

# How to characterize deformation mechanisms in rocks? From micro-experiments to *in-situ* experiments

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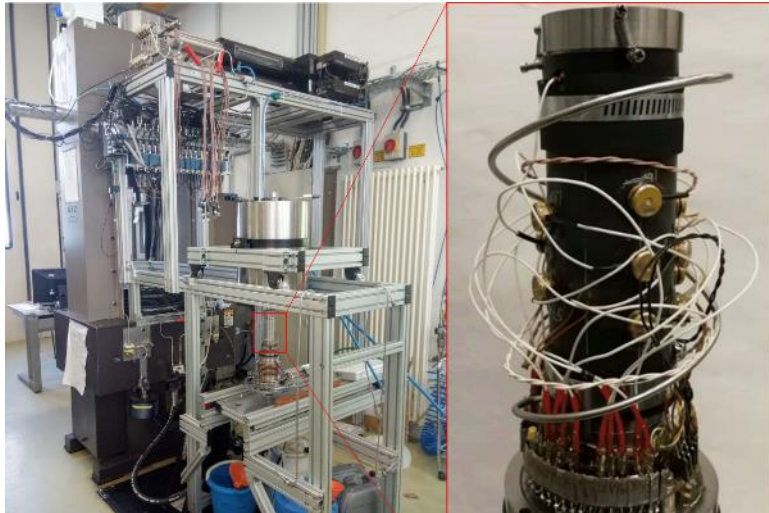
IRSN : P. Dick

Pitlochry, 26<sup>th</sup> March 2023

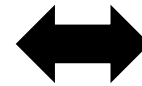


# Fracturing : from the lab to the field

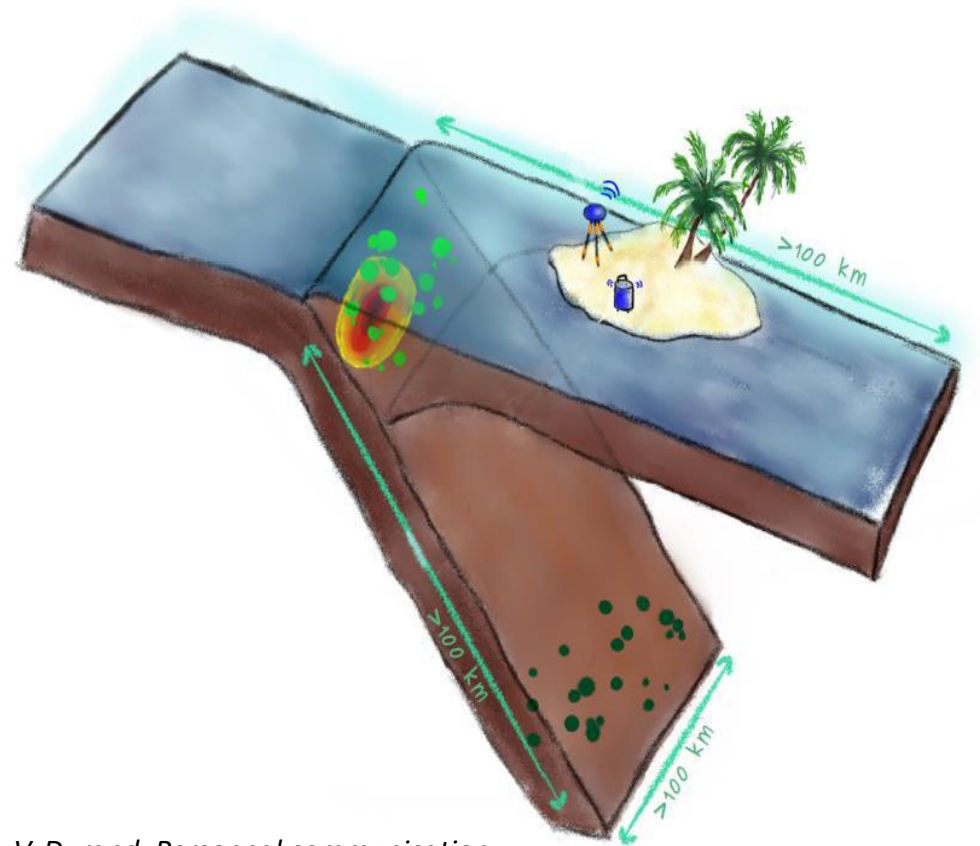
Triaxial tests : „full control“



cm



Field observations : toward the unknown



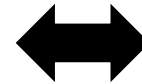
*V. Durand, Personal communication*

100km

# Fracturing : from the lab to the field

## Triaxial tests : „full control“

- Different strain measurement types (SG, LVDT)
- AE monitoring (active + passive)
- Force measurements
- Control of strain rate, temperature, pressure ( $P_c$ ,  $P_p$ ...)



## Field observations : toward the unknow

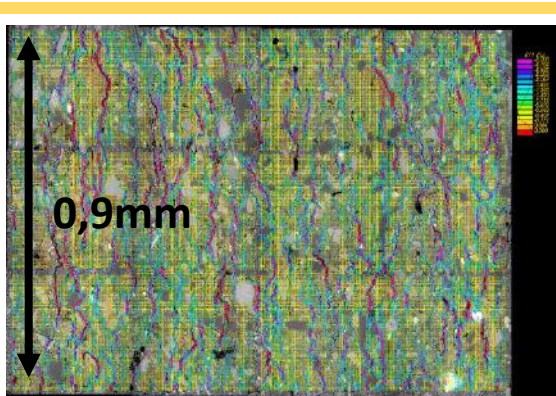
- Large scale geophysics
- Seismology
- Geodesy

cm

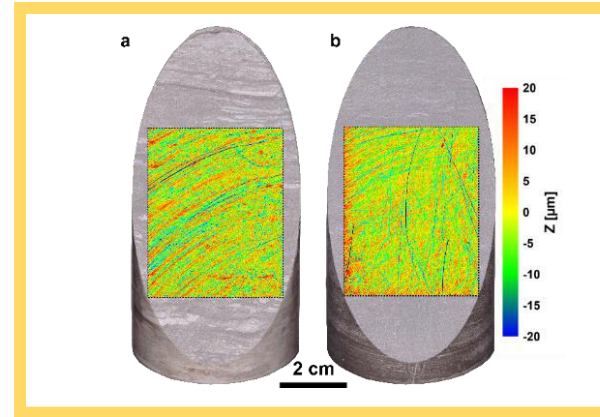
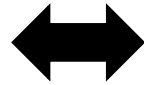
100km

# Fracturing : from the lab to the field

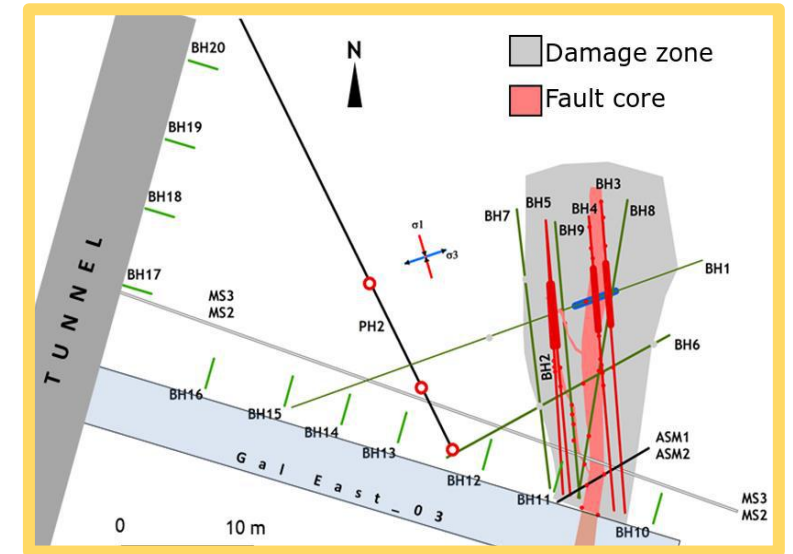
*How to link these scales and provide a mechanical understanding of fault zones?*



micro-mechanical testing



Triaxial testing

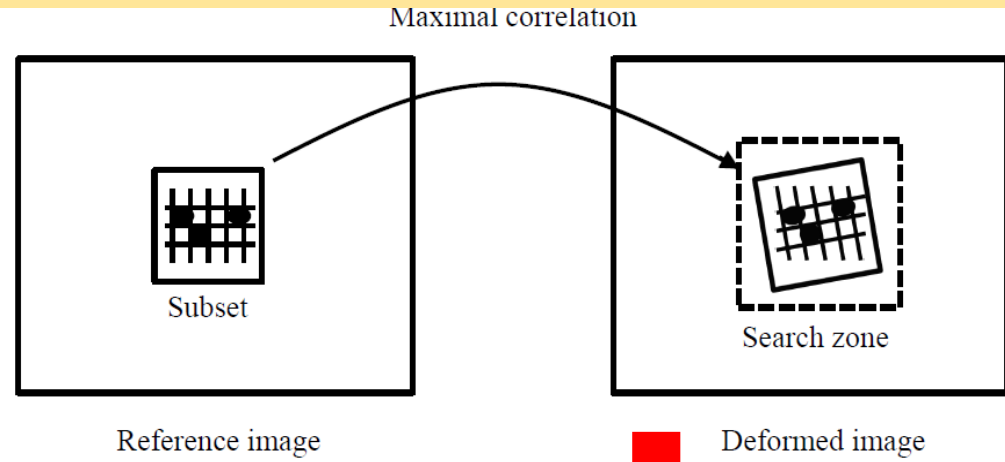


*In-situ testing*

# Micromechanics

# Micromechanics : DIC

- Digital image correlation (DIC)
- CMV (*M. Bornert, 1996*)
- Displacement field
- Computation of strain components

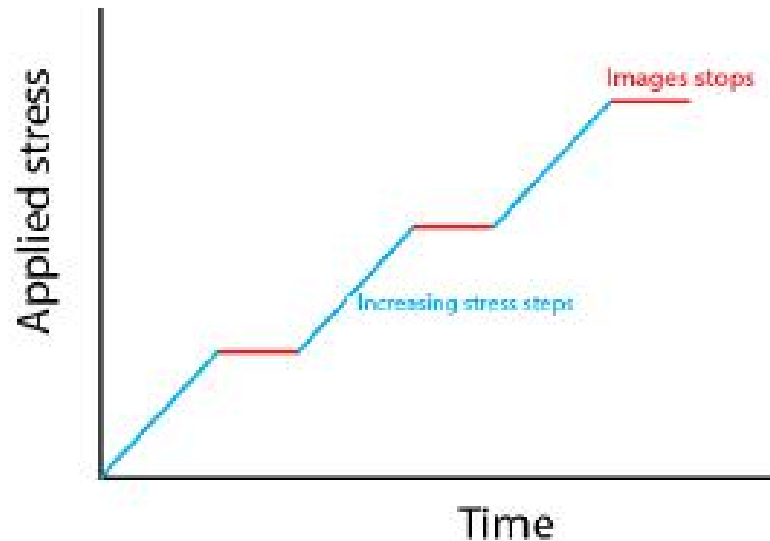
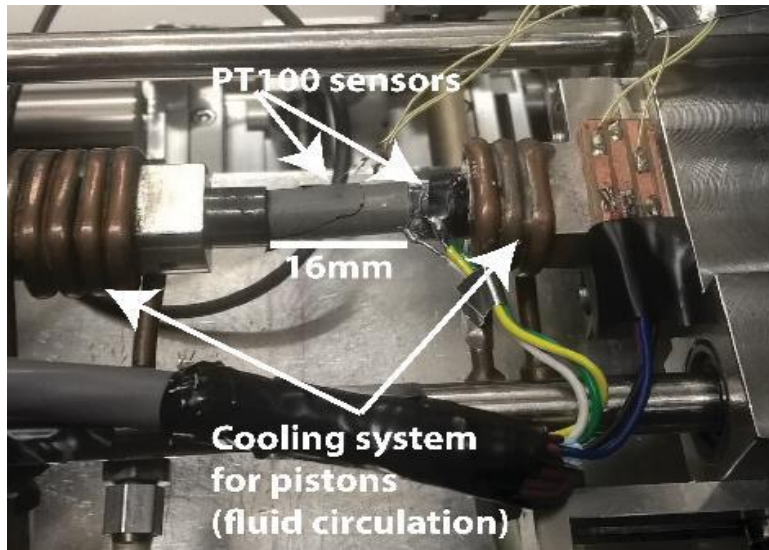


*L. Wang, 2012*

SEM imaging,  
resolution  $\sim 1\mu\text{m}$   
(and below)

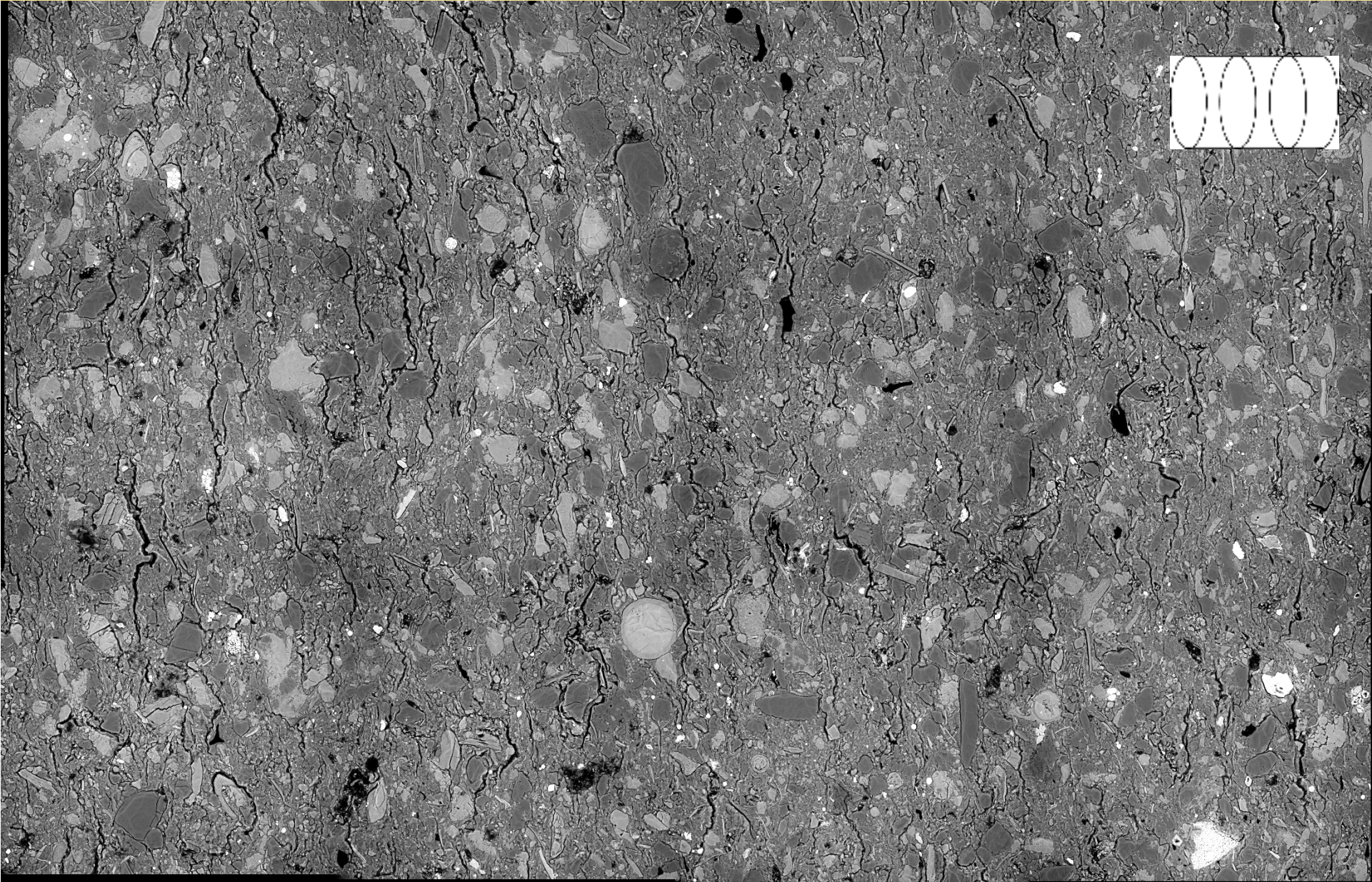
Optical  
measurements,  
resolution  $55\mu\text{m}$

