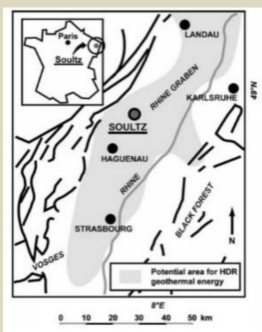
Explorations of the hydromechanical behavior of fractures and faults in Underground Research Laboratories (URL)

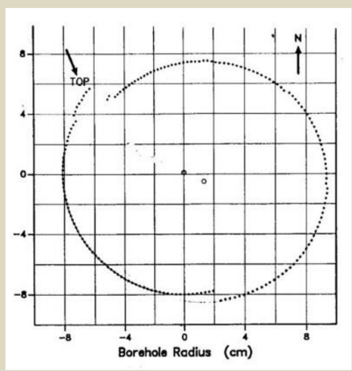
Yves Guglielmi

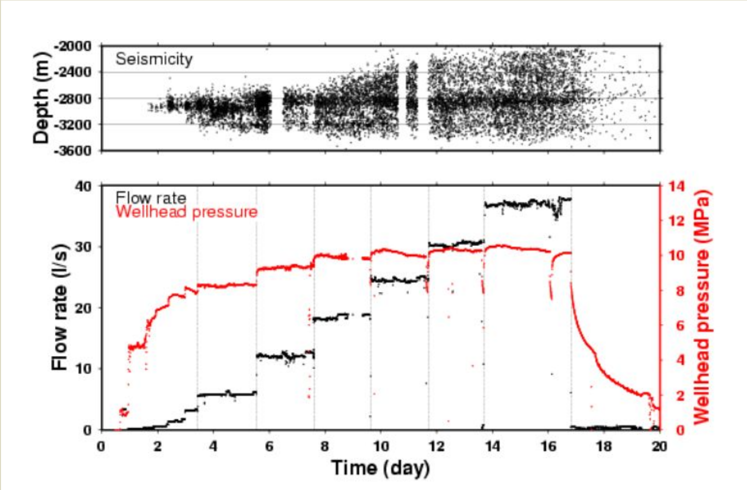
Geological Staff Scientist (LBNL)

- Large cm scale displacements on pre-existing discontinuities
- High permeability increase
- A great amount of the displacement is aseismic
- No existing device to resolve 3D-displacements on a fracture in situ

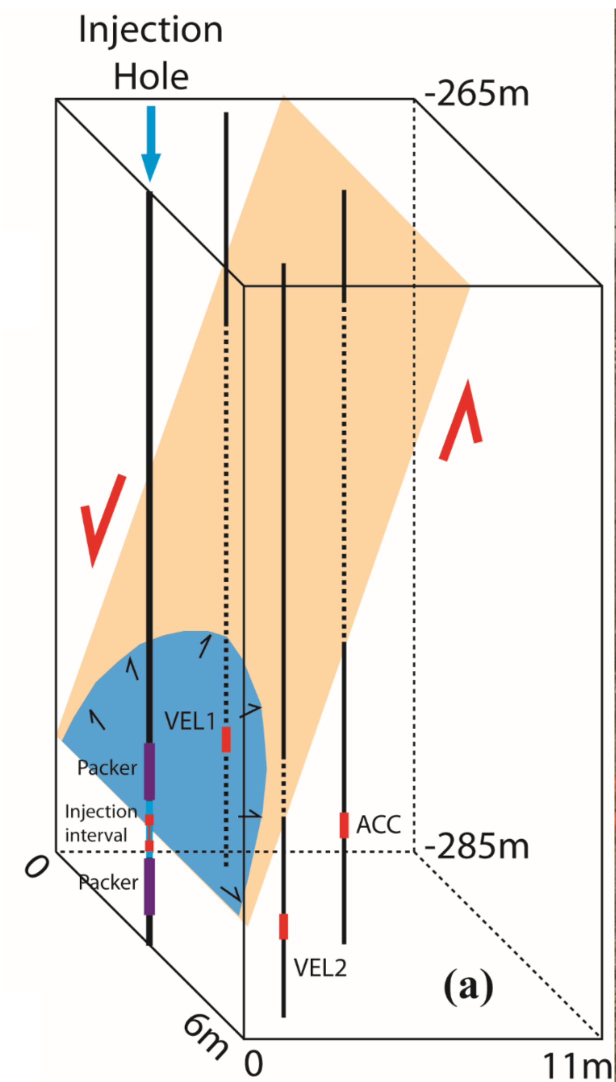


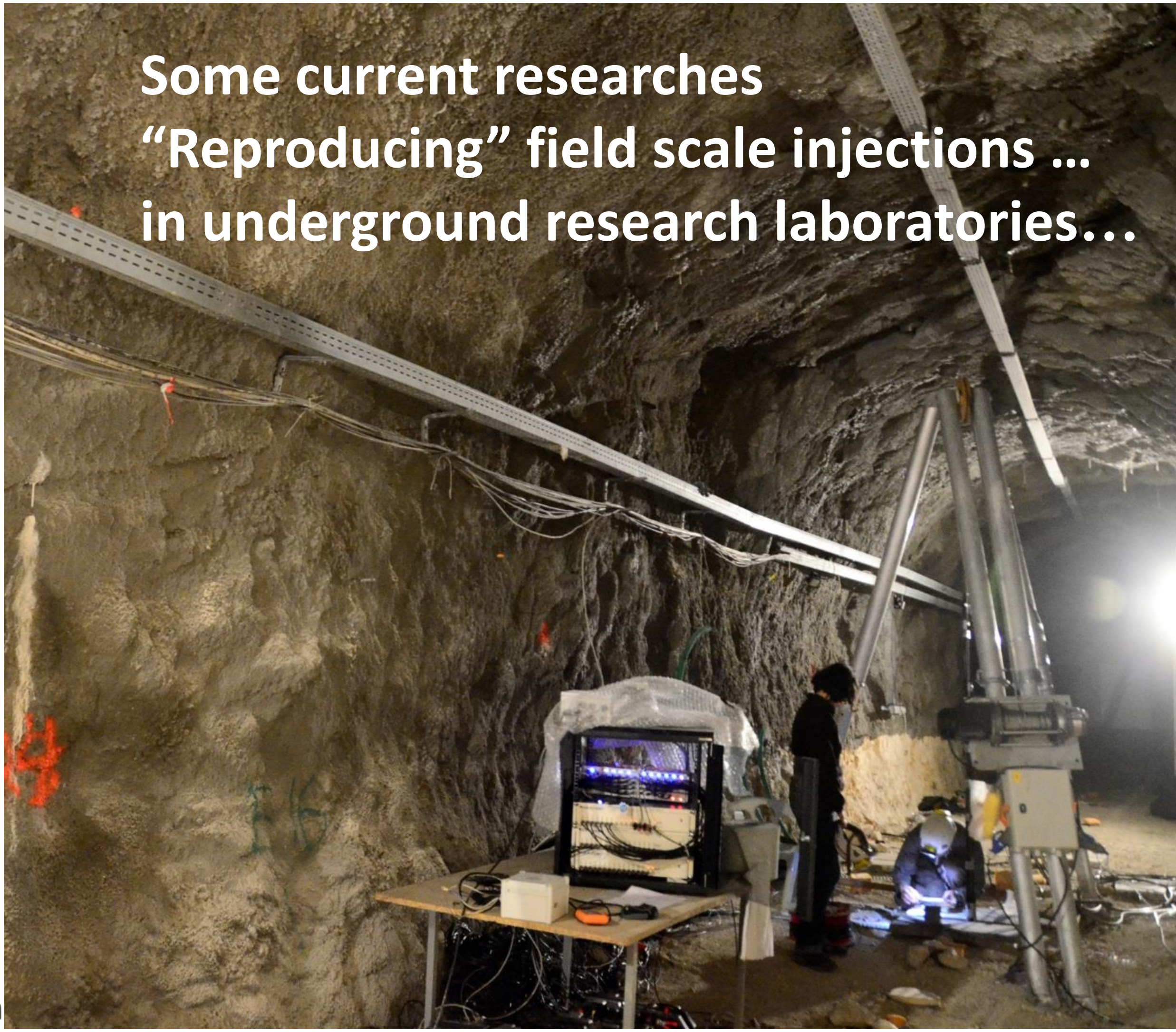
(Cornet, 1997)





