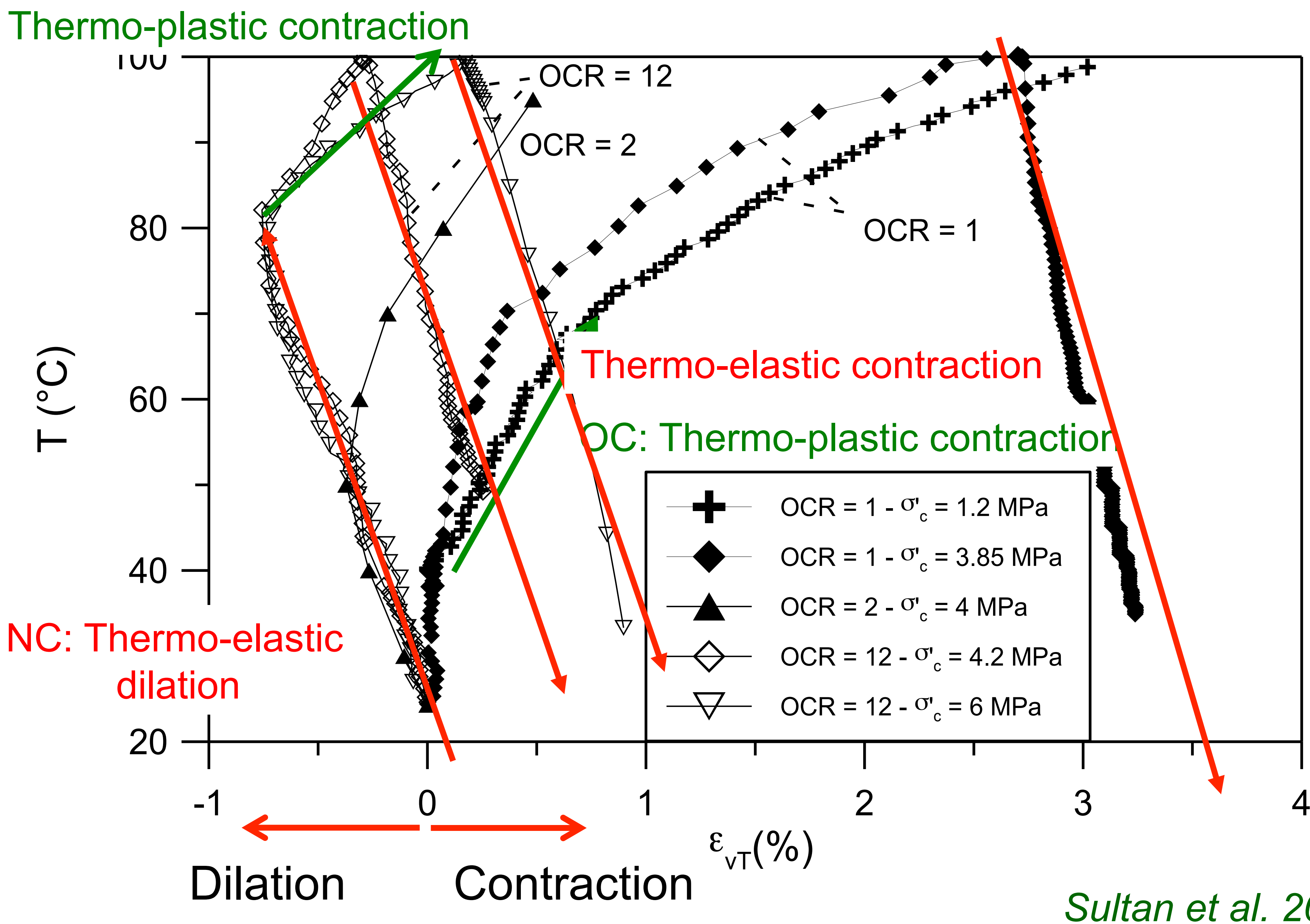
Villar 1994

Thermal triaxial cell



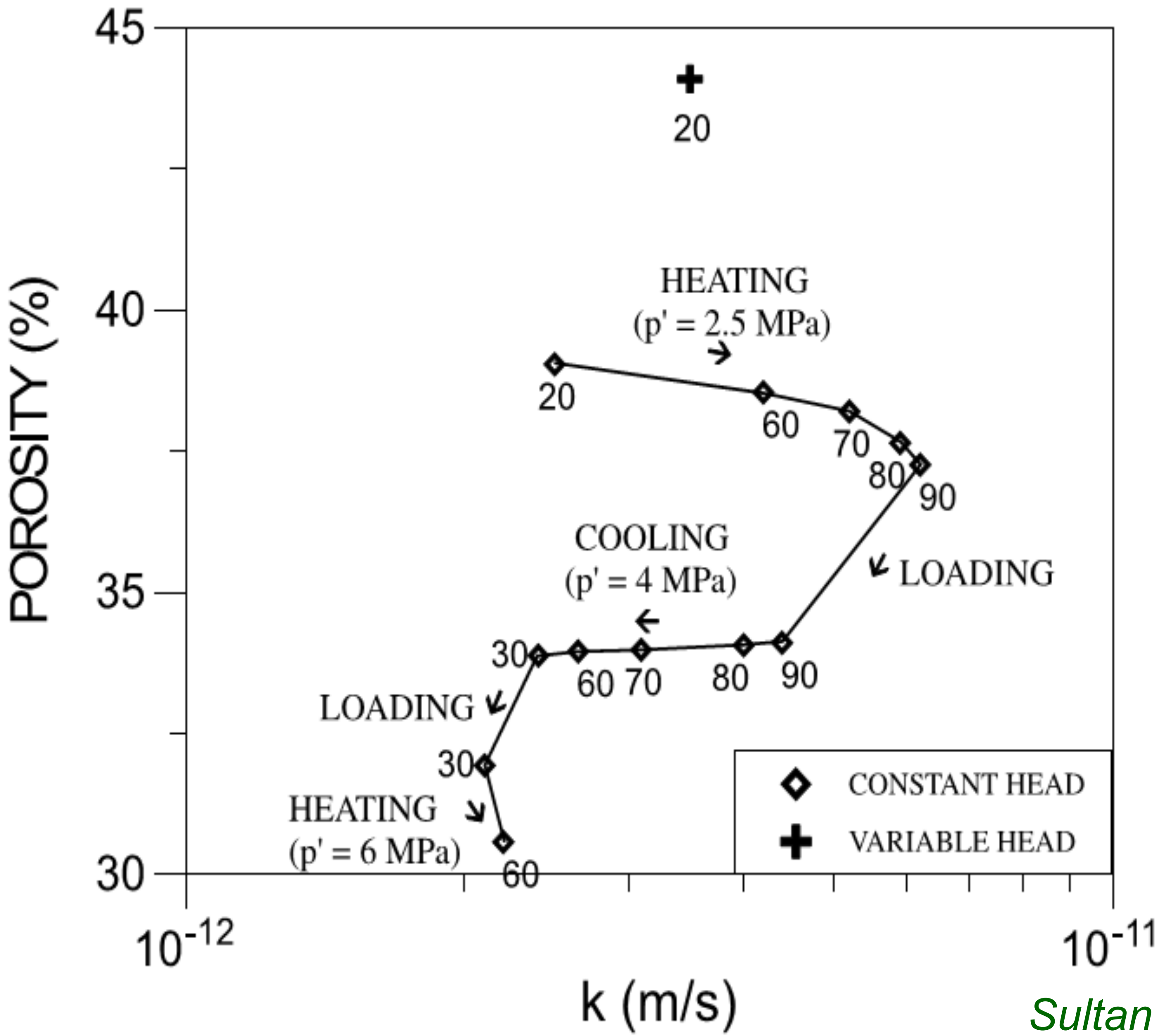
Sultan et al. 2000

Thermal volume changes (drained)



