Reflection seismic investigation in the Skellefte ore district

A basis for 3D/4D geological modeling

MAHDIEH DEHGHANNEJAD
Abstract

The Skellefte ore district in northern Sweden is a Palaeoproterozoic volcanic arc and one of the most important ones hosting volcanogenic massive sulfide (VMS) deposits, producing mainly base metals and orogenic gold deposits. Due to high metal prices and increased difficulties in finding shallow deposits, the exploration for and exploitation of mineral resources is quickly being moved to greater depths. For this reason, a better understanding of the geological structures in 3D down to a few kilometers depth is required as a tool for ore targeting. As exploration and mining go deeper, it becomes more and more evident why a good understanding of geology in 3D at exploration depths, and even greater, is important to optimize both exploration and mining.

Following a successful pilot 3D geological modeling project in the western part of the district, the Kristineberg mining area, a new project "VINNOVA 4D modeling of the Skellefte district" was launched in 2008, with the aim of improving the existing models, especially at shallow depth and extending the models to the central district. More than 100 km of reflection seismic (crooked) profiles were acquired, processed and interpreted in conjunction with geological observations and potential field data. Results were used to constrain the 3D geological model of the study area and provided new insights about the geology and mineral potential at depth.

Results along the seismic profiles in the Kristineberg mining area proved the capability of the method for imaging reflections associated with mineralization zones in the area, and we could suggest that the Kristineberg mineralization and associated structures dip to the south down to at least a depth of about 2 km. In the central Skellefte area, we were able to correlate main reflections and diffractions with the major faults and shear zones. Cross-dip analysis, reflection modeling, pre-stack time migration, swath 3D processing and finite-difference seismic modeling allowed insights about the origin of some of the observed reflections and in defining the imaging challenges in the associated geological environments.

Keywords: Skellefte district, reflection seismic, mineral exploration, 3D/4D modeling, mineralization, faults and shear zones

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urn:nbn:se:uu:diva-221225 (http://urn.kb.se/resolve?urn=nbn:se:uu:diva-221225)
Dedicated to
My love Alireza and
My lovely daughters Armita & Camelia
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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Selection of additional refereed conference and journal publications during my PhD studies, which are not included in this thesis:


- **Mahdieh Dehghannejad**, Christopher Juhlin, Alireza Malehmir and Pär Weihe, (2010), High-resolution reflection seismic imaging in the Kristineberg mining area, northern Sweden. 72nd European Association of
Geoscientists and Engineers Conference & Exhibition - Incorporating SPE EUROPEC 2010, Barcelona, Curran Associates, Inc. 5368-5371


- Pietari Skyttä, Tobias E. Bauer, Tobias Hermansson, Mahdieh Dehghannejad, Christopher Juhlin, María García Juanatey, Juliane Hüburt and Pär Weihed, (2013), Crustal 3-D geometry of the Kristineberg area (Sweden) with implications on VMS deposits. *Solid Earth*, 4:387–404
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<thead>
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<th>Abbreviation</th>
<th>Description</th>
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<tbody>
<tr>
<td>2D</td>
<td>Two-dimensional</td>
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<tr>
<td>3D</td>
<td>Three-dimensional</td>
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<tr>
<td>4D</td>
<td>Four-dimensional</td>
</tr>
<tr>
<td>CDP</td>
<td>Common depth point</td>
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<tr>
<td>CMP</td>
<td>Common midpoint</td>
</tr>
<tr>
<td>DMO</td>
<td>Dip moveout</td>
</tr>
<tr>
<td>Ga</td>
<td>A billion years (Gigayears) ago</td>
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<tr>
<td>Hz</td>
<td>Hertz</td>
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<tr>
<td>Kg</td>
<td>Kilogram</td>
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<td>Km</td>
<td>Kilometer</td>
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<td>m</td>
<td>Meter</td>
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<tr>
<td>ms</td>
<td>Milisecond</td>
</tr>
<tr>
<td>Mt</td>
<td>Megaton</td>
</tr>
<tr>
<td>NMO</td>
<td>Normal moveout</td>
</tr>
<tr>
<td>s</td>
<td>Second</td>
</tr>
<tr>
<td>S/N</td>
<td>Signal-to-noise ratio</td>
</tr>
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<td>VMS</td>
<td>Volcanogenic massive sulfide</td>
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1. Introduction

The Skellefte mining district in northern Sweden is a Palaeoproterozoic district that covers an area of 120 km by 30 km (Figure 1.1). The district is one of the most important mining districts in the country, producing Zn, Cu, Pb, Ag and Au from volcanogenic massive sulfide (VMS) and orogenic gold deposits and has a large potential for new discoveries (Allen et al., 1996; Kathol and Weihed, 2005; Carranza and Sadeghi, 2010). The Kristineberg mine in the western part of the Skellefte district and Maurliden (E & W) in the central district are the main VMS-deposits in mining operation (Bauer, 2010). The majority of shallow deposits are believed to have already been discovered and therefore the main focus is nowadays to explore at depth (>500 m), especially near existing mining infrastructures (brown- or near-field exploration). For this reason, good control on the three-dimensional (3D) architecture of the uppermost 5 km of the Earth’s crust in the Skellefte district is crucial for focusing on the most promising areas.

3D modeling is based on a combination of different types of information such as geophysical data, petrophysical information on rock properties, and information about the geology. The 3D model acts as a structural framework in which mineralization occurs and allows an improved understanding of the structural evolution of the mining district. Subsequent four-dimensional (4D) modeling adds the time aspect to the 3D models and with the aim of visualizing the geological history and supporting ore targeting. Moreover, adding geological time to the modeling allows for validation of both the conceptual models and the 3D models.

Particular interest in the Skellefte district is to define characteristics of the major deformation zones and their association with the regional structures and lithostratigraphy, where the majority of the VMS deposits are located (Figure 1.1). It is also important to investigate, if any, how the observed transitions in metamorphic grade across the district (Kathol and Weihed, 2005) are related to the structural evolution of the crust.

Results from early reflection seismic work by Elming and Thunehed (1991), Juhlin et al. (2002), and a 3D pilot study in the Kristineberg mining area (Tryggvason et al., 2006), suggested reflection seisms as one of the best suitable methods for improved understanding of crustal structures, but also for providing constraints for 3D geological modeling. To obtain knowledge on the 3D geometry of the ore-bearing volcanic rocks and their
associated structures and as a continuation of the 3D pilot geologic modeling study, a new project (VINNOVA 4D project) was formed by both industry and academia, aiming at producing geological 3D/4D models of the upper 5 km of the Earth’s crust in the Skellefte district by combining geological and different types of geophysical investigations. For this, more than 100 km new reflection seismic profiles were acquired in the Kristineberg mining area and the central Skellefte district during 2008-2010.

These data, their processing, analysis and interpretations in conjunction with other geological and geophysical data constitute the backbone of this thesis. A major component of the work was to acquire and obtain high quality reflection seismic images of the upper 5 km of the crust, providing constraints for the 3D/4D geological modeling of the Skellefte district.

This thesis is divided into two sections: a summary and a collection of papers. The summary is divided into six chapters. The summary starts with this introduction (Chapter 1). In Chapter 2, a brief introduction to the regional geology of the Skellefte district, previous work in the area and the new VINNOVA 4D project is given. In Chapter 3, important seismic processing techniques used in this research are introduced. Chapter 4 consists of a summary of the papers that are included in the second section. Conclusions are summarized in Chapter 5. A summary in Swedish is provided in Chapter 6.
Figure 1.1. Geological map of the Skellefte district showing the locations of the pilot study and new reflection seismic profiles. The Kristineberg mining area and the central Skellefte district are the focus of this thesis. Major N-S-trending shear zones: Deppis-Näsliden shear zone (DNSZ) and Vidsel-Röjnoret shear system (VRSS). Modified after Kathol et al. (2005).
2. The Skellefte district

2.1. Geological background

The Skellefte district (Figure 1.1) comprises Palaeoproterozoic supracrustal and intrusive rocks that formed in a volcanic arc setting and were deformed and metamorphosed during the Svecokarelian orogeny (Allen et al., 1996; Lundström et al., 1997; Mellqvist et al., 1999; Kathol and Weihe, 2005). The district lies in-between two major tectonic units: (i) an area with Palaeoproterozoic and reworked Archaean rocks of the Norrbotten craton north of the district, and (ii) Bothnian Basin metasedimentary rocks to the south and east of the district (Allen et al., 1996; Kathol and Weihe, 2005). The district has been interpreted as a transitional zone between these two units (Skyttä et al., 2012).

