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

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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
- Key Findings from the 2015 Mesoscale Fault Activation Experiment
- Concept of the New Experiment - Seismic Imaging of Fault Activation and Post-Activation

Accomplishments to Date

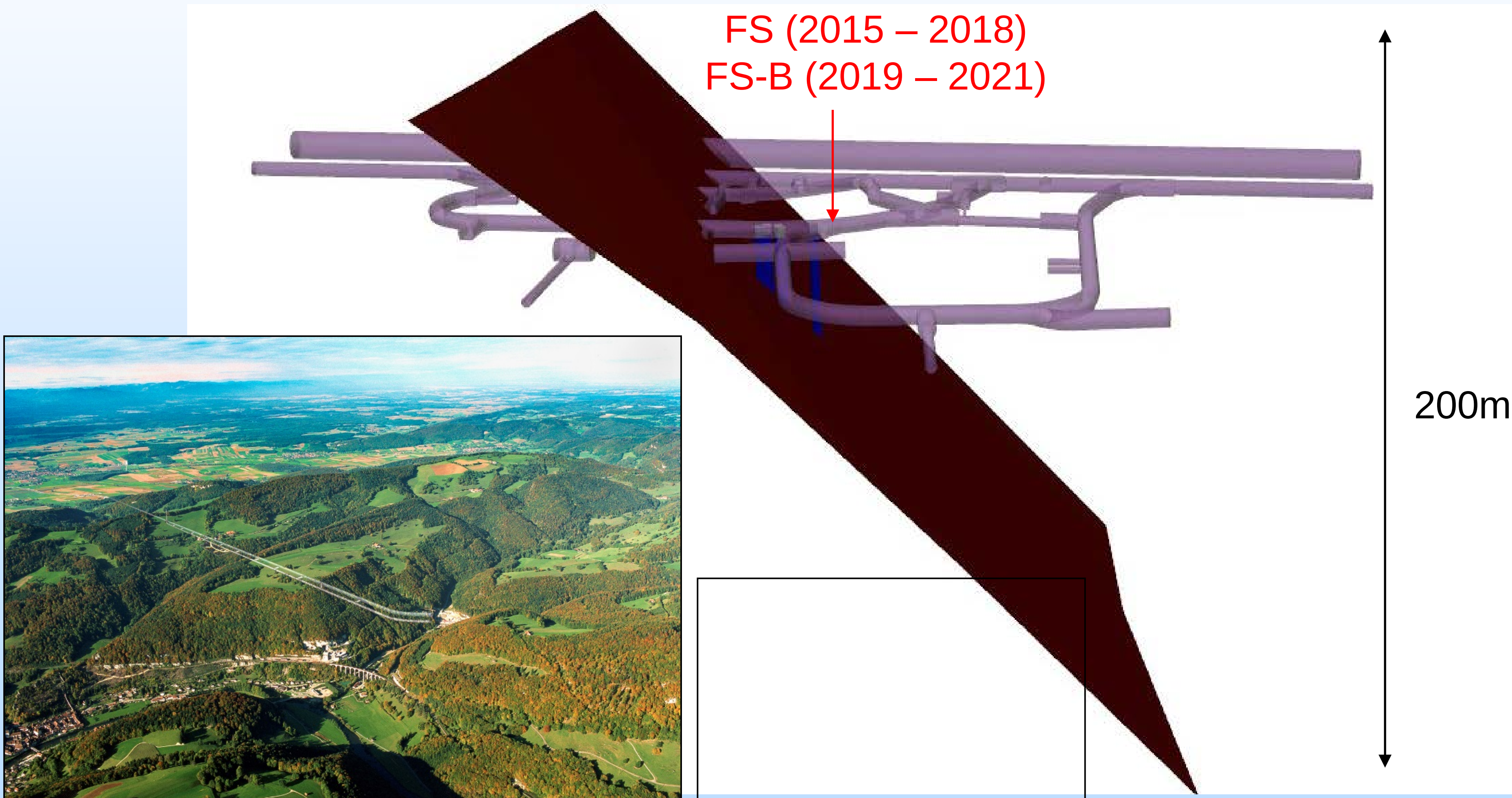
Future Plans

Synergy Opportunities

Project Summary

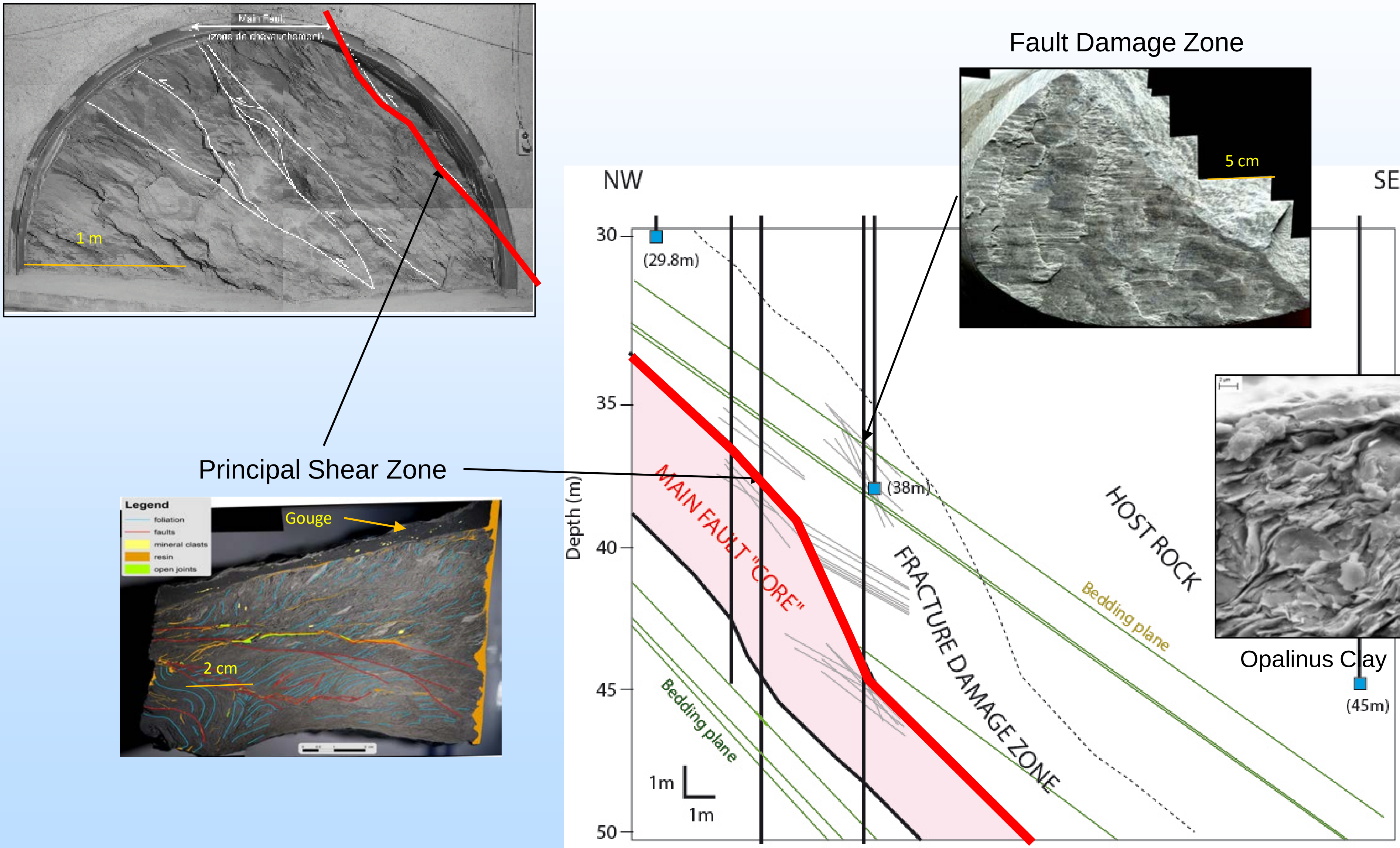
Technical Status

