Conference on
Exploration and Exploitation
of Critical Raw Materials

An innovative method to image inner structure of orthomagmatic ore deposits using regional seismicity: a case study of Akanvaara Cr-V-PGE deposit in Northern Finland.

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EGT-TWINN

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Outline

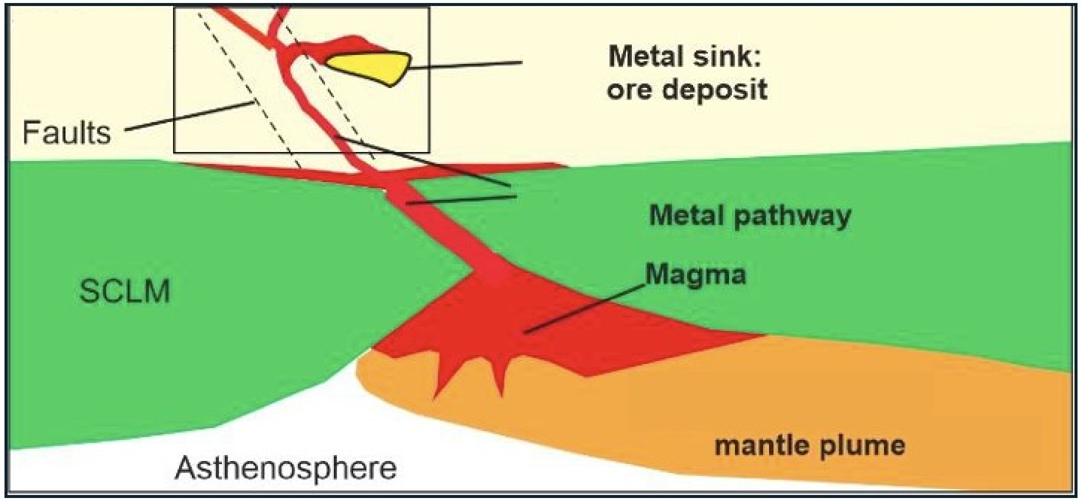
- ❑ Introduction and motivation
- ❑ Coda wave interferometry
- ❑ Passive sesimc experiment in Akanvaara deposit in Northern Finland
- ❑ Simulation of coda wave scattering in mineralised zones of Akanvaara deposit
- ❑ Data procesing and inversion results
- ❑ Conclusions

Motivation

Ore deposits exploration is a difficult task for ground surface, controlled source seismic methods mainly because of their shapes (near-vertical intrusions) and poor seismic reflectivity.

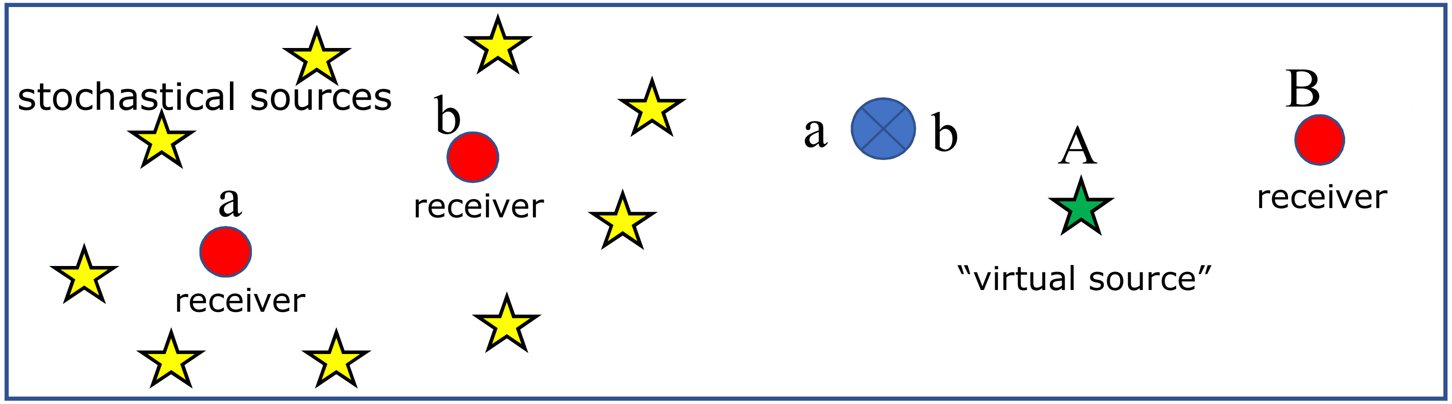
One of the ways to study orebodies by seismic methods is vertical seismic profiling, but drilling is required for this.

Using controlled source seismic methods is diffcult or impossible in naturally protected and hard to reach areas.



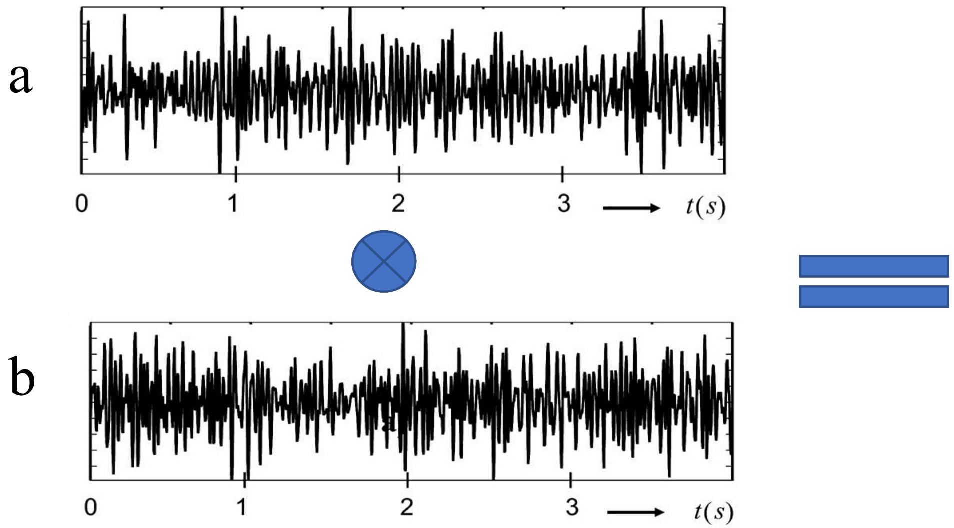
www.semacret.eu

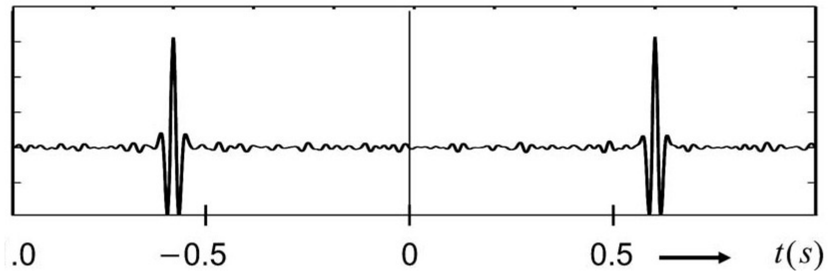
Ambient noise seismic interferometry



Passive ambient noise seismic interferometry is one of the passive seismic methods, which allows to convert ambient seismic noise into an impulse response of the studied medium

