Report of Transnational Access Projects

Project ID: C4_TA3_82_1_1

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Project team: Dr. Emmanuel Gaucher, Karlsruhe Institute of Technology

Project title: Fault Zone Coda Wave Imaging

Project acronym: FZCOWI

Hosting installation: BedrettoLab testbed (TA3-82-1)

Hosting team: Liliana Vargas Meleza, Marian Hertrich, Antonio Rinaldi, Frederick Massin, Pascal Edme, Mathilde Wimez.

Period of access: Aug-Sep 2025 Remote planning sessions; 13-24 October 2025 Data acquisition; Feb – May 2026 Remote access.

Report of activities:

The FZCOWI projects aims to utilize multiply scattered wavefields for cross-correlation based imaging and monitoring of fluid infiltrated fault zones and potentially also the effects on the surrounding host rock matrix. The high-frequency wavefields are excited by series of repeated active source sweeps that last for several tens of seconds. These sweeps are activated in parallel to the water injection into the fault formation that occurs over longer time scales (minutes to hours to days).

The associated active seismics survey with stationary source and receivers was thus conducted during a hot water injection experiment for the BEACH project in the Geothermal testbed between 2025-10-28 and 2025-11-12 (Figure 1). A signal generator (sweeps) script triggers each source by activating specific channels. One source consists of 3 sweeps of 30 seconds each. Active times indicated as “active channel” can be seen in Figures 2 and 3. Sweeps were activated every hour, at several frequencies. At 2025-10-30 12:00, the duration of the sweeps was shortened from 5 minutes to 3 minutes, because during the active time the seismic monitoring team is effectively blind because of the dominating active wavefield.

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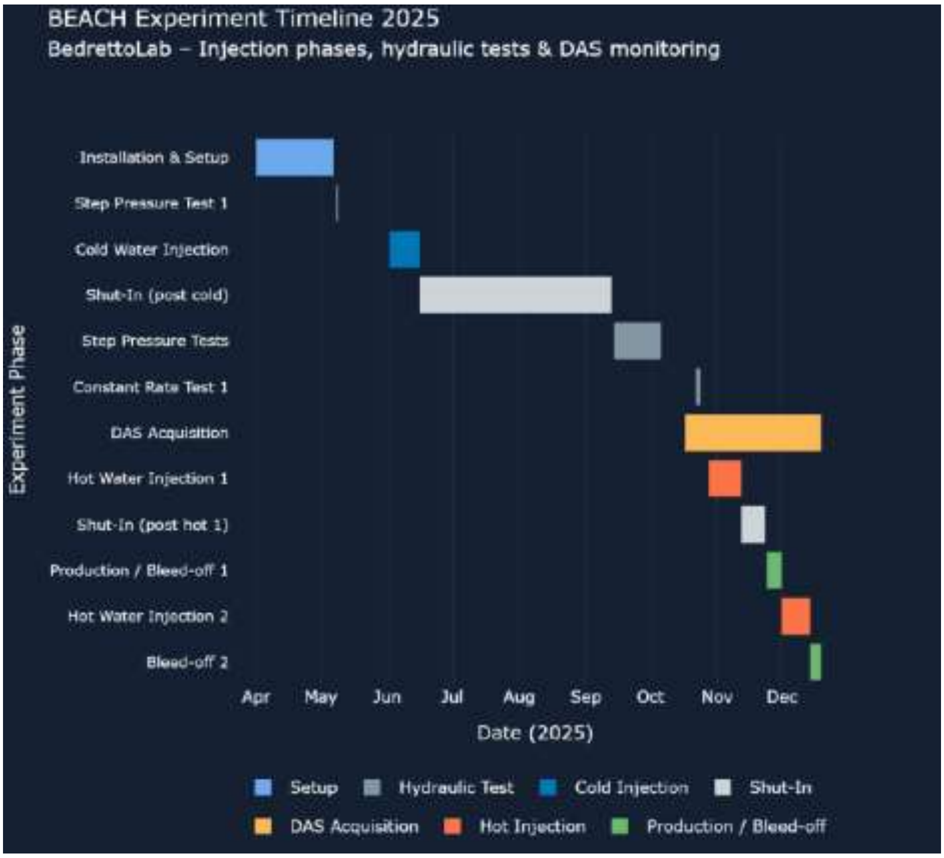

Figure 1. The BEACH Experiment timeline. The relevant injection experiments were conducted in late October and November 2025.

