Induced fault slip events and their deformation fields: insights from FEAR experiments

Aurora Lambiase[1] (alambiase@student.ethz.ch), Men-Andrin Meier[1,2], Elena Spagnuolo[3], Mehdi Nikkhoo[4], Antonio Pio Rinaldi[1], Valentin Gishig[1], Paul Selvadurai[1], David Marsan[5], Domenico Giardini[2], Stefan Wiemer[1]

[1]Swiss Seismological Service (SED), ETH Zürich; [2]Institut für Geophysik, ETH Zürich; [3]Istituto Nazionale di Geofisica e Vulcanologia (INGV); [4]Helmholtz-Zentrum Potsdam (GFZ); [5]ISTerre, Université de Savoie.

1 Introduction and Motivation

The relationship between pressure fields, aseismic slip, and seismicity remains poorly understood, both in controlled settings like BedrettoLab and at the scale of natural earthquakes. This study benefits from the rare opportunity to measure both slow deformation and seismicity with a dense and highly sensitive monitoring network. We propose a simple and effective approach to **model slip-induced deformation heterogeneities in fault activation experiments** and correlate it with induced seismicity. These models provide a foundation for **inferring seismic and aseismic slip distributions** by **inverting 3D deformation data**, offering new insights into fault mechanics and deformation processes.

2.1 The M-zero experiment

Figure 1: *Cross section of the Bedretto tunnel.*

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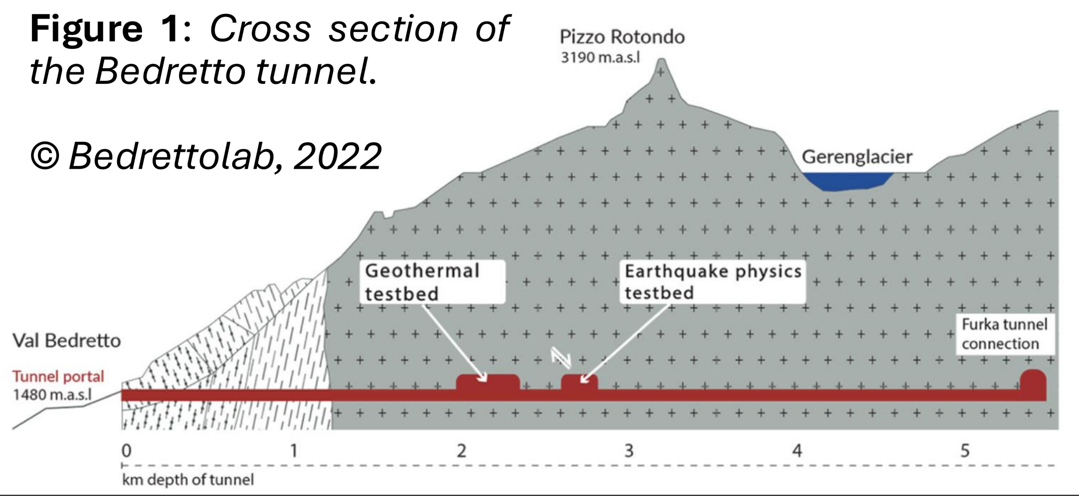


Goal:
To induce a ~Mw0 earthquake with model-informed injection protocols in the geothermal testbed of BedrettoLab

Observations:

- A Mw -0.4 event has been triggered after 4 days of preconditioning and 18 hours of high pressure (20 MPa) injection
- A clear **coseismic response in permanent deformation**, measured by 12 Fiber Bragg Grating (FBG) sensors in two monitoring boreholes (MB1 and MB5), resulting in a step-like behavior of strain vs time(Figure 2)

