Extracting 3D Information from 2D Crooked Line Seismic Data on Hardrock Environments

JOHIRIS ISABEL RODRIGUEZ TABLANTE
Dissertation presented at Uppsala University to be publicly examined in Axel Hambergsalen, Geocentrum, Uppsala, Friday, March 24, 2006 at 10:00 for the degree of Doctor of Philosophy. The examination will be conducted in English.

Abstract

Seismic methods have been used in sedimentary environment for almost 80 years. During that time, exploration geophysicists have developed a number of techniques to handle specific aspects of working in sedimentary areas. This is not the case for studies in the hardrock environment, where significantly less time and money have been invested on seismic investigations. Therefore, there is still a need to develop the right techniques appropriate for working in hardrock environments. The research presented here, covers aspects of acquisition, processing and interpretation in hardrock environments. A cost-effective alternative for two-dimensional data acquisition is presented. Acquisition parameters are also discussed and recommendations for future work are given. The main effort of this thesis, however, was to find appropriate processing methods to address some of the different problems present in datasets acquired in the hardrock environment. Comparison of two computer programs for first arrival seismic tomography was performed in order to find the most suitable one for processing crooked line geometries. Three-dimensional pre-stack depth migration was also tested to find a detailed near-surface image. A processing method geared to enhance the signal-to-noise ratio was applied to the dataset with the lowest signal amplitudes to improve the quality of the stack. Finally, cross-dip analysis and corrections were performed on two of the three datasets included in this thesis. Cross-dip analysis was also applied as an interpretation tool to provide the information needed for estimation of the true dip of some of the reflectors related to geological structures. The results presented in this thesis indicate that cross-dip analysis and corrections are one of the most powerful tools for processing and interpretation in the presence of complex geology. Therefore, it is recommended to include this method as a standard step in the processing and interpretation sequence of data acquired in hardrock environments.

Keywords: Hardrock Environment, Crooked line, Reflection Seismics, signal-to-noise, cross-dip, cross-profile

Johiris Isabel Rodriguez Tablante, Department of Earth Sciences, Villav. 16, Uppsala University, SE-75236 Uppsala, Sweden

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To Jose Luis, Isabel and Johana
List of Papers

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

I  Johiris Rodriguez-Tablante, Christopher Juhlin and Björn Bergman. *First Arrival Seismic Tomography (FAST) vs. PSTomo_eq applied to crooked line seismic data from the Siljan ring area*. Accepted for publication in *Computers and Geosciences*.


Elsevier kindly gave permission to reprint paper I
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<tr>
<td>1D</td>
<td>One-dimensional</td>
</tr>
<tr>
<td>2D</td>
<td>Two-dimensional</td>
</tr>
<tr>
<td>3D</td>
<td>Three-dimensional</td>
</tr>
<tr>
<td>CDP</td>
<td>Common Data Point</td>
</tr>
<tr>
<td>CMP</td>
<td>Common Mid-Point</td>
</tr>
<tr>
<td>dB</td>
<td>Decibel</td>
</tr>
<tr>
<td>FAST</td>
<td>First Arrival Seismic Tomography</td>
</tr>
<tr>
<td>Hz</td>
<td>Hertz</td>
</tr>
<tr>
<td>kg</td>
<td>Kilogram</td>
</tr>
<tr>
<td>km</td>
<td>Kilometer</td>
</tr>
<tr>
<td>LSQR</td>
<td>Least squares regularization</td>
</tr>
<tr>
<td>m</td>
<td>Meter</td>
</tr>
<tr>
<td>Moho</td>
<td>Mohorovicic discontinuity</td>
</tr>
<tr>
<td>ms</td>
<td>Millisecond</td>
</tr>
<tr>
<td>Mt</td>
<td>Megaton</td>
</tr>
<tr>
<td>NMO</td>
<td>Normal moveout</td>
</tr>
<tr>
<td>RMS</td>
<td>Root mean square</td>
</tr>
<tr>
<td>s</td>
<td>Second</td>
</tr>
<tr>
<td>S/N</td>
<td>Signal-to-noise</td>
</tr>
<tr>
<td>VHMS</td>
<td>Volcanic-hosted massive sulfide</td>
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</table>
Introduction

Reflection seismics is one of the most powerful geophysical methods available. It has been used by the oil industry for almost 80 years for both exploration and exploitation of sedimentary areas. Its strength lies in its capability to image geological structures at depth. The long history of applying seismic methods in the sedimentary environment has given geophysicists sufficient opportunities to develop efficient acquisition, processing and interpretation methods appropriate to a variety of targets. This is not the case in hardrock environments, where considerably less time and money have been devoted to seismic studies (Eaton, 2003).

There is a clear difference between working in sedimentary areas and in crystalline rocks. Hardrock environments normally involve complicated geological history with a great variety of deformation, steeply dipping structures and generally high P wave seismic velocities with mostly weak impedance contrasts (Salisbury, 2003). Thus, there is a need to find appropriate acquisition parameters and specialized processing methods to deal with these data sets that may often have low signal-to-noise ratios.

This thesis presents research from hardrock environments with the goal of finding cost effective acquisition and appropriate processing methods relevant for geological interpretation. Although some theoretical aspects are discussed, the main aim of the thesis is to present practical results that can be used as reference for future work in areas with similar characteristics.

The first chapter considers the subject of acquisition geometry, starting with history and continuing with practical matters related to acquisition, processing and interpretations of surveys with different geometries. The second chapter summarizes information about the datasets used for this thesis. The third chapter describes the main processing tools used for working with the different datasets to address imaging problems due to geometry and geological characteristics of the areas. The fourth chapter consists of summaries of the four papers included in this thesis. The thesis concludes with the fifth chapter, which gives the final observations and recommendations resulting from this work.
1. Seismic surveys

History

Seismic surveys have been carried out for oil-related studies since the 1920’s (Sheriff and Gerald, 1999). The first surveys consisted of single-geophone, single-fold data acquired with a limited number of channels (Dragoset, 2005). At that time, the survey design was subordinated to the equipment rather than the acquisition geometry and the geophone spacing. Later, with the gradual inclusion of more channels, more attention was paid to the geometry of the survey and geophone station interval. Already in the 1960’s, survey design included source offset from the receiver line, crooked lines, transpose shooting and obstacle compensation (Stone, 1994). However, it was in the late 1960’s that the major innovation in seismic acquisition happened as result of different factors. On one hand, the advances in technology and introduction of digital recording and processing made it possible to acquire and process a larger amount of data, and on the other, the development of the common midpoint (CMP) acquisition method revolutionized the way seismic surveys were acquired and processed (Dragoset, 2005). Until the 1980’s, most of the seismic surveys were acquired as two-dimensional (2D) profiles, but a new significant increase in computer power made it possible for the oil companies to include three-dimensional (3D) acquisition and processing as standard methods (Dragoset, 2005).

Although a few attempts were made in the past, it was not until recent decades that reflection seismic methods started to be used for engineering purposes and mineral exploration, besides those for oil and coal (Salisbury, 2003). Up to now, most of the studies done on the hardrock environment have been acquired using 2D geometries. Few non-hydrocarbon 3D seismic surveys have been reported in the literature. The main reason for this is the relatively high cost of the 3D seismic method and the lack of detailed understanding of the relevant physical properties of the crystalline rocks (Eaton, 2003).

A long history of seismic acquisition in the sedimentary environment coupled with drilling has given the oil industry sufficient knowledge for carrying out successful 2D and 3D seismic investigations. In contrast, the history of seismic surveys in crystalline rocks is more recent, and therefore, there is still effort needed to develop the correct techniques to deal with problems typical from these environments. These developments are needed
at all stages of the seismic work from finding optimum acquisition parameters to finding processing techniques that lead to better data interpretation. Therefore, the future of hardrock seismic investigation presents many challenges that need to be addressed for these specific environments.

Practical matters

Acquisition, processing and interpretation are the basic components of a seismic survey. The success of a study depends on the proper accomplishment of each of these components. A clever processor cannot overcome deficiencies in acquisition, as no interpreter can see beyond the information the data offer.

Survey types can be compared by considering their implications in each of these three stages.