The Archaean-Proterozoic boundary has been defined by a shift in Nd signatures (Lundqvist et al., 1996; Wikström et al., 1996; Mellqvist et al., 1999) that coincides with a gently south dipping subsurface crustal reflection imaged by the BABEL reflection seismic profile, interpreted as NE-verging thrusts tectonics (BABEL working Group, 1990).

Metasedimentary rocks of the Bothnian Supergroup are suggested to form the basement of the mainly 1.89–1.88 Ga felsic volcanic and volcaniclastic Skellefte Group (Allen et al., 1996; Billström and Weihe, 1996; Montelius, 2005; Skyttä et al., 2011). Allen et al. (1996) put forth that the VMS deposits formed partly as sub-seafloor replacement and partly as exhalative deposits within the volcaniclastic and sedimentary rocks and in the uppermost part of the Skellefte Group stratigraphy.

The uppermost stratigraphical unit of the Skellefte district consists of the metasedimentary rocks of the Vargfors Group (1.88–1.87 Ga), and is coeval with the subaerial, predominantly volcanic Arvidsjaur Group that is present further to the north (Skiöld et al., 1993). The sedimentary rocks of the Vargfors Group at the southern part of the Skellefte district grade into Bothnian Supergroup rocks, but the contact is drawn in a rather arbitrary manner (Kathol and Weihe, 2005).

The oldest intrusive rocks in the Skellefte district are Jörn-type granitoids (1.89–1.88 Ga), which have been suggested to be as co-magmatic with the volcanic Skellefte Group (Gonzales Roldan, 2010; Skyttä et al., 2010). The most prominent rocks are the GI-phase of the Jörn intrusive complex and the Viterlieden intrusion (Kathol and Weihe, 2005; Gonzales Roldan, 2010;
Younger intrusive rocks, GII to GIV phases of the Jörn intrusive complex and intrusive rocks of the Perthite-Monzonite suite, post-date the volcanic activity between 1.88 and 1.86 Ga (Kathol and Weihed, 2005; Bejgarn et al., 2013). Late Svecokarelian rocks ranging from 1.82 to 1.78 Ga surround the Skellefte district (Kathol and Weihed, 2005).

Structurally, a complex fault pattern and shear zones largely control the structural evolution of the district. The Kristineberg mining area is dominated by E-W striking shear zones (Skyttä et al., 2013), but in the central Skellefte, the shear zones strike WNW-ESE and are associated with NNE-SSW striking shear zones. A major WNW-ESE striking shear zone (Dehghannejad et al., 2012a) at the southern part of the central district separates two crustal domains with characteristic deformational signatures (Skyttä et al., 2012). Recent studies revealed that these shear zones have a syn-extensional origin and influenced the sedimentation in the Vargfors Group (Bauer et al., 2011 and 2013; Skyttä et al., 2012). These syn-extensional faults have been interpreted to act as fluid conduits for ore-forming hydrothermal fluids (Bauer et al., 2014). Subsequent crustal shortening resulted in inversion of the WNW-ESE syn-extensional faults at shallower levels (1.88–1.87 Ga) and was oriented SSW-NNE, and coaxial in nature (Bauer et al., 2011; Skyttä et al., 2012). This deformation resulted in the transposition of VMS deposits and a penetrative pattern of steep to sub-vertical mineral lineations (Skyttä et al., 2012). Finally, an E-W directed crustal shortening at 1.82–1.80 Ga (Weihed et al., 2002) resulted in the reactivation of major ~N-S striking high-strain zones (e.g., Deppis-Näsliden shear zone and Vidsel-Röjnoret shear system in Figure 1.1; Bergman Weihed et al., 1996; Bauer et al., 2011; Skyttä et al., 2012). Figure 2.1 shows an example of the reconstructed geological history of the central Skellefte district.

Identification of inverted faults resulting from the crustal shortening is thus essential for mineral exploration in the district. Also, since the majority of VMS deposits are located in the uppermost part of the volcanic Skellefte Group the contact relationships between the Skellefte Group and the overlying sedimentary Vargfors Group is important to identify. Therefore, some of the objectives of this thesis were to image regional-scale structures, especially fault systems, and to correlate them with the surface geology and also to provide detailed seismic images of subsurface geological structures near known VMS deposits.
Figure 2.1. Schematic cross-section, depicting the reconstructed geological history of the central Skellefte district: (a) deposition of polymict conglomerates during crustal shortening; (b) sedimentation of polymict conglomerates during the extensional phase. Progressive opening of the basin not taken into account for sedimentary stratigraphy. The dashed line marks the current erosion level (from Bauer et al., 2013).
2.2. Pilot 3D geological modeling study

Previous studies such as BABEL Working Group (1990) and (1993), a test seismic profile at Norsjö (Elming and Thunehed, 1991), Luleå seismic profile (Juhlin et al., 2002) aimed at better understanding the tectonic evolution of the district at large crustal scales. Results of these studies revealed a need for detailed study of the tectonic evolution of the district and its link to mineralization. Results of such a study would help to define better strategies for the exploration of deposits in the district and the district’s potential, especially at depth.

A 3D pilot study (GEORENGE 3D project) was then initiated in the Kristineberg mining area in 2003. For the 3D pilot study, two parallel 2D crooked reflection seismic profiles (Profiles 1 and 5 in Figure 2.2) were acquired during Fall 2003 (Tryggvason et al., 2006). The goals were to focus on understanding the contact relationships between the ore-bearing volcanic and volcano-sedimentary formations and the surrounding intrusive rocks and to provide a framework along which a 3D geological model of the area could be constructed. Results from the reflection seismic data (Tryggvason et al., 2006) revealed numerous reflections from the top 12 km of the crust some that could be correlated with the surface geology. Further studies focused on cross-profile seismic data (Rodrigues-Tablante et al., 2007), constrained 2D and 3D modeling of potential field data (Malehmir et al., 2006; 2007 and 2009a) and magnetotelluric data modeling (Hübert et al., 2009). One of the interesting results from the pilot study was a north-dipping package of reflections associated with conductivity anomalies and interpreted as structural basement to the Skellefte Group rocks and possibly from Bothnian Basin rocks.

These studies helped to improve and partly validate the seismic interpretations and led to the construction of the 3D geological model of the Kristineberg mining area down to 12 km depth (Malehmir, 2007; Malehmir et al., 2009a).
2.3. VINNOVA 4D modeling

The successful work of the pilot study led to the establishment of a new project entitled "4D geological modeling of mineral belts" (VINNOVA 4D project) in 2008 financed by the VINNOVA (Swedish Governmental Agency for Innovation Systems), Boliden Mineral AB, and initially by Lundin mining, with major emphasis on 3D/4D modeling of the geological structures of the Skellefte district.

The new project was collaboration between geologists and geophysicists from academia (Uppsala University and Luleå University of Technology) and industry (Boliden Mineral AB and Geovista AB) and based on combining the results from new high-resolution reflection seismic data with results from new detailed structural mapping of the same areas.

One of the main objectives of the new project was to improve the existing pilot 3D geological model in the Kristineberg mining area especially in shallower parts down to 5 km and develop it to the central Skellefte district to

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Figure 2.2. Geological map of the Kristineberg mining area showing the locations of the previous (black lines; Tryggvason et al., 2006) and new reflection seismic profiles (blue lines; Dehghannejad et al., 2010) and the CDP processing lines (green and orange lines). Black box in the figure shows the location of the 3D swath imaging area discussed later in this thesis. Deposits: Kr = Kristineberg, Kh = Kimheden, H = Hornträsk, Rm = Rävlidmyran, R = Rävliden, Rä = Räkå. The geological map is modified after Skyttä et al. (2009).
obtain a better understanding of the area and how to define a target for a scientific deep hole. The final model should constitute the basis for choosing a well defined drilling site to test the models, constrain the 3D architecture and eventually verify parts of the accretionary tectonics that led to the growth of the Fennoscandian Shield during the Palaeoproterozoic (Weihed, 2010).

During this project, available potential field data, geological observations (Bauer, 2010; Bauer et al., 2011; 2013; 2014; Skyttä, 2012; Skyttä et al., 2010; 2011; 2012 and 2013), new magnetotelluric measurements (Hübent et al., 2013; García, 2012; García et al., 2013) as well as potential field and deep IP measurements (Tavakoli et al., 2012a and 2012b), accompanied the reflection seismic data (Dehghannejad et al., 2010; 2012a and 2012b) and were used to facilitate their interpretations and the construction of the 3D/4D models.

