On the Relationship between Fault Reactivation and Leakage Potential: Controlled Injection Experiments at Mont Terri

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U.S. Department of Energy
National Energy Technology Laboratory
Mastering the Subsurface Through Technology Innovation, Partnerships and Collaboration:
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Presentation Outline

- Benefit to the Program
- Project Overview
  - **Goals and Objectives**
  - **Mont Terri FS Experiment Setting**
  - **Fault activation protocol**
    - Sequence of semi-controlled injections to induce fault slip and trigger seismicity
  - **Analyses of Fault Slip, Induced Seismicity and Leakage**
    - State of stress
    - Cause(s) of fault permeability variations
    - Relationship(s) with induced earthquakes
- Accomplishments to Date
- Future Plans
- Synergy Opportunities
- Project Summary

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.

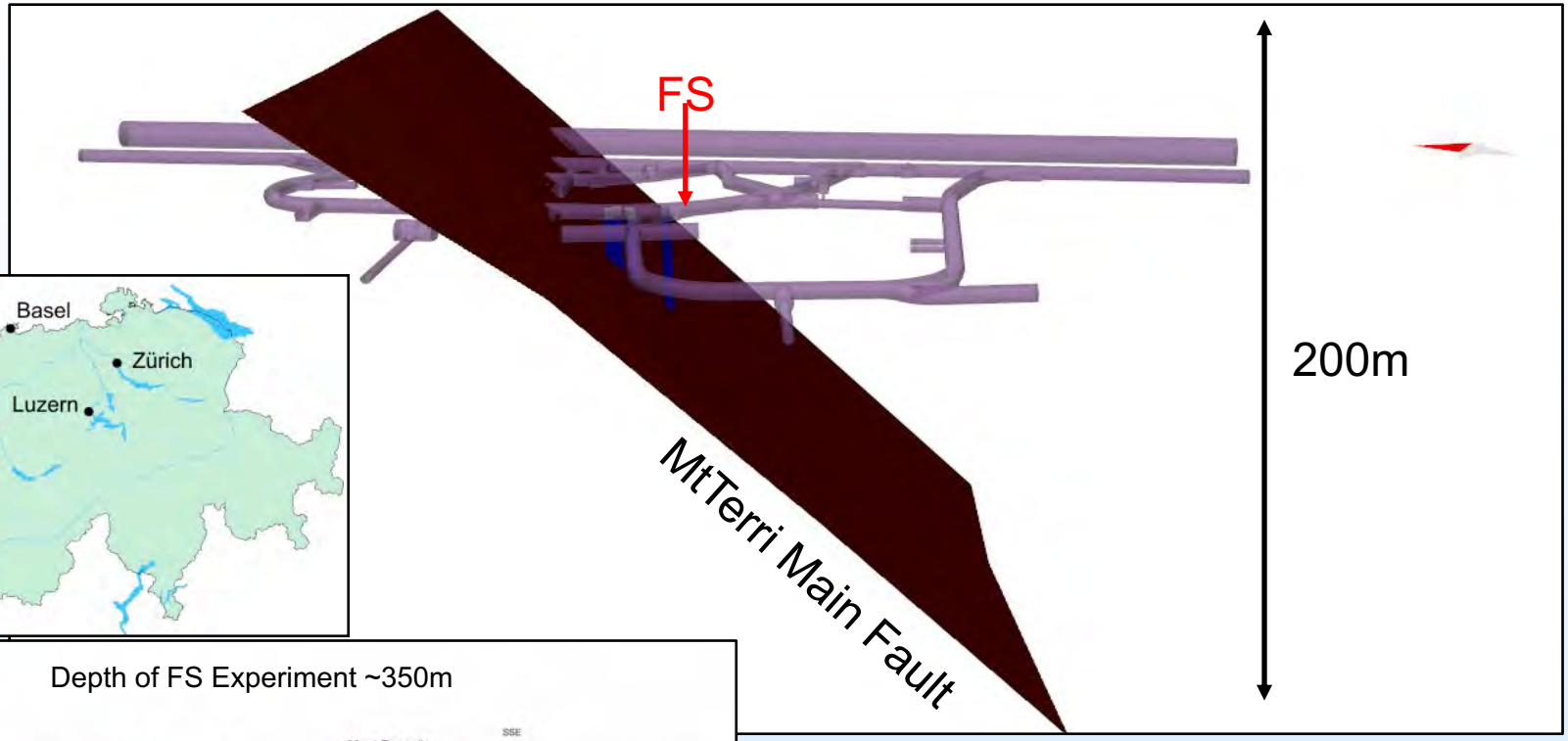
➢ This contributes to Carbon Storage Program's effort:

  – to ensure for 99% CO_2 storage permanence
  – to predict CO_2 storage capacity in geologic formations to within ±30 percent

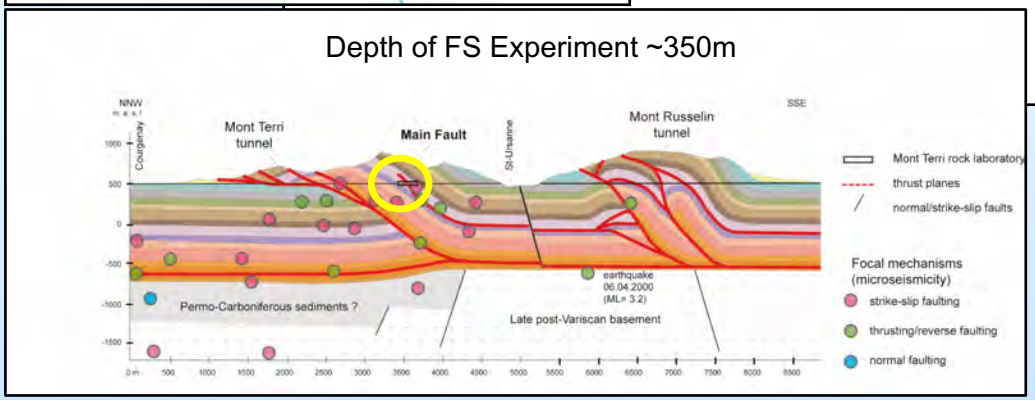
Project Overview:
Goals and Objectives

- In situ study of the aseismic-to-seismic activation of a fault zone in a clay/shale formation
- Implications of fault slip on fault leakage and caprock integrity
- Development of a protocol to characterize the seismic and leakage potential of fault zones in clay/shale formations

