Active Seismic Monitoring of CO_2 Leakage Through a Hydromechanically Reactivated Fault: Caprock Integrity Monitoring For a CCS Analog

(FWP-FP00007630)

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U.S. Department of Energy

National Energy Technology Laboratory

2021 Carbon Management and Oil and Gas Research Project Review Meeting

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Presentation Outline

Benefit to the Program

- Improved understanding of fault slip processes and long-term leakage potential
- New monitoring methods to assess and mitigate potential risk of induced seismicity affecting caprock integrity
- Validated geomechanical simulation methods for fault reactivation in low permeability caprocks

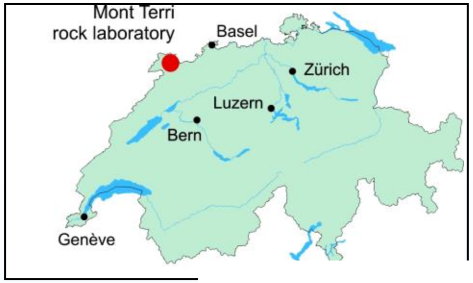
Project Overview

- Mont Terri FS Experimental Setting
- Active Seismic Monitoring Results
- Correlation with DSS-DAS-DTS optical fibers fault strain measurements
- Conceptual model of caprock fault leakage

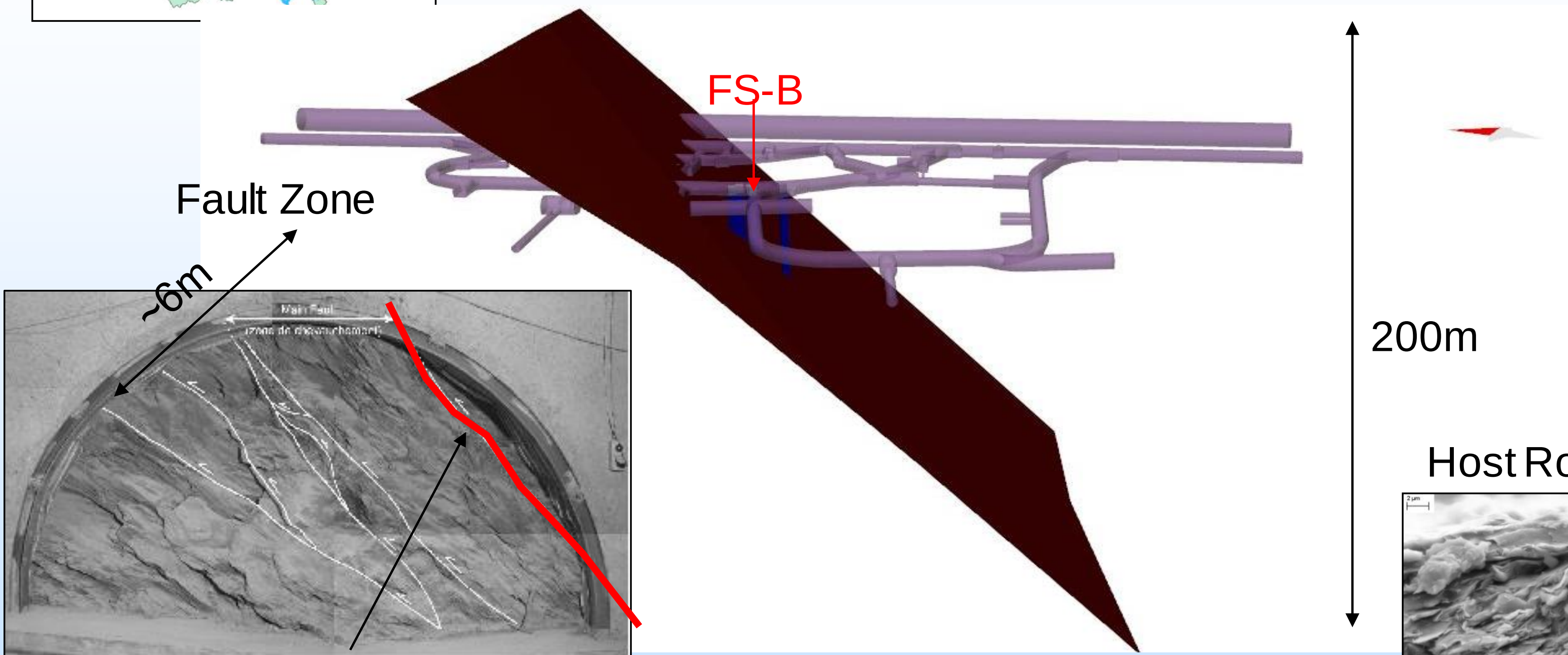
Accomplishments to Date

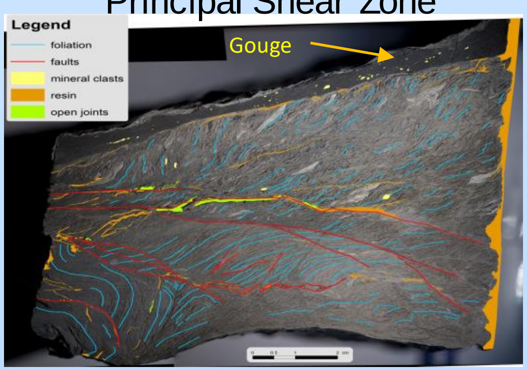
Lessons Learned and Synergy Opportunities

