Seismic imaging of shallow magma bodies at Krafla, Iceland

Regina Maaß[1], Christopher J. Bean[1], Ka Lok Li[1]

[1] Dublin Institute for Advanced Studies (DIAS), Dublin, Ireland

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

WHAT

Area is geothermically exploited

2009: **unexpected** drilling into magma at 2.1 km depth

Why was that magma pocket not detected with imaging techniques?

What do we have to do in order to see it?

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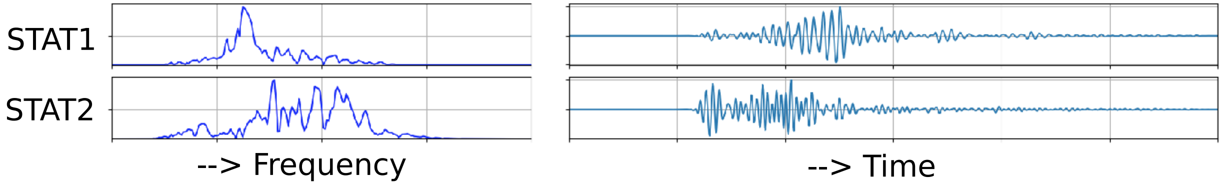
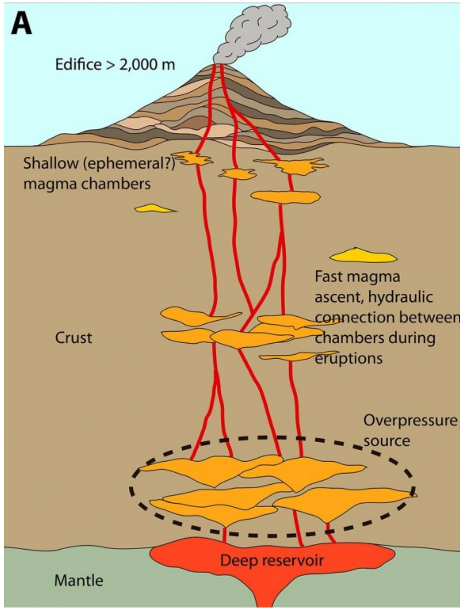
WHY



- Imaging at volcanos is challenging
- But important for natural hazard assessment and geothermal exploration
- Conventional imaging methods reach their limitations

How do we have to process seismic data in order to get a high-resolution image of the sub-surface in complex media?



From Castruccio et al. (2017, JGR)

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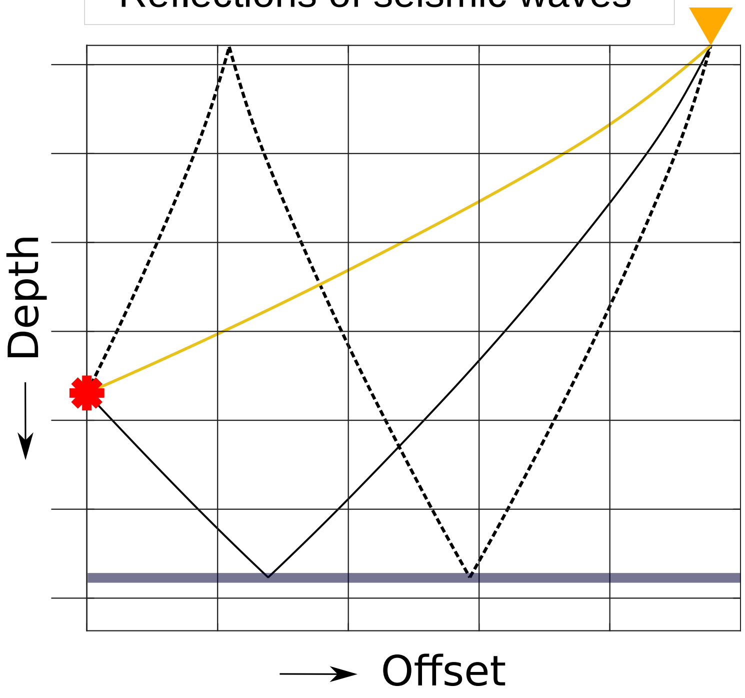
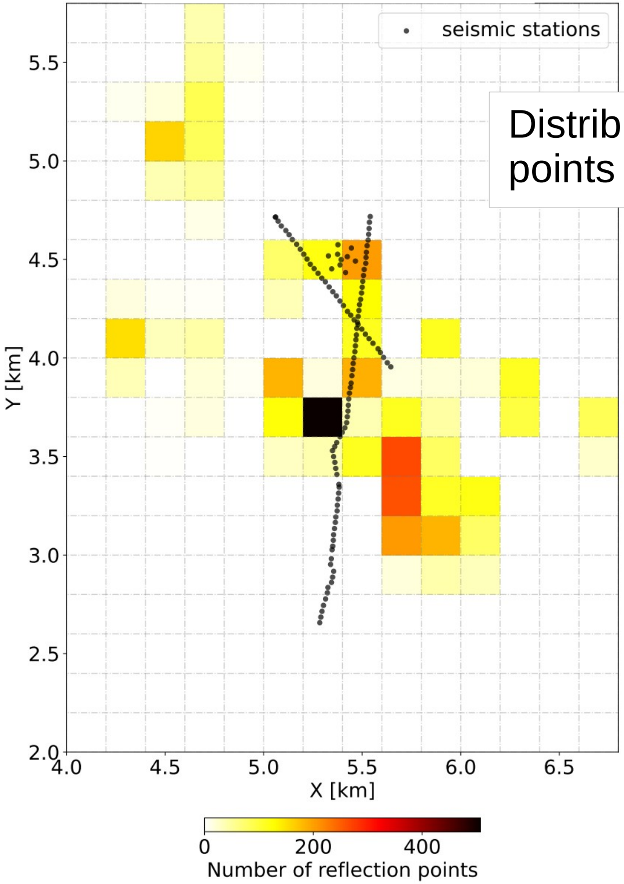
HOW

Reflections of seismic waves



Distribution of reflection points at 2.1 km depth



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(Long presentation on the screen)

