Identification of 3D fracture distribution and fracture connectivity by combined Ground Penetrating Radar imagery and tracer tests at the Äspö Hard Rock Laboratory, Sweden

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ITN Enigma

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Flow and transport in fracture networks: reducing uncertainty of DFN models by conditioning to geology and geophysical data (Ground Penetrating Radar - GPR) (2017-2020)

Develop and test a general methodology to condition Discrete Fracture Network (DFN) models to geological mapping and geophysical data in order to reduce the uncertainty of fractured rock properties and flow patterns.

Itasca consultants S.A.S and University of Rennes/CNRS : expertise in DFN modelling (Caroline Darcel and Philippe Davy) + expertise in hydrogeology (Tanguy Le Borgne and Olivier Bour)

University of Lausanne (UNIL) : expertise in GPR (Niklas Linde and Ludovic Baron)

SKB company : Swedish Nuclear Fuel and Waste Management Company (Jan-Olof Selroos)

Fractory: Common laboratory between Itasca Consultants and University of Rennes 1/CNRS

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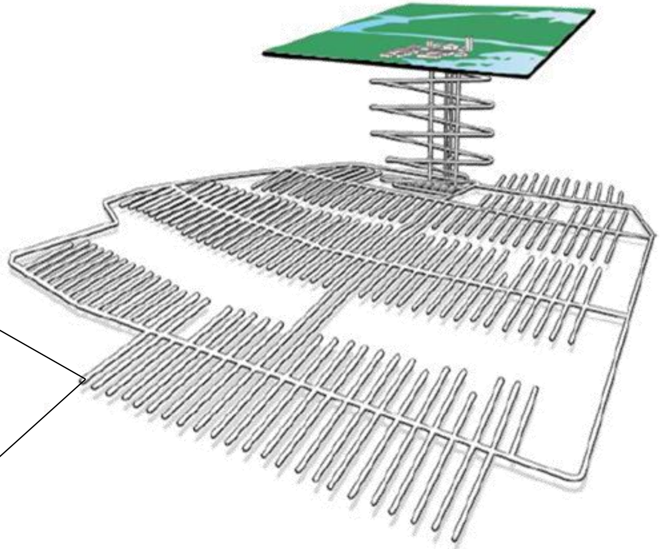
Nuclear Waste Disposal

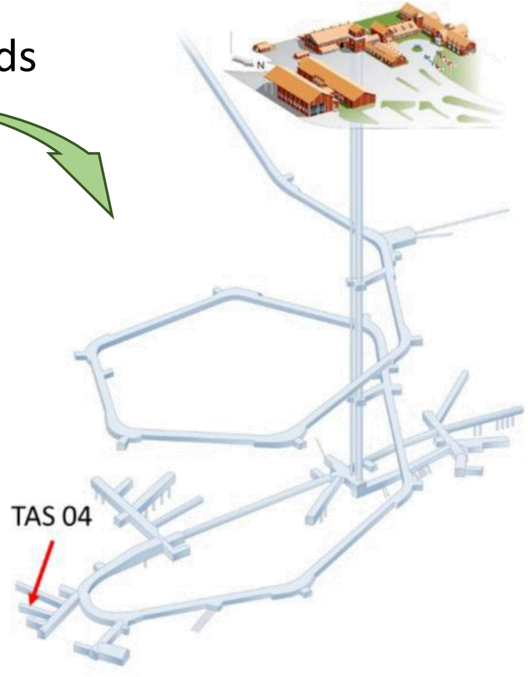
The Äspö Hard Rock Laboratory, Sweden

Underground laboratory of almost 500 m of depth on the island of Äspö in southeastern Sweden. Experiments are achieved at depth in order to develop methodologies and new technologies for a construction of Final Repository for Spent Fuel.



Swedish prototype of the final repository for spent nuclear fuel

Know-how needs



Guided tour of the Äspö Hard Rock Laboratory

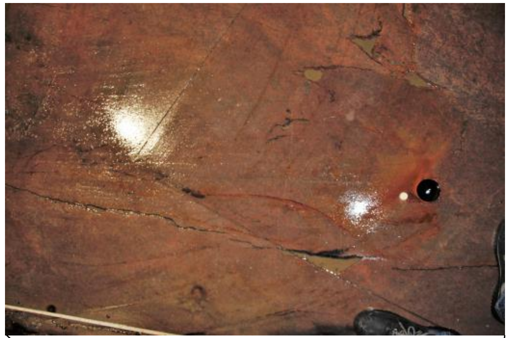
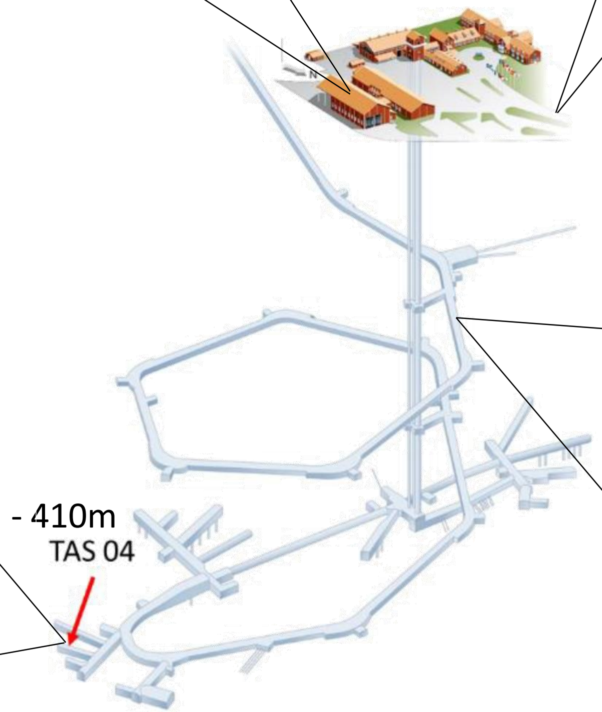
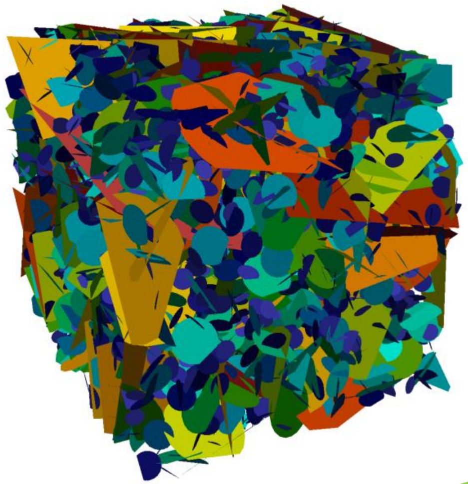


