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Supplement of

Geomechanical in situ testing of fault reactivation in argillite repositories

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Geomechanical *In Situ* Testing of Fault Reactivation in Argillite Repositories

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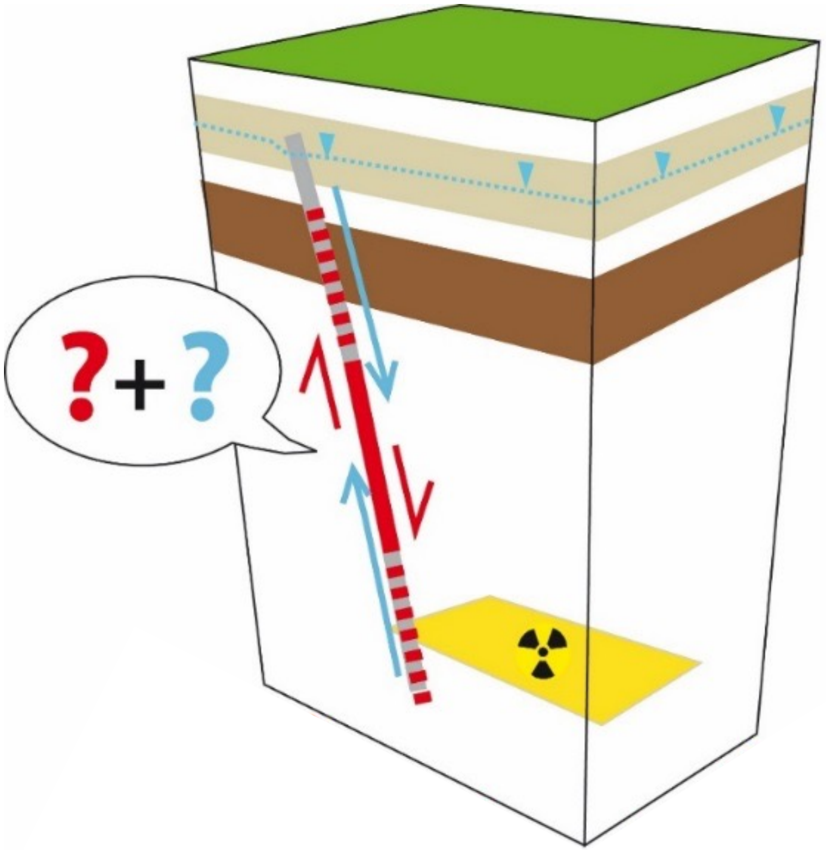
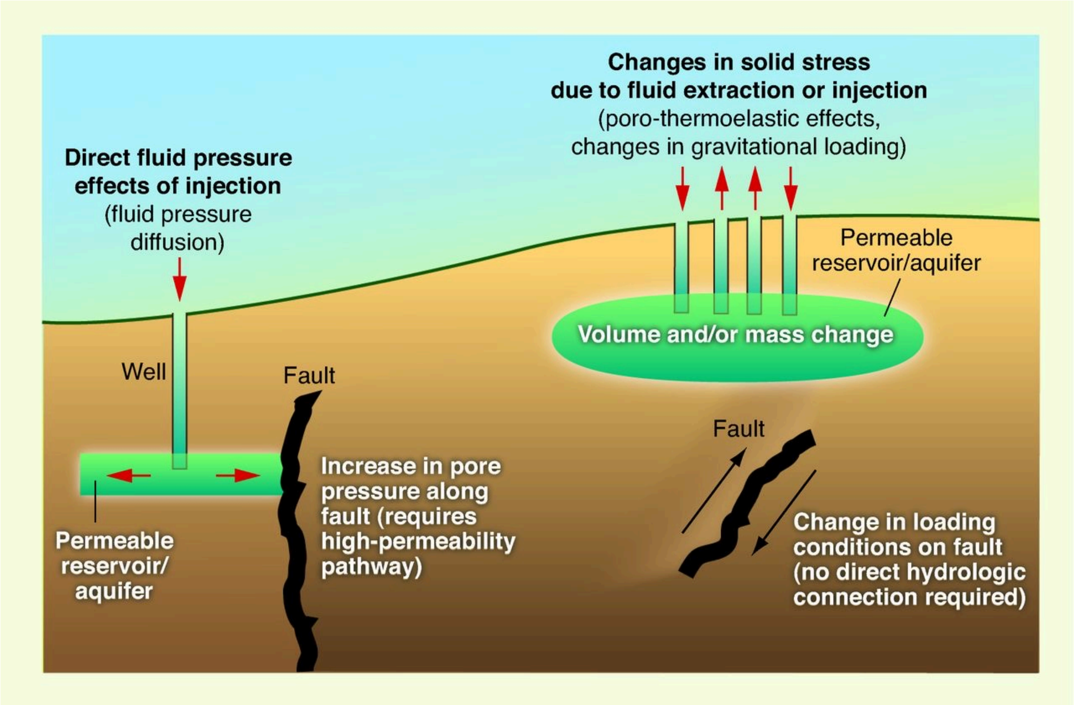
Repository Induced Effects and Potential Impacts on Nearby Faults

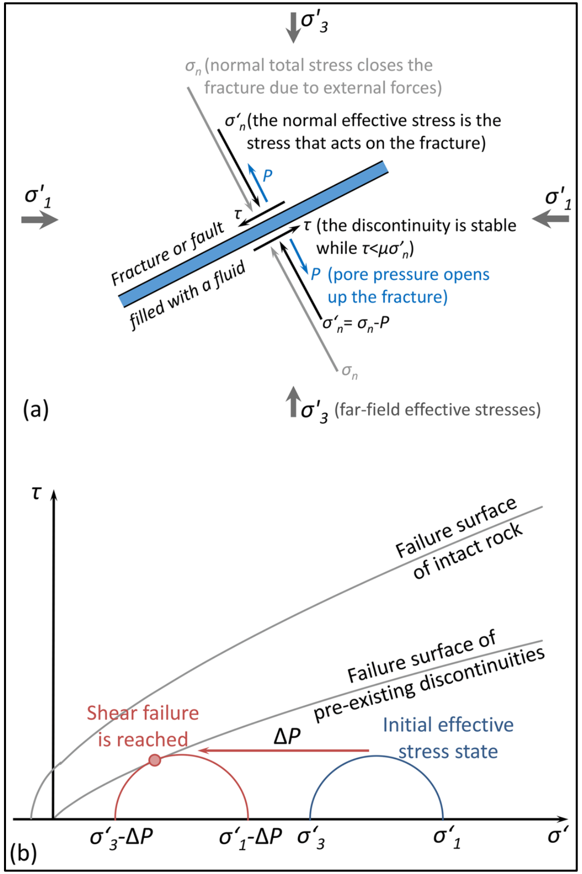
- Waste emplacement causes temperature and pore pressure increase in host rock
- Gas generation causes pressure buildup and gas transport



