Results from the In Situ Fault Slip Experiment at Mont Terri

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National Energy Technology Laboratory
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Presentation Outline

• Benefit to the Program
• Project Overview
  – Goals and Objectives
  – Mont Terri Setting and Fault Zone Geology
    • The Mont Terri Laboratory Analog to a Fault Affecting a Low Permeable Caprock?
  – Instrumention and Test Design
    • Capturing static-to-dynamic three-dimensional fault movements associated to pore pressure variations
  – Fault Slip In Situ Test Protocol
    • Sequence of semi-controlled injections to induce fault slip and trigger seismicity
  – Preliminary Analyses of Fault Slip, Induced Seismicity and Leakage
    • Processing of seismic and fault displacements
    • Analytical estimation of permeability-vs-pressure relationships
• Accomplishments to Date
• Project Summary and Next Steps
Benefit to the Program

• This project improves and tests technology to assess and mitigate potential risk of induced seismicity as a result of injection operations.

• The technology improves our understanding of fault slip processes and provides new insights into the seismic and 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

• In situ study of the aseismic-to-seismic activation of a fault zone in a clay/shale formation
  – Conditions for slip activation and stability of faults

• Implications of fault slip on fault potential leakage
  – Evolution of the coupling between fault slip, pore pressure, and fluid migration

• Tool Development and Test Protocols
  – Development of a tool and protocol to characterize the seismic and leakage potential of fault zones in clay/shale formations
A Fault Affecting a Low-Permeable Layer Analog to a Reservoir Cap Rock

Mont Terri Underground Rock Laboratory

Depth of FS Experiment ~350m
Fault Zone Structure and Complexity

A ~3m-thick core with gouge + foliation + secondary (Riedel-like) shear planes
A damage zone with secondary fault planes with slickensided surfaces

The unaltered structure of the Main Fault has been accessed through gallery outcrops and fully cored boreholes

Secondary fault surface in the fault damage zone
Passive seismic monitoring:
Two 3C-accelerometers and two geophones

Step-Rate Injection Method for Fracture In-Situ Properties (SIMFIP)
Using two 3-components borehole deformation sensor mHPP probe

- Measurement range:
  \[ U_{\text{axial}} = 0.7\,\text{mm} \]
  \[ U_{\text{radial}} = 3.5\,\text{mm} \]
- Resolution of 3\(\mu\)m
- 500 Hz sampling frequency

• 3C-accelerometers
• Flat response 2Hz-4kHz
• 10 kHz sampling frequency
Borehole Measurement of Fault Slip Induced Above Fault Opening Pressure (FOP)

Initial Test Interval Pressurization

Below FOP

Above FOP

Elastic response of chamber walls

Fault slip
Displacement of Fault Hanging Wall Below and Above FOP

Initial elastic deformation of the injection chamber

Dilatant shear

FOP
Tests Protocol

- Injection pressure imposed step-by-step in four packed-off intervals set in different fault zone locations
- Synchronous monitoring of pressure, flowrate, 3D-displacement and micro-seismicity
Seismicity Observed During Fluid Pressurization of the Fault Core/Fault Damage Zone Interface

Occurring after the Fault Opening Pressure (FOP) is reached

Monitoring across the main fault interface

Rupture at the injection source (FOP)

Injection

Monitoring

FOP Injection > FOP Monitoring

Interface between fault core and fault damage zone has weaker properties
One Main Earthquake Followed by a Swarm of Multiplet Events

Main EQ characteristics
Magnitude ~ -2.5
Source radius ~ 2.5m

Monitoring across the main fault interface

Multiplet events? Reactivation of the same/similar area

Injection N°2 in the fault damage zone
Seismicity Observed During a $\sim 0.4 \times 10^{-3}$m Inverse Slip at the Core/Damage Zone Interface

- Monitoring across the main fault interface

$\sim 0.4 \times 10^{-3}$m reverse slip

Slightly different slip mechanisms observed at injection and monitoring points

- Rotation of the principal stresses (during pressurization)?
- Influence of heterogeneities?

