Fracture slip estimation from in-situ strain measurements and logging data

unine Université de Neuchâtel | ETH zürich | Bedretto Lab

Contact:

Kai Bröker[1], Benoît Valley[1], Florian Soom[2], Paul Cook[2], Yves Guiglielmi[2], Marian Hertrich[3]

[1] University of Neuchâtel, Center for Hydrogeology and Geothermics, Switzerland
[2] Lawrence Berkeley National Laboratory, Energy Geoscience Division, USA
[3] ETH Zürich, Department of Earth Sciences, Switzerland

1 Introduction

Direct on-fault measurements of slip in boreholes

- In-situ stress fields control fault slip, influencing both slip magnitude and direction, as well as potential seismicity
- Direct on-fault observations of slip in (deep) boreholes are rare, limiting our ability to directly link stress conditions to fault reactivation
- We integrate SIMFIP probe measurements (Step-Rate Injection Method for Fracture In-Situ Properties = real-time 3D displacement) with acoustic televiewer (ATV) imaging to improve fault slip characterization

Bedretto Underground Laboratory for Geosciences & Geoenergies

- Bedretto Underground Laboratory for Geosciences & Geoenergies
- Earthquake physics testbed (Fig. 1): Experiments on Fault Activation and Earthquake Rupture (FEAR)
- Geology: Rotondo granite
- Overburden: > 1100 m and multiple large fault zones in the volume
- Borehole BFE_A_05 dips 31° towards NE (≈ N30°E)
- On this poster: test interval 1 at 81 m MD (measured depth)