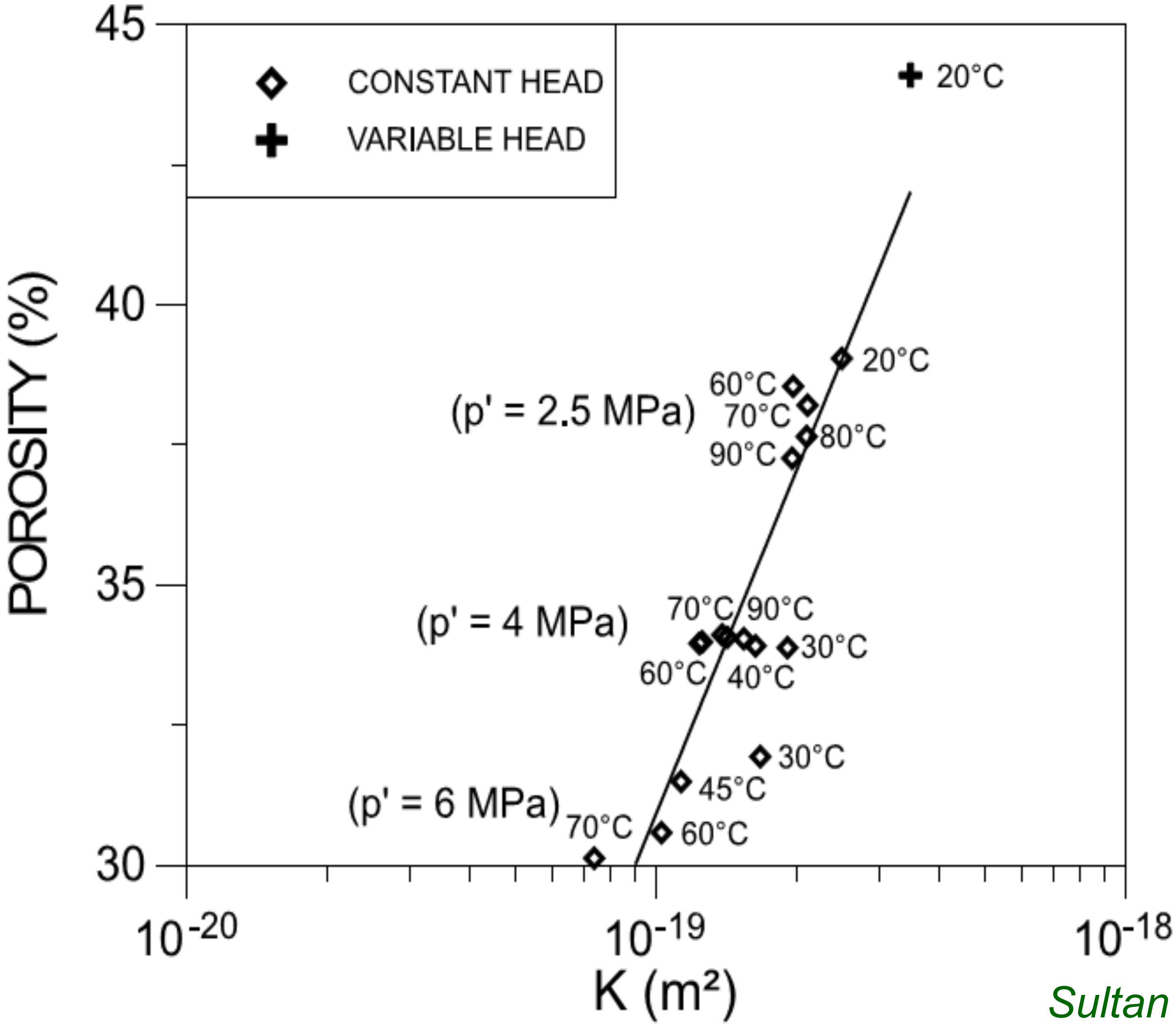
Sultan et al. 2000

Temperature effects on permeability



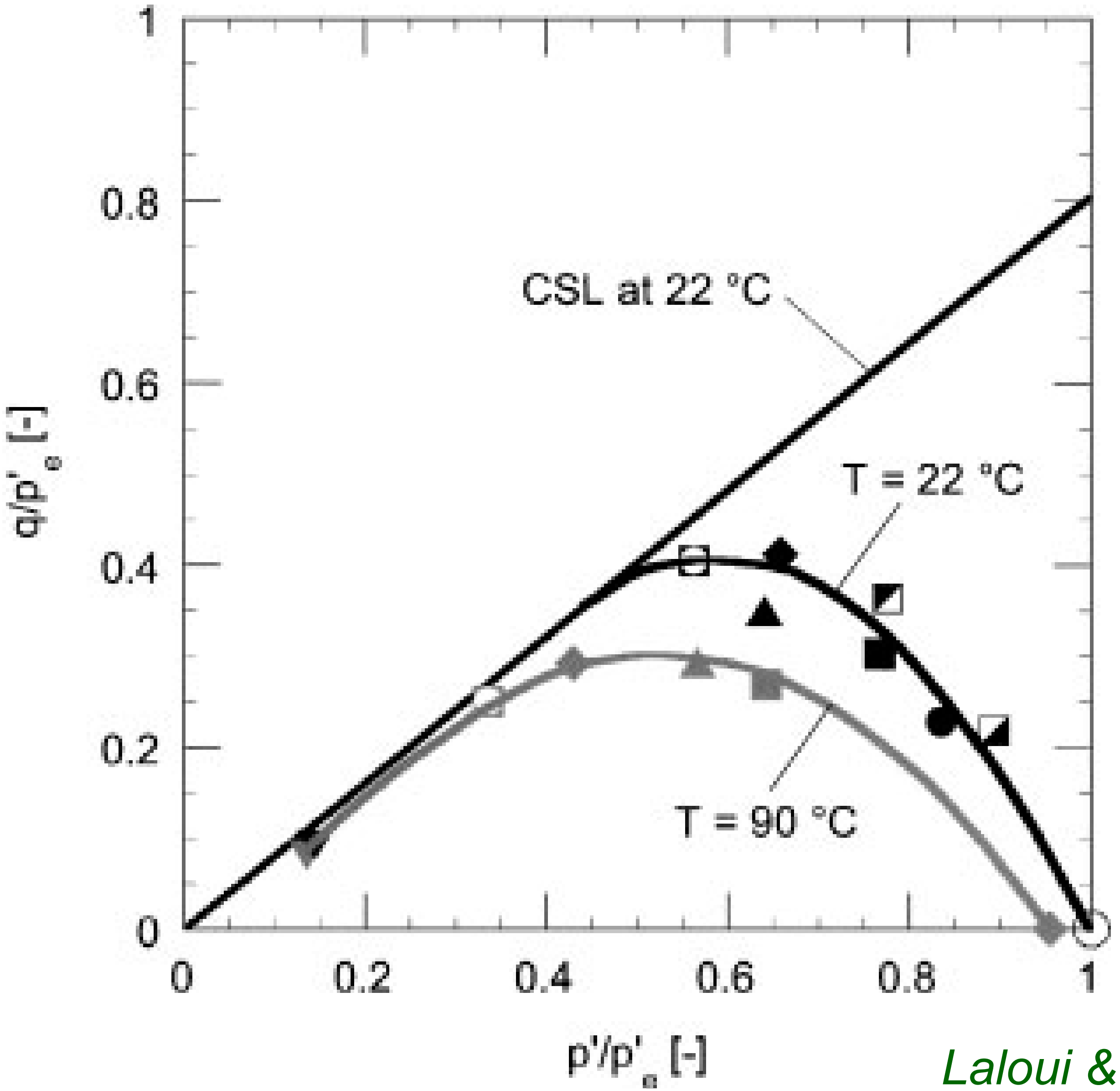
Sultan et al. 2000

Intrinsic permeability



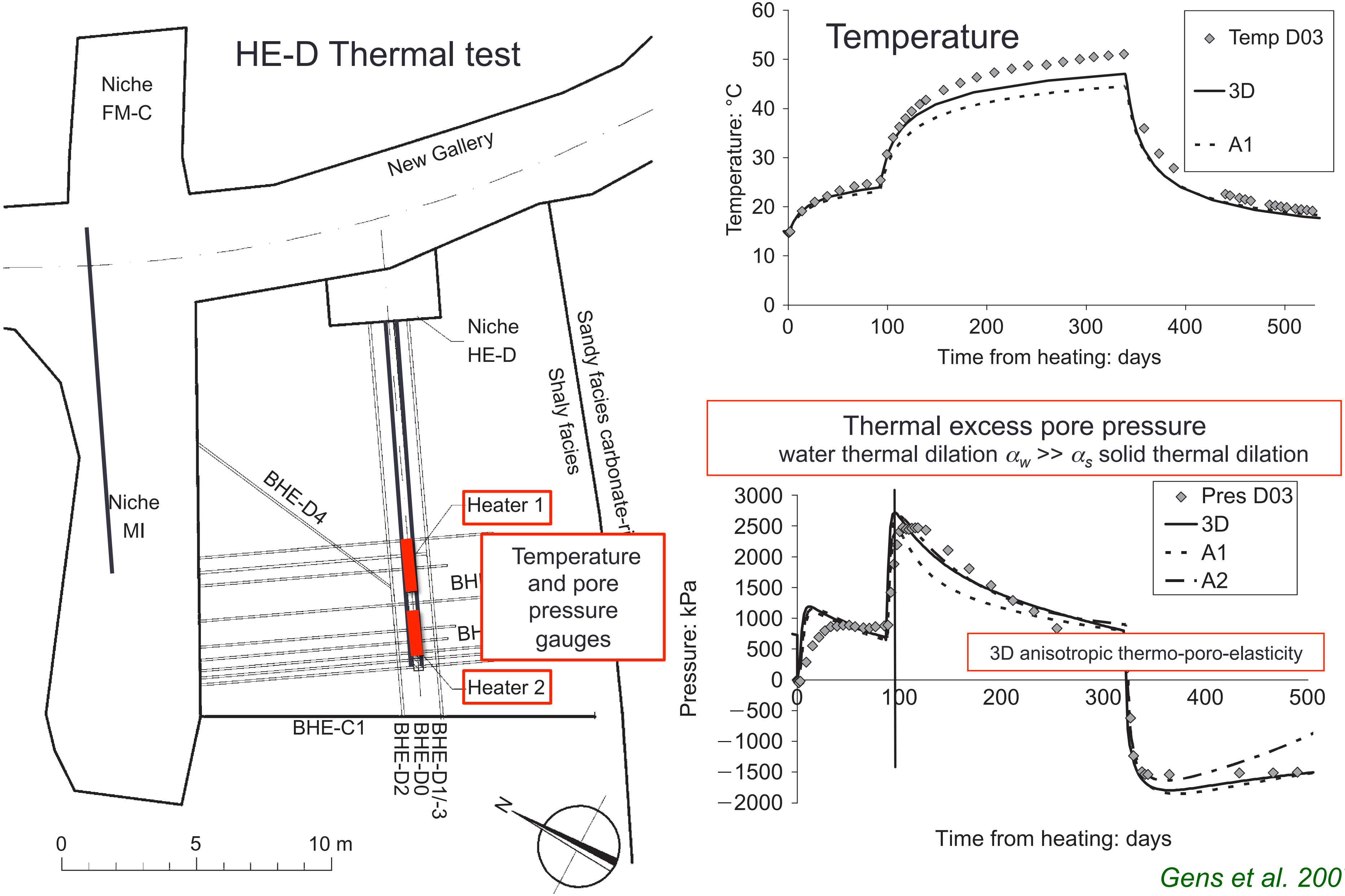
Sultan et al. 2000

Normalised yield envelopes



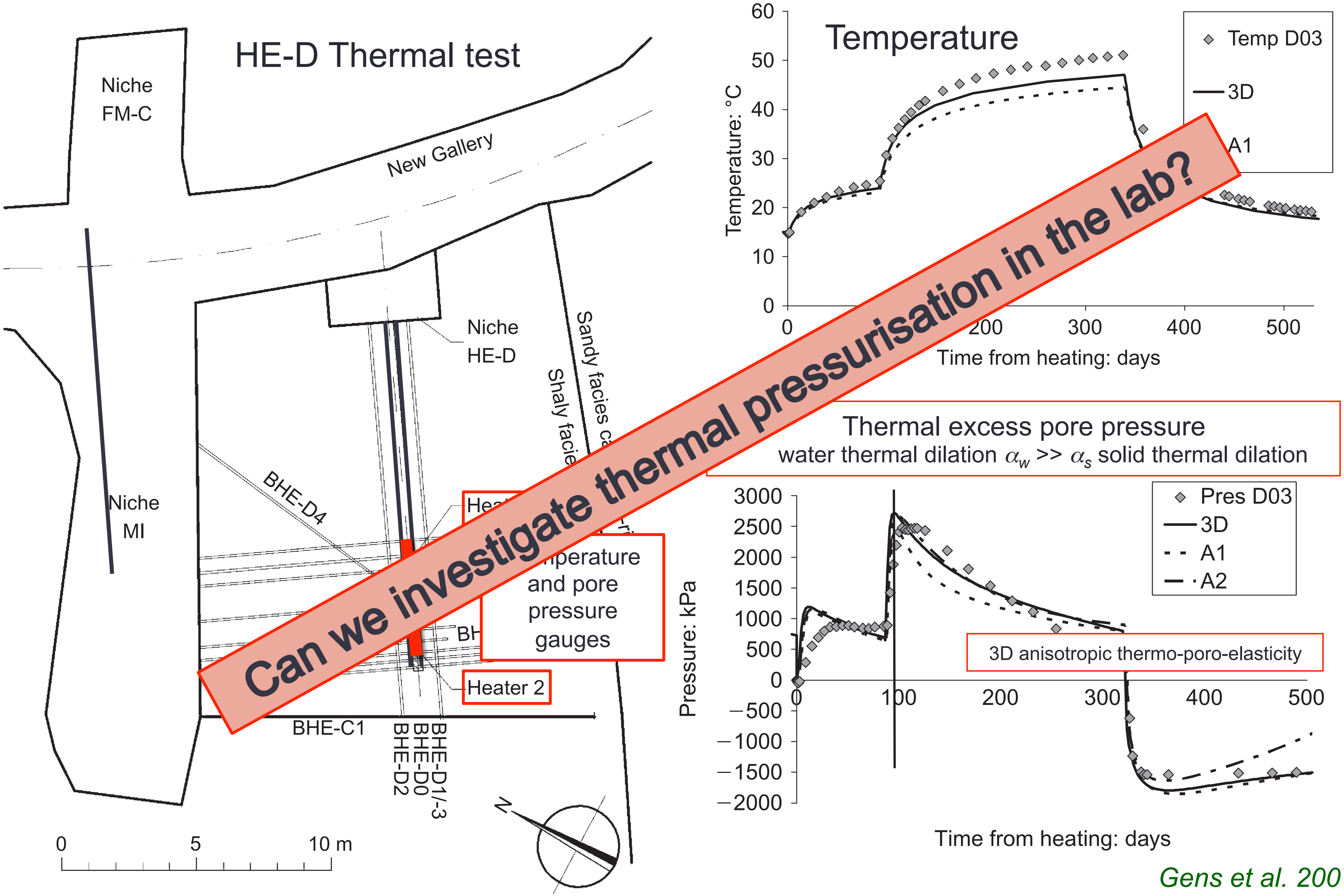
Laloui & Cekerevac 2004

