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Application of Surface-Wave Analysis for Mineral Exploration: A Case Study from Central Sweden

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Summary

Near-surface velocity models are important for deep imaging of mineral deposits with seismic exploration. The near-surface can be quite complex from loose, highly heterogeneous materials to stiff, fractured rocks. Surface-wave analysis can be an effective method to image the shallow subsurface of such challenging environments. Here, we propose a workflow that includes several processing and inversion steps. Initially, for the optimization of the processing parameters, we assess the presence of sharp lateral variations with a method based on the measured energy of Rayleigh waves. Then, using a moving window of receivers, we extract Rayleigh-wave dispersion curves along the acquisition line as the maxima of the f-k spectrum. Finally, the dispersion curves are inverted using a laterally constrained inversion scheme. The proposed methodology has been tested on legacy data from a mining field.

Introduction

Seismic reflection techniques have been proven to be an effective method for the imaging of metallic mineral deposits, since such formations exhibit high acoustic impedance contrast with their host rocks. However, due to their high costs and challenges in complex geologic environments (e.g. steep setting), these techniques are yet not established as standard for the European exploration industry. The current work lies within the framework of Horizon 2020 funded “Smart Exploration” project, with the main aim of introducing innovative exploration solutions for the highly noisy mining sites to able to detect mineral deposits even at great depths (300-1500 m).

Near-surface velocity models are important for deep imaging of mineral deposits with seismic exploration. The near-surface can be quite complex from loose, highly heterogeneous materials to stiff, fractured rocks. In the Nordic countries, the near surface usually implies glacial deposits versus crystalline bedrock. Static correction is a key step in hard-rock seismic imaging given the significant delay involved and the typical low signal-to-noise ratio data often acquired (e.g., Malehmir et al., 2012 and references therein).

Our main objective in this study is to develop a workflow appropriate for the characterization of the near surface in such an environment. We will gain information about the shallow subsurface velocity distribution by means of surface-wave (SW) analysis; a method that was born for site characterization in geotechnical engineering and is now also standard in the oil and gas industry (Socco et al., 2010). Several techniques are established so far, which, however, may not directly be applied to the geological environment of a mining site. In fact, we expect to face challenges related to the presence of fractures and high heterogeneities at the site. On the other hand, the presence of stiff rock, presents some advantages like higher seismic velocities, which might allow higher penetration depth.

In this work we present a first application of our workflow steps to a legacy dataset from one of the sites involved in the project, Blötberget mine, in the area of the Ludvika Mines of central Sweden.

Method

Since the basic assumption behind surface-wave method is that the subsurface is 1D (or very smoothly varying) beneath the receiver spread, before extracting the dispersion curves (DCs) this condition must be assessed and granted. An optimal analysis of SW requires then an indication of the presence and location of sharp lateral variations to properly design the processing for the extraction of the DCs.

The geology of the site of interest is expected to present shallow unconsolidated material (glacial tills) as well as stiff rocks that extend in some cases also at shallow depth. Such stiff rocks might present strong lateral heterogeneity due to fracturing and weathering. Moreover, since part of our investigation is expected to be applied in running exploration and mining sites, also man-made structures such as caved blocks, underground tunnels and roads may be present. Therefore, in order to optimize the processing parameters, we apply the method to detect sharp lateral variations developed by Bergamo and Socco (2014). This is used to quantify the attenuation or amplification of Rayleigh waves caused by sharp sub-vertical discontinuities, which act as reflectors or dampers of the horizontally propagating surface-wave wavefield. The method considers two parameters: the energy decay exponent (γ) and the attenuation coefficient (α_R).

The decay exponent can be computed for each trace for positive and negative offset (i.e. for the shots located on the left- and the right-hand side of each trace respectively). If the geometrical spreading is corrected for, the decay exponent of the negative and positive offset should be the same, and constant, for all traces unless there is a local sudden accumulation or decay of the trace energy. It has been proven that the decay exponent can be used to locate the discontinuity as the point where γ-positive and γ-negative diverge strongly. The attenuation coefficient is also computed for positive and negative offsets and, if these two values are stacked, they can provide the location and the frequency band related to the lateral discontinuities.

After the main lateral heterogeneities are located, we can split the data in portions, to avoid extracting dispersion curves from receiver windows which include them. It is then possible to extract DCs using a moving window of receivers in which the f-k spectrum is computed. The energy maxima are picked and, from these, the dispersion curves are obtained. The length of the window is a compromise between spectral resolution and lateral resolution. In fact, a too long window may not be representative of the local properties below the selected receivers, since lateral variations will be smoothed. On the other hand, a too narrow window will not allow picking of wide bandwidth DCs due to absence of spectral resolution. The result of the processing is a set of DCs, which, if plot in wavelength-phase velocity domain give an indication of the penetration depth of the data and the velocity distribution.

This set of DCs can be inverted to obtain the shear-wave velocity (VS) profile of the subsurface. Instead of inverting each curve separately, we adopt a scheme proposed by Socco et al. (2009). According to their method, it is possible to apply a deterministic, laterally constrained inversion (LCI) to the set of DCs, which will provide a pseudo-2D VS model. The parametrization of the LCI is optimized by applying initially a Monte Carlo algorithm.