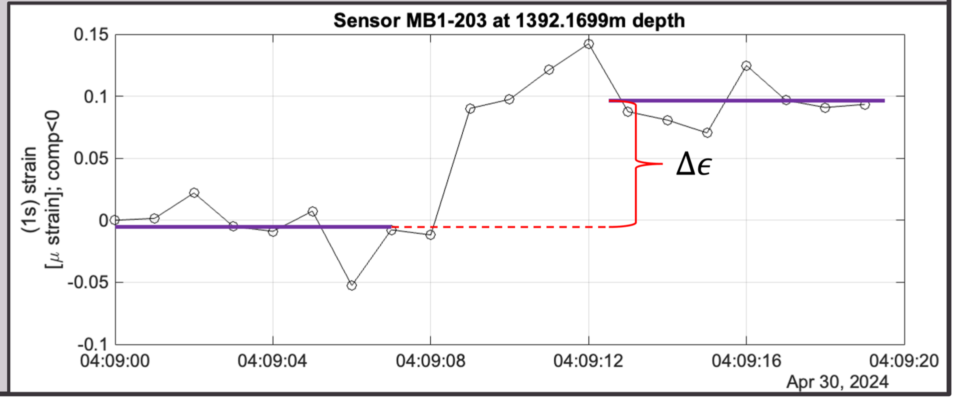


Figure 2: *Example of an FBG strain sensor's response to the M-zero mainshock. The static strain changes are computed on downsampled traces (1 Hz) in a window of 20 seconds around the mainshock time*

2.2 The FEAR1 experiment

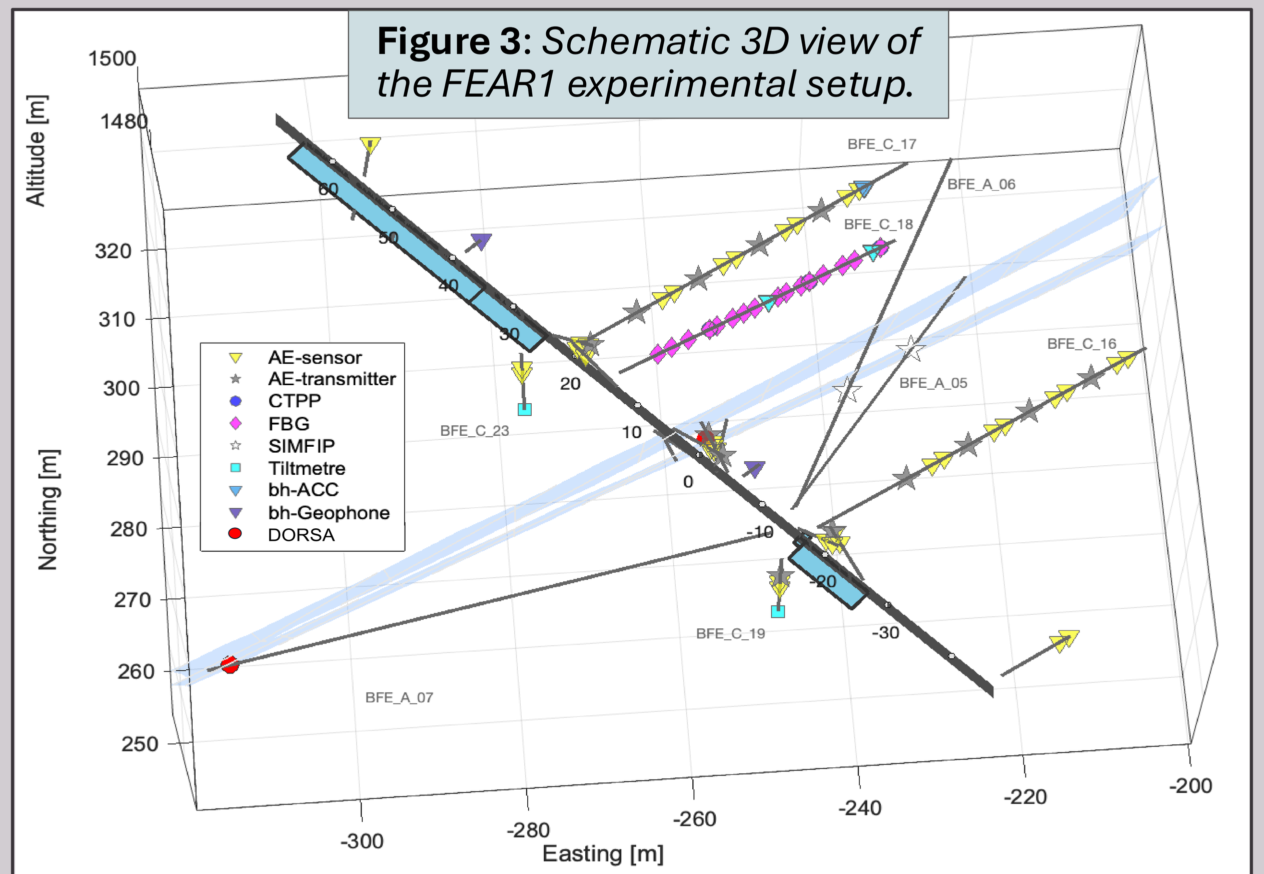
Goal: To characterize the hydro-mechanical response of the target fault zone (MC fault, Achtziger-Zupančič et al., 2024) to fluid stimulation.