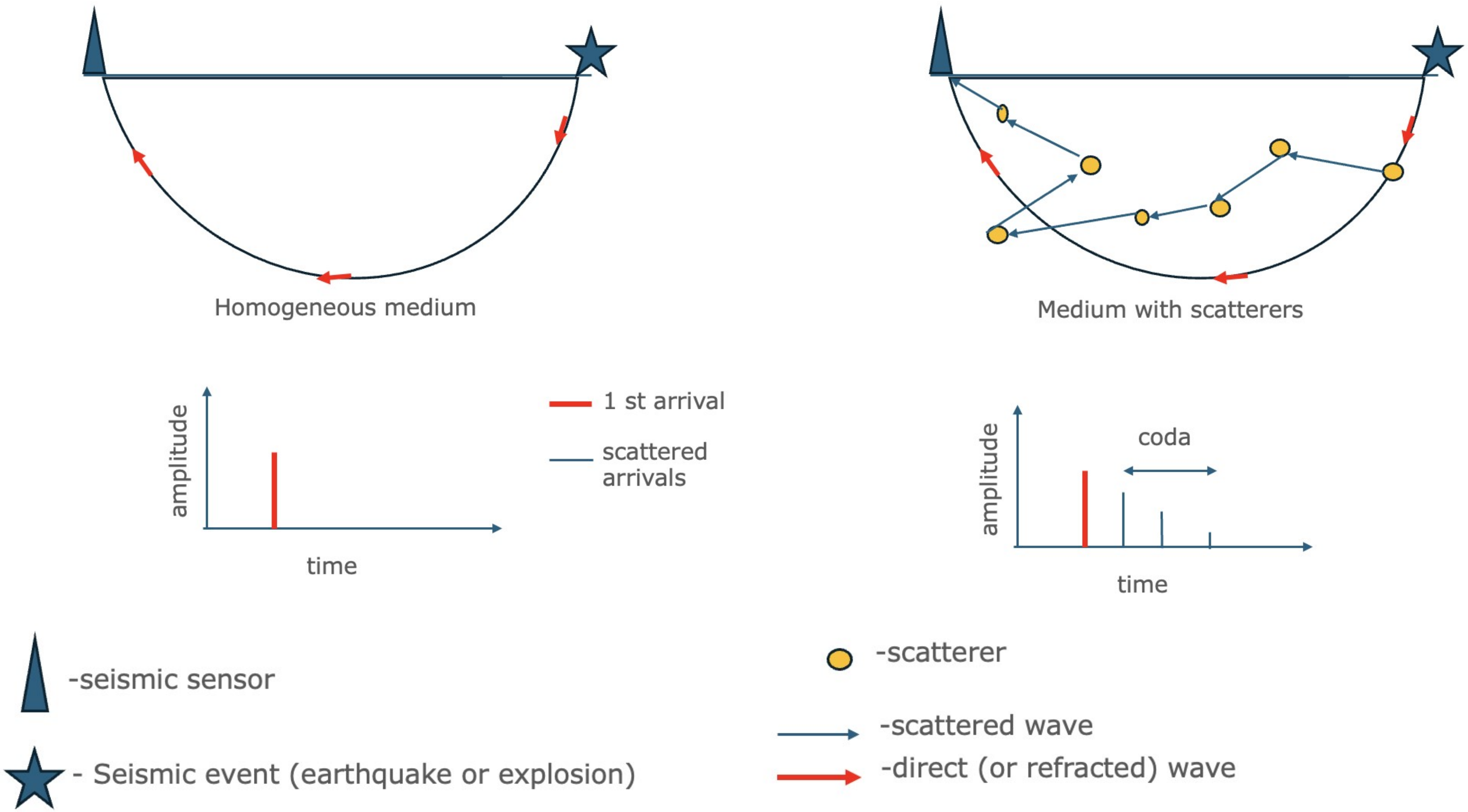
Difficult to use in remote quiet areas; Low resolution in near-surface studies (surface waves)=> difficult to use for ore deposit exploration



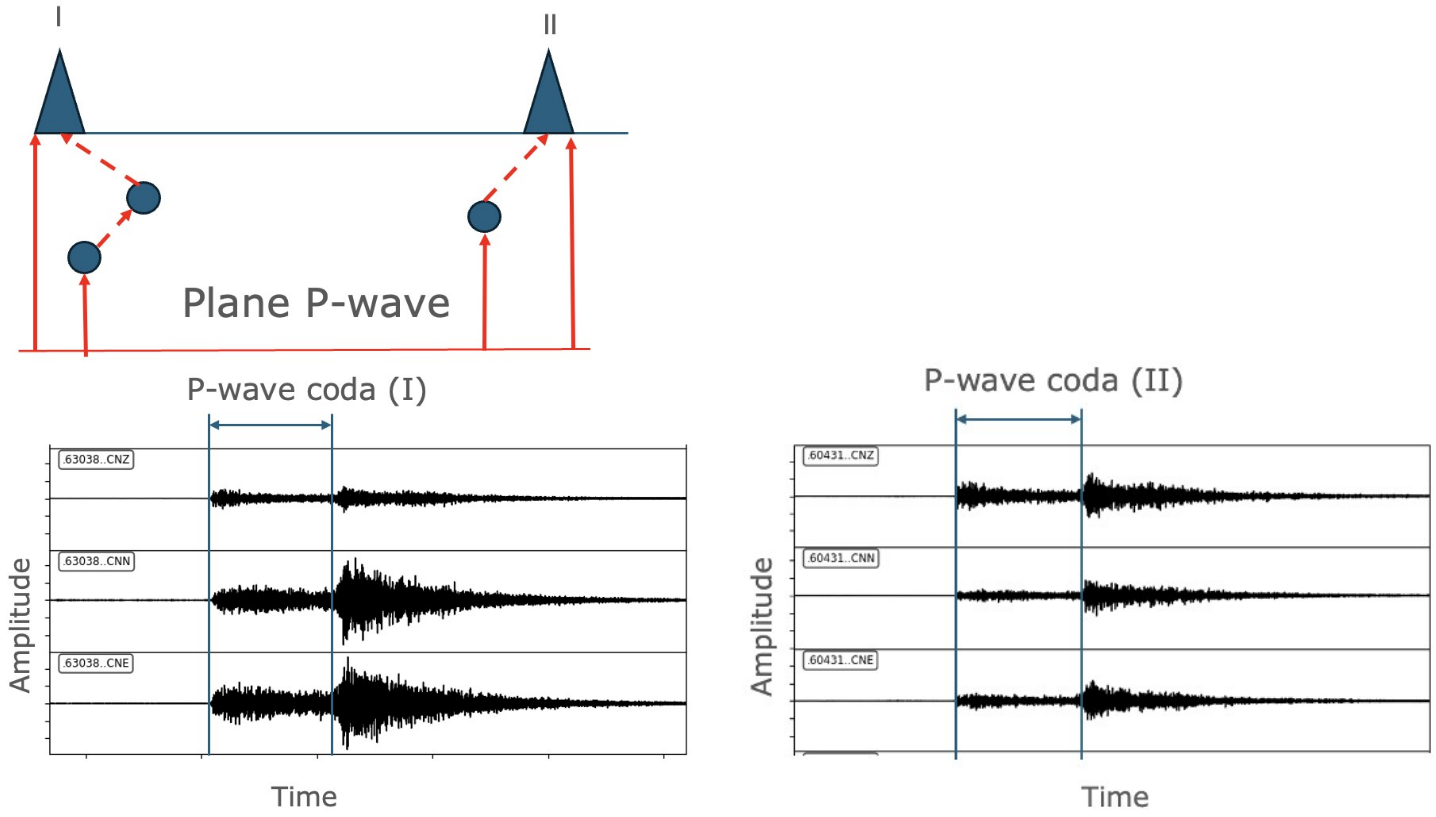


cross-correlation function (empirical Green's function)

