Induced Seismicity and CCS at Scale: Understanding Caprock Integrity Impacts Based on Mesoscale Experiments

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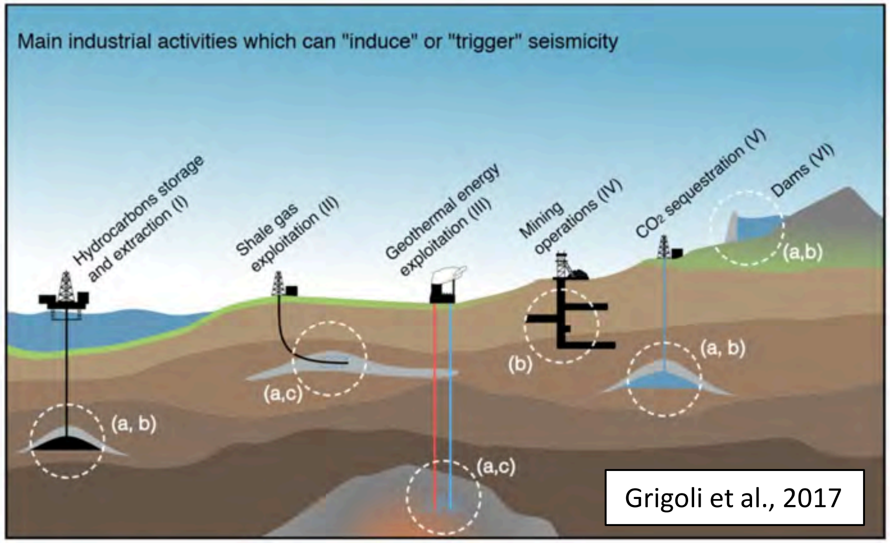
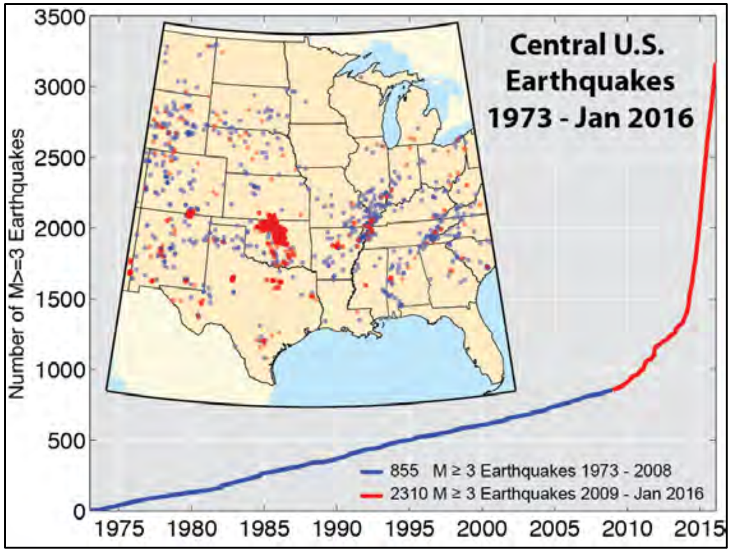
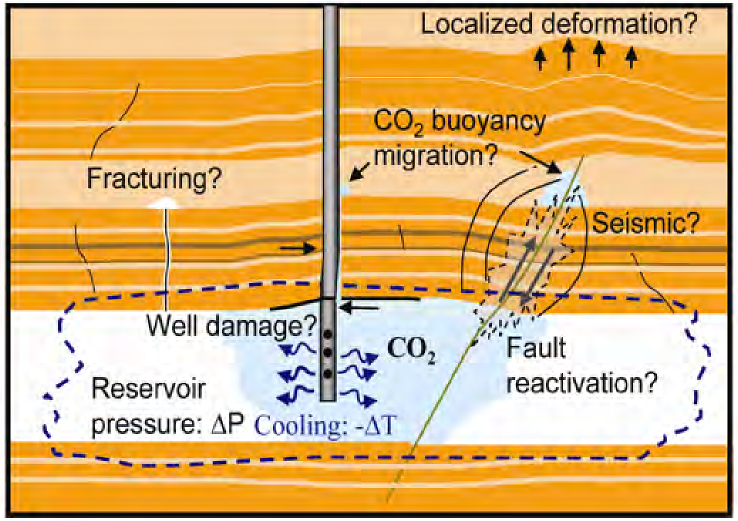
Induced Seismicity Concerns Related to CCS at Scale



Wastewater injection triggers strong earthquakes in basement rocks

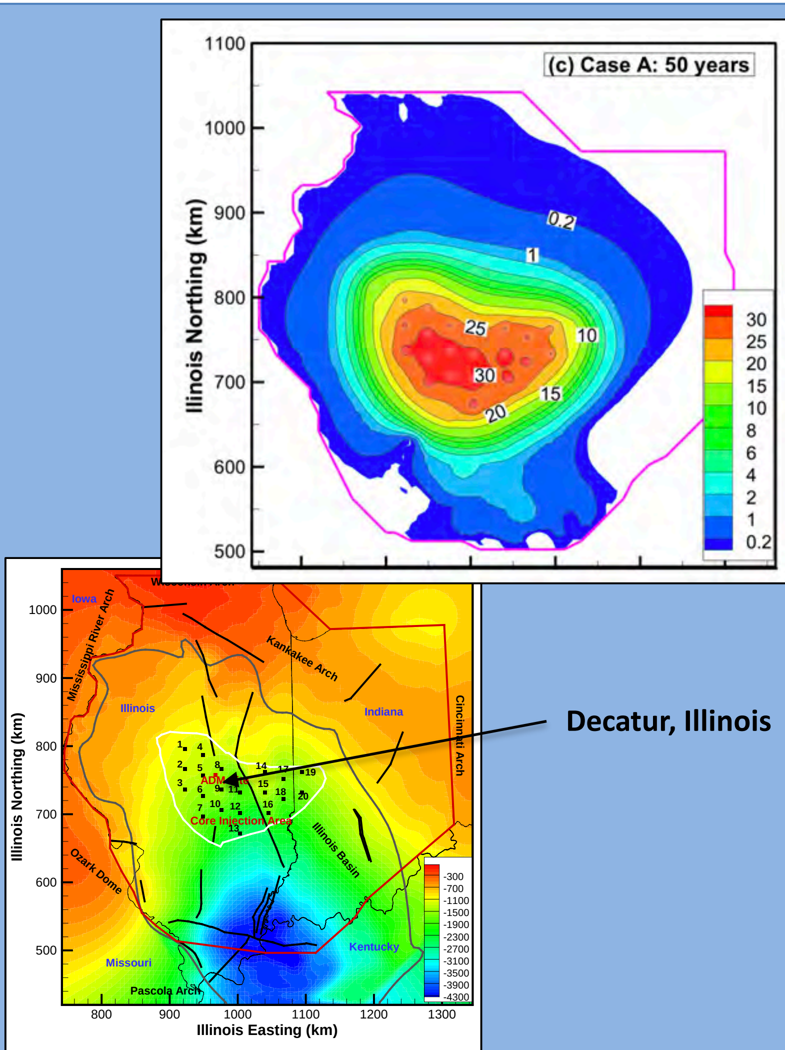


Seal integrity issues may be expected from large-scale CCS, generating leakage pathways for buoyant fluids



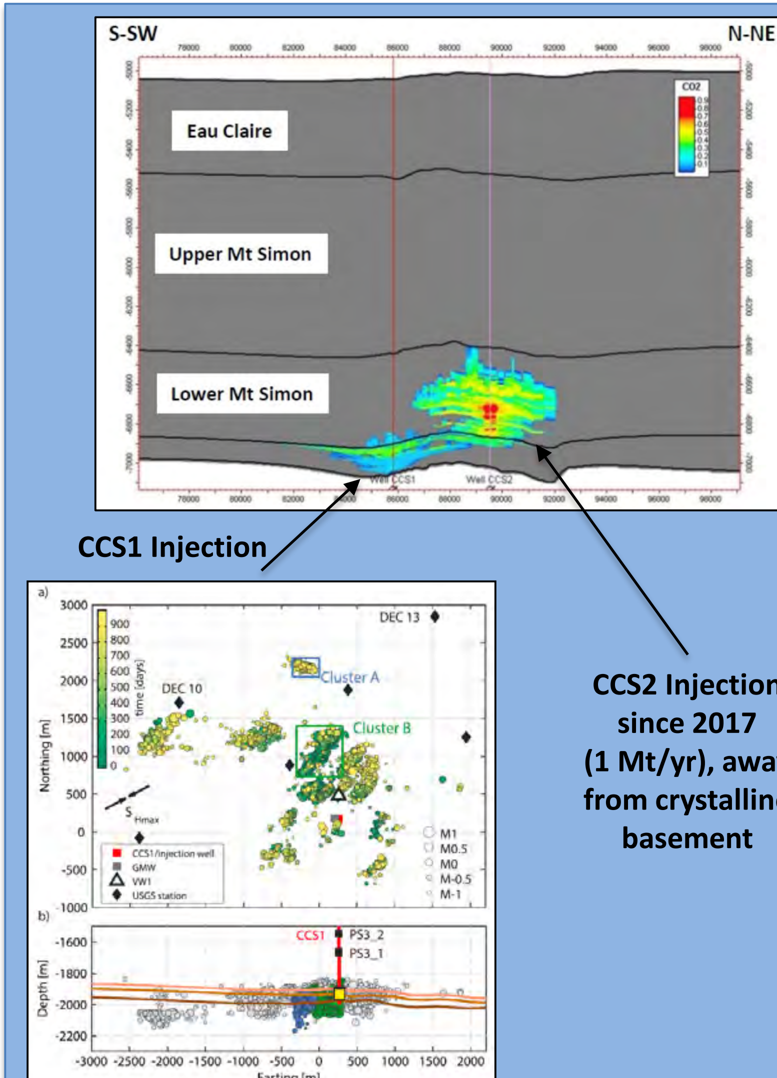
CCS at Scale: Regional and Local Impacts Assessments

Prediction of Regional Pressure Distribution for 100 Mt/yr CO_2 Injection into Mt Simon Formation



(Birkholzer and Zhou, 2009, IJGGC)

Mid-Size CCS Project in Mt Simon near Decatur: 1 Mt over 3 years at Well CCS1



(Bauer et al., 2016; Goertz-Allmann et al., 2016)

But What About Caprock Integrity?

PNAS PNAS PNAS

Earthquake triggering and large-scale geologic storage of carbon dioxide

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Despite its enormous cost, large-scale carbon capture and storage (CCS) is considered a viable strategy for significantly reducing CO_2 emissions associated with coal-based electrical power generation and other industrial sources of CO_2 [Intergovernmental Panel on Climate Change (2005) IPCC Special Report on Carbon Dioxide Capture and Storage. Prepared by Working Group III of the Intergovernmental Panel on Climate Change, eds Metz B, et al. (Cambridge Univ Press, Cambridge, UK); Szulczewski ML, et al. (2012) *Proc Natl Acad Sci USA* 109:5185–5189]. We argue here that there is a high probability that earthquakes will be triggered by injection of large volumes of CO_2 into the brittle rocks commonly found in continental interiors. Because even small- to moderate-sized earthquakes threaten the seal integrity of CO_2 repositories, in this context, large-scale CCS is a risky, and likely unsuccessful, strategy for significantly reducing greenhouse gas emissions.

carbon sequestration | climate change | triggered earthquakes

The combustion of coal for electrical power generation in the United States generates approximately 2.1 billion metric tons of CO_2 per year, ~36% of all US emissions. In 2011, China generated more than three times that much CO_2 by burning coal for electricity, which accounted for ~80% of its total emissions. (According to the Energy Information Agency of the US Department of Energy, total CO_2 emissions in China were 8.38 billion metric tonnes in 2011, with 6.95 billion tons from

corded intraplate earthquakes in south and east Asia (4). The seismicity catalogs are complete to magnitude (M) 3. The occurrence of these earthquakes means that nearly everywhere in continental interiors a subset of the preexisting faults in the crust is potentially active in the current stress field (5, 6). This is sometimes referred to as the *critically stressed* nature of the brittle crust (7). It should also be noted that despite the overall low rate of earthquake occurrence in continental interiors, some of the most devastating earthquakes

March, where the largest earthquake was M 4.7. In the Trinidad/Raton area near the border of Colorado and New Mexico, injection of produced water associated with coalbed methane production seems to have triggered a number of earthquakes, the largest being a M 5.3 event that occurred in August. Earthquakes seem to have been triggered by wastewater injection near Youngstown, Ohio on Christmas Eve and New Year's Eve, the largest of which was M 4.0. Although the risks associated with wastewater injection

(Zoback and Gorelick, 2012)

But What About Caprock Integrity?

