Seismic investigations in the Brunswick No. 6 area, Canada – Imaging and heterogeneity

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Abstract

The Brunswick No. 6 area, which is located in the Bathurst Mining Camp, New Brunswick, Canada, is the focus of this thesis. Almost a decade ago, in order to improve the understanding of the crustal structures and explore for new mineral deposits at depth, three 2D seismic profiles totaling about 30 km and 3D seismic data covering an area of about 38 km$^2$ were acquired from the study area. Petrophysical properties including compressional-wave velocity and density were also measured in two deep boreholes in the area. These data were recovered and reanalyzed, and the improved seismic images interpreted as the main part of this PhD thesis.

A prestack DMO and poststack migration algorithm was considered for processing both 2D and 3D data. Processing of 2D data revealed shallow and deep reflections, which correlate well with surface geology. Steeply-dipping reflections, some of which could host mineral deposits, were imaged down to a depth of 6-7 km. Processing of 3D data showed similar results to the processed 2D profiles. Nevertheless, the non-orthogonal nature of the 3D survey, combined with irregular distribution of offsets, azimuths and trace midpoints, caused a severe acquisition footprint masking reflections in the DMO-corrected unmigrated stacked cube. An FK-dip filter in the wavenumber domain was designed to reduce the effects of the acquisition footprint.

To better understand wave propagation and scattering effects, calculated acoustic impedance log from the available borehole data was used to estimate vertical scale length using a von Karman autocorrelation function. 2D synthetic models representative of heterogeneity in the area were generated accounting for the estimated scale length. Numerical modeling was used to study the scattering effects on the synthetic models, where some predefined targets were superimposed in the provided 2D heterogeneous medium. The effects of variable source frequency, longer horizontal scale length and petrophysical fluctuations of heterogeneous medium were also investigated. The modeling results indicate that, in the presence of large horizontal, but small vertical scale lengths (structural anisotropy), the identification of mineral deposits is possible in the unmigrated stacked sections, but can be challenging in the migrated sections.

Keywords: Brunswick No. 6, Mineral deposits, 2D and 3D reflection seismic, Acquisition footprint, Scale length, Heterogeneity, Numerical modeling

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Dedicated to:

My wife Farzaneh
List of Papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.


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Additional refereed conference proceedings and journal publications written during my PhD studies, but not included in the thesis are:


**Cheraghi, S.,** Malehmir, A., Bellefleur, G., (2012). 3D reflection seismic investigations and scaling behavior of geophysical logs in the Brunswick No. 6 area, Bathurst Mining Camp, Canada. 74th European Association of Geoscientists & Engineers (EAGE) Conference, Copenhagen, Denmark.
Cheraghi, S., Malehmir, A., Bellefleur, G., (2010). Reflection Seismic Investigations in the Brunswick No. 6 Mining Area, Bathurst Mining Camp, Canada. 72nd European Association of Geoscientists & Engineers (EAGE) Conference, Barcelona, Spain.
Contributions

Paper I: I spent the entire year of 2009 on processing the seismic data and finalizing the results. Discussions with co-authors guided the processing and eventually produced better results. I wrote the first draft of the paper and the co-authors helped me to refine it. This paper shows the capability of the reflection seismic method to image deep steeply-dipping geological formation in the Earth's crust.

Paper II: I spent about one year (September 2010 to September 2011) on processing the 3D seismic data starting from the raw field gathers. During processing, I received comments and guidance from the co-authors which helped me to improve the processing flow and final results. I wrote the first draft of the paper and the co-authors helped to improve the quality of the paper. The paper was published in Geophysics as apart of a special section on seismic methods applied to mineral exploration and mine planning.

Paper III: I conducted and completed all data processing, analysis with statistical methods, and seismic modeling between October 2011 and June 2012. I received comments and guidance from the co-authors to finalize the results. The first draft of the paper was written by me and the co-authors helped me to improve it.
Abbreviations

1D  1-dimensional
2D  2-dimensional
3C  3-component
3D  3-dimensional
5D  5-dimensional
ACF  Autocorrelation function
BMC  Bathurst Mining Camp
CDP  Common depth point
DMO  Dip moveout
FK  Frequency-wavenumber
NMO  Normal moveout
PSTM  Prestack time migration
RMS  Root-mean-squares
S/N  Signal-to-noise
VHMS  Volcanic-hosted massive sulphide
Vp  Compressional-wave velocity
Vs  Shear-wave velocity
1. Introduction

1.1. Background
As near surface mineral deposits are exploited and depleted in many mature mining camps around the world, the mining industry is looking for effective geophysical methods to explore resources located at greater depths (Eaton et al., 2003). Potential field and electromagnetic methods have proven to be successful in detecting near surface deposits (e.g., Goleby et al., 2002; Roy and Clowes, 2000). Reflection seismic surveys, however, remain the only method able to provide high resolution images of deep underground horizons and unravel complex subsurface geology (Duweke et al., 2002; Pretorius et al., 1989; Stevenson et al., 2003). During the past 20 years, the reflection seismic method has been applied to mine planning and exploration (Goleby et al., 1997; Malehmir et al., 2007, 2006; Milkereit et al., 2000, 1996, 1992; Pretorius et al., 2003; Kukkonen et al., 2011; Urosevic and Evans, 1998). Several 2D and 3D seismic surveys acquired in Canada, Europe, Australia and South Africa show the validity of the method in crystalline rock environments (Durrheim, 1986; Eaton et al., 1996; Harrison and Urosevic, 2012; Heinonen et al., 2012; Koivisto et al., 2012; Kukkonen et al., 2012; Mair and Green, 1981; Manzi et al., 2012a,b; Malehmir and Bellefleur, 2009; Malehmir et al., 2012a; Milkereit et al., 2000; Salisbury and Snyder, 2007; Urosevic et al., 2012; White and Malinowski, 2012; White et al., 2012). In particular, 3D seismic surveys were successfully used to define drilling targets in mining areas (Adam et al., 2003; Duweke et al., 2002; Eaton et al., 2003; Malehmir and Bellefleur, 2009; Milkereit et al., 2000). Beside surface seismic methods, vertical seismic profiling (VSP) methods have also been applied to crystalline rocks (Adam et al., 2003; Bellefleur, et al., 2004; Eaton et al., 2003).

Despite the fast growing application of reflection seismic surveys in studies of crystalline rocks, exploration in many subsurface environments remains challenging. Complex geology, small geological features, low acoustic impedance contrast, and the heterogeneous environment of the crystalline medium results in a low signal-to-noise (S/N) ratio. Crystalline rocks are highly metamorphosed and deformed, containing complex structures. In such an environment, both survey design and data processing methods should be geared toward successful imaging of the large and small geological targets that can be associated with mineral deposits. Survey designs and
their effects on the seismic response are less scrutinized in a crystalline environment even if they can have a significant impact on the quality of the data. Problems originating from improper survey design are usually impossible or very difficult to rectify at the processing stage. Seismic data processing also comprises several challenges in crystalline rocks. Prestack dip moveout (DMO, Deregowksi, 1986) and poststack migration algorithms have proven to be key elements of the conventional processing flow in a crystalline rock environment (e.g., Malehmir and Bellefleur, 2009; Milkereit et al., 2000). This conventional processing sequence, however, requires more in-depth analysis to improve seismic imaging in mineral exploration. For example, high apparent velocities related to steeply-dipping structures and their difference from velocities required for horizontal structures, and important static corrections of thick overburden and noise removal in a media characterized by low acoustic impedance contrasts can be particularly challenging and need to be properly addressed (Roberts et al., 2003). Scattering of seismic waves in crystalline rocks is another issue that requires more attention. Some seismic data indicate that the effects of source frequency and weak to strong scattering may cause highly reflective to transparent seismic sections (Levander et al., 1994). Most synthetic modeling of crystalline rocks has studied scattering of seismic waves in a near homogeneous environment (e.g., Clarke and Eaton, 2003; Bohlen et al., 2003; Hobbs, 2003). However, several studies that have considered the effects of heterogeneous environment in crystalline rocks show a possible decrease of S/N ratio with increasing heterogeneity (Bongajum et al., 2012; L’Heureux e al., 2009). Heterogeneity, scattering, reflections and diffractions generated by geological features need further investigations using synthetic models. The results should be compared with real seismic data in order to reveal problems and identify possible solutions and, hence, to improve the applicability of the reflection seismic method.

This PhD thesis is the result of four years study at Uppsala University, Department of Earth Sciences, Geophysics Program. It focuses on the analysis, processing, and interpretation of the 2D and 3D seismic data from the Brunswick No. 6 mining area in Canada. The main objective of the seismic processing was to delineate subsurface structures related to VHMS (volcanic-hosted massive sulphide) deposits. In particular, most effort and time was invested in the 3D data, which cover an area of about 38 km². The results of the 2D processing show the capability of the reflection seismic method to image structures down to a subsurface depth of about 9 km. The 3D processing results show the ability of the method to image structures at the regional scale and demonstrate how the survey design affects seismic imaging. The scaling behavior of crystalline rocks was also studied as part of this PhD. Scattering of seismic waves and their impact on the imaging of mineral deposits (in this case of VHMS type) in a heterogeneous environment of crystalline rocks was also investigated.
This thesis is divided into two sections: the summary and a collection of papers. The summary section is divided into five chapters. A brief description of the geological structures and the main geological formations over the Brunswick No. 6 area are given in the first chapter. The geometrical properties of the 2D profiles and the 3D survey over the area are also shortly introduced. The potential problems related to survey design and criteria to plan an optimistic survey are discussed in chapter 2. Chapter 3 introduces issues related to geological heterogeneity in a crystalline environment and scaling behavior of physical properties measured from borehole logs. Chapter 4 consists of a summary of three papers that are included in the second section of the thesis. Finally, the concluding chapter 5 considers the collective results of the papers and discusses possible research avenues to improve seismic imaging in a crystalline rock environment.

