Application of seismic interferometry to imaging a crystalline rock environment at an active VMS mine in Flin Flon, Manitoba, Canada

by

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Abstract

Seismic interferometry is a technique by which the Green’s function or impulse response between two receivers is recovered through the cross-correlation of the transmission responses recorded by those receivers. This technique has found several applications, including the generation of virtual shot gathers from ambient seismic noise for use in seismic reflection processing. In March of 2013, 336 receivers were deployed over the volcanogenic massive sulphide (VMS) deposit found at the Lalor mine in Manitoba, Canada. Approximately 300 hours of ambient seismic noise was recorded for the purpose of testing the effectiveness of seismic interferometry in imaging a crystalline rock environment. A time-domain beamforming algorithm was implemented to determine the locations of the sources present during recording. The results indicate that the vast majority of the recorded noise originated from mine and ventilation shafts located at the Lalor mine. Synthetic experiments were conducted to determine the effects such a source distribution would have on the application of seismic interferometry in the presence of dipping reflectors. The experiments show that if sources are located only on one side of a receiver line, the dip and lateral extents of reflectors will not be imaged properly. A technique involving beamforming and F-K filtering was developed to remove surface wave noise originating from near-field sources. Using this technique, the raw data was processed into virtual shot gathers free of surface wave noise. Virtual shot gathers were generated along 4 of the receiver lines and processed as separate 2-D reflection datasets. The resulting reflection profiles are compared against coincident DMO-stacked data from a larger 3-D active seismic survey conducted over the Lalor mine. Using this comparison in conjunction with knowledge of the local geology, events recovered in the passive reflection profiles are interpreted as either real reflections or spurious events, and possible explanations of their origin are given.

Keywords: Passive seismic interferometry; VMS deposit; 2-D seismic processing; Ambient seismic noise; Mining; Cross-correlation
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<th>Description</th>
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<tbody>
<tr>
<td>AGC</td>
<td>Automatic gain control</td>
</tr>
<tr>
<td>CDP</td>
<td>Common depth point</td>
</tr>
<tr>
<td>CVS</td>
<td>Constant velocity stack</td>
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<tr>
<td>DMO</td>
<td>Dip moveout</td>
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<tr>
<td>NMO</td>
<td>Normal moveout</td>
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<tr>
<td>PSD</td>
<td>Power spectral density</td>
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<tr>
<td>SC</td>
<td>Surface consistent</td>
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<tr>
<td>SCG</td>
<td>Stacked correlation gather</td>
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<tr>
<td>SI</td>
<td>Seismic interferometry</td>
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<tr>
<td>SNR</td>
<td>Signal to noise ratio</td>
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<tr>
<td>VMS</td>
<td>Volcanogenic massive sulphide</td>
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Chapter 1.

Introduction

1.1. Background and Motivation

Traditional active source seismic reflection surveys have long been used to investigate the Earth’s subsurface at a range of depths. By using carefully positioned sources and receivers and a well-established set of data processing techniques, geophysicists are able to generate an image of the subsurface in a controlled and repeatable manner. For this reason, among others, active source seismic surveys are used extensively in the oil industry to find new reservoirs, as well as to extend the known boundaries of existing ones. However, as with any technique, active source seismic surveying has its limitations. In particular, active source recordings typically have issues imaging at lower frequencies, although perhaps the more important limitation from an industry standpoint is the financial cost. Moreover, the environmental impact or simply the logistics of performing such a survey in certain areas may make one unfeasible.

Passive source seismic imaging is a relatively new field which aims to fill the void as a low cost, low frequency seismic imaging technique which may be used as an alternative to or in conjunction with traditional active source surveys.

Passive source imaging has been in use for some time in fields such as ultrasonics and helioseismology, but its application to geophysical exploration in the form of seismic interferometry (SI) has emerged only within the last decade or so. Passive SI uses the ambient seismic wavefield rather than active sources to obtain information about the subsurface. This wavefield is generated by ‘passive’ sources, which refers broadly to any source not controlled by the surveyors. The wavefields may be generated by natural sources such as earthquakes or rock fracturing, or by anthropogenic means such as passing cars, construction, or other industrial noise. The
wavefields generated by such sources are typically relatively low frequency (<30 Hz). The aim of SI is to leverage these sources to generate an image of the subsurface without the need for active sources. Combining the ability of seismic data to resolve structure at depth while eliminating the need for active sources makes SI an attractive option for low cost non-destructive geophysical exploration.

### 1.2. Seismic Interferometry by Cross-Correlation

Generally speaking, SI is a technique which allows retrieval of the impulse response between two receivers as if one of them had been a virtual source (Draganov et al., 2010). SI can be separated into two categories depending on the kind of sources used. Active source interferometry, as an example, is able to redatum sources placed at the surface to the positions of the receivers, possibly in a horizontal well at some depth, in order to bypass any complex surface geology (Wapenaar et al., 2010b). Active source interferometry is not limited to sources placed at the surface. Schuster (2009) describes the multitude of data transformations that are possible using interferometry, including transforming vertical well data into surface data, and vice versa. Schuster et al. (2004) show how SI can be used to image reflectors using drill bit at depth as a seismic source. Whereas active source SI is able to redatum controlled sources at a variety of approximately known locations to the positions of the geophones, passive source SI attempts to redatum sources from unknown locations in the subsurface to the position of the receivers on the surface. In doing so, it is able to turn the Earth's response to a source at depth into its response to the same source had it been present at the surface (Wapenaar et al., 2010a). As a systems response to an impulsive source is called its Green’s function, SI is sometimes referred to as ‘Green’s function retrieval’. This idea was first formulated by Jon Claerbout in a seminal paper which proved that the reflection response of a 1-D layered medium could be retrieved from the autocorrelation of its transmission response (Claerbout, 1968). This would later be generalized to using the cross-correlation of signals to obtain the Green’s function over an arbitrary heterogeneous, lossless, acoustic (Wapenaar 2003; Derode et al., 2003), and elastic (Wapenaar, 2004) medium.
Figure 1.1 shows the standard configuration of sources and receivers necessary for passive reflection SI. Receivers lie on the surface $\mathbb{S}_0$ above the volume to be imaged $\mathbb{V}$, and are surrounded by sources on the surface $\mathbb{S}$. Cross-correlating the signals recorded at $x_A$ with $x_B$, given by $G(x_A, x_S)$ and $G(x_B, x_S)$, results in the signal that would have been recorded at $x_B$ had there been a source at $x_A$, $G(x_B, x_A)$. The mathematics require certain assumptions to be made on both the sources and the medium. The receivers should be illuminated equally in all directions, meaning that impulsive sources should completely surround the receivers. Furthermore, while the medium inside $\mathbb{V}$ may be arbitrarily complicated, the medium outside should be homogeneous (Wapenaar et al., 2002). If these assumptions are fulfilled, then the following holds:

$$
G(x_A, x_B, t) + G(x_A, x_B, -t) \propto \oint_{\mathbb{S}} G(x_A, x_S, t) \ast G(x_B, x_S, -t) \, dx_S
$$  \hspace{1cm} (1.1)

where $G(x_A, x_B, t)$ represents the Green’s function between $x_A$ and $x_B$, and $\ast$ denotes convolution. The time reversal of the second term in the convolution makes it a cross-correlation. In practical applications the source distribution is discrete and not impulsive. Therefore Equation (1.1) is replaced with

$$
(G(x_A, x_B, t) + G(x_A, x_B, -t)) \ast A_S \approx \langle v(x_A, t) \ast v(x_B, -t) \rangle
$$  \hspace{1cm} (1.2)

where $v$ represents the recorded particle velocities and $A_S$ is the autocorrelation of the source wavelet or noise signature. The angled brackets indicate an ensemble average. In practice this average is performed either by cross-correlating very long time signals, or by summing the cross-correlations over each available source. In the case of simultaneously acting sources, or when the sources are active at unknown times, the data may be split into separate or overlapping time slices which are then cross-correlated and summed.
Figure 1.1. Theoretical source/receiver layout for SI. Receivers lay on the Earth’s surface along $S_0$ above the volume to be imaged $V$. Sources surround $V$ along $S$.

The assumptions made in the interest of mathematics are rarely fulfilled in reality. The medium outside of $V$ may not be homogeneous, or even approximately so. In this case ghost reflections may occur. These ghost reflections will depend on the depth of the source. Therefore, stacking over many sources of different depths will tend to attenuate the ghost reflections (Draganov et al., 2004). The assumption that the medium is approximately non-attenuating may also be invalid. If this is the case, then sources should be present throughout $V$ rather than just along the surface $S$ (Snieder, 2007). The phase information is unaffected if such sources are unavailable, however the amplitudes will be incorrect (Roux et al., 2005). The assumption which is most often broken, and has the largest effect on how the data must be processed, is that of isotropic source illumination. Recording over long periods of time increases the likelihood of including sources from all directions, but in most cases the source distribution will be biased in certain directions.

Performing brute force SI on data containing a biased source distribution may give results which contain non-physical events, as well as a blurring or misrepresentation of real events (Vasconcelos and Snieder 2008a; 2008b). The heterogeneity of the subsurface can actually aid in proper illumination (Wapenaar 2006), nonetheless several methods have been developed to reduce or remove the negative effects of an incomplete source distribution. A directional-balancing algorithm was developed by Curtis and Halliday (2010) which is able to remove the bias and blurring that results from incomplete or unequal illumination. This method uses a dense receiver
array around the position of the virtual source to estimate the radiation pattern. By comparing this radiation pattern to the pattern generated by synthetic data, a correction factor can be derived which is able to correct the data.

A more recent development is SI by multidimensional deconvolution, which reformulates the retrieval of the Green’s function as an inverse problem (Wapenaar et al. 2008). By deconvolving the cross-correlations of one receiver array by the cross-correlated incoming wavefield as recorded by a second, orthogonal array, SI by multidimensional deconvolution is able to compensate for directionally biased source distributions. Additionally, this inverse method is not limited in attenuating media in the same way that SI by cross-correlation is. The method requires that wavefields be separable into down-going and up-going (or incoming and outgoing) components, which may not always be possible.

Another approach is to determine the ray parameter of the sources contained in each time slice and weight the resulting cross-correlations such that each ray parameter is equally represented. Ruigrok et al. (2010) used this method to obtain high resolution images of the lithosphere. A similar method was applied by Draganov et al. (2010) to determine noise panels containing body wave noise, which are known to contribute strongly to the retrieval of reflections. It was shown that including only these panels in the application of SI improved the results over those obtained using all the data.

SI by cross-correlation can lead to results with artefacts and incorrect amplitudes if the mathematical assumptions are not met. Nonetheless, it has found numerous applications in surface wave dispersion measurement (Bensen et al., 2007; Shapiro and Campillo, 2004; Wapenaar et al., 2011), surface wave estimation and removal (Halliday et al, 2007; Halliday et al., 2010; Vermeer et al. 2010; Yan and Hermann, 2009), as well as shallow (Cheraghi et al., 2014; Draganov et al., 2009; Draganov et al., 2013; Xu et al., 2012) and deep (Ruigrok et al., 2010; Ruigrok and Wapenaar, 2012) reflection imaging. Although the requirements placed on the source distribution may be strict, in most cases they can be relaxed as incorrect amplitude information is often acceptable. On the other hand, there are no restrictions placed on the receiver array and therefore an SI survey may be performed almost anywhere. This suggests it is an ideal tool for
performing low cost reconnaissance surveys as such a survey may be done with a relatively small number of single component receivers.

1.3. Objective

Over the last decade or so many techniques have been developed to improve the application of SI, particularly in the case where the mathematical assumptions are not met. Each of these has its uses and drawbacks, and the choice of which is best for a given application depends largely on the nature of the available data. Furthermore, as SI is still in the early stages of its development, its application to reflection seismology has been restricted largely to regions which are relatively quiet in terms of anthropogenic noise and which have geology which is for the most part horizontally stratified. Therefore, there is still some question as to how passive source SI performs in regions with more complicated ambient noise fields and geological structures.

In March of 2013, approximately 300 hours of ambient seismic noise were recorded over the Lalor mine in Manitoba, Canada. This passive survey occurred shortly before a coincident 3-D dynamite source survey. Lalor is a volcanogenic massive sulphide (VMS) deposit consisting of 12 mineralized zones at depths from 570 m to 1160 m (Bellefleur et al., 2015a). It is also an active mine site, and has a complicated noise field resulting from the blasting, drilling, and traffic. The crystalline environment of a VMS deposit paired with a less than ideal noise field make applying SI quite a challenge. However, VMS deposits tend to make good targets for seismic surveys as they typically have high density relative to the host rock. The coincident 3-D active survey will provide a good baseline with which to compare the 2-D SI results. These factors combine to make the Lalor mine camp an ideal site to test the methodology of SI. As the receiver array that was used in the field does not allow for more complicated techniques, the cross-correlation technique will be used. That said, the effectiveness of the method in such an area would be an important indicator of the applicability of SI to future exploration work.
1.4. Geology

1.4.1. Geological Background

The Lalor mining camp is located 8 km southwest of Snow Lake, Manitoba, approximately 700 km north of Winnipeg, Manitoba. The Lalor VMS deposit is found within the Snow Lake volcanic arc assemblage on the eastern side of the Flin Flon Greenstone belt, which lies within the central part of the Trans-Hudson orogen. The Flin Flon belt formed during the Manikewan ocean closure and subsequent collision between the Archean Hearne, Sask, and Superior Cratons (Corrigan et al., 2009), and is one of the world’s largest VMS districts, having produced over 176 Mt of sulphide ore across 29 deposits as of 2013 (Bailes et al., 2013).

The Snow Lake assemblage is a 20 km wide and 6 km thick stratigraphic section consisting of 3 distinct subdivisions (Bailes et al., 1999). The Anderson sequence makes up the bottommost layer, and is a 2.5 km thick primitive arc sequence consisting mainly of the Welch Lake basalt, but also containing several rhyolitic flows and the Sneath Lake synvolcanic tonalitic intrusive complex. At the top of the Anderson sequence is a sulphide horizon called the “Foot-Mud horizon”, a 1 m to 5 m thick sulfidic sedimentary unit. The middle section of the Snow Lake assemblage consists of the 3 km thick mature arc Chisel sequence, a geochemically diverse succession of relatively thin and discontinuous units made up of both mafic and felsic volcaniclastic rocks. The uppermost layer of the Snow Lake assemblage is the 0.5 km thick Snow Creek rifted arc sequence composed of massive to pillowed basalts.

As Figure 1.2 shows, the Lalor mine camp lies to the west of the Snow Creek sequence and on top of the Chisel sequence. The Chisel sequence has been further subdivided into upper and lower sections (Figure 1.3), meeting at a structural contact 10 m to 200 m above the Chisel, Chisel North, Ghost, Lost, and Lalor VMS deposits (Bellefleur et al., 2015a). The contact between the subdivisions (also referred to as the Chisel-Lalor contact) is currently interpreted as a thrust fault based on contrasting geochemistry and differing dip and facing directions between the upper and lower Chisel sequences (Bailes et al., 2013). While observations at the Lalor deposit confirm the
differing geochemistry and facings above and below the Chisel-Lalor contact, a fault has not been seen at the surface, and at some outcrops the contact is considered to be conformable (Engelbert et al., 2014).

Figure 1.2. Generalized geological map of the Snow Lake arc assemblage. VMS deposits in alphabetical order: A - Anderson Lake; B - Bomber; C - Chisel Lake; CK - Cook Lake; CN - Chisel North; G - Ghost Lake; Jn - Joannie zone; L - Lost Lake; Li, Linda; M - Morgan Lake; P - Photo Lake; Pn - Pen zone; Pt - Pot Lake; R - Rod; Ra - Ram zone; Rd - Raindrop; S - Stall Lake. Modified after Bailes et al. (2013).
Hudbay Minerals discovered the Lalor deposit in 2007 via a near-vertical borehole near Lalor Lake that was drilled to investigate an electromagnetic anomaly found in 2003 by Crone Geophysics (Carter et al., 2014). Like several other deposits in the Snow Lake arc assemblage, the Lalor deposit is found just below the contact between the upper and lower Chisel sequences, at a depth between 570 m and 1160 m. The deposit is made up of 12 mineralized zones of varying size and concentrations of zinc, copper, lead, and gold. Of the 12 mineralized zones, 6 are zinc-rich, estimated at 15 Mt with a grading of 6.7% zinc, 0.63% copper, 2.01-g/t gold, and 23-g/t silver. The other 6 mineralized zones are gold-rich, with a resource estimate of 10 Mt with 2.5% zinc, 1.04% copper, 4.24-g/t gold, and 28-g/t silver (Bellefleur et al., 2015b). One of the
gold-rich zones also contains a higher grade of copper than the other zones, and is referred to as the gold-copper zone. All of the ore zones are relatively thin with an average thickness of 12 m, and a dip of 20° to 30° to the north-northeast (Carter et al., 2014). The type of mineralization varies from disseminated to massive sulphides. In general, the zinc-rich zones range from near-massive to massive mineralization, while the gold-rich zones tend to be mostly disseminated with some sulphide stringers. The zinc-rich zones also tend to be larger than the gold-rich zones, and while there is some overlap, they also tend to occur at shallower depths.

1.4.2. Physical Rock Properties

The physical properties of rocks, specifically the contrast between the values of acoustic impedance between units in contact, plays an integral role in determining whether or not a contact can be imaged using seismic methods. Acoustic impedance is given by:

\[ Z = v \rho \]  

(1.3)

where \( v \) is the seismic velocity and \( \rho \) is the density of the rock. For a rock unit with acoustic impedance \( Z_1 \) layered on top of a rock with impedance \( Z_2 \), the reflection coefficient at vertical incidence is given by:

\[ R = \frac{Z_2 - Z_1}{Z_2 + Z_1} \]  

(1.4)

A reflection coefficient as low as 0.06, generally equivalent to a difference in impedance of \( 2.5 \times 10^5 \) g/cm²s, is usually considered sufficient to generate a detectable reflection (Salisbury et al., 2003, Salisbury and Snyder, 2007).

To determine the seismic response at the contacts between the ore and the host rocks, as well as the contacts within the host rocks themselves, Bellefleur et al. (2015b) analyzed wireline logging data and geochemical data acquired in boreholes located near the Lalor deposit. Measurements of P-wave and S-wave velocity (\( v_p \) and \( v_s \)), as well as density were made on 45 core samples. Geochemical data was used to determine the protoliths of altered rock units, rather than classifying them based on visual descriptions.
of the cores. Figure 1.4 shows the results of the analysis. The coloured dots represent data points taken from the borehole logs, and the ellipses are determined via principal component analysis on the distribution of values for each rock unit (see Bellefleur et al., 2015b). The red ellipse corresponds to ore of all types of mineralization, from disseminated to solid sulphides. In general, more massive sulphide ore has higher density, and therefore a higher impedance value.

![Figure 1.4. P-wave velocity and density of the main lithological units found in the boreholes. Lines of constant impedance are also shown. Lithological units: fv – felsic volcanic; fvp – felsic volcanic protolith; iv – intermediate volcanic; ivp – intermediate volcanic protolith; mv – mafic volcanic; mvp – mafic volcanic protolith; d – diorite. Reprinted with permission from 3D seismic imaging of the Lalor volcanogenic massive sulphide deposit, Manitoba, Canada, by Bellefleur et al. (2015), retrieved from http://onlinelibrary.wiley.com ©2015 Her Majesty the Queen in Right of Canada Geophysical Prospecting © 2015 European Association of Geoscientists & Engineers](image)

Although exact values of the reflection coefficients between possible contacts are hard to determine due to the distribution of data points, Figure 1.4 can still be used to give an idea of what contacts can be expected to give reflections. Broadly speaking, any felsic units (fv, fvp) can be expected to generate detectable reflections when in contact with any mafic units (mv, mvp) or diorite (d). Units of intermediate composition (iv, ivp)
have impedance values which overlap with both the felsic and mafic units, and therefore may not generate strong reflections when in contact with anything other than a near-massive to massive sulphide ore body. While ore with impedances near the mean value of ~20 g·km/cm³·s or higher may generate reflections when in contact with nearly any other lithological unit, ore with lower impedances may be more difficult to detect. This may be especially true for the gold-rich ore zones, which were found to in general have lower impedances and be smaller in size than the zinc-rich zones.

1.4.3. Geological Model

In order to better understand the subsurface structure of ore deposits, there is a need to reconcile and integrate geological, geochemical, and geophysical data. To this end, Schetselaar (2013) developed and applied a 3-D grid modeling method to semi-continuously map and model the 3-D lithofacies architecture of another VMS deposit in the Snow Lake arc assemblage over the Flin Flon mine camp. The method uses data available from drill cores and outcrops, as well as geological information on the structural setting (faulting, folding, etc.) to model the volume of interest.

