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

SM4.4
EGU2019 - 2368

This presentation participates in OSPP

Outstanding Student Poster & PICO Contest

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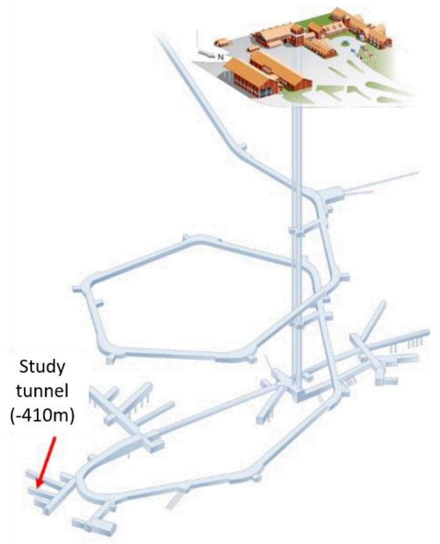
CONTEXT

Discrete Fracture Network (DFN) models are currently derived from fracture mapping (outcrops and boreholes), as well as hydraulic and tracer test. The aim of this research is to use geophysical data (Ground Penetrating Radar – GPR) in order to reduce the uncertainty on the spatial fracture extent and their 3D distribution.

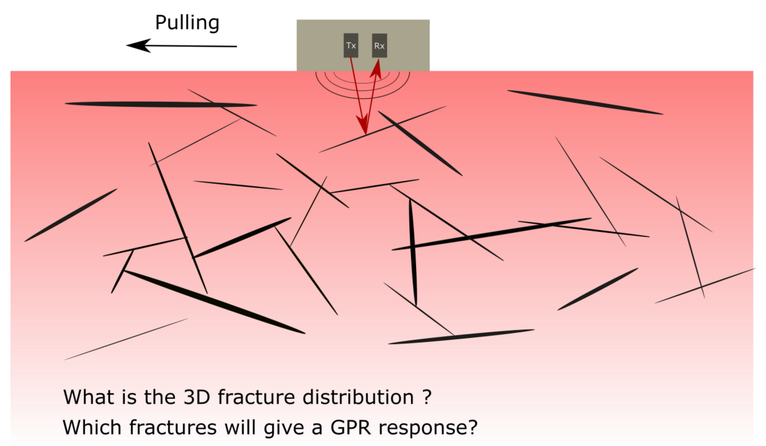
The experimental site is located within the Äspö Hard Rock Laboratory, a tunnel of 4 km length from the surface down to almost 500 m depth on the island of Äspö in southeastern Sweden. This underground laboratory is used to build the know-how for constructing hardrock repositories of nuclear waste disposal.

Here, we aim to 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.



