PASSIVE SEISMIC INTERFEROMETRY OVER THE LALOR LAKE AREA

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INTERFEROMETRY BACKGROUND

A number of studies have shown that an active mine site is a source of seismic energy due to both direct noise sources such as underground explosions and indirect sources such as mining induced seismicity (e.g. Snelling *et al.*, 2013). We suggest the reverberations from these noise sources can be processed in such a manner that they appear as if they were generated from sources located on the surface instead. As such, this 'virtual' data can theoretically replace data obtained from a traditional, far more expensive, active source seismic survey. The specialized processing required is termed interferometry as we seek to cancel out (via interference) the reverberations from below the surface, leaving behind only those from the surface itself. Important to our proof-of-concept is the validation of the technique against other, similar, methods. The new survey technique is evaluated against the information obtainable from a 3D active source collected in the same area.

In terms of theoretical developments, the importance of the paper by Claerbout (1968) cannot be overstated. Claerbout demonstrated that the reflection response of a layered medium was exactly equivalent to the autocorrelation of the measured response. Wapenaar (2004) and Wapenaar *et al.* (2002, 2004) demonstrated that Claerbout's layered earth conjecture was applicable to arbitrary 3D inhomogeneous acoustic or elastic media. This theory holds for both impulsive and white-noise sources, in addition to situations where the ambient noise sources are either at depth or the surface. Draganov *et al.* (2007, 2009) provides the earliest use of interferometry to uncover body waves for exploration. Dragonov *et al.* (2013) provides a thorough overview of recent work on the recovery of body wave reflectivity using interferometry.

In addition to the study by Snelling et al. (2013), a recent study by Boltz *et al.* (2014) indicated close to 200 events related to mining induced seismicity in a two week period alone at an active mine in Utah and detected over 1800 events in a 2 km2 area over an eight month period. Valley *et al.* (2012) looked at the harmonic content of noise sources in an active mine and found a broad spectrum (0.00001 Hz to 1000 Hz) with significant power spectral amplitudes at the higher frequencies associated with body waves. Further, we speculate that surface waves at remote mines (where surface wave sources such as traffic or coastlines are not generally a problem for active source surveys) are minimal. The actual underground workings at Lalor are not known to the authors at this time; however, during the course of our survey we were informed that a number of drills were active in the subsurface for exploration and ore extraction purposes. In addition, a number of significant detonations (at least two) were occurring daily to sink the main shaft over 1 m per day and to aid in exploration and mining. Taken together, we speculate that noise sources in the vicinity of an active mine such as Lalor may be potential sources for an interferometry survey and afford a reasonable chance to extract body waves from the ambient noise.

A few other requirements regarding the theoretical developments should be pointed out as we cannot address them at this time. The recording measurements should be in the far field of the sources. A smoothly varying medium must surround the noise-source boundary. The noise sources must illuminate the observation points with equal strength from all directions. And finally, there must exist at least two uncorrelated noise sources per wavelength (for a general inhomogeneous medium). Given that the acquisition and medium parameters of the Lalor interferometry survey are uncertain with respect to these requirements, it is nonetheless worthwhile to investigate the utility of interferometry for mineral exploration to minimize costs and field logistics. A 3D-3C active source seismic survey involves considerable amount of survey planning and permitting. At Lalor, 2.74 m wide shot lines were permitted, surveyed and eventually cut using heavy equipment to enable the shot hole drilling trucks to traverse the lines. A number of these costly issues can be avoided if a technique can be found that provides similar images, but only utilizes receivers.

PASSIVE SEISMIC INTERFEROMETRY AT LALOR

The purpose of this study was to test and evaluate a new method of seismic exploration for ore deposits. VMS deposits are good targets for seismic surveys due to their anomalous body wave velocity and density of metallic minerals (sulphides). Whilst a number of studies have indicated that 3D seismic surveys similar to those acquired for oil and gas exploration would be a useful complement to the exploration strategy of any resource company, high cost of acquisition and processing, relatively few case studies and difficulties integrating results into an exploration program have prevented widespread adoption of the technique (see for example, Cheraghi *et al.*, 2012). A key factor inhibiting industry reception to seismic is the cost related to the deployment of seismic energy sources such as explosives or Vibroseis which can be both costly and difficult to permit and survey. We seek to develop a new exploration methodology that does not require the deployment of specific energy sources at the surface, but instead utilizes the natural or man-made (ambient) noise sources either nearby or far from the survey area to perform the same or similar role.