Coda wave seismic interferometry

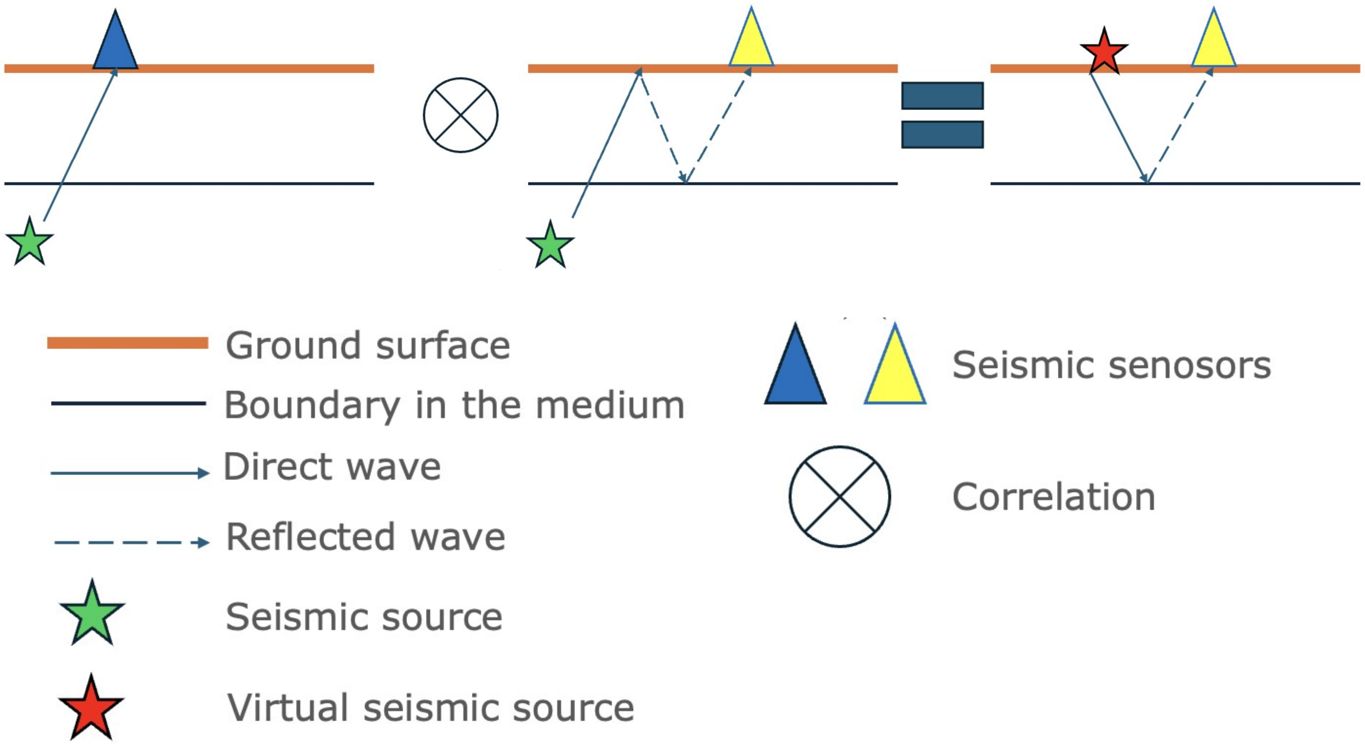


P-wave coda contains information about scatterers (features of local geological medium)=> it can be used to study inner structure of this medium



Interferometric redatuming

This is a way to convert seismic coda into impilse response of the medium to the virtual source, placed on the ground surface using correlation of the coda (Clearboiut, 1968; Shuster, 2004)



Empirical Green's tensor

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$$C_{ij}(\vec{r},\tau) = \int_{-t}^{t} f_i(\vec{r},t) f_j(\vec{r},t-\tau)dt \approx (G_{ij}(\vec{r},\tau) + G_{ij}(\vec{r},-\tau))$$

$C_{ij}(\vec{r},\tau)$ - correlation function , calculated between i and j components of the coda, recorded at point $\vec{r}$

$f_i(\vec{r},t), f_j(\vec{r},t)$ - components of seismograms, recorded at point

$G_{ij}(\vec{r},\tau)$

$$G_{ij} = \begin{pmatrix} G_{zz} & G_{zr} & G_{zt} \\ G_{rz} & G_{rr} & G_{rt} \\ G_{tz} & G_{tr} & G_{tt} \end{pmatrix}$$

G - converted PS, SP, or SS arrivals

G - reflected P and S arrivals

z, r, t – vertical, radial and transverse seismogram components

Passive seismic experiment in Akanvaara V-Cr-PGE deposit in Northern Finland

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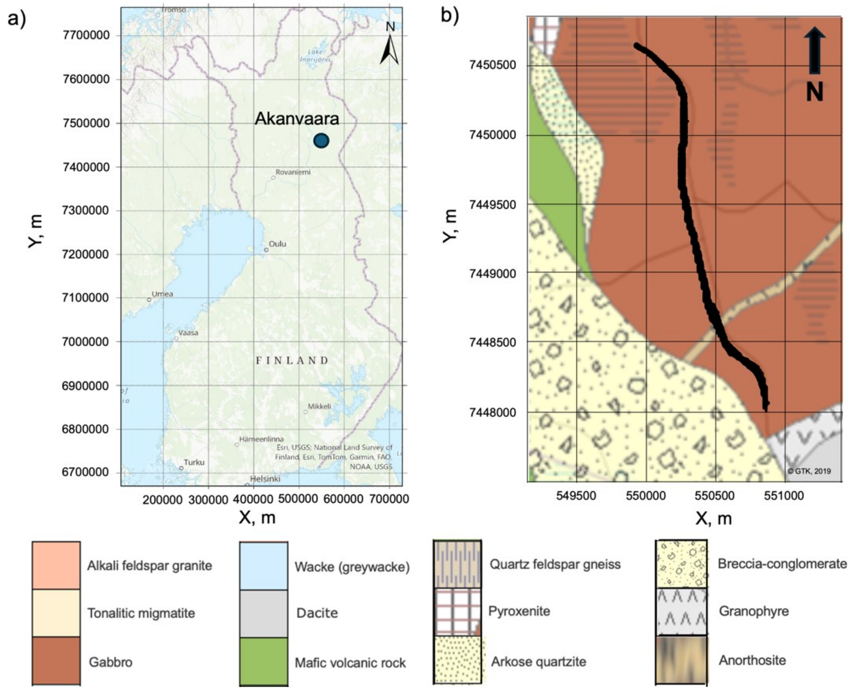
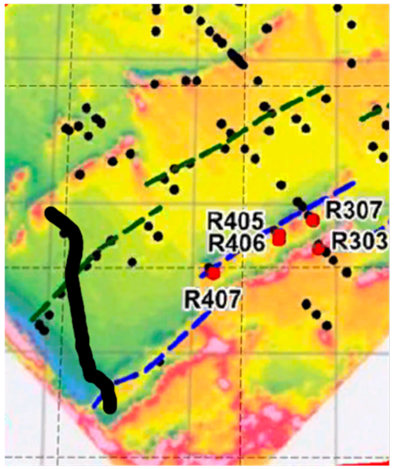
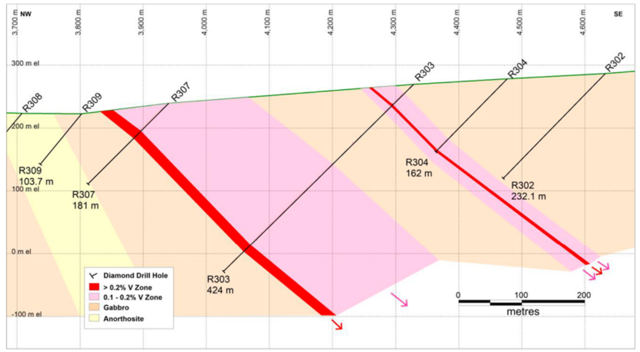


Studied area: a) on geographical map; b) Akanvaara seismic profile on bedrock map. (coordinate system is ETRS 1989 TM35FIN NE. X axis means easting, Y axis means northing)





Drilling, Mineralized Targets, Total Magnetic Field (adopted with modifications from Lutynski, 2019):

green dashed line – upper chromite vanadium target;
blue dashed line – magnetite gabbro vanadium target;
red and black circles – drill holes; black curve – passive seismic profile.

