UPPSALA UNIVERSITET

Examensarbete vid Institutionen för geovetenskaper
Degree Project at the Department of Earth Sciences
ISSN 1650-6553 Nr 529

2D Reflection Imaging of Sparse 3D Data in the Zinkgruvan Mine, Central Sweden

Reflektionsmodellering i 2D av glest 3D data från Zinkgruvan, mellansverige

Maryam Abbasian

INSTITUTIONEN FÖR GEOVETENSKAPER
DEPARTMENT OF EARTH SCIENCES

Examensarbete vid Institutionen för geovetenskaper
Degree Project at the Department of Earth Sciences
ISSN 1650-6553 Nr 529

2D Reflection Imaging of Sparse 3D Data in the Zinkgruvan Mine, Central Sweden

Reflektionsmodellering i 2D av glest 3D data från Zinkgruvan, mellansverige

Maryam Abbasian

ISSN 1650-6553

Published at Department of Earth Sciences, Uppsala University (www.geo.uu.se), Uppsala, 2021

Abstract

2D Reflection Imaging of Sparse 3D Data in the Zinkgruvan Mine, Central Sweden
Maryam Abbasian

Zinkgruvan mining area in the southern Bergslagen mineral district of central Sweden holds over 30 million tons of massive sulphide mineralization. The ever-increasing global demand for mineral/metal resources, together with metal consumption growth especially for high-tech purposes has made the exploration of these resources of particular importance. In this thesis work, as a part of the larger research-industry SIT4ME project, Seismic Image Techniques for Mineral Exploration, project sponsored by the EIT Raw Materials, three 2D-crooked reflection seismic profiles were extracted from a sparse 3D dataset in the Zinkgruvan mining area and processed in a combination since approximately 600 receivers simultaneously recorded 368 shots along these three different profiles. One of the profiles (P1) was acquired using 10 m receiver and source intervals, while the other two profiles (P3 and P4) were acquired using 20 m receiver and 10 m source intervals. The data show notable reflections on several shot gathers presenting reasonable quality, although parts are severely contaminated with electricity grid noise from a major powerline crossing the profiles. The study mainly aims at providing information applicable for near surface structural imaging in this complex geological setting. Three different combinations of CDP lines for every two different profiles were binned and processed together in order to examine 3D nature of reflections and their corresponding geological origins. Through a number of tests and careful parameter selections, reflections in the raw shot gathers were enhanced. The final sections (both unmigrated and migrated stacks) show clear reflections associated with important geological units. This thesis presents the acquisition setup, reflection seismic processing procedure, results obtained and the interpretation of the three cross profiles in conjunction with available geological data from the site. The sections show a good correlation with the available borehole data from the site.

Keywords: 2D crooked-line, reflection seismic, sparse 3D, mineralization, Zinkgruvan

Degree Project E in Geophysics, 1GE029, 30 credits

Supervisors: Alireza Malehmir and Alba Gil
Department of Earth Sciences, Uppsala University, Villavägen 16, SE-752 36 Uppsala (www.geo.uu.se)

ISSN 1650-6553, Examensarbete vid Institutionen för geovetenskaper, No. 529, 2021

The whole document is available at www.diva-portal.org

Populärvetenskaplig sammanfattning

Reflektionsmodellering i 2D av glest 3D data från Zinkgruvan, mellansverige

Maryam Abbasian

Zinkgruvans gruvområde, i södra bergslagens mineraldistrikt, i mellansverige håller över 3 miljoner ton massiv sulfidmineralisering. Den tilltagande globala efterfrågan av metall- och mineralresurser tillsammans med ökad konsumtion av metall, särskilt för högteknologiska syften, har gjort utvninning av dessa resurser av särskild vikt. I detta examensarbete, som är en del av ett större industri-forskningsprojekt sit4me sponsrat av EIT Raw Materials, extraherades tre 2D-böjda seismiska profiler från ett glest dataset i Zinkgruvan gruvområde och processerades i kombination då cirka 600 mottagare simultant registrerade 368 skjutningar från dessa tre separata profiler. En av profilerna (P1) är framtagen med 10 m mottagar- och sändarintervall, medan de andra två profilerna (P3 och P4) är farmtagen med 20 m mottagarintervall och 10 m sändarintervall. Datat visar tydliga reflektioner på flera skjutsamlingar vilket påvisar godtagbar kvalitet, även om delar är påtagligt påverkade av elektriskt grid-brus från en större strömkabel som korsar profilerna. Det här arbetet syftar främst till att ta fram information som är applicerbar för ytlig strukturmodellering i detta komplexa geologiska område. Tre olika kombinationer av CDP linjer för de två olika profilerna binnerades och processerades tillsammans för att utforska 3D strukturer av reflektioner och korresponderande geologiska utformningar. Genom ett flertal olika tester samt noggrannt utvalda parametrar, så kunde reflektioner i de ursprungliga skjutsamlingarna förstärkas. De slutliga sektionerna (både de omigrerade och migrerade samlingarna) påvisar tydliga reflektioner som kan associeras med viktiga geologiska enheter. Detta examensarbete presenterar parametrar för inhämtning av data, proceduren för reflektionsseismisk processering, resultat som kan utläsas samt tolkning av dessa tillsammans med de tillgängliga geologiska enheterna. Sektionerna påvisar bra korrelering med tillgängligt borrhålsdata från området.

Nyckelord: 2D modellering, reflektionsseismik, mineralisering, Zinkgruvan

Examensarbete E i geofysik, 1GE025, 30 hp
Handledare: Alireza Malehmir och Alba Gil
Institutionen för geovetenskaper, Uppsala universitet, Villavägen 16, 752 36 Uppsala (www.geo.uu.se)

ISSN 1650-6553, Examensarbete vid Institutionen för geovetenskaper, No. 529, 2021

The whole document is available at www.diva-portal.org

Table of Contents

1 Introduction

The growing demand of metals and industrial minerals together with their ever-increasing consumption with the annual population growth and improved living standards especially in developed countries has put pressure on the mineral exploration industry to provide resources of raw materials (Zepf et al., 2014, Malehmir et al., 2020). Fresh supply and discovery of mineral deposits is vital for green technologies also in order to help a smooth transition towards a neutral carbon world (Malehmir et al., 2020). Based and ferrous deposits are likely the first resources to be demanded as they contain economical tonnage of zinc, copper, iron, apatite, REEs, Titanium and Vanadium (Malehmir et al., 2020). They are also fundamental for our industrial growth particularly in the infrastructure industry. Therefore, solutions that can provide high-resolution subsurface images and targets for exploration are required to be developed and upscaled. In this regard, geophysical methods have and will play a major role in identifying prospecting areas and defining deep targets. They are non-invasive and have sensitivity to most metallic deposits.

Among the various geophysical methods, two methods have not yet fully uptaked by the mineral exploration industry. These are (1) reflection seismic methods and (2) magnetotellurics (or MT), which have good sensitivity to density and conductivity contrasts, respectively. Several publications have shown that reflection seismic methods have the potential in providing key information for mine planning and mineral exploration. Seismic methods have proven to provide higher resolution images of mineralization compared to other geophysical methods while the technique does not fail its resolution with depth; accordingly, the method is applicable to image the subsurface geological features at all depth (Malehmir et al., 2012; Urosevic et al., 2007) while is considered to be one of the most cost-efficient geophysical methods. Particular to this thesis and relevant to Swedish geology, an integration of various geological and geophysical data with reflection seismic data has shown to provide much reliable geological information when used for the Scandinavian Precambrian crust (e.g., Malehmir et al., 2006, 2007; Juhlin and Stephens, 2006). Examples are numerous when crustal-scale features are studied in Sweden. Nonetheless, the method is not yet totally up-taken by the Swedish mineral industry, which traditionally needs more time to uptake new technologies that are unfamiliar to them despite several successful case studies available from Sweden on particularly ferrous deposits (e.g., Malehmir et al., 2011). Earlier initiatives were helpful to partly establish the method (e.g., Dehghannejad et al., 2012 and 2013).

Given the complex geology in the Swedish bedrock, 2D seismic surveys should be done mainly for reconnaissance and parameter testings. 3D seismic surveys are desired in many hard rock environments to produce a reliable image of the subsurface structures, although they are infrequently used as they are more expensive (Malehmir et al., 2017). Moreover, high fold and resolution 3D surveys are cost demanding due to their need for thousands of shot and receiver points lines, which may require also substantial line cutting and clearance in the dense vegetation in the Nordic countries (Malehmir et al., 2020). A solution to address 3D geology and the cost of regular 3D seismic survey need to be developed. Cross 2D-recording (Rodriguez-Tablante et al., 2007; Maries et al., 2020) or sparse 3D surveys (Malehmir et al., 2020) have some potentials although they have also some major limitations.

2D seismic surveys cannot successfully produce a true picture of the subsurface structures and also the geometry of the geological features they image unless there is a dense profile networking crossing each other allowing a better control on the 3D geometry of the structures. One solution to this shortcoming is to take advantage of midpoint spread around 2D crooked-line surveys in order to analysis for example out-of-the-plane nature of the reflections or their possible cross-dip component (e.g., Larner et al., 1979; DuBois et al., 1990; Bellefleur et al., 1995; Nedimović and West, 2002, 2003).

This thesis work which was conducted as a part of a larger scientific industrial research project, three 2D crooked reflection seismic profiles were extracted from a sparse 3D dataset and processed in a combination. The study area, Zinkgruvan mining area, located in the southern part of the Bergslagen mineral district, is one of the three most prospective mining regions in south-central Sweden. The area is known for its diverse mineral deposits and the Zinkgruvan alone holds over 30 million tons of massive sulphide deposits (Jansson et al., 2017). Sulphide minerals are the major source of world supplies of a wide range of metals and are the most important group of ore minerals. Geology in Zinkgruvan is complex hence prior to this project (see also Gil et al., 2020) it was unclear if reflection seismic surveys would be successful in imaging the complex subsurface geology of the area and provide key subsurface information.

This MSc degree work was conducted as a part of the EIT Raw Materials funded SIT4ME (Seismic Imaging Techniques for Mineral Exploration) project, at the Department of Earth Sciences of Uppsala University within the Geophysics Program. In this thesis, I present results from the three 2D crooked reflection seismic profiles that were processed in a combination during my project work. I present the acquisition setup, reflection seismic processing procedure, results obtained and a glance of their possible interpretation in conjunction with available geological data from the site. The final processed sections show notable sets of reflections and can be correlated with the existing borehole data from the site.

1.1 Motivation and main objectives

The main aim of this thesis is to process, image and interpret the reflection seismic data of the three combined profiles: A, B, and C, and provide information applicable for near surface structural imaging in this particular complex geological setting. The motivation was to check if the sparse 3D dataset fails to provide reasonable information, how 2D profiles in combination can help address the 3D complex geology of the site and if their imaging potential would be superior or lower than the 3D dataset given its sparsity. While this thesis will not do the comparative study, this motivation rests until the 3D sparse dataset is processed and becomes available.

Therefore, the main objectives of this thesis are to:

- provide information applicable for near surface structural imaging,
- examine the 3D nature of the reflections and their geometry from the combined 2D data,
- provide information on possible out-of-the-plane structures, and
- obtain knowledge of the depth and extent of key horizons hosting the mineralization in the area.

2 Geological setting

2.1 Bergslagen region

Zinkgruvan is a massive Zn-Pb-Ag-(Cu) deposit situated in the southern part of the Bergslagen region, in south-central Sweden (Figure 2.1) (Hedtröm et al., 1989; Jansson et al., 2017). The region is one the most prosperous mineral districts in Sweden with more than 1000 years of continuous mining hosting over 6000 occurrences in the country (Stephens et al., 2009; Malehmir et al., 2011). The Bergslagen region is believed to have been developed on an active continental boundary in a back-arc tectonic setting featured by extension and magmatism influenced by ductile deformation and metamorphism associated with crustal shortening/subduction and tectonic alteration (Allen et al., 1996; Hermansson et al., 2008). The region is part of the southern volcanic belt of the Svecofennian domain, which is part of the Baltic Shield that mostly contains supracrustal Precambrian rocks with an age of approximately 1.90 to 1.86 Ga (Gorbatschev and Bogdanova 1993; Gaál and Gorbatschev 1987). The supracrustal rocks in Bergslagen are mostly felsic metavolcanic rocks that are estimated to be as thick as 10 km (Kumpulainen et al., 1996).

Currently, in the Bergslagen region, three polymetallic sulphide mines are being extracted: Garpenberg, Lovisa, and Zinkgruvan; the latter is the focus of this study. The predominant mineral deposits in the region are iron-oxide deposits, while polymetallic (primarily massive sulphides) are subordinates (Allen et al., 2003).

