Seismic interferometry for mineral exploration

Passive seismic experiment over kylylahti mine area, Finland

COGITO-MIN Working Group

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Introduction

Acquisition of active-source 3D seismic data in hardrock environment can be challenging and costly. Driven by research in the oil and gas industry, recent studies have been investigating the possibility of extracting the subsurface image from passive recordings by the use of seismic interferometry (SI). SI is a method to retrieve the Earth`s response at both local and global scales by correlating noise records between two receivers (Draganov and Ruigrok, 2015). This novel concept has been already tested in the mining exploration context at Lalor Lake mine site in Canada (Cheraghi et al. 2015). Retrieving reflection data using SI has proven to be much more difficult than extracting surface waves (Forghani and Snieder, 2010), which usually dominate noise records.

Here, we present the initial results of a full-scale 3D passive seismic experiment performed at the Kylylahti polymetallic mine in Polvijärvi, eastern Finland (Figure 1a), with the aim to investigate the applicability of SI for mapping the continuity of the ore host rock at the site. In this case, the presence of an active mine creates a rare opportunity to record seismic arrivals from high-energy sources related to routine mining operations. We start from the evaluation of the noise characteristics, including beamforming, then we compare synthetic modelling results with the ambient-noise SI (ANSI) imaging along selected receiver lines. Finally, we introduce mineral-exploration seismic interferometry (MESI) workflow and show the outcome of applying it to data recorded with a large-N array of sensors deployed above the underground mine.

Data acquisition and ambient-noise characteristics

The 3D passive seismic experiment was conducted over the Kylylahti polymetallic mine area, eastern Finland between early August to late September 2016 as part of the COGITO-MIN project. Seismic array consisted of 1000 receivers distributed regularly over the 3.5 x 3 km area with 200-m line spacing and 50-m inline receiver interval. The terrain conditions for the survey were varying and included both boreal forest and fields as well as inhabited areas and the mine site. Each receiver station consisted of wireless Geospace GSR recorder and 6 x 10-Hz geophones bunched together and buried whenever possible, recording at a 2 ms sample rate for about 20 hrs/day for about 30 days. As a result we recorded over 600 hours of ambient noise data per each receiver. Same grid of receivers recorded also active Vibroseis and dynamite shots (~700), making a sparse active-source 3D survey.

The survey area is located in the direct vicinity of the Polvijärvi town (population of > 4000). Two fairly busy state roads cut through the survey area. A roundabout connecting both roads is located in the centre of the array. The mine is located to the northwest from the roundabout. Access to the mine is along gravel roads, used extensively by hauling trucks. The Kylylahti mine was active during the whole recording period. Routine mining activities included: drillings (surface and underground), transporting ore and waste rock (surface and underground), scaling (underground), and mine ventilation (surface) among others. Another source of strong energy are the mine blasts which occurred daily at depths ranging from a few hundred meters down to approximately 800 meters below surface. This abundancy of noise sources is potentially useful for an SI survey and gives us an opportunity to retrieve body-wave arrivals from ambient noise recorded in Kylylahti.

The frequency spectra related to road traffic (A1 and A2 in Figure 1b) exhibit their most energetic part up to 50 Hz, with a peak at around 20-30 Hz, which is characteristic for the surface waves observed, e.g., in 2D active-source data from the area. Amplitude spectra at some distance from the road traffic (A3 and A4 in Figure 1b) indicate presence of ambient-noise sources up to 150-200 Hz. Taking into account the possible influence of power lines, we suspect that parts of the spectrum in the frequency range above 35 Hz (denoted as green rectangle in Figure 1b) can be related to energy generated by body-wave sources. Figure 1c shows an example of a beamforming output calculated and summed over 20 hours recorded on a single day in the frequency range 3-5 Hz. The maximum values, represented as bright spots, show dominant propagation of waves coming from the NNW and wide area in the E. These directions are consistent with noise sources located at the mine site and the city of Polvijärvi. The observed apparent velocities range from 2.5 to 5 km/s, with the strongest amplitudes at 3-4 km/s. Note that the surface-wave velocity observed, e.g., in active-source 2D lines, is around 2.5-3 km/s.