Project Summary

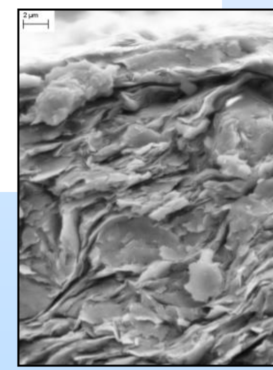


A Thick Fault Zone in a Low Permeable Clay Rock





Host Rock



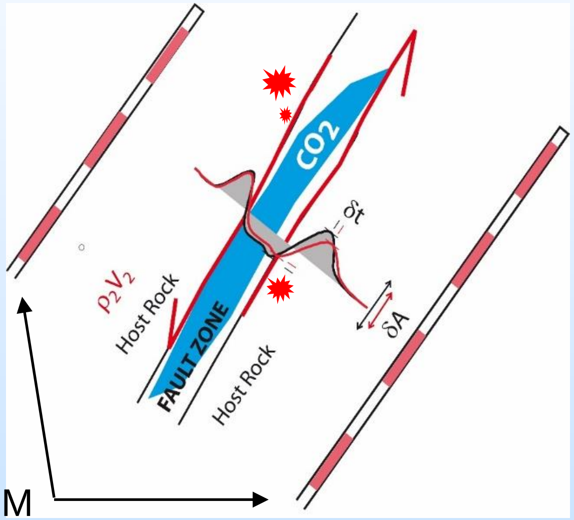
Opalinus Clay

Host Rock is analog to a Caprock !

Technical Status

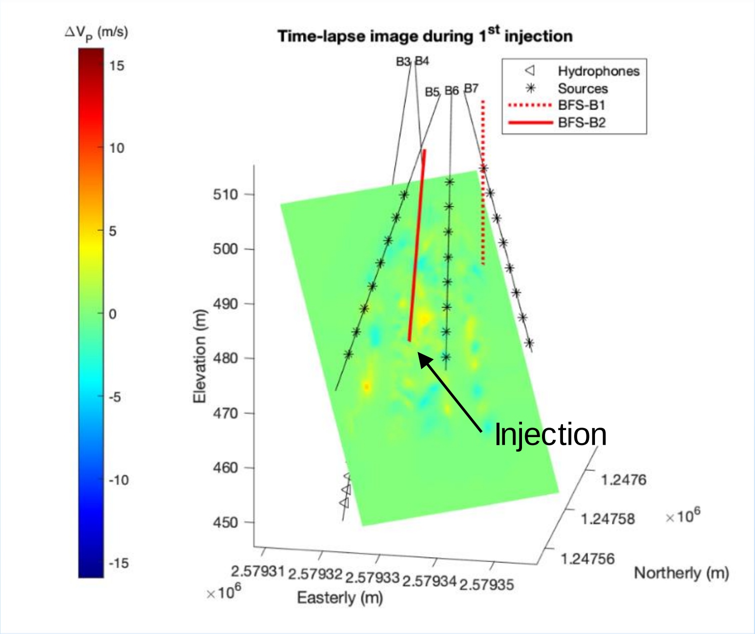
Active seismic monitoring while performing a controlled fluid injection in the fault

Concept



CASSM
monitoring wells

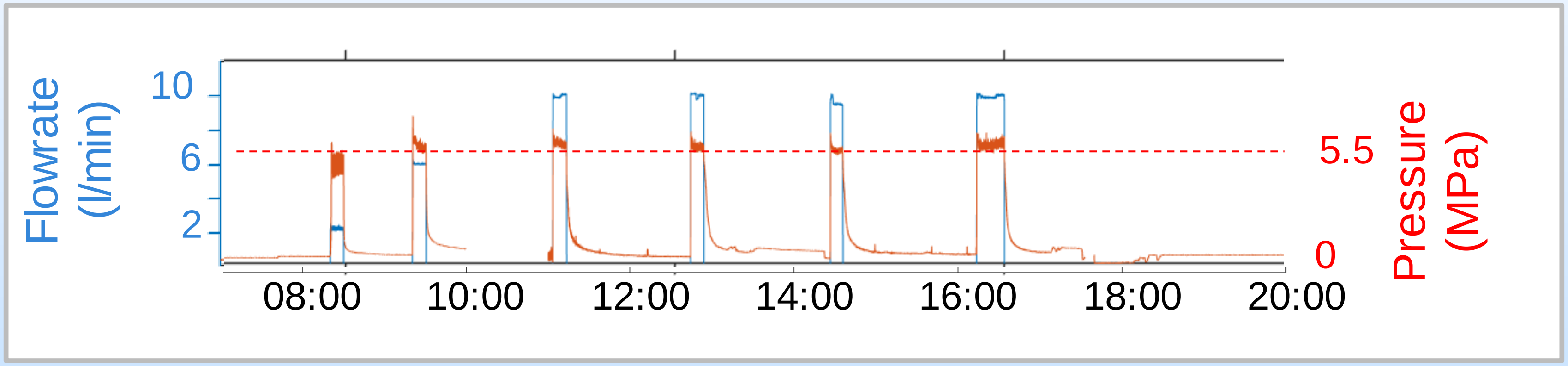
Field deployment



- A total of 5 monitoring wells for fault imaging
- 24 Sources in 3 boreholes (8 each)
- 44 Receivers (hydrophones) in 2 boreholes (22 each)
- Temporal Resolution for full survey is < 8 mins
- Fluid-coupled (can be retrieved)