1. FIRST EXPERIMENT – 3D GPR and borehole siting

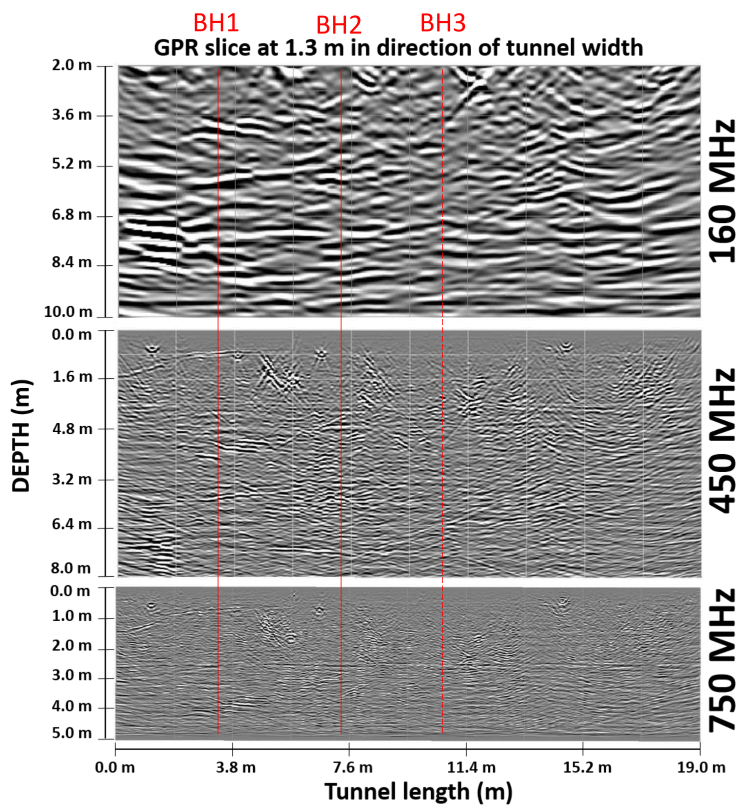
A) DESIGN & METHODOLOGY



The first field campaign aimed at imaging the 3D distribution of the main open fractures using surface GPR. Our experiments were acquired in a tunnel of dimensions 22 x 3.6 x 4.8 m located at 410 m of depth. Since the floor was sawed, the conditions to acquire surface GPR were ideal. The tunnel geology is composed of granite, diorite and granodiorite [*Ericsson et al. 2015*].

The GPR was pulled along the tunnel floor (inline configuration) along profiles separated by 0.05 to 0.10 m using 160, 450 and 750 MHz antennas with corresponding investigation depths of 10 m, 8 m and 5 m.

B) RESULTS & FIRST INTERPRETATIONS

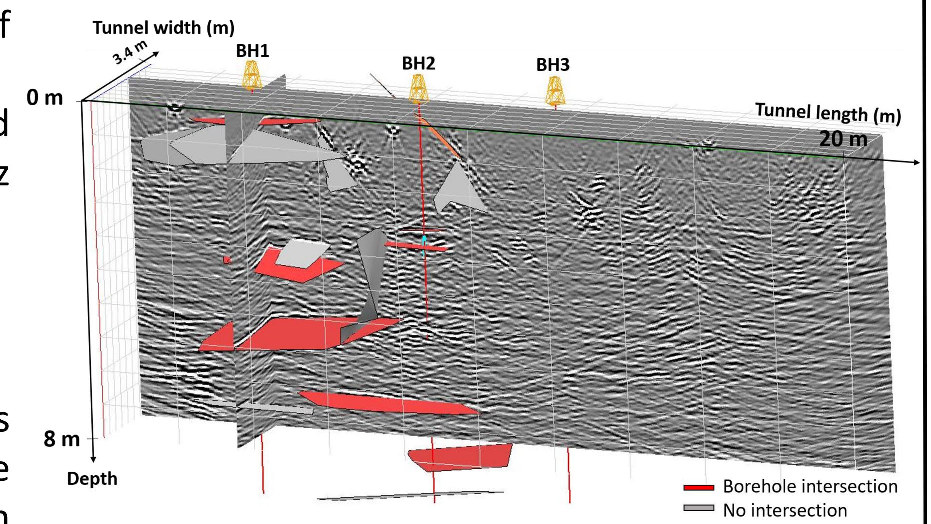


Left: **2D GPR slices after processing and migration**.

