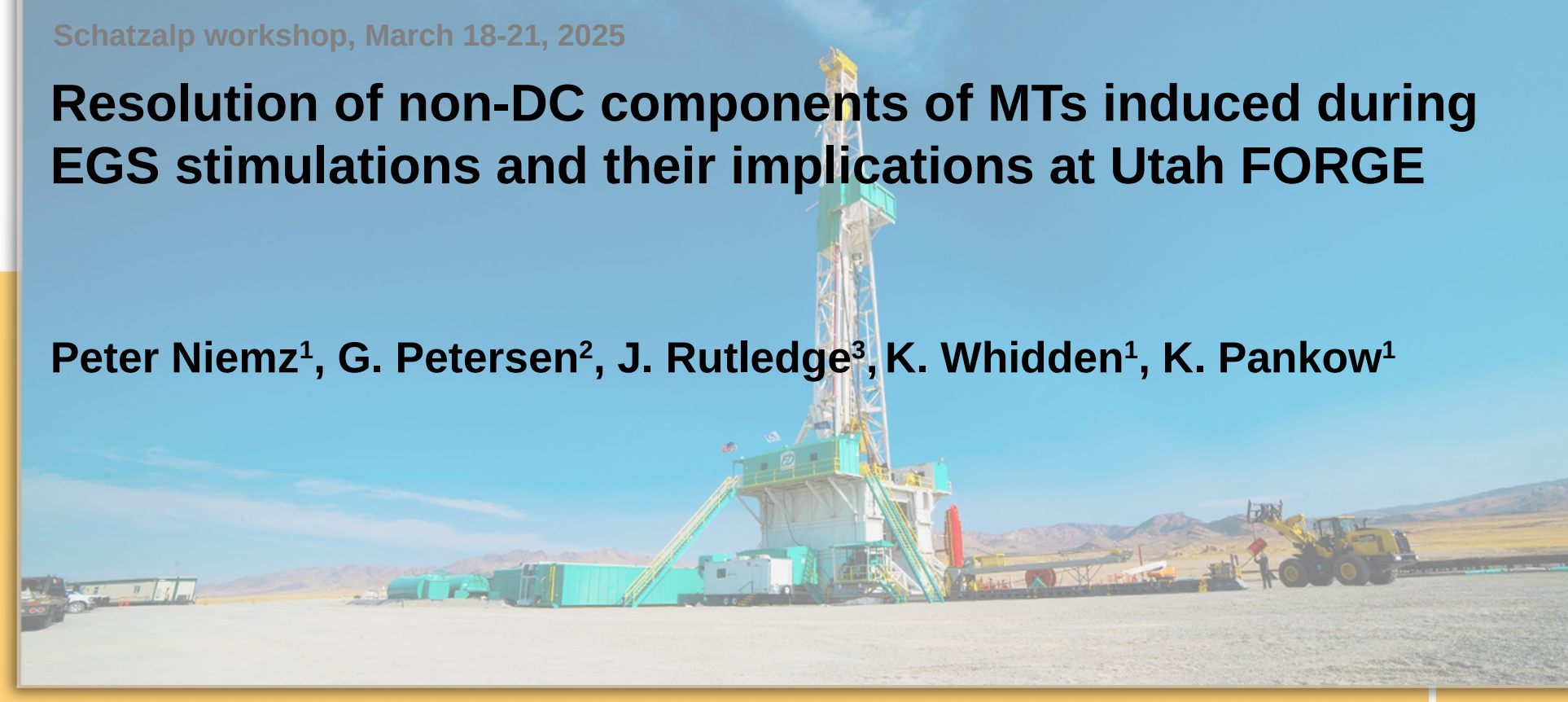
Schatzalp workshop, March 18-21, 2025

Resolution of non-DC components of MTs induced during EGS stimulations and their implications at Utah FORGE



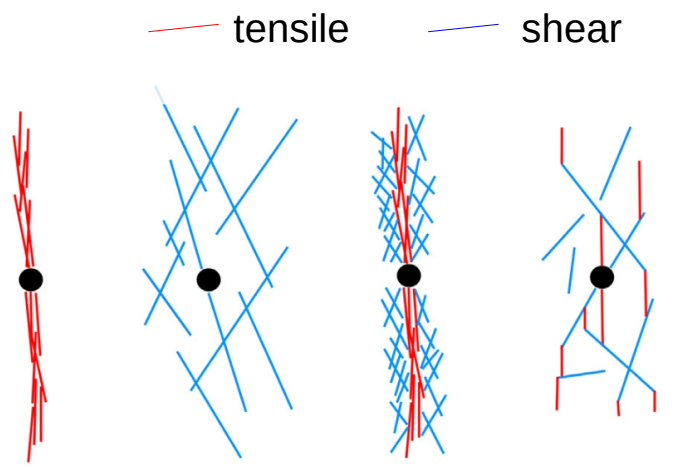
Peter Niemz[1], G. Petersen[2], J. Rutledge[3], K. Whidden[1], K. Pankow[1]

[1] University of Utah, Seismograph Stations, Salt Lake City, UT, USA
[2] GFZ - German Research Centre for Geosciences, Potsdam, Germany
[3] Santa Fe Seismic LLC, Santa Fe, New Mexico, USA

Motivation

Are double-couple (DC) components of microseismic MTs representative for the reservoir hydrofracture geometry?

Can tensile/non-DC components provide insight into permeability of the reservoir?



McClure and Horn (2014)

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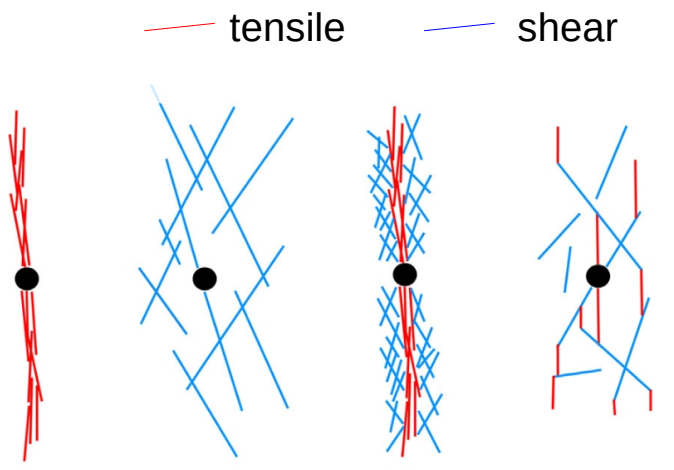
MT inversions

- velocity model resolution <> dominant frequencies
- simplicity <> complexity
- magnitude <> hypocentral distances



McClure and Horn (2014)

Motivation

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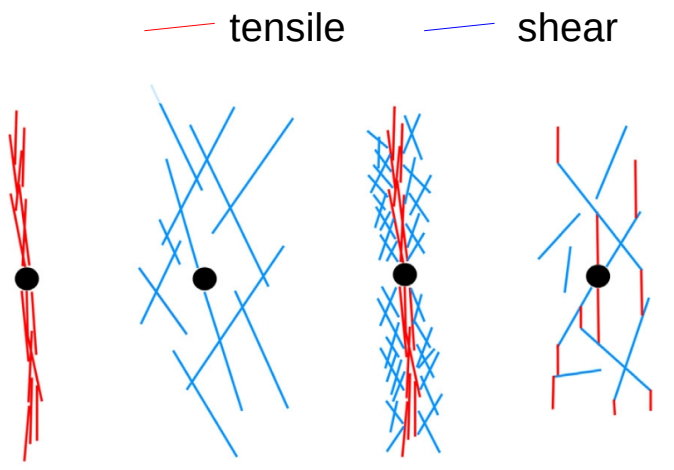
MT inversions

- velocity model resolution <> dominant frequencies
- simplicity <> complexity
- magnitude <> hypocentral distances

→ at the limits of full-waveform inversion

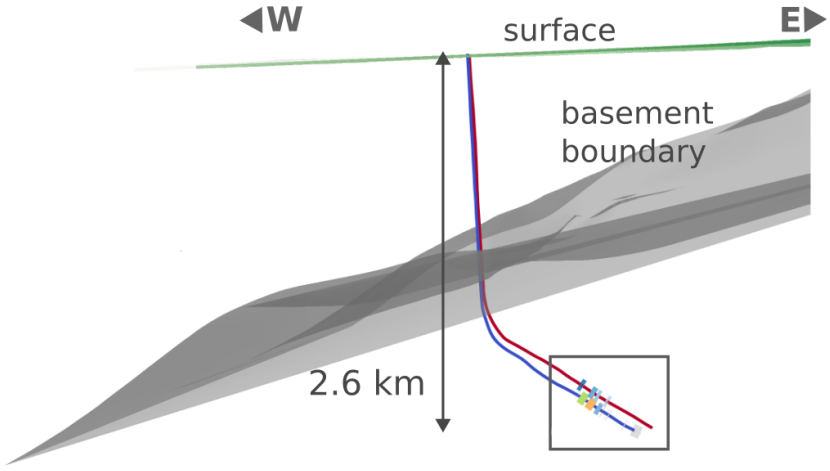
→ assessing uncertainties and limitations is important

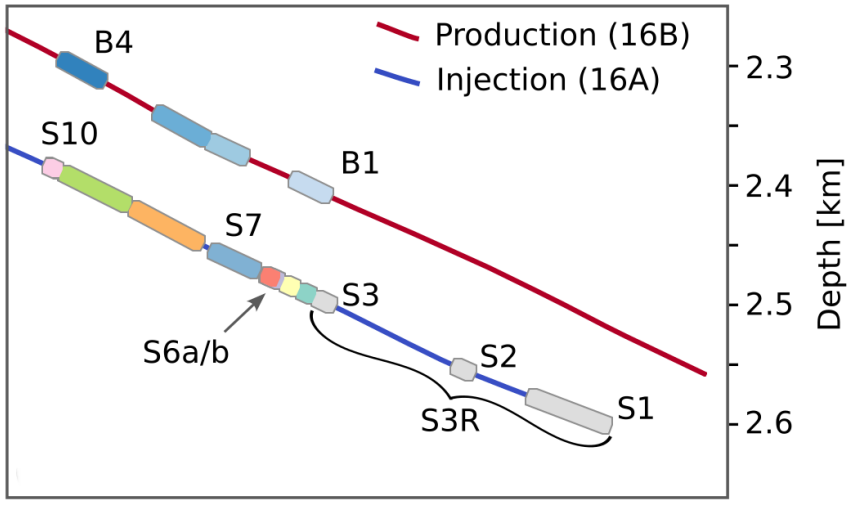


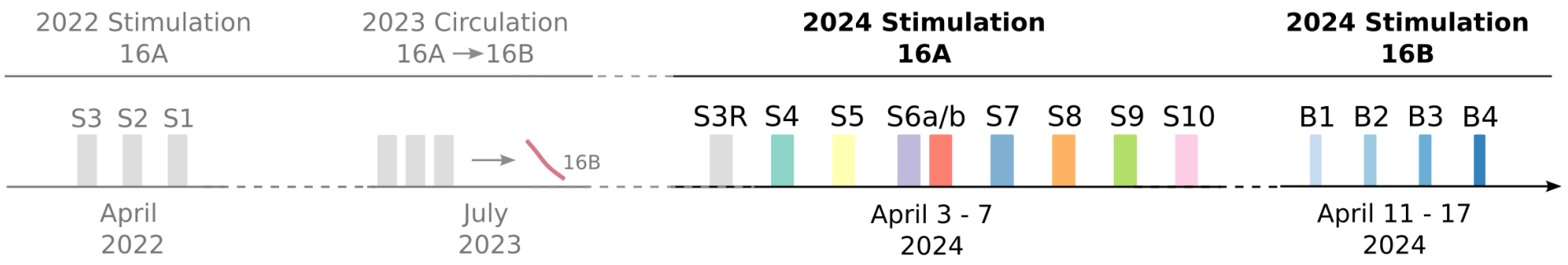
McClure and Horn (2014)