To test the feasibility of passive seismic interferometry to image ore deposits in the crystalline rock environment

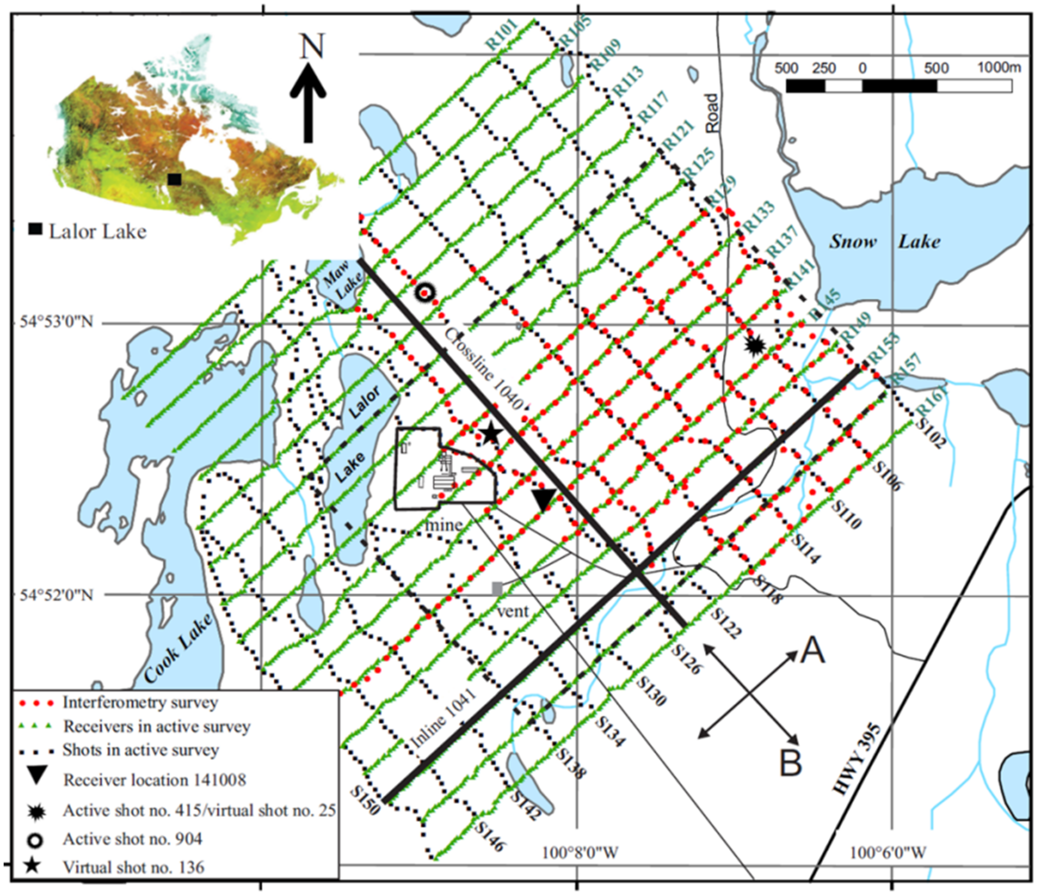

Figure 17. Map of the Lalor mining area showing shots (e.g., S102, S106, S110, ...) and receiver lines (R101, R105, R109, ...) of the active-source 3D seismic survey. The passive survey (red dots on Figure 1) was also acquired along the same lines, but covers a smaller area. The primary mine area and ventilation shaft are also shown in the figure. Direction A (southwest to northeast) and direction B (southeast to northwest) is shown on the figure. The DMO stacked sections along inline 1041 and crossline 1040 of the both active and passive surveys are shown in this paper. The dashed rectangle shows the outline of the 3D DMO stacked cube of the passive survey. Inline 1041 and crossline 1040 from the passive survey do not extend beyond this rectangle. Inset shows Canada map and the Lalor Lake area.