Earthquake triggering and large-scale geologic storage of carbon dioxide

Some Open Questions

- What is the relationship between pressure buildup, fault opening, fault slip, and fluid migration in initially very low-permeability fault planes?
- Under what conditions are leakage pathways generated and what are the underlying mechanisms?
- Are events leading to increased fault permeability associated with observable seismicity?

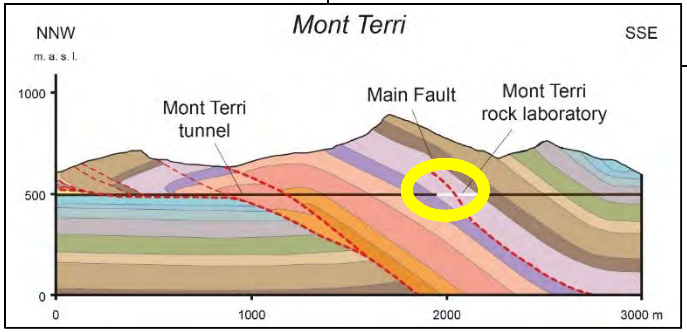
Mesoscale In Situ Fault Injection Experiments

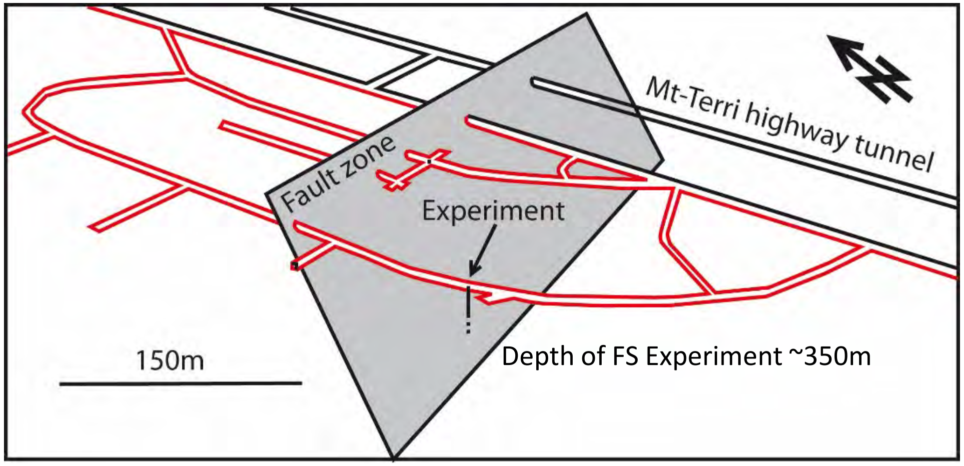
Department of Energy, total CO_2 emissions in China were 8.38 billion metric … that despite the overall low rate of earthquake occurrence in continental interiors, … Christmas Eve and New Year's Eve, the largest of which was M 4.0. Although the …

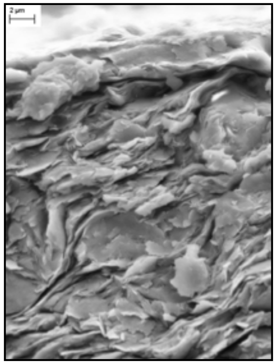
(Zoback and Gorelick, 2012)

A Test Facility for Fault Injection Experiments

A Fault in a Low-Permeability Argillite Layer At Mont Terri



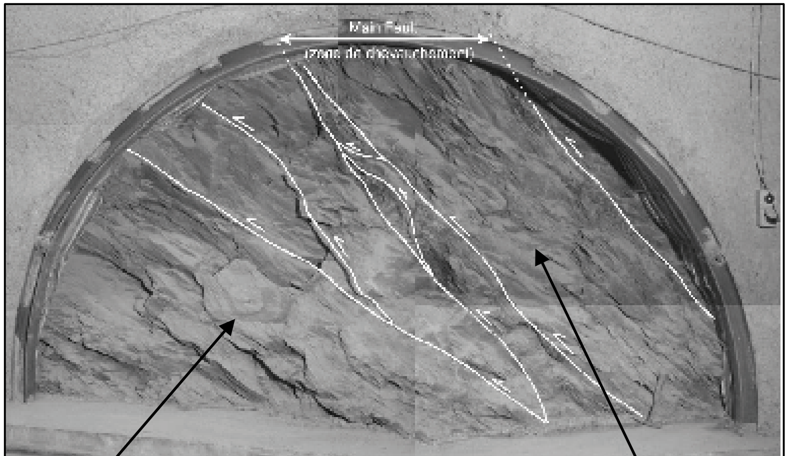




Opalinus Clay

Fault Zone Structure: Advantages of Direct Access

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



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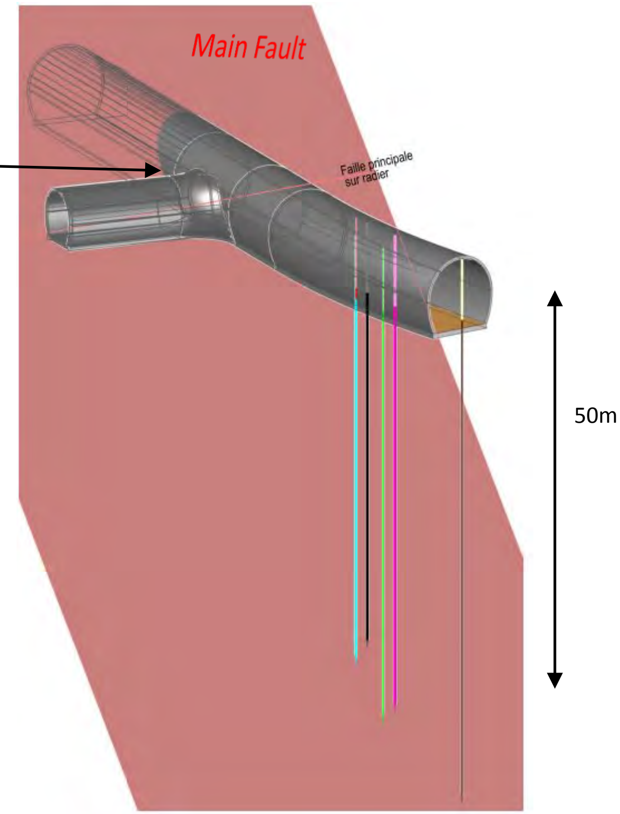
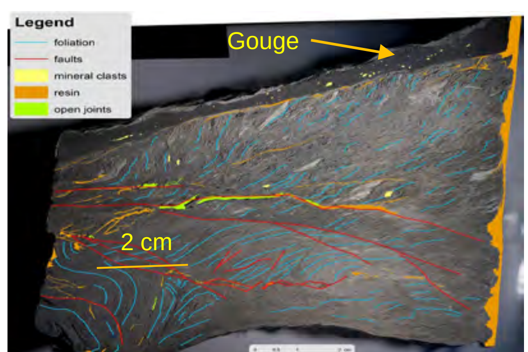
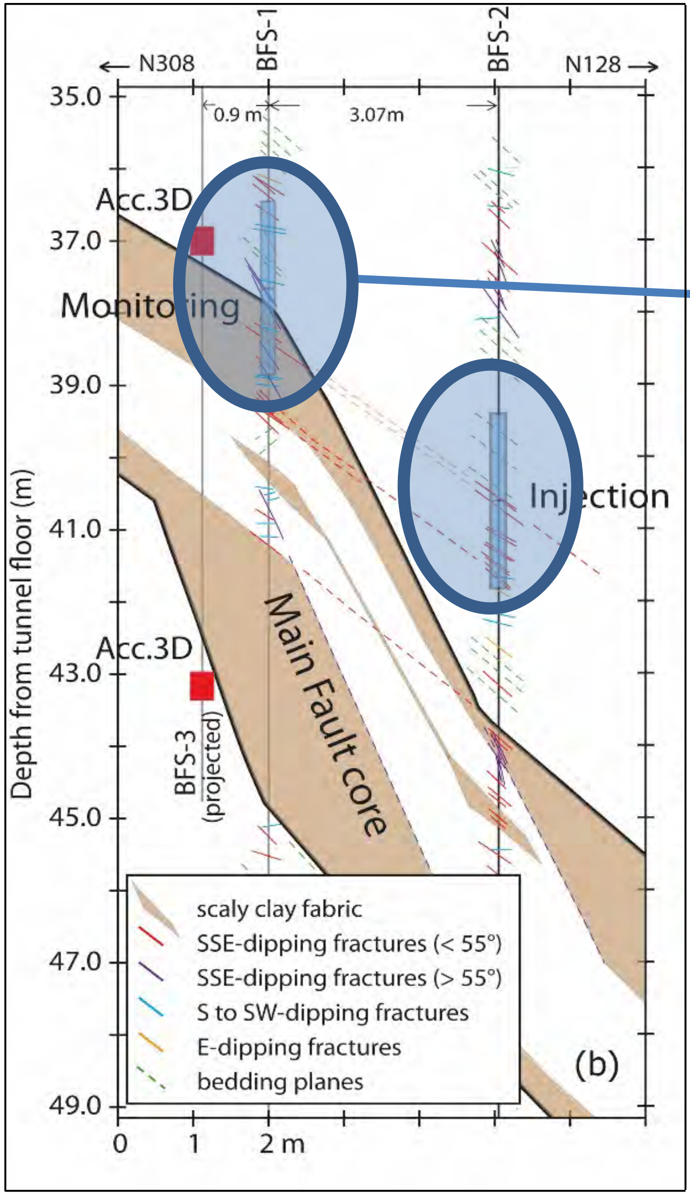


