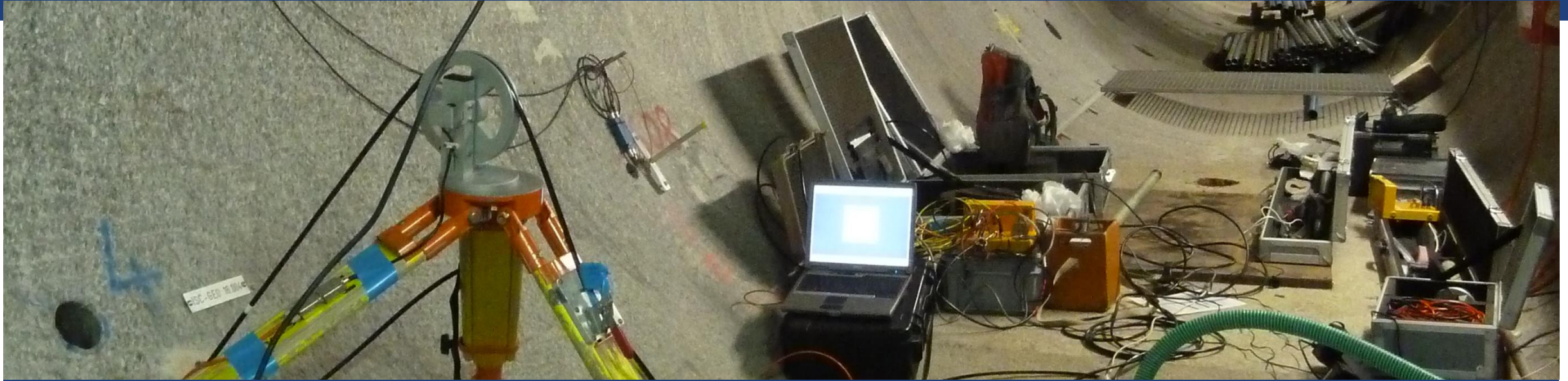




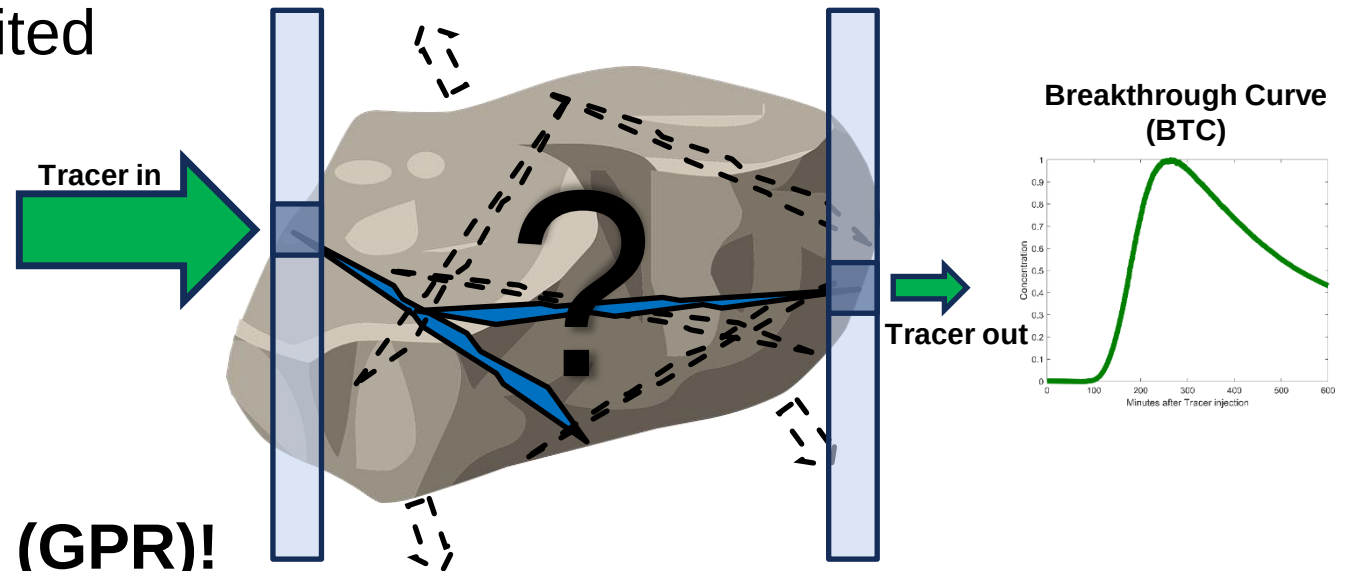
Inferring saline tracer transport characteristics from time-lapse GPR experiments

Peter-Lasse Giertzuch, Alexis Shakas, Bernard Brixel, Joseph Doetsch, Mohammadreza Jalali, and Hansruedi Maurer

Flow and Transport in Fractured Rock – Tracer Tests

- Tracer tests allow for characterization of flow and transport in fractured rock
- Fracture networks have limited access
- Sensor deployment possibilities are limited (borehole intervals)
- Spatial resolution is therefore limited
- Fracture network remains partially hidden
- Flow paths are unknown or uncertain