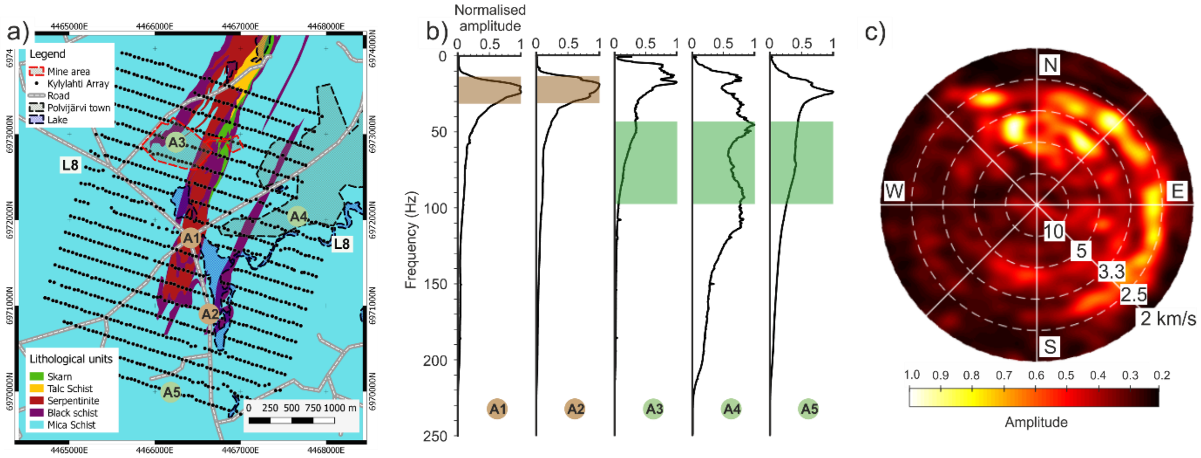

Figure 1 (a) *Location of the 3D passive seismic survey, (b) amplitude spectra calculated for the representative regions of the survey area marked by A1-A5 in panel (a), and (c) beamforming output calculated for 20 hourly panels from 27th of August.*

Synthetic modelling and 2D ambient-noise processing results

To assess the potential of SI to retrieve reflections in the study area and to provide the basis for comparison with the field data, we performed 2D synthetic experiments. In our synthetic tests, we used 2D model consisting of 4 main geological units (Figure 2a). The P-wave velocities range from 5.8 – 6.3 km/s. The massive to semi-massive sulphide mineralization is located at approximately 300 m depth (indicated by yellow colour in Figure 2a). The petrophysical characterization of the targets indicate that semi-massive to massive sulphide mineralizations should cause a strong reflected signal when in contact with any of the hosting rocks (Luhta et al. 2016). The receiver geometry was chosen to mimic the field acquisition geometry, i.e., line of 29 sensors placed on the top of the model with 50 m spacing giving a total length of line of 1400 m. We show results of the two forward-modelling experiments: (1) with sources placed on the top of the model resembling an active survey and (2) with sources regularly distributed along a rectangular polygon bounding the area of potential reflectivity. Synthetic virtual shots were retrieved by cross-correlation (Wapenaar and Fokkema, 2006). Both the synthetic active and virtual shot gathers were then subjected to a DMO and post-stack F-K migration. The migrated sections are shown in Figure 2. Provided the preferred regular noise-source distribution (green stars in Figure 2a) it is possible to obtain an image of local geology with both approaches. To further argue in favour of the SI effectivity in the geological setting of the study area, we show the results of the ANSI processing applied to passive field recordings from receiver line 8 (the line is denoted as L8 in Figure 1a). To facilitate direct comparison with the synthetic data, the 2D field result was processed in the same way.

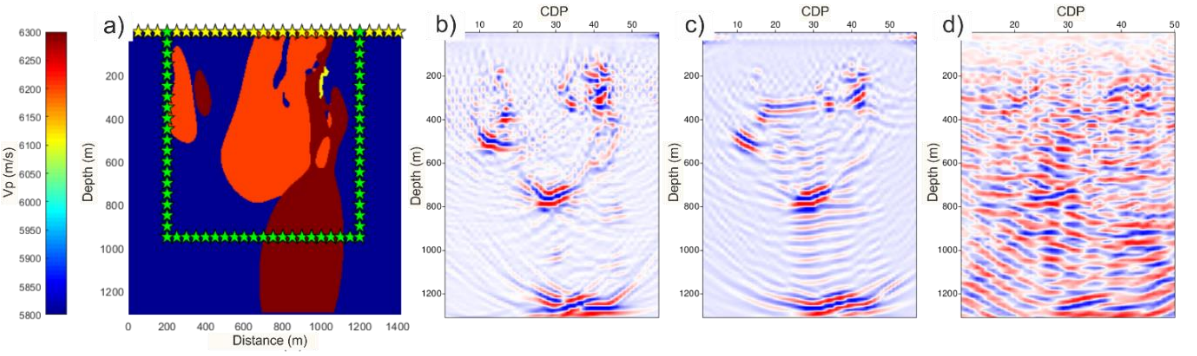

Figure 2 *(a) Velocity model used as an input for the forward-modelling study, yellow and green stars denote source distribution for the active and passive experiment, respectively. Post-DMO migration of active data (b) is compared to the SI results (c); (d) result of SI applied to field data recorded along L8.*

Figure 2d shows the depth-converted migrated section obtained using exclusively ambient seismic noise: it exhibits reflections related to the ore host rock sequence (indicated by brownish colours in Figure 2a) within the surrounding sedimentary rocks (indicated by blue colour in Figure 2a).