Utah FORGE - Stimulations 2024

Utah Frontier **O**bservatory for **R**esearch in **G**eothermal **E**nergy





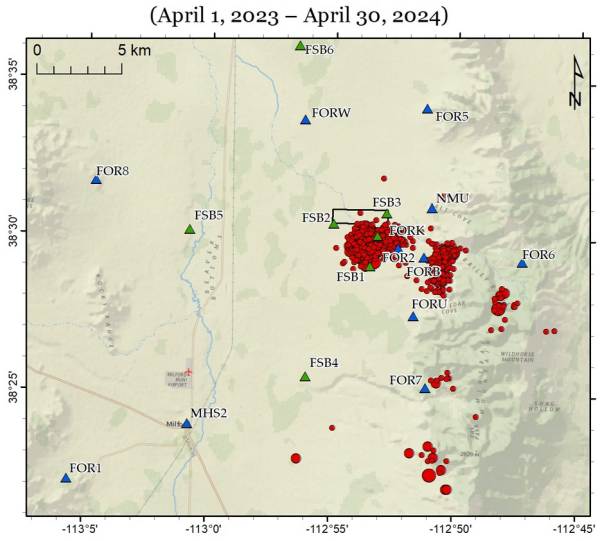


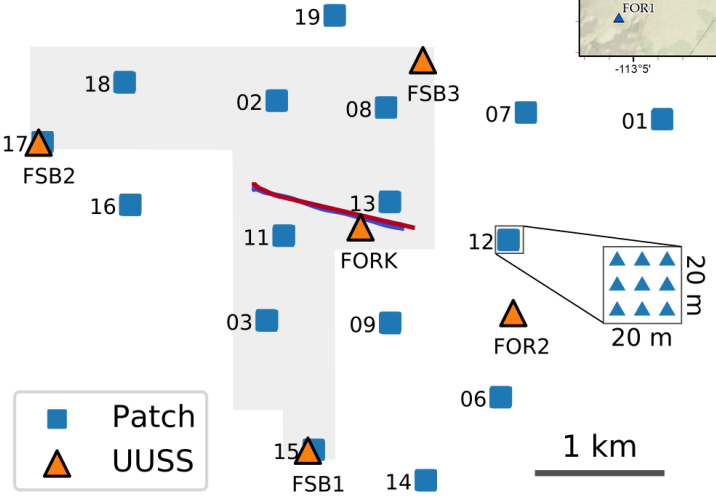
Microseismic surface monitoring at Utah FORGE

- permanent UUSS (University of Utah Seismograph Stations)
- temporary geophone patches (3x3 nodal geophones)

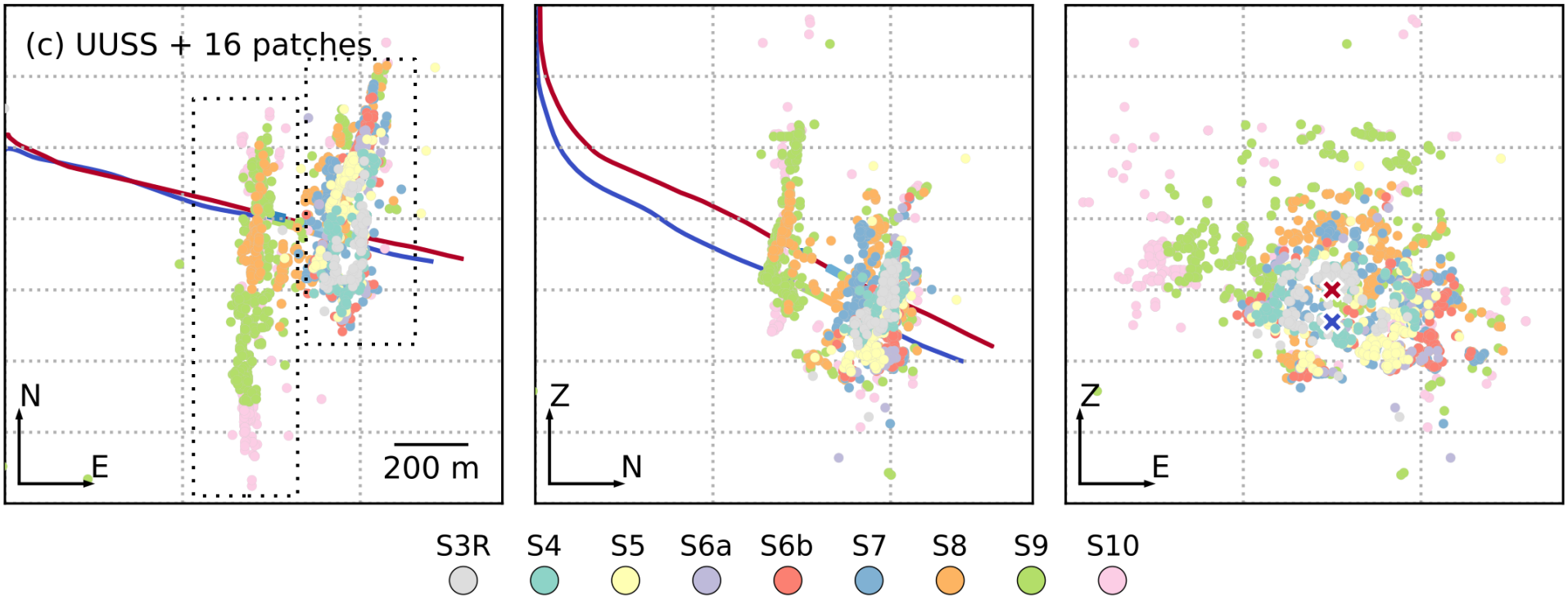
→ excellent azimuthal coverage

→ improved SNR





Stimulations 2024 – Microseismic catalog



3000 microseismic events from surface monitoring catalog (Niemz et al., 2025)

→ MT inversion targets: 230 events (M_L>0)

Methods - Probabilistic waveform-based MT inversion

Input

- Seismic waveforms 

Probabilistic inversion $|d_{obs} - d_{syn}|$

- Efficient exploration of the full model space

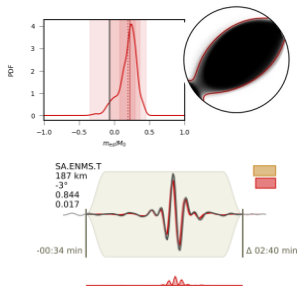
  → Bootstrap-based uncertainties
  → Parameter trade-offs

GROND

- Flexible design of misfit function:

  - **FD Amplitude Spectra**
  - **TD Full waveforms**
  - **TD Cross-correlation of waveforms**
  - **Polarities**

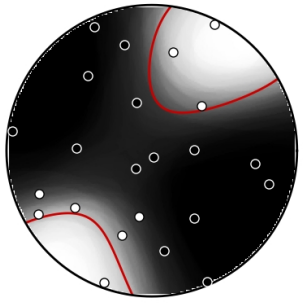
Output

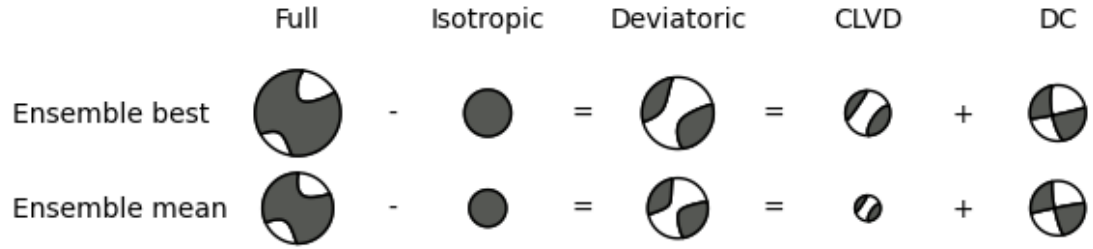


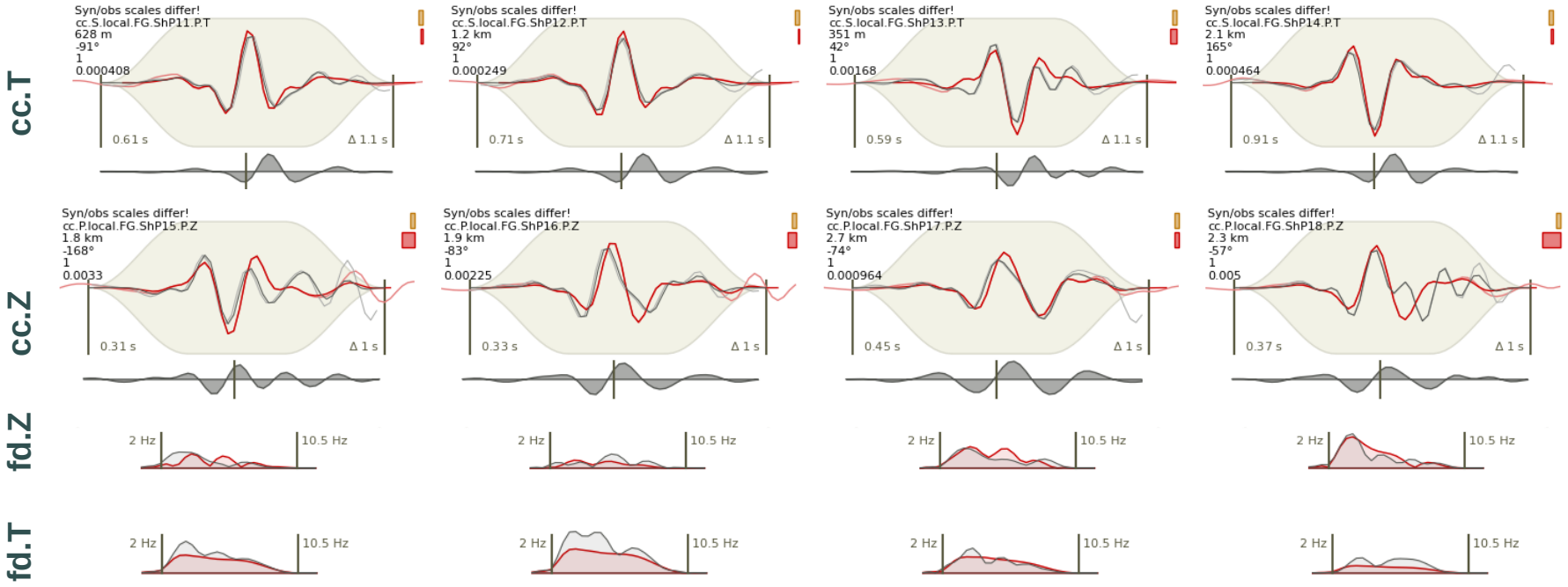
Pre-calulated Green's function data base

grond.pyrocko.org
Heimann et al. (2018)

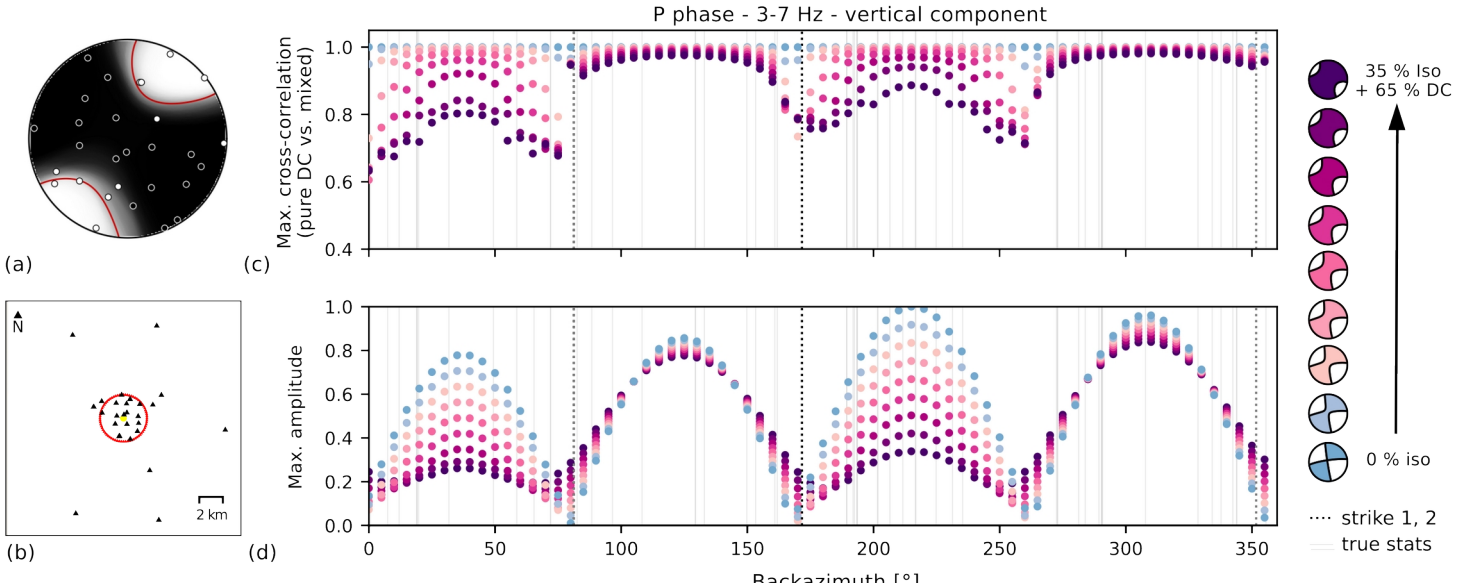
Stimulation 2024 - MT for example Mw 1.4