More than 100 km of new reflection seismic data with varying resolution and research objectives were acquired during 2008-2010. Two new profiles, high-resolution profile (HR profile) and Profile 2 in the Kristineberg area (Figure 2.2) and three new profiles in the central Skellefte district, Profiles C1, C2 and C3 (Figure 2.3) were acquired in the framework of the VINNOVA 4D project. Details about the acquisition parameters of the new seismic profiles in comparison with the previous seismic profiles of the pilot study are summarized in Table 2.1.

During this project, I was dealing with acquisition, processing and interpretation of the reflection seismic data as part of my PhD study and results of the seismic profiles were used as a backbone for the 3D geological models of the study area.
Figure 2.3. Geological map of the central Skellefte district showing the locations of the new seismic profiles (black lines) and processing CDP lines (red lines). The geological map is modified after Bauer (2010).
Table 2.1. Main acquisition parameters for the reflection seismic data (see Tryggvason et al., 2006; Dehghannejad et al., 2010 and 2012a).

<table>
<thead>
<tr>
<th></th>
<th>Profile 1</th>
<th>Profile 5</th>
<th>Profile 2</th>
<th>HR profile</th>
<th>Profile C1</th>
<th>Profile C2</th>
<th>Profile C3</th>
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<tr>
<td>Type of survey</td>
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<td>25 m</td>
<td>25 m</td>
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<td>Geophone</td>
<td>Group of six 10 Hz</td>
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<td></td>
<td>Single 28 Hz</td>
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<td>Length of profile</td>
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<td>6.3 km</td>
<td>30 km</td>
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<td>31.5 km</td>
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3. Challenges in hardrock seismic imaging

3.1. Why reflection seismic for mineral exploration?

Due to an increased demand, and prices, for metals, especially base metals, iron and high-tech metals and difficulties to find shallow deposits, a renewed interest for the exploration and exploitation of mineral resources using seismic methods at depth is attracting many researchers and industry (e.g., Eaton et al., 2003; Malehmir et al., 2012 and references therein). Various geophysical methods such as potential field and electromagnetic ones have been used by the mineral industry to investigate the subsurface and these methods have been used in mineral exploration to delineate potential mineralized zones and also discover resources at shallower depths (e.g., Roy and Clowes, 2000; Goleby et al., 2002; Malehmir et al., 2006). Reflection seismic method is the only surface method that provides high-definition images of the subsurface with suitable penetration depth for exploration and mining purposes (e.g., Schmidt, 1959; Ruskey, 1981; Wright, 1981; Cosma, 1983; Fatti, 1987; Pretorius et al., 1989; Milkereit et al., 1992; Urosevic and Evans, 1998; Duweke et al., 2002; Perron et al., 2003; Chen et al., 2004; Murphy et al., 2006; Harrison and Urosevic, 2012). Therefore, reflection seismic methods were proposed as a deep mineral exploration, and complementary, method with the ability of imaging geological structures hosting mineral deposits, and improving the knowledge of structures and stratigraphy towards providing optimum drilling targets in mining areas (e.g., Wright et al., 1994; Milkereit et al., 1996; Eaton et al., 2003; Malehmir et al., 2010). This brings new opportunities for geophysicists, but also new challenges, especially in crystalline environments (e.g., Snyder et al., 2009; Malehmir et al., 2010).

Several studies refer to that the useful application of seismic methods for mineral exploration was as the result of successful imaging of fault and fracture zones in the hardrock environment (e.g., Green, 1972; Green and Mair, 1983; Juhlin, 1995a). Large-scale seismic investigations were also very important in developing the necessary techniques for imaging challenging and complex geological structures in the crystalline environment (Milkereit et al., 1992; Juhlin et al., 1995; Milkereit and Eaton, 1998; Perron and Calvert, 1998; Ayarza et al., 2000; Roy and Clowes, 2000; Stolz et al., 2004; Urosevic et al., 2005; Willman et al., 2010).

3D surface seismic surveys are known as an ideal solution for complex geological environments (e.g., mining areas), however, due to economic
restrictions, 2D surveys are often conducted. Therefore, one of the main challenges here is the interpretation and processing of 2D seismic data, especially in the presence of 3D geology and where the data are often acquired along crooked lines, violating even 2D seismic imaging assumptions (Wu, 1996; Zaleski et al., 1997; Nedimović, 2000; Nedimović and West, 2003a and 2003b). Out-of-the-plane structures normally are present in crooked line data, and these add further challenges for both the processing and interpretation of the data acquired in mining areas. For example, Malehmir et al. (2010) showed a comparison between a strong seismic anomaly observed in 2D data with that observed in 3D data (Figure 3.1). Their observation was that a high-amplitude anomaly observed on the 2D section originated from a massive sulfide deposit, but nearly 700 m away from the 2D line (Malehmir et al., 2010). The 2D data showed the anomaly deeper than that in the 3D data. The important point is that the 2D seismic anomaly led to the discovery of the deposit through a dedicated and proper 3D seismic survey and, for the first time, demonstrated why reflection seismic methods can be used to directly delineate mineral deposits (Matthews, 2002).

Figure 3.1. Comparison between 2D and 3D surveys showing a seismic anomaly observed in 2D data with its actual location in 3D data. The seismic anomaly is from an approximately 6-8 Mt massive sulfide deposit known as the "deep zone" at about 1.2 km depth (from Malehmir et al., 2010).
Further success in this case came from a systematic exploration approach by follow up studies such as downhole seismic survey and petrophysical measurements as well as seismic modeling of the response of the deposit (Bellefleur et al., 2004 and 2012). This example shows why regional 2D seismic data followed by 3D seismic data can be very useful for not only defining new targets by imaging the host rock structures, but also for directly delineating deep-seated deposits. While 3D seismic data are not often available, the main issue remains on how to obtain as much as information as possible from the 2D crooked line data.

3.2. Key imaging aspects

The main components of a seismic survey are acquisition, processing and interpretation, and the overall success depends on proper accomplishment of each of these components. Eaton et al. (2003) suggested six aspects that need careful consideration when planning a seismic survey for mineral exploration. These are (1) acquisition of high-fold data, (2) the need to obtain high-frequency data, (3) forward seismic modeling of mineral deposits and their host rocks, (4) processing considerations with focus on refraction statics, surface consistent deconvolution, and dip moveout (DMO) corrections, (5) physical rock property measurements, and (6) migration considerations. Most of these aspects still require careful consideration when planning, however, the first three generally are given insufficient attention (Eaton et al., 2003). Only a few attempts have been performed to carry the most advanced processing methods often exercised by the hydrocarbon industry. Pre-Stack Depth Migration (PSDM), Reverse Time Migration (RTM), Common Reflection Surface (CRS) stack are now routinely tested even in complex sedimentary areas (e.g., Li et al., 2003; Jones, 2008; Gierse et al., 2009).

3.3. Crooked line seismic survey

It is worth to note that the term common midpoint (CMP) is not the same as common depth point (CDP), but the terms are often used interchangeably. We have also used both terms in this thesis; however, the correct terminology should be CMP, unless DMO has been applied.

As discussed by Wu (1996), a straight CMP line for stacking is often superior to a slalom line, so consequently 2D straight lines are more desirable than crooked lines. One important reason for this is that straight line binning better satisfies the assumptions of 2D processing algorithms than slalom line binning (Wu, 1996). As evident, straight line 2D acquisition is usually impossible over crystalline environment; 2D surveys are forced to follow exist-
ing roads for logistical and economic reasons (Nedimović and West, 2003a). Crooked line profiling, coupled with the complex structures of the geological targets, brings special challenges for 2D reflection seismic data processing and interpretation (Wu, 1996) and more attention needs to be paid to the geometry, selection of stacking lines and binning of the data (Wu et al., 1995).

Several experiments have shown that with a proper processing approach one can produce high quality seismic images and turn the disadvantages of the 2D crooked line into interpretational advantages by providing (i) cross-dip corrections to obtain more information on the possible out-of-the-plane origin of reflections (e.g., Bellefleur et al., 1995; Wu et al., 1995; Rodriguez-Tablante et al., 2007; Urosevic et al., 2007), and (ii) by 3D swath processing of the 2D seismic data (e.g., Wu et al., 1995; Nedimović and West, 2003a and 2003b; Malehmir et al., 2009b and 2011) to obtain 3D information about the reflections which otherwise it would be impossible using straight 2D lines, unless many are available that cross each other. In this thesis, both approaches were tested and each provided valuable input to the interpretation of the seismic data.

