Aseismic fault slip and leakage preceding an earthquake induced during an in-situ fault reactivation experiment in the Opalinus Clay, Mont Terri rock laboratory, Switzerland

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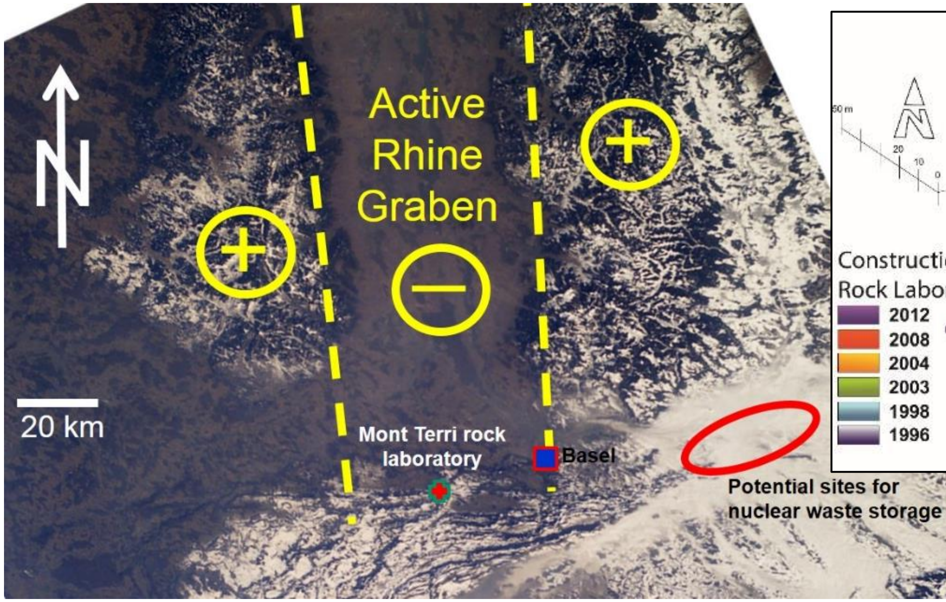
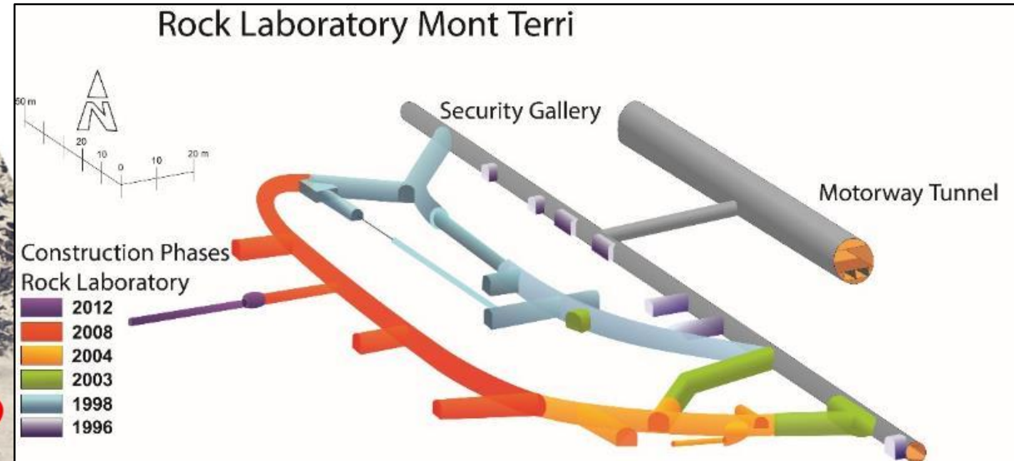
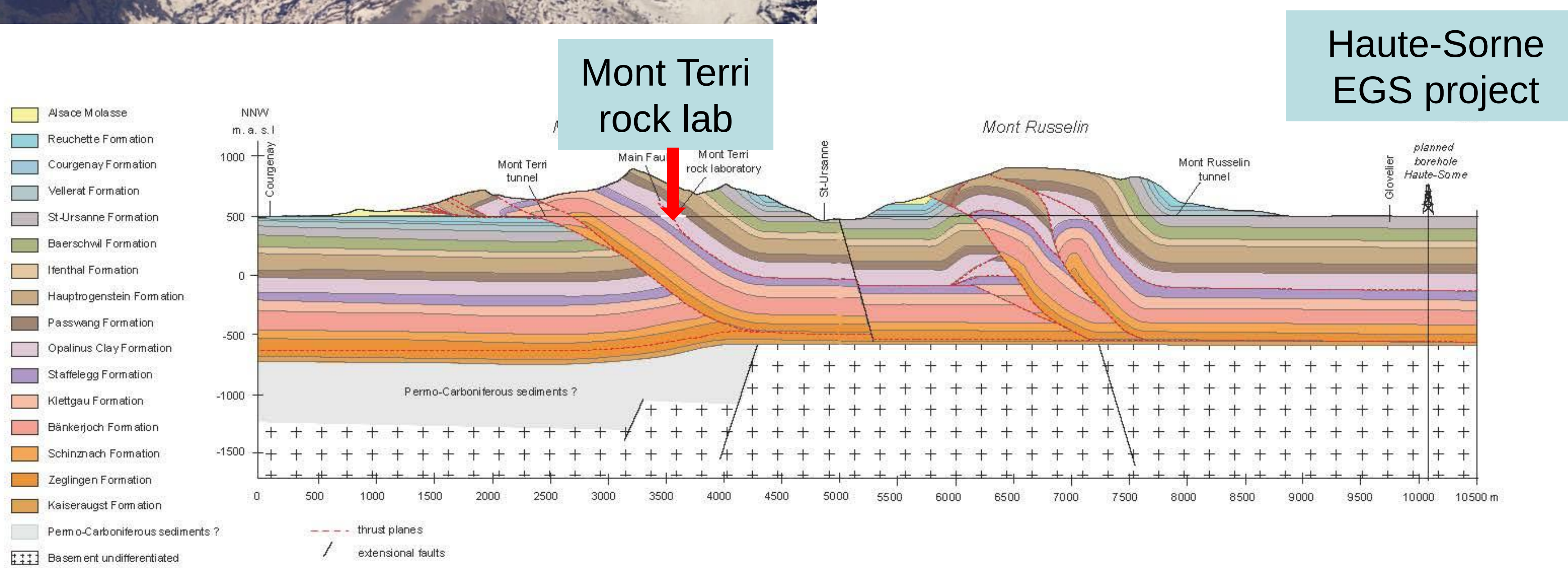
The Mont Terri underground rock laboratory – located in the Alpine foreland (Jura thrust-and-fold belt)





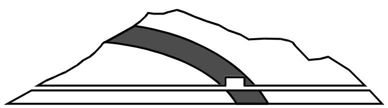


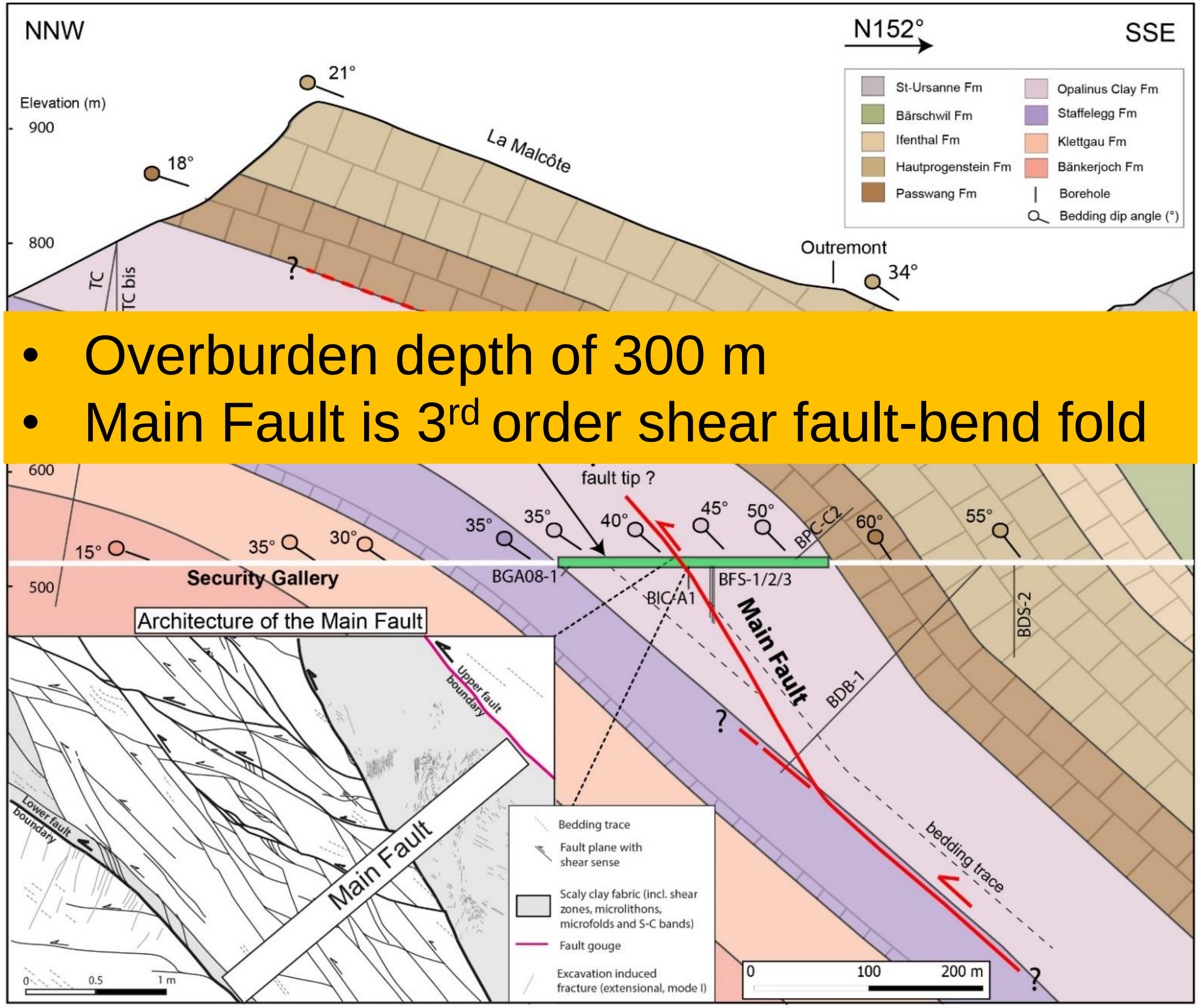
The Mont Terri Consortium: a critical mass of scientific and technological knowledge