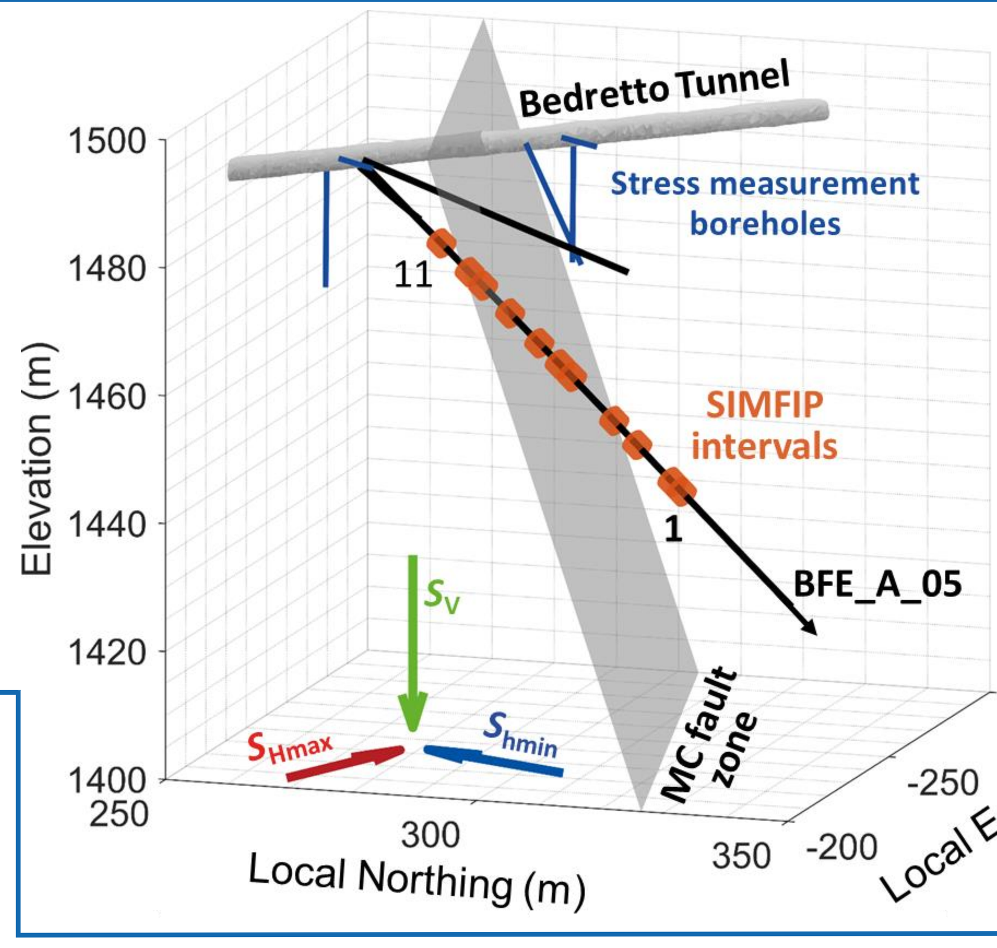


Fig. 1 Location of the SIMFIP test intervals in the Earthquake physics Testbed at the BedrettoLab. Note that not the full length of borehole