Over 220 exploration and delineation boreholes were drilled near the Lalor deposit. Using these, as well as in-mine underground drill holes focusing on the ore zones, a detailed 3-D geological model was built (Schetselaar et al., 2016). The model covers an area of 2050 m by 1330 m, oriented in a north-northeast direction, and extends to 1500 m depth. The lithological units present within this volume were categorized into 15 lithology classes based on their physical and geochemical properties, and were used to populate a gridded model with 5x5x5 m cells using the method described in Schetselaar (2013).

A cross-plot of this model is shown in Figure 1.5. This figure, and all further references to the geology of the Lalor deposit, adopts the terminology of previous literature (Bellefleur et al., 2015a,b; Schetselaar et al., 2016; Miah et al., 2015; Cheraghi et al., 2015; Schetselaar and Shamispour, 2015) in defining the hanging wall and footwalls as those units whose horizons are above and below the deposit, respectively. The complex geology present at the Lalor mine camp is evident, with near-vertical mafic
and felsic units making up the hanging wall, and generally discontinuous and highly altered units composing the footwall. Note that the ore bodies in the geological model include only those which were deemed economical in the planning of the Lalor mine. This model, along with the estimated rock properties for each unit, will be used to help interpret the results of applying SI to the passive source dataset.

Figure 1.5. Cross-plot of the 3-D geological model.

1.5. Survey Layout and Regional Infrastructure

In March 2013, a grid of 347 receivers covering ~4 km$^2$ were laid out over the Lalor mine site, and set to record for approximately 300 hours. The receivers were laid out in 7 southeast-northwest (direction A) lines and 9 southwest-northwest (direction B) lines of lengths varying between 700 m to 4000 m (Figure 1.6). The lines were set with 100 m spacing between receivers, 400 m between lines in direction A and 360 m in direction B. Of the 347 receivers which were set, 336 were recovered for processing.

Shortly after the passive receivers finished recording a 3-D active (dynamite) survey was undertaken. The 3-D survey has much denser station spacing (25 m for receivers, 50 m for shots) and covers a much larger area (~16 km$^2$). The receiver and shot lines are in directions B and A, respectively, and partially overlap the passive
receiver lines. Therefore, processed inline and cross-line stacked sections of the active survey will coincide with those generated by SI, allowing for a direct comparison between the two datasets.

An aspect of the survey which is important to understand for proper application of SI is the availability of noise sources. The Flin Flon region and Manitoba in general are relatively quiet areas in terms of seismic activity. It is expected that the majority of the noise sources will be man-made. As Figures 1.6 and 1.7 show, there are several possible noise sources on and near the Lalor property. The mine and ventilation shafts are inside the area covered by the passive array. A gravel road leads from the mine to a highway to the southeast. Further down the highway, approximately 4 km southeast of Lalor, are the Photo Lake and Chisel North mine sites. While these mines are no longer active, the mined-out open pit at Chisel North is being used as a waste rock disposal area. The site also houses a water treatment plant, pumps and waterlines, as well as 4160 V and 550 V power stations. The town of Snow Lake (population ~800) is located ~7.5 km east, while the nearest densely populated area is Flin Flon (~5500 people) which lies roughly 215 km to the west. Finally, an ore concentrator operating 5 days a week is located 15 km east of the site. While most of these potential sources will likely generate noise at or near the surface, careful processing of the data should minimize unwanted noise, allowing a successful application of SI.
Figure 1.6. Map of the Lalor property. Stars represent the passive receiver array, while the dashed black lines indicate the receiver lines that will be processed. The dashed blue box denotes the area covered by the geological model. The red, pink, and blue shapes are surface projections of known zinc, gold, and gold-copper rich zones, respectively.
1.6. Thesis Structure

This thesis is primarily concerned with field testing of ambient noise seismic interferometry to generate reflection profiles. The Lalor mine camp offers a unique set of challenges that will have to be overcome in order to achieve this goal. As the site of an active mine, the day-to-day operations at Lalor will likely act as ambient noise sources. However, due to the layout of the passive receiver array relative to these possible noise sources, the source distribution will be anisotropic. In addition to this, SI is most often applied in areas with relatively simple, layered geology. The complex geology and generally steep dips of crystalline rock environments introduce additional challenges to seismic reflection processing.

These issues will be studied in Chapter 2. The SI methodology will be introduced by applying it to synthetic data generated using a simple model of a VMS deposit. The effects of dipping layers and a directionally biased source distribution will be studied as well. Chapter 3 will characterize the data in terms of the magnitudes and arrival times of seismic events, as well as the effective bandwidth of the data. A beamforming algorithm...
will be developed and applied to the Lalor dataset in order to determine the source locations. In Chapter 4, the basic SI methodology will be applied to the dataset to determine a baseline for the quality of the results obtainable from the dataset. The methodology will then be refined based on the information gained in Chapter 3. In particular, a processing technique based on the beamforming results and F-K filtering will be developed in order to remove surface wave noise from the data. Application of this technique combined with the refined SI methodology will result in virtual shot gathers which will be used as input to seismic reflection processing. Chapter 5 will describe the procedure used to process the virtual shot gathers into seismic reflection profiles, and compare these profiles to those obtained by the 3-D active seismic survey. The reflection profiles generated using SI will be interpreted based on the known geology of the Lalor Deposit, as well as the results of the 3-D active source survey. Finally, the results and conclusions of this thesis will be summarized in Chapter 6, and suggestions for future work will be given.
Chapter 2.

Synthetic Examples

2.1. Introduction

In its most basic form, application of SI by cross-correlation is a relatively straightforward procedure. For ‘perfect’ data, i.e. recordings of impulsive sources which are evenly distributed in the subsurface, the technique can be as simple as a single step: cross-correlate each trace with every other trace, taking only the causal portion of the result. Organizing these traces into virtual shot gathers then allows the data to be processed as if it were a conventional 2-D dataset. This situation is highly unlikely to be encountered with real data, and therefore it is important to understand the different factors which influence the passive data, which in turn affect the methods that must be used to generate the virtual shot gathers. This chapter is devoted to the introduction of the basic methodology of SI, the investigation of factors which may affect the Lalor dataset, and some techniques that may be used to improve the results.

These techniques will be demonstrated with the aid of a simple model of a VMS deposit (Figure 2.1). It should be noted that this model is not a realistic depiction of the Lalor geology, but was generated using the P-wave velocities and densities from the rock types which are likely to be found there (Bellefleur et al., 2015a). A line of 121 receivers spaced 25 m apart lies on top of a gabbro unit. Beneath the gabbro is an undulating section, which represents a mafic/felsic transition in the form of volcanic breccia. Beneath this is another transitional unit with properties between those of gabbro and granite. Embedded within these transitional units are two distinct ore lenses. These lenses have a P-wave velocity similar to that of the host rock, but an anomalously high density representative of a massive sulphide. Beneath the second transitional unit is another gabbro unit, and then finally granite. These last two units have both flat and dipping sections. This model is simple enough to study the effects of source properties on the application of SI without the additional complication of complex geology, yet the
dipping layers and varying impedance contrasts between layers should give insight into the limitations of imaging by SI.

2.2. Basic Methodology

2.2.1. Generation of Synthetic Data

In the next few sections, reflection profiles generated by SI using various source distributions will be compared to those generated by placing active sources at the locations of each receiver. The model and the subsequent synthetic experiments were carried out using the finite-difference code by Thorbecke and Draganov (2011). The code takes gridded density and P-wave velocity models in the form of Seismic Unix (.su) files. To simulate the passive sources used in SI, sources may be placed randomly throughout the model using a uniformly distributed probability density function. The signatures or spectra of these sources may also be randomized. The code accomplishes this by assigning a random value between -0.5 and 0.5 to both the real and imaginary part of the signal at each frequency, up to some predefined maximum.
frequency. For the following experiments, this maximum frequency is set to 30 Hz. The use of random source signatures aims to simulate the complicated wavelets which may be emitted during, for example, rock fracturing. Alternatively, to simulate an active source survey, sources may be placed at specific locations on the model. To facilitate comparison with a synthetic SI experiment, the sources are placed at the locations of each receiver at the surface. A source is placed at the location of the first receiver, emitting a Ricker wavelet with a central frequency of 17.5 Hz. The wavefronts from this source are recorded only by its coincident receiver. This is repeated for each receiver location, resulting in a zero-offset section which may later be processed into an accurate representation of the model.

The basic procedures of SI will be outlined here for the reader who may be unfamiliar with the methodology. To demonstrate the effectiveness of the method without the additional complications of an imperfect source distribution, SI will first be applied using sources placed in Zone 2. The sources (100 in total) are placed randomly within the zone and fired one at a time. The sources have a random signature with a maximum frequency of 30 Hz, and are excited for a random length of time, between 0.1 s to 5 s. The resulting wavefield is recorded for 10 s. An example of the recorded noise is given in Figure 2.2a.

Unlike the data that one might expect to obtain in the field, the synthetic data has no unwanted coherent or incoherent noise. Therefore, no preprocessing such as removal of surface waves or panel normalization is required. In this case, the basic steps for SI may be applied directly to the raw data as follows:

1. For a given noise panel (recording of a single source), select the first trace and cross-correlate it with itself and every other trace in the panel. In this case the first trace is called the ‘master trace’. The resulting traces form a single correlation panel, whose effective source is at the position of the first trace.

2. Repeat this procedure using every other trace as the master trace, resulting in 121 correlation panels, one for each receiver.

3. Repeat this for each noise panel associated with a different random source, resulting in 100 sets of correlation panels, one for each synthetic source.

4. Sum together all the correlation panels corresponding to the same master trace. This summation over noise panels represents the
ensemble average in Equation 1.2. It should be noted that for continuous recording, summation over correlation panels may be replaced by simply cross-correlating the full recording times, although this may not be computationally viable for very long time series.

5. Cross-correlation results in data at both positive (causal) and negative (acausal) times. Under ideal circumstances these will be equal and so either may be used. Nonetheless, it is common practice to sum them together to increase the signal to noise ratio (SNR). This summation results in the ‘virtual’ shot gathers, with one computed for each receiver position.

![Figure 2.2](image)

**Figure 2.2.**  
a) Raw noise panel output from modelling a single source.  
b) Causal portion of the correlation panel generated using only the source in a).  
c) Same as b), after deconvolving the panel with an estimate of the noise signature.

### 2.2.2. Source Deconvolution

Under ideal conditions where the source distribution is regular and the sources themselves are impulsive, or at least emit a relatively simple wavelet, the procedure listed above are the only steps required for SI. After generating the virtual shots, they may then be treated as any other 2-D seismic reflection dataset and processed as such. However, caution and judgement should be used before proceeding. As indicated by
Equation 1.2, the resulting virtual shot gathers contain the autocorrelation of the source signature. If the source signature is a simple wavelet (Ricker, Gaussian, etc.), then the resulting virtual shots will be approximately equal to shot gathers obtained using an active source such as dynamite or a weight drop. Passive sources are rarely so simple, often having complex frequency and phase spectra. Additionally they may be excited for long periods of time, resulting in virtual shots which are contaminated with multiples.

Trying to process SI data whose sources are repetitive and have complex signatures is akin to processing vibroseis data which has not been correlated. As a simple example, if a 1-D synthetic experiment is carried out using an impulsive source, the resulting reflectivity series will accurately represent the geology. However, if the source used contains several multiples and does not necessarily decrease in amplitude over time, the resulting reflectivity series will be nearly impossible to interpret due to the train of multiples of varying amplitude which follow each reflection. As Figure 2.2b shows, the random signatures used in this synthetic experiment leave the resulting correlation panel with many multiples which tend to obscure the useful information. For an ideal source distribution these multiples will be largely attenuated when stacking over many sources, and would be further attenuated during 2-D reflection processing. In most real world applications this cancellation will not occur, and sources which are periodic will tend to strengthen the unwanted noise. Therefore, it is best to remove this coherent noise as early as possible in the processing sequence.

There are several methods which may be used to remove the negative effects of the noise signature. Bensen et al. (2007) recommend pre-whitening the data to remove the effects of strong narrowband events. Pre-whitening is also capable of removing the effect of a complicated source signature. For data with low SNR, this pre-whitening may also enhance unwanted noise. Another possibility is to replace cross-correlation with cross-coherence. Cross-coherence is given in the frequency domain by:

\[
\mathcal{C}(x_A, x_B, \omega) = \frac{v(x_A, \omega)^* v^*(x_B, \omega)}{|v(x_A, \omega)||v^*(x_B, \omega)|} \tag{2.1}
\]

While cross-correlation is computed by multiplying the frequency spectrum of one trace with the complex conjugate of the other (the numerator of Equation 2.1), cross-
coherence discards amplitude information by dividing the resulting cross-correlation by the amplitude spectra of each trace involved. This is useful when amplitude information is unreliable and when only accurate arrival times are required (Nakata et al., 2012). Due to the spectral division, cross-coherence may suffer from instability in noisy data, and as with pre-whitening it may increase unwanted noise in the data. Lastly, the autocorrelation term may be removed from the virtual shots by deconvolution using the source signature, or an estimate thereof. If the source signature is known for each noise panel, then the deconvolution may be applied directly to each correlation panel. In passive SI it is unlikely that the source signature will be known beforehand, so an estimate will have to be made. A reasonable approximation to the autocorrelation of the source signature may be made by simply taking the autocorrelation of the master trace (Draganov et al., 2010). The underlying assumption here is that the amplitude spectrum of the master trace is a fair approximation to that of the source. Applying a Gaussian taper to this trace to stabilize and smooth the spectrum, and deconvolving each trace in the correlation panel by it (using an appropriate regularization parameter) successfully removes the effect of the complicated source signature (Figure 2.2c).

2.2.3. Virtual Shot Gather and Reflection Profile Generation

At this stage all that remains to be done is to repeat the process over each noise panel. The procedure of pre-processing (if necessary), correlation, and deconvolution is performed over each noise panel and the results are summed, although in practice the correlation panels are summed as they are computed to avoid redundant storage of large amounts of data. Summation of the acausal and causal portions of the data may be performed before or after summation of the individual correlation panels, although it is preferable to perform it afterwards in case additional processing, such as source deconvolution, is needed on the causal/acausal sections. The result of these summations is the ‘virtual’ shot gathers, that is, the gather which would have been recorded had a source been present at the location of the master trace. Under ideal circumstances, these gathers should contain the same events present in an active shot gather. Figure 2.3 shows an example virtual shot gather compared to the active gather at the same location. Aside from the non-physical energy which arrives before the first arrival, the virtual shot matches the active shot well. Both contain the same reflections,
particularly those between 200 ms and 500 ms, although the virtual shot has a lower SNR as a result of correlation noise which was not fully cancelled during the summations.

It is assumed that the reader is familiar with standard 2-D seismic reflection processing techniques. Therefore, the procedure used to generate the synthetic sections will simply be stated here for reference:

1. Apply $t^{1.0}$ amplitude recovery
2. Sort to CDP domain
3. Velocity analysis via semblance velocity spectra
4. Normal move-out correction (NMO)
5. Residual statics and/or TRIM statics (optional)
6. Sort to common-offset domain
7. Common-offset F-K dip move-out corrections (DMO)
8. Remove previous NMO
9. Dip independent velocity analysis
10. NMO using dip independent velocities
11. Muting of non-physical energy using linear mute at $t=0$ s, with velocity slightly higher than that of the first arrivals
12. CDP stacking
13. Phase-shift migration using Gazdag's phase shift method (Gazdag, 1978)
14. Time-depth conversion
The result of applying these steps can be seen in Figure 2.4a. As a reference point, a migrated zero-offset active source section was also generated (Figure 2.4b). This section was generated simply by recording the response of each source as described earlier, taking only the zero-offset traces, and then applying an automatic gain control (AGC) followed by phase-shift migration. It can be seen that under ideal conditions, the results of SI are similar to those obtained by using active sources. Both sections contain strong reflections from both the left (L1) and right (L2a and L2b) sulphide lenses, as well as from the gabbro/granite transition at R1. The complex shape of the left lens is better defined on the active source section; however, the passive section contains a reflection originating from the gabbro/granite transition above L1, labelled as reflection H, which is not present in the active section. Reflections R2 and R3 are clearly visible in Figure 2.4b, but are not strong enough in Figure 2.4a to be recognized without prior knowledge of their existence. Similarly, the horizontal section of the lower contact at B1 is clear on both sections, but only the active sources adequately recover the dipping reflection B2.
Figure 2.4. Synthetic reflection profiles. a) Generated using SI. Events highlighted in yellow, red, and green, correspond to those which are correctly recovered in Figures 2.7a, 2.7b, and both, respectively. b) Generated using the active source zero-offset gather. Highlighted and labeled events in both profiles correspond to similarly labeled boundaries and contacts in Figure 2.1.

Neither section is able to accurately image both the tops and bottoms of the left lens. According to the Rayleigh criterion, in order to have two interfaces be properly distinguished, they must be separated by at least a quarter wavelength. Therefore for a wavelet with a central frequency of ~15 Hz, the lens would have to be at least 100 m thick. This is one downside of SI; passive sources typically contain mostly lower frequencies, which will tend to limit vertical resolution. Beyond the lenses themselves,
some of the other rock contacts are also partially imaged, with the amplitudes of those in
the SI generated image only slightly weaker than those in the active synthetic section.
The results obtained show that when sources are available throughout the medium of
interest, the results of SI are comparable to those obtained through conventional seismic
surveys, up to the difference in frequency contents. Whether or not such sources are
likely to be available in the field is a different matter altogether.

2.3. Effects of One-Sided Source Distributions

2.3.1. Virtual Shot Gathers

As with any technique, it is important to understand the limitations of SI when
applying it to a dataset. In addition to the limitation of the frequency content of passive
sources, there is also the possibility that such sources will not be present in the
distribution which is mathematically required for SI. In fact, such a distribution is highly
unlikely to be found in the field. By using very long recording times, the chances of
capturing sources in a more even distribution may be increased. Even so, when
recording in a setting such as Lalor where anthropogenic sources are likely to be the
largest contributors to the noise field, long recording times are unlikely to produce an
adequately uniform spatial distribution of sources. The areas which are likely to contain
noise sources at Lalor tend to lie only on one side of any particular line. It is therefore
important to study the effects of source distribution on the results of SI, in particular the
effects on the stacked sections when sources from only one side of the receiver line are
considered. Such a study is aimed at gaining insight into what additional processes may
be required for successful application of SI at Lalor, or at the very least to avoid
misinterpretation of the results.

To test the effects of a one-sided source distribution, the steps outlined in the
previous section are carried out again for sources placed only to the left of the receivers
(Zone 1), and again for sources to the right (Zone 3). Figure 2.5 shows the virtual shot
gathers obtained by applying SI to each dataset. The results show that the reflections
are imaged differently when illuminated by the different source distributions. The virtual
shots closest to each set of sources tend to have more complete reflections. When
using sources on the left side of the model (Zone 1), shots 1, 31 and 61 each contain several reflections, while shots 91 and 120 only contain partial reflections at the far offsets. Likewise, when using sources only on the right (Zone 3), shots 61, 91, and 120 contain more complete reflections whereas shots 1 and 31 only show partial reflections at far offsets.

![Virtual shot gathers generated using sources only on the a) left (Zone 1) and b) right (Zone 3). Events highlighted in yellow and green represent reflections recovered only when using sources in Zone 1 or Zone 3, respectively, while those highlighted in red are recovered regardless of source distribution.](image)

Viewing the shots for each dataset, it is clear that some reflections are captured only when using sources on the left (highlighted in yellow), some only when using sources on the right (highlighted in green), and some partial reflections which are recovered regardless of the source distribution (highlighted in red). The reflections or
partial reflections which are recovered regardless of source distribution are mostly at the farther offsets.

The difference between these datasets may be explained by the fact that for a point on a reflector to be imaged using SI by cross-correlation, there must exist a source whose wavefront has a ray path which connects the traces being cross-correlated and the point to be imaged. This principle is illustrated in Figure 2.6. In Figure 2.6a, an underground source is excited and the resulting wavefront propagates to the receiver \( x_A \), reflects or scatters at the surface, continues downwards and reflects off a horizontal reflector at \( R \), finally travelling back up to the receiver at \( x_B \). In this scenario, SI by cross-correlation works by removing the common ray path seen by both \( x_A \) and \( x_B \), namely the path from the source to \( x_A \), leaving only the information between the two receivers.