- 16 Partners from 8 countries (status in March 2017)
- Operated and under the lead of the Swiss Confederation (swisstopo)
- Implementers and (regulator) safety organisations
- But also oil companies and geological surveys
- More than 1000 scientists, engineers and technicians

Geological context of the stimulated fault zone

Opalinus Clay a shale formation used as host rock and caprock





- Overburden depth of 300 m
- Main Fault is 3rd order shear fault-bend fold

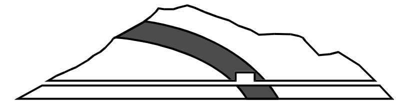
after Nussbaum et al., 2017

Decametre-scale controlled fault activation experiment

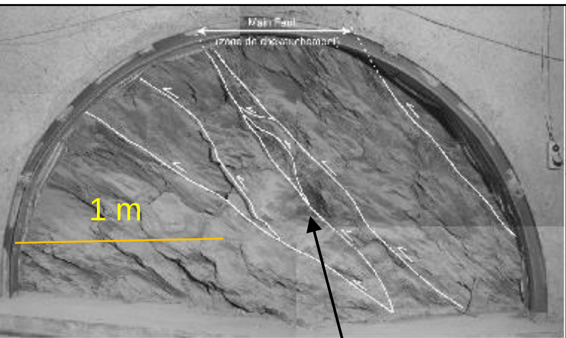
Objectives:

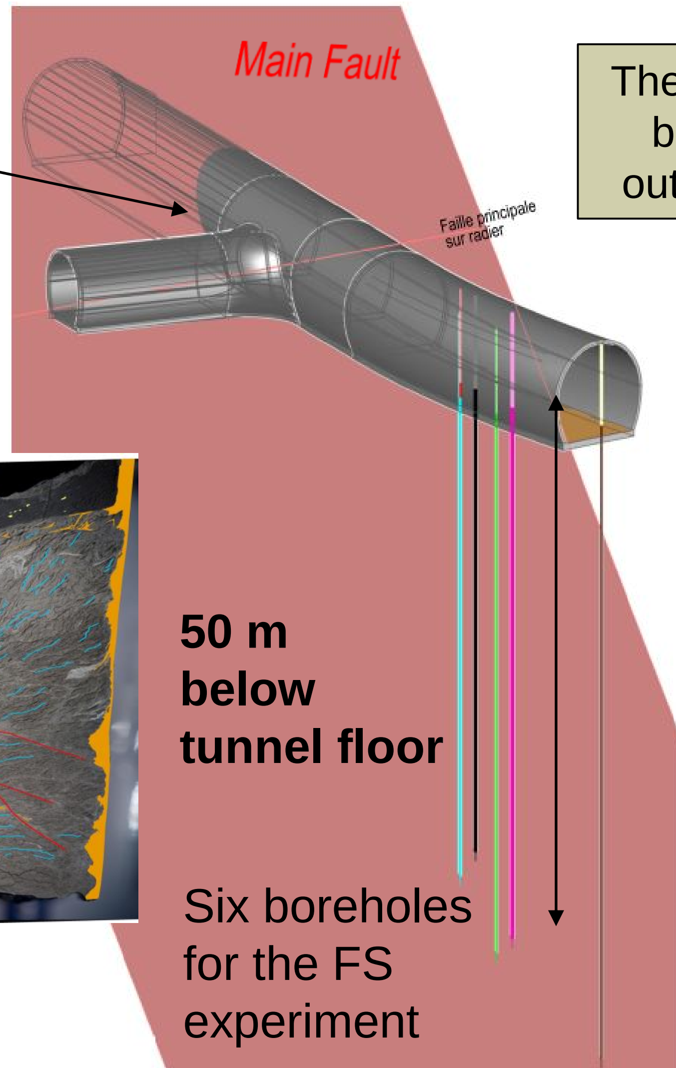
- In situ study of the aseismic-to-seismic activation of a fault zone in a clay/shale formation
  - Conditions for slip activation and stability of faults
- Implications of fault slip on fault permeability
  - Evolution of the coupling between fault slip, pore pressure, and fluid migration
- Tool development and test protocols
  - Development of a tool and protocol to characterize the seismic and leakage potential of fault zones in clay/shale formations

Geometry of the Main Fault



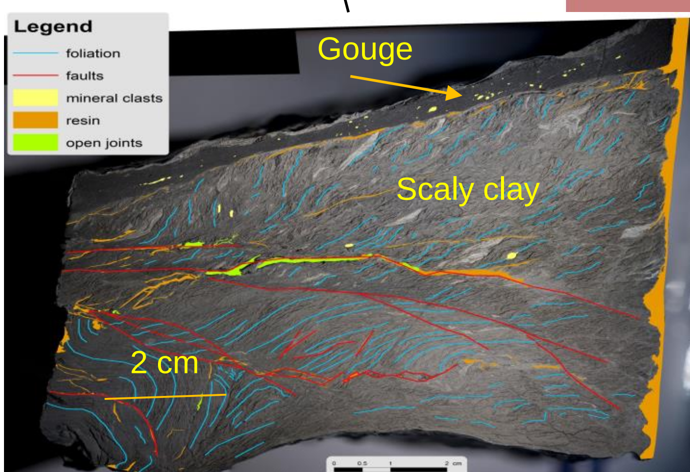
A ~1-5 m-thick core with gouge + secondary (Riedel-like) shear planes
A damage zone with secondary fault planes with slickensided surfaces