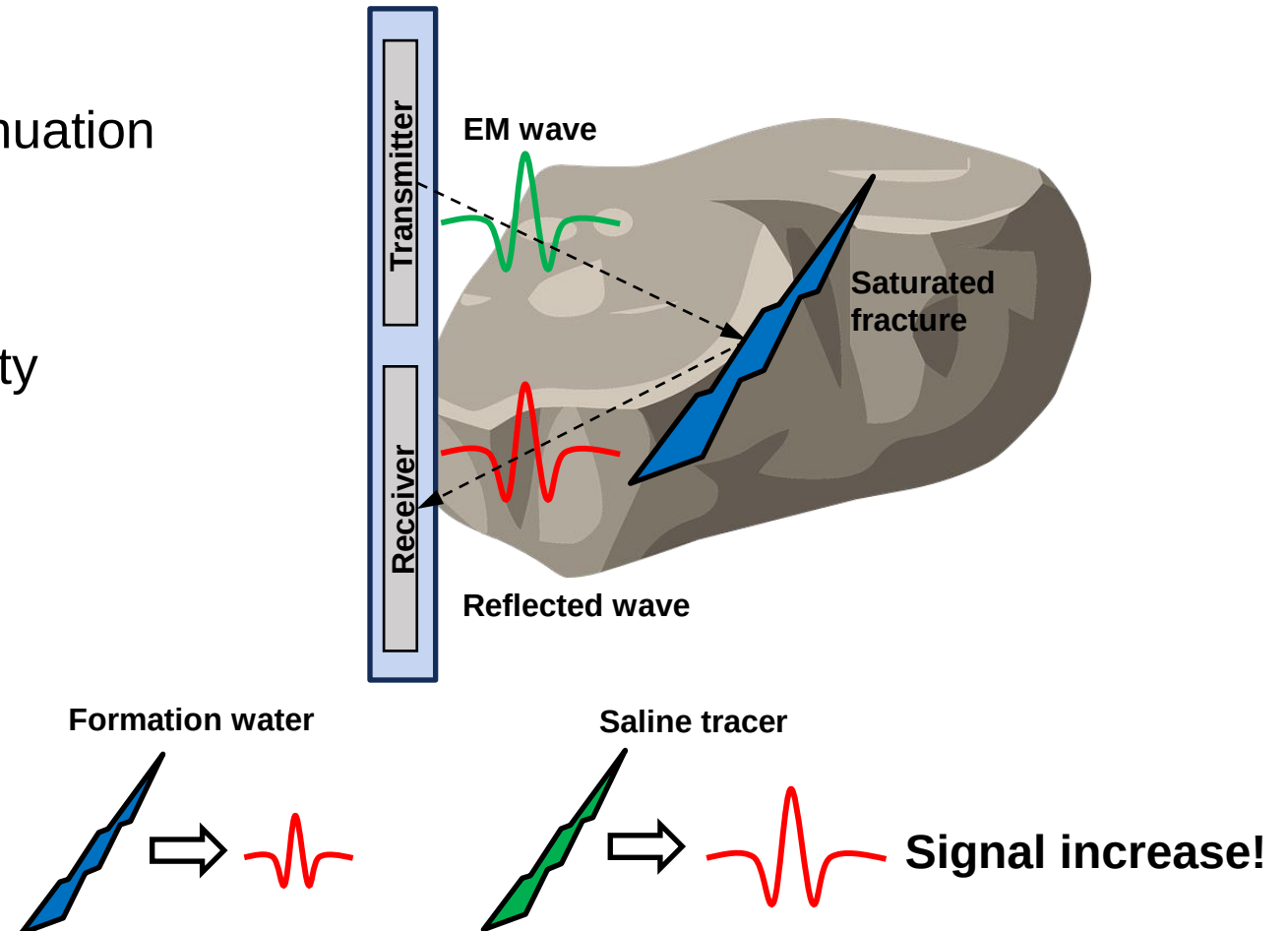
➤ **Use Ground Penetrating Radar (GPR)!**