Séance Technique du Comité Français de Mécanique des Roches
17 Mars 2016 (CNAM, Paris)





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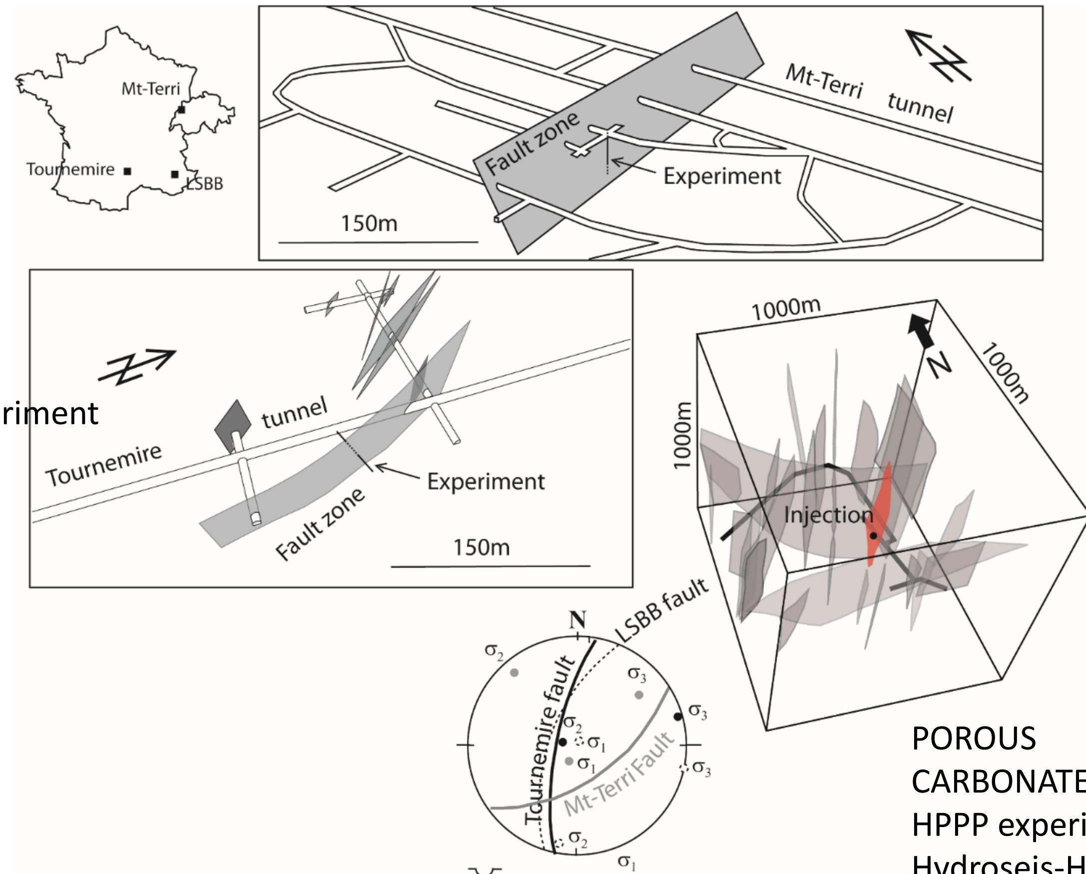
Past and Current projects in URLs …

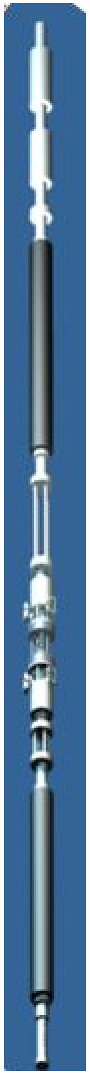


SHALES
FS experiment (2015)

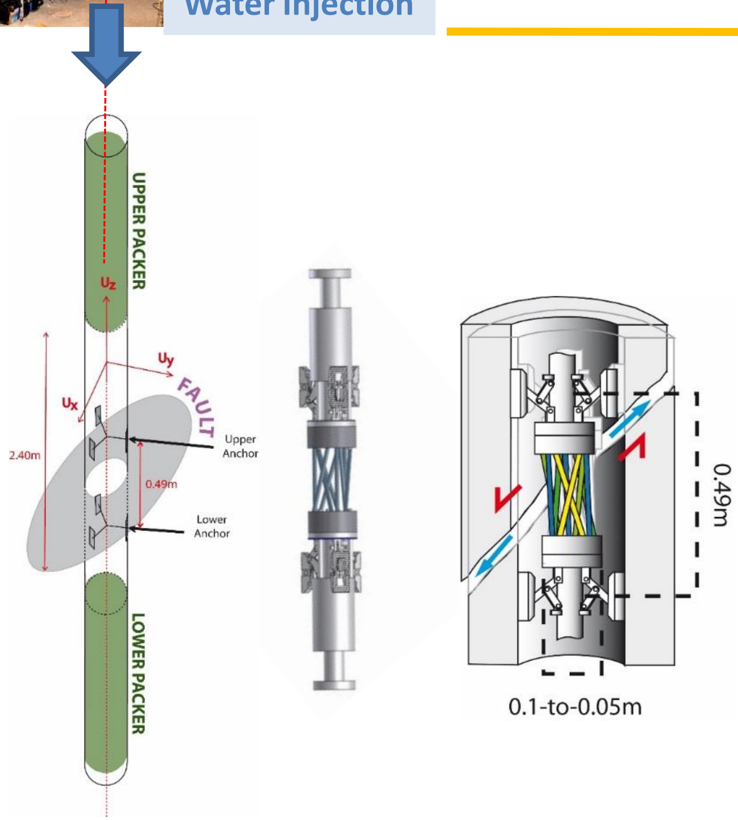
SHALES
Fluids and Faults experiment
(2014)

POROUS
CARBONATES
HPPP experiment (2011)
Hydroseis-HPMSCa experiments (2015)

