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Geothermal exploration with passive geophysical methods in the canton of Thurgau, Switzerland

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GeoHEAT

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1. Passive geophysics for affordable geothermal exploration

As part of the Horizon Europe project GeoHEAT, we aim to tackle key challenges in geothermal pre-drilling exploration, including:

- The high cost of conventional methods such as 3D seismic reflection surveys
- Limited information on deep subsurface structures (e.g., crystalline basement depth)
- The absence of transparent uncertainty estimates in geological models used for drilling decisions

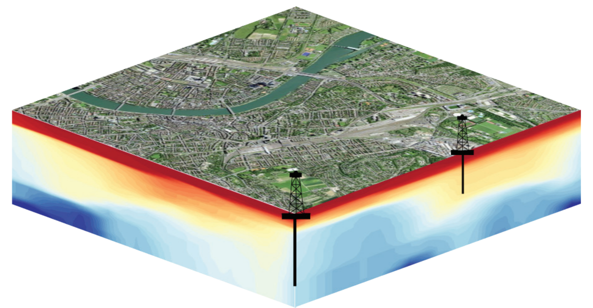


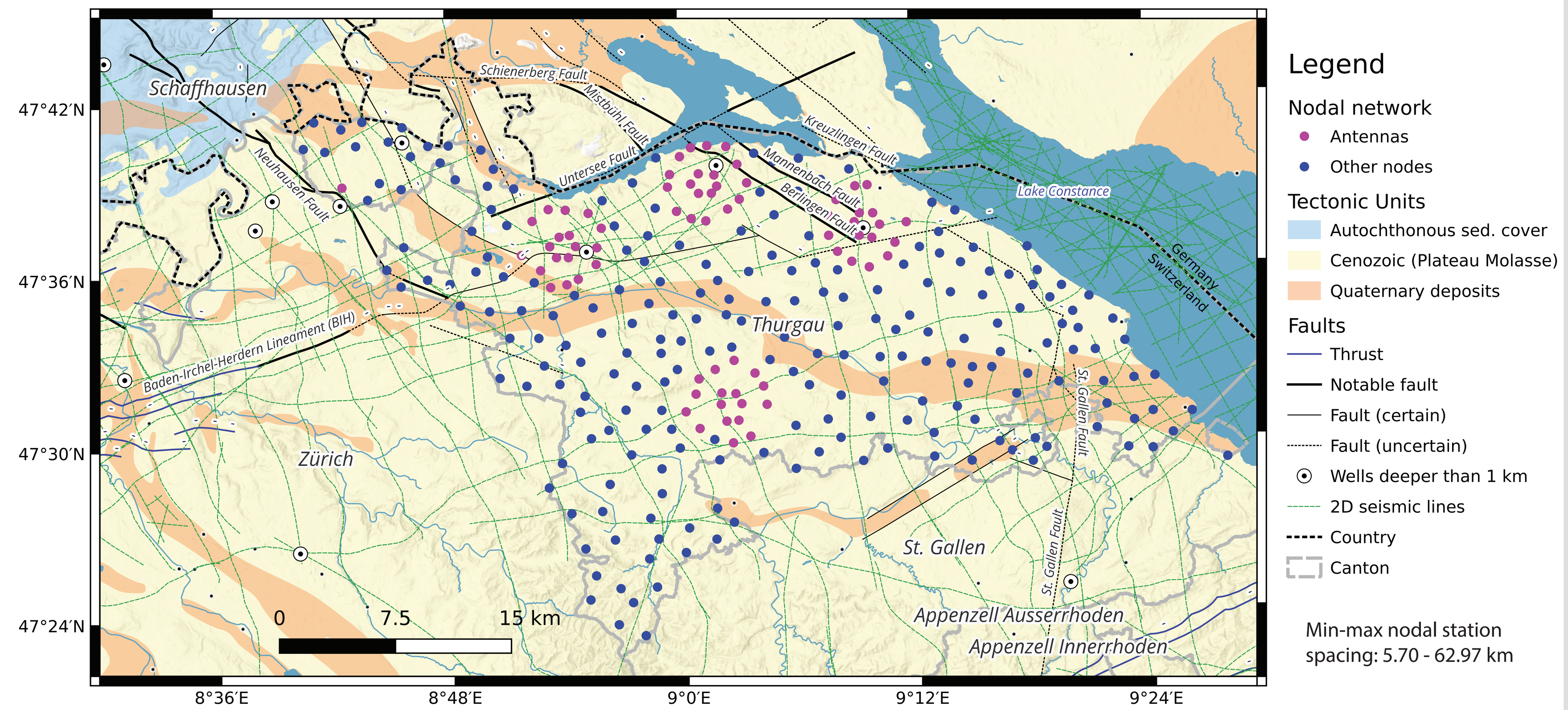
Figure 1: Sketch representation of a passive seimic model in 3D that could help select optimal drilling sites