Procedure: 14 stimulations in 3 weeks, with different injection strategies and different injection points

Data (Figure 3):

- *On fault (injection points):* pressure, flow, displacement
- Off fault *(monitoring boreholes)*: pressure, temperature, strain, tilts, seismicity

Figure 3: *Schematic 3D view of the FEAR1 experimental setup.*



Observations (Figure 4):

- Transient deformation response correlated with injection.
- Permanent deformation (FBGs, tiltmeters, SIMFIP and wall-DORSA) detected several hours after the end of each stimulation.

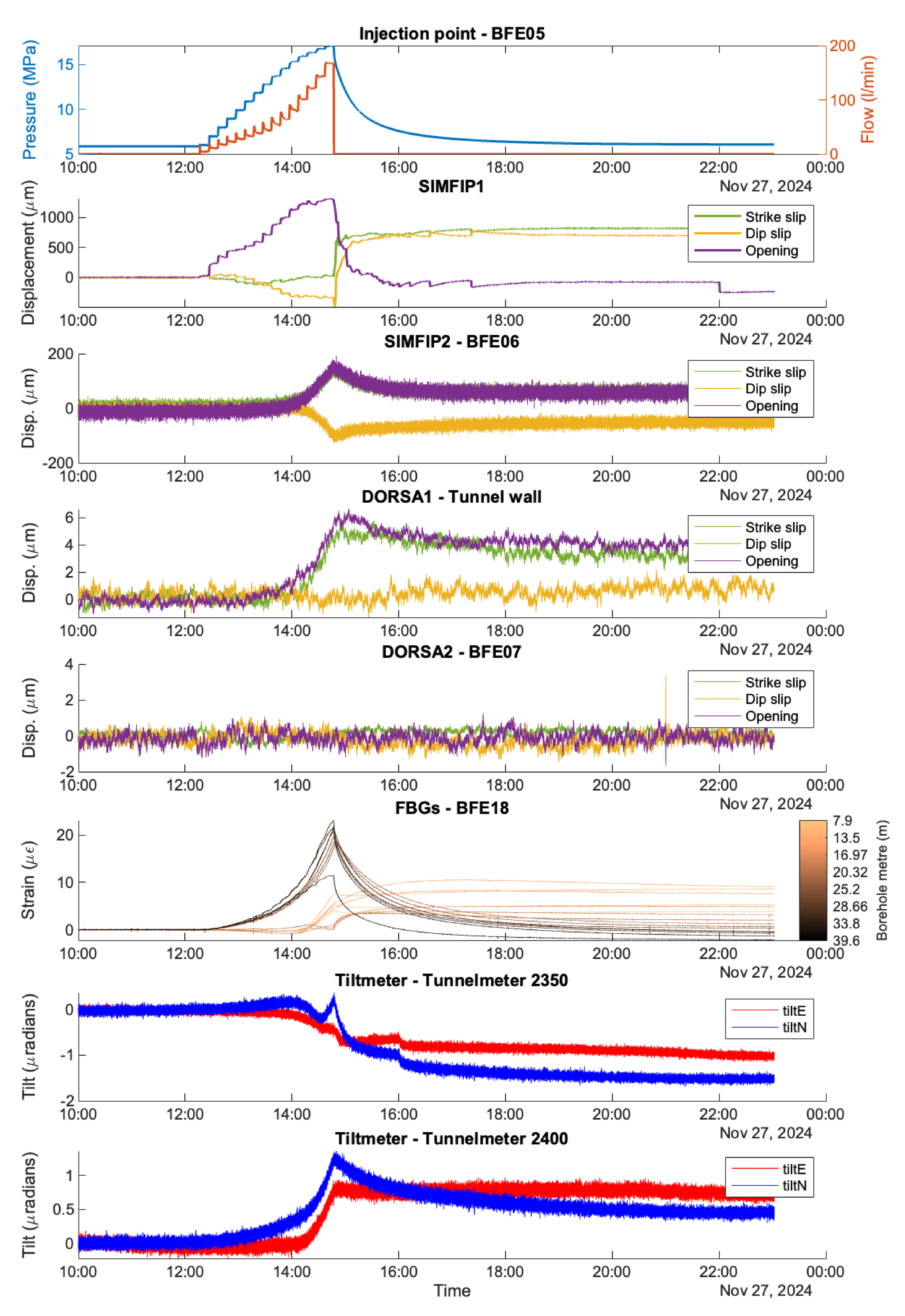


Figure 4: *Hydromechanical response during a HTPF test (Test#7) of the FEAR1 experiment*

