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EXTRACTION OF SURFACE-WAVE DISPERSION CURVES FROM AMBIENT NOISE DATA IN A MINERAL EXPLORATION SITE IN FINLAND

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Summary

We propose a workflow to obtain the path-average dispersion curves, which are the input of SW tomography, from 3D ambient noise records. The workflow starts with a pre-processing step, which separates the time windows at which significant surface-wave energy has been recorded and sorts them, based on the azimuthal direction of the SW origin. For each direction, aligned pairs of receivers are found and the path-average dispersion curves are extracted for each pair. The availability of long records allows stacking, improving the data quality. We applied the proposed workflow on a dataset recorded in 2018 in the Siilinjärvi mining site in Finland, with the purpose of increasing the knowledge of the extension of the phosphate mineralization. Comparison with active dispersion curves proves the reliability of our results and indicates that the passive data allow deeper investigation, increasing the possibility of mapping deeper mineralization targets.

Introduction

Surface-wave (SW) tomography has been widely used in global seismology to map subsurface structures, while, to a more limited extent, it has been applied also to hydrocarbon exploration (e.g., Socco et al., 2014). Recently, Hollis et al. (2018) and Papadopoulou et al. (2019) have shown the potential of using SW tomography in mineral exploration. Da Col et al. (2020) applied SW tomography to an active-source dataset acquired in 2018 at the Yara owned Siilinjärvi phosphate mine in Eastern Finland, with the purpose of investigating the depth and lateral extension of a mineralized ore body. They showed that the high data coverage achieved by the method provided a high-resolution shear-wave velocity model, to a maximum depth of 270 m. On the same acquisition campaign, also passive seismic data were recorded. Here, we propose a semi-automatic workflow to extract the path-average SW dispersion curves (DCs), used as input to SW tomography, from the passive dataset. We provide a comparison between the DCs retrieved from the active and the passive data and show that the passive ones carry information at lower frequencies, allowing deeper SW investigation.

Site description

The Siilinjärvi phosphorus mine (Figure 1a) has been exploiting alkaline carbonatite–glimmerite deposits since 1979. The main ore mineral is apatite contained in the carbonatite-glimmerite complex, while host rocks are granite and gneiss. The ore body is known to be approximately 1-km wide and 15-km long, extending down to 800-m depth, as shown by previous 2D active seismic prospections, geophysical downhole logs and laboratory analyses (Malehmir et al., 2017). New active and passive seismic data were acquired on site in 2018, with a 3D array of randomly-distributed stations. The seismic array consisted of 578 vertical geophones (10 Hz) connected to wireless stations, and almost continuously recorded for 13 days, from the 24th of September to the 6th of October. Passive data from all stations were recorded at 500 Hz and stored in 1-minute segy files. The deployment design was chosen to respect site and instrumentation logistical constraints and to optimize subsurface illumination (in terms of wavelength and azimuth coverage) in the areas of interest (Da Col et al., 2020). In Figure 1b, we divide sensor locations into three main areas, including the main pit, the gypsum pile and the forest. This last zone is an area of crucial importance for future mining activities, as it is known that the mineralized ore body extends at depth in this direction. In this work, we focus on the analysis of the passive data recorded by the 273 stations located in the forest area.

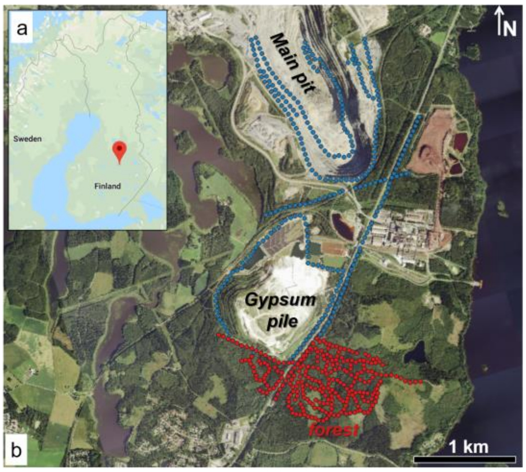

Figure 1 *a) Map of Finland showing the position of the Siilinjärvi mining site. b) Area of the 2018 survey. Red and blue dots indicate the positions of the geophones.*

Workflow

A semi-automatic workflow was designed for the analysis of the passive dataset. Each 1-minute segy file is windowed in 2s segments. On each segment, the Frequency Domain Beam Forming (FDBF) method (Zywicki, 1999) is applied to retrieve frequency-wavenumber power spectral density functions and identify dispersive events in the recordings and their propagation direction. The position of the amplitude maximum in the k_x-k_y planes at different frequencies provides the wavenumbers and azimuths of the dominant SWs propagating during that time window. Once the wavenumber is known, the phase-velocity (V_R) of the DC is retrieved as:

$$V_R = \frac{2\pi f}{|k|} \quad (1.1),$$

where the wavenumber modulus, $|k|$, is obtained as:

$$|k| = \sqrt{{k_x}^2 + {k_y}^2} \quad (1.2).$$

An example of the FDBF results is given in Figure 2. To evaluate their quality, DC points are compared with an a-priori defined "dispersion region" (red in Figure 2a), which in our case was available from Da Col et al. (2020). If a significant number of DC points are located within the "dispersion region", data quality is considered sufficient to continue the computations, otherwise, the time window is rejected. For the high-quality time windows, the maxima of the k_x-k_y planes are picked automatically (Figure 2b). For each peak, the azimuth is computed based on its location on the k_x-k_y planes (Figures 2d-2g). If the azimuth is consistent among the different frequencies (Figure 2c), the SW event is considered coherent and the time window is stored in a folder associated to that azimuth value. This pre-processing procedure is automatically repeated for all the available records.

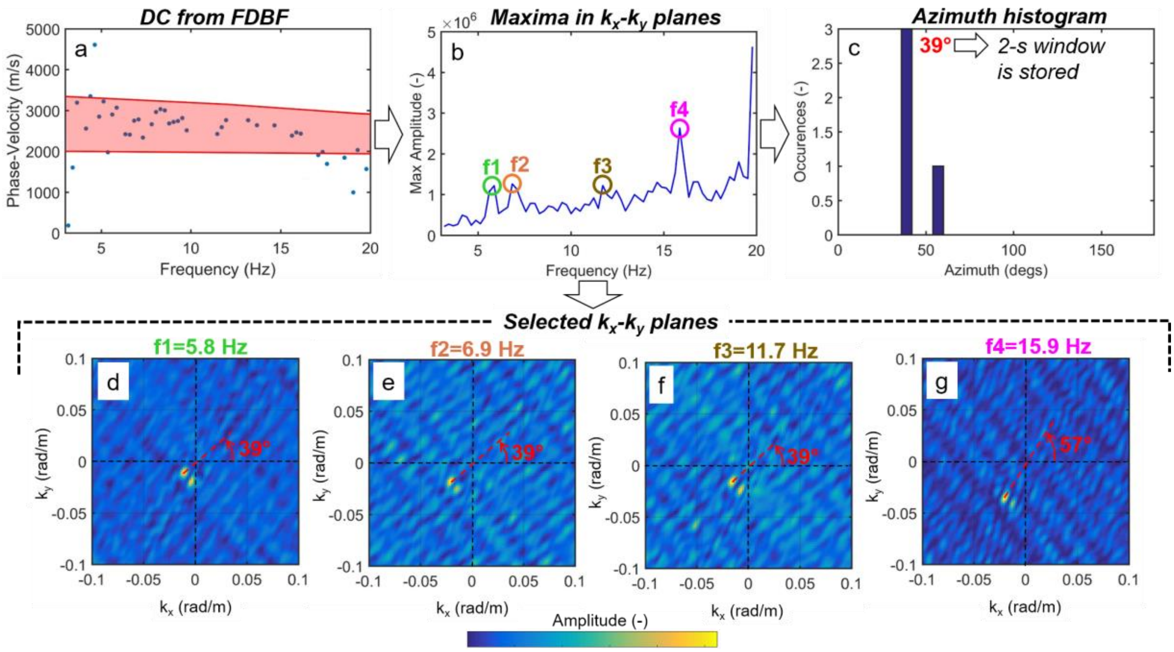

Figure 2 *DC from the FDBF method. The reference "dispersion region" is highlighted in red. b) Automatic picking of the maxima of the k_x-k_y planes, corresponding to different frequencies. c) Histogram of the azimuths of the peaks in b. d-g) k_x-k_y planes corresponding to the peak frequencies.*

For each azimuth, the receiver couples aligned at that specific azimuth are found. For each receiver couple, a modified version of the two-station method (Yao et al., 2006) is applied. The traces are cross-correlated frequency by frequency to extract cross-multiplication matrices. The procedure is repeated for all the available time windows at the same azimuth and the cross-multiplication matrices are stacked to increase the signal-to-noise ratio. DCs are finally extracted as the amplitude maxima of the stacked cross-multiplication matrices.

Results

A total number of 334880 2s time windows was extracted from the 13-day dataset. The FDBF method provided 25691 windows, containing strong SW signal, for which the azimuthal direction was estimated. The total number of occurrences compared with the number of 2s windows of each day is shown in Figure 3a, while the histogram of all the azimuth directions is reported in Figure 3b. It was found that more than 13000 events originated at an azimuth of around 39° (according to the reference system shown in Figure 3c), while a second cluster of around 7000 events is present between 51° and 57°. The occurrence peaks (Figure 3b) suggest that most of the events are located in the SW-NE direction. They are probably related to the factory area located on the NE, where the apatite concentrate is processed on site to produce phosphoric acid and fertilizers, and the workshop located towards W-SW, where industrial machines are produced and tested.

