Prominent crustal discontinuities in Reykjanes Peninsula, Iceland

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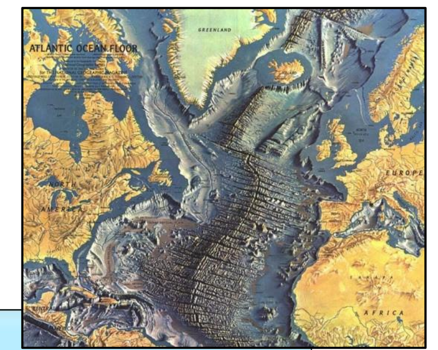
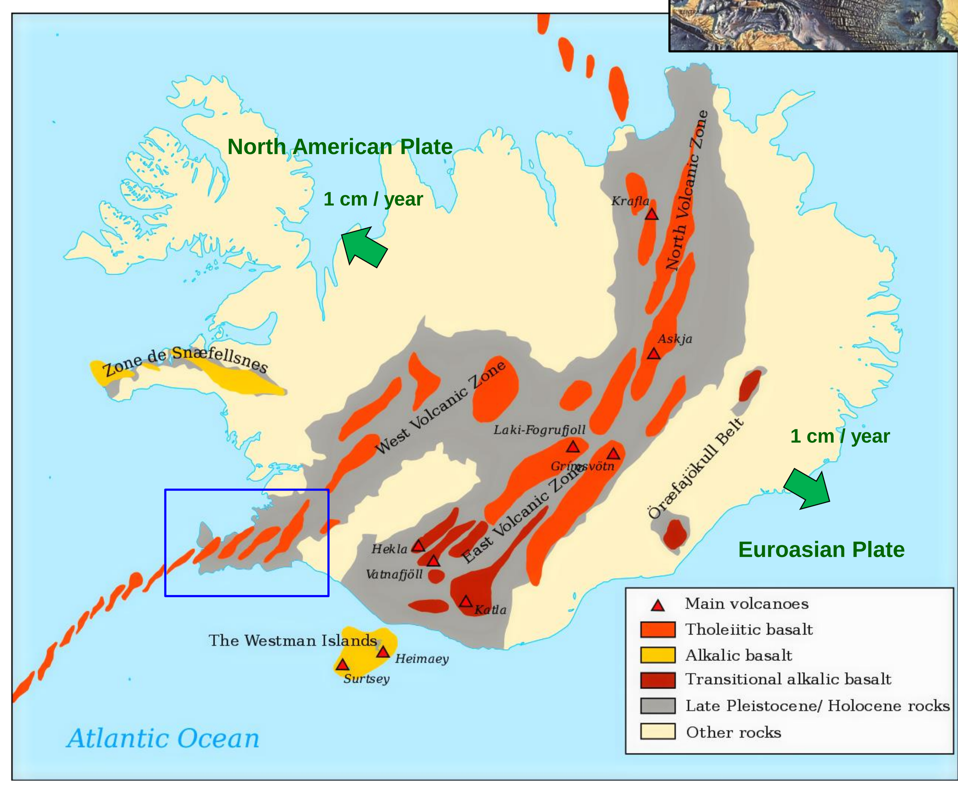
IG ASCR

Iceland at Mid-Atlantic ridge

Sea floor spreading

Iceland
rift, faults, volcanism





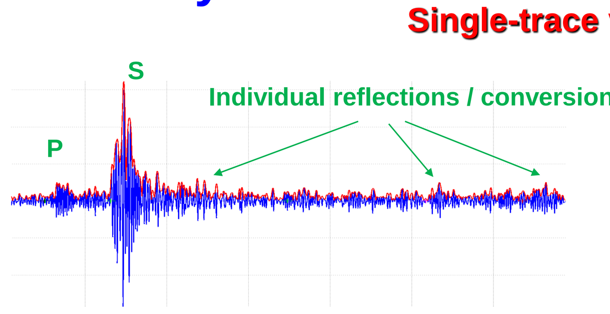
Iceland, situated in the North Atlantic Ocean between Greenland and Norway, is located above the Mid-Atlantic Ridge. It is a part of the oceanic crust forming the floor of the Atlantic Ocean. Its tectonic structure is characterized by various seismically and volcanically active centers.