An International Fault Activation Experiment



Depth of FS Experiment ~350m



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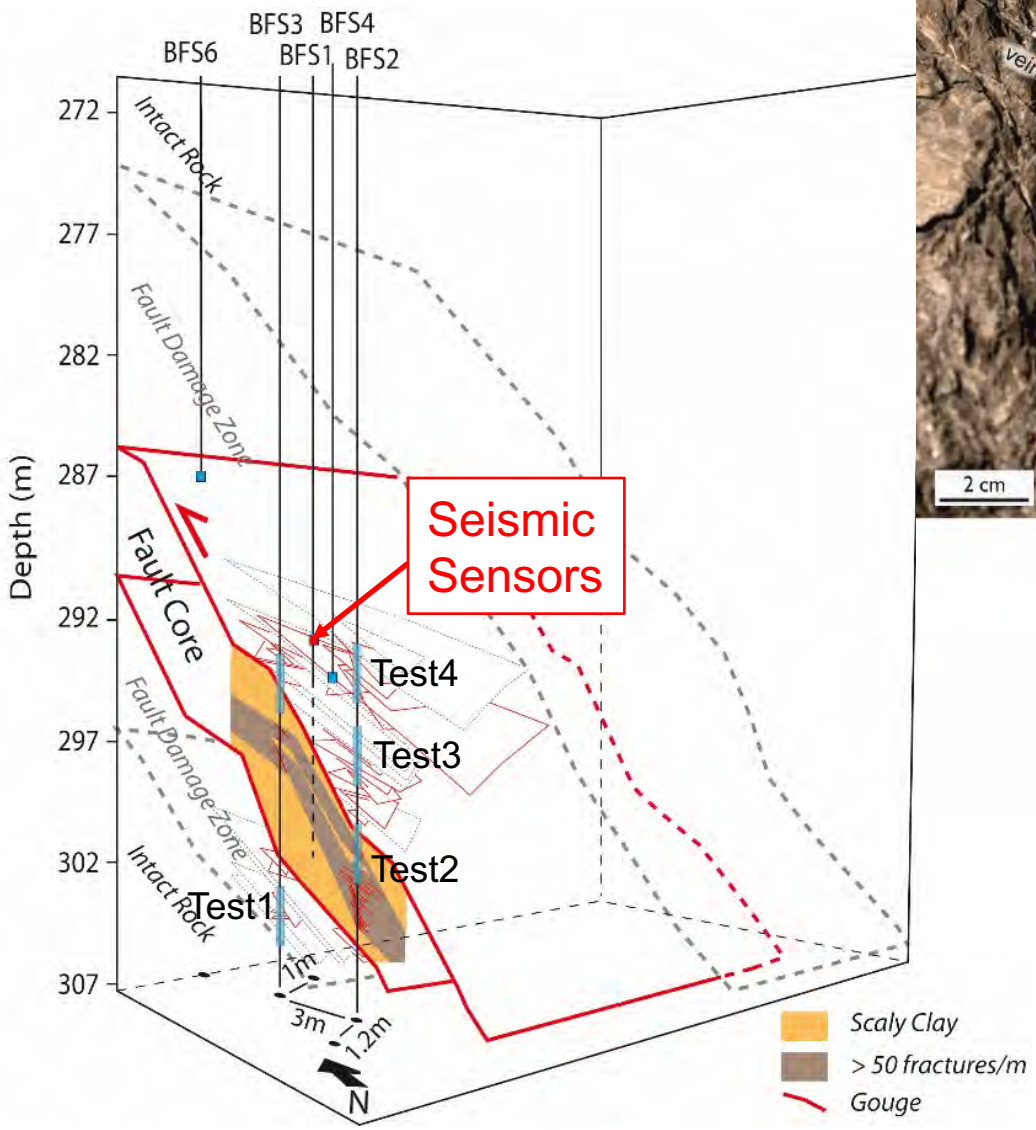
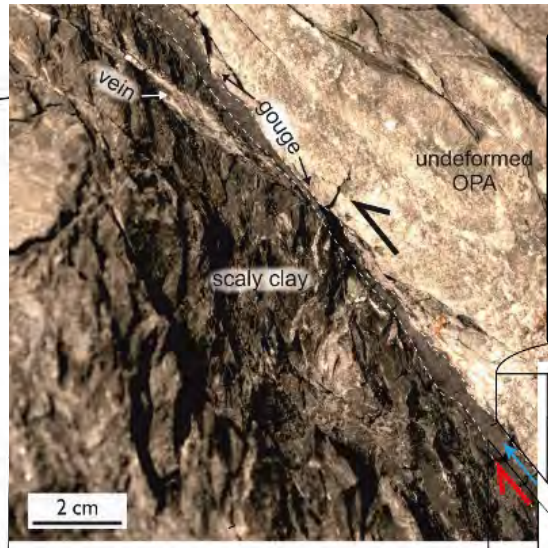
Experimental Setting