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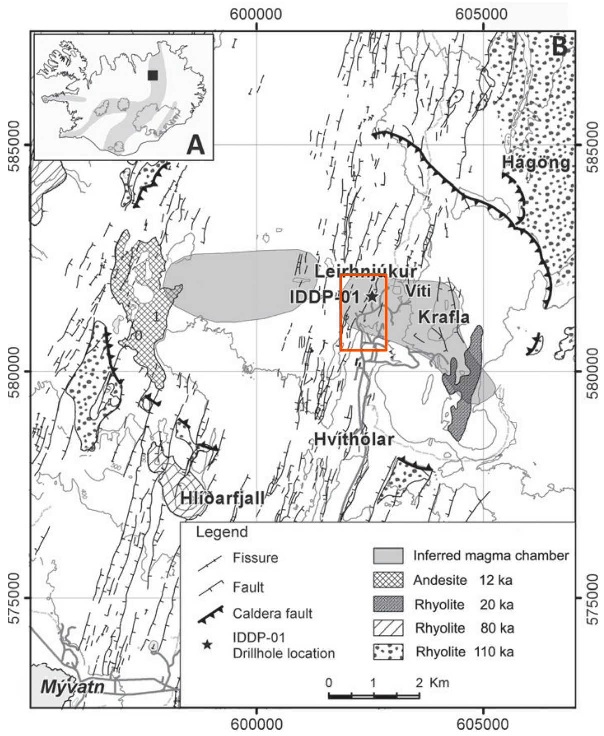

A: Iceland rift system (shaded) and location of Krafla (black square).

B: The Krafla volcanic caldera, outlined by the thick black line. The shaded areas mark the magma body inferred by Einarsson (1978, Bull Volcanol). The star marks the location of the IDDP1-borehole. The orange square delineates our study area. Figure modified from Elders (2011, Geology).

Krafla

- Volcanic caldera in the north-east of Iceland.
- One of the best-investigated volcanos worldwide.
- Einarsson (1978, Bull Volcanol) suggested the existence of a magma body at 3 km depth beneath the caldera (grey shaded areas in map).

In 2009, **rhyolytic magma was unexpectedly encountered at the IDDP1 borehole** at a shallow depth of 2.1 km during geothermal drilling.

→ This magma pocket remained undetected before the drilling, despite numerous geophysical investigations.

Why?

Steam coming out of the IDDP1 borehole

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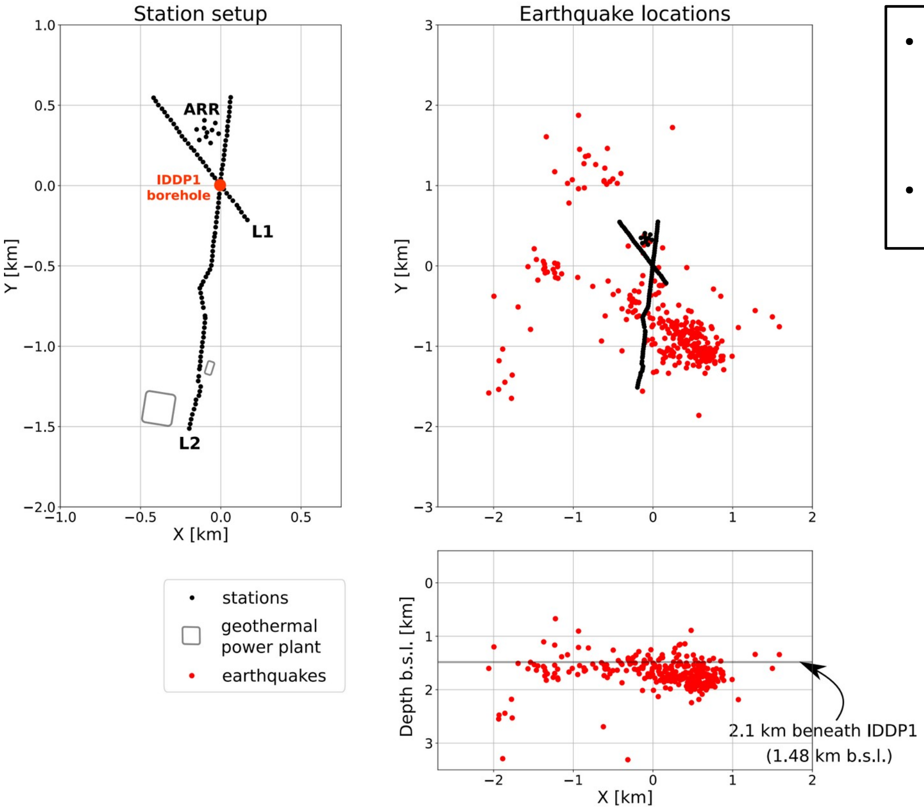
GOAL: Image the magma pocket beneath the IDDP borehole using reflections of seismic waves.



- Our research is at a local scale, but the question is really more a general one:

  How do we have to process seismic data in order to get a high-resolution image of the sub-surface in complex media?

- Krafla is ideal to test and calibrate seismic imaging, because the location of the magma body is known through drilling.

Krafla field campaign (summer 2022, 40 days)

- Deployment of > 100 continuously recording geophones (5 Hz)

  1. long line **L2**: ~ 2km long, station spacing 30 m
  2. short line **L1**: ~ 1km long, station spacing 30 m
  3. circular array **ARR**: aperture 140 m

Seismic sources

- > 300 micro-earthquakes

  → Depths 0.67 km - 3.31 km b.s.l.., local magnitudes -0.5 - 1.5
  → 18% of hypocentres above target depth (2.1 km beneath IDDP1 borehole)