In-situ thermal experiments (Mt Terri, Switzerland)



Gens et al. 2007

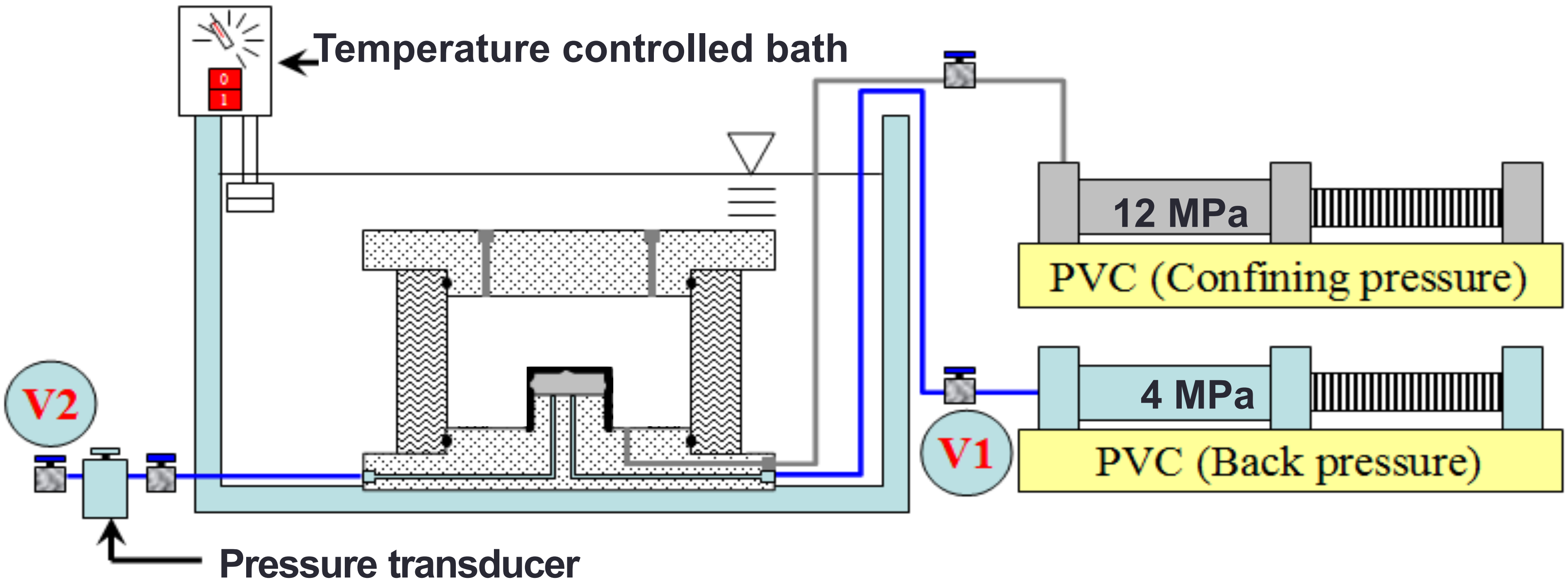
In-situ thermal experiments (Mt Terri, Switzerland)



Gens et al. 2007

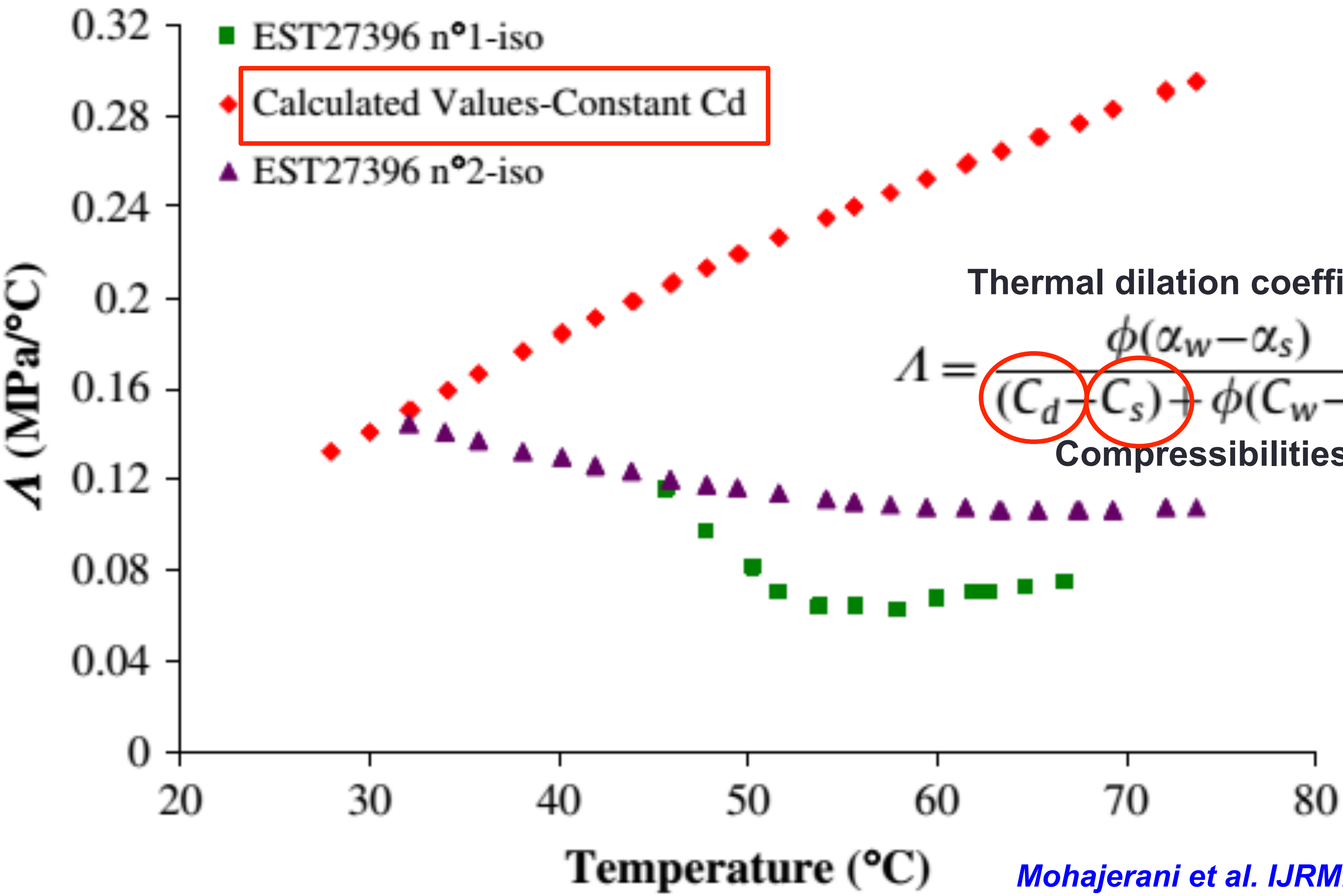
Thermal pressurization: lab device

Undrained heating under in-situ stress with pore pressure measurement



Mohajerani et al. IJRMMS (2012)