3 Deformation modeling

M-zero

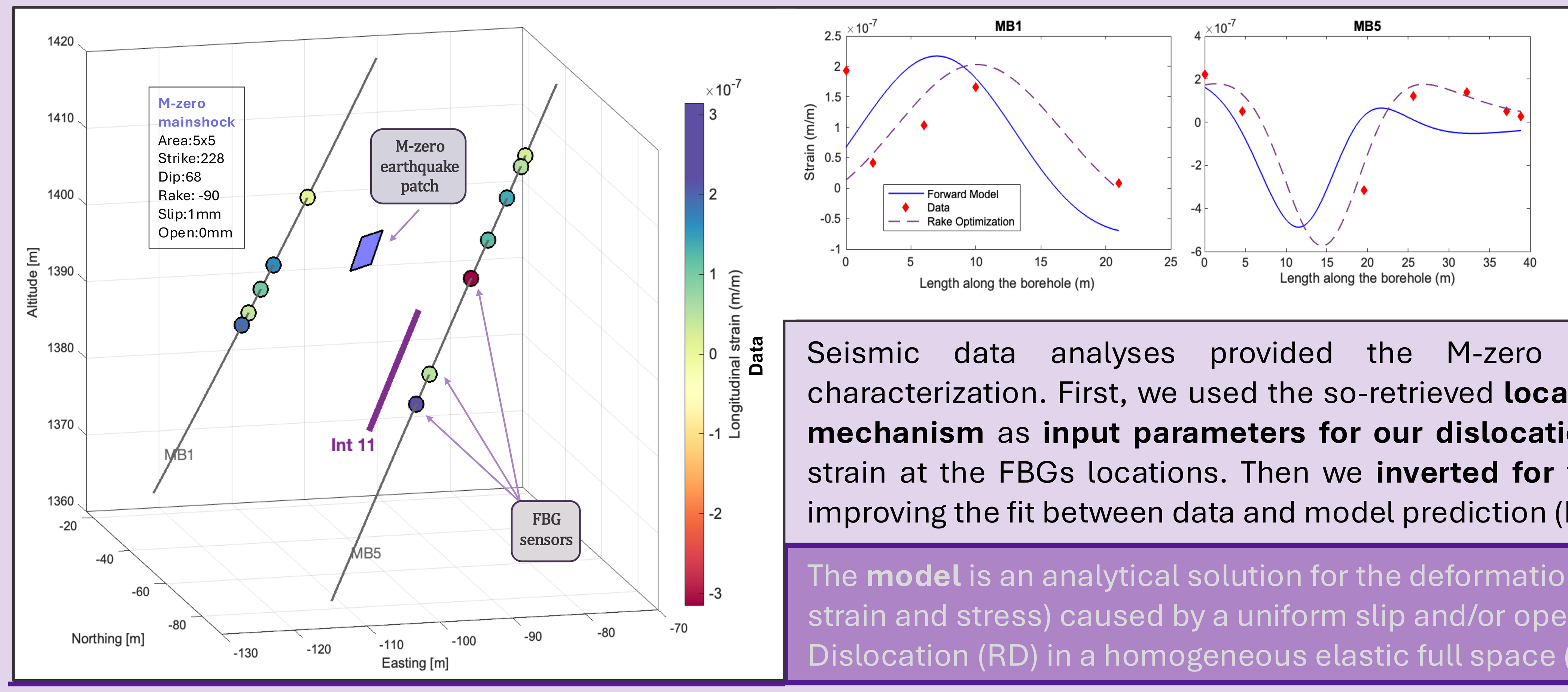


Figure 5: Comparison between *FBG strain data, forward and linear inverse model predictions.*

Seismic data analyses provided the M-zero mainshock source characterization. First, we used the so-retrieved **location, size, and focal mechanism** as **input parameters for our dislocation model** to predict strain at the FBGs locations. Then we **inverted for the slip** parameters, improving the fit between data and model prediction (Figure 5).

The **model** is an analytical solution for the deformation field (displacement, strain and stress) caused by a uniform slip and/or opening on a Rectangular Dislocation (RD) in a homogeneous elastic full space (*Nikkhoo et al., 2017*).

FEAR1

- The observed permanent deformation (Figure 4) might be a signature for the occurrence of aseismic slip events.
- We aim to model this response with three dislocation source patches (Figure 6) optimizing the slip parameters with a linear inversion (Figure 7)