Experiments in A Field Test Facility for Caprock Integrity Research

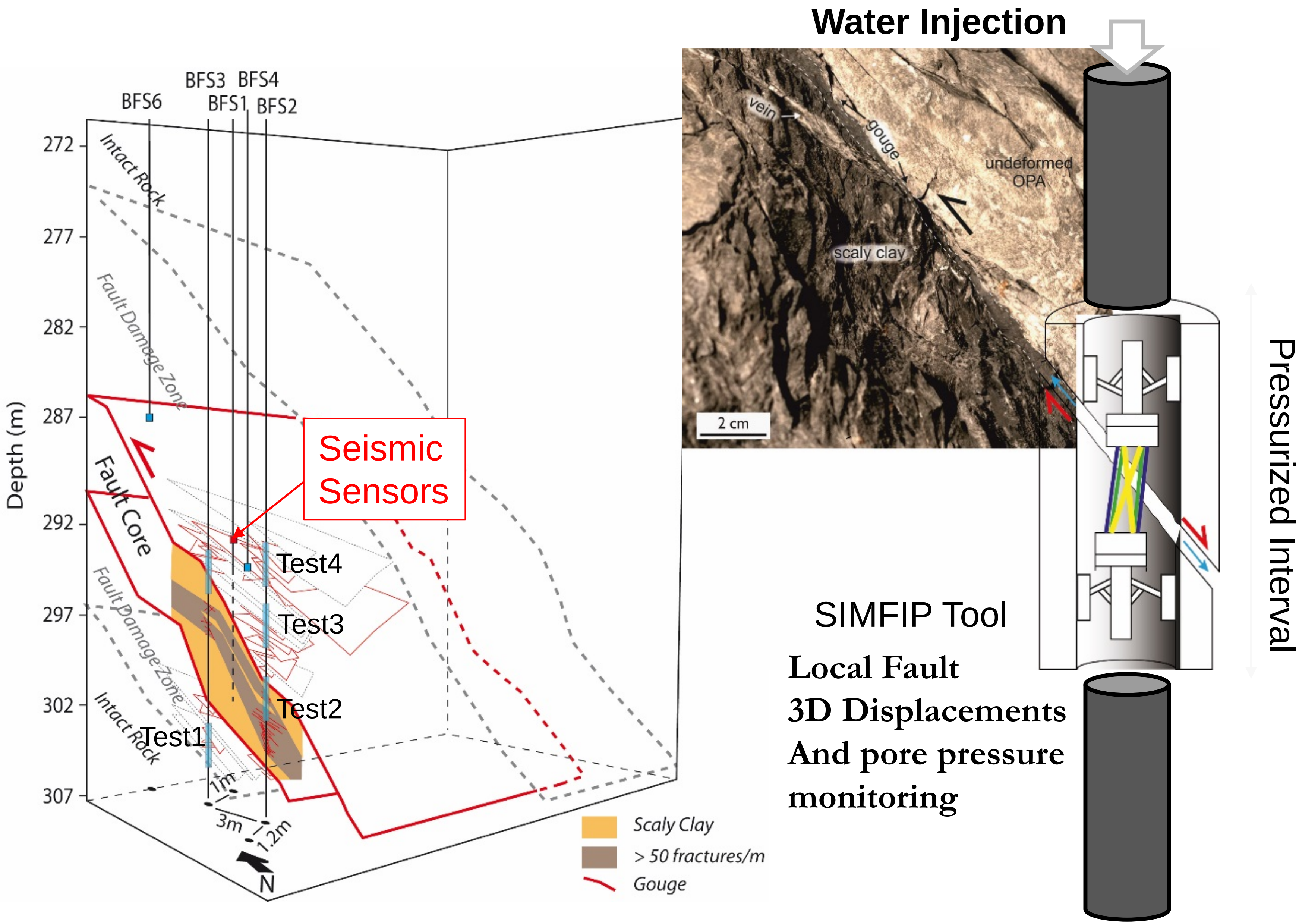


A Thick Fault Zone in a Low Permeable Clay Rock

A thick Core Zone with Gouge + Foliation + secondary (Riedel-like) shear planes
A Damage Zone with secondary fault planes with slickensided surfaces



Experimental Setting



SIMFIP Tool

Local Fault 3D Displacements And pore pressure monitoring

Key Findings from the First Mesoscale Fault Activation Experiment in 2015

What was observed !