Passive geophysical imaging methods—such as ambient noise tomography and microgravity inversion—offer cost-effective access to deep subsurface information relevant for geothermal exploration. However, the integration of such models into geological frameworks suitable for applications like geomechanical modeling remains an open challenge. How can we reliably identify and interpret faults, lithologies, fracture zones, and fluid pathways from passive tomography models, given their typically lower resolution compared to active seismic datasets?

We address this by developing an approach that combines both array-based and pairwise methodologies to maximize the extraction of meaningful geological information from ambient seismic data. This information will then subsequently be integrated into a fully-probabilistic geomodeling workflow. This workflow is being developed and tested in the canton Thurgau region in Switzerland, our selected pilot site. Here we present preliminary results of the passive seismic survey.

Figure 2: Nodal geophones are discreet and require minimal planning and permitting to deploy. Here a geophone used in Thurgau, manufactured by SmartSolo (IGU16HR-3C 5HZ)

2. Thurgau nodal seismic network (March 7 to April 8, 2025)



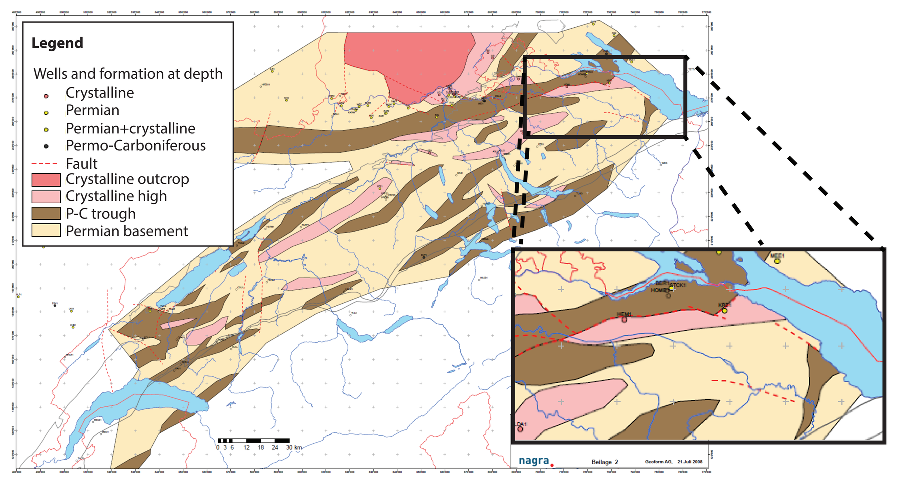


Figure 3: Presence of Permo-Carboniferous troughs (PCT), as inferred from active seismic data and gravimetry. Figure modified from Nagra report NAB 08-49

We partnered with **Geothermie Thurgau AG** to advance subsurface knowledge in the Thurgau region for geothermal and other geo-energy applications under the TEnU2030 framework. The deployment and retrieval of 299 nodes each took less than four days. A key exploration target in Thurgau and the broader region is the **Permo-Carboniferous Troughs** (PCTs)—major graben structures in the crystalline basement filled with Permian and Carboniferous sediments. PCTs are **likely associated with extensive basement fracturing and deep fluid reservoirs**. Figure 3 illustrates the presumed locations of PCTs based on seismic reflection and gravity data. **Their geometry below the basement remains poorly understood**, making them prime targets for passive seismic imaging.

4. Preliminary results: surface wave group velocity maps

Group velocity maps represent the first inversion step in ambient noise surface wave tomography and already provide insights into subsurface structures. Each map corresponds to a frequency that samples a specific depth range and is primarily sensitive to shear modulus variations. These variations reflect major changes in lithology (e.g., sediments vs. crystalline rocks), fracture density, fluid composition, and saturation.