Fig. 10. Test site at Äspö HRL after diamond wire cutting (Photo: Rickard Enér)





Objectives

Discrete Fracture Network model (DFN)

DFN derived from deterministic data:

Boreholes
- 1D
- Depth

Outcrops
- 2D
- Surface

Tunnel walls
- 2D
- Depth

My PhD

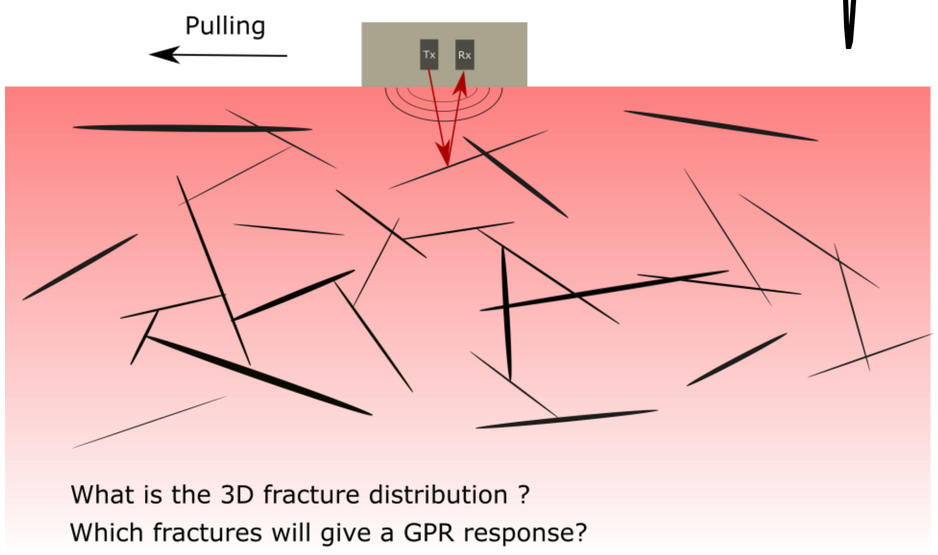
GPR
- 3D
- Depth + subsurface

Reduce the uncertainty on the spatial fracture extent and their 3D distribution

Build a methodology to condition DFN models to GPR data at scales from a few to tens of meters around the canisters containing the spent nuclear fuel