Many sources may exist with similar ray paths, including the mirror situation shown in Figure 2.6b. With such simple geology, the exact source distribution has a minor effect on the results, as sources in different locations essentially give the same information. The source distribution becomes more important with increasingly complex geology. In Figure 2.6c, a source to the right of \( x_B \) fires and emits a wavefront which travels to the surface. Assuming a planar horizontal surface, the wave reflects from the surface and then again off the dipping reflector below. Assuming reflection according to Snell’s Law, the wavefront is reflected and recorded at \( x_A \). Due to the geometry of the reflector, the reflection point \( R \) is seen by both receivers when using a source that is both relatively far to right of the receiver line, and fairly close to the surface. As Figure 2.6d shows, to obtain the equivalent reflection using a source to the left of the line, the source would have to lie at a much smaller offset, or if the ray path is extended downwards, at a much greater depth. While such sources may exist for a given survey, it will be shown in Chapter 3 that this is not the case at Lalor.
Figure 2.6. A horizontal reflector is imaged using sources on the far left (a), and right (b) side of the receiver line. In a similar situation, a dipping reflector is imaged by a source on the far right (c). To image the same reflection point with a source on the left, the source must lie nearly underneath the receiver at $x_A$ (d).

In the above discussion it was assumed that the boundaries were locally flat reflectors. There is of course a chance that the wavefront is scattered either at the surface or at the subsurface reflector, rather than perfectly reflected. In this case the wavefront may follow a more complicated trajectory which does intersect at all of $x_A$, $R$, and $x_B$, which will allow the reflection point to be imaged using SI. However, unless this occurs for a number of sources, the reflection is unlikely to recovered perfectly. On the other hand, using a source on the right to illuminate the dipping reflector leads to a reflected wavefront which is easily captured by both receivers. Therefore when imaging complex dipping geology using SI, either many sources are required to illuminate the targets from all angles, or long receiver lines are required to capture the energy reflected by dipping geology. Often the exact geology is not known prior to a survey, therefore extending the receiver lines to appropriate lengths is not always possible. Furthermore, the use of passive sources means surveyors have no control over source positions. Therefore, it is best to gather as much information as possible regarding the available sources in order to best understand the effect they will have on the results.

2.3.2. Reflection Profiles

It is clear by looking at the shot gathers that some reflections may not be fully recovered when SI is applied to datasets that contain sources on only one side of the
receiver line. Therefore, the next problem to be solved is discovering how the missing information affects the resulting reflection profile. To answer this, each dataset was processed to completion, again following the steps laid out in section 2.2.3. No steps were taken to compensate for the incomplete source distributions, so the results seen in Figure 2.7 may be compared with those in Figure 2.4 in order to gain an understanding of the effects the source distribution has. Events highlighted in yellow and green in Figure 2.7 correspond to correctly recovered reflections or partial reflections, and they are highlighted in the same colour in Figure 2.4a. Those highlighted in red in Figure 2.4a are correctly imaged in both 2.7a and 2.7b.

Both similarities and differences may be seen between the two datasets in Figure 2.7. The horizontal section of reflection H is recovered in both datasets, while the dipping sections are only imaged in Figure 2.7b. Reflection L1 is recovered differently in each dataset, with the more horizontal and left dipping sections being accentuated in Figure 2.7a, while those parts which dip to the right are recovered in 2.7b. The same is true for reflections L2a and L2b. The horizontal reflection at B1 is only recovered in Figure 2.7a, while the horizontal reflections at R1, R2, and R3 are imaged in 2.7b.
Figure 2.7. Synthetic reflection profiles using SI with sources located only on the a) left (Zone 1) and b) right (Zone 3). Events which are highlighted correspond to those of the same colour in Figure 2.4a.

Most of the reflectors present in the model are imaged in some way despite only using sources on the left or the right sides of the model, and it is not difficult to imagine that combining the partial reflections obtained in the two datasets would result in a reflection profile similar to that in Figure 2.4. This is of little consolation to the interpreter who is only given the results from either Figure 2.7a or 2.7b. From these results, one could perhaps identify the depth at which a target lies, however the geometry of the reflectors is grossly misrepresented, especially when compared to the reflection profile obtained when a complete distribution of sources is available. Overall, it is evident that only certain parts of each reflector may be correctly imaged when using completely one-sided source distributions. Further to this, the reflections are smeared and stretched up-
dip, giving the illusion of reflectors which are much larger than they really are. This reflection smearing combined with the lack of continuity that arises under these circumstances makes interpreting the reflection profile extremely difficult, if not impossible. Steps may be taken to mitigate these effects if the distribution is merely uneven, for instance if there are many sources on the left side and relatively few on the right. However, there is little that can be done if the sources simply do not exist, as is the case here. Therefore, knowledge of the locations of the sources is key to allow proper handling of the data where possible (i.e. directional balancing), or when it is not, to avoid misinterpretation of the data.
Chapter 3.

Data Characterization

3.1. Introduction

Developing an understanding of the dataset to be processed is an important step in any field of research. As the previous chapter has shown, applying the methodology of SI without an understanding of the data can lead to results which are misleading and potentially incorrect. The vast amounts of data that need to be collected in a passive survey, combined with the inherent noisiness and unpredictability of the data, make these steps even more important when applying SI. This chapter aims to study all 14 days of data to gain as much information as possible before applying SI. To this end, each 60 s data record was passed through an amplitude scanning algorithm to determine the magnitude and temporal distribution of seismic activity over the course of the survey. The power spectral densities (PSDs) of each record were then calculated to ascertain the range of frequencies present in the data. Finally, a beamforming algorithm was implemented to determine the spatial distribution of sources.

3.2. Amplitude Scanning

A key step in processing passive data is temporal normalization (Bensen et al., 2007). Different normalization techniques may have different impacts on the results of applying SI, and the best technique will depend on the quality and character of the data. Studying the temporal distribution and amplitudes of the events present in the data is therefore an important first step.

For each receiver line in the survey, data was extracted, segmented into 60 s records, and each trace had its values squared and summed to give the total energy recorded by each receiver during that time. The results from line 141 will be shown, as this is the longest line, and is generally representative of the rest of the dataset. Figure 3.1b shows the energy per receiver along the x-axis, per data record along the y-axis. It
is clear from this plot that the energy recorded is not evenly distributed among the receivers. Some receivers recorded relatively little energy throughout all 14 days (e.g. receiver #1), others receivers recorded energy evenly distributed throughout the entire recording time (e.g. receivers 14 to 18), while others still contain huge amounts of energy distributed sporadically in time (e.g. receiver #2). This is highlighted by Figure 3.1a, which shows the total energy recorded at each receiver. Receiver 2 captured far more energy than the rest, although Figure 3.1b seems to indicate otherwise. This indicates that there are likely a few events taking place near that receiver location that are contributing a large amount of energy to the trace, but are not being recorded by the other receivers. These events are therefore likely to be related to local activity, such as a passing snowmobile or foot traffic, and are not useful to the application of SI. Left unchecked, these events would contaminate the data, much like high amplitude surface waves contaminate active source data. A trace-by-trace normalization scheme should therefore be applied to the data prior to application of SI. Such a scheme will normalize each trace within each data record so that noisy traces or high amplitude local events do not mask whatever useful events may be contained within that record.

**Figure 3.1.** a) Total energy per trace recorded by each receiver in line 141. b) Energy per trace contained each 60 s data record.
It is also important to study the temporal distribution of seismic energy. However, as Figure 3.1 shows, simply calculating the total energy per 60 s trace does not give accurate information on the distribution of events that are recorded by a majority of the receivers. A different method must be used to measure the temporal distribution of energy without having noisy traces contaminate the results. A simple way to do this is to take the median value of the total energy present in each trace, in each record. This method ignores outliers and gives a more accurate representation of what useful events are present in the data. Figure 3.2a shows the median energy per record, normalized so the record with the maximum median energy has a value of 1. The spikes in this plot indicate the times of large amplitude events in the data. Figure 3.2b shows the same data as 3.2a, but with an expanded vertical axis to show the amplitude characteristics beyond only the highest amplitude events. The plot shows a cyclical pattern in the data: 12 hours of relative quiet, followed by 12 hours of increased activity, during which there are several high amplitude events. As time zero is February 29th, 2013 at 6:00 pm, the observed pattern may be explained by the fact that there is very little activity around the mine at night, but much more during the day. The large events are consistent with blasting taking place in the mineshaft a few times each day. The periods of increased activity (not including the blasting) are likely the result of daily activities in and around the mining camp.

Figure 3.2.  

a) The median values of the energy per trace, per 60 s data record.  
b) The same data with an expanded vertical axis.
The predictable nature of the data represented in Figure 3.2 suggests that the majority of the noise present in the dataset is man-made. This is not necessarily a negative thing as some of the noise, such as the blasting, will have large enough amplitudes to be of use in the application of SI. However, many other events may not be as useful. For instance, surface noise generated by traffic is unlikely to contribute to the recovery of reflections. Furthermore, any noise generated from mine-related operations is likely to be anisotropic in its spatial distribution. As the map in Figure 1.6 shows, the areas used for day-to-day operations (roads, mine/ventilation shafts, etc.) lie to the southwest of the receiver array. The amplitude information shown in this section suggests that further knowledge of the source characteristics will be vital to successfully processing the dataset as a reflection survey.

3.3. Frequency Content

Another important step in processing any seismic dataset is to determine the useful frequency content of the data. The range of available frequencies will vary depending on the sources available. Active seismic sources emit energy with a fairly broad range of frequencies, typically between 5-200 Hz. Passive sources on the other hand tend to be characterized by much lower frequencies. Although a passive survey may record a broad range of frequencies, not all of that energy is necessarily useful. Energy in the lower frequencies (<5 Hz) tend to be related to surface waves, while high frequencies (>50 Hz) tend to be related to electrical and other anthropogenic noise sources which do not contribute to the recovery of reflections.

In order to determine the useful range of frequencies present in the data, a power spectral density (PSD) analysis was carried out. The PSDs were calculated using Welch’s method (Welch, 1967) over each line, with the data split into 60 s records. The results for each line were then summed to get an estimate of the relative amount of energy recorded at each frequency over the course of the survey. As Figure 3.3a shows, the data has energy distributed within a bandwidth of 5-215 Hz, however the majority of the energy is contained within 10-50 Hz. Figure 3.3b focuses on this lower bandwidth, and shows that the frequencies with the highest energy (shown in red) are typically within the 10-30 Hz bandwidth. As with Figure 3.2, Figure 3.3 shows a cyclical
pattern of 12-hour periods with little activity, followed by 12 hours of increased activity. This reinforces the idea that the majority of higher energy events take place during the day and are likely to be related to mining activities.

Figure 3.3. a) PSD plot showing the relative energy at each frequency as a function of time. b) Same as a), with an expanded vertical axis to show the 0-50 Hz band in more detail.
The information gained through the PSD analysis provides the information required to define the most useful frequencies in the dataset. The data can safely be bandpass filtered to 5-50 Hz to remove high frequency noise. Visual inspection of the records led to the conclusion that while there are some coherent high-frequency events, the majority of the energy above 30 Hz is incoherent noise. Therefore, a bandpass filter of 10-30 Hz was applied to the data prior to any further processing.

### 3.4. Beamforming – Introduction and Synthetic Examples

#### 3.4.1. Introduction

One of the most important attributes of a passive dataset is the source distribution. That said, the exact impact the source distribution has on the final stacked section will depend on the dataset and where it is collected. Passive surveys in areas with simple, horizontally stratified geology may still result in high quality reflections with little attention paid to the details of the source distribution (see Nakata et al., 2012; Draganov et al., 2009; Xu et al., 2012). However, as was shown in Chapter 2, an incomplete source distribution in the presence of dipping reflectors can lead to misleading or possibly incorrect results. While it may not be possible to correct the effects of an incomplete source distribution, knowledge of it does at least help to avoid a misinterpretation of the results.

The most common source location method used for seismic data is known as beamforming. Beamforming has been used extensively to characterize seismic data, as well as aiding in the successful application of SI. Gerstoft and Tanimoto (2007) used narrowband frequency domain beamforming such as that described in Rost and Thomas (2002) to study microseisms generated by ocean waves. Ruigrok and Wapenaar (2012) and Ruigrok et al. (2010) use similar methods to aid in the application of SI to image the lithosphere. Draganov et al. (2010) uses the frequency domain beamforming algorithm presented in Lacoss et al. (1969) to analyze data with possible body waves for the purpose of constructing a reflection profile using SI.
In short, beamforming is a grid search over possible source locations. Like many
signal processing techniques, beamforming may be performed in either the time domain
or frequency domain. In general, frequency domain formulations are more popular due
to higher computational efficiency (Hamid et al., 2014). However, the increased
efficiency is usually dependent on the validity of at least one of the following
assumptions: the sources are in the far-field (i.e. that the incoming wavefronts may be
approximated as planar), or that the data is narrowband. The Lalor dataset is not
narrowband, and without prior knowledge of the source distribution, the validity of the
far-field assumption is unknown. For these reasons, a simple time-domain beamformer
known as a delay-and-sum beamformer similar to that presented in Kao and Shan
(2004) was used. The following sections will explain the methodology, the reasoning
behind its use, and the results of its application to the Lalor dataset.

3.4.2. Plane Wave Beamforming

Plane wave beamforming is commonly used to determine the locations of
sources in passive surveys. The method assumes the sources lie in the far-field and
generate waves which propagate through a medium of known constant velocity. Under
this assumption the wavefront is locally planar upon reaching the receiver array. As the
wave travels across an array of receivers, each receiver records the peak of the wave at
different times relative to a reference position. The time difference between the
wavefront reaching the reference point and each receiver, called the delay time, is given
by:

\[ t_i(\theta, \varphi) = -\frac{x_i \sin \theta - y_i \cos \theta}{\Delta t \left( \frac{v_c}{\sin \varphi} \right)} \]  \hspace{1cm} (3.1)

where \( x_i, y_i \) are the x and y positions of the \( i \)th receiver relative to the reference point, \( \theta \) is
the azimuth measured from north, \( \varphi \) is the angle of vertical incidence, and \( \Delta t \) is the
sampling interval. Equation 3.1 gives the delay time in the number of samples. The
\( \frac{v_c}{\sin \varphi} \) term in the denominator corresponds to the apparent velocity of the wave:

\[ v_{app} = \frac{v_c}{\sin \varphi} \]  \hspace{1cm} (3.2)
where \( v_c \) is the medium velocity. For the derivation of Equation 3.1, see Schweitzer et al. (2002). For any given source, only the receiver locations and possibly the medium velocity are known, and so solving directly for \( \theta \) and \( \varphi \) is not possible. Instead, a grid search is performed. A subset of the source parameters is chosen, given by \( (\theta_1, \theta_2, \theta_3, \ldots \theta_n) \) and \( (\varphi_1, \varphi_2, \varphi_3, \ldots \varphi_n) \), and \( t_i(\theta, \varphi) \) is calculated for each pair \( \{(\theta_1, \varphi_1), (\theta_1, \varphi_2), \ldots (\theta_1, \varphi_n), (\theta_2, \varphi_1), \ldots (\theta_n, \varphi_n)\} \).

An \( M \) sample window of data (hereafter called a data panel) containing the wavefront is selected from the original data record. For each parameter set, every trace is shifted by its corresponding delay time (Equation 3.1) and the traces are stacked together to form a ‘stack’ or ‘beam’. For an array of \( N \) receivers, the beam ‘B’ is given by:

\[
B(k, \theta, \varphi) = \frac{1}{N} \sum_{i=1}^{N} s_i(k + t_i(\theta, \varphi))
\]

where \( s_i \) is the signal recorded at the \( i \)th receiver, and \( k \) is the sample number. Once the beam is calculated, its ‘beam power’ is found by taking the total energy of the beam:

\[
B_p(\theta, \varphi) = \sum_{j=1}^{M} B(k_j, \theta, \varphi)^2
\]

The order of magnitude of the beam powers for a data panel will depend on the energy contained within that panel. Therefore, in order to make comparisons between different data panels, the beam powers are converted to a semblance spectra. The semblance value for a given parameter set is given by:

\[
S(\theta, \varphi) = \frac{B_p(\theta, \varphi)}{E_s}
\]

where \( E_s \) is the average total energy per trace contained in the data panel:

\[
E_s = \frac{1}{N} \sum_{i=1}^{N} \sum_{j=1}^{M} [s_i(k_j)]^2
\]

The semblance is a value between 0 and 1, representing the level to which the events in the data panel are aligned after applying the delay times for each \( (\theta, \varphi) \) pair.
value of 0 means the delay times shift the data out of phase, resulting in complete destructive interference and a beam power of zero, while a value of 1 means the data was shifted to be aligned perfectly, resulting in complete constructive interference and a beam power of \( E_s \). The semblance of a beamforming result is a good indicator of the reliability of those results. Performing these calculations over each set of parameters results in a semblance spectra whose maximum gives the parameters which represent the most likely direction of arrival of the wavefront.

An example of this procedure is shown in Figure 3.5. A source 10 km directly to the north of a receiver array emits a zero-phase wave (Figure 3.5a). The wave travels through a medium with a constant velocity of 3 km/s, and is recorded at an arbitrary time by the receiver array (Figure 3.5b). As a 2-D modelling code was used, the source is located at the surface, or at an angle of vertical incidence of 90˚. To simulate a source at a non-zero depth, a medium velocity of 2.9 km/s was input into the beamforming algorithm. As the apparent velocity is still 3 km/s, according to Equation 3.2, inputting a medium velocity of 2.9 km/s should result in an angle of incidence of 75.2˚. Using the geometry in Figure 3.4b, the depth of the source is given by:

\[
d = \frac{r}{\tan(\varphi)} \tag{3.7}
\]

where \( r \) is the distance between the source and the reference point. Using \( r = 10 \) km and \( \varphi = 75.2^\circ \), this gives a simulated source depth of \( d = 2.64 \) km. It should be noted that without prior information of the source location, a plane wave beamformer is unable to determine the radial distance nor the depth of the source.
Figure 3.4.  

a) Diagram showing the general source/receiver layout and the parameters needed for beamforming. 

b) Relationship between the source/receiver positions and the vertical angle of incidence, as well as between the apparent, vertical, and medium wave velocities.

The semblance spectra (Figure 3.5c) is calculated using the previously described grid search procedure, with trial azimuths every 10˚ between 0˚ and 360˚, and trial angles of incidence every 5˚ between 0˚ and 90˚. The maximum semblance in Figure 3.5c is 0.9952, giving an azimuth of 0˚ and an angle of incidence of 75˚ (or a depth of 2.68 km). These results are accurate to within the minimum error set by the grid discretization. The results may also be checked by manually applying the corresponding time shifts, and ensuring the events in the data become aligned (Figure 3.5d). As this experiment shows, a simple sum-and-delay plane wave beamformer can be quite accurate when the incoming wavefront is in fact planar.
Figure 3.5.  
(a) Layout of the source and receivers for the experiment.  
(b) Data recorded at lines A and B from a source located 10 km away, at a 0˚ azimuth and simulated angle of vertical incidence of 75.2˚ (2.64 km depth).  
(c) Semblance spectrum resulting from applying the plane wave beamformer to the data in b).  
(d) The data after applying the time shifts calculated using the source location given by the maximum of c) at θ = 0˚, φ = 75˚, d = 2.68 km.

3.4.2. Validity of the Far-Field Assumption

In the previous example, the source was far enough away from the receiver array that the wavefront could be assumed to be planar upon reaching the array. The far-field assumption is common when processing passive data, particularly for surveys in areas with few anthropogenic noise sources. So long as it is true for a sufficient amount of sources, this assumption is often made and those data panels containing noise from near-field sources are discarded. However, as was discussed earlier, the noise at Lalor
is expected to be generated largely from the nearby mining operations. If this is the case, most of the sources are likely to be within 5 km of the center of the passive receiver array.

In order to determine the validity of the far-field assumption for the Lalor dataset, an equation was derived to measure the error level involved in assuming whether a source at a certain distance from the array can be considered to be in the far-field. Consider the situation depicted in Figure 3.6. A point source at O fires and is recorded by receivers on line AB. At some time \( t_0 \), the wavefront reaches the receiver at E. At time \( t_1 \) the wavefront has expanded to the circle shown, finally being recorded by receivers at A and B. The length of the line DE gives the additional distance the wave will have travelled past E when it reaches A and B. For a wave travelling at a velocity \( v \), the time delay between the wave being recorded at E and being recorded at A and B is then given by \( h = \frac{DE}{v} \). If this time difference is below some threshold chosen so that the wave may be approximated as planar, a plane wave beamformer may then be used, as was the case in section 3.4.1. The question is then, at what distance \( r \) must the source be from the receiver at E in order to have the desired travel time delay \( h \)?

