Changes in Seal Integrity Induced by CO_2 Injection and Leakage in a Hydromechanically Reactivated Fault (FSC: Fault Slip and Chemistry)

(FWP-FP00013650, FY22-FY24)

Yves Guglielmi, Jens Birkholzer (LBNL)

Plus many FSC Team Members from LBNL, Rice University, and Mt Terri Partners

U.S. Department of Energy

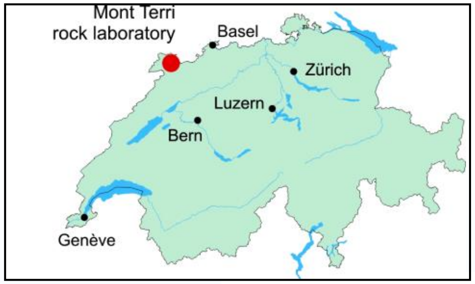
National Energy Technology Laboratory
Carbon Management Project Review Meeting
August 15 - 19, 2022

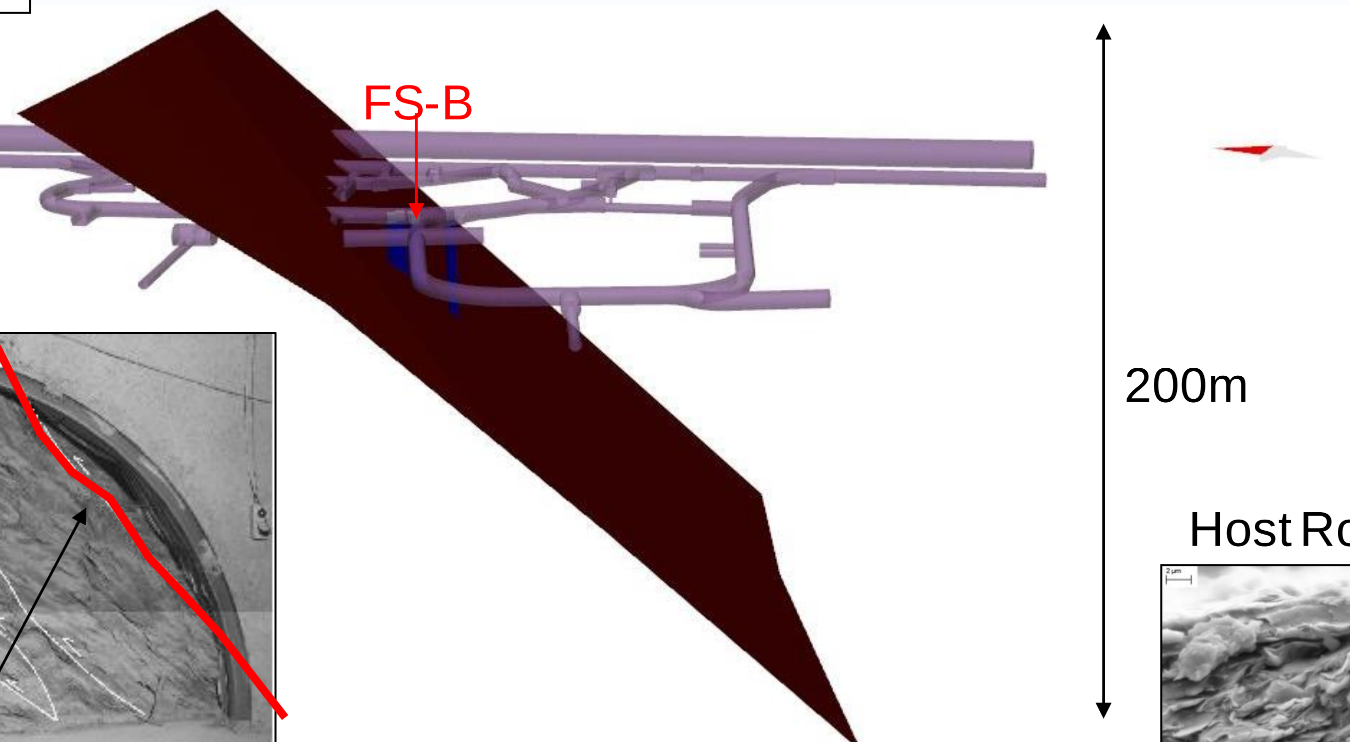
Overall Project Objectives

Utilize existing *in situ* testbed at Mt Terri Underground Research Lab to conduct controlled-injection fault slip experiments:

- **Linking mechanical activation of a caprock fault and CO_2 leakage:**
  - Can a fault zone intersecting a reservoir caprock mechanically reactivate and develop CO_2 leakage pathways?
  - How far and fast are injected fluids spatially propagating within the fault?
  - Will the caprock sealing capacity be irreversibly modified?
- **Linking fault mechanical deformation and reactive fluid transport:**
  - Are injected fluids significantly mixing with formation water?
  - What changes in water chemistry and fault mineralogy occur along the leakage pathway?
- **Spatial time-lapse imaging coupled to distributed chemical monitoring :**
  - Is the geophysical behavior different between pure water and dissolved CO_2?
  - Will we be able to to detect dissolved CO_2 leakage using a new type of fiber optic Distributed Chemical Sensing (DCS)?

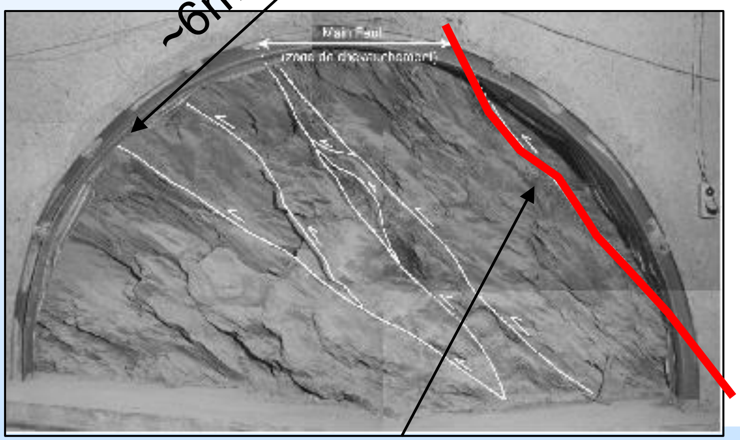
Mt Terri Testbed: A Thick Fault Zone in a Low-Permeability Argillite



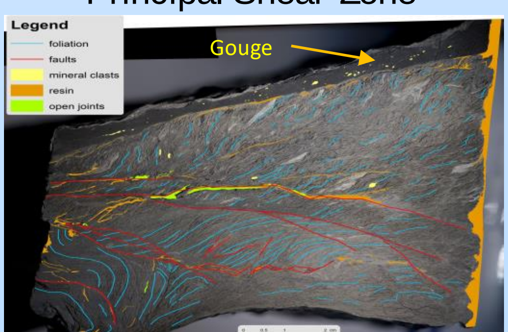


Fault Zone

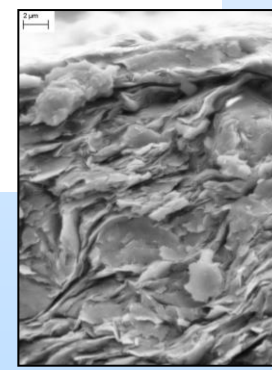
~6m



Principal Shear Zone



Host Rock



Opalinus Clay

Perfect Analog to a Caprock Fault!

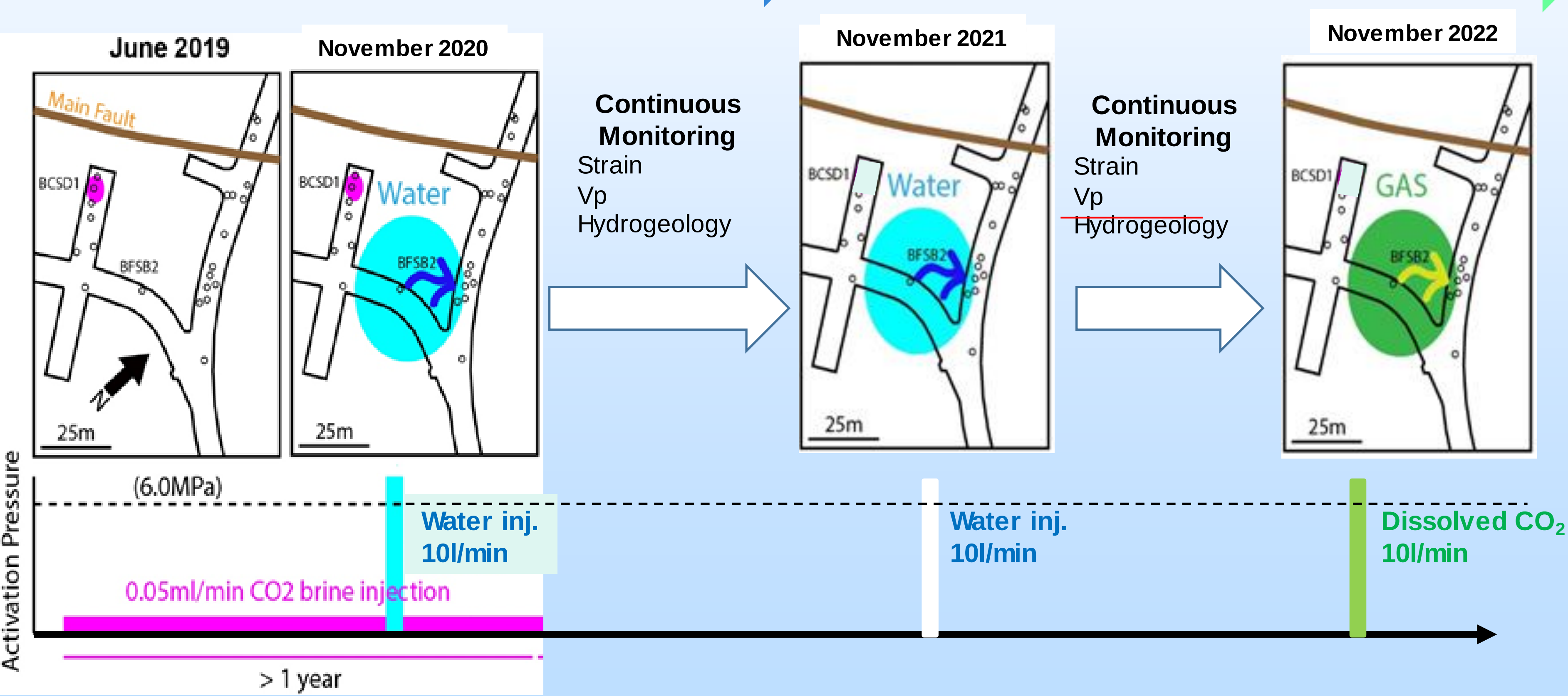
Several Experiments Since 2019

FSB (previous FWP)

- *Injection of water*
- *Hydromechanical processes*
- *Validation of a CASSM technique*

FSC (current FWP)

- *Injection of CO_2 dissolved in water*
- *Hydromechanical-chemical Processes*
- *Validation of a fiber optic DCS technique*

