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# Surface Wave Analysis from Mineral Exploration: a 3D Example from Eastern Finland

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## Summary

We present a feasibility study for surface wave tomography for mineral exploration. We apply a typical seismological approach, the Two Station Method to a hard-rock site, at exploration scale. Even with this method, we are able to separate the two propagation modes typical of these sites. After windowing the traces by picking one propagation mode in the group velocity matrix, we pick the phase velocity dispersion curve in the cross-multiplication matrix. We finally propose a plot consisting of slices of tomographic pseudo volumes, which allows us to understand the penetration depth we can have. Furthermore, it gives us a first indication of the velocity anomalies in the area.

## Introduction

In the past decade, seismic exploration methods have been gaining popularity for mineral exploration purposes. In fact, reflection seismic imaging has been proven to be a valuable tool to identify mineralized horizons, both in the shallow and deep subsurface (e.g. Malehmir et al., 2012). More recently, Papadopoulou et al. (2018) proposed inversion of surface waves as a possible method to compute static corrections, with promising results. In their work, complexity of surface-wave analysis in hard-rock settings was scrutinized. The presence of a thin, low-velocity overburden on top of a fast bedrock produces two main modes of propagation. The first, contains information about the shallow low-velocity layer and the second, faster, and poorly dispersive event, provides information about the S-wave velocity of the underlying bedrock. It is therefore of vital importance to identify and separate these propagation modes. In this work, we want to assess the feasibility of surface-wave tomography on such datasets. In particular, we show whether it is possible to see the two separate propagation modes with a Two-Station Method and whether the wavelengths (i.e. penetration depth) we can extract are adequate.

We present some field data, part of a larger dataset, acquired in September-October 2018, at the Yara-owned Siilinjärvi phosphate mine in Eastern Finland. The area has also been subject of previous geophysical studies (e.g., Malehmir et al., 2017), however, these were mainly focused on the open-pit area. In this work, we investigate the forest south of the main pit, which has a high exploration potential. The final aim of the survey is to map the southern extension of the mineralised system both laterally and in depth.

## Method

The Two-Station Method we use was implemented by Boiero (2009), following the method shown by Yao et al. (2006). The procedure involves essentially three steps. Firstly, we identify couples of receivers which are in-line with each shot with a tolerance of 1 degree. After this, by means of a multiple, narrow gaussian filter, the group velocity envelope per frequency is computed. This generates an amplitude matrix where it is possible to identify and pick a propagation mode. Based on the picking, the traces are then windowed in order to isolate the selected mode. The cross-multiplication matrix per frequency is then computed. The time lags are converted to phase velocity with an interpolator as in Yao et al. (2006).

## Field Data Example

The dataset consists of an array of approximately 600 receivers, recording continuously for 13 days. During the acquisition, several controlled shots were recorded for distinct 2D profiles. As a first processing step, we focus on these recorded active shots on a portion of the dataset. This consists of an array of 240 wireless stations using 10 Hz natural-frequency geophones positioned in a random-like fashion. The reason for this was to maximise azimuthal coverage and path length distribution, while minimising the number of used receivers. Furthermore, the terrain in the forest is challenging to walk in and receivers were therefore deployed in the logistically most accessible positions. The receivers had to also be located max 50 m away from each other to be able to communicate (due to telemetry communication of the receivers).

The explosive sources consisted of 250 g of dynamite, fired at 3 m deep boreholes, except for four shots deep in the forest, where it was not possible to drill, and the explosives were placed in very shallow (~0.5 m) hand-made holes. Sampling rate was set to 2 ms and 2.4 s long windows were extracted per each shot. Figure 1 shows the geometry of the acquisition.

The surface waves present similar propagation characteristics to those shown in Papadopuoulu et al. (2018). Even with our Two-Station Method, which could produce only apparent curves, the two events are evidently separated and the traces can therefore be windowed to pick a single propagation mode. The first, slower, event propagates in a shallow, thin soil layer and shows velocities of around 500 m/s. The second, faster, event exhibits velocities of around 2000 m/s, and carries information about the bedrock. We would like to remark that the two modes are not always visible in the data and the slower event appears stronger if the source is fired in a shallower borehole and the receivers are in the near-offset range, while at larger offsets and with deeper explosions the faster event prevails. An example of the processing steps where both propagation modes are visible is shown in Figure 2.