3.3.1. Cross-dip analysis

When seismic profiles are acquired along crooked lines, the positions of midpoints are spread out around the actual acquisition line. If there is a significant spread of midpoints perpendicular to the CMP line, then it is possible to analyze the seismic data for the possible contribution of cross-dip from out-of-the-plane structures (Wu et al., 1995).

Cross-dip is the component of reflector dip in the vertical plane perpendicular to the seismic profile (Larner et al., 1979; Wu et al., 1995; O’Dowd et al., 2004). Given constant cross-dip and medium velocity, the reflection times for the traces within a CMP gather will vary due to distance from the midpoint to the processing line (Larner et al., 1979; Wu et al., 1995). Correction $\Delta t_{ij}$ can be calculated by equation 3.1 to account for the cross-dip component (Larner et al., 1979):

$$\Delta t_{ij} = \frac{2 * y_{ij} * \sin(\gamma_i)}{V_i}$$

where $\gamma_i$ is the cross-dip angle at the $i$th CMP, $y_{ij}$ is the offline distance of the midpoint (from the stacking line), $j$ is the trace number within the CMP gather and $V_i$ is the velocity of the shallowest dipping layer (we considered it as a constant value without any lateral variations).

A noticeable example of the cross-dip correction and its effect for an observed reflection is illustrated in Figure 3.2 (data along Profile C3 of the central Skellefte district, see Figure 2.3 for the location of the profile). A comparison between Figure 3.2a and 3.2b suggests that a cross-dip correc-
tion of 30° to the west allows imaging a long reflection that is not imaged using standard stacking methods. This further challenges the 2D interpretation of these data.

![Figure 3.2](image)

*Figure 3.2.* (a) Stacked section along a portion of the Profile C3, and (b) cross-dip corrected section of the same portion as (a) using a cross-dip component of 30° to the west using a stacking velocity of 5500 m/s. Note a long reflection marked by arrows in Figure 3.2b that is not as evident in (a).
3.3.2. Swath 3D processing of 2D crooked line

If the midpoints of a 2D crooked line data are spread enough around an acquisition line, data can be treated as semi-3D data (e.g., Nedimović and West, 2003b; Urosevic et al., 2007). However, because of lack of enough data (azimuth and offset) in the crossline/perpendicular direction of the crooked line the resultant images may be significantly affected by artifacts during migration (both 3D pre-stack and post-stack migration) such as "smiles". Nedimović and West (2003b) summarized the fundamental limitations of resolving 3D structures from 2D crooked line data:

- lack of wide azimuth coverage which does not allow the full resolution of the cross-dips;
- lack of sufficient cross-line horizontal aperture in the data set to resolve the cross-line position of reflectors; and
- irregular spatial distribution of the data (e.g., CMP fold).

The first and second points can be related to any swath 3D survey. The third condition results when shot and receiver positions are along the crooked line (Nedimović and West, 2003b). However, besides these, the 3D swath imaging of the 2D crooked line (if it is possible) can be an option to extract 3D information about the geometry of geological structures (e.g., Nedimović and West, 2003b; Urosevic et al., 2007; Malehmir et al., 2009b) and also sometimes to preserve shallow reflections for correlation with the surface geology (Malehmir et al., 2011).

A previous study of 3D swath imaging of the 2D crooked line in the Kristineberg mining area (Profile 5, see Figure 2.2 for the location of the profile) was successful in imaging a series of diffractions that were not observed completely by the 2D crooked line processing (Malehmir et al., 2009b). Figure 3.3 shows the 3D visualization of one of the observed diffractions obtained using a 3D swath processing approach. The results of this study demonstrated how the 3D swath imaging can be useful and allowed the extraction of 3D information from the diffractions towards improving the interpretation of the results. Another experiment of 3D swath imaging by Malehmir et al. (2011) showed that additional source points located off a 2D crooked line, where the line was bending, could allow preservation of shallow reflections that could not be observed by 2D crooked line processing. Results were obvious: an improved image plus interpretation. So, adding a few source points is fairly inexpensive and can be considered for future surveys with 2D crooked lines (Malehmir et al., 2011; Lundberg, 2014).
3.4. Reflector modeling

Due to the crookedness of seismic profiles, energy from out-of-the-plane may degrade the stacked images (Wu et al., 1995), moreover, reflections observed in the shot gathers may not necessarily appear on the final stacked sections. To analyze how reflections on the shot gathers correspond to the reflections in the stacked section, and also in order to extract information on the 3D orientation of the more prominent reflections, 3D reflector modeling can be used based on an assumption that reflections are planar and are within a constant velocity medium (e.g., Ayarza et al., 2000; Juhlin and Stephens, 2006; Malehmir et al., 2006).

The modeling is based on calculating traveltimes of the reflector in both shot and stack domains using the true acquisition geometry of the source, receivers (for shot gathers) and CDPs (for the stack). Constant P- and S-velocity and density are assumed for both bedrock and the reflectors. Reflection coefficients are calculated based on the equations published by Aki and Richards (1980). The planar reflector is allowed to dip in any direction by different strike and distance to a reference point, until the calculated trav-
eltimes from the planar reflector match the observed traveltimes in both the shot gather and stacked section (see Ayarza et al., 2000 for details). Figure 3.4 shows an example of fitting traveltimes on both a shot gather and stacked section for reflection C1 of the HR reflection seismic data of the Kristineberg mining area.

*Figure 3.4.* (a) Modeling example for a shot gather, and (b) the unmigrated stacked section of the HR profile down to 1.5 s. The modeled traveltimes for reflection C1 match the observed traveltimes both in the shot gather and the stacked section.
3.5. Migration

Migration is a process that transforms an image from data space to model space. During migration dipping reflections move to their true positions in the subsurface and diffractions collapse to a point. Migration, thus, further improves the spatial resolution, especially the horizontal resolution compared to that of vertical resolution (Yilmaz, 2001). Actually, the main aim of migration is to make a stacked section more similar to the geological section (Yilmaz, 2001). During the migration process, a dipping reflection moves up-dip and the migrated segment becomes steeper and shorter than that in the unmigrated section (Yilmaz, 2001). Yilmaz (2001) expressed that migration strategies include:

• 2D versus 3D migrations;
• time versus depth migrations; and
• post- versus pre-stack migrations.

Crooked line seismic data challenges 2D pre-stack and post-stack migration algorithms, which are based on a straight line geometry (e.g., Schmelzbach et al., 2007). There are several studies that show how performing a 3D pre- or even occasionally post-stack migration of 2D crooked line data have a good potential to obtain an interpretable 3D image of the subsurface in comparison to 2D migrations (e.g., Nedimović and West, 2003b; White and Malinowski, 2012). However, the effectiveness of such approaches will vary case-by-case, because they depend on the crooked nature of the acquisition line. In this thesis, 2D post-stack time migration was carried out in Paper I, II and III, but in Paper IV, 3D swath processing and also pre-stack time migration was carried out. 3D post-stack migration was also carried out, but did not result in an improved image.

As long as seismic velocity varies with depth, time migration can be sufficient, but when there is strong lateral velocity variation (e.g., fracture system, intrusions, etc.), time migration is not accurate and depth migration should be considered (Yilmaz, 2001). Due to lack of velocity information (e.g., borehole sonic data) and models in the study area, the main focus was given to performing time migration in this study. However, we do not normally expect large lateral velocity variations in the crystalline environment, the velocities are not so variable in the common igneous rocks compared with the wide range in sedimentary rocks (Adam et al., 2003; Juhlin and Stephens, 2006). Therefore, a time migration approach may provide a sufficiently good image as compared with the depth migration approach.

3.5.1. Post-stack time migration

It has been discussed by Yilmaz (2001) that in the case of structural dips or with the aim of preserving diffractions in the seismic section in an area with small laterally velocity variations, post-stack time migration can be consid-
ered. Adam et al. (2003) also suggested that pre-stack DMO along with a post-stack migration algorithm still may be more useful in hardrock data processing and mining applications than pre-stack time or depth migrations. Several studies in different mining camps have shown that diffractions may originate from ore deposits (e.g., Milkereit et al., 1996; Malehmir and Bellefleur, 2009; Malehmir et al., 2010). This motivated us to use post-stack time migration to preserve diffractions since VMS deposits in the Skellefte district were one of our main targets (Paper I, II and III).