Figure 2. Active seismic survey dashboard. The active channel plot shows the times when the sweeps were active.

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Figure 3. Close-up view of one sweep with the 5 sources activated.

The signal generation of the active source(s) for the BEACH project includes the following boreholes and specifications:

```
%% Sweep Parameters
% start and stop frequency and amplitude of sweep
SWP.f_start   = 1000;
SWP.a_start   = 1;
SWP.f_end     = 20000;
SWP.a_end     = 0.15;
Rate = 200000

Boreholes with active sources
MB1_T1_70 1 < Active
MB8_T1_70 2 < Active
MB3_T1_50 3 < Active
MB3_T2_50 4
MB4_T1_50 5 < Active
MB4_T2_50 6
MB5_T1_70 7 < Active
MB7_T1_*  8
MB7_T2_*  9
MB1_T2_50 10
MB8_T2_*  11
```

Note that for stationary sources and receivers, like those in the geothermal testbed, low signal quality at some receivers may be attributed to either physical reasons, e.g., to a too long distance between source and receiver, or technical reasons such as a malfunctioning source or receiver. However, stationary

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sources/receivers are cemented, thus they cannot be retrieved to check their functional operations. Other techniques must be used, such as plotting shotgathers of colocated receivers to identify signal consistency across the receiver group and potential outliers indicating the malfunctioning of individual receivers.

The KIT team accessed the BEACH Geothermal testbed data. From the metadata we compiled a 3D illustration (Figure 4) to establish the spatial relationships between the different experimental elements, i.e., the geometry of the tunnel and boreholes, and the locations of sources, receivers, and seismicity.

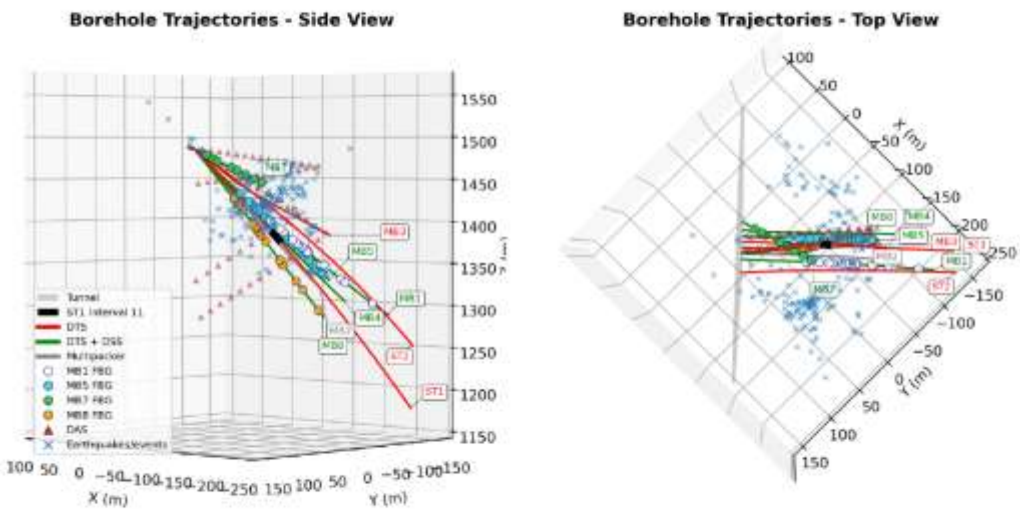

Figure 4. Illustration of the main underground experiment elements, side view (left) and map view (right).

A first sweep data processing for basic quality control (Figure 5) indicates the frequency dependent decrease in energy. Another persistent feature that is consistently observed are the highly energetic components at specific frequencies. We learn from this and complementary initial spectral observations that a successful target wavefield and cross-correlation analysis requires an understanding about the origins of these spectral lines to control and potentially mitigate their impact on downstream processing results.