Two-Dimensional Surveys

2D data are acquired along straight lines that typically consist of both sources and receivers. 2D line design is rather simple, to a point that many senior geophysicists say that it can be drawn on the back of an envelope (Stone, 1994). The acquisition of 2D data is relatively fast and simple, but it may be limited by obstacles and accessibility. Acquisition along straight lines in areas with difficult access often requires building new paths or roads. Even today, tracks made years ago through forests, swamps, tundra and deserts are evident (Sheriff and Gerald, 1999). This way of acquisition can be costly, not just economically, but also environmentally. Processing of 2D straight-line seismic data is simple and fast compared to data with other acquisition geometries.

The main disadvantage of 2D data arises in the migration and interpretation stage (Yilmaz, 1987). 2D sections are cross sections of a 3D seismic response. They include signal coming from all directions, including out-of-plane signal. 2D migration assumes that all the energy comes from the vertical plane of the line, and thus, out-of-plane signals often cause 2D migrated sections to contain false images of the subsurface (Yilmaz, 1987). Dipping events on migrated sections will not tie at crossing profiles. The direction of the profile is crucial when imaging dipping structures (Yilmaz, 1987). Figure 1 shows the situation of a dipping plane interface in a homogeneous medium and 2D lines acquired in different directions. As it can be seen, Line 1 runs in the direction of the true dip giving an accurate image of the interface. Line 2 runs in a direction oblique to the true dip. The resulting stack after migration will misplace the reflection points by moving them along Line 2 when they are actually out-of-the-plane reflections. The stack also shows the
interface with less dip than the true dip. Finally, the third possibility is shown in Line 3, which runs parallel to the strike of the plane. The stacked section resulting from this line shows a continuous horizontal reflection. Clearly, these last two sections are misleading for interpretation.

Figure 1: A) A subsurface model consisting of a dipping plane interface. Line 1 runs in the direction of the true dip, Line 2 runs in direction oblique to the true dip and Line 3 runs in the strike direction B) Simplified plots of the resulting stacks after migration along the three lines. Note that the angle $\phi$ in Line 2 is smaller than $\phi$, the true angle imaged along Line 1. No dip is detected on Line 3
Three-Dimensional Surveys

Complete spatial images are only obtained by 3D surveys (Yilmaz, 1987). 3D surveys are geared to uniform sampling over an area rather than along lines. Acquisition is more complex and usually requires careful planning for obtaining optimal fold, offset and azimuthal distribution of the data (Stone, 1995). The acquisition can be carried out in a number of ways. Typically, source lines will cross a number of parallel receiver lines. Logistics of 3D surveys demand a higher level of organization, larger crew size, and certainly, lead to higher expenses than 2D surface seismic studies.

Apart from migration, processing of 3D seismic data is not very different from that of 2D processing (Sheriff and Gerald, 1999). Nevertheless, it requires more careful application of geometry and CDP binning to ensure accurate processing of the data. Migration is the main factor in improving the signal-to-noise ratio and interpretability of 3D versus 2D data (Yilmaz, 1987). Due to the completeness of the data by spatial sampling at different azimuths, 3D migration eliminates the location uncertainties present in 2D data by completing the imaging process (Yilmaz, 1987). Figure 2 based on Sheriff and Gerald (1999), sketches the steps for one 3D migration method.

Figure 2: Schematic plot of 3D post-stack migration. The data to be migrated lie on a hyperboloid appropriate to the stacking velocity $V_s$. The migration is normally done in two steps, 2D migration in the $y$-direction moves data from $a$ to $b$, sorting and doing a second 2D migration in the $x$-direction moves data from $b$ to $t_0$. (Based on Sheriff and Gerald, 1999)
It is widely accepted that 3D surveys result in clearer and more accurate images of the subsurface that lead to better geological interpretations (Sheriff and Gerald, 1999). Hence, from the geophysical point of view they are preferable over other forms of seismic surveys. Unfortunately, economics are still restricting 3D investigations to studies that have high budgets.

Studies along Crooked Lines

Acquisition along crooked lines is a variation on the traditional 2D survey. It is when 2D lines are not straight. Lines are acquired with a crooked geometry mainly due to logistical reasons. Due to accessibility, it is much faster, simpler and less costly to acquire profiles along existing roads. Various obstacles may make it impossible to locate lines along desired locations. However, crooked lines can also give information for answering a specific geological question. Since the midpoint locations are spread over an area, they contain information about structural dip perpendicular to the acquisition line. Thus, sometimes lines are intentionally designed to be crooked to give cross-dip information (Sheriff and Gerald, 1999).

From the processing point of view, crooked lines require more specialized processing than 2D straight lines. More attention needs to be paid to the geometry, selection of stacking lines and binning of the data. One aim in the processing is to maintain a constant fold along the stack (Wu et al., 1995).

Many interpretation criteria, such as changes in dip, become more difficult to use when line direction changes (Sheriff and Gerald, 1999). However, by allowing cross-dip information to be obtained, crooked lines give more tools for structural interpretation than standard 2D straight lines. By combining in-line dip and cross-dip, it is possible to estimate the true dip and strike of an interface.
2. Datasets used for this thesis

Three different datasets were used for the studies presented in this thesis (Figure 3)

Paper I used data acquired in the Siljan Ring impact area, in central Sweden (JuHLin & Pedersen, 1987). It consists of first break traveltimes from two of the deep seismic profiles in the area, Line 5 (to the south) and Line 7 (to the north). These profiles were part of a study aimed at imaging the subsurface geometry of the impact structure. Line 7 was shot as “end-on” whereas Line 5 was shot as “split-spread”. There is also a difference in the maximum offsets between shot and receivers for these two profiles (Table 1). The northern line has about twice the maximum offset of the southern line. The charge size was between 5-10 kg, and all shots were detonated in iron-cased holes located mostly (96%) at or below the till-bedrock interface, resulting in high-quality data with a good signal-to-noise ratio. A subset of the data from these two profiles was chosen for the study presented in Paper I. The chosen data correspond to the part where both profiles overlap each other, forming a crooked line running in the north-south direction of approximately 8 km length. It crosses lithological boundaries, fracture systems and dike intrusions (Figure 3), which makes it a representative case for the geology in hardrock environments and an ideal dataset to test the resolution capacity of first break tomography. We used 70 shots and 253 geophones that produced 4701 travelt ime observations with maximum offsets of 4500 m.

Paper II used data acquired in the Luleå area, in northern Sweden (JuHLin et al., 2002). The aim of this pilot profile was to tie the marine BABEL results (BABEL Working Group, 1993) with onshore surface geology and obtain detailed images of the uppermost crust. Therefore, the acquisition parameters were geared to image both the upper few kilometers of crust, as well as depths down to Moho. The profile consisted of two small-charge higher-resolution shallow components towards both ends of the profile and an overlapping larger-charge lower-resolution deep component. It had 30 km of subsurface coverage and it was acquired along 2D crooked line geometry. The acquisition parameters are given in Table 1.

For the study presented in Paper II, the entire dataset was used for the tomography and we concentrated on the two sections of high-resolution shallow component data for the pre-stack migration.
Figure 3: Location map of the seismic lines used in this thesis. Paper number and reference location area are indicated.
Paper III used data from two nearly parallel profiles, Profile 1 and Profile 5, acquired in the western part of the Skellefte District, in northern Sweden. Many of the acquisition parameters used for the Skellefte profiles were based on the Luleå Profile, as seen in Table 1. Both profiles have an approximate length of 25 km and run in the north-south direction with a separation of about 8 km (Figure 3). The aim for the acquisition of these lines was to produce images of the subsurface structural architecture of the Skellefte District in the area of the Kristineberg mine. The results of this project are currently being used for building a 3D geological model of the area with the aim of identifying potential prospecting locations for mineral exploration. The location of the profiles was chosen so that most of the structures imaged on the surface geological map were crossed perpendicularly. The receiver spacing was 25 m and nominal shot spacing was 100 m. The charge size was between 1-3 kg. Both lines consisted of shot and receiver points and were acquired simultaneously by the use of two different recording systems (Table 1). Thus, each shot was recorded along both lines at the same time, resulting in three subsets of data; 2D data shot and recorded along Profile 1 and Profile 5 and a third data set, the Cross-profile, corresponding to the data produced by shooting on one line and recording along the other line (Figure 3). The data along Profile 1 was recorded using arrays of six geophones with a natural frequency of 10 Hz, while along Profile 5 single geophones with a natural frequency of 28 Hz were used. Due to the different capacities of the acquisition systems, both lines also differed in the number of channels. Shots were recorded on 140 channels along Profile 1 and 200 channels along Profile 5.

