Modeling Coupled Hydro-Mechanical Processes During Hydraulic Stimulation in a Highly Fractured Fault Damage Zone at the BedrettoLab

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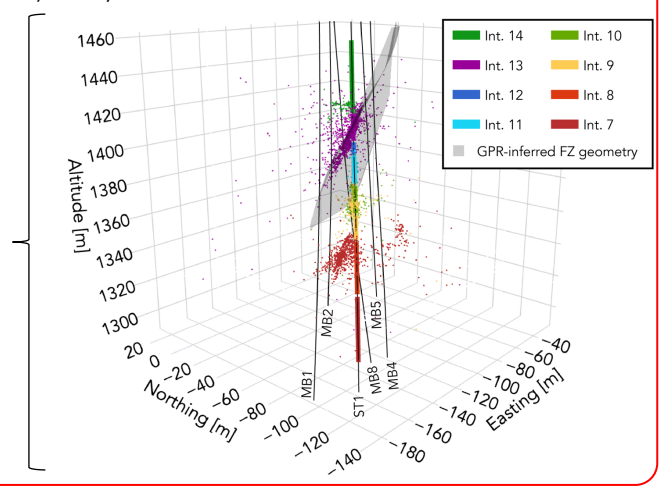
Introduction: VALTER phase 1 interval 13

Physics-based numerical models are crucial for enhancing our understanding of the coupled physical processes governing hydraulic stimulations at depth. In this work, we construct a detailed 3D numerical model to simulate the hydraulic stimulation in VALTER phase 1 interval 13 at the BedrettoLab, where:

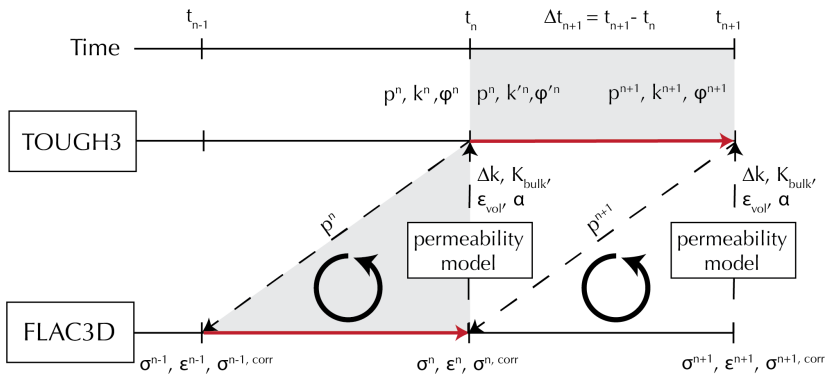
- Water was injected into a highly fractured fault damage zone at high flow rates (up to 150 L/min, *Bröker et al. (2024)*).
- The 2'417 recorded HQ seismic events predominantly align with the main fault zone (*Obermann et al., 2024*).

High-resolution monitoring zone (*Plenkers et al., 2023*) and seismicity recorded during VALTER phase 1. The gray-shaded area depicts the GPR-inferred geometry of the main fault zone by *Escallon et al. (2024)*



