Results from the In Situ Fault Slip Experiment at Mont Terri

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U.S. Department of Energy
National Energy Technology Laboratory
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Presentation Outline

- Benefit to the Program
- Project Overview
  - **Goals and Objectives**
  - **Mont Terri Setting and Fault Zone Geology**
    - The Mont Terri Laboratory Analog to a Fault Affecting a Low Permeable Caprock?
  - **Instrumentation,Test Design and Fault activation protocol**
    - Capturing static-to-dynamic three-dimensional fault movements associated to pore pressure variations
    - Sequence of semi-controlled injections to induce fault slip and trigger seismicity
  - **Analyses of Fault Slip, Induced Seismicity and Leakage**
    - Processing fault elastic properties, reactivation modes and state of stresses
    - Estimation of permeability-vs-pressure relationships
- Accomplishments to Date
- Synergy Opportunities
- Project Summary and Next Steps

Benefit to the Program

- This project improves and tests technology to assess and mitigate potential risk of induced seismicity as a result of injection operations.
- The technology improves our understanding of fault slip processes and provides new insights into the seismic and leakage potential of complex fault zones.

➢ This contributes to Carbon Storage Program's effort:

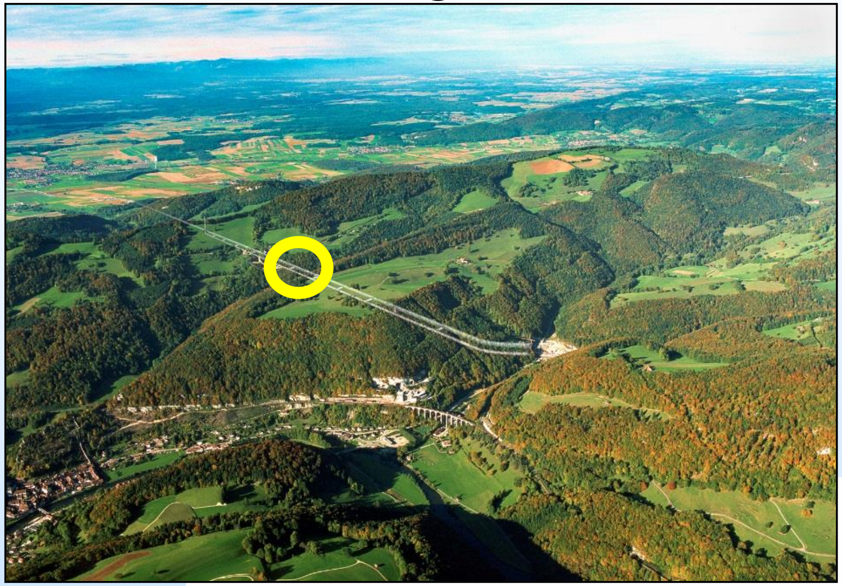
- to ensure for 99% CO_2 storage permanence
- to predict CO_2 storage capacity in geologic formations to within ±30 percent

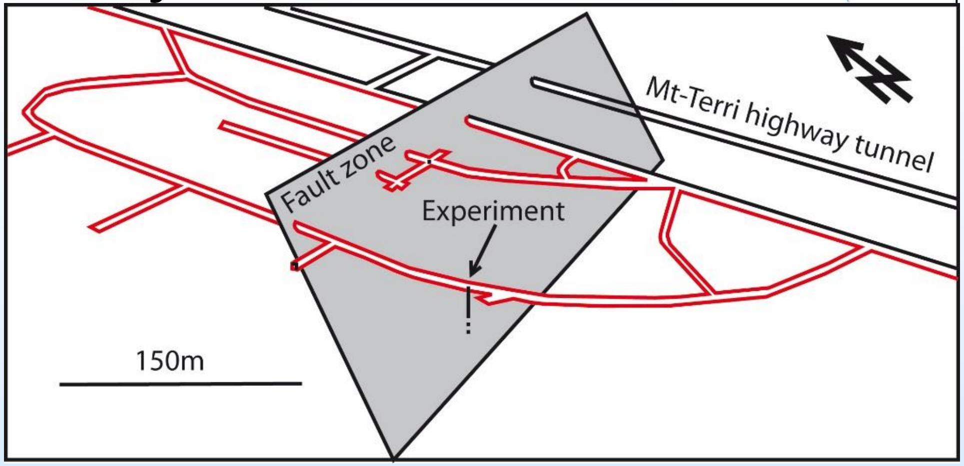
Project Overview: Goals and Objectives

- In situ study of the aseismic-to-seismic activation of a fault zone in a clay/shale formation
  - Conditions for slip activation and stability of faults
- Implications of fault slip on fault potential leakage
  - Evolution of the coupling between fault slip, pore pressure, and fluid migration
- Tool Development and Test Protocols
  - Development of a tool and protocol to characterize the seismic and leakage potential of fault zones in clay/shale formations

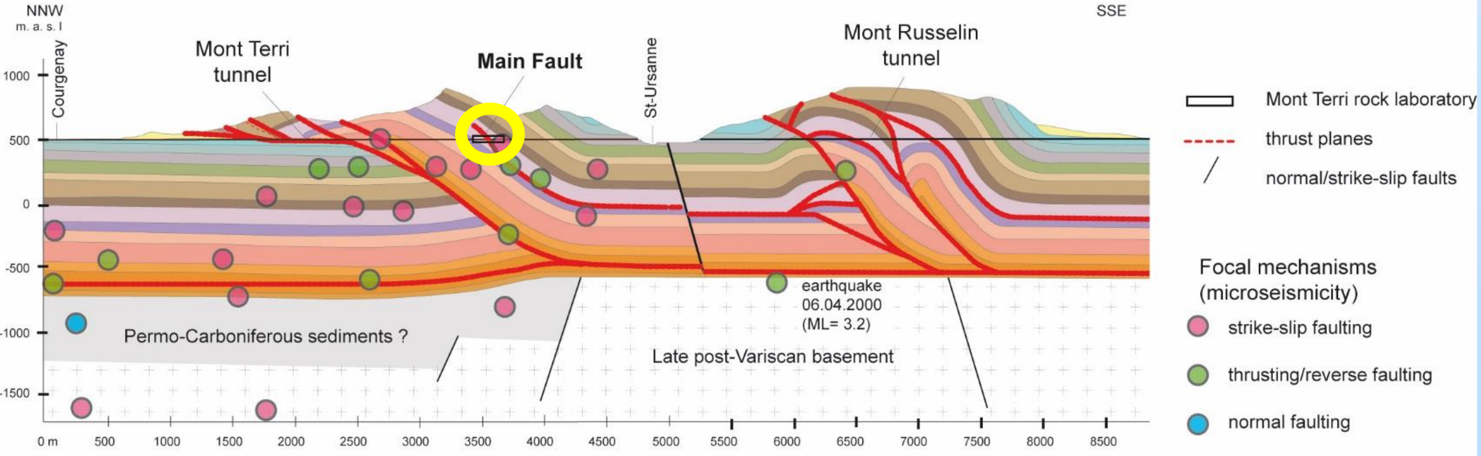
A Fault Affecting a Low-Permeable Layer Analog to a Reservoir Cap Rock