- High-frequency (>2 Hz) industrial noise generated by the power plant

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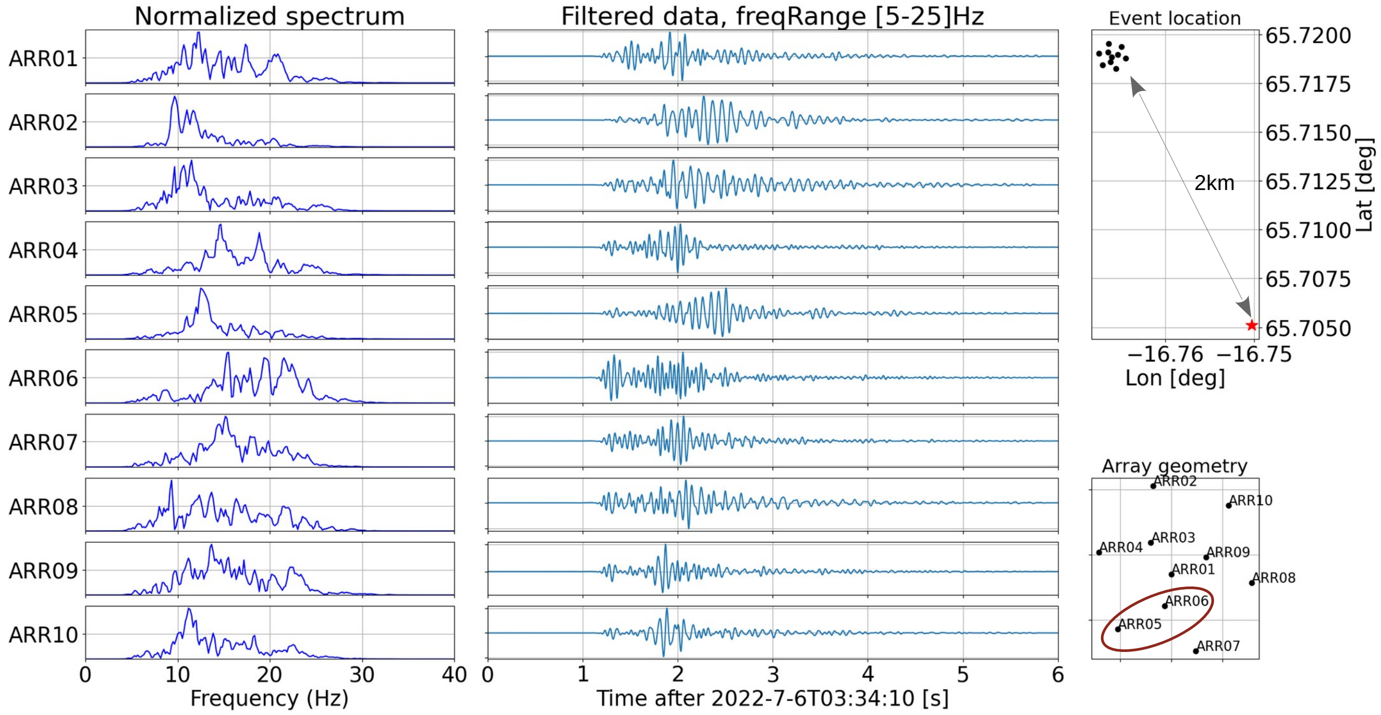
Why is seismic imaging at volcanos challenging?

- Recorded wavefield looks "messy" and lacks coherency across the stations.
- For example, stations ARR05 and ARR06 are only 50 meters apart from each other but record very different waveforms. Also their frequency content differs a lot.
- Subsurface extremely heterogeneous
  → Coherent arrivals are hidden, masked by multiply scattered waves.
  → Recorded waveforms are dominated by near-station effects.

Landscape at Krafla. Lava caves and rocks of different sizes characterize the area.



Earthquake recorded by the circular array (epicentral distance: 2km)

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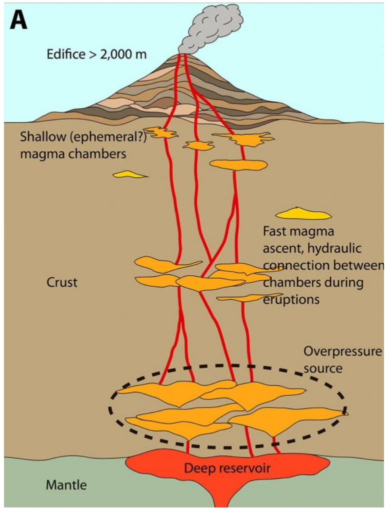


From Castruccio et al. (2017, JGR)

Why reflections?

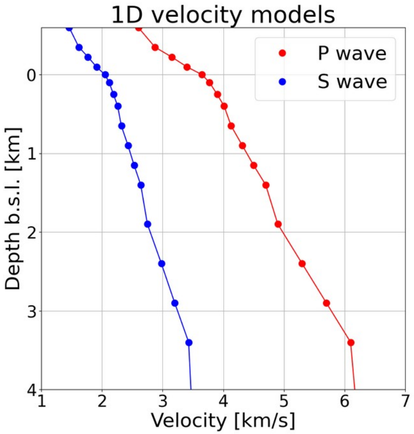
- Volcanic magmatic system consists of multiple magma pockets/bodies that are connected.
- Larger objects, such as a large deep magma reservoir can potentially be detected with seismic tomography.
- Smaller objects are smeared out by tomographic techniques.
- Seismic reflections depend on the impedance contrast between the layer above and below the reflector.
- Provided that a suitable source-receiver combination is available and the impedance contrast is strong enough, the reflected wave should be contained in the recorded wavefield, even though strong scattering masks it.

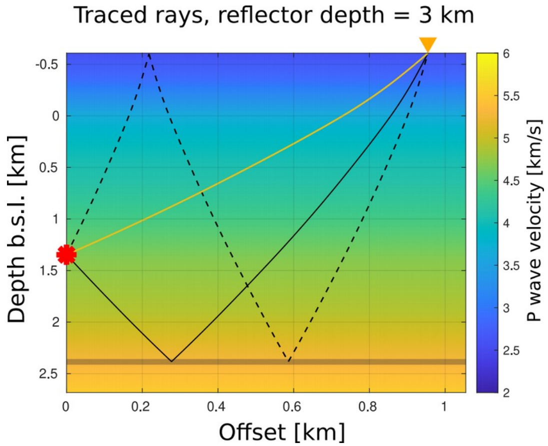
Raytracing

- We use a velocity model that only varies in 1D, provided by ISOR (but our model space is 3D!).
- We predict traveltimes for the direct P and S waves.
- We also model primary reflections and ghost reflections assuming flat reflectors at depths:

→ **3 km** (for the magma chamber suggested by Einarsson (1978, Bull Volcanol))