Data example

The data used in this study were acquired in 2015 in a historical iron-oxide mining site, Blötberget of Ludvika in central Sweden. The acquisition setup and results of a first-hand processing of this dataset are presented in Malehmir et al. (2017). The data comprise of a 2D seismic line (Figure 1), ca. 3.5 km long acquired by the means of a moving land-streamer, 240 m long and two sets of 74 wireless recorders. Recording equipment on the land-streamer consists of 100 MEMS-based sensors. In this work, we present results from the data acquired by the part of the land-streamer having receiver spacing of 2 m. The seismic source employed was a Bobcat-mounted drophammer (500 kg).

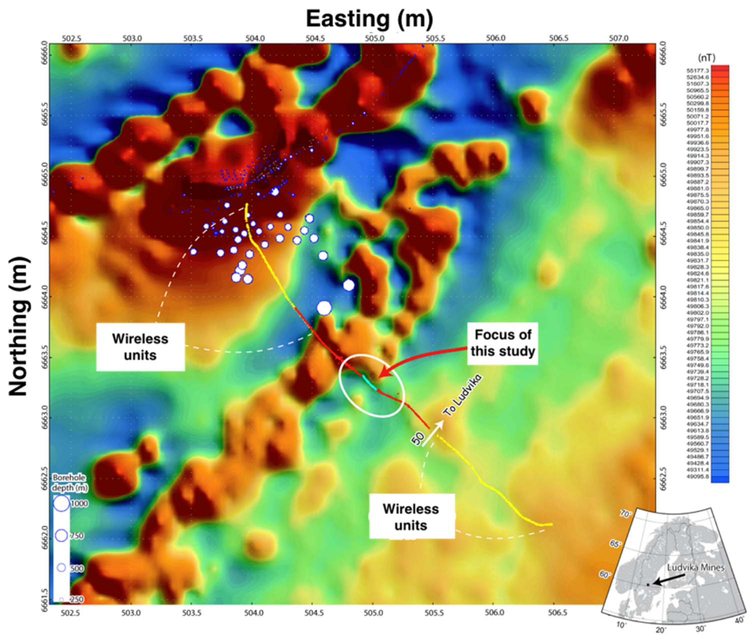

Figure 1: Geometry of the acquisition line superimposed to total-field aeromagnetic data. The group of receivers selected for the processing workflow application is highlighted in green. The white circles represent diamond drillholes.

As a first step, we sorted the data by finding the parts of the line in which, the sources and the receivers are in-line and in which the topography effects are minimal. A representative group of receivers appears to be the one highlighted in green in Figure 1 and we will therefore present the results of the processing workflow applied to this group. The portion of data here considered counts 40 drophammer shot positions.

From the proposed processing steps, we obtained the results shown in Figure 2. Plotting the decay exponent and stacked attenuation coefficient versus offset (Figure 2b and c) we observe that γ-positive and γ-negative present a strong divergence at positions 45 and 115 m, respectively. This result is also confirmed by the plot of the stacked attenuation coefficient (Figure 2c) where we observe anomalies at the same positions, as indicated by the dashed black lines. Given this possible distribution of the lateral discontinuities, we decided to extract the DCs using box windows of 12 receivers (i.e. 22 m), moving the center of the window by a step of 10m. This allowed us to extract most of the curves not including the stronger discontinuities in the processing windows. Thirteen DCs were extracted along the considered portion of the line and they are shown in Figure 2a, in the form of a pseudo-section (Rayleigh-wave velocity versus wavelength).

The DCs appear to be consistent along the whole line. The low Rayleigh velocities (approximately 200 m/s at high frequencies) are most likely due to the presence of an unconsolidated material. Because of these low velocities, the penetration depth (equivalent to, approximately, one wavelength) is low for a large part of the line. However, an area where the investigation depth is considerably higher can be found between approximately 55 and 110 m. Comparing this observation with the identified lateral variability, we can assume that in this area the lithology changes.