3.5.2. Pre-stack time migration

Pre-stack time migration is usually applicable in the case of conflicting dips of reflections while post-stack time migration cannot handle this situation (Yilmaz, 2001). In Paper IV, a 2D pre-stack time migration was used in order to extract more information from the data and also to compare the results with the 2D post-stack migration. By doing this, a shallow reflection, which was not observed before by 2D post-stack migration was observed. We also performed a 2D post- and pre-stack time migration on synthetic data to compare results against the real data. Processing of the synthetic data showed artifacts were manifested as steeply dipping events and these artifacts are stronger when the data were processed using post-stack migration than pre-stack migration. It also showed that pre-stack migrated sections contain less details than the post-stack migrated sections.

3.6. Finite-difference (forward) modeling

To support interpretation of seismic data, numerical modeling is often used to provide synthetic data for testing processing techniques and acquisition parameters (Keiswetter et al., 1996; Kazemeini, 2009). One of the methods, which has become a very popular tool for seismic applications, is finite-difference forward modeling. In complex geological environments like mining areas, forward modeling techniques can be very useful (e.g., Thomas et al., 2000; Cheng et al., 2006) to provide a better understanding of the geological signature of mineral deposits. In the context of hardrock seismic exploration, forward modeling has been used to study the dependence of the seismic response to ore body shapes and composition (e.g., Eaton, 1999; Bohlen et al., 2003; Clarke and Eaton, 2003; Hobbs, 2003). Several authors discussed how finite-difference modeling allows the investigation of wave-mode conversions that may occur at lithological contacts (e.g., Bohlen et al., 2003; Snyder et al., 2009; Malinowski and White, 2011). Bellefleur et al. (2012) also suggested that forward modeling techniques are instrumental when trying to understand the key characteristics of VMS deposits on seismic data.
Finite-difference modeling is necessary to understand the seismic response of mineral deposits and to validate geological models against seismic data (Bellefleur et al., 2012). Ideally, finite-difference modeling should be based on accurate and complete petrophysical data and 3D elastic (and maybe even visco-elastic (e.g., Malinowski et al., 2011)) modeling should be applied. However, 2D acoustic and elastic modeling algorithms can be useful because of the fast examination of geological models.

In Paper IV, both acoustic and elastic finite-difference modeling were carried out to determine the response of the geological model and validate the interpretation along the HR seismic profile in the Kristineberg mining area. The geological model used for forward modeling was created based on a compilation of geological observations and borehole data constraints from interpretation of the HR seismic profile. Finite-difference algorithms (Pratt and Worthington, 1990; Juhlin, 1995b) were used to generate the synthetic data for both acoustic and elastic modeling. A major step with any forward modeling is how to generate the model that is as close to the geology as possible and prepare it properly for various modeling algorithms. For details about the algorithms, readers are advised to read the cited papers. Figure 3.5 shows an example snapshot of the seismic wavefield from the acoustic modeling that indicates that the massive sulfide or high contrast zones should produce strong seismic signal in this area.
Figure 3.5. Snapshots of the seismic wavefield from the acoustic modeling for a shot at the center of the model at (a) 300 ms and (b) 600 ms, showing that the massive sulfide or high contrast zones (shown in red color) should produce strong seismic signal.
4. Summary of papers

This chapter presents a brief summary of the four papers which constitute the main part of my thesis. Each paper is summarized by its objectives, methods, results and conclusions. A statement of my own contribution to each paper is provided here:

Paper I: Besides participating in the seismic data acquisition during Fall 2008 (for four weeks), I mainly processed the seismic data. I carried out the cross-dip analysis and reflector modeling in order to obtain information on the 3D geometry of the reflections. Interpretation of the data was done in collaboration with my co-authors. Main writing was done by me and co-authors helped to improve it by their comments.

Paper II: Besides participating in the fieldwork to acquire three seismic profiles during summer 2009 and 2010, I processed the seismic data. Geological mapping was carried out by Tobias E. Bauer (Luleå University of Technology) and he provided the micro-photographs. Manuscript was written by me and Tobias E. Bauer had a main responsibility for the geological parts. Interpretation was carried out in close collaboration with Tobias E. Bauer and all co-authors improved the paper with their comments and suggestions. 3D modeling figures were also prepared by Tobias E. Bauer.

Paper III: Assisting on re-processing of the previous seismic data from the Kristineberg mining area (Profile 1). Preparing the geological map and 3D visualization with the HR profile and Profile 2 in the Kristineberg mining area were carried out by me. I also contributed to the interpretation of the results and their correlation with the new seismic lines (my main focus in this paper).

Paper IV: This study includes: pre-stack migration, 3D swath imaging of the 2D seismic data in the Kristineberg mining area that were done by me. Acoustic seismic modeling was carried out by Alireza Malehmir and elastic modeling was carried out by me and Christopher Juhl. 3D visualization of the data along the HR profile was performed together with Pietari Skyttä (University of Helsinki). Manuscript was written by me and Pietari Skyttä had a main responsibility for the geological parts. All co-authors improved the quality of the paper by their suggestions and comments.
4.1. Paper I: Reflection seismic imaging of the upper crust in the Kristineberg mining area, northern Sweden

4.1.1. Summary

As a part of the VINNOVA 3D/4D geological modeling project over the Skellefte district, two new crooked reflection seismic profiles, a N-S directed high-resolution one (HR) and an E-W directed one (Profile 2) were acquired in the Kristineberg mining area, western part of the Skellefte district (see Figure 2.2), in Fall 2008.

The main aims of this study were to:

• examine the capability of using high-resolution reflection seismic data to image the shallower portions of the subsurface for further correlation with the surface geology; and

• validate and refine some of the previous geological interpretations.

Earlier seismic lines (Profiles 1 and 5) focused on the deeper parts of the subsurface and used longer shot and receiver spacing. The total length of the new seismic profiles was about 20 km (6.3 km for the HR profile and 13.7 km for Profile 2). Receiver and source spacing was 10 m for the HR profile and 25 m for Profile 2. An hydraulic hammer, VIBSIST (Cosma and Enescu, 2001), was used to generate the seismic signal. For the recording system, a SERCEL 408UL from the Department of Earth Sciences, Uppsala University was used. Data processing was carried out along a straight CDP line for both profiles using a conventional processing sequence. Refraction statics, choice of temporal filter, and velocity analysis had the greatest influence on the results. DMO corrections allow crossing reflections with different dips to stack simultaneously (Deregowski, 1986), but it was not possible to obtain a good image for Profile 2 by preforming DMO and it only worked well for the HR dataset. Since major reflections appear at the edge in Profile 2, but believed to be mainly from out-of-the-plane of the profile, we only migrated the HR profile. The best migrated image was obtained using a finite-difference migration algorithm with a constant velocity of 5000 m/s. The processed seismic data imaged a series of steeply dipping to sub-horizontal reflections, some of which reach the surface and allow correlation with surface geology and recent field geological mapping.

3D visualization of the seismic data with location of the Kristineberg ore lenses is shown in Figure 4.1. This shows reflection M1 to be directly associated with mineralization and seems to generate a diffraction (K1) signal in Profile 2. It is not clear if reflection E1 is directly related to a mineralization zone. However, its strong seismic character describes a high impedance contrast and suggests a suitable target for future deep exploration to a depth about of 2.25 km.
Figure 4.1. 3D views showing the migrated seismic section along the HR profile and stacked section along Profile 2 (a and b) as well as locations of different ore zones. Projection of the Kristineberg ore body onto the HR profile indicates it to be correlated with reflection package M1 (b). Different colors in solid bodies locally represent different ore lenses in the Kristineberg deposit. Ore body geometries are kindly provided by Boliden Mineral AB.