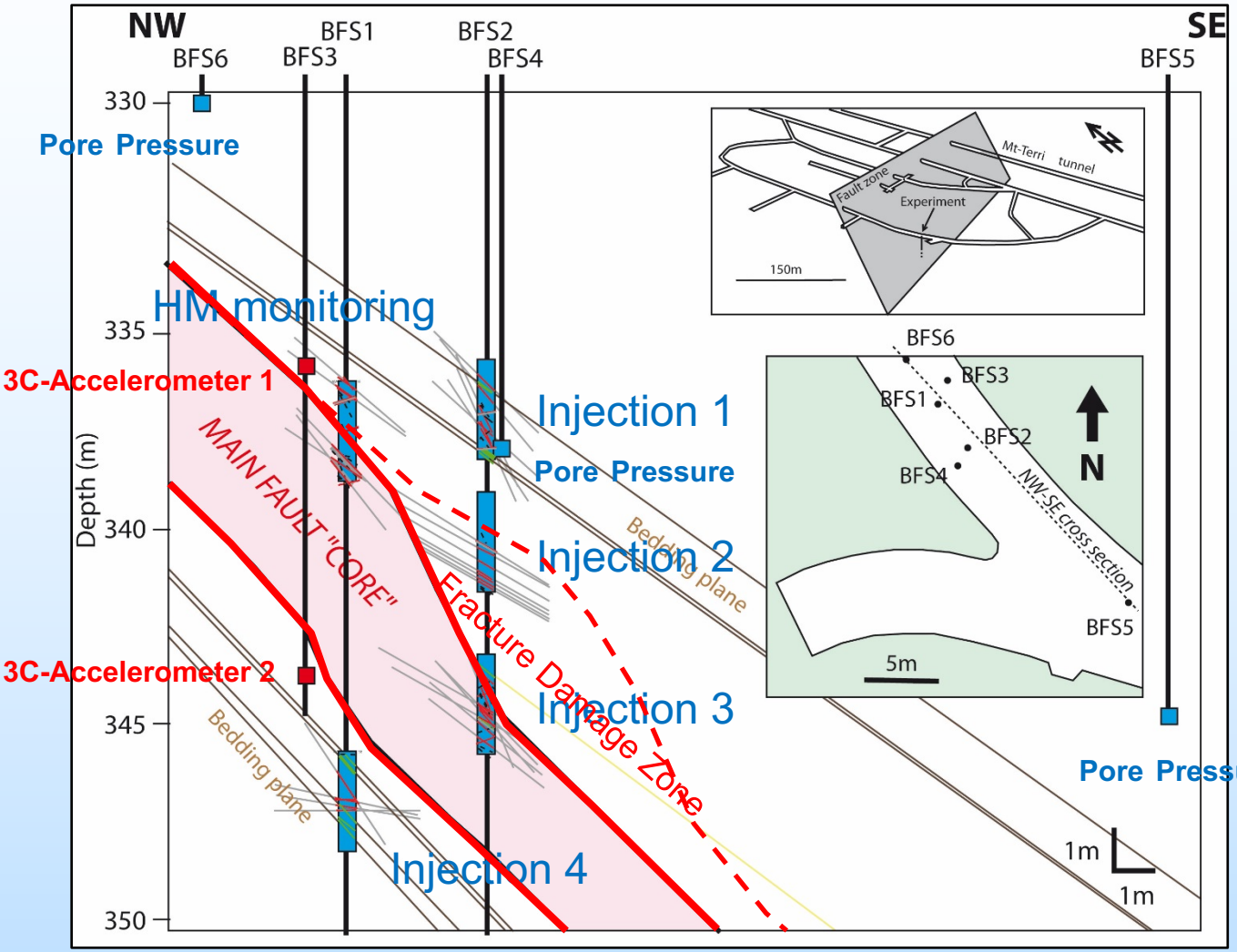
Water Injection

SIMFIP Tool

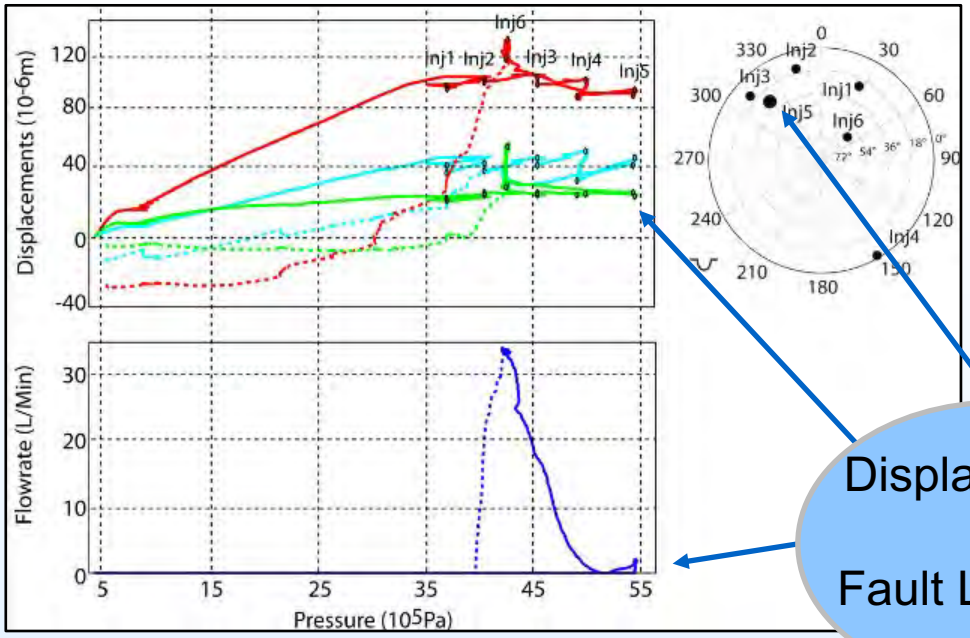
Pressurized Interval

Activation 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

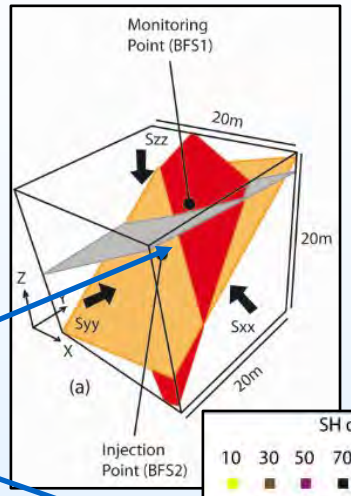


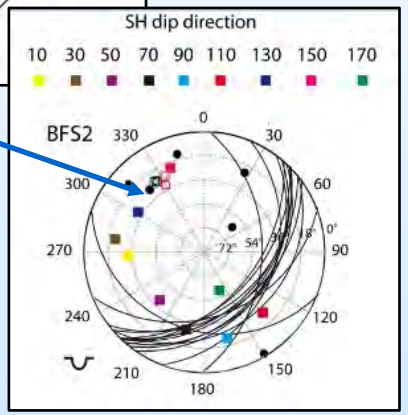
Using Displacement At Fault Leakage To Estimate Stress

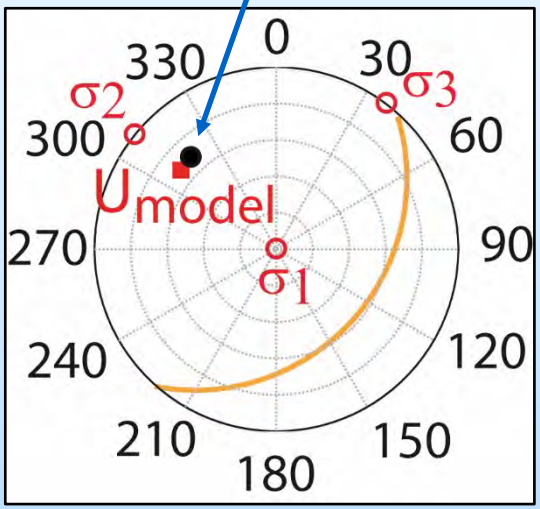


Displacement at Fault Leakage

Fully coupled HM numerical model (3DEC)