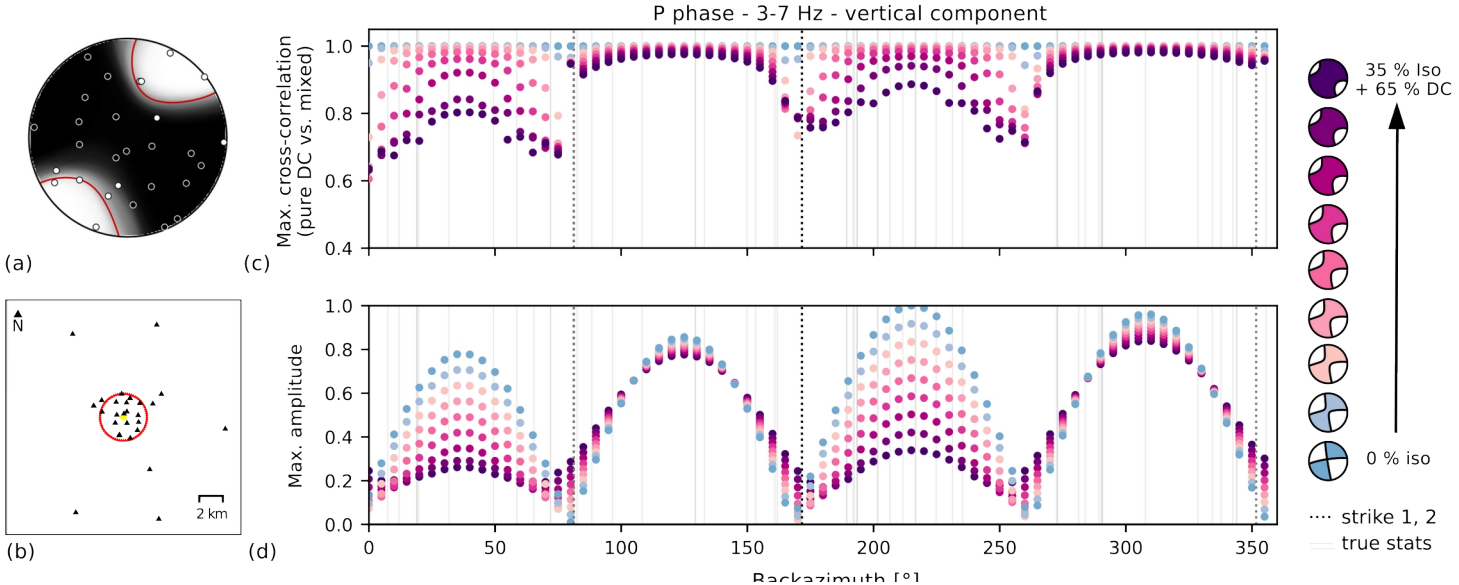


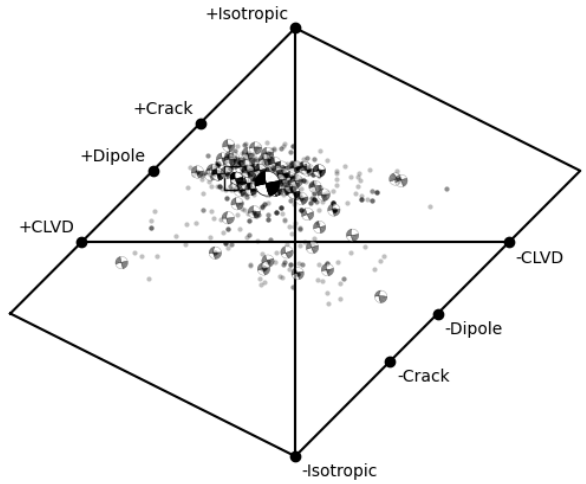
MT/Non-DC resolution testing + Uncertainties



- Comparison of synthetic waveforms with different isotropic contributions → Resolution tests

MT/Non-DC resolution testing + Uncertainties

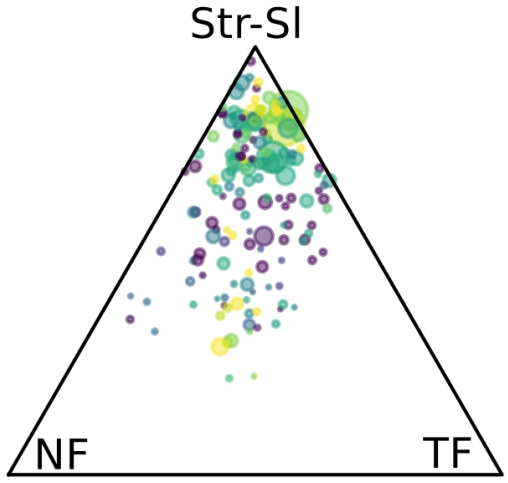


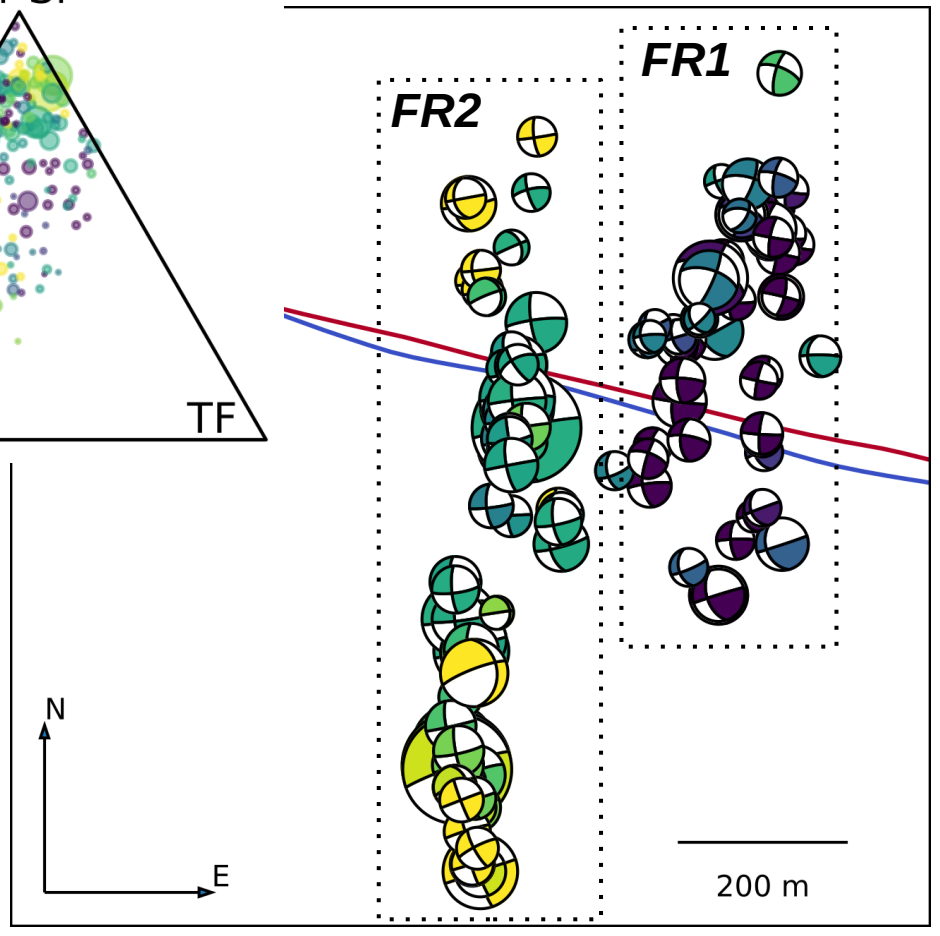


- Comparison of synthetic waveforms with different isotropic contributions → Resolution tests
- Bootstrap chains → Uncertainties for all inversion parameters
- First-motion polarities → Validation

Stimulations 2024 – DC components

- 160 stable MT solutions
- predominately strike-slip





Stimulations 2024 – DC components

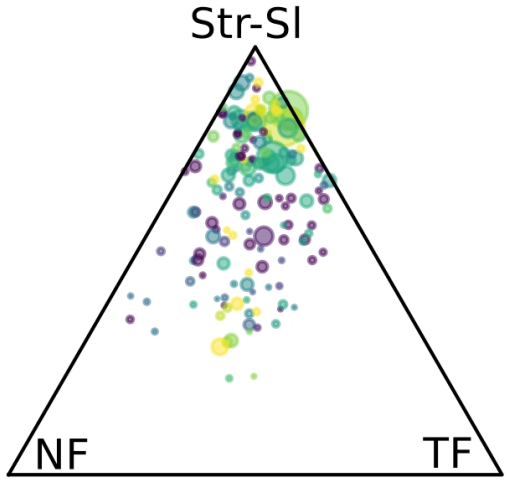
- 160 stable MT solutions
- predominately strike-slip