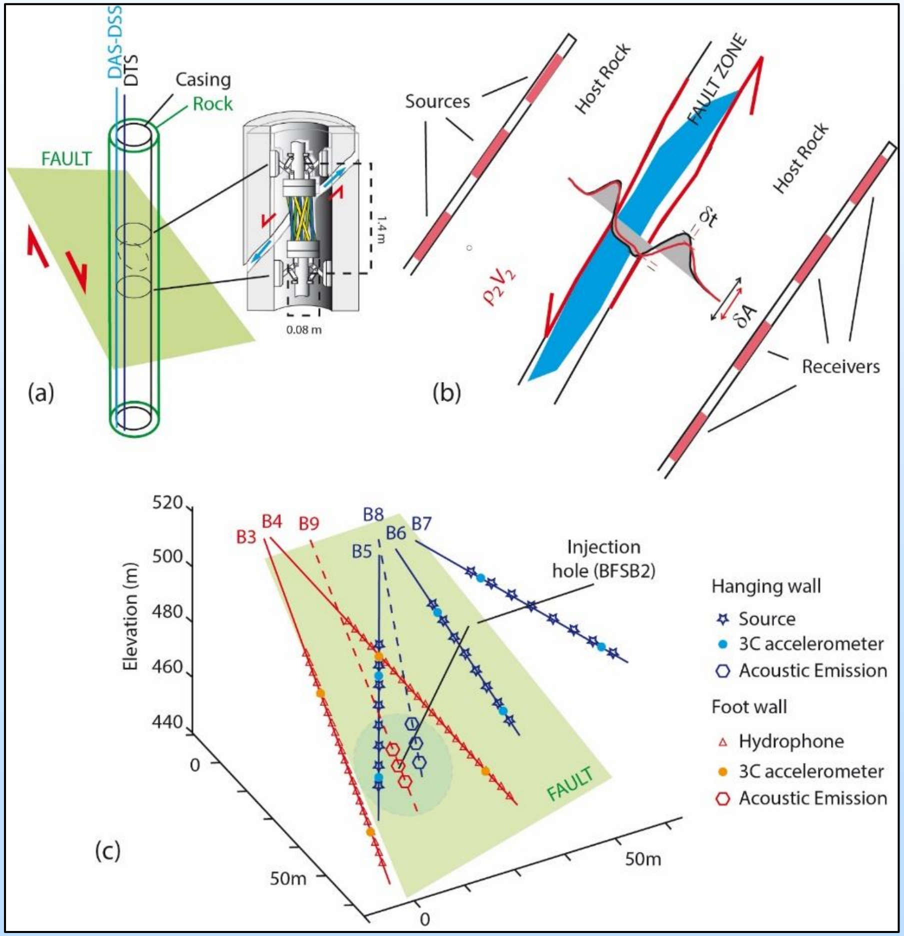


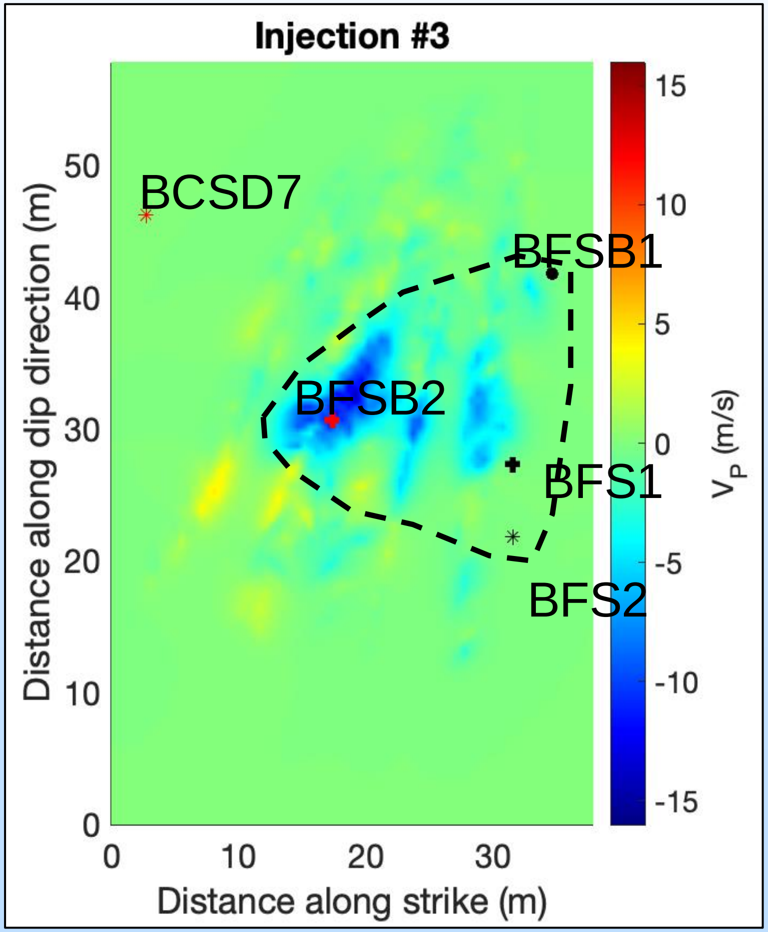
FSC Project

- **DOE funded follow-up project to FSB**
- **Started August 1, 2021 – End September 30, 2024**
  - Experiments of fault reactivation with CO_2 fluids
  - DCS (Distributed Chemical Sensing) Fiber Development
  - Advanced modeling of fault leakage and induced seismicity
- **Project Participants**
  - Y. Guglielmi, PI and J. Birkholzer, Co-PI
  - LBNL Team - H. Prieto, Admin Asst; Chet Hopp Research Engineer; J. Rutqvist, Research Scientist; Veronica Rodrigues Tribaldos, Research Scientist; Paul Cook, Research Engineer; Florian Soom, Research Engineer; T. Wood, Scientific Engineering Associate; Michelle Robertson, Program Manager; Yuxin Wu, Research Scientist; …
  - Partnering with RICE University (Jonathan Ajo-Franklin, T. Shadoan)
- **Integrated into Mt Terri consortium project and including support/participation of multiple Mt Terri partners**

Multi-Modal Monitoring

Different monitoring techniques are deployed to hydromechanically and chemically characterize a leakage pathway created in an initially very low permeable fault zone





Comprehensive Set of Fiber Optics

Co-located, contemporaneous DTS, DSS, RFS-DSS and DAS measurements complement each other in monitoring different aspects of fault reactivation processes and leakage

DCS is added in this FSC project!

	DTS	DSS	DAS	RFS-DSS
Measurement	Raman intensity shift	Brillouin frequency shift	Rayleigh phase shift	Rayleigh frequency shift
Sensitive to	**Temperature**	**Strain** (and Temperature)	**Dynamic Strain** (and Temperature)	**Strain Change** (and Temperature)
Gauge length (spatial averaging)	0.25 m	1 m	10 m	N/A
Spatial Sampling	0.25 m	0.41 m	0.5 m	5 cm
Temporal Sampling	~10 min	~ 17 min	2 kHz	~60-90 s

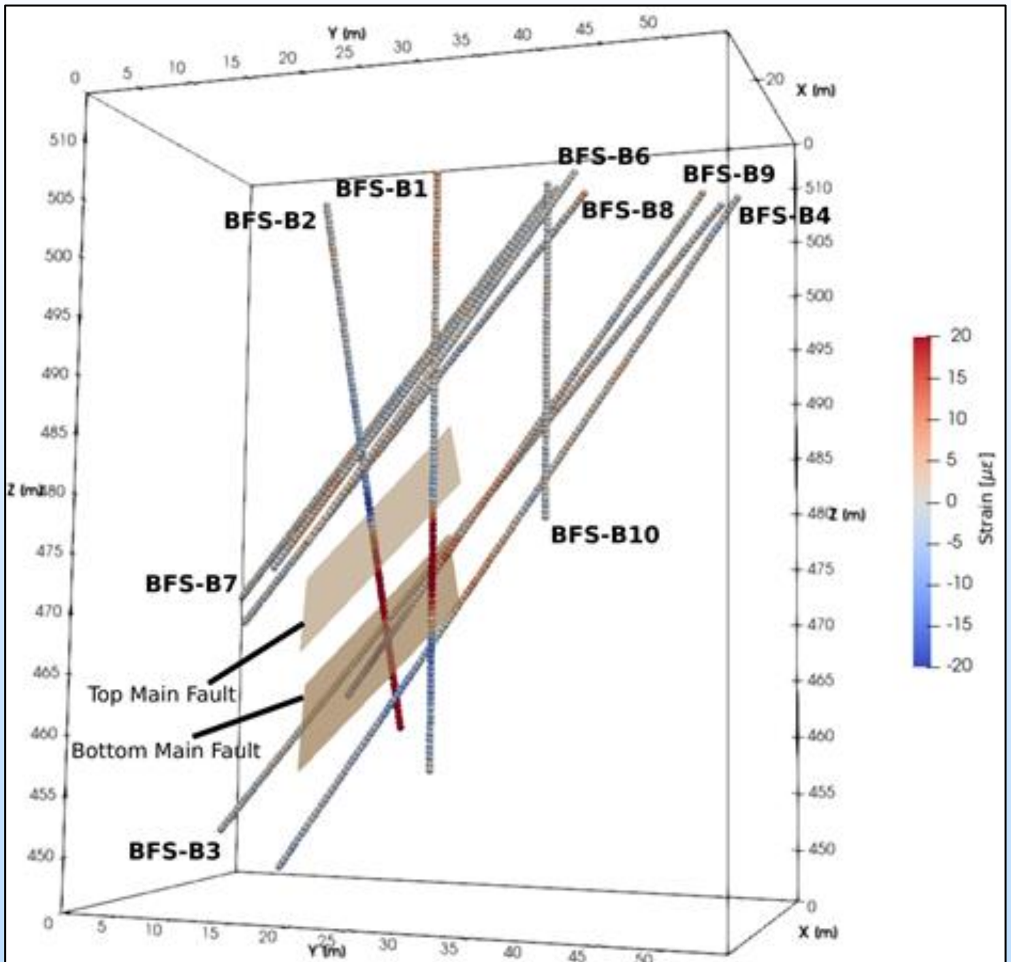
DCS

- DTS: Determine **location of hydraulic connection** at high spatial resolution
- DSS: Determine **magnitude of strain caused by hydraulic connection** at high spatial resolution
- DAS: Determine **dynamics of hydraulic connection and deformation of rock volume**
- RFS-DSS: Determine **magnitude of strain change caused by hydraulic connection at high spatial resolution**
- DCS: Determine **CO_2 concentration**