We picked 219 curves, selecting a set of paths that optimise both azimuthal and wavelength coverage. We only pick the faster propagation mode, since the mineralised ore body lies in the bedrock. The picked curves and the coverage are shown in Figure 3.

We then carried out an analysis of the available penetration depth in a pseudo-volume fashion. We call these plots "Tomographic Pseudo Slices" and they consist of a plot of the paths available inside a certain wavelength interval coloured with the phase velocity at that wavelength. Thanks to this plot, we can assess the penetration depth of the dataset, check the accuracy of the picking and find outliers, but also identify the main velocity variations in the volume. Examples of these plots can be seen in Figure 4. We see how the coverage is excellent until wavelengths of 450 m and the data also contain several curves with wavelength exceeding 500 m. Furthermore, we can already assess the presence of a low-velocity zone in the north-eastern part of the area (highlighted with a red rectangle) and a higher velocity zone in the south-west (highlighted with a black rectangle). The phase velocity values are in agreement with information from boreholes in the area.

## Conclusions

We took a typical seismological approach, the Two-Station Method, and applied it at exploration scale in a mining site. First, we observe that the two propagation modes, typical of these sites, are visible, and therefore can be isolated. This is a relevant result, since the Two-Station Method could have only shown one effective dispersion curve and therefore not give information for our purposes. We then extracted 219 dispersion curves and proposed a plot, which we call "Tomographic Pseudo Slices" thanks to which we are able to identify the main velocity variations in the volume and assess the penetration depth of our data. The wavelengths are encouraging, with excellent coverage until 450 m and several paths exceeding 500 m. The present active data will be complemented with passive data recorded at the site with the aim of increasing the penetration depth and inverted with a surface wave tomography inversion code (Boiero, 2009). We conclude that surface-wave tomography can be a tool to explore hard-rock sites and therefore also for mineral exploration.