Paper IV presents the image obtained after processing the Cross-profile dataset, produced by the simultaneous shooting and recording of the sub-parallel profiles. Fan-shooting is the term used to describe recording done along a 2D line with the source points offset from the recording line. Data were acquired in this way to take advantage of the two recording systems that Uppsala University had at the time. Thus, it was possible to acquire both profiles in shorter time than if they had been acquired sequentially and obtain the extra dataset, the Cross-profile, without any additional cost to the project. This strategy resulted in a higher amount of information and coverage of the area at lower cost.

Since the acquisition of the Profiles 1 and 5 was done following roads, the lines are crooked. Paper IV also includes cross-dip analysis of the data recorded along these profiles.
<table>
<thead>
<tr>
<th>Parameters</th>
<th>Siljan North part</th>
<th>Siljan South part</th>
<th>Luleå Shallow</th>
<th>Profile 1 Skellefte</th>
<th>Profile 5 Skellefte</th>
<th>Cross-Profile Skellefte</th>
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</thead>
<tbody>
<tr>
<td>Type of survey</td>
<td>2D Crooked</td>
<td>2D Crooked</td>
<td>2D Crooked</td>
<td>2D Crooked</td>
<td>2D Crooked</td>
<td>Fan shooting</td>
</tr>
<tr>
<td>Recording system</td>
<td>SERCEL 348</td>
<td>SERCEL 348</td>
<td>SERCEL 348</td>
<td>SERCEL 348</td>
<td>SERCEL 408</td>
<td>SERCEL 348 &amp; 408</td>
</tr>
<tr>
<td>Spread</td>
<td>End on</td>
<td>Split</td>
<td>End on/shoot through</td>
<td>Split</td>
<td>Split</td>
<td>Split</td>
</tr>
<tr>
<td>Number of channels</td>
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<td>96</td>
<td>~200</td>
<td>140</td>
<td>200</td>
<td>140 &amp; 200</td>
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<td>Geophone</td>
<td>Single 28 Hz</td>
<td>Single 28 Hz</td>
<td>Bunch of six 10 Hz</td>
<td>Bunch of six 10 Hz</td>
<td>Single 28 Hz</td>
<td>Bunch of six 10 Hz &amp; Single 28 Hz</td>
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<td>Receiver interval</td>
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<td>50 m</td>
<td>25 m</td>
<td>25 m</td>
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<td>25 m</td>
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<tr>
<td>Nominal fold</td>
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<td>12</td>
<td>25</td>
<td>17</td>
<td>25</td>
<td>35</td>
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<td>Shot spacing</td>
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<td>200</td>
<td>100</td>
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<tr>
<td>Charge size</td>
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<td>1-3 kg</td>
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<td>20 s</td>
</tr>
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</table>
3. Processing of crooked line data in hardrock environments

All three dataset used for this thesis were acquired along crooked lines in hardrock environments. Thus, the challenges of working with these datasets are of two kinds: first, the specific implications of the acquisition geometry for processing and interpretation, and second, the difficulties related with the geological setting, as explained in the introduction.

This chapter gives a short description of the most specialized processing methods I applied for working with the different datasets used in this thesis.

First Arrival Seismic Tomography

Seismic traveltime tomography is presently one of the most used methods for calculating velocity fields. It is a nonlinear inversion problem that estimates a velocity model from traveltimes, which are calculated from ray paths that depend on the velocity model. Traveltime $t$ for one source-receiver pair ray can be expressed by the non-linear line integral.

$$t = \int_{l(s(r))} s(r) dl$$

Where $s(r)$ is the slowness, $dl$ is the differential length and $l$ is the ray path, which is a function of $s(r)$.

There are two main steps in seismic tomography, the forward modeling and the solution of the inverse problem. There are different methods to accomplish both steps, but I will describe those used for the studies done in this thesis.

Forward Modeling

To propagate the traveltime field through a 3D gridded velocity model, the programs used in this thesis use a finite difference approximation to the eikonal equation of ray tracing.
where $t$ is traveltime and $s$ is the slowness (inverse of velocity) of the media. Traveltimes are calculated progressively away from a source on the sides of an expanding cube, completing one side at a time. From the traveltime field, the ray paths may be calculated.

A number of studies (e.g. Vidale, 1988; Vidale, 1990; Podvin and La­comte, 1991; Hole and Zelt, 1995) are based on this method. However, some algorithms fail to handle large, sharp velocity contrasts, as problems are encountered where the wavefronts travel as head waves at a contrast inter­face. The Vidale (1988, 1990) schemes did not handle this problem. The Hole and Zelt (1995) code is a modification of Vidale’s (1988, 1990) algo­rithms and includes head wave operators and reverse propagation using a wall source initiated on one edge of the cube to handle this problem. To in­crease the speed and improve efficiency they also included a sorting tech­nique (Press et al., 1992), which tracks the shape of the wavefronts. In this scheme the sides of the expanding cube are timed in order; starting with the face containing the node with the smallest time value and continuing pro­gressively to that with the highest time node. In this way, fewer head wave operators and reverse propagations are needed.

Constant velocity is assumed in every cell. The velocity in a cell is formed as an average value of the velocities of the nodes defining the cell.

Inverse problem
The inverse problem is solved iteratively by LSQR, which is a conjugate gradient method, based on the Lanczos bidiagonalization process (Paige and Saun­ders, 1982). Regularization is a method to solve mixed-determined problems by applying constraints on the model, in addition to using the data. These constraints require that the final model satisfy some property or condi­tions. Commonly, we look for models containing “minimum structures”, i.e. the simplest model that fits the data according to the noise level (Scales et al., 1990). Minimum structure can be measured in terms of model flatness, i.e., the first spatial derivative, or model roughness, i.e., the second spatial derivative. Thus, the objective function to be minimized in each iteration has the general form:

$$\lambda (m) = E + \lambda \mathbf{L}$$

(3)
where $E$ is the prediction error, $\beta$ is the trade-off parameter and $L$ is the solution “length” (Menke, 1984).

An important step in all tomographic sequences is building the initial model, since it highly influences the resulting velocity fields after inversion. This step requires some trial and error to find an initial velocity field that results in traveltimes “close” to those observed in the dataset.

First arrival tomography was the subject of Paper I and was used as a tool for finding a detailed velocity field in Paper II.

Figure 4 shows the two velocity fields obtained from the tomographic programs FAST and PStomo_eq for the data in the Siljan area (Paper I) together with the geological map. It can be seen how both program essentially image the same features but the velocity field resulting from FAST is smoother than the one obtained by PStomo_eq.

*Figure 4*: Velocity models obtained from two programs for seismic tomography. The middle panel corresponds to the geological map of the area. The 2D crooked seismic line is plotted with a solid black line. The arrow indicates the borehole Gravberg-1. Dashed lines represent fracture zones. Figure taken from Paper I.
Pre-stack migration

Crystalline areas are characterized by complex geology (e.g. highly deformed rocks, complex fracture systems, intrusions, etc.). These geological features result in velocity changing not just vertically, but also horizontally. If lateral variations are strong, the pre-stack depth migration is the most appropriate scheme for handling data that cannot be treated properly by stacking and post-stack migration (Yilmaz, 1987).

The description I will give for pre-stack migration is taken from Bancroft (1998). The readers are referred to this book for a complete explanation of the method.

In pre-stack migration all possible reflection points lie on an ellipse (2D migration), or an ellipsoid (3D migration), with the source and receiver being the foci of the ellipse/ellipsoid. Length of the raypath from one focus to any location on the ellipse/ellipsoid and on to the other focus will always be constant.

All 2D pre-stack traces may be mapped into the 3D volume \((x,h,t)\), where \(x\) is the CMP position, \(h\) corresponds to the half source-receiver offset and \(t\) the two-way traveltime. Source, receivers, reflectors, scatterpoints and raypaths are all located on the zero-offset plane. 3D seismic data \((x,y,t)\) would require a 4-D volume \((x,y,h,t)\). For simplicity I will concentrate in the description of the method for 2D data.