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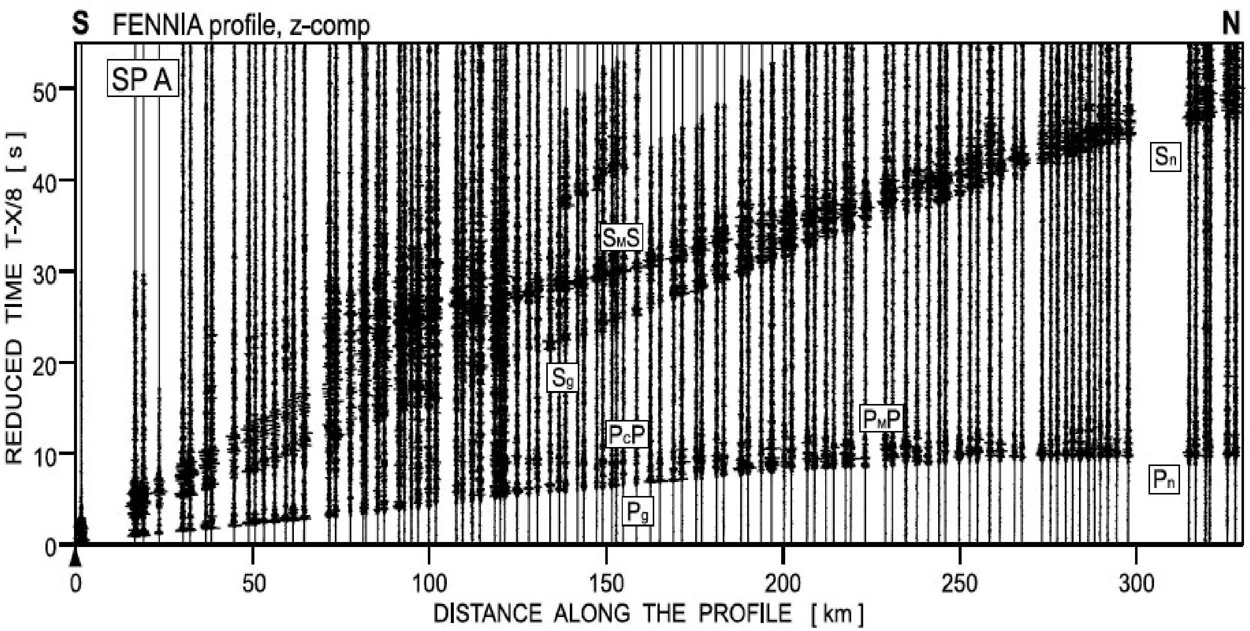
- We installed 606 seismometers (GEOSPACE LTD. USA) from the FINNSIP Finnish National Pool of mobile seismic instrumentation.

- Space between sensors - 5m

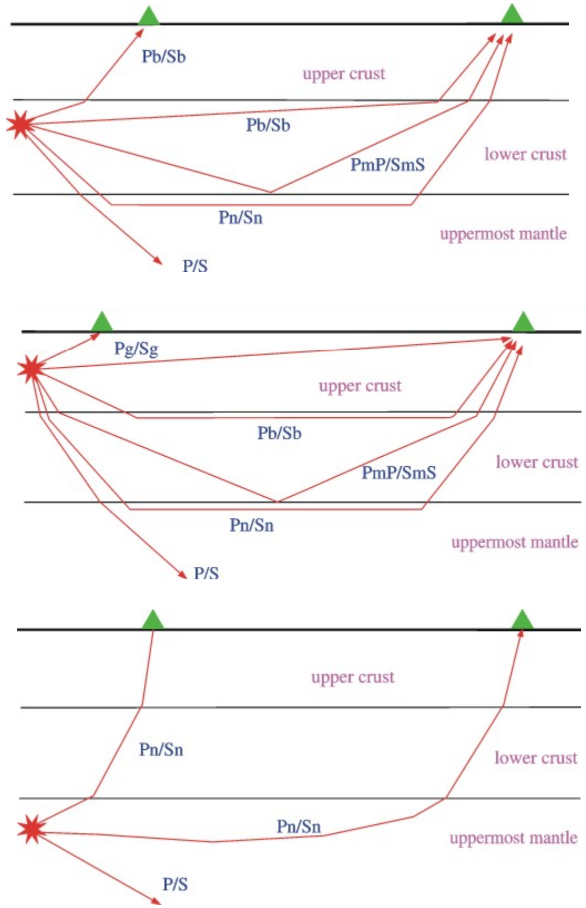
- They recorded continuous seismic data from 2.11.2023 to 9.12.2023 with a sampling frequency of 500 Hz

Data processing

Ray traces of the main crustal phases that are observed at local and regional distances from seismic sources in a simple two-layered model of the Earth's crust (Schweitzer, 2002)



Seismic record section
(example from FENNIA profile in southern Finland (Janik et. al., 2007))



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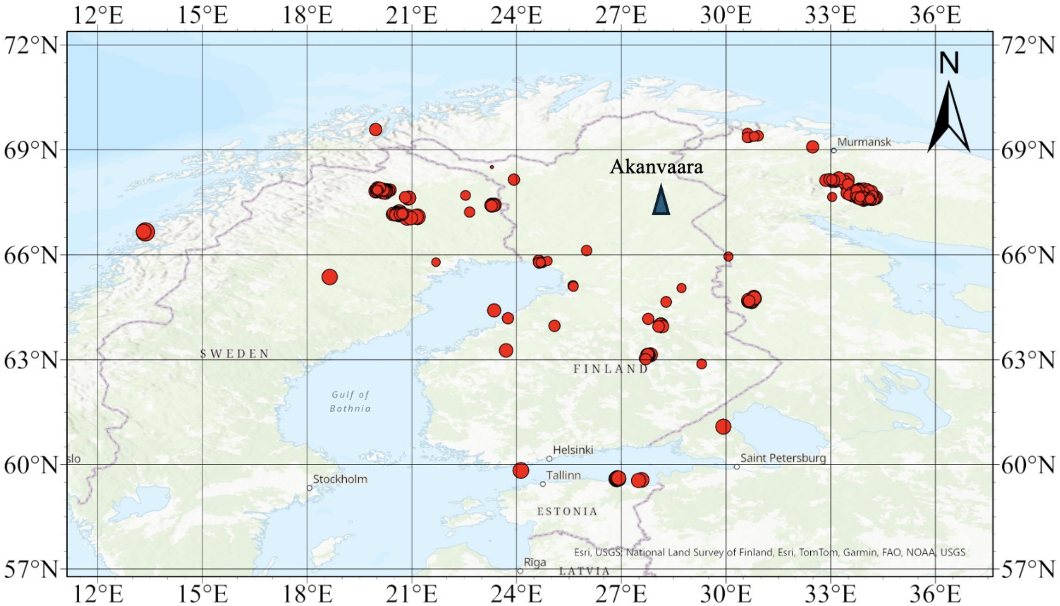
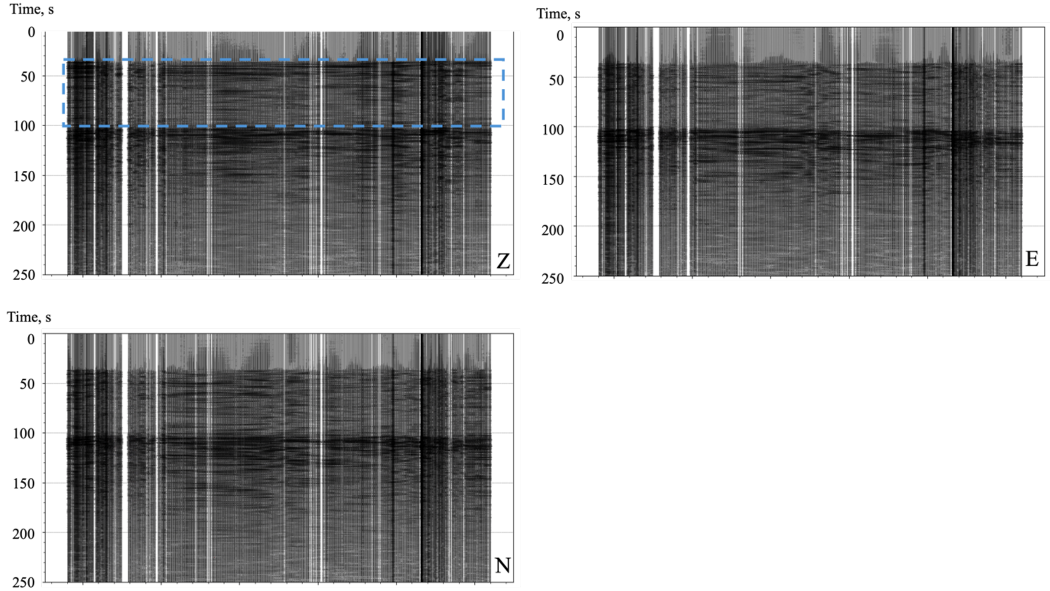


From the regional seismic catalogue (www.helsinki.fi) we selected the P-wave coda of 363 seismic events (both earthquakes and production blasts) originating at epicentral distances of 250-800 km from Akanvaara to evaluate body wave part of empirical Green’s tensor.