Mont Terri Underground Rock Laboratory





Depth of FS Experiment ~350m



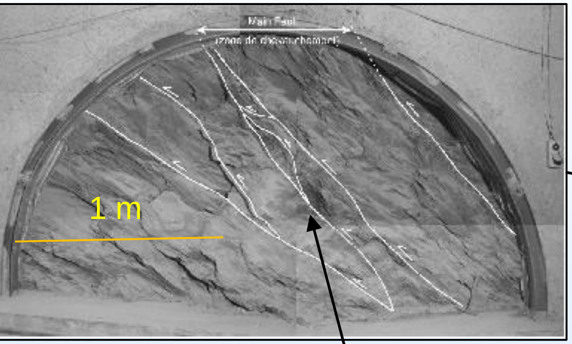
JAEA

ENSI

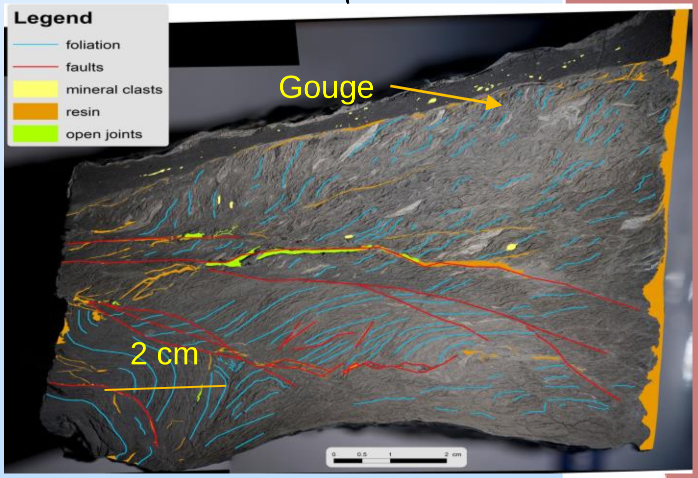
swisstopo

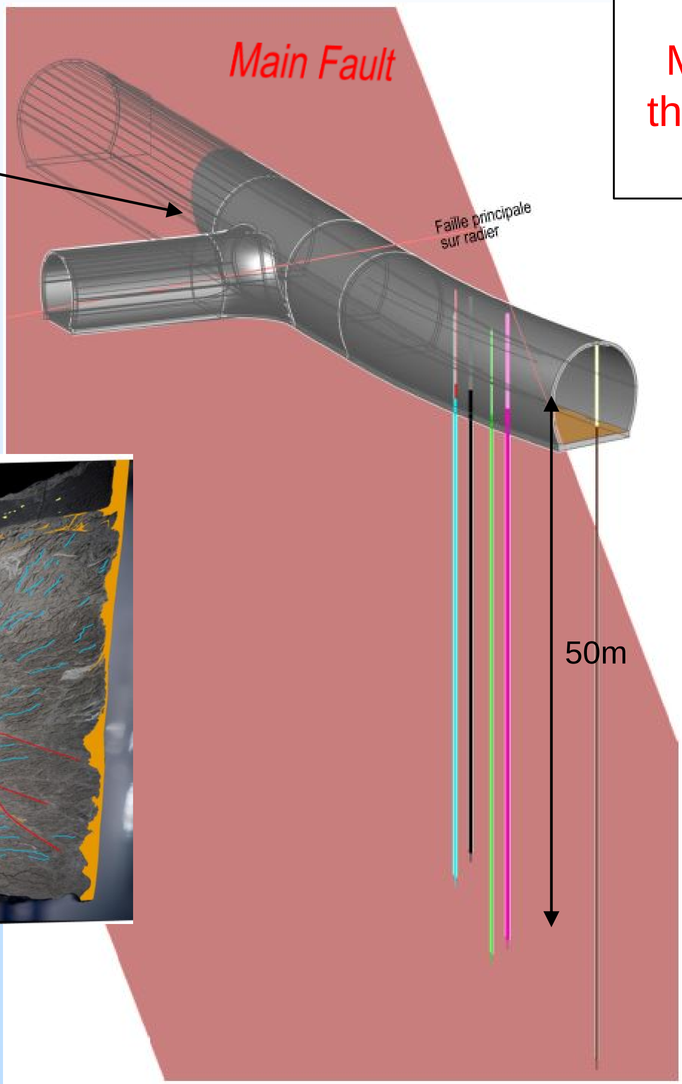
Fault Zone Structure and Complexity

A ~3m-thick core with gouge + foliation + secondary (Riedel-like) shear planes
A damage zone with secondary fault planes with slickensided surfaces



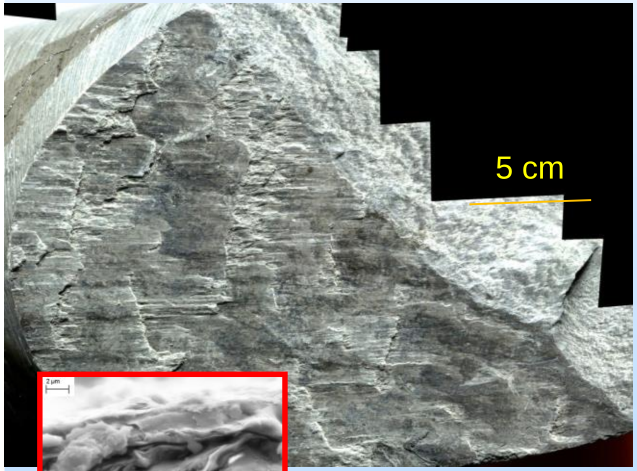
Fault Core

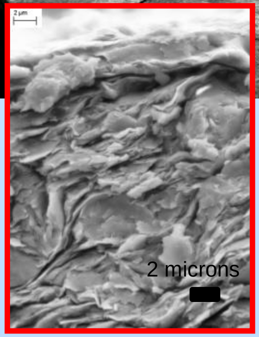




The unaltered structure of the Main Fault has been accessed through gallery outcrops and fully cored boreholes

Secondary fault surface in the fault damage zone





Opalinus Clay

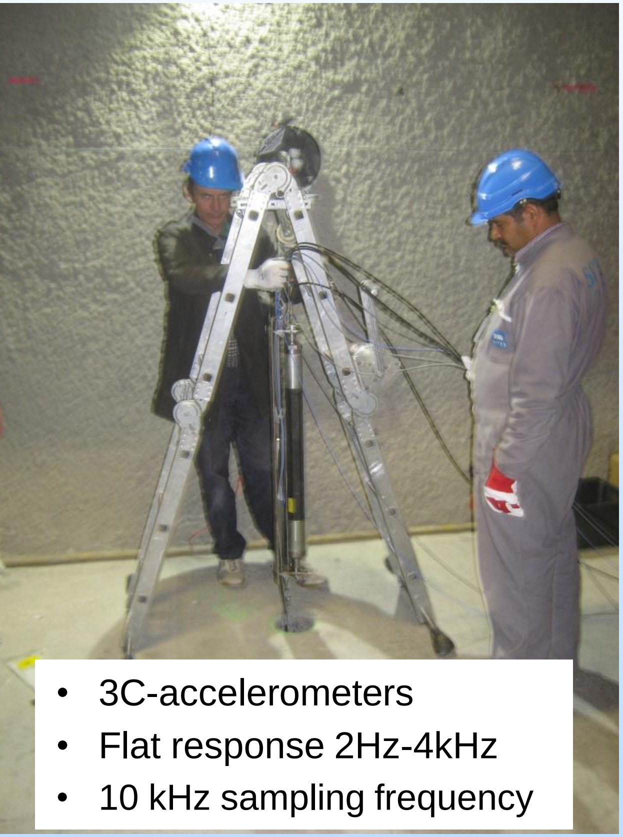
Measurement of Fault Movements and Induced Seismicity

Passive seismic monitoring:

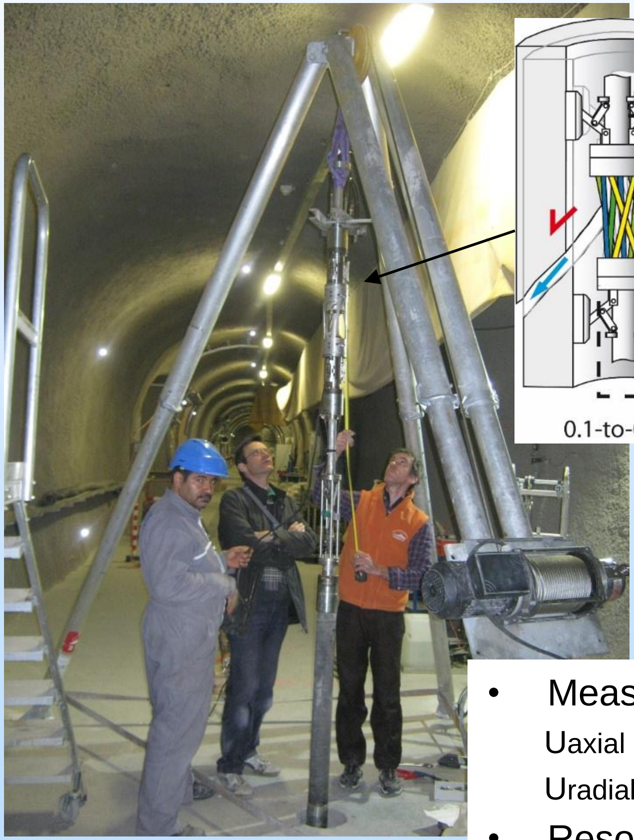
Two 3C-accelerometers and two geophones

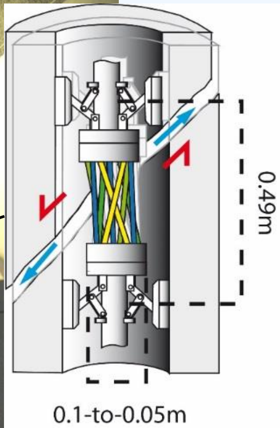
Step-Rate Injection Method for Fracture In-Situ Properties (SIMFIP)

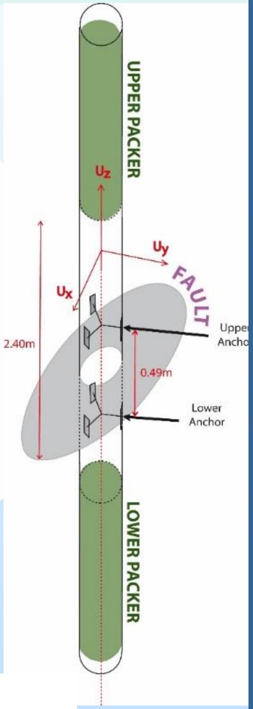
Using two 3-components borehole deformation sensor mHPP probe