TOUGH-FLAC and model setup

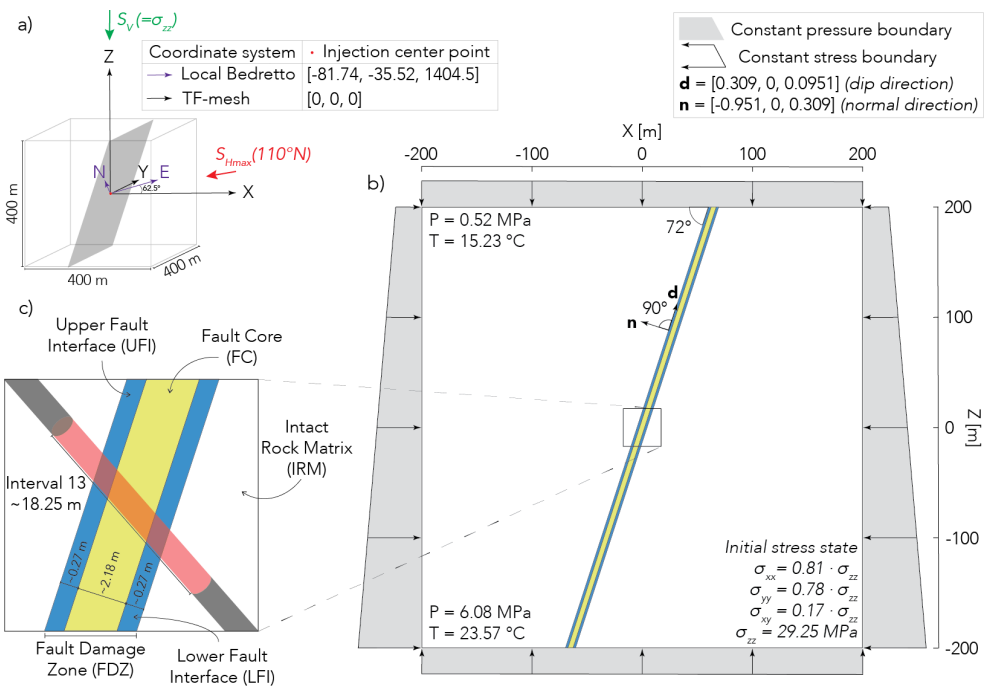
- TOUGH3 is a multiphase and multicomponent fluid flow simulator in porous/fractured media *(Jung et al., 2018)*.
- FLAC3D v7.0 solves for geomechanical equilibrium.



- Permeability model based on *Rinaldi and Rutqvist (2019)* but without tensile fracture opening and porosity changes:

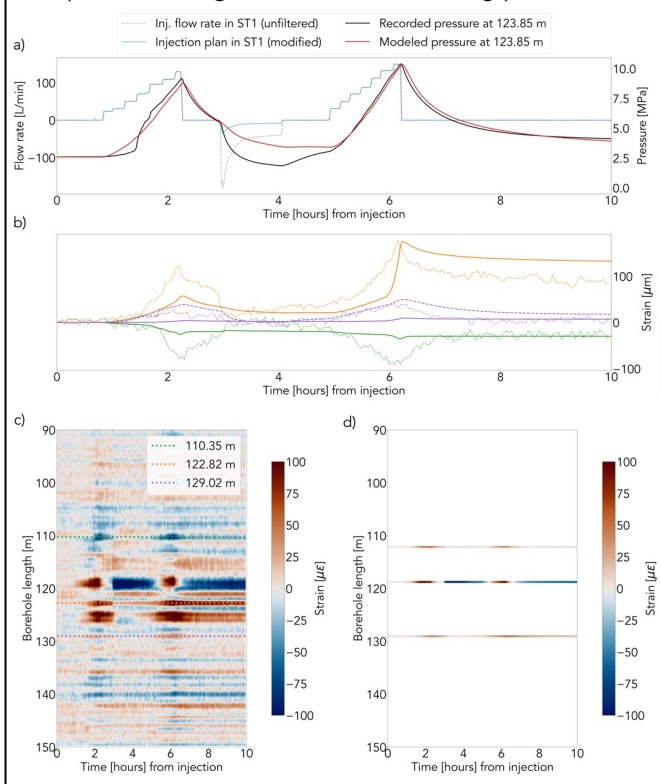
$$k = \left(\frac{b}{b_i}\right)^3 k_i \qquad \text{with:} \qquad b = b_{el} + b_{ps}$$

- Biot coefficient (α) determines the poroelastic coupling strength (*Goebel and Brodsky, 2018*) ➜ α = 0.6 for FDZ and 0.47 for IRM.