Injection-related excess pressure in the fault induced

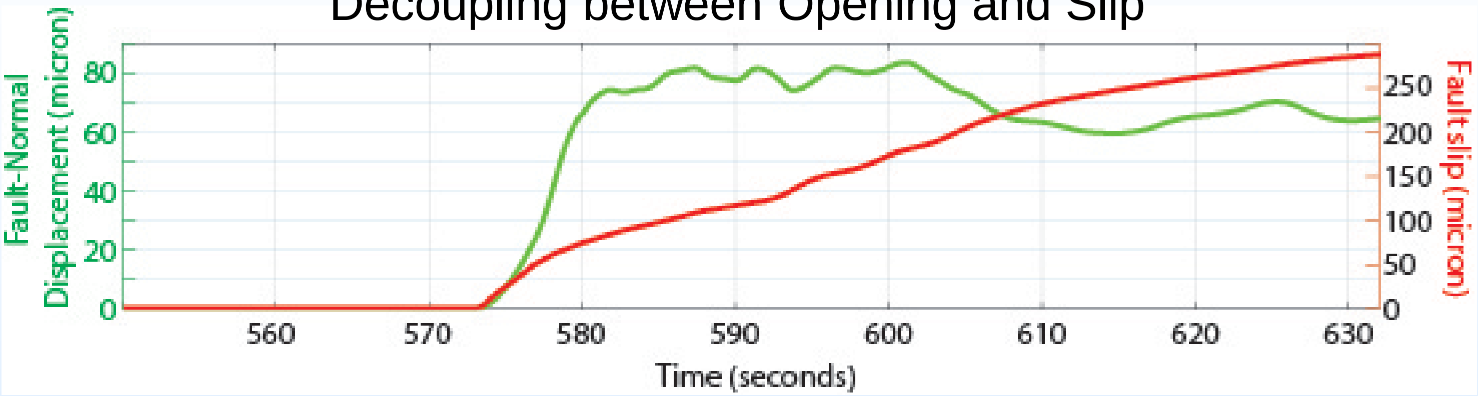
- Micro- to millimeter scale mixed-mode crack and slip events
- Six-orders-of-magnitude permeability increase
- Sparse micro-seismic events
- No clear long-term self-sealing

Some key factors influencing fault reactivation were isolated !

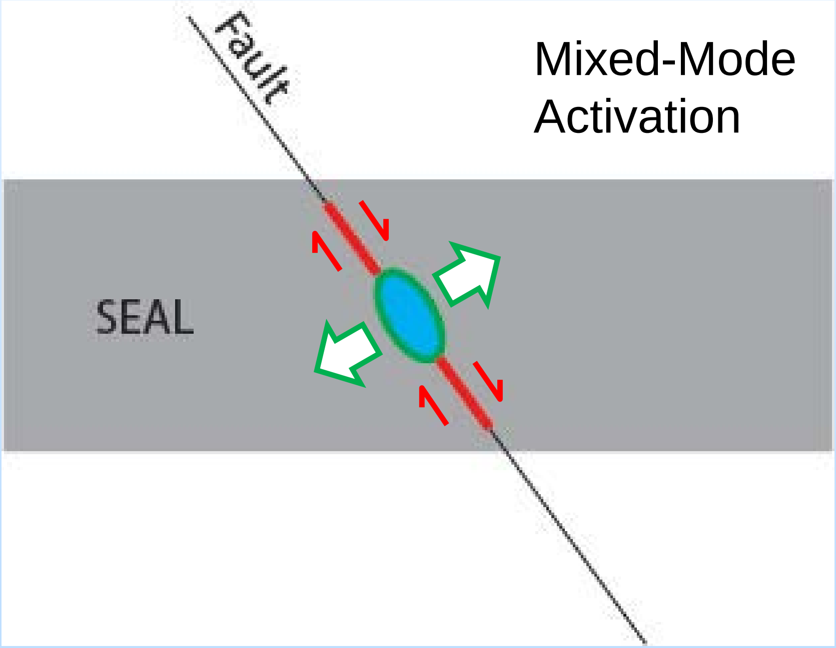
- That the very low initial permeability in the fault increased in complex manner
- That fault rupture was strongly related to stress accumulation and rotation
- That significant heterogeneity in fault geometry and pore pressure was observed

