GEOLOGICAL SURVEY OF CANADA
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ABSTRACT

Seismic reflections methods are a powerful tool to detect and image structures associated with volcanogenic massive sulphide (VMS) deposits. Seismic interferometry has recently been developed as a robust method to process passive seismic data and image geological features. In order to test the capability of seismic interferometry to image ore deposits in the crystalline rock environment approximately 300 hours of ambient noise data covering an area of 4 km² were acquired over the Lalor mining area, near Snow Lake, MB, Canada,. The interferometry survey consisted of 336 receivers installed in a grid comprising sixteen lines. The study area encompasses the Lalor deposit, a 27 Mt VMS deposit located at a depth of ~700 m. A distinct, overlapping 3D active source seismic survey was also acquired in the area and we use it here to evaluate our interferometry results. An estimate of the seismic wave field (Green's function) is retrieved by crosscorrelating the noise between all receiver locations in each hourly segment of passive seismic data. The crosscorrelated results are summed to generate 'virtual' shot gathers at each physical receiver location. The virtual data is processed along all 2D lines with conventional methods similar to those applied to active 3D data. The DMO-stacked section obtained reveals a number of events, some more coherent than observed on the active seismic section. Of particular interest is an event possibly associated with one of the lenses associated with the massive sulphide deposit. A comparable event is also observed on the active seismic data. These results are encouraging and demonstrate the benefits of ambient noise measurements and interferometry in for mineral exploration in crystalline rock environment.

INTRODUCTION

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.

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). The reverberations from these noise sources can be processed in such a manner that they appear as if they were generated from sources on the surface instead. As such, the virtual data can theoretically replace data obtained from a traditional, far more expensive, surface 3D 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-ofconcept 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 (Bellefleur and White, 2014).

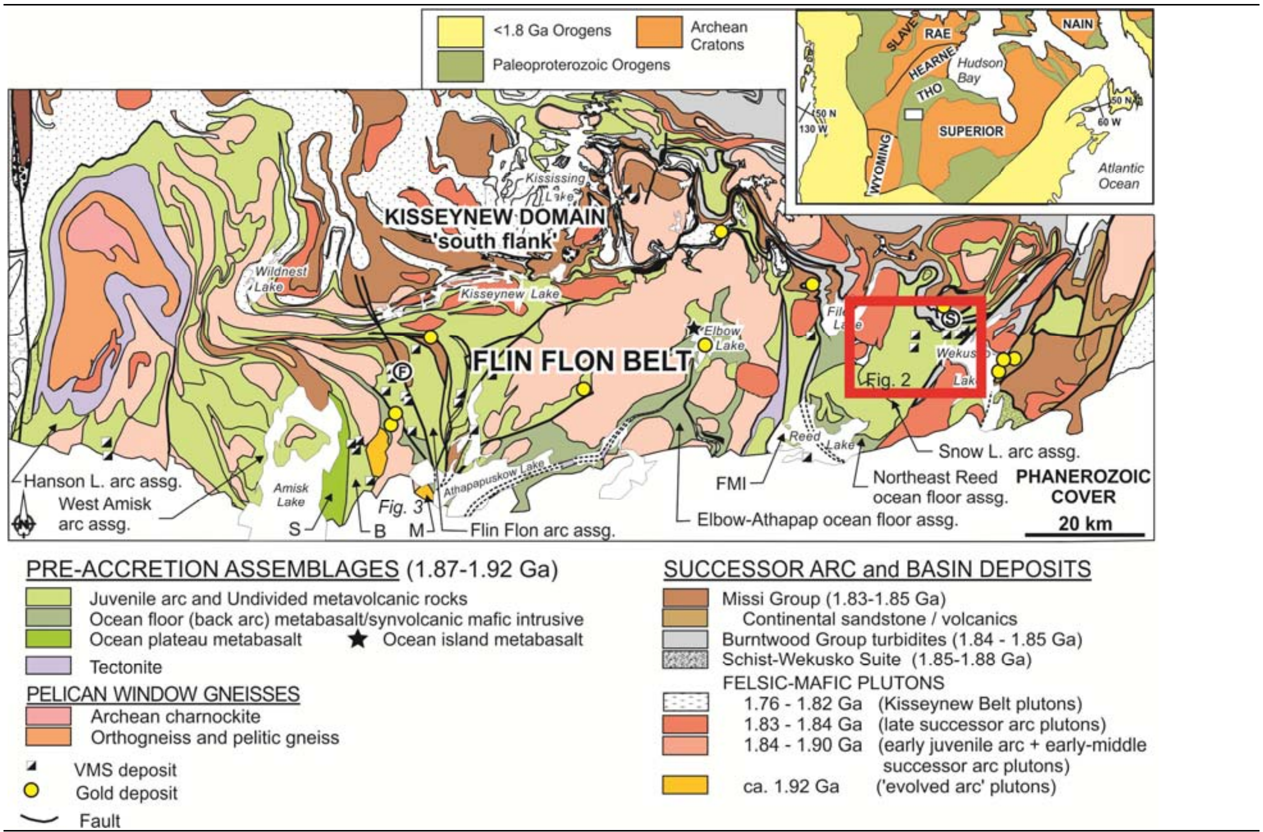

Figure 1. Location map and general geology (After Galley et al, 2009). Location of Fig.2 is identified in red outline. THO: Trans-Hudson Orogen.