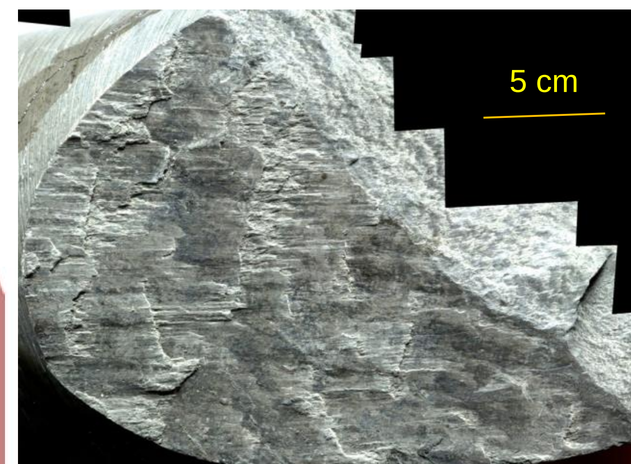


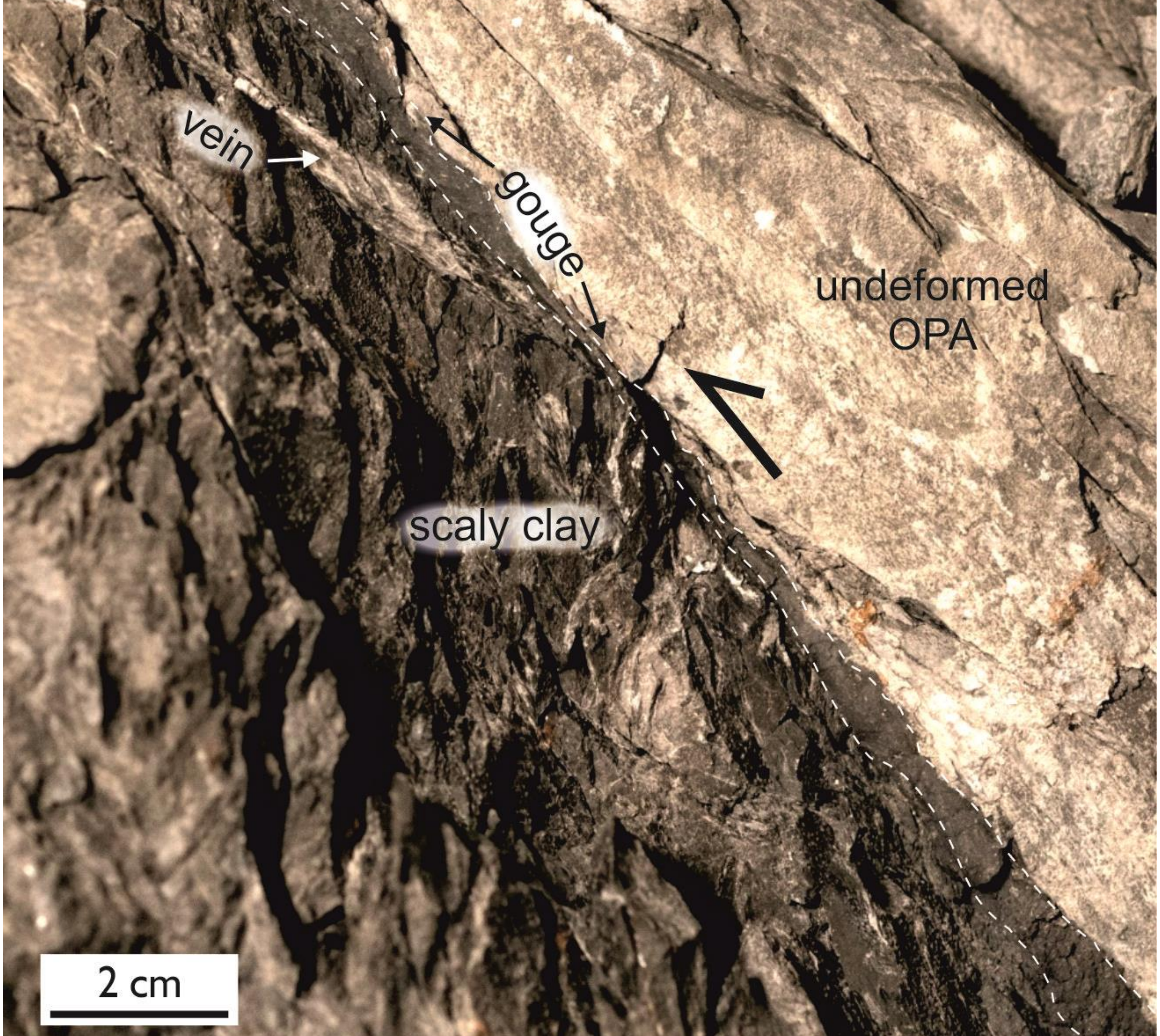
The structure of the Main Fault has been accessed through gallery outcrops and fully cored boreholes

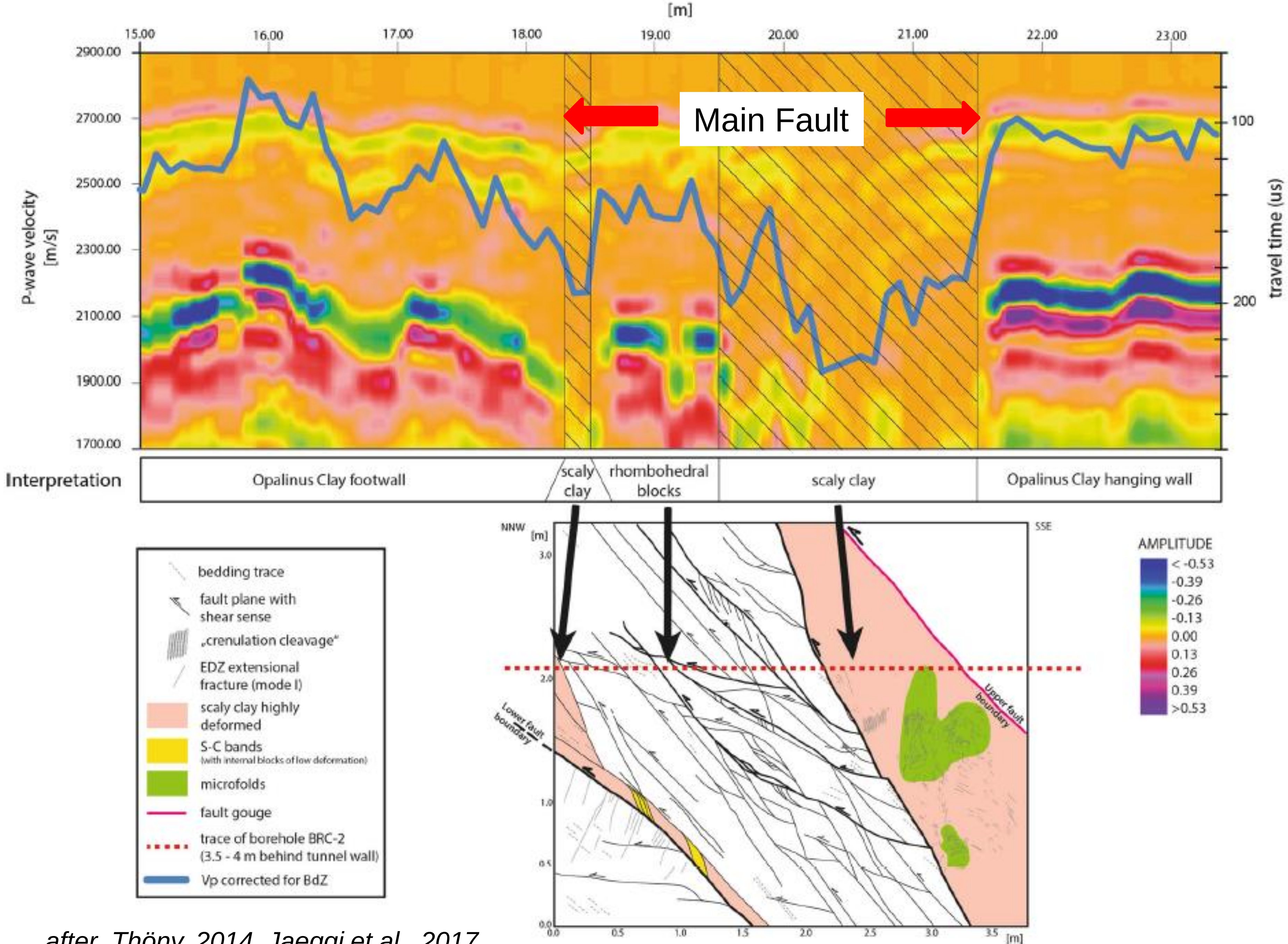
Fault Core



Secondary fault surface in the fault damage zone




vein
gouge
undeformed
OPA
scaly clay
2 cm



after Thöny, 2014, Jaeggi et al., 2017

Methodology: Borehole near-field protocols

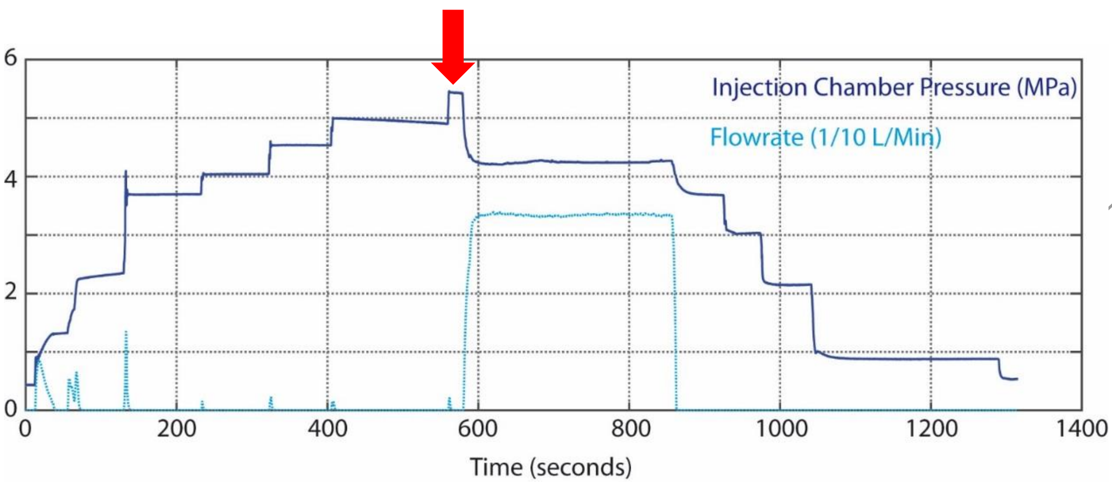
Rock Mech Rock Eng
DOI 10.1007/s00603-013-0517-1