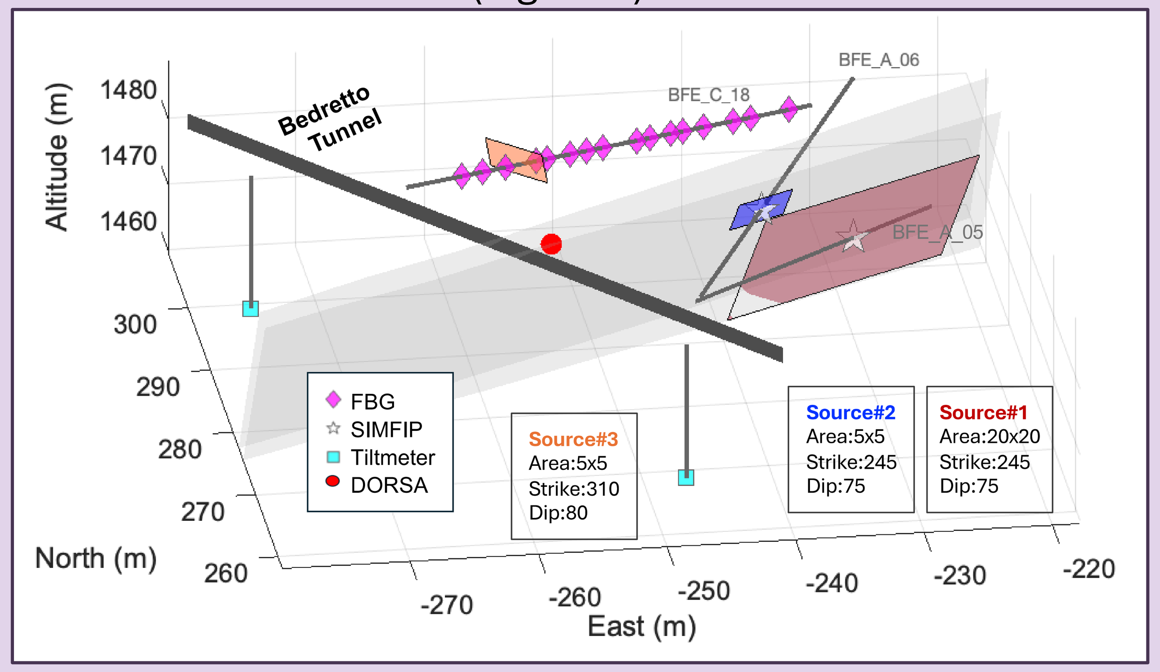


Figure 6: *Source patches configuration adopted for the deformation modeling and for the linear inversion.*