A scatter point will create a 3D surface in \((x,h,t)\) that is referred to as Cheops pyramid. The traveltimes of energy from a scatterpoint are defined by the double square root equation (Claerbout, 1985):

\[
T = -\frac{T_0^2}{4} + \frac{(x + h)^2}{V^2} \frac{\sqrt{2}}{2} + \frac{T_0^2}{4} + \frac{(x - h)^2}{V^2} \frac{\sqrt{2}}{2}
\]

(4)

As is seen from equation (4), the velocity of the scatter points defines the shape of the Cheops pyramid.

The main concept of pre-stack migration is to gather the scattered energy and place it back at the scatter point. Pre-stack migration, can be both pre-stack time migration and pre-stack depth migration and there exists several algorithms to accomplish them. The method used in Paper II was Kirchhoff pre-stack depth migration; therefore, I will limit my description to this type of migration.

In a source record, each scatter point has one source-scatter point raypath with traveltime \(t_s\) and many scatter point-receiver rays with traveltime \(t_r\). The diffraction shape is defined by the scatter point to receiver raypath and the position of the diffraction is defined by the source to scatter point raypath. Kirchhoff pre-stack migration is accomplished by assuming a scatter point
location, defining the diffraction shape and position, summing the energy on the diffraction shape, and relocating the energy at the scatter point.

Figure 5 shows a stacked section from Paper II, before and after applying Kirchhoff pre-stack depth migration.

*Figure 5: Stacked section before and after Kirchhoff pre-stack depth migration of the eastern part of the Luleå profile. Note that the reflector indicated by the arrows is clearly enhanced compared to the reflection as seen in the non-migrated stacked section.*
Optimized stack

Working in hardrock environments implies working with data that may have low signal-to-noise ratios. Thus, one of the main targets of the processing is to minimize the noise as much as possible. To achieve this, I used a processing sequence similar to the optimized stack method described by Mayrand and Milkereit (1988) for the data acquired in the Skellefte region. This method tries to maximize the signal-to-noise ratio expressed by:

\[
l_n = \frac{mS}{\sqrt{\sum_{i=1}^{n} \frac{\beta_i^2}{l}}}
\]  

(5)

where \( \beta_n \) is the S/N ratio of a simple straight stack of \( n \) traces, \( S \) is the signal, assumed to be constant, and coincident on \( m \) traces, and \( \beta_i^2 \) is the estimated variance per trace. The method is based on the assumption that \( m \) out of \( n \) traces contribute to the signal in a CDP gather and that the \( (m-n) \) traces left are mostly noise. A function \( D(l) \) is defined per CDP as:

\[
D(l) = \sum_{i=1}^{l} \frac{\beta_i^2}{l}
\]

(6)

The lowest possible noise in a CDP is achieved by finding the optimum value of \( l \) that minimizes the function \( D(l) \). The variances of the traces are estimated based on information extracted after amplitude scanning within windows where only noise is recorded. For this work, I used time windows before detection of first arrivals. The evaluation of \( D(l) \) is done on CDPs sorted by noise-variance estimates. All traces beyond the optimum subset \( l \) are excluded from the stack.

I used the optimum stack method in Paper IV as one of the editing criteria for the processing of the Cross-profile in the Skellefte area. Figure 6 shows an example of the results after applying this method alone and in combination with a criterion that removes all traces where first arrivals are not clearly detected, as was actually done for the dataset in Paper IV.
Figure 6: Improvement after applying the optimized stack method to the Cross-profile data from the Skellefte District. A) Without corrections. B) With optimized stack corrections. C) Optimized stack and first arrival detection criteria. The reflectivity observed at 3 s becomes more coherent and continuous. At CDP 1400 there is also reflectivity at about 2 s that is enhanced after the corrections.
Cross-dip analysis and correction

In the section describing the survey geometries, I mentioned that when working with crooked lines, the positions of midpoints are spread out over an area and it is necessary to define bins that collect these midpoints for stacking. Normally, the size of the bins in the in-line direction are defined by half the receiver spacing, while the cross-line direction width may sometimes become very wide if the acquisition line is significantly crooked at long offsets. For the profiles in the Skellefte area the in-line bin width was 12.5 m while the cross-line width was set to 3 km to include all the midpoints around the stacking line. This is equivalent to assuming that the lateral velocities and geological structures remain constant over a distance of 3 km, which is very unlikely for regions with complex geological history. Thus, a processing scheme that proves to be very useful for handling crooked lines is a pseudo 3D data processing technique (Wu et al., 1995), which consists of cross-dip analysis on straight stacking lines to account for lateral dip changes.

Cross-dip is defined as the component of reflection dip in the vertical plane perpendicular to the seismic profile (Larner et al., 1979, Wu et al., 1995 and O’Dowd et al., 2004). Given constant cross-dip and medium velocity, the reflection times in the seismic traces within a CMP gather will vary according to the distance between the midpoint and the effective stacking line (Wu et al., 1995). These delays cannot be corrected for by standard residual statics and reflection energy does not stack in phase after conventional NMO corrections (Larner et al., 1979 and O’Dowd et al., 2004).

Figure 7 shows a schematic three-dimensional diagram illustrating the geometry of a cross-dipping reflector in relation to the survey and stacking line. Using figure 7 as reference, the cross-dip correction, $t_{ij}$, is given by:

$$
t_{ij} = 2\sin i V_i Y_{ij}
$$

where $i$ is the cross-dip angle at the $i$th common depth point, $V_i$ is the velocity of the shallowest dipping layer, $Y_{ij}$ is the transverse offset between the midpoint and the stacking line and $j$ is the trace number within a CMP gather (Larner et al., 1979).
In regions where complex geological structures are present, more than one cross-dip angle may be needed to correct the data along the profile. Cross-dip analysis gives valuable structural information that together with the image obtained in the stack along the line makes it possible to estimate the true dip and strike direction of the geological features imaged in the profile.

Cross-dip analysis was used in Paper II for completing the geological interpretation of the main reflectors imaged in the pre-stack migrated sections. Cross-dip analysis was also used in Paper IV for extracting 3D information from both the in-line and the Cross-profile data in the Skellefte area. In addition, cross-dip corrections were used to achieve a better stack of the cross-profile.

Figure 8 shows a portion of the stack from Profile 5 in the Skellefte District before and after applying cross-dip corrections. It is clearly seen that the reflections become more continuous, and in general, more coherent, after applying a correction of 5 degrees to the east.
Figure 8: Example of the effect of applying the cross-dip correction. A) Without correction. B) With cross-dip correction of 5 degrees to the east. Note that the reflections in B are more continuous and coherent.

True dip estimation from apparent dip

For estimating the true dip and strike of some of the geological features observed in the data from the Skellefte area, I used a common method in structural geology described by Marshak and Mitra (1988). Full derivation of the trigonometrical expressions is skipped for simplicity. Using figure 9 as reference, this method calculates the strike of the dipping interface by determining the angle (\( \phi \)) in the figure between one of the apparent dip directions (direction AB in the sketch) and the strike line.
Figure 9: Sketch showing the main components for the calculation of true dip and strike of a dipping interface from two apparent dips. A) Block diagram. B) Plan view indicating geographical axis and relationship of angles used for calculating the strike (modified from Marshak and Mitra, 1988)

\[
J = 90^\circ \left[ \arctan \left( \frac{\tan \mu}{\sin \theta} \right) \right] \cot \theta
\]  

(7)

where \( \beta \) is the apparent dip in the AB direction, \( \mu \) is the apparent dip in the AD direction and \( \theta \) is the angle between AB and AD.

\[
\text{strike} = \text{AB direction} + \dot\lambda
\]

(8)

Once the strike is determined, the true dip \( \beta \) can be calculated from:

\[
\dot\lambda = 90^\circ - \beta
\]

(9)

\[
J = \arctan \left( \frac{\tan J}{\cos \beta} \right)
\]

(10)

where \( \beta \) is the angle between the true dip direction and the apparent dip in the direction AB.