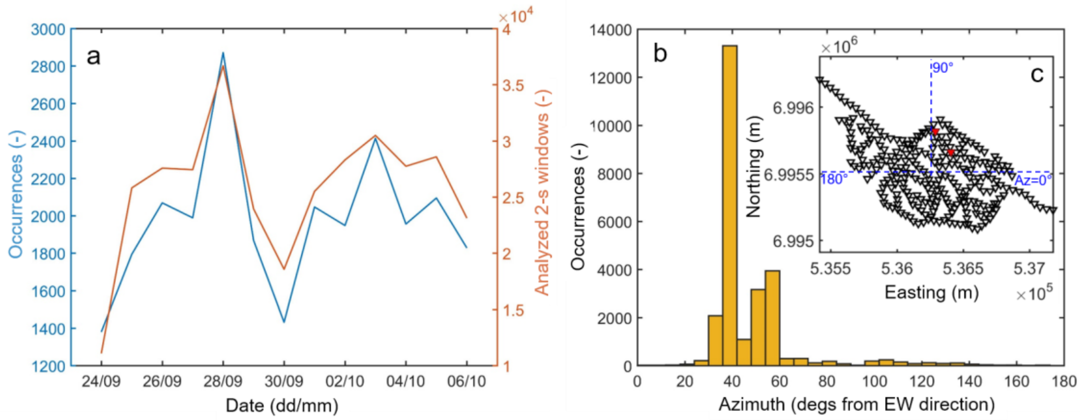

Figure 3 *a) Number of analysed 2s windows (orange) and number of 2s windows containing SW signal (blue) for each recording day. b) Histogram of SW occurrences for each azimuth direction. c) Map of the array with indication of the azimuth reference system. In red we highlight the receivers referring to the example shown in Figure 4.*

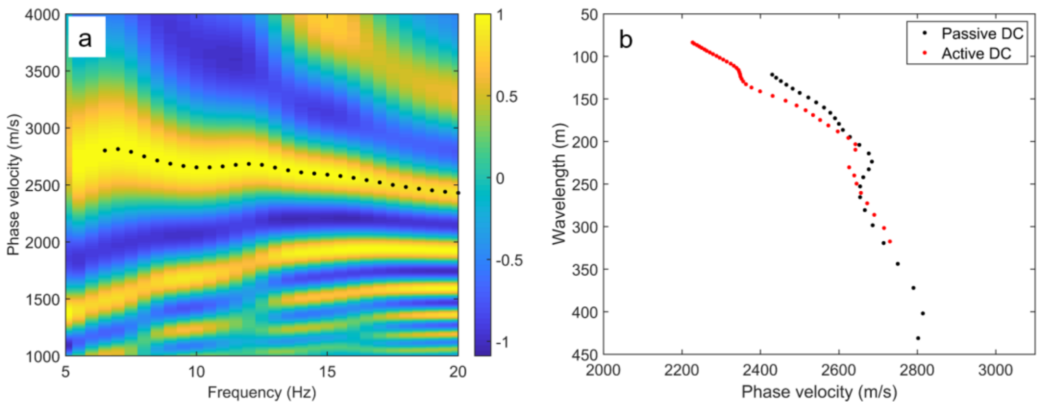

Figure 4 *Example of DC extraction: a) Stacked cross-multiplication matrix computed for the receiver couple indicated in red in Figure 3c. The amplitude maxima (black dots) provide the DC. b) Comparison between the DC corresponding to the same receiver couple, extracted by passive (black) and active (red) data.*

In Figure 4a, we show, as an example, the stacked-cross multiplication matrix, computed from the recordings of the receiver pair highlighted in red in Figure 3c. The picked DC is given by the black dots. In Figure 3b, in black, we plot the same DC in the wavelength – phase velocity domain and we compare it with the DC (red in Figure 3c) retrieved from the active data for the same receiver couple by Da Col et al. (2020). The two DCs almost overlap in the wavelength region 110 m – 320 m, showing a continuous trend and matching phase velocities. This comparison also shows that the passive DC carries information on the deeper portion of the subsurface, while, the DC extracted from the active data is sensitive to shallower subsurface layers.

Conclusions

We propose a scheme for the extraction of the path-average DCs, which are input to SW tomography, from ambient noise data, recorded on a mineral exploration site. The pre-processing steps allow the extraction of the time windows containing sufficient SW energy only, minimizing the time and computational costs of the subsequent processing steps. The distribution of azimuths and time provides information about the noise origin and allows the application of the two-station method, which requires the receivers to be in-line with the source. The method is almost fully automatic, apart from a manual quality control on the picked DCs. Due to the large size of the dataset (almost 800 GB) the computations required around 3 weeks for the pre-processing and 1 week for the two-station evaluation and stacking, running in parallel on a 10-core workstation. Preliminary results suggest that the DCs obtained by the proposed workflow are comparable to the ones obtained from active data, increasing the reliability of our results. Moreover, it was shown that passive data contain more information about the deeper subsurface portions, increasing the investigation depth and therefore, opening the possibility of mapping the mineralization target. Combined with the active DCs, they can provide high resolution SW tomography results at a wide depth range.

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