Mineral exploration seismic interferometry processing workflow (MESI)

A few SI studies show that to extract specific parts of the Green's function between receivers requires selective stacking of correlation functions with high S/N ratio in the time window of desired arrival. (Nakata et al. 2015, Olivier et al. 2015). However, for reflection imaging there is a need to have arrivals with high S/N ratio present in many time windows on several hundred traces at the same time. For this reason, a more robust approach is selective stacking of noise sources rather than directly analysing the correlation function. To retrieve body-wave reflections from ambient- noise it is necessary to have noise recordings with body-wave arrivals (Draganov et al. 2009). In the Kylylahti setting, these would be body-wave events produced by underground mine activity. Our proposed MESI workflow (Figure 3a) aims at producing virtual-shot gathers by using body-wave noise events stacked over stationary-phase areas. The key steps of the method include: detection of body-wave events with a two-step illumination-diagnosis method, applying bandpass filtering, and evaluating the location of the noise sources. Depending on the spatial distribution of the noise sources present in the recording area, we selectively stack them over stationary areas. Finally, we retrieve virtual shots with either cross-correlation or cross-coherence. Steps 1 and 5 (Figure 3a) are our modification of the ANSI workflow proposed by Draganov et al. (2013).

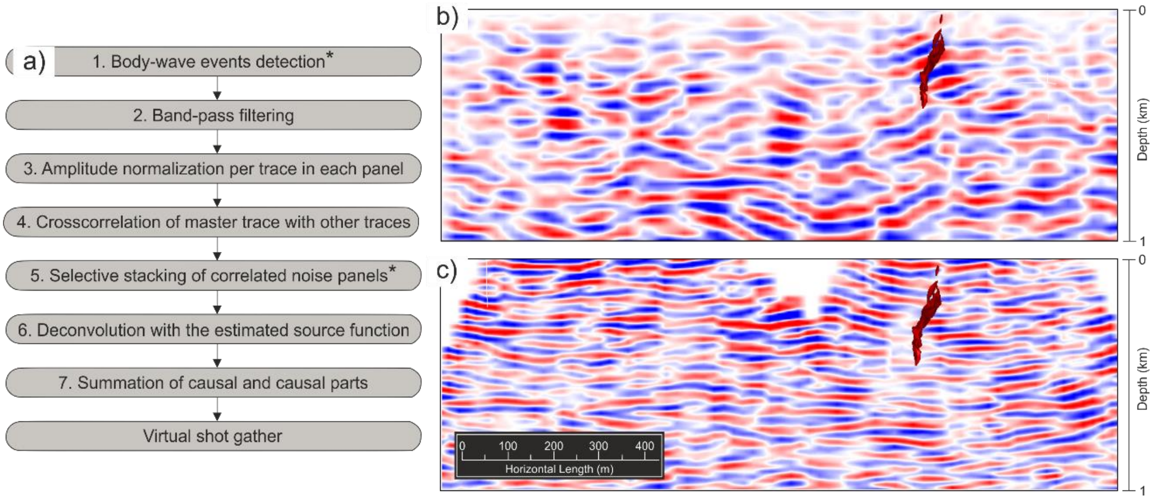

Figure 3 *(a) The MESI processing workflow; (b) Example of an inline migrated seismic section obtained from the MESI-processed data compared to (c) the migrated co-located inline section from the active data. Projection of the massive sulphide ore lens is shown as a red shape.*

Figure 3b shows the result of applying the conventional seismic mineral exploration workflow to the virtual shot gathers obtained from the MESI workflow compared to the co-located inline section from the active data (Figure 3c). The MESI retrieved section exhibits high-reflectivity regime consistent with the dipping host rock sequence of the mineralization.

Conclusions

We show an application of full-scale 3D seismic interferometry (SI) at Kylylahti mine (Finland) using ambient-noise recordings. Using 2D synthetic modelling and ambient-noise processing applied to selected receiver line, we confirm the feasibility of SI for imaging ore-hosting formations. We developed an SI processing workflow called MESI, consisting of automatic noise-panel selection, noise-sources location, and selective stacking. Finally, we presented the migrated seismic image obtained exclusively from seismic ambient noise by using the developed workflow. Migrated sections obtained from both 2D and 3D SI processing exhibit high reflectivity, consistent with synthetic gathers and directly related to the local geology.

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*The COGITO-MIN Working Group: M. Chamarczuk, C. Cosma, N. Enescu, G. Gislason, S. Heinonen, S. Juurela, E. Koivisto, K. Komminaho, T. Luhta, M. Malinowski, S. Mertanen, S. Niemi, M. Riedel, B. Singh, L. Sito, A. Taipale, T. Törmälehto, K. Vaittinen, S. Väkevä, M. Wojdyla.

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