Field scale controlled water injection in a slipping fault

6 injection cycles at constant flowrate of 2 to 10 l/min



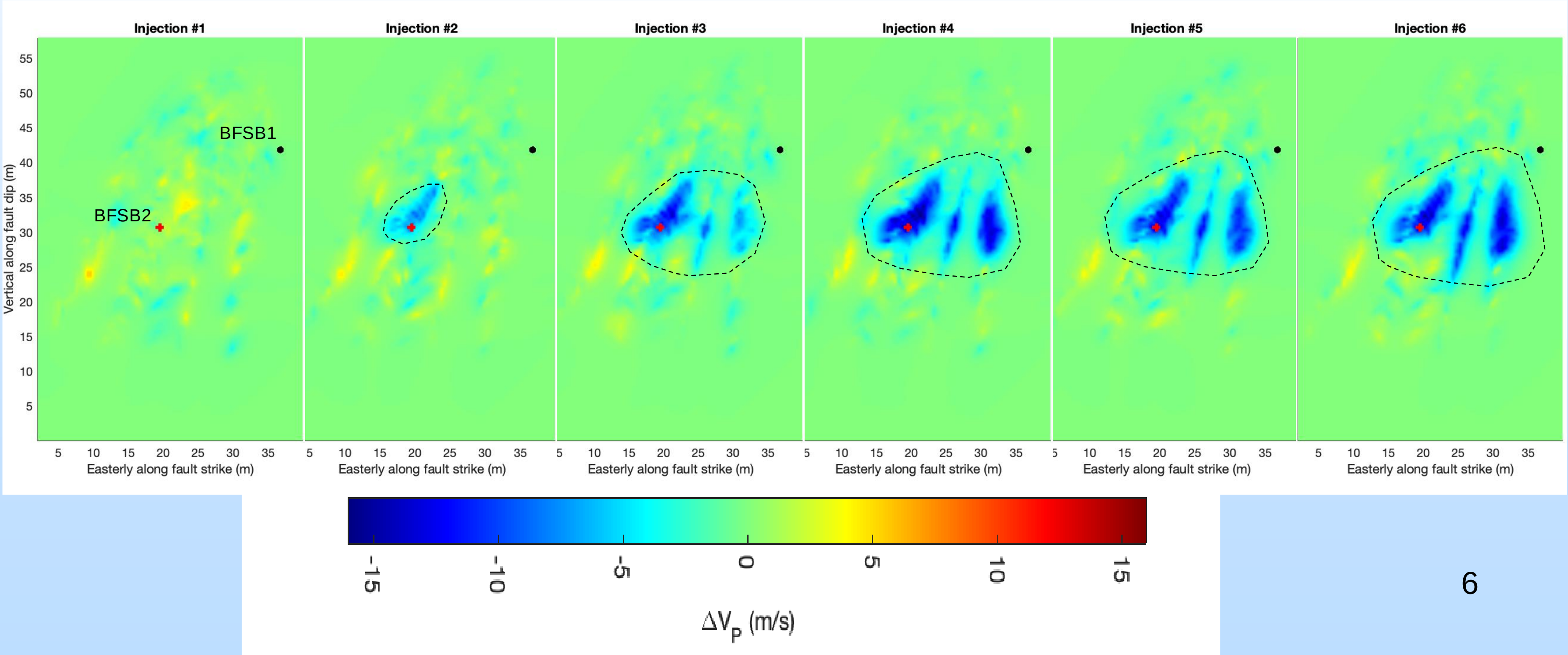
Fault starts leaking at about 5.5 MPa

Imaging Leakage Propagation in a parallel slice through the Fault

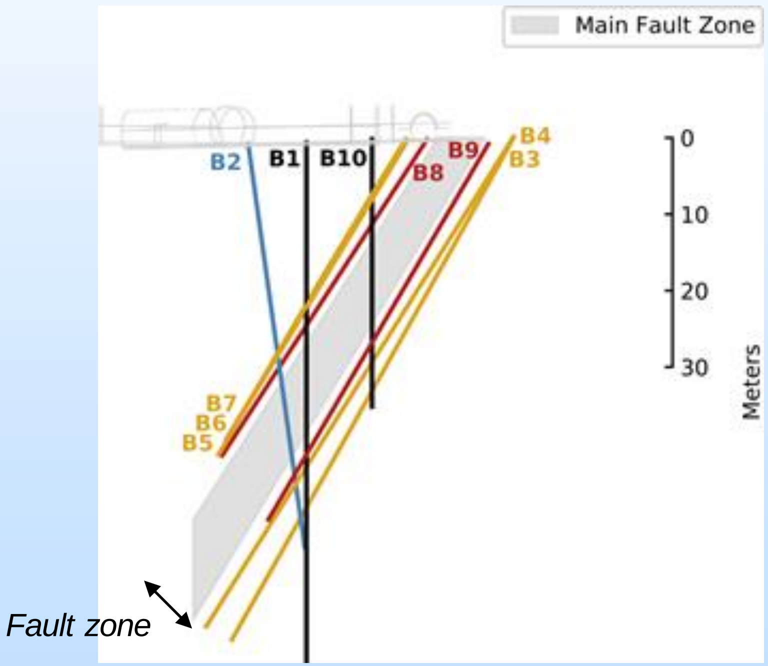
- The blue patch represents a negative V_P change showing which parts of the fault are being reactivated.