Saline Tracer Tests with Time-Lapse Ground Penetrating Radar

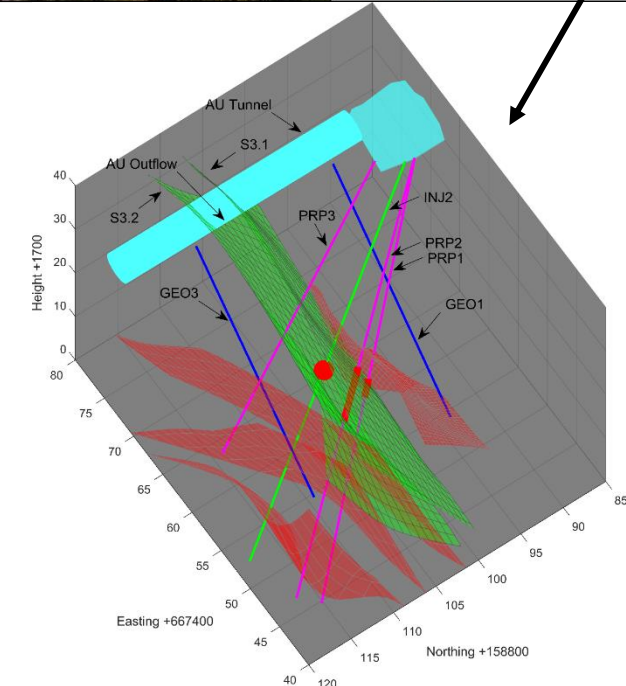
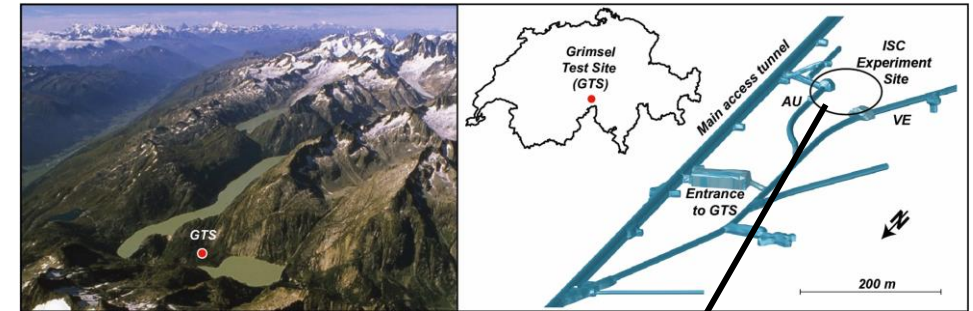
- Borehole GPR
 - Emits electromagnetic waves
 - Sensitive to electromagnetic properties
 - Suitable for crystalline rock with low attenuation
 - Good spatial resolution
- Saline tracer
 - Increases locally the electrical conductivity
 - Increases reflected GPR signal
- Time-Lapse GPR
 - Sub-mm aperture fractures induce only minimal changes
 - Difference imaging approach necessary
 - Requires extensive data processing
 - See Giertzuch et al. (2020, 2021)

A saline tracer increases the electrical conductivity



Grimsel In-situ Stimulation and Circulation Project

- Grimsel Test Site
 - In-situ experiment
 - 500m overburden
 - Fully saturated
 - Decameter scale
- Saline tracer injection in INJ2 (green)
 - At red sphere
 - Between two shear zones (S3, green)
 - Conductivity sensors in PRP boreholes (magenta) and AU Outflow
- Borehole GPR
 - In GEO1 and GEO3 (blue)
 - Undirected 250 MHz antennas

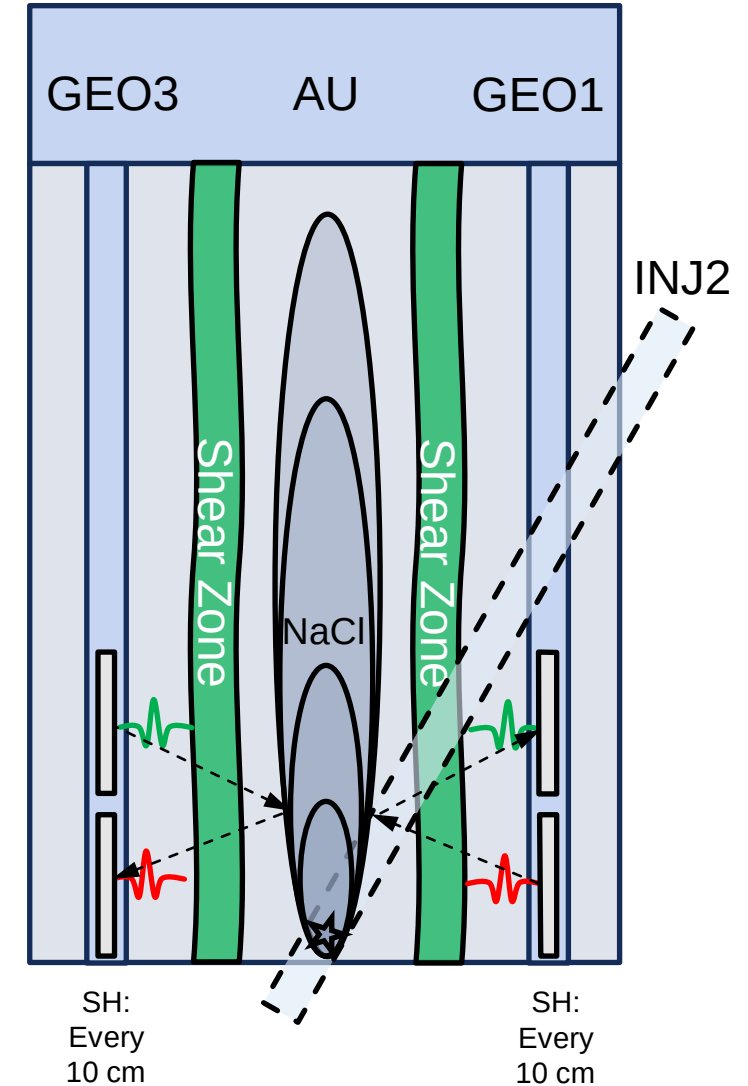


Krietsch et al. (2018)

