Active Seismic Monitoring of CO$_2$ Leakage Through a Hydromechanically Reactivated Fault: Caprock Integrity Monitoring For a CCS Analog (FWP-FP00007630)

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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

FS-B (2019 – 2021)

200m
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

**Legend**
- Gouge
- Faults
- Mineral fillings
- Open fractures

**Images**
- Principal Shear Zone
- Fault Damage Zone
- Opalinus Clay

**Measurements**
- 2 cm
- 5 cm
- 1 m
- 30 m (29.8 m)
- 35 m (38 m)
- Depth (m)
Experimental Setting

- **Test1**
- **Test2**
- **Test3**
- **Test4**

Water Injection

Seismic Sensors

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

Mixed-Mode Activation
Long Term Post Activation
No Clear Fault Self-Sealing

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

2015 Activation Experiment
Objectives of the Second Fault Activation Experiment

Imaging Rupture and Flow Paths Growth in Three-Dimensions During and After a fault activation by a CO₂ brine injection

Validating active seismic monitoring techniques to detect CO₂ leakage, fault slip and its link to induced seismicity
Experiment Concept: Coupling Downhole Hydro-Mechanical Tests With Active Seismic Monitoring

For one-hour stacking, standard error only \( \sim 6\) ns. Corresponds to \( dV \) of \( 3 \times 10^{-6} \).
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

- Injection Tests
  - Long term CO₂ brine injection at constant pressure in the inactive Fault since June 2019
  - Tuned the Strain Monitoring Network taking the opportunity of the Fault HM response to a distant loading by a Gallery Excavation

1. Injection Tests in the inactive Fault
2. Fault Zone
3. Relative Displacement

Graph showing injection times and pressures.
Fault Zone Pre-activation Hydrogeology

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

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

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**Gallery at 350m depth**

- 10m
  - BCS-D7 22–28m
  - $\sim 3$bar

- 20m
  - BFS-2
  - 6bar?
  - BFS-6
  - 7->12bar?

- 40m
  - BFS-4
  - 2bar increasing to 5bar during recovery?
  - BFS-5 45m
  - $\sim 14$bar

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**Slow Drainage of Intact Shales from the fault to unit below?**

**High permeability unit draining to valley?**
Fault Compliant Structures Identified with SIMFIP and DSS

~100 micron Local Shear Displacement

Radial shear?
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 CO₂ 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
  o Using Optical Fibers Distributed Strains (DSS) to detect compliant fault zones in a caprock with remote loadings.
  o CASSM active seismic imaging capabilities parallel and across the fault structure

• An International Experiment
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 CO₂ 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% CO₂ storage permanence
  – to predict CO₂ 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 CO₂ 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 controlled
CO₂ leak in a slipping Fault
Using SIMFIP probes and distributed strains
While Repeating Passive Seismic Imaging

**End Product**
Relating CASSM signals to CO₂ 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.
### 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