Table 3.1. A list of identities which will be used to derive the source/receiver distance required to validate using the far-field assumption.

<table>
<thead>
<tr>
<th>Identity</th>
<th>Equation Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intersecting Chord Theorem (Page, 2009)</td>
<td>(1)</td>
</tr>
<tr>
<td>( CE \times ED = AE \times EB )</td>
<td></td>
</tr>
<tr>
<td>( r = AO = CO = (CE + ED)/2 )</td>
<td>(2)</td>
</tr>
<tr>
<td>( OE = r - ED )</td>
<td>(3)</td>
</tr>
</tbody>
</table>
Figure 3.6. Source/receiver layout diagram used in deriving the distance at which a source must be from the receiver array to be considered in the far-field, and therefore have its wavefront be approximately planar.

The derivation is completed using the length of the lines AB and DE, and the identities given in Table 3.1. The proof starts using (1) and rearranging to give:

\[ CE = \frac{(AE \times EB)}{ED} \]  

(3.8)

Then using the fact that \( AE = EB = \frac{1}{2} AB \), Equation 3.8 becomes:

\[ CE = \frac{AB^2}{4ED} \]  

(3.9)

Next, (3) and (2) gives:
\[ OE = \frac{1}{2} (CE + ED) - ED = \frac{1}{2} (CE - ED) \] (3.10)

Substituting Equation 3.8 into Equation 3.10 gives:

\[ OE = (AB^2 / 4ED - ED) / 2 \] (3.11)

Finally, recall that \( OE \) is simply the distance \( r \) between the source and the center receiver, \( AB \) is the length of the line \( L \), and that \( ED \) is the difference in the distance the wavefront has travelled between \( t_0 \) and \( t_1 \), \( DE = hv \). The final equation then becomes:

\[ r = (L^2 / 4hv - hv) / 2 \] (3.12)

Equation 3.12 gives the minimum distance between the source at O and the receiver at E required to have a maximum time delay of \( h \). Fixing the velocity at the approximate surface wave velocity at Lalor, 2.95 km/s, using a line length of 4 km and plotting Equation 3.12 gives an idea of how far away a source should be before it can be considered a plane wave source. As Figure 3.7 shows, the time difference between receiver E and receivers A and B asymptotically approaches zero as the source distance increases. More importantly, for a fairly generous time delay of 0.1 s, or 50 samples at a sampling interval of 2 ms, the source must be at least 6 km away. A time delay of 0.1 s represents fairly significant wavefront curvature, and a 6 km radius around the center of the receiver array extends well beyond mine and survey area.
Another experiment was performed to make the issue with using the far-field assumption clearer. Again, a source is placed north of the center of the receiver array, but this time it is only 6 km away. As with the previous experiment, the source is modelled at the surface, but a medium velocity of 2.9 km/s is used to simulate a source at an angle of incidence of 75.2°, or a depth of 1.585 km. The resulting gather is shown in Figure 3.8a. While receiver line B records the wave exactly as it did the in the previous experiment, the receiver line A records significant curvature of the wavefront. Running the plane wave beamforming algorithm with the same grid as before on this data gives very different results from those calculated for an actual plane wave. The maximum semblance is 0.124, at an azimuth of 85° and a vertical angle of incidence of 80°. While an error of 5° on both the azimuth and angle of incidence may not seem significant, for synthetic data with a single source and no noise, the error combined with the large drop in maximum semblance is worrisome.
Figure 3.8.  a) Synthetic data recorded using the layout shown in Figure 3.5a except with the source 6 km away.  
b) Results of applying the time shifts calculated for the data in a) using a plane wave beamformer.

This experiment shows that sources at 6 km or closer to the array result in a recorded wavefront which has significant curvature. The wavefront curvature leads to unacceptably inaccurate results when using a beamformer that assumes the incoming waves are planar. As the mining related noise sources are likely to be within at least a 6 km radius of the receiver array, and given the inaccurate results and low semblance of
the synthetic experiment, the use of a plane wave beamformer on the Lalor dataset is inadvisable.

3.4.3. Spherical Wave Beamforming

To avoid the issues presented above, the beamforming algorithm must be adapted for non-planar wavefronts. Rather than assuming that the source is infinitely far away, the source distance must be included in the search parameters. Therefore, it is no longer mathematically correct to use the angle of incidence $\varphi$ as a search parameter. Recall that the angle of incidence is the angle between the source, the surface, and the chosen point of reference. The exact angle between the source and each individual receiver will actually be slightly different than this. When the source/receiver distance is large compared to the size of the receiver array, as is the case when assuming $r \to \infty$, these differences are negligible. For a beamformer which must consider finite, and potentially small source/receiver distances, the differences become large. As a result, there will be errors in the calculated travel times when using the far-field assumption.

To account for this error, another beamforming algorithm is used which searches over a three dimensional grid. As with the plane-wave beamformer, the azimuth $\theta$ is searched, along with the distance between the source and the center of the receiver array, $r$, and the source depth $d$. The delay times between arrival of the wavefront between each receiver and the reference point are calculated as:

$$t_i(\theta, \varphi) = \frac{\sqrt{(x_i - r \cos \theta)^2 + (y_i - r \sin \theta)^2 + (z_i - d)^2}}{v_c} \quad (3.13)$$

Applying the spherical wave beamformer to the data shown in Figure 3.8a gives much more accurate results than in the previous experiment. Again the azimuths were sampled at every 10° between 0° and 360°, while the depths were sampled at every 100 m between 0 m and 2000 m, and the radii were sampled every 1000 m between 0 m, and 10000 m. At a semblance value of 0.74, the results of the beamformer are: an azimuth of 0°, a depth of 1500 m (angle of incidence of 76°), and a radial distance of 6000 m. As can be seen in Figure 3.9, the data is not perfectly aligned. Nonetheless, the algorithm gives the correct location of the source, accurate to within 1° of the angle.
of incidence or 80 m of depth. Furthermore, the maximum semblance is much higher than when using the plane wave beamformer, and therefore the results may be confidently considered to be accurate.

Figure 3.9. The same data as in Figure 3.8a, after applying the time shifts calculated by the spherical wave beamformer.

3.5. Details of the Beamforming Algorithm

3.5.1. Search Grid Design

In the experiments in section 3.4, some *a priori* information was used to determine the grid to use in beamforming. As the azimuth, distance, and depth of the source was known beforehand, the search grids were designed so that the experiment could be performed quickly, while still giving meaningful results. Obviously, with real data this will not be possible. While there is reason to believe that sources will tend to lie in certain areas, on a per data panel basis, the source locations are not known.
Therefore, the search grid has to be designed to allow for a broad range of source locations, while also being computationally feasible.

The simplest choice in designing the grid is selection of azimuth discretization. This parameter has a large effect on the calculated delay times (except in the case of sources lying beneath the receiver array), and so discretization should be relatively fine. When considering receivers distributed along a single direction, e.g. receivers placed along an east-west line, there is an ambiguity between 0°-180°, and 180°-360° (i.e. for a single receiver line, a beamformer cannot distinguish between, for example, 60° and 300°). In this case a sampling of every 2.5° could be used, resulting in 72 azimuths. In most cases, and indeed in the case of the Lalor dataset, it is desirable to know which direction sources lie relative to the whole receiver array. Therefore, receivers at a variety of azimuths are required. In this case, the full range of possible source azimuths from 0°-359° must be searched, and so the sampling should be between 5° and 10°.

The choice of discretization of radius and depth are somewhat more complicated. There is a chance that a source lies directly at the center of the receiver array, either at the surface or at depth, and therefore a radius and depth of zero must be included. There is also a possibility that the incoming wave arrives as planar, either in the form of body waves emanating from a deep source, or as surface waves from a faraway seismic event, and therefore very large radii and depths must be included. Sampling the radii and depths uniformly quickly leads to a very large number of search parameters whose semblance spectra will take an unreasonable amount of time to compute. As is given by Equation 3.12 and shown in Figure 3.7, increasing the radius/depth from 0 by an amount $x$ leads to large changes in the shape of the recorded wavefront and therefore in the time delay $h$. On the other hand, increasing the radius/depth by $x$ from a point far from center of the array gives only very minor changes to the shape of the wavefront, and therefore nearly negligible changes in $h$. The solution is therefore not to uniformly sample the radii and depth, but to instead sample $h$ uniformly and determine the corresponding source distance. Doing so gives a finer grid of points close to the center of the array, and a coarser grid farther away, allowing the algorithm to consider many different wavefront curvatures without needless oversampling.
To make this idea clearer, a graphical representation of each sampling scheme (uniform radii/depth versus uniform $h$) is given in Figure 3.10. Consider a source at the surface, at increasing distances perpendicular to a receiver line, or equivalently, sources located directly beneath the center of the line at increasing depths. If these sources are placed at uniformly increasing distances away from the receivers, the shape of each recorded wavefront will be as shown in Figure 3.10a. For sources placed at 1000 m intervals the change in the wavefront’s curvature in terms of delay time is large (0.3 s) when the source is near the array, but very small (only a single sample) for sources far from the array. Clearly this is a poor and inefficient sampling scheme. As Figure 3.10b shows, choosing instead an acceptable change in the delay time $h$ gives much more uniform and efficient sampling of the change in the wavefront’s curvature as source distance increases. For the same number of radial search parameters, the second scheme is able to search a much more complete set of possible wavefront curvatures.

![Figure 3.10](image.png)

**Figure 3.10.** Arrival times for a source located perpendicular to an array, at distances beginning at 0 m and increasing by a) 1000 m and b) distances corresponding to a uniform increase in the difference between maximum arrival times of 0.05 s.

### 3.5.2. Modifications for Computational Efficiency

Even with the sampling scheme described above, there is a possibility of undersampling and oversampling the search parameter grid. Keeping in mind that there
are roughly 14 days of data giving 20100 data records, which will then be split into shorter data panels, every extra second spent calculating the semblance spectra for one panel adds days or even weeks onto the total computational time for the whole dataset. Furthermore, in most passive datasets, the majority of data panels will not contain any noise sources at all. If a very fine search grid is chosen, a large amount of computation time will be spent calculating semblance spectra for data which contain no coherent events.

To get around this, the beamforming algorithm was modified to include two separate beamforming passes of the data. For each data panel, an initial coarse grid search is performed with discretization $\delta \theta, \delta r, \delta d$, in the azimuth, radii, and depths, respectively. A threshold semblance value $T_D$ is defined. If the beamformer returns values of $\theta$, $r$, and $d$, and the maximum semblance at which they are found exceeds $T_D$, there is a strong likelihood that a source is present near that position. Data panels that meet this criteria are then passed to a second beamformer, hereafter called the detailed beamformer, which searches the area defined by the sets $[\theta - \delta \theta, \theta + \delta \theta]$, $[r - \delta r, r + \delta r]$, and $[d - \delta d, d + \delta d]$. The bounds of these search parameters are much smaller than in the coarse grid beamformer (e.g. if $\delta \theta = 10^\circ$, $\theta = 340^\circ$, the new azimuth bounds are $[330^\circ, 350^\circ]$), and therefore a much finer discretization $\delta \theta_D, \delta r_D, \delta d_D$ may be used. This method reduces the total number of search parameters needed in order to obtain precise results, therefore greatly decreasing the overall runtime.

Given prior information about possible source locations, a similar technique may be employed to further reduce the runtime. Particularly for surveys where there are known anthropogenic noise sources (e.g. highways, mine shafts, etc.), a first beamforming pass may be run over a slice of the search grid which contains the possible locations of these sources. If a source is found with a semblance value higher than $T_s$ (which in general should be larger than $T_D$), the rest of the search grid may be ignored and the data panel may be passed directly to the detail beamformer if necessary. This again has the effect of reducing the total number of search parameters, thus lowering runtime, while not compromising the accuracy of the results.
3.5.3. Drawbacks of the Beamforming Algorithm

Beamforming is a vast field of study of its own, and as it is not the subject of this project, the algorithm that was implemented is fairly straightforward and simple. Therefore, while it in general is capable of calculating source locations with a reasonable degree of accuracy, it does have its drawbacks. The main drawback is that it is only able to determine the location of a single source per data panel. If multiple sources are present, the resulting wavefield may be too complicated for the algorithm, leading to one of several possible results. One possibility is that the wavefield from multiple sources (or a complicated wavefield resulting from scattering/reflecting of a single source) interfere in such a way that the calculated semblance spectra has no values greater than $T_D$. In this case, as far as the algorithm is concerned, no source is present in that particular data panel. Another possibility is that one particular arrival or set of arrivals has a much higher amplitude than the others. This scenario may arise when a strong direct arrival is recorded followed by weaker reflected or scattered waves, or when multiple sources are present but one has a much larger amplitude than the others. For such a data panel, it is possible that the calculated semblance spectra has a peak which corresponds to the strongest arrival only. This is not necessarily an issue in the case of a single source and its direct/scattered arrivals, as the calculated source position will still be relatively accurate. However, when multiple sources are present, the algorithm is unable to distinguish between them. While these issues can be solved in a variety of ways (Rost and Thomas, 2002; Kao and Shan, 2004; Moni et al., 2013), the ability to detect multiple sources was of a lower priority and was not implemented.

To increase the performance and accuracy of the algorithm, it is best to divide the data into short time slices in order to minimize the chances that multiple sources are present during the same recording period. It is also recommended that the receivers used in beamforming cover a large sample of the survey area. Doing so reduces the chances that a single, strong event localized to a small subset of receivers is chosen by the algorithm rather than an event which is recorded by all of the receivers but is weaker in amplitude. Alternatively, separate runs of the algorithm may be performed on different sets of receivers. Compiling the results from several sets of lines may then grant a better understanding of the sources available during each time slice.
3.6. Beamforming on the Lalor Dataset

3.6.1. Introduction

With the groundwork laid in terms of the beamforming methodology, it is now time to apply it to the data obtained at Lalor. Using the information regarding the amplitude and frequency content of the data obtained in sections 3.2 and 3.3, section 3.6 will describe the process of applying beamforming to real data, as well as show the results thereof and discuss their implications.

3.6.2. Pre-Processing the Data

Sections 3.4 and 3.5 describe in detail the methodology of beamforming and the designed algorithm as well as its various parameters. The values of these parameters are dependent on the dataset, and are best determined through tests on the data. These include pre-processing parameters such as the bandpass filter used, sampling rate/resampling rate, and the length of each data panel to be passed to the beamformer. This section will detail how and why values for these parameters were chosen.

The first thing that must be decided is the length of data panel to use. As this length should be consistent throughout the processing of the dataset, the value chosen affects not only the beamforming results but also on the results of the entire SI procedure. Several factors should be considered when making this decision. The length of time per panel should be chosen to be relatively short to lower the probability of finding multiple sources in the same panel. However, the panels should be made long enough to capture the coda waves that may result from a single source. Lastly, the maximum depth of interest of the survey should be taken into consideration. As a consequence of the SI by cross-correlation procedure, the length of the virtual shots (and therefore the maximum depth that will be imaged) will be equal to half the length of the data panels used.

After considering each of the three points above, a length of 10 s was chosen. This length gives sufficient time to capture the useful parts of the wavefield. As the Lalor area is seismically quiet except for the mining activity, a 10 s data panel is unlikely to
contain more than one significant source at a time. As the amplitude and frequency information in sections 3.2 and 3.3 indicated, the high-energy events likely related to blasting occur several hours apart. Lastly, the length of the records used in the 3-D active source survey as stated in Bellefleur et al. (2015b) is 4 s. In order to obtain virtual shot gathers of this length, data panels 8 s long must be used. Rounding up to 10 s makes splitting the original 60 s records easier.

With the 10 s data panels in hand, the next decision to be made is the choice of possible filters. As Figure 3.3 showed, the strongest frequencies in the data are largely below 30 Hz. This makes a good choice as a first pass. However, the data is generally of poorer quality with low SNR, and this is especially true when higher frequencies are included. As Figure 3.11 shows, beamforming under these circumstances is not ideal. Figure 3.11a shows a portion of a 10 s data panel taken from lines 122 and 141, filtered to contain frequencies between 5 Hz and 30 Hz. A relatively strong event is evident between ~0.9-1.5 s. Figure 3.11b shows the same data after beamforming and applying the time shifts corresponding to the sources location as determined by the algorithm. This data panel also illustrates one of the drawbacks of the beamforming algorithm in that only the strongest source is located. After beamforming, the main event is relatively well aligned. Despite this, the semblance is quite low at 0.07. To put this into perspective, a baseline panel was chosen with no coherent events and had a maximum semblance of 0.035. The low SNR is a large factor in the poor semblance of the beamformed data. An additional factor is that the higher frequencies in the data reduce the temporal width of the wavelet. A shorter duration wavelet requires much more precise time shifts to be aligned. As the time shifts applied by the beamforming algorithm depend on the search grid discretization used, for reasons of computation time it is not always possible to use the precise time shifts required by a higher frequency wavelet. Figure 3.12 shows the same data as Figure 3.11, but this time the data was filtered to between 5-15 Hz. While the calculated source location is the same for both Figure 3.11 and 3.12, the semblance value for 3.12b is 0.21. If the semblance value is to be used as an indicator of sources being present in a given data panel, it is advantageous to have the difference in semblance between panels with and without coherent events be as large as possible. For these reasons, all subsequent beamforming is performed on data filtered to between 5-15 Hz.
Figure 3.11.  

a) Data taken from lines 122 and 141 after applying a high-cut filter of 30 Hz.  
b) Data after applying the time shifts obtained from beamforming.

Figure 3.12.  

a) Data taken from lines 122 and 141 after applying a high-cut filter of 15 Hz.  
b) Data after applying the time shifts obtained from beamforming.

Since the data to be beamformed now have a maximum frequency of 15 Hz, the original sampling interval of 2 ms (Nyquist frequency of 250 Hz) is slightly excessive. Data with a maximum frequency of 15 Hz can easily be represented correctly at a much
higher sampling interval. Furthermore, the precise time shifts required by the higher frequency wavelets as described above have been taken out of the data, which again should allow the sample interval to be raised without consequence. To test this, 500 randomly selected data records (3000 data panels total) were chosen and beamformed at the original sample interval of 2 ms, and again using a lower sampling interval of 8 ms, hereafter referred to as ‘Run A’ and ‘Run B’, respectively. Run A took 2.7 times longer than Run B. This was a significant speedup given the limited computational resources available. The semblance values were higher by 0.8% on average for Run A. Given the generally low semblance values (mean of 0.11) for both runs, this reduction in semblance is negligible. The different runs disagreed on the sources location for 300 data panels. Of these, 221 panels had a maximum semblance value less than 0.08 and therefore likely contain no strong coherent events. Visual inspection confirmed this for most of the panels. Furthermore, of the 300 panels whose source location was different between runs, 186 differed on location by only 5˚, which was the azimuth sample size used in both runs. From these statistics, it was concluded that increasing the sampling interval of the data from 2 ms to 8 ms does not have a significant impact on the accuracy or reliability of the beamforming algorithm, and therefore the sample interval of 8 ms was used for all subsequent runs in order to reduce the overall runtime.

The final step before actually applying the beamforming algorithm is normalization of the data. Noisy traces and localized events may lead to a disproportionate amount of energy being recorded by a single or small group of receivers during any given time slice. As was discussed earlier, the point of the beamforming is to gain information on the locations of useful seismic sources which are recorded by the majority of the receivers. Therefore prior to applying the beamforming algorithm, the data should be normalized such that the amount of energy per trace is equal, thus reducing the effect of noisy traces. With this, the data are now prepared to be input to the beamforming algorithm.

3.6.3. Beamforming Results and Implications

As was discussed earlier, to ensure the results of beamforming are reliable, a large subset of the receiver array should be used. However, as the Lalor dataset is quite
large (336 receivers distributed along 16 linear profiles), in order to ensure manageable runtimes the dataset was divided into 3 subsets, each containing 2 receiver lines. The lines chosen for each subset were lines 122 and 129 (subset A), lines 141 and 118 (subset B), and lines 118 and 145 (subset C). Lines 122 and 118 were chosen for the northeast-southwest lines as they are the only lines in that direction over 20 receivers long. Likewise, lines 141, 145, and 129 are some of the longest lines along the southwest-northeast direction. The receivers were chosen to be distributed in lines rather than randomly throughout the array to facilitate visual inspection of the data panels, as well as interpretation of the beamforming results. Simply put, it is more straightforward to recognize and classify a seismic event when viewing the traces as recorded along a linear profile.