Thermal pressurization coefficient Λ, COx claystone



Thermal dilation coefficients

$$\Lambda = \frac{\phi(\alpha_w - \alpha_s)}{(C_d - C_s) + \phi(C_w - C_s)}$$

Compressibilities

Mohajerani et al. IJRMMS (2012)

Issues in THM testing of claystones

- Is the extracted specimen tested in the lab representative of in-situ conditions?
  - Partial saturation (stress release, air coring, evaporation,…)
  - Damage (stress release, drying)
- Very low permeability:

$$k = 10^{-13} \text{ m/s } (10^{-20} \text{ m}^2 \text{ intrinsic permeability})$$

  - Initial full saturation
  - Drainage conditions

Saturated and drained testing of claystones

- **Emphasis put on:**
- Controlled saturation procedure under in-situ stress conditions to avoid swelling/damage

$$B = \frac{c_d - c_s}{c_d - c_s + \phi(c_w - c_s)}$$

- Good drainage conditions

homogeneous pore pressure field thanks to short drainage length

TIMODAZ hollow cylinder apparatus

External diameter 100 mm

Internal diameter 60 mm

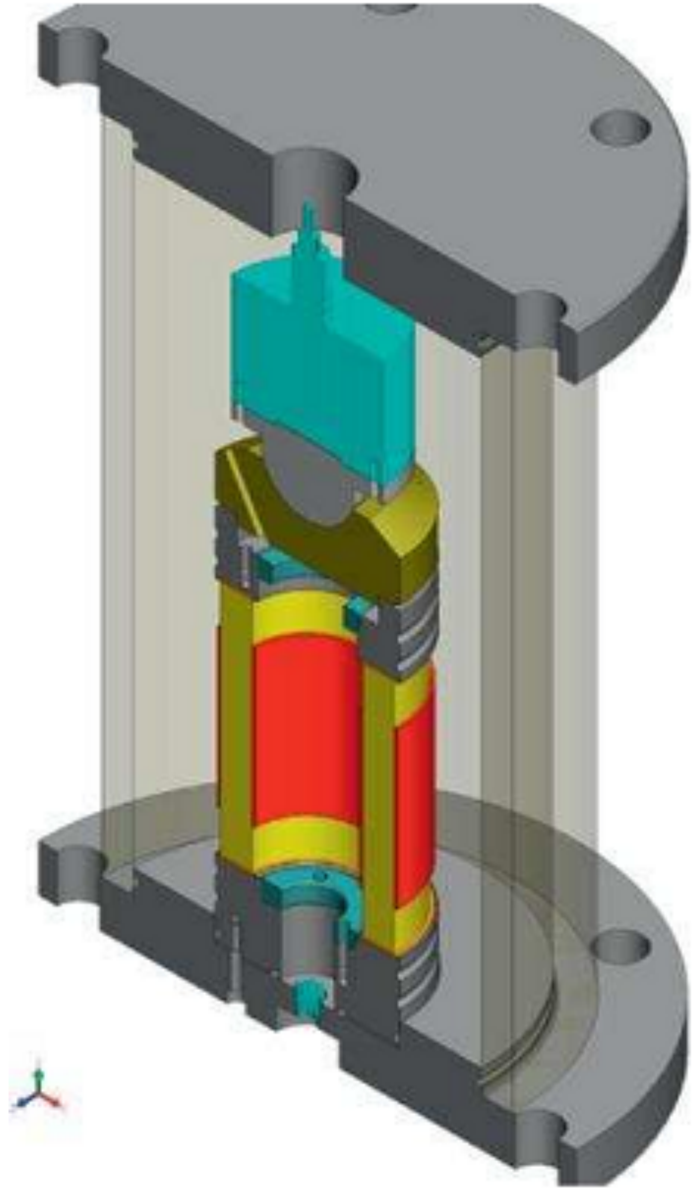
Height 70 mm

Internal and external pressures equal

Top, bottom and lateral drainage

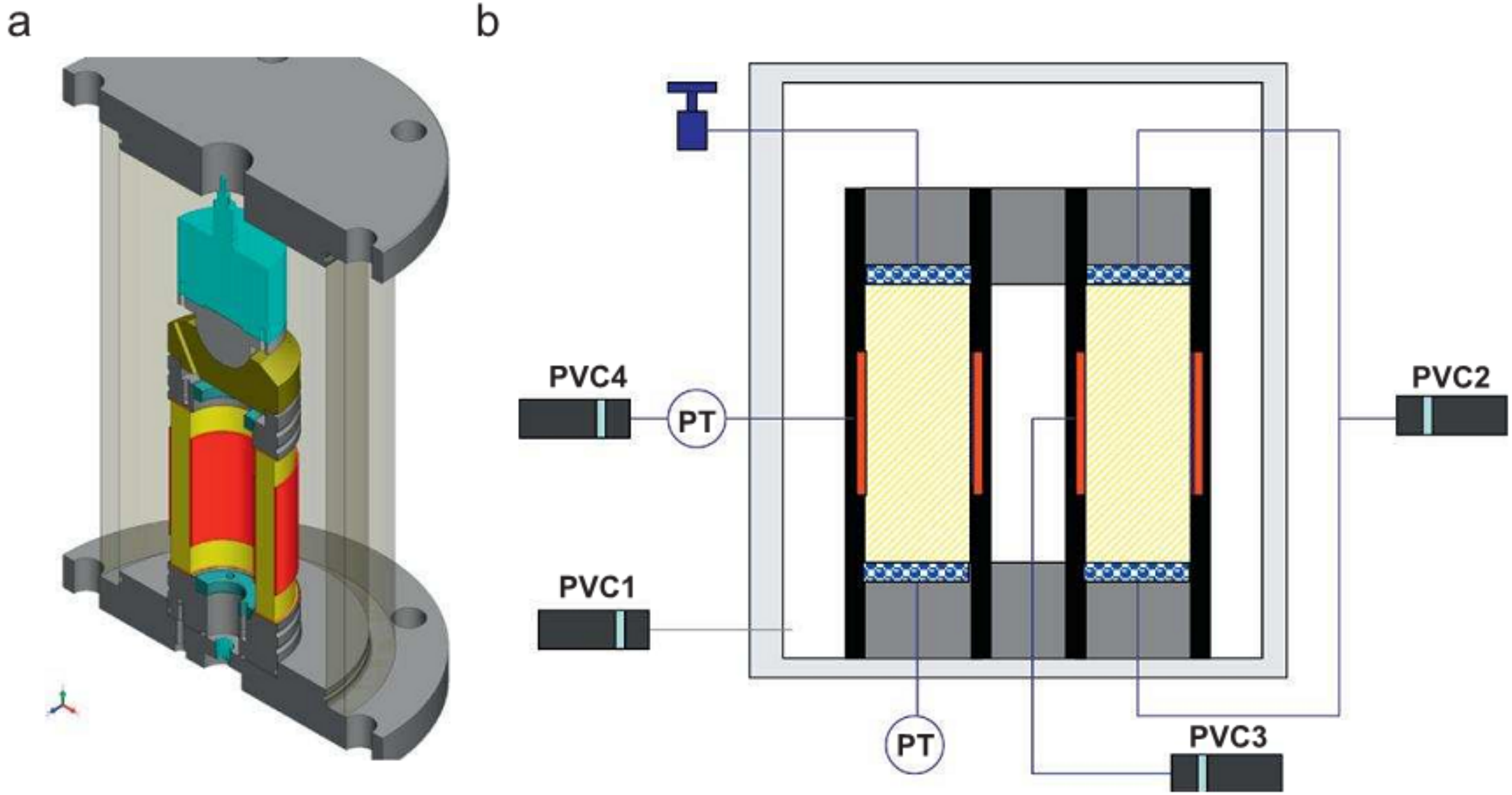
Drainage length H = 10 mm

Half the hollow cylinder thickness



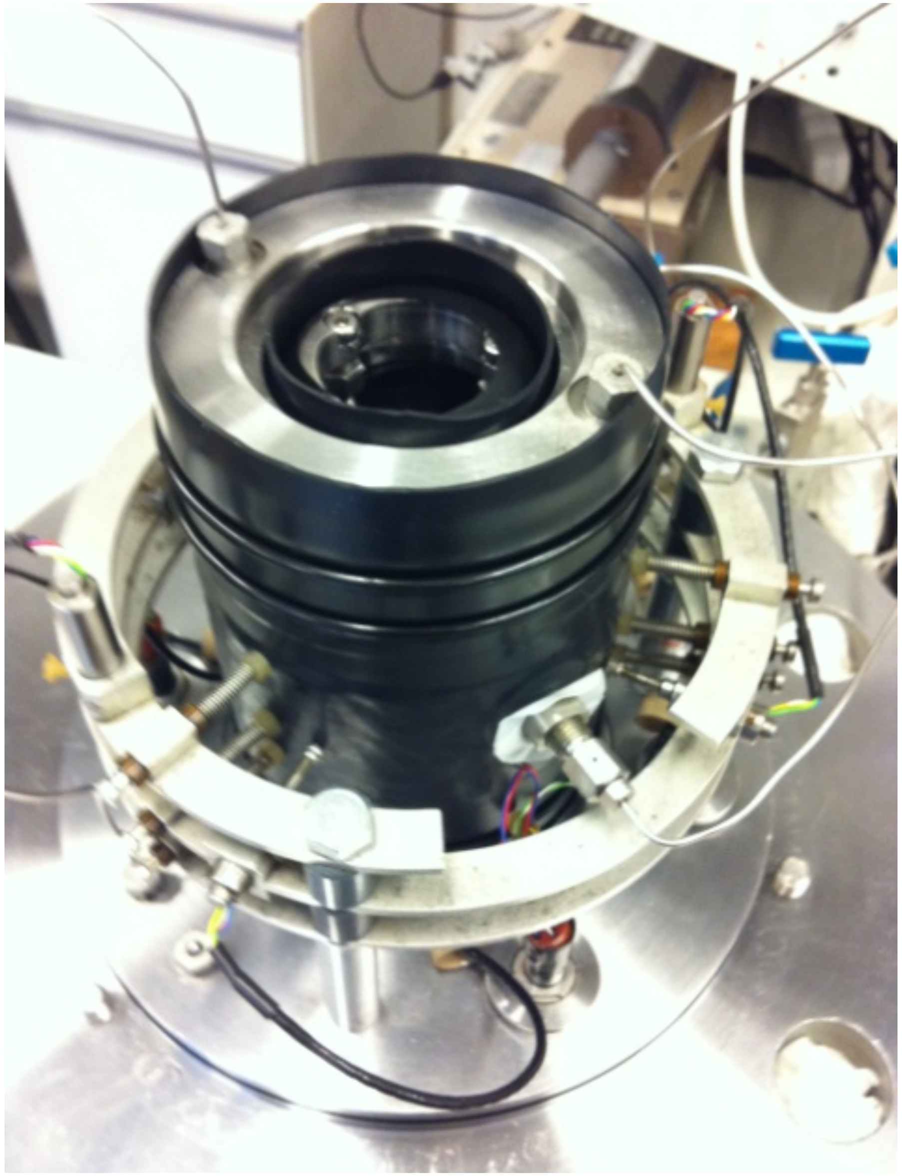
Monfared et al. IJRMMS (201

Pressure volume transducers



Monfared et al. IJRMMS (201

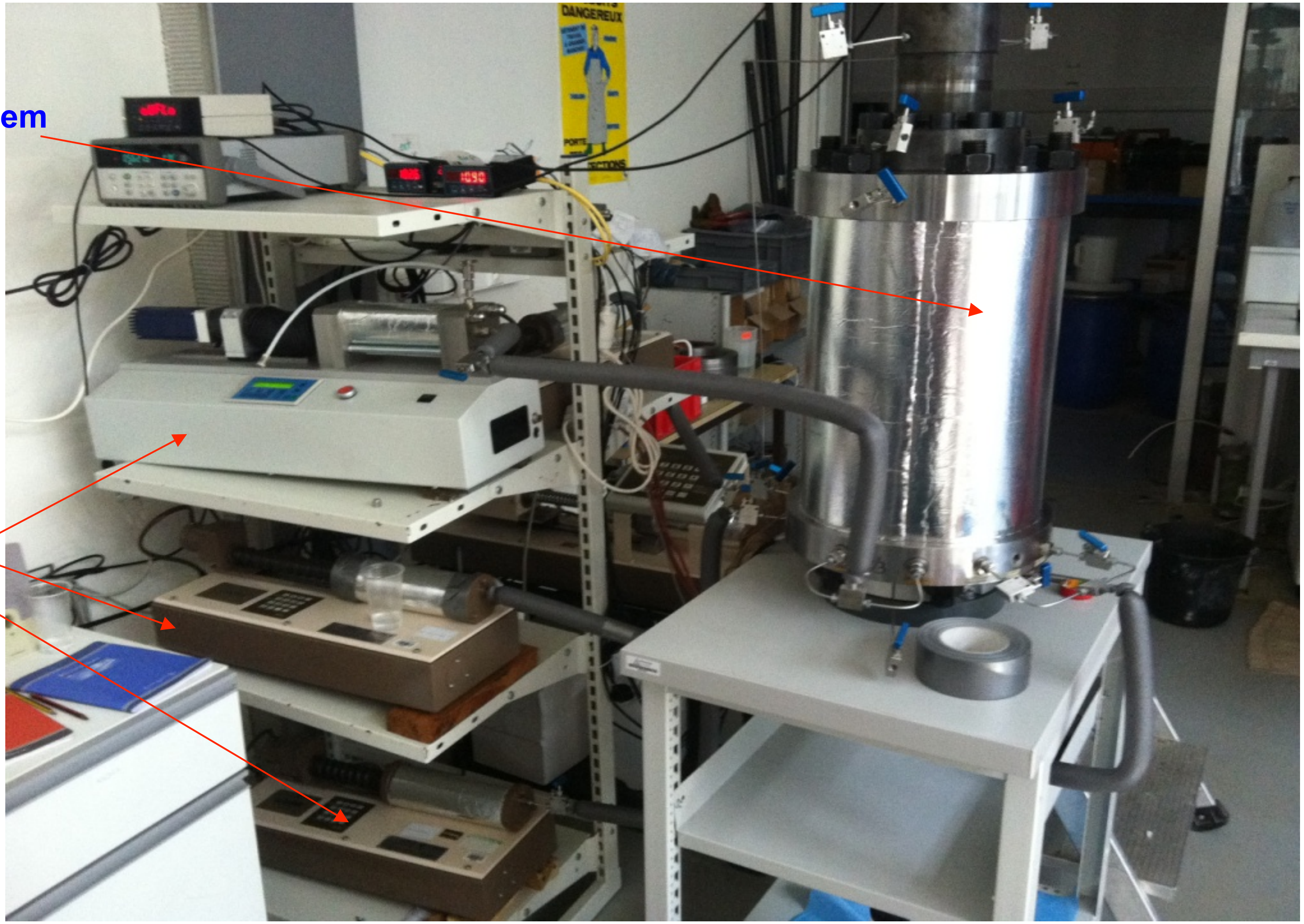
Local strain measurements



Monfared et al. IJRMMS (201

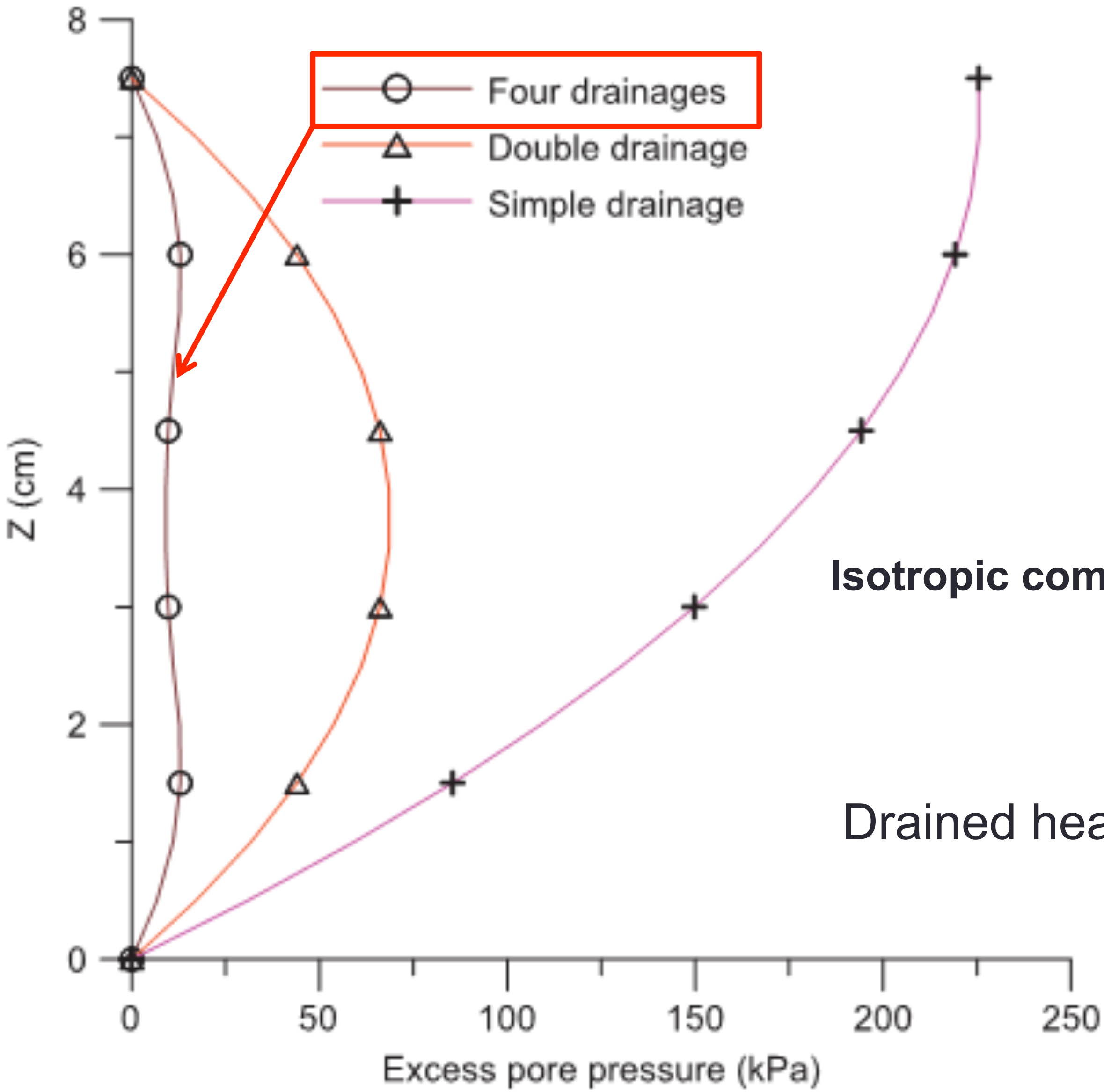
TIMODAZ hollow cylinder apparatus

Heating system
(90°C)



Pressure
Volume
Controllers

Drainage conditions (mechanical and thermal)