Injection N°2 in the fault damage zone

$\sim 10^{-5}$m strike-slip
Complex Fault Movement Induced by Fluid Injection and Pressurization

- Alternate slip (*mode 2*), no-slip and dilatant events (*mode 1-2?*)
- ~75% of the movement is aseismic
- Large pressure drop is preceding the earthquake
Impact of Fault Movement on Permeability

Factor of $10^6$-to-$10^7$ transmissivity increase above the Fault Opening Pressure permeability change after fault activation

Example of Injection 1

Dupuit-Thiem analytical estimations (Morereau, 2016)
Impact of Fault Movement on Permeability

Factor of $10^6$-to-$10^7$ transmissivity increase above the Fault Opening Pressure

*Everywhere except in the fault core!*

Fault planes reactivated during the different injection tests
Accomplishments to Date

- **Multiple fault reactivations have been produced in situ** that allow evaluating mechanisms of faulting and microseismicity induced by increased fluid pressure during injection operations.

- **A unique data set has been generated** characterized by synchronous monitoring of fault movement, induced earthquakes, pore pressure, and injection flowrate.

- **A new measurement tool and a test protocol have been developed** to characterize, in a controlled field setting, the seismic and leakage potential of fault zones.

- **The SIMFIP Probe is now being upgraded for higher pressure and temperature environments**.
Summary

Key Findings

• Complex sequence of deformations with ~75% of fault movement being aseismic
• Size of seismic source ($r_s \sim 2.5$ m) << size of pressurized zone ($r_h > 10$ m)
• Fault transmissivity variations show factor of $10^6$-to-$10^7$ increase above FOP
• Large transmissivity variations occur for micro-to-millimeter scale partly aseismic movements
• Seismic events may not be a reliable indicator for fault leakage

Future Plans

• Test and calibrate fully coupled hydromechanical models for predictions
  – Fault permeability-vs-stress relationship
  – Fault seismic-to-aseismic stability parameters
  – Validate advanced numerical models against fault slip experiments in other geologic settings
• Evaluate and measure potential for long-term fault transmissivity increases
• Validation of a protocol to characterize the seismic and leakage potential of fault zones at CO₂ sequestration depths
Relevance to SubTER Crosscut

Subsurface Stress and Induced Seismicity Pillar
is relevant to a range of subsurface applications

- Improved well construction materials and techniques
- Autonomous completions for well integrity modeling
- New diagnostics for wellbore integrity
- Remediation tools and technologies
- Fit-for-purpose drilling and completion tools (e.g., anticipative drilling, centralizers, monitoring)
- HT/HP well construction / completion technologies

Subsurface Stress & Induced Seismicity

- Measurement of stress and induced seismicity
- Manipulation of stress and induced seismicity
- Relating stress manipulation and induced seismicity to permeability
- Applied risk analysis of subsurface manipulation

Permeability Manipulation

- Physicochemical fluid-rock interactions
- Manipulating flowpaths
- Characterizing fractures, dynamics, and flows
- Novel stimulation methods

New Subsurface Signals

- New sensing approaches
- Integration of multi-scale, multi-type data
- Adaptive control processes
- Diagnostic signatures and critical thresholds

Energy Field Observatories

Fit For Purpose Simulation Capabilities
Appendix

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

• **Project participants:**
  – Yves Guglielmi (LBNL, USA) – PI – Field test analyses, tool and protocol development
  – Jonny Rutqvist, Jens Birkholzer, Pierre Jeanne (LBNL, USA) – Hydromechanical modeling
  – Christophe Nussbaum (Swisstopo, Switzerland) – Fault structure, kinematics and stress analyses
  – B.Valley, M.Kakurine (University of Neuchatel, Switzerland) – Three-dimensional fault zone geological modeling
  – Louis de Barros (University of Nice, France) – Seismic analysis
  – Kazuhiro Aoki (JAEA, Japan) – Laboratory friction tests
  – Derek Ellsworth, Chris Marone (Pennstate University, USA) – Rate and state friction laboratory experiments and modeling
## Gantt Chart

<table>
<thead>
<tr>
<th>Experiment</th>
<th>In situ clay faults slip hydro-mechanical characterisation (FS)</th>
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### Steps (Phase 20):

- **Step 2:** Pre-modeling of experiment stress/strain perturbations on the fault
- **Step 3:** Drilling and logging of the Fault zone properties
- **Step 4:** Installation of passive 3D mechanical monitoring device
- **Step 5:** HM estimation of fault zone properties
- **Step 6:** Stress measurements through the fault zone
- **Step 7:** Slip induced experiment
- **Step 8:** HM modelling of fault displacements

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**Phase 19**

**Phase 20**

**Phase 21**
Bibliography


