Adapting Controlled-Source Seismic Techniques for Earthquake Reflection Imaging in Complex Environments: Insights from Krafla Volcano, NE Iceland

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SETTING AND MOTIVATION

STUDY SITE: KRAFLA

- Volcano caldera in NE Iceland, with a large geothermal area.
- Known for the encounter of magma through drilling at 2.1 km depth at the IDDP-1 borehole [1].
- The magma pocket was undetected in prior studies.
- Here, we adapt a controlled-source technique to image the shallow crust at Krafla using **reflections from local earthquakes.**

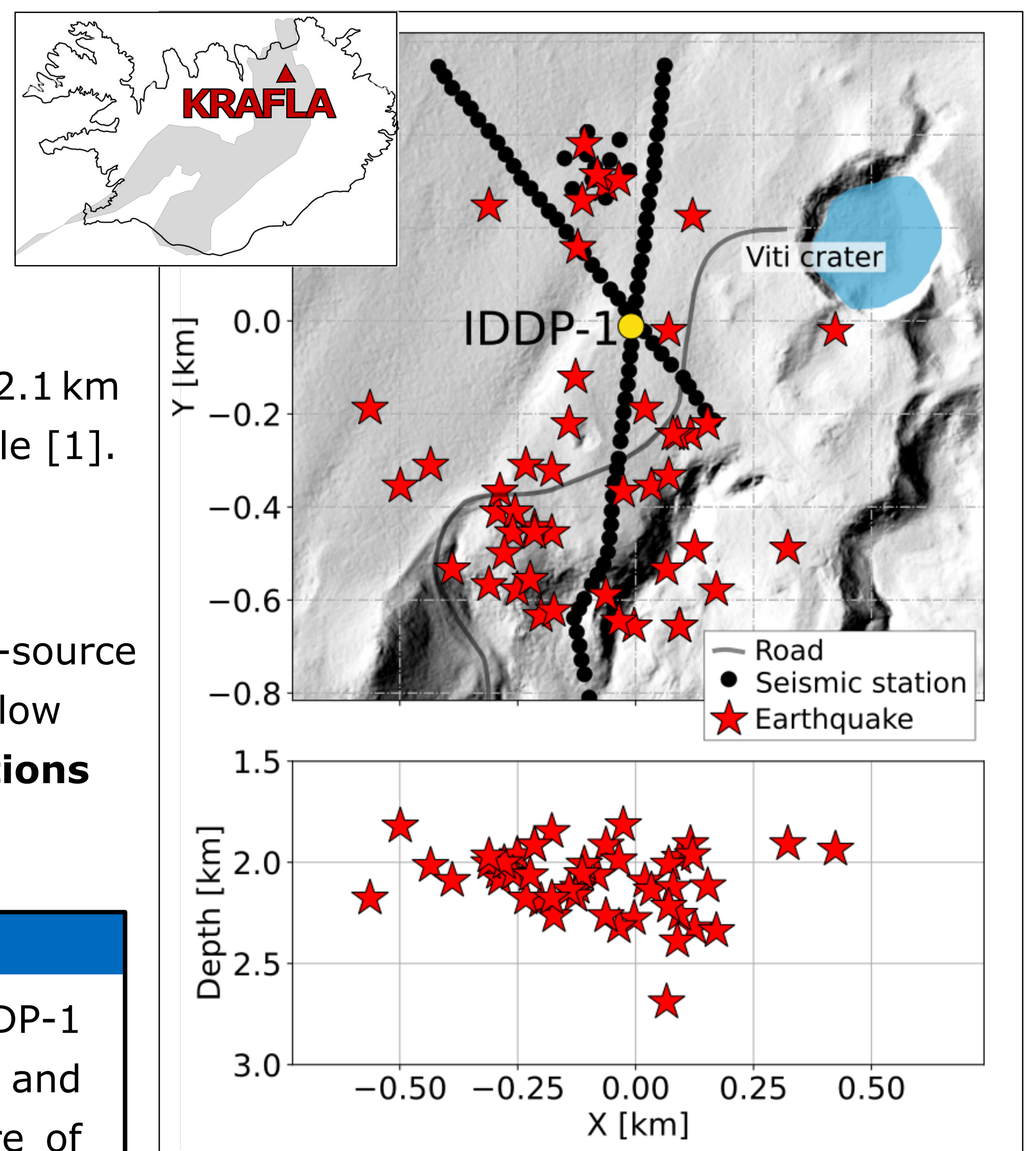


Fig. 1: Study setup.
- 48 local earthquakes (M < 1.5).
- 101 short-period (5 Hz) seismometers.
- Recorded during 5 weeks in 2022.