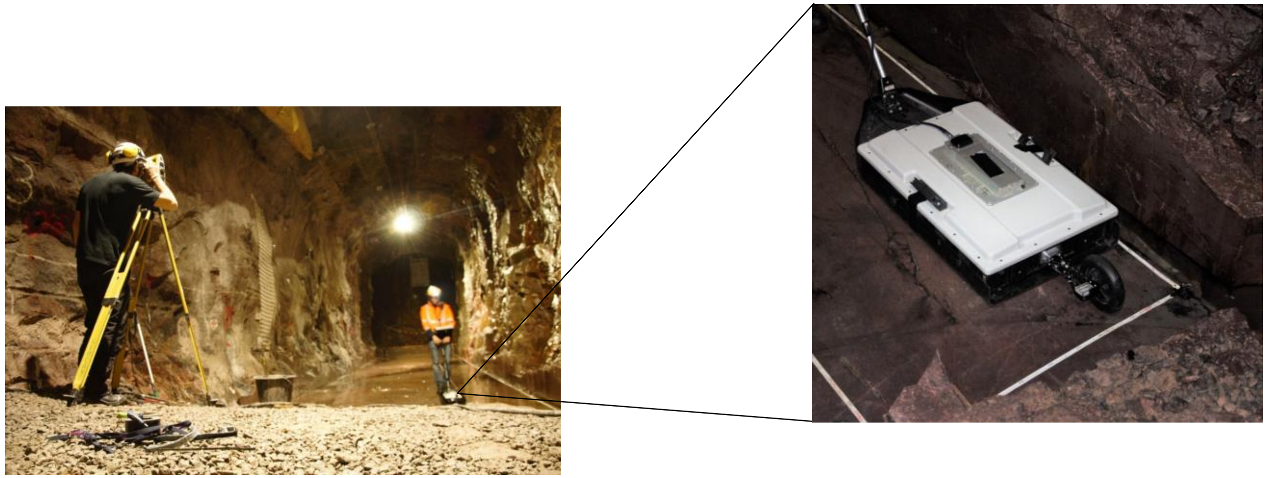
3D surface GPR

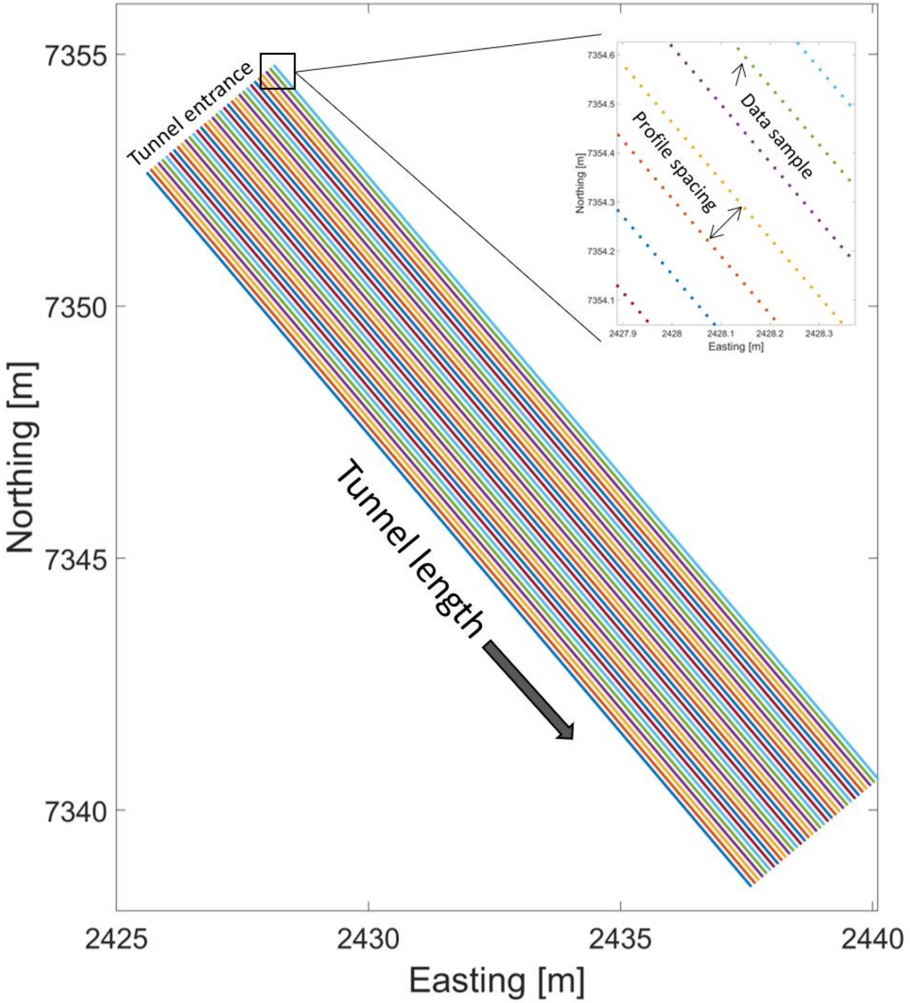
Methodology



Frequencies:
160 MHz
450 MHz
750 MHZ

Profile spacing:
0.10 & 0.05 m





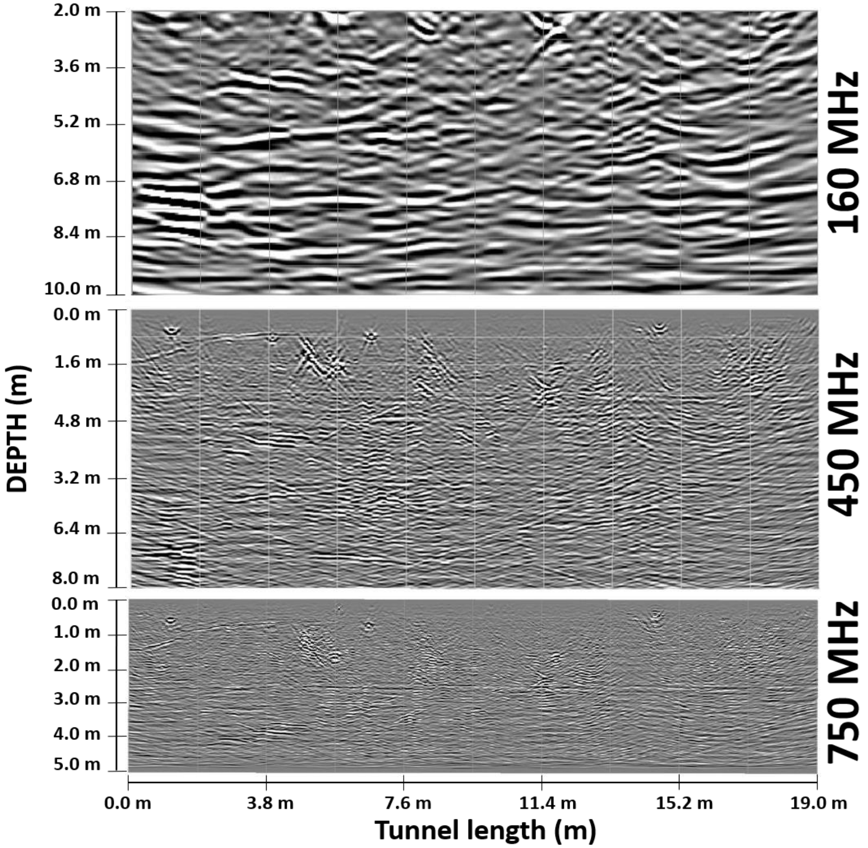
3D surface GPR

Results

2D GPR slices after processing and migration

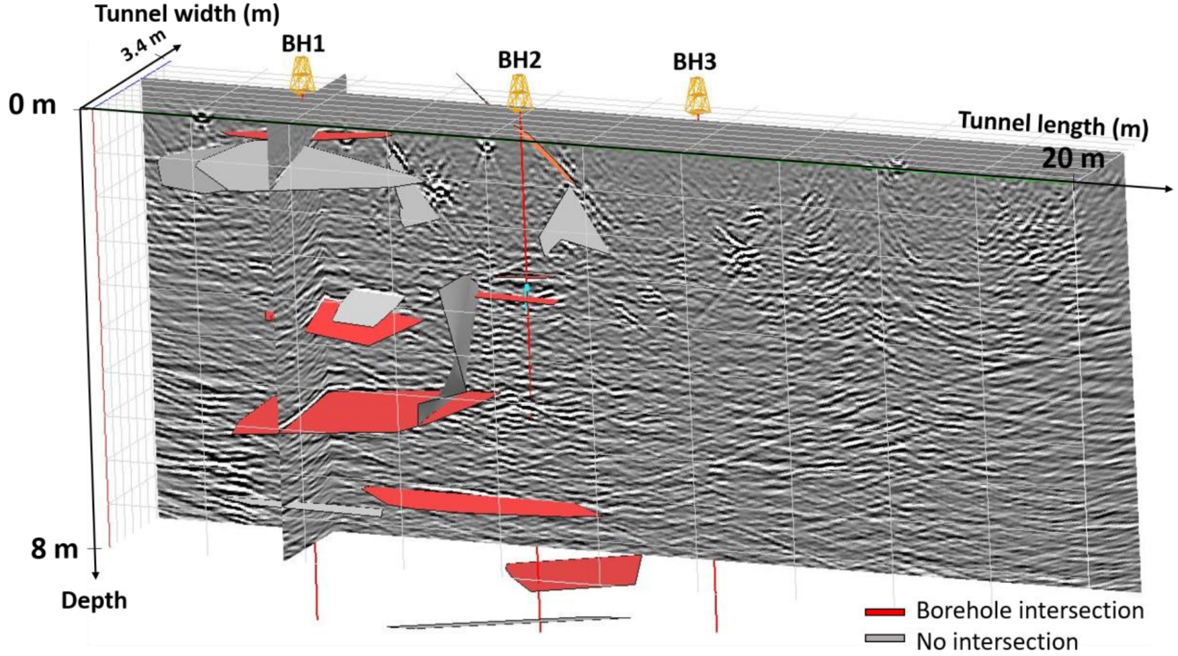
- DC removal, time-zero correction, mean trace removal, gain application, SVD filter and Kirchhoff migration were applied.