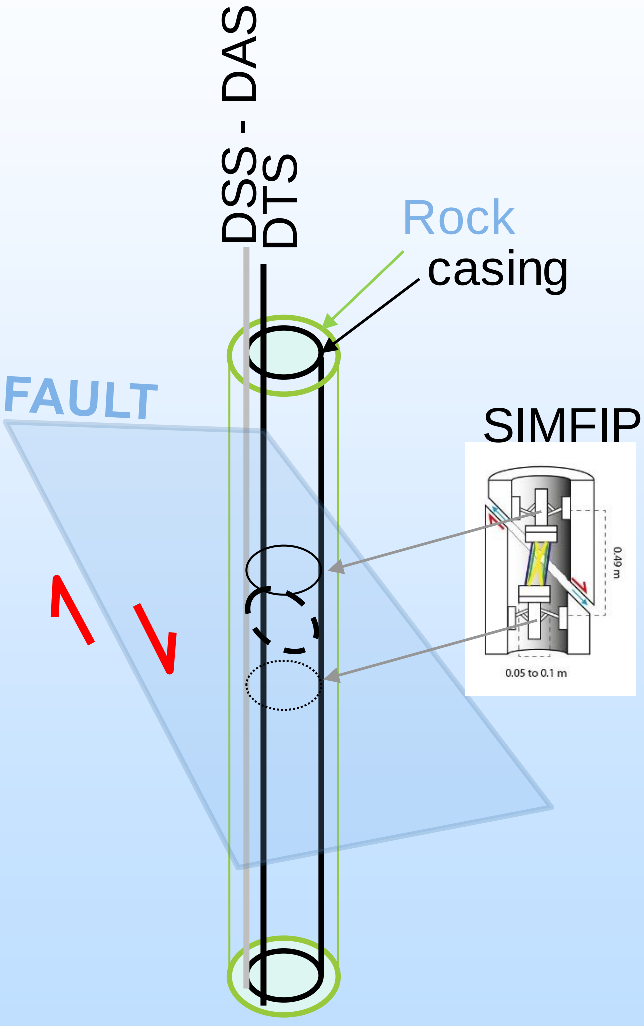
  The three patches are likely a single patch and that they were created due to the null space between ray-path coverage.

- Based on injection well location (BFS-B2) and the negative velocity patch, fluids leaked easterly along fault strike.



Comparison of p-Wave variations
With localized and distributed fiber optic sensors

