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Passive Seismic Imaging for Mineral Exploration

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SUMMARY

Ambient noise tomography is a new method that does not require an active source to image the subsurface. As a result the method is a low-cost, environmentally friendly technique that can be used to explore mineral deposits. Recent developments in compact autonomous seismic recording stations allow for continuous recording of seismic data for months at a time at low cost, further increasing the attractiveness of the method. In this presentation we show results from a recent experiment where 200 seismic stations were places adjacent to an active mine in order to image the subsurface. By using ambient noise tomography, body-wave travel time and reflection tomography, we were able to create high-resolution images of the subsurface . This in turn could significantly reduce the amount of drilling that is needed in the area to probe potential ore localising structures. The results of the experiment indicate that passive seismic methods are well suited to mineral exploration.

Key words: Passive seismic, seismic imaging, seismic reflection.

INTRODUCTION

The purpose of the introduction is to tell readers why they should want to read what follows. This section should provide sufficient background information to allow readers to understand and evaluate the paper's results. The introduction should (1) present the nature and scope of the problem, (2) review the pertinent literature (within reason), (3) describe the method of investigation, and (4) describe the principal results of the investigation.

All text in the main body of the extended abstract should be 9 pt Times New Roman font, single-spaced and justified. Main headings are placed in the centre of the column, in capital letters using 10 pt Times New Roman Bold font. Subheadings are placed on the left margin of the column and are typed in 9 pt Times New Roman Bold font. Full stops should be followed by two spaces.

To enter your introduction, highlight the above paragraphs and replace with your words.

AMBIENT SEISMIC NOISE

Ambient seismic noise refers to the continuous vibrations that are present in the earth at different frequencies. For a long time, it was believed that the seismic noise is nothing more than a nuisance. Numerous studies were devoted to minimising the seismic noise that was thought to only obscure useful signals from earthquakes or active sources. In pioneering work, Aki (1969) showed that seismic noise carries information about the

medium. Since then it has been shown that seismic noise consists of multiply scattered waves and, if processed carefully, can be used to illuminate and monitor the earths interior structure at diffferent scales.

The origin of these ambient vibrations depend on the wavelength considered. The longest period seismic noise (above 100 s) is often referred to as earth "hum". These long-period seismic waves have been attributed to atmospheric motion (Tanimoto and Um, 1999; Ekström, 2001). More recent studies have attributed the seismic noise at these frequencies to a long-period ocean gravity wave (Tanimoto, 2005; Rhie and Romanowicz, 2004, 2006).

Seismic noise in the period band between 5 to 20 seconds have been attributed to the interaction of the incoming ocean waves with the solid earth (Webb, 1998). The seismic noise in this band is referred to as oceanic microseisms. Within this band, there are two distinct peaks (at roughly 7 and 14 seconds) that can be observed universally within the earths crust. The origin of the primary microseism (14 seconds) is well understood and results from the direct interaction of incoming ocean waves with the shallow sea floor (Hasselmann, 1963). The origin of the secondary microseism is less obvious and has been attributed to the non-linear interaction of the retracting ocean waves with incoming ocean waves of the same frequency, which creates a compressional wave on the sea floor (Longuet-Higgins, 1950). High frequency seismic noise with periods below 1 second result mostly from anthropogenic sources and have daily and weekly variations linked to human activity (Bonnefoy-Claudet et al., 2006,see Figure 2.5 from). The origins of cultural noise include strong machinery, traffic and industrial activity.

Since high-frequency seismic waves attenuate relatively quickly, the dominant sources of seismic signal are highly dependent on the location of recording. In Bonnefoy-Claudet et al. (2006), the authors note that the origin of seismic noise can be classified in frequency bands as follows: (1) seismic noise below 0.5 Hz originates from oceanic and global meteorological conditions; (2) seismic noise between 0.5 and 1 Hz originate from wind and local meteorological effects; (3) above 1 Hz the seismic noise is generated by human activity. Recent work has also showed that lakes can be a strong source of noise in the frequency band of 0.5 - 2 Hz (Xu et al., 2017).

For seismic surface arrays used in crustal seismology, the interaction of the ocean with the solid earth provides stable ambient seismic noise originating from all azimuths that (mostly) satisfy the conditions necessary to reconstruct the seismic Greens function between two sensors by cross-correlating the signals recorded. For industrial applications, anthropogenic noise is necessary to satisfy the conditions required to construct Green's functions from ambient noise.

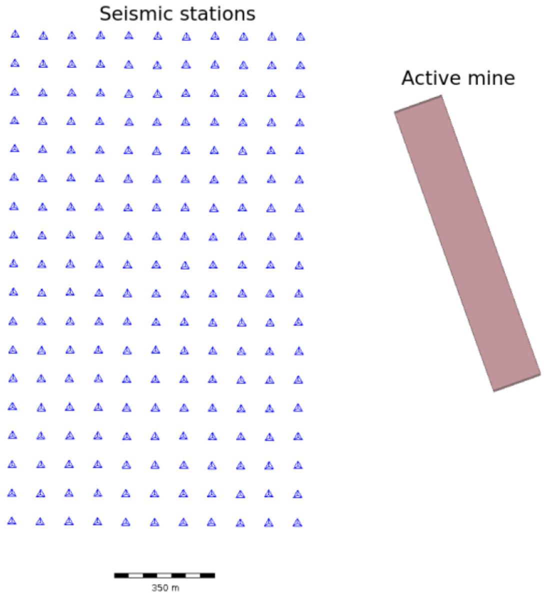

Figure 1. Plan view of the deployed seismic stations relative to the active mining operations.