# Micromechanics : SEM



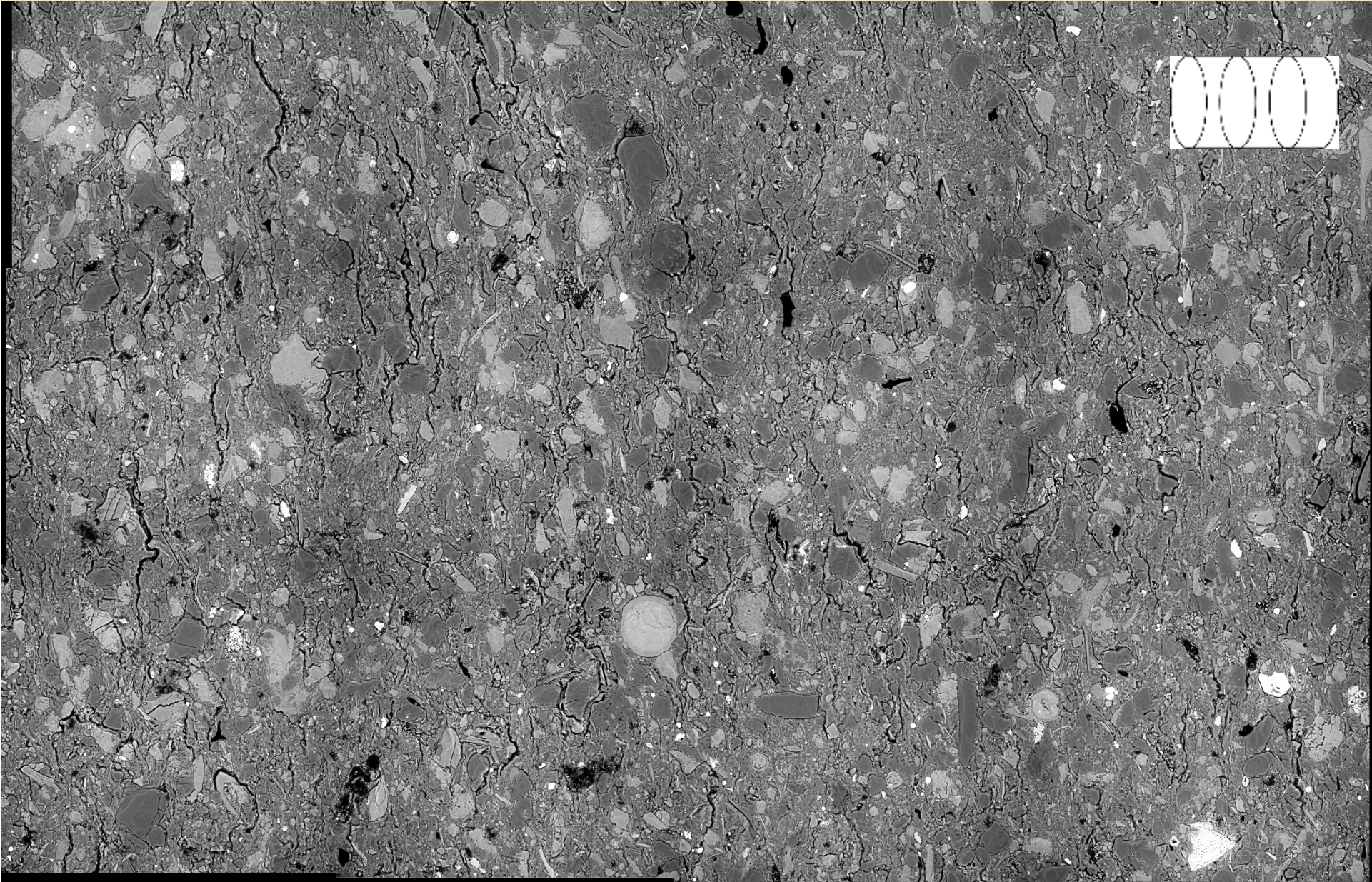
- **ESEM** : Environmental SEM, allowing **control of pressure (water vapour) and temperature**
- For sample preparation, everything is done to preserve **natural water content** :
  - Diameter 8mm*
  - Flat surface dry cut*
  - First phase of manual polishing (0,3 $\mu$ m)*
  - Ionic polishing with cryogenisation (3h)*
- **Step loading experiment.** Samples were loaded with a small rate (force controlled)
- After loading, we waited for **relaxation**
- A mosaic of 12 pictures was taken during each step for a broad investigation (= **a full picture of 900\*1200 $\mu$ m**)
- Total duration of the experiments : **24 hours, NON STOP**

# Micromechanics : SEM

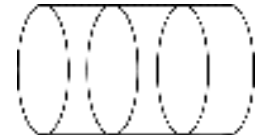
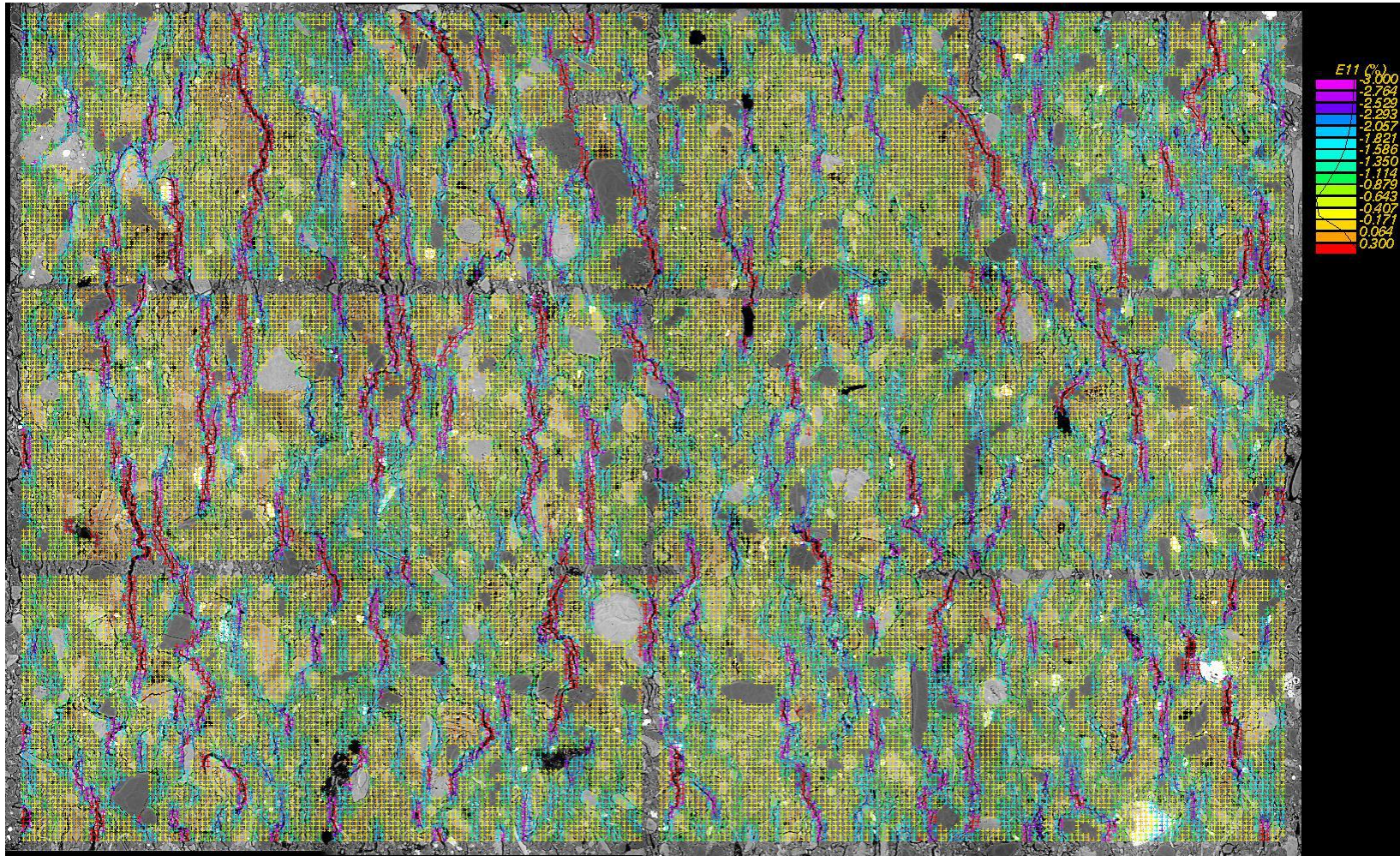




# Micromechanics : SEM



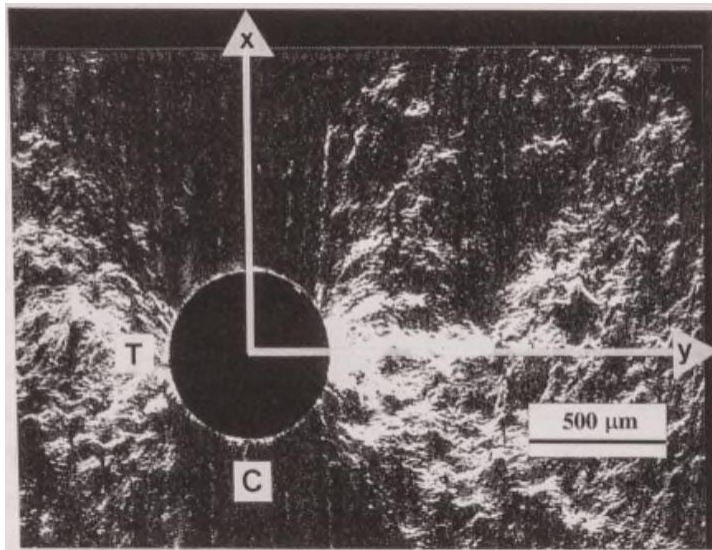
# Micromechanics : SEM



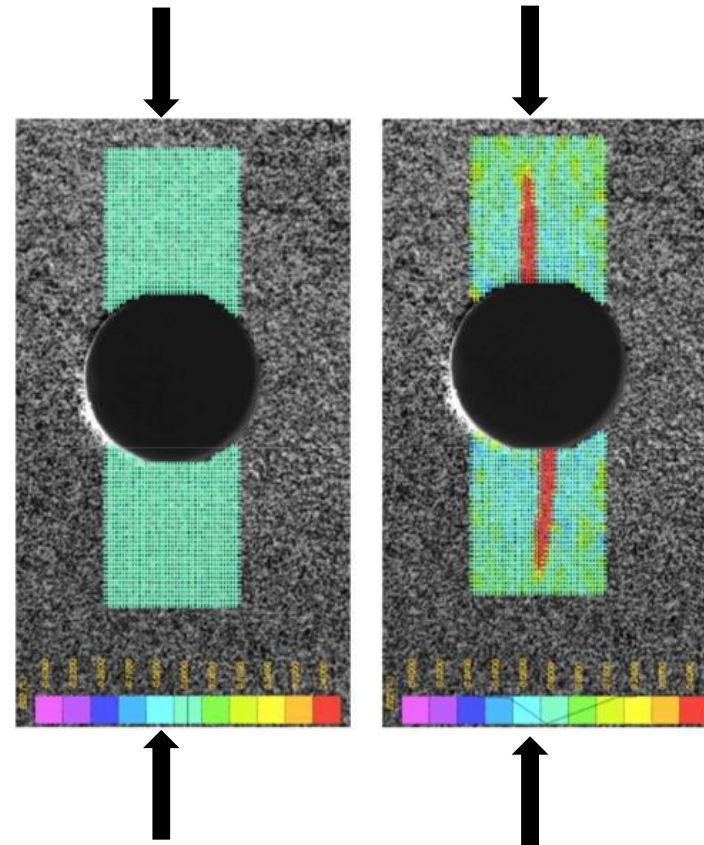
- E11 component (horizontal)

# Micromechanics : Optical experiments

Double Cleavage Drilled Compression :  
=> Using the hole as a stress concentrator



*Zioupou et al. 1995*



*Romani et al. 2015*

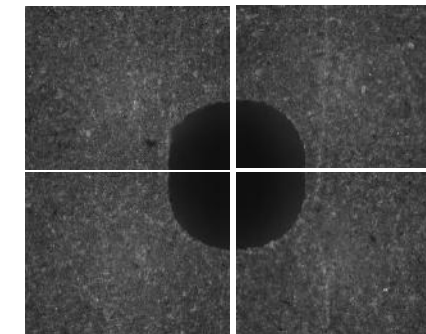
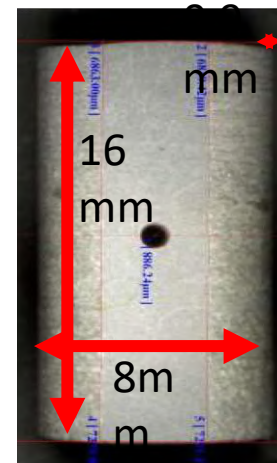
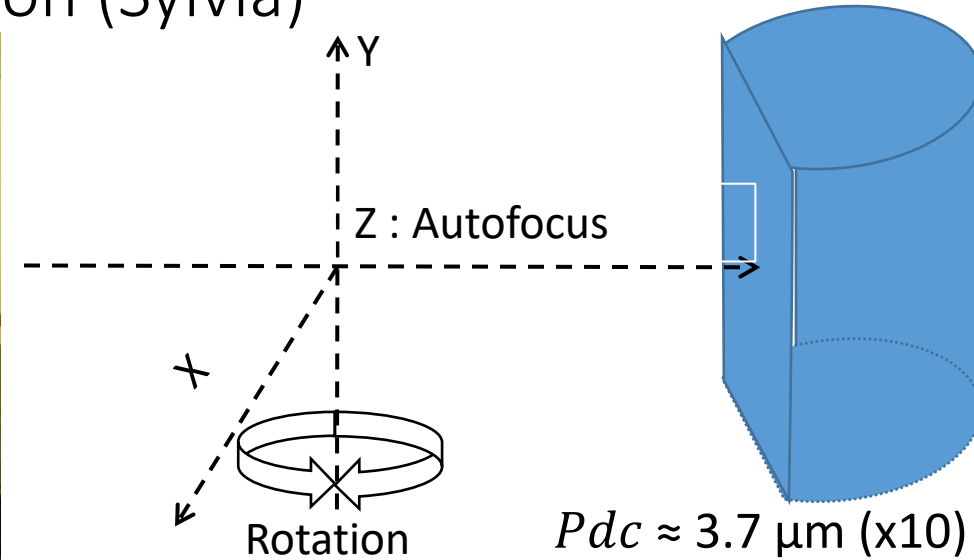
# Micromechanics : Optical experiments