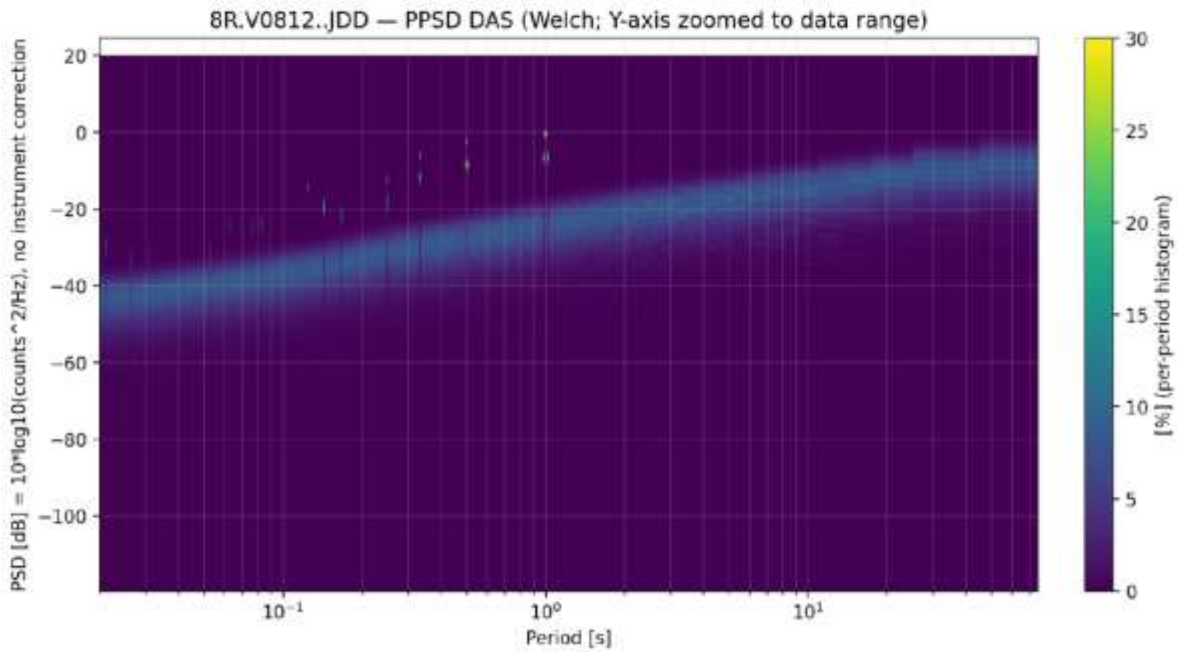

Figure 5. Probabilistic Power Spectral Density representation of an example single sweep

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Target project outcomes:

We aim to reconstruct cross-correlation functions between all receiver pairs using multiply-scattered waveforms excited by the energetic sweeps. Details of the sweeps are not important as long as they generate a sufficiently scattered broadband wavefield that supports the convergence of the correlations. The repeated sweep activities along the hot-water injection (Figure 1) allows us to construct stable correlation functions at different times.

We are not interested in the ballistic arrivals reconstructed by the correlation but analyze the coda part of the converged correlation functions for signatures of arrival time or waveform changes. The coda waves travel longer in the medium, including the water injected fault, compared to the direct or ballistic waves, and are thus more sensitive to small changes. The correlation coda wave sensitivity to medium changes has been established in numerous environments across a range of scales. Here, the controlled experiment in the Bedretto underground lab facilities allows us to systematically investigate possible relationships between the injected water in a fault and the waveform changes in the correlation coda waves. We plan to apply a newly developed coda wave change inversion approach to the obtained observations. This would be a first, because we plan to employ newly developed probabilistic sensitivity distributions (kernels) that are specifically designed for the narrow fault zone structures, and that have been only applied in synthetic experiments.

The active seismic data collected for the FZCOWI project is available at https://doi.org/10.3929/ethz-c-000802239.

The FZCOWI experiment facilitated knowledge transfer between the Bedretto team and the KIT. The KIT is a key consortium partner for the development of a new underground laboratory in Germany, the GeoLaB (https://geolab.helmholtz.de/en/). The goal of GeoLaB is the development of economically plausible geothermal systems in naturally fractured and faulted reservoirs. The KIT team has a strong interest to benefit and learn from the BedrettoLab infrastructure in order to support the development of the GeoLaB scientifically, technically, and logistically. This project is therefore a training opportunity for KIT scientists that will be involved in the GeoLaB development.

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