BFE_A_05 is show. Far-field stress taken Bröker et al. (2024).

2 Transient displacement from SIMFIP data

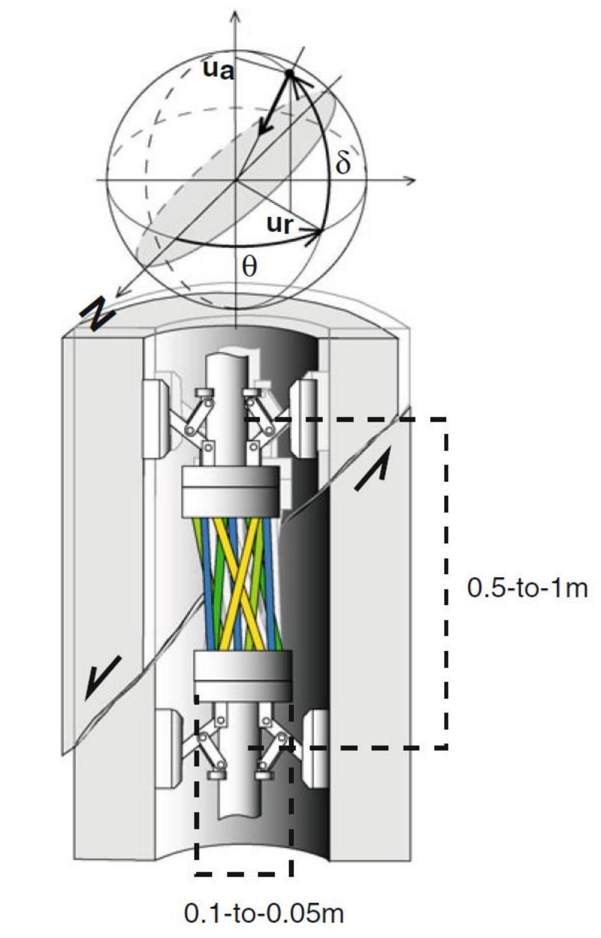
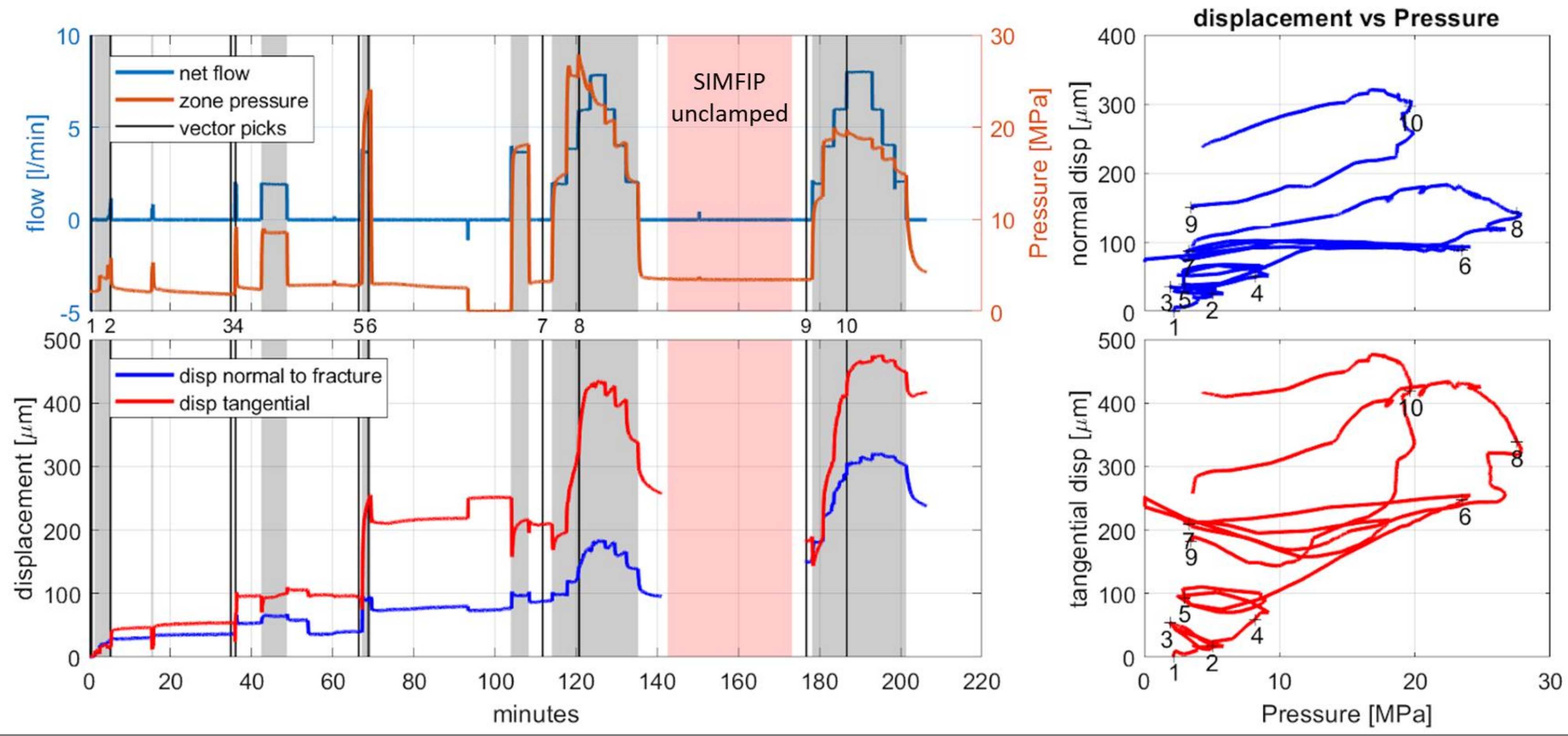