2.2 Zinkgruvan mining area

The Zinkgruvan deposit is the southernmost underground mine in Sweden and supplies Zn, Pb and Cu (Figure 2.1). The deposit is mined by Zinkgruvan Mining AB Company, which is a subsidiary of Lundin Mining Corporation. Allen et al. (1996) referred the deposit as "stratiform ash-siltstone-hosted Zn-Pb-Ag sulphide deposit (SAS-type)", which was previously accredited as "Åmmeberg-type" (Geijer, 1917). Hydrothermal alteration is evident in the mine sequence and majority of the metallic deposits in the district are spatially associated with hydrothermally altered felsic volcanic rocks (rhyolitic to dacitic), marble, skarn and metasedimentary rocks.

A detailed description of the stratigraphic setting of the Zinkgruvan deposit has been provided by Hedström et al. (1989), Allen et al. (1996) and Kumpulainen et al. (1996). The deposit features distinctive stratification and spreads for more than 5-km-along strike and to the depths of 1,600 m. The Zinkgruvan formation was characterized as the region squeezed between the 'Mariedamm volcanic unit' and the 'Vintergölen formation', which are informally known as 'Emme group' (Hedström et al., 1989; Kumpulainen et al., 1996). The Zinkgruvan formation is a succession of grey, mainly fine-grained, biotite-bearing quartz-feldspathic rocks (the metatuffites unite), calc-silicate units and marble. Jansson et al. (2017) suggested that the Zinkgruvan formation is hosting the stratiform Zn-Pb-Ag mineralization.

Zinkgruvan is a complex stratiform deposit consisting of several thin layers, which is highly tectonized, folded and deformed by various major secondary faults in the area. There are two major fault systems that have been influencing the position and continuation of the deposit: Knalla and Nygruvan faults. The western part of the Knalla fault contains several ore lenses, which have been influenced by various folding and deformation, while on the other side of the fault (the eastern side), which is the Nygruvan ore body comprises an individual ore lens. The Nygruvan produced the majority of the historical extractions from the mine (Mining data solution. Various tectonic events and alterations influence the primary structures and lithologies making identification of the original structure uncertain (Bengtsson, 2000).

The deposit is a complex hardrock setting folded in different directions and the objective of this study is to image the massive sulphide mineralization in the formation and the structures hosting it.

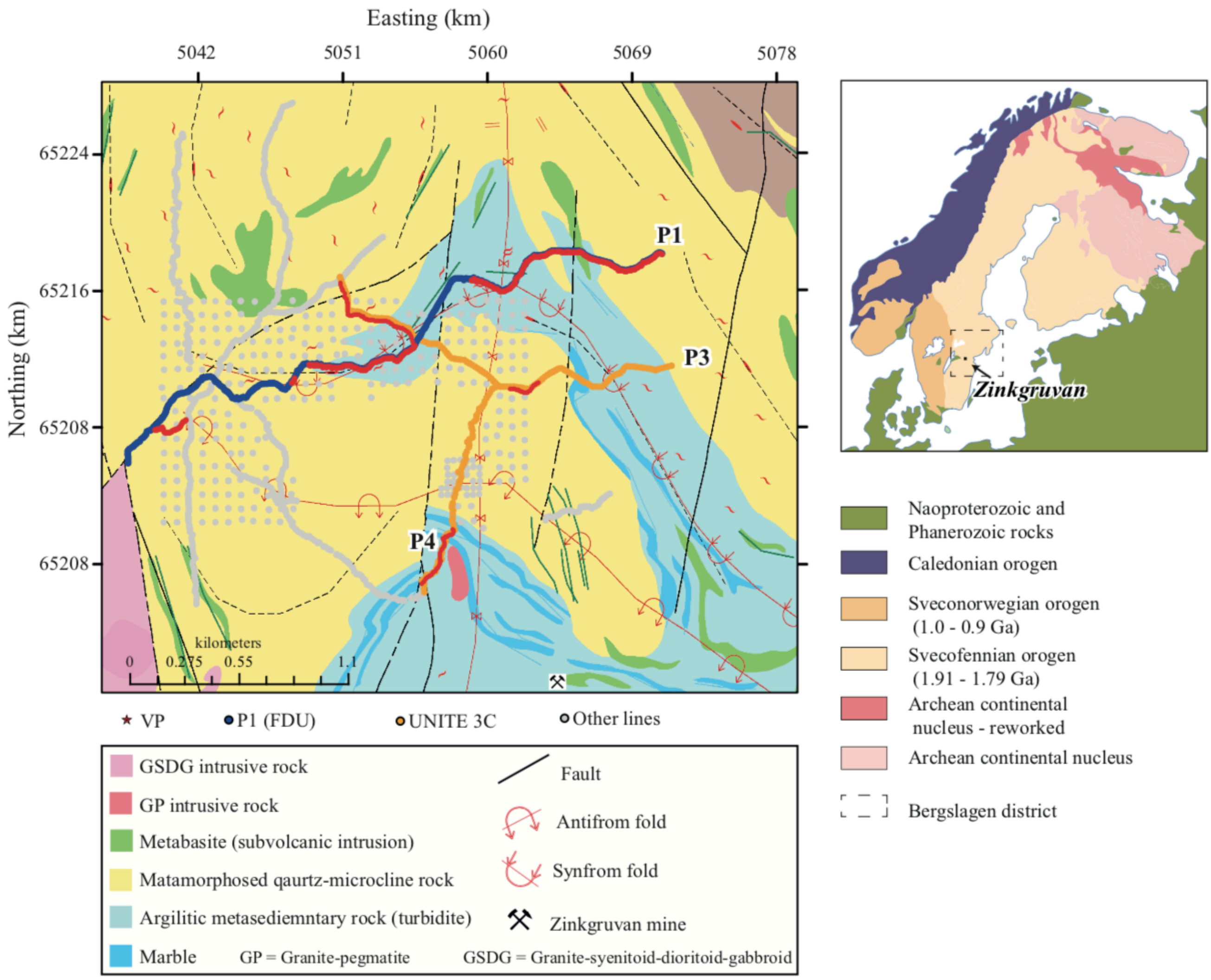


Figure 2.1 Geological map of the Zinkgruvan mining area showing the seismic profiles (blue, orange and grey lines) and major lithological units (modified from Stephens et al., 2009; SGU map). P1, P3 and P4 profiles are the focus of this study. Adapted based on Gil et al. (2020)

3 Seismic data acquisitions

The data presented in this study were acquired as part of a large scientific-industrial research project called Seismic Imaging Techniques for Mineral Exploration (SIT4ME). It involves several European institutions and co-funded by the EIT Raw Materials. As part of the project, a dense multi-method seismic dataset was acquired in the Zinkgruvan mining area of the Bergslagen mineral district of Sweden. This thesis, only focuses on a portion of the dataset that includes three 2D crooked seismic reflection profiles (P1, P3 and P4) extracted from the rather sparse 3D dataset. They are processed in a combined manner in order to explore combined 2D potential of the dataset (Figure 2.1).

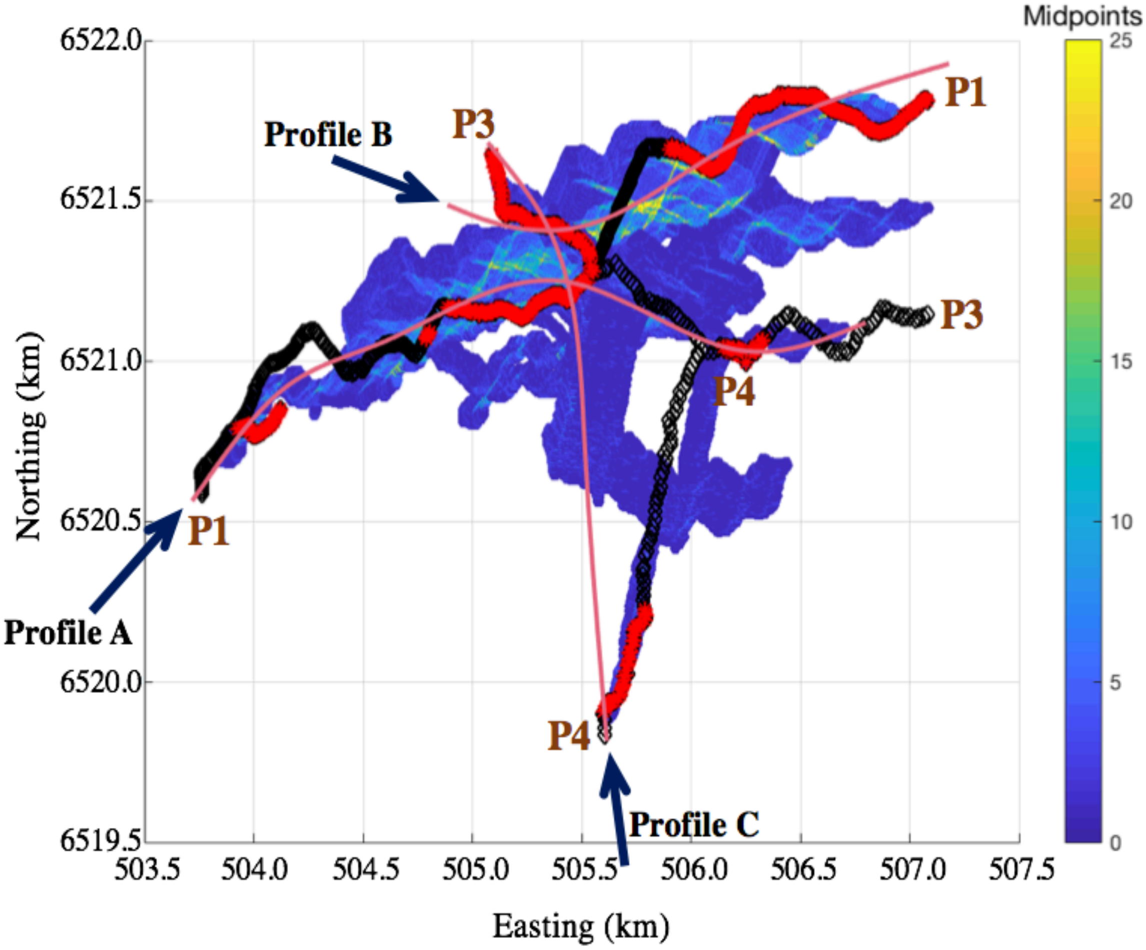


Figure 3.1 An illustration of the combined CDP lines and CDP midpoint coverage of the data used in this project work. Black dots represent the stations and red dots the shot points.

In November 2018, a multi-method seismic dataset was acquired in the Zinkgruvan mining area, including a combination of dense 2D profiles and sparse 3D grid in an area of 6 km^2 for the project (Figure 3.1) (Gil et al., 2020). The dataset was acquired using a 32t seismic vibrator (10-150 Hz) of TU Bergakademie Freiberg that was activated at every 10 m along the profiles (Figure 3.2). The acquisition spread involved 425, 1C-28 Hz cabled along with 192-3C (10 Hz) sensors simultaneously recorded 368 shots from the three different profiles (Figure 3.2). One northeast-southwest oriented seismic line (P1) with a total length of 4.25 km was acquired using 10 m receiver and source intervals, while the other two lines (P3 and P4) with a total length of 2.46 km and 1.38 km, respectively, were acquired using 20 m receiver and 10 m source spacing. The data were recorded using SERCEL 428 recording system and wireless recorders (Table 3.1). This setup provided a comprehensive dataset, which has been used for a multitude of processing and imaging approaches. Table 3.1 summarizes the main acquisition parameters of the acquired seismic lines (P1, P3 and P4).