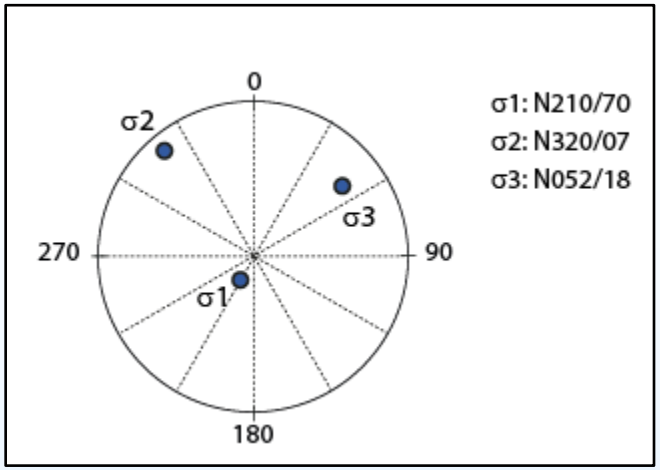






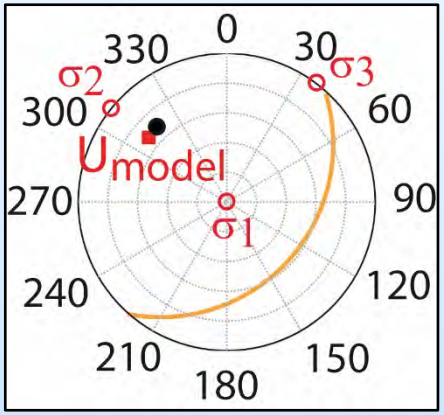
Stress Estimates Across The Main Fault

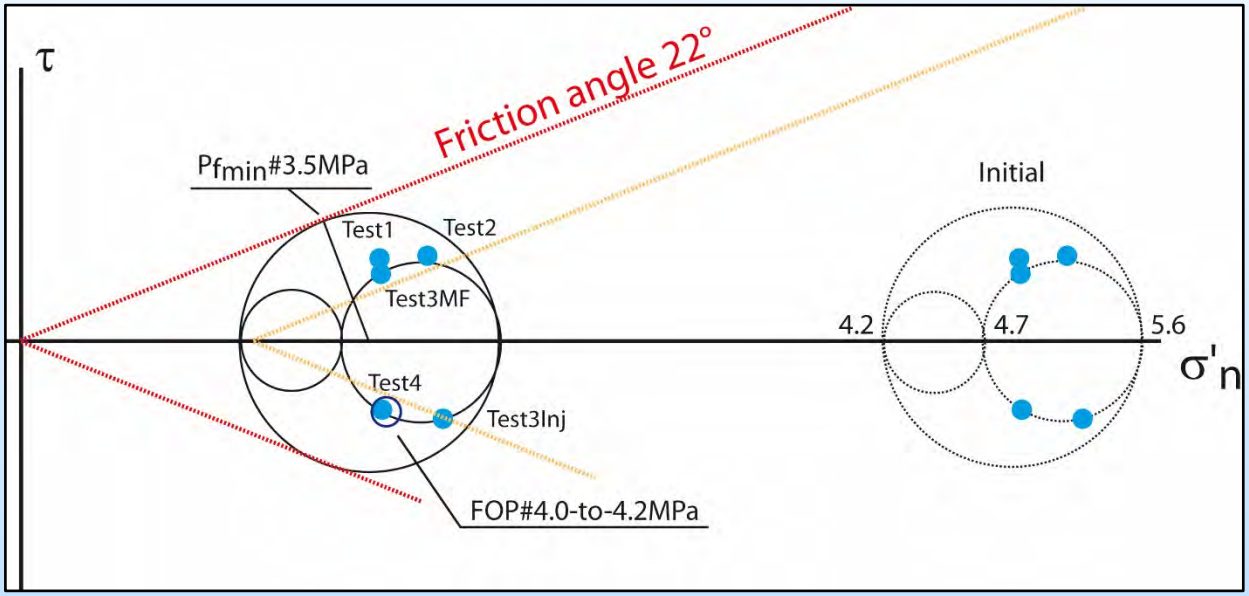
Opalinus Clay, *Martin & Lanyon (2003)*



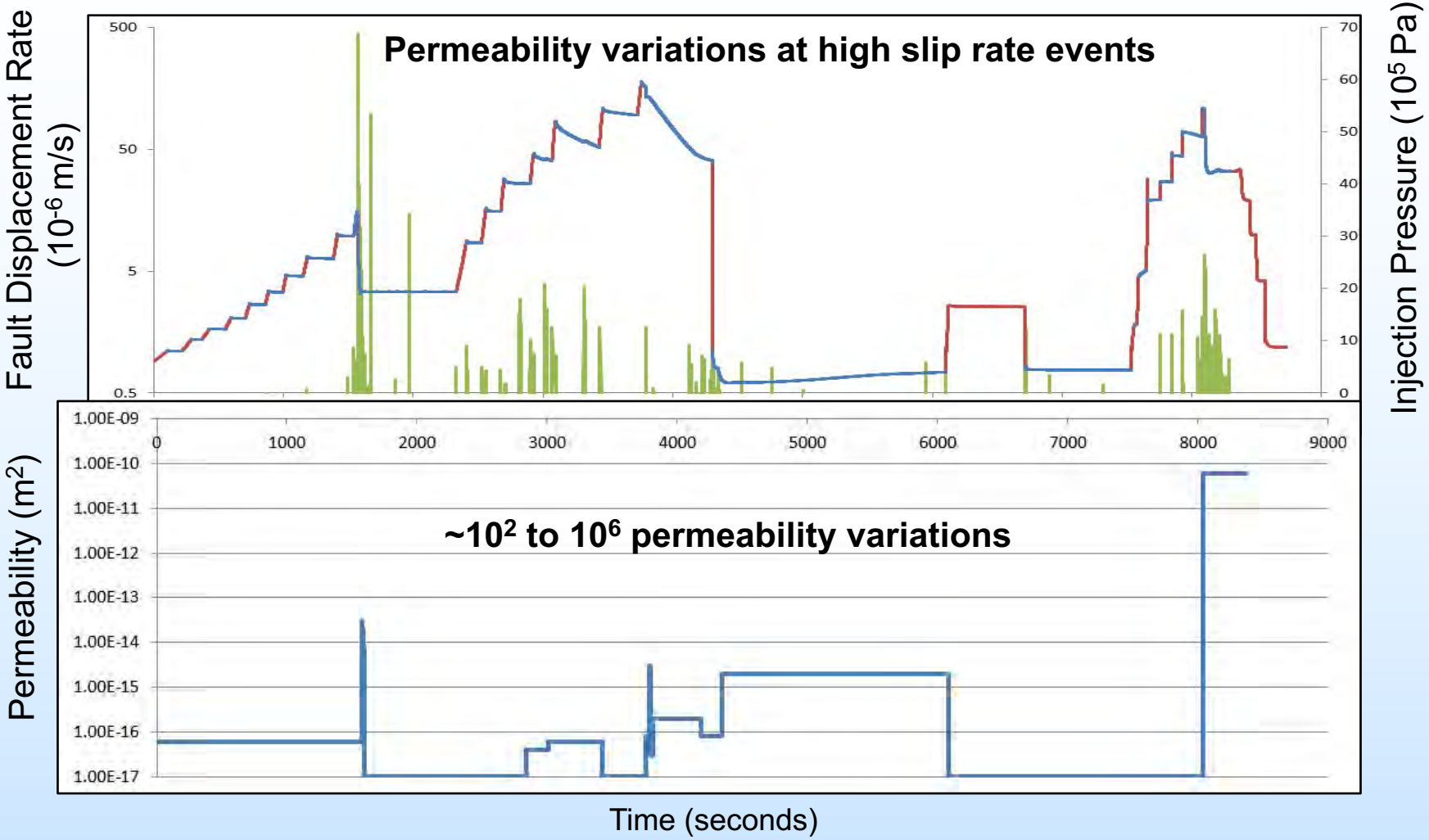
- A new way to compute stress tensor. *Results are similar to Martin & Lanyon (2003)*
- Fault zone is not deviating stress conditions
- Significant fault leakage (30-to-60 L/Min) at 4.0 to 4.2 MPa injection pressures

FS Tensor (2017)





But Fault Leakage Depends On More Than Just Effective Stress!



Fault Permeability step-by-step estimations using Tough-FLAC3D

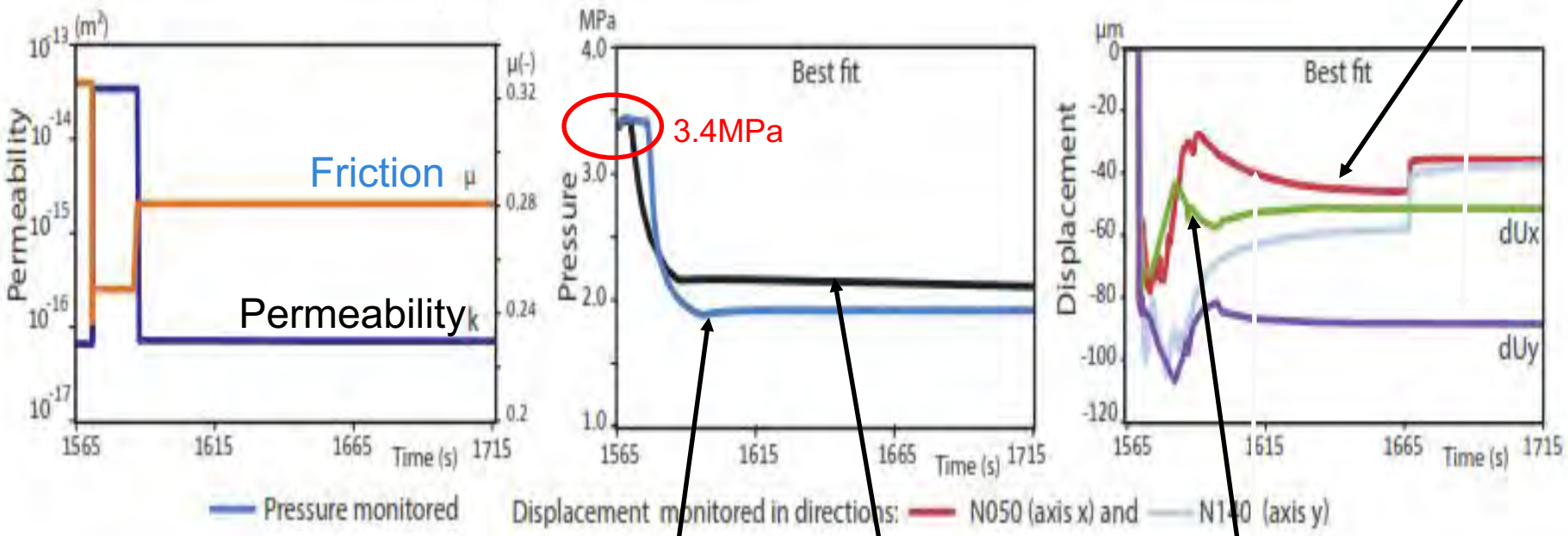
Red Pressure period is imposed in the model