## Experimental Setup : image acquisition (Sylvia)

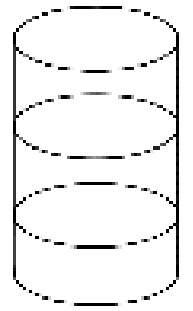
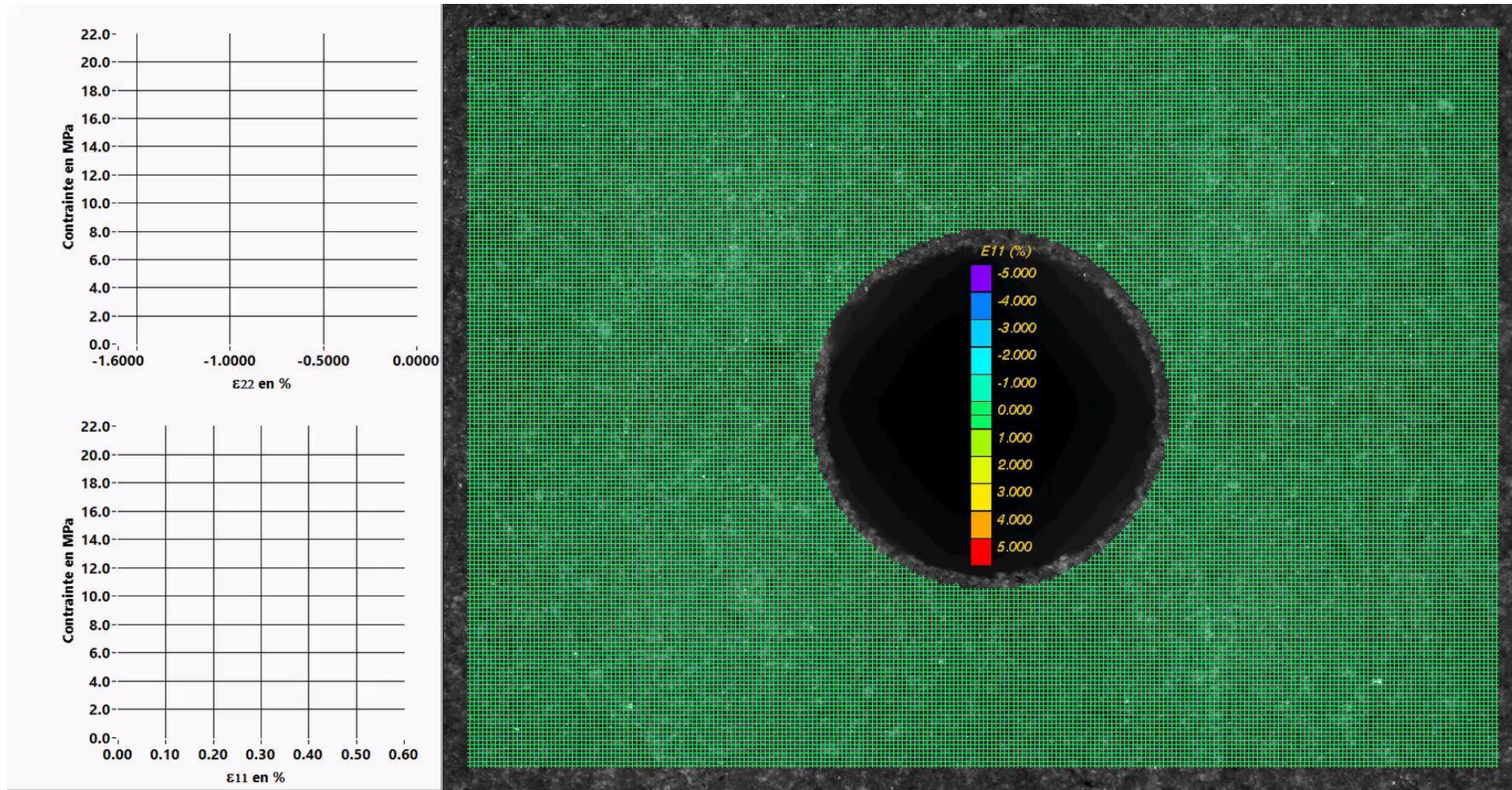


Yang et al. 2012

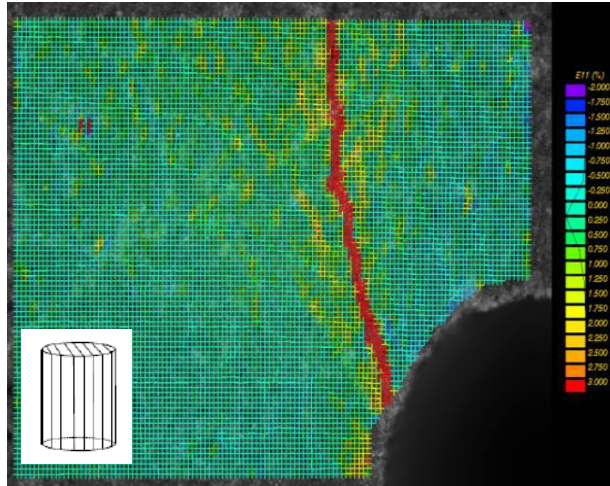
- Diameter : 8mm, length :16mm
- Diameter of the hole : 0.9mm
- Manually polished surface (dry)
- The camera is constantly taking pictures. It takes about 12s to take all 4 pictures
- Duration of the experiment : ~1hour



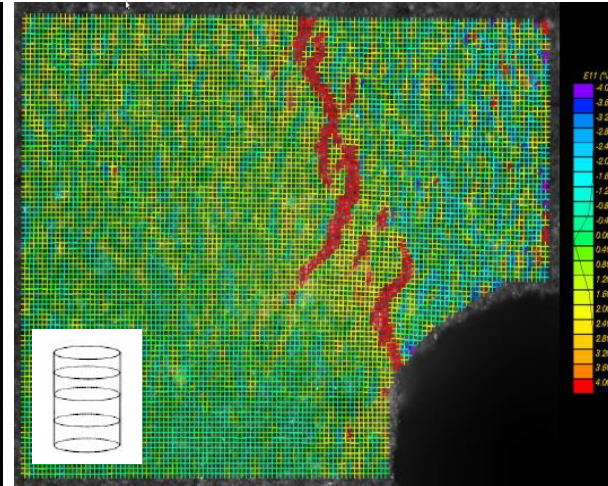
# Micromechanics : Optical experiments



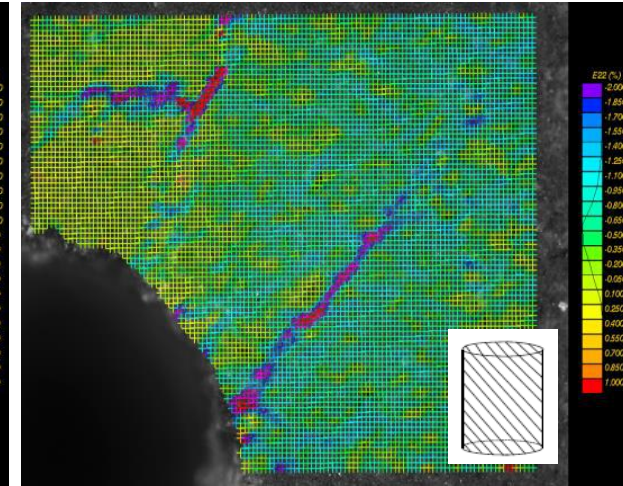
# Micromechanics : Optical experiments



- Single fracture propagating along the bedding orientation



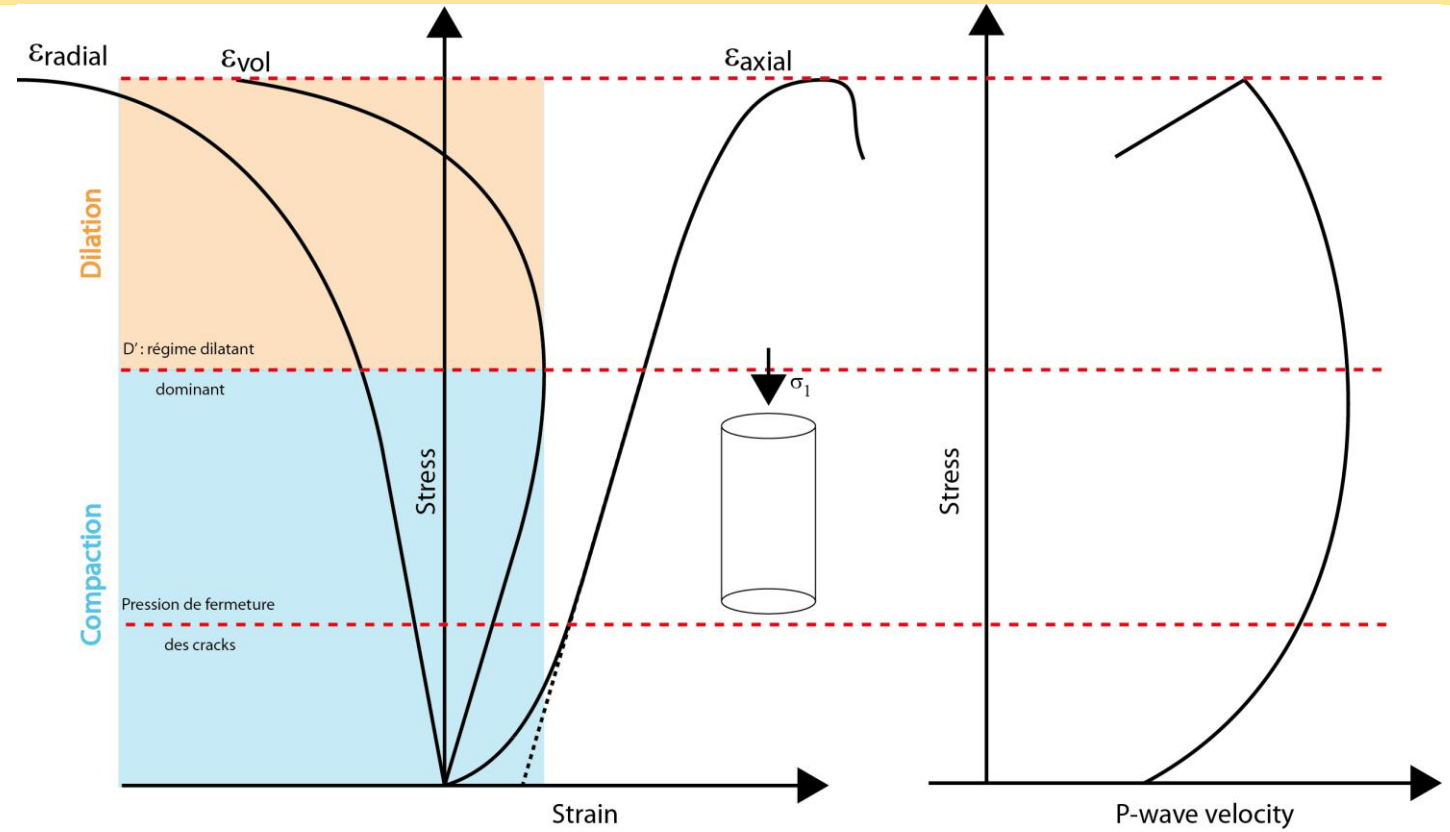
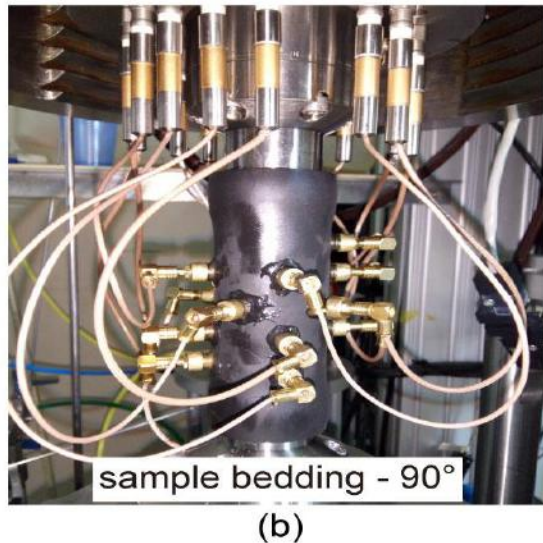
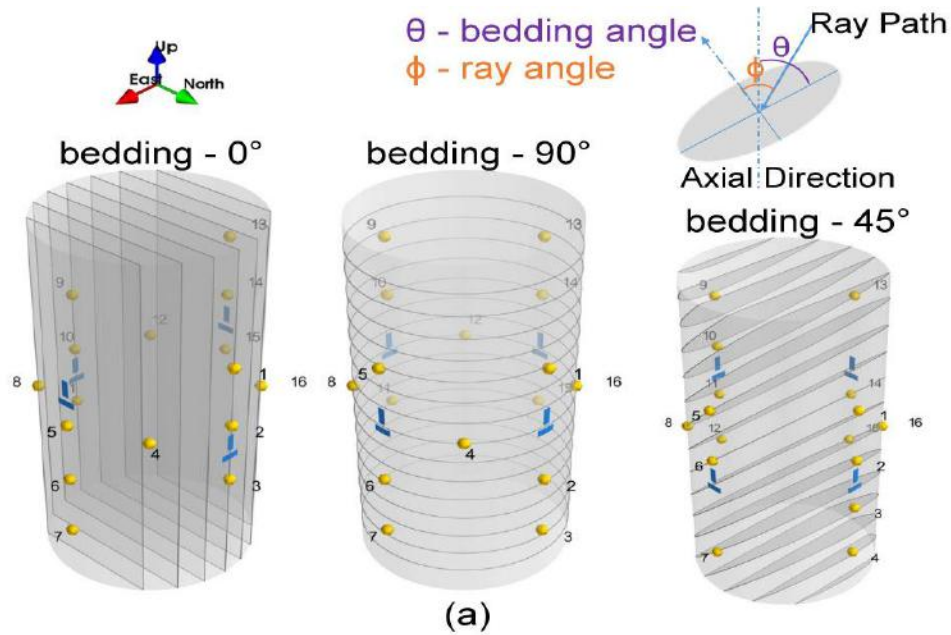
- fracture set developing at  $45^\circ$
- Both mode 1 and shearing
- Stair case shape