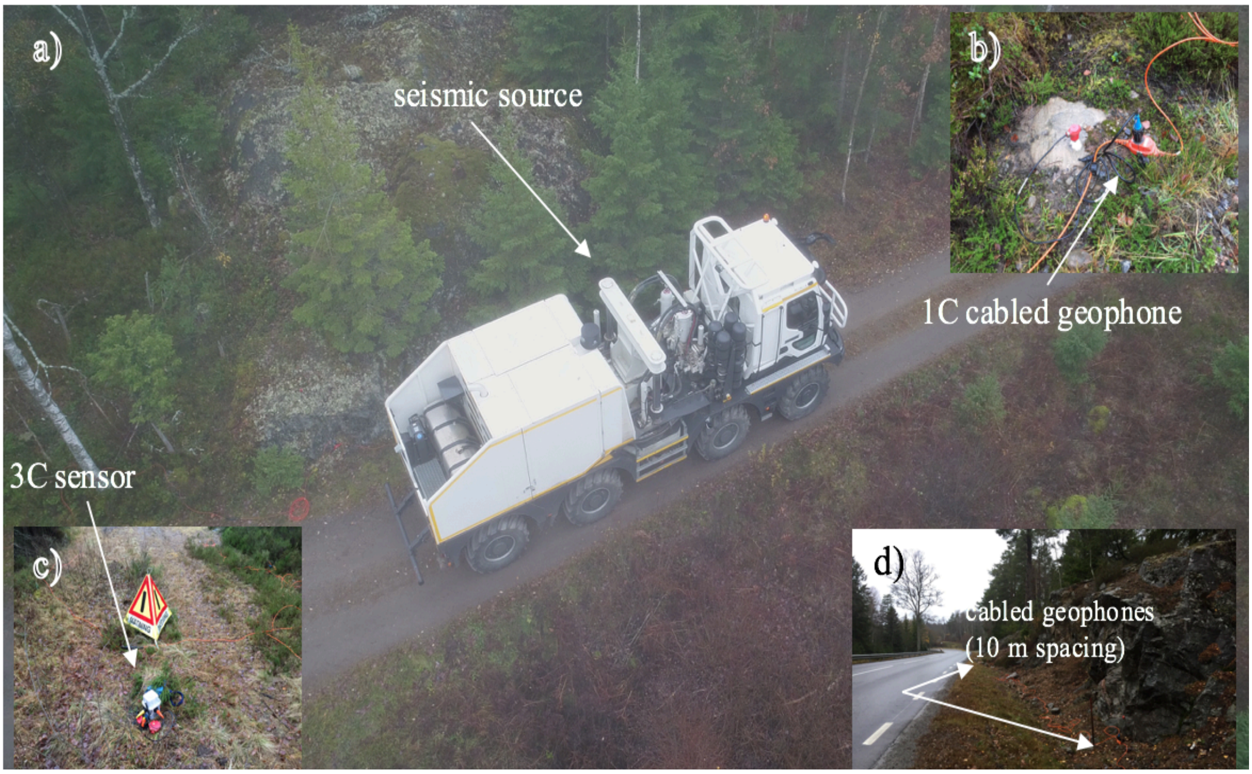


Figure 3.2 Example field photos during the seismic data acquisition showing (a) 32t seismic vibrator (10-150 Hz sweeps used) of TU Bergakademie Freiberg and (b) 1C cabled geophone, (c) 3C geophone, and (d) seismic line setup with conventional geophones (orange cables). Photos by A. Malehmir (November 2018).

The profiles processed (A, B, and C), in this thesis work are a combination of the three P1, P3 and P4 profiles. Profile A and B as shown in Figure 3.1 are different combinations of P1 and P3. Profile A provides an approximately east-west line with a total length of approximately 4 km with a CDP spacing of 5 m. Along P1 receiver and shot spacing was set 10 m. Profile B which is a combination of northern part of P1 and P3, has a length of approximately 2.7 km with the same CDP spacing of 5 m. Profile C is a combination of P4 and part of P3 with a length of approximately 2.2 km and with CDP spacing of 10 m given that a receiver spacing of 20 m was used along P3 and P4 (Figure 3.1).

In this study only vertical component data are used. For geodetic surveying, a Differential Global Positioning System (DGPS) was used and where relevant LiDAR (Laser imaging, detection, and ranging) data were used to correct for poor quality elevation data.

Table 3.1 Main acquisition parameters of seismic survey in the Zinkgruvan mining area, Fall 2018.

Survey Parameters			
Acquisition dates	November 5th to 25th 2018		
Acquisition type	Fixed spread geometry		
Source system	32t Vibrator (10-150 Hz 17 s long linear sweep)		
Field acquired Profiles	**P1**	**P3**	**P4**
Acquisition system	SERCEL 428	SERCEL UNITE	SERCEL UNITE
Number of active receivers	425-1C (28 Hz)	123-3C (10 Hz)	69-3C (10 Hz)
Number of shots	240	91	37
Receiver intervals	10 m	20 m	20 m
Shot intervals	10 m (all profiles where possible)		
Profile length	4250 m	2460 m	1380 m
Nominal fold	213	123	69
Sampling rate	1 ms		
Total number of traces	102,000	33,579	7,659

4 Methodology

In order to minimize acquisition footprint and image the near surface structure of the Zinkgruvan deposit, 2D crooked-line seismic reflection data were acquired. In this section, I present the processing steps that were applied to these three profiles, combined P1, P3 and P4, acquired in the area and briefly describe each step in the context of why and how they were applied. A conventional post-stack migration algorithm was used. By processing reflection seismic data, one aims at strengthening the resolution of the subsurface image to obtain clear reflections from various geological features. Moreover, by combining the acquired profiles I aimed at examining the 3D nature of the possible reflections obtaining a better 3D control on the nature of the reflections and their geometry.

4.1 Seismic waves

Seismic surveys are among the most widely used geophysical methods for subsurface imaging and characterization. The method is based on the analysis of the wave propagation through the Earth's subsurface (Sheriff and Geldart, 1995). Seismic methods like other geophysical methods depend on detecting contrasts of the subsurface materials (Telford et al., 1990; Sheriff and Geldart, 1995), or the location where the region is different from the others in their properties (i.e., elastic properties of rocks, for seismic methods). To simplify, seismic waves are the elastic strain energy movement whose speed depends on the properties of the medium through which the wave travels (Reynolds, 1997). Seismic sources (natural or passive and man-made or active) generate two main types of waves, which are divided depending on the way the seismic energy travels away from the source:

- Body waves – the energy travels through the interior (bulk) of the earth
- Surface waves – the energy travels near or along the ground surface.

This thesis work focuses on P-wave (body-wave) component of the elastic waves and considers all other wave types noise.

4.2 Reflection seismic data processing

The main objective of implementing seismic surveys is to achieve a proper subsurface image from the acquired data. By processing seismic data, one deals with improving the image resolution and clarity. The survey conditions along with the field acquisition parameters can greatly influence the seismic processing workflow (Yilmaz, 2001), therefore data processing steps might differ depending on different parameters and survey conditions. The processing steps for the profiles are mentioned in Table 4.1.

The seismic data processing of this study followed a standard pre-stack data enhancement (Malehmir et al., 2013) and post-stack migration to better control the processing workflow and parameters ensuring that reflections observed on shot records are preserved in the final stacked and migrated sections. Figure 4.1 shows the S/N enhancement for an example of shot gather recorded on Profile A after applying various processing steps.

4.2.1 Geometry application and first arrival picking

The first step before starting processing is to apply and decide what processing geometry should be used. A number of parameters control this including midpoint spreads and geological strikes. After assigning processing geometry (CDP line) and where needed correcting bad coordinates, first arrivals were picked in an automatic manner and then manually inspected and corrected for poor quality traces. Noisy traces including zero-offset traces were excluded from the picking.

4.2.2 Refraction static corrections

One of the main steps in processing the data acquired on land is refraction static correction. The purpose of refraction statics is to correct for the effects of the near-surface low-velocity zone and changes due to differences in source and/or receiver elevations by applying elevation and surface-consistent static corrections (Dentith and Mudge, 2014). Static corrections consist of vertical traveltime shifts to a flat datum" (Yilmaz, 2001). For refraction static corrections, the picked first arrivals are used to estimate the near-surface velocity model. After applying elevation and refraction static corrections, the near-surface traveltime changes are eliminated and reflection coherency are significantly improved (Figure 4.1b). The static corrections for each acquired profile, P1, P3, and P4, were calculated separately and then applied together in the processing workflow for combined processing lines: A, B and C. RMS values of the refraction static solutions were below 3 ms.

4.2.3 CDP sorting

Before the seismic data could be further processed and stacked, shot-receiver data has to be sorted into common midpoint (CMP) gathers. Based on the field geometry information, each singular trace is accredited to the midpoint between the shot and receiver locations related to that trace. Those traces with the same midpoint location are grouped together, making up a CMP gather. It is also quite common to incorrectly use CMP and CDP (common depth point) names interchangeably, however, this is only valid in the case of horizontally flat reflectors (Yilmaz, 2001). This thesis is not an exception of incorrectly using both terms.

4.2.4 Amplitude recovery and filtering

Further in the processing workflow, band-pass frequency filter was used and Automatic Gain Control (AGC) applied to help strengthen weaker reflection signals in the expense of normalizing all amplitude energies of wanted and unwanted events. Also, surface-consistence deconvolution filters consisting of 10 and 36 ms gaps and a 100 ms operator were employed to profile A to improve resolution and sharpen the reflections by removing cyclic events in the data.

4.2.5 Velocity analysis and NMO corrections

To remove move-out effect on reflection traveltimes due to source-receiver offset, Normal Move-Out or NMO correction is applied on CMP/CDP gathers, in order to "straighten" hyperbolic reflection traveltimes. This needs a careful choice of applied velocity since if the velocity is too low or too high, the reflection will not line up in a flat manner. With the purpose of applying NMO corrections, several constant velocities were first tested in a range of 5500-6500 with 100 m/s steps and in an iterative approach. The constant velocity of 5800-6000 m/s gave the best result and was chosen for the NMO corrections for the profiles.

4.2.6 Unmigrated stack

Once a suitable velocity function is determined, each trace in the CMP-gather is shifted in time by subtracting the corresponding move-out corrections. The move-out corrected traces in the CMP-gather are then added (stacked) together to produce one trace. This process, CMP-stack, reduces random noise, which does not line-up, while strengthening the reflection signal, which does thus improving S/N ratio of the data. Note that stacking reduces the data volume too – by a factor of the seismic fold. Much of the power of the seismic imaging derives from this step, which enhances the primary reflections (those only once reflected) at the expense of everything else. The final stacked section is shown in the result section of this thesis.

4.2.7 Post-stack migration

Migration moves dipping reflections to their true subsurface positions and collapses diffractions, thus increasing spatial resolution and yielding a seismic image of the subsurface (Yilmaz, 2001). Different post-stack migration algorithms were tested including phase-shift, finite difference, and Gazdag, and the best results were obtained using the finite-difference migration algorithm. To migrate the stacked section, a constant velocity of 5800-6000 (m/s) was applied for each profile based on the current knowledge of the approximate velocity in the area. The migrated images are shown in the result section.

Table 4.1 Principle processing steps applied for the combined profiles in this thesis.

Steps	Parameters
1)	Geometry set-up
2)	Picking first arrivals with automatic picking and manual corrections
3)	Refraction and elevation static corrections
4)	Trace editing
5)	Remove 50 Hz noise: band-stop at 50 Hz
6)	Top mute: 30 ms after first breaks
7)	Band-pass filter: 10-30-120-150 Hz
8)	Spectral equalization with BP 20-40-110-140 Hz, window 30 Hz
9)	Gapped deconvolution: 12 and 36 ms gaps, 100 ms filter length, white noise 0.1%; profile A
10)	Automatic gain control: 500 ms
11)	CMP sorting
12)	Velocity analysis (iterative)
13)	Residual static (iterative)
14)	NMO corrections
15)	Stack
16)	FX-deconvolution
17)	Trace balance: 0-1000 ms
18)	Finite-difference migration: 5800-6000 m/s
19)	Time to depth conversion using 6000 m/s