Fault Activation Mechanism in Low Permeable Cap Rock

Decoupling between Opening and Slip

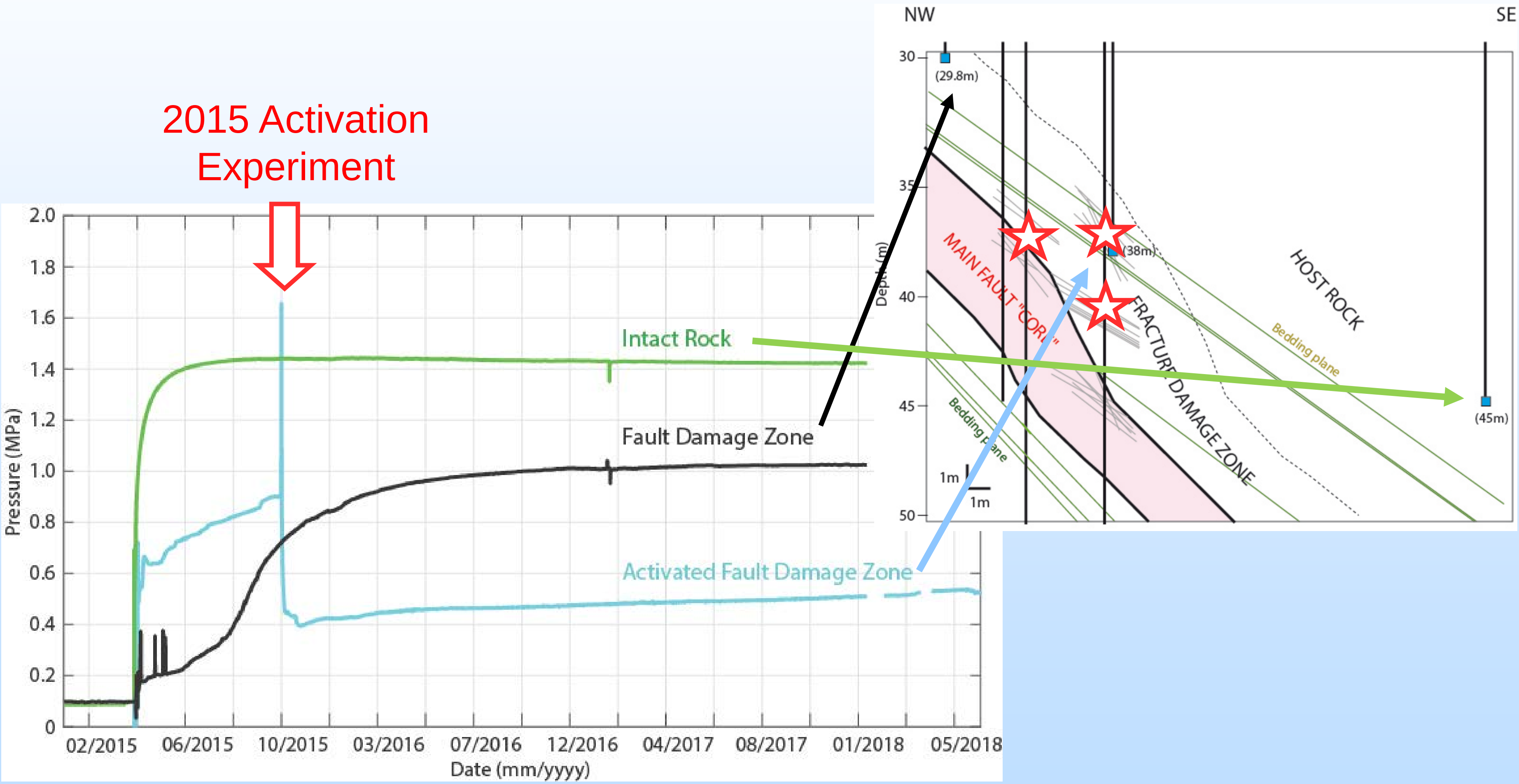


Large Leakage Events at ~Zero Normal Stress On the Fault



Long Term Post Activation
No Clear Fault Self-Sealing

No initial pressure recovery ~ 3 years after the activation experiments at Mt Terri

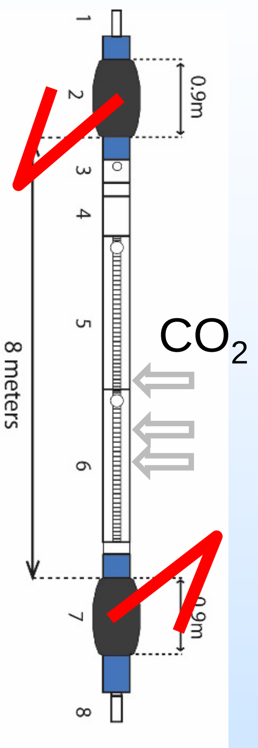


Objectives of the Second Fault Activation Experiment

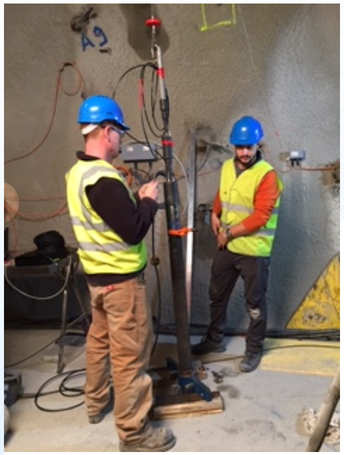
Imaging Rupture and Flow Paths Growth
in Three-Dimensions
During and After a fault activation
by a CO_2 brine injection

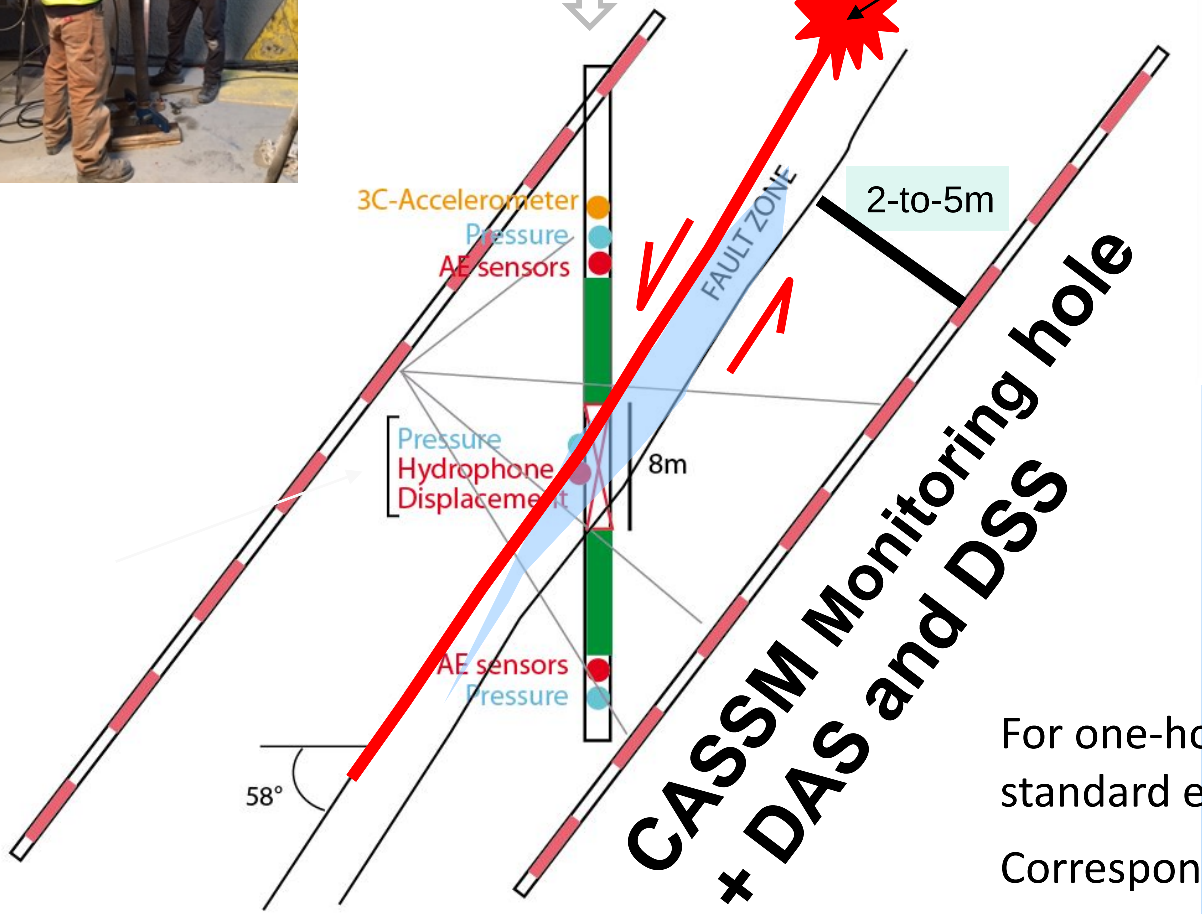
Validating active seismic monitoring techniques
to detect CO_2 leakage, fault slip and its link to induced seismicity