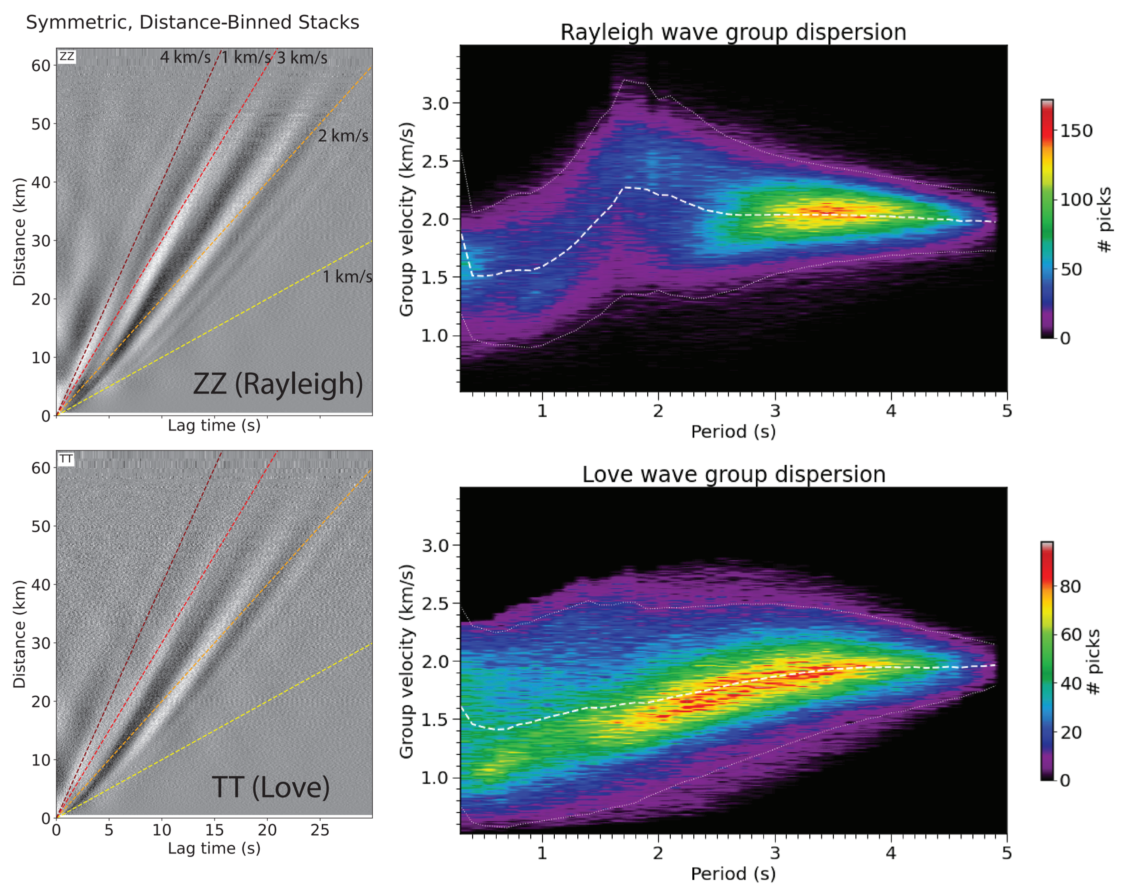


Figure 5: Left: stacked symmetric cross-correlations, grouped in 150 m inter-station distance bins, for the ZZ and TT components, corresponding to Rayleigh and Love wave energy, respectively. Right: 2D histogram of dispersion curve picks from FTAN analysis, obtained using an automated picking and quality control algorithm.