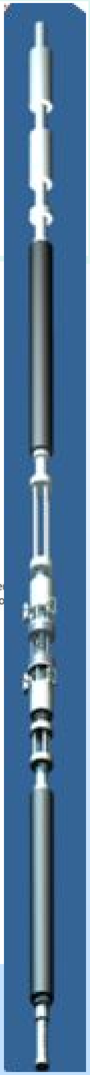


- 3C-accelerometers
- Flat response 2Hz-4kHz
- 10 kHz sampling frequency





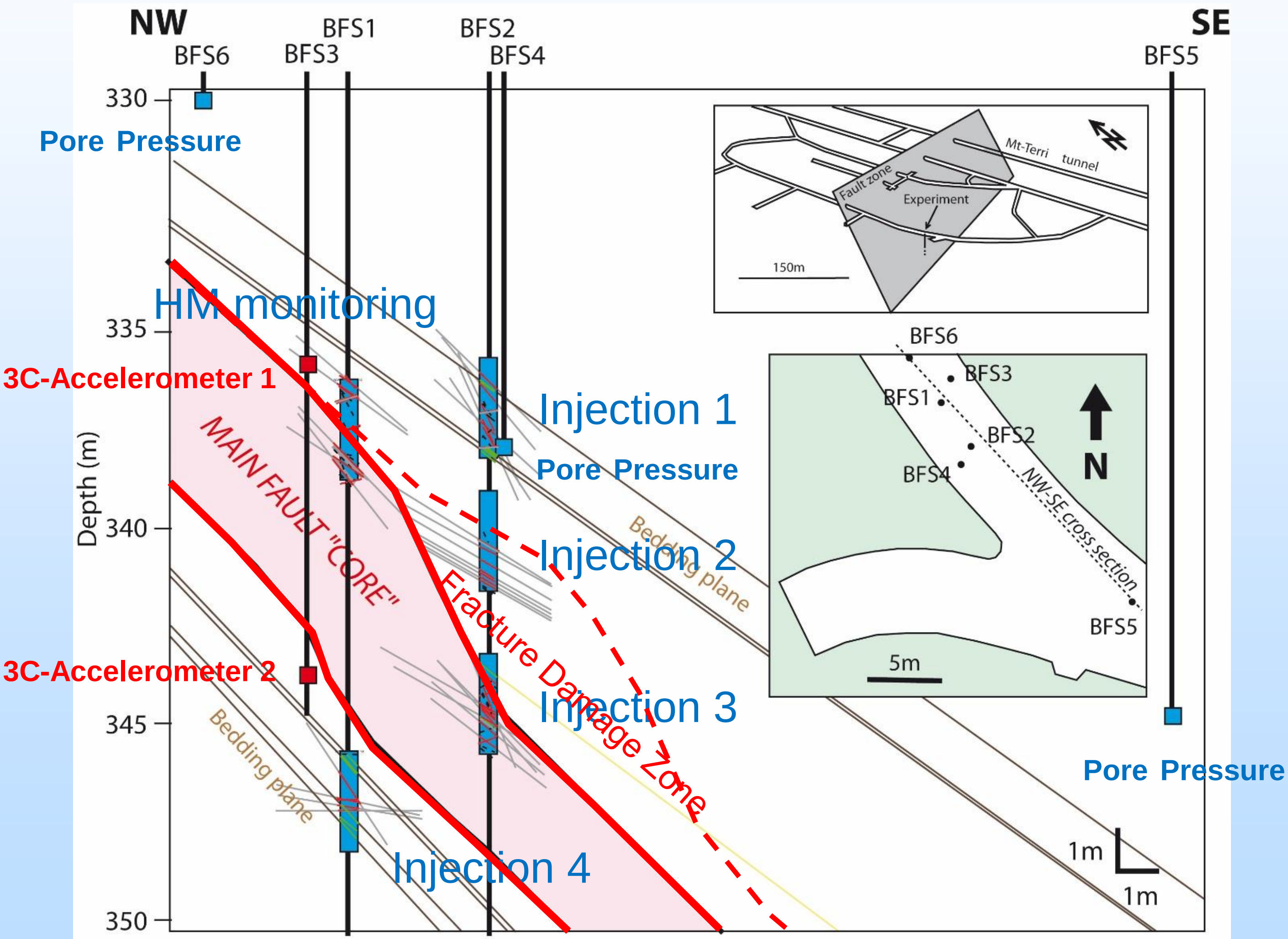




- Measurement range:
  Uaxial = 0,7mm
  Uradial = 3,5mm
- Resolution of 3µm
- 500 Hz sampling frequency

Fault Activation Protocol

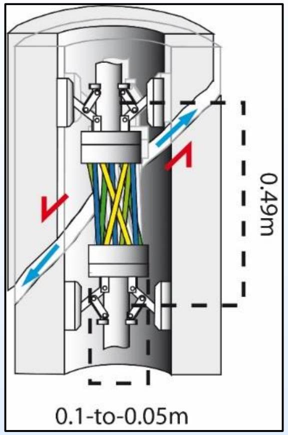
- Injection pressure imposed step-by-step in four packed-off intervals set in different fault zone locations
- Synchronous monitoring of pressure, flowrate, 3D-displacement and micro-seismicity