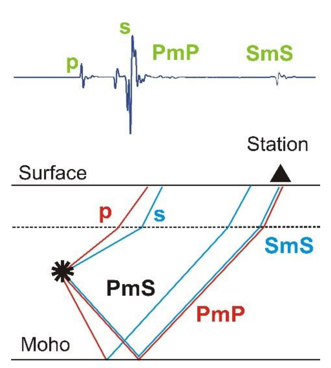
The rift in Iceland is located at the junction between the Reykjanes Ridge in the south and the Kolbeinsey Ridge in the north. The surface expression of the plate boundary is formed by the narrow belts of active faulting and volcanism extending from Reykjanes Peninsula in the southwest, which zigzag across Iceland before plunging deep to the Arctic Ocean in the north. Iceland represents the only section of the Mid-Atlantic Ridge exposed above the sea level, its active spreading and plate growth is of prominent interest of many scientists The spreading rate in Iceland is about 1.8 cm per year and the spreading directions are 105°E and 285°W.

Above the plate boundary, the spreading breaks apart the brittle crust and results in the formation of extensional cracks and faults perpendicular to the spreading direction. Formation of vertical subsurface dykes generates pathways for the uprising magma which appears at surface as swarms of linear volcanic fissures confined to narrow belts of volcanic zones. Connected by large transform faults known as fracture zones or when volcanically active as volcanic belts they cover about one third of Iceland.