GEOLOGIC SETTING

The Trans-Hudson Orogen (Fig. 1) is the result of oblique collision between the Superior and Hearne Archean terranes (Corrigan et al., 2009). Caught up in the elements of the orogeny that remain in what is now northern Manitoba is a collage of both juvenile oceanic arcs and oceanic arc and basin material underlain by continental crust. This collage has been separated into a number of distinct assemblages divided by fault systems, including those thought to be primary thrust surfaces. Each tectonostratigraphic assemblage is characterized in terms of stratigraphy, geochemical and isotopic signatures, age and inferred origin within a plate tectonic context. The easternmost structural domain is the Snow Lake assemblage (Figs.1 and 2), which itself is comprised of a number of sequences of complexly altered and metamorphosed mafic to felsic volcanic, volcaniclastic and sedimentary rocks intruded by rhyolitic and dacitic material which pre-date the felsic 1889 Ma Richard Lake pluton. The Lalor auriferous VMS deposit lies within the so-called Chisel sequence of volcanic rocks representing more evolved arc signatures (Bailes and Galley, 1999).

The polymetallic Lalor deposit contains approximately 27 Mt of ore potentially including 75 t of Au as well as 684 t of Ag, 1.38 Mt of Zn and 0.2 Mt of Cu. A relatively recent and comparatively deep (> 500 m) electromagnetic geophysical discovery by HudBay Minerals, the Lalor deposit is currently under development for commercial production. As Caté et al. (2013) and Mercier-Langevin et al. (2012) point out, the deposit is an ideal "natural laboratory" to "better understand the signature and key characteristics of auriferous VMS deposits". The preliminary work by Caté et al. (2013) supports the contention of Bailes and Galley (1999) for other VMS deposits in the area that the deposit is located at the contact between the lower and upper series within the Chisel sequence and that the hanging wall contact within the deposit is possibly a major structural feature. Caté et al. (2013) suggest that eleven styles of alteration have occurred and that there exists at least five types of mineralization including both semi-massive and massive sulphides and mineralized amphibole quartz assemblages within the deposit.