Fault Reactivation Due to Stress Changes and Pore Pressure Buildup



Ellsworth, 2013

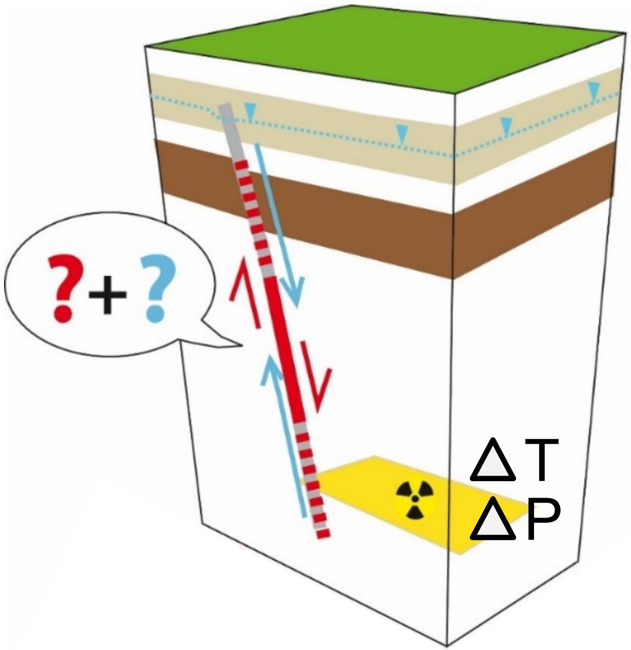


Fault Reactivation in Argillite Host Rocks

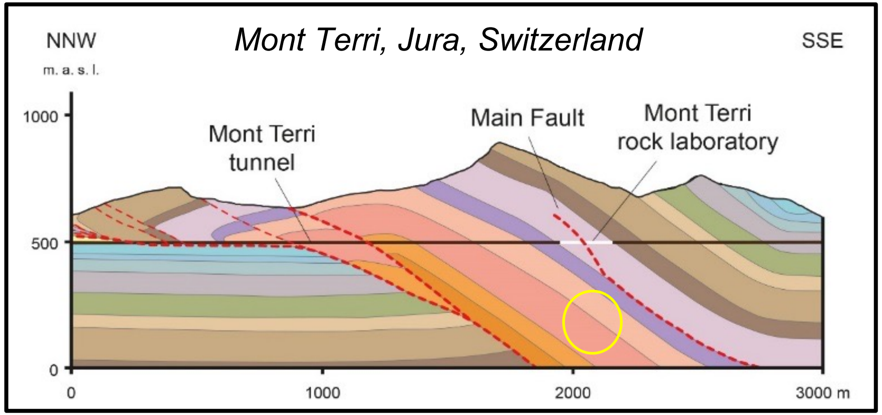
Research Questions about Natural Barrier Integrity:

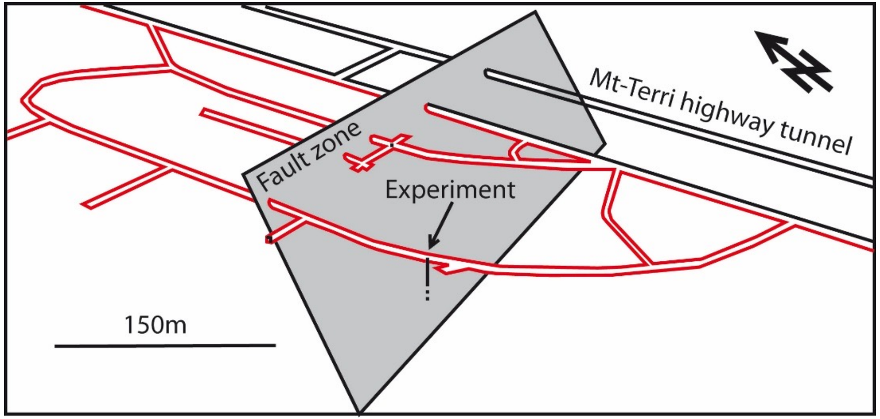
- What is the relationship between pressure buildup, fault opening, fault slip, and fluid migration in initially low-permeability faults?
- Under what conditions are permeable pathways generated and what are the underlying mechanisms?
- Are events leading to increased fault permeability associated with observable or even strong seismicity?
- What is the long-term hydrologic behavior of reactivated faults? Can sealing or healing be expected?
- What are the potential performance implications?

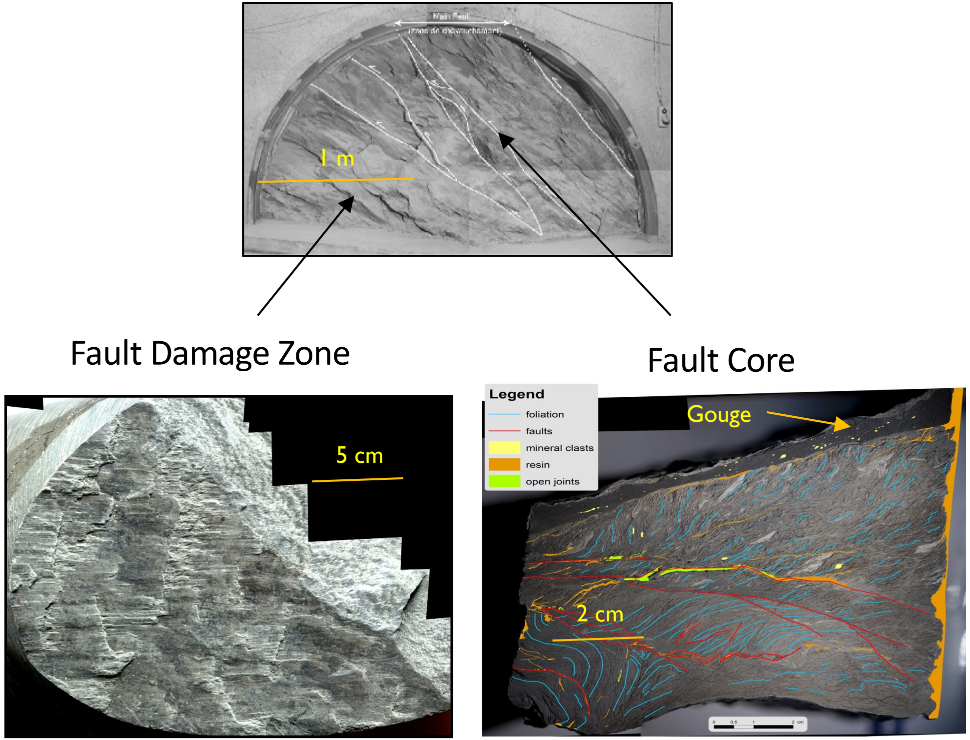
Mesoscale *In Situ* in Densely Monitored Fault Experiments