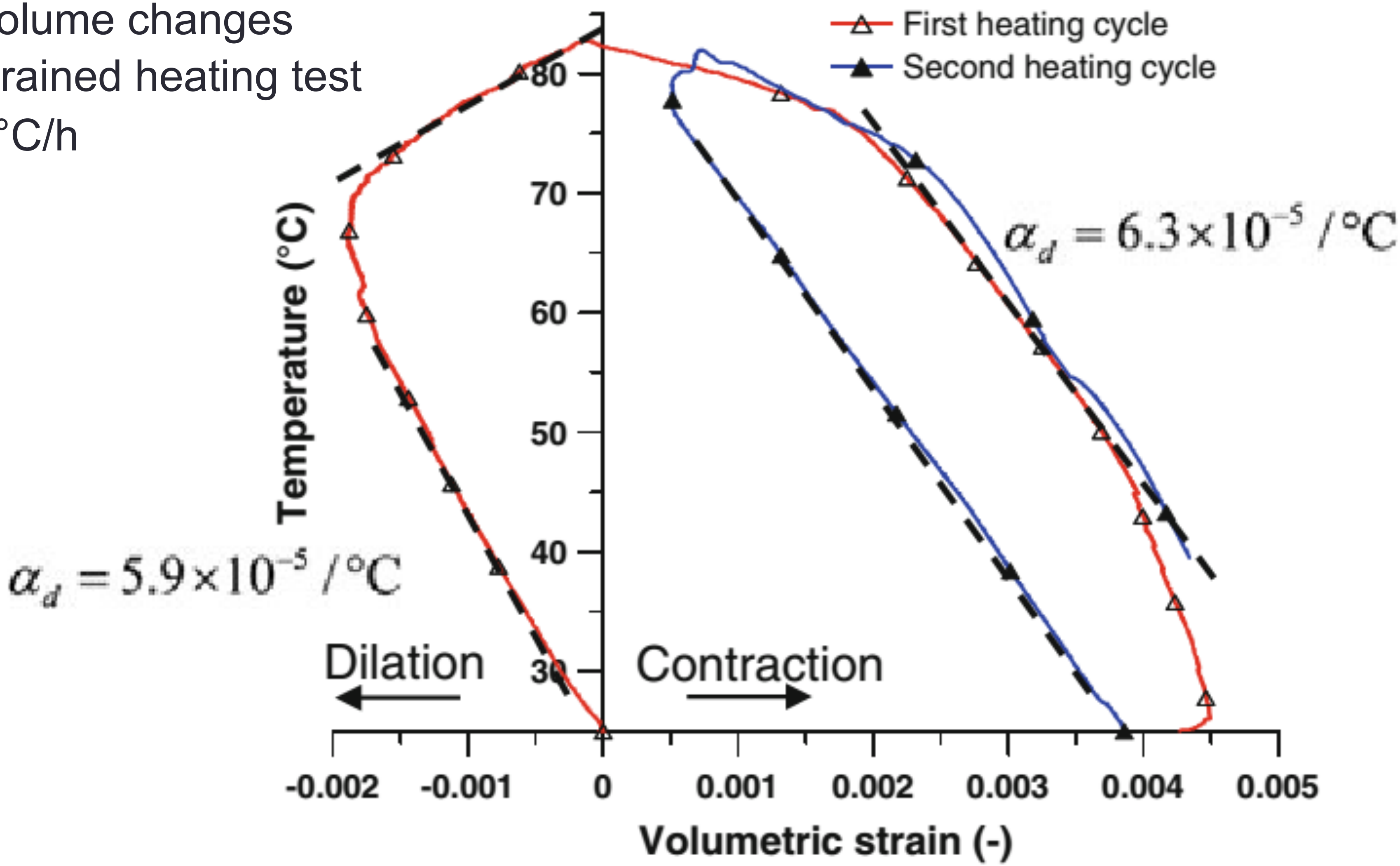
Isotropic compression at 0.5 kPa/mn

Drained heating at 1°C/h

Monfared et al. IJRMMS (201

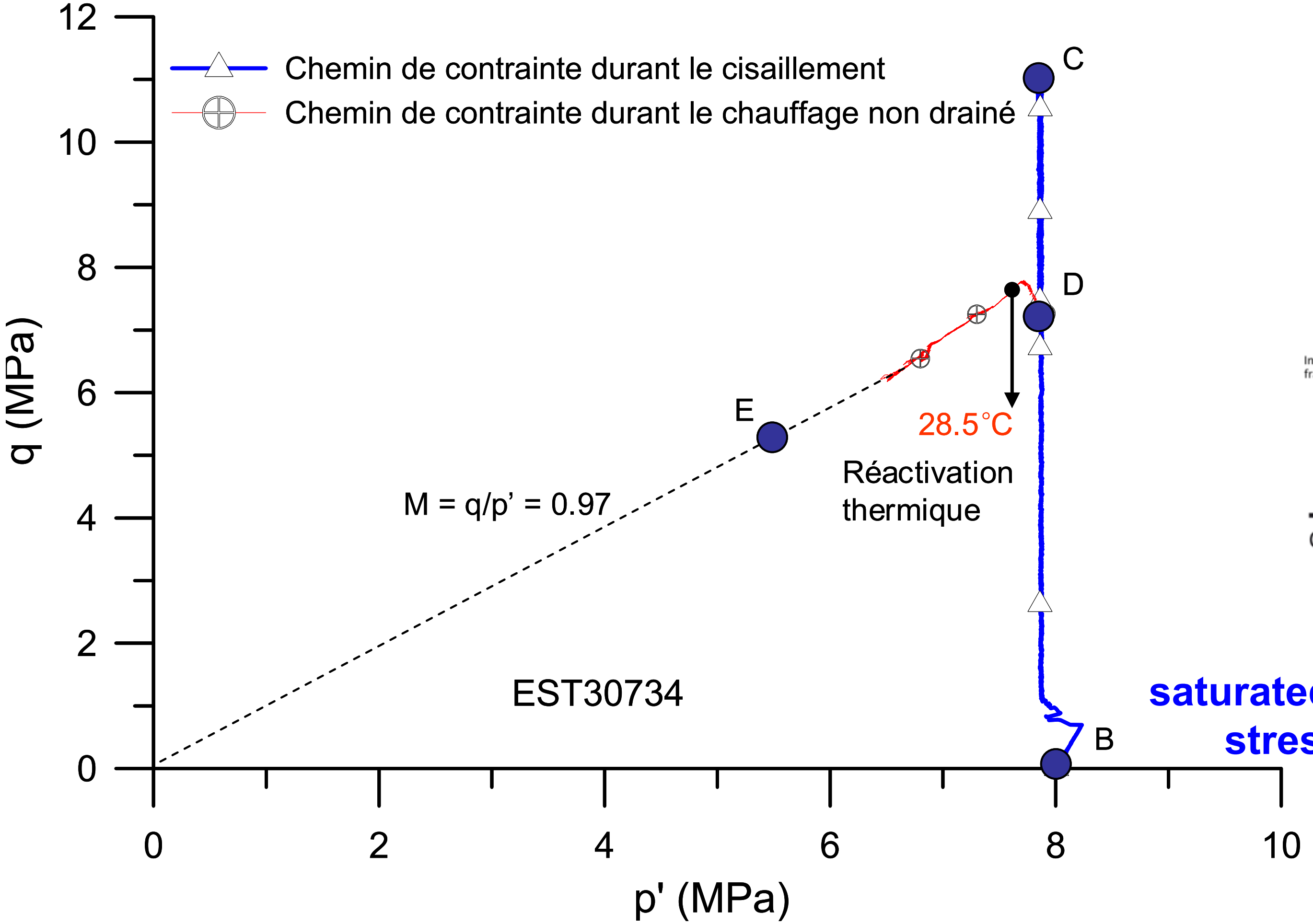
Thermal hardening of Opalinus clay

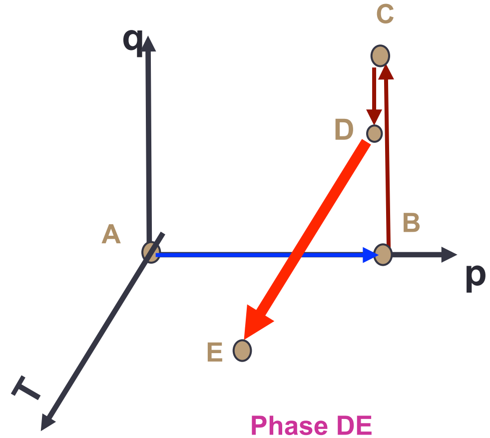
Volume changes
Drained heating test
1°C/h