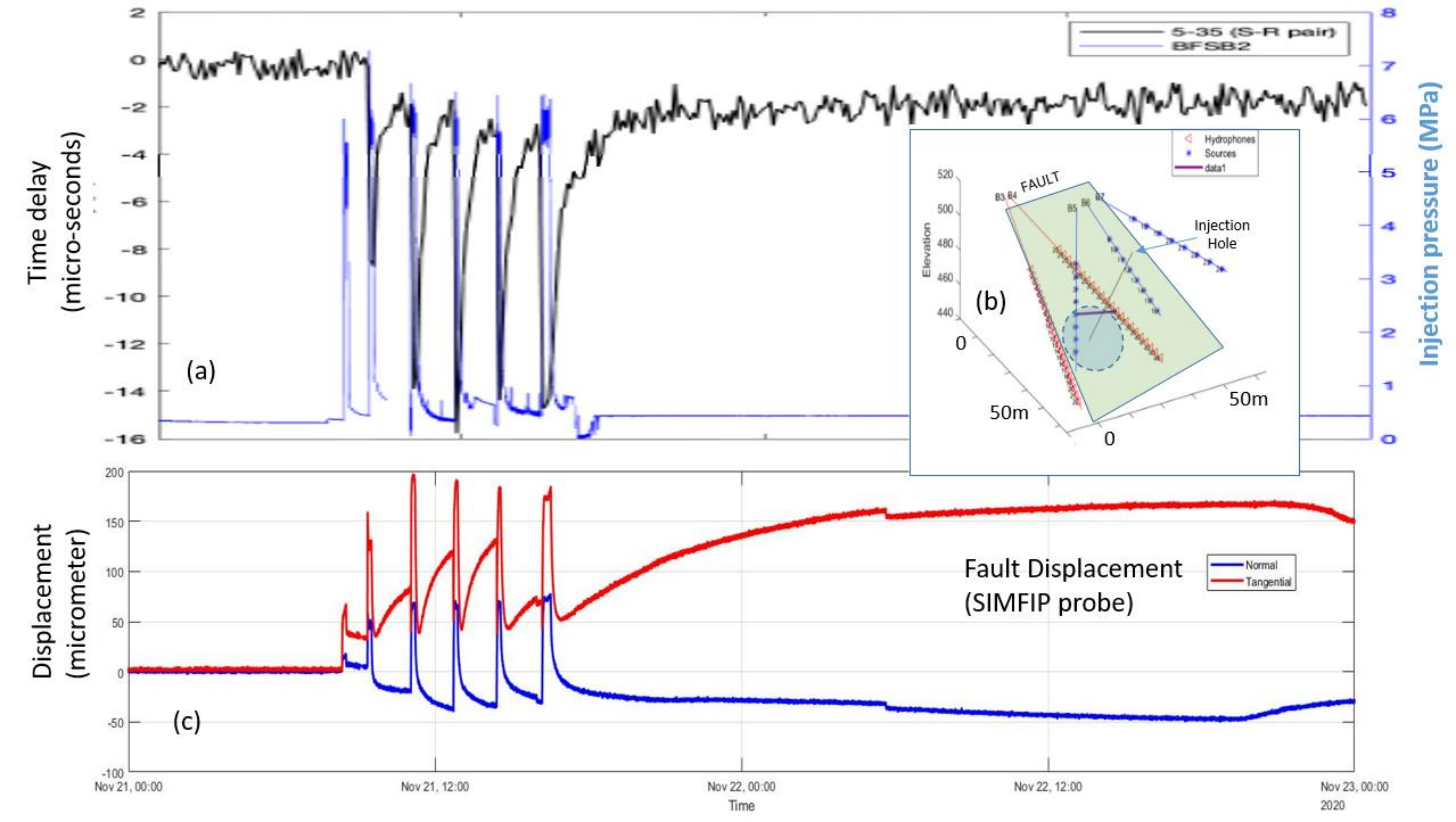




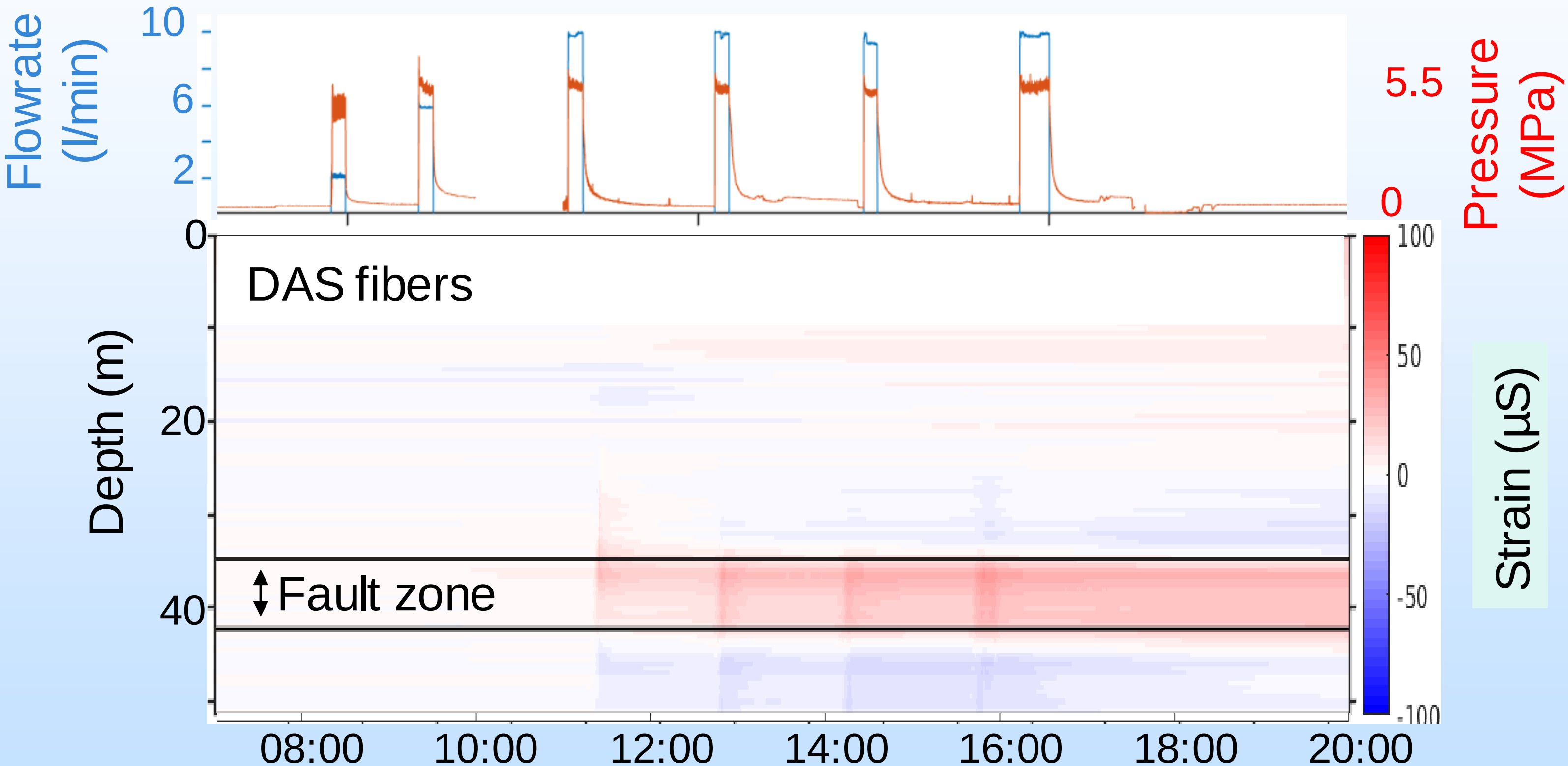
Example of B1 well

p-Wave Delays Correlate with Fault Displacements

Local fault opening and shearing