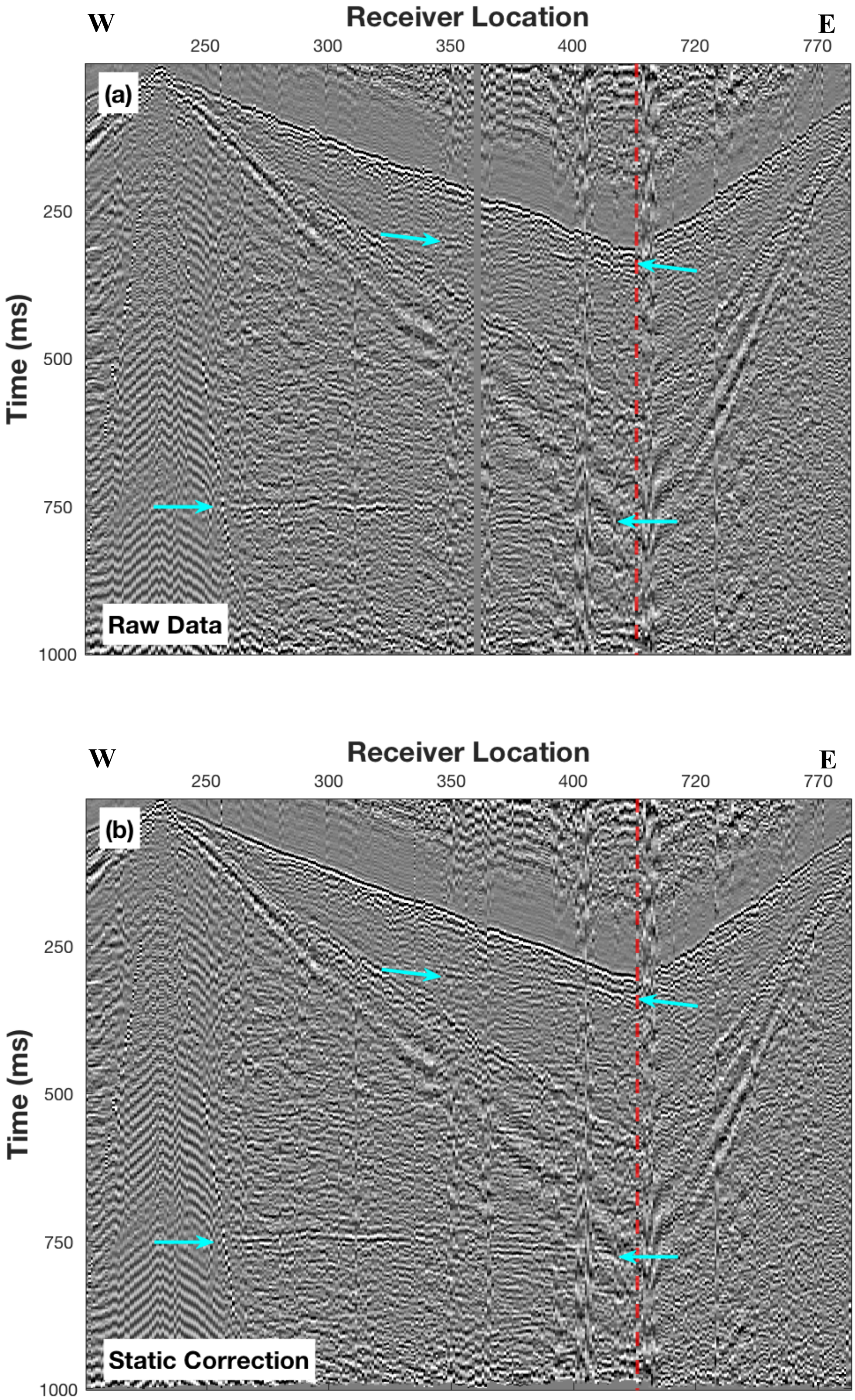


Figure 4.1 An example of shot gather (from profile A). (a) Raw data, (b) after refraction and elevation static corrections, (c) after band-pass filter and AGC, and (d) after deconvolution filter applied. Note the improvement in the quality of reflections are shown by the arrows.

5 Results and interpretations

In this section, I present the processed seismic data and their correlation with existing borehole data from the study area. To facilitate the interpretations, 3D views are used in order to allow a better 3D control on the geometry of major reflections and correlate them from one profile to another. The final sections are presented for each profile and described in detail.

Analysis of the shot gathers showed several reflection events (see an example from profile A in Figure 4.1). However, further processing steps were needed to preserve these events and enhance them in the final unmigrated and migrated sections. For profile B and specially profile C, it was difficult to observe reflections in the raw and even processed shot gathers but the reflections became evident in the unmigrated and migrated stacked sections as a result of CDP-fold stacking. Inspection of the unmigrated stacked sections suggests that the upper 3 km is highly reflective and that the geology of the site is suitable for reflection seismic studies.

5.1 General observations

The most significant set of reflections are from profile A, which is the longest CDP line among the three-processed profiles. Figure 5.1 shows the unmigrated and migrated stacked sections along with the CDP fold plot of profile A on top of the section. The western portion of the section (Figure 5.1) is more reflective compared to the east side of the section. As it is observed the most prominent reflections are located at around 0.5 s and 0.75 s, R1 and R2, in depths of approximately 1.4 km and 2.5 km with some shallower events visible in the uppermost 1 km of the section such as R3 and R4. R1 starts at CDP 200 and continues to 400, in the intersection of P1 and P3, and dipping towards the southwest. R2 is the longest and clearest reflection that extends from CDP 400 to the end of the section and is the one with higher resolution along the section. It gently dips towards the east. R3 and R4 are shallower set of reflections and dip in approximately 20-30°. They might project to the surface according to the migrated stacked section. The lower eastern part of the section contains no major event and is muted in the migrated section as it does not produce any useful information than just migration smiles around the edge of the section due to the low fold contribution as shown in the Figure 5.1.

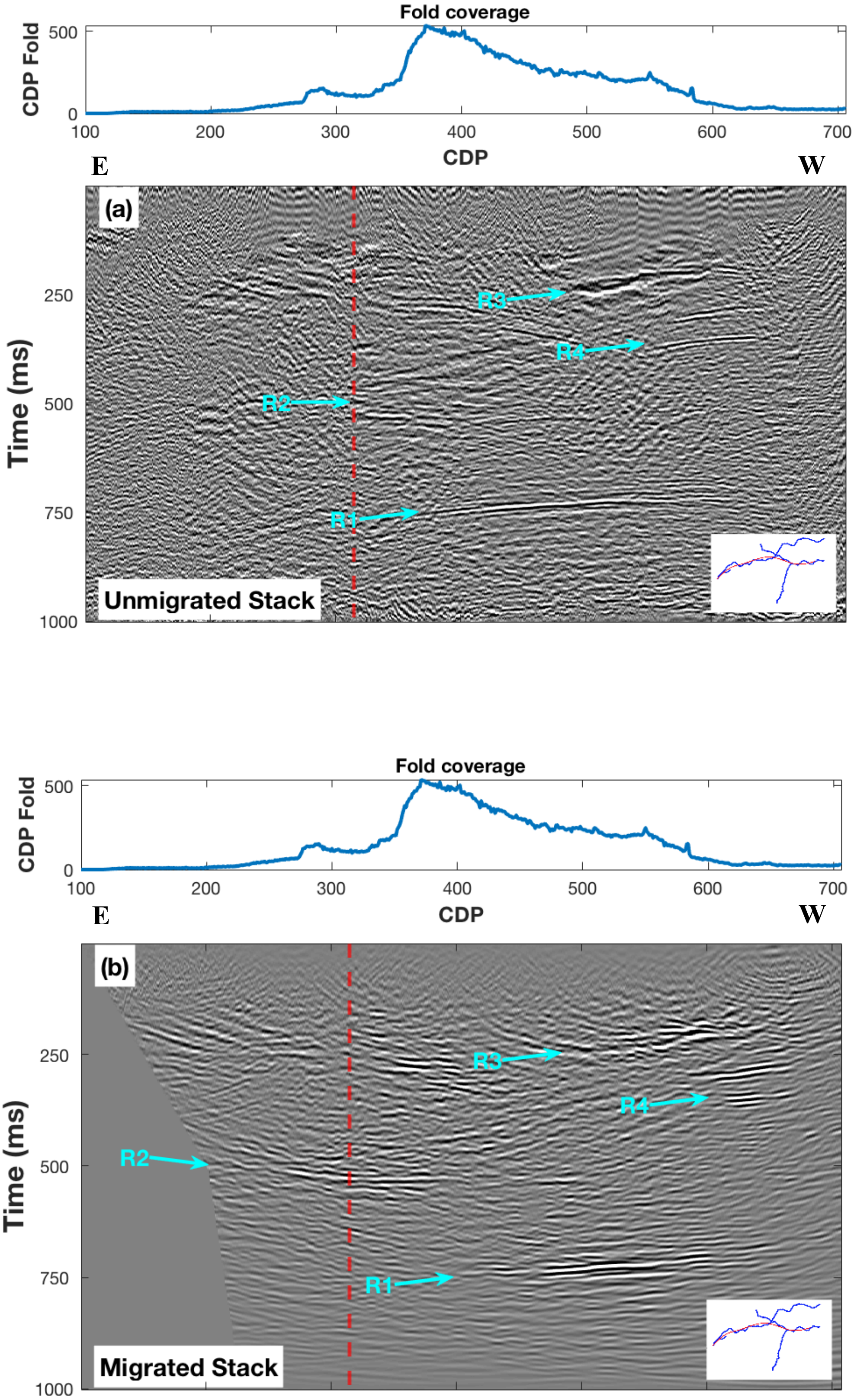


Figure 5.1 (a) Unmigrated stacked section of profile A (combination of P1 and P3) shown dwon to 1s, (b) migrated stacked section of profile A. Location of the section is shown in lower left corner. An illustration of the CDP fold in profile A is shown on top of the section. The dashed line indicates where P1 and P3 intersects; the left side of the line shows the P3 portion of the profile A and the right side shows the portion of the section belongs to P1.

Figure 5.2 shows the unmigrated section of profile B with CDP fold plot on top of the section (The migrated section of profile be has been shown in the 3D view plots). P3 and P1 are located on the western and eastern sides of the section, respectively. T1 and T2 are the major reflections in the section. T1 is situated at around 500 ms from CDP 300 to 500, at approximately 1.5 km depth, and T2 is located deeper at around 750 ms and extends from CDP 400 to the end of section, or at approximately 2.2 km depth. T2 slightly dips, 10-15°, towards the east.

Profile C shows two sets of reflections, S1 and S2 (Figure 5.3). These reflections are steeper than those seen in profile B, dipping around 25-35° towards the east. S1 is located at around 250 ms and extends to 400 ms, or at approximately from750 to 1300 m depth in the P4 portion of the section. S2 is observed in the P3 portion of the section and starts right after S1 at around 400-600 ms, nearly at 1300-1650 m depth. This section also seems to be featured with some possible surface events which are quite obvious in the figure.

5.2 3D visualization and correlation between profiles

In order to study 3D orientation of various reflections, they were visualized and studied in detail. By correlating reflections especially around the crossing point, it was possible to orient the reflectors. In this section, I present how the major reflections as highlighted on each correspondent section and connected to reflection in the corresponding crossing section. It is important to note that the comparison should ideally be done in unmigrated stacked section and in time as the migrated sections of arbitrary orientation would never properly map the reflection at a proper dip and position because of the out-of-the-plane effects.

Figure 5.7 presents the 3D visualization of the migrated section of profile A and B and the borehole data. Starting from the deeper parts of the sections, T2 in profile B corresponds to R2 in profile A. There is no borehole data to correlate with this reflection however this is the strongest reflection in the seismic sections and worth to further shed light to its origin. A speculative interpretation would be that this reflection is from mafic intrusions that are known to have intruded into the volcano- sedimentary strata.

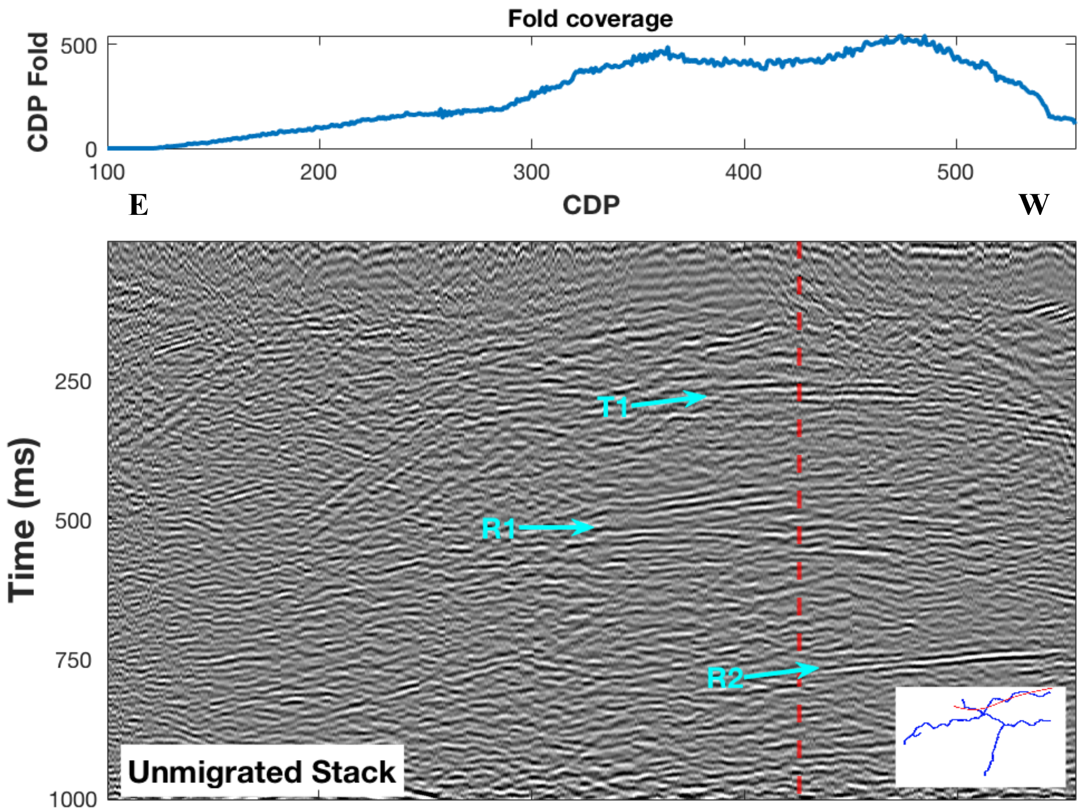


Figure 5.2 Unmigrated stacked section of profile B (combination of P1 and P3) shown dwon to 1s, Location of the section is shown in lower left corner. An illustration of the CDP fold in profile B is shown on top of the section. The dashed line indicates where P1 and P3 intersects; the left side of the line shows the P1 portion of the profile B and the right side shows the portion of the section belongs to P3.