Key questions

1.) Can we detect the IDDP-1 magma pocket in the data and what is the overall structure of the geothermal system?

2.) What challenges arise due to the source-receiver geometry?

DATA

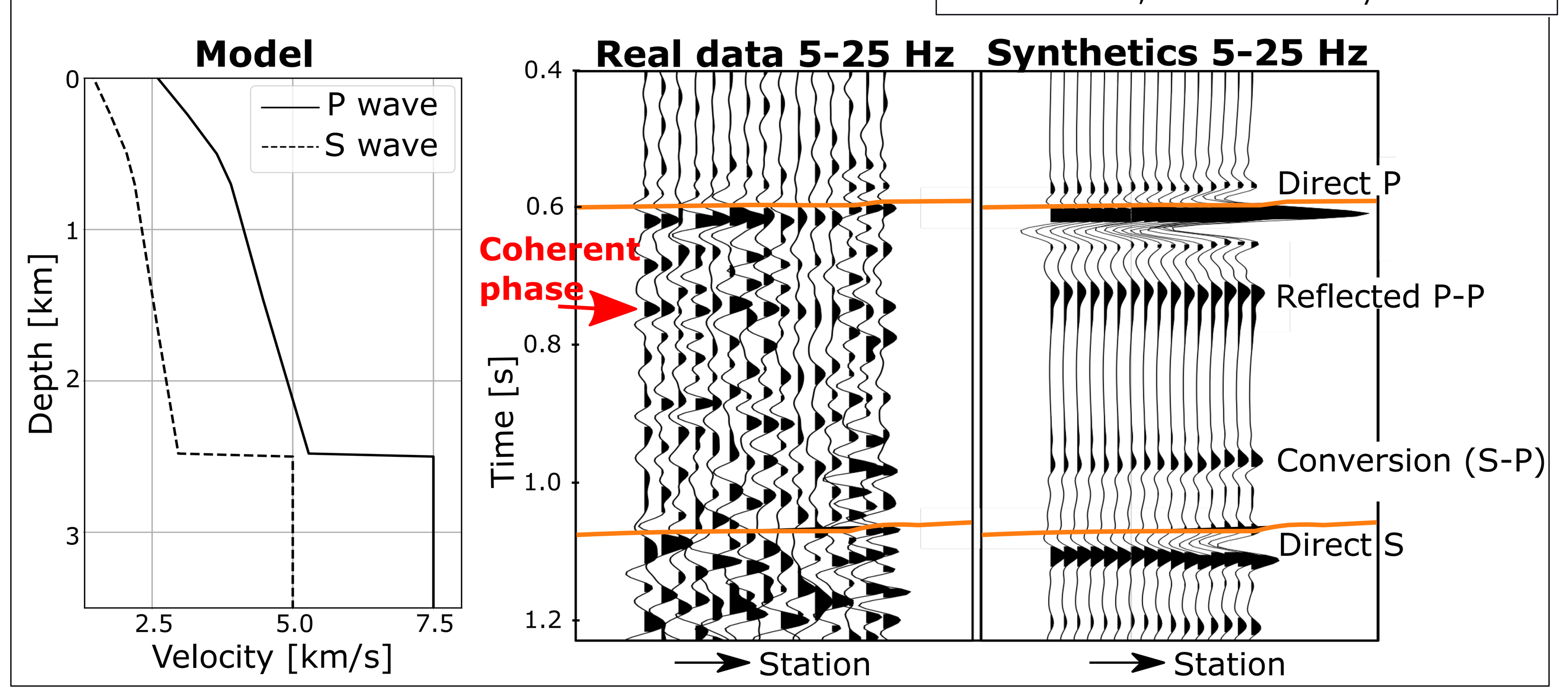
REAL DATA

- Complex with strong scattering, especially in the S-wave coda [2].
- In some events, coherent phases in P-wave coda on Z-components (Fig. 2). -> These are used in our imaging workflow.

SYNTHETIC DATA

- Full-waveform simulations with SPECFEM2D and local 1D velocity models with a reflector introduced at 2.5 km (Fig. 2).
- To benchmark code, validate results.