- Sliding along the bedding planes

# Triaxial testing (cm)

# Cm-scale triaxial testing

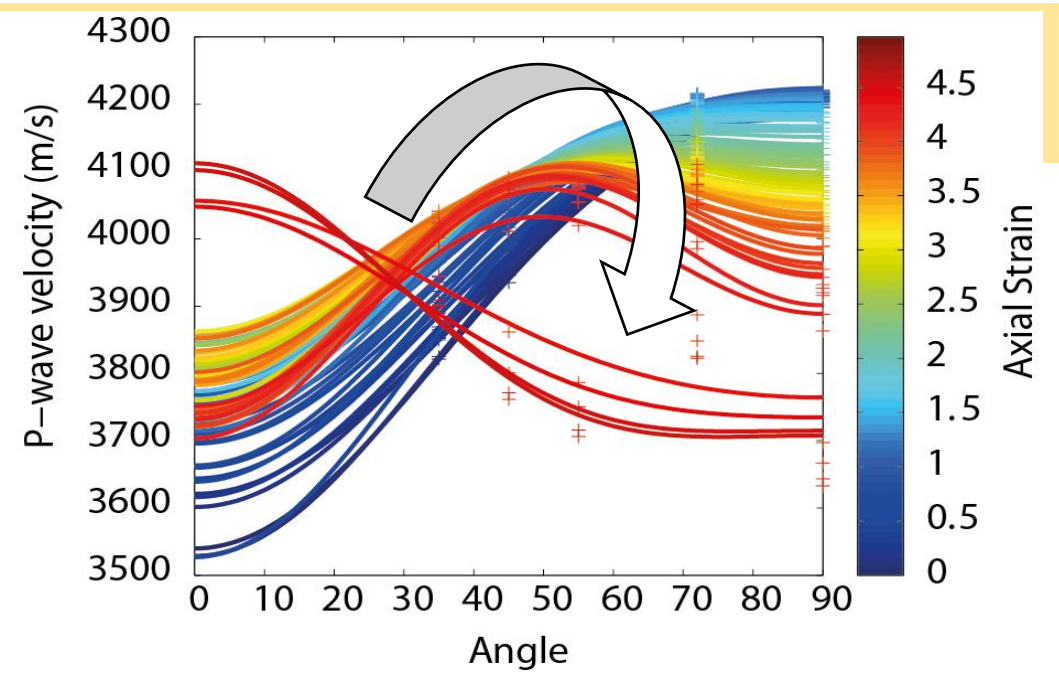
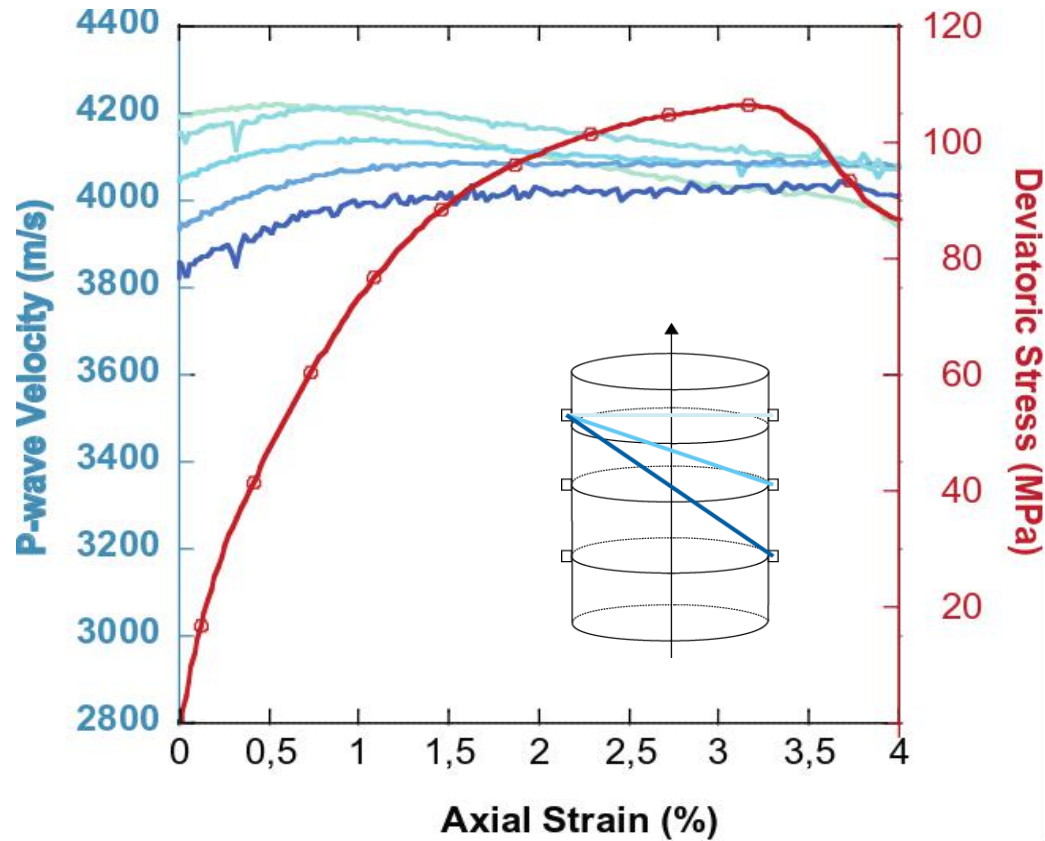


- Size : D 42 mm × L 84.5 mm
- Density: 2.57 g/cm<sup>3</sup>, dry polished
- 3 bedding angles: 0°, 90°, 45°
- 16 acoustic sensors (P/S waves)
- 4 pairs (axial/radial) of strain gauges

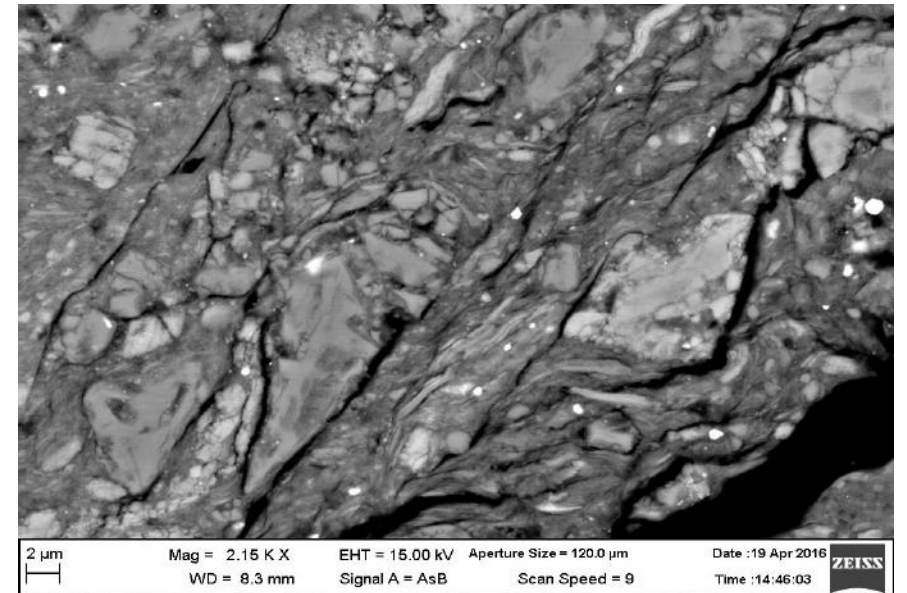


# Cm-scale triaxial testing

Mechanical behavior : stress-strain + continuous P-wave recording

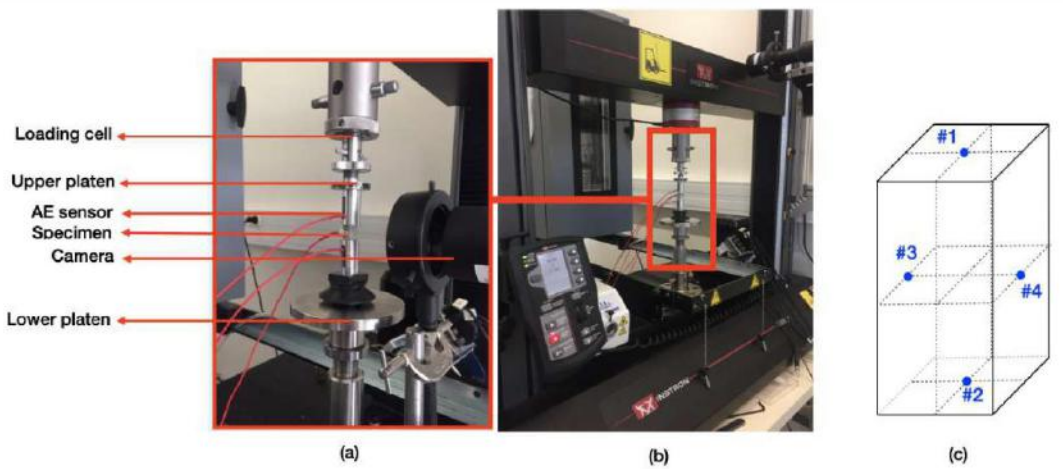


P-wave velocity model (from Thomsen's parameters)

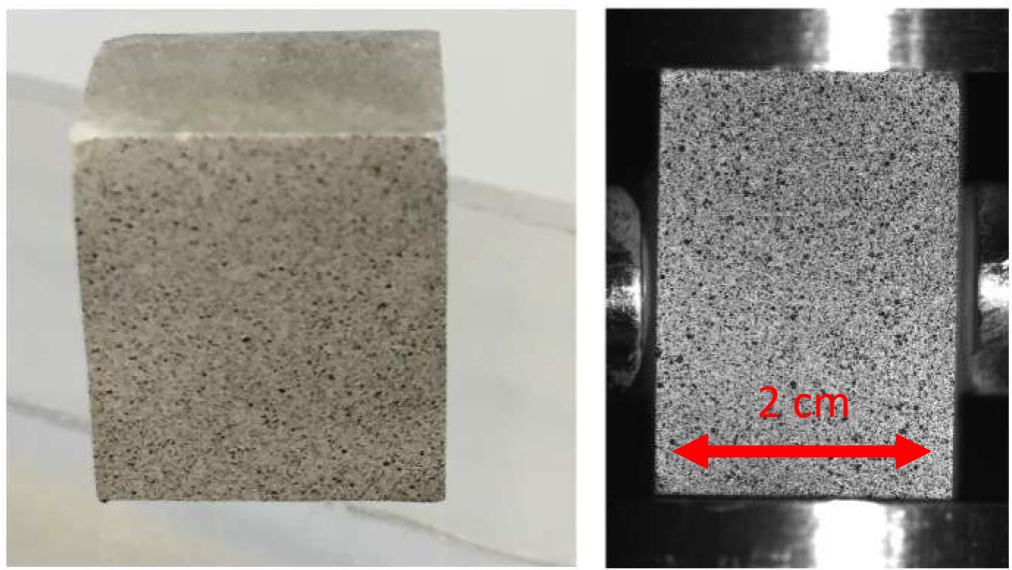
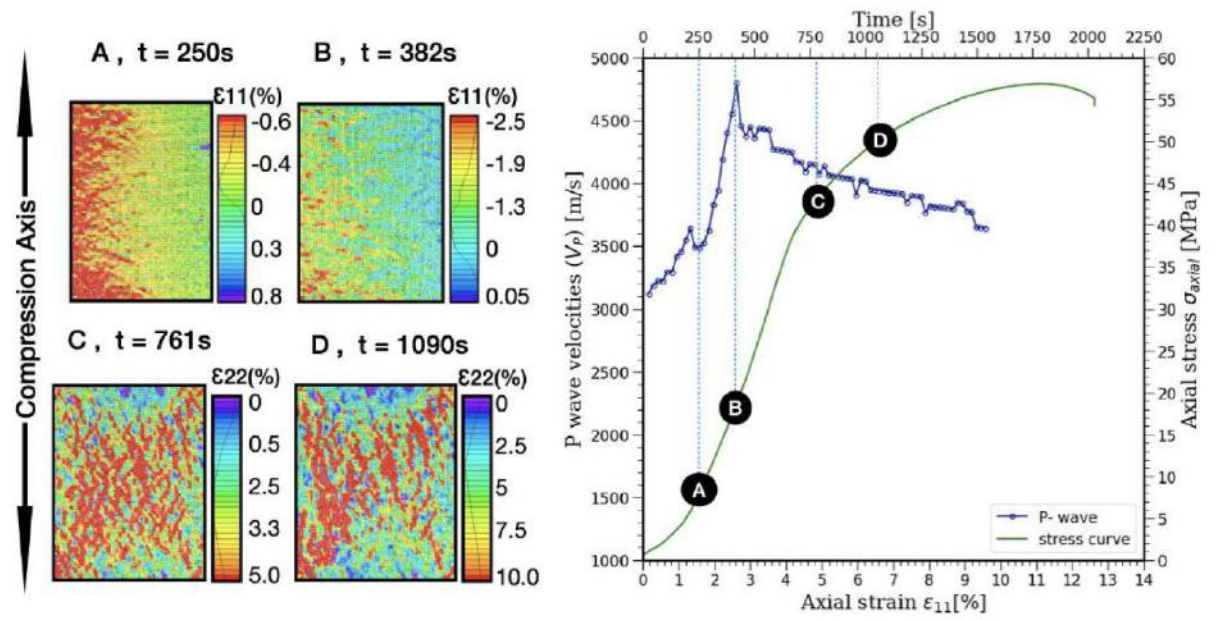