1.2. Geological setting of the Brunswick mining area

The Brunswick No. 6 area, the focus of this thesis, is situated in the Bathurst Mining Camp (BMC), approximately 27 km southwest of the city of Bathurst, New Brunswick, Canada (Figure 1.1). The Bathurst Mining Camp also hosts the Brunswick No. 12 mine, one of the largest VHMS deposits in Canada (Figure 1.1; Wills et al., 2006). The first exploration activities in Brunswick No. 6 were carried out in 1907 (Belland, 1992). In 1952, the Brunswick No. 6 deposit was discovered by drilling in areas where electromagnetic anomalies were identified. Mining activity in the area stopped in 1983 after a total production of 12.2 Mt of 5.43% Zn, 2.15% Pb, 0.40% Cu, and 67g/t Ag was exploited (Luff, 1995).

van Staal (1994) and van Staal et al. (2003) provide a thorough description of the tectonic history of the Bathurst Mining Camp. A continent-continent collision in the late Ordovician and Early Silurian shaped the Brunswick complex (van Staal, 1994). Prior to the collision, a sequence of oceanic-continental obductions occurred up to the early Ordovician and trapped large blocks of oceanic rocks (mainly ophiolite) underneath the volcanic and sedimentary rocks of the Miramichi Group. Regional scale seismic profiles in the New Brunswick region also suggest the presence of oceanic rocks trapped at shallow depths (Stockmal et al., 1990). Frequent repetitions of lithological units and thickening of volcanic rocks are evidences of thrusting and upright folding systems in the camp (van Staal, 1987).
Figure 1.1. Geological map of the Brunswick No. 6 area, New Brunswick (modified from van Staal et al., 2003) showing the locations of major mineral deposits including Brunswick No. 6 and 12. The rectangle exhibits the 3D seismic survey area. The solid black lines are 2D seismic profiles BRN991001, BRN991002 and BRN991003, which were acquired in 1999 prior to the 3D survey. Brunswick horizon, a key horizon that hosts massive sulphide and iron mineralizations, was the target of the seismic investigations. Borehole B-353 and B-357 were petrophysically logged and used for various purposes explained later on the thesis. A geologic cross-section (A-A\textsuperscript{'}), and the geometry of 3D survey are shown in subsequent figures in this chapter.

The Miramichi Group, a Cambro-Ordovician clastic metasedimentary sequence is the oldest geological formation in the area (van Staal et al., 2003). The middle Ordovician bimodal volcanic and sedimentary rocks of the Tetagouche Group overlay the clastic rocks of the Miramichi Group (Rogers and van Staal, 1997; Whalen et al., 1998; van Staal, 1994, 1987; van Staal et al., 2003). The Tetagouche Group hosts the VHMS and iron deposits, mostly along an important horizon known as the Brunswick horizon (van Staal et al., 2003). The Nepisiguit Falls Formation, which contains felsic volcanic and volcanoclastic rocks, constitutes the lower part of the Tetagouche Group that is covered by the younger rhyolite flows and rhyolitic vol-
canic/hyaloclastic rocks of the Flat Landing Brook Formation (Rogers et al., 2003). The alkali basalt flows and associated clastic and exhalative sedimentary rocks of the Little River Formation are the youngest parts of the Tetagouche Group. Massive sulphides and associated iron formation along the Brunswick horizon are typically found in the upper part of the Nepisiguit Falls Formation (Goodfellow and McCutcheon, 2003; van Staal et al., 1992). The iron formation is a key horizon for geophysical and geochemical exploration in the BMC (Gross and McLeod, 1980).

1.3. 2D and 3D seismic data

The available mining infrastructure in the Brunswick No. 6 area and the possibility to discover another world-class deposit similar to the Brunswick No. 12 motivated Noranda Inc. (now Xstrata) to conduct a detailed near surface and deep mineral exploration program in the study area. For this purpose Noranda Inc. acquired three 2D seismic profiles and made a 3D seismic survey in the Brunswick No. 6 mining area (Figure 1.1). The 2D seismic profiles were acquired prior to the 3D survey and were used to confirm the reflectivity of the main lithological units in the area. The locations of the 2D profiles were not only chosen to cross different geological formations in three different directions, but also to provide control points where the profiles intersect each other. The intersections allow correlation of geological formations between the profiles. The 3D survey covers an area of about 38 km² (Figure 1.1). The initial design of the 3D survey targeted the Brunswick horizon near the Brunswick No. 6 mine. Generally, the Brunswick horizon dips to the west as shown in the geological cross-section A-A’ (Figure 1.2). Table 1.1 shows the main acquisition parameters for the 2D profiles and the 3D survey. The geometry of the 3D survey is shown in Figure 1.3. These data are the focus of the first two papers included in this thesis. The cross-section shown in Figure 1.2 was used to generate synthetic seismic data used in the first and third papers.
Figure 1.2. Geological cross-section along the profile A-A’ (see Figure 1.1) obtained from deep and shallow boreholes including B-347 and B-348 (modified from Lentz and McCutcheon, 2006). Geological units shown in the cross-section are introduced in Figure 1.1.

Table 1.1. Main data acquisition parameters of the 2D and 3D seismic surveys carried out in the Brunswick No. 6 area (modified from Paper I, II).

<table>
<thead>
<tr>
<th>Survey parameters</th>
<th>2D profiles</th>
<th>3D survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Recording system</td>
<td>SERCEL 388</td>
<td>SERCEL 388</td>
</tr>
<tr>
<td>No. of active channels</td>
<td>481</td>
<td>2367 to 3456</td>
</tr>
<tr>
<td>Maximum offset</td>
<td>4800 m</td>
<td>6700 m</td>
</tr>
<tr>
<td>Survey length¹ / area</td>
<td>6.9, 9.2, 12 km</td>
<td>~ 38 km²</td>
</tr>
<tr>
<td>Source</td>
<td>Dynamite</td>
<td>Dynamite</td>
</tr>
<tr>
<td>Charge size / depth</td>
<td>0.5 kg / 6 m</td>
<td>0.5 kg / 6 m</td>
</tr>
<tr>
<td>Source interval</td>
<td>40 m</td>
<td>60 m</td>
</tr>
<tr>
<td>No. of shots¹</td>
<td>169, 260, 343</td>
<td>1500</td>
</tr>
<tr>
<td>Geophone frequency</td>
<td>10 Hz</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Receiver interval</td>
<td>10 m</td>
<td>22 m</td>
</tr>
<tr>
<td>Nominal fold¹</td>
<td>60, 60, 60</td>
<td>75</td>
</tr>
<tr>
<td>No. of shot lines</td>
<td>15</td>
<td>15</td>
</tr>
<tr>
<td>Shot line spacing</td>
<td>400 m</td>
<td>400 m</td>
</tr>
<tr>
<td>No. of receiver lines</td>
<td>28</td>
<td>28</td>
</tr>
<tr>
<td>Receiver line spacing</td>
<td>240 m</td>
<td>240 m</td>
</tr>
<tr>
<td>No. of active receiver lines per patch</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>Sampling rate</td>
<td>2 ms</td>
<td>2 ms</td>
</tr>
</tbody>
</table>

¹: BRN991001, BRN991002, BRN991003, respectively
Figure 1.3. Close-up of the geological map of the Brunswick No. 6 area (Figure 1.1) showing shot (north-to-south direction) and receiver (northwest-to-southeast direction) lines. The dashed rectangle shows the horizontal projection of a 3D stacked cube presented later in the thesis.
2. Acquisition and processing challenges

As the great capabilities of the seismic method in mineral exploration have already been proven (Malehmir et al., 2012b and references therein; Pretorius et al., 2003), it is now necessary to optimize data acquisition parameters and processing steps for specific object targeting (Milkereit et al., 2000). Day-to-day improvement of acquisition systems and processing software, combined with faster computer processors, is encouraging since they reduce the cost of seismic exploration surveys (Vestrum and Gittins, 2009). The acquisition of 3D seismic surveys with thousands of channels is now possible and can be done in a relatively short period of time. However, there are important issues concerning acquisition design that have to be carefully investigated prior to a 3D survey. Not only should \textit{apriori} geological knowledge be taken into account, but also target dimension, dip, and depth. Due to the increase in the market price of metal commodities, smaller deposits found at greater depths are becoming economical. Thus, seismic surveys for mineral exploration should be adapted to meet specific geological conditions and involve economic considerations. This remainder of this chapter reviews some of the issues related to data acquisition, such as the footprint problem and ways to reduce it through data processing.

2.1. 2D versus 3D

2D and 3D seismic data are fundamentally different. The main difference between 2D and 3D seismic data is the approach used (and its inherent limitations) to produce an image of the subsurface structures, which are three dimensional in the real world (Biondi, 2006). Out-of-plane reflectors with respect to an arbitrarily 2D acquisition line can cause errors in structural interpretation if 3D data are not involved (Hobbs et al., 2006). The main drawback of a 3D survey is its cost, which is often several orders higher than that of 2D surveys (Cooper 1997; Vestrum and Gittins, 2009). Inaccessible areas (e.g., rough topography, existence of swamps, etc.) and permission issues sometimes force seismologists to plan a sparse survey. A sparse 3D survey can cause an irregular wavefield sampling that has severe effects on the subsurface illumination (Vermeer, 1998; Vestrum and Gittins, 2009). Lack of geological knowledge could also contribute to this deficiency. Table 2.1 compares some characteristics of 2D and 3D seismic data sets.
Table 2.1. Some characteristics of 2D and 3D seismic data

<table>
<thead>
<tr>
<th>2D data</th>
<th>3D data</th>
</tr>
</thead>
<tbody>
<tr>
<td>• First arrivals have better statistical distribution. Refraction static solution gives a better correction for wave propagation in the near surface weathered layer (Vestrum and Gittins, 2009).</td>
<td>• 3D data provide lateral images of complex structures (e.g., steeply-dipping layers, Cooper, 1997).</td>
</tr>
<tr>
<td>• For a specific CDP fold, 2D data provide higher resolution images than 3D data in the shallow section, which could give a better connection to surface geology (White and Malinowski, 2012).</td>
<td>• 3D migrated images are more accurate for planning of drill holes (Malehmir and Bellefleur, 2009)</td>
</tr>
<tr>
<td>• Lower size of 2D data sets allows for faster testing of different velocity models using a depth-migration method and results can help to find an optimistic 3D velocity model (Vestrum and Gittins, 2009).</td>
<td>• 3D data sets are much larger than 2D data sets and, thus, provide extra information; but an appropriate processing method should be devoted to reduce time and cost of processing (Biondi, 2006).</td>
</tr>
</tbody>
</table>

It is becoming common practice to acquire a network of 2D seismic profiles to build a sparse three-dimensional geological model prior to any 3D survey (Koivisto et al., 2012; Malehmir et al., 2010; White and Malinowski, 2012). A 3D geological model supported by auxiliary information (e.g., borehole data) combined with lessons learned from a 2D survey can then play an important role in the design of a 3D survey.

2.2. Spatial sampling

Since the early 1990s, 3D survey design was based on experience and capabilities of the available technology (Stone 1994; Vermeer, 1998). In fact, 3D survey design was an extension of 2D geometries (Vermeer, 1998). 2D spatial sampling was implicitly discussed by Anstey (1986) and Ongkiehong and Askin (1988). Anstey (1986) explained that if a trace midpoint distribution in each CDP bin is regular and dense, then stacking can remove the effects of ground roll. Ongkiehong and Askin (1988) showed that signal velocity and frequency bandwidth are crucial in defining receiver spacing in the shot domain, and shot spacing in the receiver domain. Their ideas were later discussed and re-explained by Vermeer (1991) and (1990). In a 2D survey, spatial sampling can be expressed by $W(t,x_s,x_r)$, where $W$ is the wavefield, $t$, $x_s$, and $x_r$ are time, source coordinate and receiver coordinate, respectively. To achieve the 2D symmetrical sampling needed for adequate signal sampling, the reciprocity should be considered in shot and receiver gathers (i.e., the properties of continuous wavefield in both common-shot...
gather and common-receiver gather should be the same). To achieve this, receivers in a shot gather should be sampled in the same way as shots in the receiver gather (Vermeer, 1998). Small shot-receiver spacing \( \Delta x \) allows to consistently measure and sample the seismic wavefield by preserving the spatial continuity and an alias-free wavefield. The shot-receiver spacing \( \Delta x \) can be defined as following (Vermeer, 1998):

\[
\Delta x = \frac{l}{2k_{\text{max}}} = \frac{V_{\text{min}}}{2f_{\text{max}}}
\]

where \( k_{\text{max}} \) is the maximum wavenumber, \( V_{\text{min}} \) is minimum apparent velocity and \( f_{\text{max}} \) is maximum frequency.