Fig. 2 Schematic view of the SIMFIP 3D displacement measurement unit (Guglielmi et al., 2014).

- SIMFIP is a downhole probe that directly measures 3D displacement (normal opening, shear movement, and closure) of a borehole interval during fluid injection (Fig. 2)
- Probe is installed within an isolated borehole section between two inflatable packers, allowing real-time monitoring of fracture slip and deformation in response to controlled pressure changes
- We injected 250 L of water during multiple constant flow rate and step rate cycles
- We estimated the slip or activation vector by isolating only the steps where pressure, flow, and non-elastic displacement of the rock, indicate the activation of the fracture (Fig. 3)
- The activation vector is the sum of the individual picked vectors

Fig. 3 a) SIMFIP injection protocol and b) measured displacement projected onto the fracture. c) & d) show the normal and tangential displacement against pressure, respectively.



3 Permanent displacement from ATV data

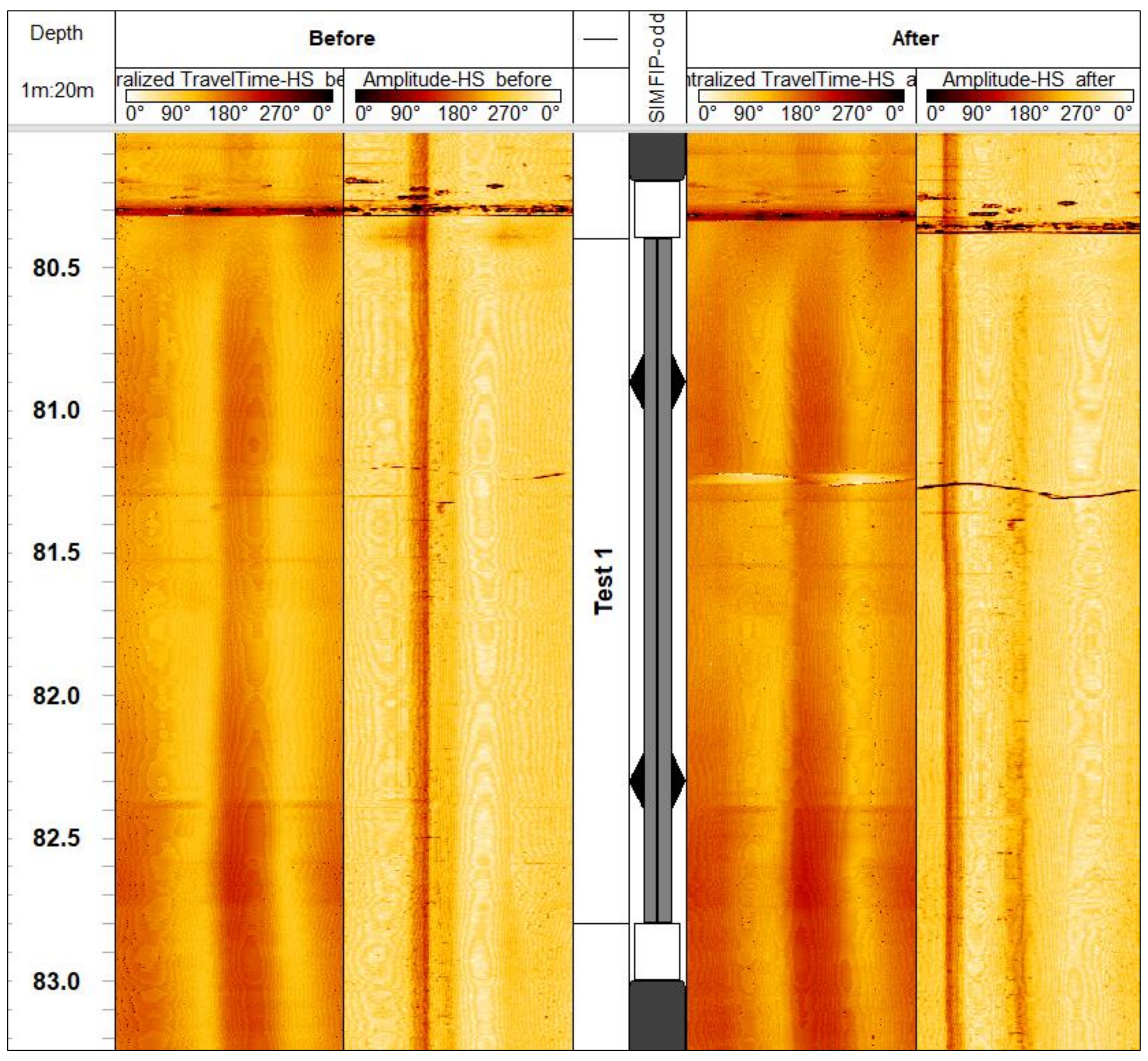


Fig. 4 Comparison of ATV logs before and after the SIMFIP test. The packer and SIMFIP clamp (black triangle) positions are shown in the middle.