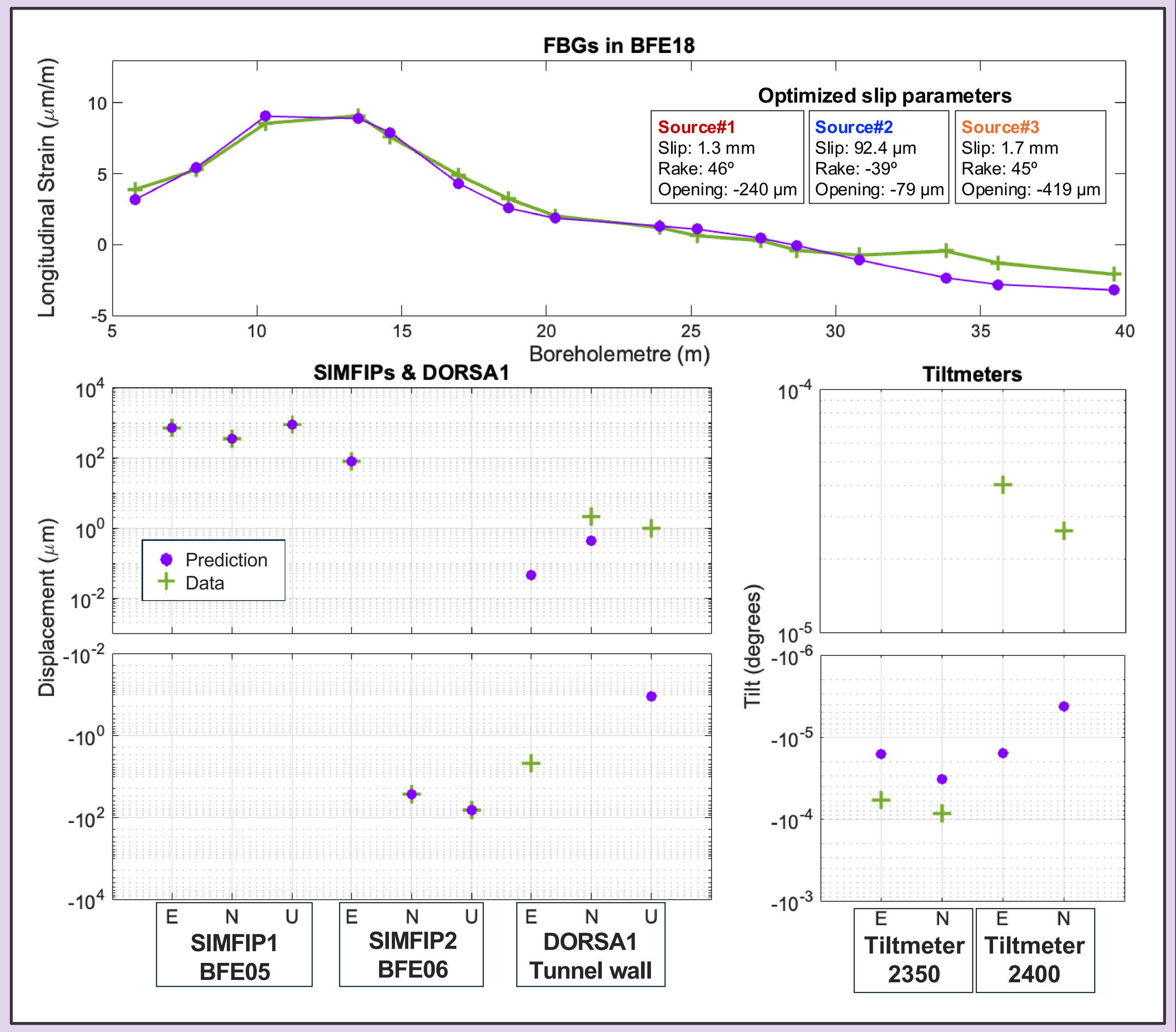


Figure 7: *Linear inversion results of the static strain response observed after Test#7 during **FEAR1** experiment.*

- Source#1 is on the MC fault, at the injection point.
- Source#2 is on the MC fault, centered at the SIMFIP2 location.
- Source#3 intersects BFE18, simulating a dislocation on an existing secondary structure, experiencing seismicity later during the experiment (Figure 8).

4 Conclusions & Future perspective

Simple dislocation models can reproduce observed patterns of **strain** for both **seismic and aseismic slip** events as sources of deformation. But, while the source process in the M-zero experiment was already constrained by seismic data, determining the distribution of aseismic slip triggered during FEAR1 remains challenging.

- Address the **non-linear inverse problem** to better characterize aseismic fault deformation potentially triggered in FEAR1.