Field Work – Data Acquisition

Two tracer tests conducted:

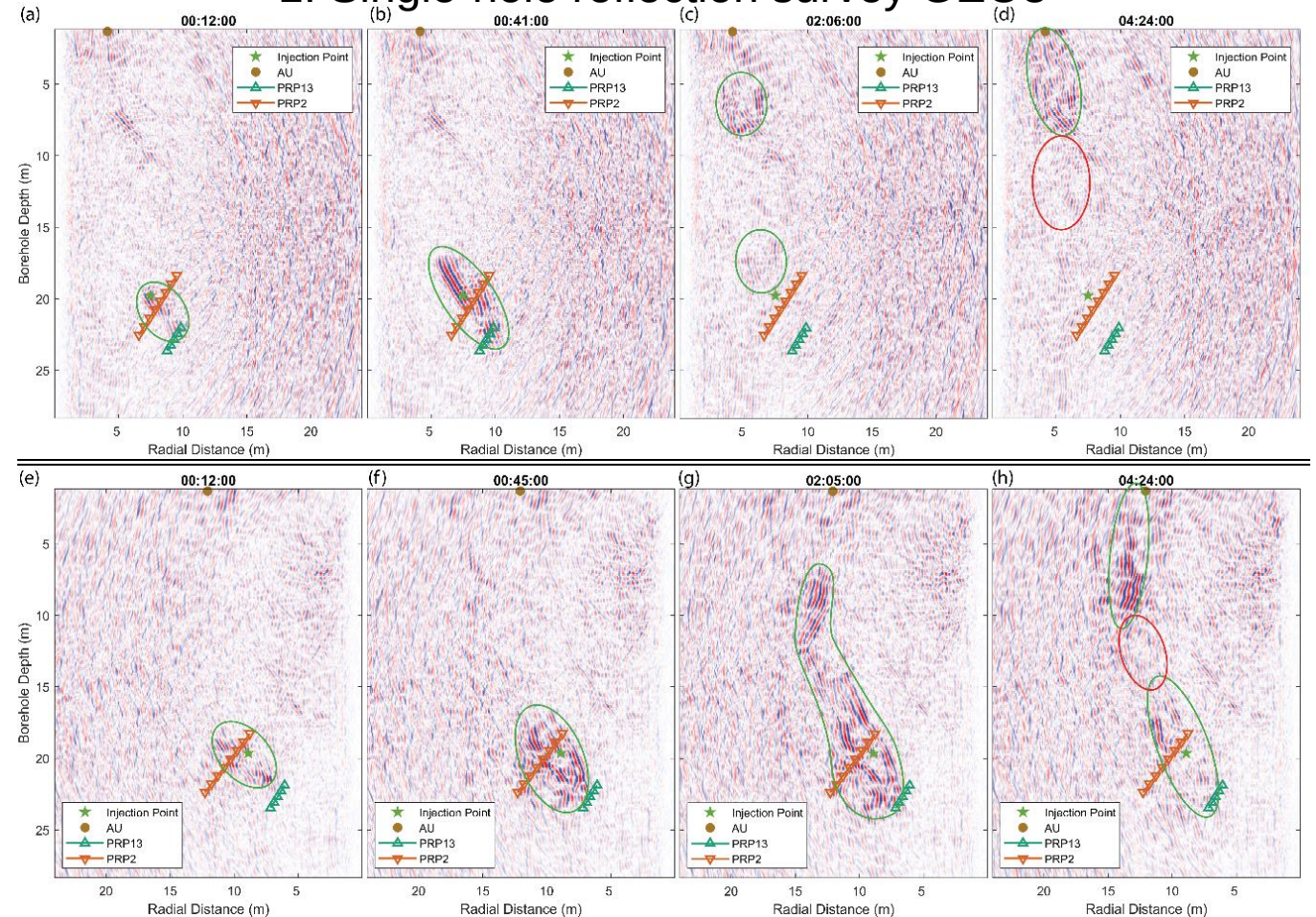
- 250 MHz borehole antennas (Malå Geosciences)
- Tracer conductivity $\sim 60\text{mS/cm}$
- 1: Single-hole reflection survey GEO3
 - $\sim 100\text{ L}$ of tracer volume
 - $\sim 50\text{ min}$ injection duration
- 2: Single-hole reflection survey GEO1
 - $\sim 200\text{ L}$ of tracer volume
 - $\sim 100\text{ min}$ injection duration



Difference Reflection Imaging – Two Boreholes

- Difference Reflection Imaging resolves tracer signal!
- Highlighted:
 - Good contrast (green)
 - Weak contrast (red)
 - Locations of conductivity sensors (PRP1.3, PRP2, AU)
- Tracer propagates from injection to AU and to PRP13