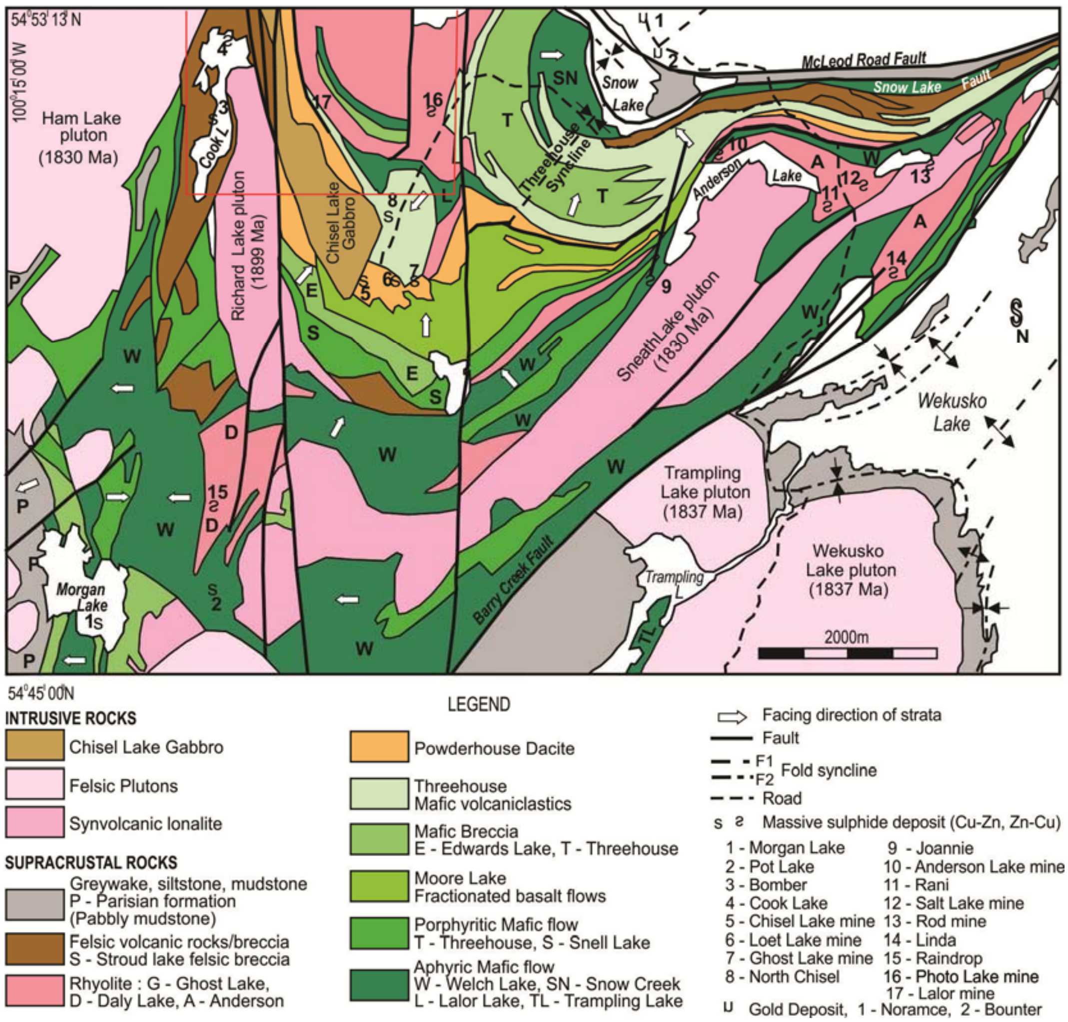

Figure 2. Detailed geology of Snow Lake. After Bailes and Galley (2006). The red box outlines the approximate location of Figure 4.

INTERFEROMETRY BACKGROUND

The geophysical roots of interferometry lie with Claerbout (1968) who demonstrated that the reflection response of a layered medium was equivalent to the correlation of the transmitted responses. Schuster et al. (2004) and Schuster (2001) clarified key relationships related to seismic imaging and Campillo and Paul (2003) demonstrated the first application of the technique to the retrieval of surface waves from a dataset. Sneider (2004) demonstrated the estimate of the Green's functions was dominated by sources near the stationary point. Through source-receiver reciprocity, Wapenaar (2004) and Wapenaar et al. (2002, 2004) demonstrated that Claerbout's layered earth conjecture is applicable to arbitrary 3D inhomogeneous acoustic or elastic media. The works by Wapenaar and others indicated that the theory held for both impulsive and white-noise sources, and in 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 the body wave reflectivity using interferometry. It is perhaps not unreasonable to conclude that the work to date has not been as successful as the studies of surface wave retrieval. Indeed, the use of interferometry on global array data to derive the surface wavefield from ambient noise is becoming commonplace (see, for example, Kao et al. (2013) for a study of Canada). The reason for this asperity in success is attributable in large part to the smaller decay in amplitude with distance of surface waves than body waves. We assume, based on a few key lines of evidence discussed below, that noise sources in an active mine should be better-suited to generate body wave noise with sufficient amplitude to ameliorate this condition. Improved images can be obtained in an area with numerous and spatially widely distributed noise sources. Such conditions should be possible at an active mine. In addition to the study by Snelling et al., (2013) mentioned earlier, 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 km^2 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) of noise sources 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 points 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.

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 (Figure 3a) to enable the shot hole drilling trucks (Figure 3b) to traverse the lines. The cables required to monitor the receivers during the subsequent shots had to be deployed by helicopter (Figure 3c.) The recording crew alone deploying gear consisted of 39 persons. A number of these costly issues can be avoided if a technique can be found that provides similar images, but only utilizes synchronized receivers.

THE 2013 INTERFEROMETRY FIELD EXPERIMENT

Figure 3. a) Mulchers used to cut lines for the active source 3D survey b) Shot hole drilling truck, c) Survey helicopter d). Interferometry installation.