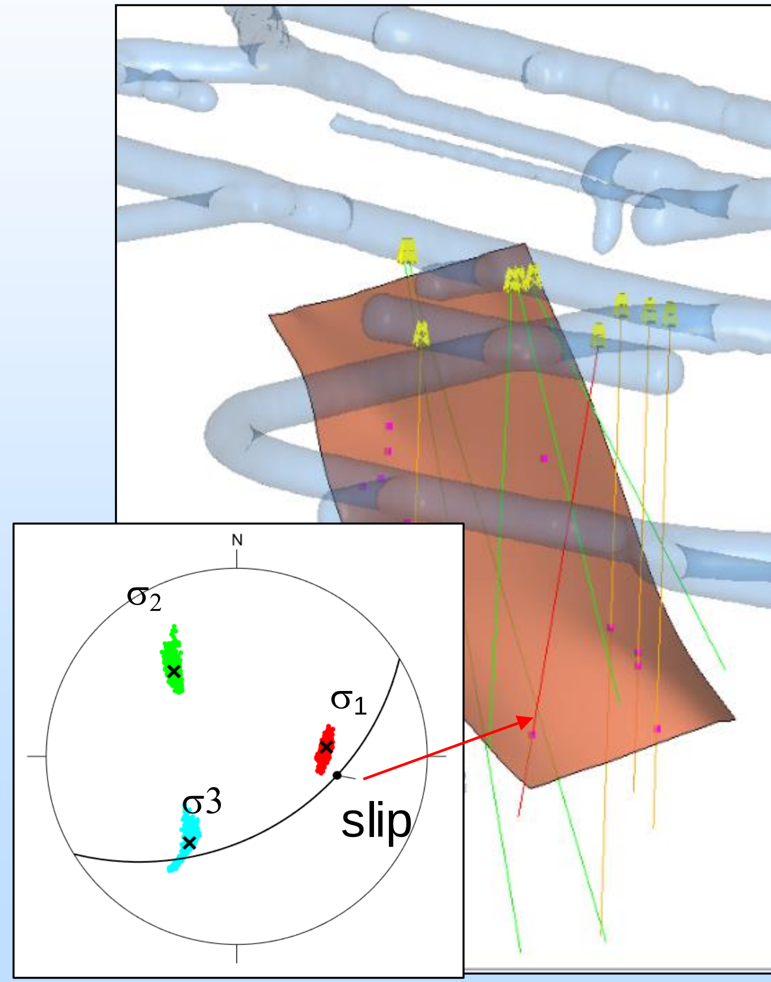
DCS: Nanoporous cladding fiber is currently in lab prototype testing phase

Complementary Strain Sensing

Strain "map" observed in multiple boreholes with DAS fibers

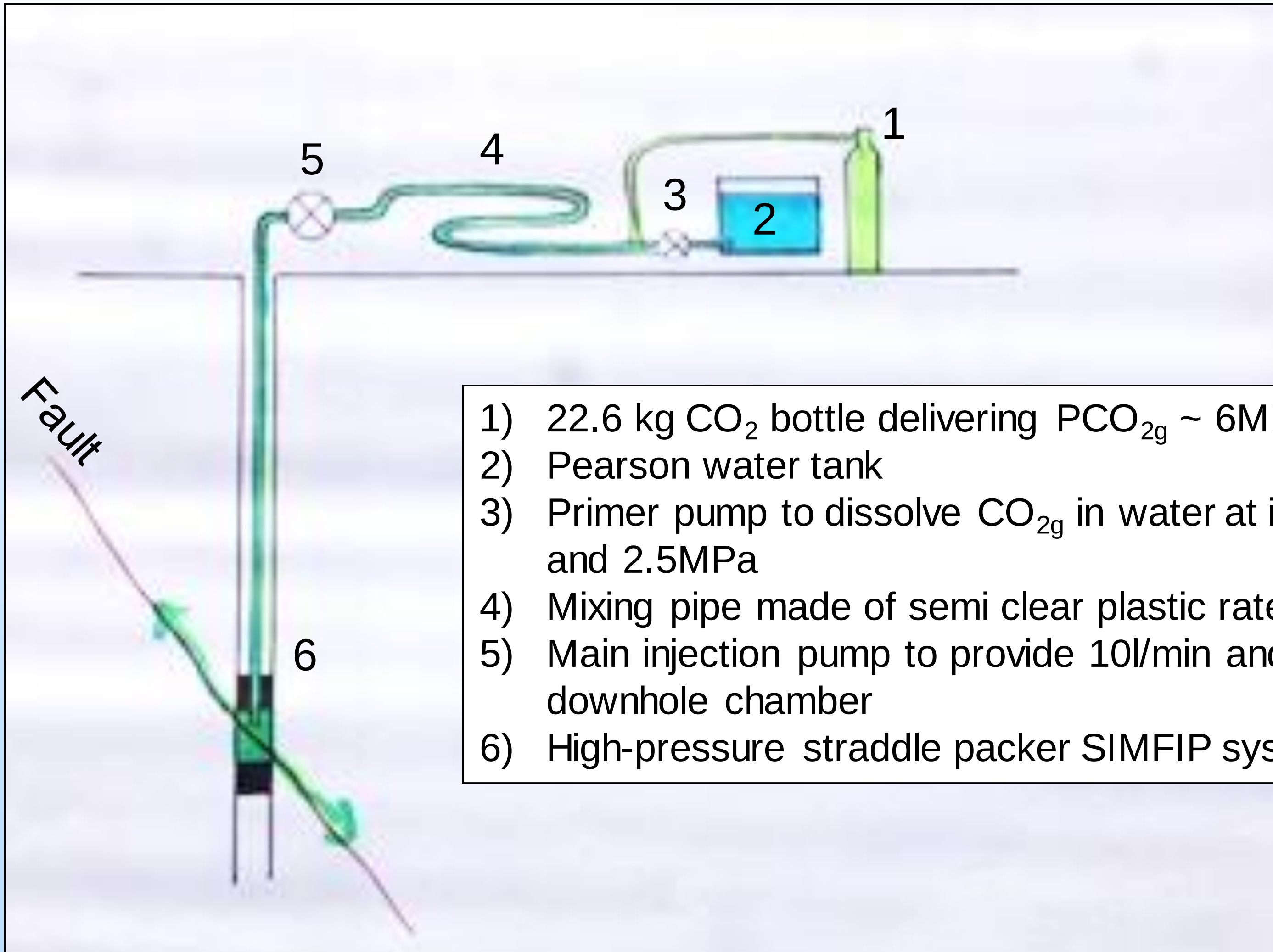


Seismic slip measured on fault with SIMFIP probe



Planned 11/2022 Injection with Dissolved CO_2

Injection of CO_2 dissolved in water at high pressure (6 MPa) and high flowrate (10 l/Min) to activate the fault

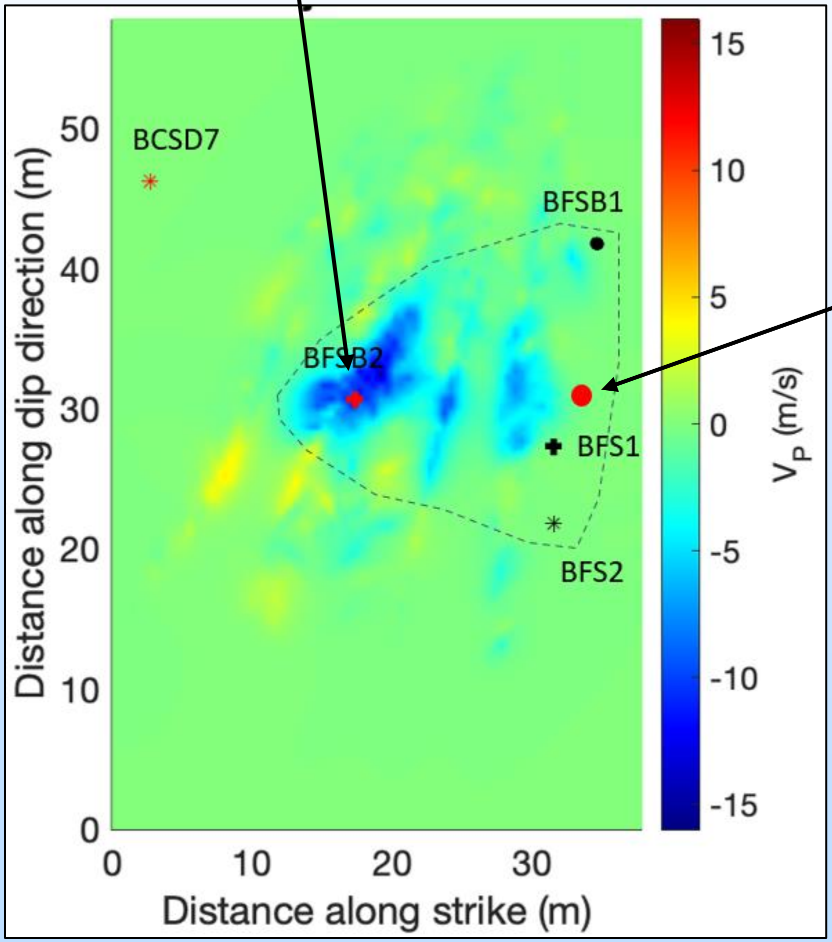


1) 22.6 kg CO_2 bottle delivering PCO_{2g} ~ 6MPa
2) Pearson water tank
3) Primer pump to dissolve CO_{2g} in water at injection flowrate and 2.5MPa
4) Mixing pipe made of semi clear plastic rated to 3.5MPa
5) Main injection pump to provide 10l/min and ~6MPa in the downhole chamber
6) High-pressure straddle packer SIMFIP system

Fluid Chemistry Monitoring

Extensive monitoring of fluid chemistry in fault zone will be added to all existing multimodal measurements

Injection Borehole



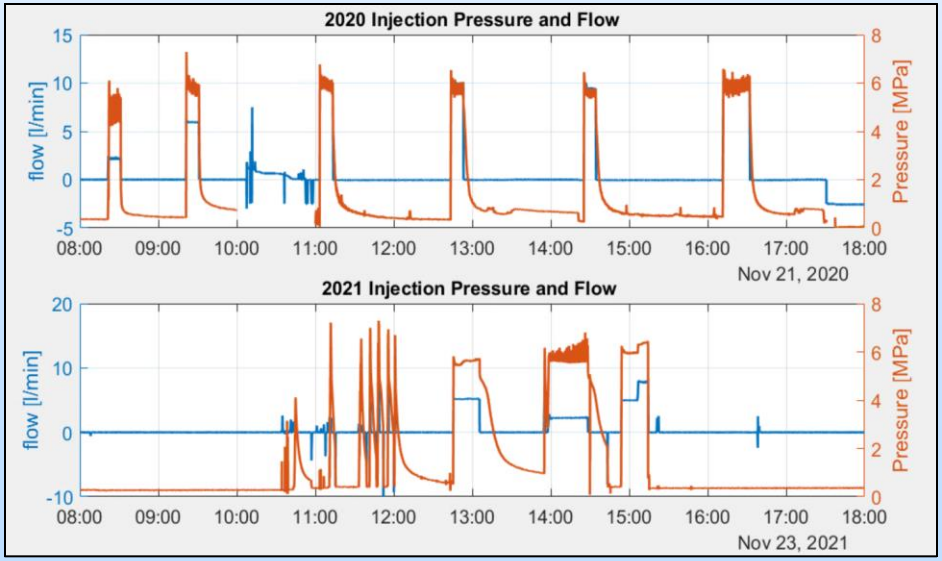
New "chemistry" borehole: Continuous chemical monitoring of leakage fluid chemistry using a portable mass spectrometer