New Instrument and Protocol developments



High Pressure Water Injection



- *A carved cylinder anchored downhole*
- *Cylinder deformations related to the forces/displacements at its boundaries*

- **Interval Pressure Tests**
- Synchronous measurements :

3 components of the displacements, Pressure, Flowrate

- 500-to-1000Hz sampling rate

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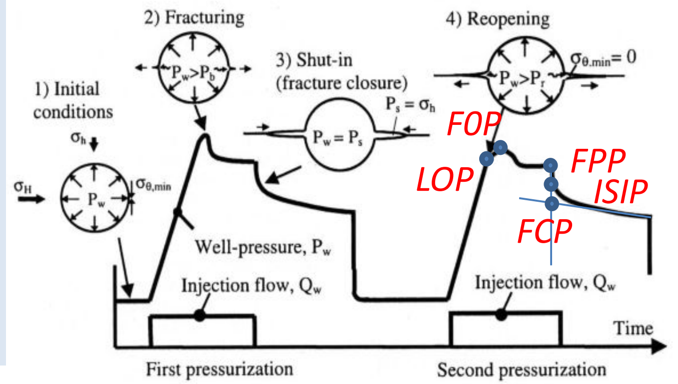
Coupling pressure and near-borehole mechanical response

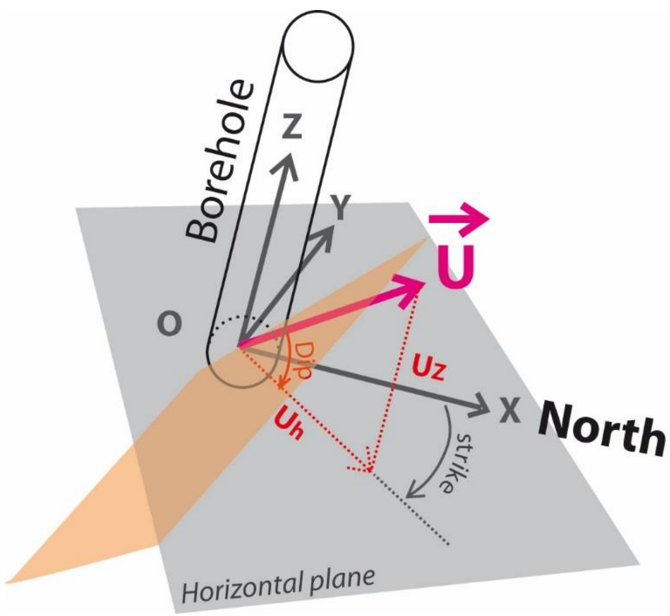
In situ estimation of fractures properties

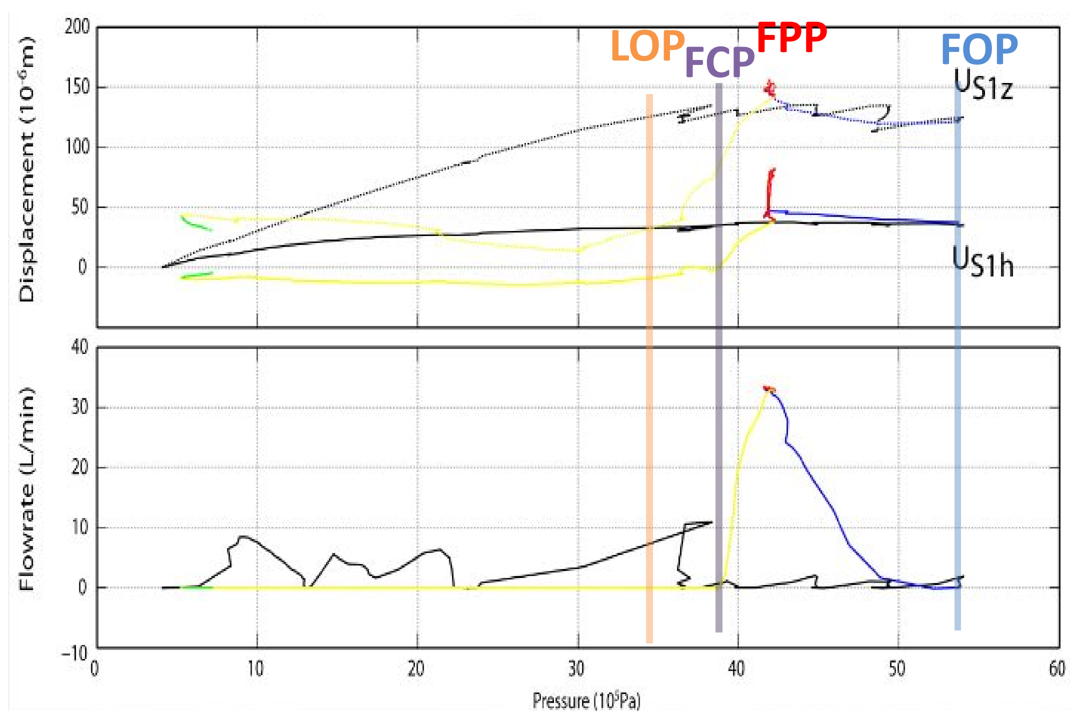
- Pre-leakage elastic response of the injection chamber
  - Anisotropic elastic effect of fractures

- During the Leak-off period
  - Importance of shear on the hydraulic behaviour of natural fracture planes



(Fontbonne, 2005)





Ex. of Mt-Terri test (FS experiment)

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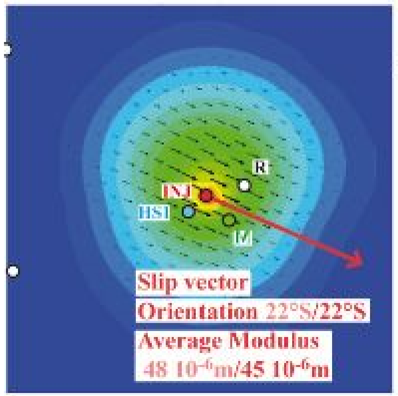
Coupling pressure and near-borehole mechanical response