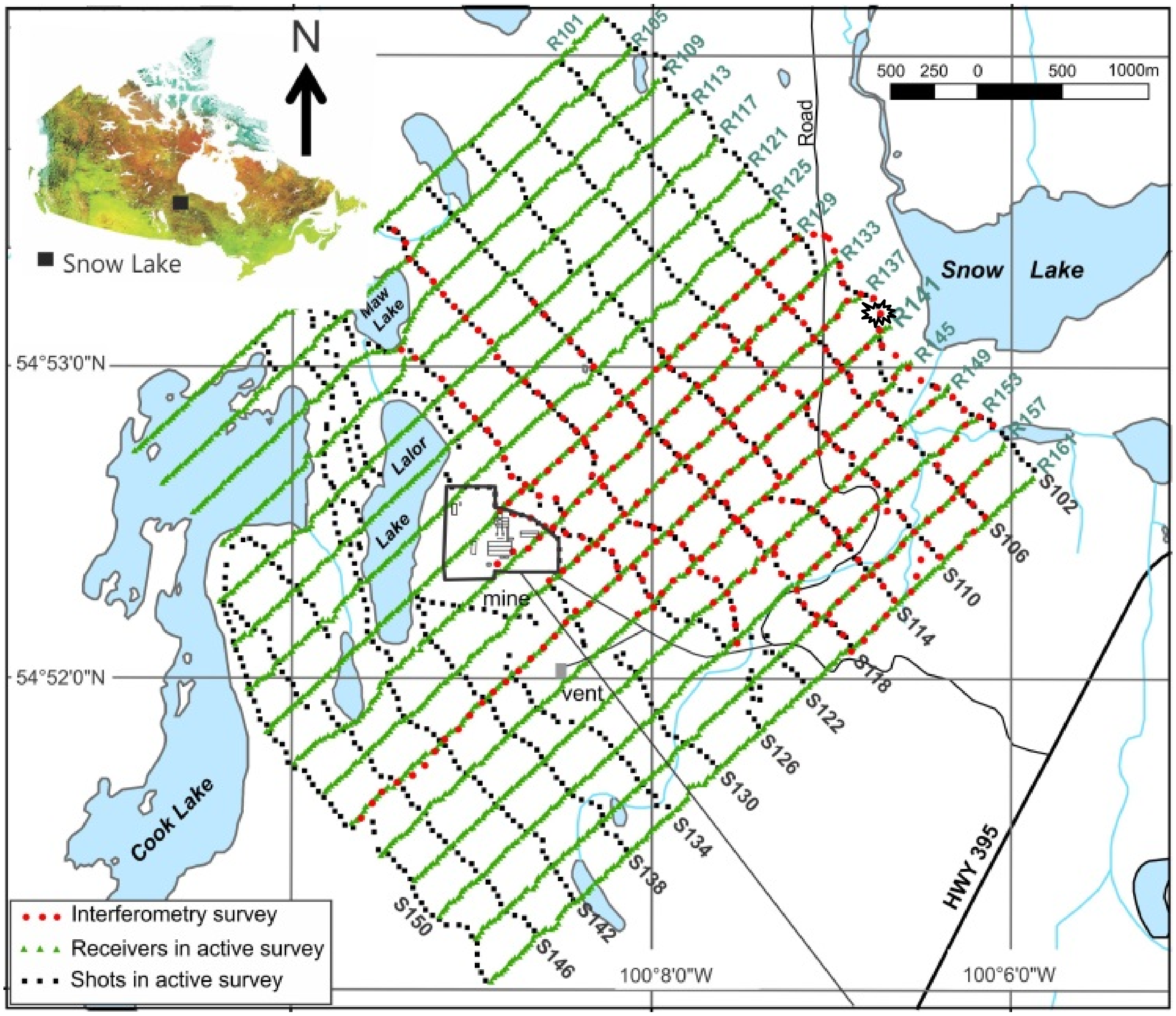

Figure 4. Geometry of the active 3D survey and the interferometry survey in the Lalor mining area. The active and interferometry surveys cover approximately 16 km^2 and 4 km^2, respectively. The mine area and ventilation shaft is also shown. The shot location for Figure 6 is also shown.

As part of the TGI-4 program, the Geological Survey of Canada acquired ~300 hours of passive seismic data at each of 336 receiver locations near Lalor Lake (Figure 4) during March of 2013. The locations and recording intervals are given in Table 1. Receivers for the interferometry survey consisted of GSR units set to record for one month with a 2 ms sampling interval and which were connected to GS-One 10 Hz vertical component geophones fitted with a marsh spike to penetrate the ice layer at the surface (see Figure 3d). The GSR data recorder from Geospace Technologies Inc. is a standalone acquisition unit that can record seismic data for up to one month. Sixteens lines were deployed along a portion of the planned 3D survey. The station spacing along each line is ~100 m. Crew size was two persons and we were able to deploy up to four crews for the installation. A crew could typically install 20-40 sites per day depending on the local topography and difficulty drilling a small hole into the frozen ground for the geophone. The interferometry data was acquired both prior to and during a larger conventional active 3C-3D seismic survey (see Figure 4) aimed at defining the signature of the deposit and geological structures to depths of over 3 km.

PROCESSING METHODOLOGY

Noise data collected prior to the commencement of the active source survey was divided into one hour segments for a total of 300 segments per receiver location. Visual inspection of the noise segments sometimes reveals reflections which could be generated by vertically traveling events (see Figure 5a-b). An image generated from noise that is unbalanced will contain artefacts or ghosts as key elements may not cancel out during the processing and stacking of the segments. To better understand the nature and spatial distributions of the noise a beamforming evaluation (B) was performed to determine the average velocity (v) in the 1000-5000 m/s range and direction (θ) (θ is between 0-360º where north is 0 and θ is increasing counter clockwise). The beamforming was performed for two frequency bandwidths (1-3 Hz and 23-25 Hz) using all hourly data segments at all receivers ($N = 336$) locations using the relation of Draganov et al. (2013):

$$B(v,\theta) = 1/\delta f \int_{f_c-\delta f/2}^{f_c+\delta f/2} \sum_{i=1}^{N} S_i(f) \exp(i\frac{f}{v}(x_i sin\theta + y_i cos\theta))df \qquad (1)$$

where δf is the frequency bandwidth, f_c is central noise frequency, and S_i is recorded noise in the frequency domain on the ith seismic station. An example of beamforming for the 173rd hour is shown in Figure 5c-d. Beamforming results for the 1-3 Hz bandwidth show peaks at 351º and 300º and is characterized with velocities of 3000 m/s and 1500 m/s, respectively. The 23-25 Hz bandwidth indicates a velocity of about 3000 m/s at 100º, almost towards the mine site. The calculated velocities of 3000 and 1500 m/s suggest that beamforming results are dominated by surface waves. The power spectral density (PSD) analysis for hour 173 along lines R141 and S122 is shown in Figure 5 (e-f). Energy reaching up to 130 Hz is observed on both lines. It should be mentioned that hour 173 is exceptional and characterized by many events related to mining activities, including underground explosions. In general, the PSD analysis shows little energy higher than 30 Hz in most segments (results not shown here).