Permeability is estimated using Darcy law with TOUGH code

Fault Permeablity Is Also Related To Strain Rate

Fault friction (μ) and permeability (k) vary with slip rate

$k = k_{ini} \times [\, f(\text{effective normal stress}) + f(\text{« strain rate »})]$



Tough-FLAC3D simulations

Measured pressure

Model

Measured borehole radial strain

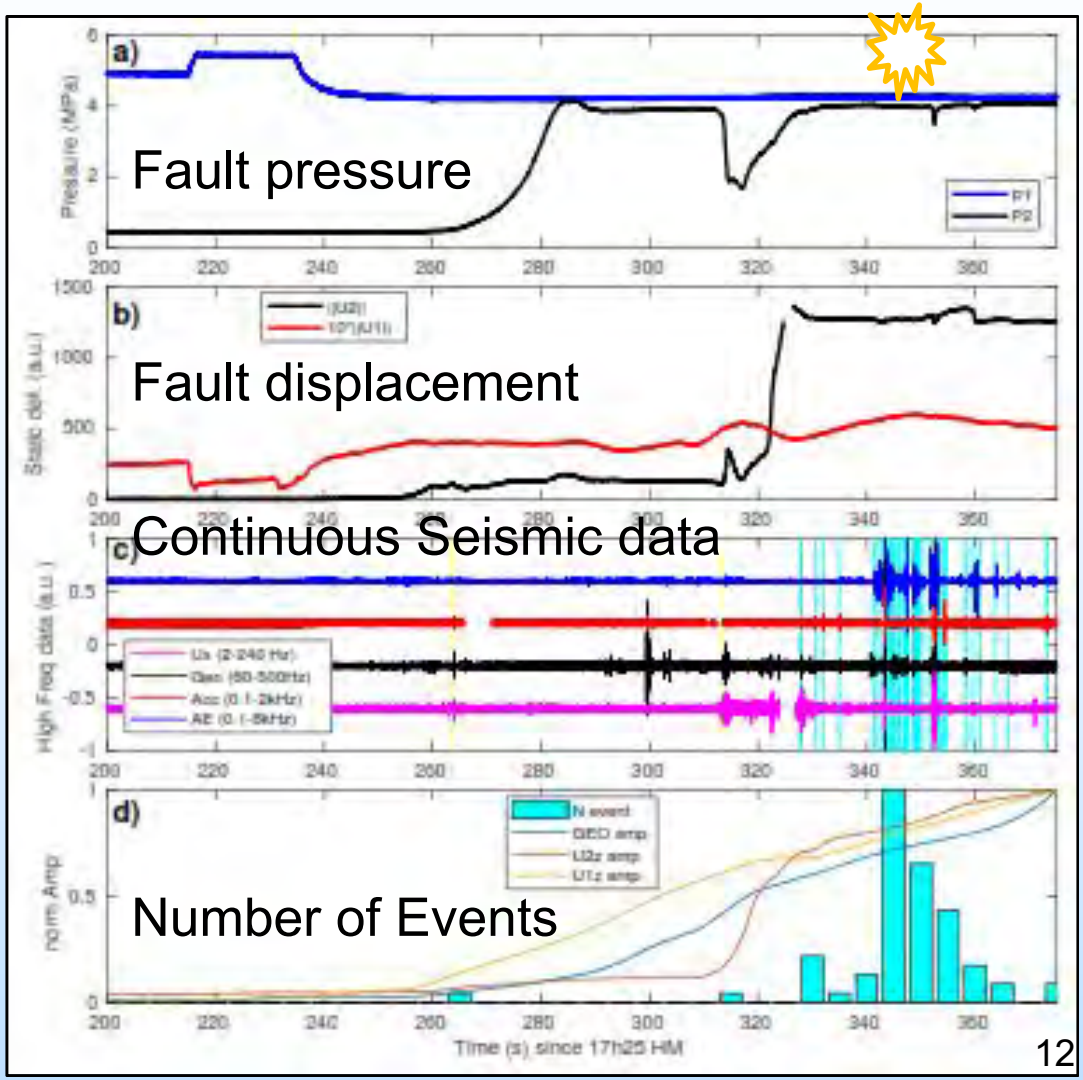
Induced Seismic Events Despite Laboratory Test Predictions