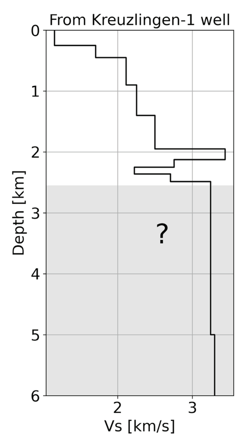
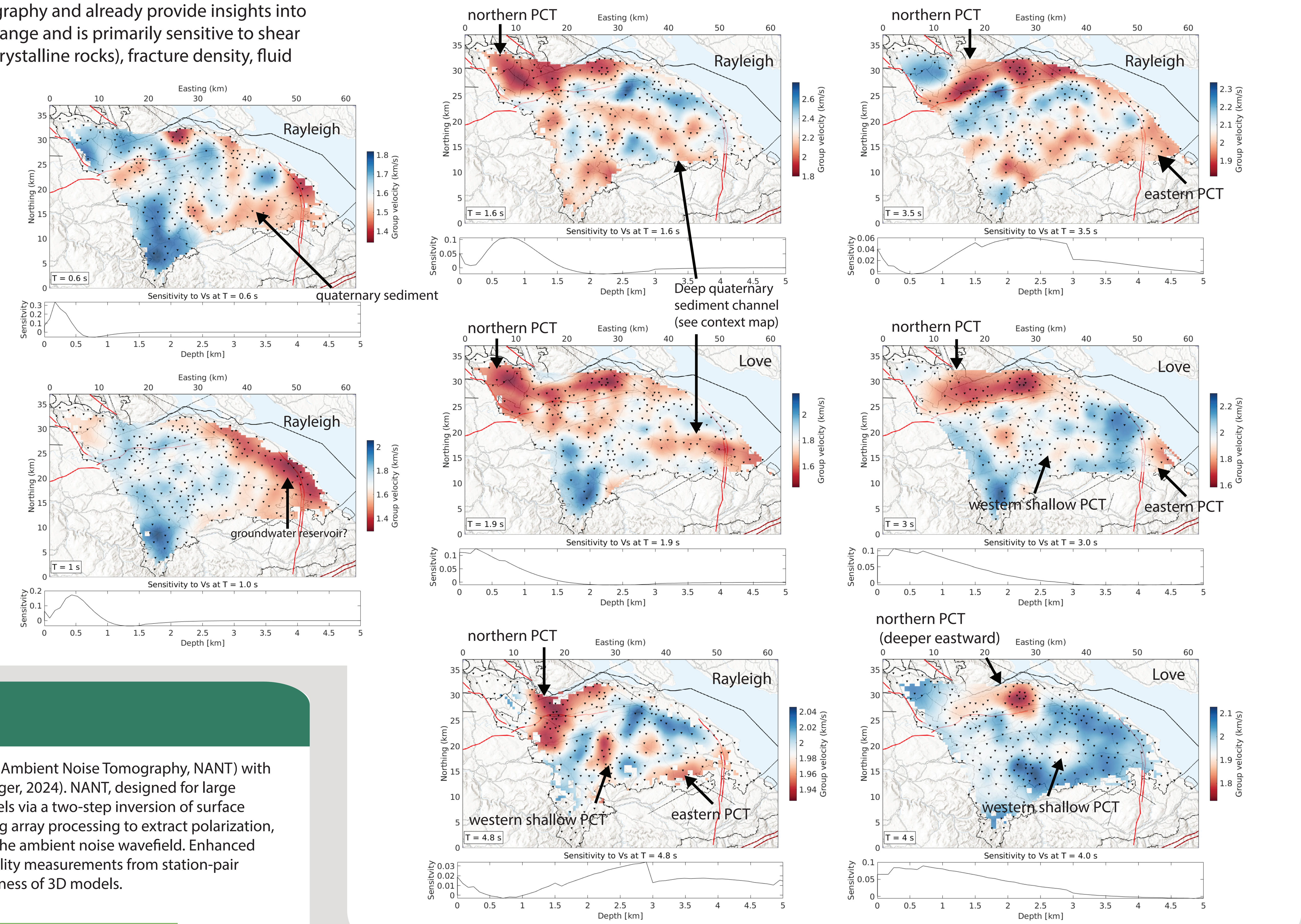


Figure 6. Velocity model derived from sonic well logs, used to calculate sensitivity kernel (approximation, as reference for interpretation only)



3. Passive seismic tomography workflow

Ambient noise surface wave tomography workflow from station-pair measurements

Cross-correlations of 75% overlapping 60-s long windows of whitened noise records

↓

Phase Weighted Stacking of all windows and all components to get an approximate Green's function tensor for each station pair.

↓

Frequency-Time ANalysis (FTAN) using the continuous wavelet transform to obtain dispersion images from which we extract dispersion curves with an automated picking algorithm.

↓

2D inversion of group velocity for each period

↓

Inversion of 1D Vs profiles along depth for each 2D grid point, combined into a 3D Vs model

We integrate pairwise cross-correlation methods (Nodal Ambient Noise Tomography, NANT) with array-based 3-component techniques (B3AM; Löer & Finger, 2024). NANT, designed for large nodal arrays, produces 3D shear-wave velocity (Vs) models via a two-step inversion of surface wave group dispersion. B3AM complements this by using array processing to extract polarization, anisotropy, velocity, directionality, and dispersion from the ambient noise wavefield. Enhanced wavefield characterization enables more and better-quality measurements from station-pair correlations, improving the depth resolution and robustness of 3D models.