Data analysis

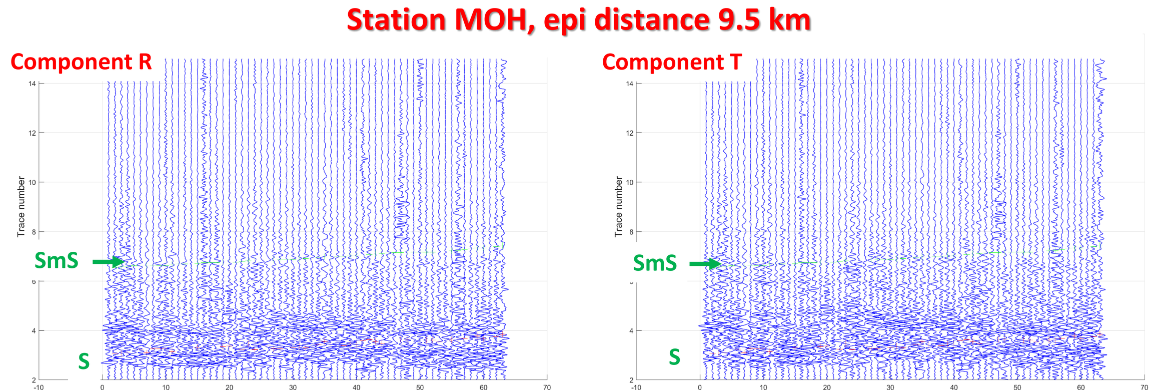
Single-trace view



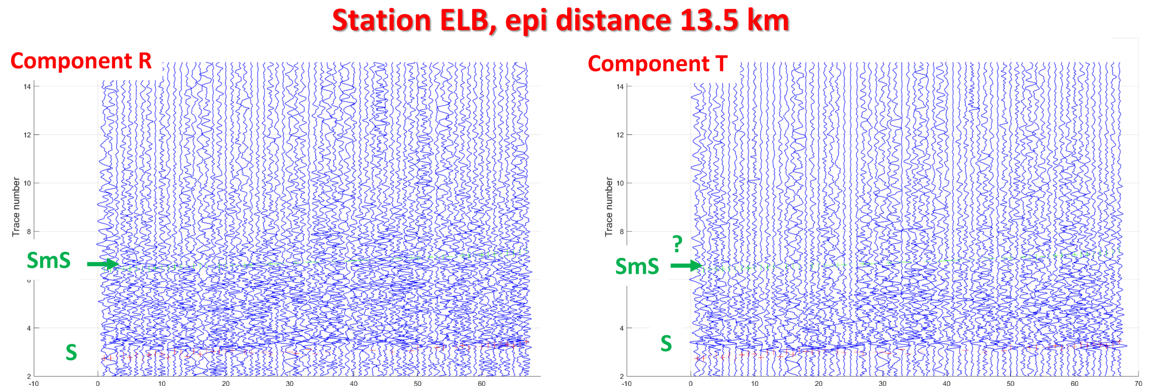


Data in seismic sections

Station MOH, epi distance 9.5 km



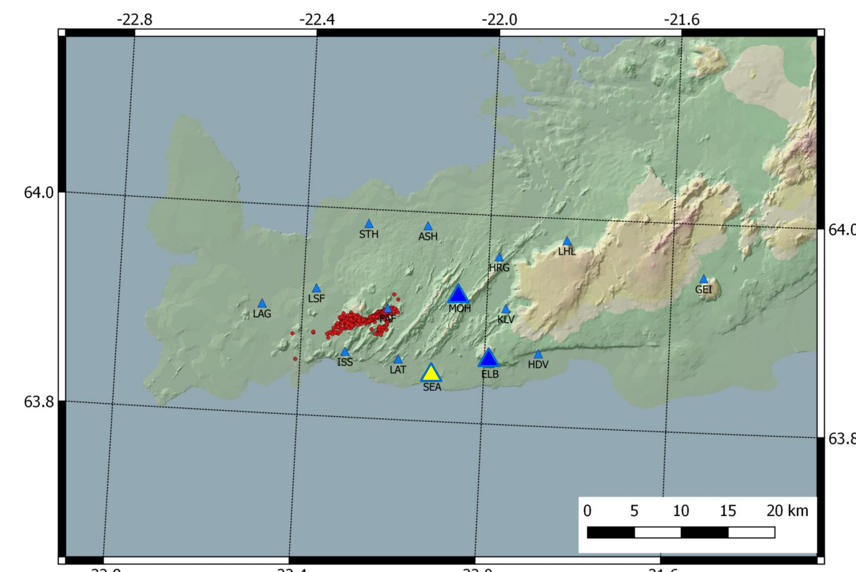
Station ELB, epi distance 13.5 km



The waveforms of local earthquakes that occurred during the 2017 swarm typically display dominant direct *P* and *S* waves followed by converted and reflected phases secondarily generated at shallow and deeper subsurface structure. Examples of horizontal recordings showing the crust/mantle *SmS* reflections for different earthquakes recorded at individual stations (filtered 1.3-10 Hz to remove high-frequency noise typical for rift environment). Note the visibility of the reflected phases at different stations.

Rifting at Reykjanes peninsula – earthquakes, data and synthetic tests

Source receiver geometry

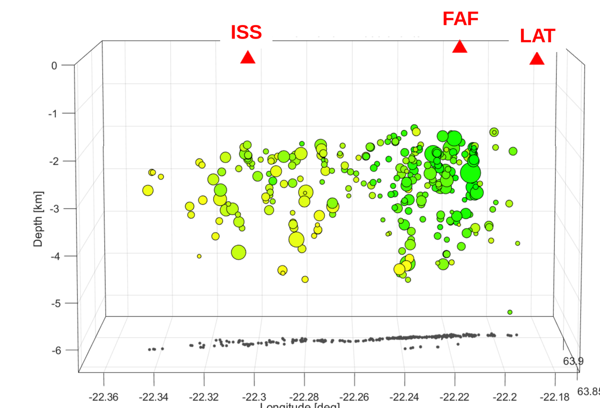


Local earthquakes – 2017 swarm
Seismic stations (SP) of REYKJANET network

We focused on active seismicity in the SW part of Iceland, where the Reykjanes Ridge segment of the Mid-Atlantic Ridge is located in the Reykjanes Peninsula. It is the landward ridge continuation connecting the Mid-Atlantic Ridge to the Western Volcanic Zone. The seismicity in this area is monitored by 15 seismic stations (short period SP) of the REYKJANET network, operated by IGF CAS.

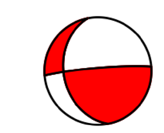
The earthquakes are released in form of earthquake swarms and are largely confined to the upper few kilometers of the oceanic layer related to a large number of faults and fissures with the high seismic activity at depths of 2 km to 6 km, however, some events may be as deep as 13 km.