Post-mortem SEM image

# Taking the best of both worlds!

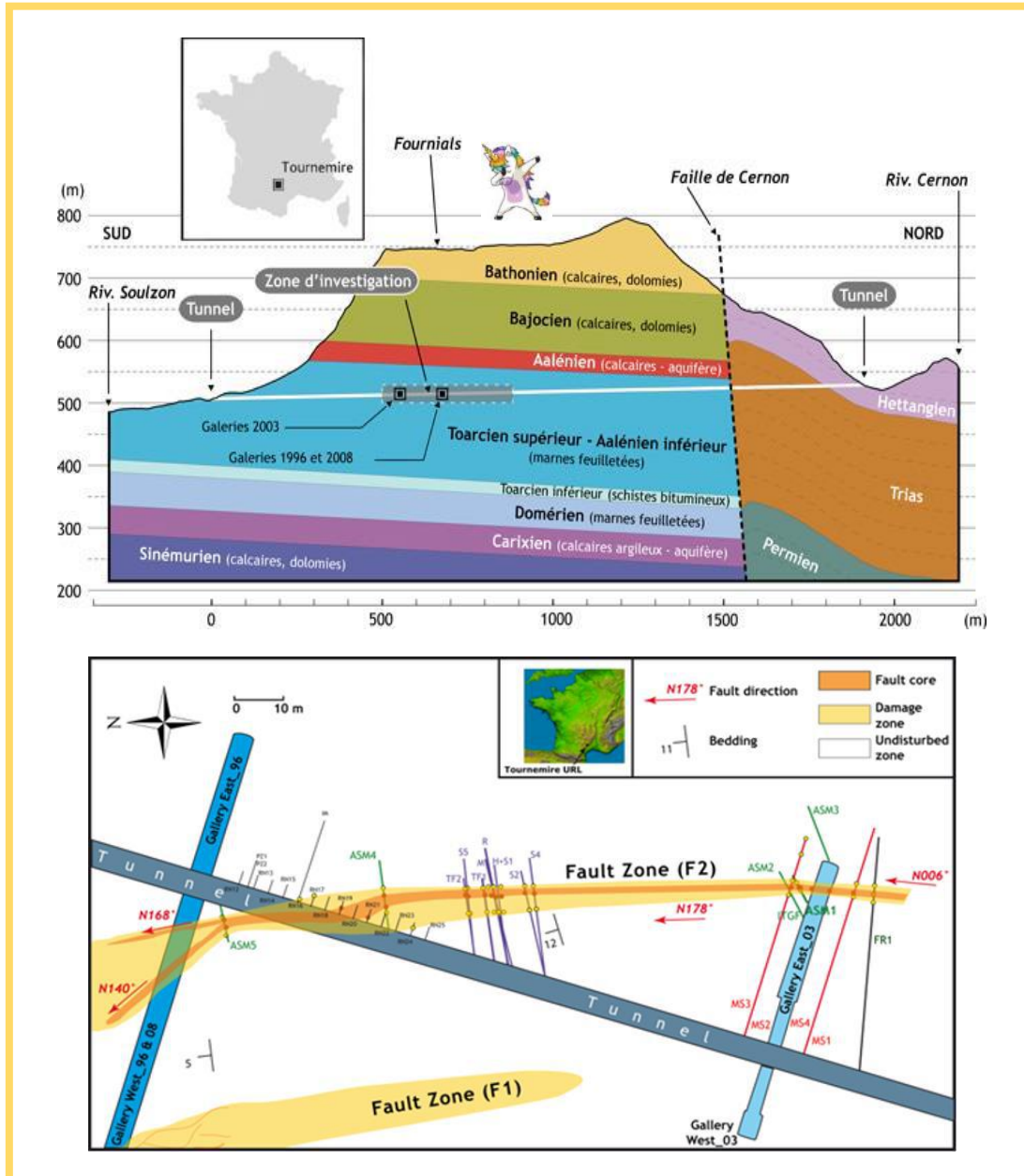


Preliminary results on coupling of DIC measurements with P-wave velocities acquisition on salt rocks

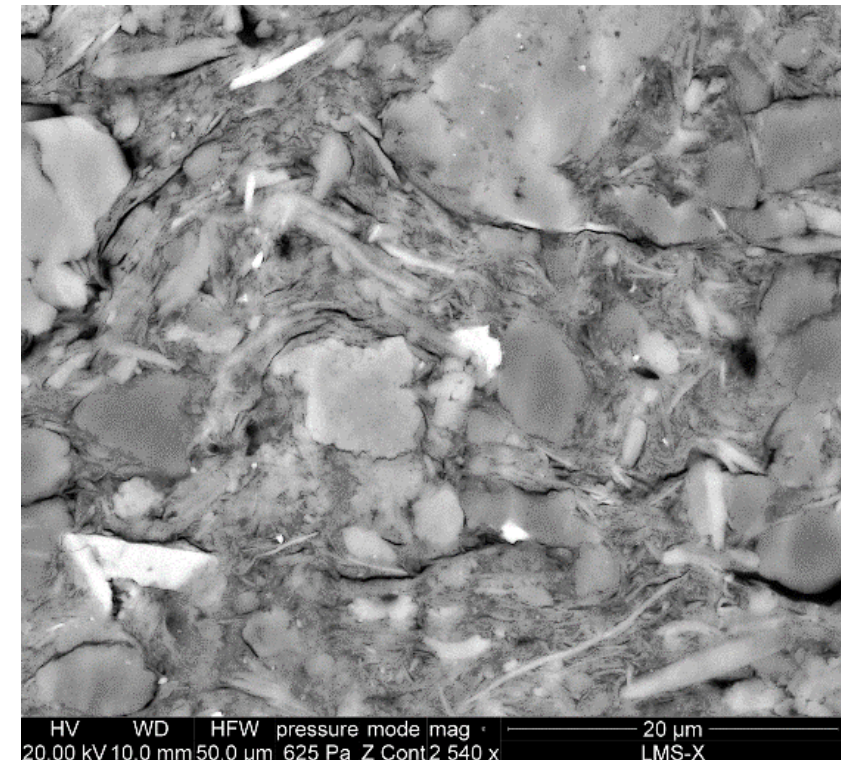


In-situ scale

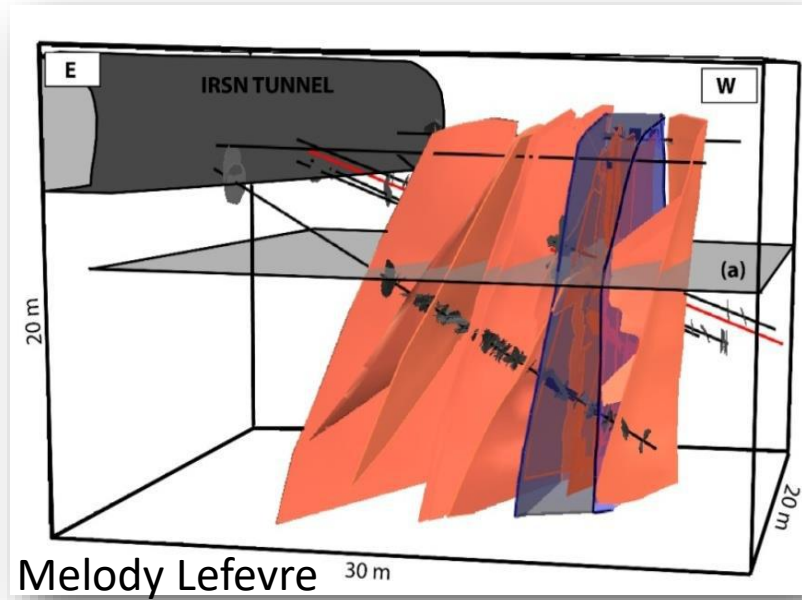
# ULR of Tournemire



- Underground Research Laboratory : URL
- Clay rich rocks are **sedimentary** rocks, presenting **fine grained particules**. They are considered for geological storage of nuclear wastes.
- Toarcian layer presents **~50% of clay minerals**
- Clay rich rocks are known to exhibit a **strong anisotropy, related to mineral shape, pore shape and bedding**.