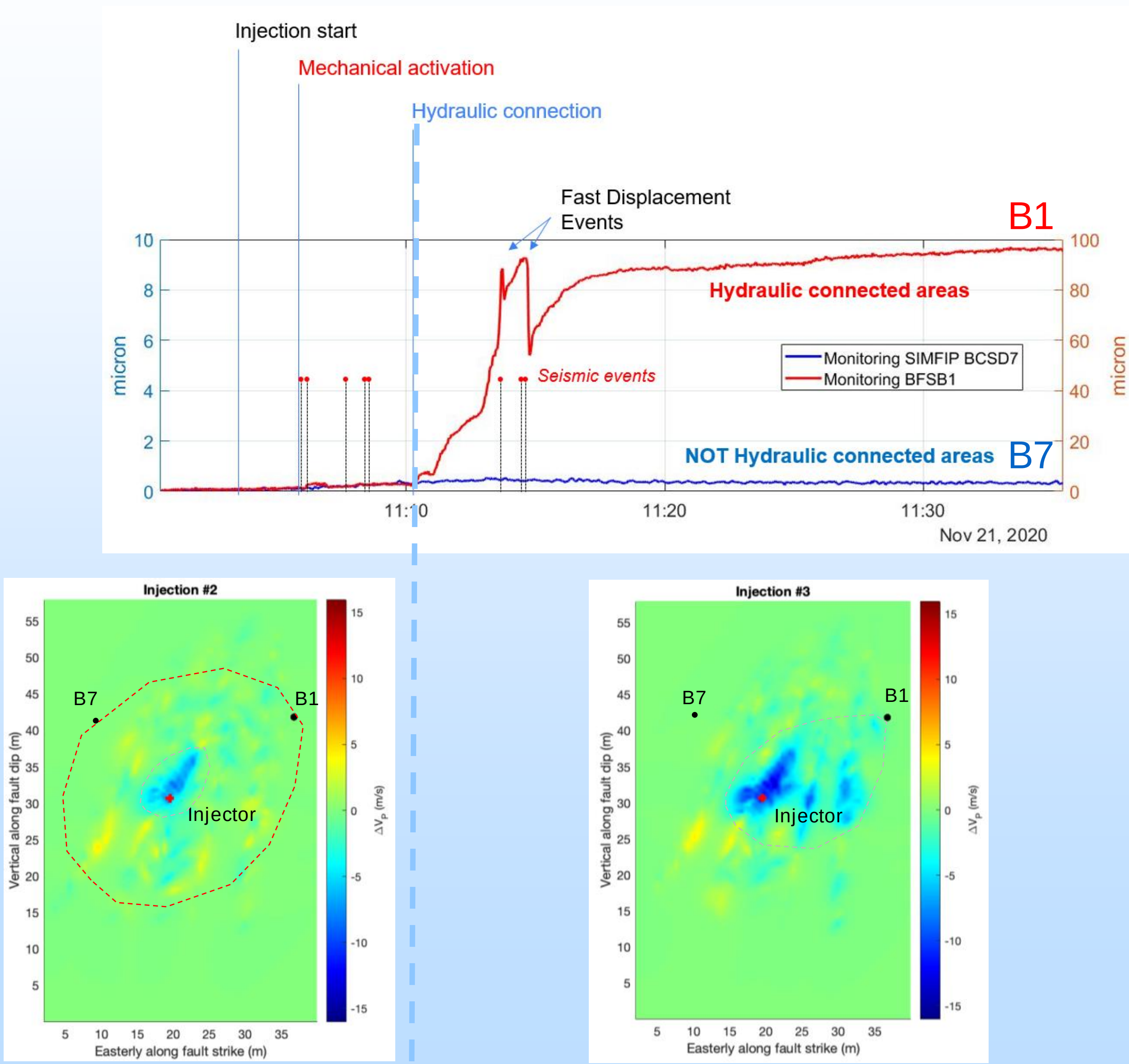


Extension (red) distributed across the thickness of the fault
Compression (blue) in the surrounding intact rock
Significant permanent strain after fault activation