To create virtual shot gathers from ambient noise, the Green's function is estimated between each pair of receiver locations using the relation (Draganov et al., 2013):

$$G_{p,q}(x_A, x_B, t) + G_{p,q}(x_A, x_B, -t) * S(t) = \langle v_p(x_A, -t) * v_q(x_B, t) \rangle \qquad (2)$$

$G_{p,q}(x_A, x_B, t)$ and $G_{p,q}(x_A, x_B, -t)$ are the Green's function and its time-reversed version between receiver positions x_A and x_B. The Green's functions are convolved with the autocorrelation of the source time function $S(t)$ of the noise sources. The right-hand side of equation (2) is the crosscorrelation of the particle velocity at x_A and x_B in p and q directions. The angular brackets imply the spatial summation is over all noise segments. It is assumed that ambient noise sources are uncorrelated and randomly distributed. Green's functions at positive and negative time lags are retrieved from the crosscorrelated noises of long passive seismic records; however as equation (2) shows we are getting only an estimate of the Green's function that has been convolved with an unknown source function.

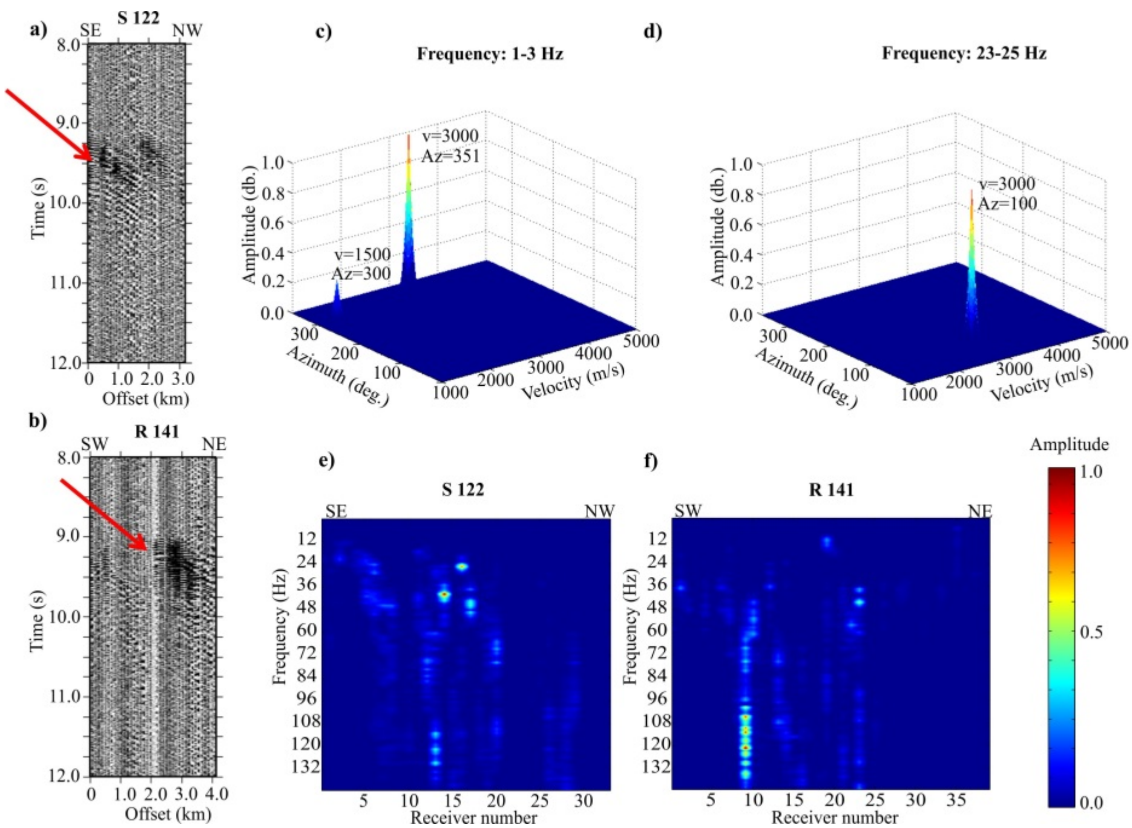

Figure 5. a-b) a portion of ambient noise along lines S 122, and R 141 (see Figure 4 for the location of the lines). The time window shows 8-12 s of minute 37 for the 173th hour segment. The red arrows show events which are potential reflections. (c-d) the beamforming analysis for all receiver locations at hour 173 for frequency bandwidth of 1-3 Hz and 23-25 Hz, respectively. (e-f) the power spectral density (PSD) analysis along the line S 122 and R 141 at hour 173, respectively.