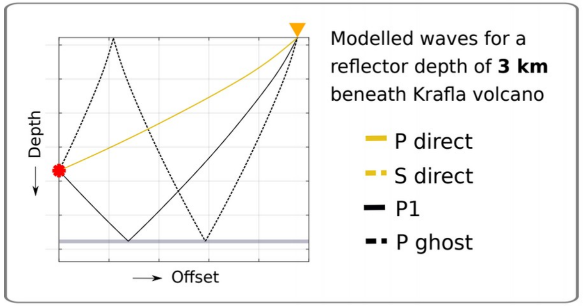
→ **2.1 km** (depth at which the magma beneath the IDDP1 borehole was encountered)

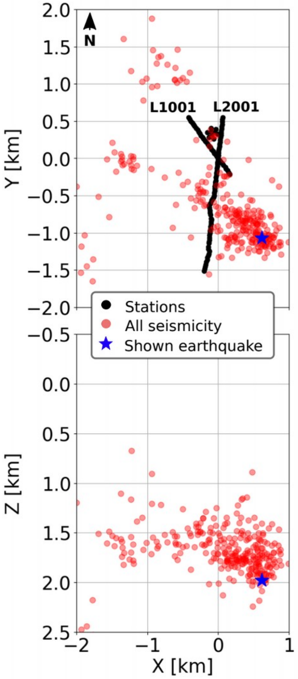


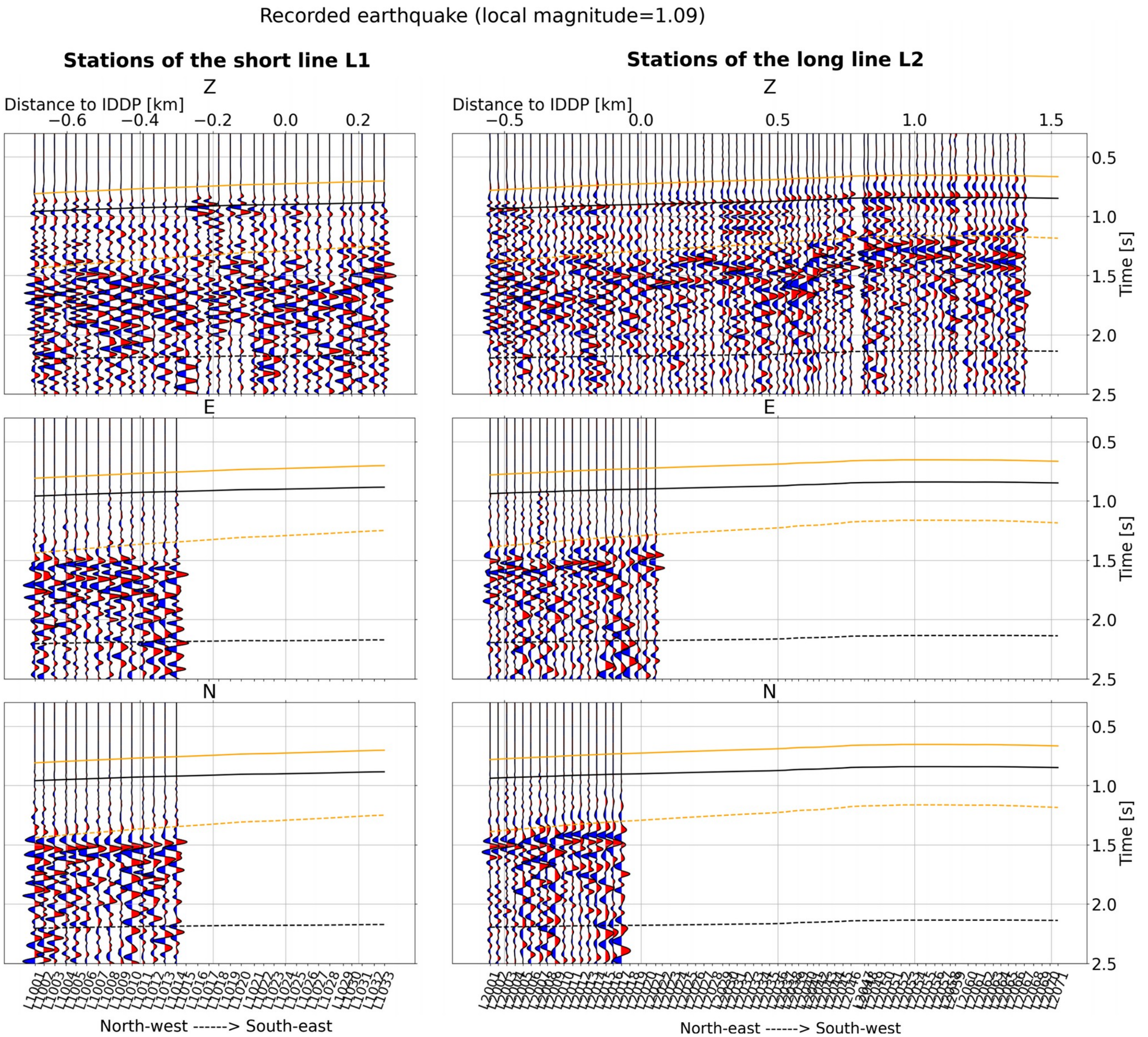


EXAMPLE 1

Here, we assume a reflector depth of 3 km beneath the caldera. This is where Einarsson (1978, Bull Volcanol) suggested the existence of a magma chamber.



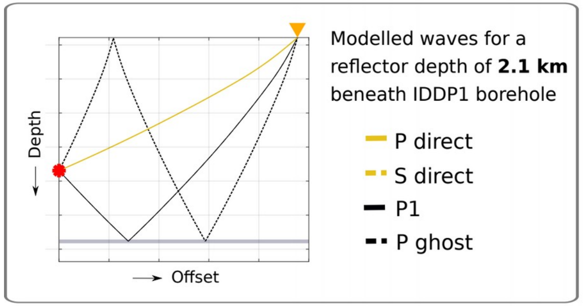




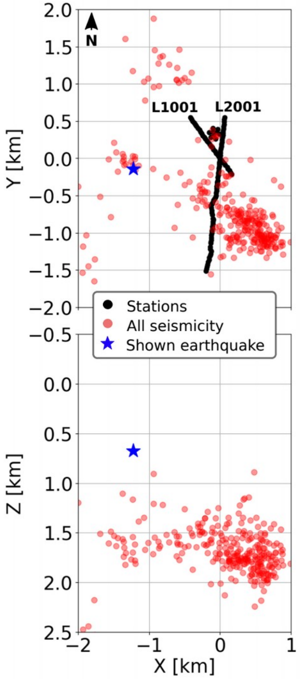
- Predicted traveltimes for direct S and P waves match very well with real data.
- Local deviations exist and are expected as we only use a homogeneous 1D velocity model.
- A coherent arrival at the predicted traveltime for the primary reflection can be seen.
- No indication of the ghost reflection in real data.