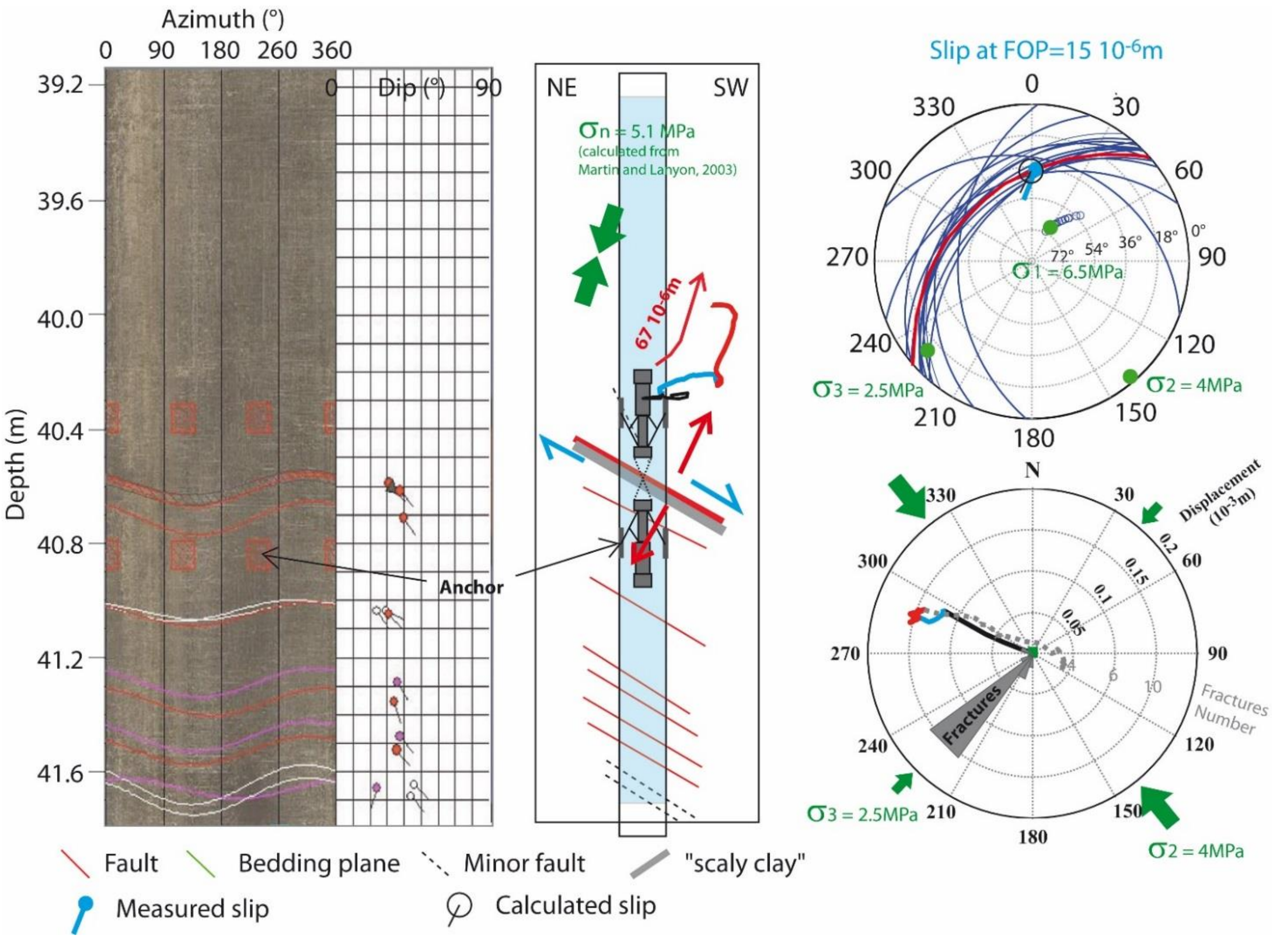
To improve the stress tensor estimation

Joint inversion of Pressure (FOP, FCP) and Displacement data (slip vector's magnitude, dip and dip direction) on the identified activated plane (dip and dip direction)

Ex. of Mt-Terri test (FS experiment)



Fully coupled Inversion of data (iTOUGH-PEST-3DEC)



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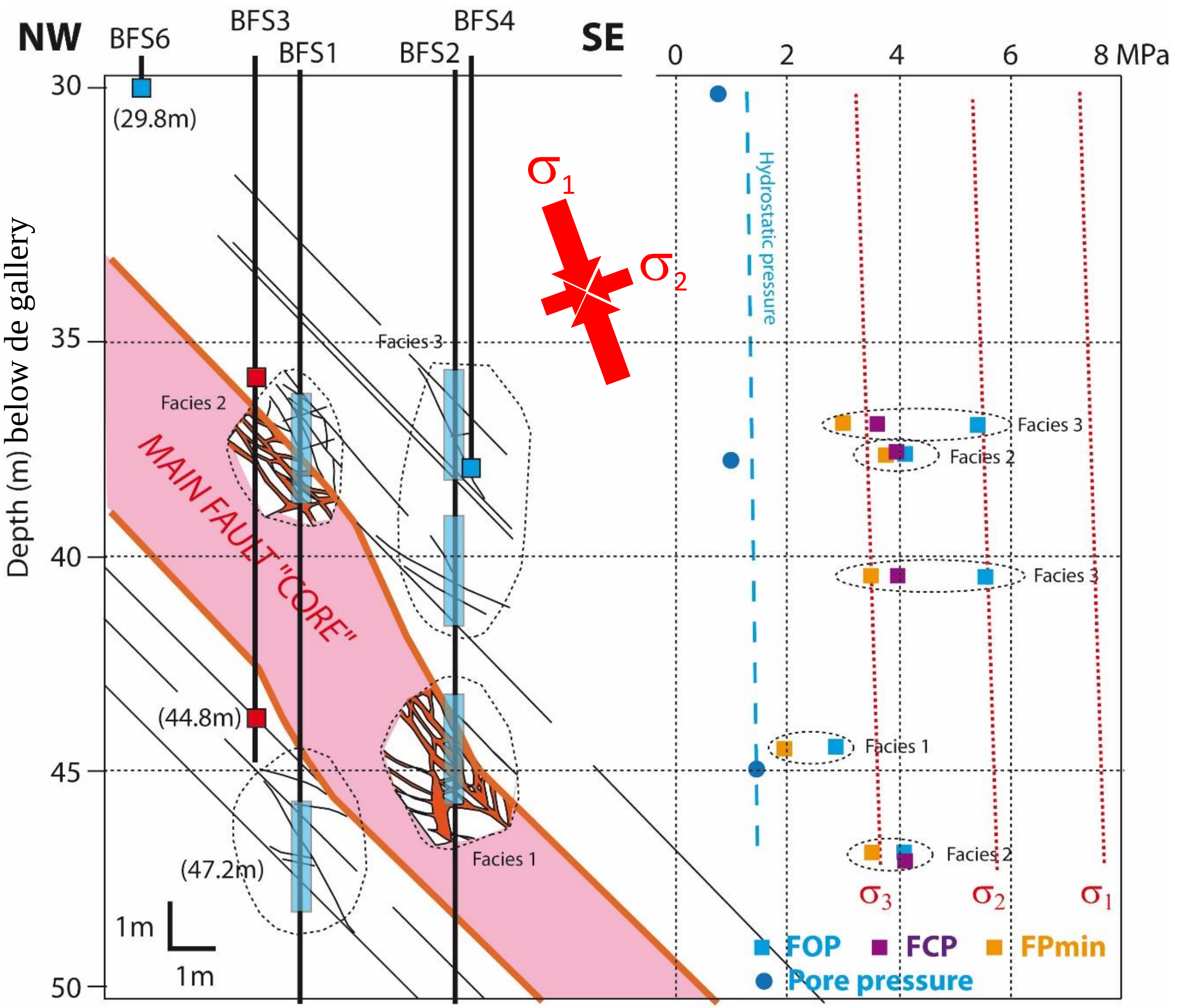
Application 1: Analysis of Fault Opening Pressures (FOP)

Strong contrasts in FOP values depending on the injection location in the fault zone

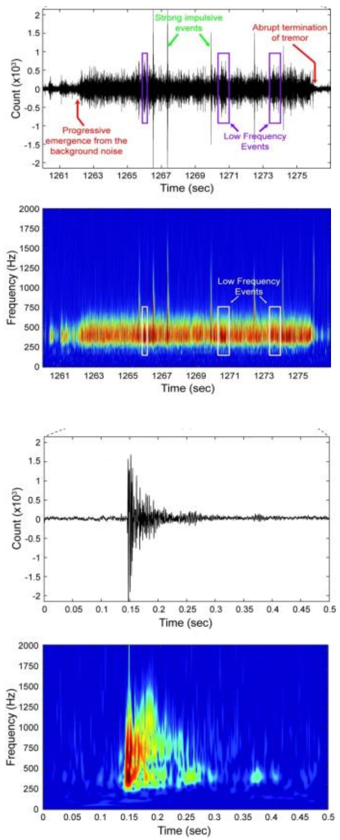
Stress rotation
Or
Heterogeneity
Orientation towards stress
?