CONSTRUCTING GREEN'S FUNCTION BY CORRELATING AMBIENT SEISMIC NOISE

Almost 50 years ago, Claerbout argued that "by cross-correlating noise traces recorded at two locations on the surface, we can construct the wave field that would be recorded at one of the locations if there was a source at the other" (Claerbout, 1968). Claerbout's conjecture was well before its time and only gained momentum in the seismology community a few decades after the approach was successfully applied to helioseismic data (Duvall et al., 1996). A few years later Lobkis and Weaver (2001) showed that the Greens function emerges between two ultrasonic sensors when cross-correlating the signal recorded in them in the presence of a diffuse ultrasonic field. Here the authors remarked that equipartition of modes or a fully diffuse wavefield is required to retrieve the Greens function. This is an condition that is relatively easy to fulfill in ultrasonic experiments, but not realistic in seismology.

Derode et al. (2003) showed that the Greens function can be retrieved by cross-correlation even in the absence of diffusivity with an argument based on time-reversal symmetry. However, time-reversal symmetry is not valid in the presence of attenuation. Wapenaar (2004) used a reciprocity theorem to show that the Greens function can be retrieved in any inhomogeneous medium by cross-correlating the recordings of two sensors located at a free surface, also in the absence of diffusivity. However, this derivation required the receivers to be located at the surface.

Snieder (2004) showed that in a homogeneous elastic medium with scatterers that act as secondary sources, one can retrieve the Greens function by cross-correlating the signals recorded by two receivers with the stationary phase approximation. This derivation did not require the receivers to be located at surface and applied to any 3D distribution of sensors. Since then there have been numerous authors who have shown mathematically that the Greens function can emerge from seismic noise recordings (for a thorough review of these derivations and a discussion of their similarity see Boschi and Weemstra (2015)).

Even though the conditions required to retrieve the full seismic Green's function from cross-correlating ambient seismic noise are rarely met, in most cases the method succeeds in retrieving an estimate of the Green's function that is suitable for our purposes of imaging the subsurface. This is also confirmed by the impressive range of applications that have been made on various scales over the last decade (for a review, see Curtis et al. (2006)).

EXPERIMENTAL SETUP AND RESULTS

To test whether this ambient seismic noise imaging method could be used as a tool for mineral exploration, we deployed 200 single-compoenent seismic stations adjacent to an active mine for a one month period. During the month, the seismic stations recorded thousands of mining induced earthquakes and strong ambient seismic noise.

The high quality data enabled us to construct estimates of the surface wave Green's functions between all stations pairs. Figure 2 shows the virtual source signals travelling across the array arranged by interstation distance. We clearly the see Raleigh wave signal propagating between the stations at roughly 3km/s.

The dispersive properties of these surface wave can in turn be exploited to create a 3D model of the S-wave velocity structure below the array.

The use of other methods in conjunction with ambient noise surface wave tomography for mineral exploration are also investigated here. In seismology, receiver functions are widely used for imaging of crustal and upper mantle structures using travel-times of boundary-layer reflections and conversions of seismic waves. Our further investigations explored whether high-frequency P-wave reflections can be retrieved by employing a processing scheme similar to that used in receiver function analysis, then focusing on local mining-induced microseismic P-wave arrivals to image the shallow subsurface.

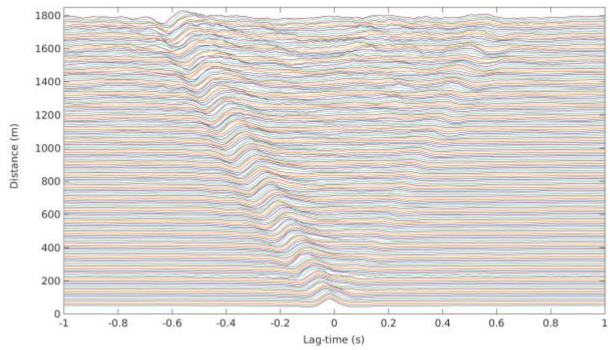

Figure 2. Raleigh wave Green's functions propagating across the array as a function of interstation distance.

CONCLUSIONS

Passive seismic methods such as ambient noise tomography provide a low cost method to image the subsurface and to greatly reduce the amount of drilling required to delineate ore localising structures. In this presentation we will present results from a recent trial where 200 seismic stations were deployed adjacent to an active mine. The quality of the data enabled us to create good virtual source signals (Green's functions) between stations pairs. These virtual source signals will in turn be used to create high resolution images of the subsurface. The preliminary results from the study indicate this passive seismic method could be well suited to mineral exploration.

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