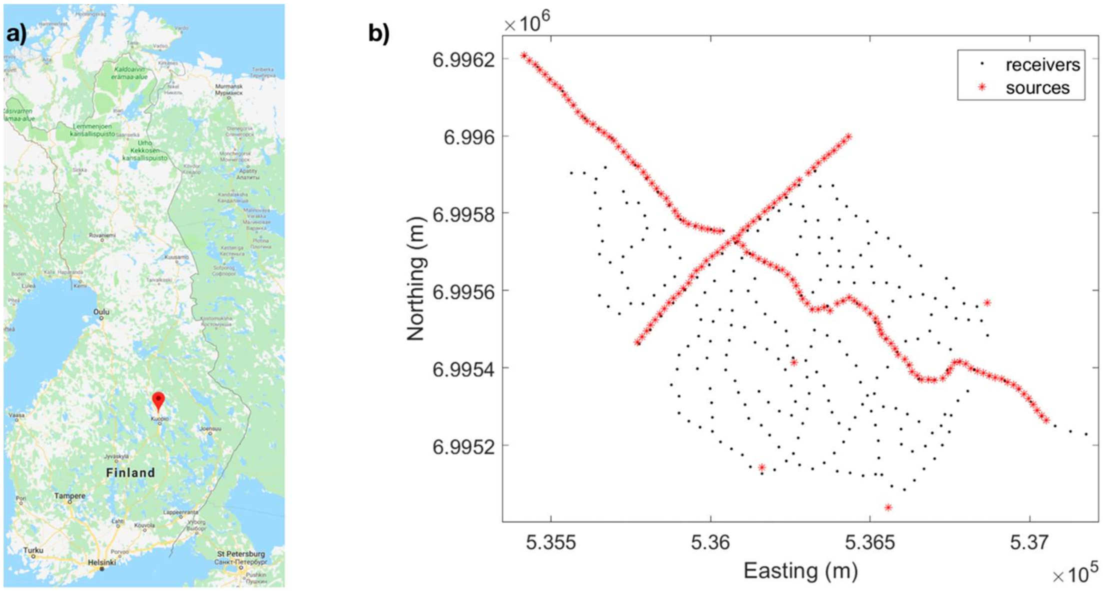

***Figure 1*** *a) Map of Finland showing the location of the Siilinjärvi mining site. b) Geometry of the survey.*

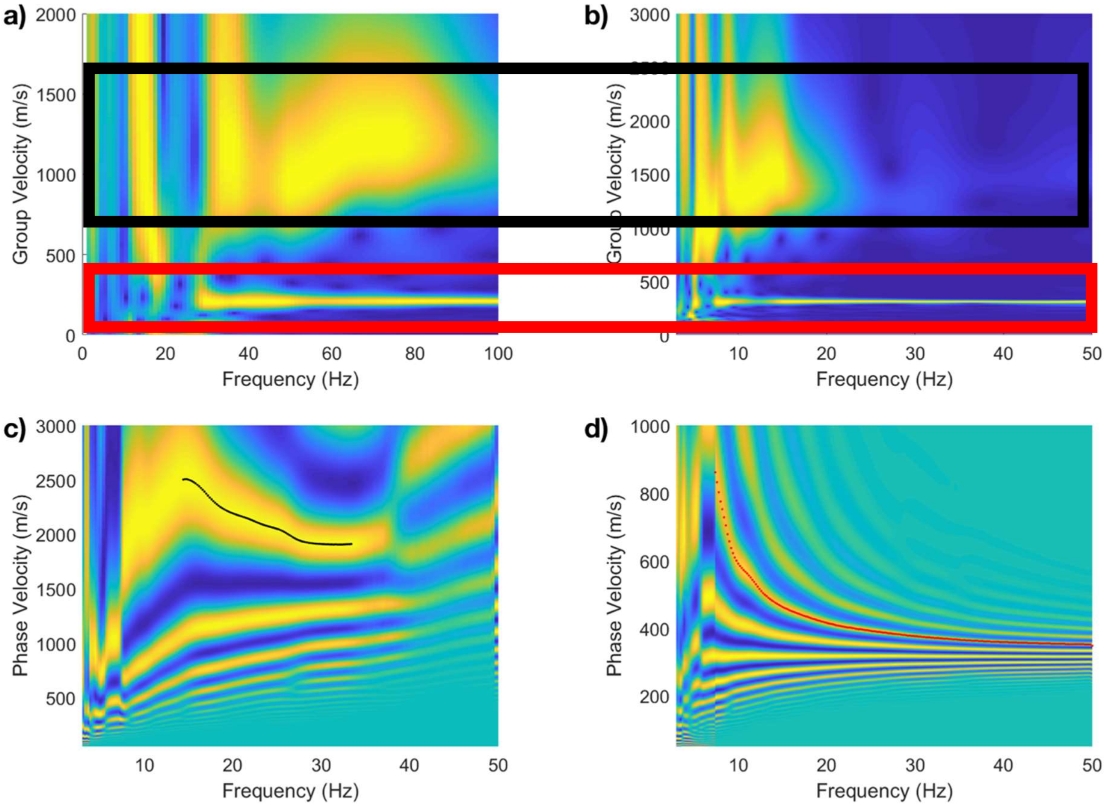

***Figure 2*** *Group velocity matrix for a) the first trace and b) the second trace. The "fast" and "slow" event are quite visible and highlighted with a black and red rectangle respectively. Phase velocity cross-multiplication matrix after windowing for c) the "fast" event and d) the "slow" event. The windowing allowed to pick successfully both propagation modes.*