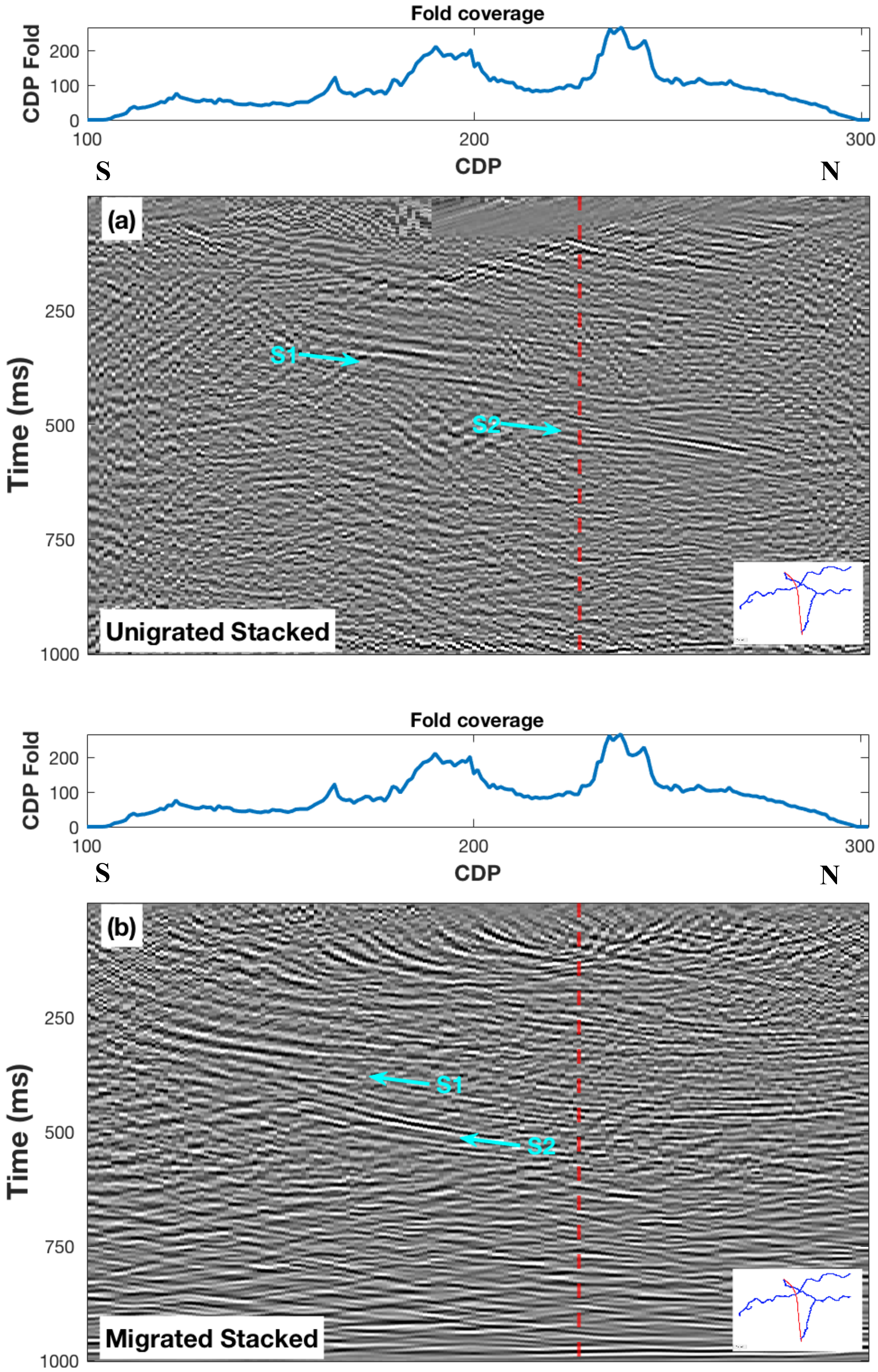
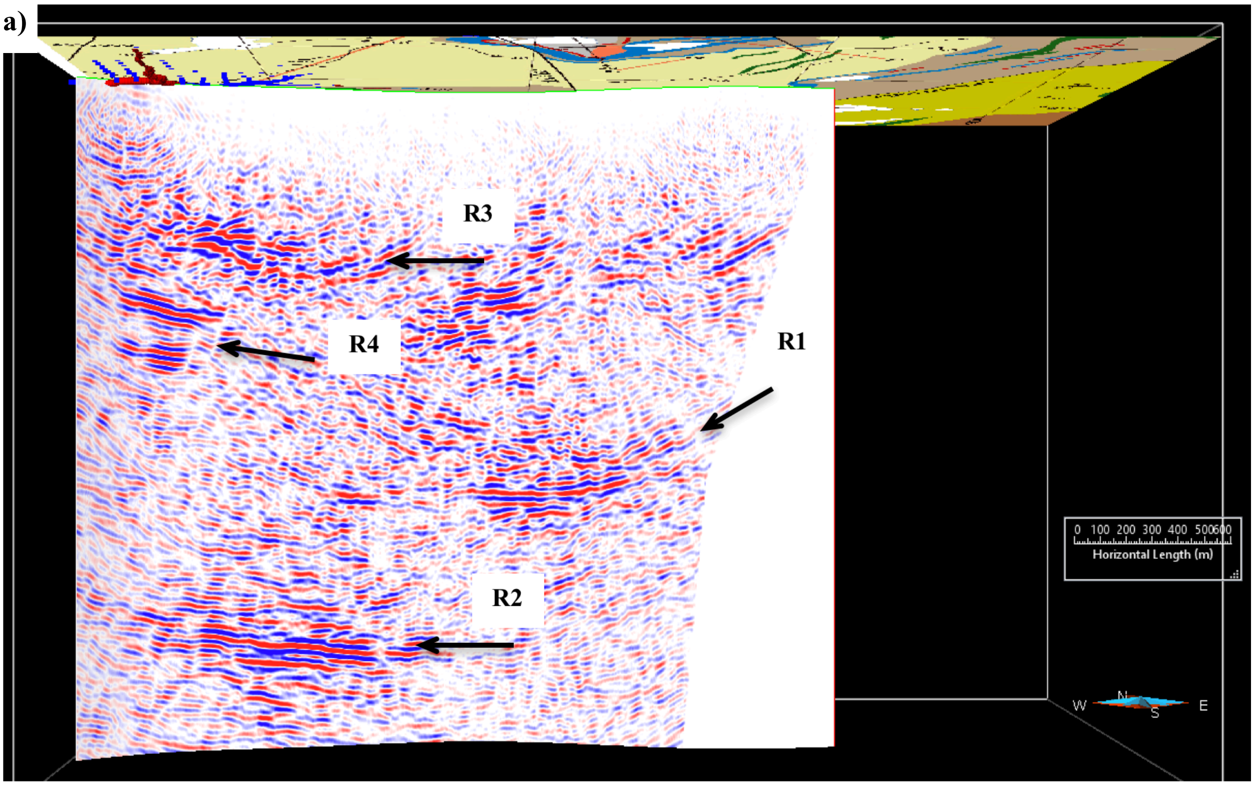
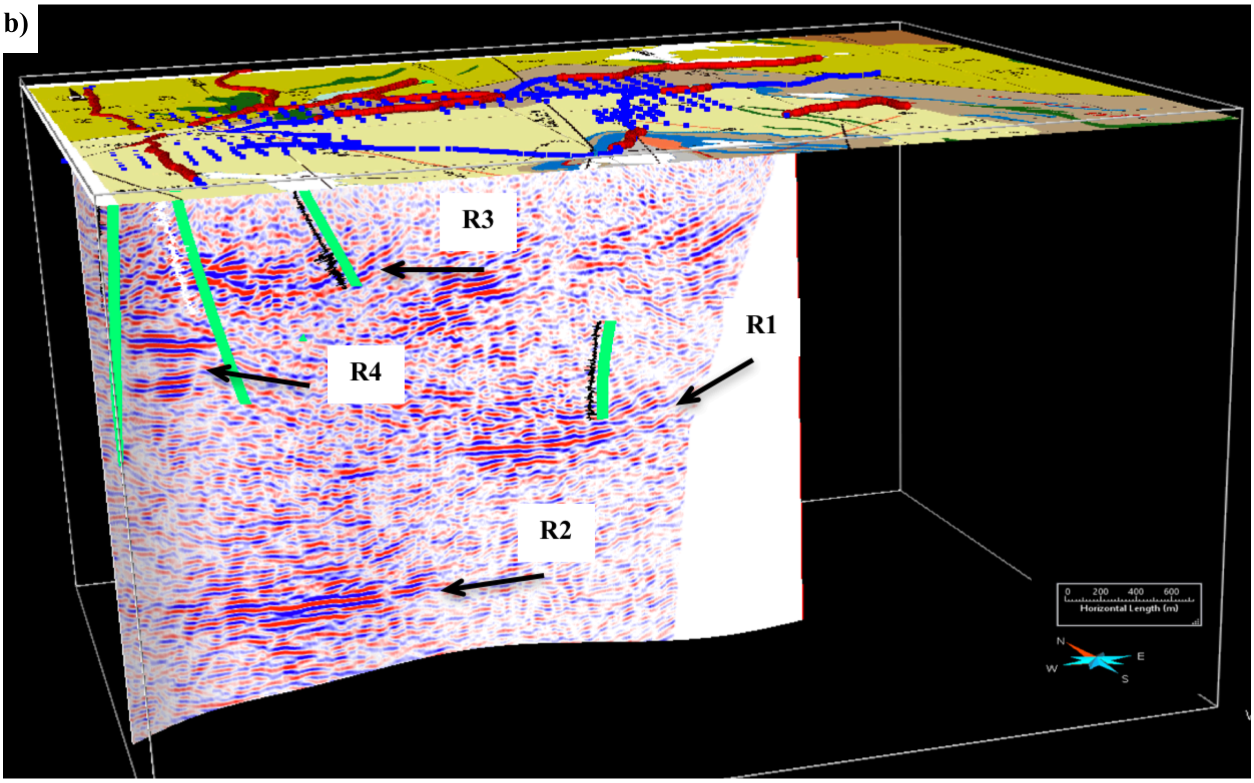
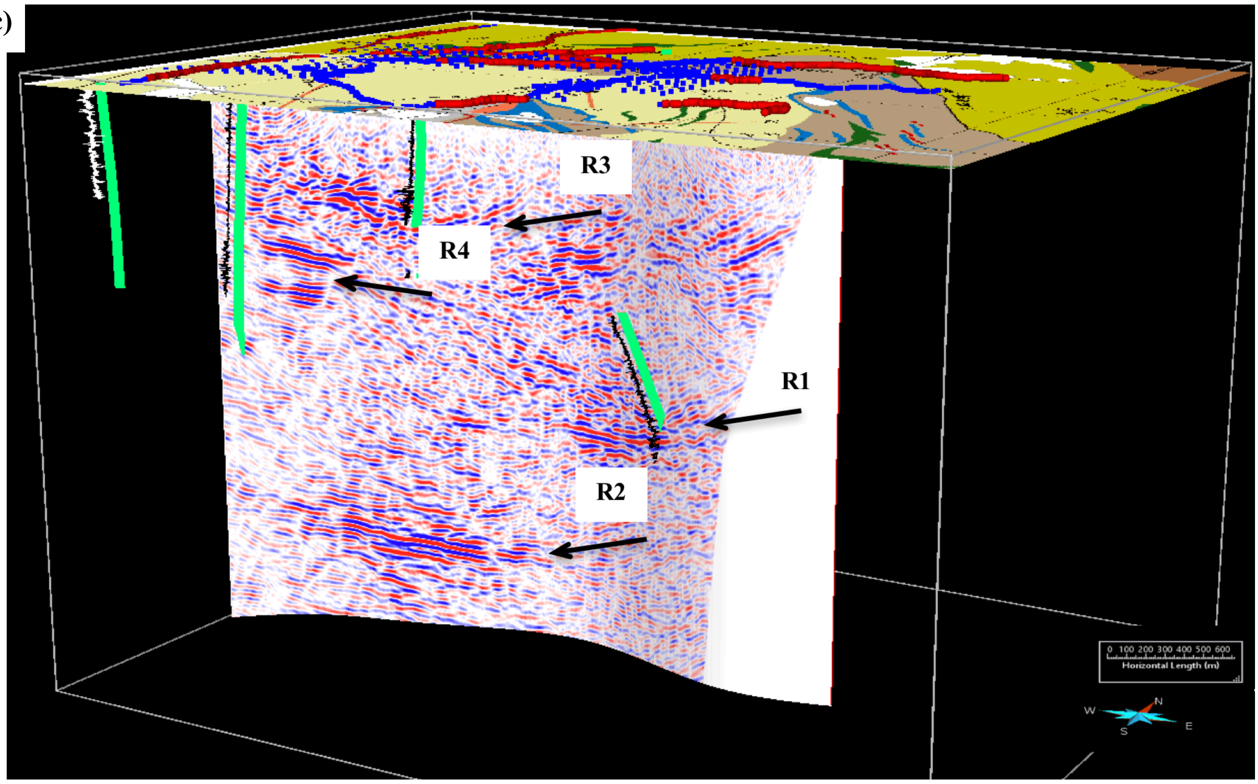


