An Innovative In-Tunnel Seismic Study for Sustainably Extracting Apatite Ore at the Siilinjärvi Mine, Eastern Finland

En innovativ seismisk studie for utvinning av apatit-malm ur Siilinjärvigruvan, östra Finland

Anna Donczew
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Anna Donczew
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Abstract

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Anna Donczew

Siilinjärvi located in eastern Finland is presently the only phosphate mine with significant phosphorus production in western Europe. Phosphate rock and phosphorus are known as a critical raw material for the European Union due to their economic importance and being prone to the supply risks. Securing their sustainable exploration as well as extraction is hence important. At Siilinjärvi, the phosphate rocks appear within a major Archean alkaline and carbonatite system deformed by several shear zones and intruded by dike systems. By understanding their spatial and temporal relationships an improved exploration and extraction of the ore is possible, which in turn will contribute to the sustainable extraction of this critical material. In October 2018 a novel in-tunnel seismic survey was conducted in the Siilinjärvi open-pit mine. The objective of the study was to employ an in-tunnel seismic survey intersecting several major shear zones running on the eastern side of the main pit, with the idea of characterising its geometry and relationship with the mineralization. The use of the existing mine infrastructure (a water-drainage tunnel) makes the acquisition of the data quite novel in open-pit mines. The water-drainage tunnel nearly in the bottom of the pit crosscutting several major shear zones and dikes was used to enable bench-tunnel seismic data acquisition. High-quality data were acquired using 144 receivers inside the tunnel, with the sources located both inside the tunnel (Bobcat-mounted vertical drophammer) and on the surface (combined explosives and Bobcat-drophammer). Results obtained show at least two reflections interpreted to originate from subvertical shear zones intersecting the tunnel illustrating the importance of such surveys for shear-zone imaging and site characterization. Based on a careful study of a number of shot records, delay in arrival times and partial amplitude lose, these reflections are interpreted to be backscattered surface-waves generated from the shear zones.

Keywords: in-tunnel seismic, reflection seismic, traveltime tomography, carbonatites, shear zones, Siilinjärvi

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Populärvetenskaplig sammanfattning

En innovativ seismisk studie för utvinning av apatit-malm ur Siilinjärvigruvan, östra Finland
Anna Donczew

Siilinjärvi i östra Finland är just nu den enda fosfatgruvan med en betydande fosforproduktion inom den Europeiska Unionen. Fosfater och fosfor är viktigt för EU på grund av deras ekonomiska betydelse och begränsade tillgång. Den fosforbärande bergarten i Siilinjärvi befinner sig i ett stort Arkeiskt alkalisk och karbonatit-komplex som är deformad av flera skjuvzoner och intruderat gångsystem. En förbättring av sökandet och utvinnandet av denna viktiga malm skulle vara möjligt genom en ökad förståelse för de spatiala och temporala relationerna i komplexet. Syftet med denna studie var att tillämpa en ny seismisk undersökning, baserad på existerande infrastruktur i gruvan, för en bättre geologisk förståelse och därmed en förbättrad exploatering. En innovativ seismisk undersökning av tunnlar gjordes i Siilinjärvis dagbrott oktober 2018. En vattendräneringstunnel nästan i botten av brottet som korsar fem skjuvzoner användes för att mäta seismiskt tunnel-data. Hög kvalitativ data samlades in genom att använda 144 mottagare inuti tunneln med källor lokalisera på botten tunneln, i form av en vertikal dropphammare monterad på en Bobcat, och på ytan i form av en kombination av sprängning och Bobcatmotera dropphammare. Två reflektioner tolkades att ha sitt ursprung från subvertikala skjuvzoner som korsar tunneln vilket visar på vikten av dessa typer av undersökningar för skjuvzons detektering och områdes karakterisering.

Nyckelord: tunnelseismik, reflektionsseismik, restidstomografi, karbonatiter, skjuvzoner, Siilinjärvi

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1 Introduction

Siilinjärvi mine in eastern Finland is currently the only phosphate mine with significant phosphorus production in the European Union. Phosphorous is the 11th most abundant mineral in the Earth’s crust, yet phosphate rocks and phosphorus are listed as critical raw materials (CRMs) for the EU (European Commission, 2017) because of their supply risks and economic importance. This is particularly reflected on the significance of phosphate fertilizers in the food supply chain. Addressing the increasing demand for fertilizers require innovative exploration and extraction efforts. Hence securing European mineral exploration as well as extraction of phosphate rocks is important for the EU’s sustainable growth and economy.

The degree project was conducted in connection with the Horizon 2020 (H2020) funded Smart Exploration project at the Department of Earth Sciences within the Geophysics Program of Uppsala University. The project was done in close collaboration with the mining company partner, Yara Suomi Oy. The objective of the Smart Exploration study in Siilinjärvi was to employ a novel seismic survey using the existing mining infrastructure for better mine planning and geological understanding. In this thesis work, I present results from a reflection seismic dataset that was acquired inside a water-drainage tunnel in the Siilinjärvi open-pit mine intersecting a number of major shear zones. I will illustrate how the seismic data could possibly enable characterizing a number of sub-vertical shear zones that correlate well with borehole data and geological observations.