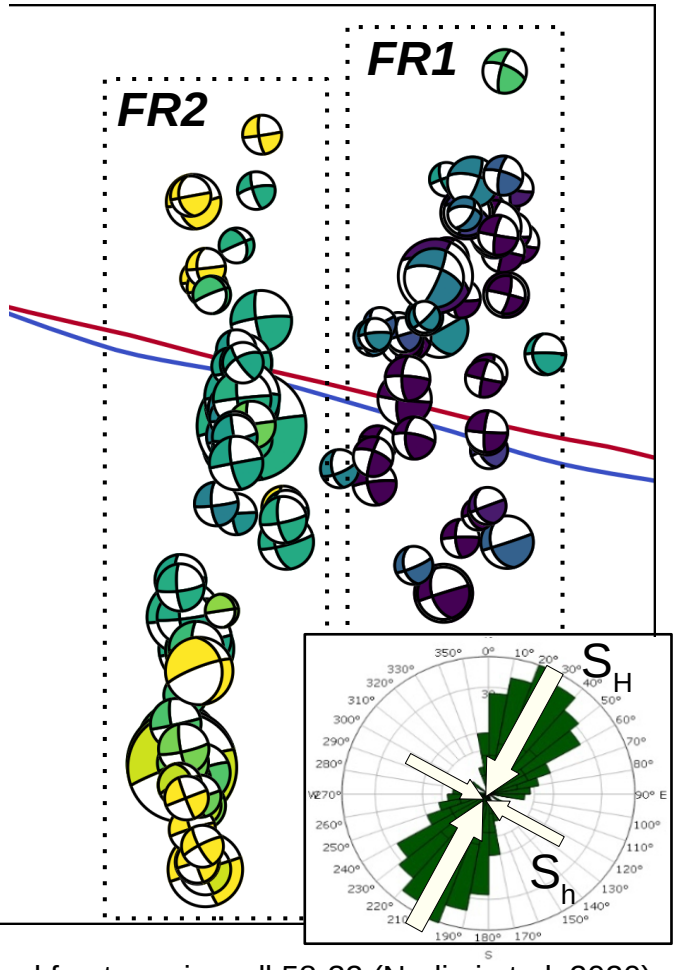
  → following regional stress field

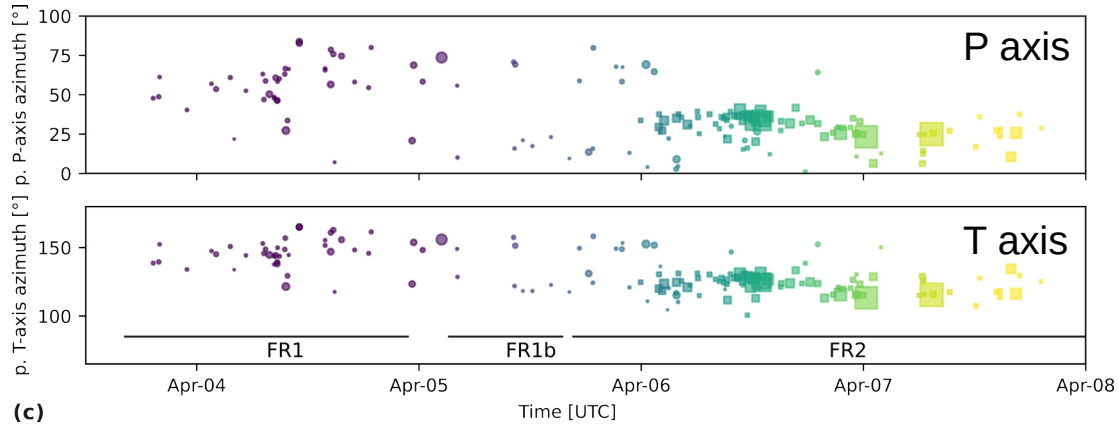
- slight rotation from FR1 to FR2

  → nodal planes +

  microseismic cloud

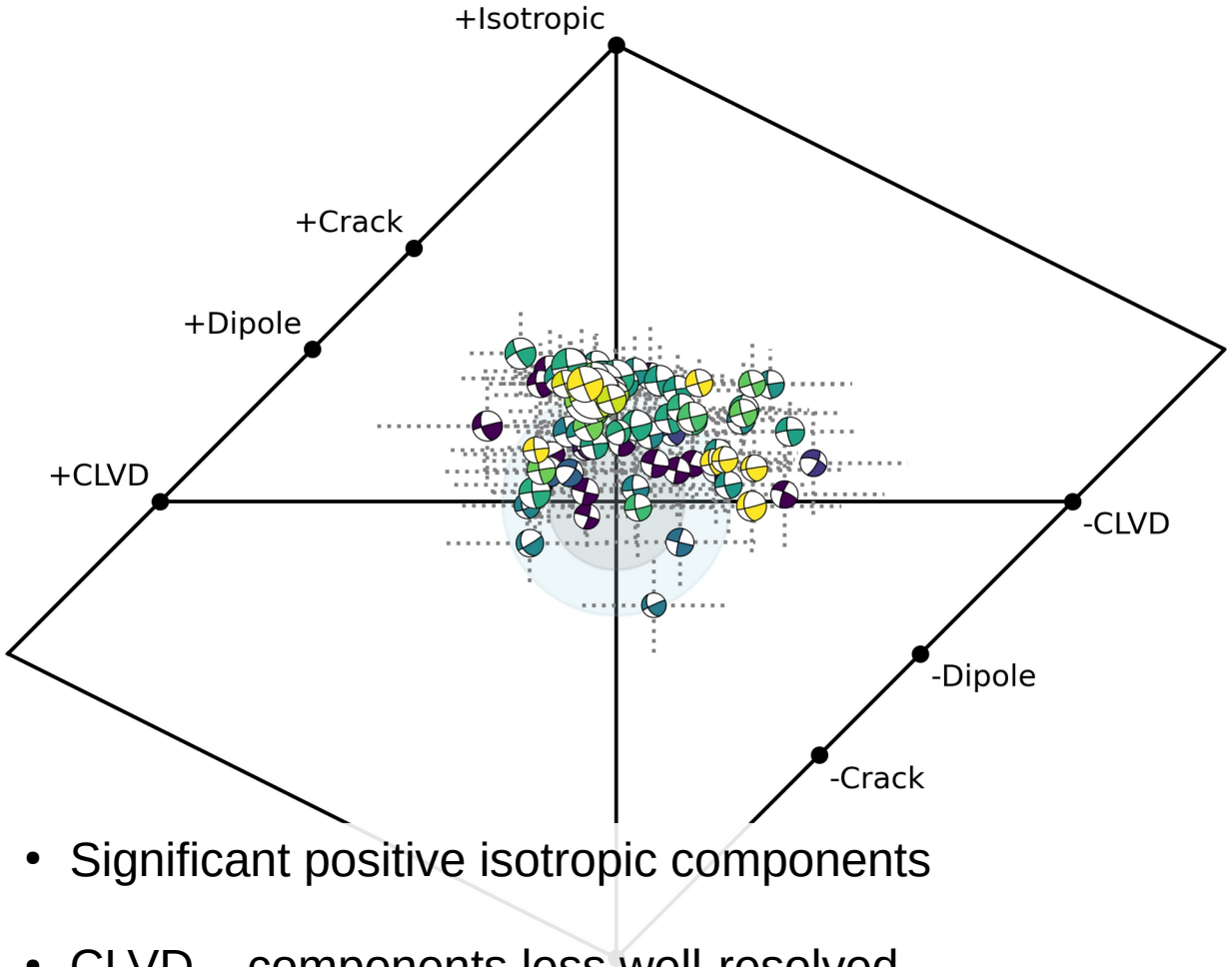






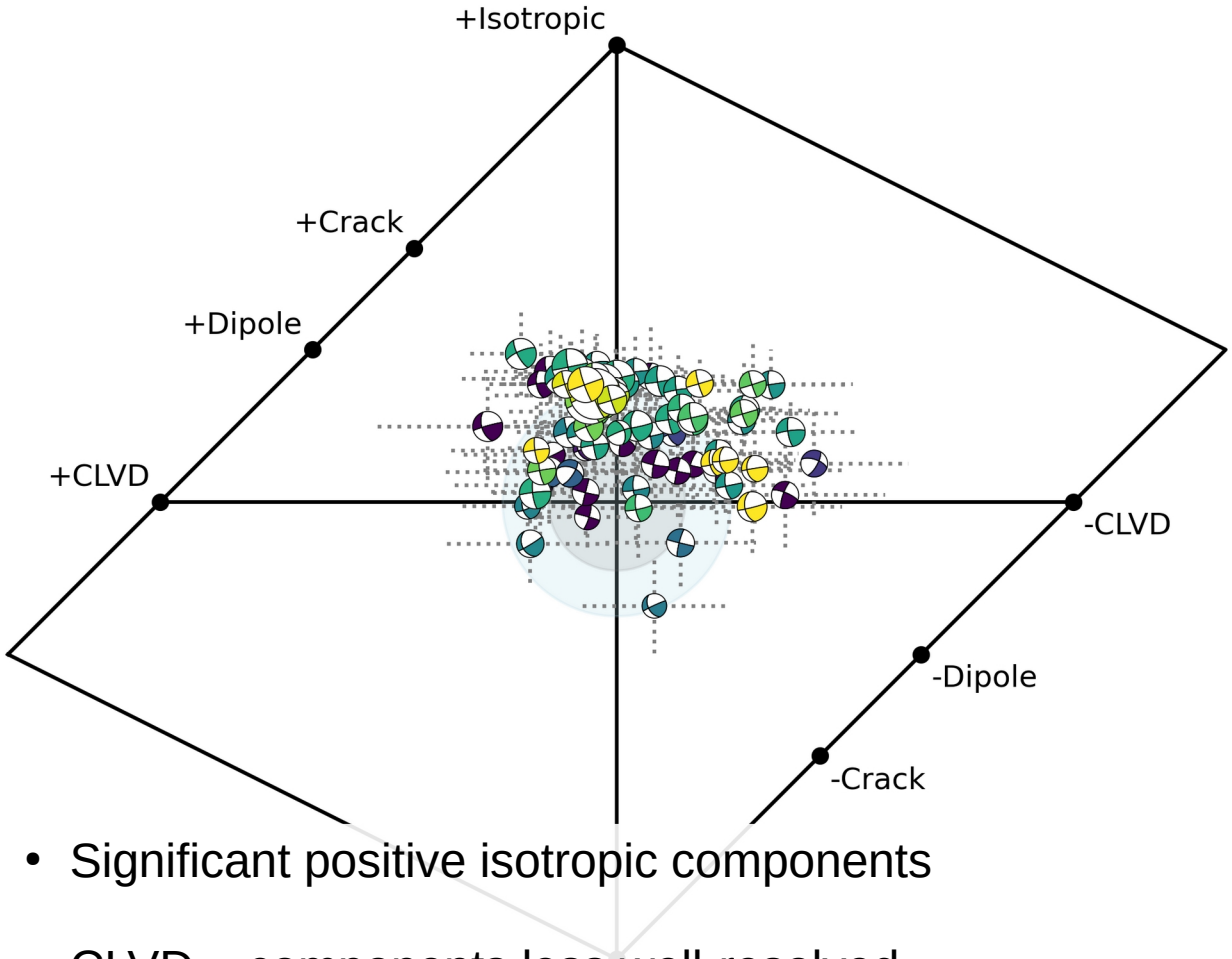
Induced fractures in well 58-32 (Nadimi et al. 2020)

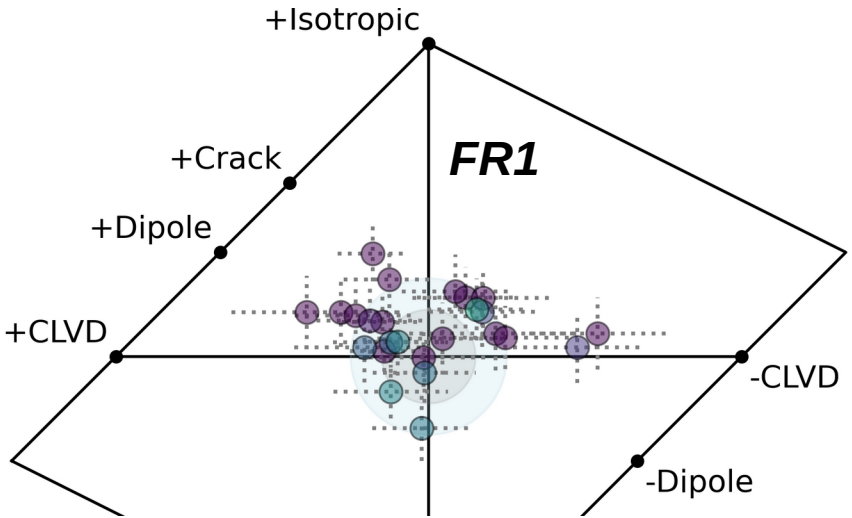
Stimulations 2024 – Non-DC components

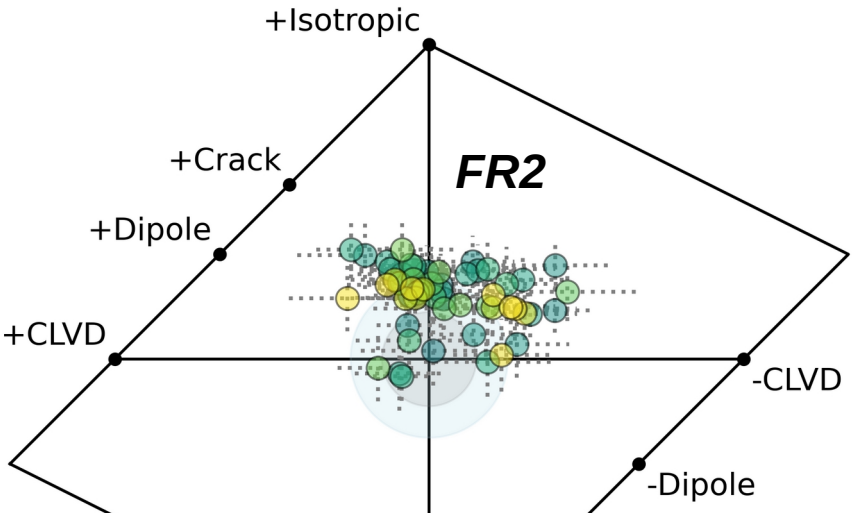


- Significant positive isotropic components
- CLVD – components less well-resolved

Stimulations 2024 – Non-DC components

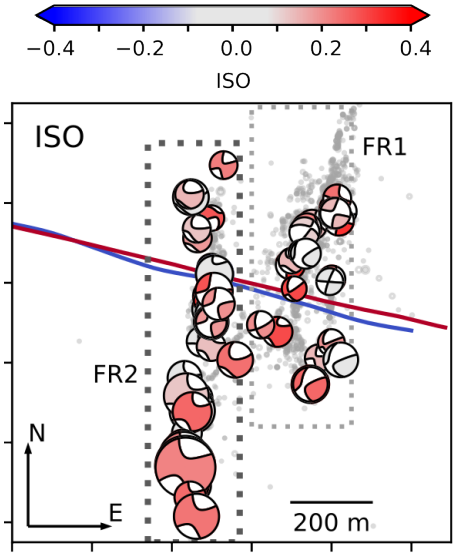


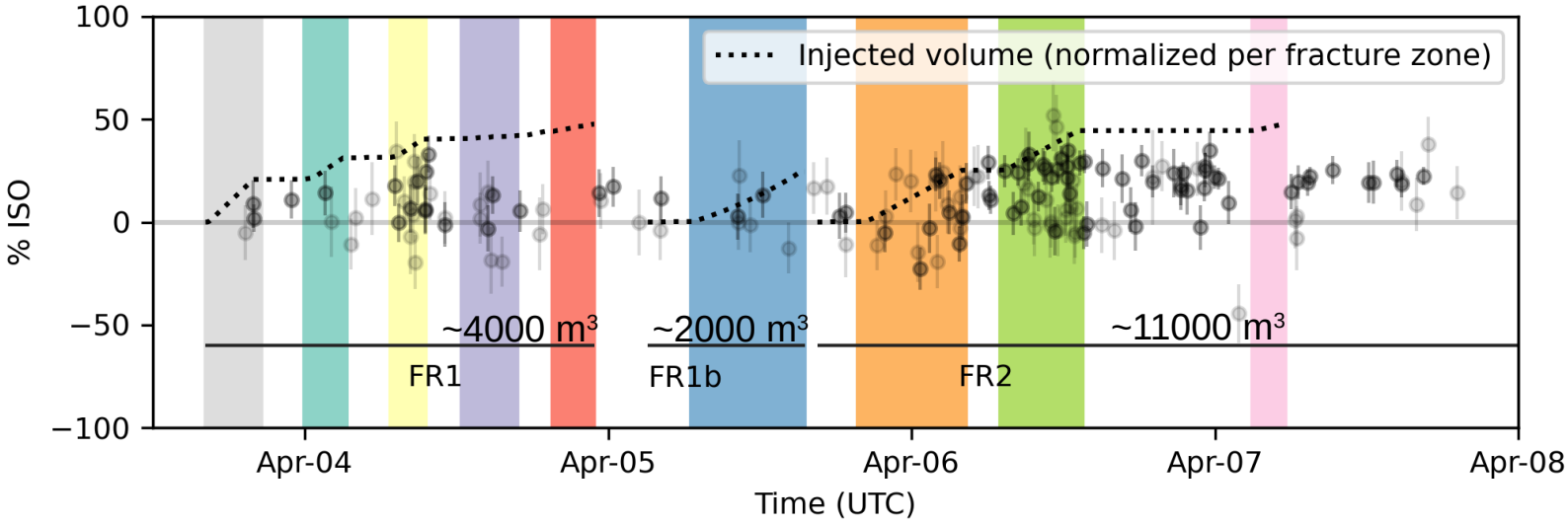




- Significant positive isotropic components
- CLVD – components less well-resolved