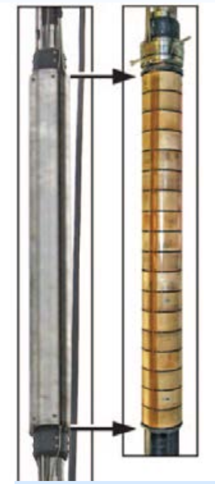
Experiment Concept : Coupling Downhole Hydro-Mechanical Tests With Active Seismic Monitoring

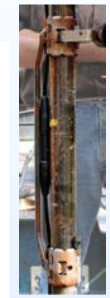


SIMFIP









Hydrophone array

Custom piezoelectric borehole source

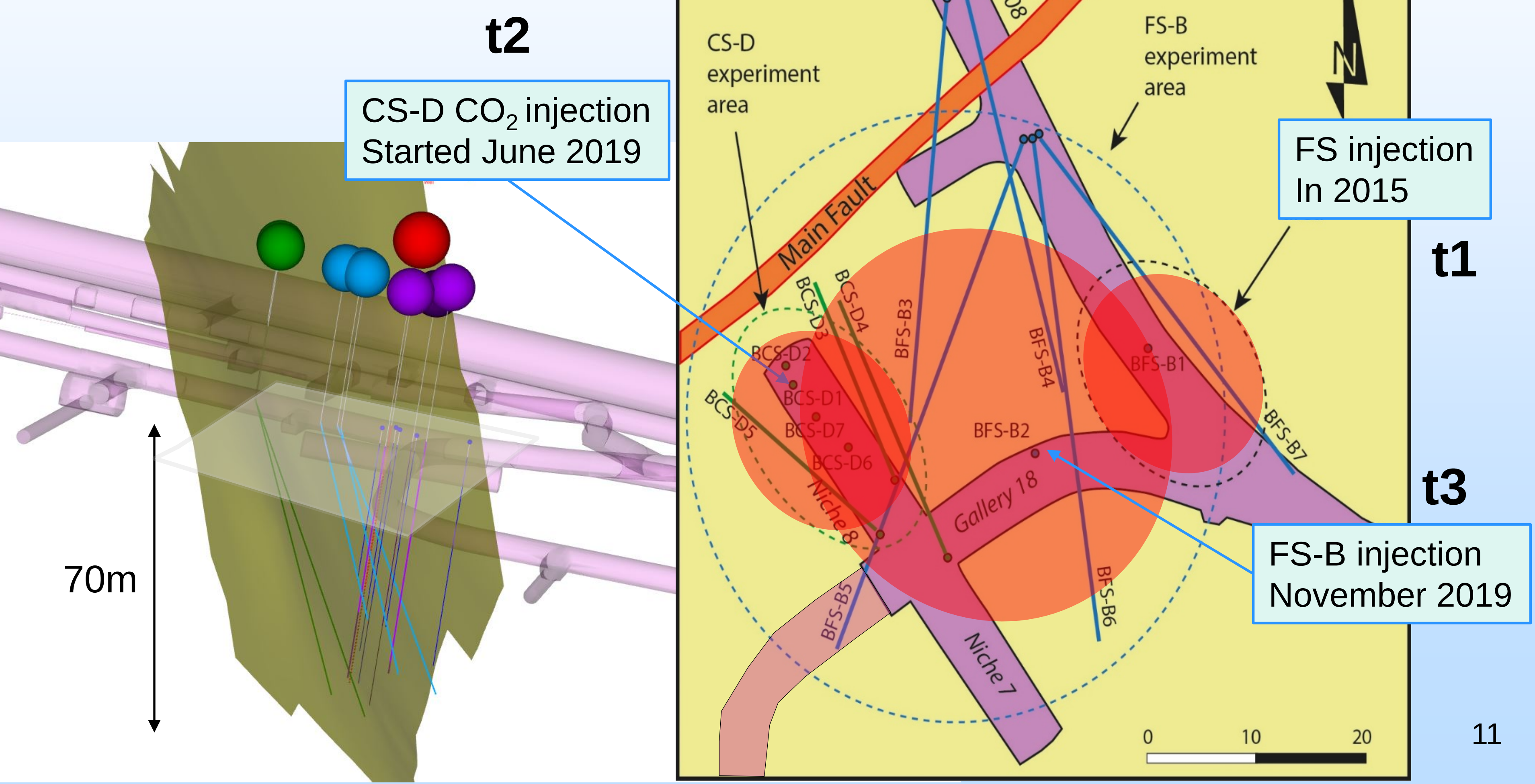
[Daley et.al. 2007]
[Silver et al. 2007]
[Ajo-Franklin et al. 2011]
[Marchesini et al. 2017]

For one-hour stacking, standard error only ~ 6ns.