1.1 Smart Exploration project

Smart Exploration is an H2020-funded project, which is the biggest EU Research and Innovation programme that focuses on investing in ideas that can be scalable from lab to the market. The Smart Exploration addresses the new mineral exploration technologies for sustainable raw materials production. The main aim of the project is to advance cost-effective and environmentally friendly geophysical exploration methods in challenging brownfield mining areas (Smart Exploration, n.d.). The project consists of 27 partners from 11 countries representing research organizations, small and medium-sized enterprises (SMEs) and mining companies. One of the six project’s exploration sites includes Siilinjärvi mine in Finland, where innovative seismic data acquisition is being tested and is the focus of this thesis work.

1.2 Study area

The study area, Siilinjärvi phosphate mine, is Finland’s second largest carbonatite complex located in eastern Finland, approximately 20 km north of the city of Kuopio. Apatite mining in Siilinjärvi started in 1979 by Kemira Oy and since 2007 mining operations are performed by Yara Suomi Oy (O’Brien et al., 2015), which currently operates the phosphate mine with production in two open pits: southern
Särkijärvi main pit and northern Saarinen satellite pit (Figure 1). The mine production is estimated to ca. 11 Mt of ore/year and is expected to be in operation (life of mine) for approximately the next 20 years with predicted closure in 2035 (subject to reappraisal) (O’Brien et al., 2015). Apatite, which is the major mine product, is processed to phosphoric acid in the flotation step. Mica and calcite concentrate are by-products from the Siilinjärvi mine operations (O’Brien et al., 2015). The phosphate-bearing rocks in Siilinjärvi are within a major Archean alkaline and carbonatite complex deformed by several shear zones and dike systems. By understanding their spatial and temporal relationships an improved exploration and extraction of this critical ore would be possible. The study profile is located inside the water-pumping tunnel, which intersects several diabase dikes and major shear zones (Figure 1b).

![Figure 1](image_url)

**Figure 1** (a) General geological map of the Siilinjärvi complex showing the two open pits, Särkijärvi and Saarinen. (b) Lidar photo with a superimposed geological map showing the location of the tunnel (green line) and diabase dikes in the Särkijärvi (main pit) mine. Modified from the Digital bedrock map 1:200,000 © Geological Survey of Finland 2012 and Ortophoto Database of the National Land Survey of Finland 06/2018.

1.3 Previous geophysical studies

Encouraged by successful application of Uppsala University’s micro-electromechanical systems (MEMS)-based broadband seismic landstreamer in noisy urban and challenging mining environments (Brodic et al., 2015 and 2017; Malehmir et al., 2017), a decision was made to test it inside a water-drainage tunnel at this site. High-resolution data (2-4 m receiver spacing and broadband frequency) and fast acquisition line set up are some of the landstreamer’s main characteristics. With no need for planting geophones, line set up can speed up making this method both cost and time-efficient (Malehmir et al., 2017). An example photo from the acquisition preparation inside the tunnel is shown in Figure 2.
High-quality seismic reflection data have previously successfully been acquired in the study area (Siilinjärvi phosphate mine) during July 2014 (Malehmir et al., 2017). The method proved to be viable for imaging dikes and shear zones in the open-pit ramps. Based on that successful study, an innovative in-tunnel seismic survey was designed and performed in the Särkijärvi open-pit mine during October 2018 as part of a larger seismic survey. Shot sources were located both inside the mining tunnel and on the benches making this survey quite novel.

![Figure 2 Example field photo inside the water-pumping tunnel during the acquisition line set up. Photo by A. Malehmir (October 2018).](image)

### 1.4 Motivation and objectives

The main aim of this thesis was to process, image and interpret the seismic data and employ traveltime tomography in order to understand the spatial and temporal relationships of the major shear zones that control the shape of mineralization running in the same direction as well as study their significance for open-pit wall stability in connection with other structures.

In this degree project, the main objectives were:

- reflection seismic processing of data acquired inside the tunnel in the Särkijärvi (main pit) to image a series of known shear zones running perpendicular to the profile and intersecting the tunnel;
- to employ P-wave first-arrival traveltime tomography on first-breaks recorded by tunnel receivers and seismic sources generated both inside the tunnel and on the benches above and away from the tunnel;
- to visualize the results in 3D and interpret them in connection with known geological observations and borehole data.
As a result of this thesis work, an extended abstract was also prepared and submitted to the EAGE-Near Surface Geoscience Conference to be held in the Hague-Netherlands. A copy of the extended abstract can be found in the Appendix A.
2 Geology

2.1 Siilinjärvi complex

The Siilinjärvi complex is an ultramafic alkaline-carbonatite complex intrusive into the neighbouring granitic-gneissic rocks (Puustinen, 1971). The complex is amongst the oldest known carbonatite systems in the world with the estimated age of $2610 \pm 4$ Ma (Heilimo et al., 2015), and was also the first carbonatite system identified in the Finnish Precambrian (Puustinen, 1971). The Siilinjärvi complex can be described as a steeply dipping (rooted) carbonatite-glimmerite tabular body of a maximum width of 900 m encompassed by fenites (O’Brien et al., 2015). At Siilinjärvi, the phosphates are hosted by a major Archean alkaline and carbonatite system, with well-mixed carbonatites and glimmerites cut by several generations of diabase dikes (Figure 3). The rocks found in this alkaline-carbonatite complex consist of glimmerite, syenite and carbonatite with the in-situ ore grade of 4.2 % $P_2O_5$. The origin of the Siilinjärvi complex is inferred to be plutonic (non-volcanic) that was formed due to passage, accumulation, and crystallization of mantle-derived carbonate-rich melt through a well-blended magma chamber (O’Brien et al., 2015; Heilimo et al., 2015).