1. Prefiltering by bandpass filter of 10-15 Hz
2. Selecting P-wave coda
3. One bit normalization
4. Calculation of correlation functions for all possible pairs of seismic channels (vertical, radial and transverse)



Empirical Green's tensor

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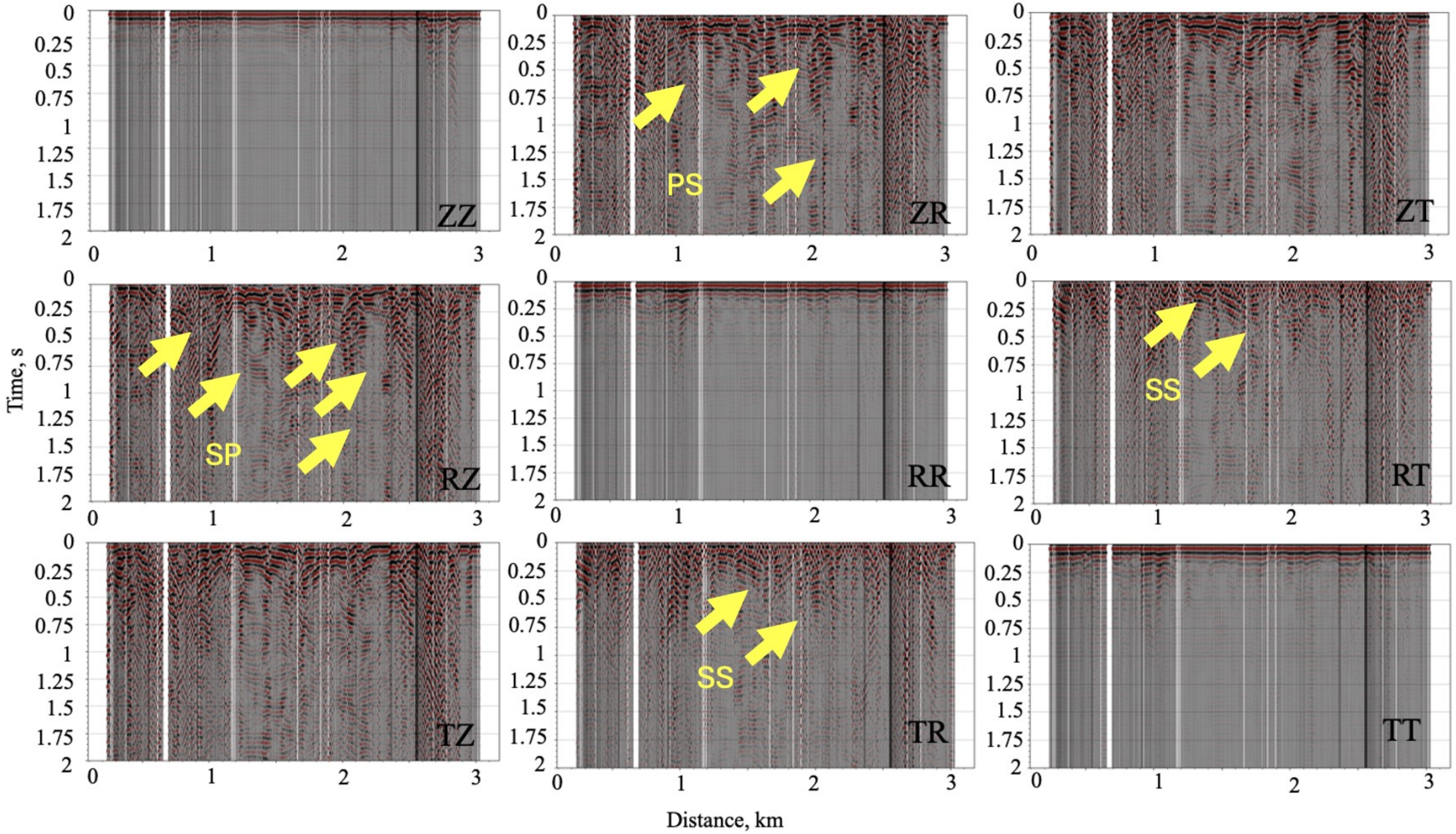

Simulation of coda wave scattering in Akanvaara mineralized zones

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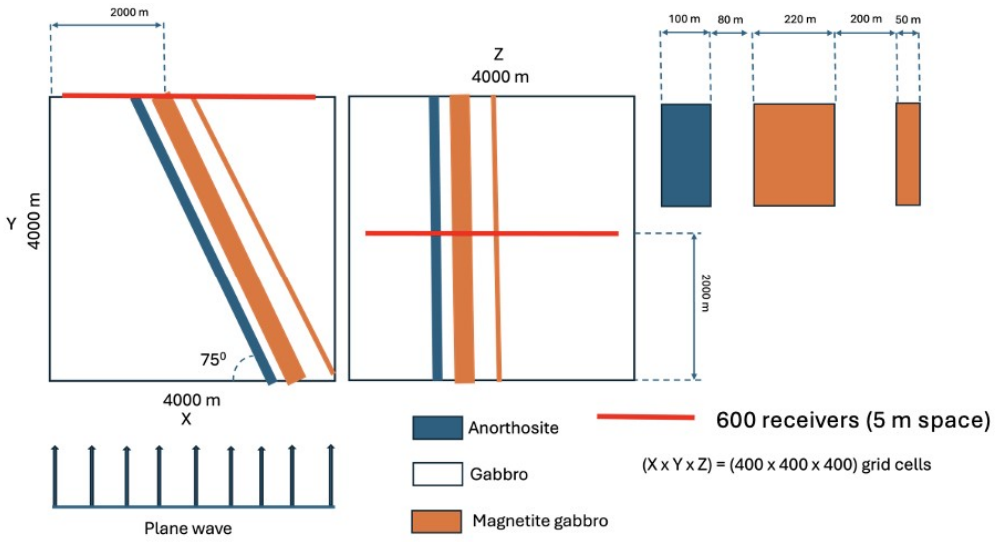
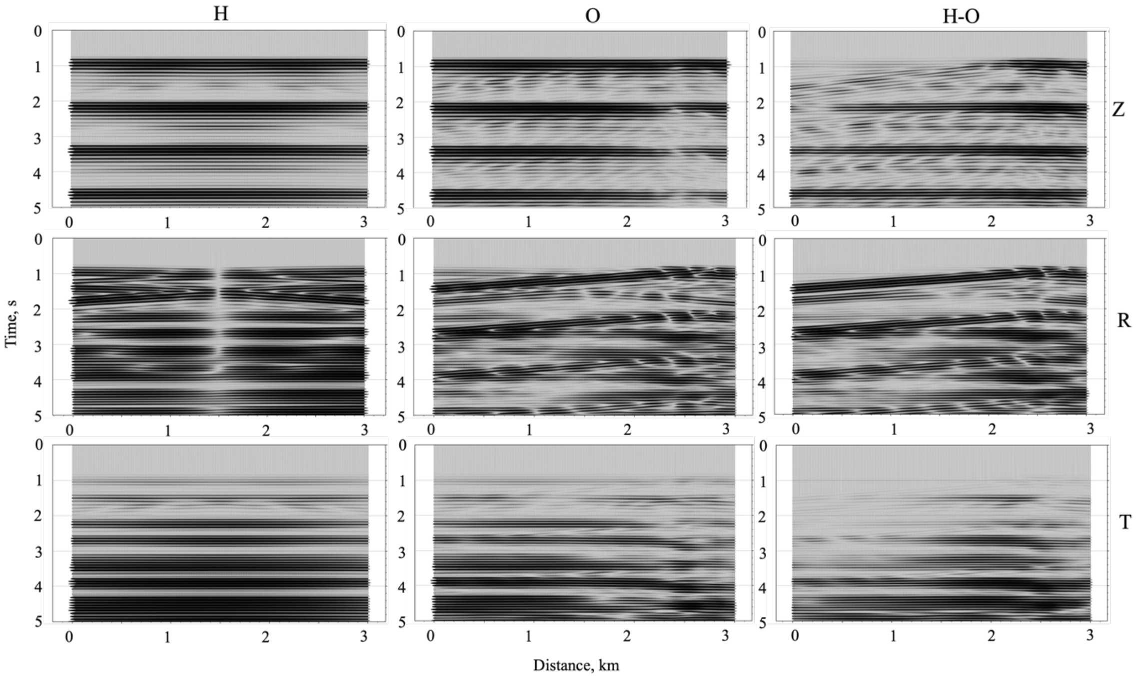