approximately 300 hours of ambient noise data were recorded on a grid of receivers over the Lalor mine, Canada, done in March 2013 immediately prior to the acquisition of a dynamite 3D seismic survey over the same area (see Figure 17). The active survey was acquired near the end of the ambient noise acquisition; therefore, it did not interfere with ambient noise measurements. Receiver stations of the passive survey are located along 9 parallel lines trending southwest to northeast (direction A, see Figure 17) and 7 parallel lines trending in the southeast to northwest direction (direction B, see Figure 17). Directions A and B coincide with the receiver and shot lines of the active survey, respectively (see Figure 17). The station spacing along each passive seismic line is about 100 m whereas the spacing between two successive lines is 360 m and 400 m for directions A and B, respectively. The passive survey covers an area of about 4 km² which corresponds to the northeast quadrant of the active survey. Table 5 shows the acquisition parameters for the passive survey.

The Lalor Lake deposit is located far from any densely populated areas and coast lines which are usually good sources of ambient noise. The Town of Snow Lake (population of 800) located approximately 8 km northeast of the survey area is the closest settlement. The nearest large town (> 5000 people) is Flin Flon, 215 km west of the Lalor

Table 5. Acquisition parameters of ambient noise measurements in Lalor Lake area.

Instrument	OYO Geospace Seismic Recorder (GSR) units set to record for one month
No. of receivers	336
Sampling interval	2 ms
Direction A station spacing/line spacing	100 m/360 m
Direction B station spacing/line spacing	100 m/400 m
Geophone type/geophone frequency	Vertical component/10 Hz
Measuring area	4 km²
Total measuring time	~300 hours

Table 6. Processing steps applied to the retrieved shot gathers of the Lalor Lake area.

1.	Elevation corrections and set up geometry (the elevation datum is considered 310 m)
2.	Picking theoretical line of first arrivals based on the coordinates of virtual shots and receivers and considering velocity of 5.9 km/s.
3.	Top mute: 20 ms after the theoretical line of first arrivals.
4.	Apply median filter to remove potential surface and shear waves (at velocities of 2.5 & 3 km/s)
5.	Sorting to CDP domain
6.	Trace balancing
7.	Velocity analysis in 5-8.5 km/s range(iterative)
8.	Residual static correction
9.	DMO corrections (5.5-6.5 km/s)
10.	Stack
11.	FX-deconvolution

Lake deposit (see Figure 18). Access to the mine is along a gravel road with generally little traffic. The nearest railroad is 65 km southeast of the Lalor Lake deposit and the area is not an active zone in terms of earthquakes. The only significant activities likely generating seismic noise are underground drilling, blasting, and hauling of minerals associated with the ongoing exploration and exploitation of the deposit (see Figure 17 for the mine location).

Ambient noise was continuously recorded in SEGD format at each receiver location of the study area for a period of 300 hours. Subsequently, noise records were divided into one hour panels for a total of 300 panels of one hour per receiver location. To better investigate the ambient noise content, we analysed the RMS amplitude for each hourly panel along all lines in directions A and B (see Figure 17 for the directions). The RMS amplitude investigation shows that underground explosions which mainly occur near 6 am and 6 pm are dramatically changing the energy level along each receiver line. Other hours are quiet or only few activities happen. Power spectral density is also calculated for frequencies between 1 and 250 Hz (the Nyquist frequency for the 2 ms sampling rate in the survey) for hourly data along the survey lines. The calculated power demonstrates that the frequency range of about 2-35 Hz contains the highest level of energy for the entire noise recording time. The noise panels were also visually inspected after the application of a 2-35 Hz band-pass filter. Some noise panels show groups of weak steeply-dipping events with high apparent velocities (about 6 km/s) and also some hyperbolic events with apparent velocity of about 4 km/s. Both the steeply-dipping and hyperbolic events could result from surface or body waves. Due to the general quietness at surface in the Lalor area and the relatively fast apparent velocity of the events, we favour body waves related to deep mining activity. The beamforming analysis over the grid of receivers provides in the frequency ranges of 1-3 Hz, 10-13 Hz, and 23-25 Hz shows evidence of both low velocity surface waves (velocity less than 3 km/s) originating from the northeast and higher velocity body waves (velocity higher than 3.2 km/s) from the mine. Our interpretation is consistent with the two main sources of ambient noise in the area, namely the underground mining activities and human activities in Snow Lake (8 km northeast of the area).