Fig. 2: Example wavefield due to an arbitrary earthquake. Velocity models used in simulations, real data and synthetics.



CIBS: THE METHOD

COMMON-IMAGE-POINT-BINNING-AND-STACKING (CIBS)

- Commonly used in controlled-source seismology.
- We adapt it for passive imaging in **new, fast & parallelized Python code.**

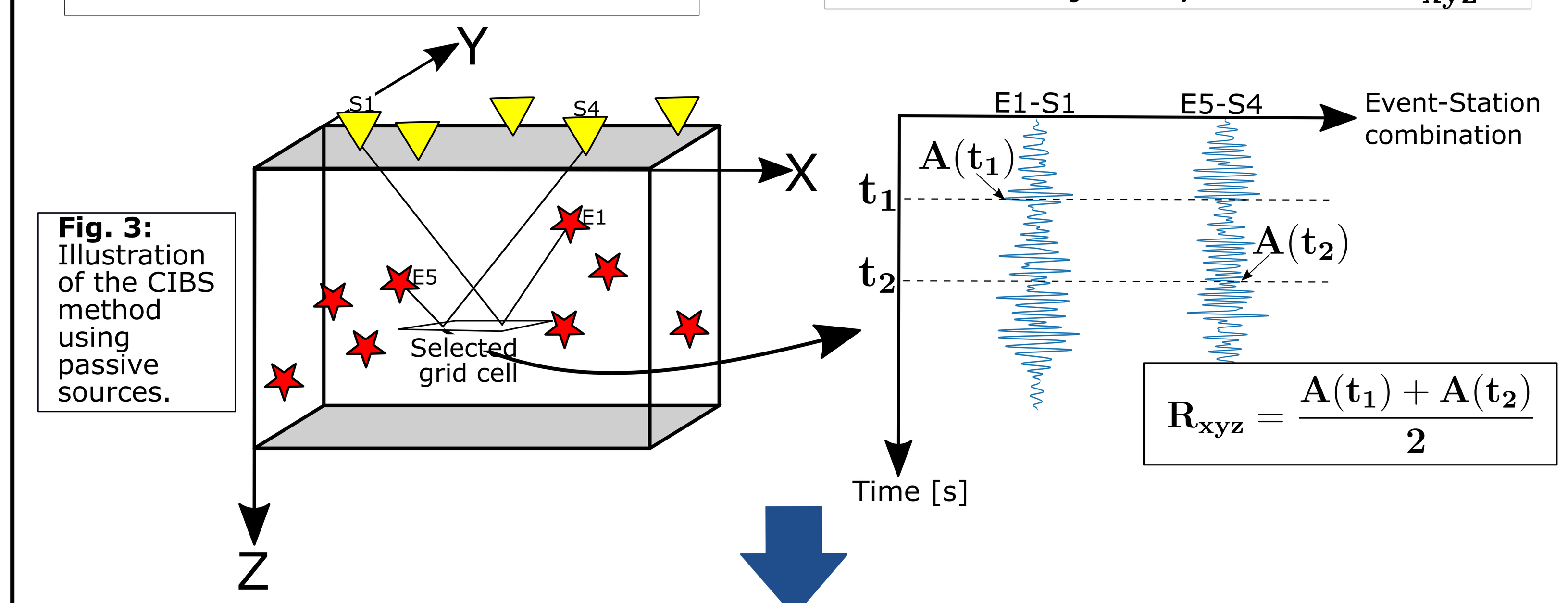
1. RAYTRACING OF REFLECTIONS AND GRIDDING

- For each station-event pair: compute theoretical traveltimes of reflections and their bounce points (X,Y) assuming a flat reflector every 20 m in depth.
- Discretize the study area into a 3D grid with cells (100 × 100 × 20 m).

2. PROCEDURE FOR EACH GRID CELL

Extract combinations of stations & events for which reflection bounce point lies within grid cell. → Display traces in a 'common-image-point-gather' and stack along the reflection trajectory to obtain $\mathbf{R}_{xyz}$

Fig. 3: Illustration of the CIBS method using passive sources.



$$\mathbf{R}_{xyz} = \frac{\mathbf{A}(\mathbf{t_1}) + \mathbf{A}(\mathbf{t_2})}{2}$$

Obtain reflectivity matrix $\mathbf{R}$: each grid cell provides reflectivity strength at this point in space.