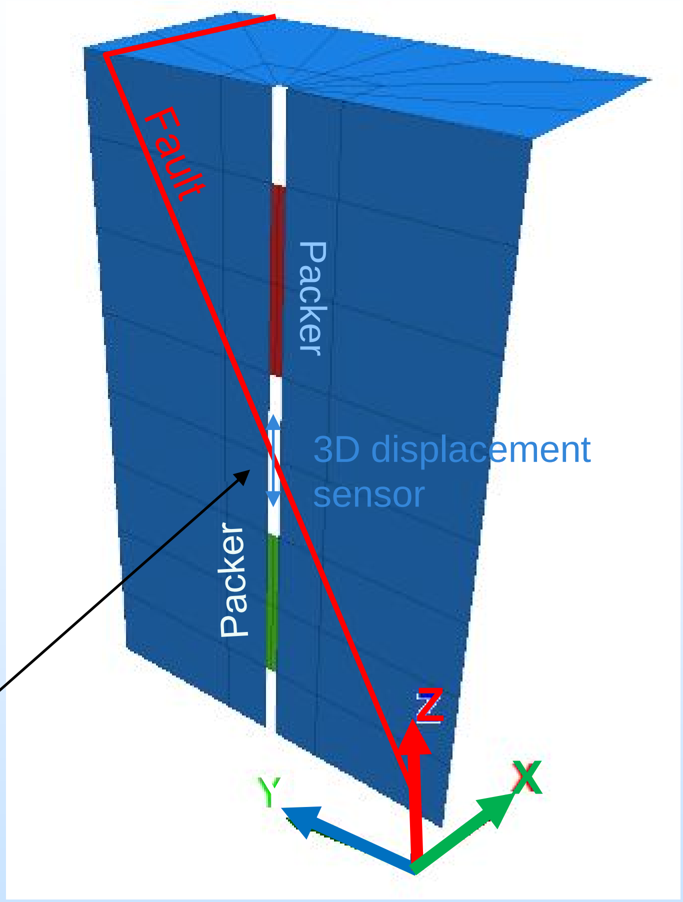


Example of Borehole Pressure-Displacement signals

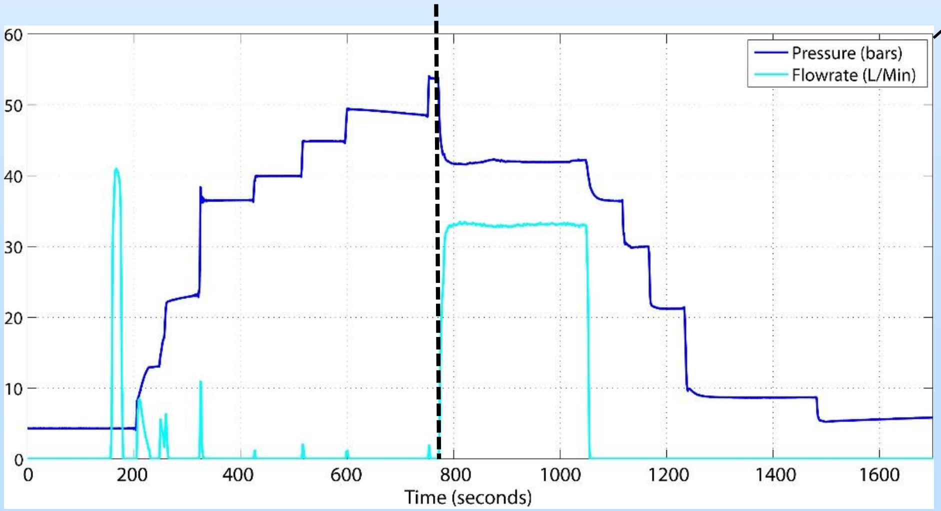
- Pressure imposed step-by-step

- **Monitoring** Injection Flowrate + Borehole wall 3D displacement



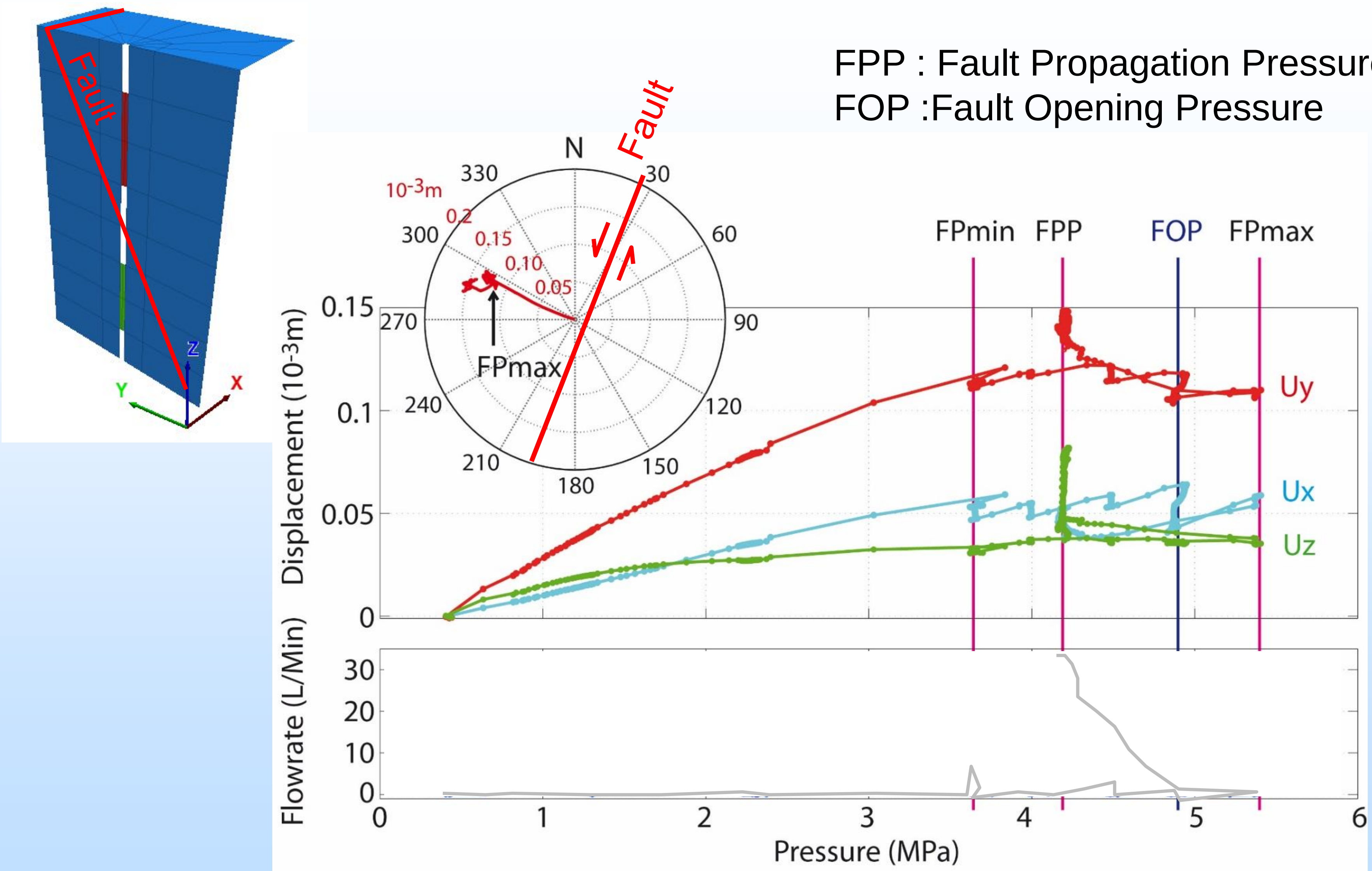


Fault Opening Pressure (FOP)



Large Fault leakage at failure in shear

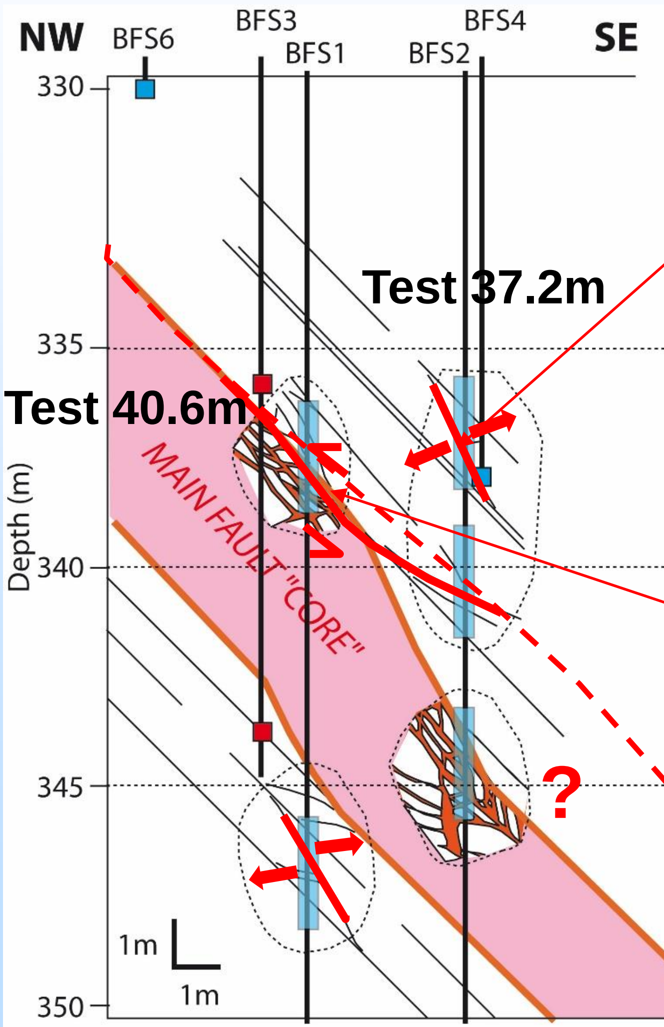
FPP : Fault Propagation Pressure
FOP :Fault Opening Pressure

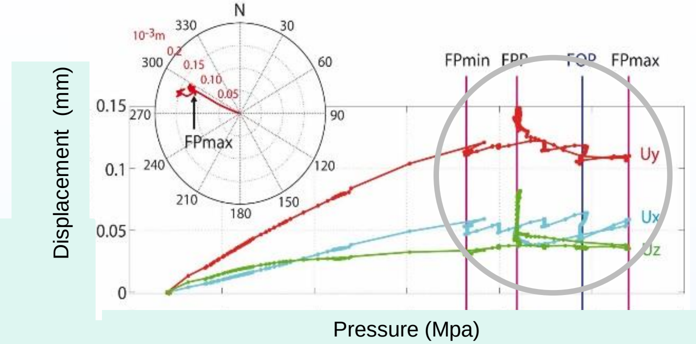


Example Test at 340.6m depth in Clay Fault Mt Terri URL (Switzerland)

Different modes of reactivation In and Out of the fault zone

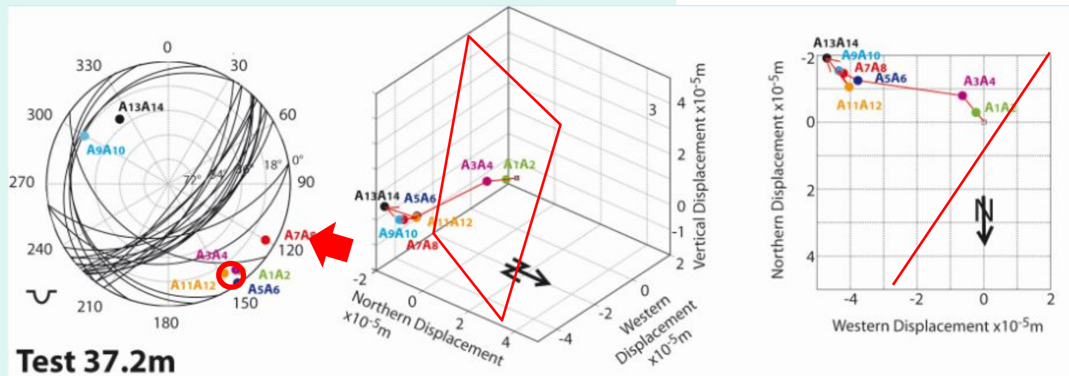
- **Shear failure (slip) mainly along the Fault Core - FDZ interface**