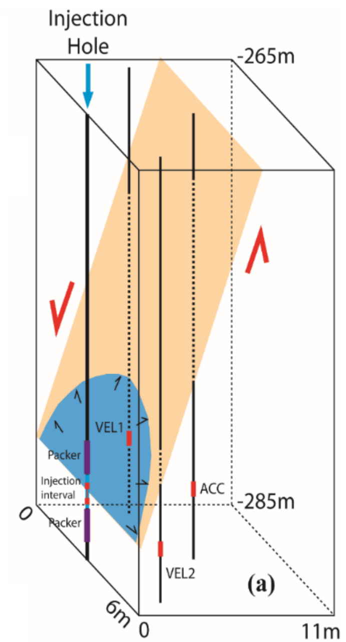
ex. of FS Mt Terri experiment

Application 2: **Monitoring aseismic to seismic transition**

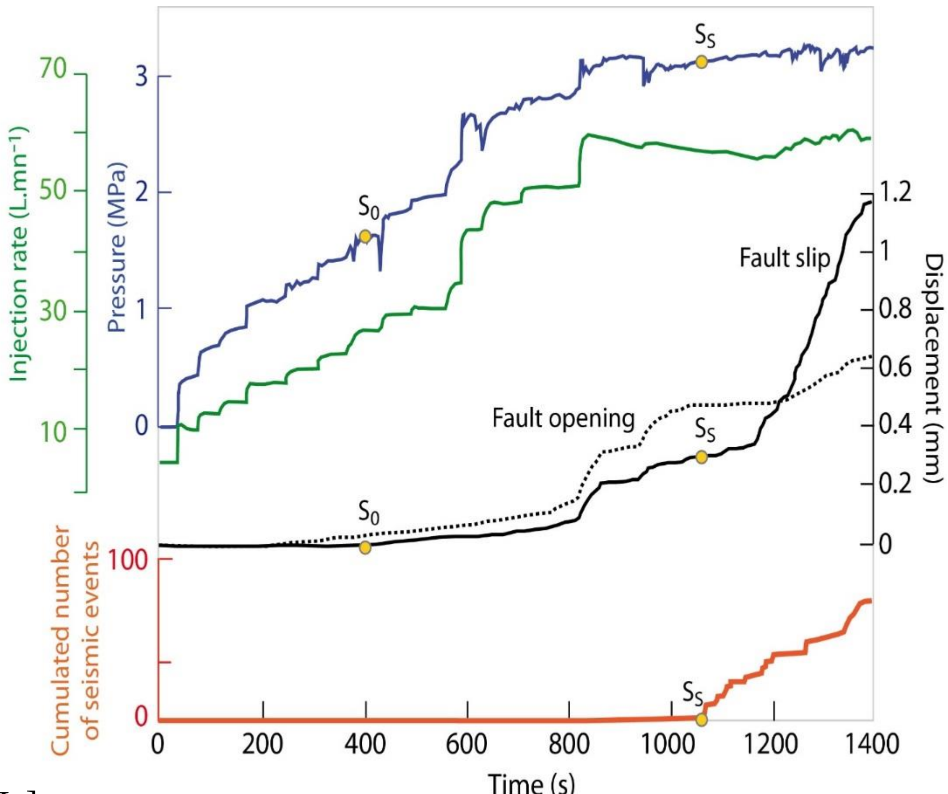
on an injected-with-water fault (Experiments in carbonates, France)



Tremors [250 – 700 Hz]

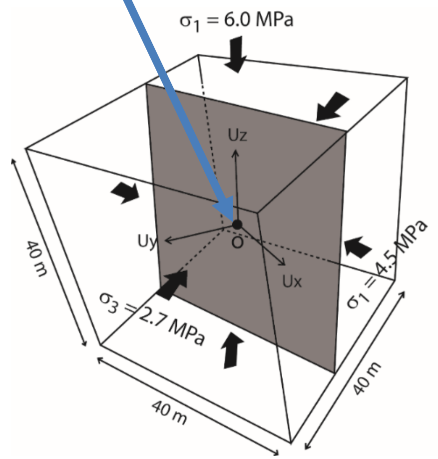


Impulsive events [200 – 1500 Hz]



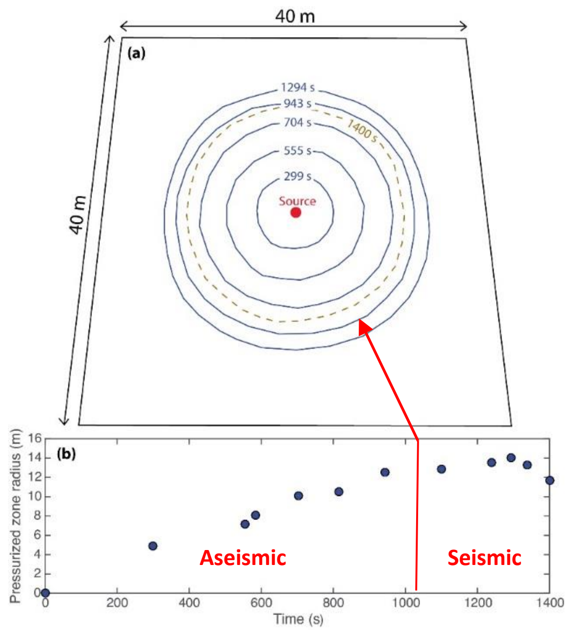
Forward analyses of the size of the pressurized zone

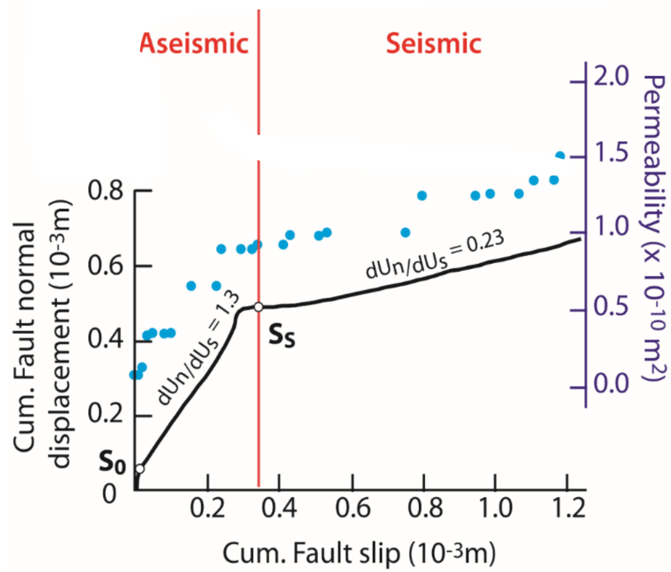
Model Loading with Measured Injected Pressure = f(t)



Fully coupled Poroelasto-plastic Distinct elements Model (3DEC)

- When seismicity occurs, pressurized fluids already flow in a large area of the fault (radius of 12m)
- High Permeability increase follows dilatancy variations





Inversion of Fault dynamic friction variations and size of rupture zone

- Reasonable match of the slip

With a « classical » rate and state law

- Best fit for a work strengthening of the fault

a-b = 0.0447 and v_o = 1.3424 × 10^{-8} mm/s.