Stimulations 2024 – Isotropic component

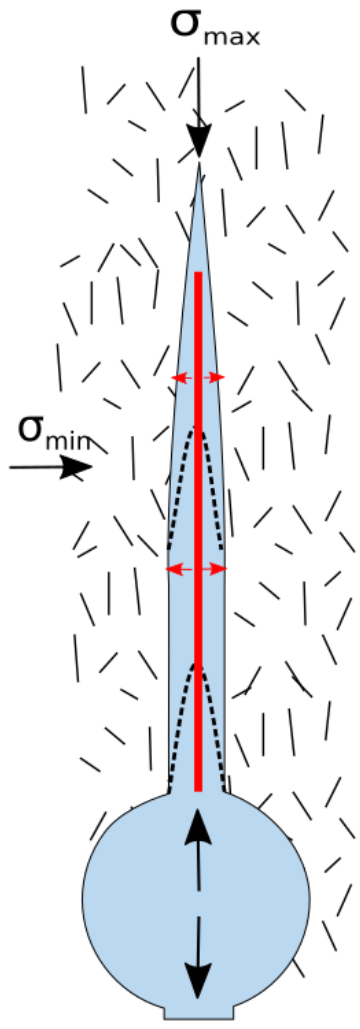




- Significant positive isotropic components

→ Maximum ISO - contribution increases over time / with injected volume
(no bleed-off during in between stimulation stages)

Conceptual models



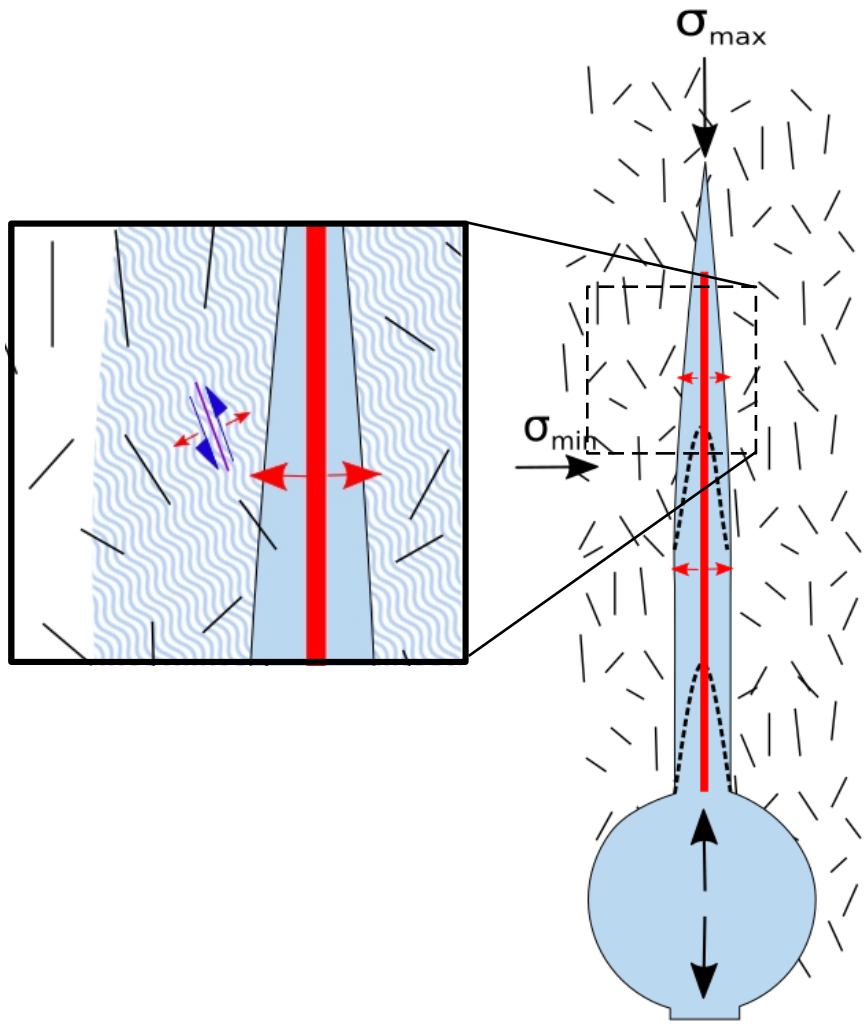
Conceptual models

ISOTROPIC components

(1) leak-off into rock around hydraulic fracture

(2) increased pore pressure
→ reduced normal stress

(3) opening possible
→ larger isotropic contributions
with increasing volume

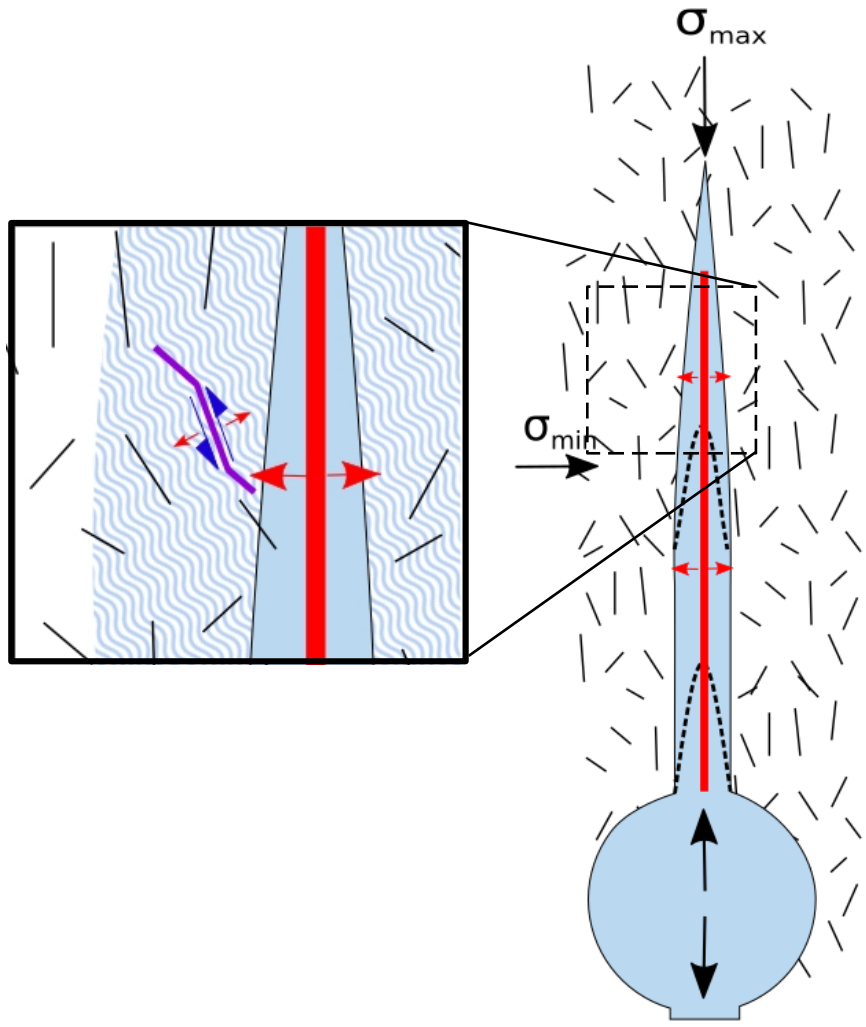


Conceptual models

CLVD components

- Resolution limits:

  → fault complexity, fracture jogs
  → inadequacies of velocity model



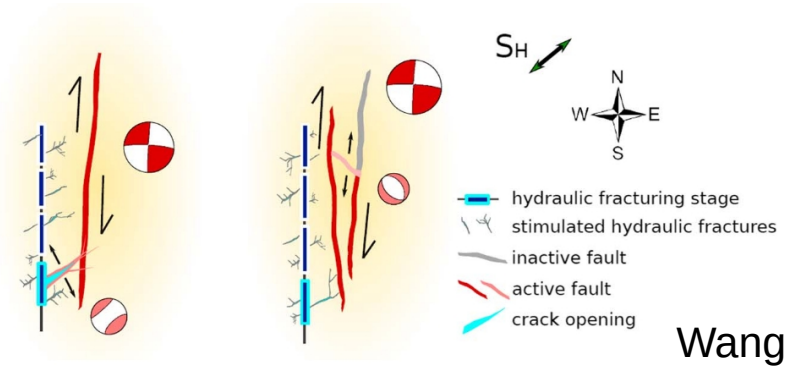
Conceptual models

CLVD components

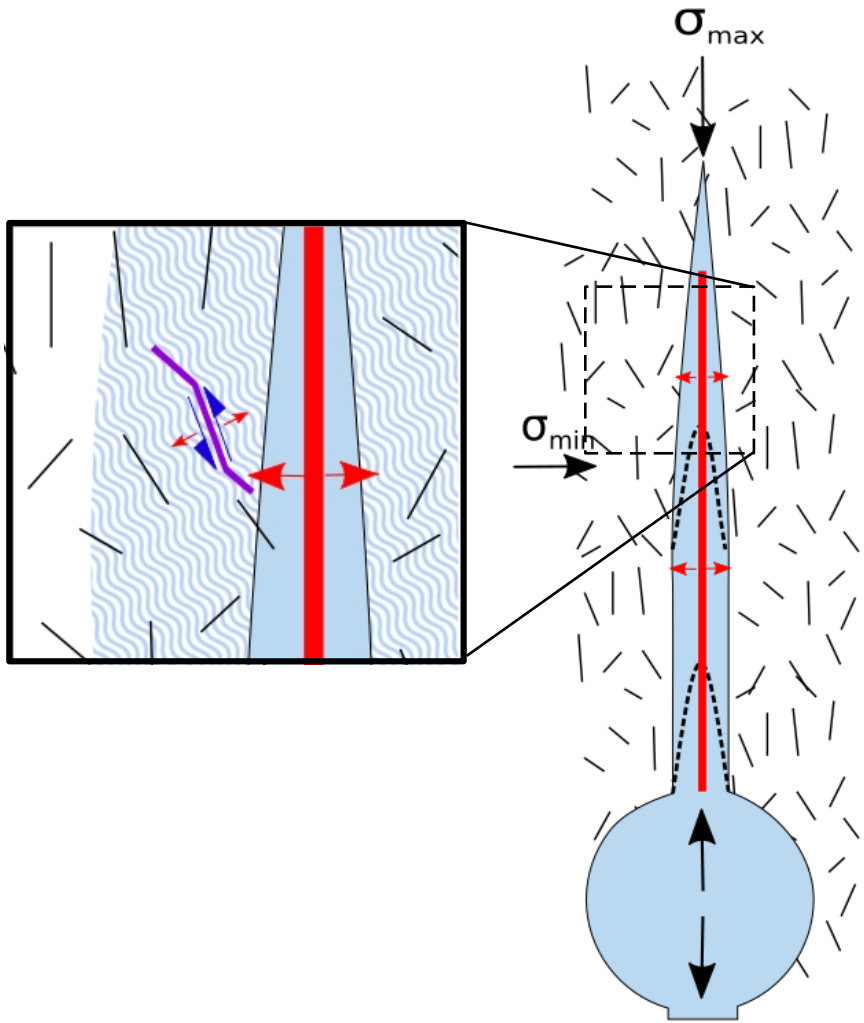
- Resolution limits:

  → fault complexity, fracture jogs
  → inadequacies of velocity model

- alternative decomposition:
  - major + minor DCs



Wang et al., 2018



Conclusion → Questions

- Dominate strike slip in agreement with stress conditions during the 2024 stimulation
  - → incl. significant positive isotropic components
  - → isotropic components increase with injected volume

Are increasing isotropic component of MTs a proxy for a more efficient fracture network?

or

What is the role of slip-dominated microseismicity in the creation of an efficient EGS?