A preliminary pass of the coarse beamforming algorithm was run over all 21060 records (126360 data panels after slicing each record into 10 s panels) using each subset. The grid discretization was 10° increments in azimuth, and a delay time \( h \) of 0.024 s, or 3 samples for both radius and depth. The results of each run were compiled and analyzed to determine trends in the data, as well as the differences and similarities between data recorded by different lines. The results of these first passes were also used to help fine-tune the beamforming parameters for a later detailed beamforming run.

There were several important sets of results from these tests. The first, shown in Figure 3.13, is the distribution of the maximum semblance values. As one might expect for a passive dataset in a seismically quiet area, the majority of the semblance values are quite low. Over 60% of data panels in both subset A and B had a semblance lower than 0.1. Subset C on the other hand, had a much lower rate of 42%. Subset C also had the highest average semblance at 0.14, whereas subsets A and B both had an average semblance of 0.1. These statistics are helpful in several ways. Firstly, the sharp cut-off in the number of events with maximum semblance values higher than 0.1 gives a good indication of where to set the semblance threshold for determining whether a given data panel contains an identifiable source. Visual inspection of a large number of data panels with low semblance confirmed this, and so \( T_D \) was set to 0.1. This value is high enough to eliminate a large number of source-less data panels, while still being low enough to include some data panels containing either weak sources, or events.
which were simply difficult to properly align. In addition to this, it was determined that the higher semblance values for subset C made it the ideal candidate to be passed to the detailed beamformer, as the separation in maximum semblance values for panels with and without visually identifiable sources was significantly greater than the other subsets.

Figure 3.13. Distribution of the maximum semblance values for each subset of data used in the preliminary beamforming runs.

A total of 65822 data panels from subset C had a maximum semblance value exceeding 0.1, and were passed to the detailed beamformer. The success of the detailed beamformer varied from failing to increase the semblance at all, to more than doubling the semblance. On average, the maximum semblance values increased by 20%. The full results of the detailed beamformer are shown as histograms in Figure 3.14. Maps of the source locations were overlaid onto a map of the mine camp (Figure 3.15), as well as a regional map (Figure 3.16). As can be seen in each of these of figures, the beamforming algorithm places the vast majority of the sources close to the
survey area. As one might have expected, the nearby mine activity constitutes the majority of the recorded noise. Source clusters C1 and C2 coincide with the mine and ventilation shafts, respectively, while C3 and C4 cover the Photo and Chisel Lake areas which are being used for offsite infrastructure. The calculated depths of the sources should not be taken to be exact, as they are highly dependent on some assumed variables, such as the seismic velocity. Nonetheless the depths suggest that the vast majority of the recorded noise is due to the nearby mining activity. Over half of all events had a calculated depth of less than 500 m. The actual depth values are likely off by a few hundred meters, but the conclusion is the same: the locations of the sources coinciding with known mine related structures and the relatively shallow depths strongly suggests that the vast majority of the noise is due to near-surface mining activity.
Figure 3.14. Histograms showing the distribution of sources as calculated by the detailed beamformer in terms of a) semblance, b) azimuth, c) distance from center of the array, and d) depth.
Figure 3.15. Plot of the source locations overlain on a map of the survey area. The white circles indicate constant radial distances of 500 m, 1000 m, and 2000 m. White Xs indicate the receivers used in beamforming.
Figure 3.16. Radially extended plot of the source locations overlain on a map of the Snow Lake region. White circles indicate radii of 500 m, 1000 m, 2000 m, 4000 m, and 6000 m.
These results complicate the application of SI to the Lalor dataset. As was demonstrated in Chapter 2, an anisotropic source distribution must be carefully treated in order to obtain useful results from a passive survey using SI by cross-correlation. The beamforming results indicate the source distribution is highly anisotropic, with very few sources to the north and east of the receiver array. As this project is concerned with processing the passive data as a 2-D dataset, and recalling that only sources in-line with a receiver line contribute positively to the Green's function, this indicates that each line will have sources almost exclusively on one side.

Visually inspecting nearly 3000 records led to another, more troubling observation. As the beamforming results suggest, a huge amount of the data contains events originating from the mine and ventilation shafts, as well as the activity due to operations around the Photo and Chisel Lake mine sites. The ambient noise from these sources manifests itself as linear events on lines which are in-line with the noise, and as hyperbolic events on lines perpendicular to the source direction. The beamforming results can be used to determine whether a given data panel contains ambient noise with a direction of arrival in-line or perpendicular to the receiver line. Data panels containing ambient noise arriving from a direction perpendicular to the receiver line may be discarded as these data panels will not contribute to the retrieval of reflections. Data panels containing ambient noise arriving from a direction nearly parallel to the receiver line are more difficult to handle. Consider the data panel shown in Figure 3.17, which is representative of much of the dataset. This data panel captured noise originating from around the mine and ventilation shafts, as recorded by lines 133 and 141. A high amplitude event is evident beginning at around 3 s due to activity in the mineshaft. This event is potentially useful in generating reflections when applying SI. However, the remainder of the data panel is contaminated by coherent surface wave noise generated by a persistent source in the ventilation shaft. This surface wave noise needs to be removed somehow, otherwise it will overpower any other events when applying SI to generate virtual shots. This is outside the scope of this chapter, and will be covered in Chapter 4.
Figure 3.17. Data taken from lines 133 and 141 showing a high amplitude event (highlighted in blue) as well as coherent background noise (highlighted in red) due to activity in the mine and ventilation shafts.
Chapter 4.

Application of SI to the Lalor Dataset

4.1. Introduction

In Chapter 2, synthetic experiments were used to examine how a one-sided source distribution may affect a reflection profile generated by applying SI. It was then shown in Chapter 3 that the majority of the sources in the Lalor passive dataset are located near the on-site mine and ventilation shafts, as well as to the south-east of Lalor near the Photo Lake and Chisel Lake mines. While some of the events originating from these locations may be useful in recovering reflections via SI, many of the data panels (including those containing potentially useful events) are contaminated by repetitive coherent background noise. This chapter aims to demonstrate the effects this noise has on the results of applying SI to the Lalor dataset, and to develop a procedure that mitigates these effects in the interest of generating quality virtual shot gathers which are usable as input to standard seismic reflection processing.

While the end goal is to generate virtual shot gathers, the conversion from stacked correlation gather to virtual shot gather via time reversal of the acausal portion and stacking with the causal portion tends to complicate any coherent events which are present due to the possibility of the superposition of events with different moveout. This makes it much more difficult to identify problems and their origins, such as the existence of persistent background noise. Therefore, the stacked correlation panels will be used instead to demonstrate the development of the processing procedure. To start, the results of applying only the basic SI procedure will be shown. These results will be improved in stages by introducing additional processing steps. First, the results of the beamforming analysis in Chapter 3 will be used to select a subset of the data in which the recorded sources lie roughly in-line with the receiver line being processed. Such sources provide the dominant contribution to the recovery of reflections via SI (Snieder, 2004; Ruigrok et al., 2008), and so application of SI to only these data panels should improve the results. Next, a strategy based on the beamforming results and F-K filtering
will be developed to mitigate the effects of the persistent coherent noise present in the data. With these strategies in place, the SI processing procedure will be finalized to generate a final set of virtual shot gathers along a subset of the receiver lines. These virtual shot gathers will then be compared with nearby shot gathers from the 3-D active source dataset.

4.2. Preliminary Applications of SI to Field Data

4.2.1. First Pass – Brute Force Approach

In order to establish a baseline for the quality of the virtual shots that can be generated by applying SI to the Lalor passive dataset, it will first be processed using only the basic SI procedure. With the exception of the choice of bandpass filter and trace normalization technique used, no information gained from Chapter 3 is used. The procedure is similar to that performed in Chapter 2 using synthetic data. The steps are briefly described in Table 4.1 with the parameters used on the real data.

Table 4.1. Preliminary procedure and parameters used to generate virtual shot gathers from raw data.

<table>
<thead>
<tr>
<th>Step #</th>
<th>Instructions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Extract the data records from the receiver line to be processed.</td>
</tr>
<tr>
<td>2</td>
<td>Bandpass filter each 60 s data record to between (5-10-25-35 Hz filter specification)</td>
</tr>
<tr>
<td>3</td>
<td>Separate each data record into 10 s data panels.</td>
</tr>
<tr>
<td>4</td>
<td>Energy normalize each data panel such that each trace has unit energy</td>
</tr>
<tr>
<td>5</td>
<td>Apply SI by cross-correlation to each panel: Choose a master trace, and cross-correlate it with every trace to generate a correlation panel. Repeat this using every trace as the master trace to generate a correlation panel for each receiver.</td>
</tr>
<tr>
<td>6</td>
<td>Remove the source function from each correlation panel by deconvolving each trace by an estimate of the autocorrelation of the source wavelet. An estimate may be made by taking a short window around time zero of the autocorrelation of the master trace for each correlation panel.</td>
</tr>
<tr>
<td>7</td>
<td>Sum all correlation panels corresponding to the same master trace location, resulting in a ‘stacked correlation gather’ (SCG) for each master trace location.</td>
</tr>
<tr>
<td>8</td>
<td>For each of resulting SCGs, sum the acausal and causal portions to generate virtual shot gathers at each receiver location.</td>
</tr>
</tbody>
</table>
Note that while the geophones used have a corner frequency of 10 Hz, the PSD analysis shown in Chapter 3 indicated that some energy is still present between 5 Hz to 10 Hz. As the change in phase angle for frequencies below the corner frequency is relatively small (< 30°), the associated arrival time errors are on the order of a few samples for a wavelet with a central frequency of 15 Hz. Therefore, to avoid further narrowing the already small effective bandwidth of the data, the filter used was designed to ramp up from 5 Hz to 10 Hz. The PSD analysis also shows that monochromatic noise at 30 Hz is present throughout the entire recording time. Furthermore, the frequencies beyond 30 Hz contain relatively little useful energy. For these reasons, the filter was designed to begin attenuating frequencies at 25 Hz, with 100% attenuation at 35 Hz.

For the synthetic data generated in Chapter 2, these steps are all that were required to generate virtual shots containing clearly visible reflections. The same is not necessarily true for real data. Figure 4.1 shows the results of applying steps 1-7 on all data from lines 133, 141, and 122, using the north-east most receiver in each line as the master trace. The only visible coherent events are a set of curved events of varying amplitudes. Higher amplitude events (highlighted in red) are repeated 3.2 s apart in each stacked correlation gather (SCG). For lines 133 and 141, the SCGs are also contaminated with weaker amplitude events with similar curvature. These events match the coherent background noise seen in Figure 3.17, and are a result of applying the SI procedure without first addressing the coherent noise which contaminates the majority of the dataset. Figure 4.1c contains events with similar timing, but with a moveout that suggests a higher seismic velocity. However, as will be shown in the following section, this noise has the same source as that seen in Figures 4.1a and 4.1b. The noise present in these SCGs overpowers any reflections which may be present. This coherent noise must be removed prior to converting the SCGs into virtual shot gathers.
4.2.2. Normalizing Azimuthal Contributions

One way to improve the quality of the SCGs generated in the previous section is simply to use the information gained from the beamforming analysis performed in Chapter 3. To start, steps 1-6 are carried out as described in Table 4.1. Prior to stacking all correlation panels with the same master trace, each is first binned according to the beamforming results for its corresponding data panel. Correlation panels whose

Figure 4.1. SCGs generated by applying steps 1-7, plus AGC, on data from:
  a) Line 133, using the 26th trace as the master trace.
  b) Line 141, using the 40th trace as the master trace.
  c) Line 122, using the 34th trace as the master trace.
data panels had beamforming results with semblance values above the threshold value as described in Chapter 3 are binned according to their calculated azimuth. To reduce the amount of storage space required, binning was done every 20° between 0° and 360°, for a total of 18 bins. Two more bins are designated to separate data panels which were unsuccessfully beamformed due to complicated, but potentially useful, events from those which contain no coherent events. Data panels whose semblance was below the threshold, but whose normalized median energy (as shown in Figure 3.1) was above 0.1 are binned into the 19th bin. All other panels not meeting either of these criteria are binned into the 20th bin. Correlation panels with the same master trace are then summed within each bin, resulting in a SCG for each receiver within each bin.

Binning the correlation panels in this way allows the contributions from each azimuth to be assessed separately. Of the total energy contained in all the bins, 7.5% of it is contained in the 11th bin, 60% is in the 13th bin, and 15% is contained in the 16th bin. These bins correspond to azimuths of 240°-260°, 200°-220°, and 130°-150°, and contain the areas covered by the mine shaft, ventilation shaft, and the Photo and Chisel Lake mine areas, respectively. Isolating the SCGs from the 13th bin further confirms that the ventilation shaft is the primary source of coherent noise in the dataset. Figure 4.2 shows the SCGs for lines 133, 141, and 122 for the 13th bin. The events highlighted are identical to those in Figure 4.1, indicating that it is the noise from the ventilation shaft that is responsible for the coherent noise seen in the SCGs. This coincides with what was shown in Chapter 3, in particular that the data panels containing sources near the ventilation shaft make up nearly 35% of the data. Clearly, a strategy must be put in place to avoid having a single repetitive source or set of sources overpower all the other data.
Figure 4.2. SCGs after AGC from the 13\textsuperscript{th} bin (azimuths between 200°-220°) on data from:

a) Line 133, using the 26\textsuperscript{th} trace as the master trace.
b) Line 141, using the 40\textsuperscript{th} trace as the master trace.
c) Line 122, using the 34\textsuperscript{th} trace as the master trace.

With the correlation panels binned by azimuth, it is now possible to process the data using the source location information in a way which should improve the quality of the SCGs. Sources that are within the stationary phase region of the receiver line give the dominant contribution to the recovered Green's function (Snieder, 2004; Ruigrok et al., 2008; Kimman and Trampert, 2010). For a linear array of receivers, the stationary phase regions lie approximately in-line with the receivers (Melo et al., 2013; Snieder et al., 2009). Strictly speaking, these relations are true only for simple media (e.g. a horizontally layered Earth). While the geology at Lalor is not horizontally stratified, application of the stationary phase principle was found to improve the resulting SCGs. Therefore, all correlation panels in bins that do not correspond to a source location within the stationary phase regions are discarded. For all remaining bins, correlation
panels with the same master trace are stacked to form SCGs within those bins. This process will be referred to as ‘stationary phase selection’. To determine which azimuths are passed by stationary phase selection, an azimuthal window of width $\Delta \theta$ is selected around both ends of the receiver line being processed. Bins corresponding to azimuths within this window are passed to the next stage of processing. In addition to keeping data based on its azimuth, data panels whose perpendicular distance to the receiver line is small (< 500 m) may also be kept, as these sources may also contribute to the recovery of reflections. However, very few such sources were found within the Lalor dataset. An example of the layout for stationary phase selection is given in Figure 4.3. The southeastern end of line 122 is oriented at an azimuth of 140˚, and its northwestern end is at an azimuth of 320˚. For $\Delta \theta = 60^\circ$, sources with azimuths from 110˚-170˚ as well as 290˚-350˚ would be passed, as well as sources from within narrow corridor around the receiver line itself.

![Source location map indicating the regions passed by stationary phase selection for receiver line 122, for $\Delta \theta = 60^\circ$.](image)

Figure 4.3. Source location map indicating the regions passed by stationary phase selection for receiver line 122, for $\Delta \theta = 60^\circ$. 
The choice of whether or not to include bins corresponding to data panels whose semblance did not meet the threshold (bins 19 and 20 in this case) was made by visually inspecting the SCGs within these bins. In general for the Lalor dataset, SCGs within the 20th bin contain mostly coherent noise from the mine and ventilation shaft that the beamforming algorithm was unable to detect based on the semblance threshold. The character of the SCGs from the 19th bin vary from line to line. While some SCGs within the 19th bin do contain some coherent events, it is not clear whether or not these events would contribute to the recovery of reflections or introduce non-physical artefacts. To be safe, data from this bin were not passed to the next processing stages.

Figure 4.4 shows the SCGs resulting applying stationary phase selection with $\Delta \theta = 60^\circ$. For lines 133 and 141, stationary phase selection does not have a noticeable effect, as the bins containing the coherent noise which contaminate the SCGs seen in Figure 4.1 are within the stationary phase regions for these lines. Therefore, the resulting SCGs are nearly identical to those seen in Figure 4.1. For line 122, applying stationary phase selection does remove the coherent noise originating from the mine and ventilation shafts. In doing so, another large source of noise becomes evident, namely the noise from the Photo Lake mine area. As the Photo Lake mine lies ~3.5 km away from the center of the receiver array, the noise manifests itself as linear events in the SCGs for line 122.
Figure 4.4. SCGs with AGC generated using stationary phase selection on data from:
  a) Line 133, using the 26th trace as the master trace.
  b) Line 141, using the 40th trace as the master trace.
  c) Line 122, using the 34th trace as the master trace.

The number of data panels containing coherent noise originating from Lalor mine and ventilation shafts (for lines 133 and 141), as well as the Photo Lake mine (for line 122), vastly outweigh the number of data panels containing sources at other azimuths within each line's stationary phase region. Therefore, simply stacking the bins chosen via stationary phase selection does not adequately attenuate the coherent noise from these sources. To address this, each bin that is kept during stationary phase selection should also be normalized to contain the same amount of energy. This will have the effect of normalizing the contribution each azimuth has towards the SCGs.

In addition to normalizing the energy of the bins, depending on the dataset it may be necessary to balance the frequency spectrum. As Figure 4.5 shows, the frequency spectrum of the SCGs generated from the Lalor dataset are very unbalanced, with large spikes at a number of frequencies. Spectral whitening of each SCG within each bin will
help to balance the frequency spectrum. This will also help to reduce the amount of repetitive coherent noise.

![Amplitude Spectrum](image)

**Figure 4.5. Amplitude spectrum of the SCG shown in Figure 4.4b.**

Figure 4.6 shows the result of applying panel normalization and spectral whitening to each SCG within each bin, and stacking those bins kept after stationary phase selection. The SCGs are improved over those in Figure 4.4, with the amount of coherent noise contained in each panel greatly reduced. In particular, the SCG for line 122 (Figure 4.6c) is improved considerably, with only 2 noticeable linear events remaining. These linear events are likely surface waves, as they have an apparent velocity of ~2900 m/s. Some hyperbolic events are still evident in Figure 4.6a and 4.6b, which again correspond to the coherent noise from the mine and ventilation shafts. In order to have a chance at recovering reflections, the surface wave noise will have to be removed from the SCGs. However, it is unlikely that processing the SCGs directly will result in the recovery of coherent reflections. A better approach is to remove surface wave noise directly from the data panels.
4.3. Removal of Coherent Background Noise

Surface wave noise originating from the mine and ventilation shafts, as well as from the Photo and Chisel Lake mine areas is evident throughout much of the data. This noise has an apparent velocity of ~2900 m/s, which is consistent with the surface wave velocity in the Lalor area. In a typical active source survey, surface wave noise such as this could be removed using an F-K or other type of filter. This is not possible for the Lalor passive dataset for 2 reasons. For lines which are in-line with the sources, the noise is recorded as low-velocity linear noise. Due to the large receiver spacing, an F-K filter designed to remove the low-velocity waves without introducing aliasing would also remove all frequencies above 14.5 Hz. This is determined by using the equation:
\[ f = K_{Ny}v \]  

(4.1)

where \( k_{Ny} \) is the Nyquist wavenumber and \( f \) is the frequency at which aliasing will occur. In this case we have \( K_{Ny} = \frac{1}{2\Delta x} = \frac{1}{2 \times 100 \text{ m}} = 0.005 \text{ m}^{-1} \), where \( v = 2900 \text{ m/s} \) is the apparent wave velocity, and \( \Delta x = 100 \text{ m} \) is the receiver spacing. An additional complication comes from the fact that many of the receiver lines record the coherent noise as non-linear. This is especially true for line 141, as it lies in between the mine and ventilation shafts, and extends past them in both directions. Because of this, the event is recorded with a high degree of curvature. Therefore, a simple F-K filter is unable to adequately remove the coherent noise.