EXAMPLE 2

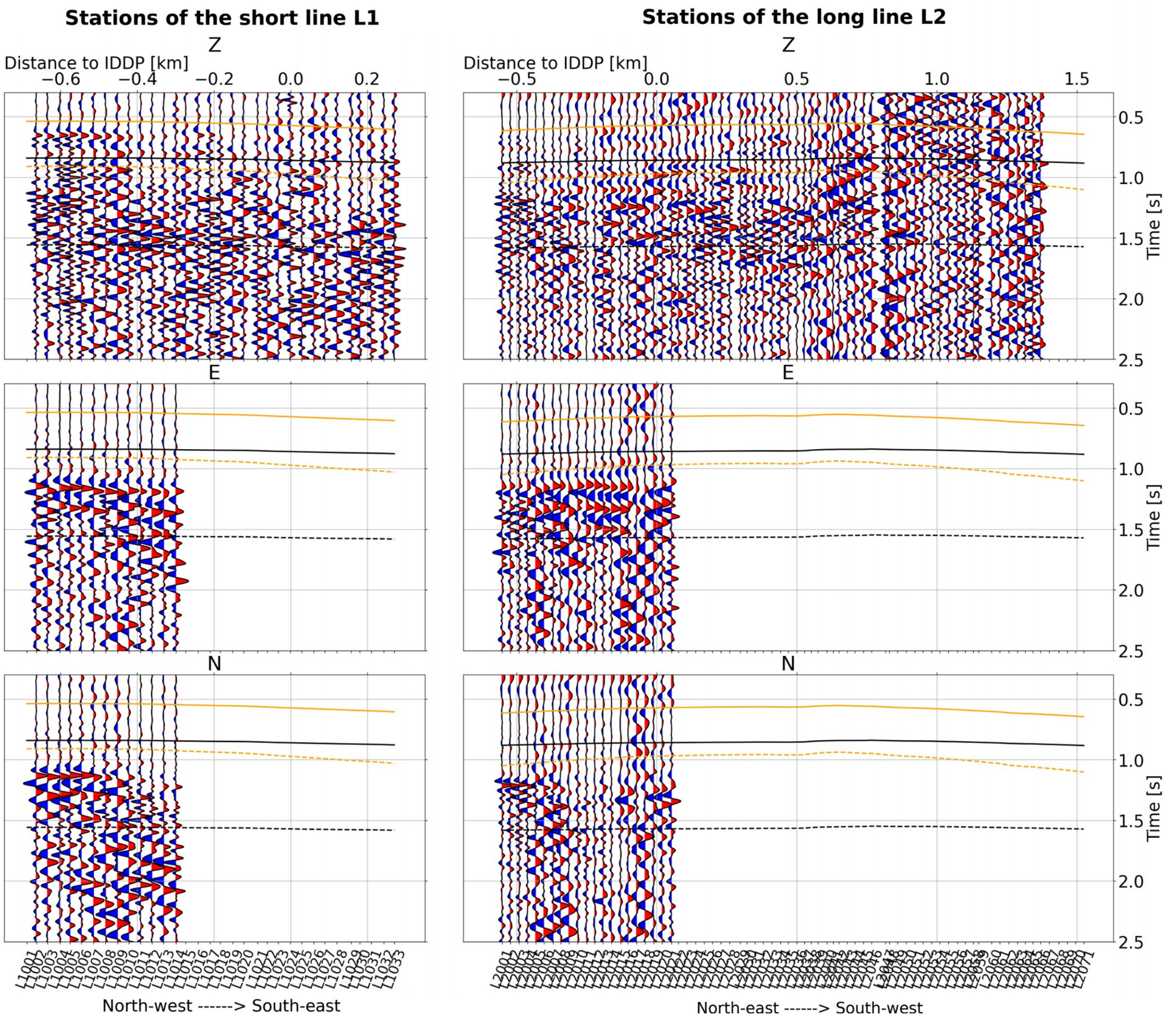
For earthquakes with depths < 1.48 km b.s.l. (2.1 km below IDDP1), we model direct and reflected waves.



- The SNR is not very good.
- Predictions for direct waves match reasonably well.
- Coherent arrivals can partly be seen for the primary reflection. However, the interpretation is challenging due to the complex wavefield.

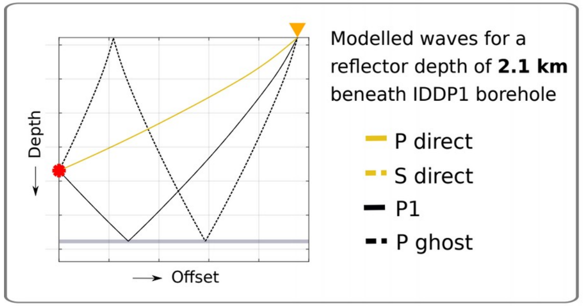


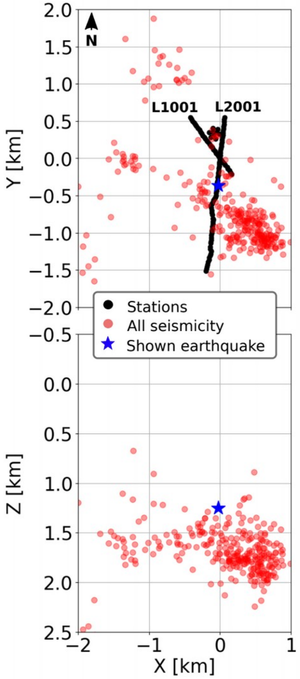
Recorded earthquake (local magnitude=-0.21)