- A clear enhancement of the pre-existing fracture can be seen in the ATV amplitude and travel time data (Fig. 4)
- Slip of a fracture that intersects a borehole should lead to positive and negative borehole radius changes on opposite sides (Fig. 5a)
- We calculate the borehole radius changes from the travel time data along axial profiles across the pre-existing fracture (Fig. 5b)
- A fitted sinusoid is used to estimate the magnitude and direction of the slip vector (Fig. 5c)
- In a last step, the slip vector is rotated from borehole high side (HS) coordinates to geographic coordinates

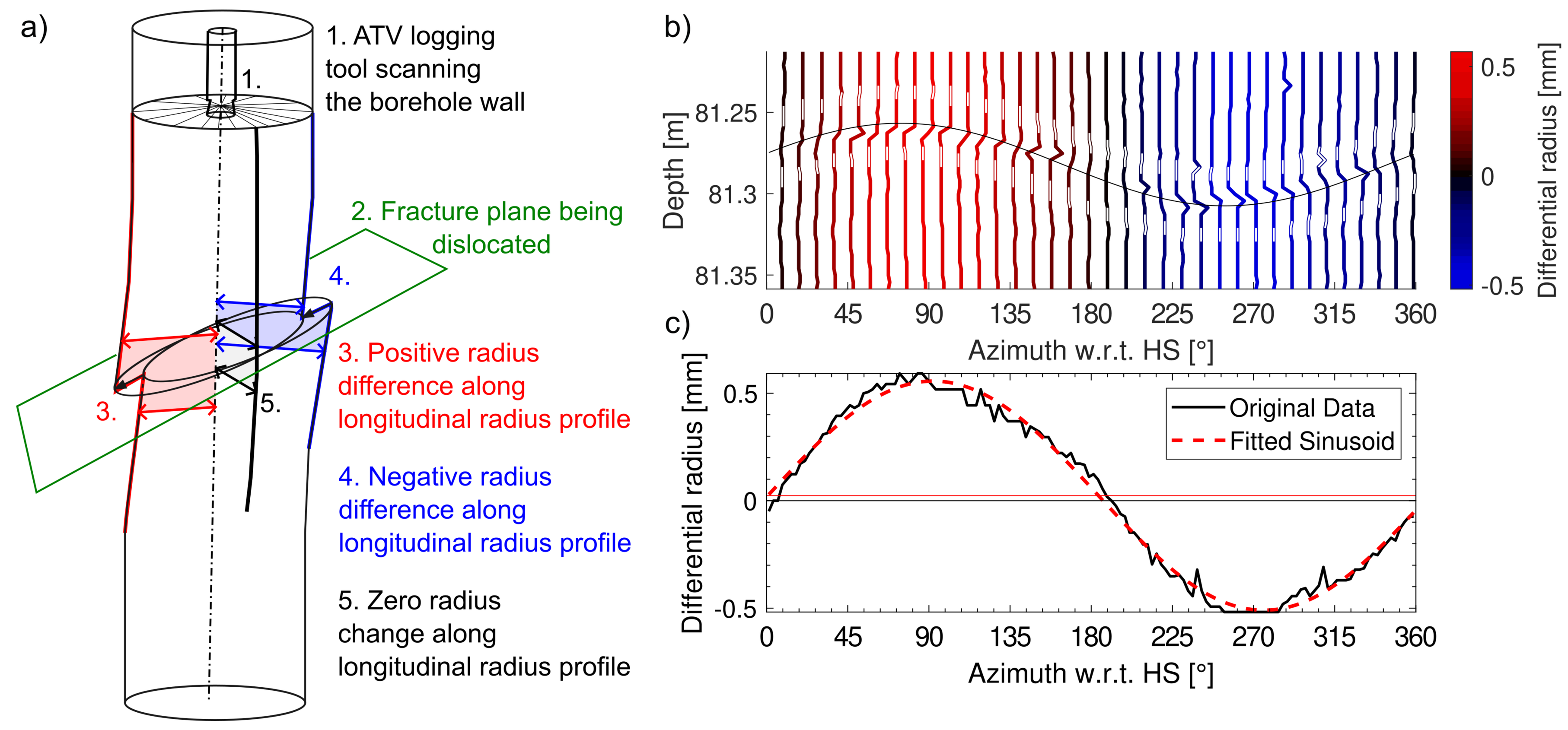


Fig. 5 a) Illustration of borehole displacement caused by the slip of a fracture intersecting the borehole. b) Borehole radius changes along axial profiles in test interval 1 derived from the ATV travel time data. For simplification, every fourth measured trace is shown. The differential radius is calculated as the difference between the fracture parallel areas above and below the fracture (shown in white). c) Differential radius against azimuth with respect to borehole high side (HS). A sinus curve is fitted to the data (red dashed line) to estimate the slip vector. The red horizontal line indicates the midline of the sinus.

4 Comparison of ATV and SIMFIP displacement

Forward modelling