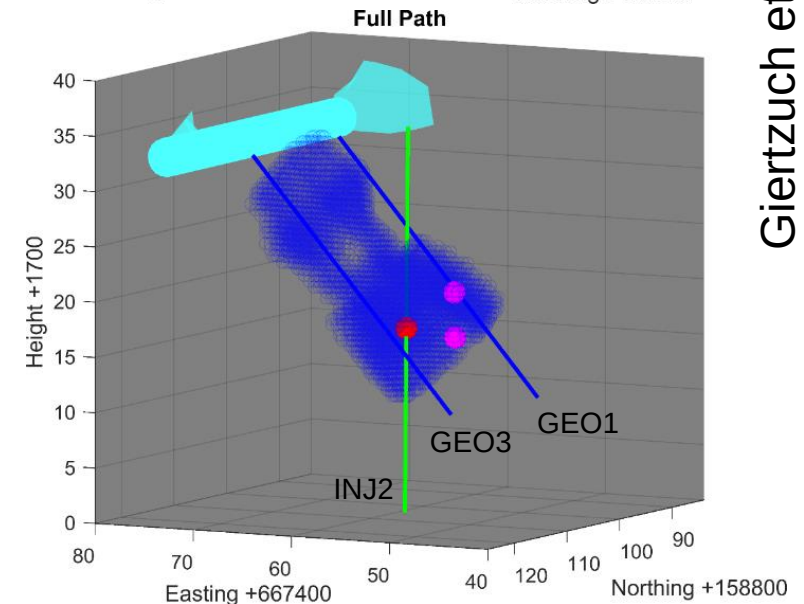
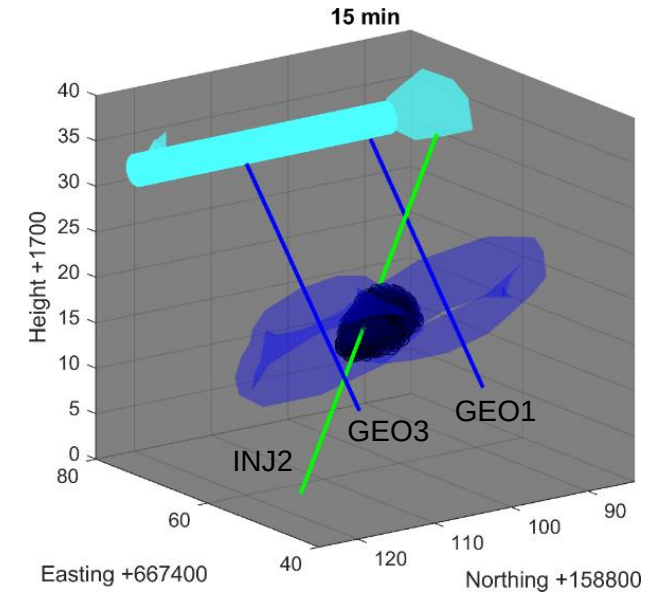
1: Single-hole reflection survey GEO3



2: Single-hole reflection survey GEO1

3D Tracer Flow Path Reconstruction

- Borehole radar is radially symmetric
 - Localization is ambiguous
 - Tracer reflection occurred from “donut” around the borehole
 - Combining data from two boreholes
 - Intersection gives a volume
 - Tracer likely to have propagated within this volume
- Tracer flow can be reconstructed in space and time!



Giertzuch et al. (2021)

Flow Velocity

- Velocity calculation
 - Requires distance and time
 - Distance between observation points often unknown
 - Assume direct connection? (dashed)
 - GPR resolves curved flow paths
 - Algorithm to reconstruct apparent flow paths from GPR data
- Cumulative distance (solid) is better estimate than direct connection (dashed)
- Average velocity along the apparent flow paths can be calculated

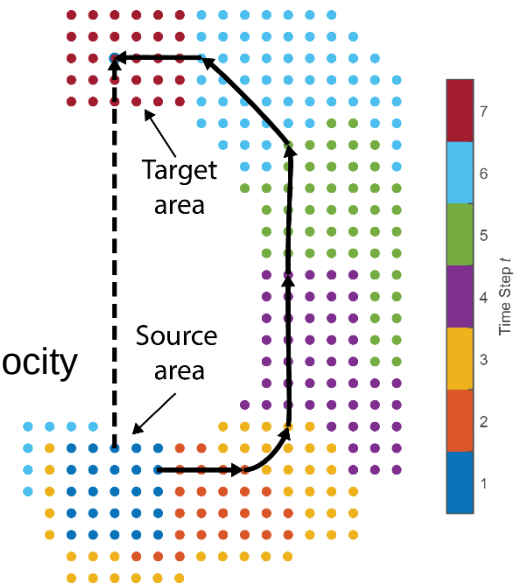
Velocity:

$$v = \frac{d}{t}$$

d = cumulative distance

v = average flow path velocity

Apparent flow paths



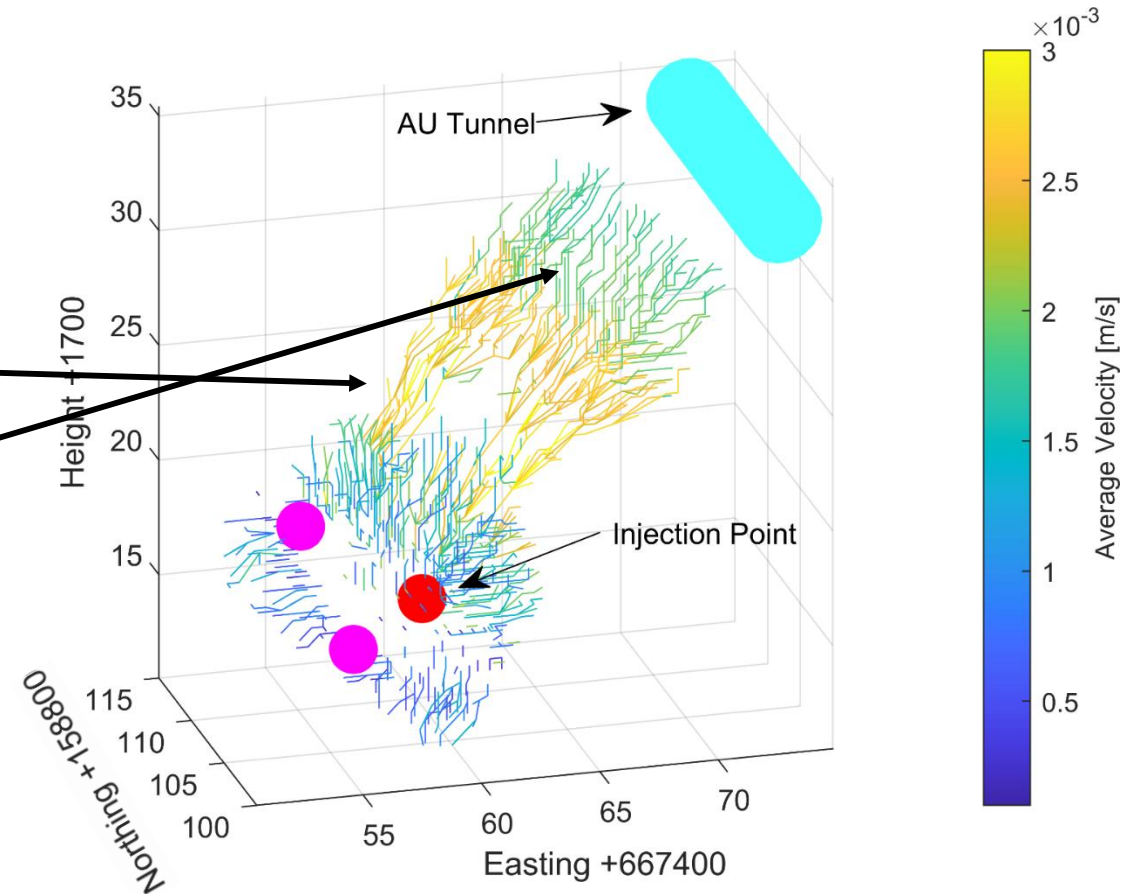
Giertzuch et al. (under review)

Average Tracer Flow Velocity Field

- Apply approach on GPR experiment data
 - Lines resemble apparent flow paths
 - Not “actual” flow paths, due to resolution limits

➤ 3D average velocity field is resolved

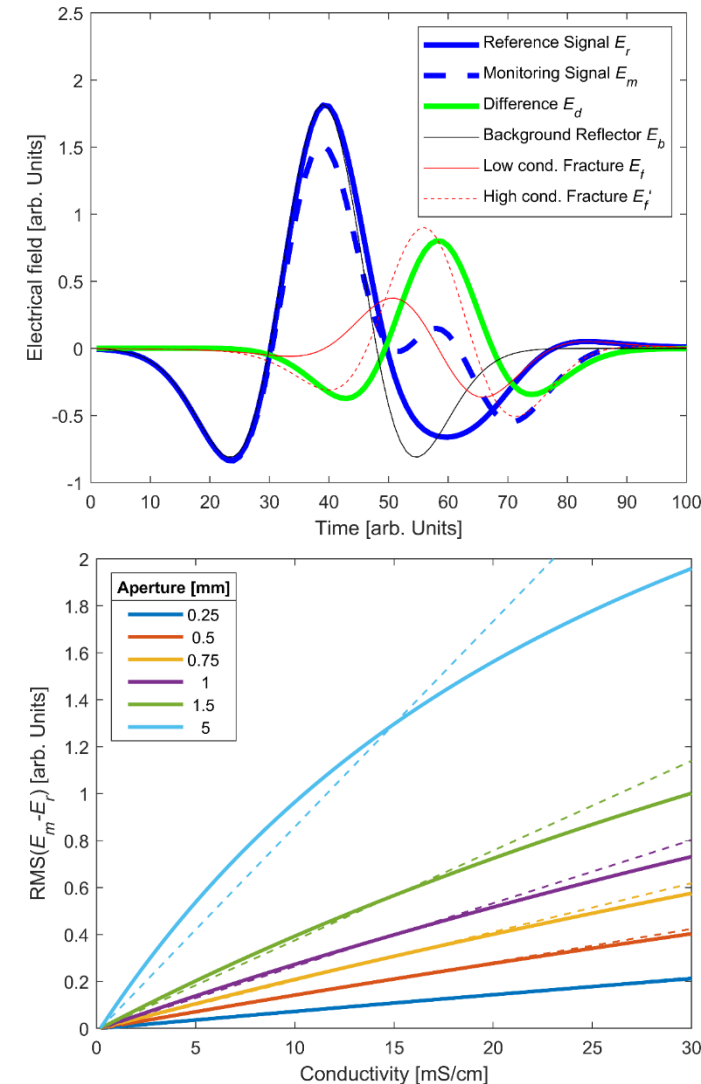
- High velocity along shear zone S3.2
- Velocity decreases closer to AU tunnel: Tracer probably leaves S3.2 into different fracture(s) that connect to AU