In Paper IV, the azimuth of Profile 1 (7°) corresponds to the AB direction. \( \beta \) is the in-line dip estimated from the stacked section (22°). 270° is direction AD and the angle calculated by comparing times to the reflectivity at the same latitude between the three profiles (9°) is \( \mu \). Consequently, \( \beta = 97^\circ \), \( \beta = 63^\circ \), giving a strike of N70°E and true dip \( \beta = 24^\circ \)
4. Summary of the papers

Paper I

In this paper, we compare results from two publicly available programs that can handle crooked line geometry. These algorithms are FAST (Zelt & Barton, 1998) and PStomo_eq (Benz et al., 1996; Tryggvason et al., 2002). The main goal of this paper was to find the most suitable program for processing crooked line geometries. The programs use basically the same forward and inverse algorithms, but the smoothness constraint in both programs is handled differently; in FAST the Laplacian operator is normalized by the prior slowness of the centre cell. FAST is programmed to take the smoothest model with the better-normalized RMS misfit, avoiding overfitting the data. Residual values are normalized by the accuracy of the traveltime picks. Consequently, a good estimation of uncertainties is required. PStomo_eq does not have any built-in mechanism for avoiding data overfit, the user should test different smoothness and monitor the behaviour of the residuals to stop the inversion sequence once the level of uncertainty of the data is reached.

Both programs have been used to study the upper crustal velocity structure in crystalline rock areas (i.e. Marti et al., 2002; Zelt et al., 2001), which confirm their efficiency for working in hardrock environments. However, each program requires either certain conditions from the data or a priori information for best performance.

We compare the accuracy of first arrival time calculations, inversion of synthetic data, and finally, inversion of real data. In particular, we show that the difference in how smoothing is applied is critical in determining the final velocity model.

The conclusion achieved from this work is that the outputs from both programs show basically the same features, the main difference is how detailed these features are. In general, FAST produces smoother models than PStomo_eq does. Tests done with synthetic data showed that FAST better models regions with smooth changes in the velocity field. PStomo_eq showed better performance in the resolution test by giving a better recovery than FAST in the checkerboard tests. PStomo_eq appears to show more clearly some of the features present on the geological map, especially thinner structures, such as dolerite dikes (Figure 4). The comparison with the sonic-log velocities from the Gravberg-1 borehole shows that the velocities from PStomo_eq model correlate better to those measured (Figure 10).
If the models are to be used as input for further seismic data processing, such as migration, then a smooth model is more appropriate, but if they are to be used for a process like static corrections, then a more detailed model is more desirable. Hence, the choice of which program to use depends on the additional information available, the expected results, and what the model will be used for.

Figure 10: Sonic-log velocities from the Gravberg-1 borehole (Juhlin, 1990) plotted at a sample interval of 0.3048 m (thin line). The 1D model velocities correspond to the average velocity of four adjacent cells at each depth step (25 m) below the surface location of the borehole. Thin dashed line corresponds to the starting model velocities. Thick dotted line is from the FAST model (figure 4) and the thick continuous line is from the PSTomo_eq model (figure 4). Enclosed by the rectangle is the area where both models were sampled by rays.
This paper presents the results obtained from re-processing of the two high-resolution shallow component parts of the Luleå profile.

In previous processing, 2D first arrival time tomography and pre-stack migration were employed to obtain a detailed image of the near surface along the profile. The results were not optimum since the algorithm for doing the tomography could not handle the crookedness of the line and the algorithm for pre-stack migration did not account for the 3D aspect of the reflector geometry. Hence, the main objective of this paper was to re-process the profile by using processing methods that take advantage of the 3D aspect of the data. We apply 3D first arrival seismic tomography as well as 3D pre-stack Kirchhoff depth migration. Seismic modeling based on processed shot gathers and the pre-stack migrated sections was also performed on the main reflectors identified in the sections. Cross-dip analyses were also performed to complete the interpretation of these reflectors.

The velocity model obtained from the tomography has values in the range of 5200 m/s to 5800 m/s. It gives more details, is less smooth and has higher velocities than that calculated previously. The RMS data fit is about eight times smaller than that obtained from the previous tomography. The resulting velocity field correlates better with the surface geological map and offers complementary information in regions with low fold due to sparse shot spacing. Normally, the velocities obtained after tomography may be used for pre-stack migration. For this study, the velocity field does not extend deep enough to be used directly for migration. Nevertheless, we used it to apply velocity statics prior to migration, which improved the migrated image. We also used these velocities as a starting point for the cross-dip and migration velocity analyses.

Integrated results from tomography, cross-dip analyses, seismic modeling and pre-stack migration gave new geometry constraints for some of the main geological units in the area. For the eastern end of the profile, cross-dip analysis shows that the northeasterly dipping reflections observed at the beginning of the stack become more coherent after applying dip corrections to the northwest, while further west the best images were obtained after dip corrections to the southeast. The pre-stack depth migrated section (Figure 11a) shows a main reflector dipping to the northeast that crosses the surface where the surface geological map shows the contact between a granitoid and metavolcanics from the Bälingberget unit. It is seen that most of the reflectors imaged in this section are located to the north of this main reflector, which indicates that it represents the contact between two different geological units. Seismic modeling based on shot gathers and the migrated section, estimates this reflector to dip 17 degrees to the northeast. We interpret this reflector as the contact in depth between the high magnetic metavolcanics and granodiorites.
The layered character observed to the north of this reflector is not evident between CDPs 300-440 for the upper 400-500 m of the migrated section (Figure 11a). The un-migrated stack shows a rather transparent area between these CDPs at times less than 250 ms. By coupling these observations to the magnetic map and the results from tomography, we constrain the spatial limits of the young granite shown in the surface geological map (Figure 3). This implies that it is a stitching pluton, as is interpreted for the Ale massif, but with a source to the north of the profile.

For the western end of the profile, the un-migrated stacked section, shows that most of the reflectivity present in the area is limited to the upper 250 ms. Cross-dip analyses show that these reflections become more coherent with westerly dipping corrections. After pre-stack migration all the shallow reflectors are enhanced (Figure 11b). Three main reflectors are identified. These reflectors are interpreted to represent the contacts of the units in the area. The estimated dip of the reflector to the east is 13 degrees to the southwest, and if extended to the surface, it intercepts the CDP line at CDP 1760, we interpret it as the limit of the metasediments to the north of the Pålmark unit. To the south of this reflector, there is a sequence of sub-parallel reflectors that seem to be limited above by a reflector that, if extended to the surface, intercepts the line at CDP 1920. We interpret this reflector as the contact between the metavolcanics of the Pålmark unit and the metasediments shown to the north in the surface geological map. The estimated dip from the migrated section is 15 degrees to the southwest.

Further west a shallower reflection is imaged in the un-migrated stacked section. In the pre-stack migrated image the corresponding reflector intercepts the surface at CDP ~2060. We estimate a dip of 26 degrees to the southwest and interpret it as the contact between the Pålmark unit and the metagreywackes of the Bothnian Supergroup.

This contact is not observed in the field along the survey line. Magnetic anomaly profiles indicated it to be a shallow west-dipping contact. It was interpreted as a vertical contact from the previous seismic processing based on the abrupt termination of reflectors at CDP 2060 in the migrated section (Juhlin et al., 2002).

Re-processing of the high-resolution shallow component part of the Luleā profile shows that applying processing methods that take advantage of the 3D aspects of crooked lines results in images that give better structural constraints in areas with complex geology.
Figure 11: Pre-stack migrated sections with geological interpretation. A) Eastern end of the profile, the red line marks the modeled reflector. B) Western end of the profiles, red and green lines mark the modeled reflectors.
Paper III

Apart from participating in the acquisition of this dataset, partly as observer and partly as party chief, my main contribution for this paper was the processing of Profile 1 and assistance in the processing of Profile 5.

This paper gives the first results of the acquisition, processing and interpretation of the data acquired in the Skellefte District. This region is the most important metallogenic province in Northern Sweden today. In the western part of the District, major VHMS deposits, e.g., the Kristineberg deposits (20.1Mt, Cu-Zn-Pb-Ag-Au) are situated. The seismic data were acquired to establish the tectonic framework at depth.