# Petrophysics : bringing the field in the lab



Intact zone



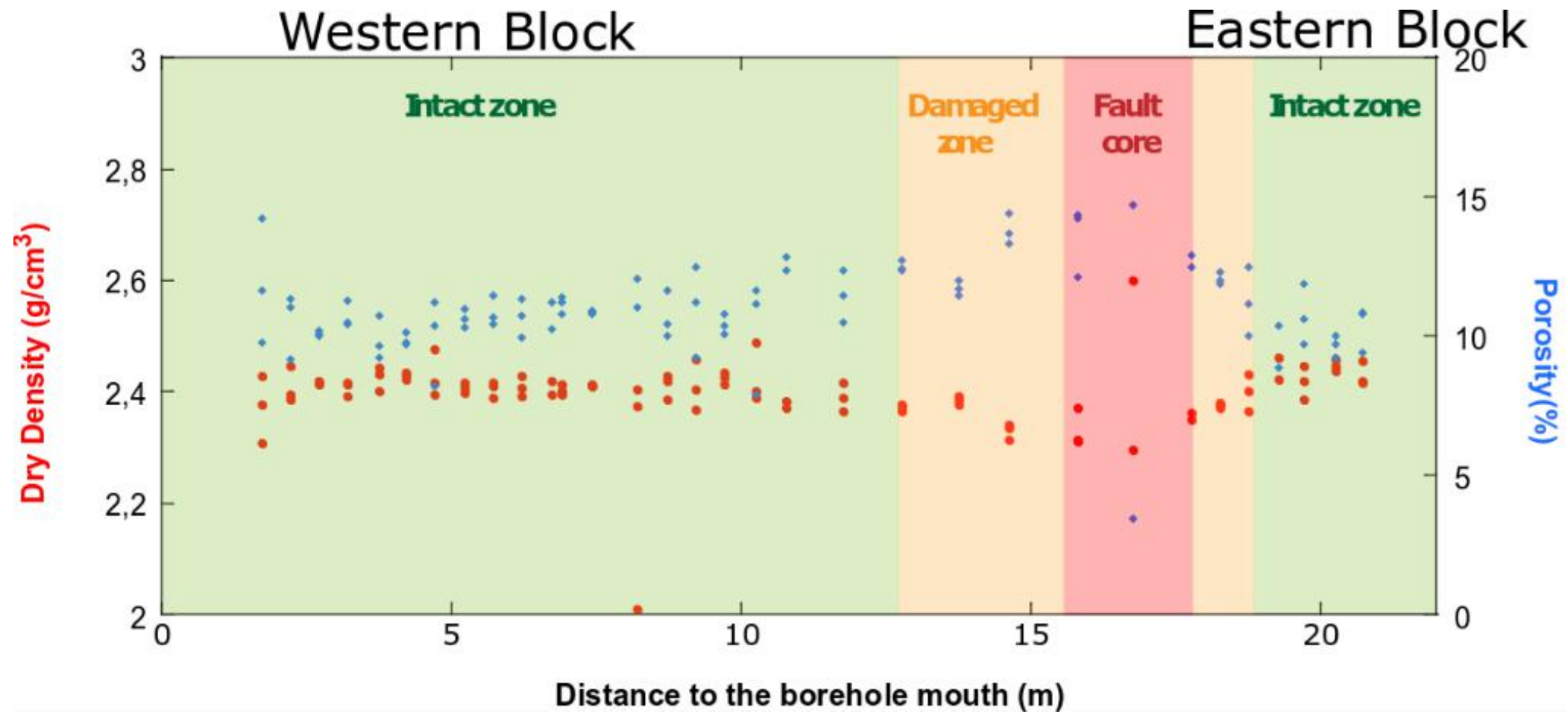
Damaged zone



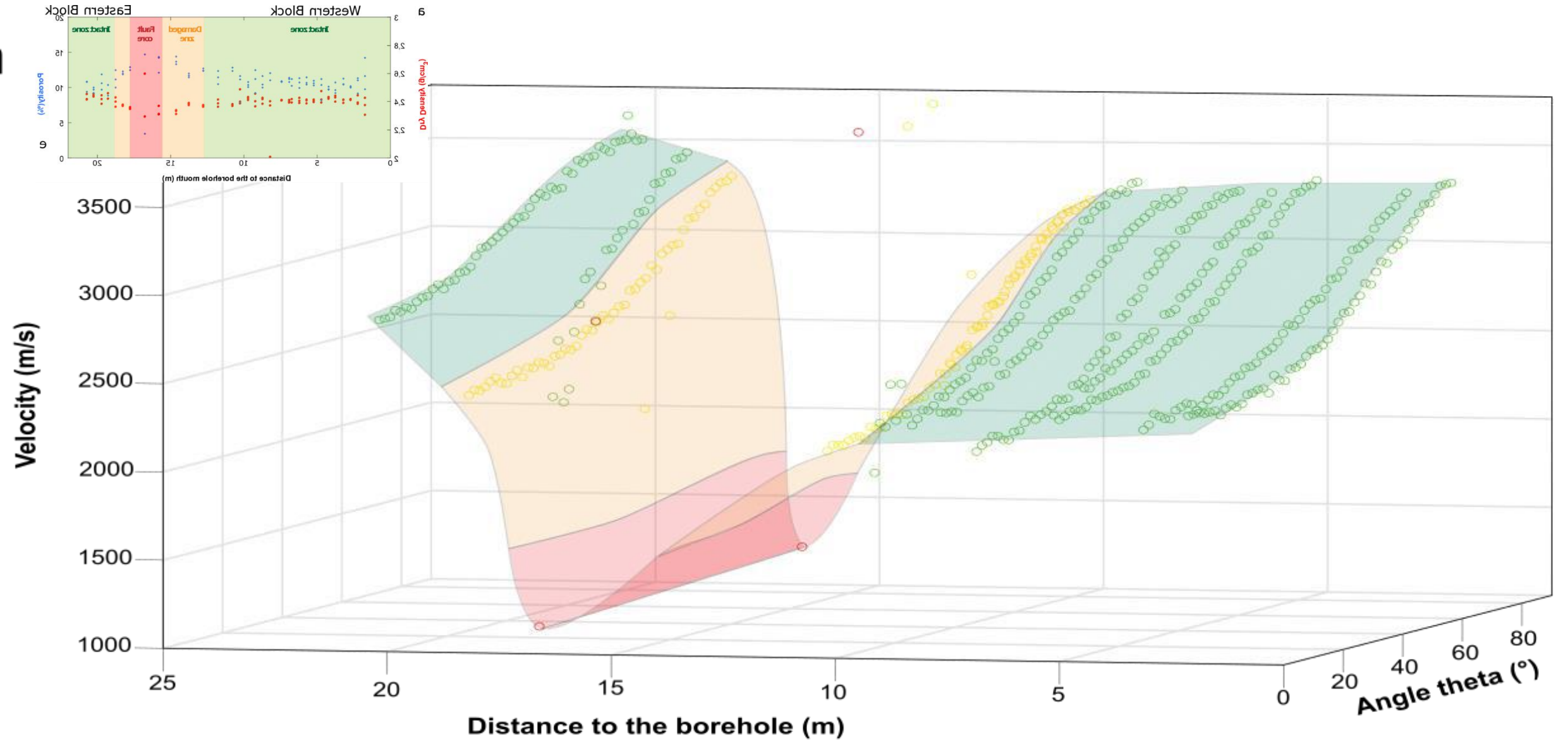
Fault core



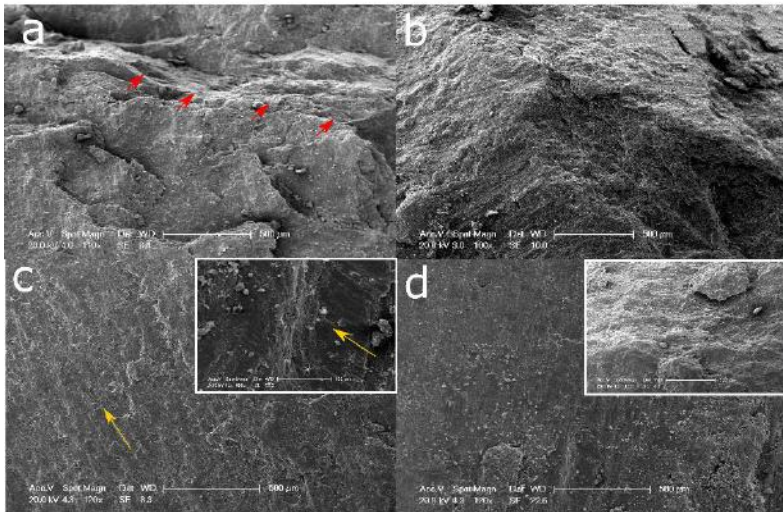
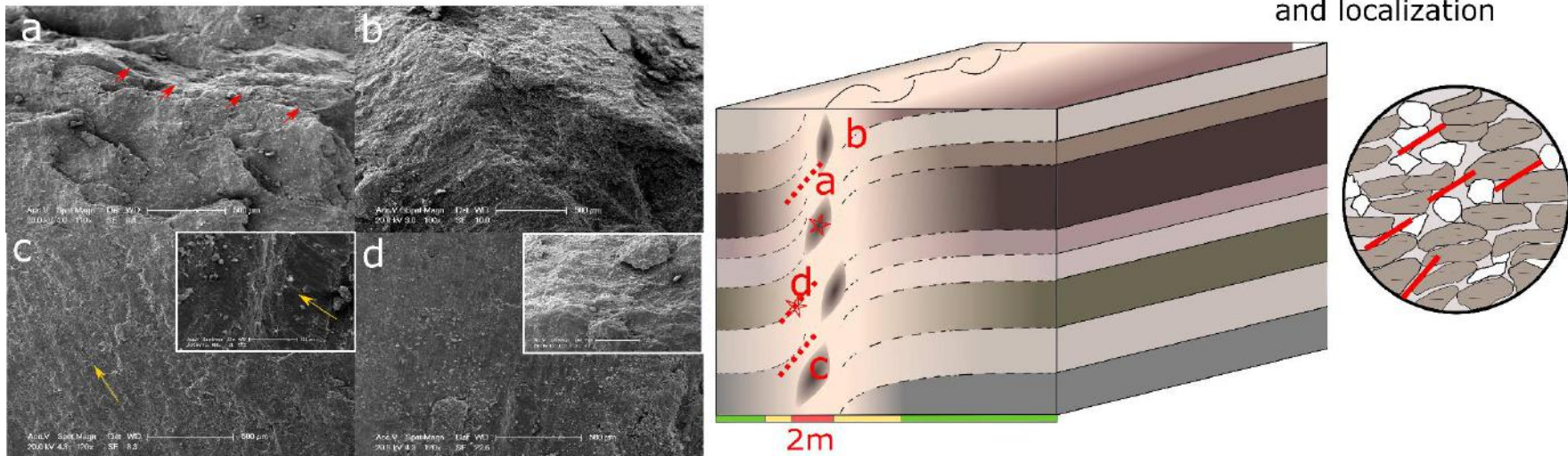
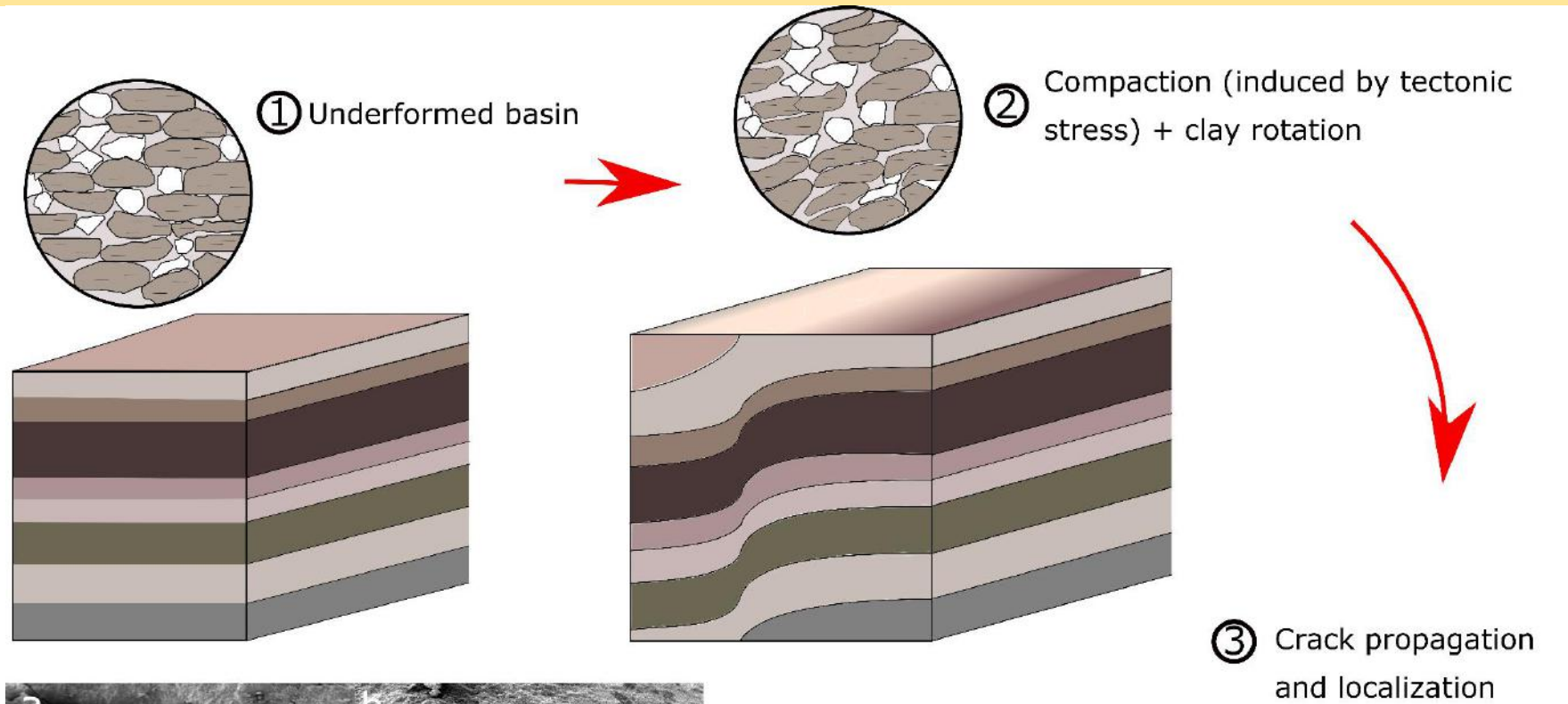
# Petrophysics : bringing the field in the lab



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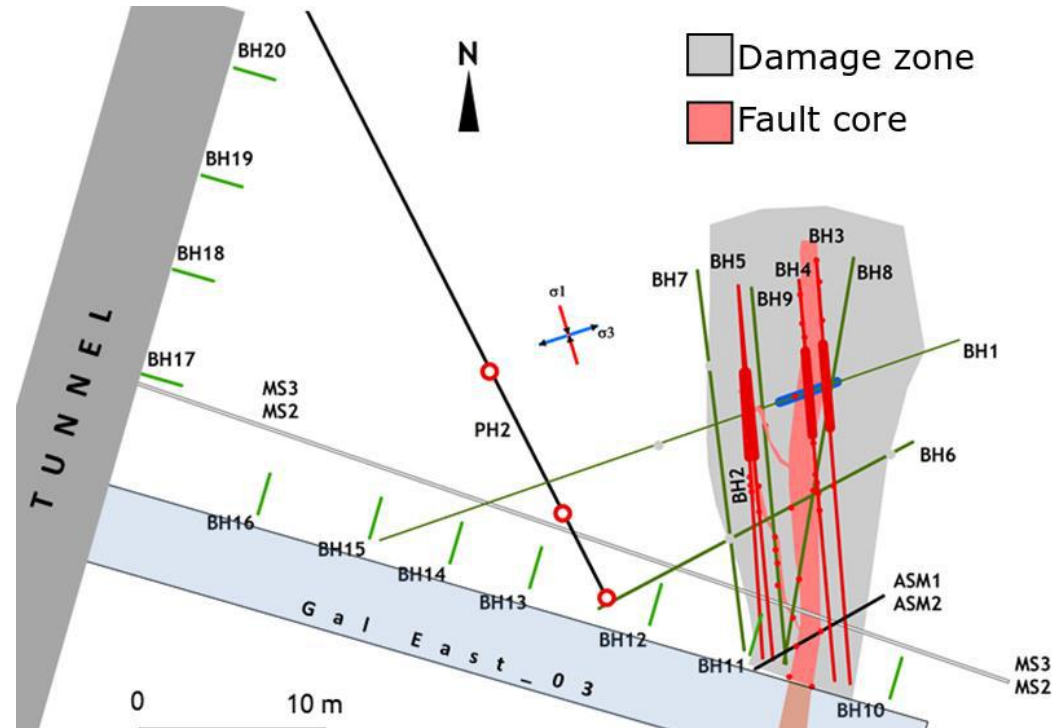




# CHENILLE: Coupled beHaviour undErstaNding of fauLts: from the Laboratory to the fiEld

Bonnelye et al. 2023

# CHENILLE experiment : drilling



9 boreholes :

- 4 “heating boreholes” equipped with heaters and FO for distributed temperature measurement
- 4 acoustic monitoring boreholes for HF seismic boreholes
- 1 injection borehole equipped with in injection probe for gas injection and 3D displacement measurement
- 15 “short boreholes” for high resolution active seismic acquisition before/after experiment

# CHENILLE experiment : overview

## Stimulation

THM Stimulation

Seismic monitoring

Temperature

Strain

Pressure

Heating system  
(BH2-5)

SIMFIP probe (BH1)

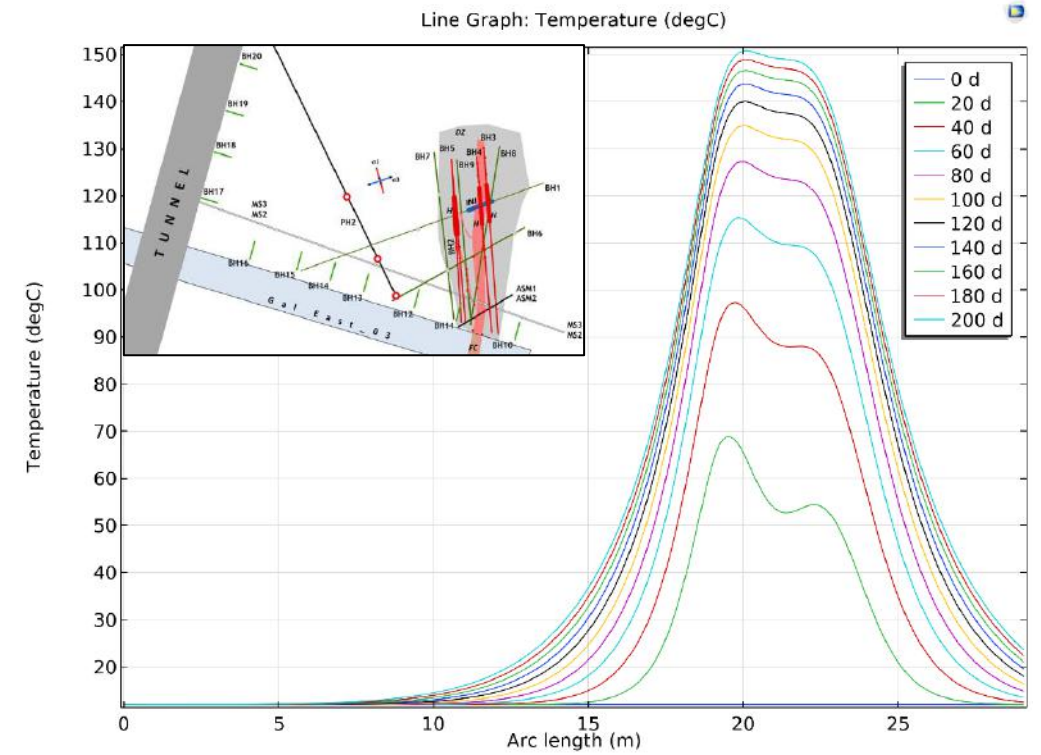
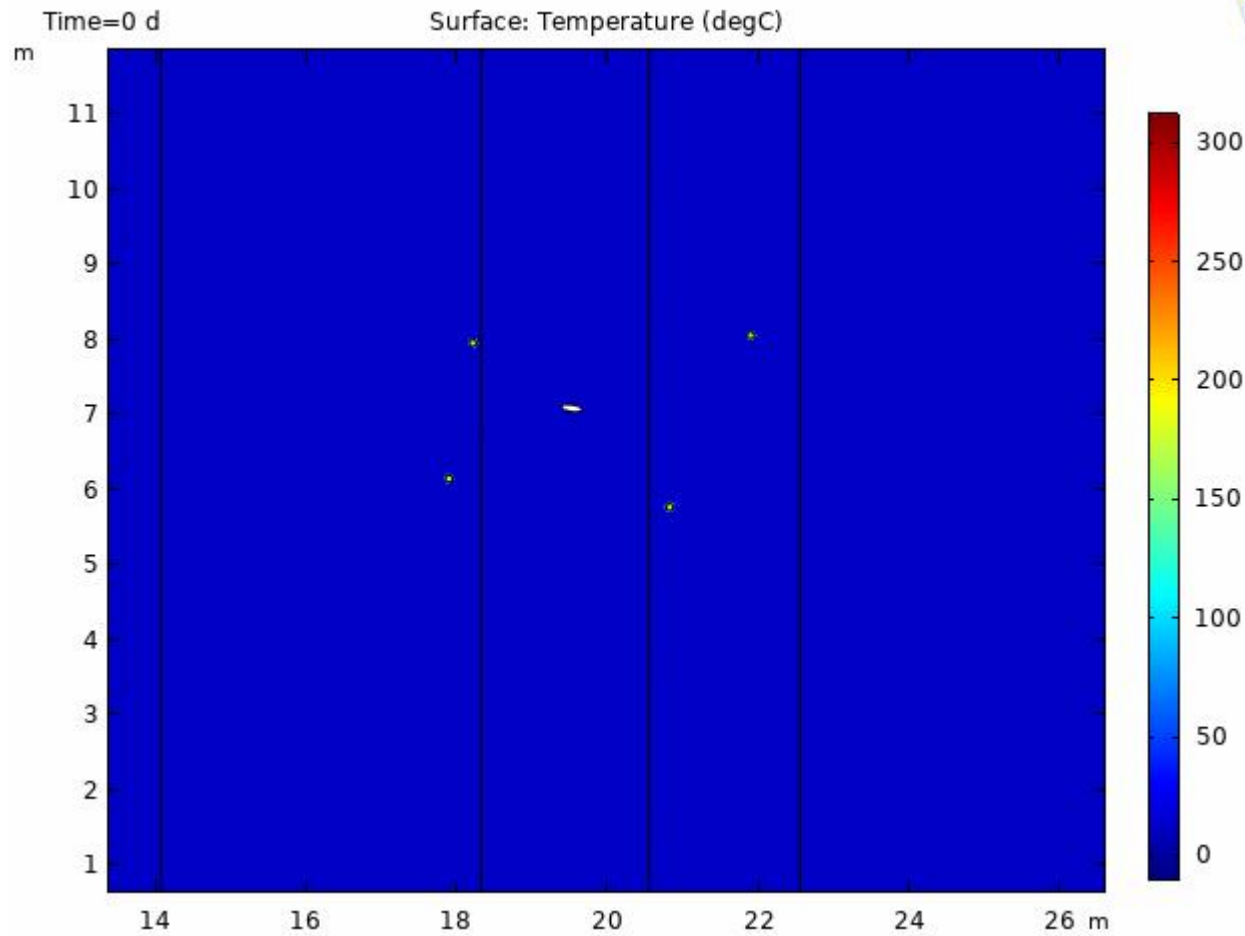
Passive seismic  
(Acoustic  
sensing)  
(BH6-9)