For a 3D survey, spatial sampling involves measurements of a 5D seismic wavefield \( W(t, x_s, y_s, x_r, y_r) \), where \( t \) is time, \( (x_s, y_s) \) and \( (x_r, y_r) \) are shot and receiver coordinates, respectively. The concept of the reciprocity is ideal for 3D surveys. To achieve continuous sampling of the wavefield, the whole area should be sampled with a dense grid of shots and receivers, which increases significantly the cost of a 3D survey. Instead, the wavefield is measured in coarser grids of shots and receivers. In 3D land surveys, two common geometries are often used to acquire 3D data: (1) areal geometry with receivers placed in a dense areal grid, while shots are taken on a coarse grid (or vice versa); (2) line geometries with receivers densely sampled along parallel receiver lines and shots densely acquired along parallel shot lines. Both areal and line geometries have different sub-categories which are discussed in detail by Vermeer (1998). The most popular 3D acquisition design in mineral exploration is the orthogonal geometry (parallel shot lines are perpendicular to parallel receiver lines) and the non-orthogonal geometry (parallel shot lines are aligned or oblique to parallel receiver lines or the other way around, Malehmir et al., 2012a; Milkereit et al., 2000; Paper II). The concept of symmetric sampling can satisfy the continuous wavefield sampling for both orthogonal and non-orthogonal geometries (Vermeer, 1998; the following text in the paragraph is also referring to this reference). The orthogonal and non-orthogonal geometries are characterized by shot and receiver point distances, shot and receiver line distances and maximum inline and crossline offsets. The aspect ratios of receiver point spacing/shot point spacing, receiver line spacing/shot line spacing and maximum inline offset/maximum crossline offset define the geometry of a 3D survey. To attain a symmetric sampling and alias-free signal, all these aspect ratios should be equal to one. Additionally, the 3D symmetric sampling rule requires a regular geometry. This requirement means that all cross-spreads, i.e., all traces that have a shot line and a receiver line in common have equal-size midpoint areas and inline and crossline symmetry (Figure 2.1). While equal shot and receiver intervals are not always possible due to, for instance,
cost or terrain obstacles, the criteria of equal maximum inline offset and maximum crossline offset leads to symmetric sampling and sensible offset distribution; shot arrays (shots acquired in a cross-spread) and receiver arrays reduce aliasing in both shot and receiver domains. A geometry with an aspect ratio of maximum inline offset/maximum crossline offset equal to 1 provides wide azimuth geometry, whereas, unequal maximum inline and crossline offset (narrow azimuth) does not provide symmetrical sampling (Figures 2.1 and 2.2).

Figure 2.1. Spatial sampling of the orthogonal geometry (modified from Vermeer, 1998). (a) Wide azimuth and (b) narrow azimuth geometry. Trace midpoint coverage area is shown in grey.
2.3. Sparsity and acquisition footprint

The presence of natural obstacles, inaccessible areas or limited budget does not favor a dense 3D survey with small shot and receiver intervals (Hindriks and Duijndam, 2000). However, larger shot and receiver line intervals cause a higher degree of sparsity, a measure showing how dense a 3D survey is (Vermeer, 2010). The asymmetrical sampling and sparsity of geometry result in irregular trace sampling, i.e., traces are missing for some ranges of offsets and azimuths (Cordsen et al., 2000; La Bella et al., 1998). Figure 2.3 shows example 3D bins from a real survey with irregular offset and azimuth distributions.

Here is an example of how irregular offsets can be problematic; 3D DMO processing requires as many traces as possible in each range of azimuths and offsets for constructive interference to form reflections. Without many traces, repetitive or periodic artifacts will be generated after DMO processing. These artifacts are referred to as geometry imprinting or acquisition footprint (Gardner and Canning, 1994; Gesbert, 2002; Gulunay et al., 2006; Hindriks and Duijndam, 2000; Marfurt et al., 1998). Artifacts generated by DMO processing mask the seismic image and mislead interpreters. Some methods have been tested to reduce the acquisition footprint effects; e.g., reconstruction of irregularly sampled seismic data (Duijndam et al., 1999; Hindriks and Duijndam, 2000; Kabir and Verschuur, 1995) and transforming seismic data to the FK domain and removing the artifacts in depth or time sections (Gulunay et al., 2006; Marfurt et al., 1998). Reconstruction or mix-
ing of traces would very likely be challenged by the complex nature of geology in the crystalline environment and low signal-to-noise ratio (Kaplan et al., 2010). Thus, a careful seismic survey design, which avoids a severe acquisition footprint is preferable to attempt to reduce the negative effects afterwards during the processing. Table 2.2 summarizes some typical 3D seismic surveys conducted in a crystalline environment.

![Figure 2.3. Bin-offset redundancy and bin-azimuth graph (modified from Paper II). (a), (b), and (c) show three different bin locations from the 3D survey near the Brunswick No. 6 mine. The bin redundancy plot shows gaps (white parts) indicating missing offsets in the plot. The spider plot of azimuth distribution in (a) indicates a wide azimuth distribution whereas (b) and (c) represent narrow azimuth distributions. The plots show that maximum offset in (c) is larger than (a) and (b); bin location (a) has the shortest offsets among the three presented CDP bins.](image)
### Table 2.2. Characteristics of some major 3D seismic surveys around the world.

<table>
<thead>
<tr>
<th>Survey</th>
<th>Primary goal</th>
<th>Geometry</th>
<th>No. of shots</th>
<th>SLI (m)</th>
<th>SPI (m)</th>
<th>RLI (m)</th>
<th>RPI (m)</th>
<th>A /SPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acquired in Canada:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brunswick No. 6 deposit¹</td>
<td>Regional/deep exploration</td>
<td>NOR</td>
<td>1500</td>
<td>400</td>
<td>60</td>
<td>290</td>
<td>22</td>
<td>~38/39</td>
</tr>
<tr>
<td>Flin Flon mining camp²</td>
<td>Deep exploration</td>
<td>NOR</td>
<td>940</td>
<td>200</td>
<td>50</td>
<td>200</td>
<td>25</td>
<td>~17/55</td>
</tr>
<tr>
<td>Halfmile Lake, New Brunswick³</td>
<td>Deep exploration</td>
<td>OR</td>
<td>690</td>
<td>406</td>
<td>60</td>
<td>406</td>
<td>20</td>
<td>~18/38</td>
</tr>
<tr>
<td>Matagami, Quebec⁴</td>
<td>Ore delineation</td>
<td>OR</td>
<td>956</td>
<td>400</td>
<td>50</td>
<td>250</td>
<td>40</td>
<td>~20/47</td>
</tr>
<tr>
<td>Sudbury basin⁵</td>
<td>Deep exploration</td>
<td>OR</td>
<td>1050</td>
<td>600</td>
<td>50</td>
<td>300</td>
<td>30</td>
<td>~30/35</td>
</tr>
<tr>
<td>Millennium, Saskatchewan⁶</td>
<td>Mine planning</td>
<td>NOR</td>
<td>&gt; 3000</td>
<td>50-100</td>
<td>20-40</td>
<td>100</td>
<td>14</td>
<td>~6.5/461</td>
</tr>
<tr>
<td>Acquired in Europe:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kevitsa mine, Finland⁷</td>
<td>Mine planning</td>
<td>OR</td>
<td>~3300</td>
<td>80</td>
<td>45</td>
<td>70</td>
<td>15</td>
<td>~9/366</td>
</tr>
<tr>
<td>Acquired in South Africa:</td>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kloof-South, Witwatersrand⁸</td>
<td>Deep exploration and mine planning</td>
<td>OR</td>
<td>4155</td>
<td>450</td>
<td>50</td>
<td>400</td>
<td>50</td>
<td>~96/43</td>
</tr>
<tr>
<td>Acquired in Australia:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Kambalda⁹</td>
<td>Deep exploration</td>
<td>OR</td>
<td>~2200</td>
<td>10-100</td>
<td>20</td>
<td>90</td>
<td>10</td>
<td>~3.5/628</td>
</tr>
</tbody>
</table>

1: Paper II; 2: White et al. (2012); 3: Malehmir and Bellefleur (2009); 4: Adam et al. (2003); 5: Milkereit et al. (2000); 6: Juhojuntti et al. (2012); 7: Malehmir et al. (2012a); 8: Manzi et al. (2012b); 9: Urosevic et al. (2012).
Table 2.2 presents the main acquisition parameters for several 3D seismic surveys acquired around the world. Approximately 30% of the 3D surveys acquired for mine planning and deep mineral exploration are non-orthogonal, even if orthogonal survey geometry is preferred. Also, 30% of the surveys covered an area less than 10 km$^2$ (Millennium, Kevitsa mine, and Kambalda) and these were typically acquired for mine planning. The Kambalda 3D survey had the smallest area but most dense shot coverage (3.5 km$^2$ and 628 shots/km$^2$, respectively). Shot line interval and receiver line interval for mine planning range from 10-100 m and 70-100 m, respectively. Shot point interval and receiver point interval for mine planning range 20-45 m and 10-15 m, respectively. Shot line and receiver line intervals for deep exploration tend to be larger and range from 200-600 m, and 200-400 m, respectively. Shot point interval and receiver point interval for this purpose are typically between 50-60 m, and 20-50 m, respectively. The largest survey amongst all, the Kloof-South survey, covers an area of 96 km$^2$ but its shot density of 43 shots/km$^2$ is close to those of other deep exploration surveys (Table 2.2).

2.4. DMO consideration in 3D processing

It was mentioned in section 2.3 that irregular sampling geometry generates artifacts during DMO processing. In this section, the DMO equation (Deregowski, 1986, 1982) is revisited again to explain the effects of irregular sampling on DMO processing. This discussion is based on Vermeer (2012). Figure 2.4 shows a dipping reflector and the ray path from the source ($S$) to the receiver ($R$). DMO processing moves the trace from midpoint position ($M$) to output point ($O$), which is normal to the reflector at point $D$ (real reflection point between the source and the receiver, see Figure 2.4).