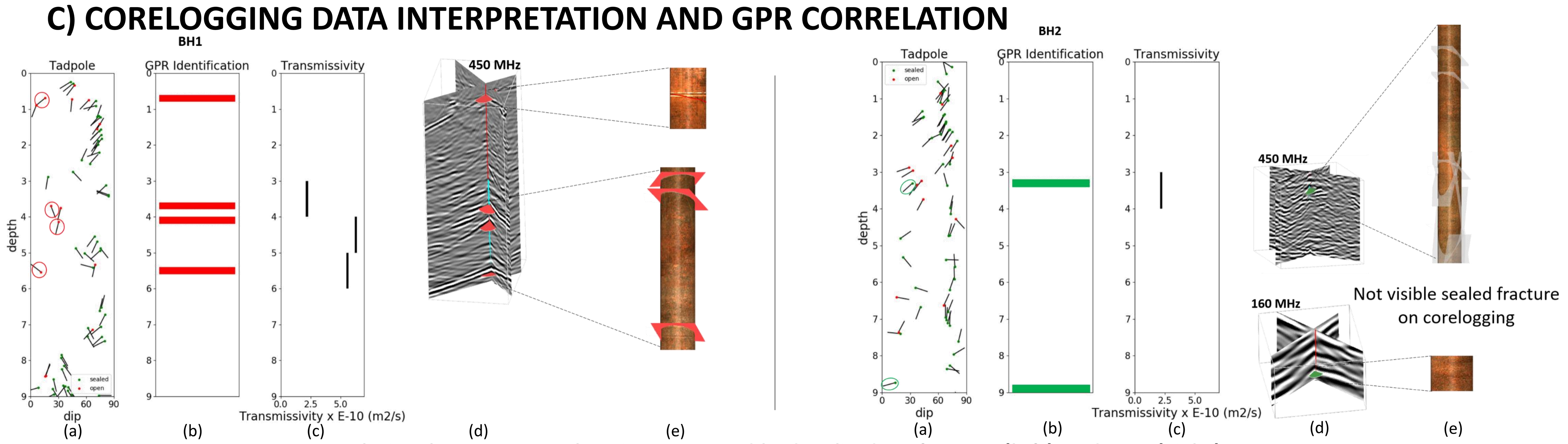
- DC removal, time-zero correction, mean trace removal, gain application, SVD filter and Kirchhoff migration were applied.
- The horizontal and vertical resolutions are 0.8 m and 0.2 m for 160 MHz, 0.25 m and 0.06 m for 450 MHz and 0.18 m and 0.04 m for 750 MHz.
- Proposed boreholes (BH1 to BH3)

Right: **GPR model, borehole siting and drilling**

- Three zones were defined based on GPR reflections from, supposedly, more permeable to less permeable 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).



C) CORELOGGING DATA INTERPRETATION AND GPR CORRELATION

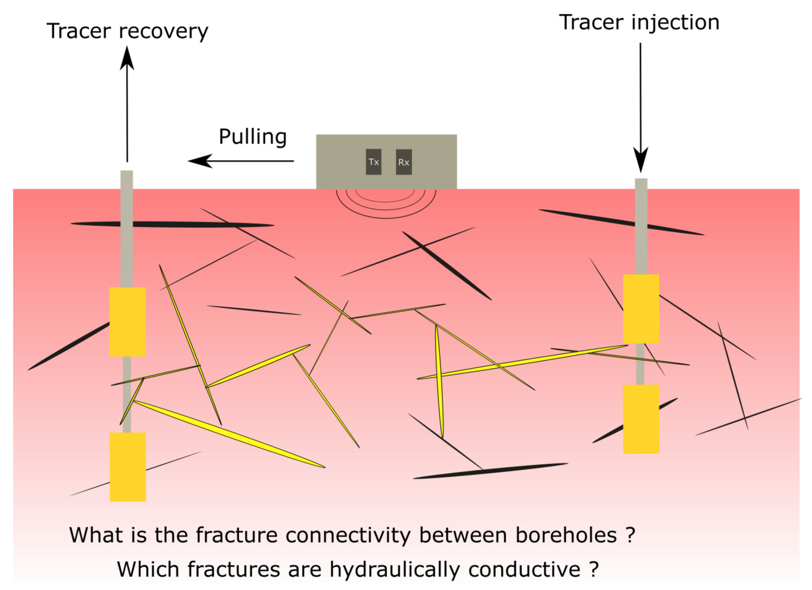


Correlation between corelogging, GPR and hydraulic data for BH1 (left) and BH2 (right).

(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.