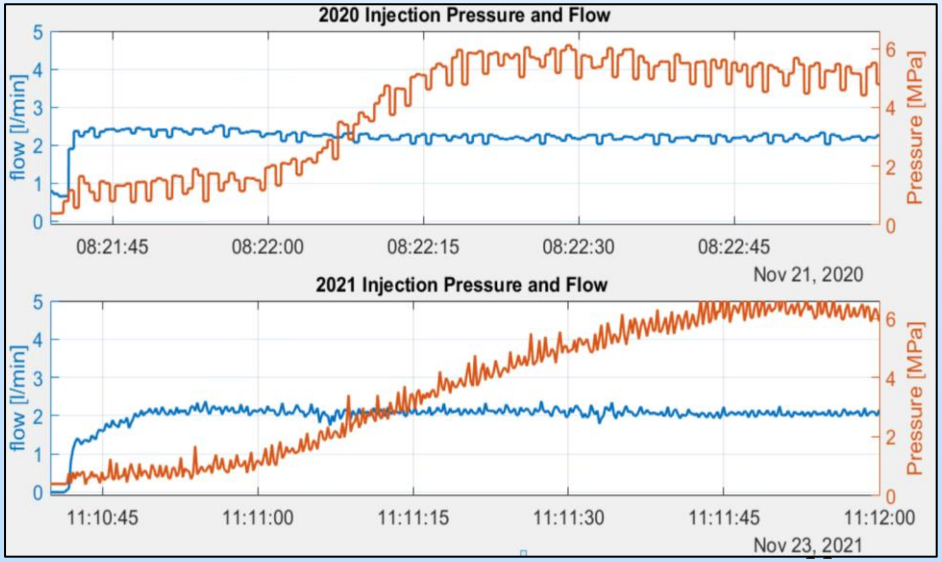
After some lab developments, different DCS fibers designs will be tested in the borehole during an injection experiment in 2023

Progress and Current Status of Project

- **2020 FSB Experiment:** 2 to 10 l/min; Pmax 6 to 7.3 MPa; Instantaneous Shut-in pressure 4.8 to 5.1 MPa
- **2021 FSC Experiment:** 1 to 8 l/min; Pmax 4.2 to 7.2 MPa; Instantaneous Shut-in pressure 5.0 to 5.1 MPa

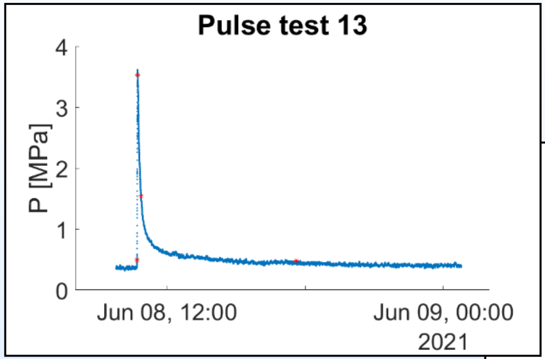
Same Fault Activation Pressure and Leakage Pathways Observed in 2020 & 2021

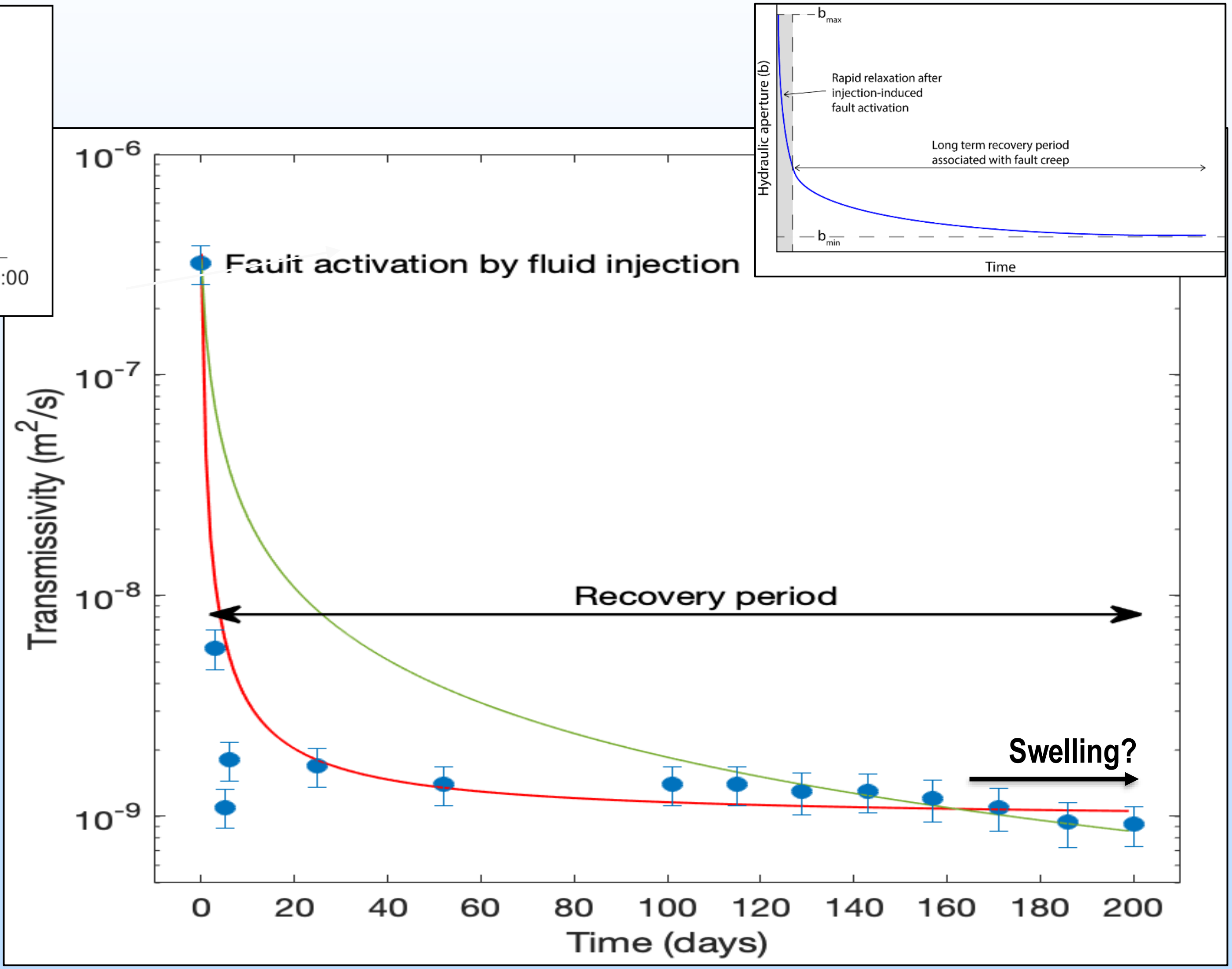




Monitoring of Fault Sealing

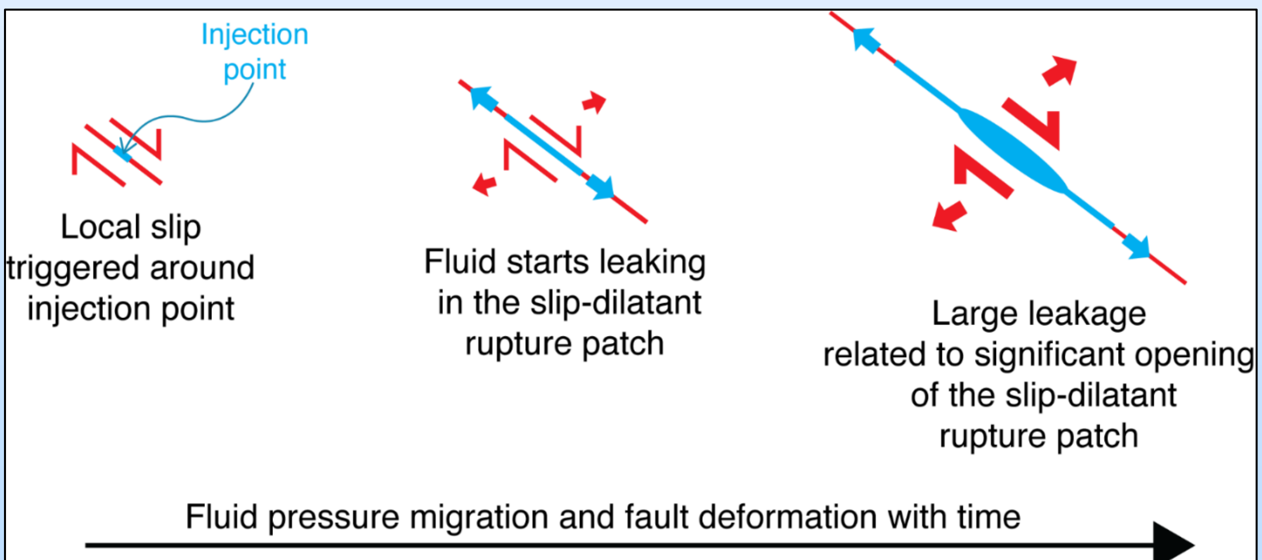
November 2020 to November 2021

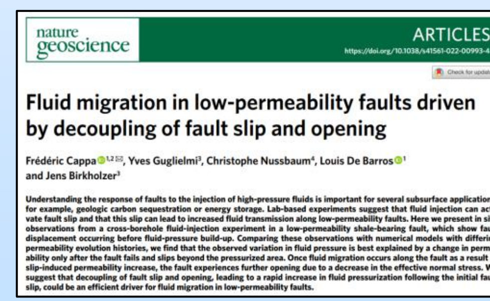




Important Outcomes To Date: Fault Slip Processes (Nature Geoscience 2022)