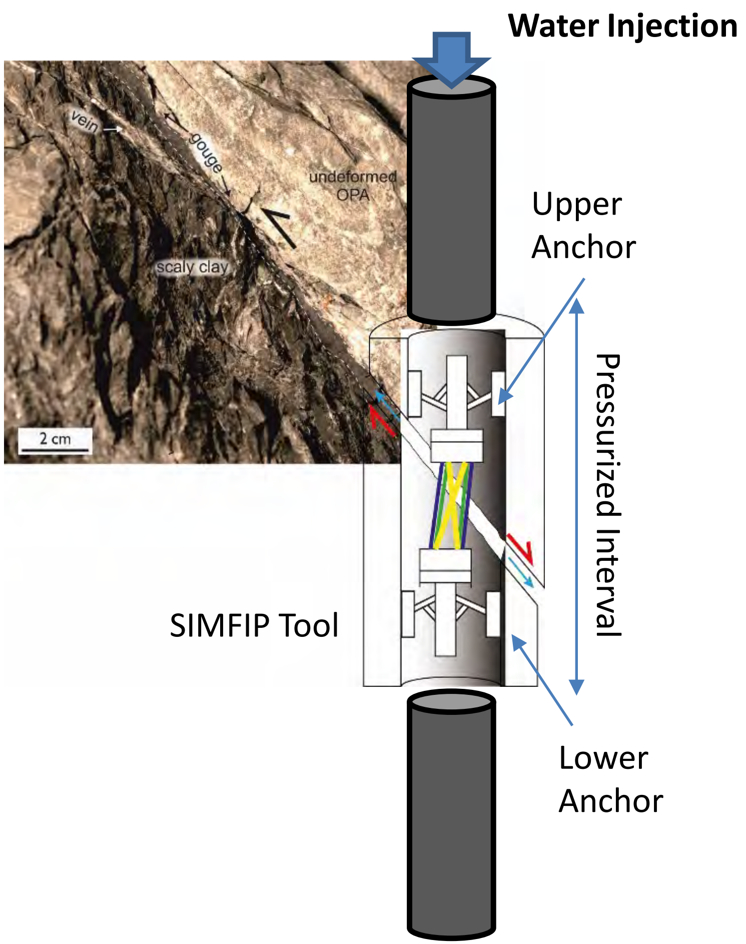
Fault Damage Zone

Fault Core

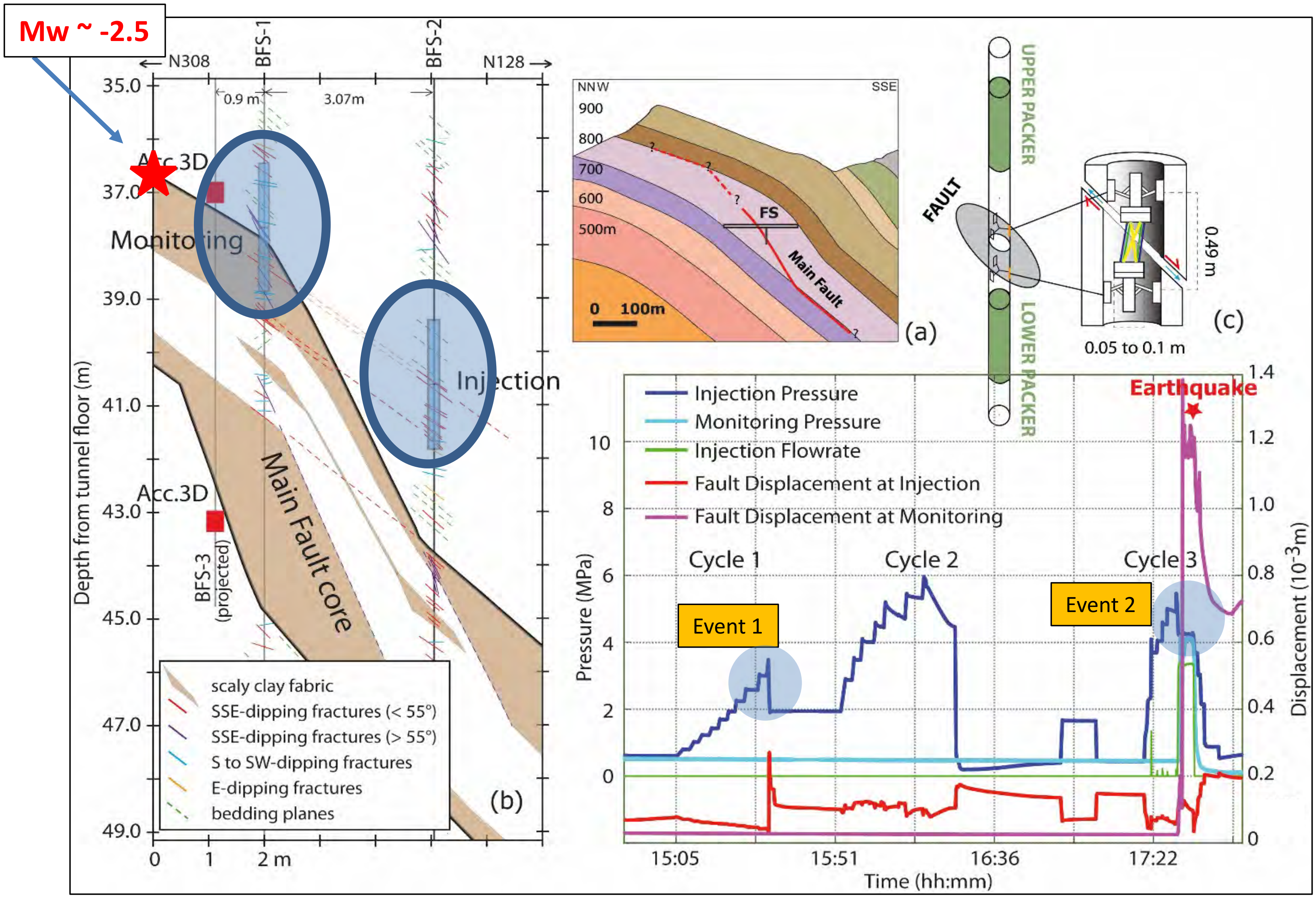


Controlled Fault Activation Experiments



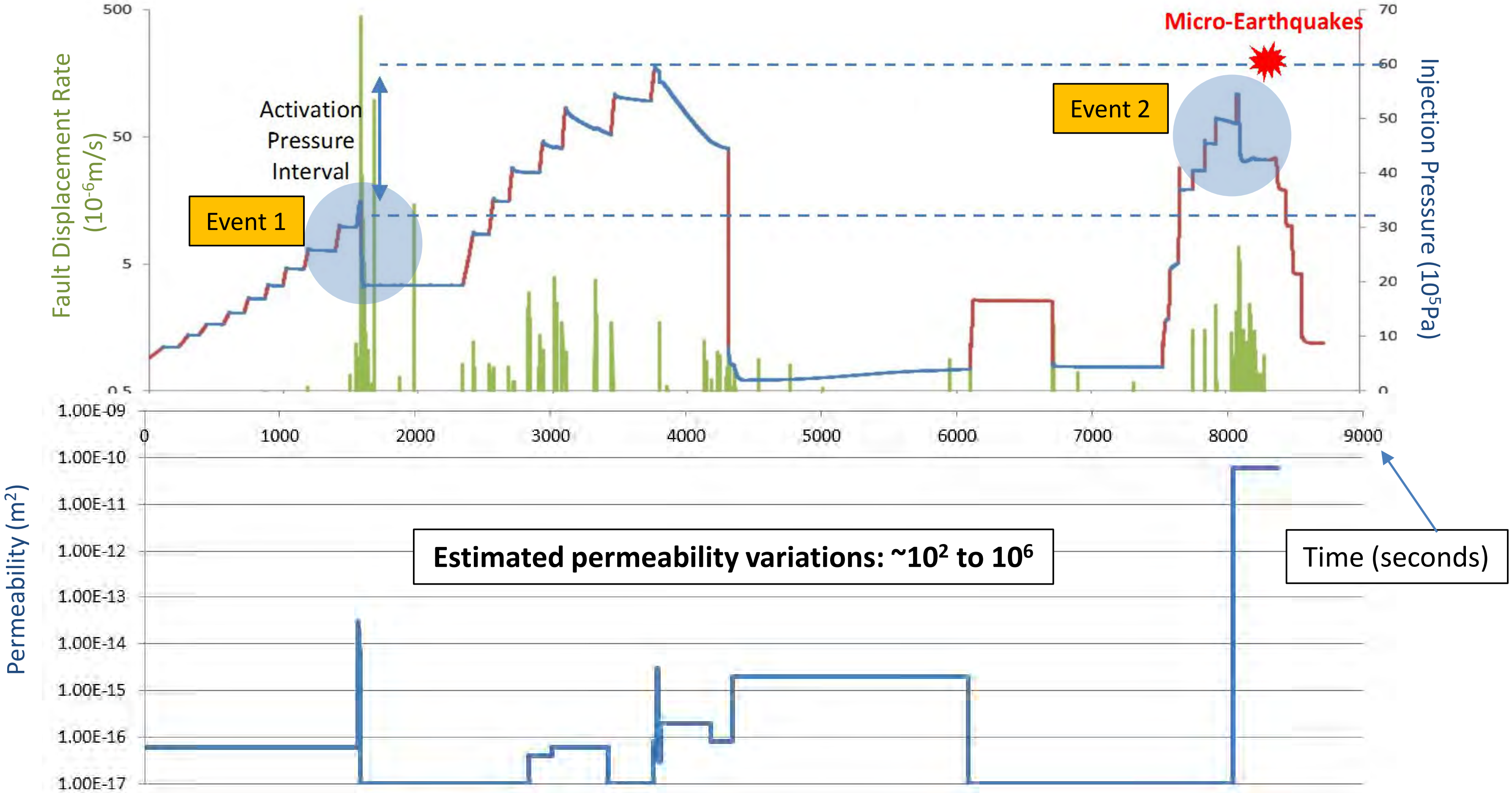


Complex Fault Behavior Induced by Stepwise Pressurization

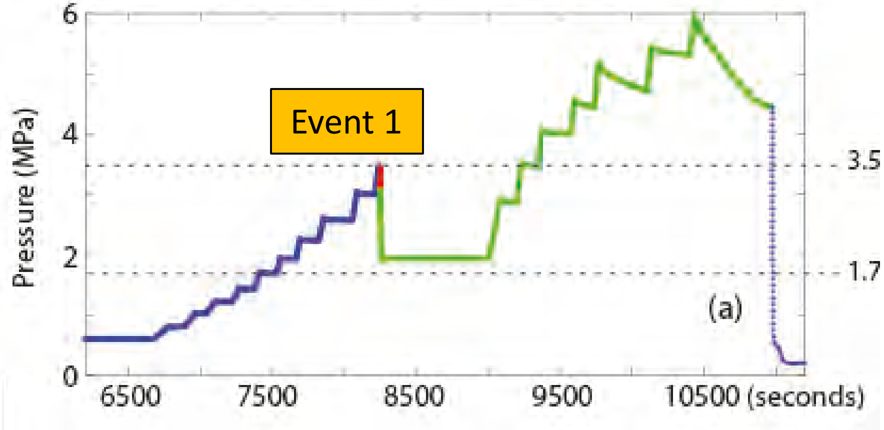


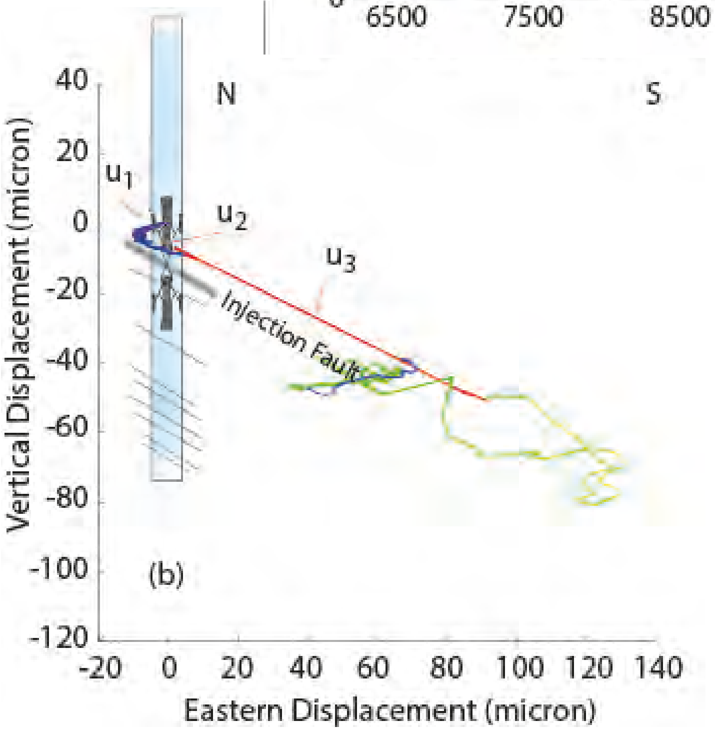
Permeability Evolution Estimated from Pressure Drop

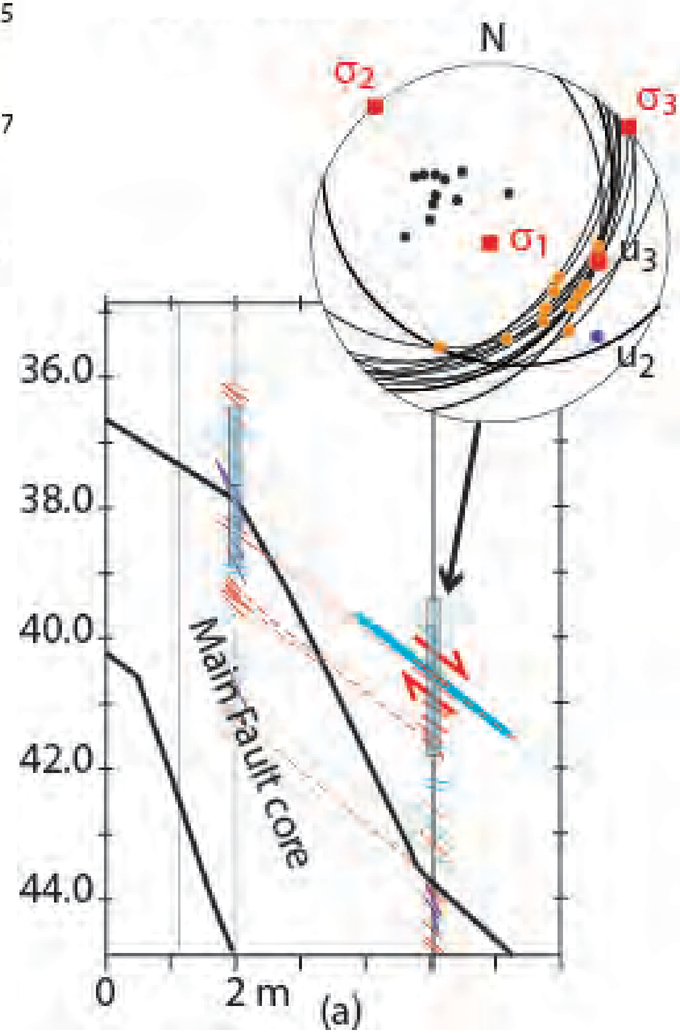
Strong Variations Associated with Pressure and Displacement Rate