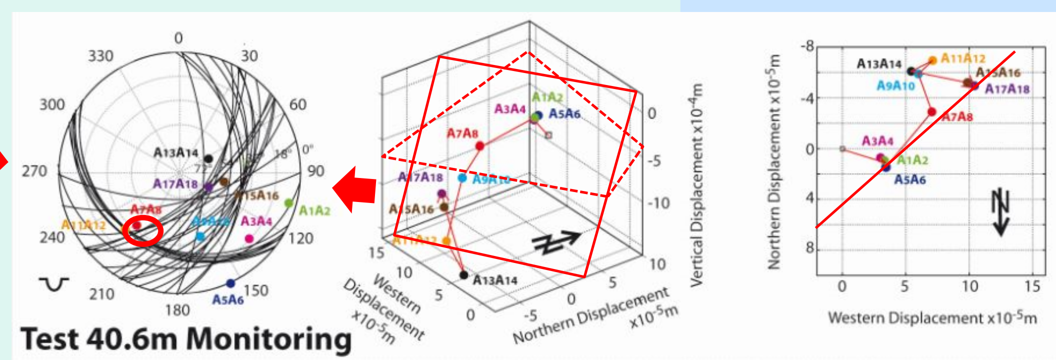


Measured Plastic Vectors

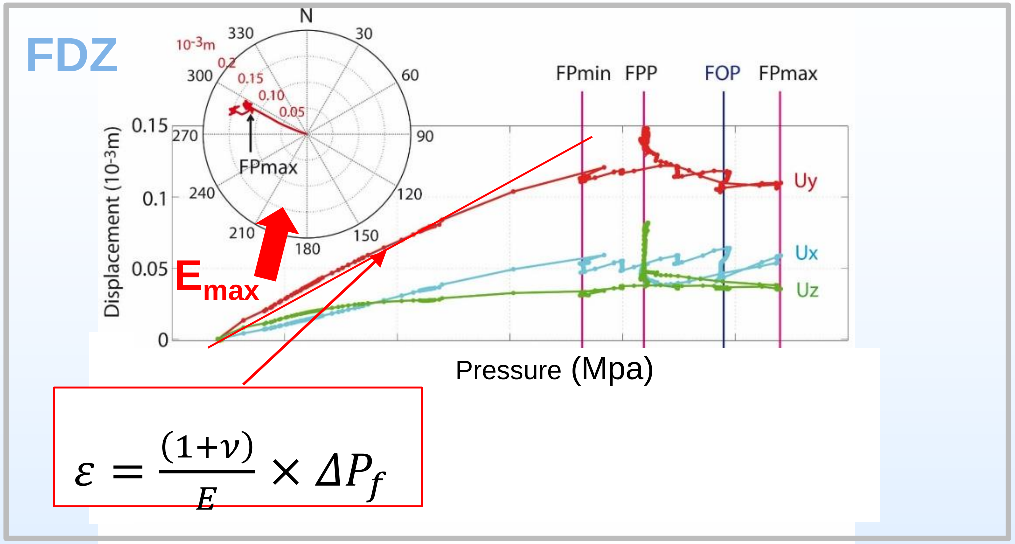
Host rock : Mainly Dilatant - Normal Opening



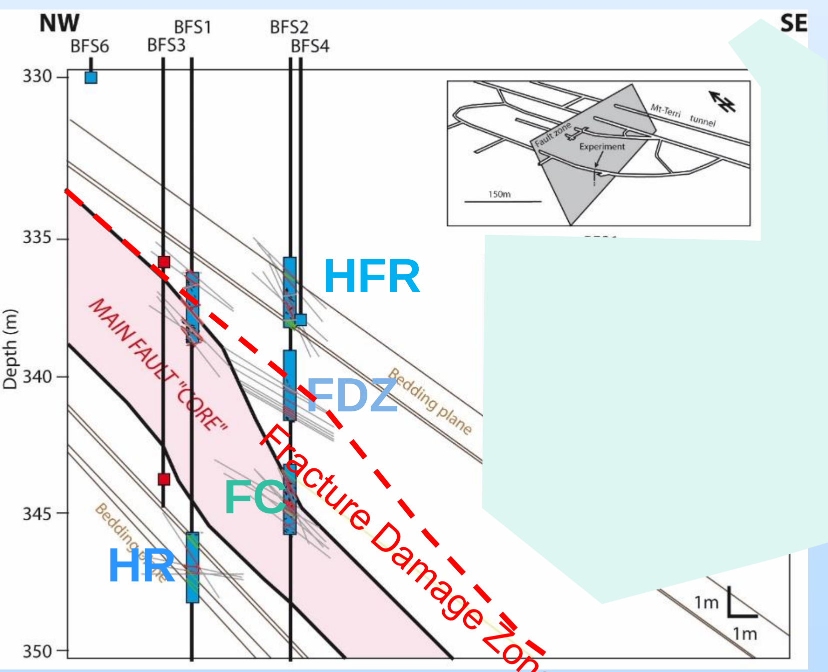
Main Fault Interface: Mainly Shear - Slip



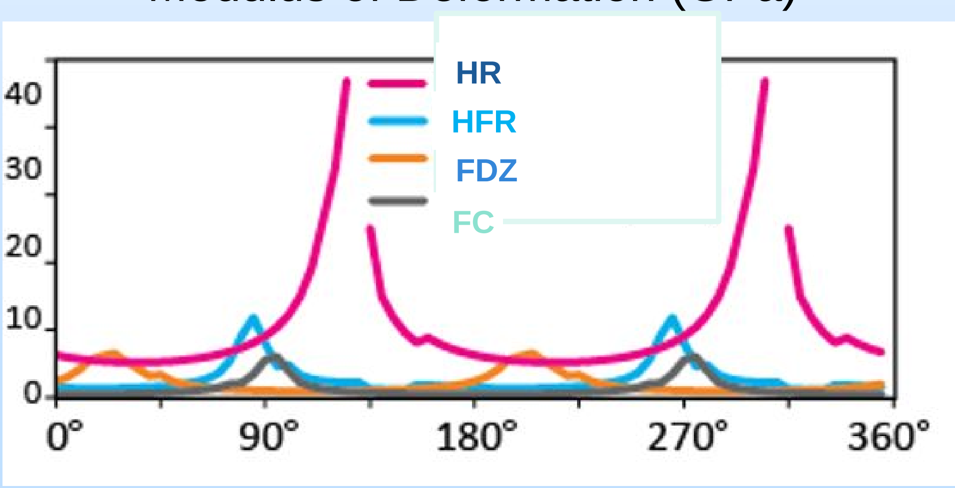
Role of Contrasted Elastic Modulus (and fracture toughness)



- E $_{fault\ core}$ ~ E $_{host\ Rock}$ / 10
- From bedding influence to fracture influence



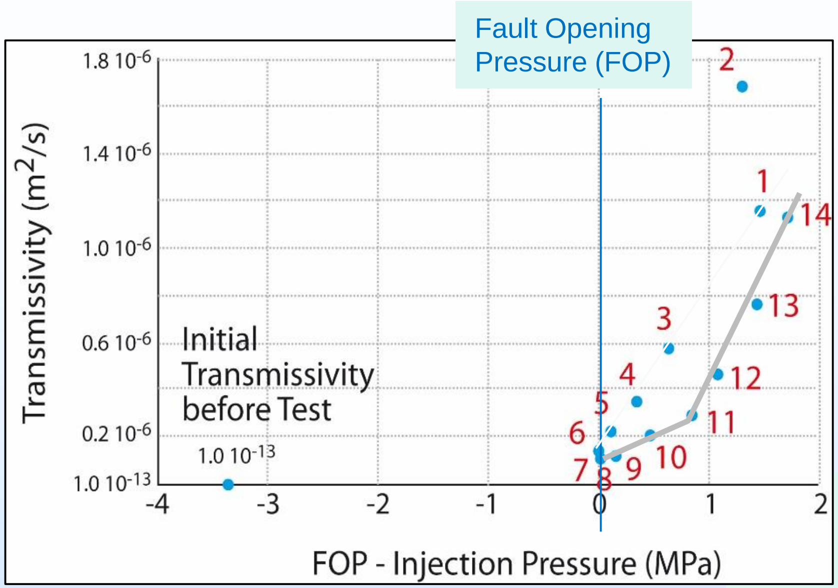
Modulus of Deformation (GPa)

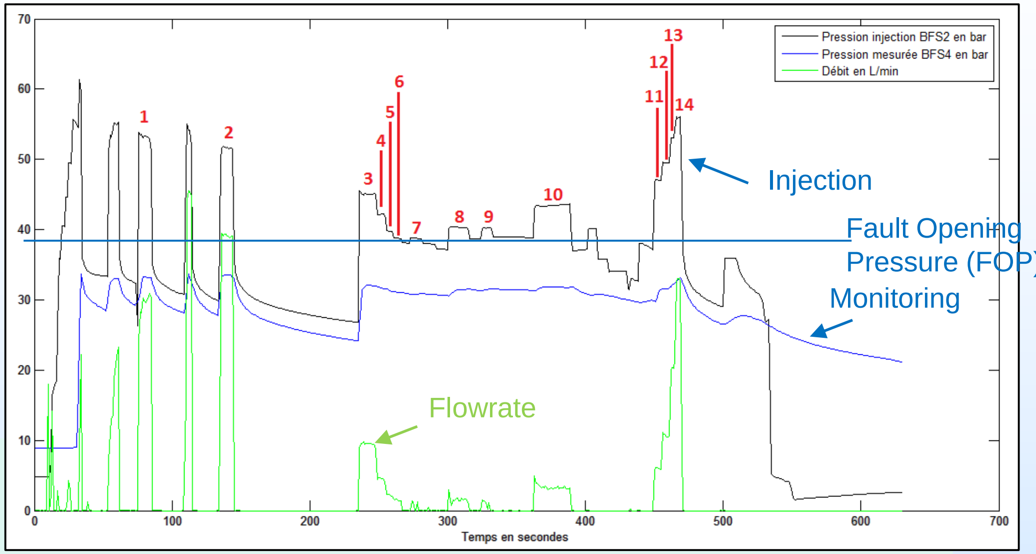


(Jeanne et al., accepted 2017)