The Mont Terri Rock Lab Has a Perfect Fault for *In Situ* Seal Testing







From Laurich et al., Structural Geology, 2014; Solid Earth, 2018

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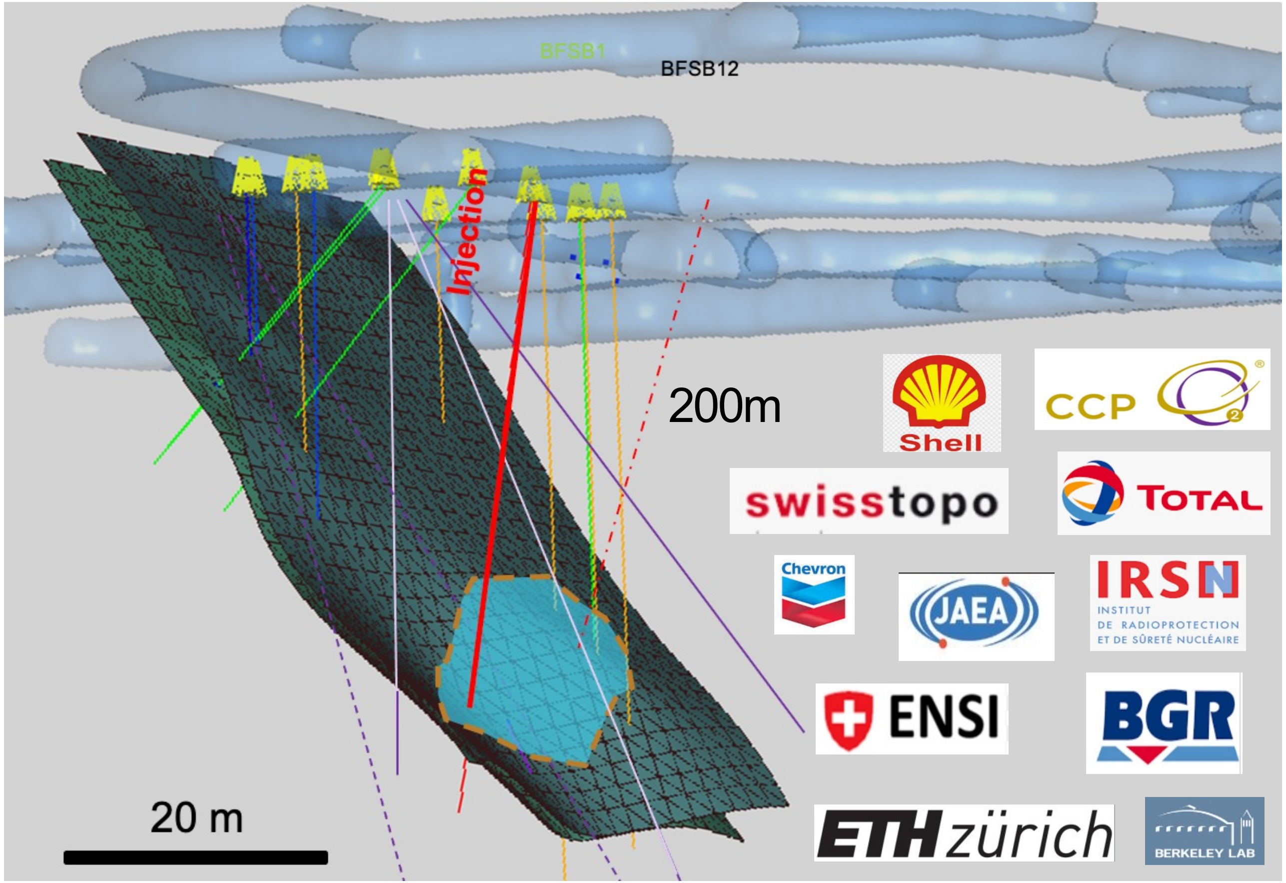
A Testbed for Controlled Fault Injection Experiments: Elucidating the Coupling Between Pressure, Flow and Deformation

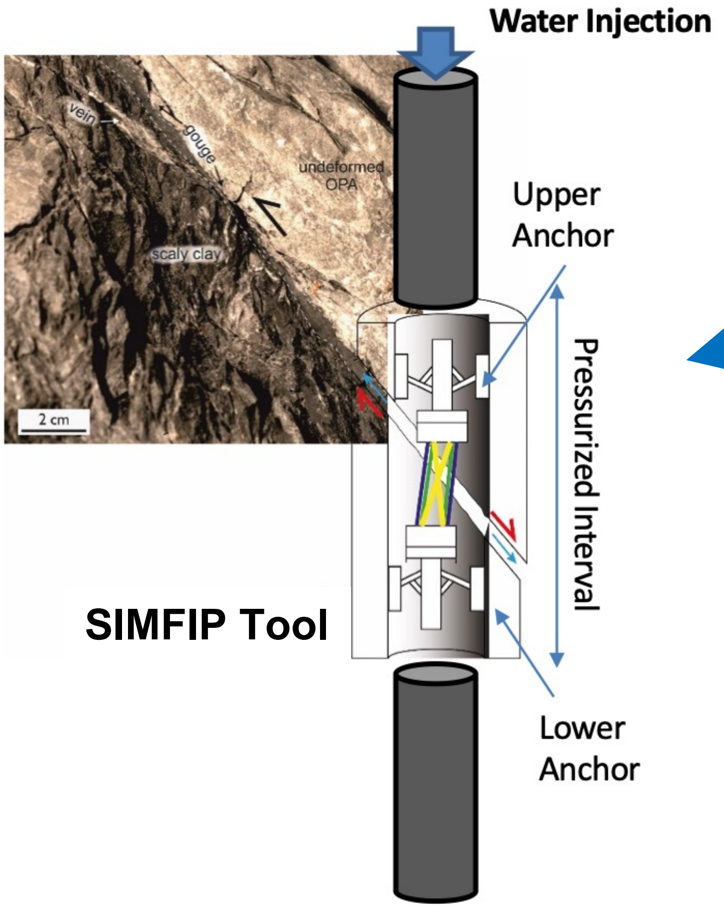
2015 Kick-Off Experiment:
Fundamental hydromechanical behavior of activated faults in a seal analog

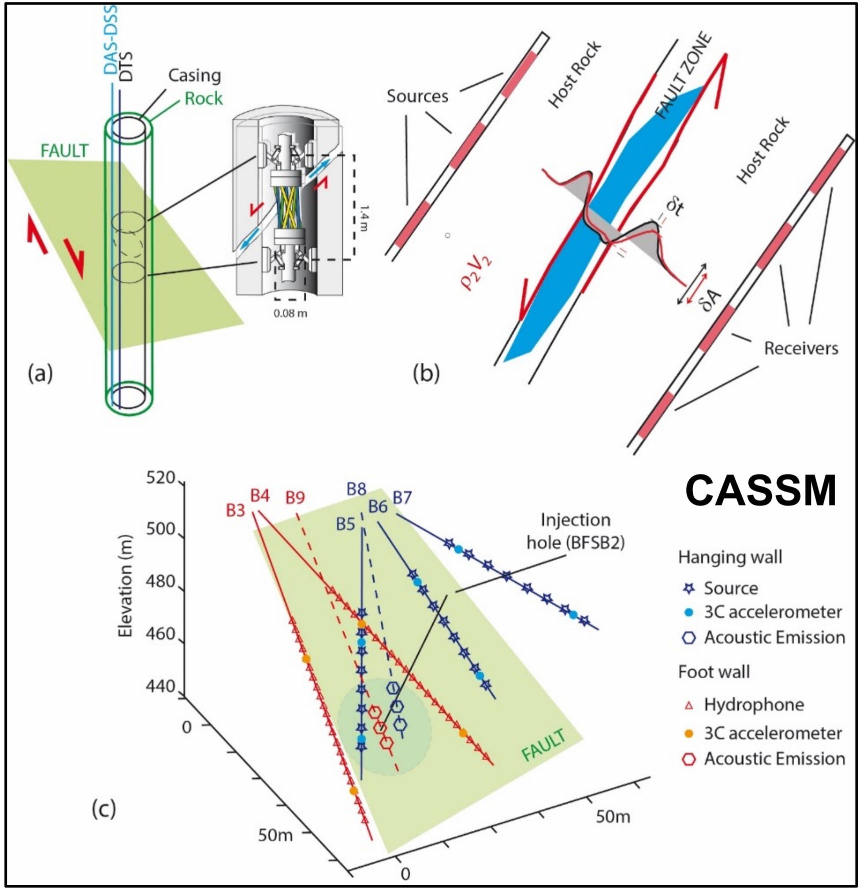
2020, 2021, and 2023 Experiments:
Follow-up injection experiments with larger patch size, longer injection and post-injection cycles, and additional monitoring