Event 1: Shear on a Single Plane with Moderate Patch Size







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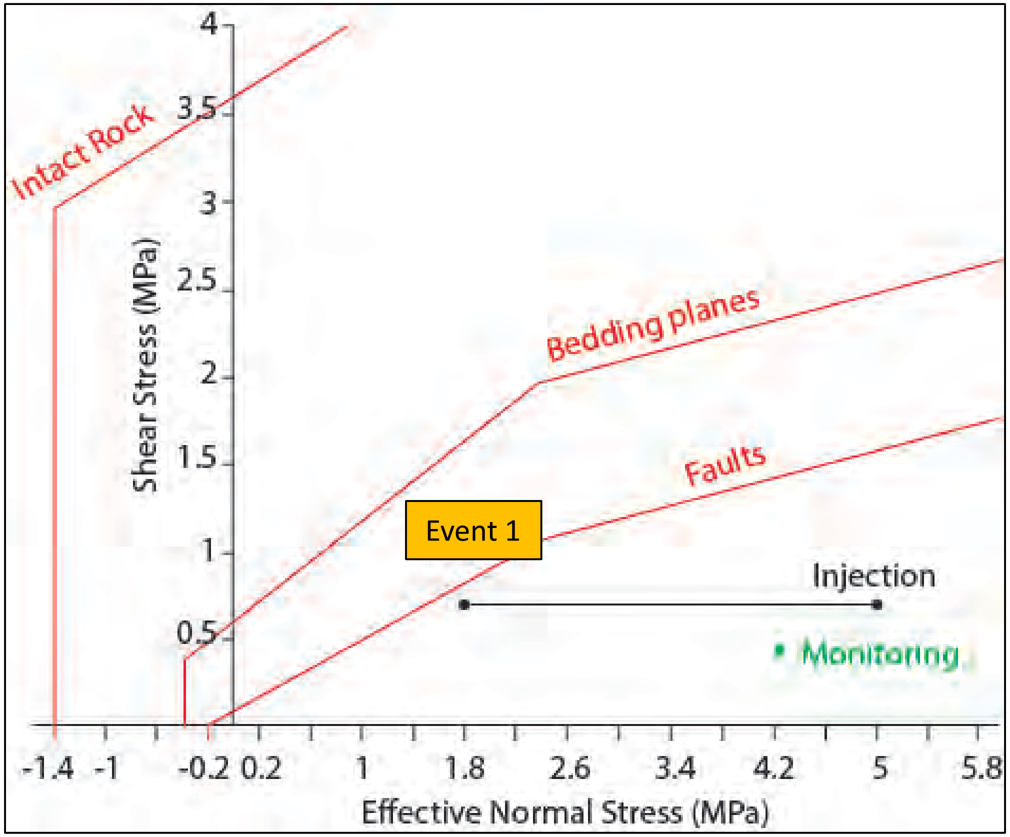
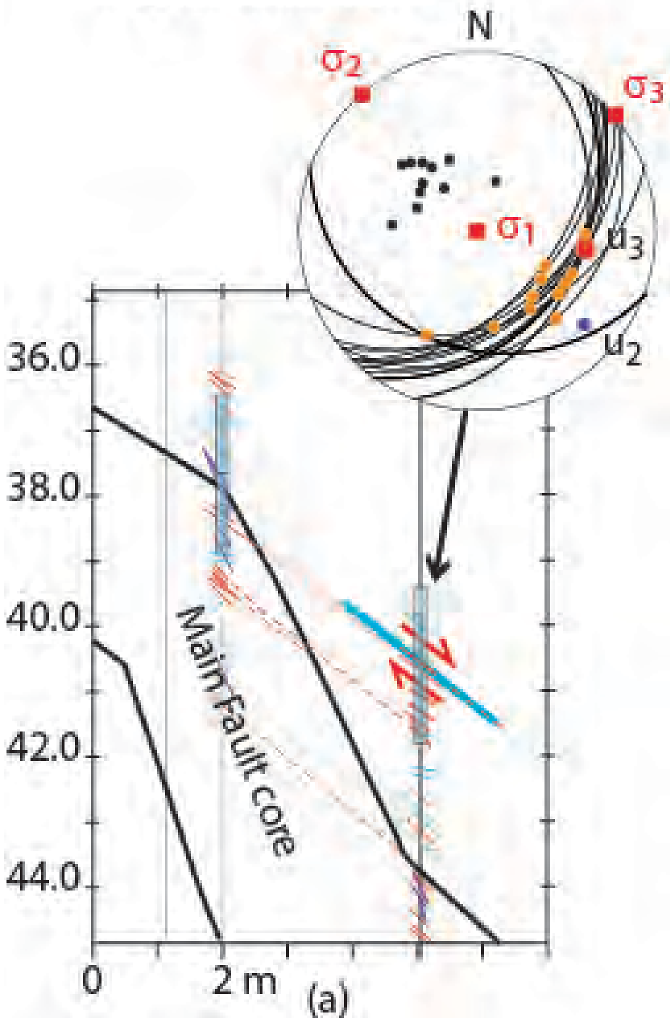
Rupture Initiation at Coulomb Failure





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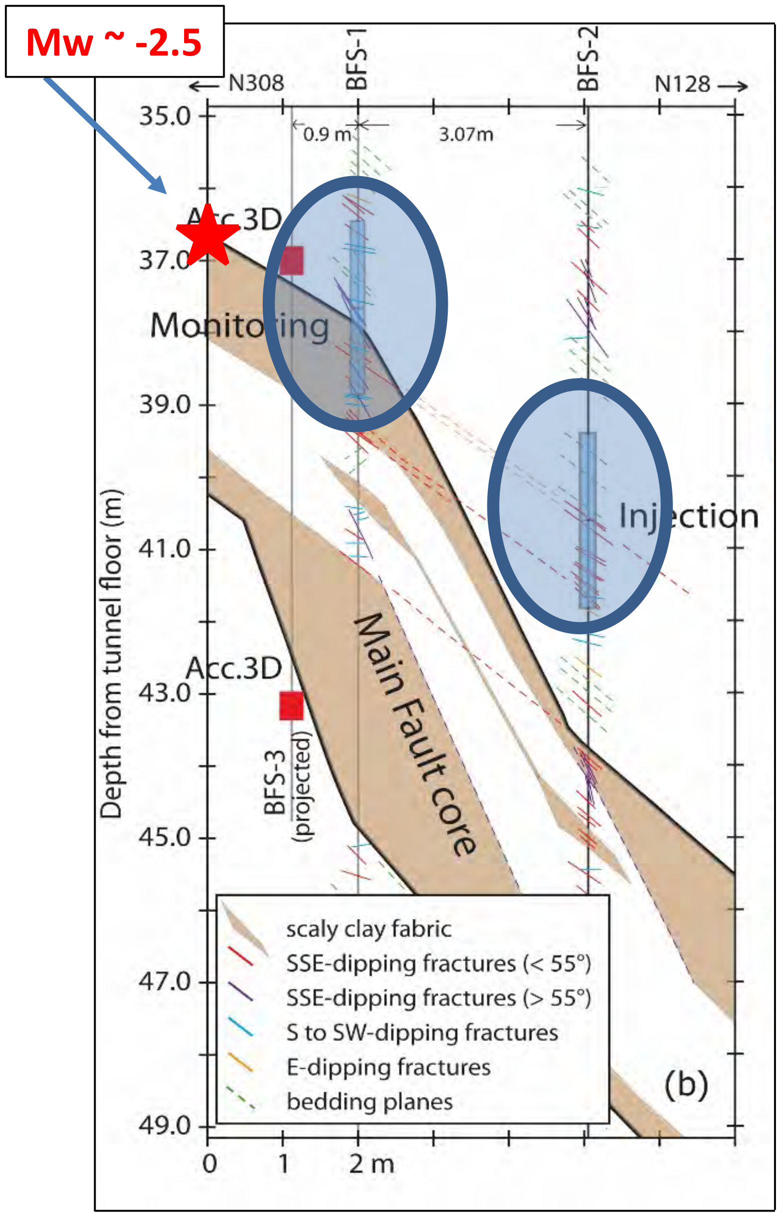
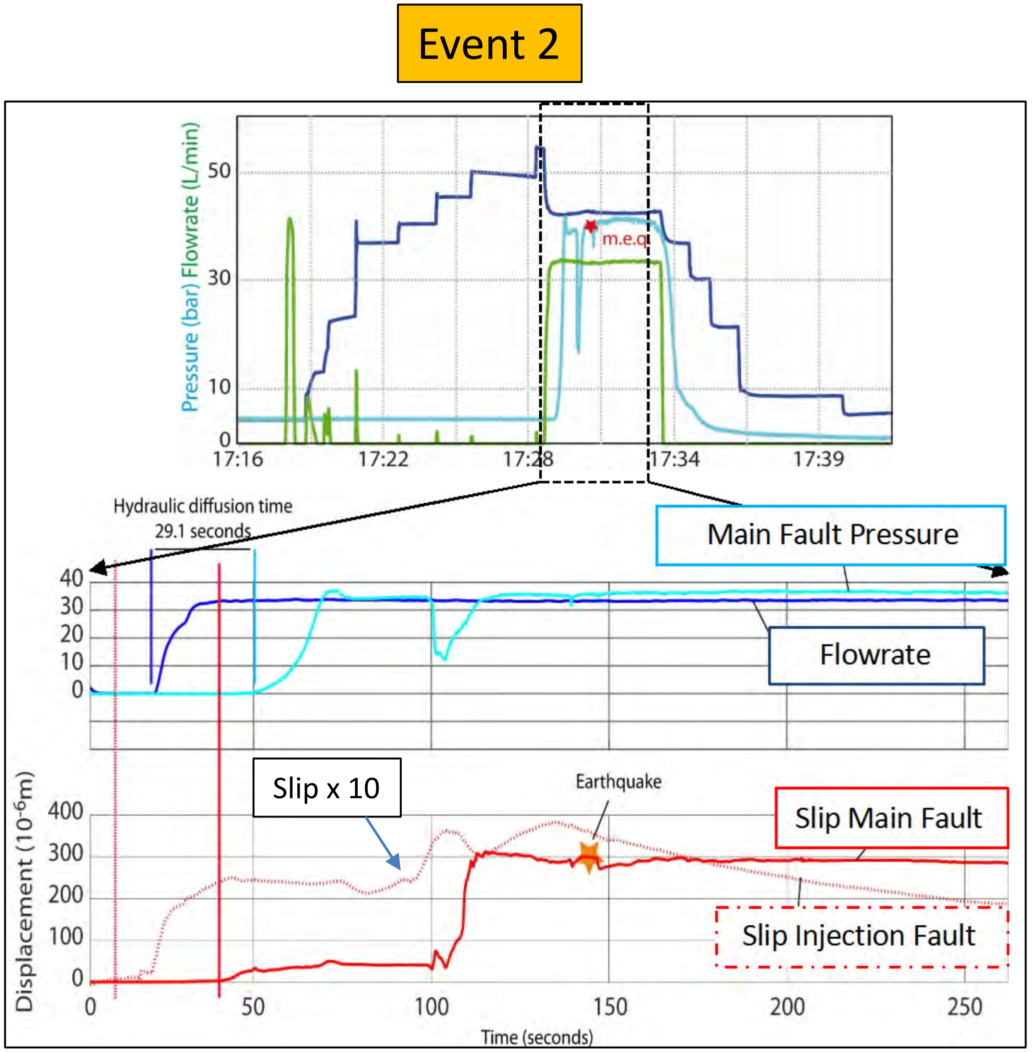
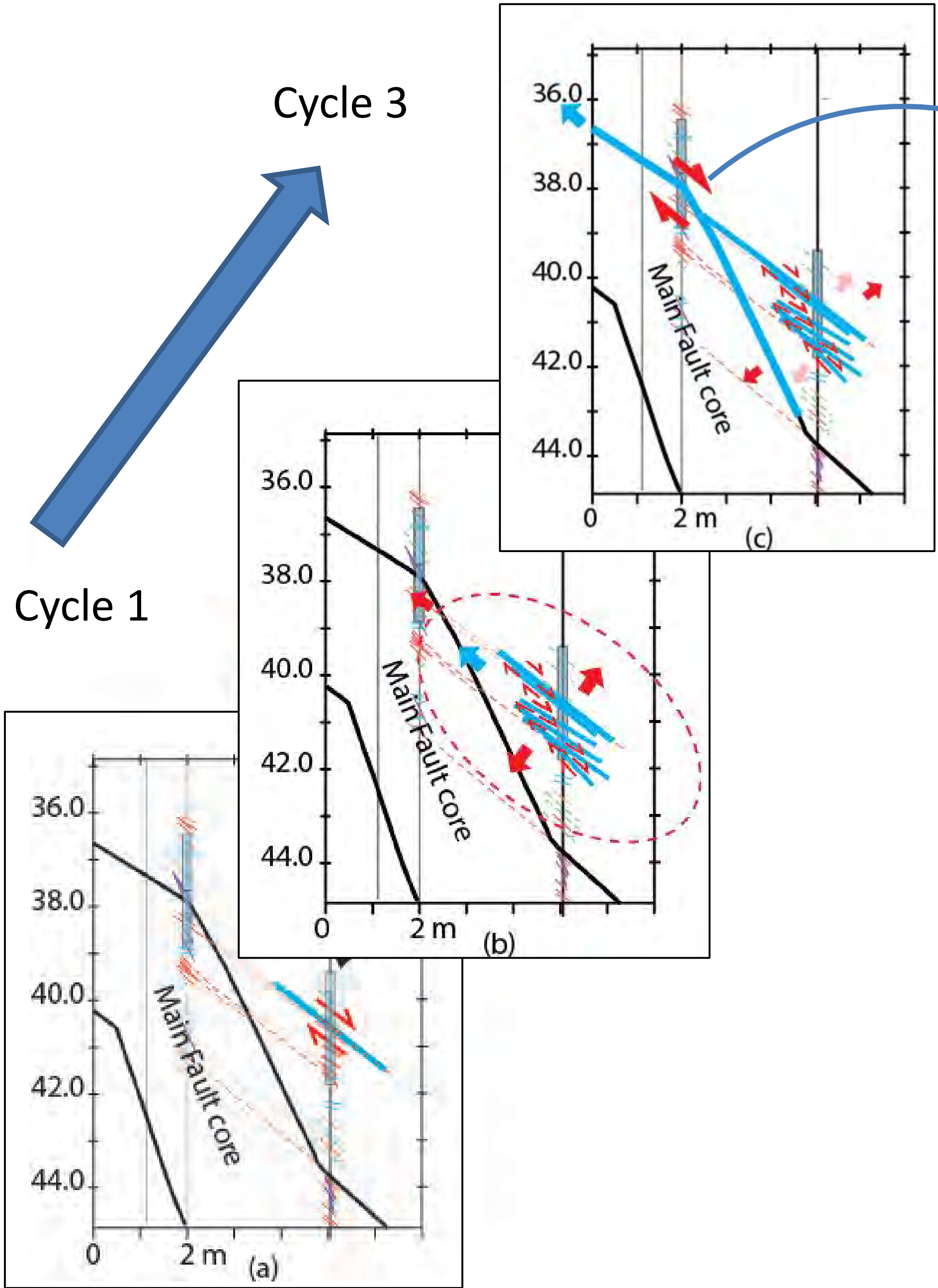
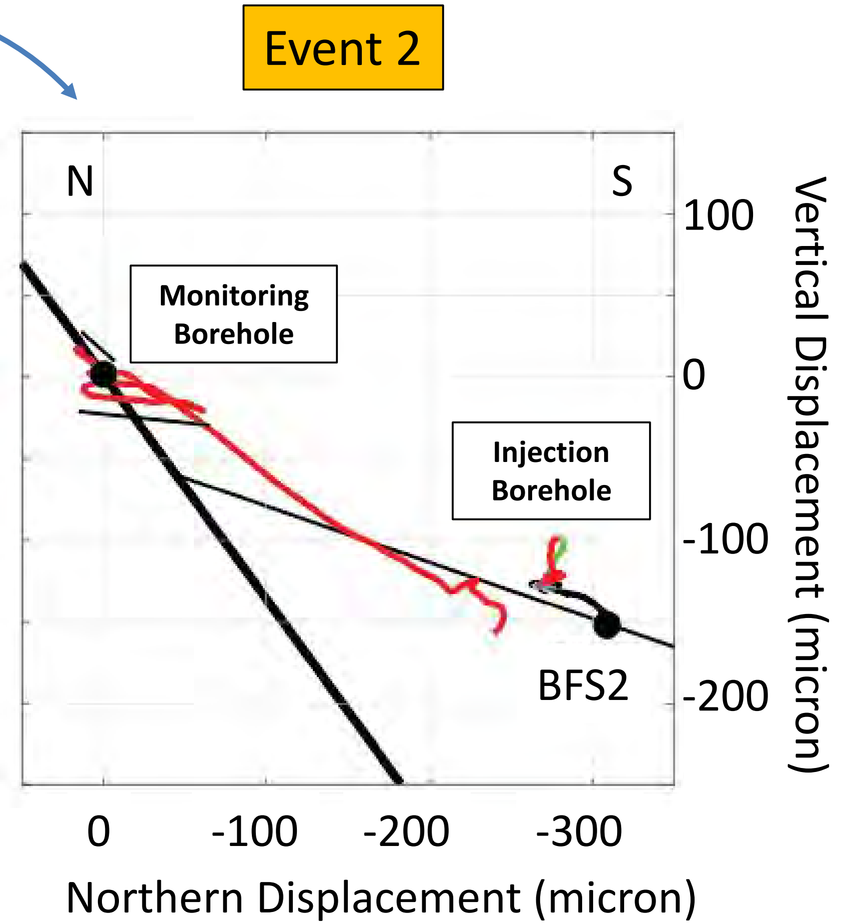
Event 2: Propagation From Secondary Fault to Main Fault