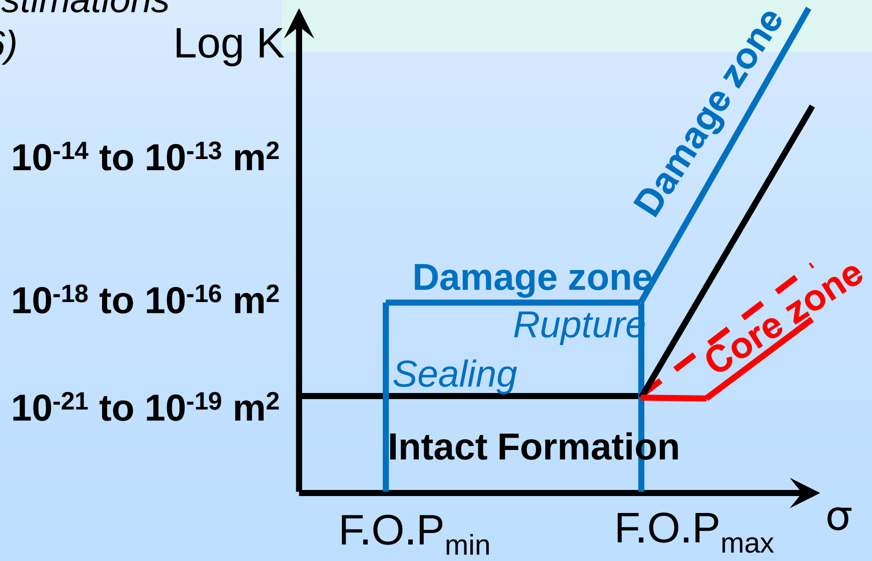
Local Factor of 10^6-to-10^7 permeability increases

(FOP-Injection Pressure) ~ ($\sigma_n - \tau/\mu$) or σ_3

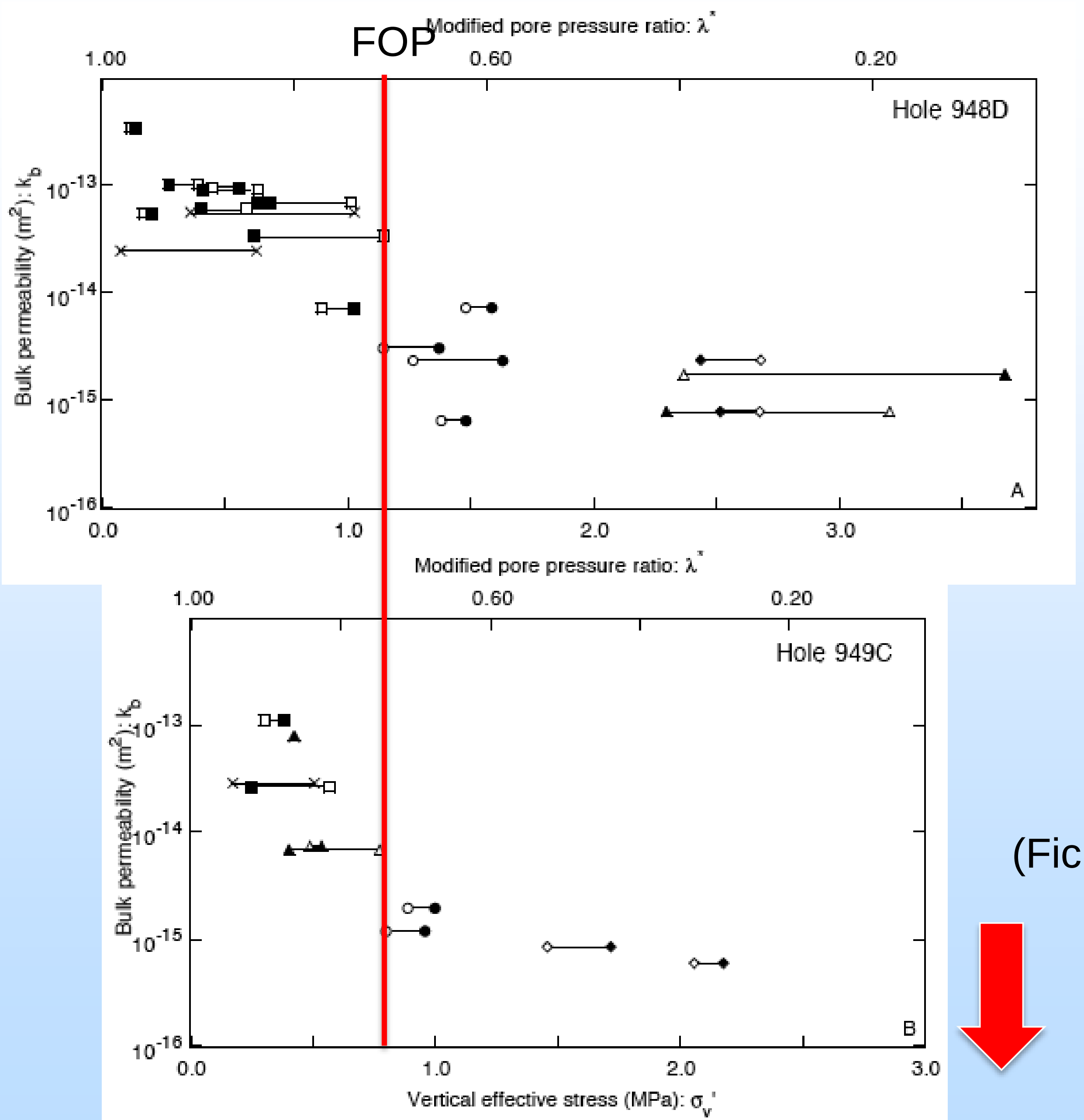




Dupuit-Thiem analytical estimations (Henry et al., 2016)