2. SECOND EXPERIMENT – Tracer test and GPR monitoring

A) DESIGN & METHODOLOGY



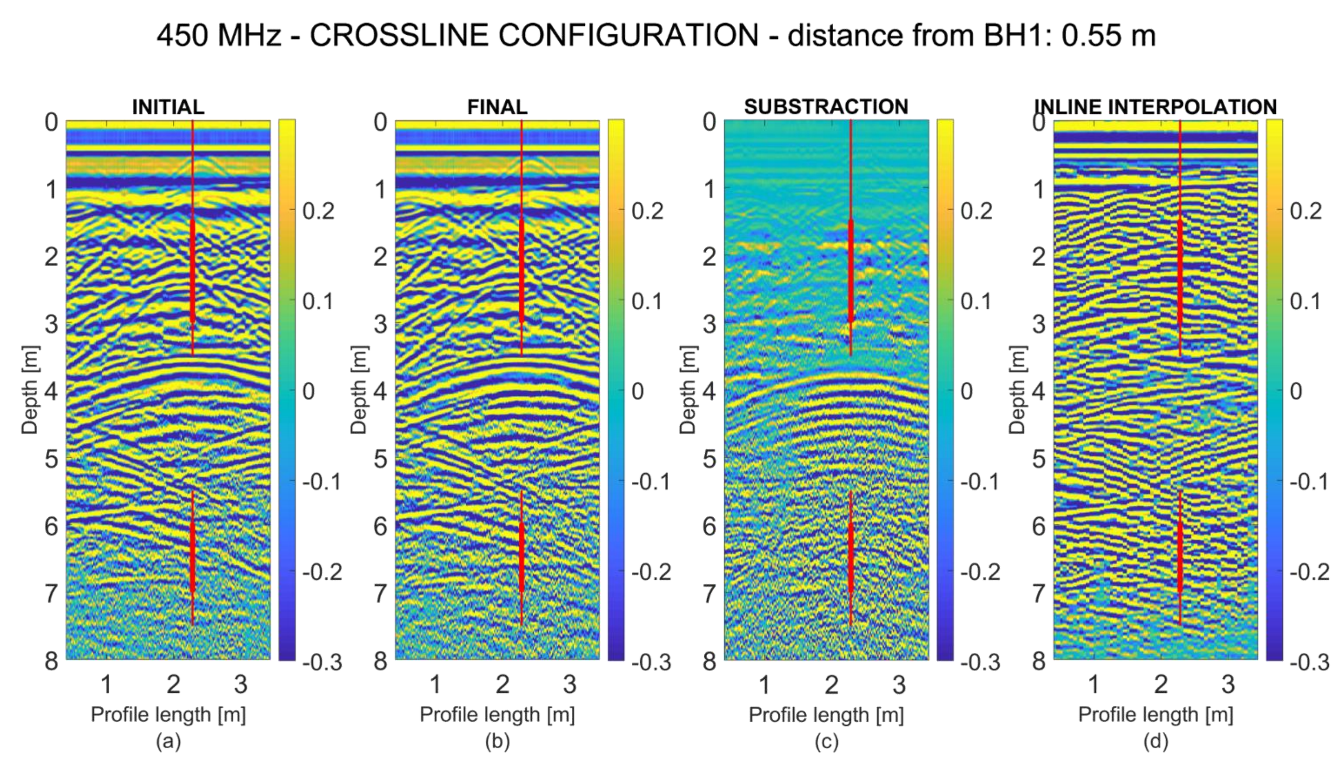
To infer fracture connectivity patterns, we conducted surface GPR during tracer test injections. Because of the saline formation water (≈1850 mS/m), we injected deionized water to achieve an electrical contrast. At the same time, we used traditional Uranine and Rhodamine tracers.