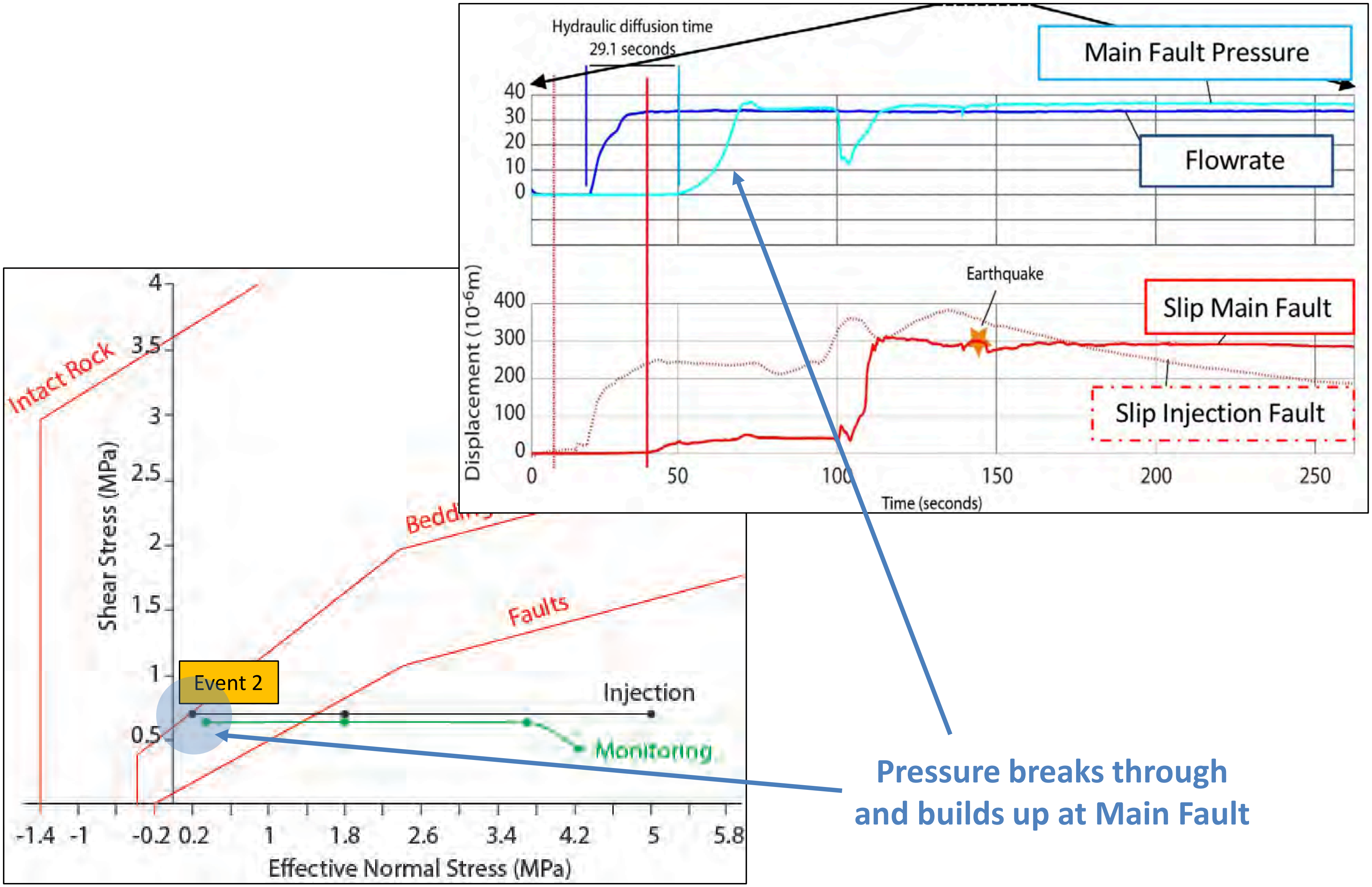


Event 2: Shear on Main Fault Plane



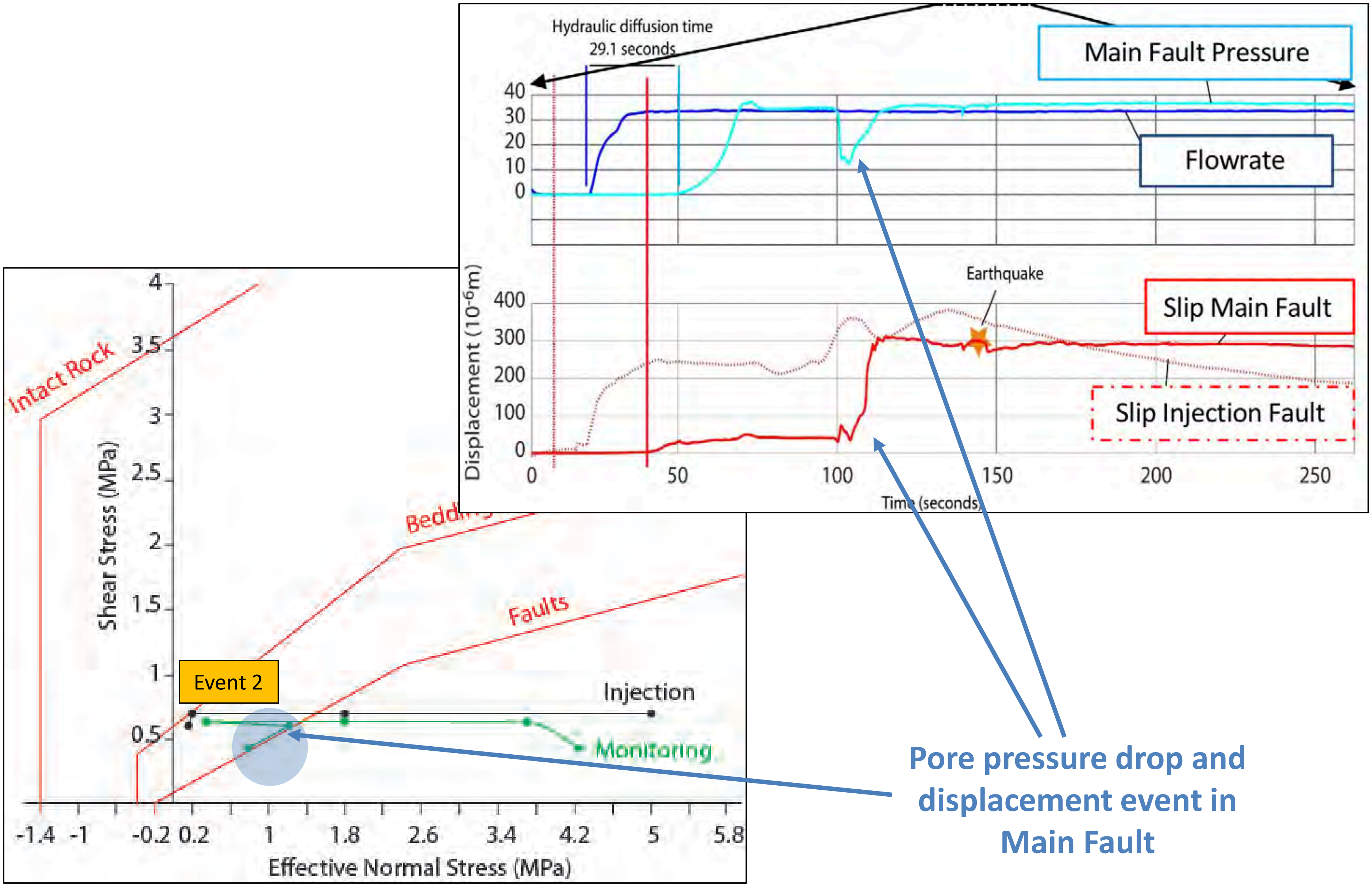


Event 2: Rupture Initiation Above Coulomb Failure Line



Pressure breaks through and builds up at Main Fault

Event 2: Rupture Propagation Along Coulomb Failure Line



Pore pressure drop and displacement event in Main Fault

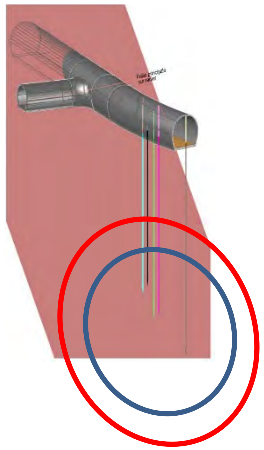
Summary and Key Findings

- Complex transient coupling between fault opening, fault slip, pore pressure, and fluid migration is observed in situ
- Fault permeability increases initially (and locally) due to normal opening, eventually allowing fault slip to occur with shear dilation creating larger permeable path
- Fluid propagation s is associated with mainly aseismic slip, meaning that micro-seismicity is not be a good indicator for seal integrity issues
- Nature of M_w = -2.5 seismic event is currently unclear
- Long-term fault activation and leakage behavior remains uncertain though some post activation creep acceleration was observed

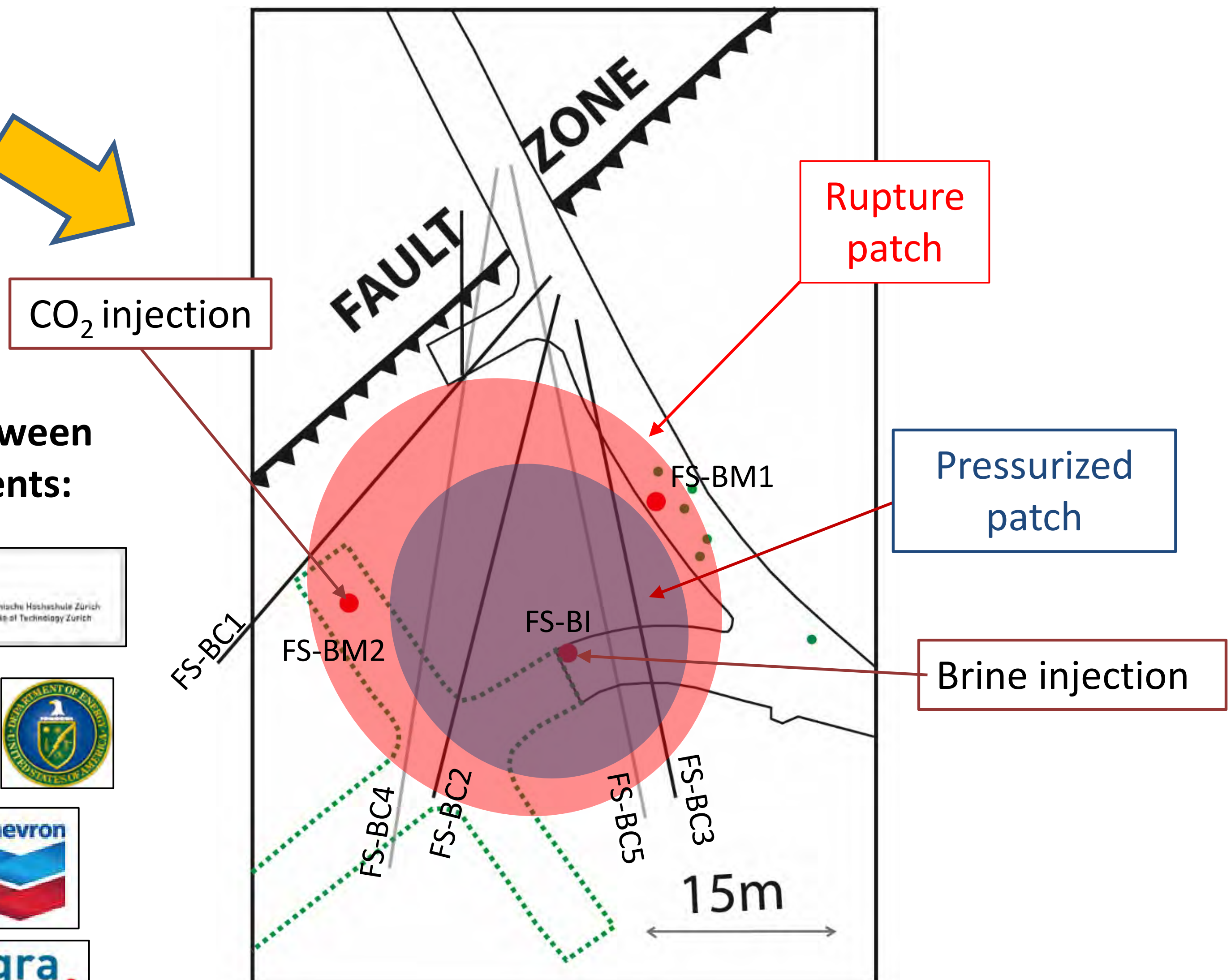
Just starting:

A Follow-up Experiment at Mont Terri with Larger Patch Size, Longer Injection and Post-Injection Cycles, and Additional Monitoring Methods

Future Plans – New Long-Term Fault Slip Experiment



Semi-continuous imaging of **fault activation and CO_2 leakage** in a ruptured fault



Close Collaboration between FS-B and CS-D Experiments:

Mont Terri Project

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

swisstopo

BERKELEY LAB

TOTAL

ENSI

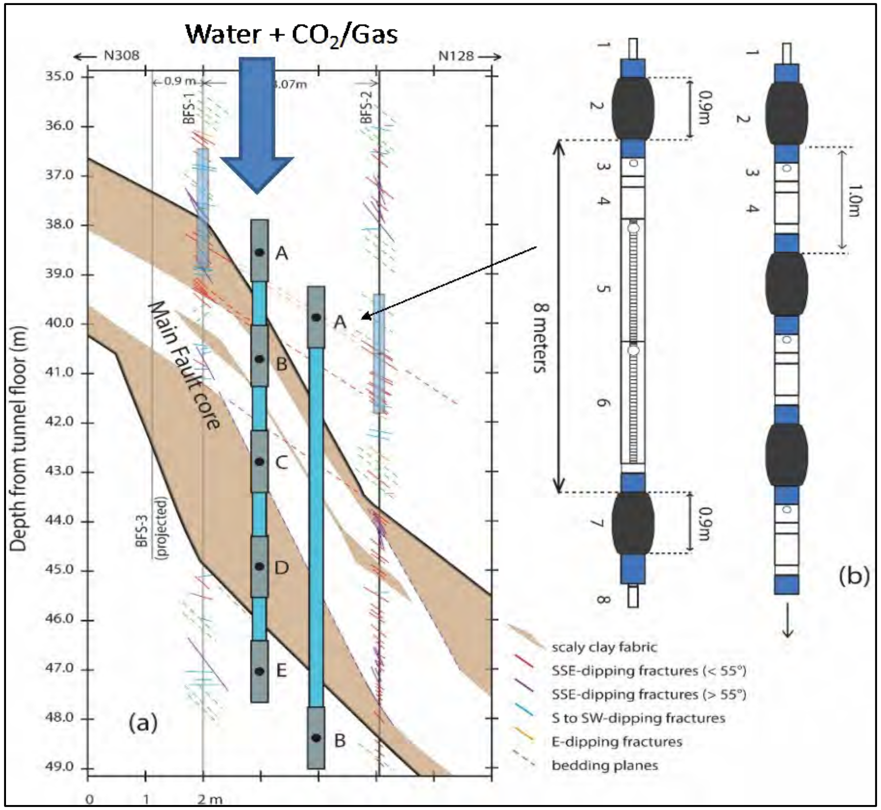
Chevron

BGR Bundesanstalt für Geowissenschaften und Rohstoffe GEOZENTRUM HANNOVER

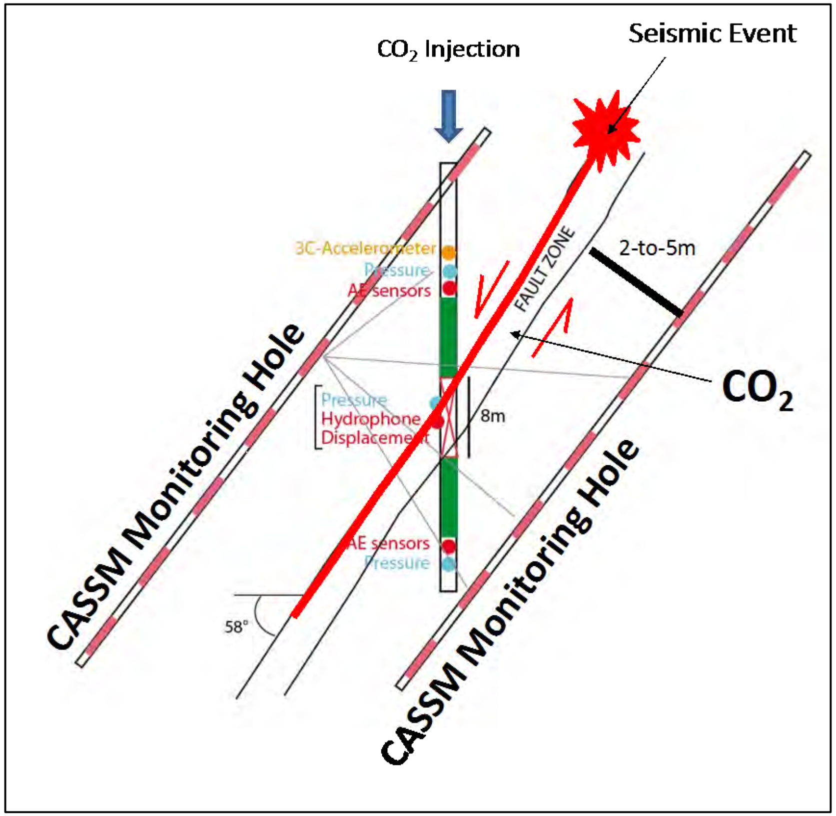
nagra

Advanced Monitoring Methods

Distributed Fault 3D-Displacements, Pressure and Electrical Resistivity Monitoring in Multi-Packer String



Semi-Continuous Seismic Imaging of Activated Fault Patches



We Are Looking for New Team Members

Earth Research Scientist

Bay Area, California, United States

Research/Science   GO-Energy Geosciences   85608

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Berkeley Lab's Earth and Environmental Sciences Area (EESA) has an exciting opening for an Earth Research Scientist to join their Geophysics Department.