- The horizontal and vertical resolutions are 0.8 m and 0.2 m for 160 MHz, 0.25 m and 0.06 m for 450 MHz and 0.18 m and 0.04 m for 750 MHz.

GPR slice at 1.3 m in direction of tunnel width



GPR model, borehole siting and drilling

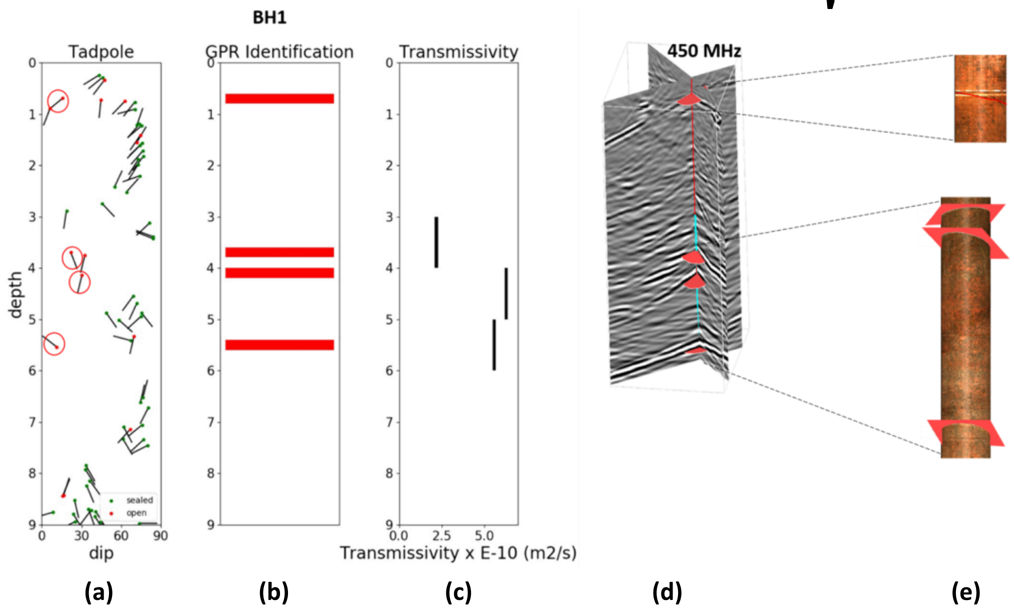
- Three zones were defined based on GPR reflections from, supposedly, more permeable to less permable regions. One borehole of 9.5 m was drilled in each zone (BH1 to BH3).
- Connectivity between all boreholes were observed during the drilling (pressure response).