Giertzuch et al. (under review)

DRBTC – Difference Radar Breakthrough Curve

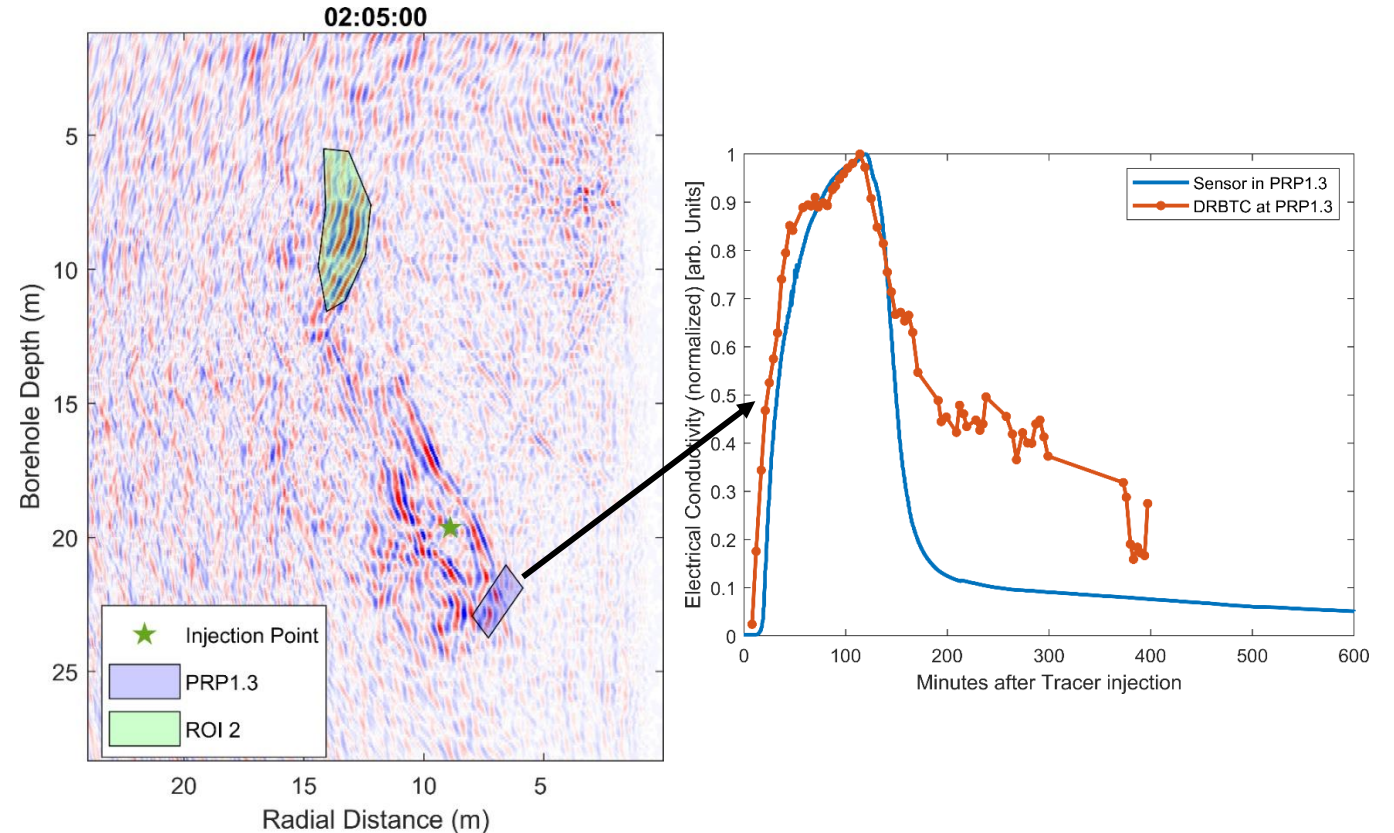
- Breakthrough Curves from GPR
 - Conductive tracer increases signal
 - Wave interference can cause unexpected signal decrease
 - Requires data differencing!
 - Root-mean-square value of difference radar data
 - For sub-mm fracture apertures
 - Correlates linear with fluid conductivity
 - Only relative information, no absolute conductivity
- Definition of Regions of Interest (ROI) in reflection data
 - Allows localized Difference Radar Breakthrough Curves (DRBTC)



Giertzuch et al. (under review)