THANK YOU

McClure and Horne (2014): An investigation of stimulation mechanisms in Enhanced Geothermal Systems. International Journal of Rock Mechanics & Mining Sciences (72), 242–260.

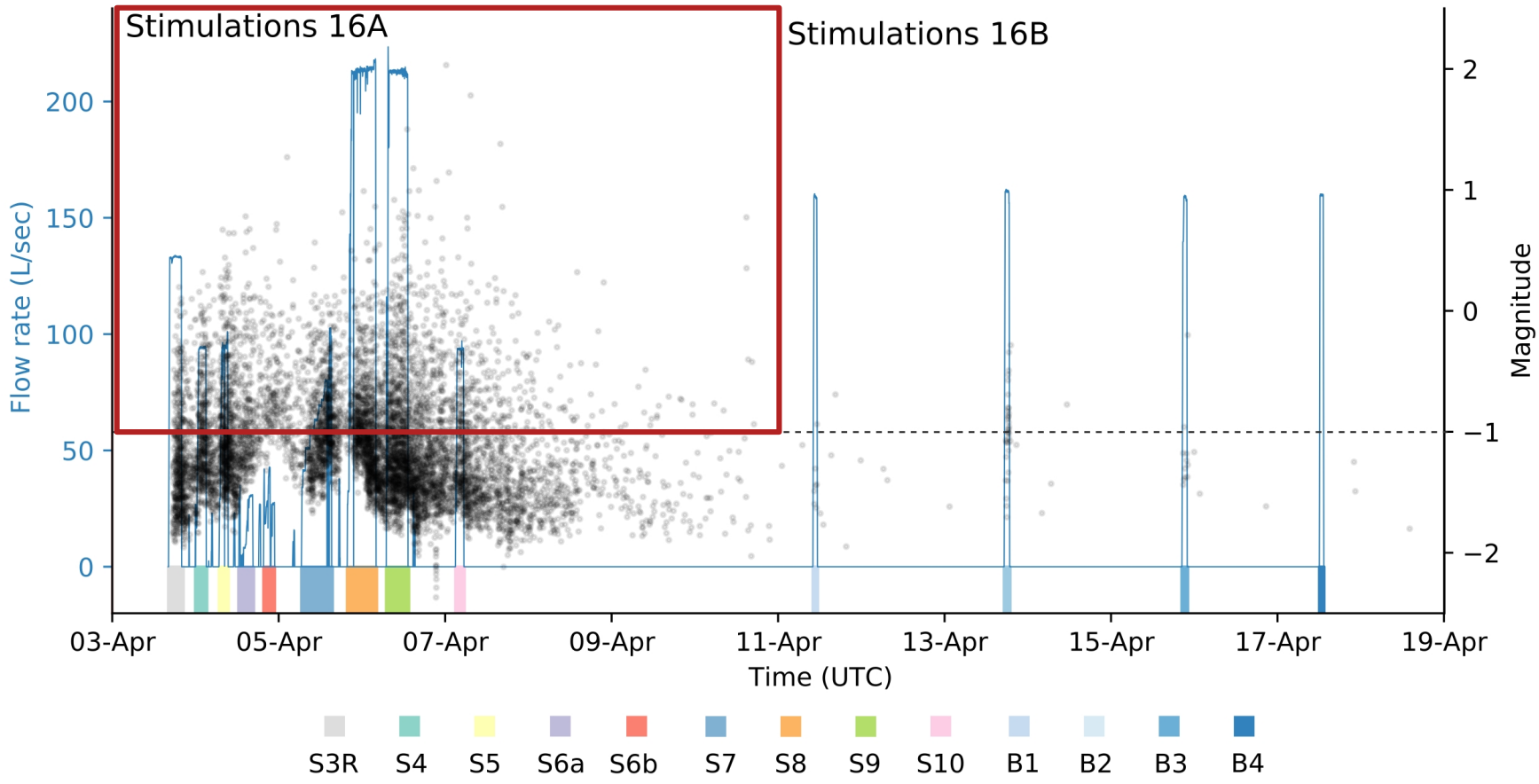
Nadimi et al. (2020): Utah FORGE: Hydrogeothermal modeling of a granitic based discrete fracture network. Geothermics, 87, 101853.

Niemz et al. (2025): Mapping Fracture Zones with Nodal Geophone Patches: Insights from Induced Microseismicity During the 2024 Stimulations at Utah FORGE. SRL.

Wang et al. (2018): Faults and non-double-couple components for induced earthquakes.Geophysical Research Letters, 45.

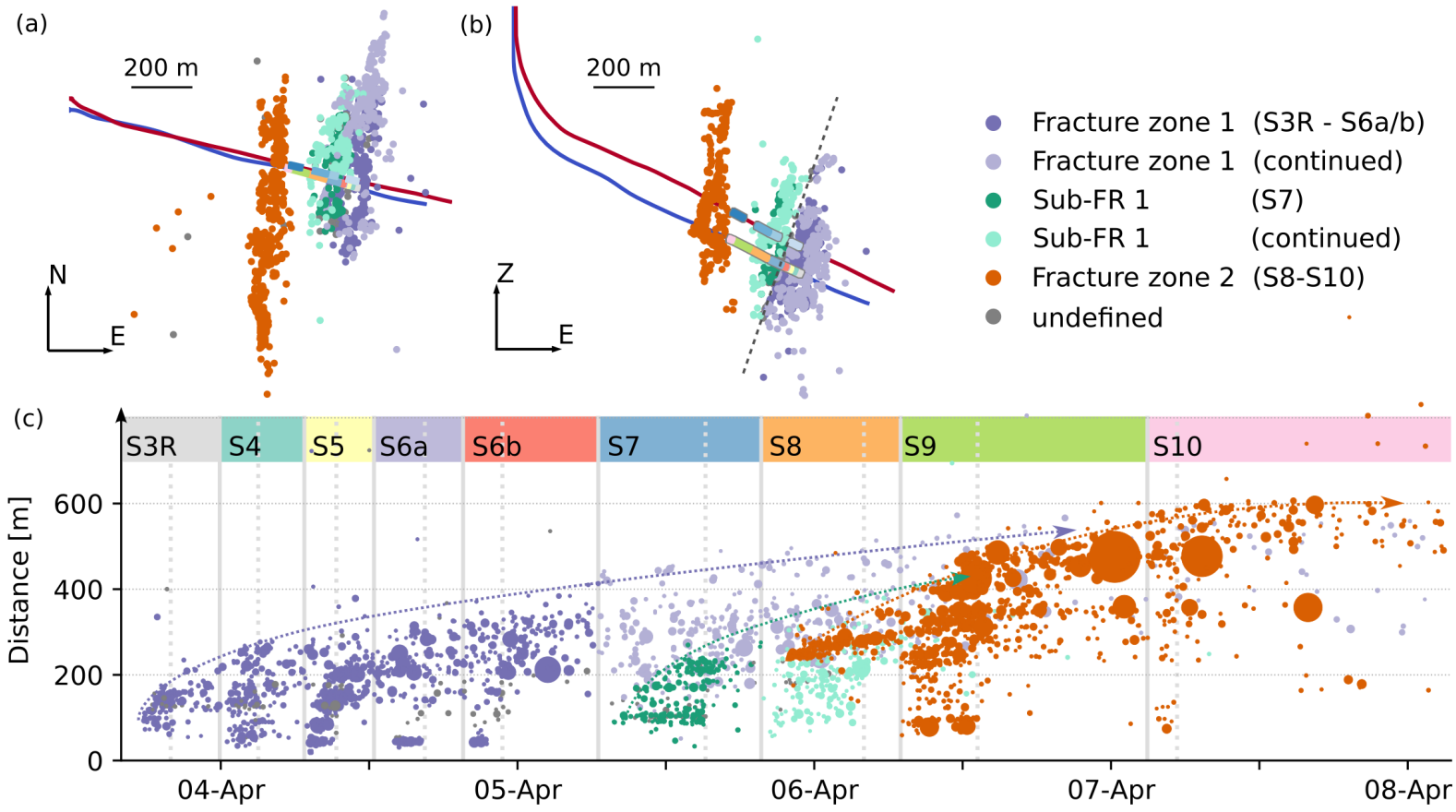
Funding provided by the US DoE with additional support from Utah Trust Lands Administration, Beaver County, the Governor’s Office of Energy Development, and Smithfield Foods.

Stimulations 2024 – Microseismic catalog



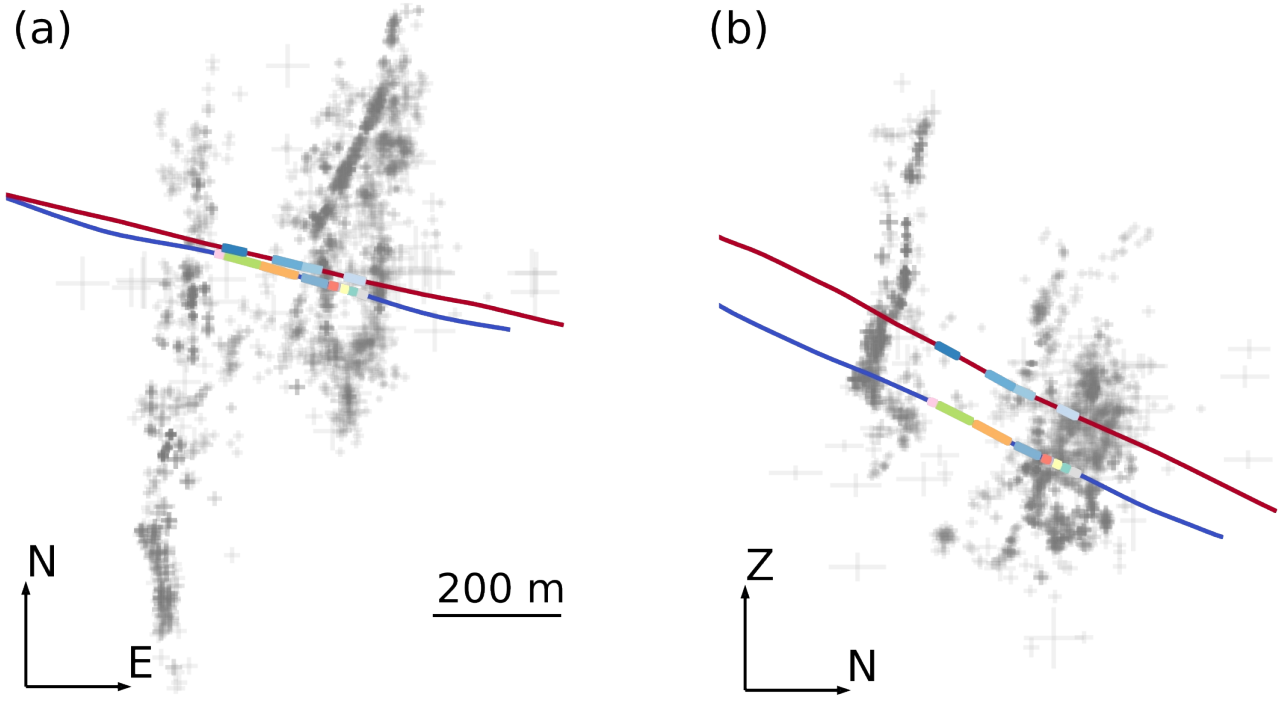
Surface monitoring catalog (Niemz et al., 2025)

Stimulations 2024 – Flow pathes



→ Pathways for fluid flow during the August/September circulation tests between the wells

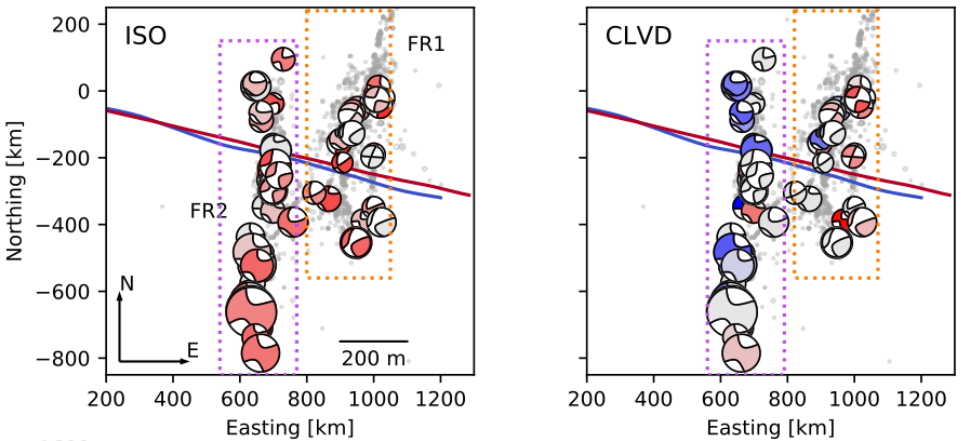
Utah FORGE 2024 – Location uncertainties