Passive Observations:
Long-term post-activation evolution of fault permeability



Multi-Modal Monitoring





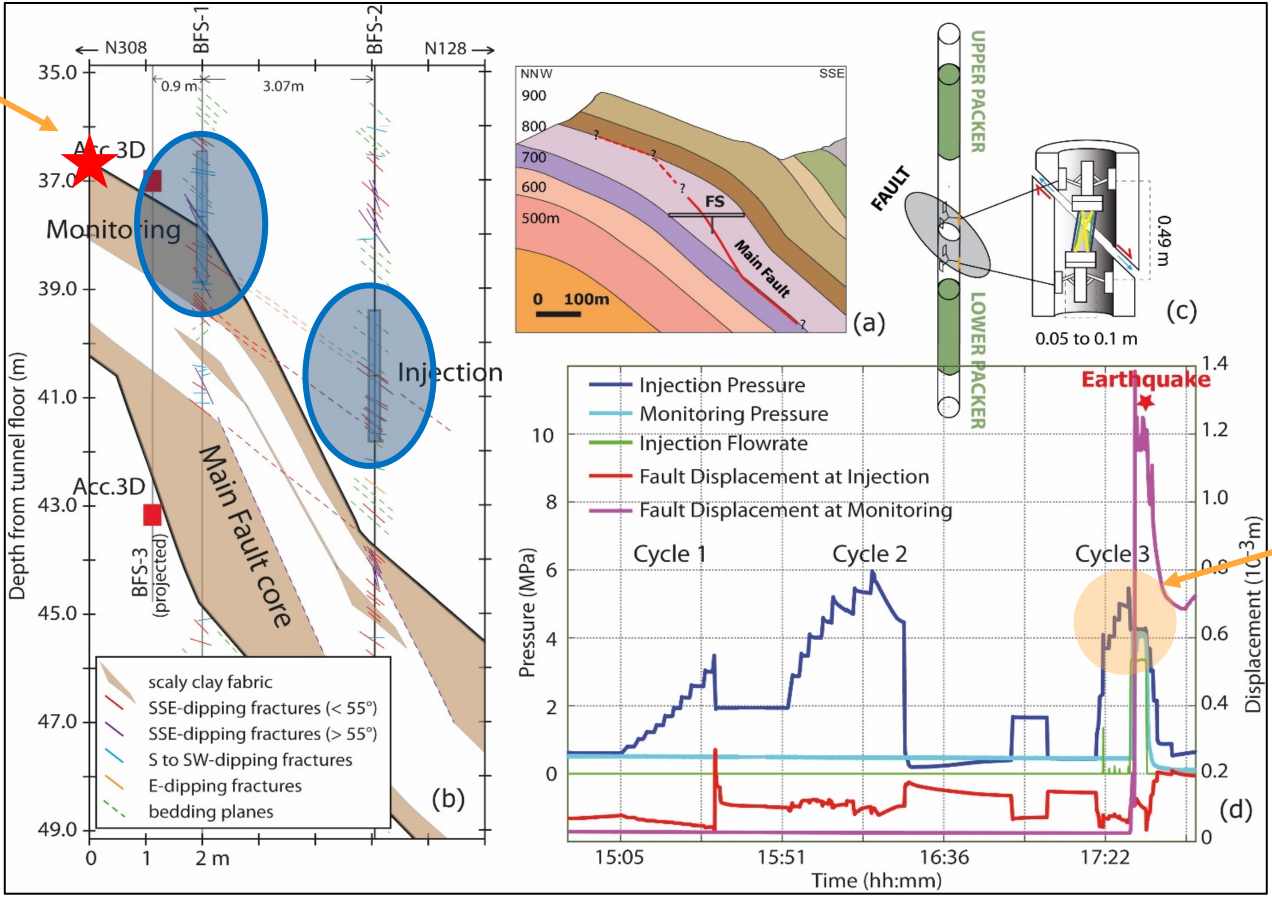
SIMFIP = Step-Rate Injection Method for Fracture In-Situ Properties

CASSM = Continuous Active Seismic Source Monitoring

Impressions from Experimental Campaign

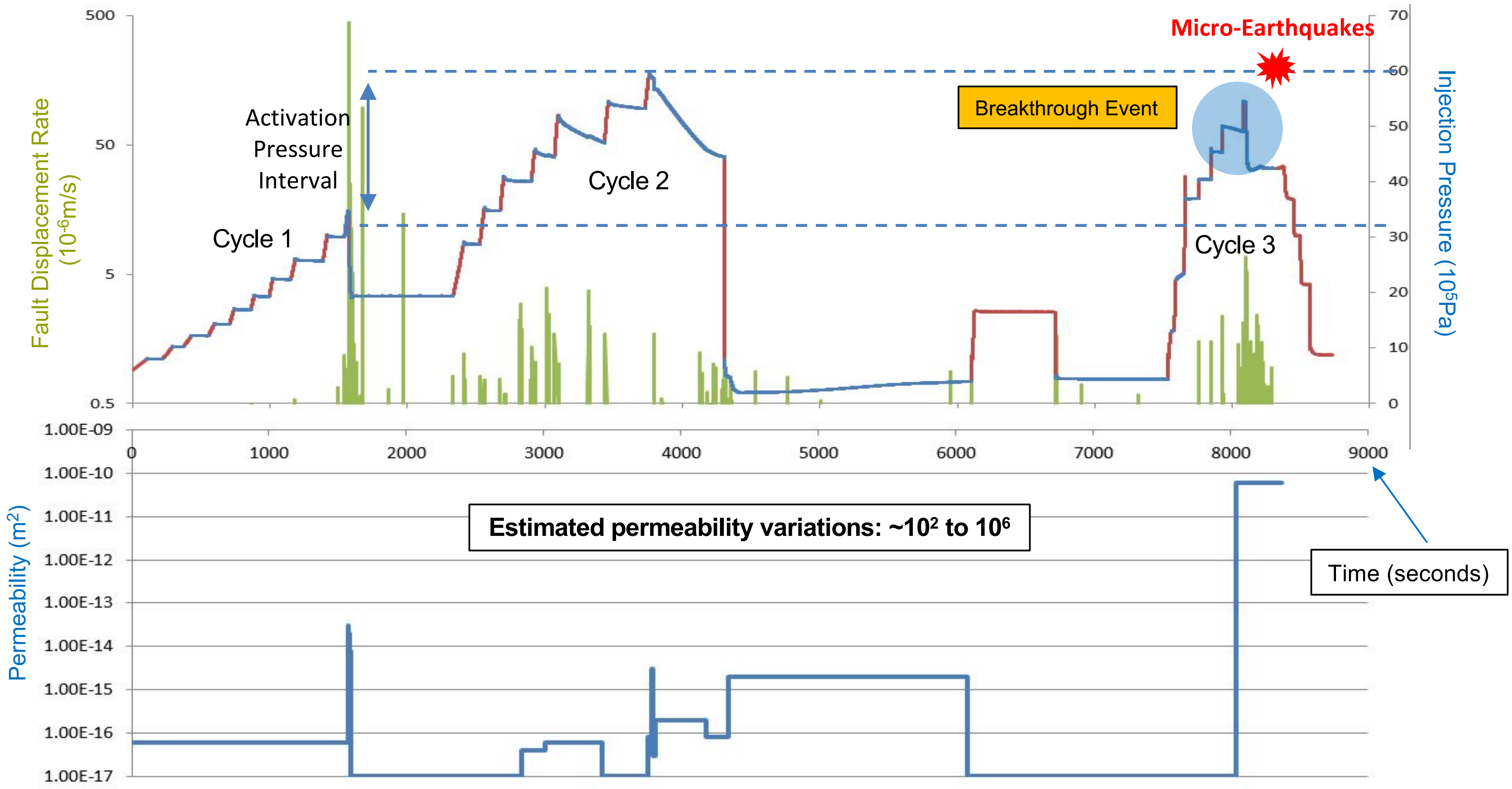
Test Procedure: Cycled Short-Term Injections with Rest Periods