To get around the issue posed by the non-linear coherent background noise and large receiver spacing, the information gained through beamforming is used to flatten the events prior to applying an F-K filter. As the locations of the sources responsible for the noise are known, within the error bounds set by the beamforming grid, the time shifts required to flatten the events may be calculated. The source locations as calculated through beamforming are approximate, and so the calculated time shifts may not fully flatten the events. To ensure that the events to be removed are as horizontal as possible, the data is flattened in 2 stages. First, the time shifts calculated from Equation 3.13 are applied to approximately flatten the background noise (Figure 4.7a). Secondly, to further align the noise, correlation-style trim statics are calculated for the approximately flattened data panel and applied. A time window is used to scan over the flattened data to find the time window in which the semblance is highest. This window corresponds to a section of the data panel containing background noise which is nearly aligned. The time window is summed across the traces to form a stack. Each trace in the original time window is then cross-correlated with the stack to form a stack correlation panel. A maximum allowable time shift \( L \) is defined, and the stack correlation panel is time windowed between \( -L \) and \( L \). The maximum value within this window of each trace in the stack correlation panel is then found. The location of each maximum on the time axis gives the amount of time to shift the corresponding trace on the original data panel to attain maximum coherence with the stack trace. The shifts are then applied to the data panel and the semblance is recalculated. This procedure is repeated for a pre-defined number of iterations, or until the increase in semblance falls below
some threshold. The sum of the calculated statics for each iteration are applied to the original data panel, resulting in further alignment of the background noise and increasing the semblance. For the data shown in Figure 4.7, the semblance increases from 0.175 in Figure 4.7b to 0.388 in 4.7c.

![Figure 4.7](image)

**Figure 4.7.**  a) A data panel from line 141 containing a high amplitude event beginning at 3 s, as well as coherent background noise from sources in the ventilation shaft.  
b) The data in a) after applying time shifts calculated based on Equation 3.15, using the location of the source generating the coherent background noise.  
c) The data in b) after applying additional time shifts calculated using correlation trim statics.

The background noise now has an infinite apparent velocity, and so an F-K filter may now be applied without introducing aliasing into the data. A filter is carefully designed to isolate energy from around the wavenumber axis ($K = 0$), which in the time domain corresponds to horizontal events. A cut-off velocity $v_c$ is defined such that
events in the flattened panel with apparent velocity $v > v_c$ are kept. For each frequency $f$ the cut-off wavenumber $K_c$ is found such that

$$K_c = \frac{f}{v_c}$$

(4.2)

is satisfied, and a low-pass Butterworth filter is built according to:

$$G_{pass}(f, K) = \sqrt{\frac{1}{1 + \left(\frac{K v_c}{f} \right)^2 n}} = \sqrt{\frac{1}{1 + \left(\frac{K}{K_c} \right)^2 n}}$$

(4.3)

where $n$ is the order of the filter. Figure 4.8 shows the filter built in this way using $n = 4$ and $v_c = 30000 \text{ m/s}$. Note that this filter does not keep 100% of the energy within the zone defined by $v_c$. Using a higher order filter will allow more energy to be kept within this zone, at the expense of a sharper cut-off which may create artefacts in the filtered data due to Gibb’s phenomenon.

**Figure 4.8.** F-K filter designed to pass data with apparent velocities greater than 30 km/s. The dashed lines indicate the location of the cut-off velocity.
The filter may be applied to the data in 2 ways. It may be converted into a rejection filter via:

\[ G_{\text{reject}}(f, K) = 1 - G_{\text{pass}}(f, K) \]  

(4.4)

and then applied directly to the transformed data via multiplication in the F-K domain. This method removes most of the energy within the zone defined by \( v_c \), however it may also introduce artefacts into the data. If these artefacts were present in enough of the filtered data panels, they would stack during the SI procedure, creating coherent noise in the SCGs. As the aim of this procedure is to remove coherent noise, an alternative method is used. An estimation of the coherent noise to be removed is found by applying \( G_{\text{pass}} \) to the transformed data and transforming the resulting data back to the time domain, thereby keeping only those events with \( v > v_c \). Figure 4.9a shows the noise estimate resulting from applying the pass filter in Figure 4.8 to the flattened data in Figure 4.7c. Each trace \( n_i \) in the estimated noise panel is then multiplied by a scalar \( a_i \) and subtracted from the corresponding trace \( s_i \) in the flattened data panel:

\[ y_i(k) = s_i(k) - a_in_i(k) \]  

(4.5)

where \( k \) is the sample number. Each \( a_i \) is chosen so that \( y_i \) has minimal energy. These scalars may be found by solving the well-known least-squares minimization problem:

\[ \min_{a_i} \| a_in_i - s_i \|^2 \]  

(4.6)

In the case of 1-D signals, the solution to this is given by:

\[ a_i = \frac{\sum_{k=1}^{M} y_i(k) * n_i(k)}{\sum_{k=1}^{M} n_i^2(k)} \]  

(4.7)

where \( M \) is the number of samples in the data panel. Subtracting the noise estimate from the flattened data panel in this way helps to ensure that the coherent background noise is completely removed while preventing the introduction of filtering artefacts.

Figure 4.9c shows the result of subtracting the data in 4.9a from that in 4.7c, using the method described above but with each \( a_i = 1 \). While the majority of the
horizontal energy is removed, a few horizontal events are still visible. When the $a_i$'s are instead calculated using Equation 4.7, the horizontal events are completely removed, as seen in Figure 4.9c. While the high amplitude event (now centered on 4 s) is mostly intact, some sections of the event which were made horizontal by the time shifting were also attenuated. After subtracting the noise estimate from the flattened data, the previously applied time shifts are removed. As Figure 4.9d shows, the coherent background noise has been removed. In addition to this, secondary events are visible after the main high-amplitude event that are not visible in Figure 4.7a. It is unclear whether or not the new events in this particular data panel will contribute to the recovery of reflections when applying SI. However, it is certainly possible that there are weak amplitude reflections in the dataset are being masked by coherent noise that will be made visible by filtering.

![Figure 4.9](image)

**Figure 4.9.** a) Coherent noise estimate obtained by applying the F-K pass filter to the data in Figure 4.7c. b) Result of subtracting the data in a) from the data in Figure 4.7c using Equation 4.6 with $a_i=1$. The red ellipses indicate areas where horizontal events have not been completely removed. c) Same as b) but with each $a_i$ calculated using Equation 4.7. d) Data in c) after removing the previously applied time shifts.
4.4. Generation of Final Virtual Shot Gathers

While the examples shown in the previous section use a single data panel from line 141, the method is easily adapted to other receiver lines. For line 133, the main source of noise contaminating the data is the same as that for line 141. The only difference is the time shifts that will be required to flatten the coherent noise. Whether the dominant background noise in any given data panel originates from the mine shaft or the ventilation shaft may be determined by applying the relevant shifts for each source location, and taking those which lead to the higher semblance value. For lines oriented north-west to south-east, the Photo Lake mine is the only major source of coherent background noise. It is possible to apply different time shifts and different filters to each data panel based on its beamforming results if desired. For the Lalor dataset, lines which are in-line with the mine and ventilation shafts are most heavily impacted by the coherent noise emanating from those areas, and likewise for receiver lines lying in-line with the Photo Lake mine.

With this in mind, the final procedure is implemented to generate the SCGs and virtual shots along each line. This procedure along with the parameters used to generate the final set of virtual shot gathers are summarized in Table 4.2. Figure 4.10 shows the result of applying steps 1-14 to generate SCGs for lines 133, 141, and 122. At this point the SCGs do not contain any obvious coherent events which could be reflections. More importantly, they do not contain any of the previously seen repetitive coherent noise, linear or non-linear, which is the basis on which the SCGs have been judged up to this point.
Table 4.2. Finalized procedure and parameters for generating virtual shot gathers from raw data.

<table>
<thead>
<tr>
<th>Step #</th>
<th>Instructions</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Extract 60 s data records from the receiver line to be processed</td>
</tr>
<tr>
<td>2</td>
<td>Bandpass filter 5-10-25-35 Hz</td>
</tr>
<tr>
<td>3</td>
<td>Separate data records in 10 s data panels</td>
</tr>
<tr>
<td>4</td>
<td>Normalize each trace to have unit energy</td>
</tr>
<tr>
<td>5</td>
<td>Apply time shifts required to flatten the dominant coherent noise present</td>
</tr>
<tr>
<td>6</td>
<td>Apply the F-K subtraction filter (cut-off velocity of 12 km/s)</td>
</tr>
<tr>
<td>7</td>
<td>Undo the previous applied time shifts</td>
</tr>
<tr>
<td>8</td>
<td>Apply SI by cross-correlation</td>
</tr>
<tr>
<td>9</td>
<td>Deconvolve each correlation panel with the autocorrelation of its master trace</td>
</tr>
<tr>
<td>10</td>
<td>Bin each correlation panel based on its beamforming results</td>
</tr>
<tr>
<td>11</td>
<td>Stack correlation panels with the same master trace position within each bin.</td>
</tr>
<tr>
<td>12</td>
<td>Energy normalize the SCGs within each bin</td>
</tr>
<tr>
<td>13</td>
<td>Spectrally whiten the SCGs within each bin</td>
</tr>
<tr>
<td>14</td>
<td>Apply stationary phase selection, stacking SCGs corresponding to the same master trace within each bin kept.</td>
</tr>
<tr>
<td>15</td>
<td>Sum the causal and acausal portions of the SCG</td>
</tr>
</tbody>
</table>

Up until now we have used the SCGs to judge the character of the data which resulted from processing the Lalor dataset using SI. The SCGs were used rather than virtual shot gathers simply because it is easier to diagnose possible problems, such as the existence of coherent noise, prior to summing the acausal and causal portions. With the coherent noise successfully removed, the final step in Table 4.2 can be applied to generate the virtual shot gathers. After doing this, the virtual shot gathers are converted to segy format files, and imported into the ProMAX processing environment.
Figure 4.10. SCGs generated after applying steps 1-14 in Table 4.2, followed by AGC, for data from:
   a) Line 133, using the 26th trace as the master trace.
   b) Line 141, using the 40th trace as the master trace.
   c) Line 122, using the 34th trace as the master trace.

Due to the low SNR of the Lalor dataset, the added correlation noise inherent to the SI procedure, and the large receiver spacing, it is difficult to assess the quality of the virtual shot gathers. The large receiver spacing alone makes it difficult to track coherent events across a given shot gather. Therefore the quality of the virtual shot gathers generated using the procedure outlined in Table 4.2 will be compared to those generated using the procedure outlined in Table 4.1, which will be referred to as sets A and B, respectively. For lines 141 and 133, coincident receiver lines from the 3-D active source survey will also be used for comparison.

As a first point of comparison, Figure 4.11 and 4.12 show an active source shot gather from the end of line 141. The location of the source is 150 m to the north-east of
the last receiver on the north-east end of passive receiver line 141. The positions of the active source shot gathers shown here relative to the passive receiver lines is given in Figure 4.17. While they are not clear on the 2 s shot gather in Figure 4.11, there are a number of reflections in this gather. A set of reflections are visible at 1200 ms and 1600 ms, highlighted by the yellow ellipses. Figure 4.12 shows the top 500 ms of the same shot gather. A reflection with an apparent dip of 25 km/s is visible between 360 ms to 400 ms, highlighted in yellow.

Figure 4.11. Top 2000 ms of shot gather 102150 of the 3-D active source survey. The shot point is coincident with receiver #40 of the passive survey.
Figure 4.12. Top 500 ms of shot gather 102150 of the 3-D active source survey. The shot point is coincident with receiver #40 of the passive survey.

Figure 4.13 shows virtual shot gathers generated at the 32nd and 40th receivers along line 141 from both sets A and B. This figure demonstrates the variability in the quality of the virtual shot gathers between sets, as well as between shot gathers within the same set. Figure 4.13a contains an event, highlighted in yellow, located at 400 ms, at a position 800 m from the end of the line. This event has similar dip, location, and timing as that seen in Figure 4.12. There is also a short coherent event at 1650 ms, which has similar dip and location to those in Figure 4.11. It is possible the events
highlighted in Figure 4.12 and 4.13a correspond to the same reflectors. In contrast, the virtual shot located at the 40th receiver from set A contains no strong coherent events, and in particular none which match any of those seen in Figure 4.11 or 4.12. As discussed previously, the large receiver spacing and inherent noisiness of passive data makes generating virtual shot gathers containing strong, coherent reflections a difficult task. Nonetheless, virtual shots from set A are free of strong noise, coherent or otherwise, and reflections may become evident when the set is converted to the CDP domain and stacked. Conversely, the virtual shots from set B contain strong coherent noise which travels out and down from the zero-offset trace at a velocity of 2900 m/s, and turns back up after a certain point. This noise is the same as that seen in Figures 4.2b, 4.4b, and 4.6b centered on time zero.
Figure 4.13. Virtual shot gathers from line 141 generated by:
Applying the procedure in Table 4.2 using receiver a) #32 and b) #40 as the master trace.
Applying the procedure in Table 4.1 using receiver c) #32 and b) #40 as the master trace.
The best virtual shot gather in terms of visible reflections comes from receiver line 133. Figure 4.14 shows the virtual shot gathers from set A and B with the shot point located at the first receiver. As with the gathers from line 141, when only the basic SI procedure is applied, no coherent events are visible except for strong surface wave noise. However, when the full procedure is applied, all surface wave noise is removed. Further to this, for the virtual shot gather shown in Figure 4.14a, a set of reflections becomes visible beginning at 300 ms. Figure 4.15 and 4.16 show the nearest shot gather from the 3-D active source survey, whose shot point is located 470 m to the north-east of the virtual shot point in Figure 4.14. This shot gather contains a set of reflections with the same location and dip as those seen in Figure 4.14. There are also several sets of deeper reflections not seen in the virtual shot gather.

In general, the shot gathers from the 3-D active source survey contain many more clear reflections than the virtual shot gathers generated using SI. Most reflections that do exist in the virtual shot gathers tend to be within the first 1000 ms, while reflections occur in the active dataset throughout the full 2000 ms. Deeper reflections are in general more difficult to recover using SI as the body waves needed to image deep reflectors will have much lower amplitudes due to geometrical spreading (Bellefleur et al., 2015b). In general, the availability of clear, continuous reflections in the virtual shot gathers is sparse. Given the challenges presented by crystalline rock environments including complex geology, steeply dipping reflectors, low SNR, and difficulties with low frequency imaging (L'Heureux et al., 2009; Milkereit and Eaton, 1998; Bellefleur et al., 2012), combined with the low SNR and large receiver spacing of the Lalor passive dataset, the fact that any reflections are visible is encouraging. Furthermore, it is not unreasonable to expect that further reflections will become visible after processing the virtual shots as a seismic reflection dataset, in particular upon sorting and stacking in the CDP domain.
Virtual shot gathers from the 1st (south-west most) receiver in line 133. Virtual shot gathers were generated using:

a) The final SI procedure outlined in Table 4.2, including coherent noise removal.

b) The basic, preliminary SI procedure outlined in Table 4.1.
Figure 4.15. Top 2000 ms of shot gather 126141 of the 3-D active source survey.
Figure 4.16. Top 500 ms of shot gather 126141 of the 3-D active source survey.
Figure 4.17. Map showing the positions of the active shot points (ASPs) used for comparisons relative to the positions of the passive receiver lines and the virtual shot points (VSPs).
Chapter 5.

Seismic Reflection Profile Processing

5.1. Introduction

The previous chapters have focused on analyzing and processing the passive source data recorded at Lalor in order to generate virtual shot gathers along the passive receiver lines. In Chapter 4, the results of applying a basic SI procedure were given, and new processing steps were introduced sequentially until a procedure was in place that was able to generate virtual gathers free of coherent noise. Examples were given for each step in order to visualize the impact of each additional process. In arriving at the final processing procedure, a total of 70 separate sets of virtual shot gathers were generated using different combinations of processing techniques, parameters, and receiver lines. The culmination of these tests is the procedure outlined in Table 4.2. This procedure was used to generate virtual shot gathers free of coherent noise along passive receiver lines 141, 133, 122, and 118, hereafter collectively referred to as the ‘SI dataset’. The goal of this chapter is to provide details on the analysis and 2-D reflection processing of the SI dataset, and to present interpretations for the resulting reflection profiles.

The processing flow used to generate the 3-D reflection cube in Bellefleur et al. (2015b) was adapted to the low fold and low SNR SI dataset. The processing flow is largely the same, including steps such as a spherical divergence correction, static corrections, normal moveout (NMO) corrections, residual statics, dip moveout (DMO) corrections, and CDP stacking. Other steps, such as spiking deconvolution and post-stack time migration are not performed on the SI dataset as they were found to have a negative impact on the resulting images. In addition to using a similar processing flow, certain parameters within the flow, such as NMO and DMO velocities, were guided by those used to generate the 3-D reflection volume.

In this chapter, the 2-D reflection processing flow will be described, and data examples for the major processing stages will be given from receiver line 133. The final
reflection profiles generated along passive receiver lines 133, 141, 118, and 122 will be compared against coincident in-line and cross-line sections from the active source DMO stacked volume. Events in each passive source reflection profile will be compared against reflections seen in the active source data. Where available, the geological model presented in Schetselaar et al. (2016) and Bellefleur et al. (2015b) will be used to correlate possible reflections with the structure of the hanging wall and footwall.

5.2. Overview

5.2.1. Data Acquisition

In March of 2013, the Geological Survey of Canada recorded approximately 300 hours of ambient seismic noise over the Lalor mine in Manitoba, Canada. The dataset includes 336 receivers distributed across 7 southeast-northwest and 9 southwest-northeast oriented lines. Of these, 4 receiver lines (122, 118, 133, and 141) were processed into virtual shot gathers using the SI procedure outlined in Chapter 4. As the virtual shot gathers were generated via cross-correlation, the source wavelet in the gathers is a zero-phase Klauder wavelet. Each line of virtual shot gathers was converted to a SEG-Y file and imported into ProMAX. Geometry was loaded based on the receiver locations. Each line has one virtual shot point coincident with each receiver. The acquisition parameters are summarized in Tables 5.1 and 5.2.

Table 5.1. Acquisition parameters along the receiver lines to be processed.

<table>
<thead>
<tr>
<th>Receiver Line</th>
<th># of Shots/Channels</th>
<th>Number of CDP’s</th>
<th>Profile Length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>141</td>
<td>40</td>
<td>80</td>
<td>4116</td>
</tr>
<tr>
<td>133</td>
<td>26</td>
<td>52</td>
<td>2502</td>
</tr>
<tr>
<td>118</td>
<td>24</td>
<td>48</td>
<td>2705</td>
</tr>
<tr>
<td>122</td>
<td>34</td>
<td>68</td>
<td>3184</td>
</tr>
</tbody>
</table>
Table 5.2.  Acquisition parameters common to each receiver line.

<table>
<thead>
<tr>
<th>Instrument</th>
<th>OYO Geospace Seismic Recorder (GSR)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling Interval</td>
<td>2 ms</td>
</tr>
<tr>
<td>Geophone Type/Frequency</td>
<td>Vertical Component/10 Hz</td>
</tr>
<tr>
<td>Shot/Geophone Spacing</td>
<td>100 m</td>
</tr>
<tr>
<td>CDP Spacing</td>
<td>50 m</td>
</tr>
<tr>
<td>Shot Record Length</td>
<td>2500 ms</td>
</tr>
</tbody>
</table>

5.2.2.  Geometry

The passive receiver were laid out in approximately straight lines, with the possible exception of line 122. Nonetheless, a straight line assumption was made in binning the receivers of each line into 50 m CDP bins. For each line, there is a virtual shot point coincident with each receiver. As a result, there are twice as many CDP bins as receivers for each line. The fold of the CDP bins starts at one, increases by one at each bin until reaching its maximum at the center of the profile with a value equal to the number of receivers in the line, and decreases back down to one at the far end of the line. The area of the Lalor mine camp covered by the passive receivers is fairly flat, with maximum elevation difference of 20 m. The receiver layout, as well as elevations and missing receivers are illustrated in Figure 5.1.
5.2.3. Processing Flow and Parameters

Each of the final seismic reflection images were obtained using the processing procedure outlined in Table 5.3. Unless explicitly stated otherwise, the parameters for each process are the same for each receiver line.
### Table 5.3. Processing flow and parameters applied to retrieved virtual shot gathers

<table>
<thead>
<tr>
<th>Step</th>
<th>Process/Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Geometry assignment and CDP binning</td>
</tr>
<tr>
<td>2.</td>
<td>Elevation static correction, datum = 330 m, Replacement Velocity = 5900 m/s</td>
</tr>
</tbody>
</table>
| 3.   | Amplitude recovery using $t^x$ gain function:  
      | Lines 141, 133: $x = 1.2$  
      | Lines 122, 118: $x = 1.0$ |
| 4.   | Spectral Whitening, 5-10-25-30 Hz |
| 5.   | Top mute along the theoretical first arrivals, assuming P-wave velocity of 5900 m/s |
| 6.   | First pass velocity analysis:  
      | Trial constant velocity stacks with velocities between 5500 m/s and 8000 m/s |
| 7.   | NMO using time (ms) – velocity (m/s) pairs: 0-6000, 1000-7000 |
| 8.   | Residual statics  
      | Surface consistent maximum power autostatics:  
      | Maximum allowable static:  
      | Line 122: 8 ms  
      | Lines 141, 133: 12 ms  
      | Line 118: 10 ms  
      | CDP Correlation (TRIM) autostatics, 8 ms maximum shift |
| 9.   | Automatic gain control, 500 ms window length |
| 10.  | Dip moveout correction:  
      | Bin traces into common-offset gathers with 50 m trace spacing  
      | Common offset F-K DMO using NMO velocities  
      | Apply inverse NMO |
| 11.  | Second pass (dip independent) velocity analysis:  
      | Trial CDP stacking using velocities between 5500 m/s and 7000 m/s |
| 12.  | NMO using dip-independent time (ms) – velocity (m/s) pairs:  
      | Lines 122, 118: 0-6000, 2000-7000  
      | Line 141: 0-6000, 1000-7000  
      | Line 133: 0-5800, 700-6500 |
| 13.  | CDP Stacking |
| 14.  | F-X Deconvolution |
5.3. Description of Key Processes

5.3.1. Application of Statics

For typical active source seismic reflection data, elevation static corrections are calculated to take into account the differences in elevation between stations, and refraction statics are calculated to account for velocity variations within the weathering layer. For the SI dataset, elevation statics were calculated for each receiver and applied as both shot and receiver statics. The elevation statics are calculated for each receiver based on the equation:

\[ \Delta t_i = \frac{e_d - e_i}{v_r} \]  

(5.1)

where \( e_d \) is the datum elevation, \( e_i \) is the elevation of the \( i \)th receiver, and \( v_r \) is the replacement velocity. The datum was chosen to be 330 m, and the replacement velocity 5900 m/s. These are the same values used to process the 3-D active source survey. The elevation statics range from 3.4 ms to 7.2 ms, with a mean value of 4.9 ms.