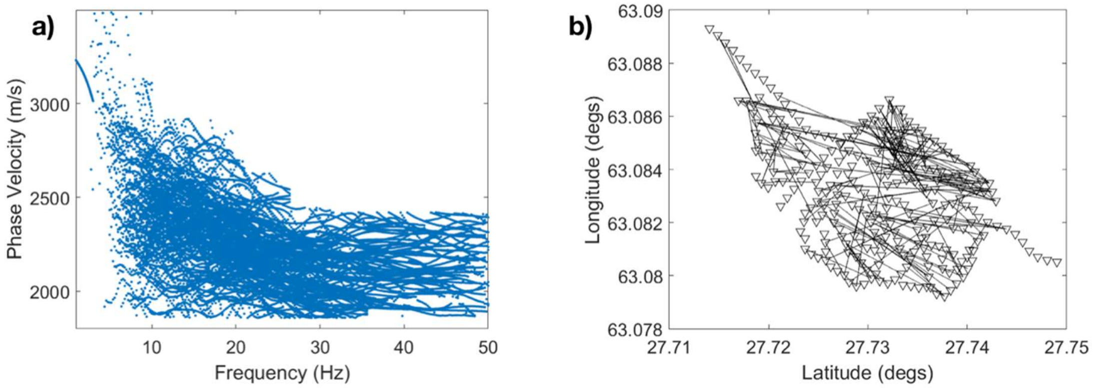

***Figure 3*** *a) Plot of the 219 picked dispersion curves. We picked the "fast" event, since the mineralisation lies in the bedrock. b) Plot of the paths along which the curves have been computed.*

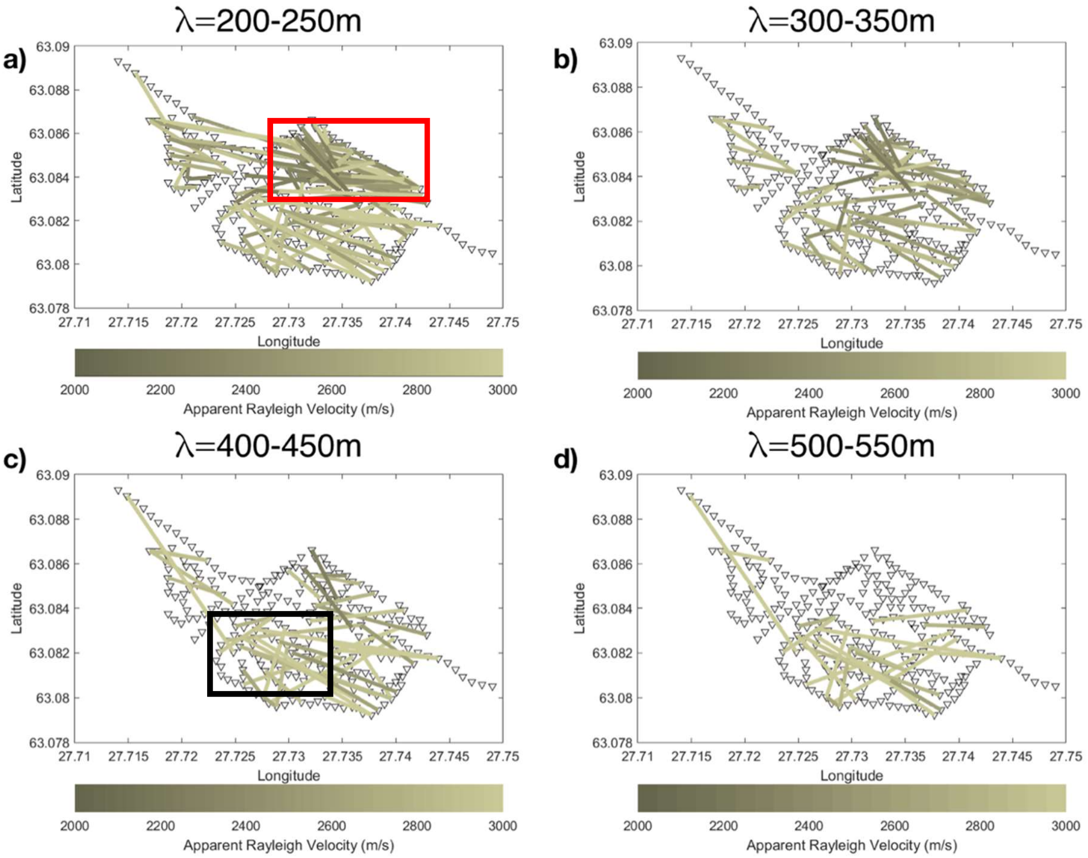

***Figure 4*** *"Tomographic Pseudo Slices" at wavelengths of a) 200-250 m, b) 300-350 m, c) 400-450 m, d) 500-550 m. Coverage is excellent until 450 m wavelength; some longer paths also provide even higher wavelength (>500 m). We notice a lower velocity zone in the north-eastern part of the array (red rectangle) and a possible higher velocity zone in the south-west (black rectangle).*

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