![Figure 3](image)

**Figure 3** An UAV photograph from the southern wall of the Särkijärvi mine (main pit) showing alternating black biotite glimmerite-rich matrix and carbonatite (white sövite) rich bands crosscut by different generations of diabase dikes. Photo by A. Malehmir (October 2018).

The main ore mineral in Siilinjärvi is apatite, which is of light green to somewhat gray color. It occurs mostly in glimmerite and carbonatite (sövite) ore rocks and accounts for approximately 10 vol% of the rocks (O’Brien et al., 2015). Glimmerite-carbonatite complex comprise the main ore body that is surrounded by fenites that are the result of metasomatism of Na and K-rich fluids circulating during the emplacement of the complex within the surrounding granitic-gneissic rocks (O’Brien et al., 2015).

Several post-mineralization shear zones and dike systems have influenced the geometry and affects mining operations in the Siilinjärvi mine. In the eastern part of the main pit, these shear zones
sometimes cause wall stability issues (e.g., rock failure) particularly in combination with gently dipping structures including diabase dikes.

### 2.2 Dikes

Dikes are intrusions that crosscut older rocks and stratigraphy. Two main types of dikes can be distinguished within the Siilinjärvi complex. Mica-bearing dikes that intersect the neighboring bedrock, and diabase dikes of basaltic composition, that crosscut the whole area (O’Brien et al., 2015). The latter ones are vital for this study, as they can be found also in the near proximity of the water-drainage tunnel, where seismic data were acquired. Diabase dikes manifest themselves mainly in northwest-southeast or north-northwest-south-southeast directions and their thicknesses vary from centimeters to several meters (hardly up to 60 m) (O’Brien et al., 2015) (Figure 4).

### 2.3 Shear zones

Shear is “a deformation resulting from stresses that cause or tend to cause contiguous parts of a body to slide relatively to each other in a direction parallel to their plane of contact” (Jackson et al., 2005). A shear zone can also be defined as a tabular zone, where strain is greatly higher than in the enclosing rock (Fossen, 2010). Shear zones occur more often in the plastic regime with depths being controlled by temperature gradient and crust’s mineralogy (Fossen, 2010). Shear zones present in the eastern side of the Siilinjärvi’s open pit appear steep to sub-vertical and might be influenced by strike-slip movements. They strike dominantly in a north-south direction and also control the shape of mineralization running in the same direction. Sharp contact between the eastern side of the Särkijärvi’s pit and neighboring fenites is noticeable (O’Brien et al., 2015).
3 Seismic data acquisition

The results presented in this thesis were acquired as a part of a larger-scale seismic campaign involving individuals from various partners and members of Smart Exploration project (Malehmir et al., 2019). Seismic field campaign comprised of a number of active- and passive-source experiments, both within and outside the main pit, and I focus here only on the portion of it acquired inside the water-drainage tunnel.

![Image](image.png)

**Figure 4** An UAV photograph taken outside the tunnel showing mining benches on the eastern wall of the Särkijärvi open pit, just above the tunnel entrance and the entrance to the water-pumping tunnel where data were acquired as part of this study. Photo by A. Malehmir (October 2018). Note a number of moderately-to-gently dipping diabase dikes (yellow dotted line) intersecting the N-S running shear-zones expected to be intersected in the tunnel data.
One east-west-oriented seismic profile with a total length of 286 m was acquired inside the almost horizontal tunnel located on the eastern side of the Särkijärvi open pit (Figure 4). The tunnel crosscuts a number of vertical/subvertical shear zones (S1, S2, S3, S4, S5; Figure 5). For the data acquisition, total of 144 receivers with a 2 m spacing were used. The acquisition spread involved 120, 3C MEMS landstreamer-mounted sensors and 24 vertical coil-based 1C geophones (7 cm spike, 10 Hz natural frequency, Figures 2 and 6a) were used. Data were recorded using a GPS-time synchronized (accuracy of microsecond) Sercel Lite™ acquisition system. A Bobcat-mounted drophammer (500 kg) (Place et al., 2015) was used as the seismic source that was activated at every 4 m spacing (i.e., every second receiver position) inside the tunnel (Figure 6). Given the noisy mining condition with massive mining trucks, drilling and hauling generating unwanted vibrational noise, five hits were recorded within a 30 s record length at every shot position and used later in a shift-and-stack manner to improve the

Figure 5 Aerial photo showing the location of the tunnel, receivers (yellow dots), seismic sources generated away from the tunnel (green triangles and purple stars) in the Särkijärvi (main pit) open-pit mine. Several steep to sub-vertical shear zones (e.g., S1-S5) intersect the tunnel orthogonally. These shear zones are speculated to have controlled the main geometry of the Siilinjärvi complex. Modified from the Digital bedrock map 1:200,000 © Geological Survey of Finland 2012 and Ortophoto Database of the National Land Survey of Finland 06/2018.
signal-to-noise ratio (Park et al., 1996). Table 1 summarizes the main acquisition parameters of the tunnel seismic survey.