We show the first results using standard processing. Although the structural geology is complex, stacked sections of the data reveal numerous reflections that can be correlated with surface geology (Figure 11 and Figure 12). Visible on both profiles is a pronounced north-dipping band of reflections marking the boundary between relatively transparent crust above it and crust significantly more reflective beneath it. We interpret the reflective crust to represent the Bothnian Basin, bordering the Skellefte District to the south. This result is important for considering models for the development of the Skellefte District and for defining new exploration strategies in the area. The depth at which the reflectivity begins signals the maximum thickness of the younger Revsund granitoids. A thickness of 3 km south of the Skellefte District is therefore obtained, which is supported by Bouguer gravity data available for the area. A reflection dipping about 60° to the south is observed on Profile 1 where it crosses the Kristineberg mine (Figure 11), and is tentatively interpreted as related to the Kristineberg and Rävliden massive sulfide ore body. The mine appears to be located in a major synform along Profile 1, extending down to about 2.5-3 km depth. Steeply dipping (>70°) reflectivity observed along Profile 5 (Figure 12) is interpreted as associated with mafic to ultramafic sills interbedded in the metasedimentary sequence. A bright spot of reflected and diffracted seismic energy at 3 km depth observed along Profile 5 is interpreted to either represent an ultramafic intrusion or sulfide mineralization. Assuming that the reflectivity is located (nearly) vertically beneath Profile 5 and an approximate and uniform westerly plunge of the area of about 30° places the source of the reflectivity at the upper boundary of the Skellefte volcanic rocks.

Our results confirm that the acquisition parameters were sufficient for achieving clear images of the main geological structures present in Profile 1 and Profile 5. The seismic reflection profiling presented has been particularly effective for imaging the major structures around the ore body, demonstrating that the seismic-reflection technique can be used for delineating complex structures significant for mineral exploration. Stacks of the full 20 s of data successfully show that even when the charge size used is relatively
small (1-3 kg), we can image the Moho for both profiles at about 14 s (Figure 13).

Figure 11: Migrated line drawing of Profile 1, W1 marks the North-dipping event interpreted as the contact between the Bothnian Basin and the Skellefte Group. K1 is the reflectivity associated with the syncline by Kristineberg mine.
Figure 12: Migrated line-drawing of Profile 5. B1-B2, B3-B4 reflectivity interpreted as associated with mafic to ultramafic sills. W1 is the north-dipping reflectivity also identified on Profile 1. The stippled line marks the depth to where the surface of the Skellefte volcanics along Profile 1 would project (solid where expressed on the surface). H1 is the diffraction pattern interpreted as either an ultramafic intrusion or sulfide mineralization.
Figure 13: Line drawing of Profile 1 and Profile 5. The whole crust is reflective down to about 14 s (M). W1 marks the north-dipping feature separating more reflective crust below from less reflective crust above it. The upper crust in Profile 5 is more reflective than seen in Profile 1, B1 and B2 marking south dipping reflectivity. H1 marks a “bright spot” of reflectivity, containing reflections and diffractions. K1 is the reflectivity associated with the syncline by Kristineberg mine.
Paper IV

This paper is the logical continuation for Paper III. It presents the results from the processing of the Cross-profile together with cross-dip analyses of the in-line data. The Cross-profile data is characterized by an irregular geometry and midpoint distribution. Small charge sizes relative to the large offsets and the nature of the upper crystalline crust in the Skellefte District result in weak reflections that are easily masked by the ambient noise, therefore, efficient methods are required to enhance the quality of the data as much as possible. The optimized stack method (Mayrand and Milkereit, 1988) in combination with criteria for removing traces where first arrivals cannot be properly picked gave the best results in enhancing the S/N ratio on the Cross-profile. After enhancing the S/N ratio we found that the cross-dip analysis method of Wu et al. (1995) provided valuable constraints on the geometry of some of the reflections when correlating the three data sets.

Due to the long offset between the profiles (6500-12000 m), the first arrivals recorded for the Cross-profile data are first observed at approximately 1.2 s on shot gathers. This implies that the Cross-profile does not image the upper 4-5 km of crust in the area. At times later than 2 s, the only continuously reflective feature is north-dipping reflectivity seen at CDPs ~900 to 1500 (Figure 14) that correlates well with that observed on Profile 1 and Profile 5. Aside from the north dipping reflectivity, sub-horizontal reflections observed on Profile 1 between CDPs 500-800 at 3-3.5 s can be correlated to the Cross-profile between CDPs 600-800 at the same time, indicating that these reflections truly are sub-horizontal. These observations indicate that the Cross-profile, within the limitations due to the acquisition parameters, images the upper crustal reflectivity present in the area.

Cross-dip analysis and corrections on the Cross-profile show that the north-dipping event has a dip component to the west. This is corroborated by the results from cross-dip analysis of the in-line data and by the dip analysis done by correlating between the three profiles. By using a method for calculating true dip and strike from two apparent dips (Marshak and Mitra, 1988), we estimated that the reflector dips at about 24 degrees in the north-northwest direction and has been interpreted as the boundary between the Bothnian Basin meta-sediments to the south and the overlying Skellefte volcanics. Its presence on all three profiles supports this interpretation and indicates that it is an important feature of the Skellefte District. In general, it was observed that the profiles gave stacks that are more coherent after cross-dip corrections to the west.
Figure 14: Stacked section of the Cross-profile after the full processing sequence. N indicates north-dipping reflectivity that can be correlated on the three datasets.
On Profile 1, reflections from the southern limb of the synform, where the Kristineberg mine is located, have an easterly dip component, indicating that the axis of the synform runs in the west-northwest direction (Figure 15), this observation is consistent with the surface geology. In Profile 5 we observed that the ultramafic sills also have an easterly dip component (Figure 16). On a larger scale, in spite of the small charge size, the Moho has been imaged on all three data sets at about 14 s as the termination of reflectivity in the crust. Again, a similar pattern on all three data sets gives added credence to this interpretation (Figure 17).

The stacking charts obtained from the in-line data show that, in general, Profile 5 has higher noise than Profile 1. The reason for this is mainly instrumental since arrays were used for recording Profile 1, resulting in higher attenuation of noise than in Profile 5 where single geophones were used. On average, the difference between the amplitudes of signal and noise is roughly 50 dB for Profile 1 and about 40 dB for Profile 5. For the Cross-profile the difference is about 30 dB, another indication of the low signal-to-noise ratio in the Cross-profile compared to the in-line data. We see that the optimized stack method successfully removed most of the noisy traces. Further editing based on the first arrivals was necessary due to the similarity in the magnitudes of signal and noise, which affected the determination of the optimum l value per CDP.

The seismic dataset corresponding to the Cross-profile in the Skellefte District presents additional challenges than those normally present when processing in-line seismic data. A specialized processing sequence focusing on enhancing the S/N ratio was effective in producing a stack that images the main features of the area, within the limits imposed by the large offsets and small charges. Results from the Cross-profiles correlate well with those obtained for the in-line data. The integrated results give additional information about the structural geometries of some of the main geological units in the Skellefte District. This corroborates that after careful processing, crooked lines and Cross-profile acquisition geometries can maximize the amount of information that can be obtained from an area when small budgets and equipment limitations do not allow for 3D seismic.
Figure 15: Stacked section of Profile 1. Values for the applied cross-dip corrections are indicated per zone. N indicates north-dipping reflectivity that can be correlated on the three datasets. S marks the southern limb of the Kristineberg synform.
Figure 16: Stacked section of Profile 5. Values for the applied cross-dip corrections are indicated per zone. N indicates north-dipping reflectivity that can be correlated on the three datasets.
Figure 17: Stacked section of the Cross-profile after the full processing sequence for the entire 20 s of data. N indicates the north-dipping reflectivity. Interpreted Moho is indicated. Time-variant scaling was applied prior to plotting.
5. Final remarks

As stated earlier in this thesis, the main stages of a seismic survey are acquisition, processing and interpretation. This thesis covers research related with the three stages for studies carried out in the hardrock environment.

**Acquisition**

This work confirms that in spite of the challenges of working with crooked lines, these geometries are the simplest and most economical options for 2D acquisition. They produce sections of sufficient quality for imaging the main structures, even in areas of high geological complexity, as is often the case in crystalline rock regions.

We show a novel way of acquiring data by simultaneous recording along two lines. In this way, we maximize the amount of data acquired for a reduced cost.

This study also shows that even with shot charges as small as 1-3 kg, lower crustal images can be successfully obtained.

Other acquisition parameters, such as receiver and shot spacing, were sufficient for achieving good images for the 2D crooked line data. However, due to the geological complexity and the generally low impedance contrasts in hardrock areas, I would recommend acquisition with shorter shot and receiver spacing than those used in the Skellefte District. This will achieve higher resolution and will increase the fold.