- Fluid migrates in the initially very low permeability fault only AFTER the fault fails locally and primarily slips beyond the pressurized area
- This creates potential hydraulic pathways in the slip-dilatant rupture patch
- The patch is opens further due to a large effective normal stress decrease that allows more fluid leakage to occur
- Fault slip is largely aseismic thus hard to observe
- After activation the fault permeability decreases strongly, but not to a complete seal




nature geoscience
ARTICLES
https://doi.org/10.1038/s41561-022-00993-4

Check for updates

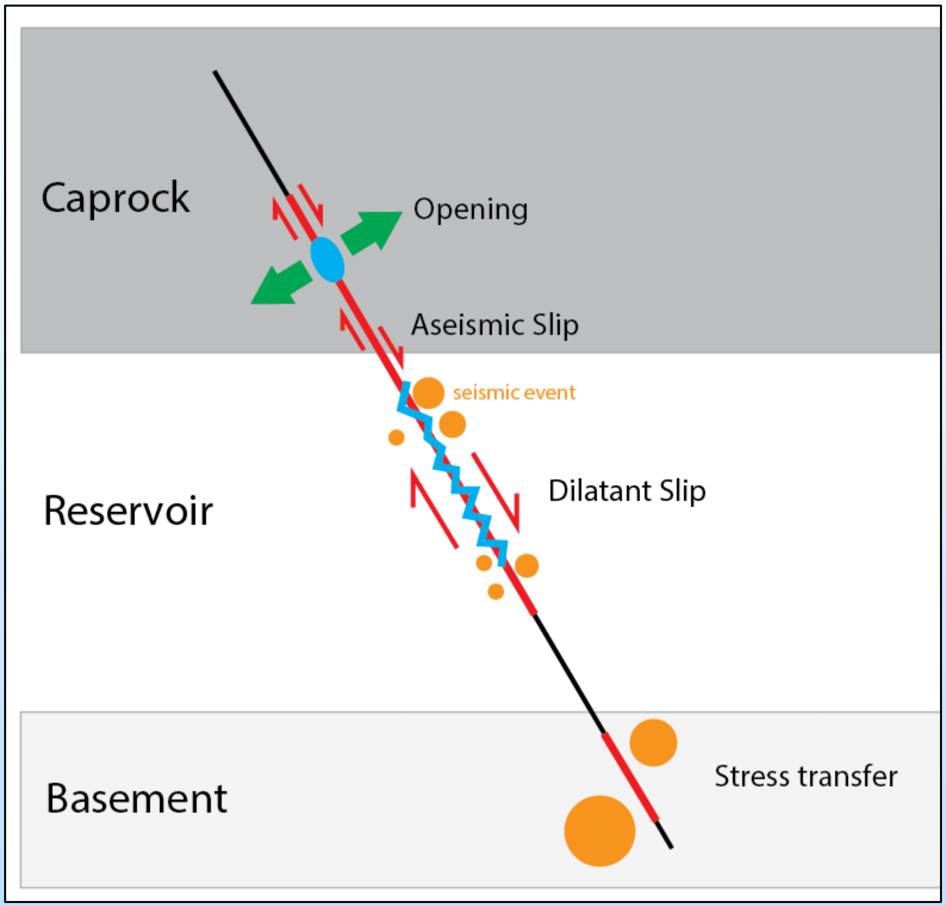
Fluid migration in low-permeability faults driven by decoupling of fault slip and opening

Frédéric Cappa[1,2], Yves Guglielmi[3], Christophe Nussbaum[4], Louis De Barros[1] and Jens Birkholzer[3]

Understanding the response of faults to the injection of high-pressure fluids is important for several subsurface applications, for example, geologic carbon sequestration or energy storage. Lab-based experiments suggest that fluid injection can activate fault slip and that this slip can lead to increased fluid transmission along low-permeability faults. Here we present in situ observations from a cross-borehole fluid-injection experiment in a low-permeability shale-bearing fault, which show fault displacement occurring before fluid-pressure build-up. Comparing these observations with numerical models with differing permeability evolution histories, we find that the observed variation in fluid pressure is best explained by a change in permeability only after the fault fails and slips beyond the pressurized area. Once fluid migration occurs along the fault as a result of slip-induced permeability increase, the fault experiences further opening due to a decrease in the effective normal stress. We suggest that decoupling of fault slip and opening, leading to a rapid increase in fluid pressurization following the initial fault slip, could be an efficient driver for fluid migration in low-permeability faults.

Nature Geoscience, *2022, doi: 10.1038/s41561-022-00993-4, Fluid migration in low-permeability faults is driven by decoupling of fault slip and opening - Frédéric Cappa, Yves Guglielmi, Christophe Nussbaum, Louis De Barros, Jens Birkholzer*

Important Outcomes To Date: Implications for Geologic Carbon Sequestration (IJGGC 2022)



- Slip trigger
- Discrete pressurized zone
- Mainly aseismic reactivation
- Long-term sealing

- Pressure trigger
- Distributed pressurized zone
- Seismic reactivation
- Stress Transfer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Review article

Field-scale fault reactivation experiments by fluid injection highlight aseismic leakage in caprock analogs: Implications for CO_2 sequestration

Yves Guglielmi[a,*], Christophe Nussbaum[b], Frédéric Cappa[c,d], Louis De Barros[c], Jonny Rutqvist[a], Jens Birkholzer[a]

ARTICLE INFO

Keywords:
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Fault
Fluid injection
Induced seismicity
Leakage
Field scale experiments

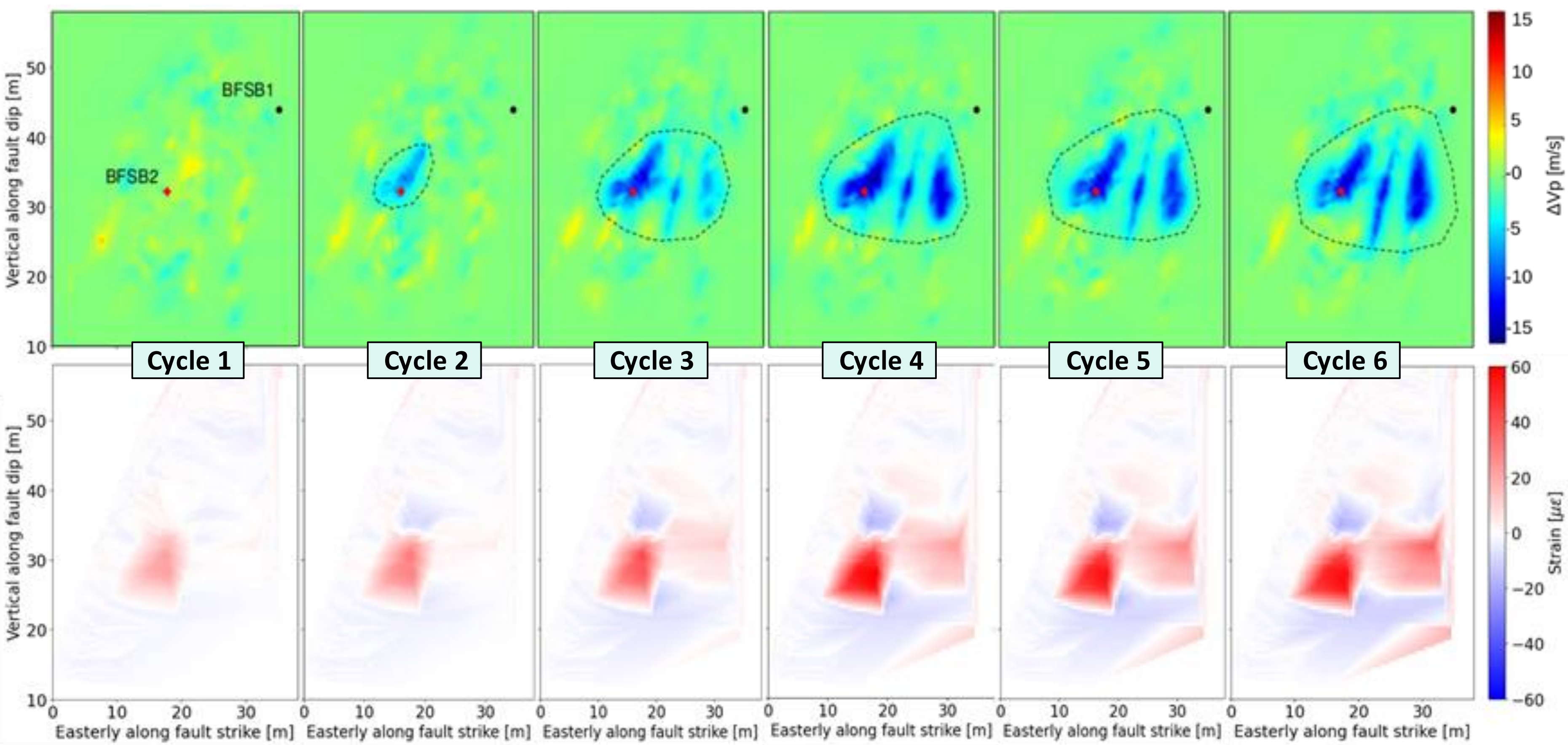
ABSTRACT

Observations on tens-of-meter scale experiments of fault activation by fluid injection conducted in shales allow exploring how aseismic and seismic events may jeopardize the integrity of a sealing caprock overlying a CO_2 sequestration reservoir. We contrast the behavior of shale faults with another set of experiments conducted in carbonates. Significant fluid leakage occurs along the initially low-permeability shale faults when rupture is activated. Most of the leakage pathway closes when fluid injection ceases and fluid pressure drops. Dilatant slip on the fault plane alone does not explain the observed leakage behavior, which is also caused by fault opening favored by the softness of the shale, and by the structure of the fault zone that prevents fluids from diffusing into the adjacent damage zone. Experiments show a large amount of aseismic deformation. Small-magnitude seismicity (M_w < -2.5) is observed outside the pressurized leakage patch. Stress transferred from this aseismic deformation patch can build up to stress-criticality and favor seismicity. Thus, in terms of fault activation in caprocks, aseismic fault slip leading to increased permeability and a loss of seal integrity is of great concern.

IJGGC, *2022, doi: 10.1016/j.ijggc.2021.103471, Field-scale fault reactivation experiments by fluid injection highlight aseismic leakage in caprock analogs: Implications for CO_2 sequestration - Yves Guglielmi, Christophe Nussbaum, Frédéric Cappa, Louis De Barros, Jonny Rutqvist, Jens Birkholzer*

Ongoing Work: Low Frequency DAS vs. CASSM Vp Tomography

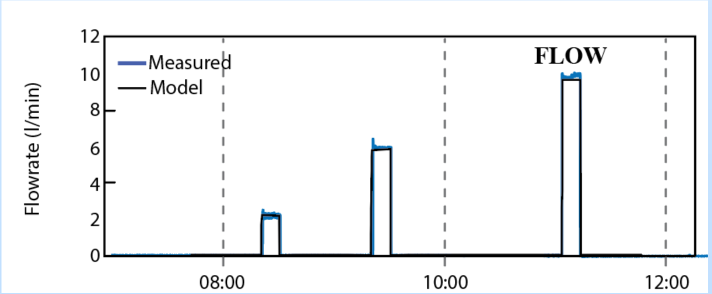
DAS extensional signal agrees with CASSM negative ΔVp anomaly delineating the asymmetry of the reactivated fault patch