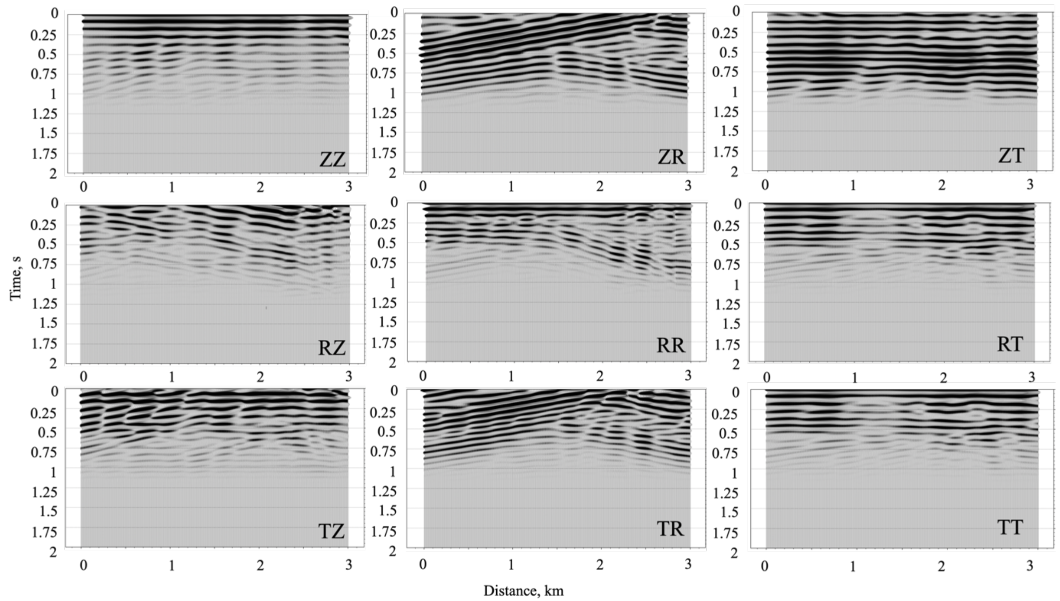
We used SOFI3D (Bohlen, 2002) software and the Centre of Scientific Computing infrastructure (csc.fi) to calculate sythetic seismograms

As sources, we used P and S plane waves, arrived vertically from the models bottom to surface.

Task	Sub task	Source type	Mechanical properties of layers ((Schön, 2015, Dortman, 1994)								
			Anorthosite			Gabbro			Magnetite gabbro		
			Vp, m/s	Vs, m/s	Rho, kg/m³	Vp, m/s	Vs, m/s	Rho, m/s	Vp, m/s	Vs, m/s	Rho, m/s
1	1.1	P	6100	3450	2680	6450	3550	2950	6750	3175	2980
	1.2	S									
2	2.1	P	5500	3400	2630	6800	4100	3050	6100	2700	2970
	2.2	S									
3	3.1	P	5500	3400	2630	6800	4100	3050	7400	3650	2990
	3.2	S									
4	4.1	P	6700	3500	2730	6800	4100	3050	6100	2700	2970
	4.2	S									
5	5.1	P	6700	3500	2730	6800	4100	3050	7400	3650	2990
	5.2	S									



We calculated correlation functions for all possible pairs of synthetic seismic channels to get synthetic Green's tensor



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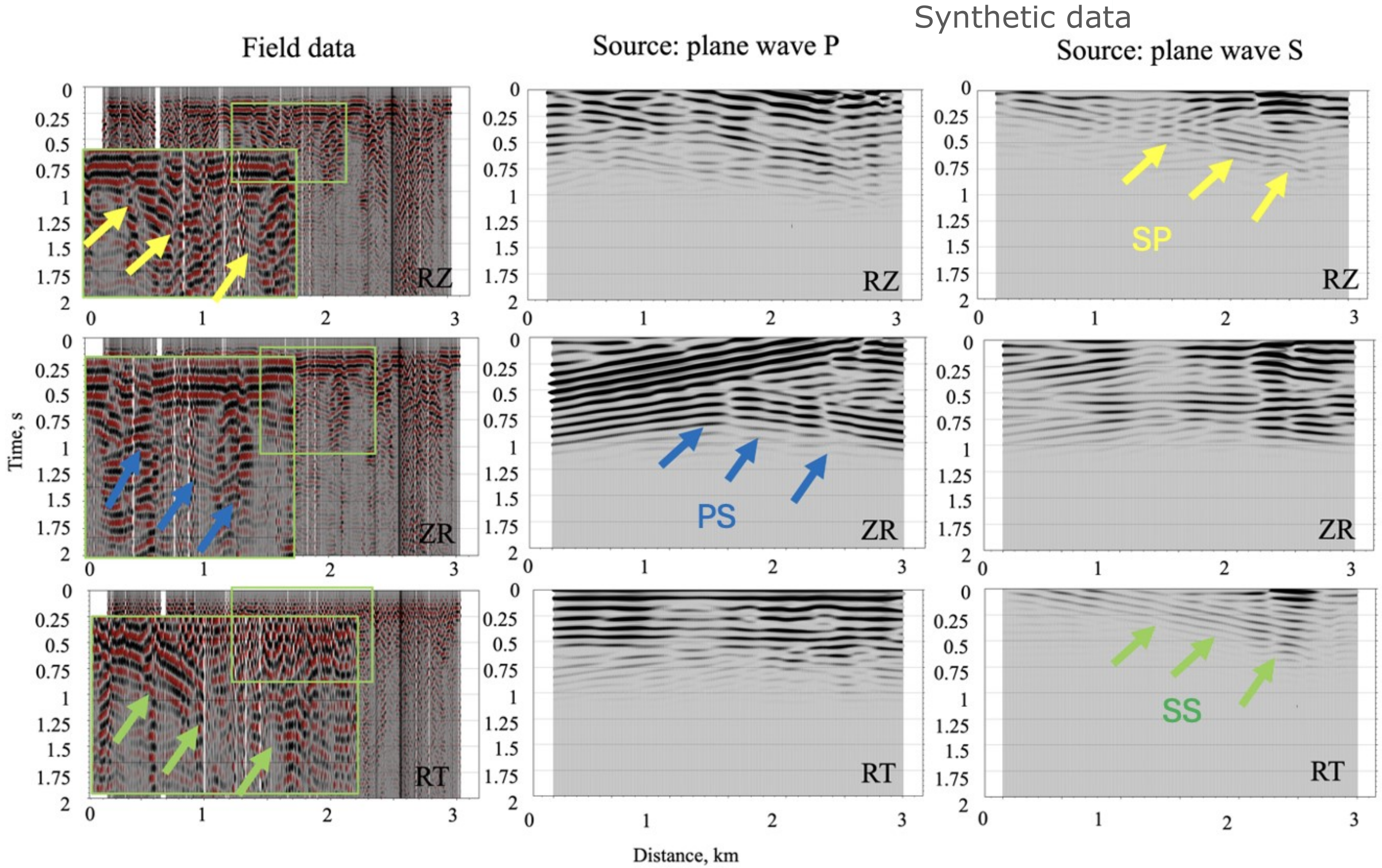
Comparison of empirical and synthetic Green's tensors