In addition to the tunnel seismic data, shots, explosives and Bobcat drophammer, were also generated above and away from the tunnel receivers but recorded on the tunnel receivers to enable providing a semi-3D dataset for traveltime tomography (Figures 4 and 5). GPS-time tagging was used for time-stamping and sampling of the initiation of the impact times in order to merge the datasets and correct for zero-time delays.

In this study only vertical component data from the 3C (vertical, transverse and radial components) receivers are used although during the preparation of the data, geometry and zero-delay times were corrected for all the 3C data. Vertical component data is used to image desired geological structures on a shot gathers. Remaining horizontal components can be used in the future processing for analyzing the motion of the particles, as data for all of the 3C has been prepared for the further analysis.

**Figure 6** Example field photos inside the water-pumping tunnel during the seismic data acquisition showing (a) seismic line setup with landstreamer (MEMS-sensors) and its continuation with conventional geophones (orange cables) and (b) Bobcat-mounted drophammer used as the main seismic source. Photos by A. Malehmir (October 2018).
Table 1 Main acquisition parameters of the bench-tunnel seismic survey at the Siilinjärvi phosphate mine, 2-3.10.2018.

<table>
<thead>
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<th>Survey parameters</th>
<th></th>
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<tbody>
<tr>
<td>Date of acquisition</td>
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<tr>
<td>Acquisition system</td>
<td>Sercel Lite™</td>
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<tr>
<td>Number of profiles</td>
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<tr>
<td>Profile length</td>
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<tr>
<td>Sampling rate</td>
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<tr>
<td>Number of traces</td>
<td>9,936 (after vertical stacking)</td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>Receiver parameters</th>
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<tbody>
<tr>
<td>Number of receivers</td>
<td>Totally 144 receivers (120-3C MEMS on the landstreamer and 24 conventional coil-based 1C spike geophones)</td>
</tr>
<tr>
<td>Receiver spacing</td>
<td>2 m</td>
</tr>
</tbody>
</table>

<table>
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<tr>
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<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Seismic reflection (tunnel)</td>
<td></td>
</tr>
<tr>
<td>Source type</td>
<td>Mainly 500-kg Bobcat-mounted drophammer</td>
</tr>
<tr>
<td>Number of hits per source location</td>
<td>5</td>
</tr>
<tr>
<td>Nominal source spacing</td>
<td>4 m</td>
</tr>
<tr>
<td>Total number of source points</td>
<td>69</td>
</tr>
</tbody>
</table>

| Traveltime tomography (mine benches) |   |
| Source type | 500-kg Bobcat-mounted drophammer and explosives |
| Number of hits per source location | 5 |
| Nominal source spacing | Irregular pattern and where permitted |
| Total number of source points | 8 (explosives), 5 (Bobcat drop-hammer) |

| Geodetic surveying | DGPS |
4 Methodology

In order to image the shear zones running through the eastern wall of the Siilinjärvi open-pit mine, reflection seismic data together with traveltime tomography data were collected. In this section, I present the processing steps that I have applied to the data acquired inside the water-pumping tunnel and briefly cover the core logging information that is relevant for this work. In the reflection seismic data, I aimed to obtain clear reflections that could possibly image the shear zones and while running the first-break traveltome I expected to see low-velocity zones indicating fractures and zones of weaknesses from the shear zones.

4.1 Seismic waves

Analysis of wave propagation through the earth is vital for the seismic method (Sheriff and Geldart, 1995) as much of my thesis work at the end comes to an understanding of seismic response of the shear zones than direct imaging of them through reflection processing. Simply, seismic waves are the movements of the elastic strain energy whose speed is dependent on the properties of the medium through which the wave travels (Reynolds, 1997). Two main types of seismic waves can be distinguished (1) body waves (propagating through the body of the elastic media) and (2) surface waves (propagating near the surface at shallow sub-surface diminishing with depth). Given much of the discussion coming later on the interpretation of the results, it is worth to explain these further.

4.1.1 Body waves

There are two types of body waves. The first, and the most important in reflection and refraction seismics is referred to as primary or compressional wave (P-wave), as it always arrives first on a seismic record because it is the fastest wave type. P-wave can travel through solids and liquids. For the primary wave, propagation direction is parallel to particle motion. Given that most conventional seismic surveys use vertical receivers, most of the reflection seismic data are considered to be of P-wave. The second type of wave is called secondary, shear or transversal wave (S-wave) as it is usually the second event (approximately twice slower) arriving after the P-wave occurrence. S-wave propagation direction is perpendicular to particle motion (plane-polarized) (Reynolds, 1997). The S-wave do not propagate through fluids (Sheriff and Geldart, 1995). Seismic data may contain shear-wave signal that is generated near the surface through P-to-S conversion or conversion in the subsurface but arriving obliquely to receivers. It is therefore not usual to observe both P- and S-waves in vertical-type geophones.