- Magnitude much larger

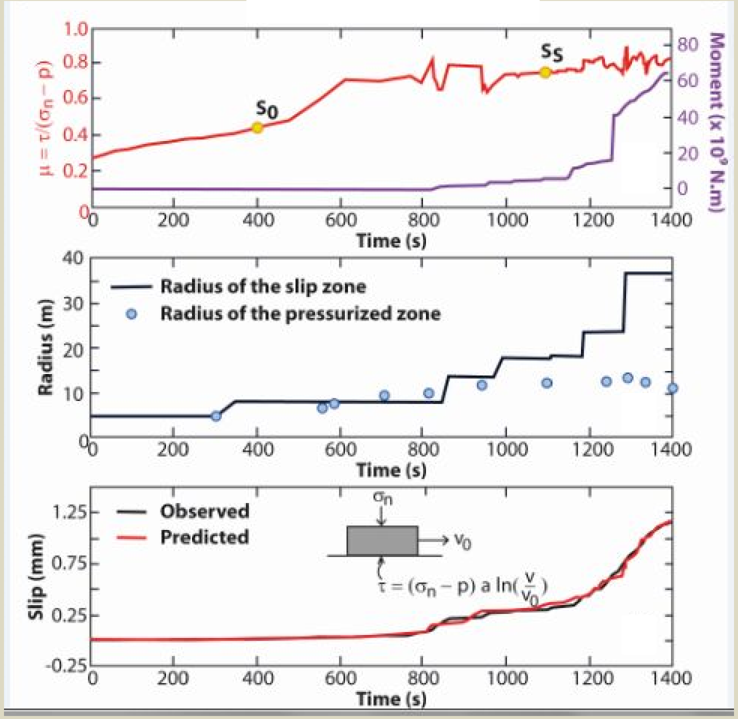
than the one estimated from seismicity

M_o = 65 × 10^9 N.m

moment magnitude of about M_w =1.17

- Seismicity when

size of rupture zone > size of pressurized zone



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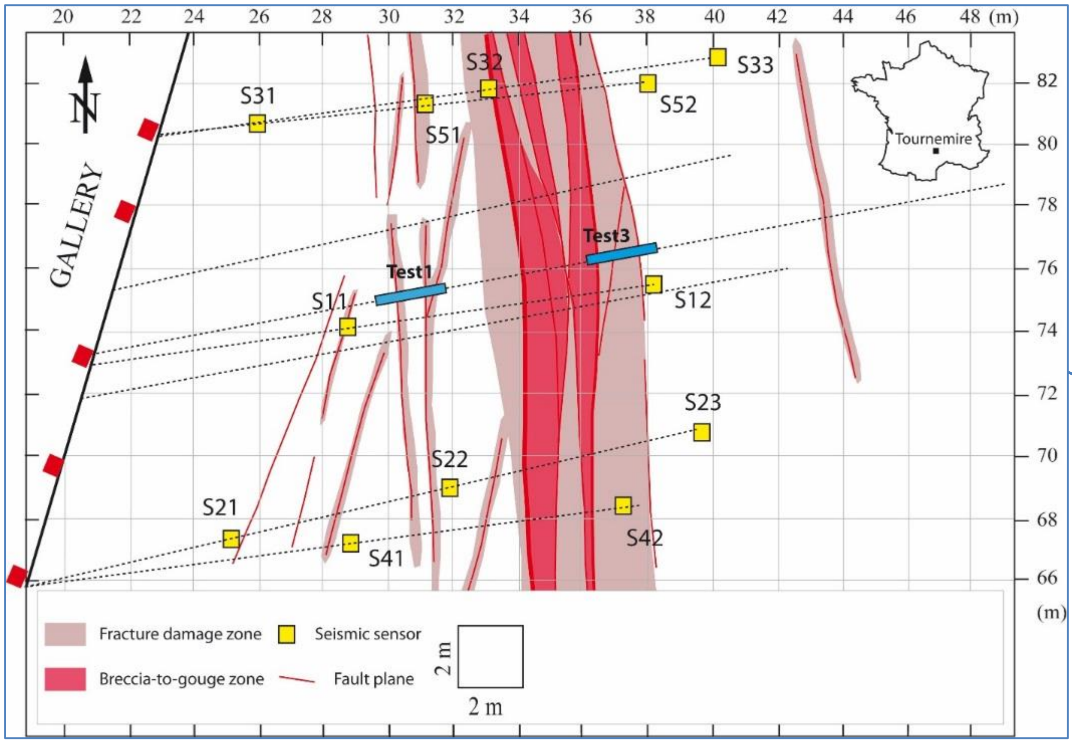
Application 3: New insights about location of seismicity

Induced by HM tests in a fault zone

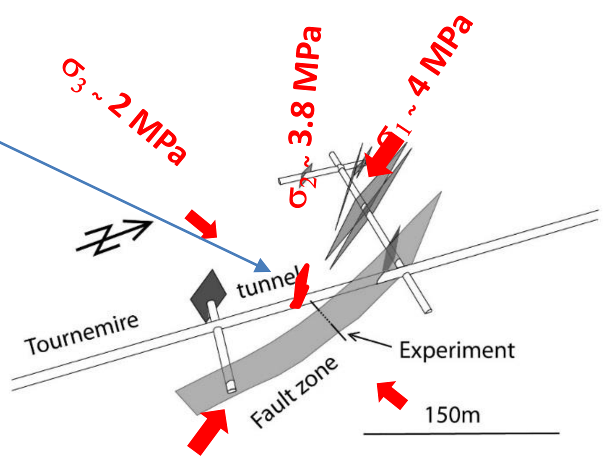
Fault
size # 100-200m
Offset # 5-to-10m
Strike-slip (mainly)

- One inclined injection hole (INJ)
- Several monitoring holes

(accelerometers, distributed strain, pore pressure, electric resistivity)