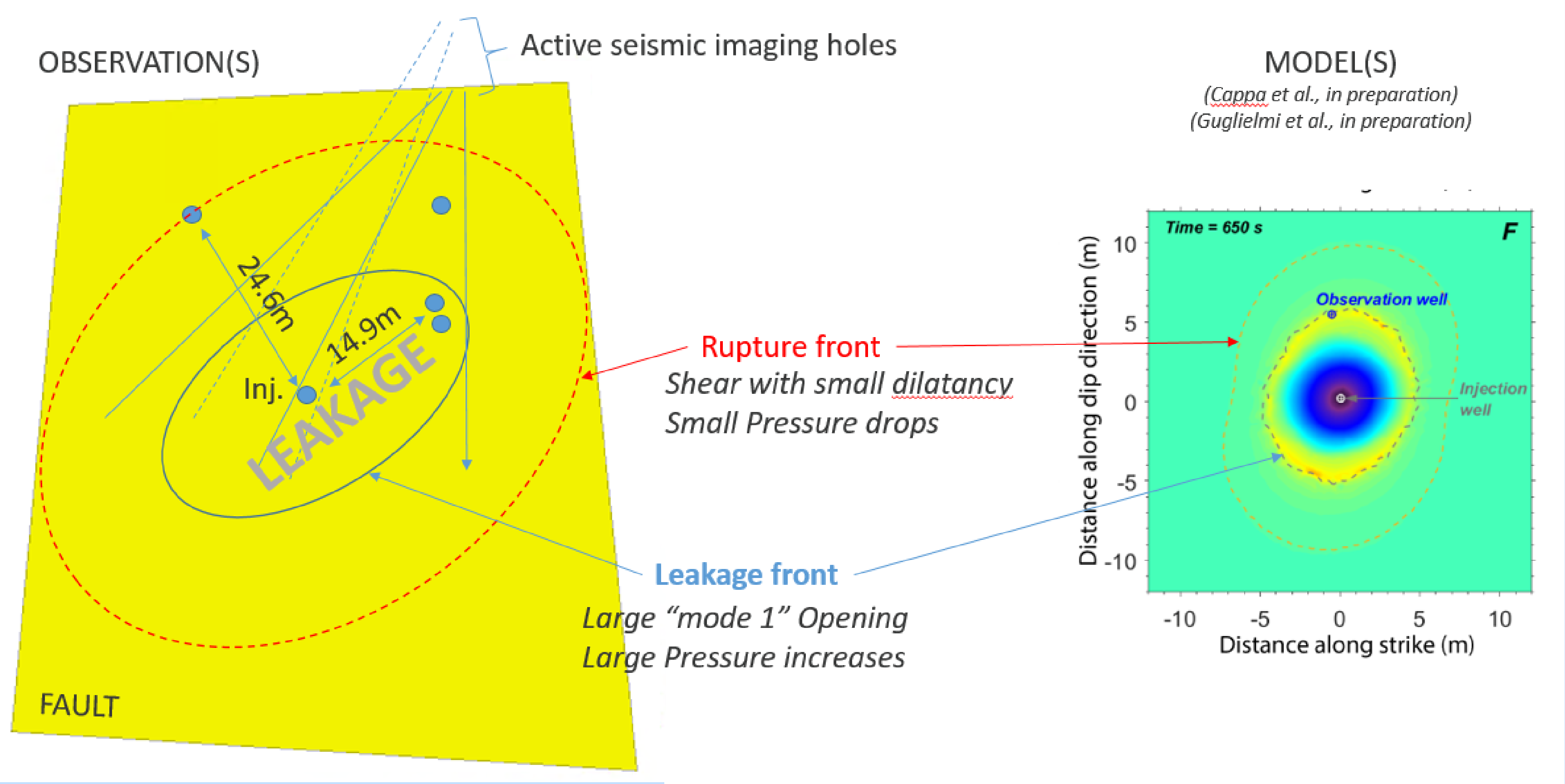
Example of monitoring well B1

Slip front preceding Water front



Conceptual model of fault leakage

Active seismic is mainly seeing the leakage front



Accomplishments to Date

- **CASSM active seismic imaging system functioned well**
  - Over the course of ½ year including over the FSB Experiment 1
  - High repeatability
    - Thus, very small velocity perturbations (< 1 m/s) can be recovered
  - During activation - p-waves travel times delays of up to 16 microseconds and reduction in amplitude
  - Strong attenuation of the rock – no s-waves
  - Travel time tomography were delivered successfully

- **Conceptual model to explain/calibrate p-waves variations**
  - Leakage is more localized than fault shear

    Combination of micro-crack dilation in the leakage fault patch
    (pressure dependent response)
    and long-term damage response, possibly related to shear.
  - Fault shear is preceding fault opening and leakage

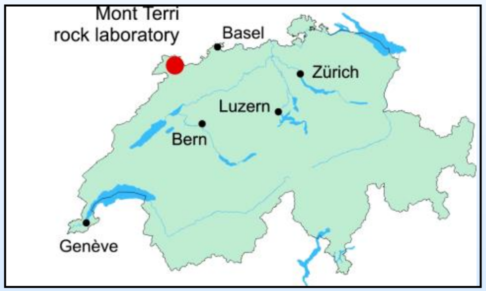
Lessons Learned

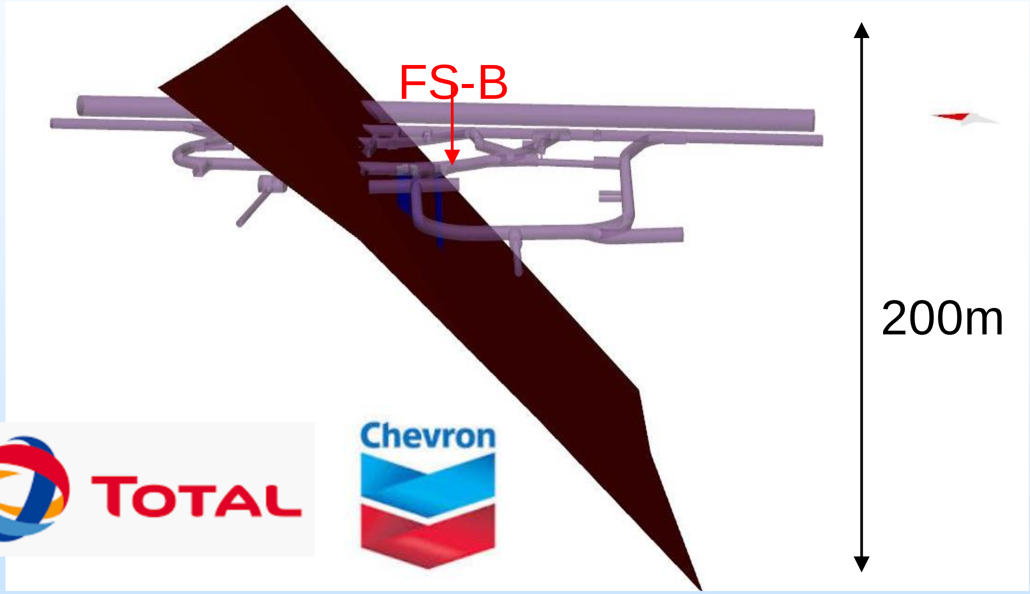
- **Research gaps/challenges**.
  - Pure water was injected in the fault!
    - How will both fault and monitoring system(s) respond to CO_2 brine ?

- **Long term effects**
  - Field experiments in shales require very long lead times (~3 months) before the instruments are in equilibrium with the formation and experiment can start.
  - Post activation fault self sealing involves slow processes, and small signal amplitudes at the limit of detection on sensors (technical challenge)

Synergy Opportunities

- The CASSM approach is integrated into a field scale controlled fault activation experiment "FS-B" funded by an international consortium including 11 partners





Mont Terri Project

Shell

TOTAL

Chevron

BERKELEY LAB

ETH zürich

BGR

ENSI

swisstopo

JAEA

IRSN INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

CCP

Project Summary

- **CASSM system has been deployed and tested during a controlled fault activation in shales**

- **Time lapse V_p images allowed tracking the spatio-temporal fault leakage evolution**

- **Decreases in p-waves velocities were correlated to complex strain and displacement associated to high pore pressure and distributed across the entire fault zone thickness**

- **A model of caprock leakage associated to fault rupture is proposed**
Decoupling between slip and opening may drive high-pressure fluid migration in shale faults

Appendix

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

Benefit to the Program

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

- Describe the project goals and objectives in the Statement of Project Objectives.
  - How the project goals and objectives relate to the program goals and objectives.
  - Identify the success criteria for determining if a goal or objective has been met. These generally are discrete metrics to assess the progress of the project and used as decision points throughout the project.