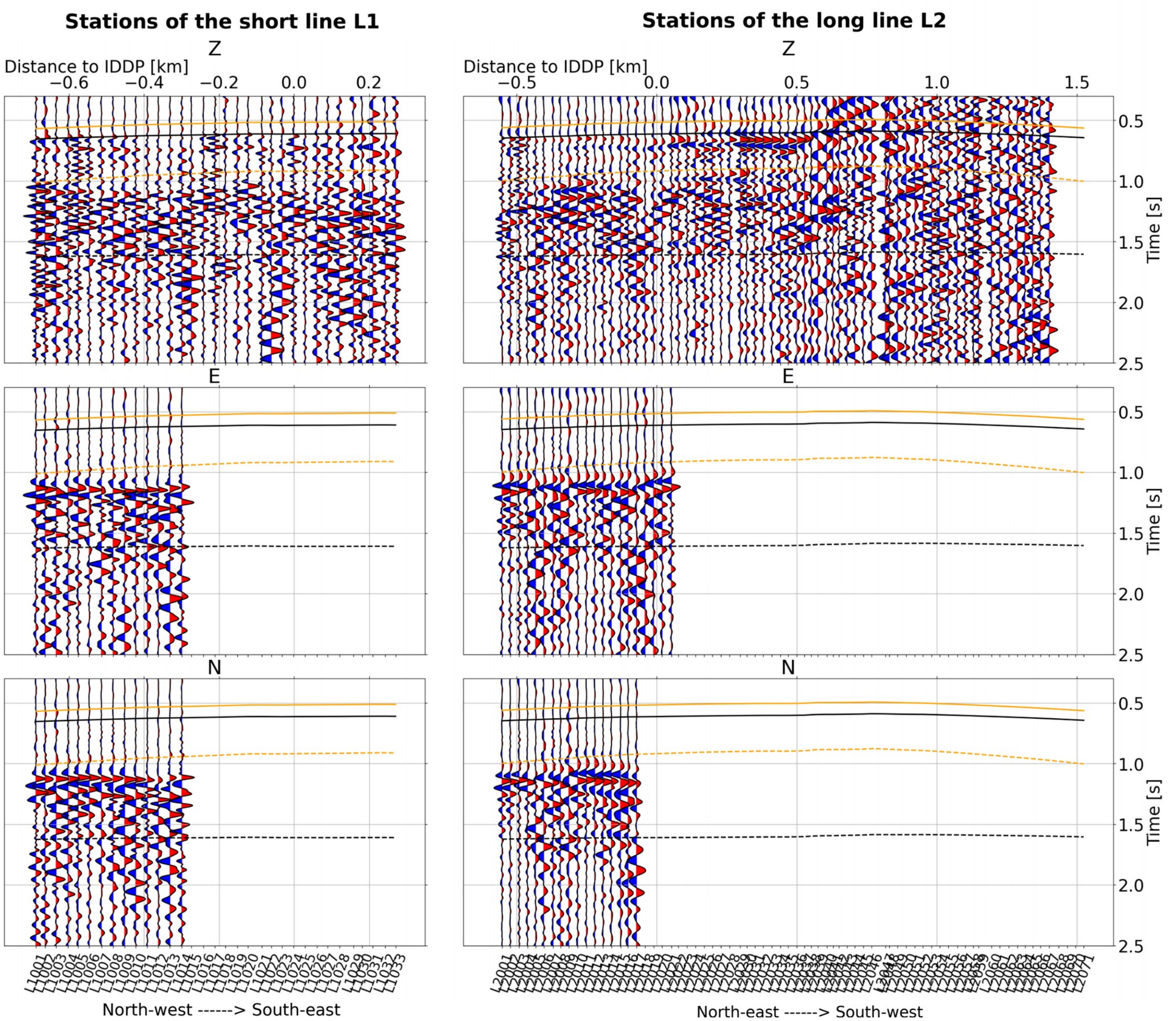


EXAMPLE 3

Another example for modelled waves (reflector at 2.1 km beneath IDDP1, 1.48 km b.s.l) is shown here.







- Coherent arrivals at the predicted traveltimes for direct waves and primary reflection can be seen in real data.
- But: traveltime difference between the direct P wave and the primary reflection very small.
- This is because the hypocentre is just above the reflector. This is the case for most quakes with depths < 1.48 km b.s.l.
- Often, the primary reflection is expected to arrive within the first period of the direct P wave.
- This complicates a direct interpretation and makes it difficult to isolate the reflected wave in the wavefield.