Since knowledge of a detailed crustal structure is essential for all advanced studies of seismicity and focal parameters of the earthquakes, we concentrated on velocity model and prominent discontinuity depth retrieval in the area. We selected the best located events of the 2017 swarm in Reykjanes Peninsula and refined their locations by manual picking. This resulted in processing of waveforms from earthquakes with magnitudes >1 recorded at 15 REYKJANET seismic network stations. The waveforms typically displayed dominant direct P and S waves followed by converted and reflected waves secondarily generated at shallow and deeper subsurface structure. We tested a multi-azimuthal approach in data processing of [1,2] to increase resolution of these phases in the waveforms. We applied the waveform cross-correlation of the P and S waves, and rotated, aligned and stacked the seismograms to extract the reflected phases. In the interpretation, we focused on the most prominent interface at the crust/mantle boundary, the Moho, and processed its reflected SmS phases. These phases were inverted for laterally varying Moho depth by ray tracing and a grid search inversion algorithm and verified by modeling of full waveforms computed by the discrete wave number method.



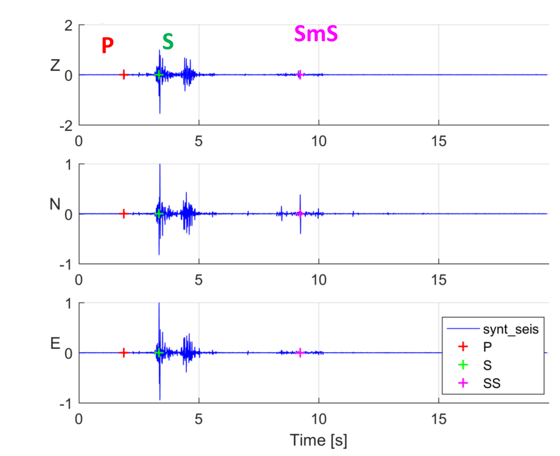
EQ swarm 2017
M > 1
Shallow depths

Numerical modelling with discrete wave-number method

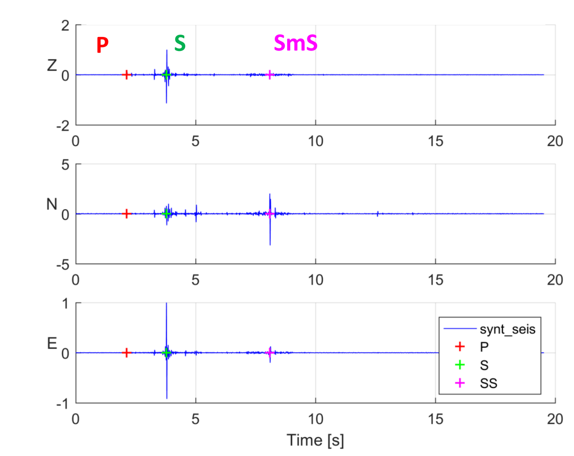


Station SEA, distance ~9 km

Source at 3 km depth



Source at 7 km depth

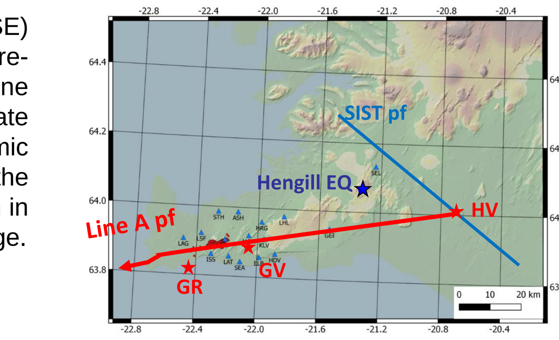


The waveforms generated by local tectonic earthquakes are significantly affected by velocity structure and by the source-receiver geometry. This applies especially for shallow earthquakes as is the case of the Reykjanes 2017 swarm. The numeric full-waveform modelling calculated by the discrete wave-number method [4] disclosed significant variations in the wavefields with contamination of phases secondarily generated at shallow structure. The Moho *SmS* reflected phases are better pronounced at horizontal components and for deeper sources.