Refraction statics require picking along the first arrivals of seismic energy. For SI by cross-correlation, this method is unreliable due to the non-physical energy that is present prior to the theoretical first arrivals in the virtual shot gathers. Therefore, an alternative method was tested; refraction statics for each passive receiver were extrapolated from the 3-D active source survey. The refraction statics for each passive receiver were calculated by taking a weighted average of the 5 nearest available statics from within 100 m. The resulting refraction statics for the passive receivers are shown in Figure 5.2. The refraction statics range from -2.5 ms to 11.6 ms, with a mean value of 2.1 ms.

Overall, the values of the elevation and refraction statics are small, and therefore the effect of applying each is minor. Figure 5.3 shows the results of stacking the data from line 133 using no statics (a), after applying elevation statics (b), and after applying both elevation and refraction statics (c). Note that the x-axis label ‘distance’ refers to the distance between the CDP location of each trace and the first CDP location along the coincident active source reflection profile. The active source profiles often extend past
the passive receiver lines. Measuring the distance in this way allows the SI generated reflection profiles to be directly compared to the correct portion of the active source profile.

![Figure 5.2](image.jpg)

**Figure 5.2.** Refraction statics for the passive receiver lines, extrapolated from those calculated for the 3-D active source survey.

Figure 5.3 shows the results of applying steps 1-7 in Table 5.3, with and without elevation and refraction statics, and then stacking. The elevation statics vary only slightly along line 133, and so the main difference between Figure 5.3a and 5.3b is that each trace is shifted downwards slightly. Application of the refraction statics results in the opposite of the intended effect, degrading the coherency of the events rather than enhancing them. While events H2, F1, and F4 remain relatively unchanged, events H1, F2, and B1 suffer a loss of continuity. The most noticeable change is that event F2 no longer resembles a coherent reflection. In general, application of the refraction statics had either no effect or a negative effect on the stacked images for each receiver line.

Due to the slight degradation of the stacked images, the refraction statics were not included in the final processing flow. While the elevation statics have only a minor
effect on the stacked sections, they place the reflection profiles at the same datum as those obtained from the 3-D active source survey. For this reason, elevation static corrections were included in the final processing flows.

![Figure 5.3. Preliminary stacked sections along line 133 using a) no static corrections, b) elevation statics, and c) elevation statics + refraction statics.](image)

5.3.2. **Amplitude Recovery**

Several methods of gain recovery were tested to balance trace amplitudes. The parameters for amplitude correction were chosen such that the coherent events in the resulting stacked section have approximately equal amplitudes. For lines 133 and 141, a $t^{1.2}$ correction was used, and for lines 118 and 122, a $t^{1.0}$ correction was used. For all
lines, the maximum application time was 1200 ms. Times later than this had a constant gain factor applied, equal to the value used at 1200 ms.

5.3.3. Spectral Whitening

Multiple sets of deconvolution parameters were tested, but none were found to improve the quality of the shot gathers or the stacked sections. As an alternative to deconvolution, spectral whitening using a filter specification of 5-10-25-30 Hz was performed. This frequency range was subdivided into 25 windows of equal width, and the spectrum of each window was equalized. This had the effect of slightly reducing the background noise seen in the virtual shot gathers and stacked sections, as well as making the visible events more coherent. As is the case with deconvolution, it was important that the spectral whitening be performed after amplitude recovery. Reversing the order of these operations drastically reduced the continuity of the events seen in the stacked sections.

5.3.4. First Pass Velocity Analysis

Several aspects of the SI dataset made the velocity analysis very difficult. High trace spacing and low fold made it difficult to track reflections across CDP gathers. Stretch muting after NMO further reduced the fold at early times. Accurate refraction statics, which were crucial in improving the continuity of reflections in the active source data (Bellefleur et al., 2015b) were unavailable, and as such, most visible reflections in the virtual shot and CDP gathers have significant jitter. While velocity analysis was initially attempted by examining the effects of NMO directly on the CDP gathers, the factors listed above made this nearly impossible. Additionally, it was found that allowing the velocities to vary laterally along the profiles had no effect on the resulting stack. Therefore, velocity analysis was performed by examining constant velocity stacks (CVS’s).

While examining CVS’s was much more straightforward than looking at the CDP gathers directly, caution had to be used when determining the veracity of events which were stacked. The fold near the ends of the lines decreases to one, and as a result,
events appearing at the ends of the line in a CVS have to be carefully examined and checked against the active source data in order to determine if the events are non-physical or real reflections. A set of CVS’s with velocities ranging from 5500 m/s to 7500 m/s, every 500 m/s, is shown in Figure 5.4. Each of these stacks was compared against the DMO stacked active source reflection profile along line 133 shown in Figure 5.5. At this point in the processing, all coherent events occurring in the passive source reflection profiles at similar positions to those in the active profiles were considered to likely be real reflections. Closer inspection and interpretation will be reserved until later in this chapter.
Figure 5.4. Constant velocity stacks used to pick stacking velocities along line 133. Stacking velocities of: a) 5500 m/s, b) 6000 m/s, c) 6500 m/s, d) 7000 m/s, and e) 7500 m/s.
There are several events which are present in each CVS regardless of stacking velocity. While varying in amplitude and continuity, a set of horizontal events, highlighted by the yellow ellipses, are seen in each CVS. These events occur near the beginning of the profile where CDP fold is very low, which when combined with the fact that these events are not seen in the active source profile suggests that these are non-physical events and not real reflections. Event F1 has similar timing and location on both the passive and active source stacks, and so it is possible that they correspond to the same reflectors. While event F1 is present with varying amplitudes in each CVS, it is most coherent and has dip most consistent with that seen in the Figure 5.5 when using a stacking velocity of ~6000 m/s. Other events are partially visible in each CVS, but are
noticably more coherent in some than others. Although event H2 (which is also seen in Figure 5.5) is visible in each CVS, it is most coherent when using stacking velocities between 5500 m/s and 6000 m/s. The same is true for event H1. Events F4 and B1 are more continuous when using stacking velocities greater than 7000 m/s. In general, the shallower events are more coherent when using lower stacking velocities, while deeper events require higher velocities. There do not seem to be any events which would benefit from a laterally varying velocity function. Based on this, the first pass NMO velocities were taken to increase linearly from 6000 m/s at time zero to 7000 m/s at all times after 1000 ms.

5.3.5. Residual Autostatics

To increase the coherence of the events seen in the NMO stacked sections, surface consistent (SC) residual statics in the form of maximum power autostatics followed by CDP correlation statics were applied. The maximum power autostatics algorithm used by ProMAX is a modification of that presented in Ronen and Claerbout (1985). One or more horizons are picked, along with a time window for each horizon, and SC residual statics are calculated that maximize the power of the NMO corrected CDP gather at times corresponding to each horizon and time window. The static shift applied to each trace cannot exceed a pre-defined maximum. The CDP correlation statics use a cross-correlation method to determine the time shifts required (up to a pre-defined maximum) to best align events within each CDP gather in a non-surface-consistent manner. For both types of residual statics, the maximum allowable shift and time windows used were chosen conservatively, and horizons were selected along visible events in the NMO stacked sections to limit the likelihood of generating non-physical events in the stacked sections. The residual statics parameters used for line 133 are listed in Table 5.4.

Figure 5.6a shows the original NMO stacked data, along with the horizons chosen for the SC residual statics. The top horizon was chosen to coincide with events F1 and F2, and the time window used (500 ms) includes events H1 and H2. The bottom horizon runs along event B1, and again uses a 500 ms long time window in order to include event F4. Many tests of the placement and window length of the horizons were
performed, and the above configuration was found to give the best compromise between the enhancements of different events. The result of applying the SC residual statics is shown in Figure 5.6b. Each event, with the possible exception of H2, is considerably more coherent. The coherency is enhanced further after applying the CDP correlation statics, as seen in Figure 5.6c. The shallower events H1 and H2 are no longer as clear, however all deeper events now more closely resemble those seen in Figure 5.5. While F1 itself is still horizontal, the collection of events between F1 and F2 has begun to resemble the set of dipping reflections seen between 400 ms and 600 ms in the active source data. Event F4 exhibits the same features on both the passive and active source stacks: a section which dips down to the right between distances of 2700 m and 2900 m, followed by a horizontal section between 2900 m and 3700 m. Event F3, which was previously unseen in the passive source data, has also become visible. Event B1 is slightly more coherent after residual statics. A more noticeable difference is the introduction of a previously weak event below it. As with B1, this event does not directly correlate to any event seen in the active source data.
Figure 5.6. NMO stacked sections along line 133 with a) no residual statics, b) SC residual statics, and c) SC residual statics and CDP correlation statics. The horizons used for SC autostatics is indicated by the red lines in a).

Table 5.4. Parameter values for residual statics along line 133.

<table>
<thead>
<tr>
<th>Surface Consistent Residual Statics</th>
<th>CDP Correlation Autostatics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Maximum Correction (ms)</td>
<td>Maximum Correction (ms)</td>
</tr>
<tr>
<td>Window Length (ms)</td>
<td>Window Start Time (ms)</td>
</tr>
<tr>
<td>CDP Smash</td>
<td>Window End Time (ms)</td>
</tr>
<tr>
<td>12</td>
<td>8</td>
</tr>
<tr>
<td>500</td>
<td>150</td>
</tr>
<tr>
<td>5</td>
<td>1200</td>
</tr>
</tbody>
</table>
5.3.6. Dip Moveout Correction

After applying NMO using the velocities given in Table 5.3 followed by residual static corrections, the data was prepared for common offset F-K DMO. The data was sorted into common offset gathers, with a secondary sort by CDP bin. In order to ensure uniform trace spacing within the common offset gathers, the data is sorted into offset bins every 200 m, and zeroed traces are added to replace missing CDPs within the common offset gathers. This results in a common offset gather every 200 m, with a trace spacing of 50 m within each gather.

After generating the common offset gathers, an automatic gain control (AGC) is applied with a 500 ms window length, and F-K DMO is performed on each gather. The algorithm uses a single velocity function for all gathers. This velocity function would typically be a lateral average of the picked NMO velocities. As the the NMO velocities used here are already laterally constant, they were used directly as input into the DMO algorithm. The algorithm used by ProMAX applies constant velocity DMO corrections followed by the application of a stretch factor that makes time corrections to the data based on the velocity variations in time. This factor helps to adjust for overcorrections made by constant velocity DMO. The algorithm also performs dip filtering as part of the DMO correction. This step is included to remove noise generated by the DMO operator's impulse response, and has the desirable side effect of removing unaliased coherent noise with impossibly steep dip.

Figure 5.7 shows the result of stacking the DMO corrected data with the first-pass NMO velocities. All horizontal or shallowly dipping events (F1, F3, F4, and B1) are more coherent, while more steeply dipping events such as F2 have been slightly attenuated. Event H2 is barely distinguishable from the other short, dipping events above 300 ms. This is partly due to its deterioration after the residual statics, and partly because the dip-dependent NMO velocities used are no longer correct for dipping events. Despite this, the image is clearer overall, as the majority of events have become more coherent and the dip filter which is included in the DMO process has reduced the amount of background noise.
5.3.7. Dip-Independent Velocity Analysis

Following DMO, the first pass NMO corrections were removed and a second velocity analysis was performed. This was again performed using constant velocity stacks, with velocities between 5500 m/s and 7000 m/s. As was the case with the first pass velocity analysis, different stacking velocities resulted in stacked sections which varied only slightly, and allowing the velocities to vary laterally again had no effect on the results. In general, the post-DMO stacking velocities are lower than those used pre-DMO. The exact time-velocity pairs used for each line are given in Table 5.3.
5.3.8. F-X Deconvolution

The final step in processing the SI dataset was F-X deconvolution using a Weiner-Levinson prediction filter (Treitel, 1974). The purpose of this process is to reduce background noise and make events in the DMO stacked sections more coherent. The parameters used vary from line to line, and are listed in Table 5.5. Each parameter was tested using different values in order to produce stacks with clear, coherent events, while maintaining the integrity of the data and refraining from applying excessive lateral smoothing.

Table 5.5. Parameters for F-X deconvolution.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Line 133</th>
<th>Line 141</th>
<th>Line 122</th>
<th>Line 118</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percentage of added white noise</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
<td>10%</td>
</tr>
<tr>
<td>Horizontal window length (traces)</td>
<td>6</td>
<td>7</td>
<td>10</td>
<td>8</td>
</tr>
<tr>
<td>Time window length (ms)</td>
<td>400</td>
<td>300</td>
<td>300</td>
<td>500</td>
</tr>
<tr>
<td>Time window overlap (ms)</td>
<td>100</td>
<td>75</td>
<td>75</td>
<td>150</td>
</tr>
<tr>
<td>Filter length (samples)</td>
<td>5</td>
<td>4</td>
<td>8</td>
<td>6</td>
</tr>
</tbody>
</table>

The percentage of white noise added was kept constant for each receiver line. Values higher than 10% resulted in the reflection profiles appearing overly smoothed, while lower values did not remove sufficient background noise. The number of filter samples varied from line to line, depending on the character of the events present. According to the ProMAX manual for F-X deconvolution, higher values should be used if events with conflicting dips are present. A value of 6 was used for lines 133, 122, and 118, as these stacked sections contained closely-spaced events with different dips. The events in the stacked section for line 141 are all of similar dip, so the number of filter samples was set to four (the minimum allowable value). The remaining parameters (vertical window length, overlap, and horizontal window length) were found not to have any strong dependence on the character of the data (e.g. event dip). Therefore, these parameters were tested and values were selected based on the clarity of the resulting images. The resulting stacked sections are shown in the following section.
5.4. Final Reflection Profiles and Interpretations

5.4.1. Introduction

The virtual shot gathers generated along lines 122, 133, 118, and 141 were processed into reflection profiles using the processing flow outlined in Table 5.3. While the parameters used in the processing of each line varied slightly, the overall processing flow is the same. In the following sections, the final reflection profiles generated along each receiver line are compared against the coincident reflection profiles from the 3-D active source survey, and against the geological model generated in Bellefleur et al. (2015b) where available as indicated by the dashed lines in Figure 5.1. Both active and passive source datasets are converted to depth sections using a constant velocity of 5900 m/s, as was done in Bellefleur et al. (2015b).

When compared to the active source reflection profiles, the events stacked into the passive source reflection profiles fall into three categories:

1. Events that directly correlate with a reflection in the active source data, which has very similar position and dip.
2. Events or clusters of events which occur at similar positions as reflections in the active source profiles, but not necessarily with the same dip.
3. Events which have no comparable reflection in the active source data.

Events which fall under the first category are the most desirable, as they can be directly compared to the active source data, making interpretation much simpler. The majority of the events seen in the passive source reflection profiles fall into the 2\textsuperscript{nd} category. These events are more difficult to interpret. Some events in this category may in fact be related to those seen in the active source sections, but appear different due to either the biased passive source distribution or to the difference in frequency content between the passive and active source surveys. Other events in this category may be non-physical events which coincidentally happen to occur in positions similar to reflections in the active source profiles. Events in the 3\textsuperscript{rd} category are the most difficult to interpret. They do not correlate with any reflections seen in the active source data, and tend to occur at depths greater than the available borehole logs. An educated guess must be made as to whether the event is real or spurious. In the following
sections, these categories will be used to classify the events seen in each of the passive source reflection profiles.

5.4.2. Receiver Line 133

Of the four processed receiver lines, line 133 gave the most encouraging results when compared to both the active source reflection profiles and the geological model. This is likely due to the position of the receivers relative to the sources available at Lalor. High amplitude sources were available at an azimuth within the stationary phase region, since receiver line 133 lines in-line with the mine shaft. While these sources are useful in recovering reflections, a very high percentage of the total number of sources used are located at the mine and ventilation shafts. As was shown in Chapter 2, reflection profiles generated using such a source distribution will tend to image dipping reflectors with incorrectly imaged lateral extents, and possibly incorrect dip.

Figure 5.8 shows a side-by-side comparison of the final DMO stacked passive and active source reflection sections. Of the events seen in Figure 5.8a, only events H2, F3, and F4 can be classified as category 1. Event H2 lies at the same position (~900 m depth, distances between 2700 m to 3100 m), and has similar dip in both Figures 5.8a and 5.8b. The amplitude of the event is significantly lower in the passive source reflection profile when compared to the amplitude of the background noise, and so it is difficult to say with certainty that it corresponds to a real reflection. Nonetheless, assuming that it is in fact a reflection, it most likely originates from the contact between felsic and mafic volcaniclastic units in the hanging wall above the Lalor deposit. This contact is seen around 800 m depth in Figure 5.9, which shows a slice of the geological model coincident with receiver line 133.

Events F3 and F4 occur with similar curvature in both sections at a depth of ~2250 m. While F4 occurs with strong continuity between 2500 m and 3500 m in both sections, F3 is much shorter in the active source section than in the passive source section. It is possible that the lower frequency wavelet of the passive source dataset was able to more continuously image the reflector which gives rise to F3. It is also possible that F3 and F4 are a single reflection which appears as a peak-trough-peak in
the passive source image due to the symmetry of the Klauder wavelet. The reflections occur at a depth too great to be verified by the geological model or borehole logs. Nevertheless, several possible explanations exist based on the depth and continuity of the reflection. Possibilities for its origin include the contact between the Lower Chisel and Anderson sequences, an extension of the Richards Lake pluton, or a nearly horizontally lying mafic intrusion (Bellefleur et al., 2015b).

Events F1 and F2 fall under category 2, and therefore are more difficult to interpret. They occur near the center of the profile, and cannot necessarily be dismissed due to low fold. When compared to the active source profile and the geological model, the depth and positions suggest that these events originate from a dipping reflector, possibly a contact between mafic volcaniclastic rocks in the hanging wall and a gneiss/schist with felsic protolith in the footwall, or between units in the footwall with contrasted mafic and felsic protoliths. If this interpretation is correct, based on the experiments in Chapter 2, the biased source distribution would result in reflections with incorrect dip and which extend further east than they should. This is the case for both events F1 and F2. While this does not necessarily mean that these events are reflections, it does reiterate the importance of understanding the source distribution when interpreting reflection sections generated through SI. It would be easy to mistake these events for nearly horizontal layered reflectors in the absence of information which indicates otherwise.
Event H1 falls somewhere between categories 2 and 3. Although it occurs at the same depth as a short anomaly in the active source data, the lateral position and dips are too different to classify it as category 2. Furthermore, while the event is visible on both sections, its amplitude is low compared to other events in each section. The
The shallow depth of H1 suggests that it may be a non-physical event, possibly on both the passive and active source sections, as the fold at that depth is very low due to the stretch muting applied during the NMO correction. In addition to this, the geology at depths less than ~800 m consists mostly of vertical rock units which are unlikely to generate reflections with the dip seen on either reflection profile. However, based on its length, depth, and dip in the active source section, it may be a reflection from a short, shallowly dipping section of a contact between felsic and mafic volcanic rocks in the hanging wall.