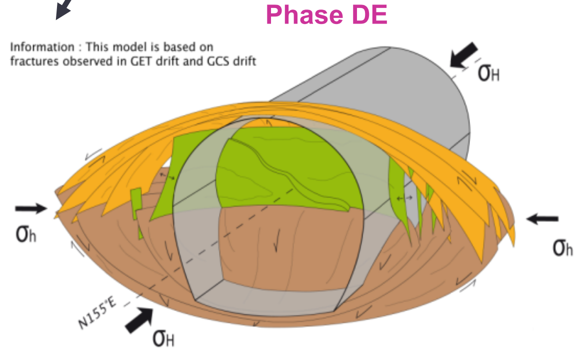


Monfared et al. RMRE 2014

Thermal reactivation of shear plane



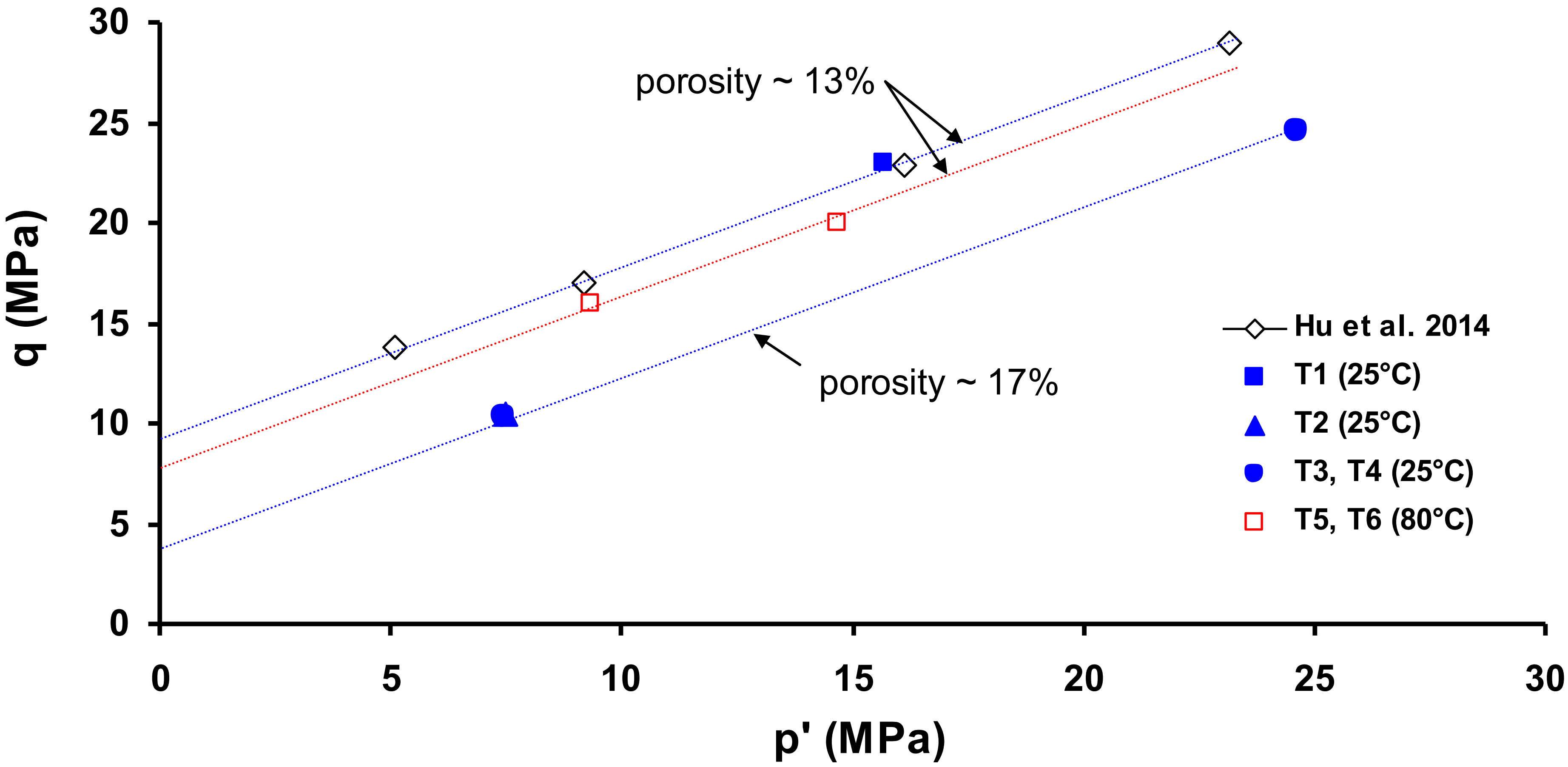




saturated under ~ in-situ stress conditions

Menaceur (2014)