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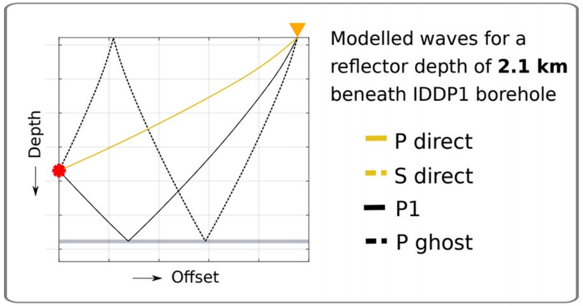
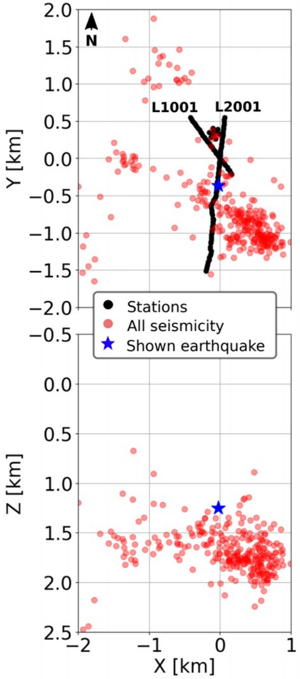
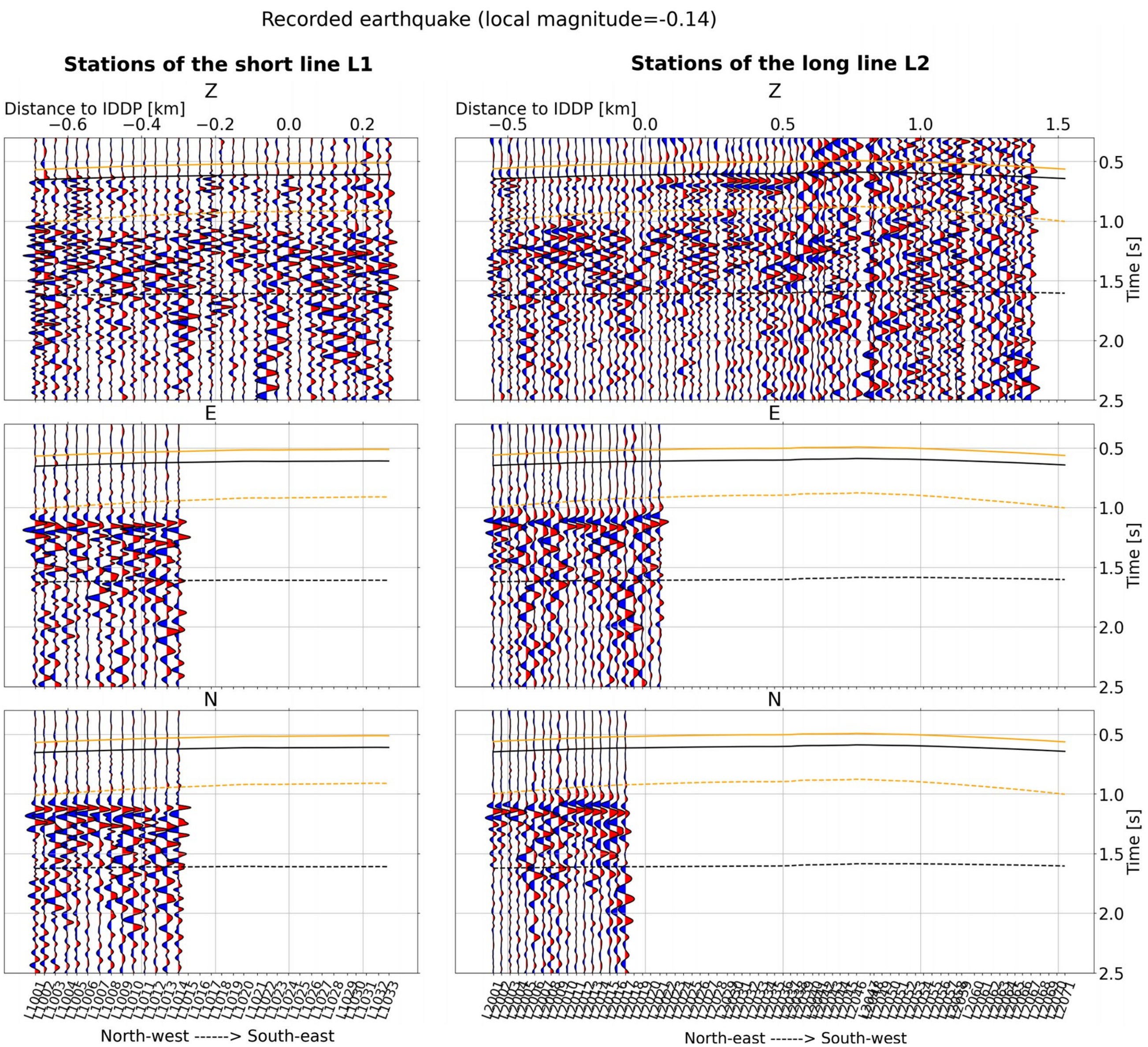


- BUT: a lot of interesting information contained in the P wave coda and the recorded wavefields in general!

Starting from here, we want to **decompose the wavefield into its constituents** by applying methods involving interferometry and techniques known from applied seismics. **Ultimately, we want to isolate the reflected waves in our data.**





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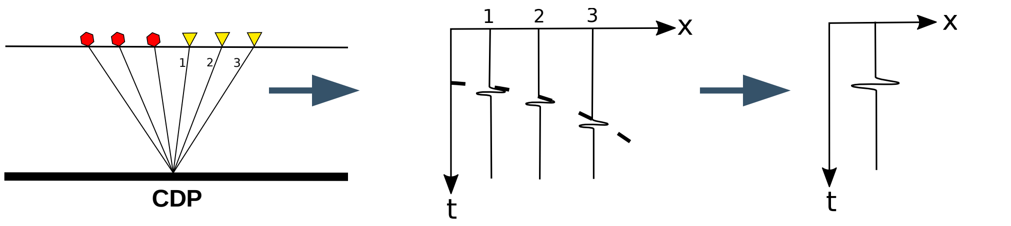
CDP (common-depth-point) binning and stacking

- Method commonly known from applied seismics.
- Aims at increasing the SNR of reflections by sorting traces according to their reflection points at depth.
- We use the 1D velocity model to compute coordinates of reflection points.

CDP binning and stacking (classical workflow from applied seismics)

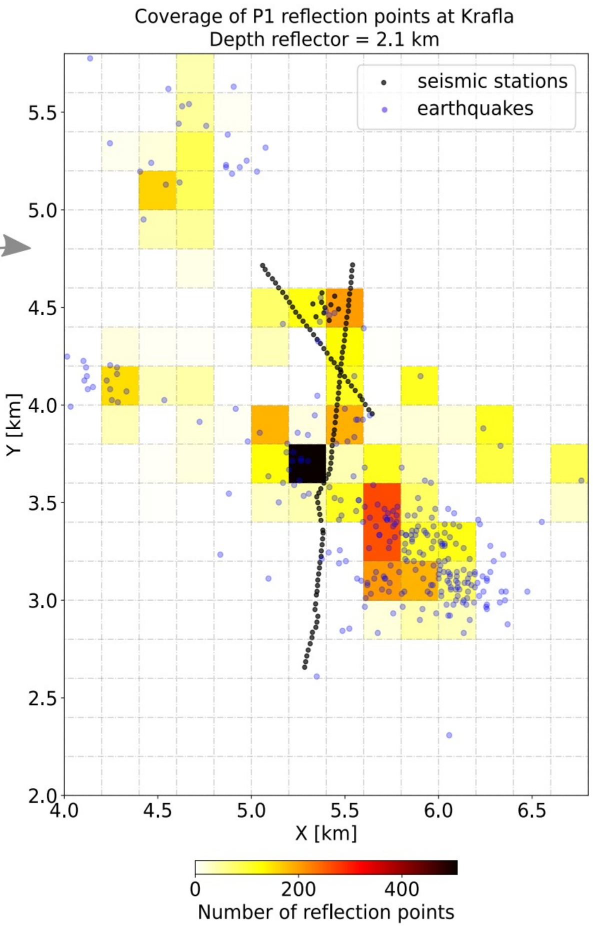


1. Source-receiver combinations for which the points of reflection fall into pre-defined bins are selected.

2. These traces are then sorted according to their offsets and displayed in “CDP-gathers“

3. After correcting for the hyperbolic moveout, the traces are stacked to increase the SNR of the reflection.

How many reflection points (primary P reflection) at 2.1 km depth fall into 200m x 200m large bins given our distribution of sources and receivers?