For acquisition as in the Cross-profile, it would be helpful to place the acquisition lines closer to each other and in this way reduce the offset. Alternatively, an increase of the charge size would enhance the signal-to-noise ratio. Shorter receiver and shot spacing would also be crucial for improving the quality of the stack.

**Processing**

There are standard steps in seismic processing, however each dataset is different and there are always specialized steps needed to address specific problems. Nearly 80 years of working experience in sedimentary areas has resulted in a variety of “cookbooks” for working with different problems in
seismic processing. This is not the case for the hardrock environment where there is a shorter working history. Thus, we need to develop our “recipes” to address the specific problems related with the rock properties and structural characteristics of hardrock areas.

The main effort of this thesis was to find appropriate processing methods and techniques to address problems present in datasets acquired at reduced cost in the hardrock environment.

The challenges were due both to logistics and to the physical properties of the study areas.

This work confirms that 3D seismic tomography is most appropriate when working with crooked lines. Velocity models for complex areas can be obtained and used directly for correlation with surface geology as well as with tools for improving the performance of other processing steps. We found that programs such as FAST are more appropriate when subsequent processing, such as migration, is planned for a dataset. A program such as PStomo_eq is better for direct interpretation and static corrections.

When signal-to-noise ratios are low, processing including editing criteria based on first arrival detection and the optimized stack method, proved to give the best results.

From all the corrections and processing steps tested on these datasets, cross-dip corrections were the most effective way of improving our stacks. Just as deconvolution is rather standard for suppressing multiples in marine data, my conclusion after working with the Skellefte datasets is that cross-dip analysis and corrections should be included as a standard step in the processing of crooked lines in the hardrock environment.

Interpretation

As shown in Paper I, we found that programs such as PStomo_eq give velocity models that can be better correlated with surface geology, helping in this way, to confirm or improve the geological constraints in complex areas. Since the depth of the velocity model in Paper II did not reach deeper than 200 meters it could not be used for migration, but instead it was used for static corrections and geological interpretation. The geological interpretation from this velocity model correlates well with the surface geological map and, together with the magnetic map, might indicate the answer to the question of origin and geometry of some of the granites in the area.

In Paper III we present the first geological interpretation for some of the main geological units in the Skellefte area.

Following the last statement of the previous section, I would like to emphasize that cross-dip analysis was one of the most powerful tools for the interpretation of the Skellefte dataset. I propose it as a standard tool for interpretation in areas where complex deformation patterns are present, as is
normally the case in hardrock environments. In Paper IV it is shown that the combination of results from cross-dip analysis together with the in-line dip, gave the necessary information for estimating the true dip and strike of one of the main geological units in the area. Cross-dip analysis for other reflections gave additional 3D geological constraints for some of the main features present in the sections.

The conclusion from this thesis is that a combination of 2D crooked line and cross-profile acquisition is an affordable way to acquire datasets that, after appropriate processing, can maximize the 3D geological information obtained from a hardrock environment.
Reflexionsseismik har använts av oljeindustrin i nästan 80 år för både prospektion och utvinning i anslutning till sedimentära miljöer. Metodens styrka ligger i möjligheten att avbilda geologiska strukturer på djupet. Den långa användningen av seismiska mätningar i sedimentära miljöer och stora ekonomiska resurser har möjliggjort utveckling av effektiva metoder för att insamla, bearbeta och tolka data, anpassade till många olika ändamål. I områden med kristallin berggrund är situationen en annan, eftersom avsevärt mindre tid och pengar har avsatts för seismiska studier.

Det finns en tydlig skillnad mellan arbete i sedimentära och kristallina miljöer. Kristallina miljöer involverar normalt komplicerad geologisk utveckling med en stor variation av deformation, kraftigt lutande strukturer samt generellt höga P-våghastigheter i kombination med svaga impedanskontraster. Det finns därför behov av att utveckla lämpliga metoder för datainsamling och databearbetning i sådana miljöer, vilket ofta innebär att hantera ett lågt signal/brus förhållande.

Avhandlingen presenterar forskning från kristallina miljöer med syfte att utveckla kostnadseffektiva metoder för datainsamling och databearbetning relevanta för geologisk tolkning. Även om vissa teoretiska aspekter diskuteras så är avhandlingens huvudsakliga mål att presentera praktiska resultat som kan användas som referens för framtida arbeten i liknande områden.

Datainsamling, databearbetning och tolkning är de grundläggande komponenterna i en seismisk undersökning. Framgången av en studie är beroende av att samtliga komponenter samverkar. Förfinad bearbetning kan inte kompensera för brister i datainsamlingen, eftersom ingen tolkare kan se bortom informationen i mätdata.

Avhandlingen innefattar forskning relaterad till samtliga tre komponenter av en seismisk undersökning, med inriktning på kristallina miljöer.

### Datainsamling

Detta arbete bekräftar att data insamlade längs krokiga linjer (exempelvis skogsvägar resulterar i seismiska sektioner av tillräcklig kvalitet för avbildning av de mest framträdande strukturerarna. Detta gäller även i områden med heterogen geologi, vilket vanligen är fallet i kristallina miljöer.
Sådana krokiga linjer är oftast det enklaste och mest ekonomiska alternativet för 2D data insamling.

Vi presenterar en metod för att insamla data genom simultan registrering längs två mätlinjer så att data även finns för en kross-profil mellan de båda mätlinjerna. På detta sätt maximerade vi mängden insamlade data inom en begränsad budget.

Studien visar även att det är möjligt att använda laddningar som inte är större än 1-3 kg för att avbilda strukturer ända ned till gränsen mellan jordskorpan och manteln, vanligen kallad Moho.


För datainsamling liknande den i den korsande profilen så skulle det vara lämpligt att placera de seismiska linjerna närmare varann för att därigenom reducera avstånden mellan skott och mottagare. Ett alternativ är att öka laddningsstorleken för att öka signal/brus förhållande. Att minska avståndet mellan skotten samt avståndet mellan mottagarna skulle även vara väldigt värdefullt för att öka kvaliteten av den seismiska sektionen.

**Databearbetning**

Det finns några standardsteg inom databearbetning, men eftersom varje dataset är unikt krävs alltid att bearbetningen anpassas till de specifika problemen.

Tyngdpunkten för studien som presenteras i avhandlingen har legat på att utveckla bearbetningsmetoder anpassade till några av de problem som uppstår vid datainsamling i kristallina miljöer och då arbetet utförs inom begränsade budgetramar.

Utmånningar orsakades av både de logistiska faktorerna och av de fysikaliska egenskaperna i de undersökta området.

Arbetet bekräftar att seismisk hastighetstomografi i 3D är mest lämplig för seismiska linjer med krokig utsträckning. Det är möjligt att bestämma hastighetsmodeller för komplexa miljöer och att direkt använda dessa för korrelation med geologi vid markytan samt för att underlätta övrig databearbetning. Vi fann att program som FAST är lämpliga när ytterligare bearbetning som migration är planerad för ett dataset (migration är en term som, något förörenat, anger att reflexionernas läge räknas om från tid till djup). Ett program som Pstomo_eq är dock mer lämpligt för direkt tolkning och för
s.k. statiska korrekctioner (tidsförskjutningar av seismogrammen som syftar till att höja signal/brus förhållandet).

Vid lågt signal-till-brusförhållande är det lämpligt att använda databearbetning baserad på gångtiden för den direkta vågen mellan skott och mottagare samt en speciell metod för CDP-summering (s.k. optimized stack method).

Av alla de bearbetningssteg som provats på de dataset som ingår i avhandlingen så har det effektivaste visat sig vara korrektioner för effekten av att reflektorerna inte enbart har en lutning i profilens riktning utan även har en lutning i ett plan vinkelrätt mot profilriktningen, s.k. cross dip corrections. Min slutsats är att liksom reduktion av multiplareflektioner är ett standardsteg för bearbetning av marina seismiska data så är cross dip corrections ett standardsteg vid bearbetning av data insamlade längs krokiga seismiska linjer.