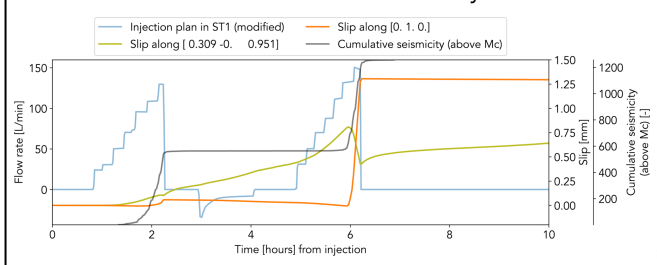
Results – observations fit & fault slip

- We compare our model results with observed pressure changes and strain measurements at the closest monitoring borehole to injection (MB8).
- Our model effectively replicates the observations, particularly the strain pattern along MB8 and the resulting permanent deformation (plasticity).



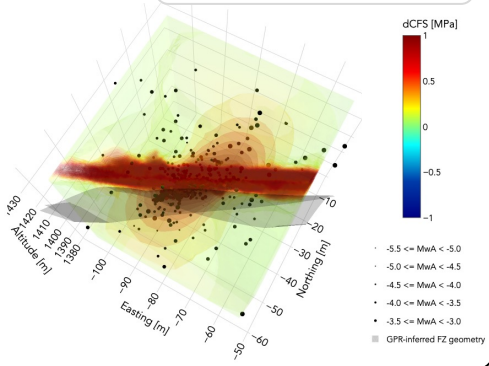
Data and model fit to observations for MB8:
a) Hydraulic data and pressure fit; b) Strain timeseries comparison above (green), within (orange) and below (purple) the FDZ; c) DSS; d) FBG; e) TF-model waterfall plot

- How to relate to induced seismicity?



Comparison of the modified injection plan (blue) with LFI slip at MB8 along strike (orange) and dip (olive green) directions and cumulative seismicity (above Mc). Cycle 2 slip indicates strike-slip to normal faulting, aligning with a 11.13° rake from positive Y towards the dip, based on the in-situ stress state.

- ΔCFS at 6 hours from injection is mapped with all events from the next 30 minutes. The modeled planar fault zone shows high ΔCFS values, while the grey-shaded structure represents the GPR-inferred fault zone.
- Most seismic events aligned with either the modeled or GPR-inferred fault zone.
- However, some events occur outside the FDZ, mainly in regions of higher ΔCFS.



Conclusions and Outlook

- Key observations (pressure and strain) are reproduced under the assumption of a planar fault zone with two interfaces and strong poroelastic coupling.
- The model struggles to capture elastic changes, to which the data is more sensitive.
- Model results and in-situ stress measurements suggest predominant strike-slip to normal faulting upon reactivation.
- We aim to:
  - Use fitted planes to seismicity clusters to relate them to model parameters.
  - Use focal mechanisms to better constrain the dominant slip behavior.

References

Bröker et al. (2024): Hydromechanical characterization of a fractured crystalline rock volume during multi-stage hydraulic stimulations at the BedrettoLab. *Geothermics*, 124; ***Escallon et al. (2024)***: Modelling and inferring fracture curvature from borehole GPR data: A case study from the Bedretto Laboratory, Switzerland. *Near Surface Geophysics* 22, 235-254; ***Goebel and Brodsky (2018)***: The spatial footprint of injection wells in a global compilation of induced earthquake sequences. *Science*, 361, 899-904; ***Jung et al. (2018)***: TOUGH3 User's Guide DISCLAIMER; ***Obermann et al. (2024)***: Seismic Response of Hectometer-Scale Fracture Systems to Hydraulic Stimulation in the Bedretto Underground Laboratory, Switzerland. *JGR: Solid Earth*, 129(11); ***Plenkers et al. (2023)***: Multi-Disciplinary Monitoring Networks for Mesoscale Underground Experiments: Advances in the Bedretto Reservoir Project. *Sensors*, 23(6); ***Rinaldi and Rutqvist (2019)***: Joint opening or hydroshearing? Analyzing a fracture zone stimulation at Fenton Hill. *Geothermics*, 77, 83-98.