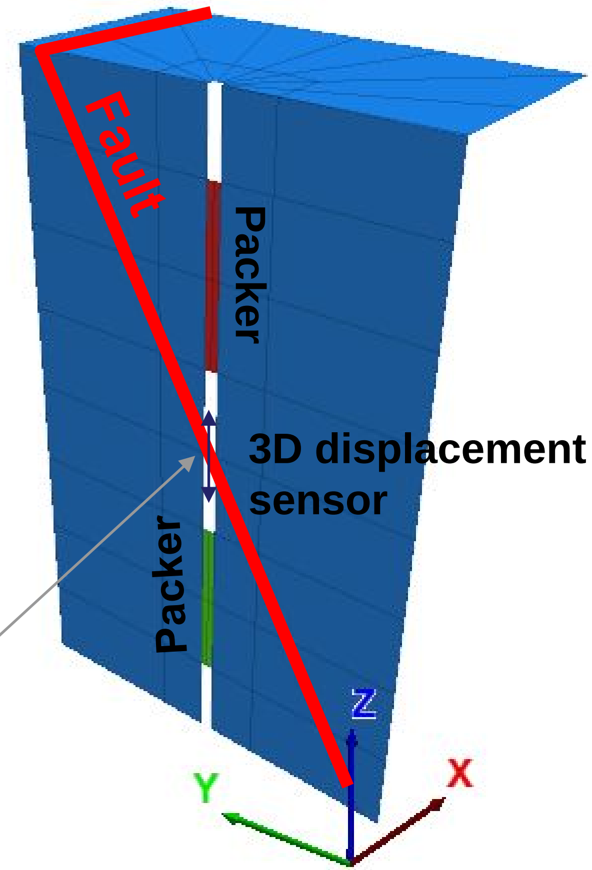
ISRM SUGGESTED METHOD

ISRM Suggested Method for Step-Rate Injection Method for Fracture In-Situ Properties (SIMFIP): Using a 3-Components Borehole Deformation Sensor

Yves Guglielmi · Frederic Cappa · Hervé Lançon · Jean Bernard Janowczyk · Jonny Rutqvist · C. F. Tsang · J. S. Y. Wang

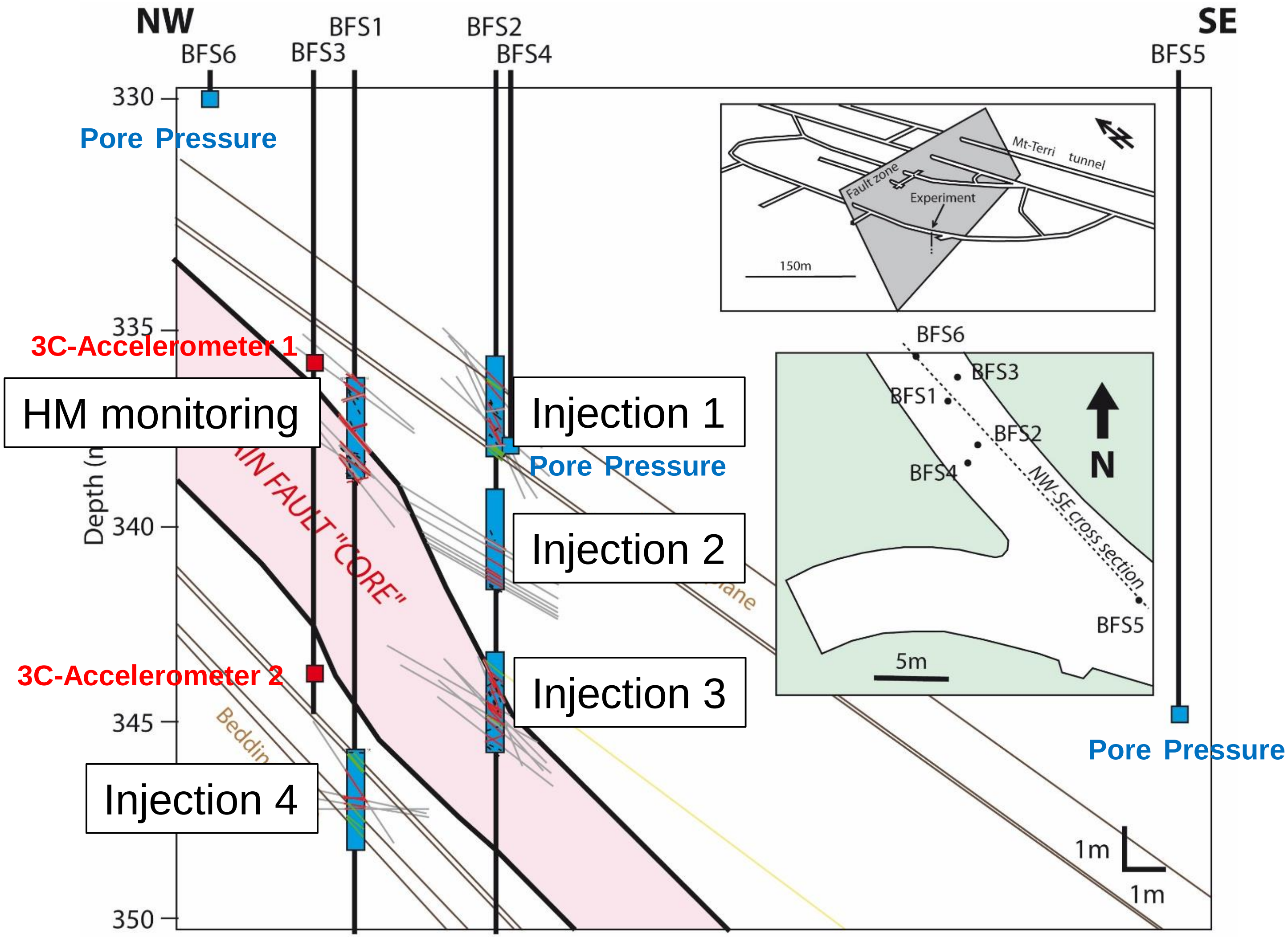
Fault Opening Pressure (FOP)





- **Injection pressure imposed step-by-step** in packed-off intervals set in different fault zone locations
- **Synchronous monitoring** of pressure, flowrate, displacement and micro-seismicity

Experimental setup



Measurement of fault movement and induced seismicity

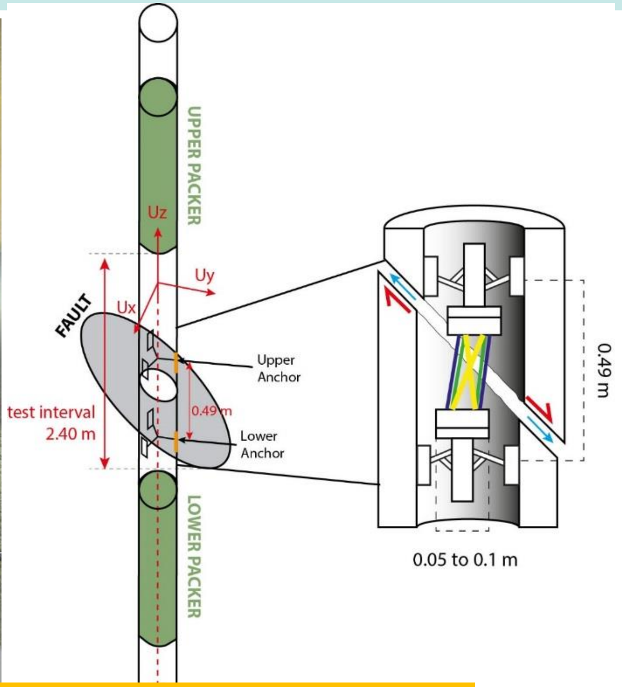
Passive Seismic Monitoring

Two downhole 3C-accelerometers and two geophones

- 3C-accelerometers
- Flat response 2Hz-4kHz
- 10 kHz sampling frequency

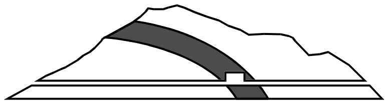
Step-Rate Injection Method for Fault In-Situ Properties (SIMFIP) *Guglielmi et al., 2013*