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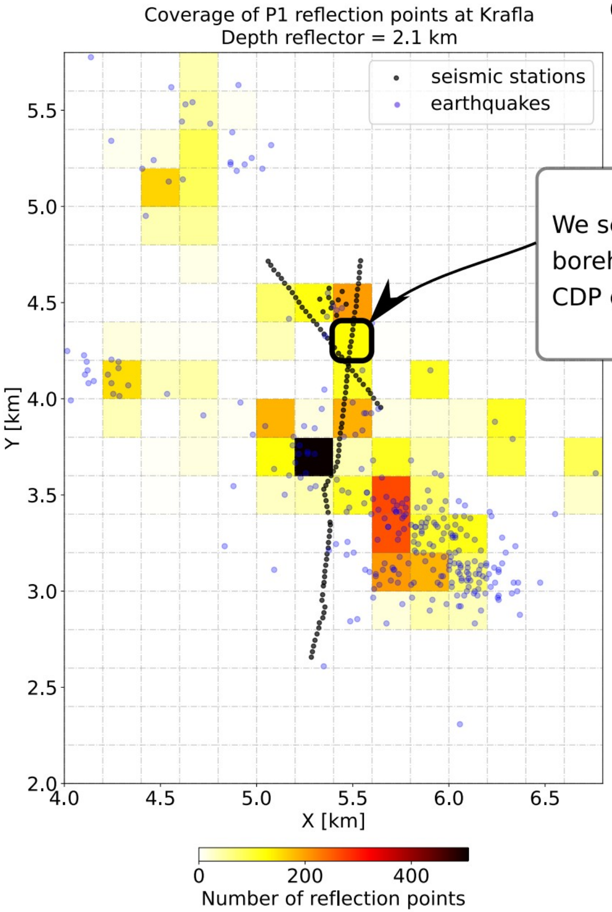
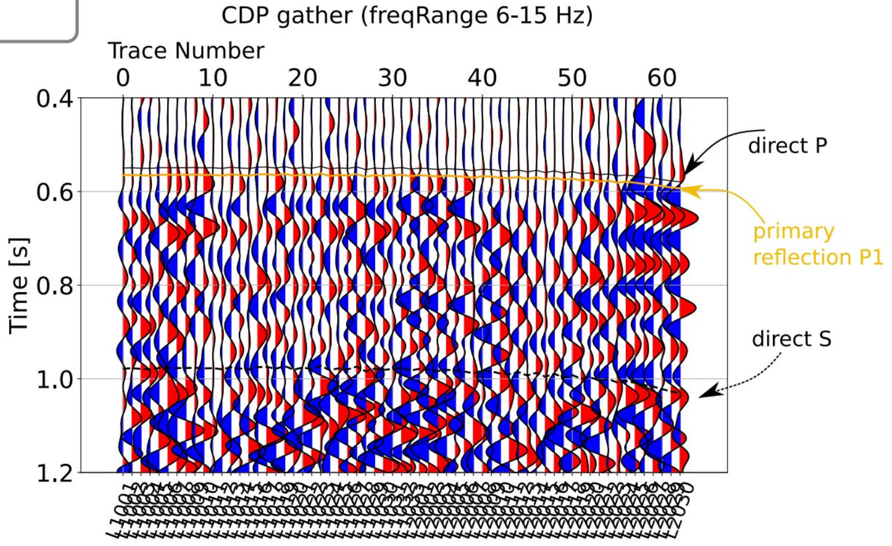


We select the bin close to the IDDP1 borehole and plot the corresponding CDP gather.

- Coherent arrivals between direct P and direct S waves visible.
- Problem: hypocentres are right above the reflector.

  --> Difference in traveltime between the direct P wave and the primary too small, we can‘t isolate the reflection.



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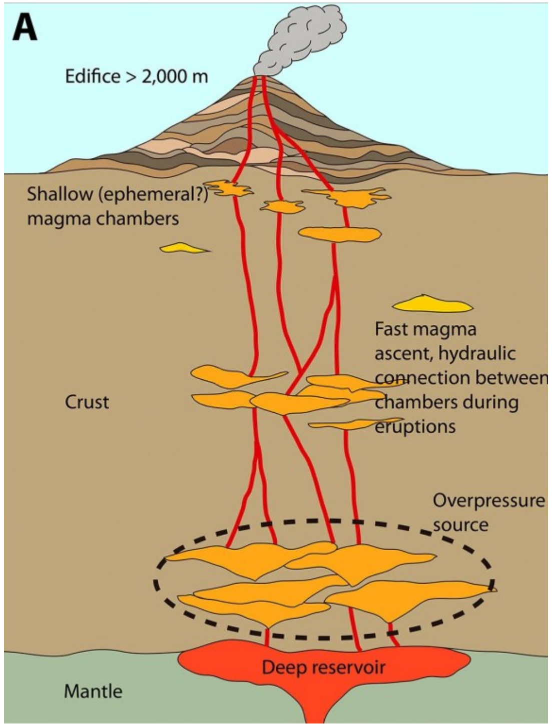
Summary



From Castruccio et al. (2017, JGR)

Seismic Imaging of heterogeneous media is challenging because of the complexity of the wavefield.

- Small magma bodies are smeared out by tomographic techniques.
- Strong scattering due to geologic heterogeneities mask coherent reflections.
- Degree of scattering is higher in the uppermost crust → makes it even more difficult to image shallow objects.

Using a simple 1D velocity model, we predict traveltimes for direct and reflected waves.

- Traveltimes of direct waves match well with real data.
- This means that the velocity model is reliable → very useful for future analyses.

Coherency-based methods will be used for wavefield separation.

- Methods from applied seismics (e.g., CDP binning) will be used in combination with interferometry (e.g., redatuming of sources through cross-correlation).