The Earth Research Scientist will conduct collaborative multidisciplinary research on basic and applied topics mainly in the field of rock mechanics. The position will require a broad interest in field/experimental strain/stress measurements and in numerical modeling of fully coupled thermo-hydro mechanical and chemical processes in fractures and fault zones.

This role will be working on applications related to geological sequestration of CO_2, geothermal field development and nuclear waste repository site long term integrity. Some fundamental research interests are (i) understanding the effects of fault permeability variations on the growth of aseismic to seismic slip caused by fluid injection, (ii) exploring the effects of remote earthquakes on faults' permeability and (iii) imaging the long term post rupture three-dimensional evolution of eventual fault hydraulic channeling and sealing. In parallel, this profile includes research on borehole instrumentation involving strain measurements and their integration into seismic monitoring networks. The researcher will be strongly involved into the future developments and testing dedicated to in situ probing of hydromechanical perturbations in fault zones using SIMFIP probes developed at LBNL.

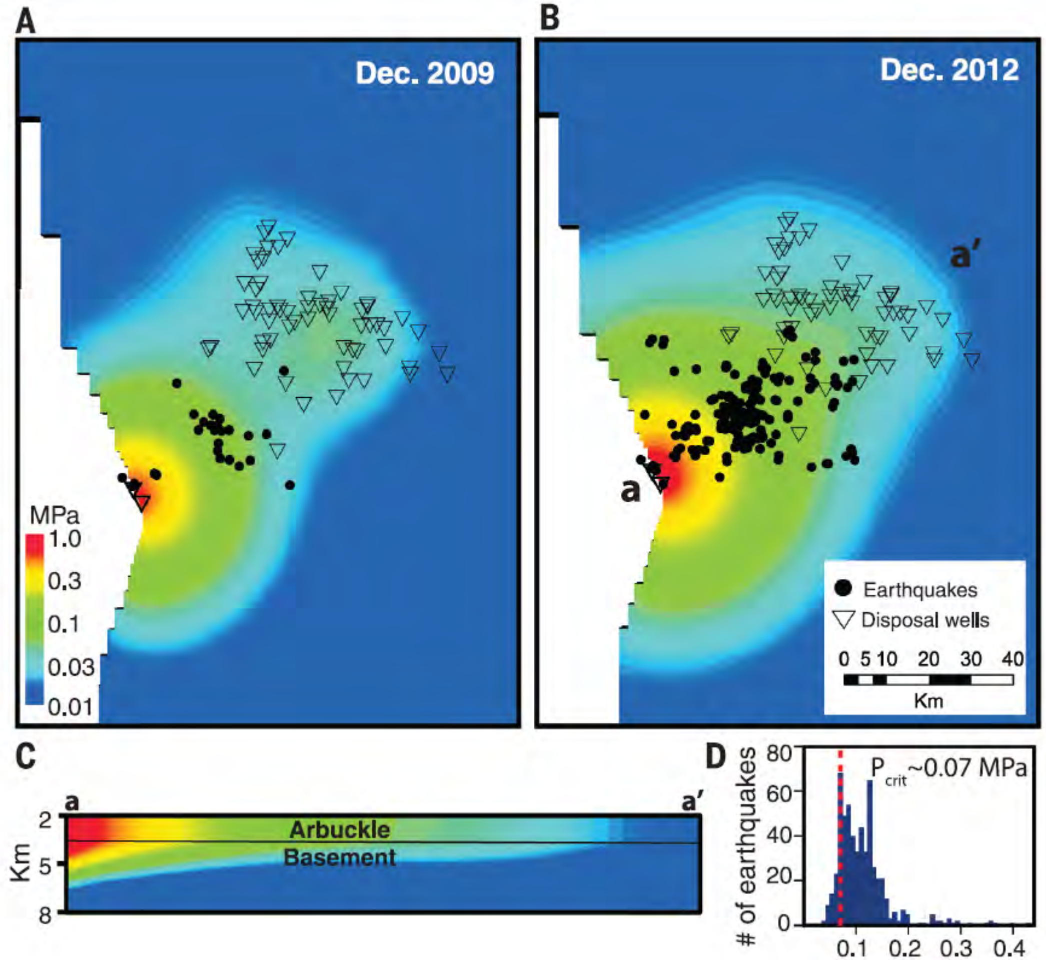
The activities may support site-specific evaluation of storage potential and environmental impact, sensitivity analysis and optimization of injection, induced seismicity risk evaluation, management, and monitoring strategies, field test design, and characterization of fault zones using hydrogeologic and monitoring data.

Thank You

Large Induced Seismicity Events from Wastewater Disposal

- Subsurface fluid disposal caused several M>5 earthquakes in deep basement rocks
- Mostly triggered by wastewater injection from oil and gas production, at small triggering pressures **(0.07 MPa in OK)**
- Observed in at least 8 states (AR, CO, KS, NM, OH, OK, PA, TX) & Canada
- In Oklahoma, hazard remains high despite decreasing injection volumes

Oklahoma: Disposed of 935 Mt wastewater into Arbuckle formation since 2009 **(~100 Mt/yr)**



(Keranen et al., 2014, Science)

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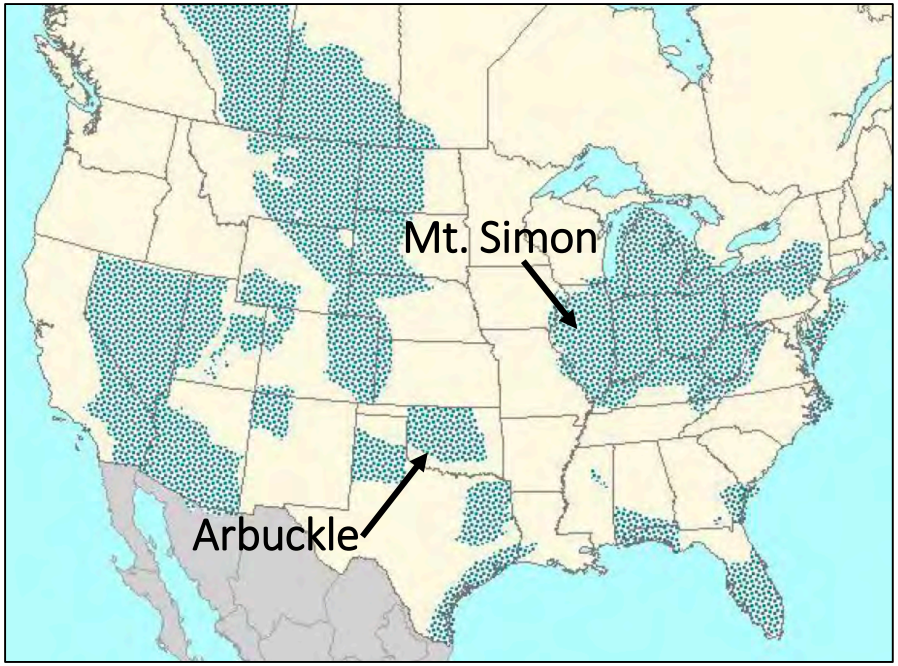
Induced Seismicity Highly Relevant for CCS at Scale

- For CCS to have global impact, the CO_2 volumes to be injected underground would be regionally similar or larger than wastewater injection in OK
- Deep saline basal aquifers of regional extent are considered high-capacity targets for CCS at scale
- Such capacity estimates ignore constraints stemming from regional pressure buildup and induced seismicity

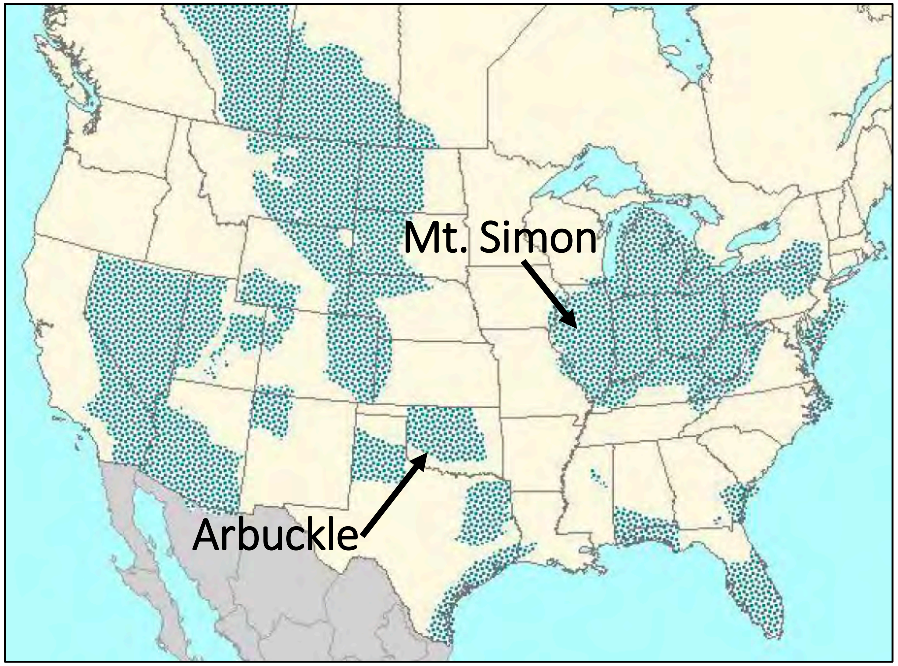


Deep Saline Formation	Capacity ($MtCO_2$)
Basin & Range	889,055
Madison	379,968
Frio	261,774
Mt. Simon	225,473
Arbuckle	191,050
Jasper	188,971
Lyons	142,520
Granite Wash	118,572
Total U.S. DSF Capacity	**2,729,632**

(IEA GHG 2005 report)

Induced Seismicity Highly Relevant for CCS

- Deep saline basal aquifers of regional extent are high-capacity targets for CCS at scale
- For CCS to have global impact, the CO_2 volumes to be stored underground would be regionally similar or larger than wastewater injection in OK
- Geomechanical impact of wastewater disposal & CCS is comparable (despite different chemistry)



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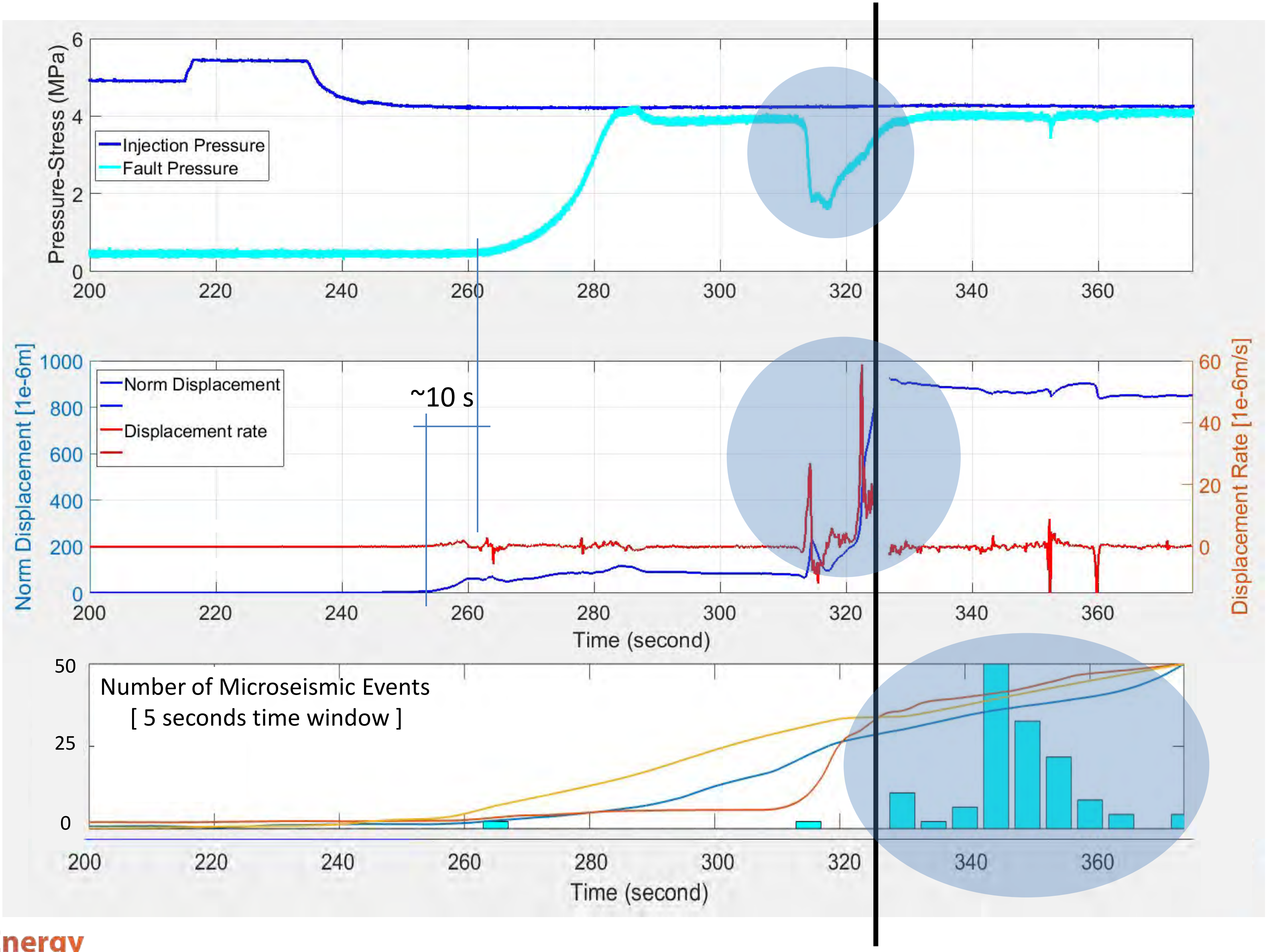
Controlled Fault Activation Experiment - Objectives