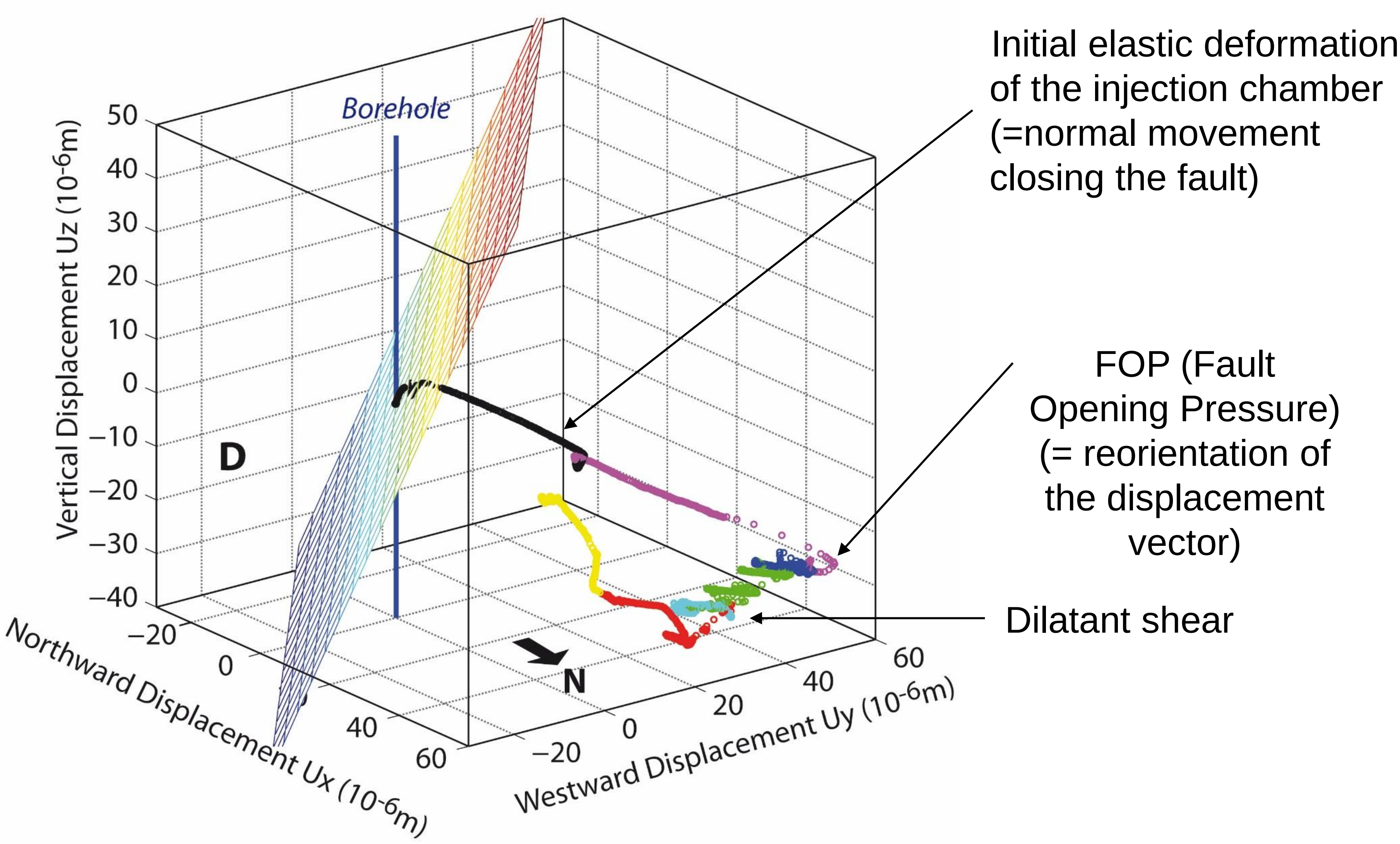
Two 3C-borehole deformation sensor mHPP probe



- Measurement range:
  Uaxial = 0,7mm
  Uradial = 3,5mm
- Resolution of 3µm
- 500 Hz sampling frequency

3D Displacement of fault hangingwall below and above FOP

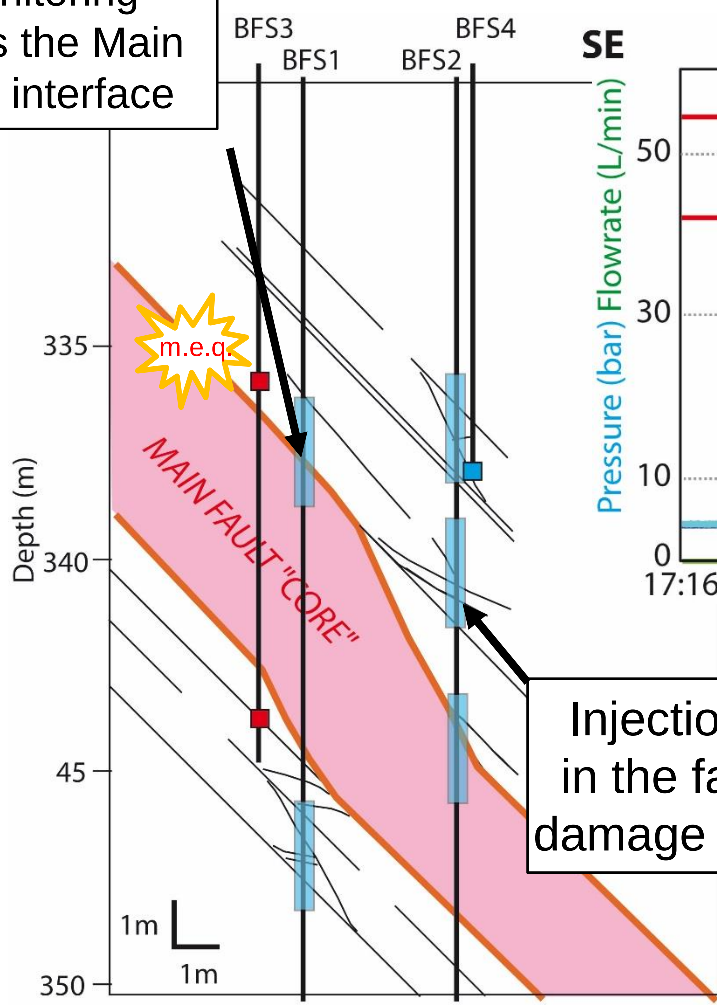




Seismicity observed during fluid pressurization

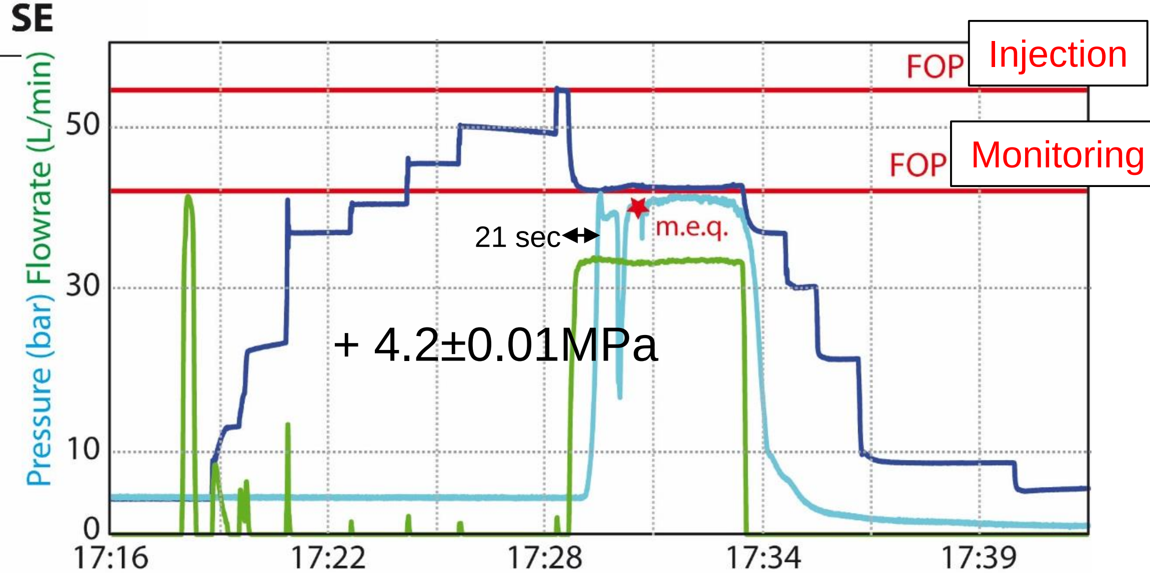
- Occurs along the interface between fault core zone and damage zone
- Occurs after the Fault Opening Pressure (FOP) is reached

Monitoring across the Main Fault interface



Injection 2 in the fault damage zone

Rupture at the injection source (FOP)