Comparison with Barbados active decollement fault

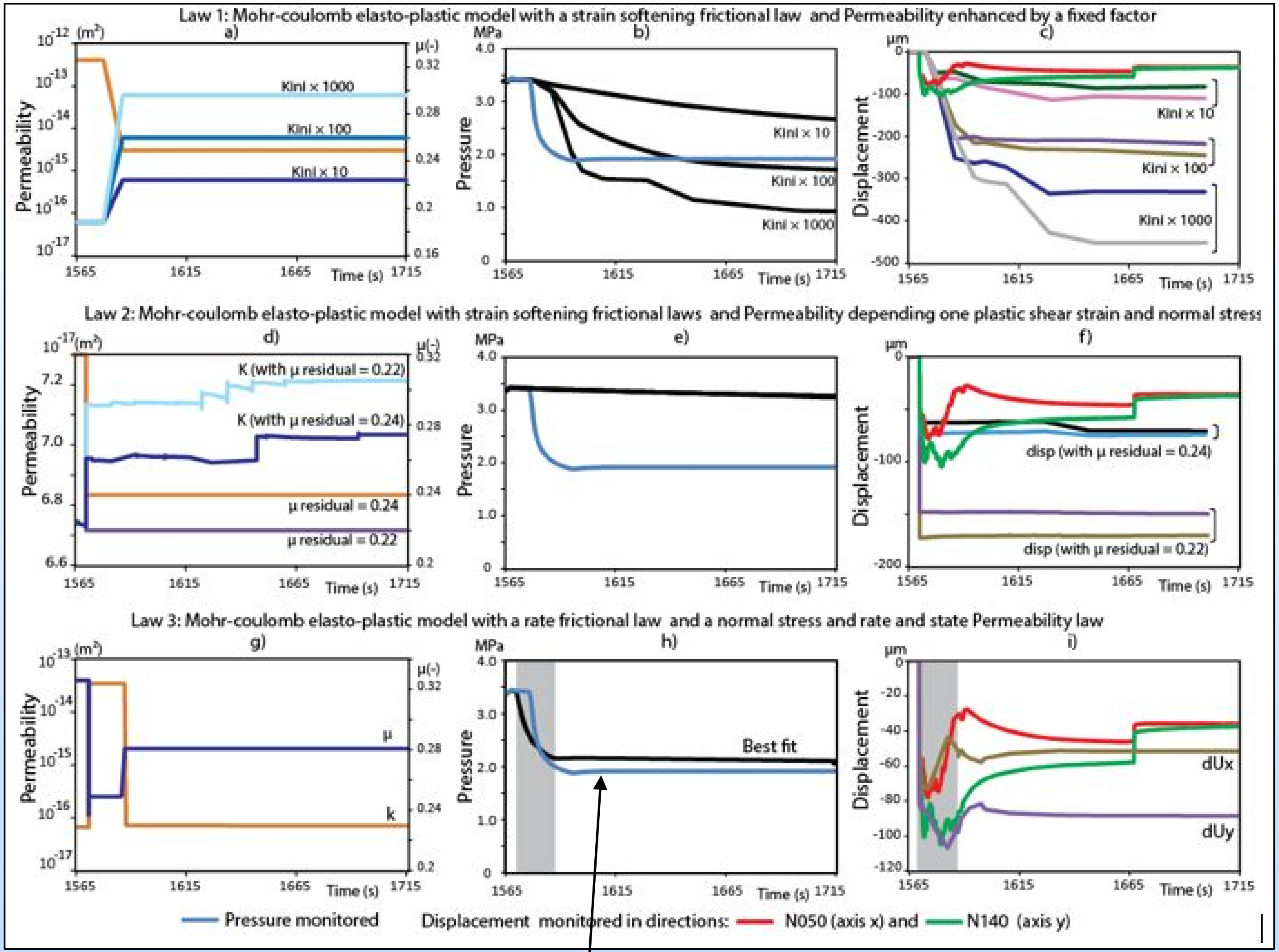


- Comparable behaviors and orders of magnitude
- Threshold could in both cases correspond to shear activation

(Ficher and Zwart, 1997)

Intact formation
$10^{-19} – 10^{-18}$ m^2

Above FOP, the local Factor of 10^6-to-10^7 permeability increases is better explained when related to strain rate…



Mohr-Coulomb
K_h empirical

Strain softening
K_h related
to dilatant slip

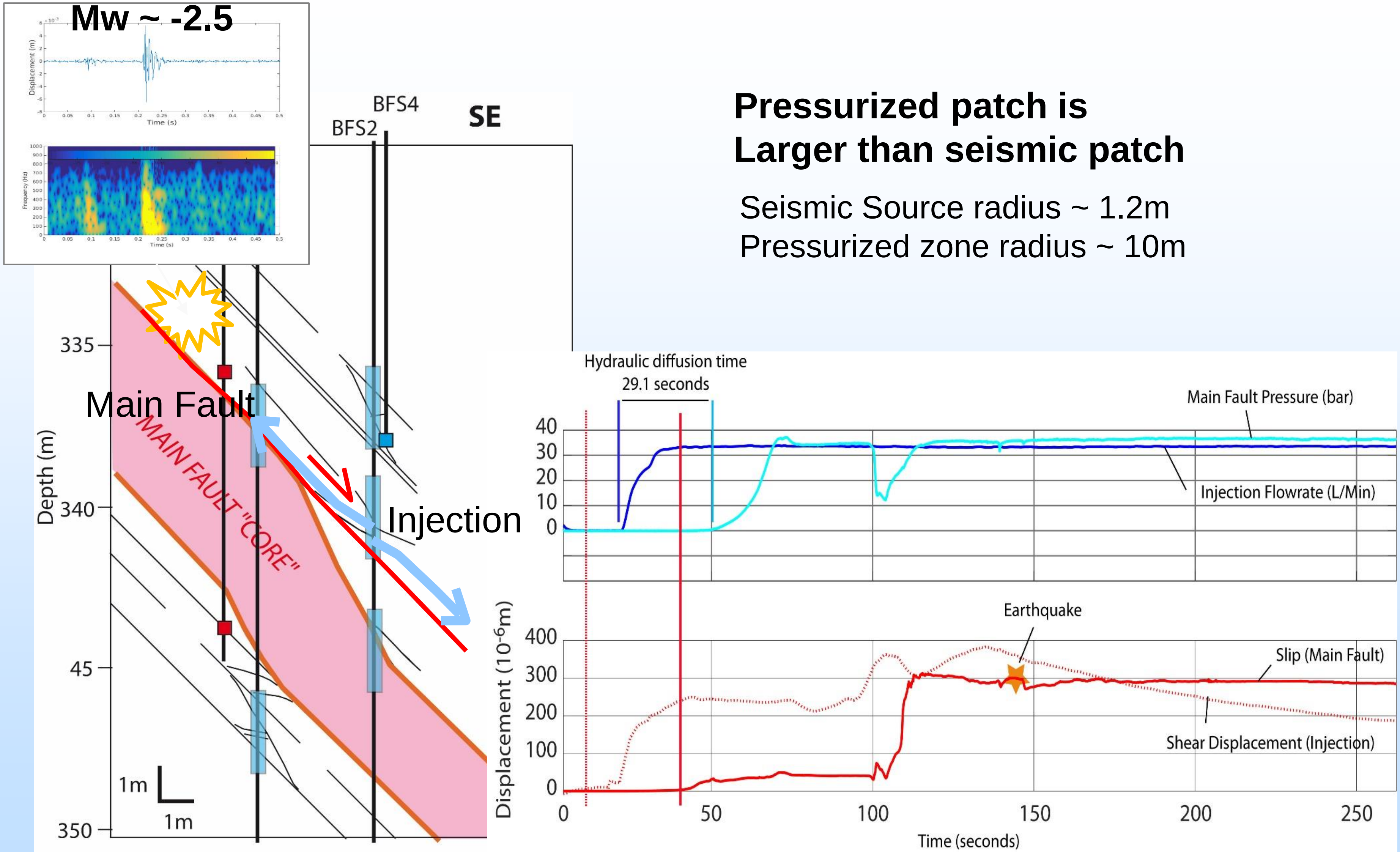
Strain rate
dependency
Of
Friction
And K_h

Experimental pressure curve

Aseismic slip preceeding Leakage and Seismicity

Pressurized patch is Larger than seismic patch

Seismic Source radius ~ 1.2m
Pressurized zone radius ~ 10m



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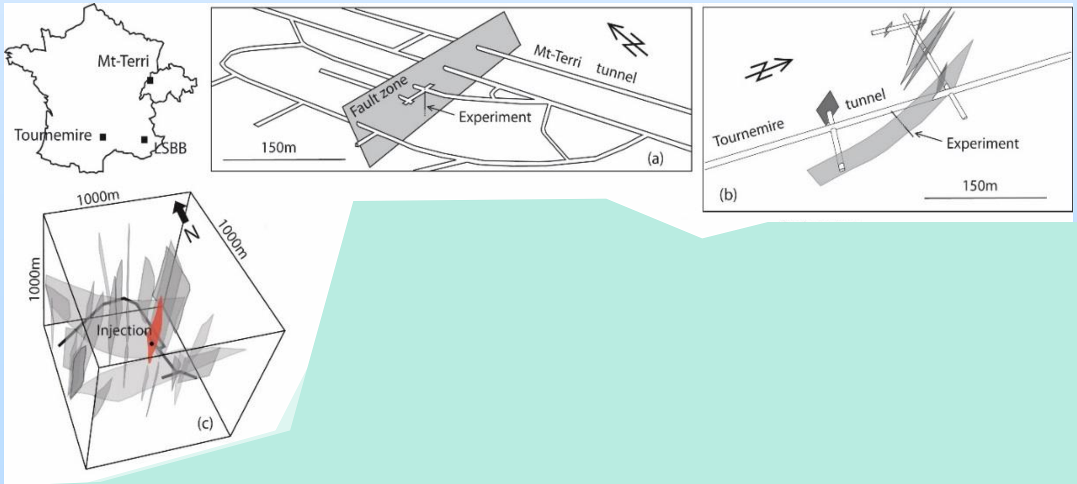
Accomplishments to Date

- **A unique fault reactivation data set has been generated** characterized by synchronous monitoring of fault movement, induced earthquakes, pore pressure, and injection flowrate
- **A new measurement tool and a test protocol have been developed** to characterize, in a controlled field setting, the seismic and leakage potential of fault zones
- **Comparison with other field activation experiments and natural active fault leakage observations**



Synergy Opportunities

- **The SIMFIP Probe**

is now being upgraded for higher pressure and temperature environments

- It will be operated to monitor hydrofracking and hydroshearing experiments planned

in the EGS-Collab project SIGMA-V

- **Operating pressure 40MPa**
- Measurement range:

  U_{axial} = 0,7mm

  U_{radial} = 3,5mm
- Resolution of 5µm
- 1000 Hz sampling frequency

Summary

Key Findings

- Insights on the seismic nucleation phase common to all experiments
  - **Large patch of aseismic slip associated with high dilation**
  - **High increase in permeability (mainly in the Fault Damage Zone)**
    - With effective Coulomb stress
    - With Dilatant Shear strain « rate » distributed in the Fault Zone volume

    (which drives a « sparse » seismicity)

- Location and Origin of seismicity induced by fluid injections?