Corresponds to *dV* of $3x10^{-6}$.

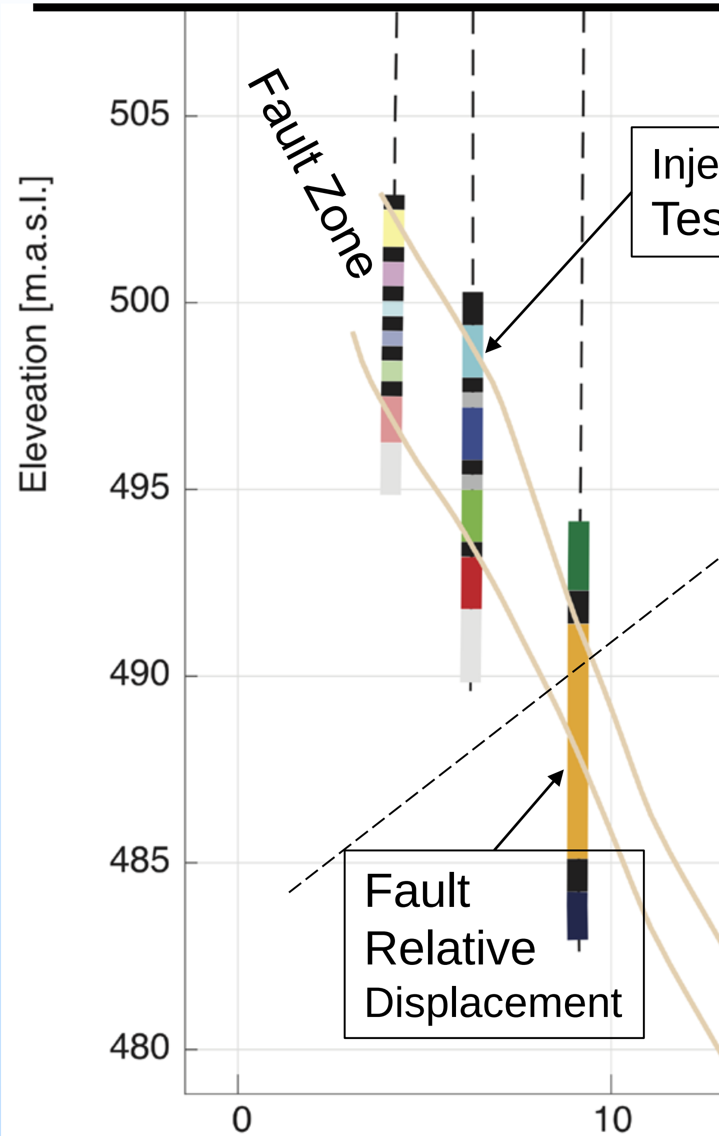
Accomplishments to Date

- Installation and Pre-Tests of CO_2 injections in the CS-D zone
(collaboration with ETH (Switzerland) tracking CO_2 geochemistry in real time)
- Drilling and Preparation for deployment in the FS-B volume



Accomplishments to Date
Pre-Tests in the CS-D zone

Tuned the Strain Monitoring Network taking the opportunity of the Fault HM response to a distant loading by a Gallery Excavation



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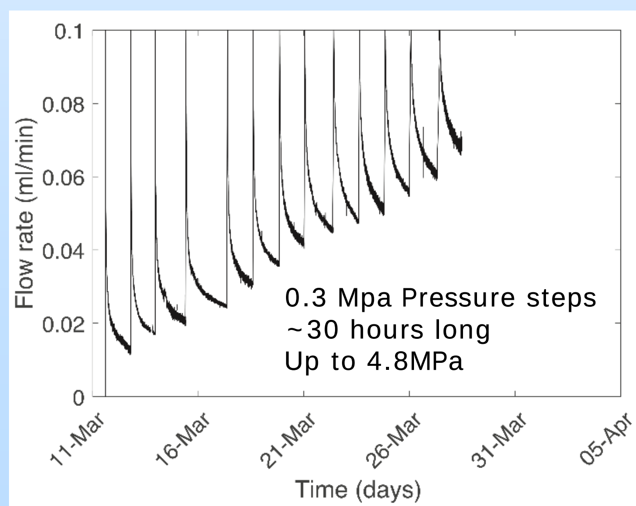
Injection Tests **in the inactive Fault**



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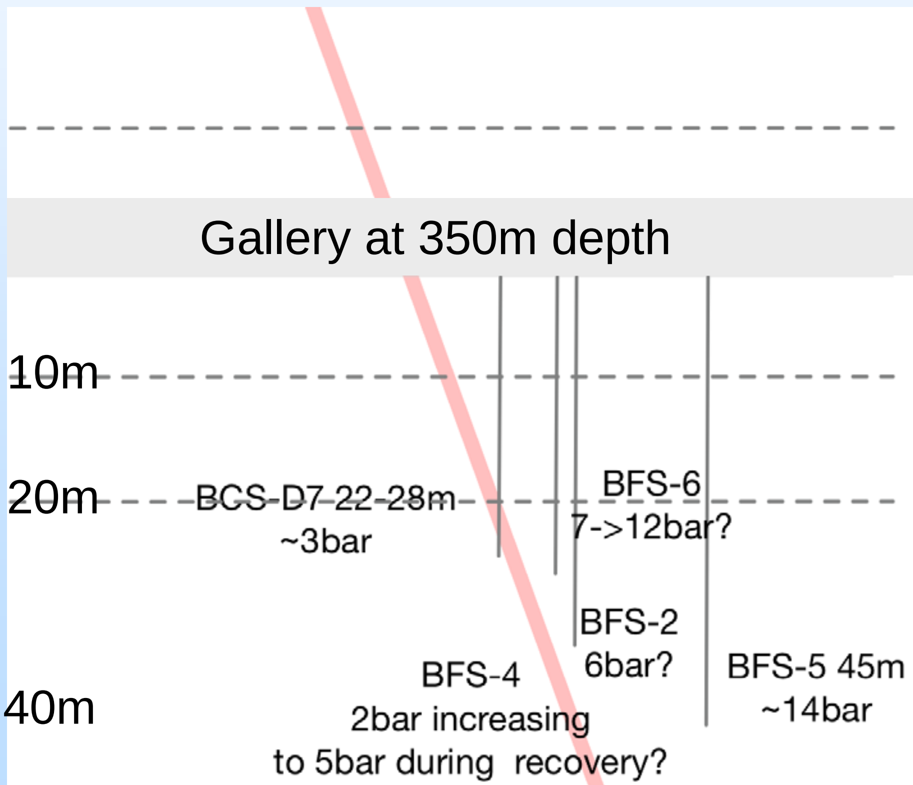
Long term CO_2 brine Injection at Constant Pressure **In the inactive Fault**