The amplitude of event B1 has been greatly reduced following DMO correction, subsequent NMO with dip-independent velocities, and F-X deconvolution. This, when combined with the fact that it does not correlate with any reflections seen in the active source section, suggests that event B1 may be a non-physical event. It is also possible that it corresponds to some large scale feature within the Anderson sequence which was not imaged by the active source data due to destructive interference from a complex reflectivity series. However, the geology is unconstrained at the depth of the event (Belleville, personal communication, April 21, 2016) and therefore it is impossible to determine its origin with certainty.

5.4.3. Receiver Line 141

Receiver line 141 is the longest line in the passive array, and thus has the highest nominal fold. Regardless, it was the most difficult to process due to the position of the mine and ventilation shafts relative to the receivers. The mine and ventilation shafts are located at roughly 1 km along the receiver line. This made the removal of surface waves a difficult task, as was discussed in Chapter 4. While the process implemented to remove the surface waves was successful, it likely affected the data from line 141 differently than the data from other receiver lines in-line with and offset from the noise sources.

Figure 5.10 shows a side-by-side comparison of the DMO-stacked reflection sections generated along line 141 using the active and passive source datasets. While the active source reflection profile contains many reflections of varying amplitudes, the
passive source reflection profile contains only two notable sets of events, both of which can be classified as category 2. Event F5 is a cluster of events which occurs at a similar position as a complex set of curved reflections in the active source section. Due to lack of lateral continuity, it is difficult to determine if the cluster of events in F5 arises from separate reflectors or if it corresponds to a single reflection with multiple peaks and troughs. The reflections in the active source section dip relatively steeply below 2000 m depth. While these reflections are much weaker, they can be traced across the section up to a depth of 1500 m, whereas in the passive source section the reflections terminate abruptly at a position of 2400 m. While F5 is too deep to be interpreted using borehole logs, it is possible that it originates from the contact between the Lower Chisel and Anderson sequences. However, due to the repetitive nature of the event, the depth of the reflector is unclear, and therefore it may also be a result of a felsic intrusion deeper within the Anderson sequence. Refer to Bellefleur et al. (2015b) for further discussion on the nature of the reflections at this depth within the active source survey.

Figure 5.10. Reflection profiles from a) active source and b) passive source datasets along line 141.

Event A1 matches those seen in the active source reflection profile well in depth and dip. Although the reflections can be tracked across the length of the active source profile, they are reduced in amplitude between 600 m and 1800 m. Conversely, this is the only section of the passive source reflection profile which contains strong coherent reflections. This is likely due to the source distribution of the passive source dataset. The mine and ventilation shafts are located roughly 1000 m along receiver line 141,
which places them directly over the top of these reflections. Waves originating from these sources which are reflected by a nearly horizontal reflector at this depth and position could be recorded by receivers further to the north-east end of the line. At positions past 2000 m (where the reflections terminate), the angle of incidence between the sources and a reflector would be too great, and reflected waves would reach the surface at too great an offset to be recorded by the available receivers. Based on its depth, A1 could be either a reflection from a mafic/felsic contact within the Anderson sequence, or a reflection from the bottom contact of the Anderson sequence.

5.4.4. Receiver Line 122

Receiver line 122 is the 2\textsuperscript{nd} longest line in the array, and the longest line in the south-east/north-west oriented lines with 34 receivers, giving it 68 CDP bins. Because the receivers were not placed in a perfectly straight line due to terrain, the line spans a profile of 3184 m. The line was processed as a straight line, but this does not seem to have affected the results. The reflection profile generated along line 122 has an interesting collection of events, spanning all three of the previously discussed categories. Figure 5.11 shows a side-by-side comparison of the active and passive source reflection profiles along line 122, and Figure 5.12 shows a slice of the geological model along a section of the receiver line. The distances given in these figures is measured from the most north-western CDP in the active source reflection profile (i.e. the images go from south-east on the left to north-west on the right).

Event F6 is within the depth and range of the geological model and matches fairly well with the reflection seen in the active source section. It consists of a single short horizontal reflection centered at ~1200 m depth, and is seen clearly in both the passive and active source sections. Comparing the position of F6 to the stratigraphy seen in Figure 5.12, it seems likely that F6 corresponds to the same units as event F1 seen along line 133. Specifically, F6 correlates well with the transition from mafic hanging wall units to intermediate and felsic units within the footwall.

Event F7 consists of two slightly dipping reflections and one horizontal reflection between 1300 m and 1500 m depth. Similarly to event F2 in Figure 5.8, the F7 events
likely originate from the contact of mafic and felsic protoliths within the footwall. These reflections appear more coherent in the passive source section than in the active source section. This is partly due to the background noise present at these depths in the active source section. Another possibility is that the reflections appear weaker in the active source section due to destructive interference within the highly altered footwall, whereas most of the closely spaced contacts within the footwall are invisible at the longer-wavelength wavelet used in the passive source section.
Figure 5.11. Comparison of reflection profiles along line 122 from the a) active source and b) passive source dataset.
Figure 5.12. Slice of the geological model along receiver line 122. The dashed lines indicate where the hanging wall and footwalls begin and end. Solid lines indicate possible origins for the corresponding events.

While event H3 occurs at a depth that is within the range of the boreholes, it is outside of the area covered by the geological model. Furthermore, the event does not appear in the active source section, and therefore is classified as category 3. It is possible that the event is not a real reflection as the CDPs at a depth of ~600 m have low fold. It is also possible that this reflection is not seen in the active source survey due to destructive interference within the complicated hanging wall units. Based on the geological model, it is possible that event H3 corresponds to the continuation of the contact between mafic and felsic units in the hanging wall, as indicated in Figure 5.12. This interpretation assumes the felsic unit in the hanging wall of the geological model continues horizontally or approximately so for anywhere between 300 m to 1 km. If this is the case, the low frequency passive source wavelet may able to image the impedance contrast between the mafic and felsic units while disregarding small amplitude reflectivity spikes caused by alternating thin mafic and felsic units.
Although it occurs in the center of the passive source reflection profile, and with high coherency, event B2 falls under category 3 as it is located at a depth and position at which there are no reflections in the active source profile. It is possible it is an artefact of the incomplete source distribution, however as Figure 5.13 shows, it ties reasonably well to event B1 in Figure 5.8b. They occur at similar depths, and while the events do not tie perfectly from line 133 into line 122, it is possible that both events B1 and B2 image the same boundary. If this is the case, then event B2 may correspond to a felsic intrusion within the Anderson sequence.

Unlike receiver lines 133 and 141, the positions of the available sources are favourable for imaging the more steeply dipping reflectors seen along line 122. This is evident with event A2 (Figure 5.11), which consists of a set of deeper reflections whose dips match very closely between the active and passive source sections. As with many of the reflections seen in the SI dataset, event A2 is not continuous for the full length of the reflection seen in the active source dataset. Nonetheless, since it occurs at a similar position and with approximately the same dip, it is classified as category 1. Based on its depth and position, it likely originates from the same contact as event A1 seen along line 141 (Figure 5.10). Due to the poor quality and discontinuous nature of the reflections seen in the passive source reflection profile along line 141, the lines do not tie together well. However, events A1 and A2 do tie together continuously in the active source sections (Figure 5.14), suggesting that they both image the same contact, possibly the bottom of the Anderson sequence.
Figure 5.13. Line tie between passive receiver lines 133 and 122. The image goes from the eastern most CDP in line 133 to where line 133 and 122 meet, and then continues north along line 122.
The deepest event seen in the SI data is event N2. It occurs at nearly 5 km depth, almost exactly in the middle of two separate sets of reflections, N1 and N3, seen in the active source section. Both N1 and N3 have similar dip and continuity as event N2. Nevertheless, a difference of 500 m depth is too great to confidently correlate N2 with either set of reflections. As with previous category 3 events, it is possible that the lower frequency wavelet of the SI dataset was able to image a reflector the active source dataset was not (and vice-versa); however, the lack of similar events and geological constraint at this depth makes it impossible to say whether event N2 corresponds to a real reflection or not.
5.4.5. Receiver Line 118

Receiver line 118 is the shortest line that was processed, containing only 24 receivers laid out in a straight line from south-east to north-west. As a result, the fold is low even at the center of the profile. The geological model only covers ~250 m of the center of the reflection profile, and typically the model is less well constrained near its boundaries. For these reasons, the geological model is not used to interpret the reflection profile generated along line 118. This, combined with the fact that all of the events seen in the passive source reflection profile along line 118 (Figure 5.15) are classified as category 2, makes interpreting the events seen even more difficult than the previous profiles.

The shallowest set of events in Figure 5.15 is defined by F8. While the depth and positions of the events found in the passive source section match a collection of shallow, low amplitude reflections seen in the active source section, the dips do not match, and the events are not particularly coherent in either section. Based on the depth and the discontinuous nature of the reflections, it is possible they correspond to the contacts between gneiss/schist with contrasting mafic and felsic protoliths within the footwall. Due to the highly altered nature of the footwall, contacts with sufficient impedance contrasts to generate reflections tend to be relatively short. Figure 5.16 shows the line tie between the west-east portion of line 133 with the north-south portion of line 118. The tie-in between events F1, F2, and F8 is poor (Figure 5.16) as none of these events are continuous within their own profiles. Nonetheless, based on the depths of each individual event, it is not unreasonable to suppose that events F1, F2 and F8 have similar origins. Conversely, it is also possible that the short events seen in F8, particularly those closer to the end of the profile, are non-physical events which have been stacked in due to low fold and poor quality data.
Figure 5.15. Comparison of the reflection profiles along line 118 from the a) active and b) passive source datasets.

Figure 5.16. Line ties going from west-east along line 133 and continuing a) north-south and b) south-north along line 118.

Perhaps the most interesting event in the passive source reflection profile along line 118 is F9. It occurs at the same depth (2000 m) and location (centered on 2000 m) as a set of reflections seen in the active source data, however the character and dip between the datasets is very different. In the passive source section, event F9 is shallowly dipping down to the left between 1900 m and 2750 m, whereas in the active source section it dips slightly down to the left between 1400 m to 1900 m, and then dips up to the left until 2700 m. Due to the fact that event F9 does not appear in the active source section, it could be regarded as a non-physical event, possibly introduced by the
residual static corrections that were applied. However, as Figure 5.16 shows, event F9 ties in almost perfectly with events F3 and F4 from the passive source reflection profile along line 133. As events F3 and F4 correlated well with reflections in the active source data, it seems likely that F9 corresponds to a real reflection, albeit one with possibly incorrect dip, originating from the same contacts as F3 and F4.

The final event seen in this profile is B3. Like events F8 and F9, it occurs at a similar position to a set of reflections seen in the active source data, but with a dip that is much shallower than that seen in the active source section. This is unusual, given that the source distribution used to generate this reflection profile is largely to the south. According to the synthetic experiments, a northward dipping reflector should be imaged with nearly the correct dip. As with most of the events found in the passive source data, F9 occurs at too great a depth to be verified by geological information, and it does not tie in well with event B1 from line 133. Since a reflector with the dip seen in the active source section should have been imaged relatively well with the sources that were available, it is most likely that B3 is a non-physical event which coincidently has a depth similar to a set of reflections found in the active source reflection profile.
Chapter 6.

Conclusions

6.1.1. Summary

The field of SI has been expanded greatly over the past decade due to the theoretical breakthroughs achieved by many researchers. However, the application of the interferometric method has thus far been mostly limited to imaging simple, sedimentary strata, much as traditional seismic reflection methods were once limited (Nedimović, 2000). In this study, SI was applied to passive data recorded over a complex, crystalline rock environment at the Lalor mine camp, Manitoba, Canada. As the basic SI methodology is not well equipped to handle near-field sources and unbalanced source distributions, particularly in areas with complex geology, improvements to the method were made. These additional processes were found to greatly improve the results of applying SI to the dataset, largely due to a reduction in surface-wave noise. It was shown that despite theoretical limitations when applying SI with a limited or unbalanced source distribution, meaningful and useful results may still be achieved as long as the characteristics of the data and the available sources are well understood.

Synthetic experiments carried out using a simple model strongly indicated the importance of understanding the character of the available data prior to processing, in particular the distribution of sources. Applying the basic SI methodology to data containing sources on only one side of a 2-D line resulted in reflection profiles that either failed image or improperly imaged the reflectors present in the model. Due to the geometry between the available sources and the reflectors, only contacts which dip downwards in the direction of the sources gave strong reflections. Reflectors which dipped downwards away from the sources were either not imaged at all, or were imaged with shallower dip than they should have been. While some strategies have been developed to account for one-sided source distributions, most were inapplicable to this dataset. It was decided that the effects of a one-sided source distribution on the resulting reflection profile would be acceptable so long as the characteristics of the
sources were well understood, and in this way misinterpretation of the results could be avoided.

A thorough analysis of the data was performed in order to gather information on the magnitudes, frequency content, and distribution of sources available throughout the dataset. The majority of the recorded energy was contained in frequencies between 10 Hz and 30 Hz. The energy was found to be distributed unevenly in time with several high magnitude events occurring each day. Furthermore, the amount of energy recorded varied from receiver to receiver. The most important finding of the analysis was in regard to the spatial distribution of sources. A near-field beamforming algorithm was designed and implemented, and the results indicated that the vast majority of the available sources were located at one of three locations, all located within 3 km of the passive receiver array. While the majority of the energy from these sources was in the form of surface-waves, weak amplitude secondary events could also be seen.

Applying a brute force methodology of SI resulted in virtual shot gathers which were contaminated with surface waves and non-physical arrivals. Three additional processing stages were implemented to reduce this contamination. Firstly, data panels were binned based on source location, and only those bins corresponding to azimuths within the stationary phase regions were passed to further processing. Secondly, time shifts determined using a beamforming and residual statics analysis were applied to the data panels to align surface wave noise. The surface wave noise was removed using a carefully designed F-K filter, and the time shifts were removed. Finally, the azimuthal bins of correlation panels generated following the cross-correlation procedure were normalized and stacked such that each bin had equal weight. In conjunction with the rest of the SI methodology, these additional steps resulted in virtual shot gathers free of surface wave noise, and which in some cases contained reflections comparable to those found in the active source data.

Virtual shot gathers were generated along four of the passive receiver lines and processed as 2-D seismic reflection datasets. Initial NMO stacked sections contained weakly to moderately coherent events, which in general were made considerably stronger after the application of residual static corrections. The passive source DMO
stacked data were compared to coincident DMO stacked data from the 3-D active source survey. While the character of the reflections differed in each dataset due to differing frequency content, many similar reflections were found. While no reflections from the ore body were found in the passive source dataset, several reflections correlated well with contacts within the hanging wall and footwall of the Lalor deposit, as well as contacts between the hanging wall and footwall. Several deeper reflections were also apparent, however these are difficult to confidently interpret due to the lack of geological constraints at depth. The reflections found in the passive dataset in general agreed with the findings of the synthetic experiments. Reflections which dipped downwards away from the location of the available sources tended to have much flatter dip than those seen in the active source data. In general, the misrepresentation of a reflectors dip was much less pronounced in the real data than in the synthetic experiments, possibly benefitting from scatterers at depth which act as secondary sources.

### 6.1.2. Limitations of the Methodology

While the methodology which was implemented in this thesis was successful in improving the results of applying SI to the Lalor dataset, several of the techniques were needed only due to certain parameters of the dataset. In particular, the F-K filtering technique which was implemented to remove surface waves was designed to account for near-field sources recorded by an array with large receiver spacing. If the receiver array that is used has sufficient spatial sampling, and the sources are sufficiently far away, the technique used becomes redundant and possibly less effective than alternative methods. Furthermore, while the technique was able to remove non-linear surface wave noise as recorded by receiver line 141, the resulting reflection profile contained few coherent reflections. This was most likely due to degradation of the reflected arrivals during the filtering process.

The beamforming algorithm used also had its own limitations. Specifically, it was only able to identify a single source per noise panel. While this was deemed acceptable for this study due to the relatively low level of seismic activity around the Lalor mine camp, future studies may require modifications to the beamforming algorithm which
would allow for multiple source identification. Furthermore, the application of the beamforming results in the form of stationary phase selection is only applicable when the dataset is being processed as 2-D reflection data. The binning and weighting of the stacked correlation gathers by source azimuth is applicable in both the 2-D and 3-D case. However, as was seen in the resulting reflection profiles, this method of source balancing is not able to completely account for a biased source distribution, and artefacts and/or incorrect imaging of reflectors may still occur.

The proposed methodology was able to produce reflection profiles containing reflections which were, for the most part, easily compared to reflections found in the active source dataset. While potentially useful as a reconnaissance survey, it is not clear whether the passive source reflection profiles are of high enough quality to be of use in geological interpretations when considered separately from the active source reflection profiles. Furthermore, as the parameters used to process the active source data was used to guide the processing of the virtual shot gathers, it is likely that the results would have been different had the active source data not been consulted, or had a coincident active source survey not been conducted.

6.1.3. Future Work

A problem that arose several times in this study was that of the receiver spacing. In order to be able to effectively resolve reflections in the raw data, the virtual shot gathers, and the CDP gathers and resulting stacked sections, a denser receiver array should be used. A denser array would aid in the recovery of reflections via SI by increasing SNR. Traditional methods could be used to eliminate linear noise from the raw data, without the need of the filtering method that was introduced in this study. Having a denser array would also increase the fold of the CDP gathers, further increasing the SNR of the resulting reflection profiles, and making it easier to confidently interpret reflections. If sufficient receivers are available, the receiver array could be designed to allow for the removal of surface waves via array forming.

Finite resources are available to perform seismic surveys, and it is not always possible to obtain more receivers for a denser array. As was shown in this study, it is
key to have a good understanding of the noise sources which will be available. A short reconnaissance survey could be conducted using as few as three receivers, and beamforming could be used to determine the locations of any periodic or constant sources of noise. Having this knowledge prior to conducting a passive survey would facilitate the planning and design of the optimal receiver layout. Receiver lines could then be laid out such that the sources lie in the stationary phase regions for a 2-D survey, or such that the array is surrounded by sources (if possible) for a 3-D survey. At the very least, the array could be designed in such a way that any unwanted noise is easily removable, either by linear noise filtering or array forming.

SI by cross-correlation was applied in this study due to its simplicity. While SI by cross-correlation places no requirements on the receiver array in terms of receiver spacing and recording capabilities (e.g. 1-component versus multiple component recordings), it does require that sources be available at a variety of azimuths and angles of vertical incidence. Recent developments to the SI methodology, such as multidimensional deconvolution (Wapenaar et al., 2008), are able to account for an incomplete source distribution at the cost of requiring that the wavefield be separable into incoming and outgoing components. For surface land data, this typically requires that the geophones record multiple components, for instance vertical particle velocity and pressure, or particle velocity in the vertical, radial, and transverse directions. In order to be able to apply the latest in SI processing techniques, multi-component geophones should be used in future surveys. Using multi-component geophones in future surveys would also allow for recovery of shear-wave reflections, calculation of dispersion curves, and subsequent inversion for near surface velocities.

The synthetic experiments outlined in Chapter 2 were used to understand how dipping reflectors would be imaged when applying SI with a one-sided source distribution. However, the particular the model used in the experiments was a very simplified version of a VMS deposit. Further synthetic experiments should be performed using the geological model of the Lalor deposit to study the effects of different source distributions in the presence of scatterers and generally more complex geology. Furthermore, the experiments performed in this study were done using a 2-D modelling code. While for horizontally stratified geology 3-D effects are negligible to the
application of SI, synthetic experiments should be undertaken to determine how complex geology in 3-D affects reflection profiles generated through SI. These experiments should be performed using both deterministic and stochastic rock property models as stochastic models have been found to generate synthetic responses more closely matching real data (Schetselaar et al., 2016).

Refraction statics were key to improving the quality of the reflections in the 3-D active source survey. In general, refraction statics have not been applied to past ambient noise datasets collected over layered geology. However, a method of calculating refraction statics will be crucial if SI is to be applied in increasingly complex geological settings. Previous studies have examined surface waves recovered using SI to generate dispersion curves and near-surface velocity models, although the results are less accurate than those generated using active source data. Future studies should be conducted to refine the methodology used to generate near-surface velocity models using SI, or to incorporate active source data to calculate refraction statics for passive receiver arrays.
References