Laboratory friction tests on gouge material

Frictional strengthening fault behavior

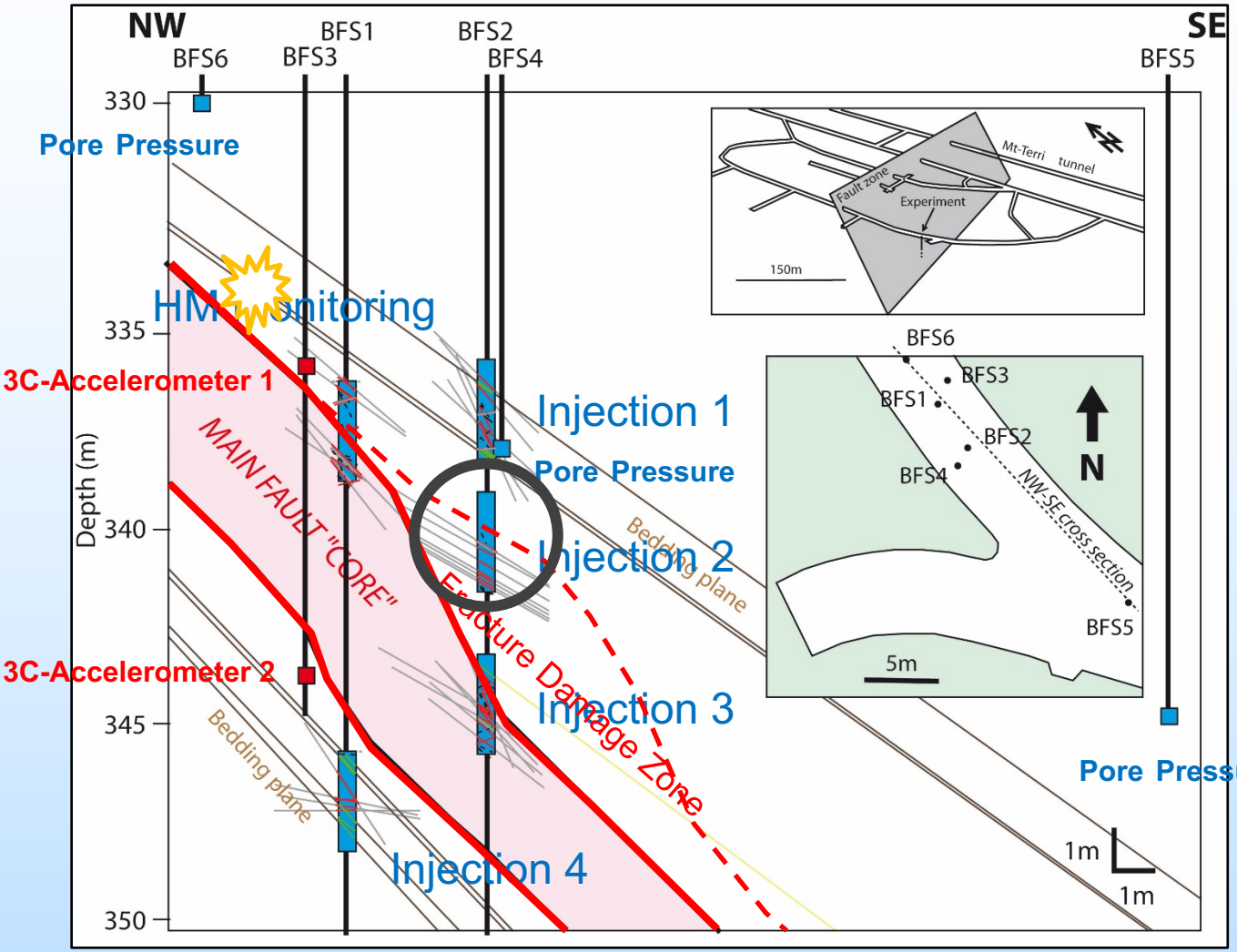
No predicted induced events

Field test → About 50 seismic events



Activation 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



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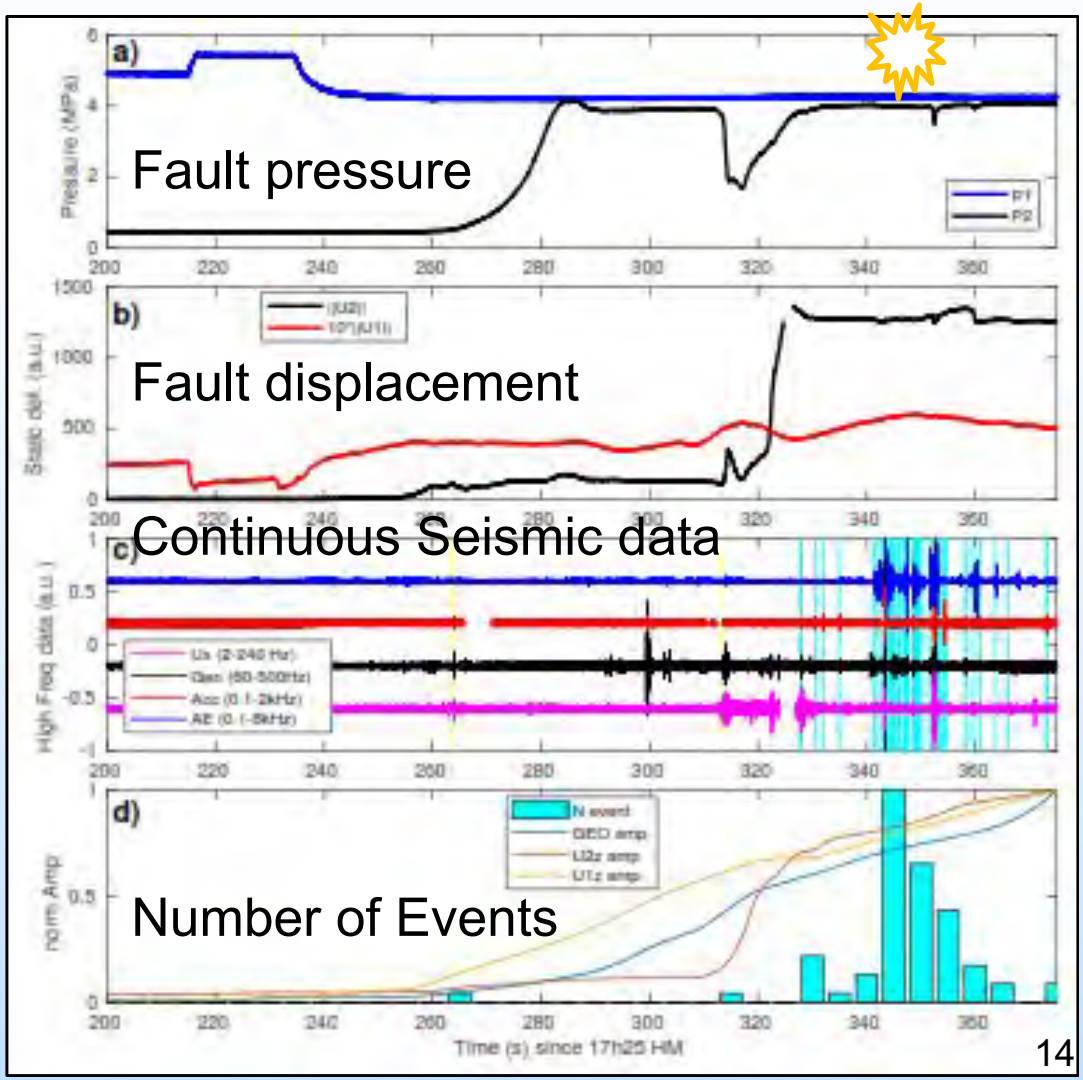
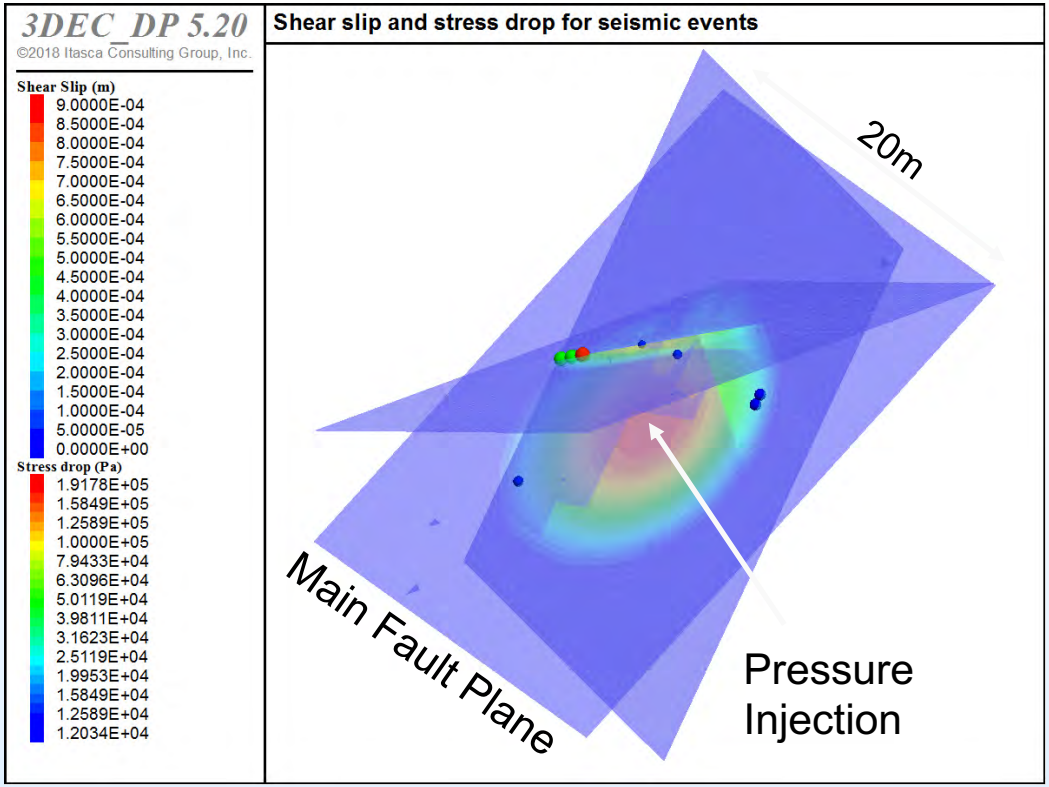


Seismicity Associated To Fault Structure?