![Figure 2.4](image)

*Figure 2.4. Source ($S$) and receiver ($R$) positions to measure reflection point $D$ along a dipping reflector (modified from Vermeer, 2012). The line at the surface connecting the source to the receiver (line ASR) is not necessarily in dip direction and thus $\theta$ can be an apparent dip ($D$ will be out of the vertical plane connecting $S$ and $R$ when $\theta$ is apparent dip). $h$ shows half of offset between the source and the receiver, $r$ is the distance between the midpoint $M$ and the output point $O$ (surface image of reflection point $D$ along a line normal to the reflector surface), and $a$ is the vertical distance between $D$ and its image on the surface (point $O$).*
Since the subsurface dip is unknown during DMO processing, all traces that can contribute to a particular output point \( O \) will move to it. The traces contributing to the output point form a DMO panel \( r \). In the following text, the criteria for correctly imaging point \( D \) from a DMO panel are discussed. If the velocity above the reflector shown in Figure 2.4 is constant and equal to \( V \) then the normal-incidence reflection time at point \( O \) is:

\[
t_O = \frac{2a}{V}
\]

(2.2)

The NMO correction for a trace in \( O \) is:

\[
t_n = \frac{2}{V} \left[ (a - r \sin \theta)^2 - h^2 \sin^2 \theta \right]^{1/2}
\]

(2.3)

by considering the DMO equation (Deregowski, 1982):

\[
t_d = t_n \sqrt{1 - \left( \frac{r}{h} \right)^2}
\]

(2.4)

and combining equations 2.3 and 2.4, the DMO correction at the output point \( O \) is:

\[
t_d = \frac{2a}{V} \left[ 1 - \left( \frac{ar + (h^2 - r^2) \sin \theta}{ah} \right)^2 \right]^{1/2}
\]

(2.5)

Equation 2.5 shows that the DMO time correction at point \( O \) is always less than or equal to the normal-incidence time in \( O \). The DMO corrected time is equal to the normal-incidence time only if:

\[
ar + \left( h^2 - r^2 \right) \sin \theta = 0
\]

(2.6)

If \( \theta = 0 \) the equation 2.6 is valid for \( r = 0 \), i.e., midpoint \( M \) and output \( O \) coincides for a horizontal reflector and for shooting along strike. Otherwise, the equation 2.6 can be solved only if \( r \) and \( \sin \theta \) have opposite signs. In order for DMO to work for both positive and negative dips, DMO panel must contain traces on both sides of the output point.

Figure 2.5 shows a graphical representation of the equation 2.6 for a reflector depth along the normal-incidence equal to 10 m \( (a = 10 \text{ m}) \), an apparent dip of \( \theta = -30^\circ \), and \( |h| \leq 100 \text{ m} \), which forms a non-linear curve and is called the locus of contributing midpoints. This curve implies that when there is a regular distribution of midpoints surrounding the output point (apex of the hyperbola) in a DMO panel, the DMO formula (equation 2.5) properly calculates the DMO correction.
2.5. Conventional processing considerations for 3D data

The flow of seismic data processing used for crystalline rocks is typically somewhat different from the one applied to sedimentary basins, often for hydrocarbon exploration (Perron and Calvert, 1998; Wu et al., 1995). Several researchers show that prestack DMO and poststack migration algorithms are accepted as the main imaging components of the conventional 3D processing flow in the crystalline environment (e.g., Malehmir and Bellefleur, 2009; Milkereit, et al., 2000). The general steps in the processing are: (1) geometry set up and binning; (2) refraction static corrections for the weathered overburden or loose sediments; (3) coherent noise removal, for example, shear-wave and ground-roll; (4) velocity analysis and residual static corrections; (5) DMO corrections; (6) stacking and (7) migration.

Proper migration of 3D seismic data requires CDP bin size designed to avoid aliasing. The optimal bin size can be calculated by using the following formula (Yilmaz, 2001).

\[
\Delta r \leq \frac{V_{rms}}{4f_{max} \sin \alpha} \tag{2.7}
\]

where \(V_{rms}\) defines the \(rms\) average velocity above the target reflector, \(\alpha\) is the dip of the geological structure, and \(f_{max}\) is the maximum non-aliased frequency used to resolve the target reflector.

For square bins with a size of \(\Delta r\) by \(\Delta r\), a seismic signal with a frequency higher than \(f_{max}\) will be aliased in both the inline and crossline directions. More attention should be paid to aliasing frequency when designed bins are rectangular. In that case, aliasing frequencies in the inline and crossline directions are different and should be considered in the processing flow.
3. Effects of heterogeneity

It is proven that the Earth is laterally heterogeneous from the crust, through the mantle and into the core (Wu and Aki, 1988) with the scale length of heterogeneity varying from the grain size of rocks to tens of kilometers (Pilkington and Todoeschuck, 2004). Scaling behavior of the crust is studied by both geologists and geophysicists (e.g., Sato et al., 2012 and references therein). From the geological point of view, geochemical variations of rocks exposed at the surface or rocks formed within the deep crust or mantle (e.g., volcanic rocks, kimberlite and deep rocks thrust to the surface) as well as different tectonic regimes and associated faulting and folding contribute to heterogeneity. Geophysical studies including seismic studies and borehole petrophysical measurements indicate some variations of elastic properties related to the heterogeneity of rocks in the crust (e.g., Bansal et al., 2010; Bean, 1996; Goff and Holliger, 1999; Holliger, 1996; Line et al., 1998; Pilkington and Todoeschuck, 2004). Shallow and deep seismic surveys also reveal that heterogeneous rocks with a broad range of scales could affect the seismic imaging of potential targets (Bongajum et al., 2012; Holliger et al., 1994, 1993; Hurich, 1996; Hurich and Kocurko, 2000; L’Heureux et al., 2009; Kneib, 1995). This chapter briefly explains the effects of heterogeneity on seismic data (i.e., scattering) and reviews the methods commonly used to define the scale of heterogeneity and its implications for seismic exploration.

3.1. Scattering and propagation regime

Generally, the interaction of seismic waves with spatial variations of physical properties of a medium is defined as scattering when the size of variations range from a few seismic wavelengths to a small portion of a wavelength (Frankel and Clayton, 1986). The interaction of seismic waves with a small-size object (size less than or equivalent to one wavelength), for example, faults, pinches and orebodies, scatters seismic waves in all directions and causes a hyperbola-shape event in a shot gather or stacked image which is referred to as a diffraction (Khaidukov et al., 2004).

Seismic wave scattering in crustal rocks depends on the scale of heterogeneity, composition, shape and preferential orientation of physical properties (L’Heureux, 2009). The effects of scale length on wave propagation can
be observed in terms of travel time, waveform and amplitude changes (Wu, 1989). Wu and Aki (1988) analytically discussed scattering phenomena and the wave propagation regime in terms of different scale lengths and wavelength (Figure 3.1).

Figure 3.1. Valid regions for different scattering regimes (modified from Wu and Aki 1988) based on different values of scale length ($a$), wavenumber ($k = \frac{2\pi}{\lambda}$), and propagation length ($L$).

The wave propagation regime can be defined by the scale length ($a$), the propagation length ($L$) and wavenumber ($k = \frac{2\pi}{\lambda}$). Figure 3.1 shows the valid region for each respective propagation regime in $ka$ versus $L/a$ space. The following definitions are based on Wu and Aki (1988).

- Quasi-homogeneous: when $ka<0.01$ and the medium is homogeneous and the heterogeneities are too small to affect the waves.
- Rayleigh scattering: when $ka<<1$ and scattering causes apparent attenuation in wave propagation.
- Large-angle scattering (Mie-scattering): when $0.1<ka<10$. In this region the scattering has the most effect and the size of heterogeneities are comparable to wavelength. The incident wave is scattered in a different direction, while the scattered wave moves at a large angle in relation to the incident direction.
- Small-angle scattering: when $ka>>1$. Here the backscattered wave is weak and most of the scattered wave is propagated forward, causing travel time and amplitude variations. The small-angle scattering is also called forescattering. By considering diffraction and interference problems, this region can be divided into three subdivisions (Aki and Richards, 2002; Flatte et al., 1979):
1. Geometrical optics regime: the Fresnel radius is smaller than the scale of heterogeneity and diffraction may be neglected. Ray theory can be used to explain wave propagation.
2. Diffraction regime: the Fresnel zone is large enough for diffraction to be considered.
3. Saturated regime: rays split into numerous micro-rays that interfere with each other. It is not possible to distinguish between the primary wavefield and later arrivals.

It is clear that in order to fully understand the scattering regime, the scale of heterogeneity should be well investigated.

3.2. Statistical properties of the heterogeneous crust

Borehole logging data typically provide observations of subsurface geology at scales from a few meters to several hundreds of meters (Pilkington and Todoeschuck, 2004). Amongst the various logging data generally available, the compressional-wave velocity ($V_p$) and density are particularly relevant to seismic wave propagation. The measured $V_p$ or density variations along a borehole can be used to study the scaling behavior or cyclicity of those properties. It has been demonstrated that scaling behavior can be observed over a wide range of frequencies, $f$, over which the power spectrum of a measured petrophysical property decays according to $\frac{1}{f^{0.5-1.5}}$, which is the $1/f$ flicker noise (e.g., Bean, 1996; Holliger and Goff, 2003). Figure 3.2 shows an example of the calculated power spectrum for a $V_p$ log acquired in the study area (Paper III). The absolute value of the slope of the best-fit line to $V_p$ is 1.1570. This value is well within the range of flicker noise (i.e., between 0.5-1.5) and indicates the existence of scaling that could vary from a few centimeters to hundreds of meters. However, the exact scale length cannot be estimated from this figure.

An isotropic elastic medium can be characterized with Lamé parameters ($\lambda$ and $\mu$) and density ($\rho$) (Sheriff and Geldart, 2006). If $\lambda$, $\mu$, and $\rho$ have constant background values (i.e., $\lambda_0$, $\mu_0$ and $\rho_0$) and some small fluctuations with a zero mean (i.e., $\delta\lambda$, $\delta\mu$ and $\delta\rho$), and heterogeneity scales are much smaller than the width of a propagating wave that travels through the medium, then $\delta\lambda$, $\delta\mu$, and $\delta\rho$ can be considered as random variables and the heterogeneous medium can be studied as a random medium (Korn, 1993). The random medium could host a mass of heterogeneities, which have some general statistical properties given by variance and average size.
Figure 3.2. 1D power spectrum of $V_p$ measurements from a borehole in a crystalline environment (modified from Paper III). The straight line represents the best least-squares line fitted to the spectrum and it has the negative slope “d”.

To study wave propagation in a random medium it is assumed that $V_p$ and $V_s$ (shear-wave velocity) are correlated (Korn, 1993) and velocity changes linearly with density according to Birch’s law (Birch, 1961). The velocity fluctuation, $\sigma(x)$, in a random media can be described as:

$$\sigma(x) = \frac{\delta V_p}{V_{p0}} = \frac{\delta V_s}{V_{s0}} = k^{-1} \frac{\delta \rho}{\rho_0}$$

(3.1)

where $x$ is the coordinate of a measuring point and $k$ is a coefficient that ranges between about 0.3 for sedimentary rocks to 0.8 for lower crustal rocks. The measured petrophysical fluctuation has a mean and a standard deviation equal to 0 and $\varepsilon^2$, respectively. The spatial variation of $\sigma$ can be characterized by an autocorrelation function (ACF).