To create virtual shot gathers from ambient noise, a Green's function is retrieved between each pair of receiver locations by calculating of cross-correlation. The cross-correlated noise produces a Green's function at positive and negative time lags, corresponding to the causal and acausal parts of the Green's functions. Prior to cross-correlation, the noise energy in each panel was filtered to preserve the frequency content between 2-35 Hz. This frequency bandwidth was chosen based on power spectral density calculation, visual inspection of the noise panels, and the beamforming analysis discussed earlier. All traces of each panel were subsequently normalized by applying a trace-by-trace process to ensure that energy from all subsurface sources was equally weighted. For each hourly noise panel, the cross-correlation is calculated for each possible pair of receiver locations (i.e., 336 receiver locations in the area representing about 110000 calculations/panel for a total of 33 million calculations done over all 300 noise panels). For one panel, the cross-correlation of noise at a specific receiver with noise at other receiver locations forms a virtual shot gather, as if a shot was acquired at that specific receiver location. The final virtual shot gathers were obtained by summing the causal and acausal parts of the cross-correlated signal at each receiver pair, and then by summing virtual gathers from all panels. The decision to sum the causal and acausal parts of the signal is based on the beamforming analysis which demonstrates noise sources from different directions. A total of 336 virtual shot gathers were generated following this procedure. The virtual shot gathers were processed following a conventional seismic processing flow to evaluate the applicability of the ambient noise interferometry for seismic imaging in crystalline rocks. Because of the complex structures in the study area and the absence of clear reflected waves in the virtual shot gathers, interpretation of the seismic section is challenging. We applied both 2D and 3D processing approaches. In both cases, processing focused on the imaging of high-velocity reflections (with moveout velocities >5 km/s) typical of body-waves propagating in crystalline rock environments. Table 6 shows the key steps of the 2D and 3D processing of the virtual shot gathers. The steps were kept as close as possible to the processing flow used for the active data.

The availability of the coincident active-source 3D data provides an opportunity to compare the passive processing results directly with the active source data. However, the bandwidths of the sections derived using the two ap-