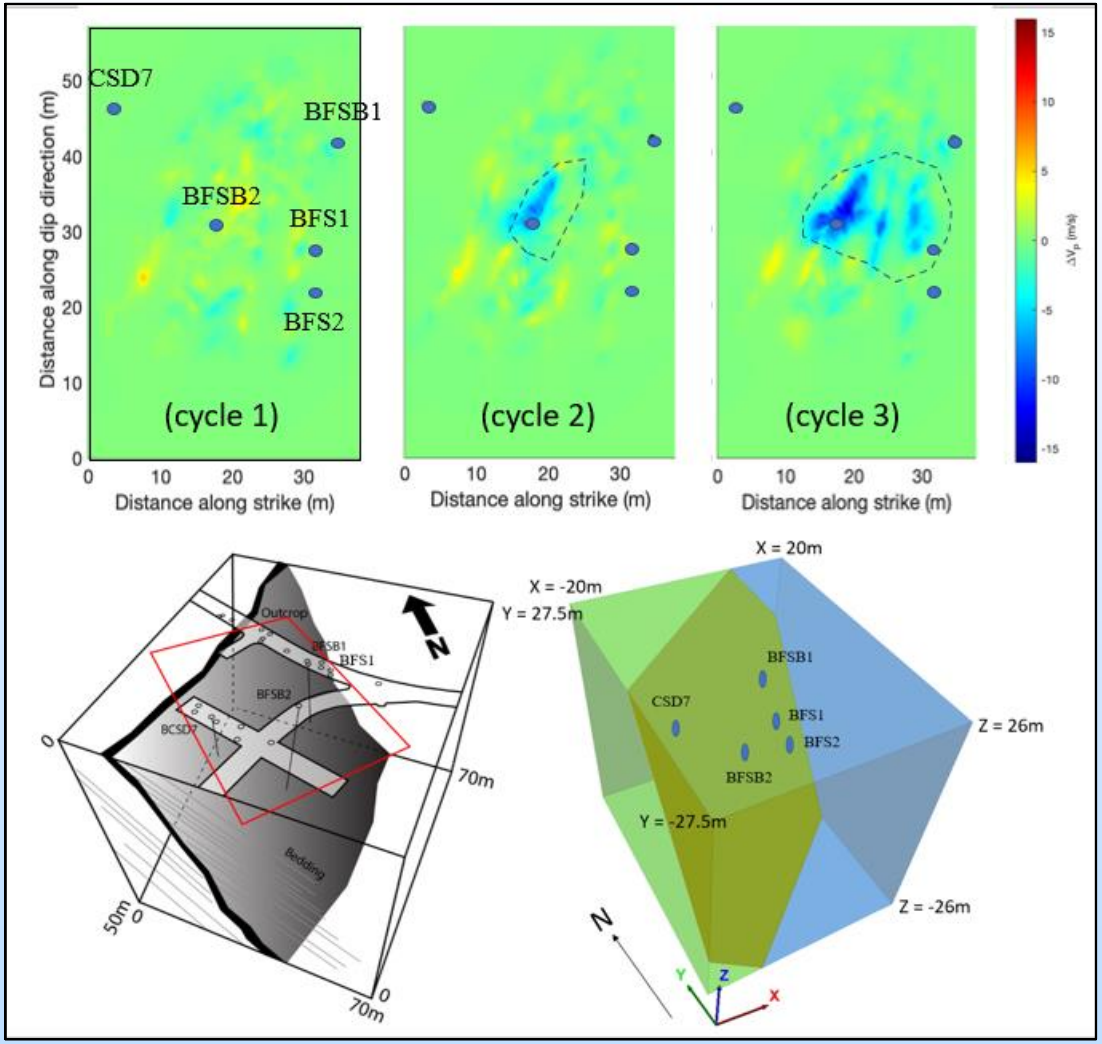
Ongoing Work: Hydromechanical Model

- Fault zone represented as a single plane in 3DEC
- Stress applied at all model boundaries
- Pore pressure 1.4 MPa
- Fully coupled HM quasi-static
- Mohr-Coulomb failure on fault
- Flow only in ruptured fault patch

Model loaded with injected flowrate



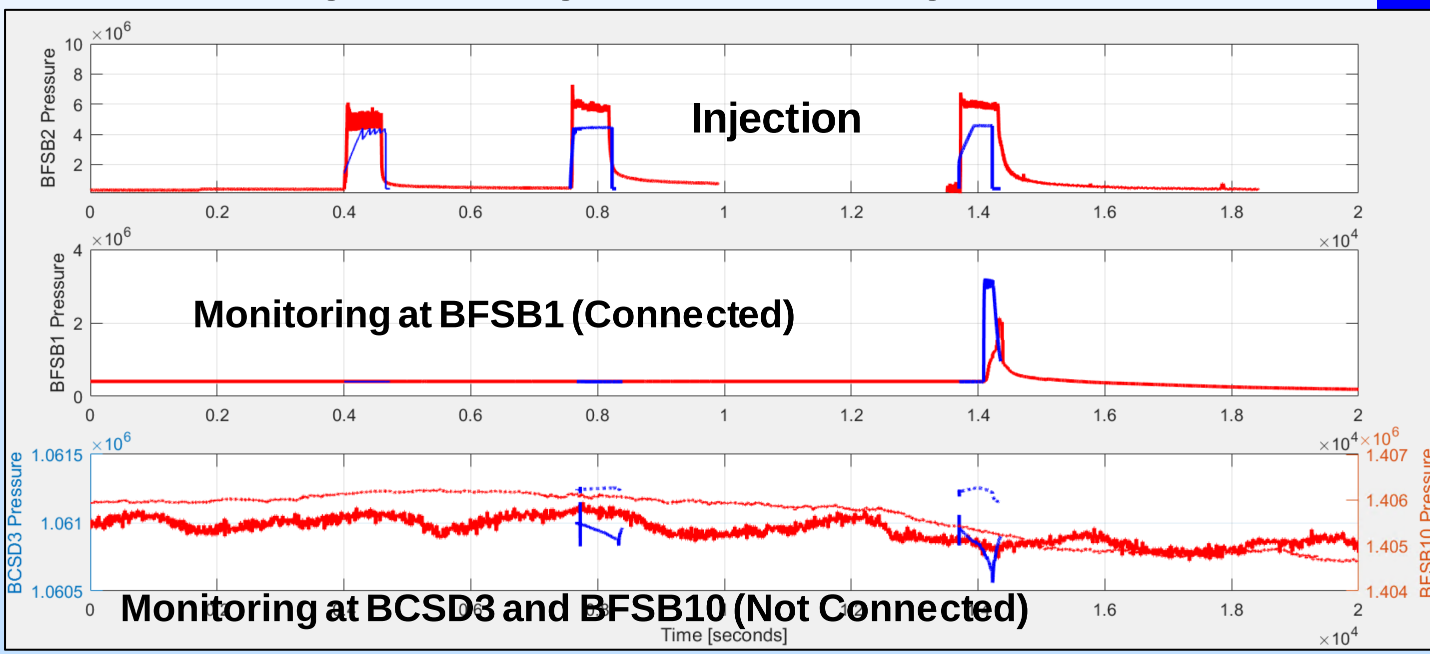
Time (hr)

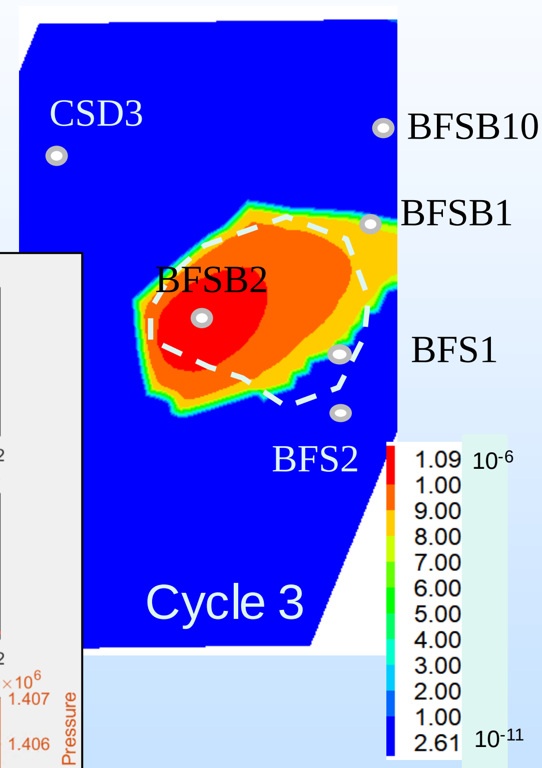


Hydromechanical Model Reasonably Reproduces:

- Maximum injection pressure of 5.1 MPa
- Timing of hydraulic connection with BFSB1
- Slight pressure drop at non-connected BCSD3 and BFSB10 boreholes

Cycle1 Cycle 2 Cycle 3





Simulated Transmissivity (m^2/s)

Measured pore pressure

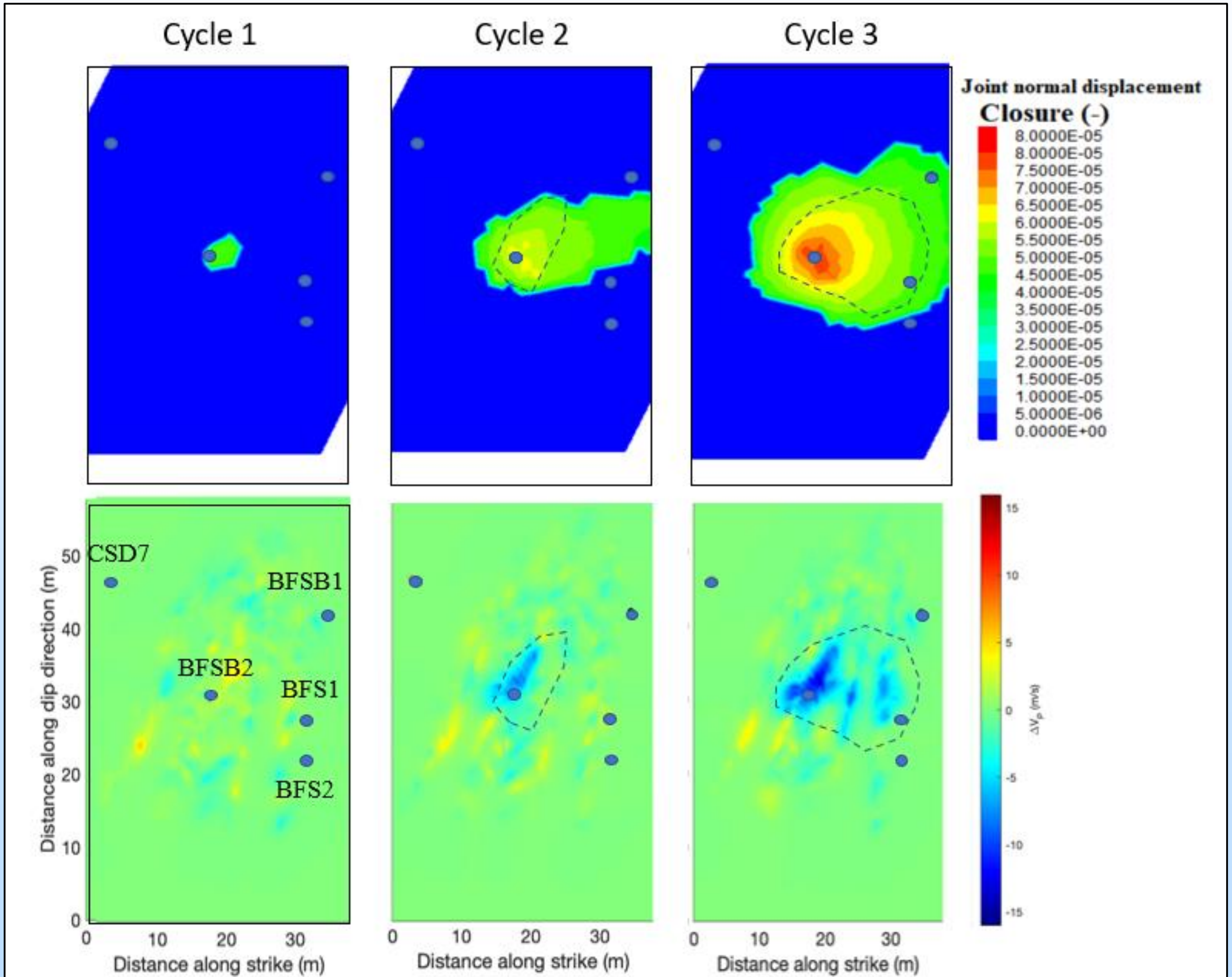
Simulated pore pressure

Hydromechanical Model Reasonably Reproduces:

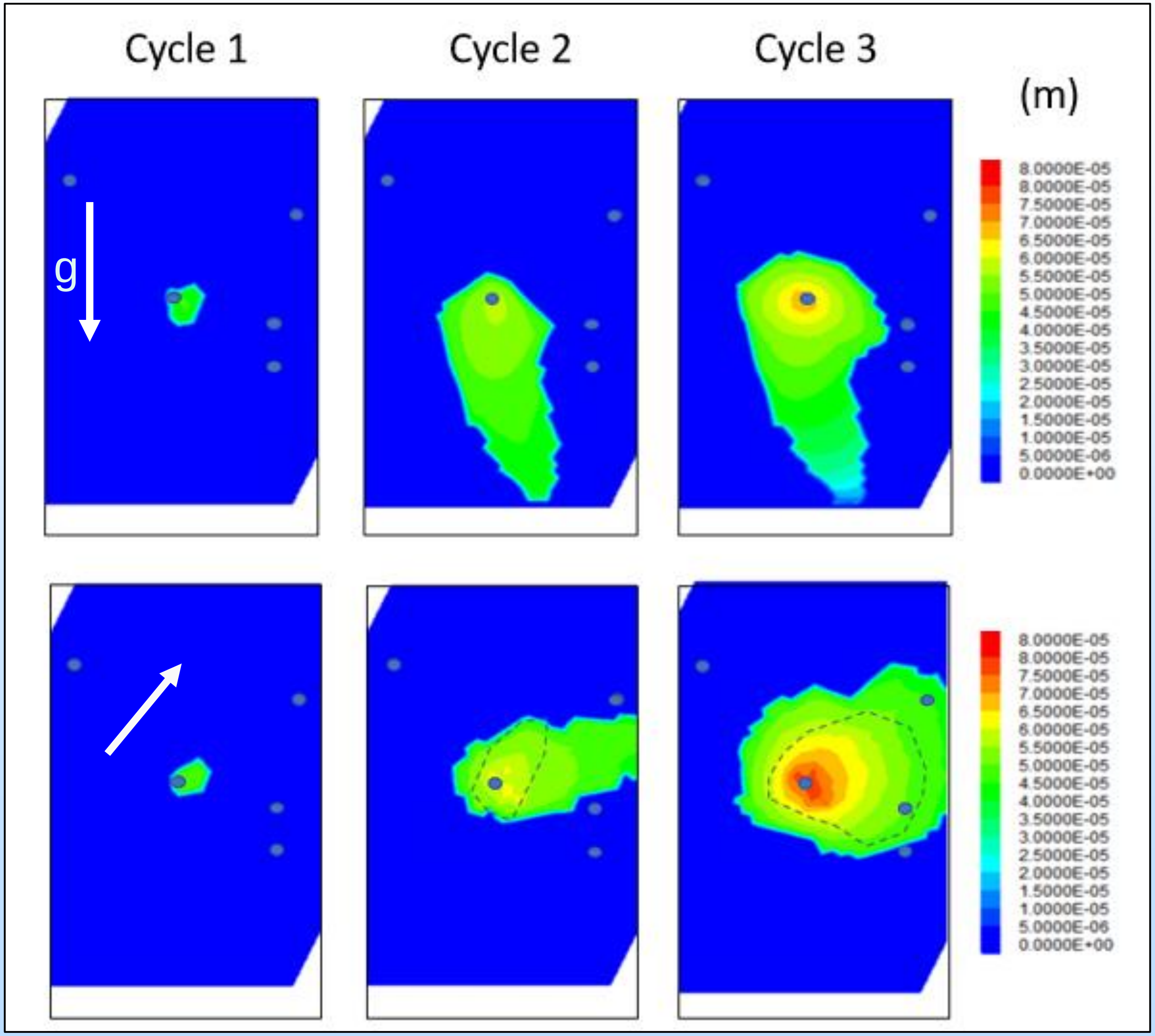
- Timing and magnitude of Vp changes
- Asymmetry of fault patch
- Calculated fault opening from SIMFIP and strain fiber optics

Simulation

CASSM Data



Best-Fit Analysis: Leakage Direction is Highly Sensitive to Stress Gradient

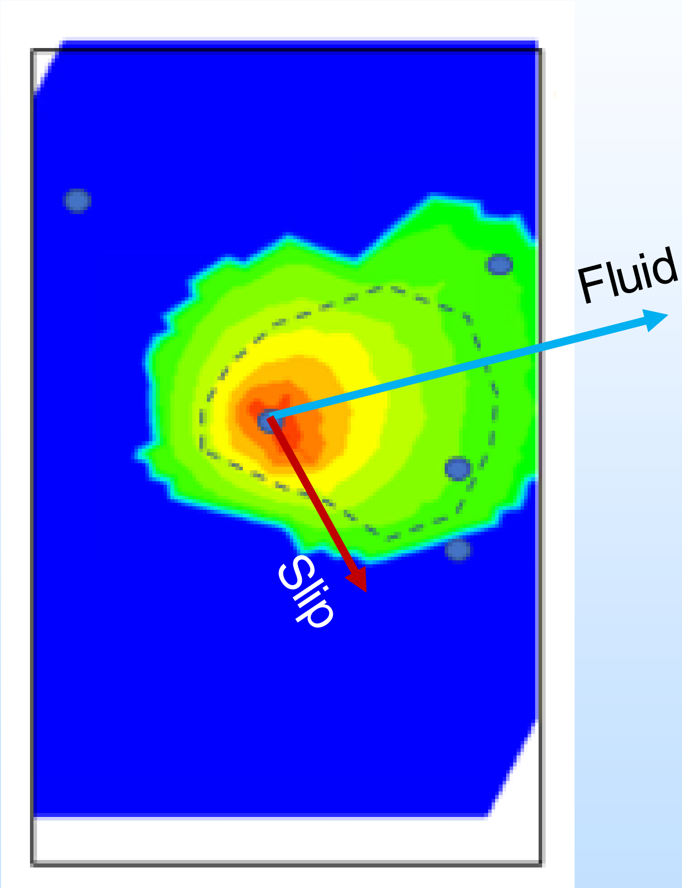


Only gravity does not explain the leakage path direction of propagation

Best fit when a stress gradient is imposed in addition to gravity

New Finding: Decoupling Between Fault Slip Direction and Leakage Direction

Slip follows stress tensor orientation

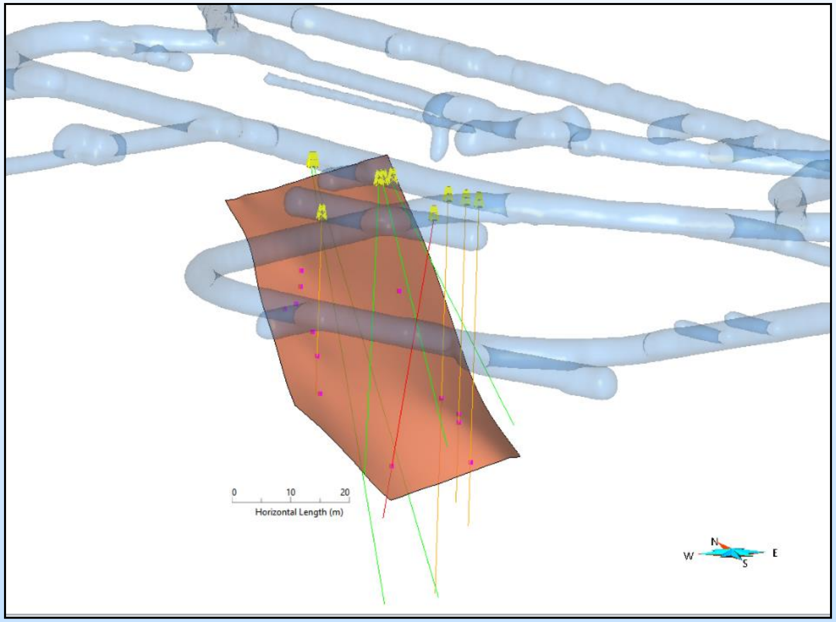


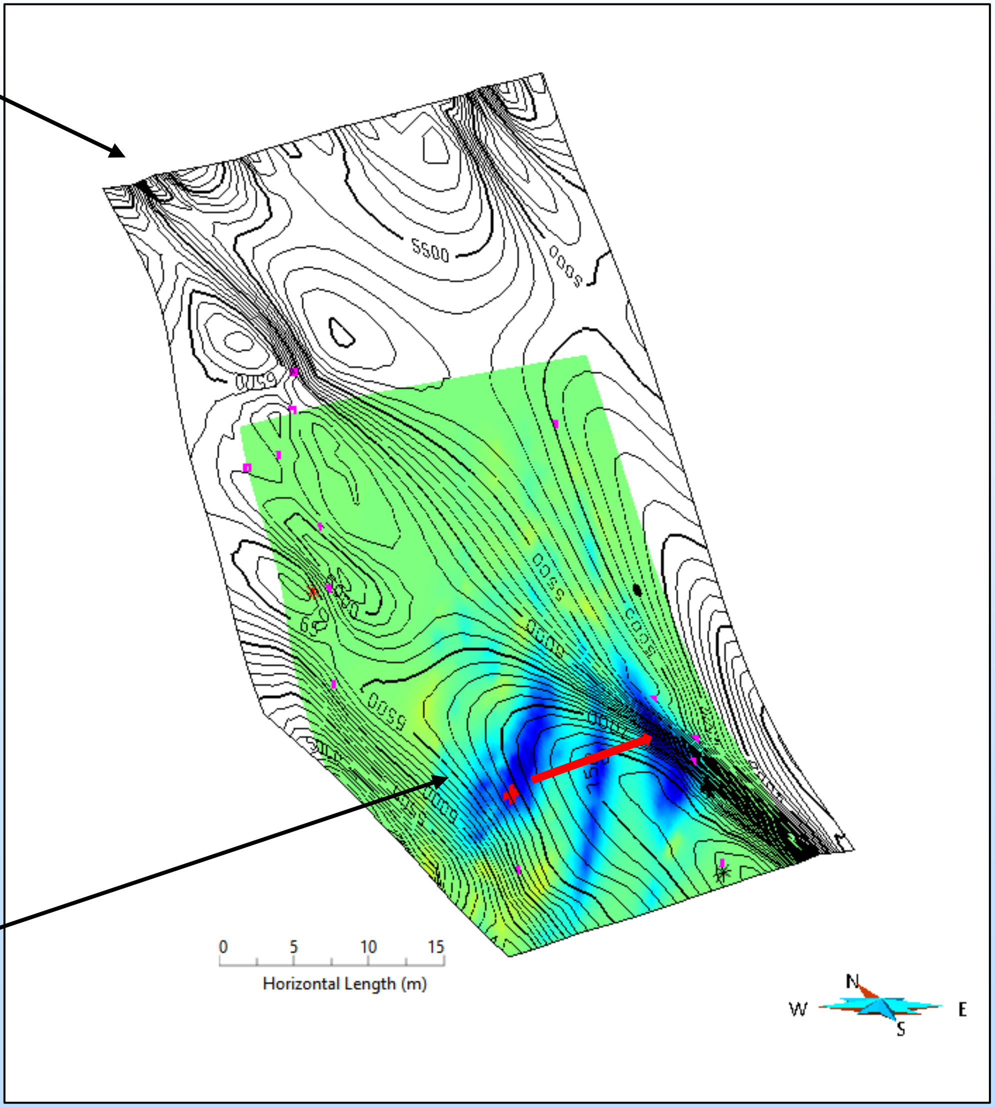
Fluid migration follows stress gradient for a given tensor orientation

Is this an inherent characteristic of initially low-permeability faults where flow only occurs at rupture?