- Wallace-Bott hypothesis: Fault slips in direction of maximum shear stress on fault plane
- We predict the slip vector based on the far-field stress tensor and fracture orientation
- Input stress tensor: Normal faulting given by Bröker and Ma (2022), Bröker et al. (2024) based on mini-frac tests in close-by geothermal testbed

Table 1 Comparison of the different slip vectors.

	Trend [°]	Plunge [°]	Magnitude [mm]
ATV	144	-11	0.59
SIMFIP	174	6	1.15
SIMFIP projected onto fault	154	15	1.07
Forward model	159	27	-

Slip vector comparison

- SIMFIP measures transient and permanent 3D displacement, but permanent displacement magnitude is not meaningful in this test interval due to declamping of the probe during the test
- ATV measures only permanent displacement along fracture plane
- Fig. 6 compares the slip vectors with SIMFIP displacement vector projected onto fault plane (yellow dashed arrow) for comparison
- All vectors show a dominant left-lateral strike slip movement, SIMFIP also measures some normal opening
- Angle between proj. SIMFIP and ATV slip vector = 27.8°
- Possible reasons for discrepancy:
  - ➢ Location of the measurement (directly on fault plane vs. some distance from it)
  - ➢ SIMFIP displacement might be influenced by complex deformation of whole rock volume
  - ➢ ATV only measures radial changes of the borehole wall itself