Active seismic  
imaging  
(BH10-26)

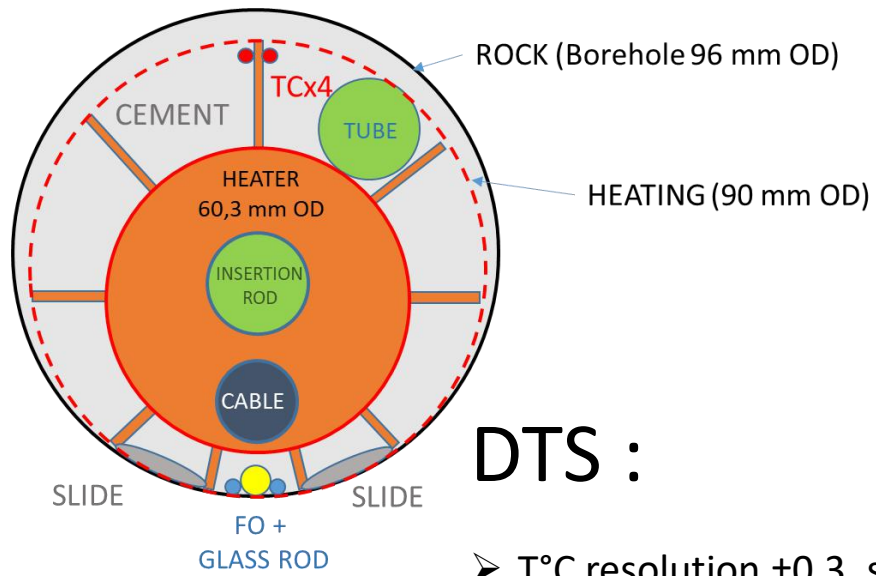
Fibre optics (BH2-5)

# CHENILLE experiment : thermal loading

Comsol simulations :



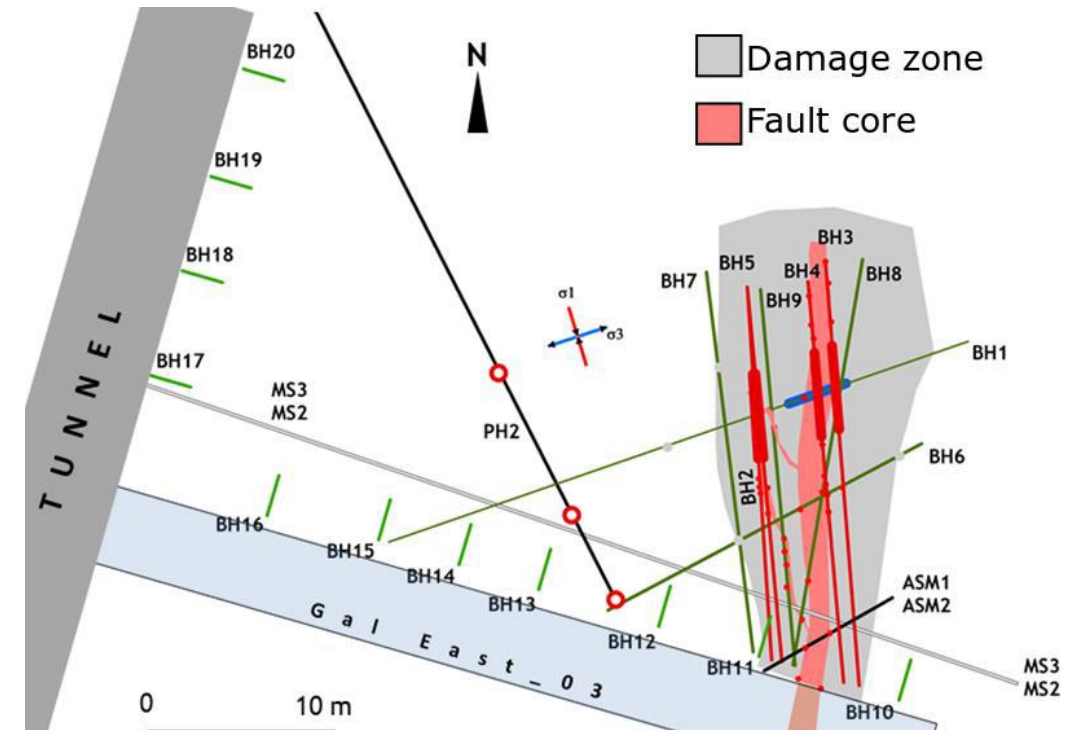
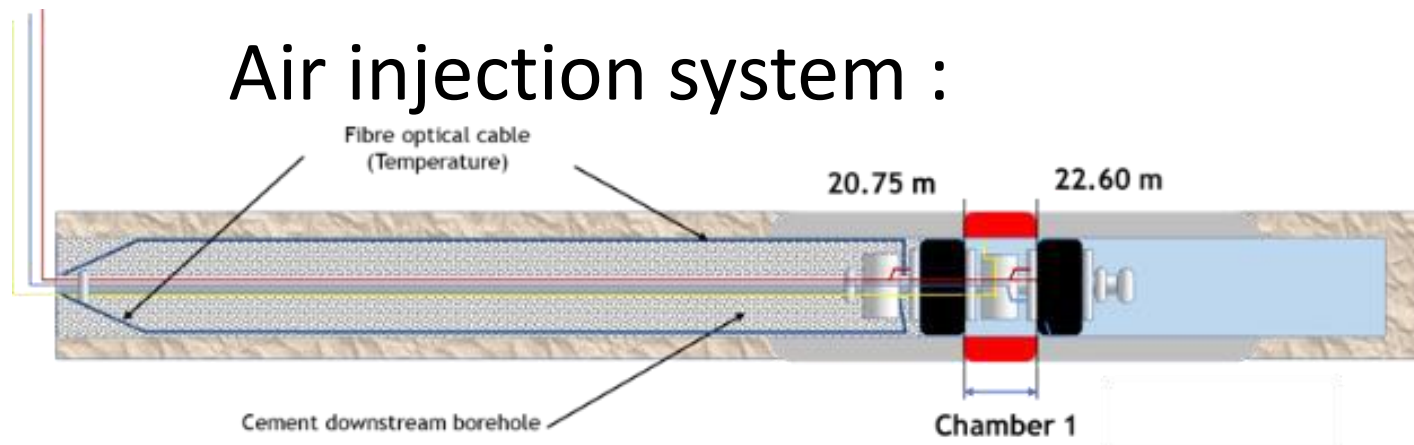
# CHENILLE experiment : thermal & hydraulic loading



**DTS :**

➤ T°C resolution  $\pm 0.3$ , spatial resolution 1m

**Air injection system :**



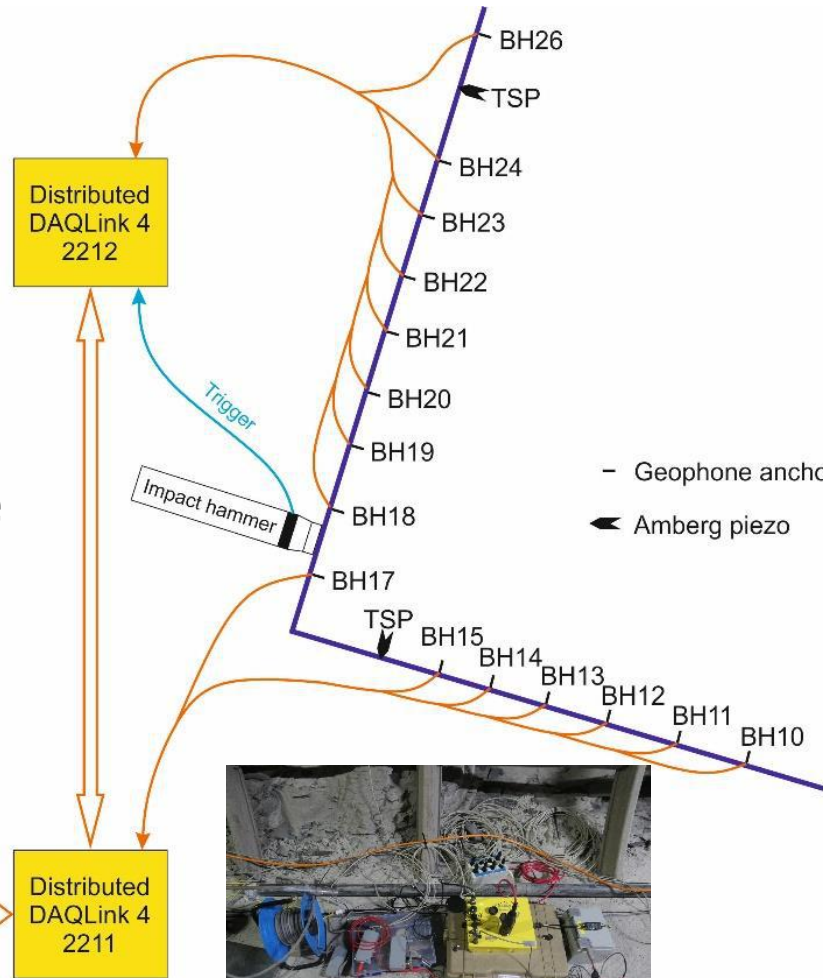
# CHENILLE experiment : active seismic



Pneumatically driven Impact Source



Combined DAQLink and TSP recording



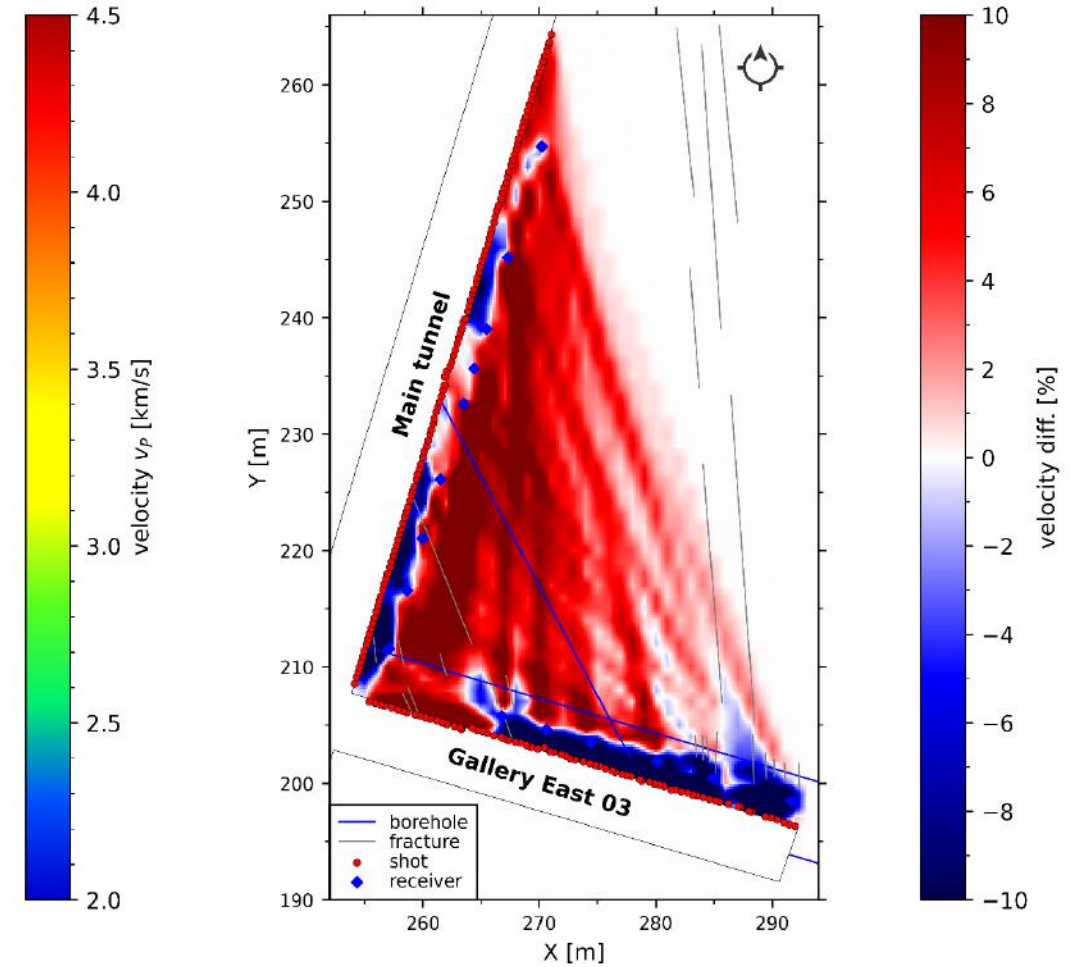
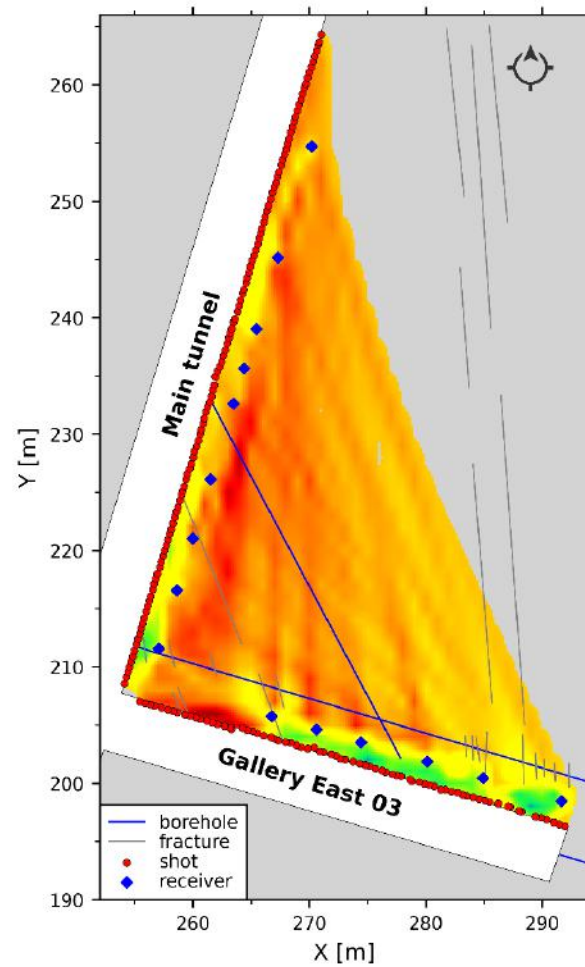
Installation of receiver tubes