TAKE-HOME MESSAGES

WE ADAPTED CIBS FOR PASSIVE-SOURCE DATA IN COMPLEX SETTINGS.

METHODOLOGICAL IMPLICATIONS

- Direct waves & unwanted phases might create spurious reflectors.
- Due to similar apparent velocities of phases related to source-station geometry.
- **Caution is needed** when applying CIBS or similar methods to passive data!
- Currently, we are working on reducing artifacts through muting and phase-weighted stacking.

GEOLOGICAL IMPLICATIONS

- Reflectors around 2.5 km depth. -> Potentially linked to IDDP-1 magma pocket or brittle-ductile boundary.
- Reflectors around 2.1 km depth -> Might be top of IDDP-1 magma pocket. -> But direct P waves mask potential reflections, complicating interpretation.

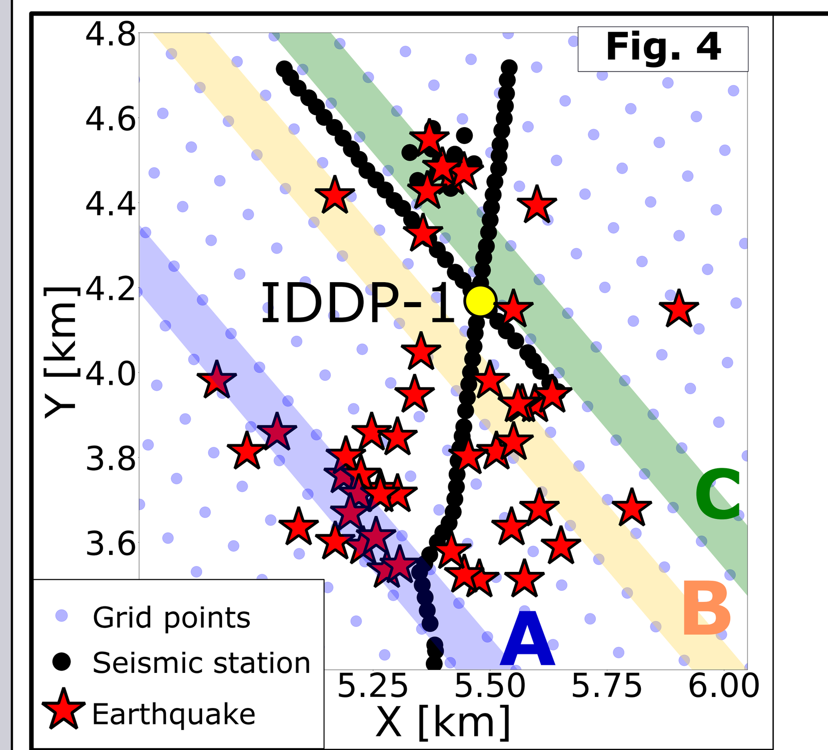
The CIBS Python code will be made freely available on GitHub.

References

[1] Elders et al., 2011: Origin of a rhyolite that intruded a geothermal well while drilling at the Krafla volcano, Iceland. Geology, 39 (3): 231–234. doi: https://doi.org/10.1130/G31393.1

[2] Maass, R.; Li, Ka Lok; Bean, C.J., 2025: Improving passive reflection seismic imaging in complex geological settings through site effect reduction: application to Krafla volcano, Iceland, Geophysical Journal International, 241, 2, 756–769, https://doi.org/10.1093/gji/ggaf072