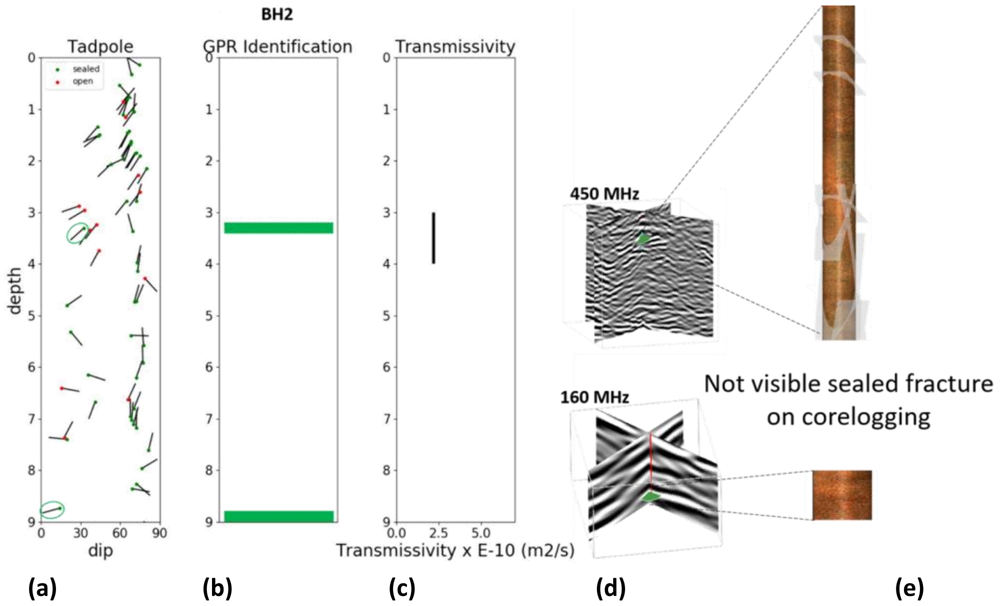


Paradigm GOCAD®

3D surface GPR

First interpretations



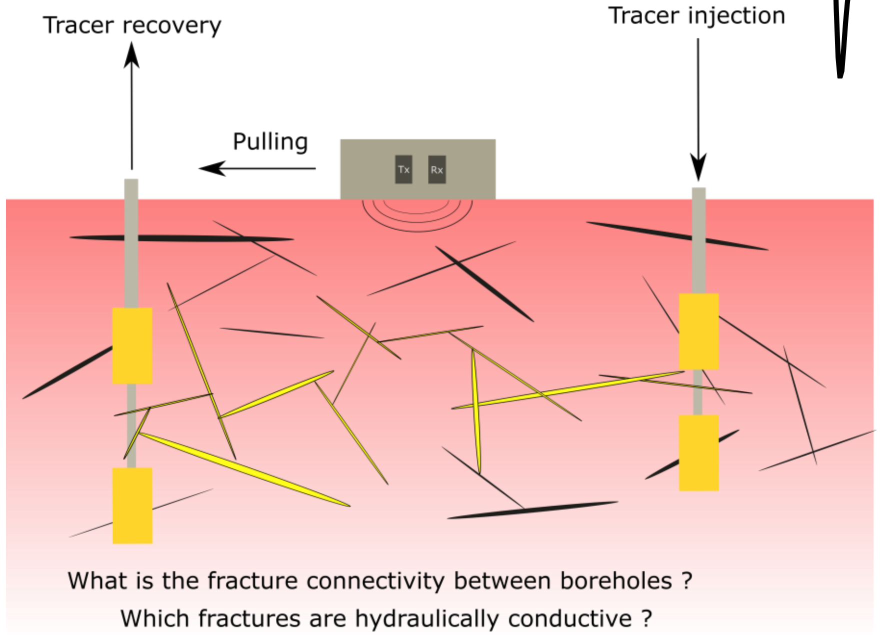


Correlation between corelogging, GPR and hydraulic data for BH1 (left) and BH2 (right)

(a) Tadpole plots are an easy representation to show the dip and the dip direction of fractures at depth;
(b) Fractures from corelogging identified on GPR sections;
(c) Transmissivity measurements (1-m flow sections along the boreholes) from hydraulic test. The most transmissive borehole (BH1) agreed with GPR classification;
(d) GPR sections with fractures correlation from boreholes. GPR reflections from BH1 are more sensitive to conductive open fractures while GPR reflections from BH2 are more sensitive to sealed fractures. Since the fractures in BH3 are mostly vertical, surface GPR could not image them;
(e) Corelogging images from Optical Televiewer measurements.