Fault Geometry Undulations Appears to Cause the Stress Gradient Changes

Contours: Normal stress on fault





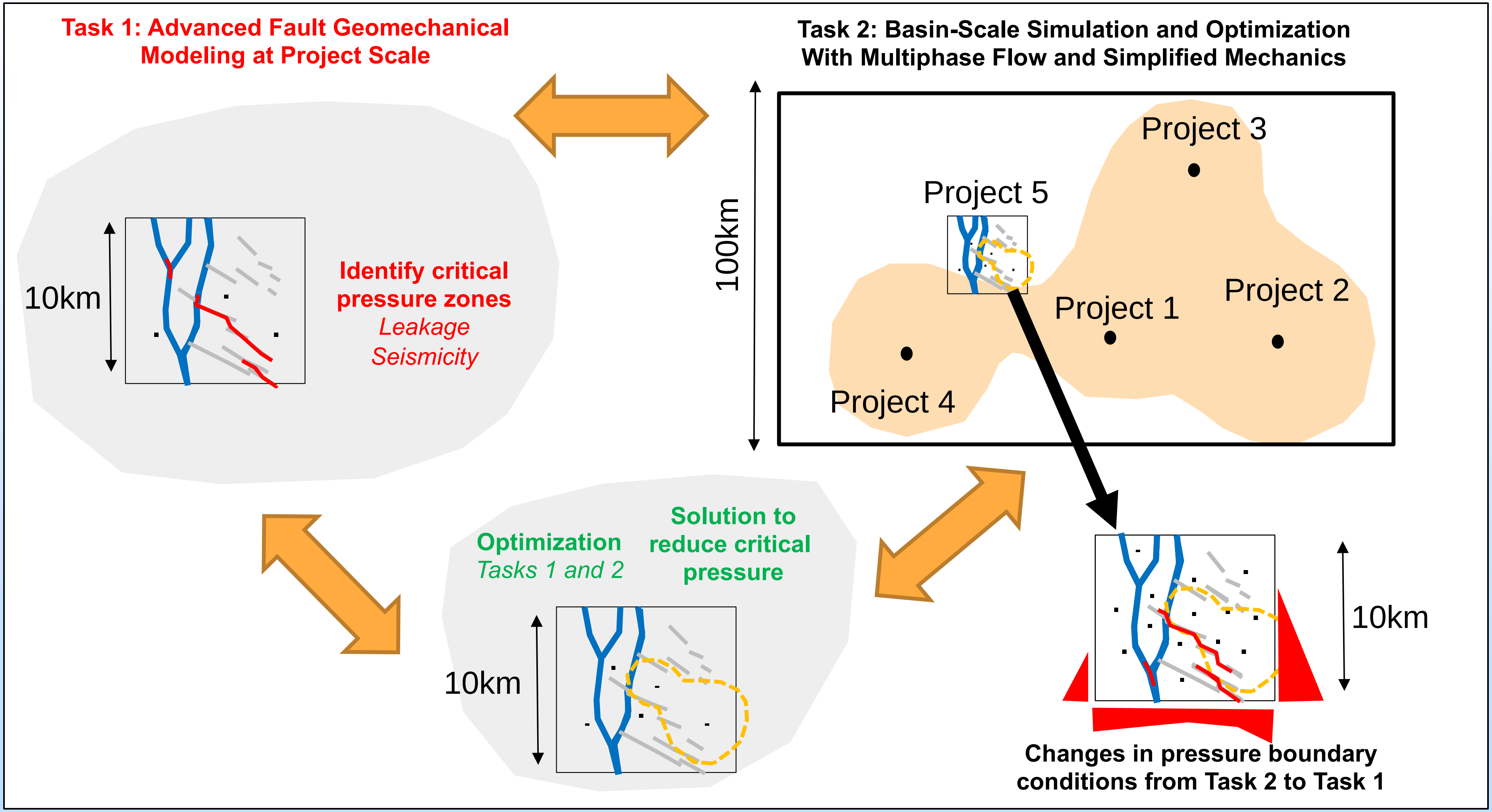
Colors: Projected Vp changes

Accomplishments To Date

- A field laboratory dedicated to faults and multiple international collaborations
- Testing multiple techniques during controlled field-scale fault activation experiments
- New insights on caprock integrity impacts from fault reactivation

Synergy Opportunities:

Inform New LBNL Project on Basin-Scale Storage Optimization Using Geomechanical Studies

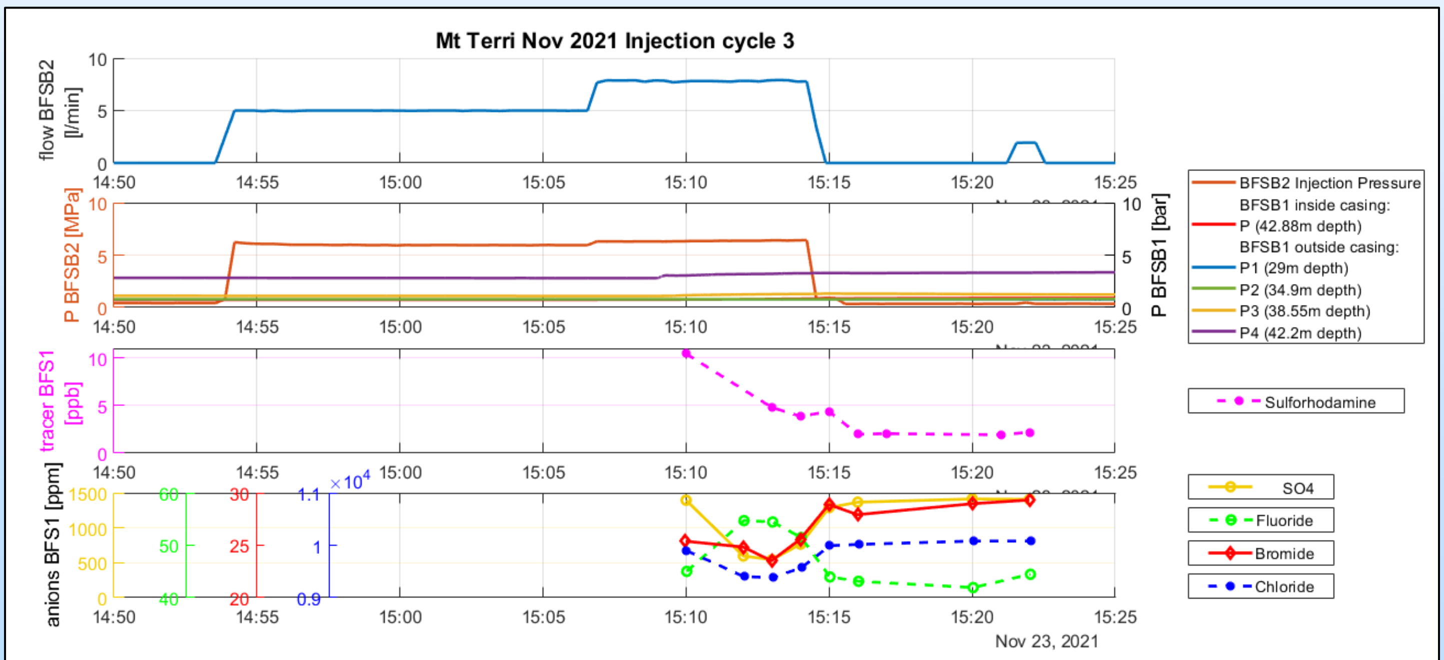


Backup Slides

Ongoing Work: Background Chemical Monitoring

November 2021 - Injection Experiment

- Injection of conservative tracer (salt, temperature, sulforhodamine)
- Analyses of chemical variations in recovered pore water (Na^+, K^+, Mg^{2+} , Ca^{2+}, Sr, Br, $SO4^{2-}$, alcalinity, total CO_2(aq), NO_3-, Fe^{2+}, AlO_2, SiO_2, Li, O_2)



- Most tracers did not break through!
- Chemical content is consistent with formation water
- 2021 experiment helps design 2022 experiment

Appendix

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

Organization Chart

- **Team·members·and·their·role:¶**

Task·1:·Yuxin·Wu,·Research·Scientist·and·a·postdoctorant·1/SEA·researcher.¶

Task·2:·Y.·Guglielmi,·PI·and·Research·Scientist;·P.·Cook,·Scientific·Engineering·Associate;·Postdoctorant·2;·Yuxin·Wu,·Research·Scientist·and·a·postdoctorant·1/SEA·researcher¶

Task·3:·Y.Guglielmi,·PI·and·Research·Scientist;·Veronica·Rodriguez-Tribaldos·Research·Scientist,·Chet·Hopp·Postdoc;·P.·Cook,·Scientific·Engineering·Associate;·F.·Soom,·Scientific·Engineering·Associate;·T.·Wood,·Scientific·Engineering·Associate;·Michelle·Robertson,·Program·Manager.¶

Task·4:·Y.·Guglielmi,·PI·and·Research·Scientist;·J.·Birkholzer,·PI·and·Research·Scientist;·Chet·Hopp·postdoc;·J.·Rutqvist,·Research·Scientist;·Julia·Correa,·Research·Scientist;·Veronica·Rodrigues·Tribaldos,·Posdoc·1·and·2.¶

Task·5:·Y.·Guglielmi,·PI·and·Research·Scientist;·J.·Birkholzer,·PI·and·Research·Scientist;·H.·Prieto,·Admin·Asst¶

Gantt Chart

FS-C experiment	¤															
Steps:	¤	Q4 FY21	Q1 FY22	Q2	Q3	Q4	Q1 FY23	Q2	Q3	Q4	Q1 FY24	Q2	Q3	Q4	Q1 FY25	Q2
Task 1 – DCS Fiber Design and Production	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤
Sub-Task 1.1 – OTDR design and construction	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤
Sub-Task 1.2 – Laboratory validation	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤
Task 2 – Field Test Preparation for Water Chemical Monitoring at Mt Terri	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤
Task 2.1 – Installation of water and gas chemical monitoring	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤
Task 2.2 – DCS installation at Mt Terri	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤
Task 3 – Experiments of Fault Reactivation with CO_2 fluids	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤
Task 3.1 – Perturbations of leakage water chemistry related to fault deformation	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤
Task 3.2 – Cyclic injection of CO_2-brine and CO_2-gas	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤
Task 4 – Data Analyses, Geomechanical and Chemical Modeling	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤	¤