Mw ~ -2.5

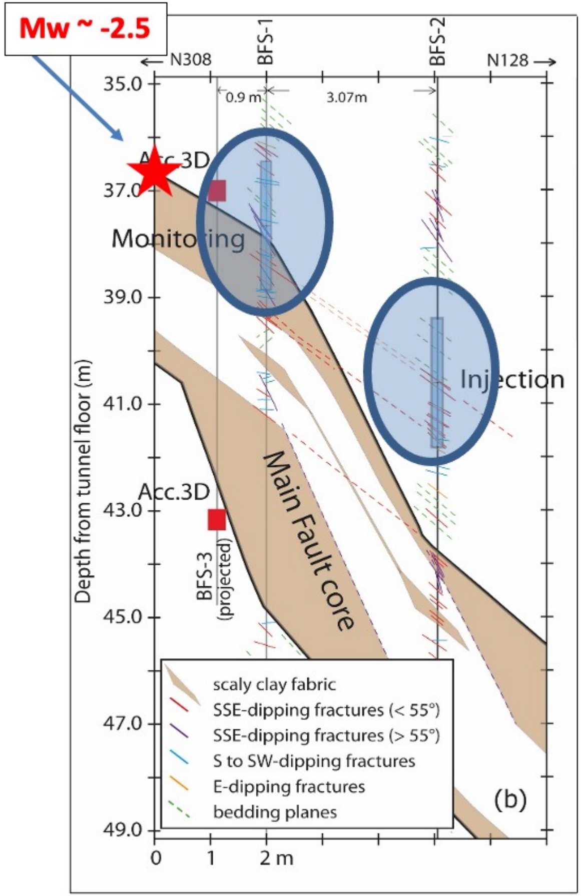


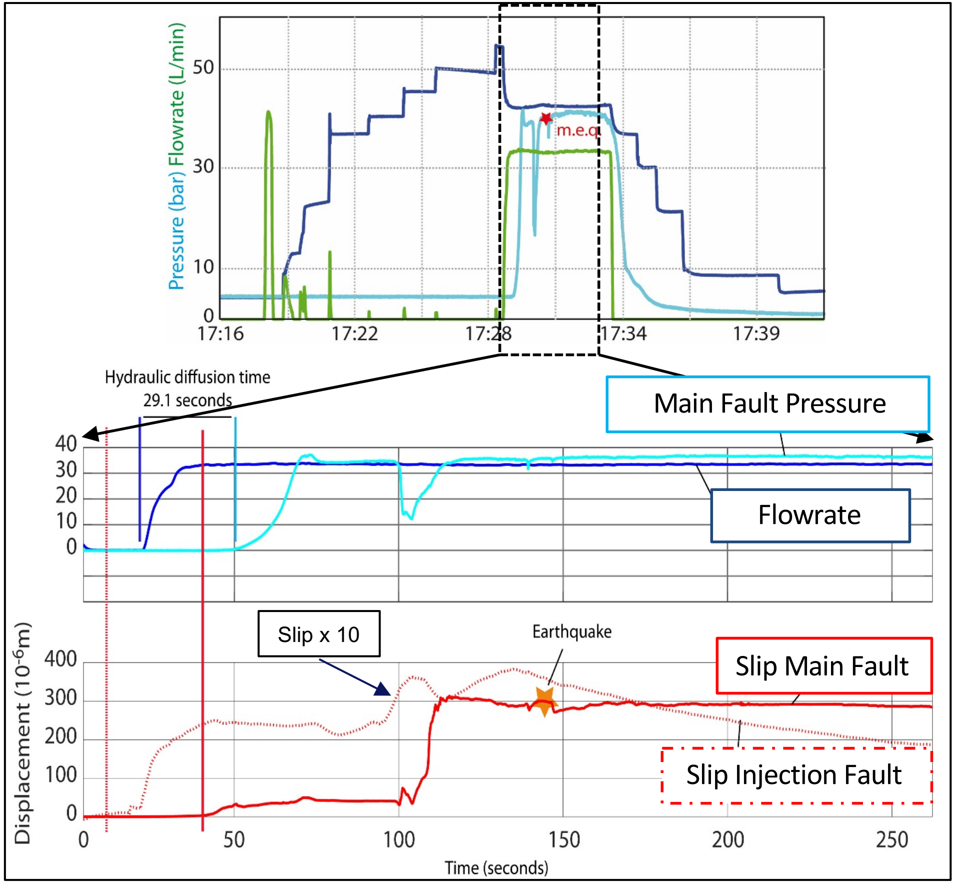
Breakthrough Event

Fault Reactivation Causes Strong Permeability Increase

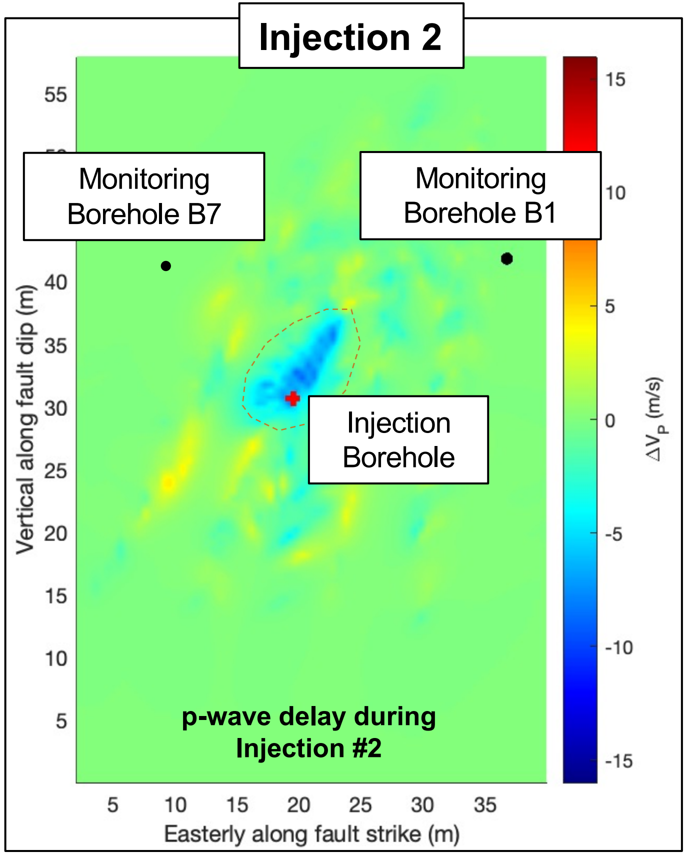


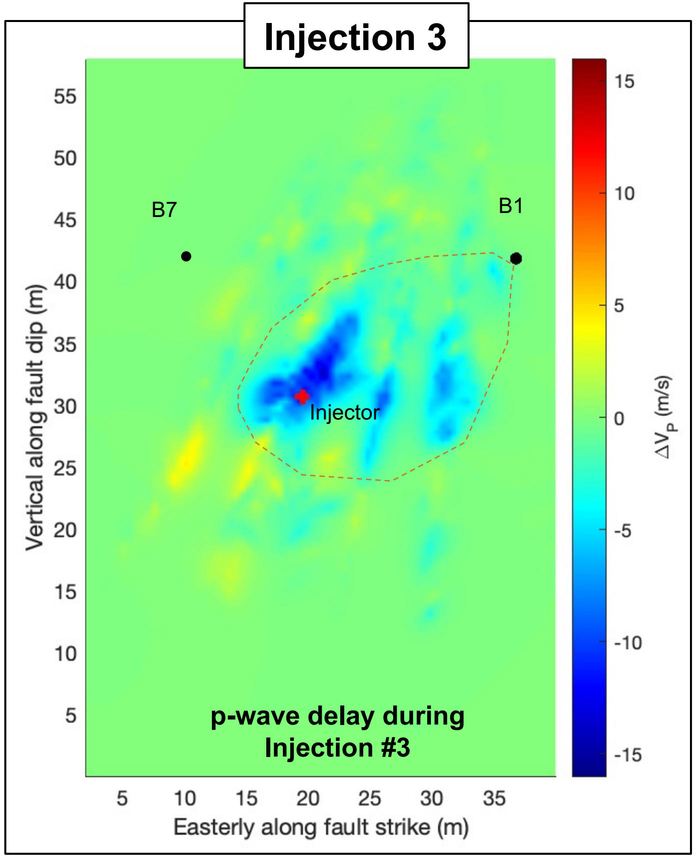
Complex Coupling Between Displacement, Pressure, and Flow