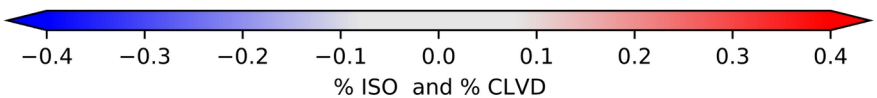


Based on 100 bootstrap solutions in GrowClust

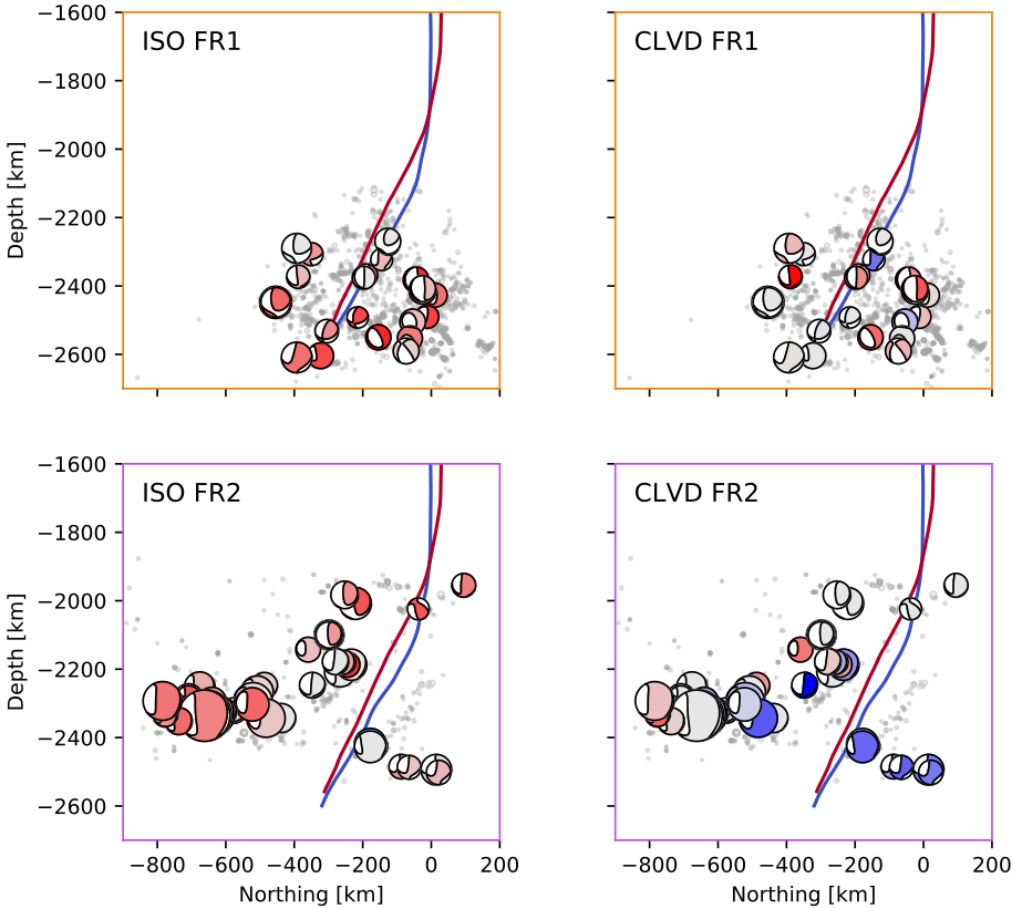
Stimulations 2024 – Non-DC components

Map views





Depth sections

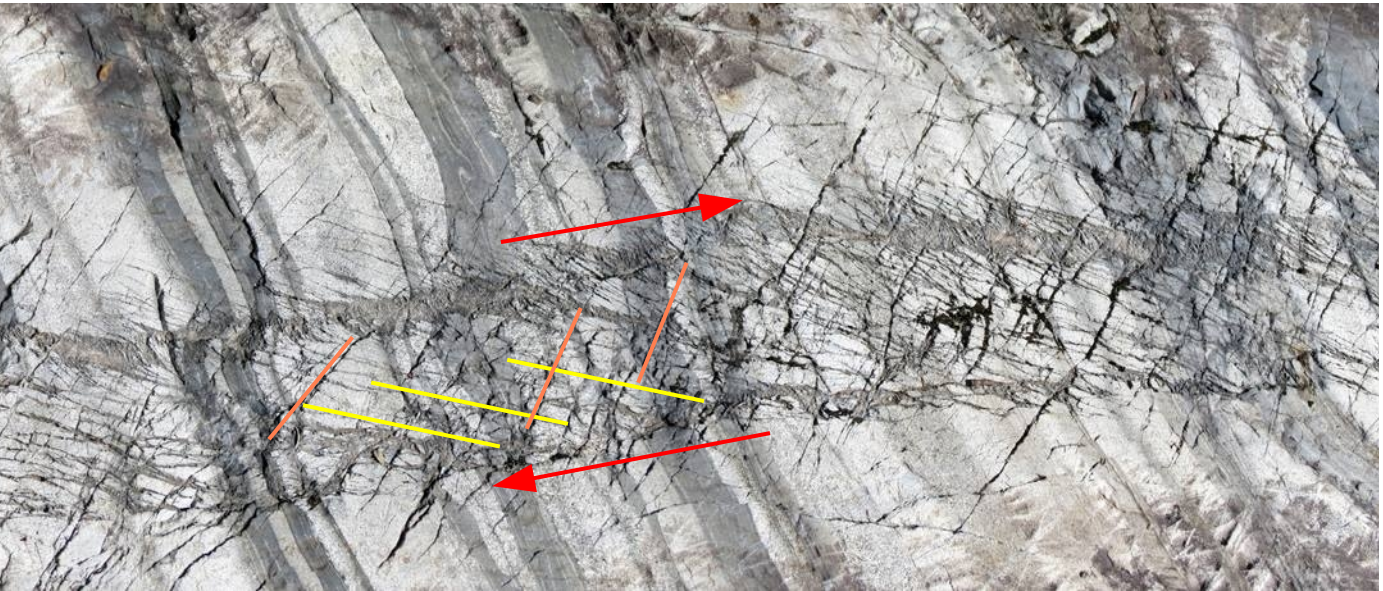


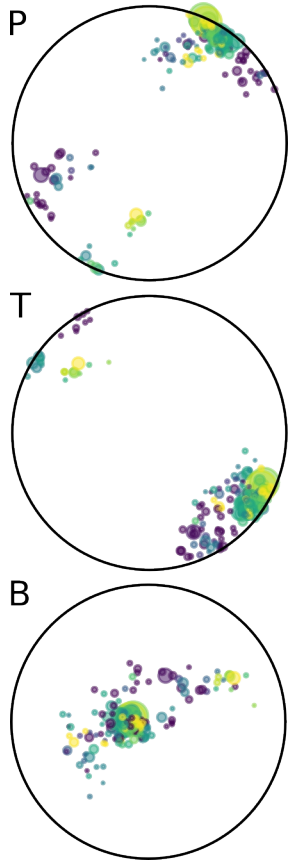
- Significant positive isotropic components
- CLVD – components less well-resolved

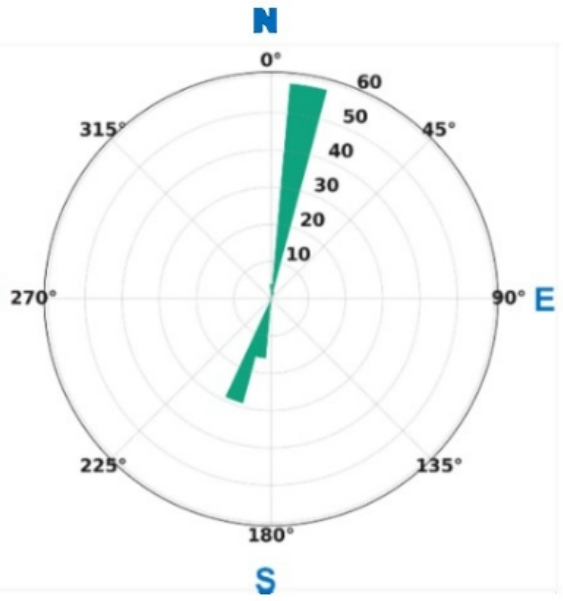
Strike slip dominance with rotated slip axes

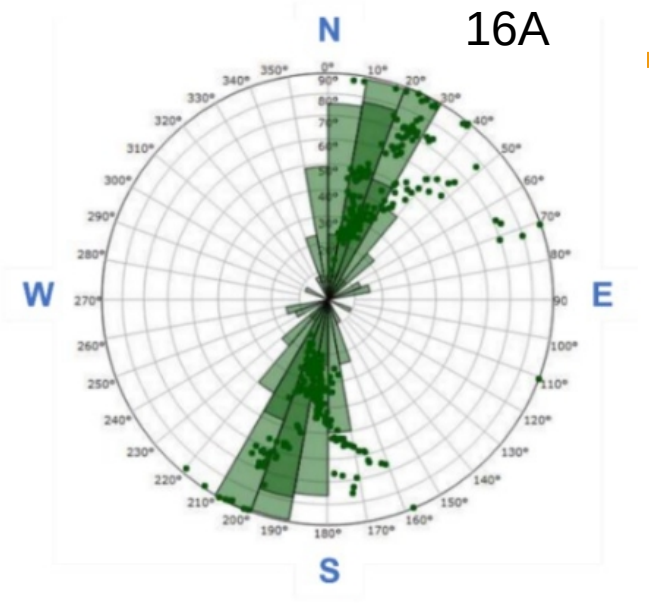
a) preexisting small scale fractures/faults with small variations in strike

b) Riedel shear









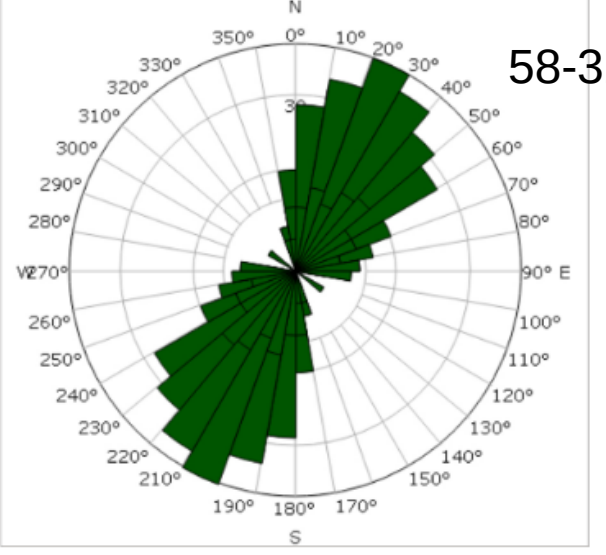


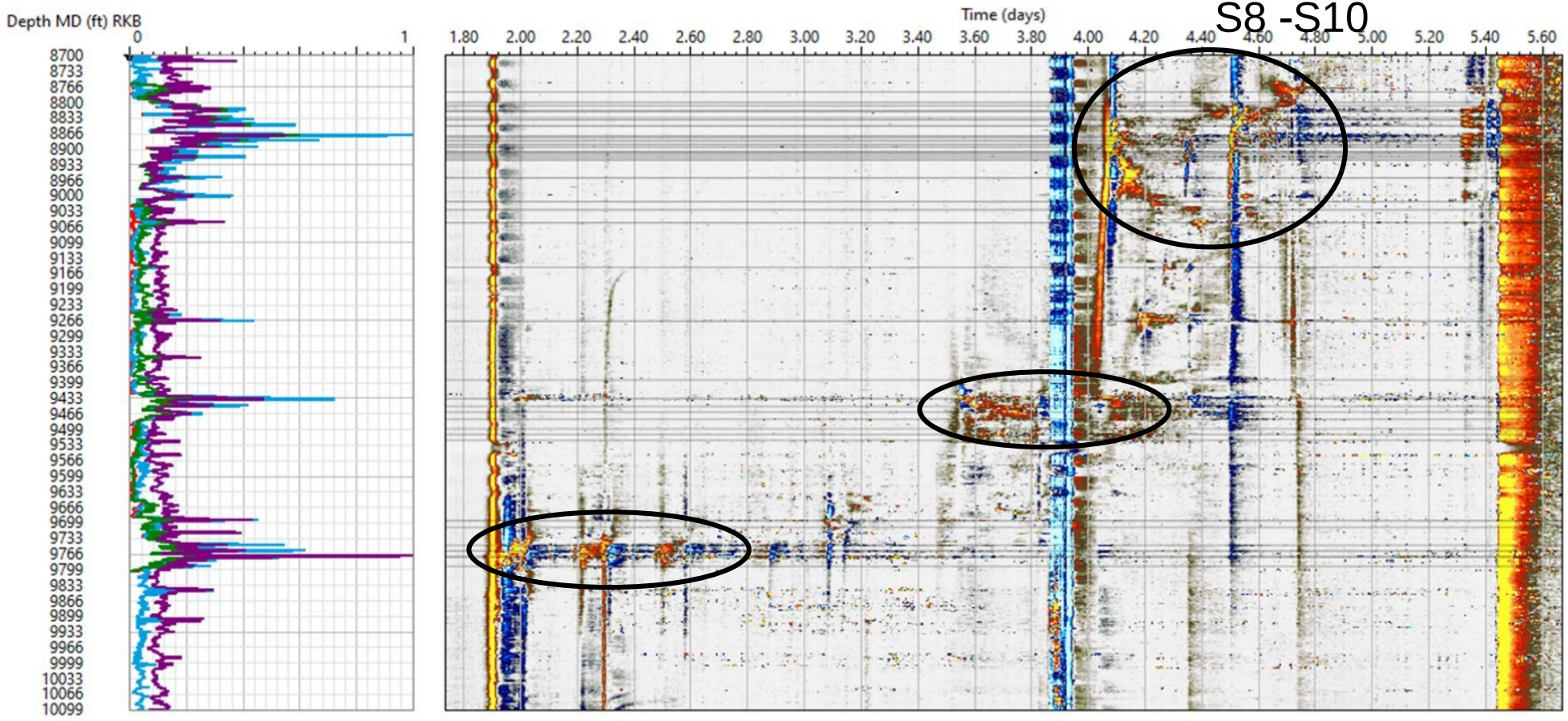
Fig. 10. Well 58-32 rose plot. This plot represents the drilling induced fracture sample set from the actual FMI fractures ranging from 968-2297 m measured depth.