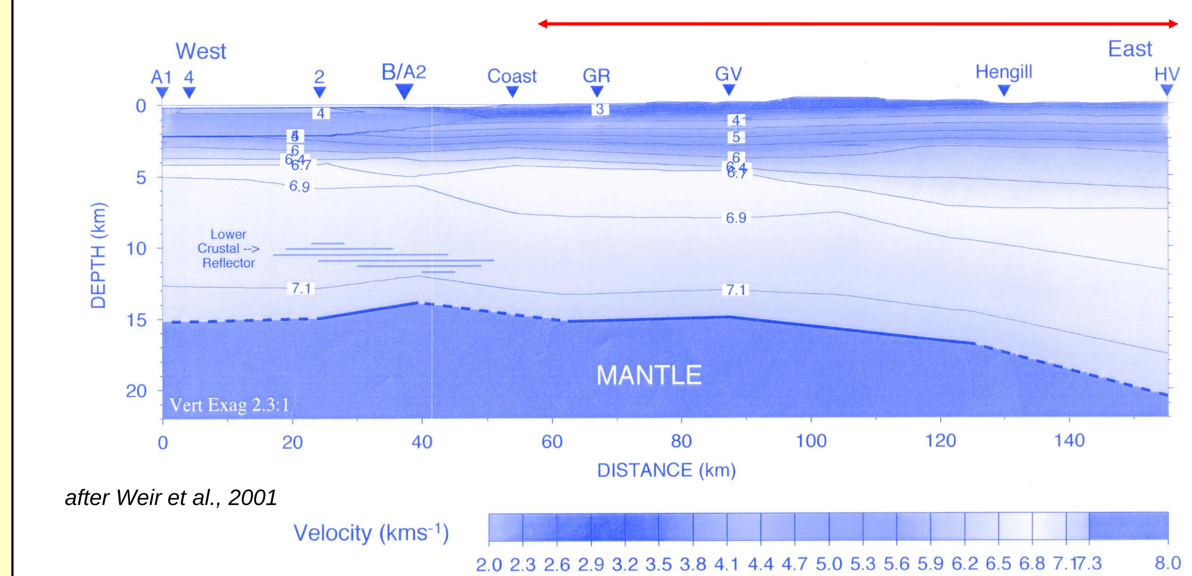
Local tectonic earthquakes

Previous investigations and results

The Reykjanes-Iceland Seismic Experiment (RISE) was conducted in 1996 as a combined onshore-offshore seismic survey with two along-axis and one across-axis profiles. Line A followed the plate boundary on the Reykjanes Peninsula. Seismic modelling along this profile revealed that the thickness of zero-age crust decreases from 21 km in southwest Iceland to 11 km on the Reykjanes Ridge.



Refraction experiment RISE
Traveltime model line A

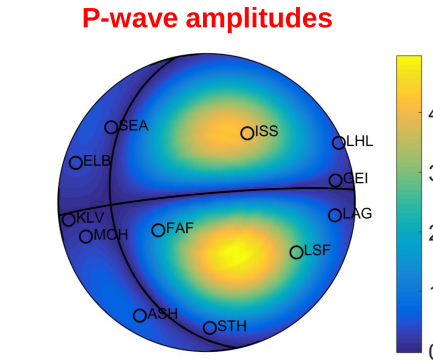


after Weir et al., 2001

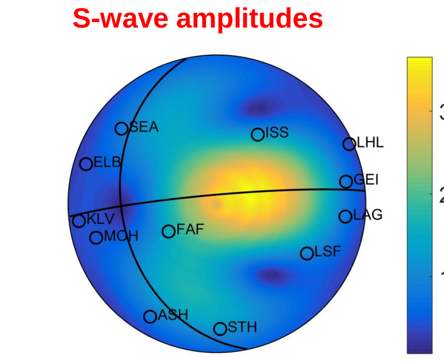
Focal mechanism and focal sphere coverage