RESULTS AND DISCUSSION



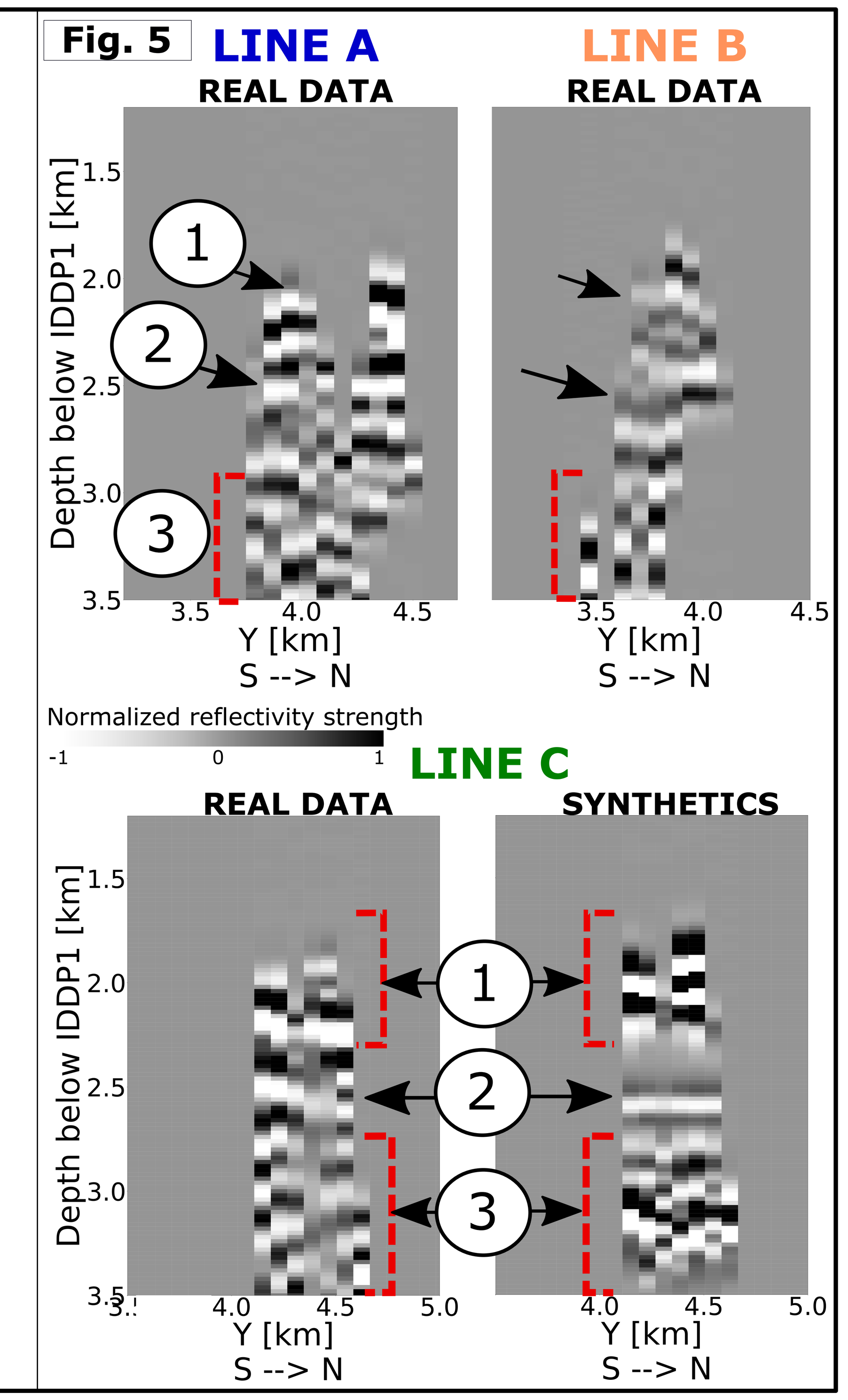


Fig. 4 and 5:
- We show vertical cross-sections along selected lines (Fig. 4).
- White/black color shows reflectivity strength as function of depth and Y-position.
- Gaps in images mark areas with no contributing event-station pairs.
- For LINE C, we compare real with synthetic data.

1 Reflectors (~2.1 km)	2 Reflectors (~2.5 km)	3 Reflectors (> 3 km)
Unexpected in synthetics (no reflector in the model at this depth!).	**Expected** in synthetics. Great, our code works!	**Unexpected** in synthetics (no reflector in the model at this depth!).

PROBLEM: ARTIFACTS DUE TO DIRECT WAVES

- Method stacks amplitudes along reflection trajectories, suppressing other phases with different apparent velocities.
- BUT: small study area and earthquake-station geometry result in similar apparent velocities for different phases, e.g., direct P- and S waves (Fig. 2).

-> Unwanted phases create spurious reflectors/artifacts in images.

1	2	3
• Reflections from the IDDP-1 magma pocket expected. • BUT: Direct P waves interfere with reflections.	• No artifacts expected. -> Brittle-ductile boundary/ Bottom of IDDP-1 magma pocket?	• S waves create artifacts at these depths. • S wave signature can be clearly seen in real data (e.g., in LINE C).
-> Unclear if reflectors are real.	**-> Real reflectors.**	**-> Reflectors are likely not real.**

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 858092.