4.1.2 Surface waves

Waves that propagate parallel or close to a free-surface with velocity decreasing with depth are called surface waves, of which Rayleigh and Love waves can be differentiated. Rayleigh waves travel only
through a free surface of solid media and are also referred as *ground roll* in reflection seismic data. Rayleigh wave velocity is usually 0.9 of S-wave velocity (Dentith and Mudge, 2014), they are often dispersive. Love waves are polarized shear waves, with particle motion, elliptical, parallel to the free surface. In conventional seismic data processing, surface waves are usually considered to be noise. In the case of this study, surface-waves will be generated near and around the tunnel walls (like tube-waves) whose wavelength would be a function of the source frequency and shear-wave velocity of the media. An estimation was done in this study to be on the order of 25-50 m based on an average shear-wave velocity of 2700 m/s and dominant frequency of 50-100 Hz, respectively.

4.2 Software used

Software used in this degree project and their specifications are listed below:

- Claritas™ – Reflection seismic processing software
- Paradigm GOCAD® and Paradigm SKUA® - data 3D visualization software
- PS_tomo code – traveltime tomography code
- MATLAB

4.3 Preprocessing

Achieving a subsurface image from seismic data is the main objective of conducting seismic surveys. Field acquisition parameters, together with the survey conditions can greatly steer seismic processing workflow (Yilmaz, 2001), thus data processing steps might vary depending on many parameters and surveys.

Prior to the processing, data had to be inspected rigorously to obtain zero-times of every individual hit. Given the logistical challenges and high noise levels due to vibrational noise from mine crushers and mining machinery at the site, the data quality is reasonable and clear first (P-wave) and secondary (S-wave) arrivals can be observed (Figure 7). With the exception of the very first few shots, the five hits had to be picked manually for more than 55 shot points (Figure 8) and later vertically stacked to allow improvement of signal-to-noise ratio (S/N) of shot gathers for traveltime picking and reflection data processing. Figure 9a,b shows a comparison between an example raw shot gather (only one hit) and a shot gather after vertical stacking (five repeated hits). By summing up the five records corresponding to the consecutive shots, the random noise component should be canceled leaving only the signal (Dentith and Mudge, 2014). Improvements of the S/N ratio in the latter case are noticeable. Landstreamer receivers recorded three-component data (two horizontal and one vertical), however for the purpose of this study, the vertical component has been separated and the remaining two horizontal components were not being taken into the further processing steps, due to the time constraints of this project. Summary of the main processing steps is described in Table 2.
**Figure 7** An example of raw shot gather with marked direct and refracted P-wave (dashed green line), direct and refracted S-wave (dashed pink line) and airwave (dashed yellow line). Note the possible reflections visible on the raw shot gather at the receiver location 5055 and 5094. Surface-waves while are not so strong in this case, they are expected to appear very close to the shear-wave arrivals.

**Figure 8** An example of the five consecutive hits recorded within 30 s time window that were later picked manually and through a shift and vertical stack procedure for stacking formed the shot gathers used in this study.
4.3.1 Field geometry application and direct arrivals picking
Survey coordinates were delivered by Yara Suomi Oy, and field geometry was inserted in the header into the seismic data using Claritas™. High-quality P- and S-wave arrivals were observed on all shot gathers originating from the Bobcat-source deployed inside the tunnel. Both P- and S-wave direct and refracted arrivals recorded inside the tunnel receivers were picked in an automatic manner and later corrected manually. Noisy traces were excluded from picking. The picking resulted in 9,340 P-wave arrivals and 9,742 S-wave arrivals.

4.4 Reflection seismic processing

4.4.1 Static correction
For data acquired on land, effects of the near-surface low-velocity zone and changes due to differences in source and/or receiver elevations can be corrected for 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). Here, a simple two-layer refraction model was used, as data have been acquired in a fairly horizontal tunnel with elevation only changing a couple of meters along the tunnel. The refraction correction then would be various gravel thicknesses and compaction used to make the road inside the tunnel. Picked first breaks were used for creating the near-surface velocity model and later for the refraction static corrections. Reviewed residual results after two iterations showed RMS below 2 ms and nearly flat lines, with minor exceptions, meaning that the calculated solution was good. Refraction static corrections were applied to the data helping to obtain much more coherent features as evident in the first and secondary arrivals (Figure 9c).

4.4.2 Direct arrivals removal
A number of steep features in the first few shots generated on the easternmost part of the tunnel were noticed and earmarked through the processing work to make sure if they end up in the final sections. The further processing steps aimed to preserve those features and focused on the removal of the direct P- and S-wave arrivals. A median filter targeting first and secondary waves worked well and helped to preserve these events as intact as possible (Figure 9d).
Figure 9 (a) An example of raw shot gather from the tunnel line (amplitude balancing is applied for display purpose), (b) after vertical stacking of repeated hits (improvement in the signal-to-noise ratio can be noticed), (c) after refraction static corrections, and (d) after removal of source-generated arrivals using a dedicated median filter.

4.4.3 CMP sorting

Before the seismic data could be further processed and stacked, shot-receiver data has to be sorted into common midpoint (CMP) gathers. This is done using the field geometry data and selecting the traces that have the same midpoint between the source and receiver position as shown in Figure 10. It is also quite common to use CMP and CDP (common depth point) names interchangeably, however, this is
only valid in the case of horizontally flat reflectors and horizontal layers above (Yilmaz, 2001). In Claritas, CDP sorting is done automatically by using DISCGATH function that allows sorting to CDP in a processing flow, by reading the shots with previously applied geometry information.