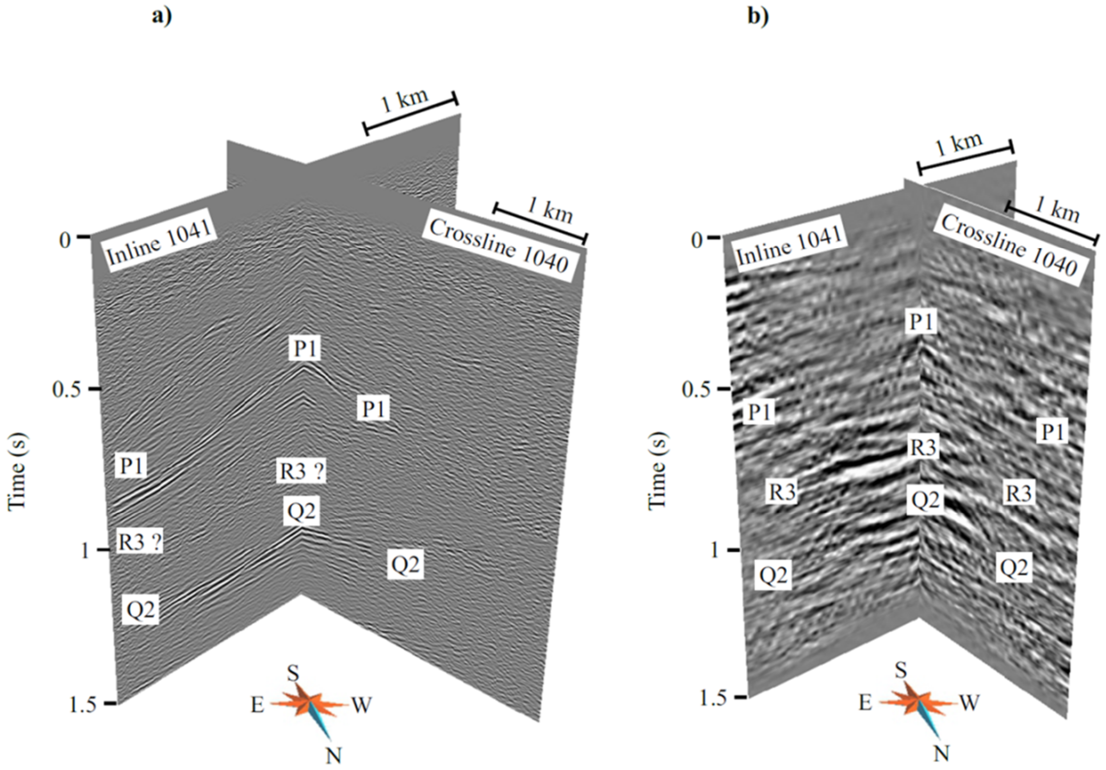

Figure 18. The DMO stacked sections along inline 1041, crossline 1040 (see Figure 17 for the locations). (a) The active-source survey. (b) The passive interferometry survey. Note that the minimum frequency in (a) is 30 Hz. See text for interpretation of P1, Q2, and R3 reflections.

proaches differ as frequencies less than 30 Hz are filtered out of the active P-wave data while the highest frequency in the passive data is 35 Hz. The passive 3D DMO stacked cube covers a smaller area than the active 3D DMO stacked cube and mostly has lower image quality (see Figure 17 for the location of the passive survey DMO stacked cube). A comparison of the 3D processed images along inline 1041 and crossline 1040 of both surveys is shown in Figure 18. Reflections P1 and Q2 are imaged in both inline and crossline directions of the active survey image (Figure 18a). Reflection P1 is a coherent and continuous moderately-dipping reflection in the inline direction of the active survey whereas it is shorter (only about 1 km long) and has shallower dip in the crossline direction (Figure 18a). Only the shallowly-dipping parts of P1 are imaged with the passive seismic survey (Figure 18b). In particular, parts of P1 near the end of inline 1041 and close to the intersection with crossline 1040 are imaged (see Figure 18b). P1 appears to extend further in the crossline direction of the passive cube. However, this part of P1 is not observed on the active seismic data. The dip of P1 on the passive crossline (Figure 18b) is also very close to the dip observed on the active data (Figure 18a) Reflection Q2 is imaged as a subhorizontal reflection in inline and crossline directions of the active and passive survey images (Figure 18). Q2 shows higher amplitude in Figure 2b at intersection of the inline and crossline at 1.25 s. Reflection R3 is a high amplitude reflection between P1 and Q2 near 0.75-1 s of the passive survey image (Figure 18b). R3 is mostly sub-horizontal on inline 1041 but has a slight dip to the northwest on crossline 1040. In comparison, R3 is not clearly imaged on the active seismic cube (Figure 18a).

CONCLUSIONS

Ambient noise acquired over the Lalor Lake mining area has provided an opportunity to test passive seismic interferometry over a complex crystalline rock environment. The underground mining activity and human activity at the Town of Snow Lake are the main sources of the ambient noise. The recorded ambient noise from these noise sources comprises both surface and body waves. Estimated Green's function obtained by cross-correlating of the recorded noise between all possible pair of receivers forms the virtual shot gathers used in this survey. Comparison of the 3D processing results of the passive and active survey images is encouraging. In general, results of the passive survey show fewer reflections. However, best results for 3D passive processing were obtained for subhorizontal reflections.