FOP Injection > FOP Monitoring

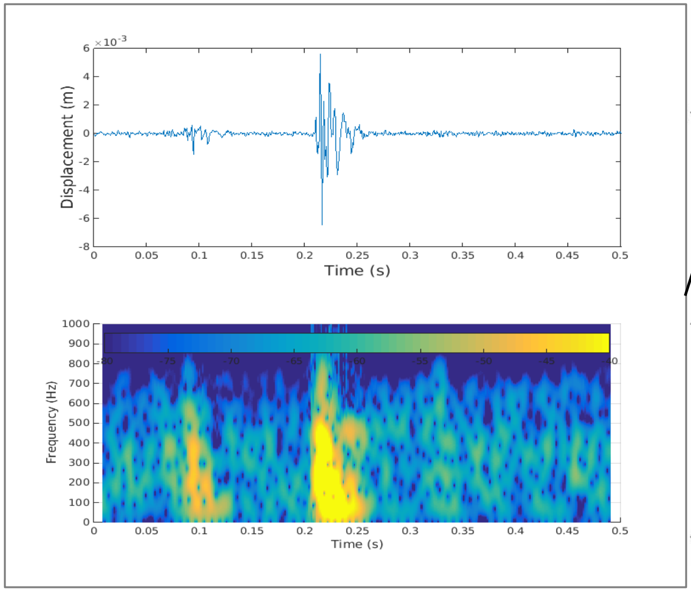
⇨ Interface between fault core and fault damage zone has weaker properties

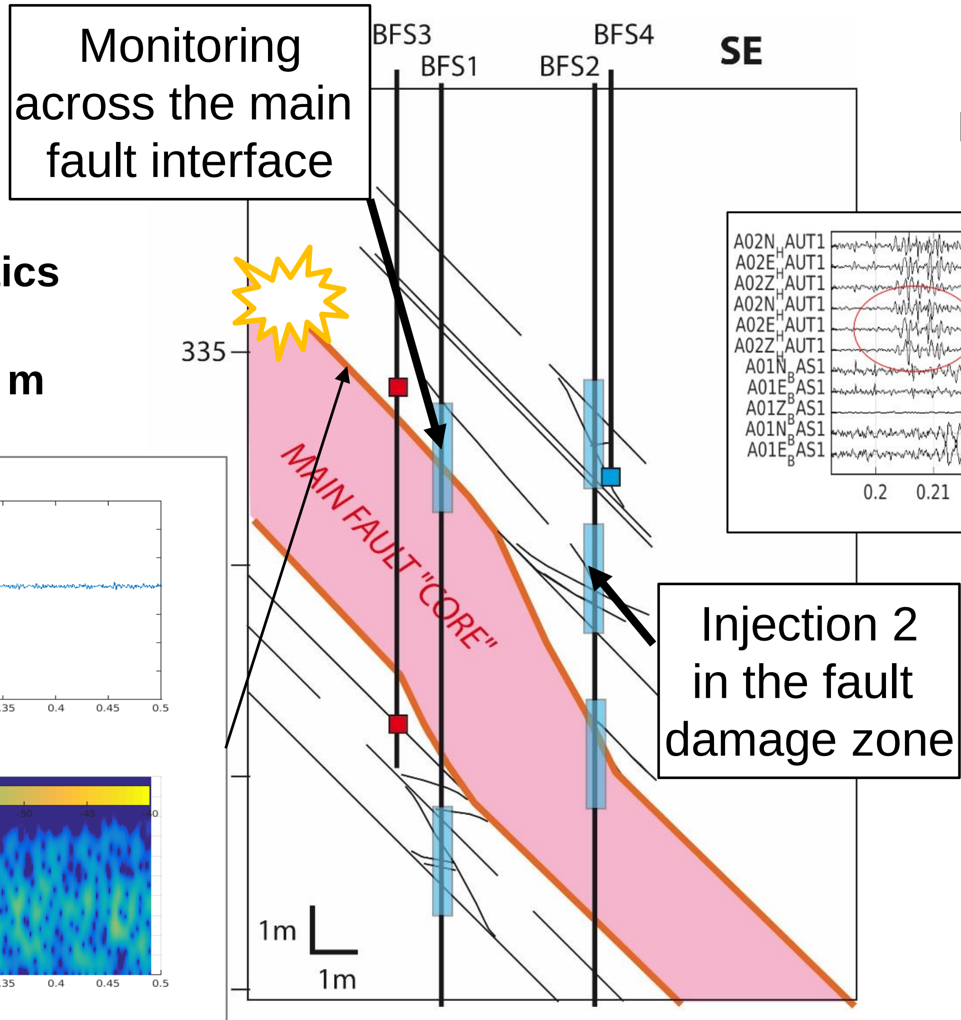
One main earthquake followed by swarm of ca. 15 smaller events

Main EQ characteristics

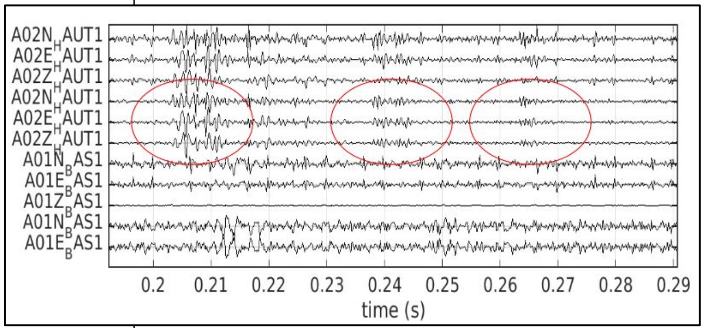
Magnitude ~ -2.5

Source radius ~ 1.2 m





Smaller events? Reactivation of the same/similar area



Spectral analysis and corner frequency of the main EQ

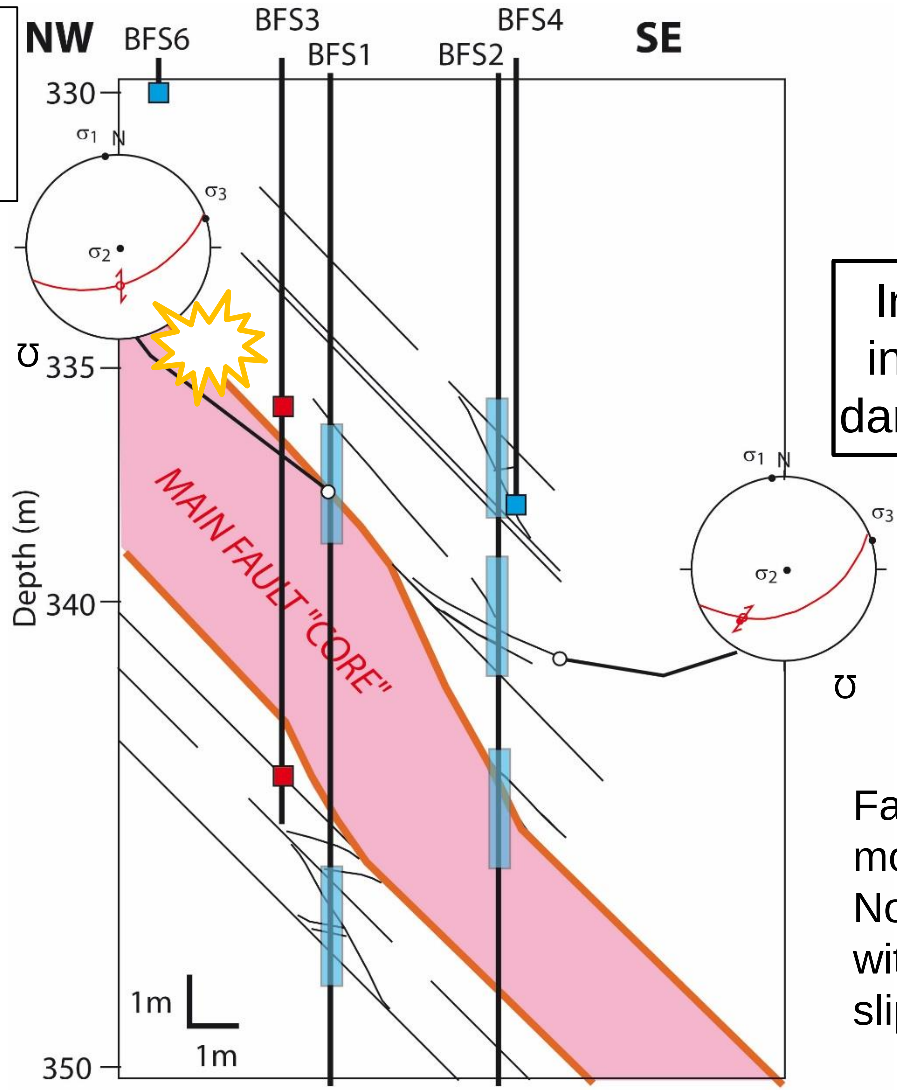
Relationship between seismicity and slip

Monitoring across the Main Fault interface

~0.4 mm reverse slip

-> Slightly different slip mechanisms observed at injection and monitoring points