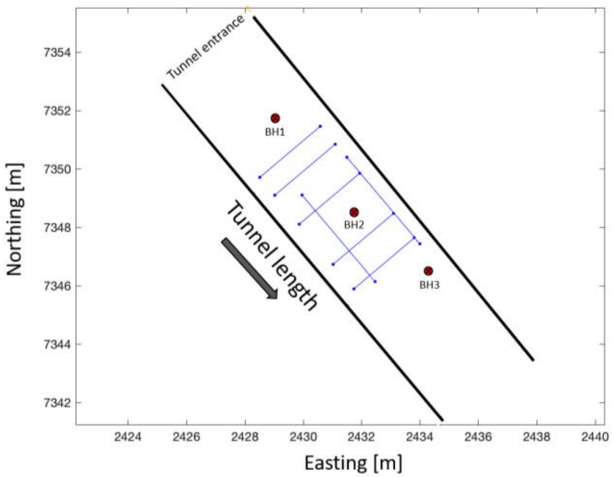
Tracer test & GPR monitoring

Methodology



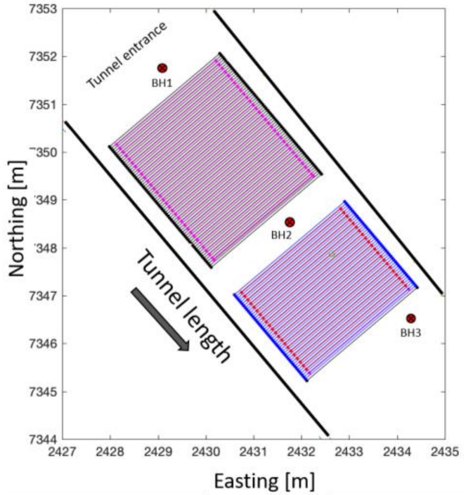
2D GPR profiles every hour during 8 hours

160 & 450 MHz

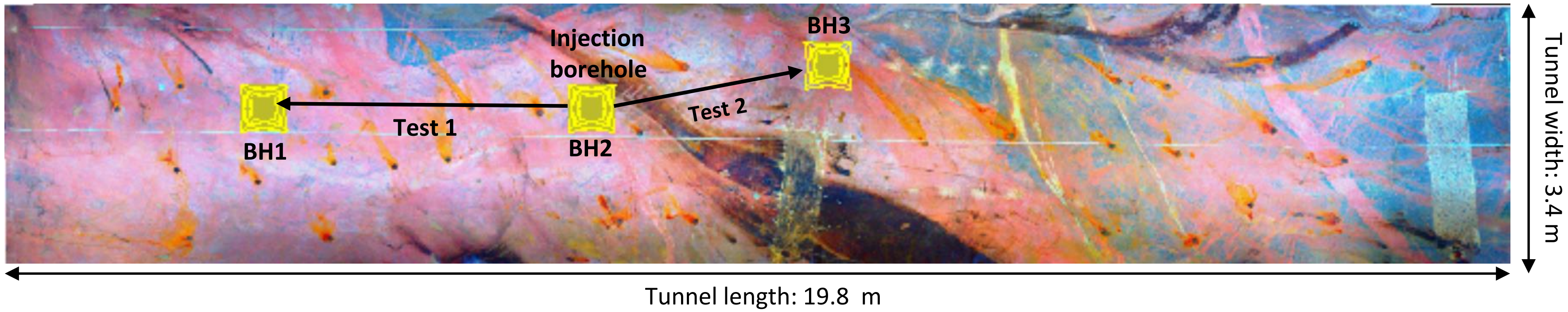


3D GPR surveys before and after injections

160 & 450 MHz



(Tunnel top view)



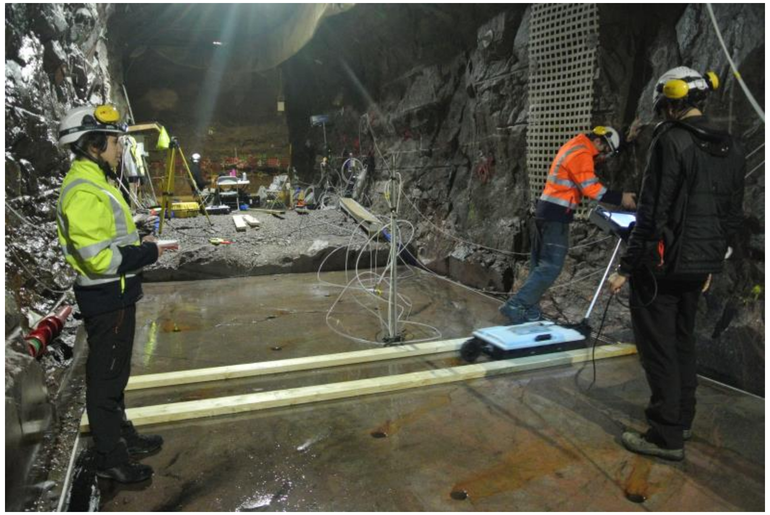
Test 1: Deionized water + Uranine tracer

Test 2: Deionized water + Rhodamine tracer

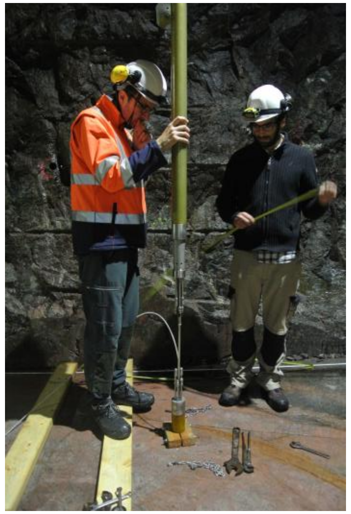
- Saline watertable (≈1850 mS/m)
- Most permeable 1-m sections: 10^{-9} to 10^{-10} m^2/s
- Injection rate: 10 mL/min (accumulated injection volume of 10 to 13 L for 24 hours using pressure differences exceeding 40 bar)