Project Overview

Goals and Objectives

Goals

- During a fault Activation

How do leakage pathways organize in the rupture zone ?

- Can we improve the monitoring?

Through the imaging of aseismic rupture…

- Can we improve fault leakage prediction

and induced seismicity?

How to upscale lab. Friction laws?

Concept

Field scale controled
fluid leak in a slipping Fault
using SIMFIP probes and distributed strains
while Repeating Passive Seismic Imaging

End Product

Relating CASSM signals
to CO_2 leak, Fault slip
And seismicity

Organization Chart

- **Project participants: International Collaborations**
  - Yves Guglielmi (co-PI), Jens Birkholzer (co-PI), Jonny Rutqvist, Martin Schoenball, Jonathan AjoFranklin, Michelle Robertson, Todd Wood, Paul Cook, Florian Soom, Chett Hopp (LBNL, USA)
  - Christophe Nussbaum and team (Swisstopo, Switzerland)
  - Alba Zappone and team (ETH, Switzerland)
  - Frederic Cappa, Louis de Barros (University of Nice, France)
  - Participants from Nagra, Ensi, Total, Shell, Chevron, JAEA, IRSN, BGR.

Gantt Chart

	2018		2019				2020				2021			
	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4	T1	T2	T3	T4
Task1 Managment	■	■	■	■	■	■	■	■	■	■	■	■	■	■
Task 2.1 Assembling At LBNL	■	■		■	■									
Task 2.2 Installation at Mont Terri		■		■		■								
Task 2.3 BackGround Monitoring		■	■	■	■	■								
Task 3 Repeated activations						■	■	■	■	■				
Task 4 Data Processing and Modeling			■	■	■	■	■	■	■	■	■	■	■	■

Milestones

2019T1 - Report 1 on SIMFIP + f.o. + CASSM Installation and background monitoring

2019T4 - Report 2 on SIMFIP + f.o. + CASSM Installation, background monitoring and pre-test CO_2 injection in an inactive fault. Numerical pre-modeling of injection induced fault rupture and seismicity (based on the continuing analyses of FS experiment)

2020T2 - SIMFIP and CASSM joint Report on the first fault activation period.

2020T4 - Report and Numerical comparisons between the first and the second fault activation periods and on fault evolution during non-activation periods

2021T2 - SIMFIP and CASSM Report on fault sealing tests

2021T4 - Geomechanical model of long term integrity evolution of the fault. Joint analyses of SIMFIP and CASSM data. Report on Monitoring methods calibration.

Bibliography

- C.,Hopp, Y., Guglielmi, A., P., Rinaldi, F., Soom, Q., Wenning, P., Cook, M., Robertson, M., Kakurina, A., Zappone (submitted to JGR). The effect of fault architecture on slip behavior in shale revealed by distributed fiber optic strain sensing.
- A., Zappone, A., P., Rinaldi, M., Grab, Q., C., Wenning, C., Roques, C., Madonna, A., C., Obermann, S., M., Bernasconi, M., S., Brennwald, R.,K., F., Soom, P., Cook, Y., Guglielmi, C., Nussbaum, D., Giardini, M., Mazzotti, S., Wiemer (2021). Fault sealing and caprock integrity for CO2 storage: an in situ injection experiment. Solid Earth, Vol. 12, issue 2, 319-343.
- Maria Kakurina, Yves Guglielmi, Christophe Nussbaum, Benoît Valley (2020). In situ direct displacement information on fault reactivation during fluid injection. Rock Mechanics and Rock Engineering, Vol. 53, issue 10, 4313-4328.
- Yves Guglielmi, Christophe Nussbaum, Jonny Rutqvist, Frédéric Cappa, Pierre Jeanne, Jens Birkholzer (2020). Estimating perturbed stress from 3-D borehole displacements induced by fluid injection in fractured or faulted shales. Geophysical Journal International, Vol. 221, 1684-1695, 1684-1695.
- Guglielmi, Y., Nussbaum, C., Jeanne, P., Rutqvist, J., Cappa, F., & Birkholzer, J. (2020a). Complexity of fault rupture and fluid leakage in shale: Insights from a controlled fault activation experiment. Journal of Geophysical Research: Solid Earth, 125, e2019JB017781. https://doi.org/ 10.1029/2019JB017781.
- T.S.Nguyen, Y.Guglielmi, B.Graupner and J.Rutqvist (2019). Mathematical Modelling of Fault Reactivation Induced by Water Injection. *Minerals* 2019, *9*(5), 282; https://doi.org/10.3390/min9050282.
- M.Kakurina, Y.Guglielmi, B.Valley and C.Nussbaum (2019). Slip perturbation during fault reactivation by a fluid injection. Tectonophysics, Volume 757, 20 April 2019, Pages 140-152.
- F.Cappa, Y.Guglielmi, C.Nussbaum and J.Birkholzer (2018). On the Relationship Between Fault Permeability Increases, Induced Stress Perturbation, and the Growth of Aseismic Slip During Fluid Injection. Geophysical research letters, Volume45, Issue20, 28 October 2018,Pages 11,012-11,020.