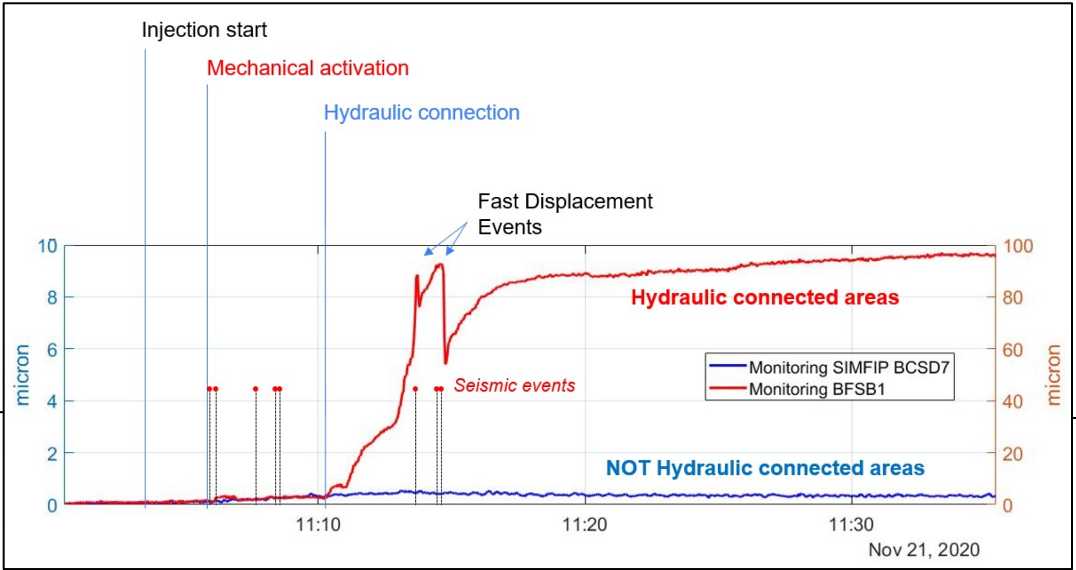
From Point Measurements to Fault Patch Monitoring via CASSM



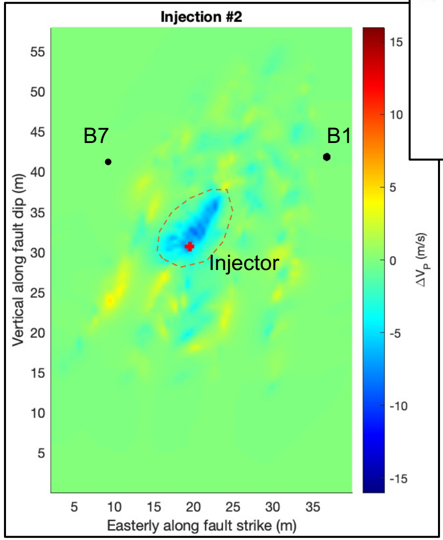


CASSM = Continuous Active Seismic Source Monitoring

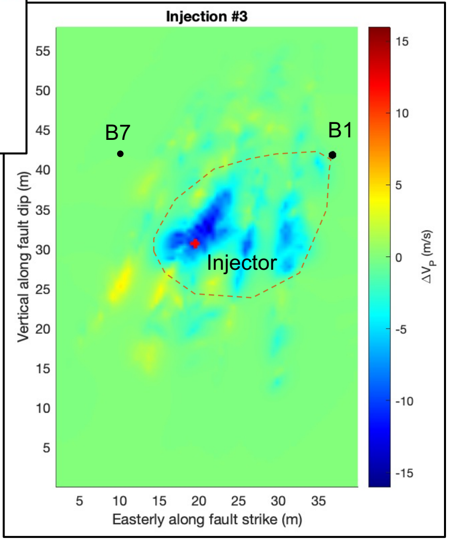
Shear Displacements Before and During Injection



p-wave delay during Injection #2

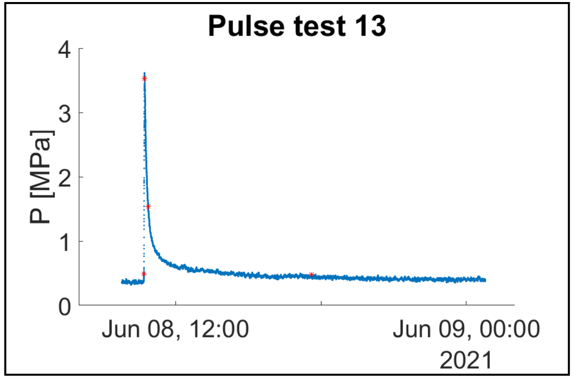


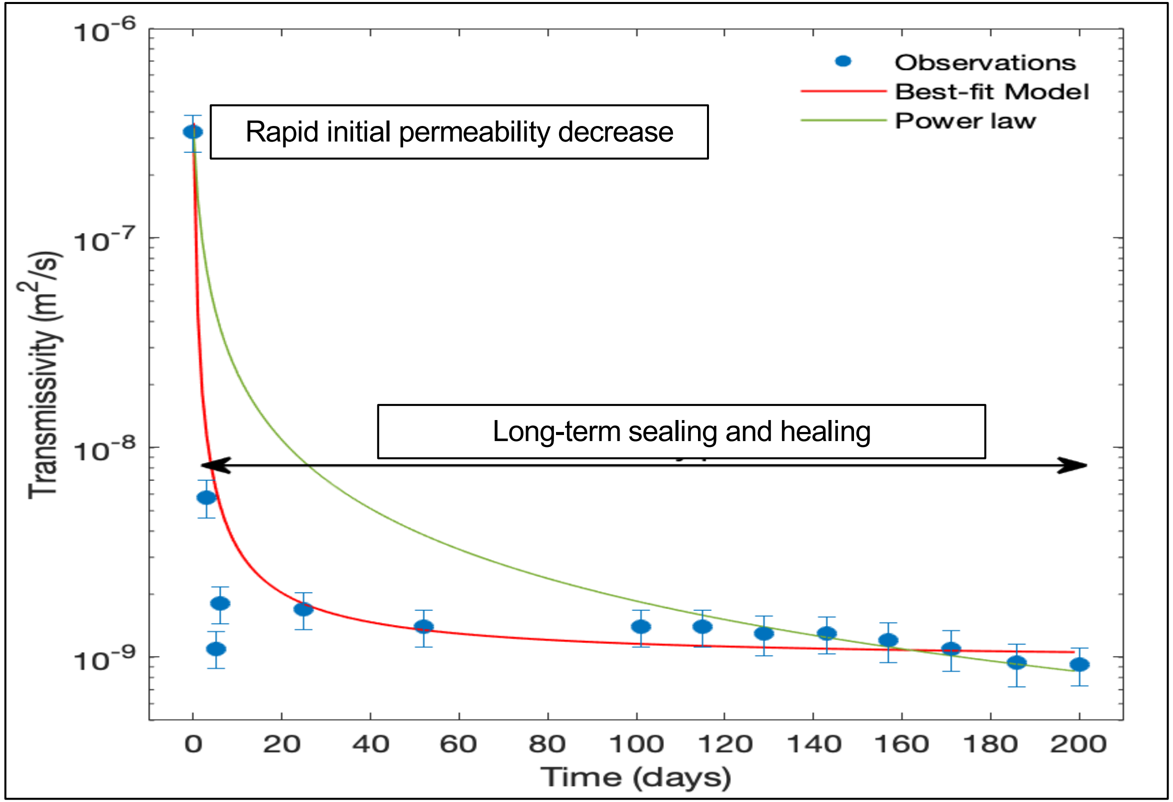
p-wave delay during Injection #3



CASSM Plus SIMFIP Confirm That Slip Front Precedes Fluid Propagation which in turn triggers further fault opening and flow in the fault