Several ACFs have been used to investigate wave propagation in a random medium; Gaussian, exponential and von Karman type are examples of these functions (Ishimaru, 1978; Klimeš, 2002).

The Gaussian ACF (Sato et al., 2012) is described as:

$$R(r) = \sigma^2 e^{-\frac{r^2}{a^2}}, r = \sqrt{x^2 + y^2 + z^2}$$

(3.2)

where $R(r)$ is the ACF, $r$ is the lag, $\sigma^2$ is the standard deviation of the random media, and $a$ is the scale length. The general form of the von Karman ACF (von Karman, 1948) in 3-dimensions is:
\[ c(r) = \frac{r^n k_v(r)}{2^{n-1} \Gamma(n)}, r = \sqrt{\left(\frac{x}{a_x}\right)^2 + \left(\frac{y}{a_y}\right)^2 + \left(\frac{z}{a_z}\right)^2} \] (3.3)

where \( c(r) \) is the von Karman ACF, \( r \) is the lag, \( n \) is Hurst number which varies between 0 and 1, \( k_v(r) \) is the modified second-order Bessel function, \( \Gamma(n) \) is the gamma function, \( x, y, \) and \( z \) are spatial locations, and \( a_x, a_y, \) and \( a_z \) are scale lengths of heterogeneity in two horizontal directions and the vertical direction, respectively. The exponential ACF is a special case of von Karman ACF when Hurst number \( (n) \) is equal to 0.5.

Figure 3.3 shows a comparison between 1D (Z direction) Gaussian and von Karman ACFs. For the same predefined amount of lags and scale length, the Gaussian ACF drops to zero faster than all the von Karman ACFs shown in Figure 3.3. The Gaussian ACF cannot describe wave propagation in a random medium when short wavelengths are involved. Several studies suggest using the von Karman ACF as a valid estimator for studying statistical properties of the heterogeneous crust (Bongajum et al., 2012; Goff and Jordan 1988; Goff and Holliger 1994; Holliger et al., 1996; L’Heureux et al., 2009).

\[ \text{Figure 3.3. 1D Autocorrelation function (ACF) for (a) Gaussian and (b) von Karman type with Hurst number between 0.1-0.9 (modified from Sato et al., 2012). Scale length and standard deviation for both plots are 150 m and 297 m, respectively. The curve with Hurst number equal to 0.5 in (b) approaches an exponential ACF.} \]
3.3. Estimating scale length using von Karman type ACF

Petrophysical logs (e.g., \(Vp\) or density) can be considered as a series consisting of a general trend and a small-scale stochastic component (Chatfield, 1980). The general trend can usually be considered as the effect of burial depth (Holliger, 1997; Holliger et al., 1996) or lithology (Goff and Holliger, 1999). The small-scale stochastic component cannot be described explicitly (Bendat and Piersol, 2000) and estimators such as the von Karman ACF are used to predict it (Holliger et al., 1996). To estimate scale length, the general trend should be removed (Priestly, 1981). After removing the general trend, the autocovariance of the residuals (i.e., the stochastic component) is compared with the 1D (Z direction) von Karman ACF (see equation 3.3). The best-fit of the von Karman ACF line to the measured values (using a least-squares fit) defines the maximum scale length at which the stochastic environment remains fractal (Goff and Jordan, 1988; Holliger, 1996). Figure 3.4 shows an example estimate of the vertical scale length for a \(Vp\) log data and comparison with a von Karman ACF.

![Figure 3.4. Calculated autocovariance graph for the stochastic part of the \(Vp\) borehole logging data (modified from Paper III). The dashed curve shows the best-fitted 1D von Karman type ACF to the data. Vertical scale length and Hurst number are estimated to be 14 m and 0.33, respectively.](image)

Horizontal scale length can also be calculated by comparing cross-correlation graphs of two adjacent boreholes with von Karman type ACF (e.g., Wu et al., 1994). However, this method cannot be applied if the distance between the two boreholes is longer than real horizontal scale length (see Paper III).
3.4. Effects of heterogeneity on seismic imaging

The heterogeneous character of both shallow and deep crust has been studied using borehole petrophysical measurements and seismic investigations (e.g., Holliger et al., 1996, 1994, 1993; L’Heureux et al., 2009). No borehole has reached the lower crust and, therefore, the heterogeneity of the lower crust has only been predicted using synthetic models. The physical parameters entered into the models and their spatial variations are based on small outcrops of the lower crust that have been brought to surface (Holliger et al., 1994, 1993). A comparison between synthetic images with observed seismic data can reveal ambiguities in the heterogeneous nature of the lower crust and can help to improve our understanding of deep geological processes, such as the nature of active seismic zones and structural formations in the lower crust and characteristics of the Moho (Sato et al., 2012). In the shallow crust, deep boreholes have provided suitable information to study scale length and heterogeneity (e.g., Bansal et al., 2010).

Heterogeneous synthetic seismic models based on estimated scale lengths from borehole logging data can also be compared with real seismic sections to better understand the effects of survey design, source frequency and processing flow on seismic imaging (Bongajum et al., 2012; L’Heureux et al., 2009). For example, L’Heureux et al. (2009) showed that scattering in crystalline rocks with small scale-length could generate transparent seismic sections. At scale lengths similar to or longer than the seismic wavelength, scattering produces high amplitude seismic signals (reflection-like noisy signals) that can dominate seismic records and complicate the identification of the response of smaller targets. Bongajum et al. (2012) investigated the effects of steeply-dipping layers with a scale length larger in the dip direction than orthogonal to the dip direction. They showed that dip dependent scale length does not have a considerable effect on the location of seismic targets; an issue that needs to be further investigated.
4. Summary of papers

This chapter summarizes the three papers that are included in the thesis. Objectives, methodology, results and main conclusions are briefly described for each paper.

Paper I presents the results of three 2D seismic profiles that pass over the Brunswick No. 6 area and intersect each other at a few points. Processing results demonstrate the ability of the reflection seismic method to image steeply-dipping structures (shallow and deep), which show good correlation with the surface geology.

Paper II presents the 3D seismic survey over the Brunswick No. 6 area. The paper explains potential issues related to the survey design and possible improvements, which could have been considered to obtain better seismic images. Although the 3D imaging results support the results from the 2D profiles, the paper discusses some major differences between the two surveys.

Paper III investigates the effects of the heterogeneous nature of crystalline rocks on seismic imaging. The estimation of scale lengths, synthetic models generated from them and imaging of predefined targets in such models are discussed in this paper.

4.1. Paper I: Crustal-scale reflection seismic investigations in the Bathurst Mining Camp, New Brunswick, Canada

In March 2009, just one month after I joined Geophysics Program at the Department of Earth Sciences, Uppsala University, I started to process 2D seismic profiles (mainly BRN991002 and BRN991003) over the Brunswick No. 6 area. The receiver spacing and shot spacing for all three profiles were 10 m and 40 m, respectively. A CDP bin width of 5 m was used in the processing flow of all profiles. The processing flow was designed to reduce coherent and source-generated noise and enhance the S/N ratio, resulting in higher quality seismic images. Figure 4.1 shows raw and processed shot gathers from the profile BRN991002. The original field data were in the SEGD format. I converted the data to SEGY format and set up the geometry of the seismic profiles from available hard copy observer logs. The first arri-
val times were picked automatically with a neural network algorithm and the picks were edited manually. The main processing steps included: refraction static corrections, noise removal, residual static corrections (connected to velocity analysis), DMO processing (only for profile BRN991001), stacking and migration.

Figure 4.1. Example of (a) raw and (b) processed shot gathers from profile BRN991002, showing strong coherent source-generated and random noise that was reduced during the processing, resulting in enhanced reflections marked by the black arrows.

4.1.1. Summary
The main objectives of this study were:

- To correlate seismic data with available surface and borehole geological and geophysical observations.
- To provide a better understanding of the deep framework of key stratigraphic horizons and thrust faults.
- To assess the mineralization potential based on the continuity of reflections associated with key stratigraphic horizons at depth, in particular with the Brunswick horizon.
- To provide insights on large scale structures in the Brunswick No. 6 area.

Petrophysical studies from the two boreholes in the area, B-353 and B-357 (see also Malehmir and Bellefleur, 2010), indicate that the Brunswick horizon, which hosts most VHMS deposits, and its felsic host rocks (e.g., the Nepisiguit Falls Formation) and mafic/ultramafic rocks (e.g., gabbro) have the highest acoustic impedances and could generate reflections in the seismic image. Volcanic/volcanoclastic rocks of the Flat Landing Brook Formation
and metasedimentary rocks of the Miramichi Group have the lowest acoustic impedances and appear transparent in the processed seismic images. Also, measured high velocities for the Brunswick horizon and gabbro (6000-6500 m/s), which are generally steeply-dipping formations reveal even higher apparent velocity for those formations in velocity analysis.

All unmigrated and migrated stacked sections image subsurface formations down to 3 s (about 9 km depth). They show several groups of reflections that reach the surface and correlate well with the observed surface geology (see Figure 4.2).

![Figure 4.2](image)

*Figure 4.2* Unmigrated stacked section along BRN991003 which shows a series of shallow and deep reflections that dip steeply to the southwest. The surface location of FAB VHMS deposit (see Figure 1.1) is shown and may be associated with the strongest part of the P2 reflection. Dashed line shows the intersection part with profile BRN991002. See text for detailed interpretation of the events marked on the section. Geological units shown on top are introduced in Figure 1.1

A series of transparent zones are interpreted to be generated by the Flat Landing Brook Formation and the Miramichi Group, whereas a contact of transparent/reflective packages is interpreted as thrusted faults (see transparent area between P1 and P2 in Figure 4.2). All profiles show good correlation at their intersection points where it is generally possible to track the reflections from one profile to another (Figure 4.3).
Figure 4.3. Portions of unmigrated stacked sections along (a) BRN991003 and (b) BRN991002, which shows the correlation between the reflections in both profiles. See text for detailed interpretations of I1, I2, P1, and P2.

The imaged reflections can be divided into three different groups. The first group is characterized by short and high amplitude shallow reflections (e.g., R1 in Figure 4.2), which are generated by mafic/ultramafic rocks (gabbro). The second group comprises steeply-dipping reflections corresponding to the Nepisiguit Falls Formation. They extend down to about 6-7 km depth in the unmigrated stacked sections (P1 and P2 in Figure 4.2). Reflection modeling work carried out by Malehmir and Bellefleur (2010) suggests a dip of 60°-70° for these reflections. High amplitude reflections possibly generated by the Brunswick horizon are also observed in the group of reflections associated with the Nepisiguit Falls Formation along BRN991001 and BRN991003 (e.g., see reflection generated by FAB deposit in Figure 4.2). The third group includes subhorizontal reflections in the depth range of about 5-8 km (I1 and I2 in Figure 4.2). I1 and I2 are interpreted as thrusted nappes and suggest the presence of a mafic/ultramafic dominated ophiolitic slab beneath rocks of the Miramichi Group (Rogers et al., 2003). This interpretation is only based on the seismic data and needs additional geophysical and geological constraints. The deep reflections are observed in all the three profiles.