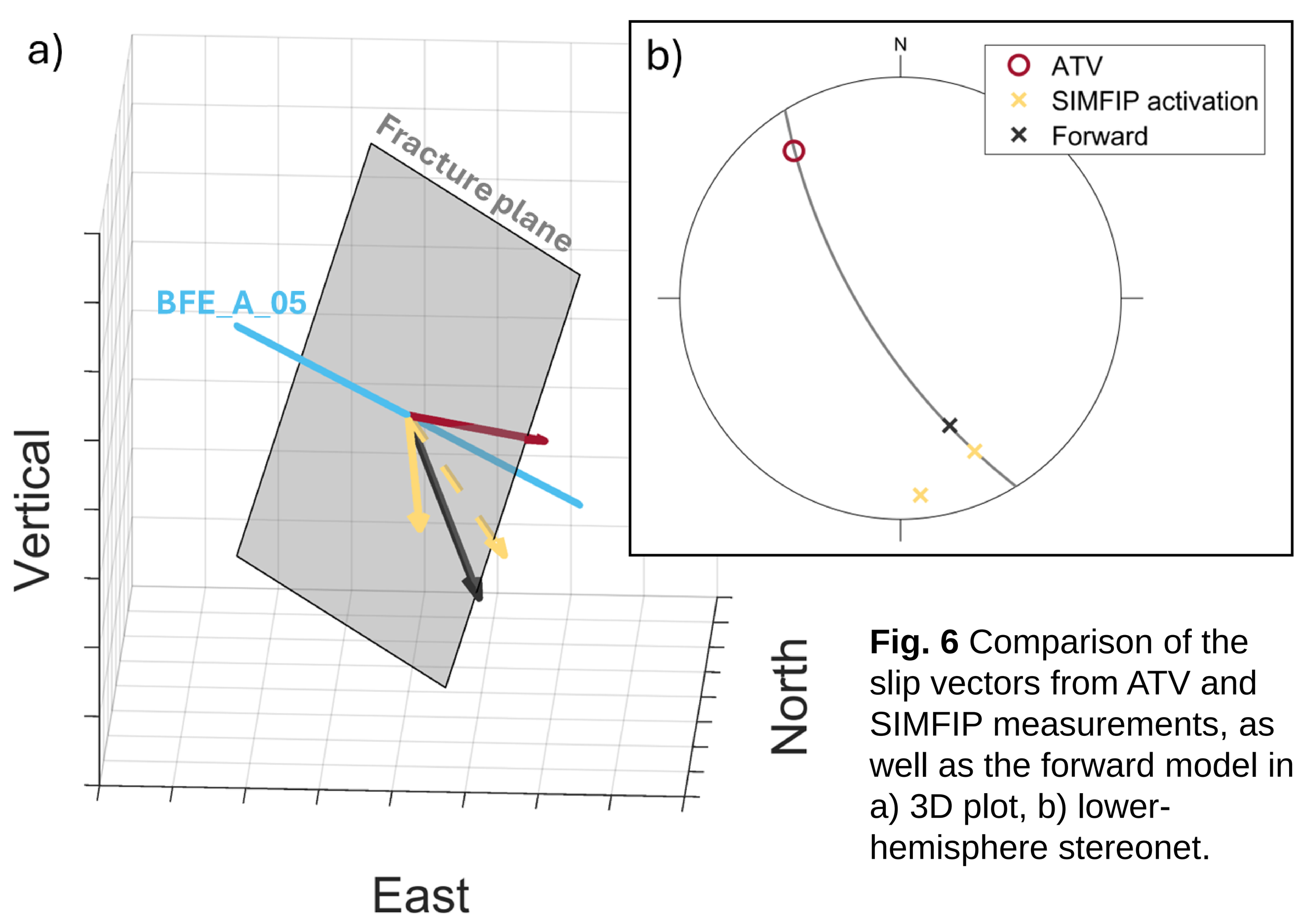


Fig. 6 Comparison of the slip vectors from ATV and SIMFIP measurements, as well as the forward model in a) 3D plot, b) lower-hemisphere stereonet.

References

Bröker, K. and X. Ma (2022). "Estimating the Least Principal Stress in a Granitic Rock Mass: Systematic Mini-Frac Tests and Elaborated Pressure Transient Analysis". In: Rock Mechanics and Rock Engineering 55 (4), pp. 1931–1954. https://doi.org/10.1007/s00603-021-02743-1

Bröker, K., X. Ma, S. Zhang, N. G. Doonechaly, M. Hertrich, G. Klee, A. Greenwood, E. Caspari, and D. Giardini (2024). "Constraining the stress field and its variability at the BedrettoLab: Elaborated hydraulic fracture trace analysis". International Journal of Rock Mechanics and Mining Sciences 178, 105739. https://doi.org/10.1016/j.ijrmms.2024.105739

Guglielmi, Y., F. Cappa, H. Lan¸con, J. B. Janowczyk, J. Rutqvist, C. F. Tsang, and J. S. Y. Wang (2014). "ISRM Suggested Method for Step-Rate Injection Method for Fracture In-Situ Properties (SIMFIP): Using a 3-Components Borehole Deformation Sensor". In: Rock Mechanics and Rock Engineering 47112(1), pp. 303–311. https://doi.org/10.1007/s00603-013-0517-1