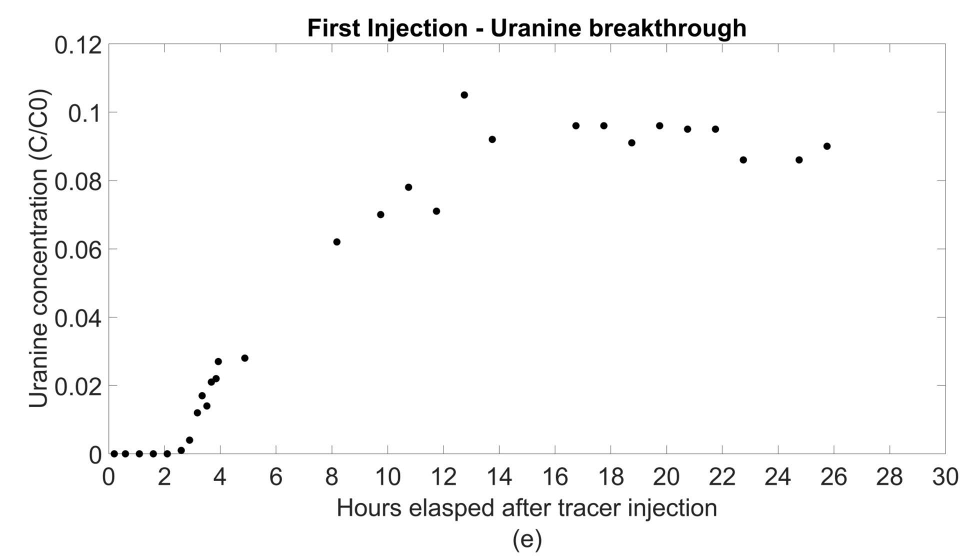
First Injection of Uranine in BH2 between 3.2 – 3.7 m depth with a withdrawal in BH1 (3-6 m depth in transmissive zone).

Second Injection of Rhodamine in BH2 between 3.2 – 3.7 m depth with a withdrawal in BH3 (4-5 m depth in transmissive zone).

Both injections were pursued for 24 hours, with an accumulated injected volume of 10 to 13L (using pressure differences exceeding 40 bar), to increase the chance of observing a GPR time-lapse signature. Seven 2D GPR profiles were acquired along the tunnel width (crossline configuration) every hour during 8 hours using 160 MHz and 450 MHz antennas. 3D GPR surveys were acquired before and after the injections.

B) FIRST RESULTS (Uranine injection)





(a) GPR measurements before the tracer injection;
(b) GPR measurements after the tracer injection;
(c) Subtraction between the two GPR profiles
(d) Interpolation of 3D GPR measurements acquired during the first experiment (inline configuration)
(e) Tracer recovery (first tracer arrival in BH1 after 3 hours)

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.

To highlight the tracer signature, we proceed by substracting GPR profiles acquired before and during the tracer injection. To analyse the packer's influence on the signal (strong diffractions), we compare with data aquired during the first experiment (before the installation of the boreholes).

CONCLUSION & PERSPECTIVES

The first experiment aimed at imaging the main open fractures. These 3D GPR results were used to locate three boreholes. The GPR results and corelogging data suggest that some open fractures are very well imaged (BH1) by the GPR while others are hidden by sealed fractures (BH2). The second experiment was designed using initial hydraulic tests to locate flowing sections for the injection and withdrawal of tracer to study fracture connectivity. 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

Up to now, the results are insufficient to infer the tracer movement and additional processing/interpretation is needed. These data will be further used to reduce uncertainties and improve conditioning of site-specific hydraulic DFN models.

References

Ericsson, L. O., J. Thörn, R. Christiansson, T. Lehtimäki, H. Ittner, K. Hansson, C. Butron, O. Sigurdsson, P. Kinnbom (2015), A demonstration project on controlling and verifying the excavation-damaged zone. Experience from the Äspö Hard Rock Laboratory. *SKB R-14-30*. Svensk Kärnbränslehantering AB.

ITN Enigma

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Sklodowska-Curie Grant Agreement No 722028