Cross-dip analysis (described in section 3.3.1 and described in detail by Nedimović and West (2003a)) and reflection modeling (described in section 3.4) were carried out to study the out-of-the-plane nature of some of the reflections and to obtain additional information about their 3D geometry. Reflections were modeled to extract information on their 3D orientation in
both shot gathers and stacked sections, using the true acquisition geometry (described in section 3.4 of this thesis). The surface projections of some of the steeply dipping reflections onto a combined high-resolution aeromagnetic and ground magnetic map and the geological map are shown in Figure 4.2. Figure 4.2 shows that reflection C1 represents a shear zone at the boundary between the Skellefte Group volcanic rocks and the Vargfors Group metasedimentary rocks and reflection R1 appears to correlate well with mafic-ultramafic sheet-like intrusions. We could also obtain the 3D orientation of reflection W1 that was also observed in both previous profiles (Tryggvason et al., 2006). We attributed this reflection to a fault zone within the Viterliden intrusion or internal lithological boundaries in it (see Figure 4.2). Cross-dip analysis could help us to obtain a cross-dip component of 30°-40° to the north for reflection N1 which relates it to the mafic-ultra mafic rocks or the contact between the Skellefte and Vargfors Groups.

4.1.2. Conclusions

The new seismic data and results in the Kristineberg area confirmed some of the previous interpretations, but also provided additional and local-scale constraints on the subsurface geology. High-resolution data along the HR profile proved to be successful in imaging reflections potentially associated with mineralization zones, and suggest that the Kristineberg mineralization and associated structures dip to the south down to at least a depth of about 2 km, although this needs further support. The study further illustrates that shorter shot and receiver spacing is required to successfully image the complex geological structures of the Kristineberg mining area.
Figure 4.2. Surface projections of the modeled reflector planes mapped onto (a) the geological map and (b) combined high-resolution aeromagnetic and ground magnetic map of the Kristineberg area. Most of the modeled reflections correlate well with magnetic lineaments derived either from lithological boundaries, faults or mafic-ultramafic sill intrusions. Aeromagnetic data are published with kind permission from the Geological Survey of Sweden and the ground magnetic measurements are kindly provided by Boliden Mineral AB.
4.2. Paper II: Crustal geometry of the central Skellefte district, northern Sweden – constraints from reflection seismic investigations

4.2.1. Summary

In the continuation of the VINNOVA 3D/4D geological modeling project, three new sub-parallel reflection seismic profiles were acquired in the central Skellefte district during summer 2009 and 2010 (Figure 2.3).

The aims of this study were to:

• image regional-scale structures down to a depth of about 5 km and their correlation with surface geological studies; and
• to provide a base for 3D/4D modeling in the central part of the district.

Three profiles (Profiles C1, C2 and C3, see Figure 2.3) were acquired with a length of about 30 km for each. Shot spacing and receiver spacing was about 25 m except in places where profiles cross the Skellefte river or where due to road inaccessibility it was not possible to have a regular shot spacing. For the data acquisition and generating seismic signal, we used the same system that was used in the Kristineberg mining area (VIBSIST and a SERCEL 408UL, but with more channels, up to 400). For processing, we chose a straight CDP line for Profiles C1 and C2, and a slalom CDP line for Profile C3 using 12.5 m wide bins for stacking. Refraction statics, deconvolution, choice of temporal filter and velocity analysis were again major processing steps which had the greatest influence on the results. Implementation of DMO corrections also failed for these datasets, attributed to the irregular shot spacing as well as irregular offset distribution in the data (Deregowski, 1986). For the migration, we used a phase-shift migration algorithm with a constant velocity of 5800 m/s, except for Profile C1, where a finite-difference migration algorithm with a constant velocity of 5600 m/s gave the best result.

In general, all these three seismic profiles resulted in imaging gently to steeply dipping and sub-horizontal reflections as well as diffraction packages (D1-D4 in Figure 4.3a). Reflections and diffractions are interpreted to be from major faults and shear zones and/or represent lithological contacts. Figure 4.3 shows a portion of the stacked section and migrated one along Profile C3. A comparison between the stacked and migrated sections along this portion suggests that diffractions D1-D4 are generated at the edge of a series of faults at the contact between metasedimentary rocks and their underlying Skellefte Group metavolcanic rocks (e.g., D1 and D2) or may represent lithological contacts within the Skellefte Group or the contact between the Skellefte Group rocks and their unknown basement (e.g., D3 and D4).
Figure 4.3. (a) A portion of the stacked section along Profile C3, where the profile passes the Maurliden deposit, and (b) the migrated section along the same portion of the Profile C3 (b). Note that surface geology is shown on top is along the acquisition line.

Since there are sharp changes in the geometry of the acquisition lines (Figure 2.3), we decided to analyze the cross-dip component of the main reflections. Figure 4.4 shows an example of the effect of the cross-dip correction.
for reflection R1 that was observed in the southern portion of both Profiles C1 and C3, suggesting that reflection R1 has a cross-dip component of 15°-20° to the east. Another example of the cross-dip correction has already been shown in Figure 3.2.

![Figure 4.4](image)

*Figure 4.4.* (a) Stacked section along a portion of Profile C1, and (b) cross-dip corrected section of the same portion as (a) using a cross-dip component of 15° to the east using a stacking velocity of 5500 m/s. (c) Stacked section along a portion of Profile C3 and (d) cross-dip corrected section of the same portion as (c) using a cross-dip component of 20° to the east using a stacking velocity of 6000 m/s. Note reflection R1 is imaged longer and stronger in (b) and (d).

Reflection seismic modeling was carried out to obtain the orientation of the major reflections. This modeling helped us to better interpret and correlate the reflections from one profile to another one. A 3D visualization of the seismic data and comparison with surface geological observation was performed (Figure 4.5). This shows most of these reflections correlate with surface geological observations, and most extend to the surface, correlate well with geological features either observed in the field or interpreted from the aeromagnetic map of the study area. For example, we suggest that reflection R1 to be from a shear zone separating meta-sedimentary rocks to the south from meta-volcanic rocks to the north.
4.2.2. Conclusions

The three seismic profiles in the central Skellefte helped us to better understand the geological structures and shear zones at depth. We could correlate the main reflections and diffractions with the major faults and shear zones and/or lithological contacts. Results of these three seismic profiles provided constraints for the construction of the first large-scale 3D geological model of the central Skellefte ore district to about 5 km depth. Further study and data are required to determine the origin of the observed reflection in Figure 4.5.
3.2b. It is generated from the top of the Skellefte Group rocks, lithological contacts within the volcanic succession, partly from unknown basement to the Skellefte Group rocks or from some other feature. Seismic data at the Maurliden deposit area show a number of interesting features, thus, a couple of seismic profiles perpendicular to Profile C3 would allow a better and more constrained interpretation of them.

4.3. Paper III: Re-processing and interpretation of 2D seismic data from the Kristineberg mining area, northern Sweden

4.3.1. Summary

In this study, one of the previous seismic profiles from the 3D pilot geological modeling study (Tryggvason et al., 2006; Malehmir et al., 2007) in the Kristineberg mining area (Profile 1, see Figure 4.2) was re-processed and re-interpreted.

The aims of this paper were to:
• improve the seismic near the mine; and
• correlate the re-processing results with the data along the HR profile.

The crooked line acquisition geometry, low fold coverage, complex geology and sparse outcrops in the area, made the data re-processing and re-interpretation challenging. Re-processing of the seismic profile was performed by focusing on important processing steps crucial for the crystalline environment. In particular, refraction static corrections and data filtering combined with a good estimation of stacking velocities were important steps in improving the seismic results. Figure 4.6 shows a portion of the unmigrated stacked data near the Kristineberg mine from the previous work and the re-processed one. This comparison demonstrates that the re-processed seismic section is significantly improved with more reflections observed at both shallow and deep levels; also in terms of event continuity and resolution. The re-processed seismic section shows higher frequency content than the previous seismic section. After testing various migration algorithms, Stolt migration with a constant velocity of 6000 m/s was used and preserved the steeply dipping reflections while produced less migration artifacts.

Cross-dip analysis (Nedimović and West, 2003a) also was carried out to obtain additional information about the main reflections. The analysis suggests a cross-dip component of 55° to the west for the main reflections in the central portion of the line which is consistent with the geological observations that most geological structures plunge to the west at this location.

Figure 4.7 shows 3D visualization of the re-processed seismic data with the recent seismic profiles in the area. With this visualization, we better correlated the new observed reflections with the results of the recent seismic
profiles in the area. The majority of the reflections are interpreted to originate from fault zones and in some cases lithological contacts. We can see that reflection K1 is likely in direct association with the main Kristineberg mineralization.