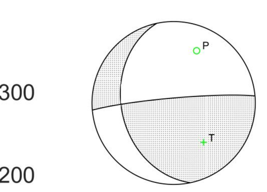
Prevailing focal mechanism

P-wave amplitudes



S-wave amplitudes

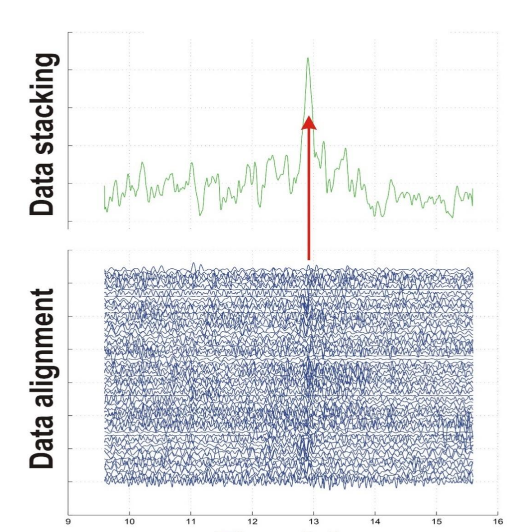




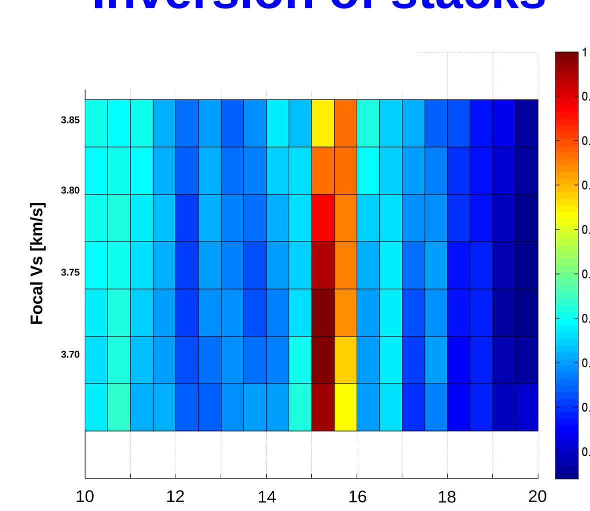
Apart from velocity structure and source receiver geometry, the waveforms are significantly affected by focal mechanisms of earthquakes. Prevailing focal mechanism characteristic for the earthquake swarm 2017 in Reykjanes Peninsula, Iceland. The moment tensors for the focal mechanisms were calculated by the AMT computer code which combines ray tracing in a smooth velocity model, calculation of the ray-theoretical Green functions and the generalized linear inversion. Projection of REYKJANET seismic stations for P and S waves on focal sphere indicated.

Data processing and inversion

Alignment and stacking



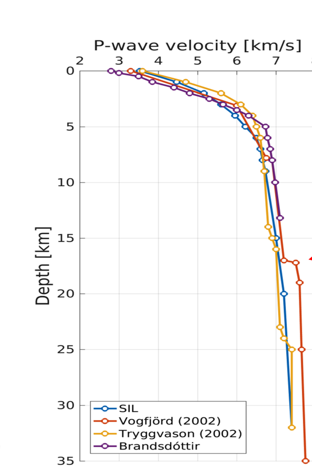
Inversion of stacks



Velocity – depth profiles

thin crust – active Holocene volcanic systems (at the rift)
thicker crust – Tertiary basalts with lava piles (further from rift)

3 layers
0.5 km
3/5 km
15/1 km



Vp/Vs = 1.7

after Jakoubková, 2018

Data recorded at individual stations were sorted according to the their calculated traveltimes of *SmS* reflections using the ray-tracing approach. Data were aligned and stacked to extract the crust-mantle reflected *SmS* phases.