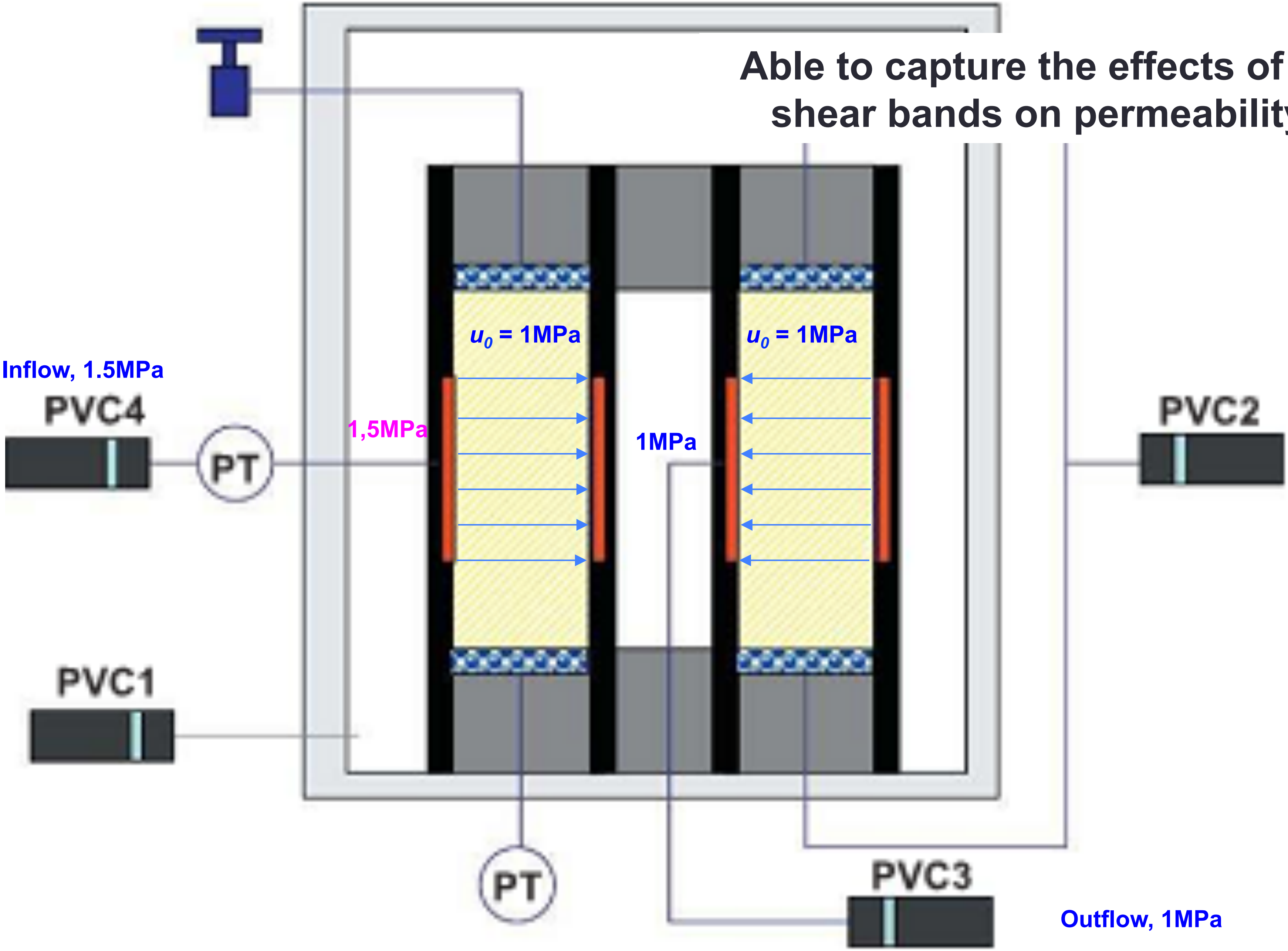
Failure criterion (temperature), COx



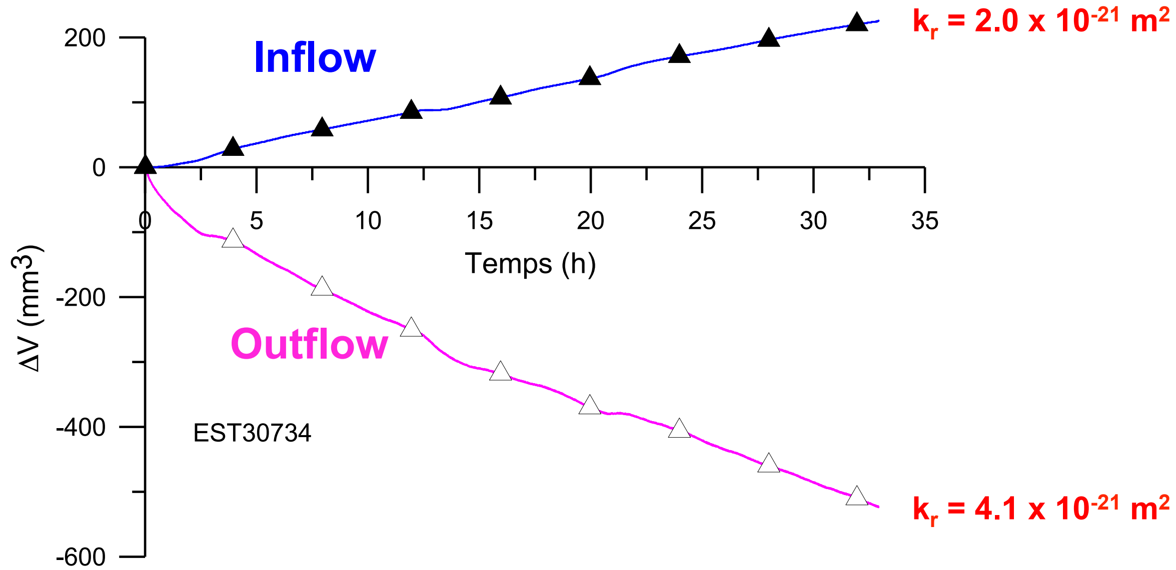
Menaceur et al. IJRMMS 2015

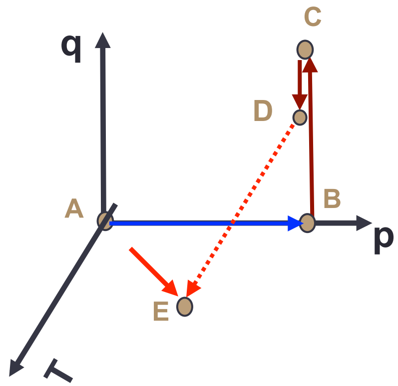
Radial permeability test

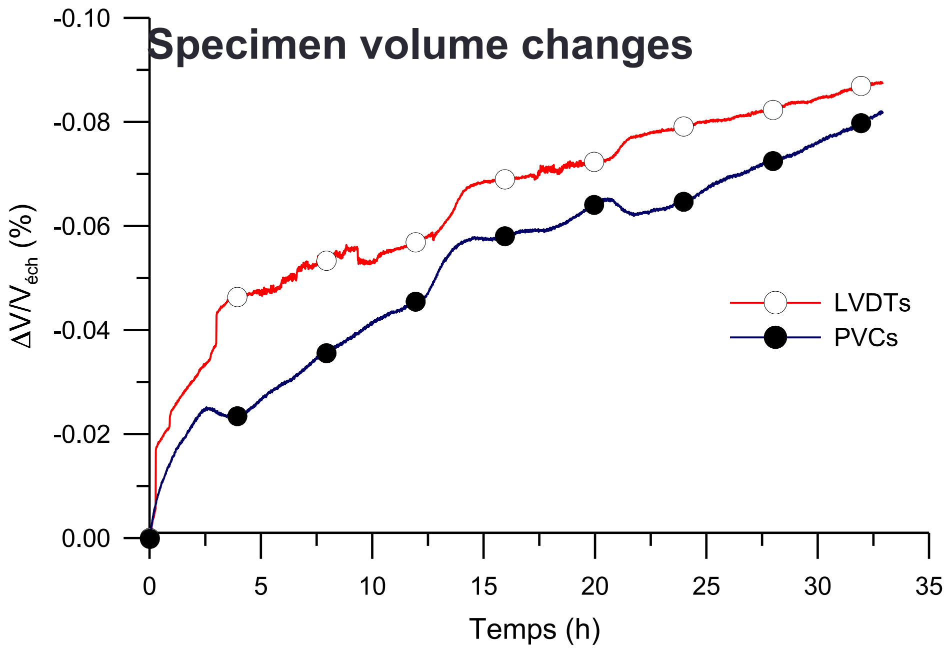
Able to capture the effects of shear bands on permeability



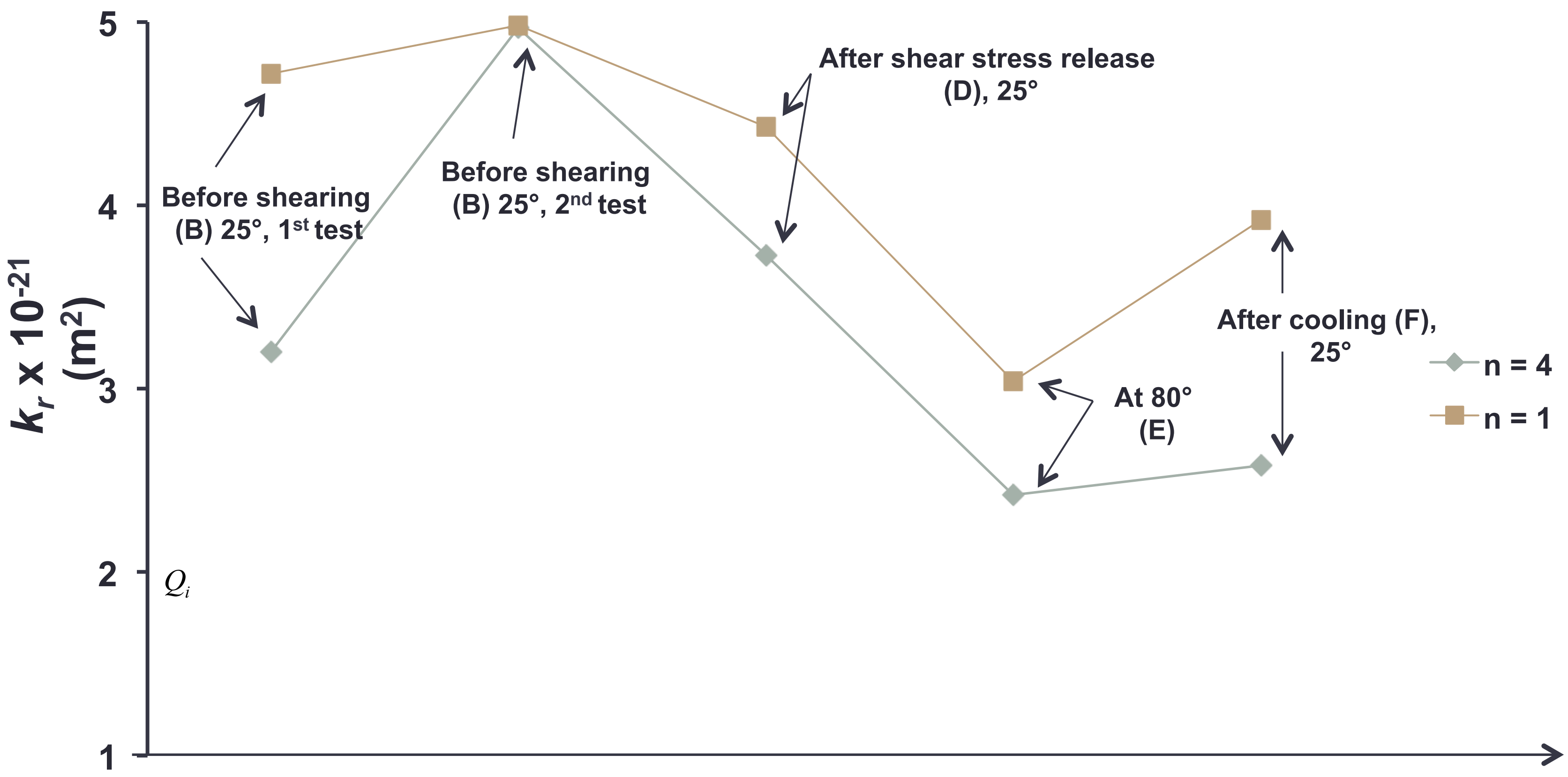
Radial permeability test, sheared specimen



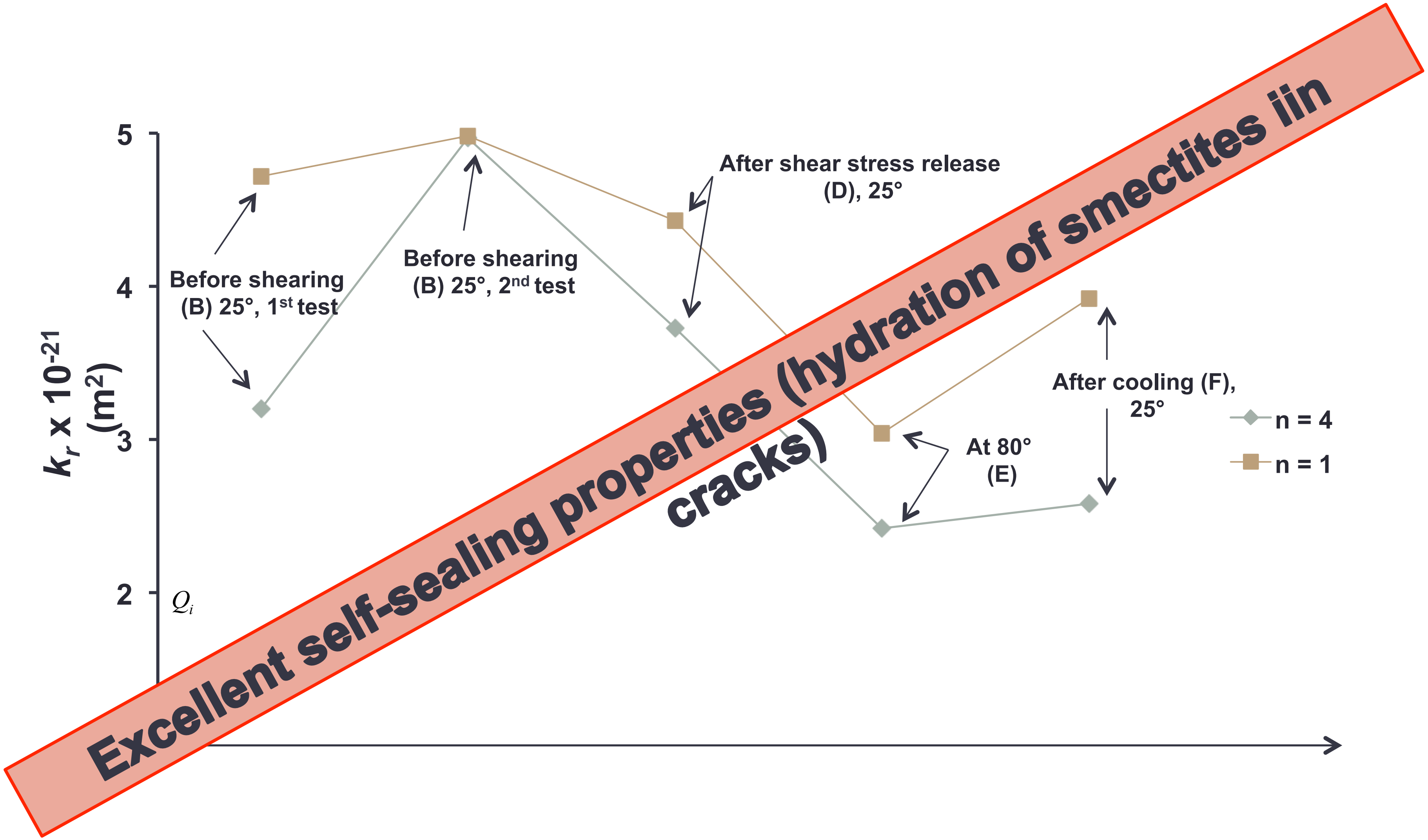




Changes in permeability, COx claystone



Changes in permeability, COx claystone



Concluding remarks

THM couplings related to various geomechanical problems:

- Unsaturated soils (collapse)
- Radioactive waste disposal (claystones and bentonites)
- Reservoir rocks (multiphase chalk)

- Importance of clay
- Importance of clay-water interaction (DDL, smctite hydration)
- Importance of microstructure
- Difficult lab testing invery low permeability claystone and shale (host rocks for waste isolation, caprocks for CO2 sequestration, shale gas and oil)
  - Special new devices with short drainage length:
    Complete saturation and good drainage conditions
- Thermal pressurisation
- Thermal hardening
- Excavation damaged zone (EDZ)
  - No effects of cracks on permeability and excellent self-sealing behaviour (initial and 80°C)
- Help better understand and model THM phenomena