Processing of each hourly segment of noise included bandpass filtering between 2-30 Hz. The chosen bandwidth is based on the beamforming and PSD analyses. Noise at each receiver location is normalized to its maximum amplitude. The crosscorrelation is calculated for each possible pair of locations in the segment (i.e., about 110000 calculation/segment for a total of 33 million calculations in the survey). The beamforming analysis shows several possible directions for the origin of the seismic waves, indicating that the retrieval of the estimate of Green's function may be better for some receiver pairs at positive time

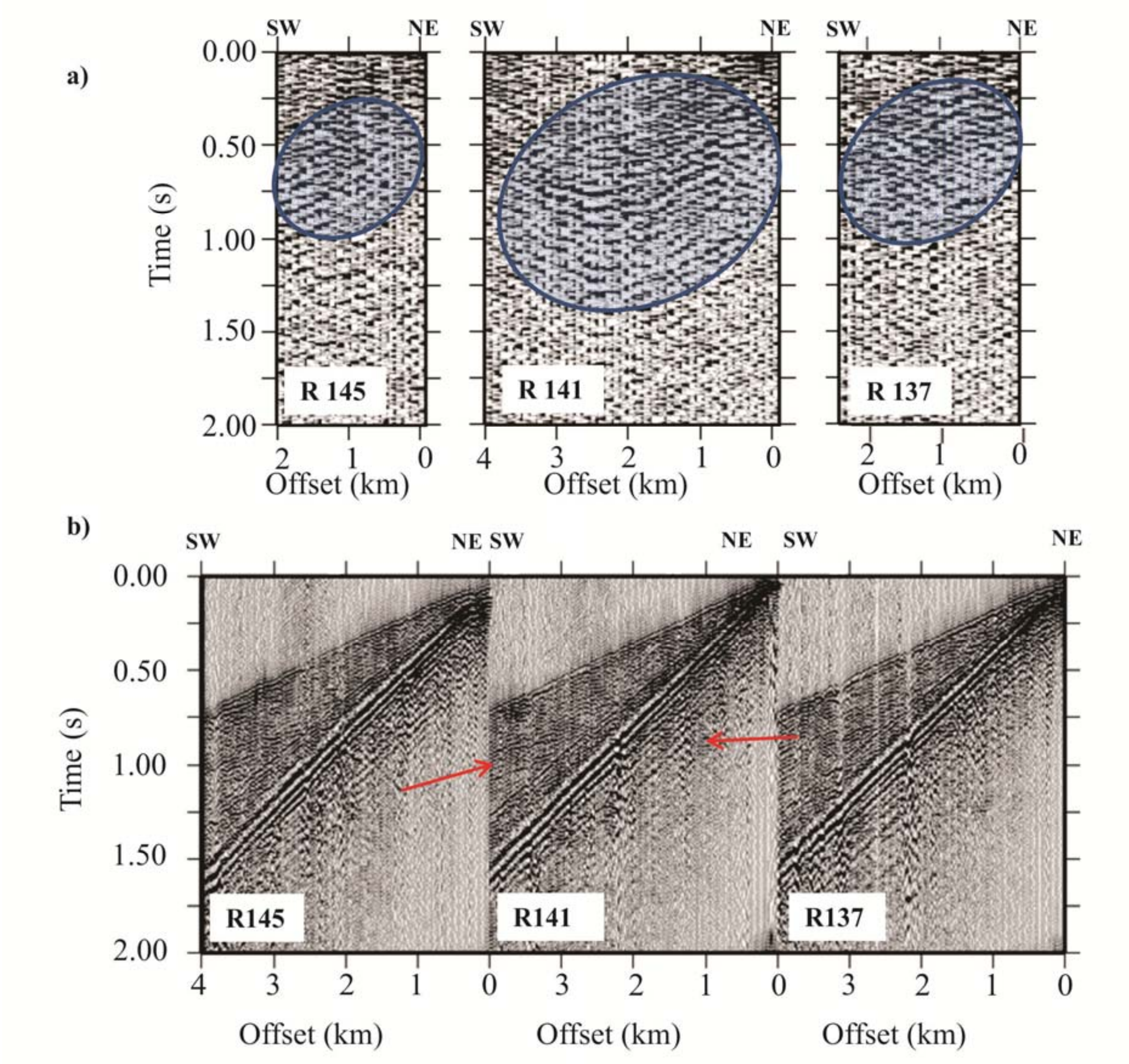

Figure 6 Comparison of a) interferometry virtual shot gather with b) active 3D shot along lines R 137, R141, and R 145 when the shot point is on line S 102 (see Figure 4). The receiver lines on R137 and R145 are shorter in the interferometry survey. The shaded areas show imaged coherent events (see text for more details). The arrow shows a reflection imaged in active survey along line R 141.