Long-Term Fault Behavior (Ongoing)





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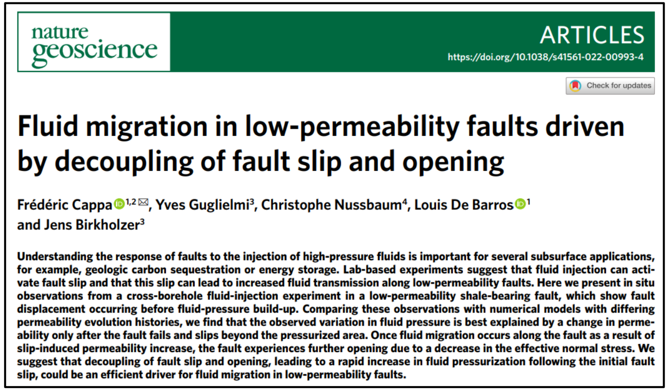
Key Findings from Fault Reactivation Studies in Argillites

- Fault reactivation causes a large permeability increase in the fault zone:
  - Fluid migrates in the initially very low permeability fault only AFTER the fault fails locally.
  - Slip signal precedes fluid arrival and creates some permeability in the slip-dilatant rupture patch.
  - The patch opens further due to a large effective normal stress decrease.
  - This allows more fluid leakage to occur.
- Slip is largely aseismic thus hard to observe by micro-seismic monitoring
- As injection stops, we observe a rapid permeability drop followed by slow sealing and possibly healing of the fault



nature geoscience

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

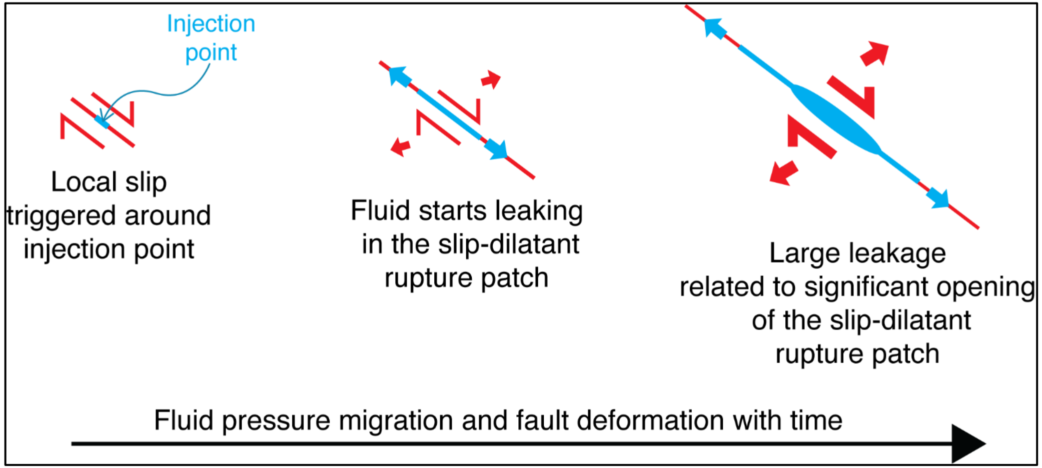
Check for updates

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.

Cappa et al., 2022



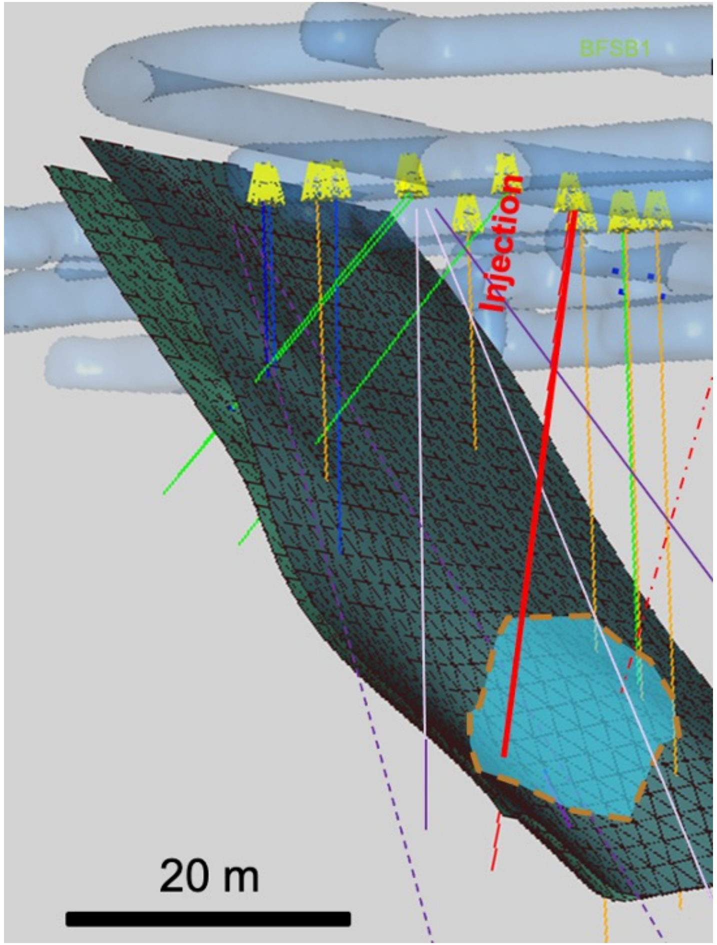
Next Steps: Fault Behavior at Elevated Temperature (Starting Soon)

Thermal Fault Slip Feasibility Experiment:

- Deploy a heat source into a single hole located outside the Main Fault in the same testbed
- Heat to about 80°C and passively monitor fault THM response using already deployed instruments
- Conduct fully coupled THM numerical modeling and use feasibility study results to design larger-scale dedicated THM experiment

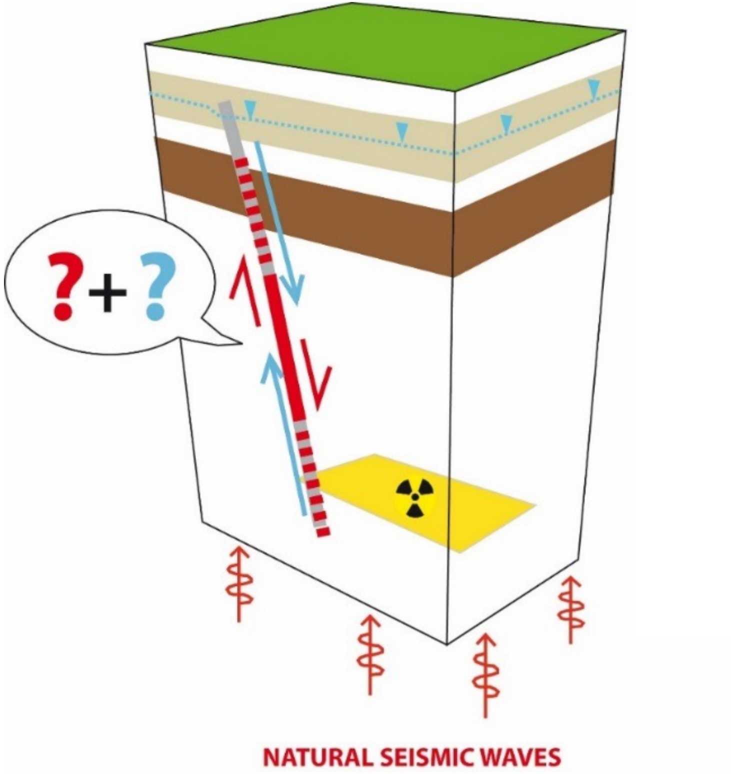
Objective:

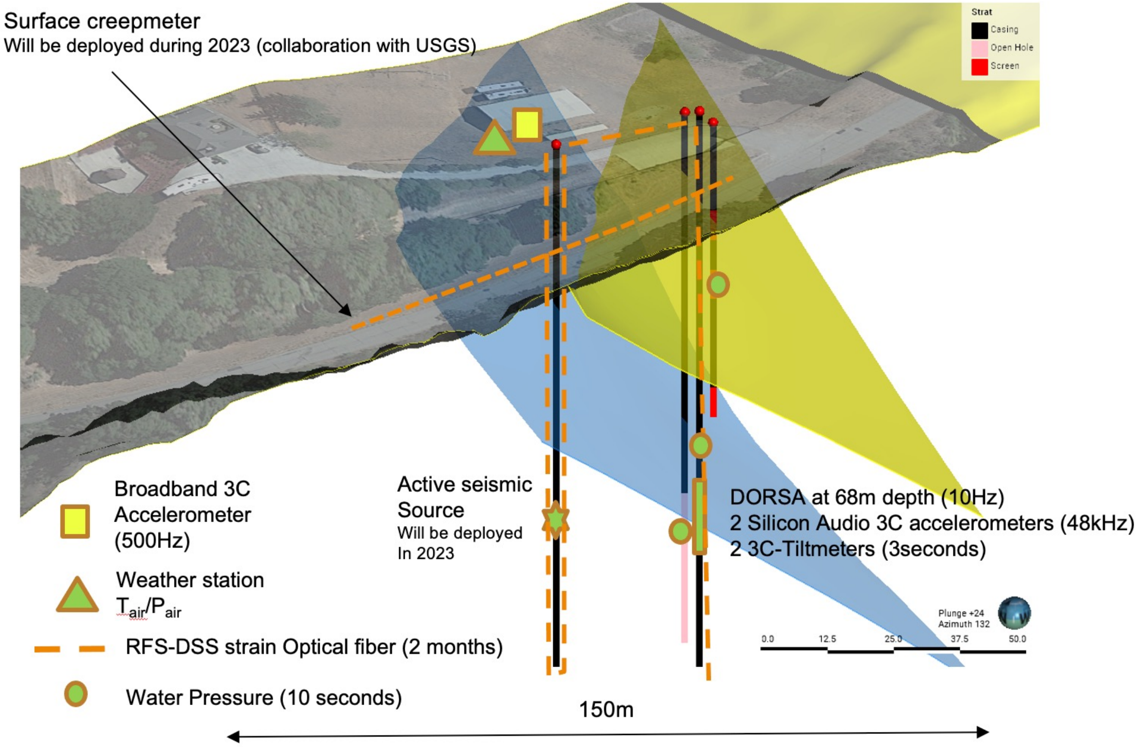
- Effects of injecting non-isothermal fluids on fault reactivation and permeability evolution
- More realistic experimental conditions and driving forces



A Testbed to Probe Effects of Distant Earthquakes on Barrier Integrity

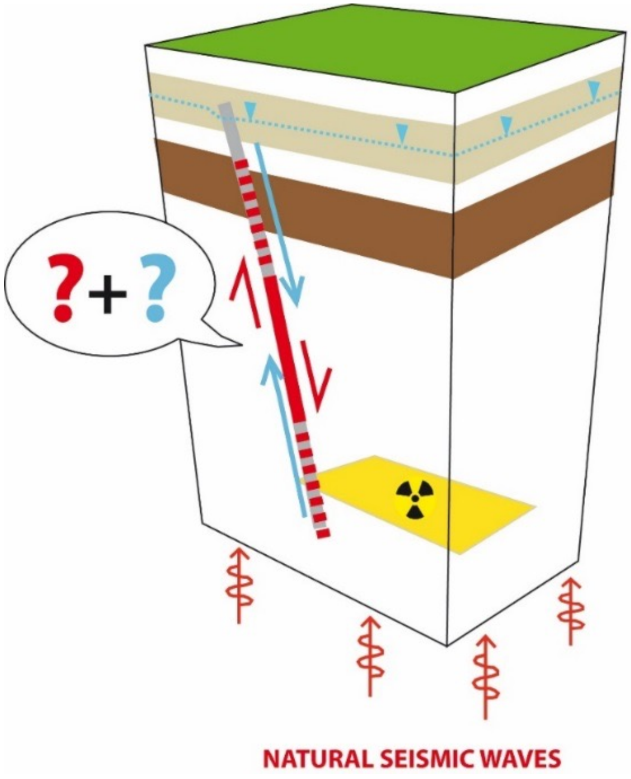
A fault testbed nearby the major San Andreas Fault in California was established & instrumented in 2022. The site features 3-D displacement borehole sensors across the faults together with other long term monitoring tools.

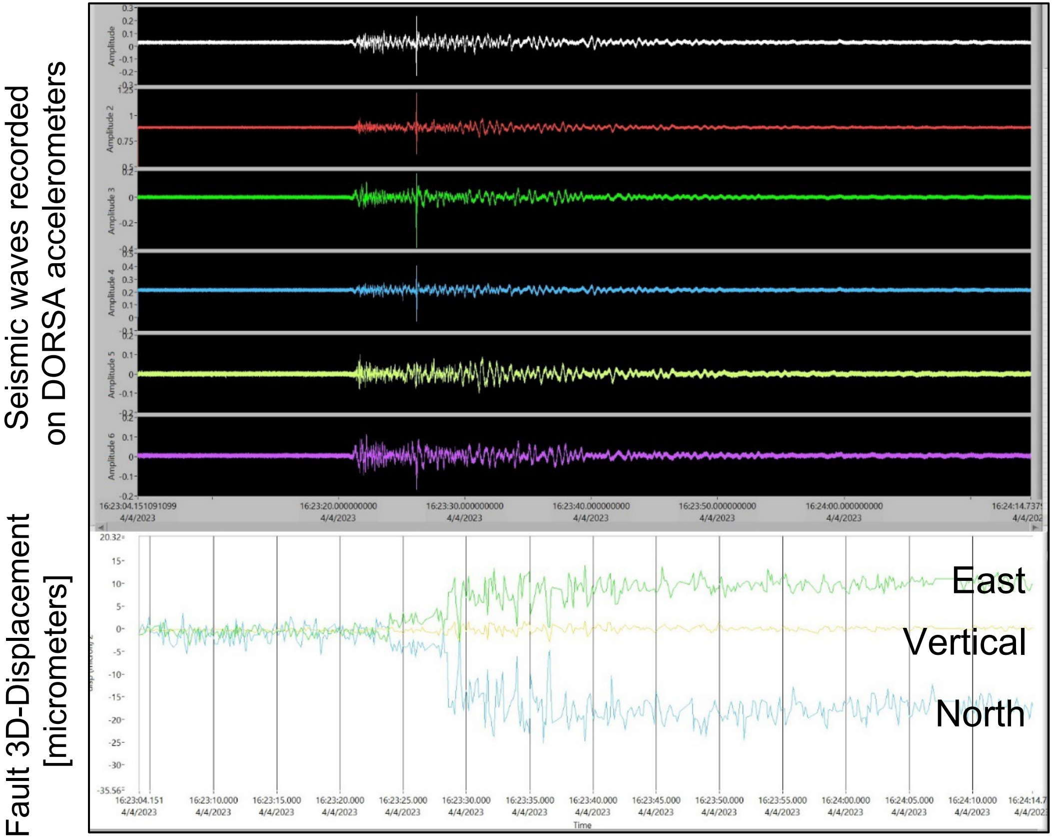




Breaking News....Displacement Induced by Distant M_W 4.4 Earthquake

In April 2023, a Mw 4.4 earthquake occurred about 50 km away from the testbed site. The SIMFIP displacement sensor successfully recorded small fault displacements associated with this distant seismic event.





Thank you

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