Figure 4.6. A portion of (a) the previous and (b) re-processed unmigrated stacked section. Both sections are comparable for strong reflections; improvements (black arrows) in seismic reflections can be noticed at all levels (b) with relatively higher frequency content (modified from Ehsan et al., 2012).
Figure 4.7. 3D views (a and b) showing visualization of the re-processed migrated seismic section of Profile 1 with the HR profile, Profile 2 (unmigrated section) as well as mineralization surfaces from borehole data in the Kristineberg mine. Reflection K1 clearly correlates with the location of the mineralization horizon (dark blue, green and light blue). Reflections M1 and E1 correlate well on both Profile 1 and the HR profile. Blue surfaces in the western side of the 3D view (b) are Rävliden massive sulfide deposits. The depth of the seismic profiles is 3800 m. No vertical exaggeration. Ore body shapes are kindly provided by Boliden Mineral AB (modified after Ehsan et al., 2012).

Comparison of the re-processed results with the newly acquired seismic data, earlier potential field modeling results and geological observations from the area helped to better explain the structural complexity of the Kris-
tineberg mining area with the aid of a rift model and a sequences of compressions and oblique slip movements using the simple sketch shown in Figure 4.8. During volcanic activity (Figure 4.8a) a large number of normal faults, were generated. North-south and east-west compressional regimes reactivated these major faults (Figure 4.8b), but in a reverse movement and also generated new ones along weak structural and contact lithologies (Skyttä et al., 2010). Local basin inversion is also expected during this episode (Bauer et al., 2011). The Revsund granite (post-tectonic), the youngest intrusion in the area, cross-cut major structures in the study area (Figure 4.8c).

4.3.2. Conclusions

Seismic data re-processing of the Kristineberg seismic profile (Profile 1) was performed with a special focus on the data near the mine and on the processing steps crucial for data acquired in the crystalline environment. It showed that with careful attention to refraction static corrections as well as retaining useful high frequencies in the data, it is even possible to obtain a reasonably good seismic image of subsurface structures from low fold seismic data (about 17). Combined with the newer seismic data more information about large-scale geological structures was obtained. This can be helpful for exploration in the area or at least to help better understand the tectonic evolution of the study area.
Figure 4.8. A simplified geological model across the Kristineberg area (modified after Skyttä et al., 2011), showing (a) syn-extensional volcanism (e.g., Skellefte volcanic rocks), mineralization, sedimentation and intrusive activity (e.g., Viterliden intrusion), (b) subsequent crustal shortening leading to basin inversion (Bauer et al., 2011) and related transposition of the mineralized horizons. (c) Post-tectonic Revsund type granite intruded at about 1.8 Ga and cross-cut major geological structures. K1, K2, and E1 schematically represent reflections from the re-processed migrated seismic section (from Ehsan et al., 2012).
4.4. Paper IV: 3D constraints and finite difference modeling of massive sulfide deposits: The Kristineberg seismic lines revisited, northern Sweden

4.4.1. Summary

In this study we carried out pre-stack time migration, swath 3D imaging of the 2D crooked line and generated synthetic seismic data using both acoustic and elastic finite difference algorithms for the Kristineberg data.

The aims of this study were to:
• provide further insight about the nature of the main reflections;
• provide 3D geometrical information on a reflection observed in the western part of Kristineberg; and
• better understand processing challenges in the Kristineberg mining area.

Petrophysical measurements carried out by Malehmir et al. (2006 and 2013) indicate that the massive sulfide samples have large grain size variations and densities as high as 4300 kg/m³, but most show low P- and S-wave velocities. Still, due to their high density, we expect that they can produce strong seismic signal. However, this depends on the S/N, the orientation of seismic lines with respect to the dominant dip, good ground coupling, and the degree of signal distortions through the near surface. Results of the measurements are summarized in Table 4.1, and this was used for the finite difference seismic modeling.

**Table 4.1. Compilation of physical property measurements in the Kristineberg area (Malehmir et al., 2006 and 2013). Reflection coefficient (R) is calculated for the P-waves and is relative to a background velocity of 5750 m/s and density of 2700 kg/m³. Superscript numbers are referred to the legend of Figure 4.9.**

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Density (kg/m³)</th>
<th>V_P (m/s)</th>
<th>V_S (m/s)</th>
<th>R</th>
</tr>
</thead>
<tbody>
<tr>
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<td>2850</td>
<td>5500</td>
<td></td>
<td>0.0048</td>
</tr>
<tr>
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<td>6250</td>
<td>3500</td>
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</tr>
<tr>
<td>Altered volcanics³</td>
<td>2800</td>
<td>5650</td>
<td>2600</td>
<td>0.0094</td>
</tr>
<tr>
<td>Massive sulfide⁴</td>
<td>4300</td>
<td>5000</td>
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<tr>
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<tr>
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<tr>
<td>Metasediments⁷</td>
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<td>3150</td>
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<tr>
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<td>5750</td>
<td>3150</td>
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</tr>
</tbody>
</table>

Based on the results from the post-stack migration of the HR profile in the Kristineberg area, a constrained geological cross-section was constructed using seismic results from the HR profile, borehole data from the mine, as
well as surface and ground geological observations (Figure 4.9; D. Coller, personal communication, 2011).

Figure 4.9. (a) Post-stack migrated seismic section along the HR profile, and (b) interpreted geological cross-section along the HR profile. A constant velocity of 5800 m/s was used for the time-to-depth conversion. The numbers shown in the geological legend are related to physical properties listed in Table 4.1.
Figure 4.9 shows that the Kristineberg ore laterally projects to a highly reflective zone (M1) that dips towards the south and may flatten out at a depth of about 2.2−2.5 km. Two sets of flat-lying reflectors at these depths (E1 and E2) are considered to be important geological targets for future deep exploration. The geological cross-section shows that the reflective zones, possibly indicative of mineralization, occur predominantly within the felsic volcanic rocks. Figure 4.9b and its interpretation was used further to study the seismic response of the massive sulfide ore bodies and their host rock structures using finite difference seismic modeling methods.

Re-processing of the HR profile near the Kristineberg mine was done using a pre-stack time migration algorithm. A pre-stack Kirchhoff time-migration algorithm operating in the common-offset-domain was used. Since no sonic log information is available, it was not possible to build a constrained velocity model for the migration. However, large, long wavelength velocity changes are not expected in this crystalline environment in comparison with sedimentary environments (Adam et al., 2003; Juhlin and Stephens, 2006). Thus, our approach in this work was to use constant migration-velocity stacks and inspect visually the quality of the obtained migrated stacked sections. We ran a series of pre-stack time migration tests using velocities ranging from 5500 m/s to 6500 m/s with 100 m/s increments. The best results were obtained using a velocity of 5800 m/s. Figure 4.10a and 4.10b show a comparison between post-stack and pre-stack migrations along the HR profile. We could image a high-amplitude gently dipping reflection (S1) that was not observed before and this is now presented within the main reflective zone above the ore horizon (Figure 4.10b). This processing resulted in a migrated section that appeared to contain less artifacts, but also showed less detail than the post-stack migrated section (Figure 4.10a and 4.10b).

2D acoustic and elastic finite difference modeling along the HR profile was carried out to compare the results of post-stack and pre-stack migrations and also to support our interpretation of the seismic data (Figure 4.10c, 4.10d, 4.10e and 4.10f). Processing of the synthetic data suggest that processing artifacts are present that manifest themselves as steeply dipping events. These artifacts are stronger when the data are processed using post-stack migration methods but reduced with the application of pre-stack migration (Figure 4.10c and 4.10e). Steeply dipping structures are not imaged clearly on the synthetic data, note that reflection C1 is only observed in the post-stack migrated section and C1 at a depth below 3000 m is a processing artifact as it is demonstrated from the post-stack migration of the synthetic data.

In order to provide 3D geometrical information on a shallow flat-lying reflection (L1), observed west of the Kristineberg mine on both previous and new seismic data (Profiles 5 and 2 see in Figure 2.2 for the location of the profiles, stacked sections are shown in Figure 4.11a and 4.11b), we com-
bined data from the two crossing profiles where the reflection was observed and then we processed the data in 3D (see box in Figure 2.2 showing the location of the 3D swath imaging). The observed reflection has a dip component to the southwest and this is noticeable on crossline 1040 (Figure 4.11c). We suggested that this reflection correlates with the contact of the metasedimentary and metavolcanic rocks and has a dip of about 30°. The dip is calculated based on the apparent dip observed on the stacked section for a given velocity of 5750 m/s (see Stolt, 1978). Later Boliden Mineral AB confirmed these dips from borehole data in the area, making the reflecting horizon an ideal candidate for further study.