- In situ study of the aseismic-to-seismic activation of a low-permeability fault zone hosted in a shale layer
  - Conditions for slip activation and fault stability
- Implications of fault slip on permeability
  - Evolution of the transient coupling between fault opening, fault slip, pore pressure, and fluid migration
  - Long-term healing and sealing
- Tool Development and Test Protocols
  - Development of a tool and protocol to characterize the seismic and leakage potential of fault zones

Seismic Swarm AFTER Pressure & Displacement Rate Change



Micro-Seismicity: about 50 microseismic events

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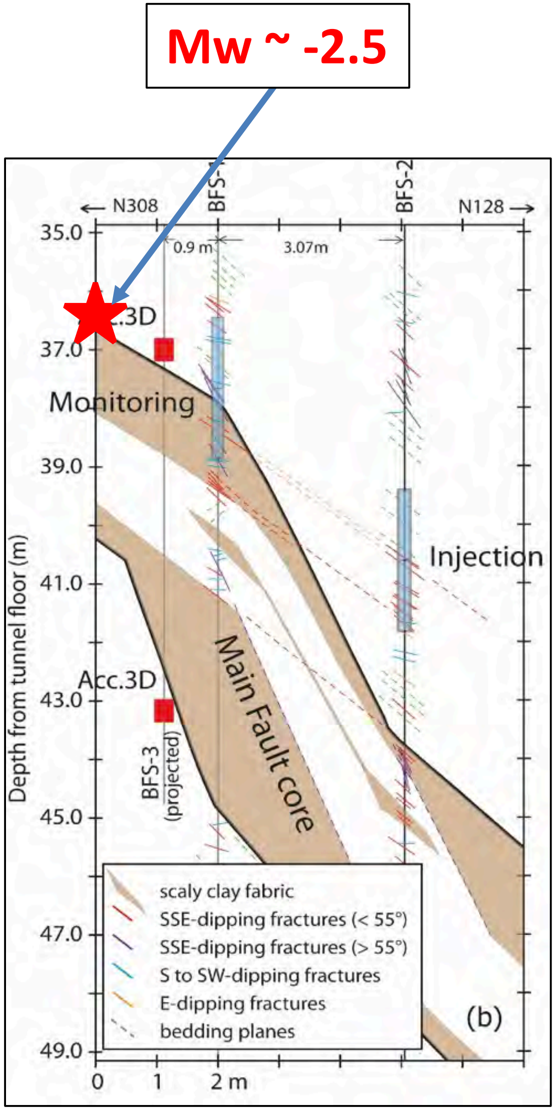
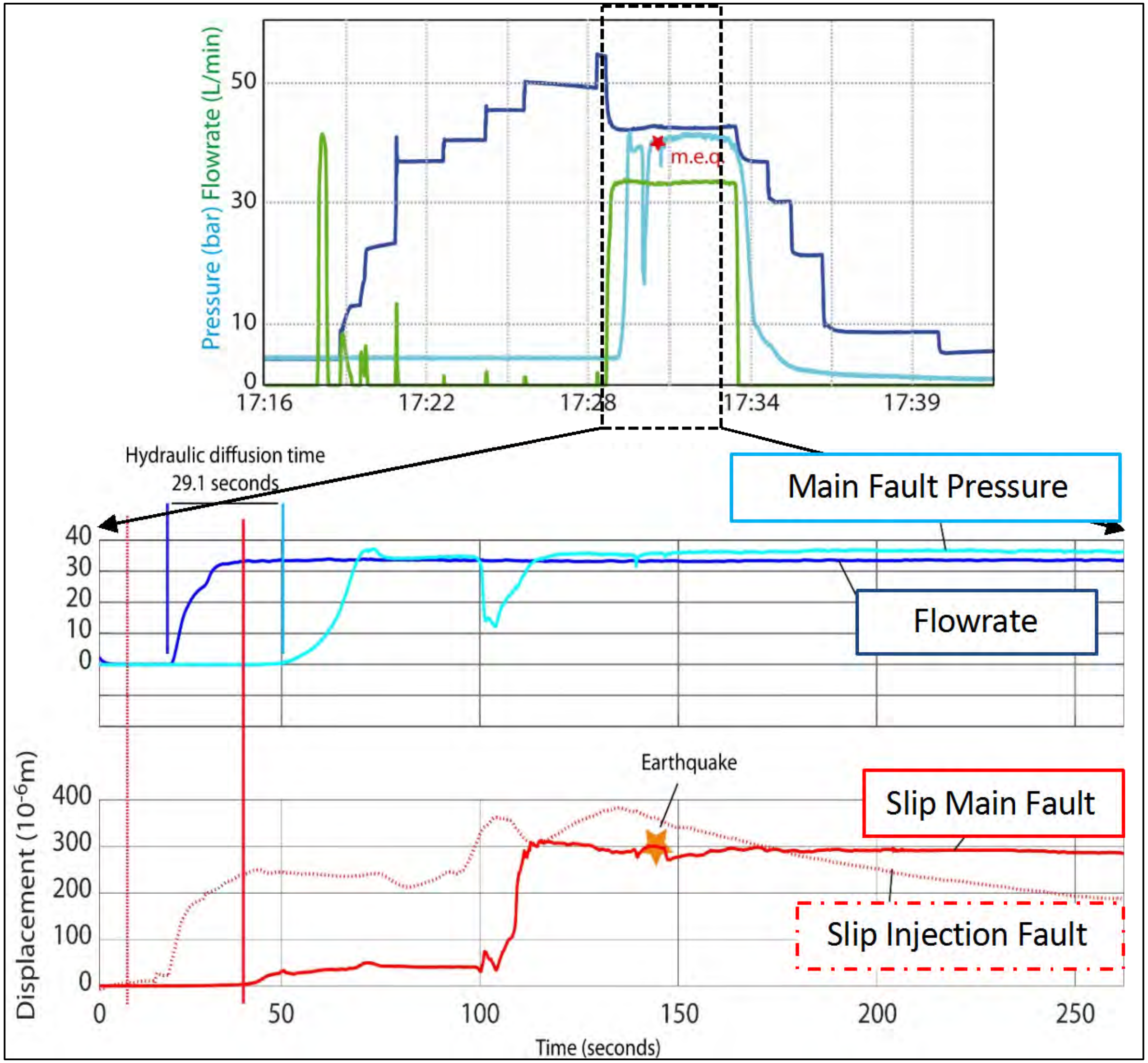
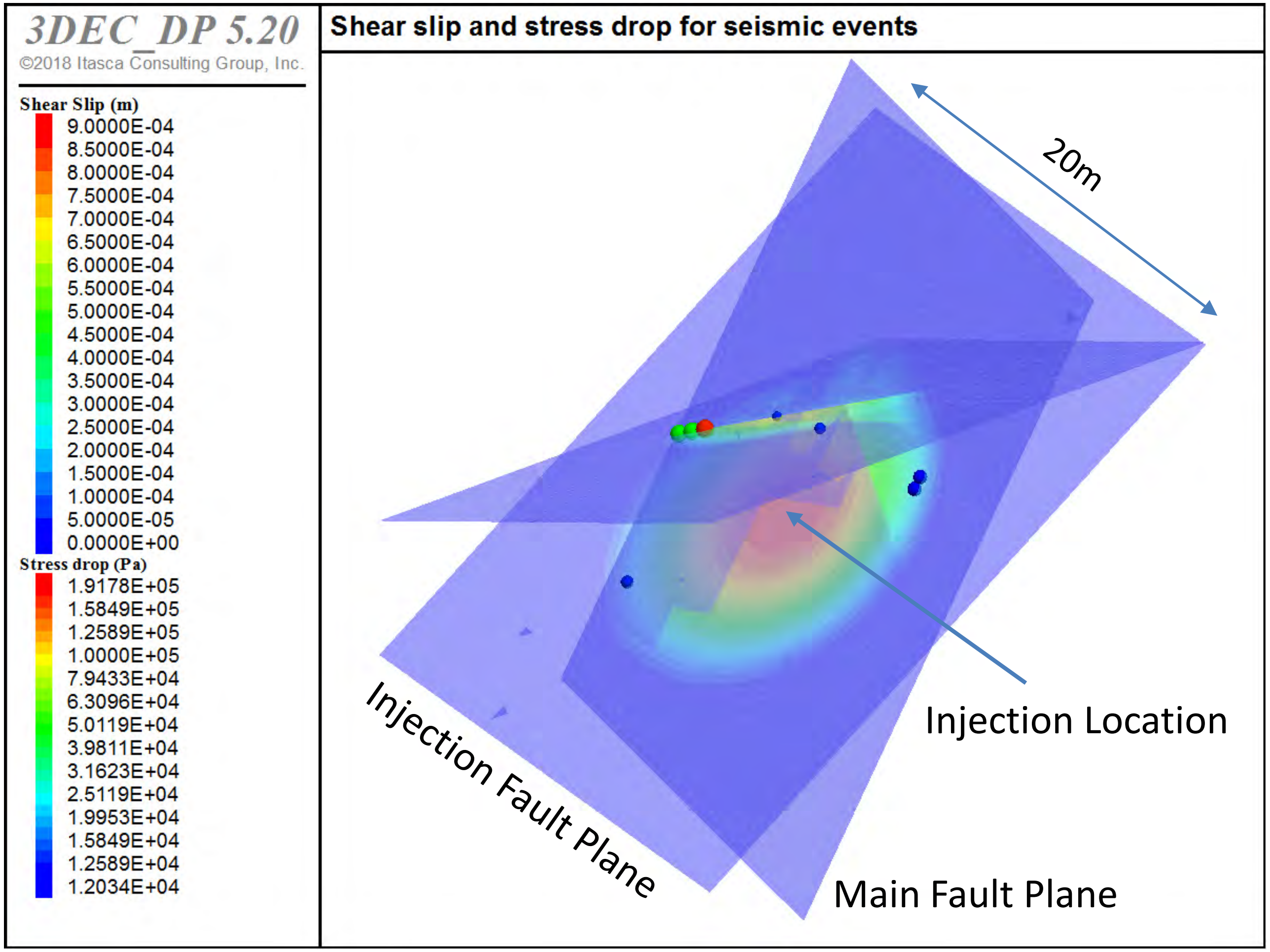
Event 2: Complex Transient Behavior After Breakthrough





Simulated Interactions between Seismicity and Leakage



Fully Coupled Hydromechanical Numerical Modeling (see Cappa Keynote)

HM Coupling:

- Effective stress ($\sigma_n' = \sigma_n - P_f$)
- Modified cubic law, with $b_h = b_{hi} + f\Delta u_n$

Rate-and-State Friction:

$$\mu = \mu_o + a ln \frac{V}{V_o} + b ln \frac{V_o \theta}{d_c}$$

- **Mainly aseismic slip**
- **Earthquakes located**
  - At the pressurized tip
  - At fault plane intersections
  - Stress decreases of 0.01 to 0.2 MPa
  - Magnitudes of -4.5 to -3.5