To better understand the effects of the processing flow on imaging complex structures of the study area, the geologic cross-section shown in Figure
1.2 was used to generate synthetic seismic data with an acoustic finite-difference modeling algorithm (Brenders and Pratt, 2007). One hundred synthetic shots with shot and receiver spacing of 10 m were generated along a 1.2 km long profile. The sampling rate was set to 1 ms and the processing flow was similar to that applied to the three profiles. A migrated stacked section of the synthetic data is shown in Figure 4.4. A comparison between the real and synthetic sections shows that the processing flow used to process the real data can image the contact between the major reflective/transparent geological units over the area. Also, the Stolt migration method used in the processing is able to properly image steeply-dipping reflections. However, tight folds within or at the contact between the volcanic and metasedimentary rocks are not recognized in the real data nor revealed by the processing.

![Migrated stacked section of the synthetic data superimposed on the model used to generate the data](image)

*Figure 4.4. Migrated stacked section of the synthetic data superimposed on the model used to generate the data. See text for a detailed description of the results. Geological units shown on the seismic image are introduced in Figure 1.1*

### 4.1.2. Conclusions

The processing flow chosen for the Brunswick No. 6 2D profiles demonstrate the excellent imaging capability of the poststack migration method in a crystalline rock environment. The complex geology, steeply-dipping formations and folded and faulted rocks make seismic exploration a challenge in the Brunswick No. 6 area. Nevertheless, processing of the 2D seismic profiles reveals that the Nepisiguit Falls Formation, which hosts the Brunswick horizon, can be observed as a steeply-dipping reflective package in all the three profiles and act as a key marker to map the subsurface architecture of the study area. However, it is not possible to link any high amplitude reflections of that package to the Brunswick horizon. Two sets of deep reflections
observed on the three profiles suggest the maximum depth of 5-8 km for the Brunswick belt.

4.2. Paper II: 3D imaging challenges in steeply dipping mining structures: New lights on acquisition geometry and processing from the Brunswick No. 6 seismic data, Canada

Processing of 2D profiles in the Brunswick No. 6 mine area revealed the capability of the reflection seismic method to map the key geological units in the study area. The availability of the 3D dataset over the same area encouraged me to further investigate the distribution of the main lithological units and structures at depth. I started to work on the 3D data in September 2010, after I finished writing the first paper. The non-orthogonal 3D data cover an area of about 38 km² with 15 shot lines in the south-north direction, and 28 receiver lines with an azimuth of 67° (Figure 1.3). Other geometrical properties of the 3D survey are shown in Table 1.2. A total of 1500 shots were acquired in 6 m deep holes using 0.5 kg of dynamite. Each shot was recorded using vertical component geophones distributed in 17 patches with 2367 to 3456 active channels. The maximum offset in the shot gathers was about 6.7 km. Data record length was 3 s, but I only considered the top 2 s (about 6 km) for the data processing. A processing flow similar to the one used for the 2D profiles was applied to the 3D data. About five millions first arrivals were picked with a neural network algorithm and then manually edited. Refraction static corrections, noise removal, CDP binning, residual static corrections (connected to iterative velocity analysis), DMO corrections, stacking, and migration (Stolt method) were the main processing steps. While I was expecting a much better seismic image than the 2D data, processing results using the conventional poststack migration method provided a much poorer image. The non-orthogonal nature of the Brunswick No. 6 3D data combined with the design of the patches (i.e., narrow azimuth) strongly affected the final results, which are discussed in detail in this paper.

4.2.1. Summary

The main objectives of the 3D processing over the Brunswick area were:

- To evaluate the acquisition geometry in the Brunswick No. 6 area and its effects on the seismic results.
- To demonstrate and characterize the acquisition footprint in the data.
• To process the seismic data by considering different binning scenarios.
• To use processing results to better map the subsurface architecture in the study area.

Since the survey was non-orthogonal with unequal shot and receiver lines, the distribution of trace midpoint azimuths and offsets were first evaluated (Figure 4.5). The midpoint azimuth graph suggests a northeast-to-southwest oriented distribution which is an indication of a narrow azimuth 3D survey.

![Figure 4.5.](image)

Using equation 2.7, a nominal bin size of 10-30 m was determined by considering the maximum useful frequency of 120 Hz, the maximum reflector dip of 60°-70°, and the RMS velocities of 5500-6000 m/s. Two main directions were considered for CDP bins:

• CDP bins parallel to the shot lines with inlines in the east-west direction (scenario A).
• CDP bins parallel to the receiver lines with inlines oriented northeast-to-southwest (scenario B).

To choose the optimal binning geometry, several DMO corrected unmerged stacked cubes were generated with square and rectangular CDP bins for both scenarios. The best results were obtained by using 11 m by 30 m rectangular bins of scenario A. This bin size was finally chosen for the processing. Figure 4.6 shows the CDP fold coverage of the selected binning geometry. The irregular 2D distribution of the trace midpoints is also shown in Figure 4.6 (this distribution is unique for all binning strategies in both scenarios). It can affect processing results and potentially create a significant acquisition footprint.
In general, the acquisition footprint was moderate in the shallow time-slices related to all the processed cubes in either scenario. Gulunay et al. (2006) explained that a seismic time-slice transformed to a wavenumber domain forms a spike at the coordinate $k_x = k_y = 0$ while spatial periodicity of the acquisition footprint manifests itself as spikes at non-zero coordinates (Cordesen et al., 2000). For further investigations, the trace midpoint locations were transformed into the wavenumber domain and sorted according to the offset range in each bin. Each offset range is equal to a multiple of the minimum bin dimension. The number of midpoints in each offset range of each bin was considered to obtain the amplitude spectrum. This procedure was done for all CDP bins in both scenarios. The $k_x - k_y$ spectrums of trace midpoint distributions for 11 m by 30 m and 30 m by 30 m bin geometries of scenario $A$ are shown in Figure 4.7. This figure shows potential issues with the acquisition footprint. The effect of the acquisition footprint for the bin size of 30 m by 30 m (Figure 4.7b) was interpreted to be larger than the one for the bin size of 11 m by 30 m (Figure 4.7a).
An acquisition footprint was observable in the DMO-corrected unmigrated stacked cube as short horizontal high amplitude reflections. Some studies (e.g., Gulunay et al., 2006; Marfurt et al., 1998) explained that noise generated by an acquisition footprint can be attenuated by applying a dip filter in the inline direction or time slice of 3D data transformed to the wavenumber domain. Most available geological data in the study area suggest the presence of steeply-dipping structures (Malehmir and Bellefleur, 2010). Thus, the acquisition footprint was reduced with a simple FK-dip filter that removed the horizontal events, even though this filter significantly reduced the possibility of imaging horizontal structures. The dip filter designed and applied to the Brunswick 3D data removed almost all horizontal reflections from the 3D cube, including events associated with the acquisition footprint. However, the filter did not affect the steeply-dipping reflections. The quality of the data increased considerably after the application of the dip filter (see Figure 4.8).
Figure 4.8. A portion of the DMO-corrected unmigrated stacked cube shown for inline 1106, crossline 1091, and time slice at 500 ms (a) before and (b) after application of the dip filter. See Figure 1.1 for the surface projection of the cube. See text for interpretation of the events marked as P1, P2, and I1.
Although the 3D data have lower quality than the 2D data, many reflections were imaged in the DMO-corrected unmigrated stacked cube. Many reflections reach the near surface and allow their interpretation. Results from the previous 2D interpretations were considered during the 3D interpretation. The steeply-dipping structures of the Nepisiguit Falls Formation (P1 and P2 in Figure 4.8) were imaged down to a depth of 4-5 km. Similar to the 2D results, the transparent characteristics of the Flat Landing Brook Formation and the Miramichi Group helped to delineate them. High amplitude, deep crustal reflections (I1 in Figure 4.8) are also observed. They are attributed to the ultramafic rocks located beneath the Bathurst Mining Camp (see Rogers et al., 2003). Figure 4.9 presents a comparison between the migrated stacked section along the BRN991003 2D profile and an inline from the migrated stacked cube along BRN991003. The 2D profile has a better resolution and provides clearer reflections in the shallow part of the section, whereas the 3D migration more accurately positioned the reflections of the Nepisiguit Falls Formation (as determined through better correlation with the surface geology).

![Figure 4.9](image.png)

*Figure 4.9. Comparison between (a) migrated sections along the BRN991003 2D profile (see Figure 1.1) and (b) a cross-section extracted from the migrated stacked 3D volume along the BRN991003 2D profile. See text for interpretation of P1, P2, R1, and I1. Geological units shown on top are introduced in Figure 1.1.*

**4.2.2. Conclusions**

The non-orthogonal 3D survey in the Brunswick No. 6 area is characterized by a narrow azimuth geometry and an irregular distribution of trace mid-points. CDP binning and bin orientation choice were crucial for successful data processing, which required a significant effort to test different binning geometries. Based on those tests, an optimal rectangular bin size was chosen to process the 3D data. The effects of the acquisition footprint, although inevitable, were attenuated by applying a simple FK-dip filter in the wavenumber domain. The 3D data showed lower resolution than the 2D data.
at shallow depths, but accurately imaged reflections of the Nepisiguit Falls Formations and should help to plan future explorations of this area.

4.3. Paper III: Scaling behavior and the effects of heterogeneity on shallow seismic imaging of mineral deposits: A case study from Brunswick No. 6 mining area, Canada

Seismic acquisition and processing of 2D and 3D data acquired over the Brunswick area revealed that mineral deposits are usually a challenge to image. As demonstrated previously, the field survey parameters (including source frequency) and the various steps of the conventional processing are not always optimal to image small size orebodies (not longer than several tens of meters). In this paper, I aimed to study the effects of the heterogeneity of the host rocks on the imaging of small size mineral deposits. Generating heterogeneous petrophysical models that were subsequently used to simulate and study wave propagation in such an environment accomplished this aim. Petrophysical borehole measurements in two deep boreholes in the Brunswick No. 6 area (Figure 1.1) provided direct observations to study heterogeneity effects and its scale in the study area; this research began in October 2011.

4.3.1. Summary

The main objectives of my third paper were to:

- Evaluate scaling behavior of the borehole sonic and density data and to estimate scale lengths which may statistically be representative of the heterogeneity in the study area.
- Use the estimated horizontal and vertical scale lengths for generating 2D heterogeneous models of the compressional- and shearwave velocities, as well as density in the study area.
- Study the seismic response of some specific targets with specific shapes (e.g., circle and ellipse) within the 2D heterogeneous models using 2D elastic finite-difference (FD) modeling.
- Investigate the effects of source frequency, scale length and fluctuations in the heterogeneity on imaging mineral deposits.