- Correlate the characterized **aseismic slip** with the observed **seismicity** to quantify its contribution to triggering and controlling seismic activity (Figure 8).

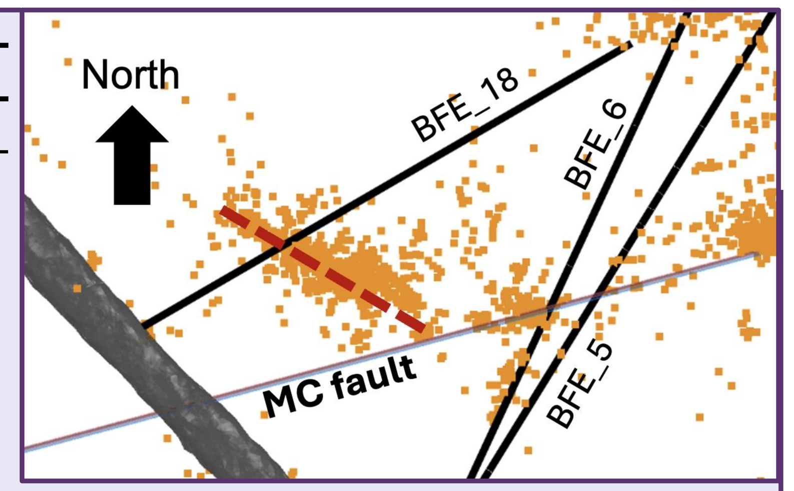


Figure 8: *Part of the detected seismicity as of the end of the FEAR1 experiment. Courtesy of Alberto Ceccato*

References

- Nikkhoo, M.; Walter, T. R.; Lundgren, P. R.; Prats-Iraola, P. Compound Dislocation Models (CDMs) for Volcano Deformation Analyses. *Geophys. J. Int.* **2017**, *208* (2), 877–894.
- Achtziger-Zupančič, Peter Alberto Ceccato, A. S. Zappone, Giacomo Pozzi, Alexis Shakas, Florian Amann, Whitney Maria Behr, Daniel Escallon Botero, Domenico Giardini, Marian Hertrich, Mohammadreza Jalali, Xiaodong Ma, Men-Andrin Meier, Julian Osten, Stefan Wiemer and Massimo Cocco. "Selection and characterization of the target fault for fluid-induced activation and earthquake rupture experiments." Solid Earth (2024)