DRBTC – Difference Radar Breakthrough Curve

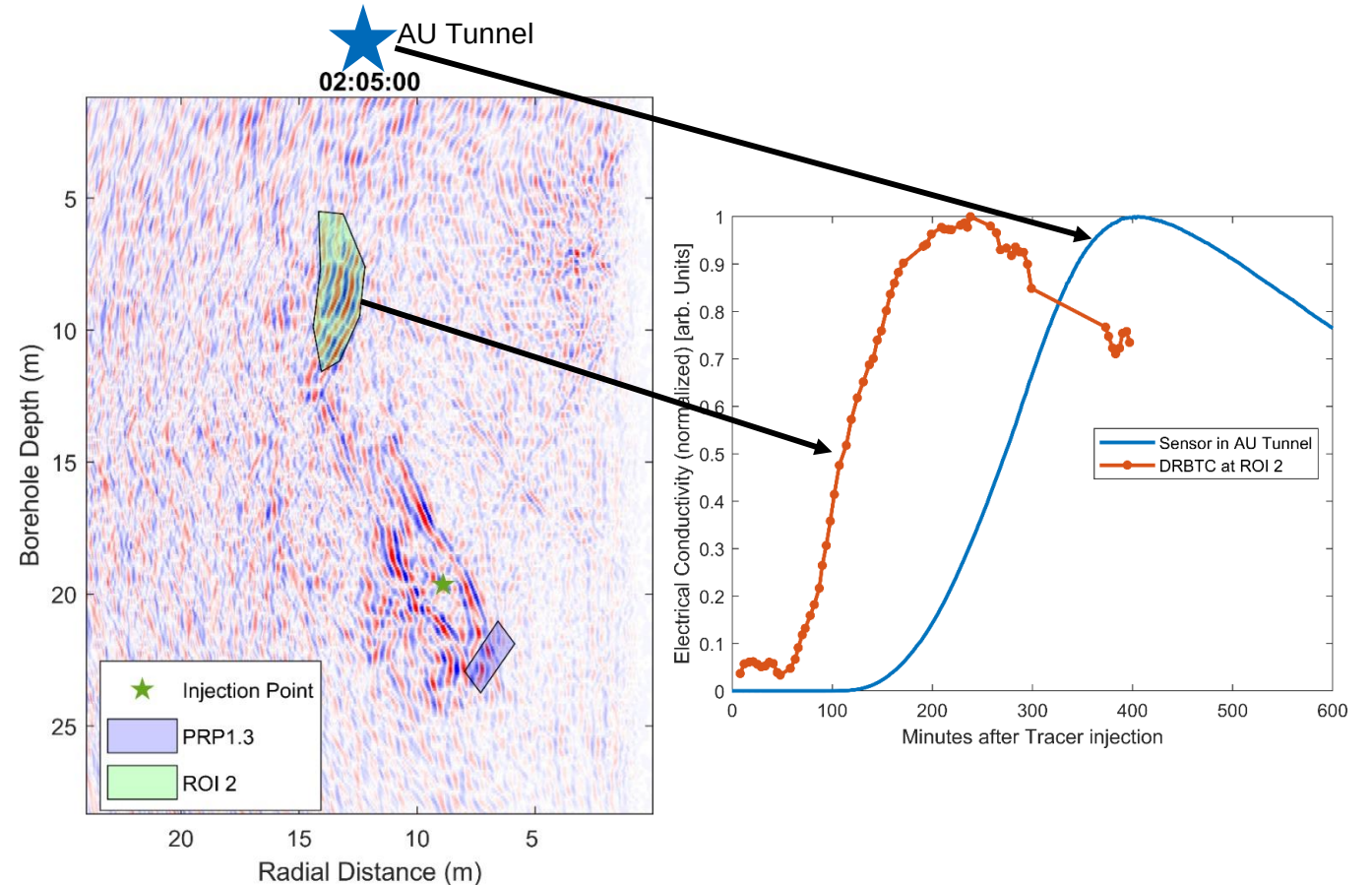
- ROI in PRP1.3
 - Conductivity borehole sensor available
 - Compare conductivity sensor and DRBTC
- Good agreement for early times!
 - Later times suffer from GPR system instabilities and radial ambiguity



Giertzuch et al. (under review)

DRBTC – Difference Radar Breakthrough Curve

- ROI 2
 - High signal-to-noise ratio for GPR
 - No borehole available
 - GPR only option for hydrological data!
 - Compare conductivity sensor in AU Tunnel and DRBTC
 - Reasonable agreement (different locations)
- GPR capable of resolving DRBTC for regions in the subsurface that cannot be monitored otherwise!



Giertzuch et al. (under review)

Conclusions

- GPR offers high spatial resolution
 - Can help to overcome the problem of fracture network accessibility
- GPR can monitor saline tracer propagation in sub-mm fracture apertures
 - Difference imaging approaches are necessary but non-trivial
 - Tracer propagation can be constrained in 3D from two GPR boreholes
- GPR offers average tracer propagation velocities
 - Along apparent (curved) flow paths
 - Better estimate than direct connections
- GPR can provide difference radar breakthrough curves (DRBTC)
 - Any position in the GPR data possible
 - But varying signal-to-noise ratios
 - Offers only relative, not absolute data

References

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