Figure 5.3 (a) Unmigrated stacked section of profile C (combination of P3 and P4) shown down to 1s, (b) migrated stacked section of profile C. Location of the section is shown in lower left corner. An illustration of the CDP fold in profile A is shown on top of the section. The dashed line indicates where P3 and P4 intersects; the left side of the line shows the P4 portion of the profile A and the right side shows the portion of the section belongs to P3.


a)
R3
R4
R1
R2
0 100 200 300 400 500 600
Horizontal Length (m)
W
N
S
E


b)
R3
R4
R1
R2
0 200 400 600
Horizontal Length (m)
N
W
E
S

c)



d)

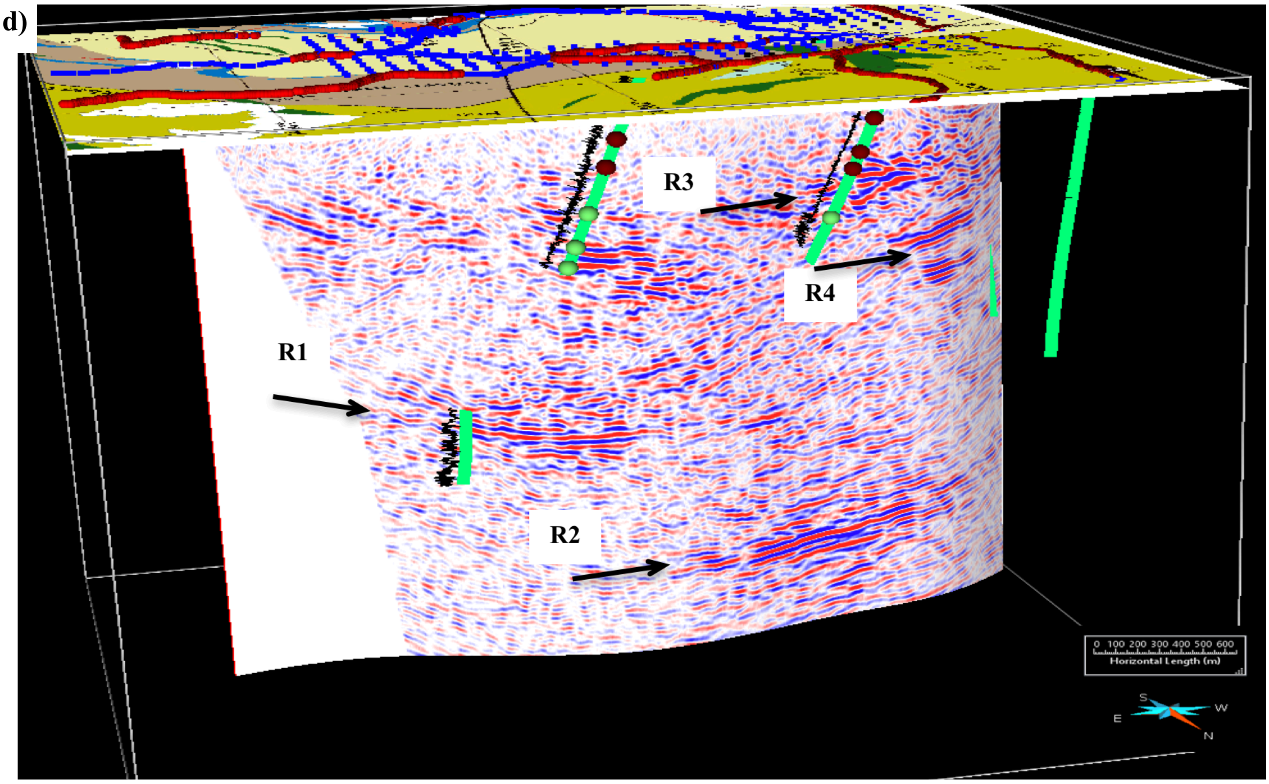


Figure 5.4 3D visualization of profile A and borehole data from the site, (a) W-E 3D view of the profile with the reflection events in the section, (b-d) 3D view of the profile from different directions to have a better view how the borehole data (density contrast) correlate with the reflections from this study.

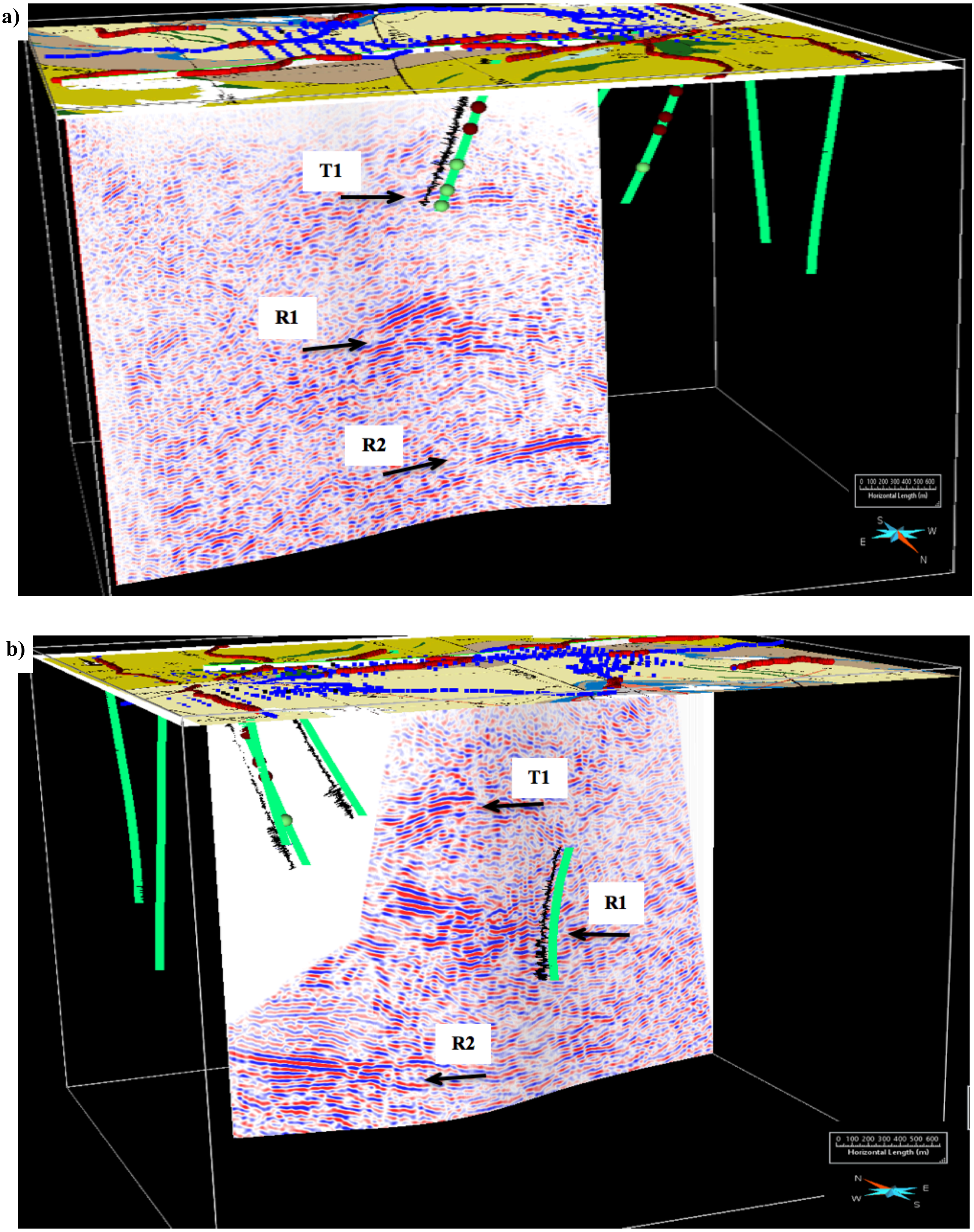


Figure 5.5 3D visualization of profile B and borehole data from the site, (a) E-W 3D view of the profile with the reflection events in the section, (b) 3D view of the profile from different direction to have a better view how the borehole data (density jumps) correlate with the reflections from this study.

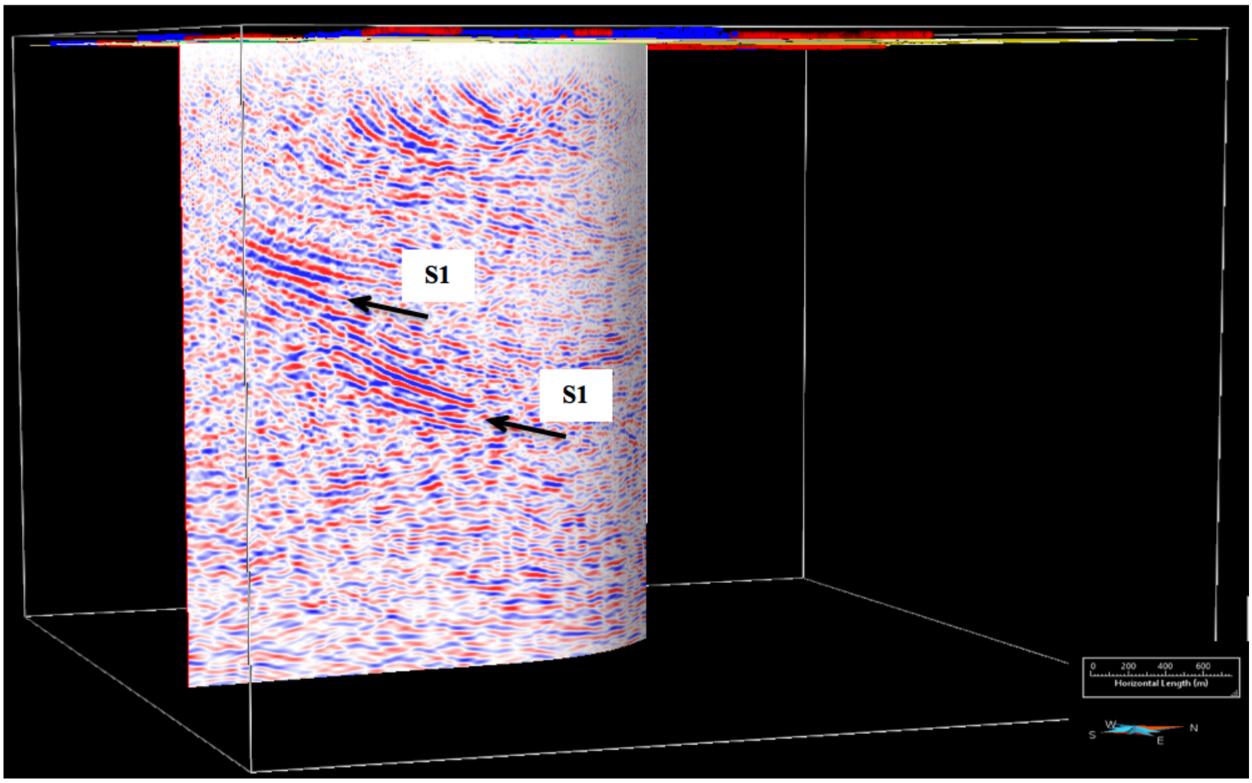


Figure 5.5 3D visualization of profile C and the major reflections in the section.