**Figure 10** An example CMP gather. Note raypaths (straight assuming a constant velocity media) coming from different source (S) and receivers (G) combinations with the same midpoint M (from Yilmaz, 2001).

### 4.4.4 Gain application and filtering
A geometric spreading correction was used to account for amplitude decay with time by using the spherical divergence operator (SPHDIV). Next, bandpass filter was used (30-50-250-300 Hz) (SPEQ) and Automatic Gain Control (AGC) was applied for display purposes and strengthening weaker signals and reducing source-related noise.

### 4.4.5 NMO corrections
Normal move-out (NMO) corrections are applied to remove the additional time delay due to source-receiver offset. NMO correction is used on a CMP gather, in order to “straighten” hyperbolic reflection traveltimes. It is worth to note that if applied velocity is too low or too high, the reflection will not align in a flat manner. With the purpose of applying NMO correction, several constant velocities were first tested in an iterative approach. The constant velocity of 6000 m/s gave the best result and was chosen for the NMO corrections although as will be discussed no convincing results were obtained.

### 4.4.6 Partial stack
Unfortunately, conventional prestack data enhancement and stacking did not produce as convincing results as expected from the events observed in the shot gathers. Therefore, obtaining full stack and migration was not possible. Deconvolution was also tested. However, it was not possible to preserve reflections and hence this processing step was ceased. Reflection processing continued using partial stack with the first three shots as input data and the focus changed to understand the nature of the
reflections than getting them imaged in a conventional stacked and migrated section. I will discuss reasons for this and what the reflection origin might be later in the thesis.

Table 2 Summary of main processing parameters of the reflection seismic

<table>
<thead>
<tr>
<th>Steps</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1)</td>
<td>Read SEG data</td>
</tr>
<tr>
<td>2)</td>
<td>Shift &amp; vertical stack of repeated hits</td>
</tr>
<tr>
<td>3)</td>
<td>Add geometry</td>
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<tr>
<td>4)</td>
<td>First-break picking with automatic picking and manual correction</td>
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<tr>
<td>5)</td>
<td>Shear wave picking with automatic picking and manual correction</td>
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<tr>
<td>6)</td>
<td>Refraction static corrections</td>
</tr>
<tr>
<td>7)</td>
<td>Removal of first arrivals (median filter)</td>
</tr>
<tr>
<td>8)</td>
<td>Shot gathers sorted into CMP</td>
</tr>
<tr>
<td>9)</td>
<td>Spherical divergence correction (SPHDIV)</td>
</tr>
<tr>
<td>10)</td>
<td>Bandpass filter (30-50-250-300 Hz) (SPEQ)</td>
</tr>
<tr>
<td>11)</td>
<td>Automatic Gain Control (AGC, 250 ms)</td>
</tr>
<tr>
<td>12)</td>
<td>NMO corrections (constant velocity 6000 m/s)</td>
</tr>
<tr>
<td>13)</td>
<td>Partial stack</td>
</tr>
</tbody>
</table>

4.5 Traveltime tomography

To obtain a better understanding of the shear zones and image the area between the tunnel and the surface, data for first arrival tomography were prepared. This included picking first arrivals (P-wave) from the tunnel recordings with the sources (explosives and Bobcat-drophammer) located on the mine benches. Data quality was a bit worse with respect to the first case, when sources were located inside the tunnel, nevertheless, first break picking was possible on all acquired shot gathers. First break picking produced 1,249 P-wave first breaks. Noisy traces were excluded from the picking. Both P- and S-arrivals were merged and prepared for employing the traveltime tomography with the use of the PS_tomo tomography algorithm, developed at Uppsala University (Tryggvason et al., 2002).

4.6 Drill cores

Unfortunately, water-drainage tunnel was not geologically detailed mapped immediately after its excavation. Additionally, the tunnel was directly coated with cement after its excavation. Therefore, although very important for the validation of the seismic data, in-tunnel geological data is not available. Hence, borehole R-623 was chosen to study geological variations due to its close proximity to the acquisition tunnel. Drill core logging data, including rock quality (RQD) and lithology parameters together with pictures from the core logging (wet and dry) of the core R-623 were provided by Yara
Suomi Oy. Core logging information was visualized in GoCad and corresponding core log sections were analyzed with respect to the crosscutting shear zones and the tunnel. Examples of carbonatite and glimmerite sections are shown in Figure 11 and an example of an interpreted shear zone is visible at borehole length of 107.5 – 110.55 m (Figure 12).

**Figure 11** A-12 m section of the R-623 drill core (wet) showing white carbonatite (sövite) and black biotite glimmerite. Courtesy of Yara Suomi Oy.

**Figure 12** An example shear zone occurrence in the drill core R-623 (dry). Shear zone (S4) can be distinguished at the depth of 107.5 – 110.55 m. Courtesy of Yara Suomi Oy.
5 Results

In this section, I present processed seismic data and their 3D visualization with geological data from the site and discuss presence of reflections with respect to the known shear zones. I also attempt to interpret the obtained results and argue the origin of the recorded events that likely makes this study and observation very unique.