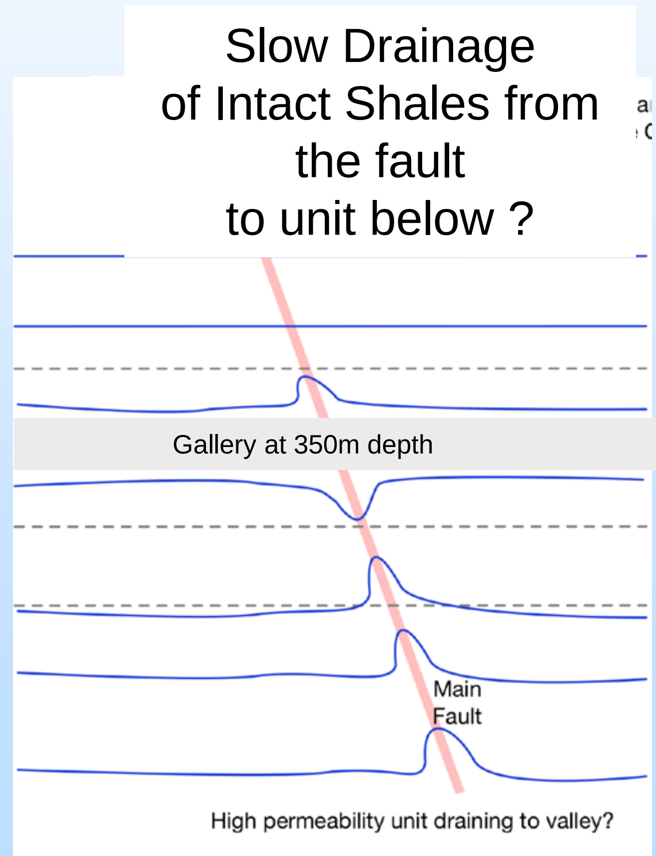
Since June 2019

Fault Zone Pre-activation Hydrogeology

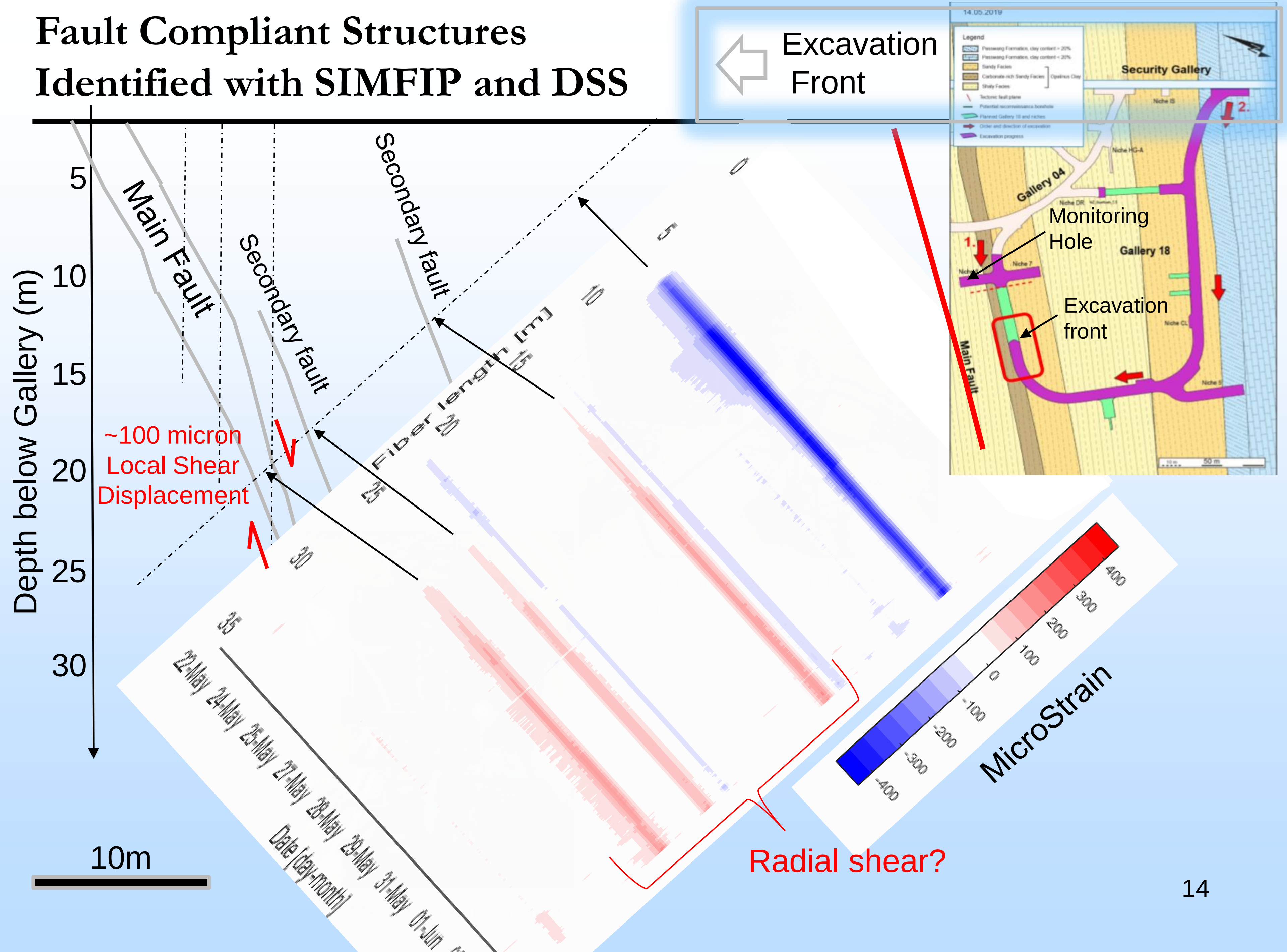
- **Heterogeneity of Pore Pressures** reveals that fault permeability of ~10^{-18} to $10^{-20} m^2$ is slightly higher than intact rock *(in agreement with lab-scale estimations)*

- **At Coulomb Shear Failure Pressure of ~4.8MPa**, Injectivity in the fault core is small ~0.08 ml/min.