The autocovariance functions of density and compressional-wave velocity ($V_p$) measurements from the two boreholes in the Brunswick No. 6 area (B-353 and B-357) were compared with predefined von Karman type ACF (see equation 3.3) in 1D (along the borehole) to estimate the vertical scale length.
Since borehole B-353 is deeper (700 m) than borehole B-357 (520 m) and the sampling interval of the borehole B-353 is smaller (5 cm) than B-357 (20 cm), logging data in borehole B-353 provided more accurate estimates of the scale lengths. The estimated scale lengths and Hurst numbers from density and $Vp$ values in the borehole B-353 are shown in Table 4.1.

Table 4.1. Estimated values of the Hurst number ($\nu$) and the scale length for density, sonic $Vp$, and acoustic impedance logs from the borehole B-353.

<table>
<thead>
<tr>
<th>Property</th>
<th>Hurst number</th>
<th>Scale length (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Density</td>
<td>0.2165</td>
<td>33.6749</td>
</tr>
<tr>
<td>Sonic $Vp$</td>
<td>0.3365</td>
<td>14.0430</td>
</tr>
<tr>
<td>Acoustic impedance</td>
<td>0.4986</td>
<td>19.5914</td>
</tr>
</tbody>
</table>

Table 4.1 indicates that the vertical scale lengths estimated for density and $Vp$ (33 m and 14 m, respectively) are different. The calculated acoustic impedance graph, which is a product of density and $Vp$ values, could be a better estimator of the scale length. The estimated vertical scale length for acoustic impedance is about 20 m. Logging data in the boreholes B-353 and B-357 were used to tentatively estimate the horizontal correlation lengths. The distance between the boreholes B-353 and B-357 is about 2 km and cross-correlation of the logging data between them had a poor fit with a von Karman type ACF. This poor fit is a strong indication that the horizontal scale lengths should be shorter than the distance between the two boreholes. However, because of the absence of information (i.e., no close boreholes with logging data), the vertical and horizontal scale lengths were assumed to be the same ($a_x = a_z$) in this study.

Four models were used to study seismic scattering due to small-scale heterogeneity (Figure 4.10). Density, P- and S-wave velocities were defined for all models. A 2D von Karman type ACF and the scale length calculated from the acoustic impedance log were considered to generate both $Vp$ and density heterogeneous models that are representative of the Brunswick No. 6 area. There is no measurement of shear-wave velocities ($Vs$) in the area and $Vs$ velocity variations were considered to be 55% of $Vp$ values. The length and the depth of the models were 5 km and 2.5 km, respectively. A circular (Figure 4.10a) and an elliptical body (Figure 4.10b) were introduced in the heterogeneous background to study the impact of heterogeneity on the imaging of possible VHMS deposits.
Figure 4.10. Constructed $V_p$ models for the medium based on an average vertical and horizontal scale length of 20 m and (a) the circular target (massive sulphide), (b) the elliptical target (massive sulphide), (c) the geological section shown in Figure 1.2, and (d) the geological section in Figure 1.2, but with its own heterogeneity estimated from the log data within each individual geologic unit. The models were used to generate synthetic seismic data. The two arrows in (a) show the locations of the first and the last synthetic shots generated over the models. CDP positions are also presented for all models.

The circular target has a radius of 62 m whereas the elliptical target has a short axis equal to the radius of the circular target and the major axis 2.5 times the minor axis. The elliptical target is tilted 60° from the horizontal plane, in agreement with the general dip in the Brunswick area (Malehmir and Bellefleur, 2010). A P-wave velocity of 6600 m/s and a density of 4300 kg/m³ were assigned to the circular and elliptical bodies. These values are representative of VHMS deposits (Salisbury et al., 2003). The circular and elliptical targets, if extended to 3D, could host 4 Mt and 6 Mt VHMS mineralization, respectively. The geological cross-section through the Brunswick No. 6 mine area (see Figure 1.2) was also used to test the effects of background heterogeneity on the imaging of key lithological contacts (Figure 4.10c). Finally, the same geological cross-section with its intrinsic heterogeneity determined from the logging data in each formation was also considered in the modeling (Figure 4.10d). Table 4.2 shows the $V_p$ and density values of each formation in the cross-section. The 2D heterogeneous models (i.e., $V_p$, $V_s$ and density with identical structure/realization) were gridded using a 2 m by 2 m cell size.
Table 4.2. Average compressional-wave velocity ($V_p$) and density of various geological formations in the Brunswick No. 6 area obtained from the borehole B-353

<table>
<thead>
<tr>
<th>Lithology</th>
<th>$V_p$ (m/s)</th>
<th>Density (kg/m³)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gabbro</td>
<td>6400</td>
<td>3000</td>
</tr>
<tr>
<td>Massive sulphide</td>
<td>6600</td>
<td>4300</td>
</tr>
<tr>
<td>Nepisiguit Falls Formation</td>
<td>5650</td>
<td>2700</td>
</tr>
</tbody>
</table>

Synthetic shots were generated using an elastic finite-difference open source software available in the Seismic Unix package (Juhlin, 1995). A total of 500 vertical receivers with a 10 m interval were placed along the model. One hundred synthetic shots with a 40 m interval were placed at the surface over 4 km of the model (see the two arrows in Figure 4.10). An explosive Ricker source wavelet with a center-frequency of 70 Hz was initially considered to generate synthetic shots. The synthetic shot gathers were processed using a sequence similar to the one used for the 2D profiles in the Brunswick area. Figure 4.11 shows the DMO-corrected unmigrated and migrated stacked sections over the model with the elliptical target. Diffractions from the target in the DMO-corrected unmigrated stacked section are strong and well defined (Figure 4.11a). The migrated stacked section (Figure 4.11b) also images the target, but it could easily be misinterpreted and considered as short reflections.

Figure 4.11. (a) DMO-corrected unmigrated stacked section between CDPs 300-800 over the model shown in Figure 4.10b. The arrows on (a) mark the diffractions generated from the top and the base of the elliptical target. Scattered signals from the heterogeneous medium are also visible. (b) Migrated section of (a); the grey ellipse represents the spatial position of the elliptical target. The asymmetric diffractions (in terms of amplitude variations along the diffraction) collapse at the location of the elliptical target. The seismic signal is also observable in the migrated section, but could be misinterpreted as a short reflection. Scattered signals from the heterogeneous medium are also visible.

Figure 4.12 presents a synthetic shot gather from the geological cross-section in the heterogeneous medium (model shown in Figure 4.10c) and a real shot gather along the BRN991001. There are similarities and differences between
the real and synthetic shot gathers. Both the synthetic and real shots have relatively similar direct compressional-wave and shear-wave velocities, implying that the average velocities estimated for the medium are realistic. The main difference is the presence of strong back-scattered shear-waves in the synthetic shot. These are caused by a shear-wave propagating horizontally and intersecting heterogeneities and geological contacts at the surface of the model. The shear-waves are reflected/back-scattered at the heterogeneity/contacts. In the real data, the direct shear-wave propagates along the thick and relatively homogeneous unconsolidated sedimentary layer. This overburden layer is not present in the model.

![Figure 4.12](image)

**Figure 4.12.** (a) A raw synthetic shot gather (vertical component) from the model with the geological section shown in Figure 4.10c. Gb and Msl are the signals from the gabbro and massive sulphide formation (see Figure 4.10). (b) A raw shot gather from the BRN991001 2D profile shown in Figure 1.1; the arrows indicate the observed reflections in the shot gather. See text for details.
Further investigations were done to better understand the effects of scattering. These investigations included:

- **Longer horizontal scale length**: for a vertical scale length of 20 m and aspect ratios $\frac{a_x}{a_z}$ of 4, 7, and 70, additional synthetic models were generated with source and receiver characteristics similar to the model shown in Figure 4.10b. The modeling results showed that diffractions are still distinguishable in the DMO-corrected unmigrated stacked sections, but the migrated sections show slight mis-locations of the target with longer horizontal scale lengths.

- **Shorter scale length**: the estimated scale length of 20 m represents the maximum length at which the medium shows a power law. However, this scale length may not entirely characterize the stochastic environment in the Brunswick No. 6 area. Thus, a model with a scale length of $a_x = a_z = 10$ m was generated, while the other constraining parameters were kept similar to the model shown in Figure 4.10b. The diffraction obtained for the model with shorter scale length was weaker (Figure 4.13), which conflicts with the concept that shorter scale lengths tend to be similar to a homogeneous medium (Wu and Aki, 1988).

![Figure 4.13. DMO-corrected unmigrated stacked sections of the models shown in Figure 4.10b using (a) $a_x = a_z = 10$ m and (b) $a_x = a_z = 20$ m. The model shown in (a) generates strong scattering as illustrated by the RMS amplitudes calculated for a window between 0 ms to 320 ms (see inset figures in (a) and (b)). See text for detailed discussion about the modeling results.](image-url)

To investigate the effects of the shorter scale length, the RMS amplitudes of the unmigrated stacked sections above the target (between 0 ms to 320 ms) for both models were calculated (Figure 4.13). The 10 m scale length model generates higher scattering amplitudes in comparison with the 20 m scale length model. This difference is ex-
plained by the statistical assumptions used to construct of the heterogeneous models. Both models assumed a Gaussian distribution for the petrophysical properties. This assumption implies that the mean and standard deviation are kept fixed for the 10 m and 20 m models. As a result, a larger number of stronger scatterers are generated (Figure 4.10b) to maintain this distribution when smaller scale lengths are used in the models. This implies that the observed scattering for the smaller scale length is overestimated. Future studies, which aim to investigate the effect of scale length, should preserve the relative strength of the heterogeneity versus background (for different scale lengths). Nevertheless, it is worthwhile to mention that the scattering from heterogeneity in the two models presented here does not entirely mask the target response on the DMO-corrected unmigrated stacked sections, a point that is the main focus of this paper.

- **Effect of source frequency:** the synthetic data generated for the model shown in Figure 4.10b used a Ricker wavelet with a dominant frequency of 70 Hz. Other synthetic models with source frequencies of 50 and 90 Hz were also generated for that model. The results showed that increasing source frequency results in better diffraction imaging.

- **Effect of heterogeneity fluctuations:** the model shown in Figure 4.10b is based on acoustic impedance fluctuations of one standard deviation ($\sigma_{im}$). Modeling results for a new model with fluctuations of $1.5\sigma_{im}$ shows more seismic scattering and a weaker signal from the elliptical target. Higher fluctuations (e.g., $2\sigma_{im}$ or $3\sigma_{im}$) were not considered because they generate velocities above 7000 m/s, which are unlikely in this geological environment.