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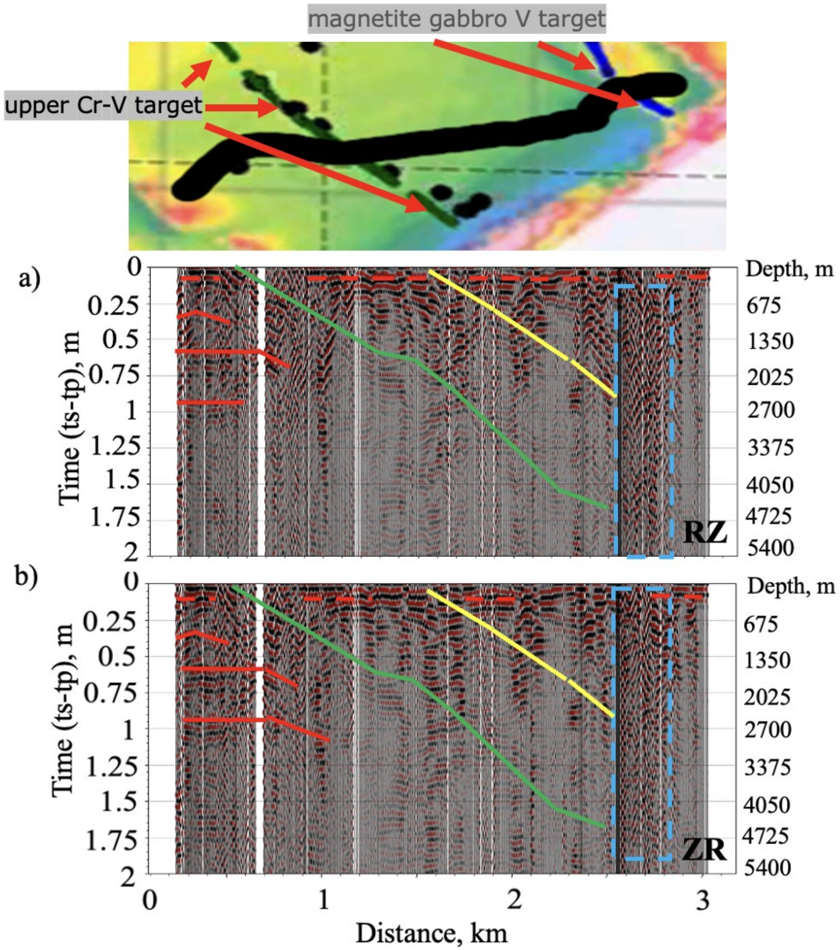
Interpretation of the converted arrivals



$$H = (V_P - V_S) * t_{ps}$$

H – depth;

Vp – P-wave velocity (6800 m/s)

Vs – S-wave velocity (4100 m/s)

(green line) – converted arrivals (probably gabbro and anorthozite contact);

(yellow line) – converted arrivals from Cr-V mineralization zone;

(red dashed line) - converted waves, originated at the boundary between mafic and ultramafic rocks at the depth of 350 m)

(blue dashed line) - fault zone;

(red line) - converted arrivals originated on unidentified boundaries

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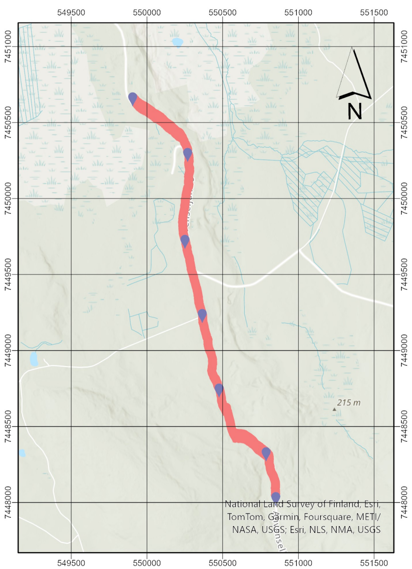
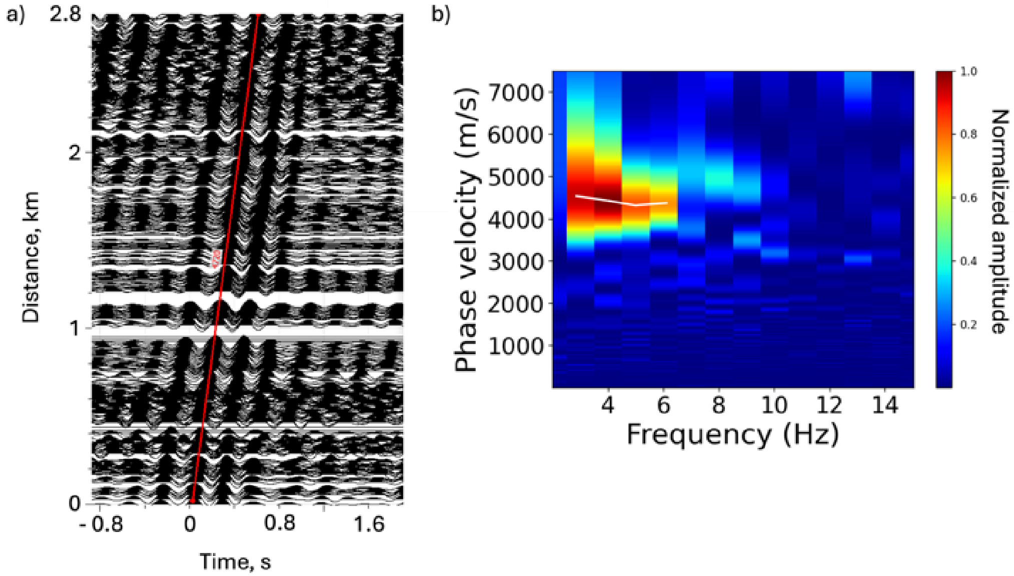
Surface waves analysis

1. We selected coda of 30 surface waves arrived in-line with our profile
2. We applied bandpass filter 2-20 Hz to selected parts of reords and one bit normalization
3. We calculated cross-correlation functions between virtual sources and recivers
4. We used MASW method to obtain dispersion curves from cross-corelation functions