Fault Compliant Structures Identified with SIMFIP and DSS



Lessons Learned

– Field experiments in shales require very long lead times (~3 months) before the instruments are in equilibrium with the formation and experiment can start.

– Evidence of Significant Leakage at High Overpressures in almost fully unloaded fault patches affecting a caprock analogue

Imaging is expected to show how extensive these permeable patches are?

– No clear self sealing – *Possibility for a leak below activation pressure*

- Since 12 June 2019, a CO_2 brine is injected at constant 3.8 MPa pressure (below the Coulomb failure pressure).
- A ~0.03ml/min leakage is observed without fault activation

Synergy Opportunities

- **An opportunity to apply and compare different techniques to detect fault slip and leakage monitoring in a clay-rich caprock**
  - Using Optical Fibers Distributed Strains (DSS) to detect compliant fault zones in a caprock with remote loadings.
  - CASSM active seismic imaging capabilitities parallel and across the fault structure

- **An International Experiment**

Mont Terri Project

swisstopo

IRSN INSTITUT DE RADIOPROTECTION ET DE SÛRETÉ NUCLÉAIRE

nagra.

BGR Bundesanstalt für Geowissenschaften und Rohstoffe GEOZENTRUM HANNOVER

TOTAL

Chevron

ENSI

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

DEPARTMENT OF ENERGY UNITED STATES OF AMERICA

Project Summary

- **Key Findings**
  - Contrasted fault activation modes in a reservoir-seal system, and their consequences on leakage and induced seismicity
  - High accuracy in situ estimation of the leakage potential to a CO_2 brine of a non-activated fault zone
- **Next Steps**
  - Deployment of the CASSM in October 2019 and background characterization
  - First fault leakage activation in December 2019 / January 2020
  - Post activation monitoring in 2020.

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

Goals

- During Activation

How do leakage pathways organize
in the rupture zone ?

- After Activation

Can a Fault heal/seal in Clay Materials?

- How does CO_2 change the coupling

between Fault rupture and leakage
at the tens of meter scale?

- 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
CO_2 leak in a slipping Fault
Using SIMFIP probes and distributed strains
While Repeating Passive Seismic Imaging

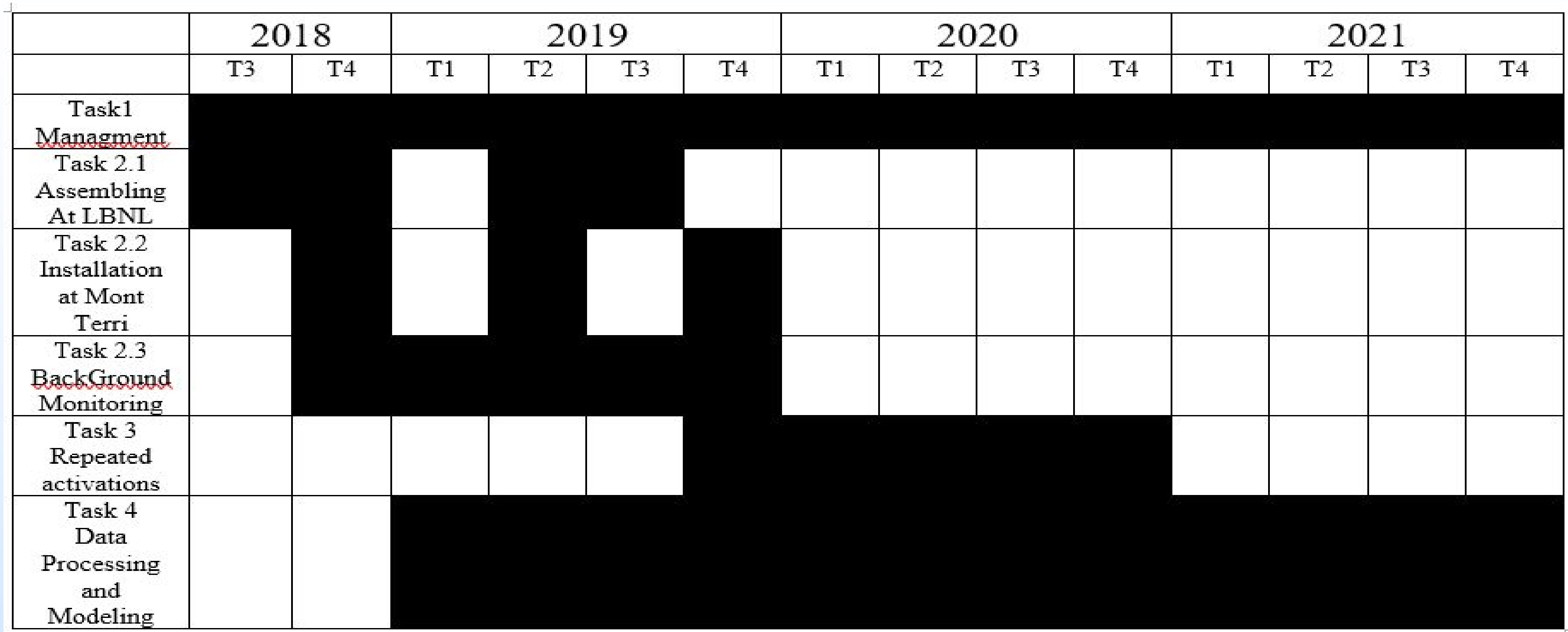
End Product

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



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 CO2 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.

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- **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.**