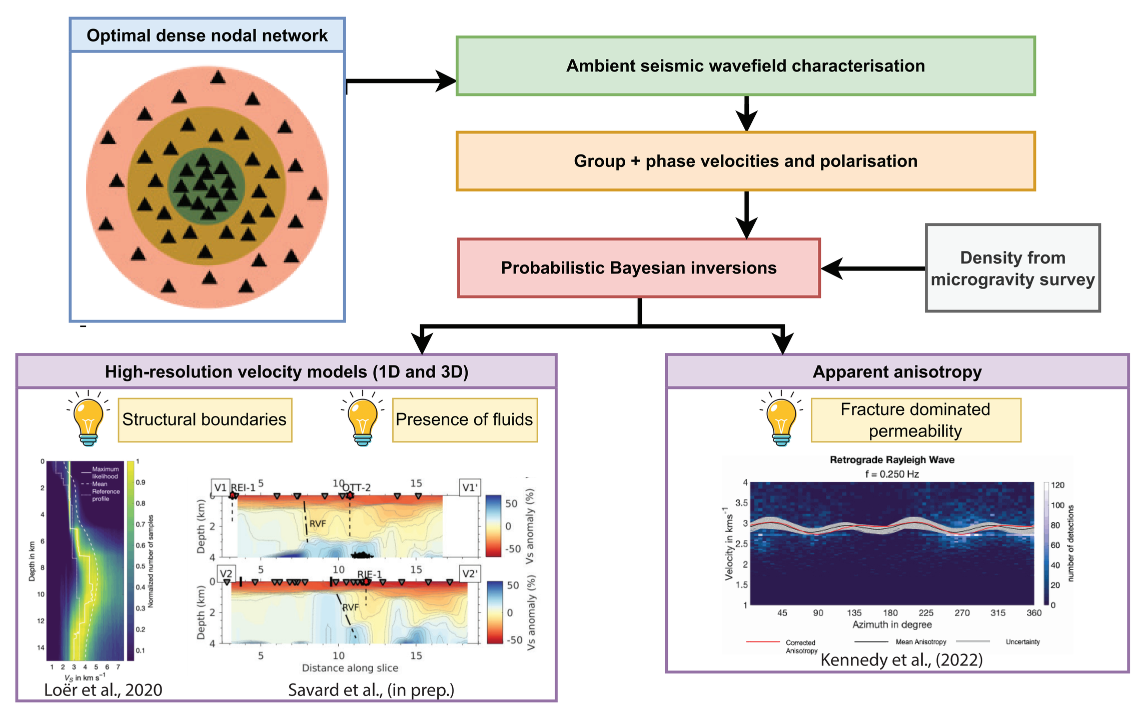


Figure 4. Passive seismic imaging workflow

5. Next steps

- Characterize the ambient wavefield using 3C beamforming and update dispersion curve estimates.
- Perform probabilistic 3D shear-wave velocity (Vs) inversion.
- Integrate the resulting 3D Vs model ensemble and gravity data into a probabilistic geological modeling framework (Wellmann & Caumon, 2018).
- This uncertainty-aware geomodel will be combined with social and logistical criteria to identify optimal drilling locations. A second, higher-resolution passive seismic survey is planned at one of the selected sites.

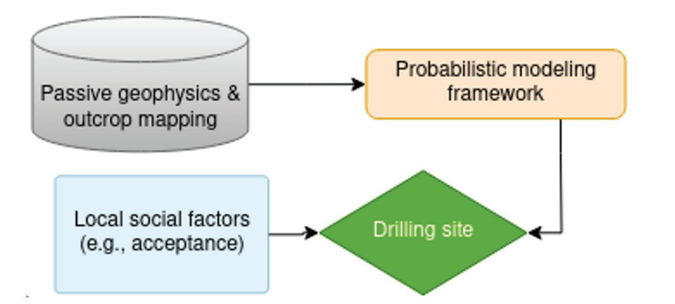


Figure 7. Reservoir-scale assessment workflow to select drilling sites (GeoHEAT proposal)