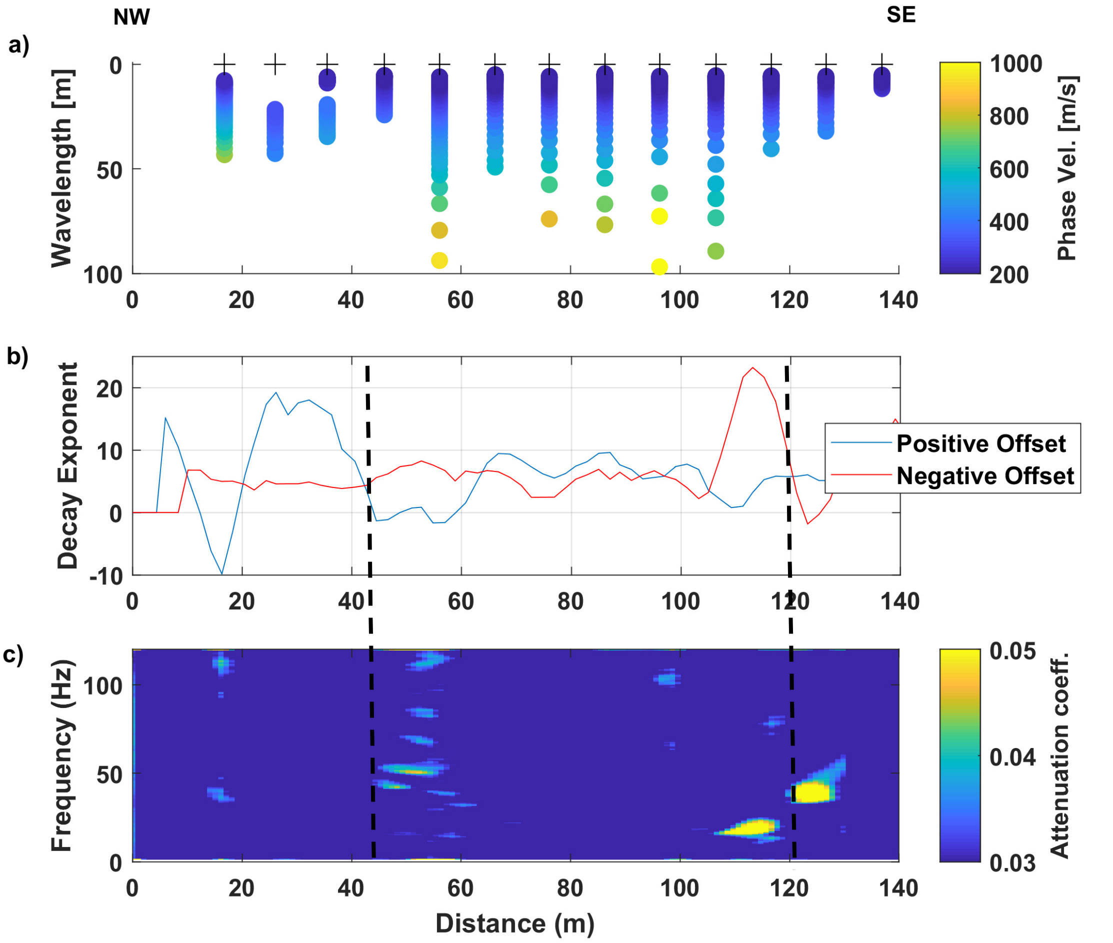

Figure 2: a) Pseudo-section obtained from the DCs. The colour scale indicates Rayleigh-wave velocity. b) Decay exponent. Lateral variations occur where values referred to positive and negative offset diverge. c) Stacked attenuation coefficient. Higher values indicate lateral variations.

The thirteen DCs were inverted using the scheme presented in the Method section. Initially we applied a Monte Carlo global search algorithm; 10^6 profiles were computed and the best fitting one was used as initial model for the LCI. The inversion result (VS versus depth along the line) is presented in Figure 3. We can detect a shallow layer with low shear-wave velocities, which is probably due to the existence of unconsolidated material. It can also be observed that in the middle of the line (offset between 55 and

105 m) there is an abrupt increase of VS for the deeper layers. This result is consistent with the conclusion reached during data processing that in this area the lithology changes. Moreover, since the selected receiver line crosses the magnetic lineament where possibly mineralization occurs (Figure 1), the transition towards higher seismic velocities might be related to the presence of a mineralized body.

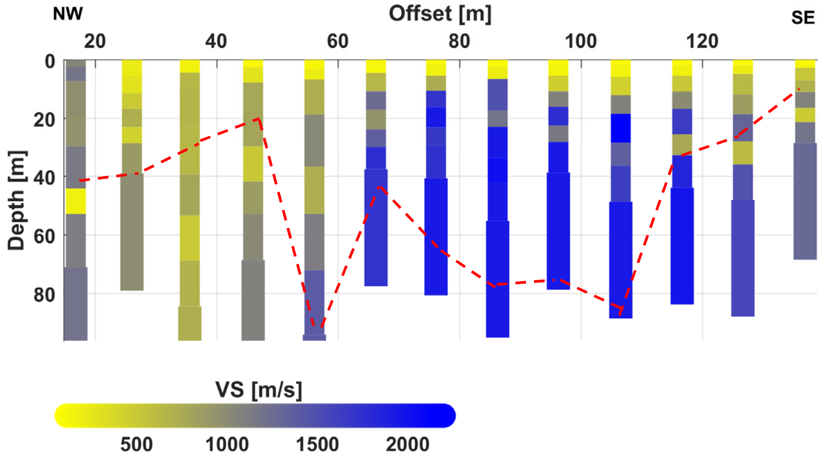

Figure 3: Result of the laterally constrained inversion showing a sharp change in the shear-wave velocity around 70 m offset. The red dashed line indicates the maximum investigation wavelength of each corresponding DC, below which the inversion results are not considered reliable.

Conclusions

The quality of the DCs and the inverted profile prove that the methodology used, which is common for processing of data for oil and gas exploration is promising also for more challenging geological settings. The described methodology will be applied to the whole line and static corrections will be computed from our results.

Acknowledgments

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Smart Exploration Official WebSite; https://smartexploration.eu/.