Figure 5: (a) The azimuth of drilling-induced fractures in deviated well 16A(78)-32, inferred from the stress inversion using Method 2, suggests that the orientation of S_{Hmax} ranges from N5°E to N30°E. (b) The azimuth of drilling-induced fractures in deviated well 16A(78)-32, observed from the image logs, suggests that the orientation of S_{Hmax} ranges from N10°E to

Ye and Ghassemi (2024): The Updated Wellbore Stress Models for Utah FORGE. PROCEEDINGS, 49th Workshop on Geothermal Reservoir Engineering, Stanford University, Stanford, California, February 12 -14, 2024, SGP -TR-227

Nadimi, S., Forbes, B., Moore, J., Podgorney, R., & McLennan, J. D. (2020). Utah FORGE: Hydrogeothermal modeling of a granitic based discrete fracture network. Geothermics, 87, 101853.

Stimulations 2024 - Frac hits at 16B measured via fiber optics



NEUBREX Energy Services

UTAH FORGE

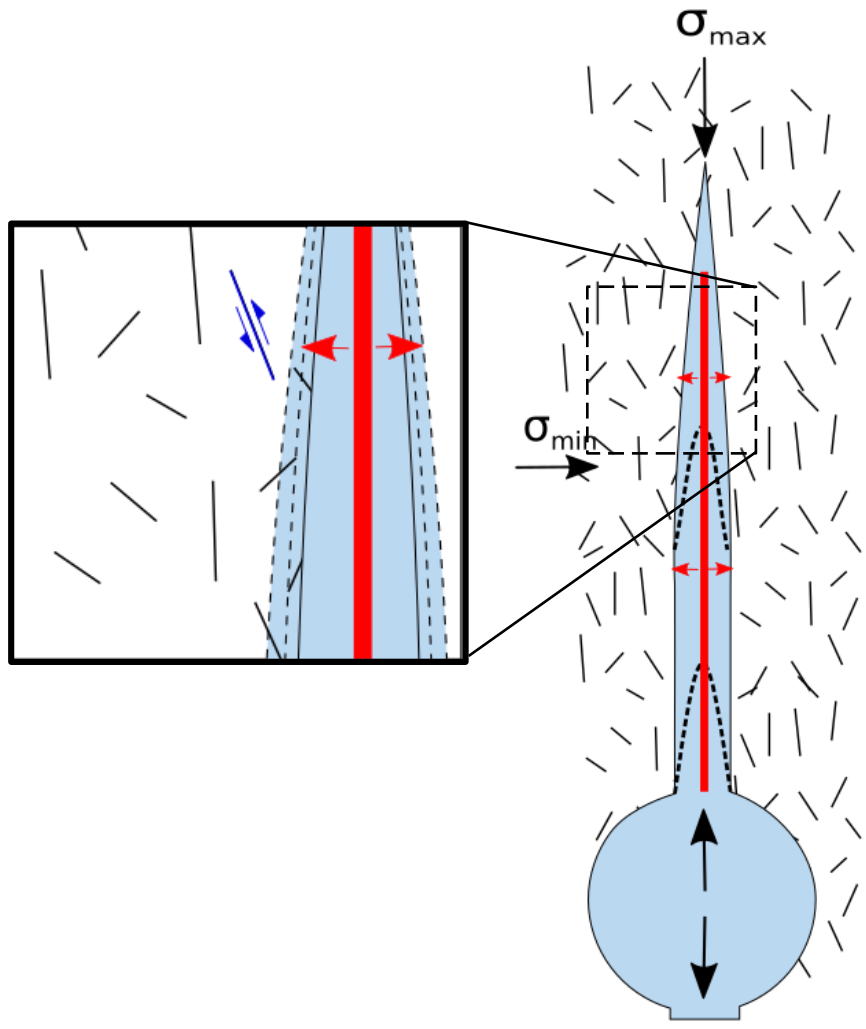
EVO2 - 16A FRAC

16B RFS DSS Strain Change Rate

STRAIN CHANGE RATE με_T

-0.4 0.4

Conceptual models



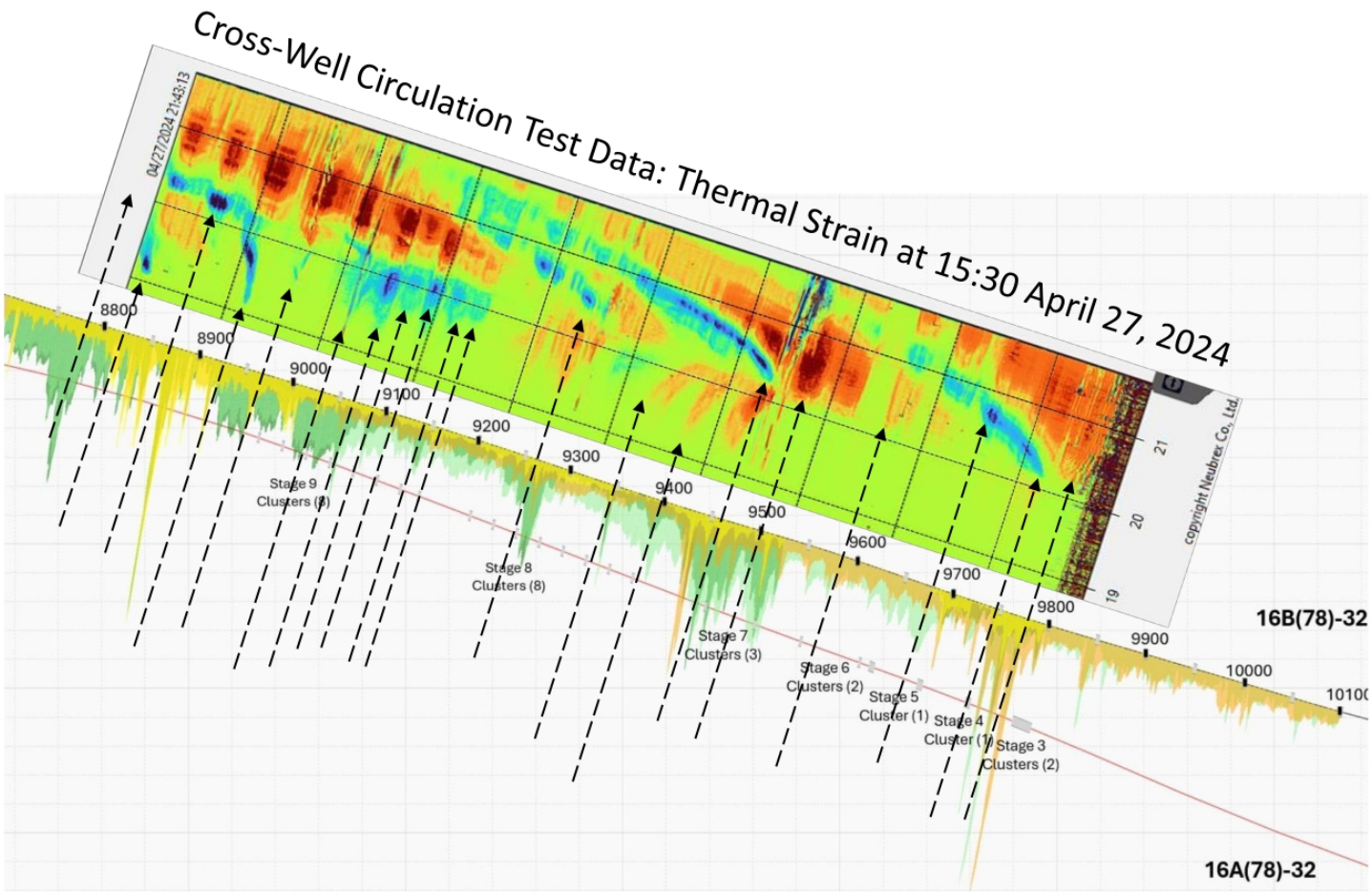
ISOTROPIC components

(1)slip along preexisting fracture in the fracture wall

(2) quasi-instantaneous marginal opening of the HF

(3) composite signal from two sources close in space

Utah FORGE 2024 – DAS-based Frac Hits



16B(78)-32 Fracture Driven Strain

16A(78)-32 Frac Stages

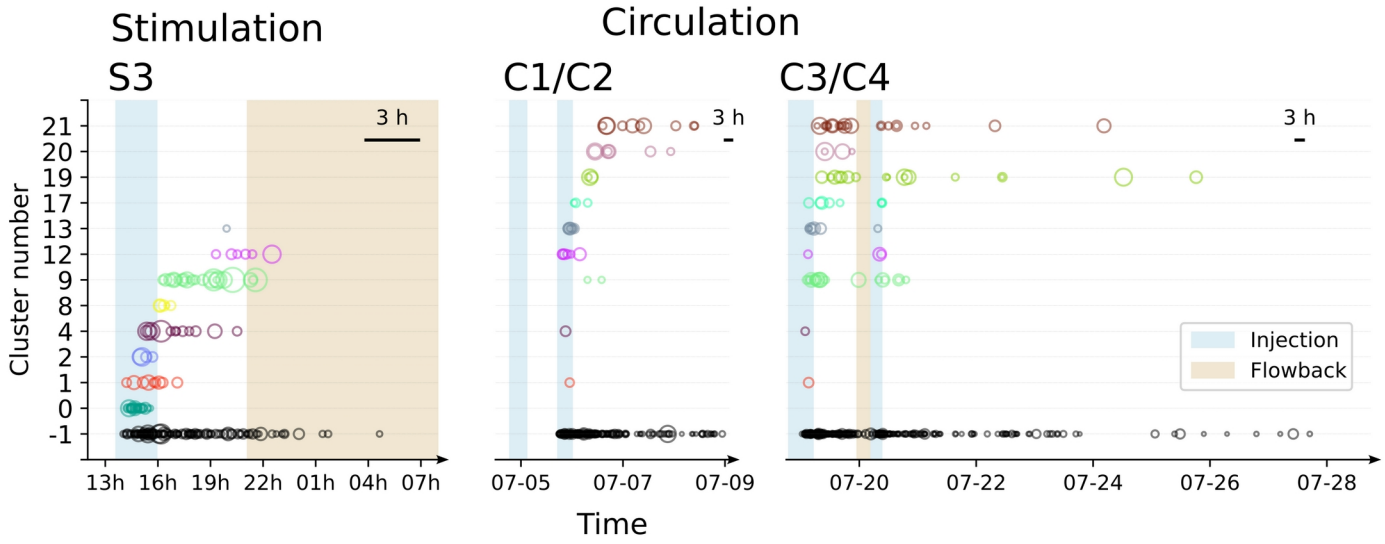
Courtesy of Neubrex

Event similarity

Repeated activation and newly activated volumes

- Applying **waveform-based** earthquake clustering (*Clusty,* Petersen and Niemz, et al., 2021)
- Combining stimulation and circulation

→ identifying overlapping activity + new clusters



Event similarity

Repeated activation and newly activated volumes

- Applying **waveform-based** earthquake clustering (*Clusty,* Petersen and Niemz, et al., 2021)
- Combining stimulation and circulation

  → identifying overlapping activity + new clusters