Fully Coupled Hydromechanical Numerical Modeling

- **Mainly aseismic slip**
- **Earthquakes located**
  - At the pressurized tip
  - At intersections between second-order fractures and Main Fault
  - Stress drops of 0.01 to 0.2 MPa
  - Magnitudes of -4.5 to -3.5

HM coupling:

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

$$\Delta U_n = \frac{\Delta \sigma_n'}{k_n}$$

$$Q = \frac{(b_{hi} + f\Delta U_n)^3 w \rho g}{12\mu} \Delta h$$

Rate-and-State friction:

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

Accomplishments To Date

- **New Understanding**

  Basic phenomenology of coupled fault slip, leakage and induced seismicity (new constitutive laws for IS-related permeability)

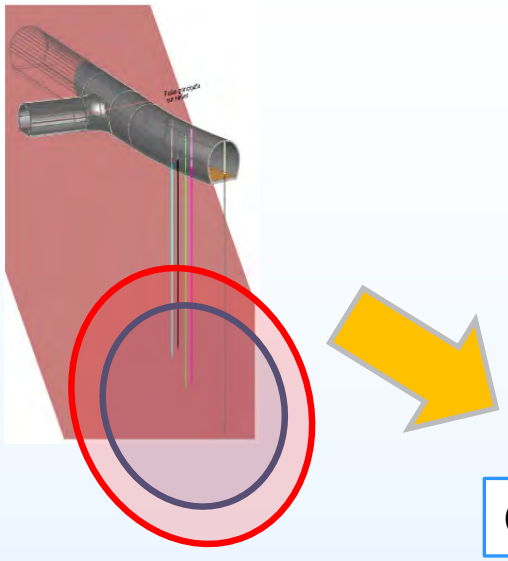
- **New Data for Sharing and Collaboration**

  A large database on the same fault zone, at both field and laboratory scales, could be made available for advanced statistical analyses (statistical correlations between injection and seismic attributes)

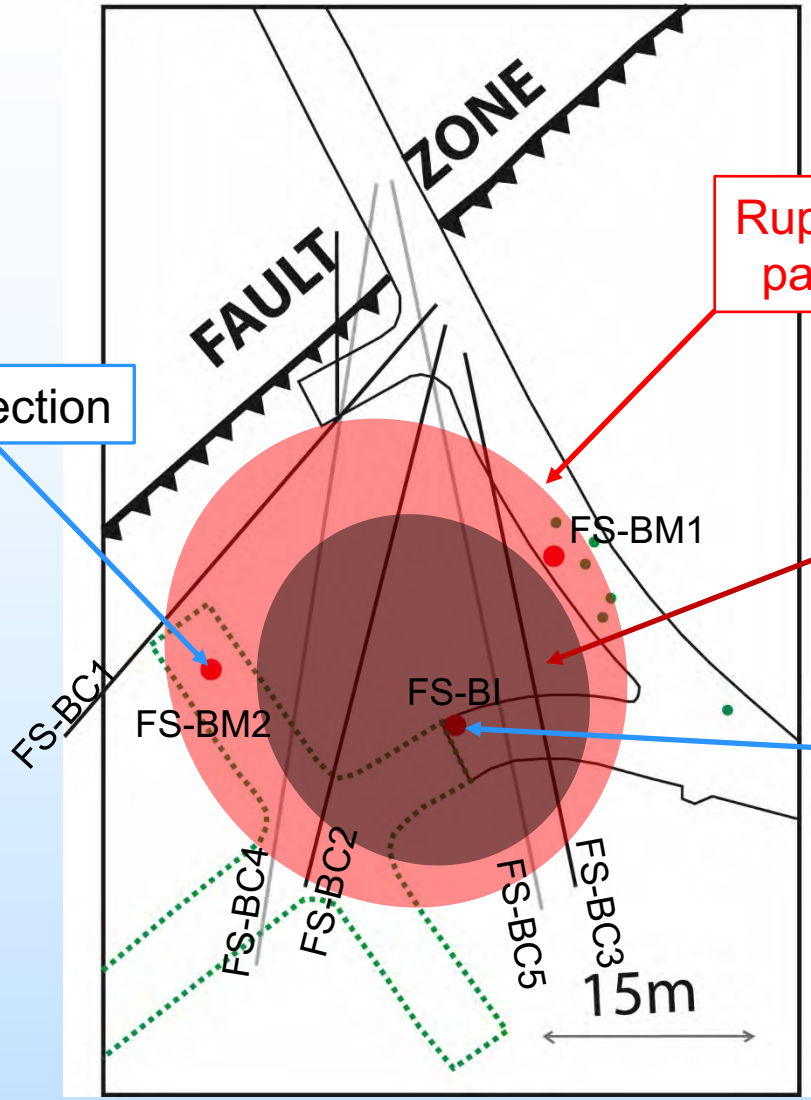
- **New Capability Developments**

  Continued developments of the SIMFIP tool to *in situ* probe seismic activity and leakage potential in complex fault zones

Future Plans – New Long-Term FS-B Test



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



Mont Terri Project

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nagra.

BGR Bundesanstalt für Geowissenschaften und Rohstoffe GEOZENTRUM HANNOVER

ENSI

TOTAL

Chevron

ETH Eidgenössische Technische Hochschule Zürich Swiss Federal Institute of Technology Zurich

Future Plans – New Long-Term FS-B Test

FS: Basic Phenomenology of Coupled Fault Slip

- Influence of stress and strain on fault leakage
- Relationships between fault permeability and induced seismicity
- Testing of different permeability laws

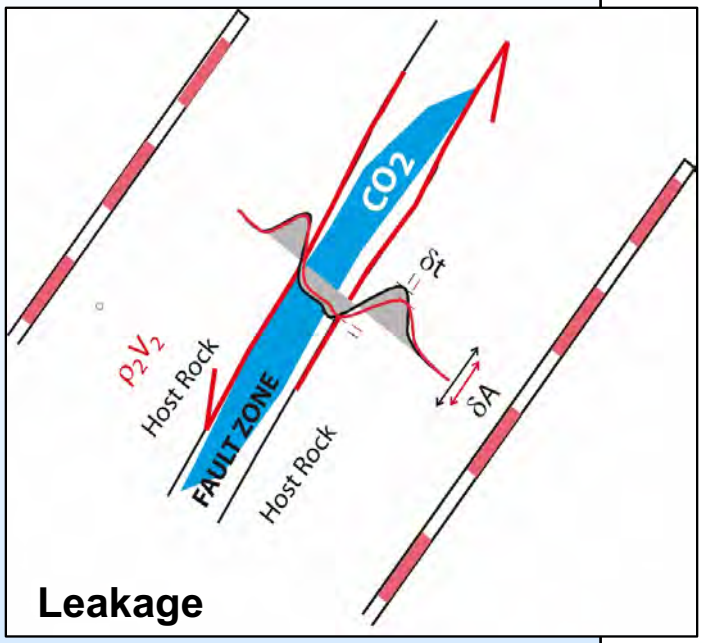
FS-B: Detailed Semi-Continuous Imaging of Fault Activation and Long-Term Leakage Behavior