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



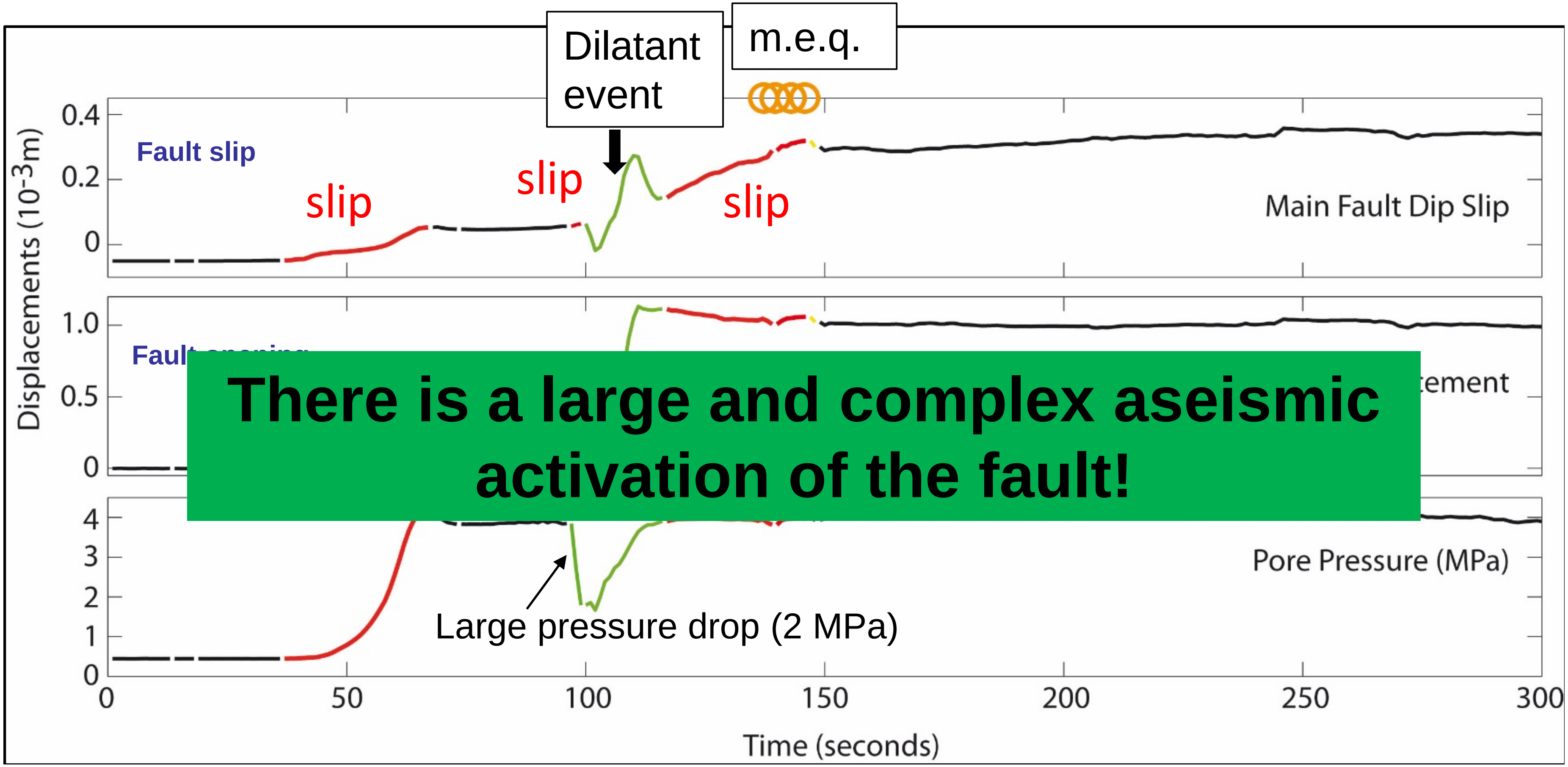
Injection 2 in the fault damage zone

~10 μm normal faulting strike-slip

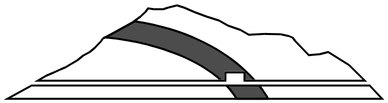
Fault movement: Normal faulting with a strike-slip component

Complex fault movement induced by fluid pressurization

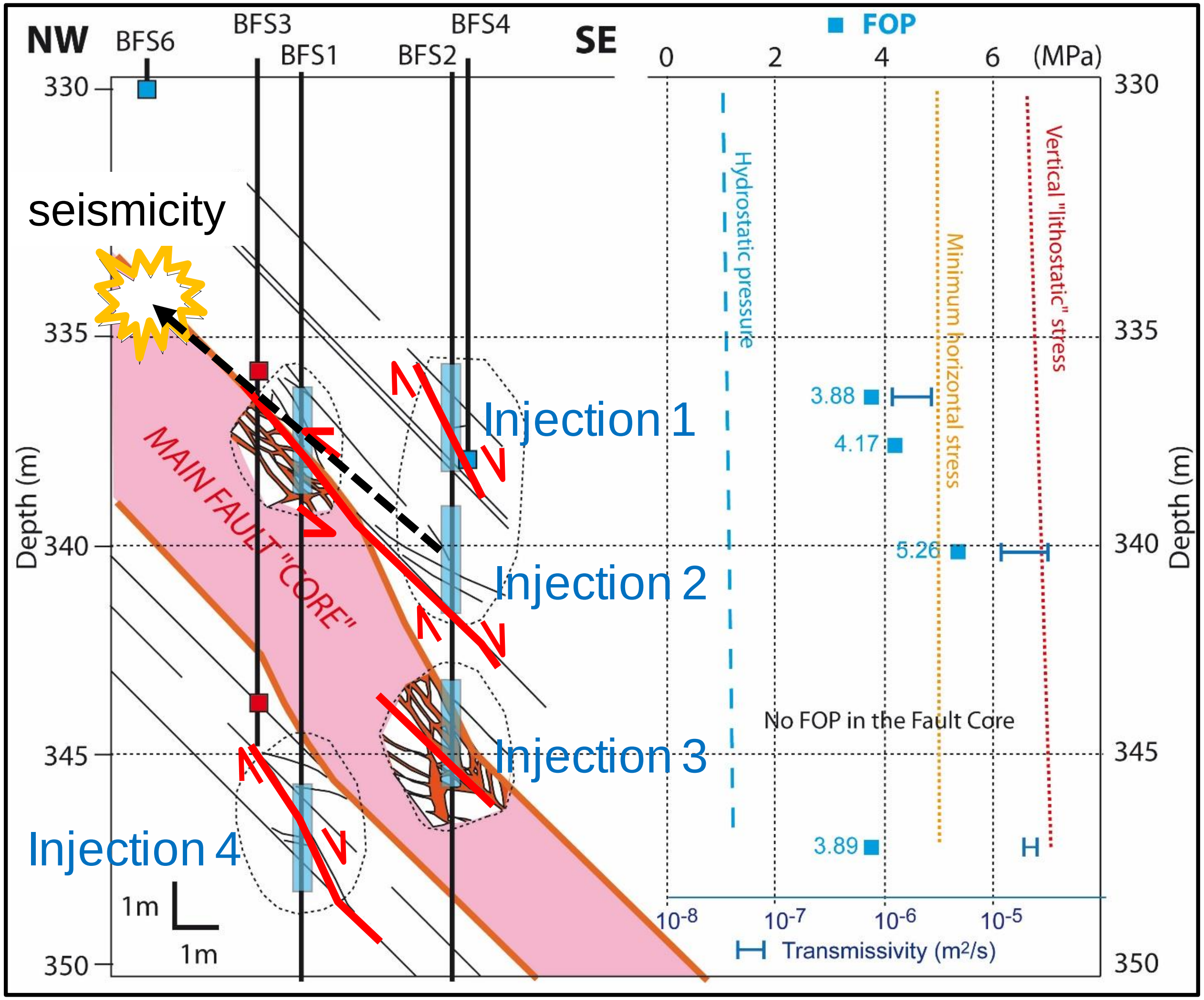
- Alternate slip, no-slip periods and one high-dilatant event
- ~75% of the movement is aseismic
- Large pressure drop (2 MPa) is preceding the induced seismicity
- Seismicity only occurs « last » and is not correlated to significant changes in slip velocity or to the dilatant event

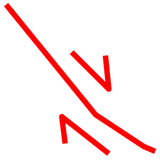


Impact of fault movement on permeability



- Factor of 10^6-to-10^7 transmissivity increase above the Fault Opening Pressure
- Observed in all injection test sections except for the fault core (injection 3)