**Tolkning**

Som visas i artikel I har vi funnit att program som Pstomo_eq producerar hastighetsmodeller som bättre kan korreleras med geologi vid markytan, vilket gör det enklare att bekräfta eller förbättra de geologiska antagandena i komplexa miljöer. Eftersom hastighetsmodellen i artikel II inte nådde djupare än 200 m p.g.a. datainsamlingens parameter, så var det inte möjligt att använda den för migration, men istället användes den för statiska korrektioner och för direkt geologisk tolkning. Den geologiska tolkningen baserad på hastighetsmodellen överensstämmer väl med ytgeologin och kan, tillsammans med den magnetiska kartan, indikera svar på frågor om ursprung och förekomst beträffande några av områdets graniter.

I artikel III presenterar vi den första geologiska tolkningen av några av de huvudsakliga geologiska enheterna i Skelleftefältet. För att anknyta till föregående avsnitt så vill jag understryka att cross dip corrections var ett av de mest kraftfulla redskapen för tolkning av data från Skelleftefältet. Jag föreslår det som ett standardverktyg för tolkning i områden med komplex deformation av berggrunden, vilket normalt är fallet i kristallina miljöer. I artikel IV visas att kombinationen av resultat från cross dip corrections med konventionell uppskattning av reflektorlutningar i profilriktningen resulterar i bestämning av verklig stupning och strykning för en av de mest framträdande geologiska enheterna i området. Cross dip corrections för andra reflektioner gav ytterligare information om den tredimensionella geometrin för några av de andra geologiska enheterna.

Sammanfattningsvis visar avhandlingen att en kombination av två, eller flera, krokiga seismiska 2D-linjer är ett billigt sätt att insamla dataset som, efter lämplig bearbetning, kan maximera mängden geologisk 3D-information i kristallina miljöer.
La sísmica de reflexión ha sido usada por la industria petrolera por casi 80 años para la exploración y producción en ambientes sedimentarios. Éste método geofísico permite la visualización de estructuras geológicas en profundidad. La larga trayectoria de la sísmica en ambientes sedimentarios le ha permitido a los geofísicos trabajar con data adquirida bajo condiciones físicas muy diferentes, desarrollando así métodos adecuados para la adquisición, procesamiento e interpretación de datos según el caso. La sísmica en rocas cristalinas no ha alcanzado aún ese nivel de experticia, ya que su uso en estos ambientes se inició hace sólo un par de décadas cuando una serie de proyectos internacionales comenzaron a emplear éste método como una herramienta para estudios ingenieriles y de exploración minera.

Los ambientes cristalinos se caracterizan por tener historias geológicas complejas, presentando rocas que han sido expuestas a una gran variedad de procesos de deformación. Por lo general, se encuentran estructuras con buzamientos abruptos, los valores de velocidad de onda P son uniformemente altos ~5500-6000 m/s y los contrastes de impedancia son de baja amplitud, lo que implica baja relación señal/ruido.

Ésta tesis presenta una investigación hecha en ambientes cristalinos, con el objetivo de encontrar métodos de adquisición económicamente eficientes, así como una buena combinación de técnicas de procesamiento que produzcan resultados de utilidad para la interpretación geológica.

Aunque algunos aspectos teóricos son discutidos, el mayor objetivo de ésta tesis es presentar resultados prácticos que puedan ser empleados como referencia para trabajos futuros en áreas con características similares.

Los principales componentes de un estudio sísmico son la adquisición, el procesamiento y la interpretación. Estas tres etapas son igualmente importantes para el éxito del proyecto, ya que no existe procesamiento capaz de corregir errores de adquisición, así como no existe un intérprete que pueda ver más allá de lo que la data ofrece. Ésta tesis abarca una investigación hecha en cada uno de estos componentes para el caso de trabajos en rocas cristalinas.
Adquisición

Éste trabajo confirma que a pesar de las complicaciones que puede implicar el trabajar con “crooked lines” o líneas torcidas, éste tipo de geometría es la opción más económica y simple en la adquisición 2D. Se pueden producir secciones de suficiente calidad para visualizar las principales estructuras geológicas, aún en casos de alta complejidad como suele ocurrir en ambientes cristalinos.

Mostramos un método de adquisición innovador, en el que se graban simultáneamente dos líneas 2D paralelas, de ésta manera se producen tres sets de datos: dos provenientes de las líneas 2D y uno con data del área entre ellas, el perfil que llamamos en ésta tesis “Cross-profile”. De ésta manera se maximiza la cantidad de data adquirida a un costo reducido.

Aquí también se muestra que con cargas de apenas 1-3 kg de dinamita, se puede obtener buenas imágenes de la corteza inferior hasta Moho.

Otros parámetros de adquisición como los intervalo de disparo y de receptor fueron suficientes para lograr buenas imágenes de las datos 2D de línea torcida. Sin embargo, debido a la complejidad geológica y los bajos contrastes de impedancia en áreas cristalinas, yo recomendaría usar intervalos de disparo y receptor más cortos a los empleados en el área del Distrito de Skelefte, para así lograr una mayor resolución e incrementar la cobertura.

Para la adquisición del “Cross-profile” sería recomendable ubicar las líneas con una distancia menor entre ellas. Una alternativa es incrementar el tamaño de las cargas en los disparos y así mejorar la relación señal/ruido. Igualmente una reducción del intervalo de disparo y receptor también sería recomendable para mejorar la calidad de las secciones apiladas.

Procesamiento

El mayor esfuerzo de ésta tesis fue el conseguir métodos y técnicas de procesamiento adecuados para trabajar con datos adquiridos con bajos presupuestos en ambientes cristalinos. Los desafíos que presentan estos datos son de origen logístico y geológico.

En éste trabajo se confirmó que la tomografía 3D es la más adecuada cuando se trabaja con líneas torcidas. Se pueden obtener modelos de velocidad de áreas complejas para correlacionarlos con la geología de superficie, así como para emplearlos en la mejora de otros pasos de procesamiento. Nosotros comprobamos que programas como FAST son más apropiados si el campo de velocidad va a ser usado como entrada en procesos como, por ejemplo, migración. Mientras un programa como PSTomo_eq es más adecuado para producir modelos que se usen directamente para interpretación y corrección de estáticas.
En casos de datos con baja relación señal/ruido, se obtuvieron los mejores resultados al incluir criterios de edición basados en la detección de primeras llegadas y método de apilamiento optimizado.

De todas las correcciones hechas y pasos de procesamiento probados en estos datos, las correcciones de “cross-dip” fueron las más efectivas en la mejora de las secciones apiladas. Así como la deconvolución es un paso estándar para suprimir múltiples en la data marina, mi conclusión después de éste trabajo es que los análisis y correcciones de “cross-dip” deben ser incluidos como pasos estándares en el procesamiento de líneas torcidas en ambientes cristalinos.

Interpretación
En el Paper I, se mostró que PStomo_eq produce modelos de velocidad detallados que pueden ser utilizados directamente para interpretación. Como el modelo obtenido para la data del Paper II no alcanza profundidades mayores a los 200-250 m, éste modelo no se pudo emplear para migración, sino que se usó para correcciones de estáticas y para la interpretación geológica. La interpretación geológica correlaciona bien con el mapa de geología de superficie y junto con la información del mapa magnético, se pudo responder incógnitas relacionadas con el origen y geometría de alguno de los granitos en la zona.

El Paper III presenta las primeras interpretaciones de alguna de las principales unidades geológicas del área minera de Skellefte.

Al igual que en la sección anterior, me gustaría enfatizar que los análisis de “cross-dip” fueron la principal herramienta de interpretación para la data de Skellefte. Yo propongo dichos análisis como una herramienta estándar en la interpretación de áreas geológicas con patrones de deformación complejos, como suele ser el caso en regiones de roca cristalina. En el Paper IV se mostró que la combinación de resultados de los análisis de “cross-dip”, junto con la información de buzamiento aparente en la sección apilada para la data 2D, proporcionaron los datos necesarios para el cálculo de rumbo y buzamiento real de una de las principales unidades geológicas de la zona. Los análisis “cross-dip” de otras reflexiones dieron información geológica 3D de algunos de los principales patrones de reflectividad presentes en las secciones apiladas.

La conclusión de ésta tesis es que la combinación de líneas torcidas 2D y adquisición “Cross-profile” es una vía económica para adquirir data que, luego de un procesamiento apropiado, puede maximizar la información geológica 3D obtenida en ambientes de roca cristalina.
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