lags and at negative lags in other pairs. For this reason, we summed the retrieved Green's function and its time-reversed function together for a more complete calculation. Finally, results from all hourly segments are spatially summed to generate final results. Figure 6 shows a comparison of an interferometry virtual shot with an active shot along lines R 137, R 141, and R 145 (see Figure 4) for a co-located active and virtual shot points on line S 102 (see Figure 4 for shot location). A 2-30 Hz bandpass filter was applied to the active seismic data in order for it to possess the same frequency content as the virtual data. In the 2-30

Hz range, the active seismic data is dominated by surface and refracted S-waves. Line R 141 shows a low-frequency reflection in the active survey (see arrows in Figure 6b). There are more coherent events between 0-1 s in the virtual data (shaded area in Figure 5a). The apparent velocity of events in the virtual shot gather is near 3500-4500 m/s, close or slightly higher than the low-frequency events in the same area in the active data (Figure 6b). These coherent events could be reflected body waves (consistent with S-wave velocities in the area). A possible reason for the differences between active and virtual data is that ambient noise sources have irregular distribution and could be reflected from the areas which do not correspond to arrival in the active data. Difference in bandwidth is also another explanation.

All 2D lines of the interferometry survey were processed with conventional processing steps similar to those applied to the active 3D data. The main steps were, (1) static corrections, (2) filtering of surface waves (3) sort to CDP domain, (4) velocity analysis, (5) DMO corrections, (6) stack, and (7) FX-deconvolution. It should be noted that the 2D virtual sections have lower fold and resolution than the active data. Results for the active survey benefitted from 3D processing algorithms. Figure 7 presents a comparison of DMO corrected stacked sections along line R 141 (Figure 4). In general, the active survey provides a clearer image of the subsurface units to a depth of 3 km, but there are important similarities. The UC reflection near the top of the Balloch basalt can be identified on both images and, perhaps surprisingly, is more coherent in the interferometry data than the active section. The Lalor deposit (#10 lens?) is tentatively imaged as diffractions labelled VM in both sections in Figure 7. The deeper reflection BB (near the base of the lower Chisel sequence) is partly imaged in the interferometry section (Figure 7b),but appears at shallower depths.