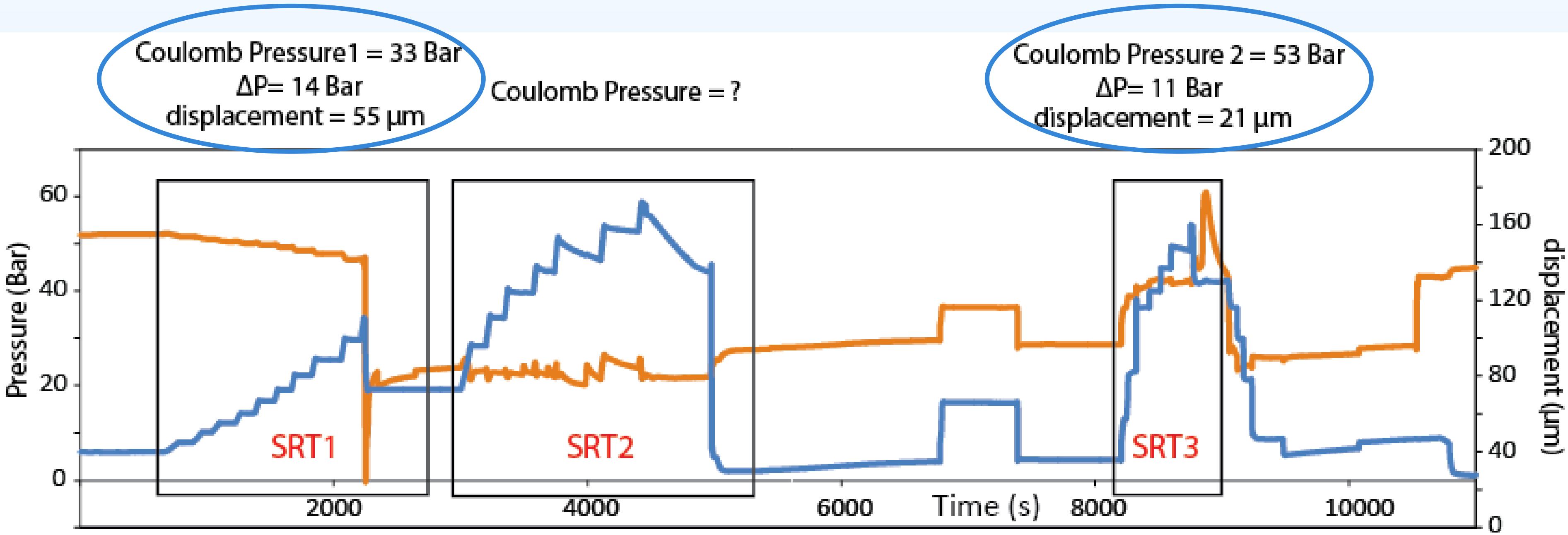
A combination of fracture mechanics and earthquake nucleation concepts

- Effect of strength + permeability properties variations in the fault zone
- Accelerated creep with large dilation could cause a frictional transition (and episodic instability)

Future Plans

- Develop and calibrate a physics based fully coupled hydromechanical approach for predictions of seismic-to-aseismic fault rupture and leakage at CO_2 sequestration depths *(considering dilation in contact-yielding concepts?)*

- Evaluate and measure potential for long-term fault sealing capabilities in cap-rocks



- **New FS-B experiment :** Test of existing techniques of repeated active seismic imaging, passive microseismic and strain monitoring to characterize and to monitor fault slip and long term leakage evolution.

Relevance to SubTER Crosscut

Subsurface Stress and Induced Seismicity Pillar
is relevant to a range of subsurface applications

Intelligent Wellbore Systems
- Improved well construction materials and techniques
- Autonomous completions for well integrity modeling
- New diagnostics for wellbore integrity
- Remediation tools and technologies
- Fit-for-purpose drilling and completion tools (e.g. anticipative drilling, centralizers, monitoring)
- HT/HP well construction / completion technologies

Subsurface Stress & Induced Seismicity
- Measurement of stress and induced seismicity
- Manipulation of stress and induced seismicity
- Relating stress manipulation and induced seismicity to permeability
- Applied risk analysis of subsurface manipulation

Permeability Manipulation
- Physicochemical fluid-rock interactions
- Manipulating flowpaths
- Characterizing fractures, dynamics, and flows
- Novel stimulation methods

New Subsurface Signals
- New sensing approaches
- Integration of multi-scale, multi-type data
- Adaptive control processes
- Diagnostic signatures and critical thresholds

Energy Field Observatories

Fit For Purpose Simulation Capabilities

Appendix

– These slides will not be discussed during the presentation, but are mandatory.

Benefit to the Program

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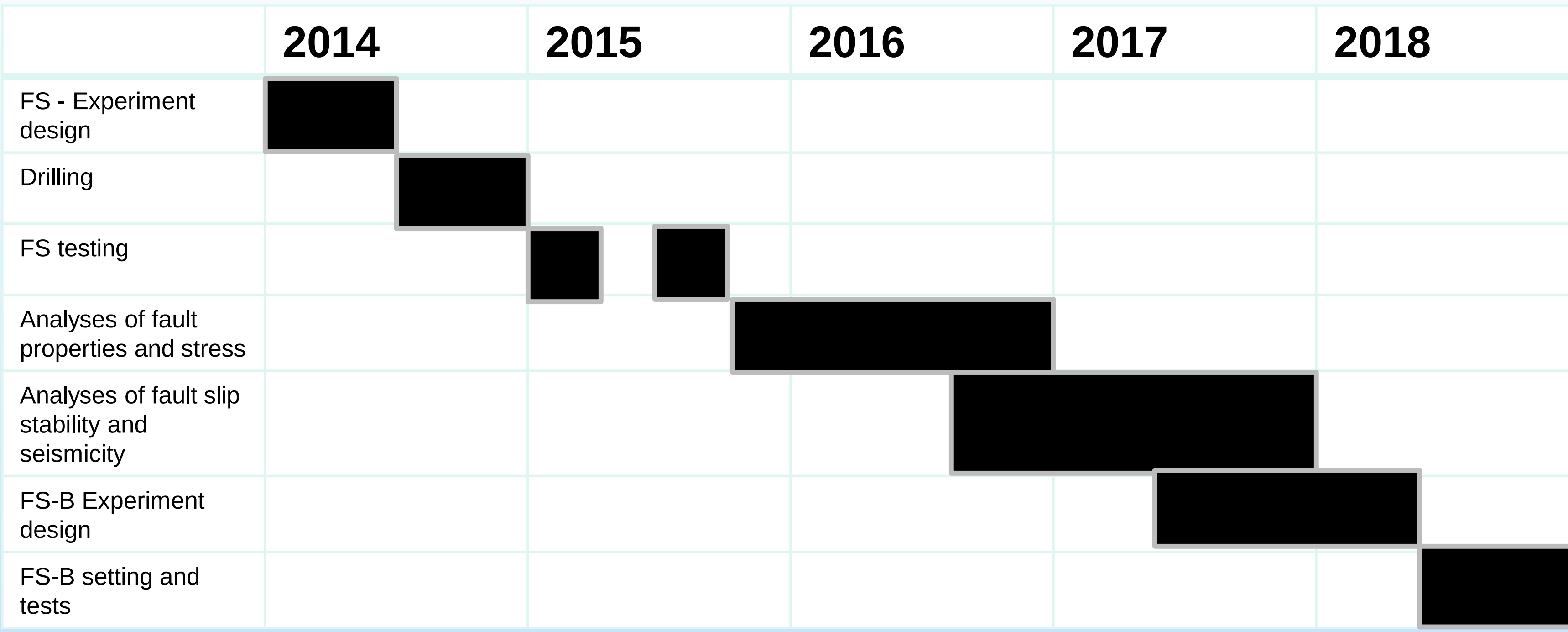
Organization Chart

- **Project participants: International Collaborations**
  - Yves Guglielmi (LBNL, USA) – PI – Field test analyses, tool and protocol development
  - Jonny Rutqvist , Jens Birkholzer, Pierre Jeanne (LBNL, USA) – Hydromechanical modeling
  - Christophe Nussbaum (Swisstopo, Switzerland) – Fault structure, kinematics and stress analyses
  - B.Valley, M.Kakurina (University of Neuchatel, Switzerland) – Three-dimensional fault zone geological modeling
  - F.Cappa, Louis de Barros (University of Nice, France) – Seismic analysis
  - Kazuhiro Aoki (JAEA, Japan) – Laboratory friction tests
  - Derek Ellsworth, Chris Marone (Pennstate University, USA) – Rate and state friction laboratory experiments and modeling

Gantt Chart


2014
2015
2016
2017
2018
FS - Experiment design
Drilling
FS testing
Analyses of fault properties and stress
Analyses of fault slip stability and seismicity
FS-B Experiment design
FS-B setting and tests

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