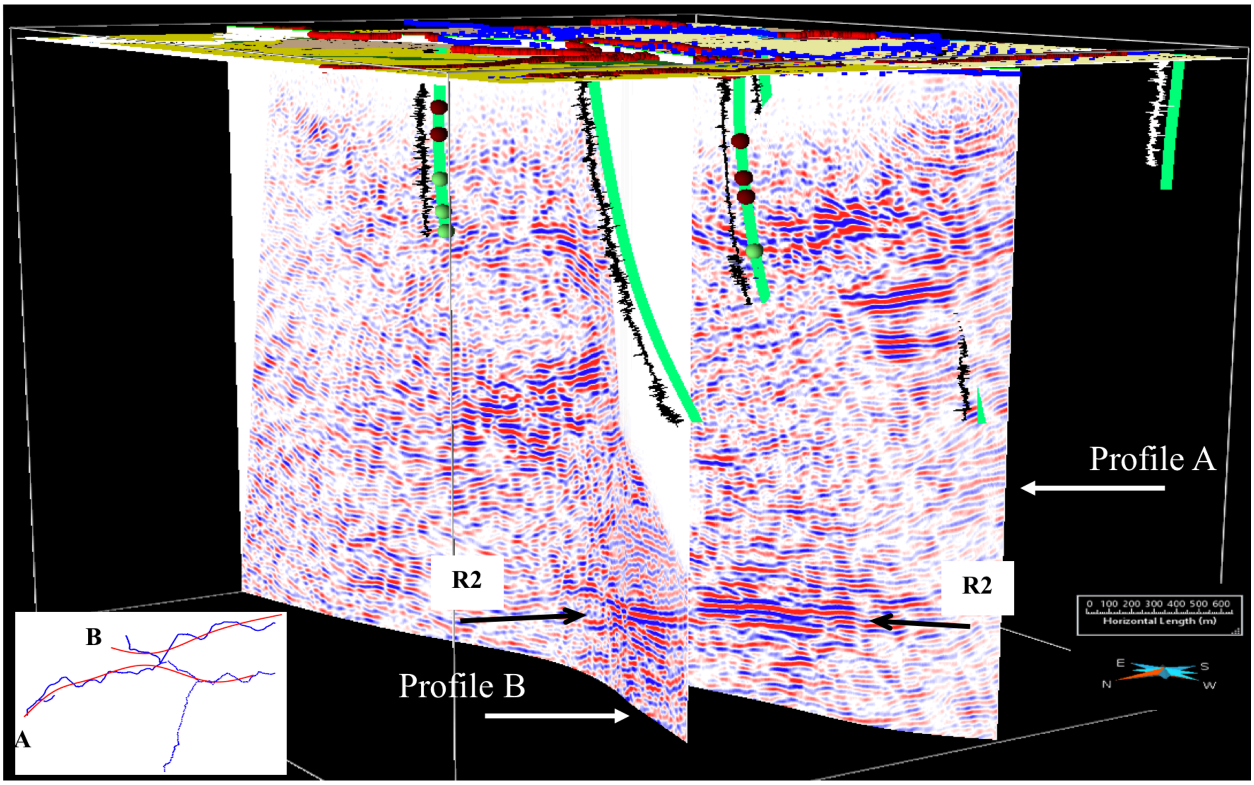


Figure 5.7 3D visualization of the migrated stacked sections of profile A and B. The figure shows how the reflections correlate from one profile to another and with the borehole data. The location of the profiles is shown in the lower left corner of the figure.

Figure 5.7 presents the 3D visualization of the migrated section of profile A and B and the borehole data. Starting from the deeper parts of the sections, T2 in profile B corresponds to R2 in profile A. There is no borehole data to correlate with this reflection however this is the strongest reflection in the seismic sections and worth to further shed light to its origin. A speculative interpretation would be that this reflection is from mafic intrusions that are known to have intruded into the volcano- sedimentary strata.

R1 and T1 in sections A and B, respectively, can also be correlated to approximately the same depth and as mentioned earlier, they continue at the intersection of P1 and P3, and seems to have a true dip towards the west. The upper part of T1, shown in Figure 5.7, looks to be an independent reflection crossing T1, at the intersection of P1 and P3. This reflection does not show up towards P3 and can be inferred as a possible off-plane feature. There are some surface events in the west portion of the sections with correspondent borehole data and correlate together with a true dip towards the east.

There is no evident reflection to be correlated in the intersection of profiles B and C (Figure 5.8 a). S2 in profile C can be correlated to R1 in profile A and T1 in profile B. Therefore, considering that R1, T1 and S2 are its true dip, which is towards the northwest. S1 appears only in profile C and might be interpreted as out-of-plane reflection or shallowly dipping part of S2 (Figure 5.8). R1. T1 and S2 appear within the Zinkgruvan formation hence they show the depth extent that the mineralization can be explored for, a great outcome from this study and the seismic survey at the Zinkgruvan study area.

6 Discussion

Prior to this study there was no seismic study available from the study area and the current project as a complementary study to that of Gil et al. (2020, in revision) are encouraging and show the seismic reflection potential of various geological structures and power of the seismic methods in resolving deep and key structures at the Zinkgruvan mining area. The results could only be compared to the borehole data from the site which shows the density log in some portions of the
sections. The study was carried out in a 2D crooked-line sense from the 3D sparse dataset with the idea of that if the sparse 3D dataset could not provide useful information due to the sparsity of the data and extreme irregular offset-azimuth coverage, the high 2D fold may provide alternative images to help 3D interpretation of the geology of the site.

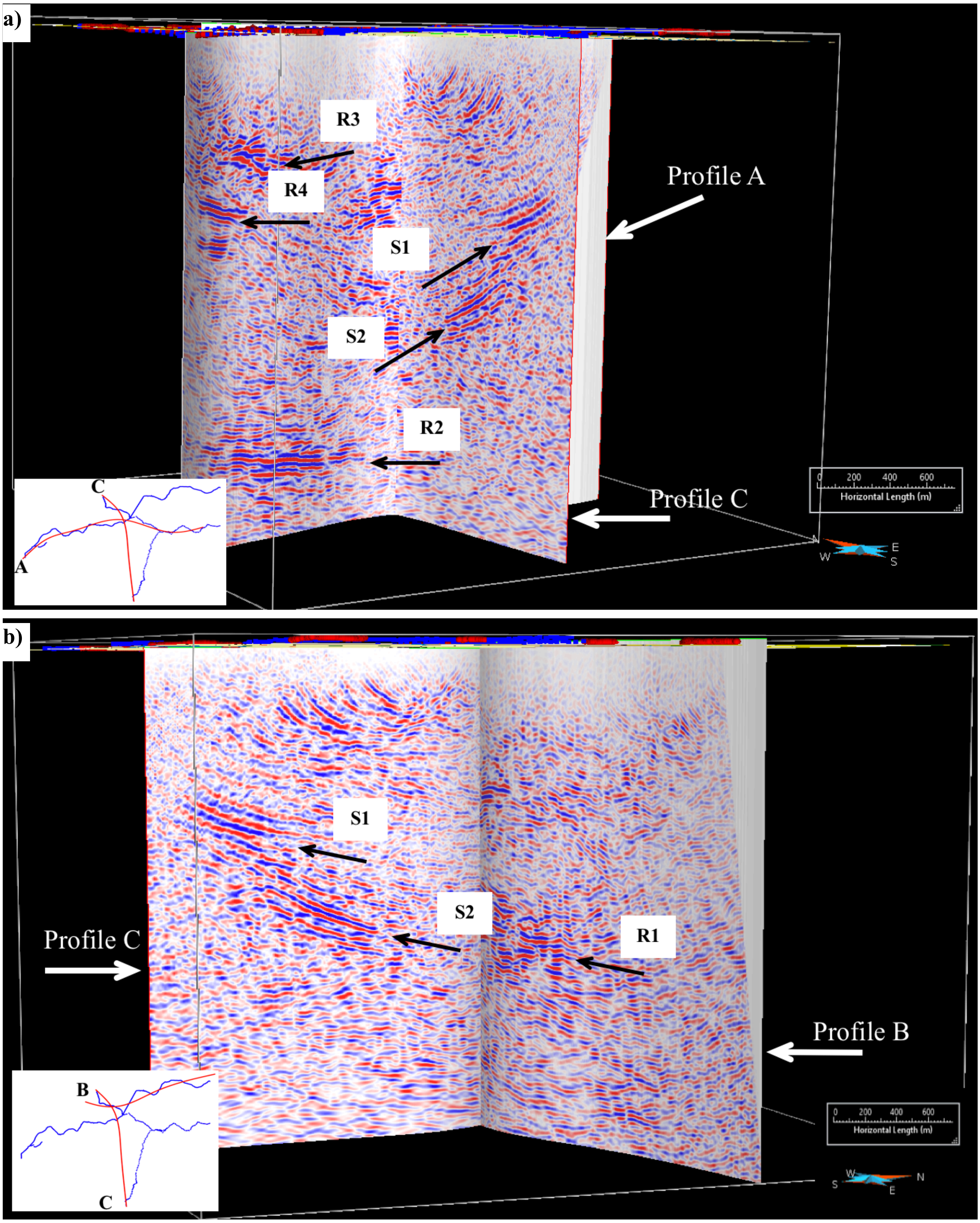


Figure 5.8 (a) 3D visualization of unmigrated stacked sections of profile A and C and the major reflections in the profiles, (b) 3D illustration of unmigrated stacked sections of profiles B and C and the major reflections from the profiles. The lower left corner plots show the location of the profiles.

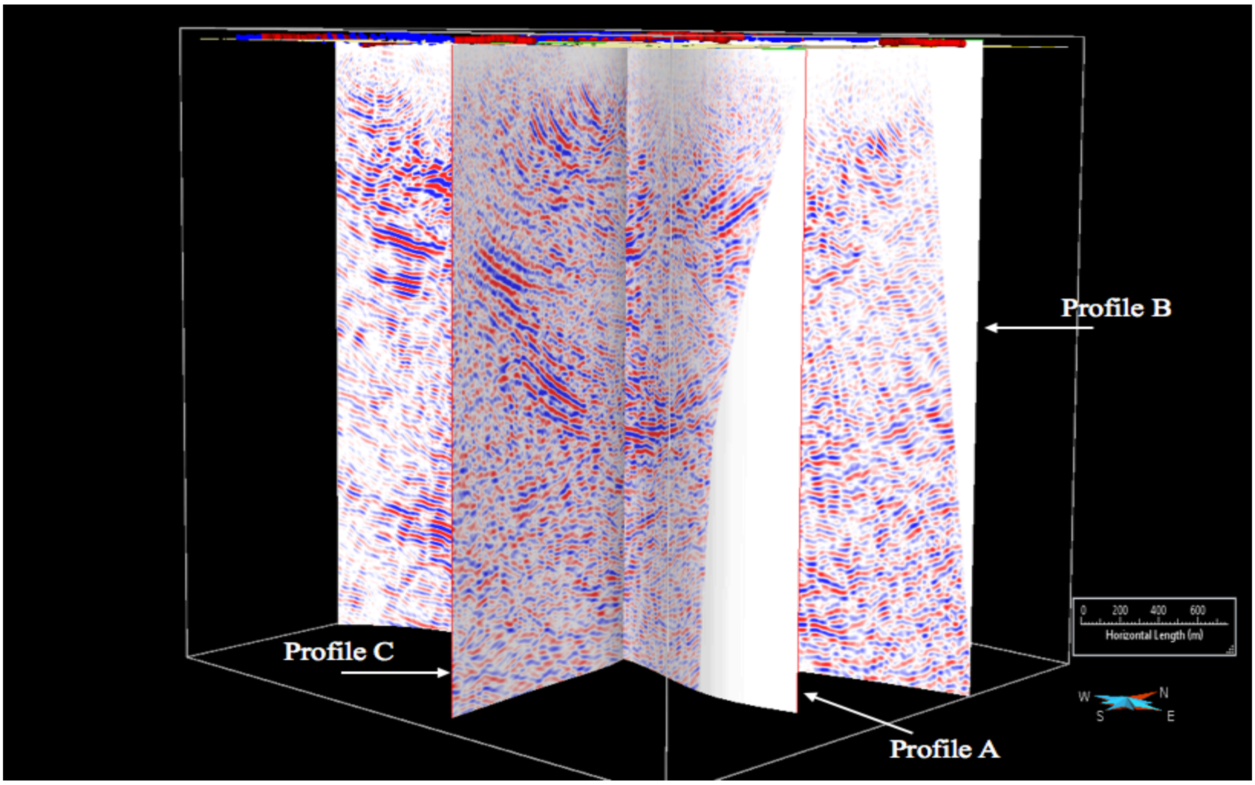


Figure 5.9 3D visualization of the migrated stacked sections of profiles A, B, and C.

Earlier studies of 2D crooked-line surveys (e.g. Wu et al., 1995; Malehmir et al., 2011) confirmed that by selecting proper processing parameters and high fold coverage, one could improve the resolution of the seismic sections and the accuracy of the subsurface image. Also, by providing cross-dip information from 2D crooked-line data, it is possible to infer 3D geometry (e.g. Wu et al., 1995; Malehmir et al., 2012; Urosevic et al., 2007), an approach which could complement this study however due to the lack of time it was excluded from the MSc thesis work.

The final processed sections provide high quality image of the reflections appeared in the uppermost 3 km in the shot gathers and by interpreting the 3D view of the sections the reflections specially in the crossing points could be analyzed and oriented. Figure 5.9 shows the 3D visualization of the migrated stacked section of the processed profiles. It can be seen from this figure how the major reflections discussed earlier are correlating together at the crossing point.