Tracer test & GPR monitoring

Methodology



VIDEO



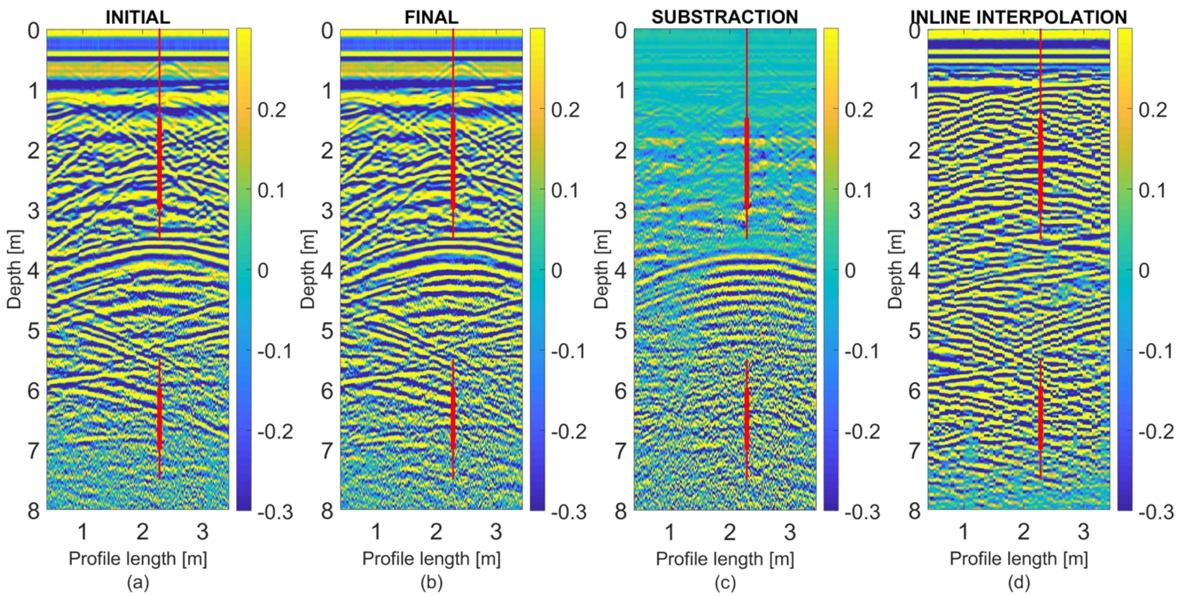
Tracer test & GPR monitoring

First results

2D GPR slices in crossline configuration from 3D measurements

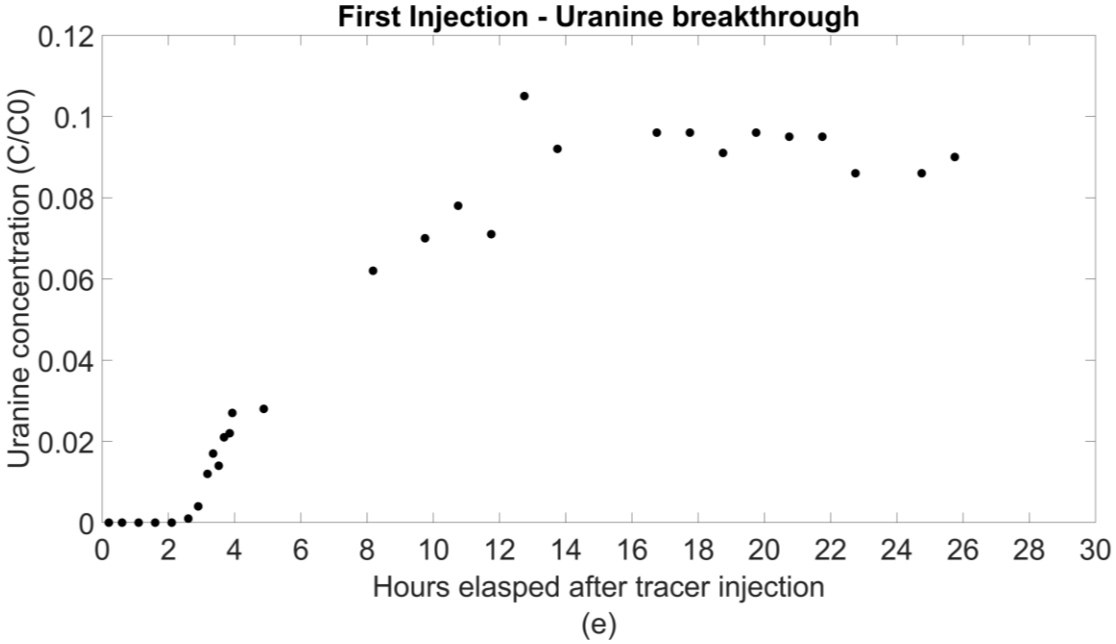
The profile represented is situated 0.55 m from BH1, where we can see strong GPR reflections corresponding to open fractures found in the corelogging. A projection of the packer configuration in BH1 is represented in red.