4.4.2. Conclusions

Pre-stack migration allowed imaging a reflection (S1) that was not observed from the previous processing results and we suggest this reflection to be an important target for future mineral exploration in the study area. Processing of the synthetic data suggests that processing artifacts are present that manifest themselves as steeply dipping events. Using pre-stack migration for the HR profile resulted in a section containing less artifacts, but also showed less detail than the post-stack migration. These artifacts are stronger when the data are processed using post-stack migration methods but reduced with the application of pre-stack migration. The 3D swath processing also was useful to define an attitude of the contact between the metasedimentary and metavolcanic rocks, and indicating an approximately 30° southwestly dip. This contact also is an important target for further mineral exploration in the area.
Figure 4.10. Comparison between post-stack migrated sections (a, c and e) and pre-stack time migrated sections (b, d and f), for (a) real data along the HR profile, (c) synthetic acoustic data, and (e) synthetic elastic data, suggesting a good correspondence between the real data and the synthetic migrated sections. M1 represents a highly reflective south-dipping zone where major VMS deposits occur. E1 and E2 are two sets of strong reflections observed in the real data. S1 is only observed in the pre-stack migrated section of the real data (b). Steeply dipping structures are not imaged clearly on the synthetic data, note that reflection C1 is only observed in the post-stack migrated section and C1 at a depth below 3000 m is a processing artifact as is demonstrated from the post-stack migration of the synthetic data. A constant velocity of 5800 m/s was used for the time-to-depth conversion (based on Dehghannejad et al., 2012).
Figure 4.11. (a) A portion of the stacked section along Profile 2 and (b) Profile 5, showing a flat-lying reflection (L1) marked by arrow at about 450 ms observed in both profiles. (c) The 3D view of an inline and a crossline extracted from the stacked seismic volume, demonstrating that the reflection L1 dips about 30° towards the southwest.
5. Conclusions

The 2D crooked line reflection seismic data acquired over the crystalline environment present challenges and opportunities. Results from these data sets clearly demonstrate that reflection seismic data can be of great value to the mining industry for precise targeting of extensions of existing deposits and mapping new potential targets. 3D integration of seismic results with verified geological observations and other geophysical results show an important interdisciplinary approach in the district.

These 2D crooked line reflection seismic data clearly allowed imaging of diffractions, sub-horizontal to steeply dipping reflections related to lithological structures, shear zones and potentially mineralized zones.

In Paper I, results along the seismic profiles in the Kristineberg mining area allowed imaging of reflections associated with mineralized zones or structures in the area, and one could note that the Kristineberg mineralization and associated structures dip to the south down to at least a depth of about 2 km. The high-resolution seismic data in the area showed much more detailed structures and provided local-scale constraints on the subsurface geology than the seismic data from the pilot studies.

In Paper II, results from the three seismic profiles in the central Skellefte district showed a different seismic character compared with those from the Kristineberg mining area, and in conjunction with detailed geological observations, led us to correlate main reflections and diffractions with major faults and shear zones in the area. These results provided constraints for the construction of the first large-scale 3D geological model of the central Skellefte ore district to about 5 km depth.

In Paper III, results of the re-processing of a seismic profile from the pilot study demonstrated how further improvements were possible by giving especial attention to some of the processing steps. Refraction static corrections as well as retaining useful high frequencies in the data helped to obtain an improved seismic image of subsurface structures from low fold seismic data, providing more information about large-scale geological structures. Results of the re-processed line had higher quality and together with the high-resolution line (HR) allowed better quality interpretations.

In Paper IV, pre-stack migration allowed imaging a reflection that was not observed from the previous processing results near the Kristineberg mine and suggested this reflection to be an important target for future mineral exploration in the study area. Finite-difference modeling was helpful to de-
determine the response of the geological model and validate the interpretations along the seismic profile in the Kristineberg mining area. Processing results of the synthetic data compared to the real data suggested that pre-stack migrated sections contain less artifacts, but also show less detail than the post-stack migrated sections. These artifacts that manifested themselves as steeply dipping events were stronger when the data were processed using post-stack migration methods compared with pre-stack migration methods.

Cross-dip analysis, reflection modeling, swath 3D processing allowed the 3D geometry of some of the observed reflections to be obtained and it is suggested that these be carried out as routine processing and analysis approaches for the 2D crooked line reflection seismic data.

At the end, I would like to highlight a few lessons that can be helpful for future studies:

• Shorter shot and receiver spacing was required to successfully image the complex geological structures of the district;
• While acquiring 2D crooked reflection seismic data, extra shots on either or both sides or parallel roads would not only increase the seismic fold but also allow increased midpoint coverage and these would then be helpful to extract 3D information from the semi-3D data;
• Accurate 3D forward modeling using finite-difference modeling algorithm and a physical property database would help to better understand the seismic response of ore deposits and to validate geological models;
• Use of multicomponent sensors could be useful to be tested in the future to constrain seismic interpretations and may allow the prediction of composition and information about anisotropic structures;
• A significant effort could be made to produce high-quality true-amplitude sections (amplitude versus offset (AVO) analysis). This is, however, a significant challenge in hardrock areas characterized with low S/N and discontinuous reflections that are difficult to image without the application of pre-stack automatic gain control to partly balance the amplitudes;
• Downhole seismic studies can be useful for suitable exploration targets;
• 3D seismic surveys following the 2D studies can increase the accuracy of structural images of the subsurface, and also can provide stratigraphic information that is not present in 2D seismic data. A detailed deep exploration-drilling program should only be considered after the implementation of 3D surveys.
6. Summary in Swedish

Skelleftefältet i norra Sverige har tolkats som en paleoproterozoisk vulkanbåge. Det är ett av de viktigaste malmdistrikten i Sverige och malmkropparna är av typen Vulkaniska Massiva Sulfider (VMS) och producerar i huvudsak basmetaller, men även guld och silver. Prospektering och brytning av mineralresurser flyttas mot större djup på grund av svårigheten i att finna ytnära malmkroppar, men också tack vare de höga metallpriserna. Därför är det viktigt att bättre förstå de tredimensionella geologiska strukturerna ner till några kilometers djup. En sådan tredimensionell förståelse av berggrunden är viktig för att hitta fler malmkroppar samt för att planera framtida gruvdrift.

Efter ett lyckat pilotprojekt med 3D geologisk modellering i de västra delarna av skelleftefältet (omkring Kristineberg gruvan) lanserades 2008 ett nytt projekt ”VINNOVA 4D modeling of the Skellefte district” i syfte att förbättra existerande geologiska modeller på grunda djup, samt utöka modellen mot de centrala delarna. Mer än 100 km (krokiga) reflektionsseimiska profiler mättes in, bearbetades och tolkades integrerat med geologiska observationer och potentialfältsdata. Resultaten användes för att förbättra existerande 3D geologiska modeller, men gav även ny information om geologi och potentiella malmfyndigheter på större djup.

Två nya (i de närmaste vinkelräta) profiler i Kristineberg området förbättrade den existerande lokala geologiska modellen jämfört med modellen från pilotprojektet och visade även på förmågan att lokalisera starkt mineraliserade zoner med reflektionsseismik i området. Den mineraliserade zonen i Kristineberg samt strukturer associerade med denna stupar mot syd ner till ett djup av ungefär två kilometer. I de centrala delarna av Skelleftefältet visade tre (nästan parallella) profiler en annan seismisk karaktär jämfört med seismiskt data från Kristineberg området. De starkaste reflektionerna och diffractionerna kunde korreleras med förkastningar och skjuvzoner i området. Dessa resultat kunde användas för att konstruera en första 3D geologisk modell över de centrala delarna av Skelleftefältet ner till ett djup av ungefär fem kilometer. Tolkning av observerade reflektioner och svårigheter med standard seismisk processering förbättrades och förenklades med hjälp av användandet av Cross-dip analysering, reflektions modellering, pre-stack tidsmigrering, swath 3D processering samt Finit-differens seismisk modellering. Även om 3D seismiska data är oftast att föredra för att uppnå en precis lokalisering av potentiella mål för exploatering i gruvdistrikt, visar re-
sultaten från denna avhandling att även 2D seismiska profiler kan ge mycket värdefull information i gruvdistrikt, särskilt då resultaten kan verifieras med geologiska observationer och andra geofysiska data.
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