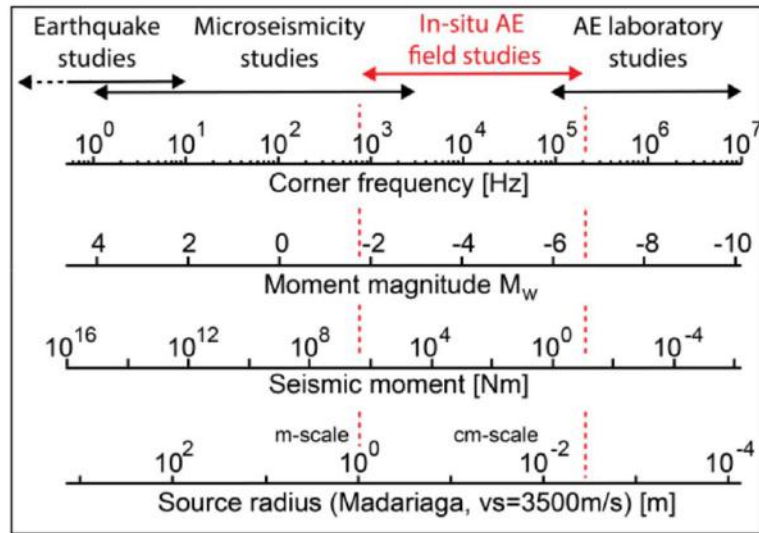
Screwed 3C-receiver rods

# CHENILLE experiment : active seismic

- Traveltime tomography by simulr16
- Low velocity zones near tunnel walls (EDZ)
  - Lower velocities in the E part of Ga East 03
  - High velocities at concrete tubing in the W part of the gallery
- Velocities decreasing from west to east
- Low coverage in area of interest near the fault structure



# CHENILLE experiment : passive seismic

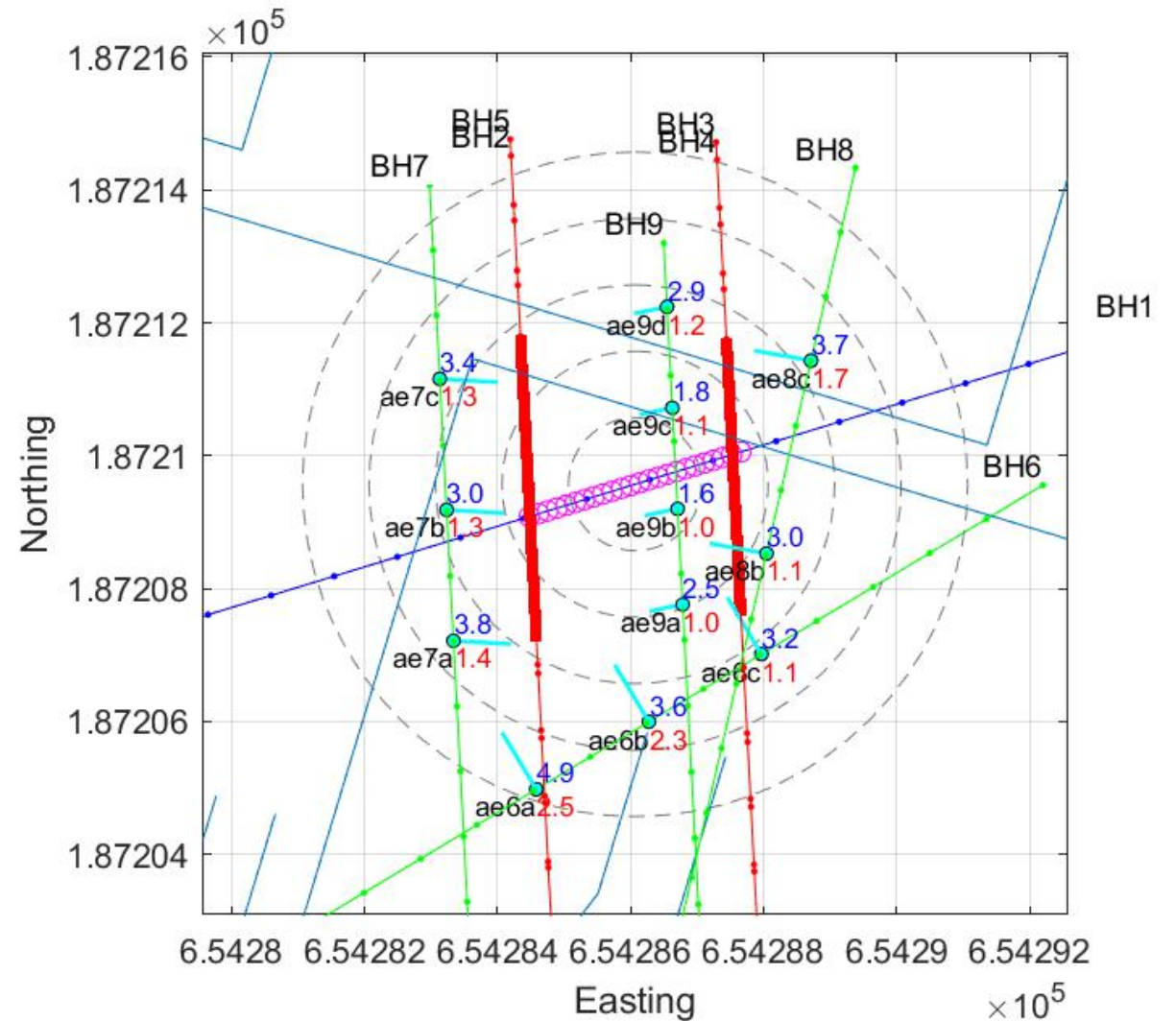


Manthei and Plankers 2018

16 sensors :

- 12 high frequency field AE sensors (1-100kHz)
- 4 accelerometers

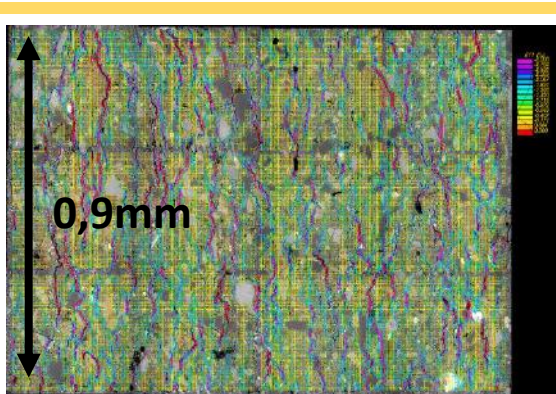
Boese et al., 2021



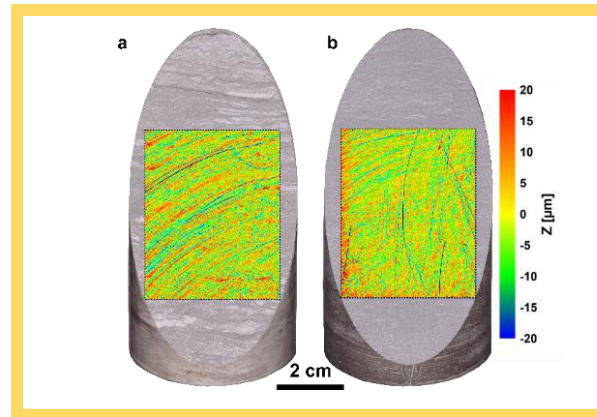
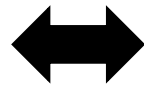


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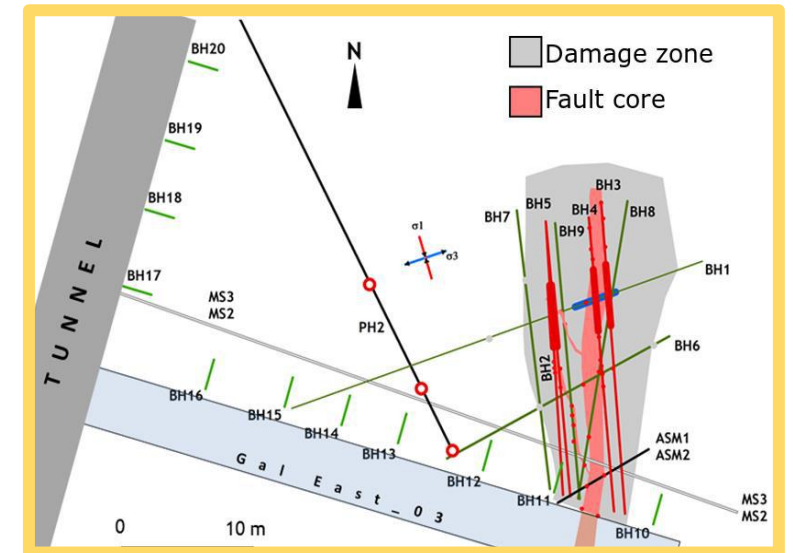
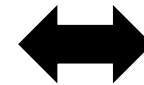
*How to link these scales and provide a mechanical understanding of fault zones?*



micro-mechanical testing



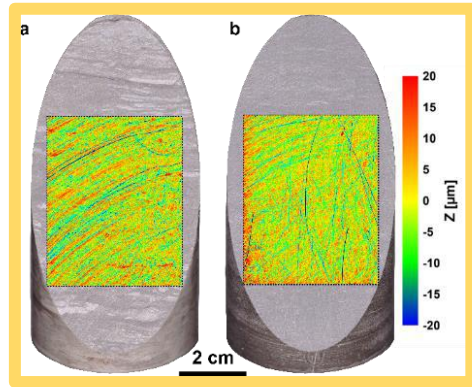
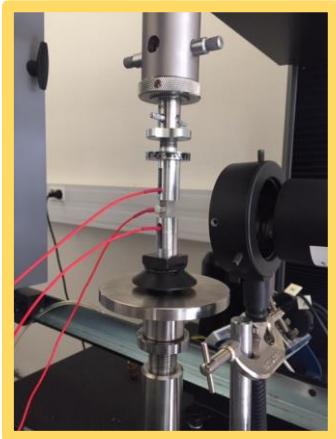
Triaxial testing



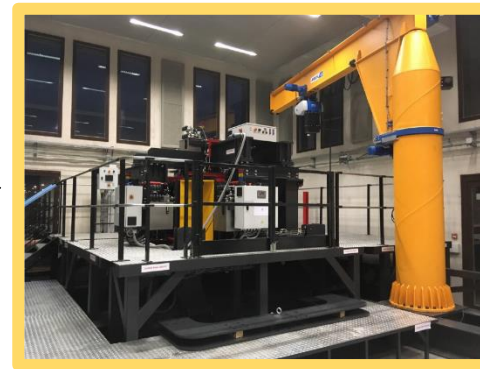
*In-situ testing*

# Fracturing : from the lab to the field

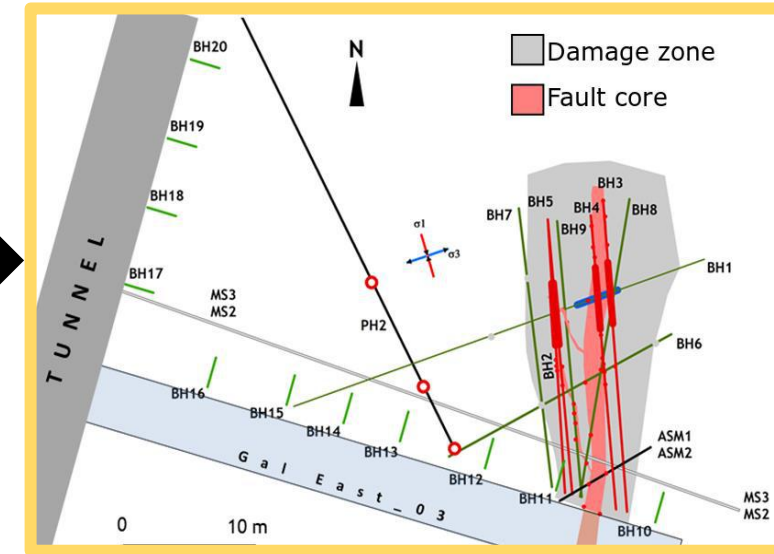
*How to link these scales and provide a mechanical understanding of fault zones?*



Triaxial testing  
*Schuster et al., 2022*



Analog testing



*In-situ testing*

micro-mechanical testing  
+ AE monitoring ( PhD of M.  
Lusseyran)

μm

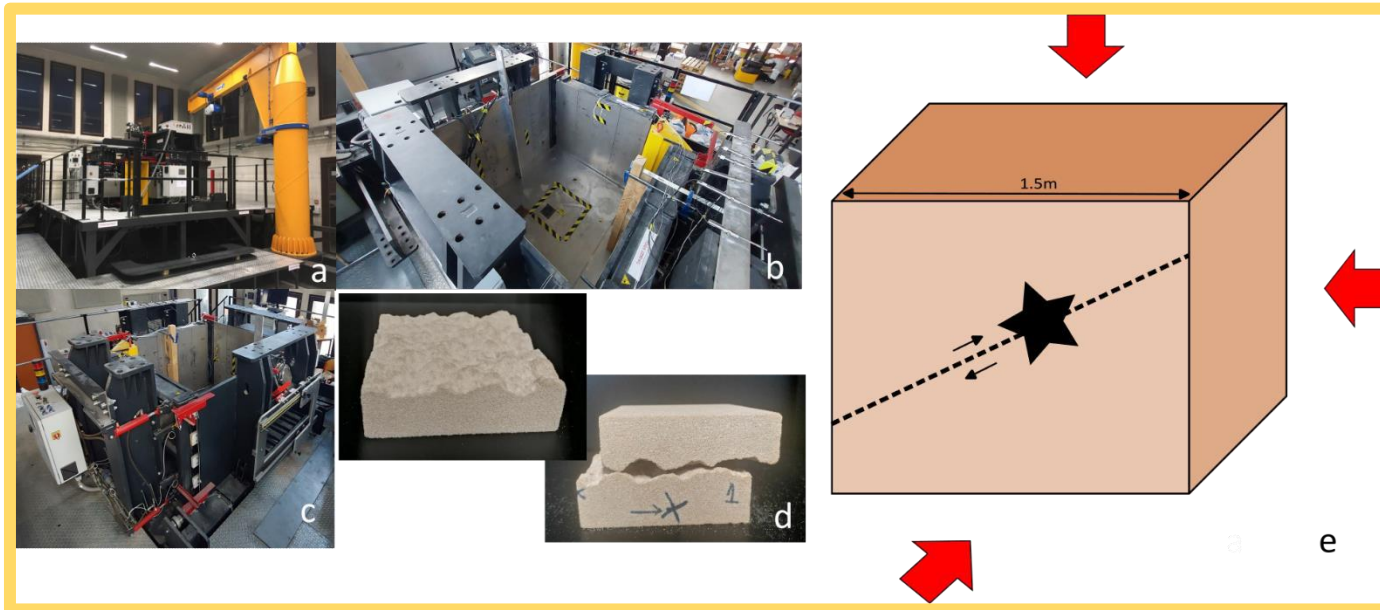
cm

10m

34

# Analog testing

DIMITRI : Dispositif de Modélisation Analogique Triaxial



- Use of analog materials (3D printed sand with binder, polystyrene...)
- Insertion of sensors in the material for better stress-strain measurements
- Use of multi-frequencies acoustic sensors

Thanks 😊



# Thermal diffusivity parameters

Material	Density, $\rho$ ( $\text{kg}\cdot\text{m}^{-3}$ )	Thermal conductivity ( $\text{W m}^{-1} \text{K}^{-1}$ )		Heat capacity ( $\text{J kg}^{-1}\cdot\text{K}^{-1}$ )
		horizontal	vertical	
Undisturbed clay rock	2400	2	0.7	1000
Fault core	2300	2	0.7	1000
Damage zone	2350	2	0.7	1000
Heater (steal)	7850	44.5	44.5	475