4.3.2. Conclusions

Seismic modeling studies based on the scale length of 20 m estimated from the calculated acoustic impedance log demonstrate that the effective imaging of small geological targets, such as massive sulphide deposits, can be challenging even in this theoretically weak scattering regime and especially on migrated stacked sections. Diffraction signals from the massive sulphide deposits are visually easier to identify in the unmigrated stacked sections, implying that data analysis should focus on the unmigrated stacked sections and prestack data rather than the migrated stacked sections alone. Tests conducted for heterogeneous models, with different scatterer aspect ratios and horizontal scale lengths much larger than the vertical scale length, showed that the heterogeneous medium could generate coherent noise in the form of high amplitude signals that mask the imaging of mineral deposits. Further-
more, it could also result in slight mis-location of the target if isotropic processing methods are used. The seismic image from the model with scale length smaller than the maximum fractal dimension (20 m) showed stronger scattering and a weaker diffraction signal. Source-frequency tests (frequency range of 50-90 Hz) over the lenticular models indicate that lower frequencies introduce more scattering into the seismic image and could mask the target response. Also, comparisons of models with different standard deviations for the acoustic impedance fluctuations showed that increasing the standard deviation causes more scattering in the model, which increases to a point at which the diffraction signal from the target can be difficult to observe.
5. Conclusions

After more than 20 years of applications, reflection seismic methods for mineral exploration in areas dominated by crystalline rock are still at an early development stage and not routinely used by the industry. There are various challenges that cause the methods to perform differently in different geological environments. Typically, rocks in a crystalline environment are highly deformed and metamorphosed and often have been subject to several stages of faulting and folding. Low S/N ratio is characteristic for most crystalline environments and this fact is accepted by many researchers. Despite this complexity, the seismic methods still have the potential to distinguish mineral deposits with sizes not longer than one seismic wavelength. This potential can be fulfilled with suitable survey design and acquisition parameters followed by a processing sequence tailored to image mineral deposits at depth. Information about the surface geology, petrophysical borehole measurements and a better understanding of the medium hosting mineral deposits are also necessary to improve survey design and seismic data processing towards successful orebody imaging. Such information, when combined with numerical modeling, can also be used to investigate the response of an orebody, and the effects of scaling behavior and scattering of heterogeneity, on seismic data, thus validating our perception on the ability to image mineral deposits at depth.

Paper I presents an example of the application of 2D seismic surveying for shallow and deep regional mineral exploration in the Brunswick No. 6, Bathurst Mining Camp, Canada. A prestack DMO and poststack migration algorithm was able to image structures from near surface down to a depth of 9 km. Available petrophysical data helped to obtain better velocity models for stacking and migration whereas good correlation between the seismic sections and surface geology further helped to constrain the interpretations. Reflections observed at intersection points of the 2D profiles also provided regional constraints on the attitudes of the main structures. In particular, the sequence between reflective/transparent formations was interpreted as thrusted faults that are mapped at the surface. The steeply-dipping reflective package of the Nepisiguit Falls Formation comprises the highly prospective Brunswick horizon which cannot be specifically identified within the group of reflections. However, the entire package can be used to guide exploration in this area of the camp. Most of the steeply-dipping reflections in this area were mapped down to a depth of 6-7 km. This is also the suggested thickness
for the rocks of the Brunswick mining camp. This interpretation requires additional geophysical and geological constraints.

Paper II focuses on the Brunswick No. 6 3D survey and the effects of survey design on seismic imaging. The CDP bin design was crucial for DMO corrections and alias-free migration. Several bin sizes were considered and tested, and the best binning design was chosen according to visual criteria on DMO-corrected unmigrated stacked cubes. The non-orthogonal survey geometry and the design and acquisition of each receiver patch caused irregular seismic sampling. The irregularly sampled seismic data generated an acquisition footprint that masked the imaging of the real structures. The acquisition footprint noise is characterized by short horizontal reflections compared with the generally steeply-dipping reflections associated with the main geological structures in this area. This criterion was considered to separate signal and the processing artifacts (i.e., the acquisition footprint) in the wavenumber domain. An FK-dip filter was designed to reduce the acquisition footprint. Although the 3D data were of lower quality than the 2D data, the package of reflections associated with the Nepisiguit Falls Formation was successfully imaged. This formation hosts most major VHMS deposits in the Brunswick No. 6 area.

Heterogeneity and scaling behavior in crystalline rocks was investigated in paper III. A von Karman autocorrelation function was used to estimate the vertical scale length from petrophysical logging data available in two boreholes. The cross-correlation of $V_p$ measurements between the two boreholes did not show any von Karman characteristics, which indicates a horizontal scale length less than the distance between the boreholes. Due to a lack of information, the horizontal scale length was considered to be equal to the vertical scale length and heterogeneous models were generated based on $V_p$, $V_s$ and density random medium functions. Synthetic seismic data in these models showed that, even with an assumption of isotropic media (equal horizontal and vertical scale lengths) and weak scattering regime, scattered waves from the simulated heterogeneous medium could cause misinterpretation on the migrated stacked images. Models with longer horizontal scale length than the vertical scale generated reflection-like signals in the synthetic seismic image, which distorted the seismic response from small but economic mineral deposits. Also, synthetic models with a scale length shorter than the one estimated with the von Karman ACF provided weaker diffractions from the targets. The predefined Gaussian distribution of physical properties and larger number of small size scatterers could explain the weaker diffraction observed for the shorter scale lengths. The investigation of frequency bandwidth in 50-90 Hz range showed that higher source central frequency increases the S/N ratio and produces stronger diffraction image.
5.1. Future work

2D and 3D processing of seismic data in the Brunswick No. 6 area provided new examples of the application of seismic methods for mineral exploration in the crystalline environment. The processing approach was fairly conventional and included prestack DMO corrections and poststack migration. Further investigations could consider the application of prestack time migration (PSTM) to both the 2D and 3D data. However, prestack migration methods require a precise velocity model which, given the complex geology, could be challenging to obtain. Traveltime tomography may be useful to provide such a detailed velocity model, at least for the shallow depths. Application of PSTM with a tomography velocity model may reveal more details at shallow depths.

It was mentioned that the irregular trace distribution of the 3D data resulted in an acquisition footprint after the DMO processing. The application of an FK-dip filter in the wavenumber domain (inline direction) reduced the effects of the acquisition footprint. Another way to reduce the acquisition footprint noise is to transform each time slice of the DMO-corrected unmigrated stacked cube to the wavenumber domain and mute the acquisition footprint. Such an approach was not attempted in this thesis. Trace interpolation methods, which are normally used in the sedimentary environment to account with irregularly sampled data, could also be tested for the Brunswick No. 6 3D data.

Scattering of seismic waves was studied in 2D synthetic models and only the vertical component of scattered/reflected waves was simulated. Further studies should consider three-component (3C) receivers along models. Also 3D synthetic models could also be useful to better understand wave propagation in the crystalline environment and improve survey design, optimize seismic source parameters and refine the processing flow.
Bathurst Mining Camp är ett av de viktigaste gruvområdena för produktion av basmetaller i Kanada. Brunswick nr. 6 tillhör Bathurst Mining Camp och ligger ca 27 km sydväst om staden Bathurst i provinsen New Brunswick. För att hitta nya mineraliseringar har 30 km 2D seismik (tre profiler) och 38 km 3D seismik mätts i området. Petrofysiska egenskaper (hastighet av kompressionsvåg och densitet) har också mätts i två djupa borrhål (B-353 och B-357, se Figur 1.1). Det är en utmaning att använda seismiska metoder för den komplexa kristallina geologin i Brunswick nr. 6. De seismiska undersökningarna visar geologin på djupet i Brunswick nr. 6 och avslöjar några områden som bör undersökas i mer detalj.

Totalt 772 skott med explosiv källa avfyrades längs 2D profilerna, för varje skott användes 0.5 kg dynamit placerat i 6 meter djupa borrhål. Skotten utfördes med 40 meters avstånd längs profilerna. Mottagare, geofoner, var placerade med 10 meters avstånd. Maximalt avstånd mellan källa och mottagare var cirka 4.5 km. Data spelades in under 3 s, vilket motsvarar cirka 9 km djup, och hela inspelningstiden användes för processering. Den konventionella processeringen av 2D profiler var: geometri, plockning av förstaankomster med en neural nätverksalgoritm och efterföljande manuell kontroll, refraktionsförskjutning, borttagande av koherent brus (t ex skjuv-vågor och mark-vågor), residualförskjutning (kopplat till hastighetsanalys, DMO korrigering, stackning och migrering (Stolt metod)). Processeringen av 2D data avslöjade ytnära och djupa reflektioner som korrelerar till geologin på markytan. En sekvens av omväxlande reflektivt och transparant berg längs alla tre profiler tolkades som överskjutningssförkastningar. Även brant stående reflektioner som kan vara mineraliserade kunde avbildas ner till 6-7 km djup. Två andra uppsättningar av reflektioner på 5-8 km djup observerades i alla tre profiler. De tolkades som överskjutningsskollor, vilket kan indikera att Brunswick-bältet går ner till ett djup av maximalt 8 km djup.

För 3D mätningarna gjordes totalt 1500 skott. Liksom för 2D användes 0.5 kg dynamit i 6 m djupa borrhål. Varje skott spelades in med vertikal-komponent-geofoner som var distribuerade i 17 grupper med mellan 2367 och 3456 aktiva kanaler. Maximalt avstånd mellan källa och mottagare var 6.7 km. Data spelades in i 3 s men bara de första 2 s (cirka 6 km) användes för processering. Processeringen liknar den ovan beskrivna för 2D profilerna. Cirka fem miljoner första-ankomster plockades med neural nätverksalgorithm följd av manuell kontroll. Huvudstegen i processeringen var refraktions-

2D och 3D processering av Brunswick nr. 6 visar att heterogenitet kan påverka den seismiska bilden och förvränga utseendet av målet. Tillgänglig petrofysisk data från borrhål ger en god möjlighet att avslöja heterogenitet i 1D (Z riktning) i området. Eftersom B-353 är djupare än B-357 (700 m respektive 520 m) och mätningsintervallt var mindre (5 cm respektive 20 cm) ger detta borrhål mer exakt uppskattning av skallängden. Den vertikala skallängden uppskattades genom att jämföra autokovariancefunktionen av den uppskattade akustiska impedans-loggen med von Karmans autokorrelationsfunktion. Den uppskattade vertikala skallängden är cirka 20 m. Det 2D heterogena mediet beräknades genom att anta att skallängden i vertikal och horisontell riktning var lika (20 m). Vågutbredning och spridning av seismiska vågor i detta medium studerades med numerisk modellering för cirkulära och linsformade strukturer, men också för en geologisk profil, dvs. för en representativ komplex geologi i det studerade området. Syntetiska seismiska bilder visar att diffraktion av cirkulära och linsformade kroppar kan observeras i DMO-korrigerade stackade profiler, men spridningseffekter kan dölja seismiska signaler i migrerade stackade profiler. Dessutom visar syntetiska modeller med längre horisontal än vertikal skallängd att spridda vågor från simulerade heterogena medium kan orsaka feltolkning av migrerade stackade bilder. Undersökning av frekvenser i intervallen 50-90 Hz visade att högre frekvens från källan ökade signal/brus förhållanden och producerar starkare diffraktioner i bilderna.
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