5.1 Reflection seismic

Processing of the reflection seismic data provided images and results from an example shot gather are displayed (Figure 13) and described below. At the time of the careful inspection of the raw shot gathers, two events (R1 and R2) were observed at the first few shots, hence the further processing steps were aimed to preserve and enhance those reflections (Figure 13). Unfortunately, the remaining shot gathers did not provide any visible reflections and the focus was put only on understanding the nature of these reflections observed in the very first few shot positions recorded on the tunnel seismic line. For peculiar reasons that will be discussed later, this position favored reflections and not at other positions. Note also that the tunnel seismic data is in a 3D space hence a 2D imaging may strictly be difficult to image the reflections. This fact can be due to the shot locations being located completely between the shear zones S1-S5 or wave propagation complexity within such an environment. As mentioned before, full stack and migration of the data did not result in obtaining a true image of the subsurface, therefore it is important to note that the true location of the occurring events R1 and R2 have to be analyzed carefully.

R1 and R2 are quite steep in the shot records (~40-45°), short events that have an origin time at the intersection with S-wave or surface-waves (a matter to be discussed later). At the place where reflection intersect S-wave a amplitude lose and traveltime delay can be noticed. This delay somewhat also occurs at the same seismic trace intersecting P-wave arrivals.

5.2 Traveltime tomography

Data were prepared for the tomography employment and a general model was run and tested. Unfortunately, due to time constraints, the execution of the full tomography was not possible, this is preparing the starting models and later processing and data visualization. This is then being suggested as a further study to image the shear system that stretches also between the mine benches and the tunnel.
Figure 13 Steep events marked as R1 and R2 visible across all processing steps, (a) at an example of raw shot gather from the tunnel line (amplitude balancing is applied for display purpose), (b) after vertical stacking of repeated records, (c) after refraction static correction, (d) after applying a dedicated median filter to attenuate source-generated noise.
5.3 3D visualization of results

Resulting shot gather (observed at least in 3-5 shot gathers) from reflection seismic has been analyzed and visualized in 3D using GoCad software. Shear zones that intersect the tunnel and control the ore geometry have been projected to enable more precise interpretation. Unfortunately, information on dikes and other features located within the studied area was not available for the purpose of this study.

Figure 14 shows 3D visualization of the eastern part of the Särkijärvi pit with the location of the water-drainage tunnel and intersecting shear zones (S1-S5), together with the shots generated on benches above and away from the tunnel (red and green spheres). Shear zones S3 and S4 crosscut the seismic profile exactly at where events R1 and R2 are originated in the shot records, respectively (Figure 14c). An enlarged portion of the processed shot gather with marked events is also shown in Figure 15. It can be noted, that shear zone S1 is located just at the beginning of the acquisition line. Hence, due to the source noise at the first shot location, it is not possible to image this zone. Shots from the beginning of the tunnel did not also show any reflection from this shear zone.

![Figure 14](image)

*Figure 14* 3D visualization of the eastern part of the main pit benches (grey) with superimposed (a) models of the five shear zones (S1, S2, S3, S4, S5) intersecting the tunnel, (b) example processed shot gather showing the steep R1 and R2 reflections and (c) their possible correlation with the shear zones S2 and S4. Location of the explosive sources (red color) and Bobcat-mounted drophammer sources (green color) on the mine benches are also shown.

During the data acquisition inside the tunnel, an UAV-based video was also recorded. Careful inspection of the video material enabled detection of the water leakages exactly at the locations of the occurring reflections R1 and R2 (e.g., around receiver positions 5054 and 5094, respectively). Figure 16 shows the example of the water leaking on the tunnel wall and the exact location can be traced by referring to the known landstreamer station number. There are no side tunnels at the locations of the recorded reflections that could produce these events, therefore, they can be considered to be geologically associated. It is most likely that they can be interpreted as a reflection from the shear zones as they are mapped at these locations. Shear zones S1 and S2 are not observed in this shot gather clearly and it can...
be argued that shear zone S5 can be weakly observed near the tunnel entrance. A large first break delay may be associated with this or filled materials to prepare for the entrance of the tunnel.

Figure 15 (a) 3D visualization of the eastern part of the Särkijärvi open pit with superimposed shear zones (S1-S5) and processed shot gather and (b) close-up portion to show the two reflections R1 and R2.

Figure 16 (a) An UAV photograph taken inside the water-drainage tunnel during the seismic data acquisition showing seismic line setup with landstreamer and visible leakage on the wall around receiver 5094, and (b) simplified tunnel plan presenting the section where the leakage was present.

Drill core information, including lithology and RQD from borehole R-623 were projected with respect to the tunnel acquisition location, intersecting shear zones and eastern side of the open pit (Figure 17). It is worth to note the diabase occurrence in the wall of the shear zone S3, where also reflection R1 occurs. Unfortunately, modelled diabase dikes intersecting the tunnel were not available and therefore could not be shown in relation to the tunnel and crosscutting the shear zones. It could be useful in the future to correlate reflection R1 with regard to diabase occurrences.
Figure 17 (a) 3D visualization of the eastern part of the Särkijärvi open pit with superimposed shear zones (S1-S5), water-drainage tunnel and borehole R-623 with marked lithology and (b) RQD.
6 Discussion

Present knowledge suggests this is one of the few studies investigating the imaging of sub-vertical structures by utilizing in-tunnel reflection seismic data. Therefore, despite the good quality of the data and rigorous processing methods employed the interpretation has been challenging, partially due to lack of available literature covering this type of study. The survey design was coordinated to be both time and cost-effective in the given mining environment as also discussed by Malehmir et al. (2017) from an earlier survey using the landstreamer on the pit ramps and mining benches.