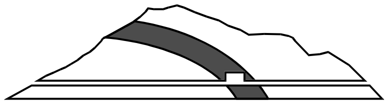


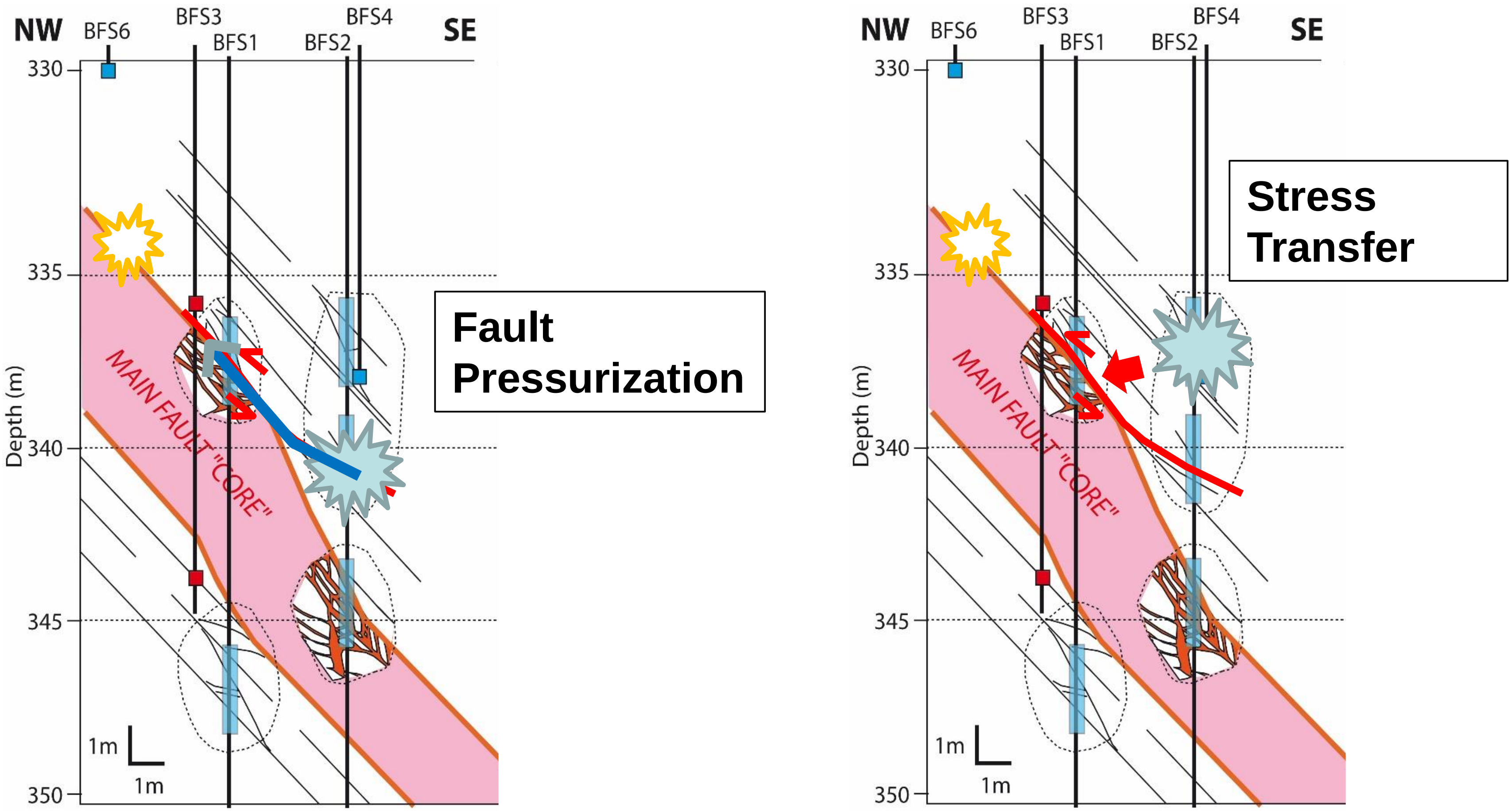


- All fault segments were activated in normal faulting mode in injections intervals
- Seismicity was triggered during injection 2 for the highest slip magnitude (0.4 mm)

Guglielmi et al. 2016

Stress transfer and effective Coulomb stress effects





Slow ruptures of faults and fractures:

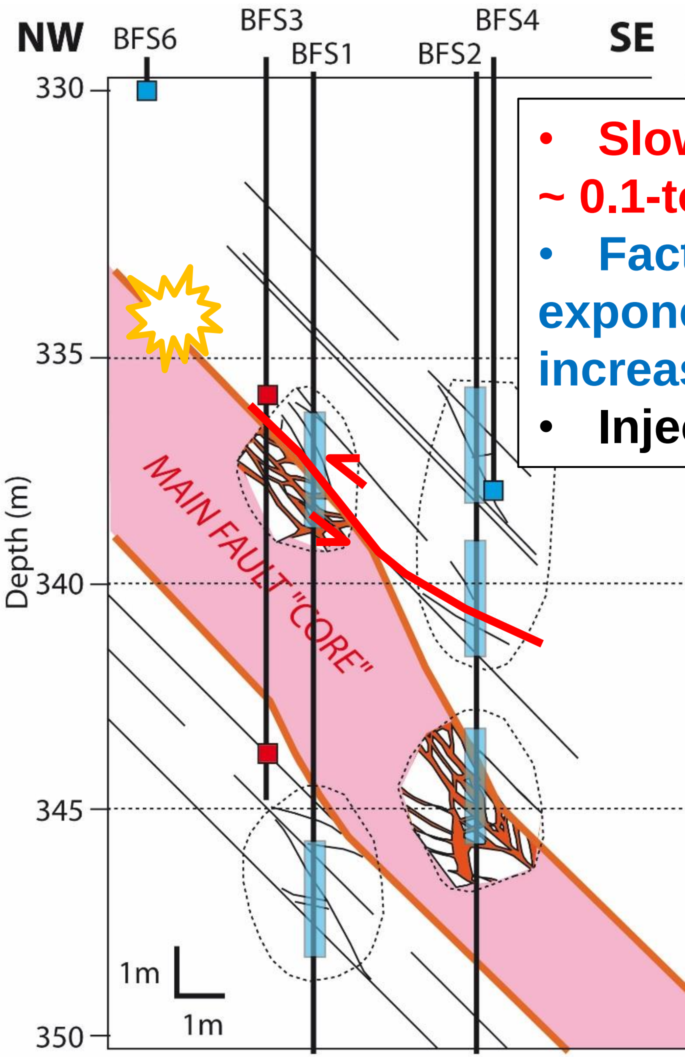
- Radiate low or « unconventional » seismic waves
- Represent large seismic moment in the total rupture
- May be associated to fluid pressurization, to significant permeability increases, and to variation in fault rock strength

Summary and Preliminary Findings

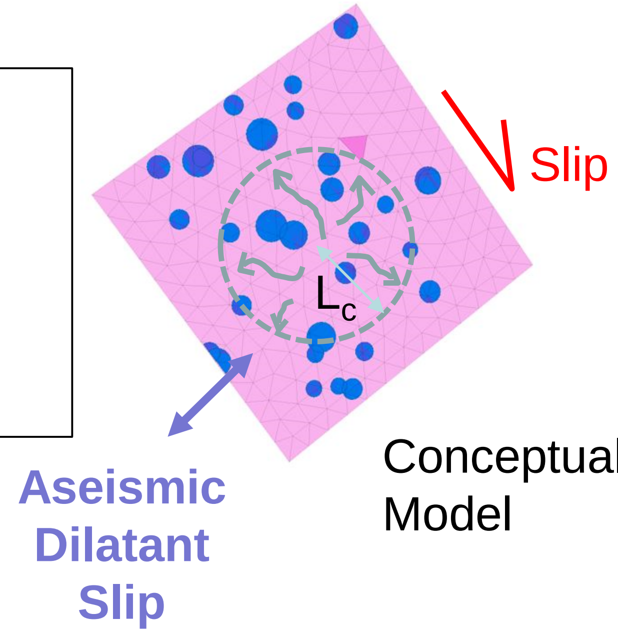
- **Multiple fault reactivations have been produced in situ that allow evaluating mechanisms of faulting and microseismicity induced by increased fluid pressure during injection operations**
  - Factor of ~100 variation of the slip magnitude depending on location
  - Multiple dilatant slow slip (~ 0.1-to-30 μm/s) associated with fluid pressurization with factor-of-1000 increase of permeability, and terminated by a magnitude ~ -2.5 main seismic event associated with a swarm of very small magnitude ones.
  - Size of seismic source (r ~ 1.2 m) << size of pressurized zone (r ~ 5-7 m)

- **Small (micrometer to millimeter) fault displacements are associated with large permeability variations**
  - Though a large fraction of the permeability variations seems reversible
  - Seismic events may not be a reliable indicator for fault leakage

Next experiment (FS-B): Imaging slow rupture effects on the loss of integrity of caprocks



- **Slow slip**
  ~ 0.1-to-30 x 10^{-6}m/s
- **Factor of 10^6-to-10^7 of exponential transmissivity increases**
- **Injected volume ~ 8m³**



Can we image the volume(s) affected by the slow rupture?

- Pressurized zone volume
- Stress transfer zone volume
- Slow slipping patch radius
- Seismic patch radius

Acknowledgments

Paul Bossart (swisstopo)

Bastian Graupner (ENSI)

Kazahiro Aoki (JAEA)

Jens Birkholzer (LBNL)

Klaus Wieczorek (GRS)