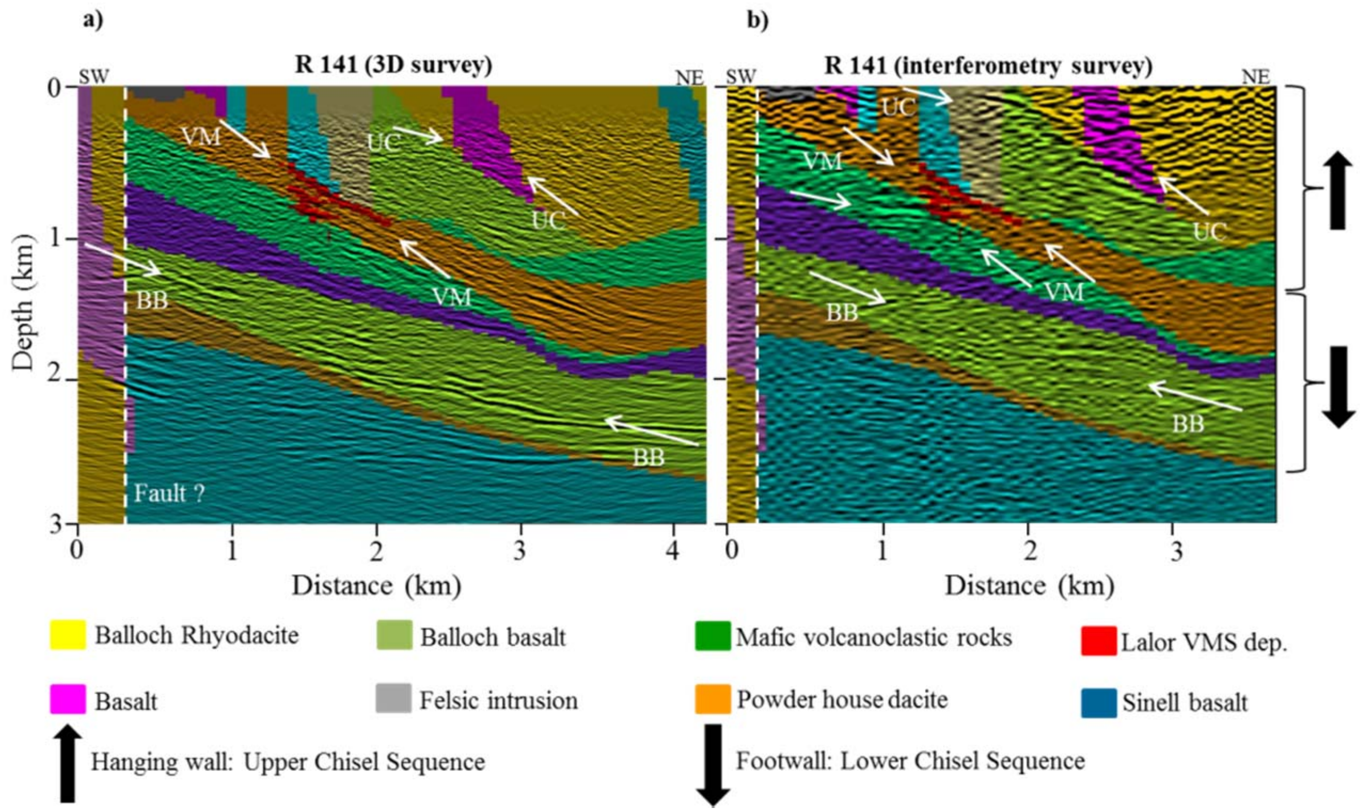

Figure 7 The DMO-corrected stacked section along line R 141 superimposed on the geological model (after Bailes et al., 2013) for a) the active 3D survey, b) the interferometry survey. The dashed subvertical line in the geological model is interpreted as a possible fault. Arrows and notation are discussed in the text.

SUMMARY

A test survey to evaluate the suitability of interferometry for mineral exploration was completed in March of 2013. The survey was conducted at an active mine site and where the results can be directly compared to traditional active source seismic reflection data. Receivers (only) were deployed in the test survey at 336 locations along a grid covering one quadrant of the active source survey. Virtual shot gathers have been created at every receiver location. A few of the virtual gathers can be compared against a shot gather from the active source survey. There are differences, but there are similarities. The virtual shot gathers have been processed in two dimensions along a single line and are compared against the 3D active source results extracted along the same line used for the interferometry. There are differences in the two results requiring further study however these preliminary results (including the identification of a signature related to the sulphides) indicate the technique is promising and may be a new tool in the arsenal of exploration methods for mineral exploration. Further work is on-going. We are continuing to process the interferometry data in 3-D for better comparison against the active source survey.

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We would like to acknowledge Hudbay Minerals Inc. for both their logistical support on site and for providing accommodation in Snow Lake. The GSR units were graciously provided by the Petroleum Technology Resource Center, and SaskPower provided support for a few days in Estevan, SK to aid in the reaping of the data from the recorders. We are extremely grateful to SAExploration, Inc., Calgary for folding our crews into their safety procedures and for retrieving our recorders at the end of their active source survey. Geospace Technologies Inc. is thanked for their flexibility in accommodating the late return of two geophones. We thank Lisa Roach for thoughtful comments reviewing the manuscript.

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Table 1. Recording locations and times for the 2013 Lalor Lake Interferometry Survey.

Line	Station	Latitude	Longitude	Deployment Duration	Deployment Time Utc	Resync Time Utc
102	102001	54.88031	-100.10179	22 23:49:24	2013-02-26 16:20:42.000000	2013-03-21 16:10:06.998000
102	102002	54.88113	-100.10456	23 1:37:23	2013-02-26 16:28:13.000000	2013-03-21 18:05:36.998000
102	102003	54.88180	-100.10557	23 1:31:11	2013-02-26 16:32:58.000000	2013-03-21 18:04:09.998000
102	102004	54.88233	-100.10702	17 18:41:49	2013-02-26 16:38:10.000000	2013-03-16 11:19:59.998000
102	102005	54.88270	-100.10848	22 21:29:41	2013-02-26 20:30:41.000000	2013-03-21 18:00:22.998000
102	102006	54.88339	-100.10965	22 21:20:52	2013-02-26 20:37:36.000000	2013-03-21 17:58:28.998000
102	102007	54.88401	-100.11086	22 1:29:6	2013-02-27 16:27:35.000000	2013-03-21 17:56:41.998000
102	102008	54.88459	-100.11206	22 1:18:17	2013-02-27 16:33:10.000000	2013-03-21 17:51:27.998000
102	102009	54.88540	-100.11238	22 0:50:25	2013-02-27 16:37:40.000000	2013-03-21 17:28:05.998000
102	102010	54.88629	-100.11228	22 0:48:13	2013-02-27 16:42:29.000000	2013-03-21 17:30:42.998000
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157	157009	54.86965	-100.11820	22 14:38:48	2013-02-26 23:02:10.000000	2013-03-21 13:40:58.998000
157	157030	54.87523	-100.10791	23 18:34:35	2013-02-25 20:08:36.000000	2013-03-21 14:43:11.998000
157	157031	54.87579	-100.10671	23 18:33:15	2013-02-25 20:13:53.000000	2013-03-21 14:47:08.998000
157	157032	54.87638	-100.10558	23 18:32:3	2013-02-25 20:18:27.000000	2013-03-21 14:50:30.998000
157	157033	54.87704	-100.10455	23 18:34:17	2013-02-25 20:24:40.000000	2013-03-21 14:58:57.998000
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157	157035	54.87834	-100.10233	22 23:36:1	2013-02-26 15:31:03.000000	2013-03-21 15:07:04.998000
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161	161036	54.86817	-100.11488	23 1:14:5	2013-02-25 21:21:34.000000	2013-03-20 22:35:39.998000