Test location
IRSN underground facility
Depth # 250m
Strike-slip stress regime

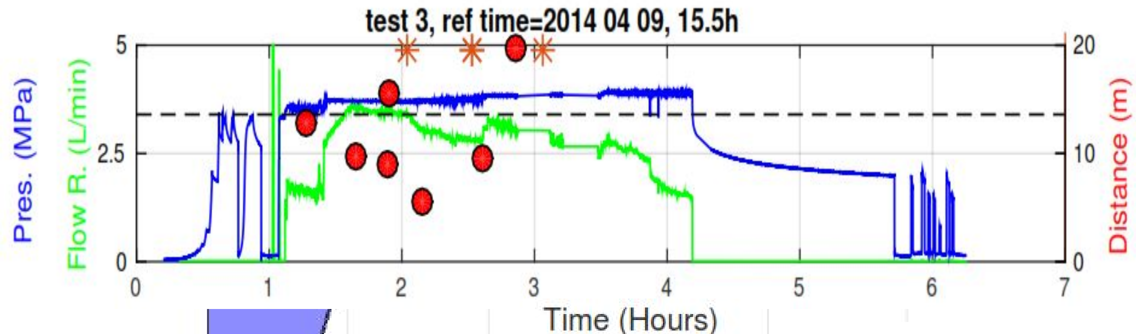


Measured slip mainly is aseismic

And

Induced seismicity is not on the activated plane

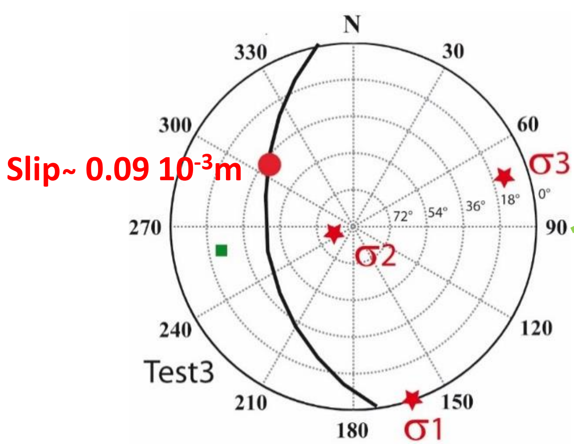
(De Barros et al., submitted)

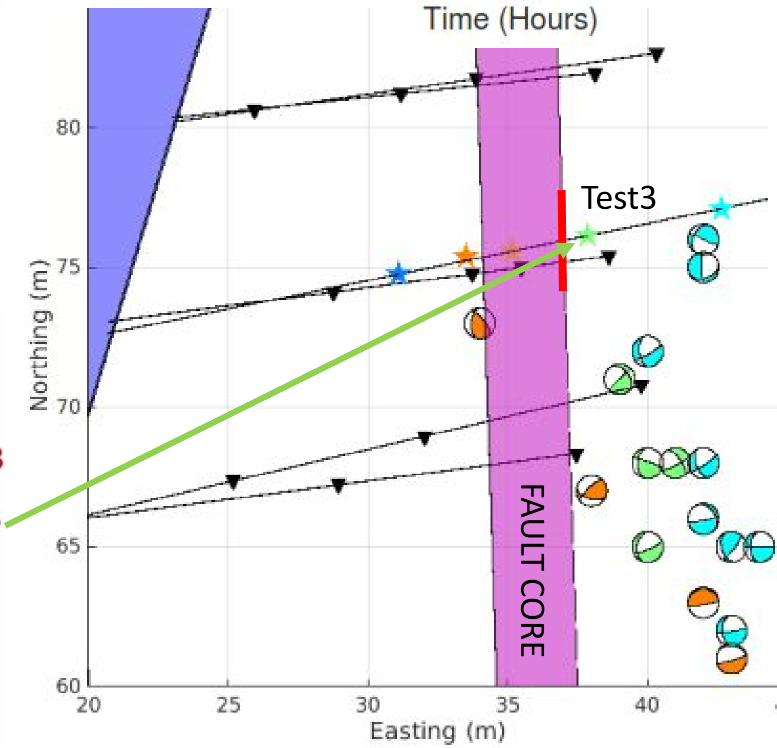


- Seismicity mainly occurs > 100seconds after FOP
- No seismicity at the injection source
- Magnitudes < -3.7

(slip < 0.001 10^{-3}m ; radius of the slipping zones 0.3m)

- Some focal mechanisms could match



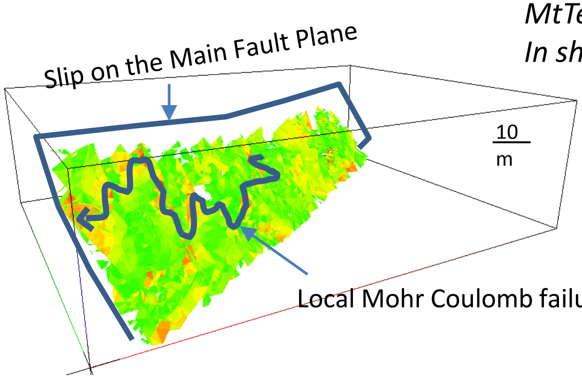


Conclusion: Hydromechanical activation of faults

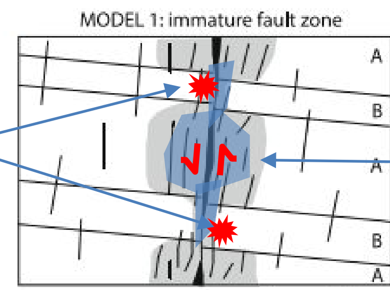
- A lot of non-linear hydromechanical effects that produce:
  - Local Coulomb failure on *well oriented* planes
  - Small displacements but high permeability increase

➡ **Fault permeability can increase a lot without fault activation ?!?**

MtTerri fault
In shales



Rustrel fault
In layered carbonates



➡ **Initial aseismic highly dilatant slip**
Is it a « typical » fluid pressurization effect?

➡ **Friction variations can be described with a rate and state « laboratory » law**
Autosimilarity from mm to dam scales?

➡ **Origin of seismicity ?**
Different strength and permeability properties of the fault or of layers off the slipping surface

Conclusion: A New Test to characterize Fractured Rocks In Situ

Rock Mech Rock Eng
DOI 10.1007/s00603-013-0517-1

ISRM SUGGESTED METHOD

ISRM Suggested Method for Step-Rate Injection Method for Fracture In-Situ Properties (SIMFIP): Using a 3-Components Borehole Deformation Sensor

Yves Guglielmi · Frederic Cappa · Hervé Lançon · Jean Bernard Janowczyk · Jonny Rutqvist · C. F. Tsang · J. S. Y. Wang

Prototype validated in a relevant environment

- About 20 – to – 25 tests in the different URLs
- Measurement range:

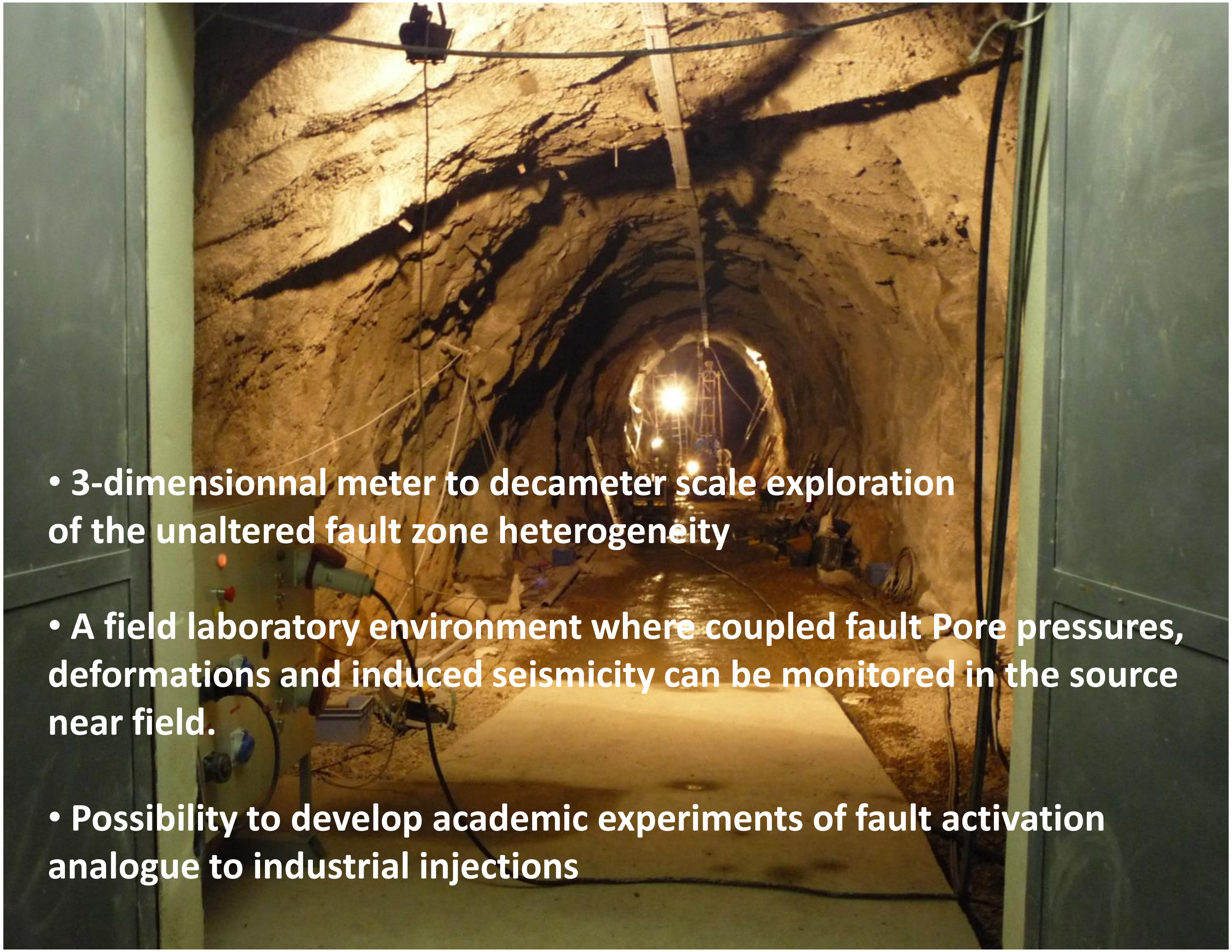
U_{axial} = 0,7mm

U_{radial} = 3,5mm

- Resolution of 3µm
- Current operating pressures 6MPa

Next probes developed to operate at 15MPa

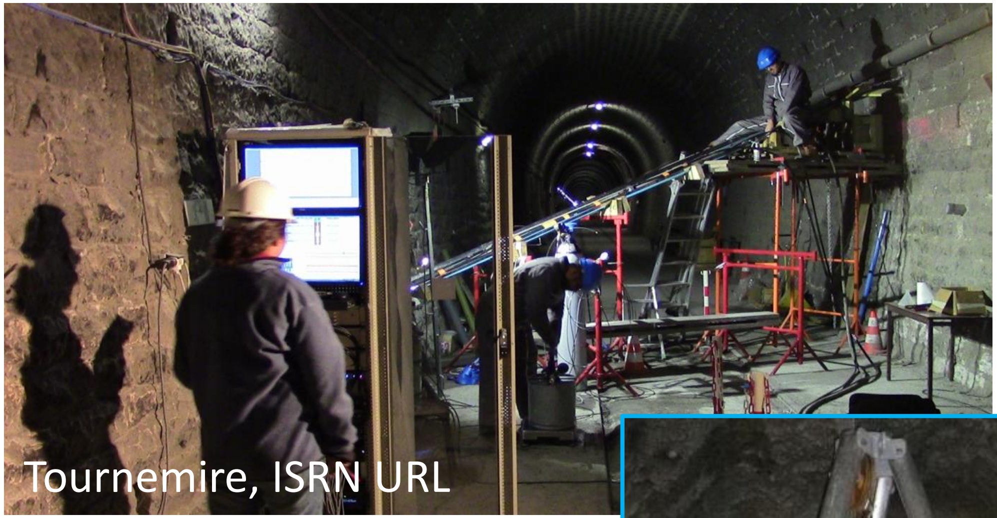
Underground Research Laboratories (URL) Good locations to conduct experiments on faults



- 3-dimensionnal meter to decameter scale exploration of the unaltered fault zone heterogeneity
- A field laboratory environment where coupled fault Pore pressures, deformations and induced seismicity can be monitored in the source near field.
- Possibility to develop academic experiments of fault activation analogue to industrial injections

LSBB laboratory in Carbonates, France

Thank You !



Collaborators:

F.Cappa
L.De Barros
J.Durand
P.Henry
C.Nussbaum
D.Elsworth
…

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References

Guglielmi Y., Cappa F., Avouac J.P., Henry P., Elsworth D. (2015). Seismicity triggered by fluid-injection-induced aseismic slip. Science 12 June 2015, Vol. 348, Issue 6240.

Derode B., Guglielmi Y., De Barros L., Cappa F. (2015). Seismic responses to fluid pressure perturbations in a slipping fault: Fault reactivation by fluid pressures. Geophysical Research Letters. 04/2015; DOI: 10.1002/2015GL063671.

Guglielmi, Y., Elsworth, D., Cappa, F., Henry, P., Gout, C., Dick, P., Durand, J., (2015a). In situ observations on the coupling between hydraulic diffusivity and displacements during fault reactivation in shales. Journal of Geophysical Research Solid Earth, 120, doi: 10.1002/2015JBO12158.

Guglielmi Y., Cappa F., Lançon H., Janowczyk J.B., Rutqvist J., Tsang C.F. and Wang J.S.Y. (2013). ISRM Suggested Method for Steo-Rate Injection Method for Fracture In-Situ Properties (SIMFIP): Using a 3-Components Borehole Deformation Sensor. Rock Mechanics and Rock Engineering, ISSN 0723-2632, DOI 10.1007/s00603-013-0517-1

De Barros L., Daniel G., Guglielmi Y., Rivet D., Caron H., Payre X., Bergery G., Castilla R., Dick P., Barbieri E., Gourlay M. (submitted). Fault structure, stress or pressure control of the seismicity in shale? Insights from a controlled experiment of fluid-induced fault reactivation. Submitted to Journal of Geophysical Research.

Cornet, F.H., Helm H., Poitrenaud H. & Etchecopar A. Seismic and aseismic slips induced by large-scale fluid injections. *Pure Appl. Geophys.*, **150**, 563-583 (1997).