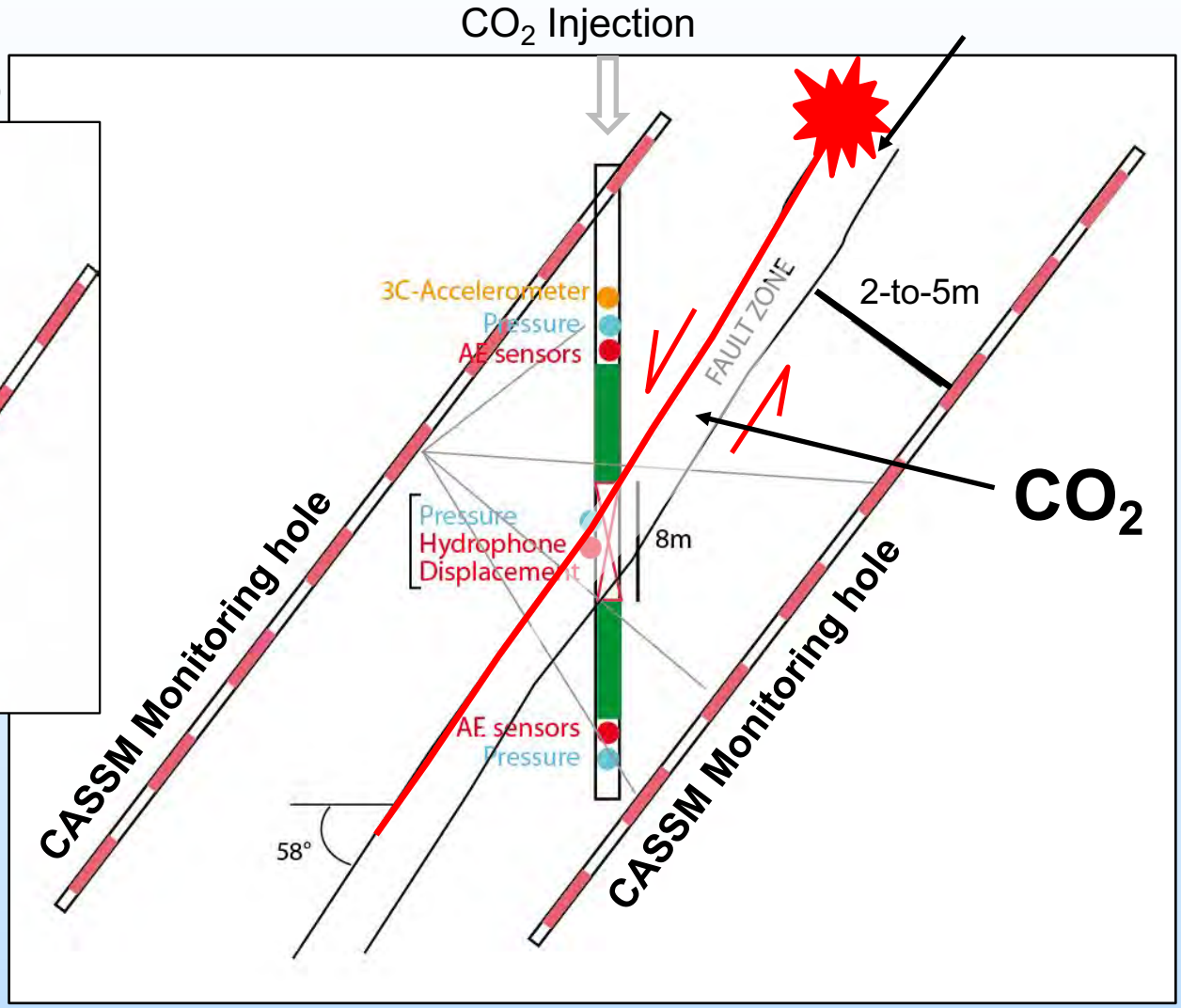
- Evolution of permeability and leakage potential before, during and after activation (**long-term effects** of healing and sealing)
- Effects on permeability of cyclic loading and inactive periods
- Injection with water as fluid; **leagage testing with water and CO_2**
- Relationship between rupture patch and leakage patch
- Testing of **fault sealing** options
- Improved methods for **imaging coupled processes** in reactivated faults

Synergy Opportunities

FS-B Experiment: An opportunity to apply active seismic (CASSM) imaging for fault slip and leakage monitoring

Relating CASSM signals
To CO_2 leak and to fault slip





Summary

Key Findings from Fault Slip Experiment

Strong increase in permeability for micrometer scale fault displacements

- Changes in effective stress magnitudes and orientation are not sufficient to explain changes in fault permeability
- Changes in **strain rate or slip velocity** apparently contribute to permeability variations

Seismic reactivation of a velocity-strengthening clay-rich fault zone

- Are Laboratory Experiments a Good Enough Indicator of Field-Scale Behavior?

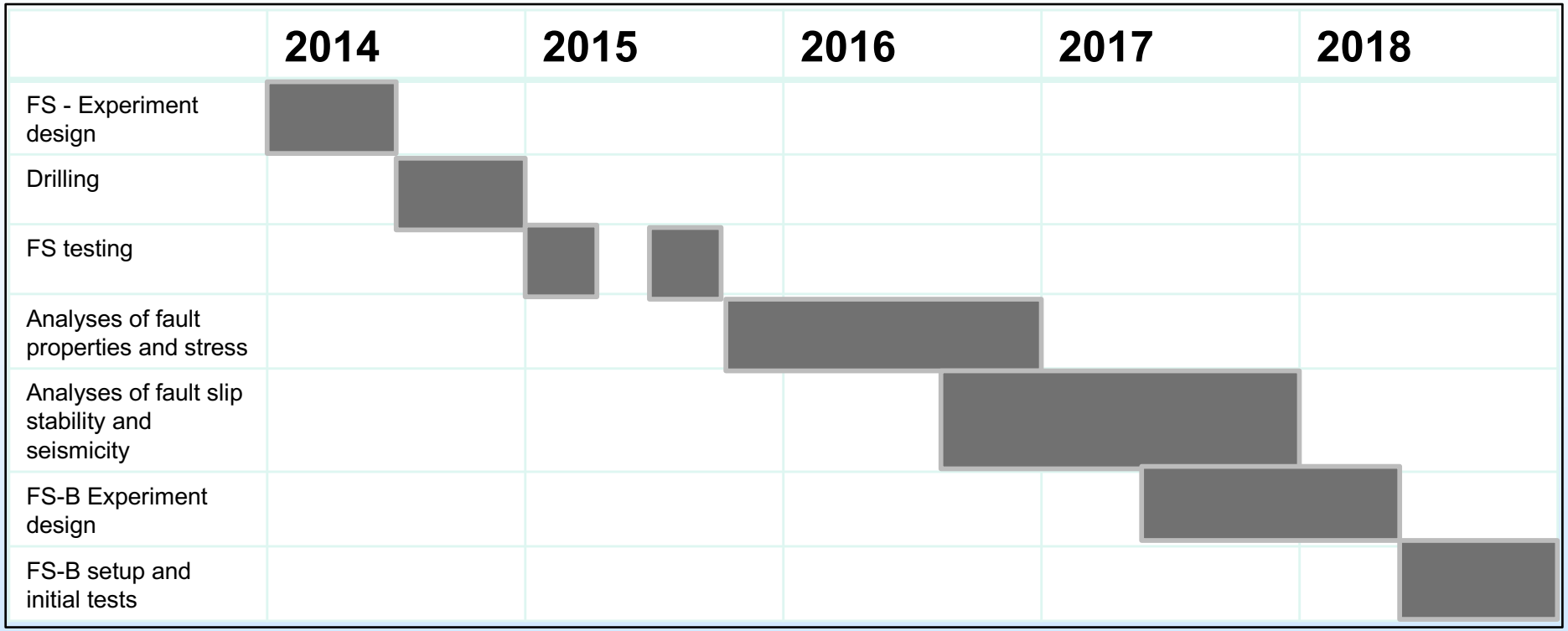
Appendix

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

Organization Chart

- **Project participants: International Collaborations**
  - 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
  - Benoit Valley, Maria Kakurina (University of Neuchatel, Switzerland) – Three-dimensional fault zone geological modeling
  - Frederic Cappa, Louis de Barros (University of Nice, France) – Seismic analysis
  - Kazuhiro Aoki (JAEA, Japan) – Laboratory friction tests
  - Derek Ellsworth, Chris Marone (Penn State University, USA) – Rate and state friction laboratory experiments and modeling

Gantt Chart


2014
2015
2016
2017
2018
FS - Experiment design
Drilling
FS testing
Analyses of fault properties and stress
Analyses of fault slip stability and seismicity
FS-B Experiment design
FS-B setup and initial tests

Bibliography

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