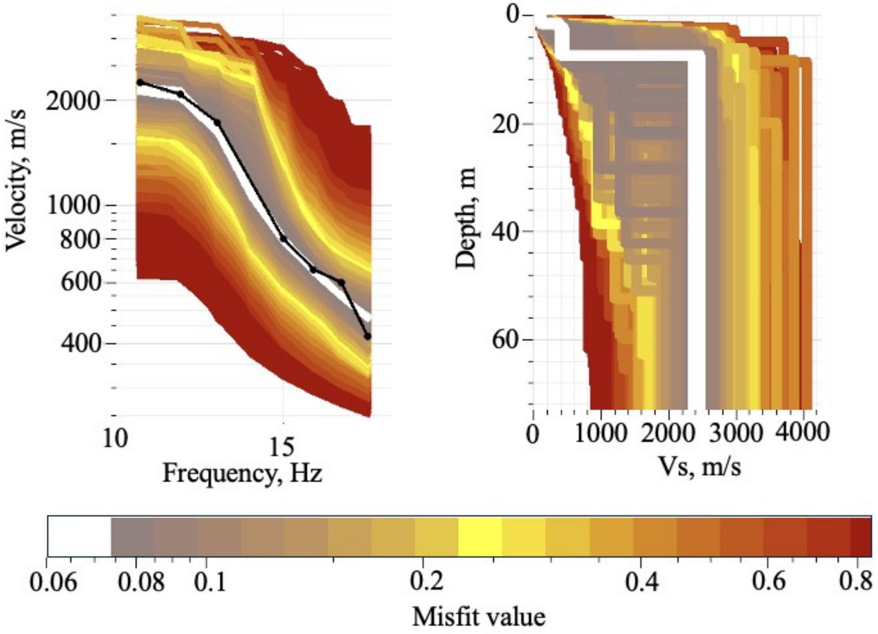
- seismic profile

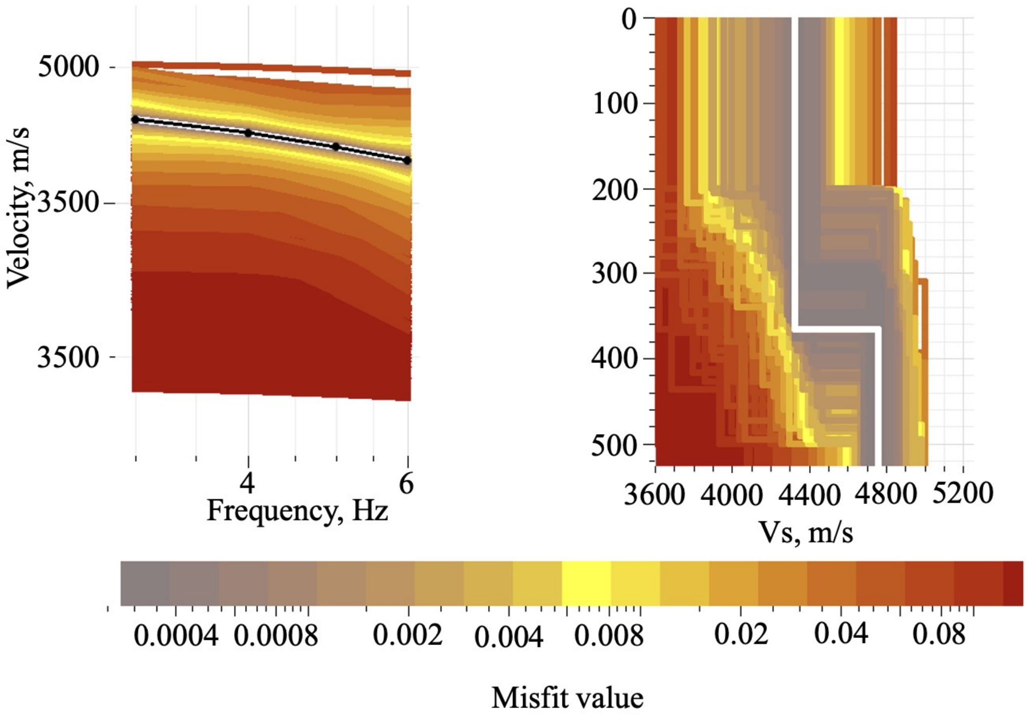
- virtual sources



a) cross-correlation functions
b) Phase velocity-frequency spectra of cross-correlation functions

Dispersion curve inversion

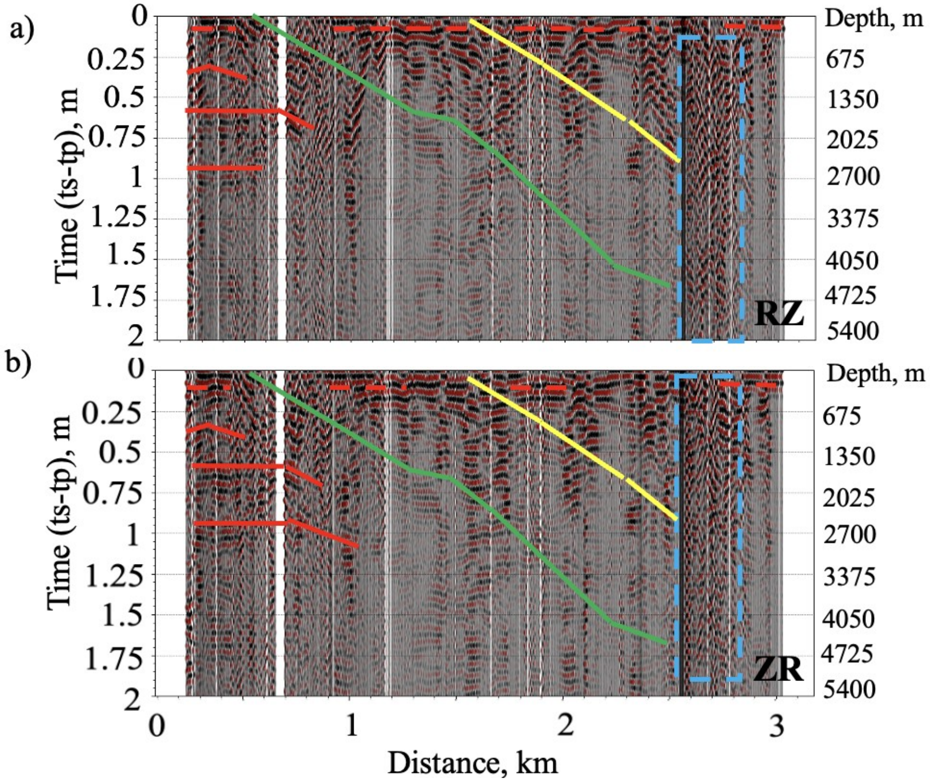


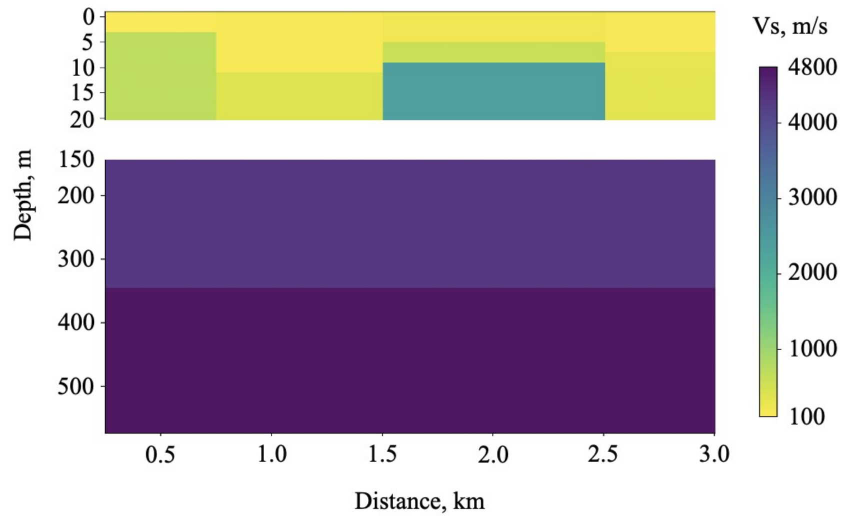


High frequencies
(near surface parts)
White line – S-wave velocity model with minimum misfit

Low frequencies
(deeper interior)

Results





2D S-wave velocity model of the medium along the profile, obtained by dispersion curves inversion

– converted arrivals (probably gabbro and anorthozite contact);

– converted arrivals from Cr-V mineralization zone;

- converted waves, originated at the boundary between mafic and ultramafic rocks at the depth of 350 m)

- fault zone;

- converted arrivals originated on unidentified boundaries

Conclusions

1. Numerical simulation and data processing results show that converted arrivals can be obtained by correlation of P wave coda of regional seismic events and used to deliniate boundaries inside the Akanvaara intrusion;
2. Surface wave coda wave interferomerty allowed us to obtain S-wave velocities of Akanvaara Cr-V-PGE deposit in Northern Finland from ground surface down to 500 m. The velocities agree with petrophysical a-priory information

4. Converted arrivals, originated at Cr-V mineralization zone are traceble to depths of 2500-2700 m.
5. Converted arrivals from lithological contact inside the intrusion (gabbro and anorthosite) is traceble to depths of 4000-4700 m.
6. The method, presented in current study is cost effective and environmently friendly comparing to controlled source seismic methods, and can be considered as an alternative, more effective tool for brownfield exploration of ore deposits.

Acknowledgements

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Thank you for your attention!