450 MHz - CROSSLINE CONFIGURATION - distance from BH1: 0.55 m



Tracer recovery

First tracer arrival in BH1 after 3 hours



Tracer test & GPR monitoring

Discussion

Challenges of observing the tracer movement with GPR are mainly due to:

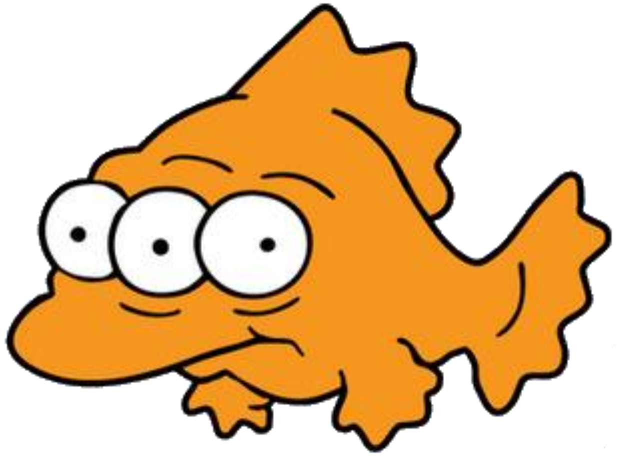
- Very low fracture transmissivity (2.2 E-10 to 7.0 E-10 m^2/s)
- Very small injected volume (i.e., thin open fractures)
- Only 20% to 30% of mass recovery
- Strong diffractions from packers hide the fracture signature
- Low electrical contrast between saline formation water (≈ 1800 mS/m) and deionized water used with tracer (≈ 1600 mS/m).

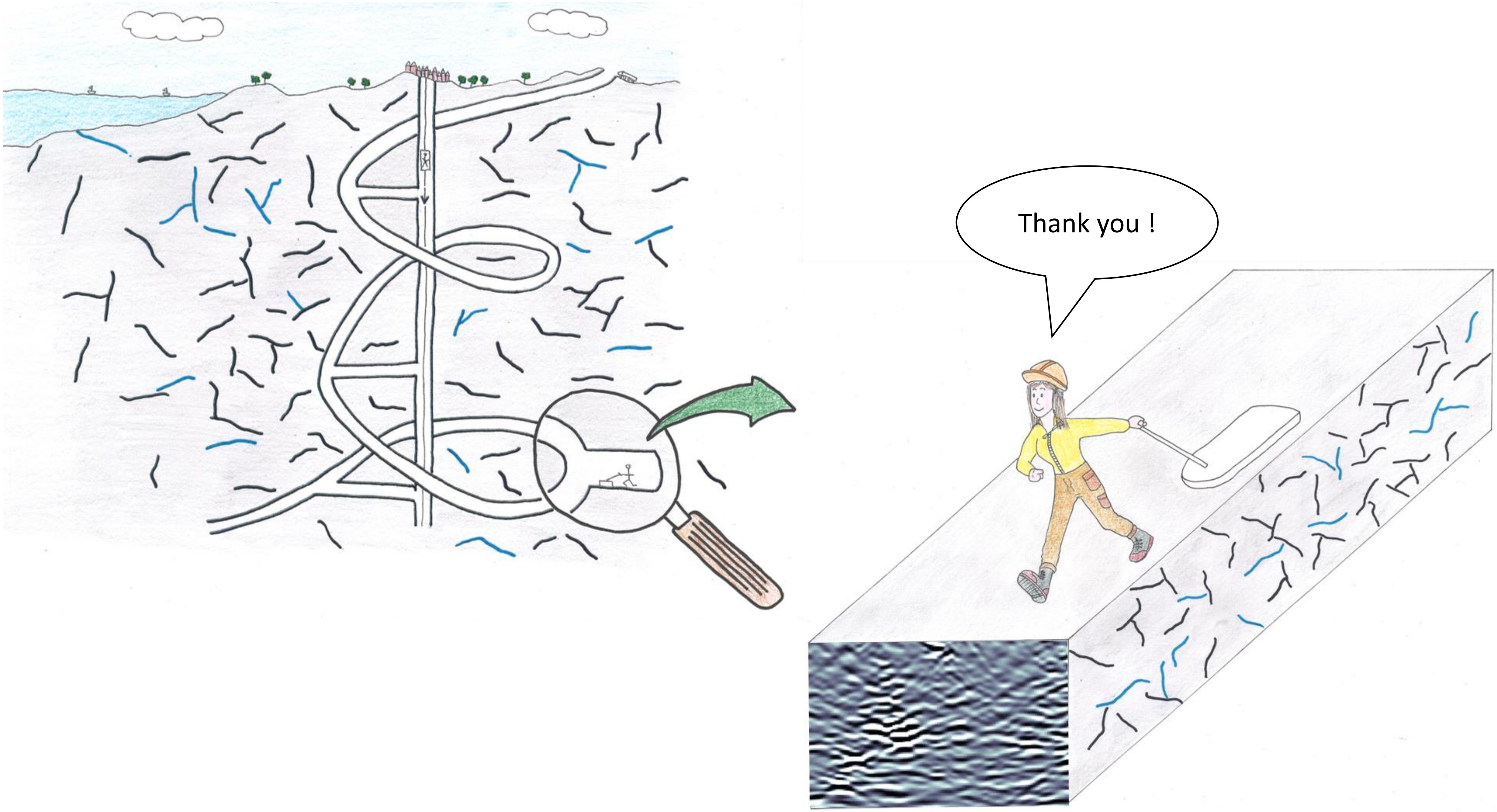
→ Up to now, the results are insufficient to infer the tracer movement and additional processing/interpretation is needed.

Perspectives

- GPR processing improvement to observe tracer pathways and fracture connectivity in subsurface
- Fracture statistics (tunnel, borehole, and GPR data) for TAS04 tunnel and global Äspö Hard Rock Laboratory
- Build a geo and hydro-DFN model of TAS04 tunnel (by conditioning)

Will GPR method provide additional information on the fracture network characteristics in the vicinity of repository holes and decrease uncertainties ?




Thank you !