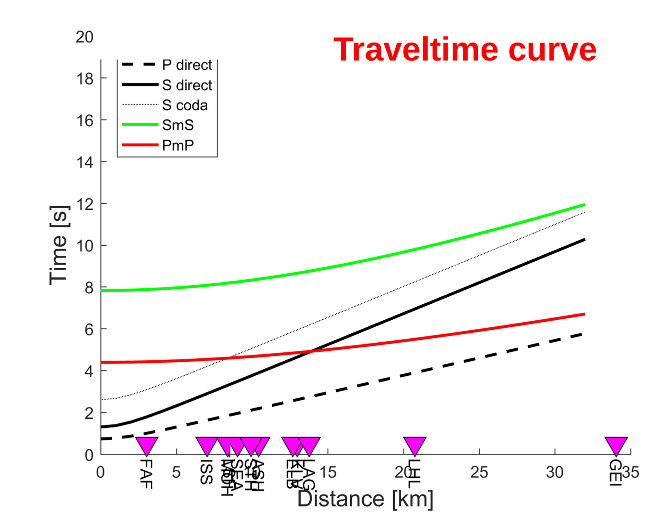
Arrival times of stacks at individual stations were inverted for laterally varying Moho depth reflections using two-point ray tracing with 1-D velocity model (Vogfjord, 2002) in modifications and with the application of a grid search algorithm. Results of the inversion were obtained for each component and each station to get the information on lateral variations of the reflector.

Analysis of phase detectability

To avoid misinterpretation of phases, the analysis of phase detectability was carried out based on traveltime curves prior to the further data processing.

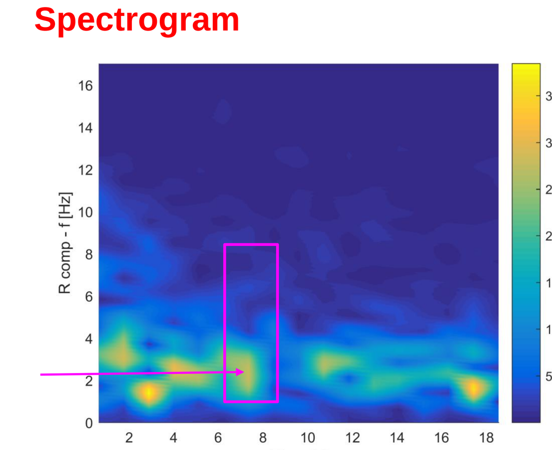
For the source at 3 km depth and the reflector at 15 km only near vertical stations have to be considered for crust/mantle SmS detection. In a similar way, PmP reflections are not possible to consider for interpretation at any of the REYKJANET stations.

Traveltime curve



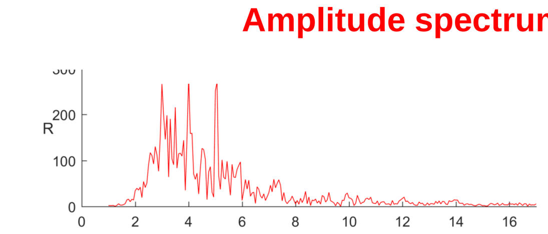
Signal processing for noise elimination

Spectrogram



Analysis of amplitude spectra and spectrograms of recorded events revealed low frequency content for reflected SmS signal. This resulted in filtering of 1.3-10 Hz and suppressing the noise.

Amplitude spectrum



Discussion and conclusions

- Depth of uppermost interface ~0.5 km
- Depth of crustal discontinuity 3-5 km
- Crust-mantle Moho discontinuity ~15-17 km

Effect of anisotropy or topography?

Tools applied

Focal mechanisms analysis
Source receiver geometry
Full waveforms modelling (DWN)
Ray tracing
Data alignment and stacking
Grid search algorithm

Prospects for future

Verification of the interface, lateral variations, and effects of anisotropy.

References

1. **Hrubcová, P., et al. Moho depth determination from waveforms of microearthquakes in West Bohemia/Vogtland seismoactive area. *J. Geophys. Res.*, 118, 120-137, doi: 10.1029/2012JB009360, 2013.**
2. Hrubcová, P., et al. Shallow crustal discontinuities inferred from waveforms of microearthquakes: Method and application to KTB Drill Site and West Bohemia Swarm Area, *J. Geophys. Res. Solid Earth*, 121, 881-902, doi: 10.1002/2015JB012548, 2016.
3. Weir et al., *J. Geophys. Res.*, 106, B4, 6347-6368, doi: 0148-0227/01/2000JB900358, 2001.
4. Bouchon, M. A simple method to calculate Green's functions for elastic layered media, *Bull. Seis. Soc. Am.*, 71, 959-971, 1981.

Acknowledgements

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