A major observation in this particular study is that there seems to be a cut in reflections observed in the intersection of different profiles in the unmigrated stacked section. This can be seen, for example, in R1 in the unmigrated stacked section of profile A (Figure 5.1) which starts in P1 portion of the section and seems to be suddenly stopped in the intersection. There are some possible reasons to be discussed here. One reason could be the low fold coverage in that portion of the section. This can be confirmed by the CDP fold plot on top of the section (Figure 5.1) which shows low fold coverage in the portion of the section near to the intersection. By comparing the fold coverage within the section, it is quite understandable that higher fold coverage results in higher resolution of the reflections. Also, the sudden change of the profile orientation with respect to the dip and strike of the underlying geological target might explain the low resolution of the reflections. Particular to R1, as mentioned before, its continuation can be followed in T1 in profile B to the NW.

The suggestion for a future study is to test other processing parameters such as DMO (dip move-out) or cross-dip corrections and analysis, which can give a better control on the geometry of the reflections and their possible geological attributes.

7 Conclusions

This MSc degree work aimed at delineating subsurface geological structures of the Zinkgruvan mining area using 2D crooked-line reflection seismic profiles extracted from a sparse 3D dataset and processed in a combination. Although parts of the dataset suffer from significant noise from a powerline crossing the profiles and also the processing challenges from 2D crooked-line survey, the final unmigrated and migrated seismic sections show good quality with clear reflections that can be correlated from one profile to another.

In particular, a reflective package is observed consistent with the location of the massive-sulphide-bearing Zinkgruvan formation extending down to approximately 100 m. This reflective package is prospecting hence the seismic study has in minimum provided guidelines where the exploration can be focused at depth and showing its power at the site. Future comparisons should study full-scale 3D imaging potential of the dataset versus the approach taken in this thesis to study both resolution and 3D reliability of the sections. A 2D seismic processing would still suffer from out-of-the-plane features even in data are extracted from midpoint clouds hence 3D imaging would remain to be an ultimate solution and irreplaceable.

8 Acknowledgements

First and foremost, I would like to express my sincere appreciation to my supervisor Alireza Malehmir for granting me the possibility to be part of the SIT4ME project. It was a pleasure to have the opportunity to work with you and the Geophysics group at Uppsala University. I appreciate your patience in dealing with my endless questions and in challenging me on my scientific journey to complete my MSc degree. Thank you for your encouragement, which helped me to learn as much as I, now, know about seismic data processing and applied geophysics. I would, also, like to thank my second supervisor, Alba Gil, for her help in preparing the seismic data and for her valuable feedback.

I would like to acknowledge Bojan Bordic for his help on the seismic software and with technical problems, as they arose. He, always, had time to explain the complexities of seismic processing and this helped me gain a much better understanding of the field. Thank you for helping me to start the data processing and for, always, having a smile and a positive comment for me!

I am grateful to Mike for helping me with the technical issues in my coding. I would like to thank my examiner, Ari Tryggvason and reviewer, Elizavet Koya for scrutinizing my thesis and for their valuable feedback.

I give special thanks to the SNSN team for their help and support during my time working within them. I must single out Dr. Björn Lund, the director of SNSN, for his support and encouragement, which motivated me and kept me going.

I wish to thank Gunnar Eggersson for being a kind and patient officemate. He welcomed all the guests, entering the office, we shared, to help me with the thesis. Thank you, too, to Karin Berglund who helped me with the Swedish translation of my thesis. Tack så mycket.

I would like to thank my friends Eli and Tatiana for all the fika sessions and the long chats we had, while collaborating as SEG members. Their positive energy motivated me. I would, especially, like to thank my dear Mary for all her support, nice words and feedback on my writing. Thank you so much, Mary, for being such a kind and caring friend, who helped ease the, sometimes, difficult periods during this time of my life.

And last but not least, I would like to thank my loving family for always being present to support me on my scientific journey, such a long way from home. Thanks God for WIFI and Whatsapp! Without your support, love and understanding, I would, definitely, not be the person, I am, now.

9 References

Allen, R.L., Bull, S., Ripa, M. & Jonsson, R. (2003). Regional stratigraphy, basin evolution, and the setting of stratabound Zn-Pb-Cu-Ag-Au deposits in the Bergslagen, Sweden, SGU-FoU project 03-1203/99, *Geological Survey of Sweden and Boliden Mineral AB*, vol. 156, pp. 99.

Allen, R.L., Lundstrom, I., Ripa, M. & Christofferson, H. (1996). Facies analysis of a 1.9 Ga, continental margin, back-arc, felsic caldera province with diverse Zn-Pb-Ag-(Cu-Au) sulfide and Fe oxide deposits, Bergslagen region, Sweden. *Economic Geology*, vol. 91(6), pp. 979–1008.

Bellefleur, G., Barnes, A., Calvert, A., Hubert, C. & Mareschal M. (1995). Seismic reflection constraints from Lithoprobe line 29 on the upper crustal structures of the northern Abitibi greenstone belt, *Can. J. Earth Sci*., vol. 32, pp. 128–134. DOI:10.1139/e95-011

Bengtsson, V. C. (2000). Lithogeochemical characteristics of a profile across the Nygruvan orebody, Zinkgruvan, Central Sweden, Department of Geology, Earth Sciences Centre, Göteborg University, Box 460, SE-405 30 Göteborg, Sweden.

Dehghannejad, M., Juhlin, C., Malehmir, A., Juanatey, M.A.G., Skyttä, P., Weihed, P. & Bauer, T. (2013).
Reflection seismic imaging in the Skellefte ore district, northern Sweden. In Biennial SGA Meeting: Mineral deposit research for a high-tech world 12/08/2013-15/08/2013, *Sveriges Geologiska Undersökning*,
vol. 1, pp. 126-129.

Dehghannejad, M., Malehmir, A., Juhlin, C. & Skyttä, P. (2012). 3D constraints and finite- difference modeling of massive sulfide deposits: The Kristineberg seismic lines revisited, northern Sweden. Geophysics, vol. 77(5), pp. WC69-WC79.

Dentith, M. & Mudge, S.T. (2014). *Geophysics for the Mineral Exploration Geoscientist by Michael Dentith*, Camb. Core. DOI: 10.1017/CBO9781139024358

DuBois, L., Levato, L., Besnard, J., Escher, A., Marchant, R., Olivier, R., Ouwehand, M., Sellami, S., Steck, A. & Wagner, J.J. (1990). Pseudo- 3DstudyusingcrookedlineprocessingfromtheSwiss Alpine western pro- file: Line 2 (Val d'Anniviers- Valais), *Tectonophysics*, vol. 173, pp. 31–42. DOI:10.1016/0040-1951(90)90201-I

Gaàl, G. & Gorbatschev, R. (1987). An Outline of the precambrian evolution of the baltic shield, *Precambrian Research*, pp. 15-52. DOI: 10.1016/0301-9268(87)90044-1

Geijer, P. (1917). *Falutraktens geologi och malmfyndigheter*. Sver, Geol. Undersøk., Ser. C, Arbok, 10.

Gil, A., Malehmir, A., Buske, S., Alcalde, J., Ayarza, P., Lindskog, L., Spicer, B., Carbonell, R., Orlowsky, D., Carriedo, J. & Hagerud, A. (2020). Reflection seismic imaging in the Zinkgruvan mining area, central Sweden. *EAGE-NSG Annual Meeting*, Belgrade-Serbia, September 2020.

Gil, A., Malehmir, A., Buske, S., Alcalde, J., Ayarza, P., Martínez, Y., Lindskog, L., Spicer, B., Carbonell, R., Orlowsky, D., Carriedo, J. & Hagerud, A. (2021). Reflection seismic imaging to unravel subsurface geological structures of the Zinkgruvan mining area, central Sweden. *Ore Geology Reviews*, vol. 137, 104306.

Haldar, S.K. (2018). *Mineral exploration: principles and applications*. Elsevier.

Jansson, N. F., Zetterqvist, A., Allen, R. L. and Billström, Malmström L., (2017). Genesis of the Zinkgruvan stratiform Zn-Pb-Ag deposit and associated dolomite-hosted Cu ore, Bergslagen, Sweden. *Ore Geology Reviews,* vol. 82, pp. 285–308.

Kumpulainen, R.A., Mansfeld, J., Sundblad, K., Neymark, L. and Bergman, T. (1996). Stratigraphy, age, and Sm-Nd isotope systematics of the country rocks to Zn-Pb sulfide deposits, Ammeberg District, Sweden, *Economic Geology*, vol. 91(6), pp. 1009–1021.

Larner, K. L., Gibson, B. R., Chambers, R. & Wiggins, R. A. (1979). Simultaneous estimation of residual static and crossdip corrections. *Geophysics*, vol. 44, pp.1175–1192. DOI:10.1190/1.1441001

Malehmir, A., Tryggvason, A., Juhlin, C., Rodriguez-Tablante, J. & Weihed, P. (2006). Seismic imaging and potential field modelling to delineate structures hosting VHMS deposits in the Skellefte Ore District, northern Sweden. *Tectonophysics*, vol. 426(3-4), pp.319–334.

Nedimović, M. R. & West, G. F. (2002). Shallow three- dimensional structural from two- dimensional crooked line seismic reflection data over the Sturgeon Lake Volcanic Complex, *Economic Geoogy.*, vol. 97, pp. 1779–1794. DOI:10.2113/97.8.1779

Malehmir, A., Tryggvason, A., Lickorish, H. & Weihed, P. (2007). Regional structural profiles in the western part of the Palaeoproterozoic Skellefte Ore District, northern Sweden. *Precambrian Res*earch, vol. 159, pp. 1–18. DOI: 10.1016/j.precamres. 2007.04.011

Malehmir, A., Andersson, M., Lebedev, M., Urosevic, M. & Mikhaltsevitch, V. (2013). Experimental estimation of velocities and anisotropy of a series of Swedish crystalline rocks and ores. *Geophysical prospecting*, vol. 61(1), pp. 153–167.

Malehmir, A., Dahlin, P., Lundberg, E., Juhlin, C., Sjöström, H. & Högdahl, K. (2011). Reflection seismic investigations in the Dannemora area, central Sweden: Insights into the geometry of polyphase deformation zones and magnetite-skarn deposits*. Journal of Geophysical Research: Solid Earth*, 116 (B11).

Malehmir, A., Dahlin, P., Lundberg, E., Juhlin, C., Sjöström, H. & Högdahl, K. (2011). Reflection seismic investigations in the Dannemora area, central Sweden: insights into the geometry of poly- phase deformation zones and magnetite-skarn deposits. *Journal of Geophysical Research*, 116, B11307.

Nedimović, M. R., & West, G. F. (2003a). Crooked- line 2D seismic reflection imaging in crystalline terrains. *Part 1, data processing, Geophysics*, vol. 68, pp. 274–285, DOI:10.1190/1.1543213

Reynolds, J.M. (1997) *An Introduction to Applied and Environmental Geophysics*. Wiley.

Rodriguez-Tablante, J., Tryggvason, A., Malehmir, A., Juhlin, C. & Palm, H. (2007). Cross-profile acquisition and cross-dip analysis for extracting 3D information from 2D surveys, a case study from the western Skellefte District, northern Sweden. *Journal of Applied Geophysics*, vol. 63(1), pp.1–12.

Sheriff, R.E. & Geldart, L.P. (1995) *Exploration Seismology by R. E. Sheriff*. Camb. Core. DOI: 10.1017/CBO9781139168359

Skellefte Ore District, northern Sweden, *Tectonophysics*, vol. 426, pp. 319–334. DOI:10.1016/j. tecto.2006.08.006

Stephen, I.D., Smith, M.J.L., Stirrat, M.R. & Perrett, D.I. (2009). Facial skin coloration affects perceived health of human faces. International journal of primatology, vol. 30(6), pp. 845–857.

Telford, W.M., Geldart, L.P. & Sheriff, R.E. (1990) *Applied geophysics*. Cambridge university press.

Urosevic, M., Bhat, G. & Grochau, M. (2012). Targeting nickel sulfide deposits from 3D seismic reflection data at Kambalda, Australia, *Geophysics*, vol. 77, pp.123–132.

Wu, J., Milkereit, B. & Boerner, D. (1995). Seismic imaging of the enigmatic Sudbury structure. *Journal of Geophysics Research*, vol. 100, pp. 4117–4130.

Yilmaz, Ö. (2001) *Seismic Data Analysis, Investigations in Geophysics.* Society of Exploration Geophysicists. DOI: 10.1190/1.9781560801580

Zepf V., Reller, A., Rennie, C., Ashfield, M., Simmons, J. & BP, (2014). *Materials Critical to be Energy Industry - An Introduction*, 2nd edition. BP, London, pp. 1–94.

Examensarbete vid Institutionen för geovetenskaper
ISSN 1650-6553