By analyzing the reflections R1 and R2 visible on the first few shot gathers, it is likely that the two steep events are in fact originating from shear- or surface-wave arrivals. To support this theory, I have considered three different scenarios and possible responses from the sub-vertical structures (a) in a constant velocity medium (Figure 18a); (b) in a gradual velocity increase medium (Figure 18b); (c) and finally in the case where structures are not vertical but are steeply dipping (Figure 18c). Based on those scenarios, I conclude that the reflections R1 and R2 correspond to the first scenario, presented in Figure 18a, with reflections originating from where it is likely surface waves are arriving.

The arguments for this interpretation are the following:

1) Observed events R1 and R2 are short in length (time), meaning they are likely controlled by their wavelength. As mentioned before, reflections are observed only on certain (first few) shot gathers, with a particular orientation towards the imaged structures, implying that the surface waves need time to become dispersive (different frequencies travel at different speeds). There are no reflections observed from the other receiver position, which supports this statement.

2) Zone of reflections (R1 and R2) can also be well correlated with the shear zone locations being modeled to be sub-vertical.

3) When considering a constant velocity media and sub-vertical shear zone, P-wave reflections will only be propagating downward, meaning they will not be visible on the shot record (response will not be recorded by surface receivers). In this scenario, surface-wave backscattered reflection can only be recorded. Surface-waves have an elliptical motion towards the vertical component of the receivers implying a favorable condition to be recorded by the vertical component of the tunnel receivers.

4) In the case of the gradual velocity increase (Figure 18b), any P-wave reflection from sub-vertical structures should also originate from the P-wave arrivals (i.e., first breaks). This is highly unlikely in this particular case, as observed events show a clear correlation with the shear/surface arrivals.

5) Furthermore, instantaneous amplitude (flatten to the S-picks) of the analyzed shot gather has been scrutinized and correlated with the P- and S-direct arrivals with respect to the observed reflections R1 and R2 (Figure 19). Clear decrease in amplitude can be noticed from the amplitude graph, favoring the shear/surface wave nature of the analyzed events.
Decrease in velocities in S-traveltime/offset and P-traveltime/offset graphs in correlation to the shear zones is not so obvious hence it remains to be challenging to state by studying only the vertical component data, whether the origin of the backscatter reflection is from the surface-waves or the shear wave. Given the 3C (3-component) nature of the tunnel receivers, particle motion analysis can be useful to check if the reflections have an elliptical motion (surface-wave) or linear one (shear-wave).

Based on the above-mentioned discussion, I speculate that the visible reflections are originating from the vertical to subvertical structures. In this study I have also favoured the origin of reflections coming from shear zones over the other geological structures like for e.g., dikes. This is due to the difference in the physical properties of the shear zones against dikes. In the first case, decrease in observed amplitude is being expected due to the more attenuative nature of the shear zones, whereas this is not the case for the dikes.

A topic requiring further notice is the resolution of the seismic data in imaging such a small zone. Based on a careful study of the dominant wavelength in the data (estimated to be around 70-100 Hz) and an assumption that the surface-waves are nearly as much as shear-waves (estimated to be around 2500-2800 m/s), a dominant wavelength of 25-30 m can be expected. This implies a vertical resolution, the ability to resolve top and bottom of a bed Rayleigh's criterion, on the order of (a quarter of a wavelength) 8-10 m. When carefully studying the reflections in the shot records, only a single reflection is observed from the shear zone. This means they are not resolved rather only detected. The detection limit of seismic data is typically considered to be on the order of a 30th of the dominant wavelength which then puts this to only one meter. This means features of high seismic contrast can still be detected by the seismic data but not fully resolved.
Figure 18 Three scenarios of waves propagation and occurrence of seismic reflection, when reflection seismic survey is employed inside the tunnel and (a) subvertical shear zones are within a constant velocity rock medium, (b) within a gradually increasing with depth rock medium, and (c) shear zones are steeply dipping and not necessarily sub-vertical.
Figure 19 Correlation between various elements of the shot gather acquired inside the tunnel showing S-wave traveltime picks normalized by offset, P-wave traveltime picks normalized with offset, P-to-S traveltime ratio, instantaneous amplitude of a window around the shear-wave arrivals. The decay of amplitude at the receiver 5054 and 5096 is visible and can be correlated with the observed reflections R1 and R2 at the same receiver locations.
7 Conclusions

This degree project has investigated mapping sub-vertical shear zones from an in-tunnel seismic data acquired in the Sillijärvi’s open-pit-apatite mine in eastern Finland. Tunnel-surface seismic data were acquired in the eastern part of the Särkijärvi open pit, from receivers located inside the water-drainage tunnel and sources located both in the tunnel and on the mine benches. Considering the logistical challenges and significant noise levels coming from mining operations, the acquired data were of good quality with clear reflections observable in the shot gathers.

This study has illustrated the potential of in-tunnel reflection seismics for sub-vertical structures (shear zones) imaging. Data processing was challenging, however, two sets of reflections associated with the shear zones were preserved and enhanced through the processing allowing them to be interpreted in this study. I speculate that the nature of the short and relatively steep events originates from the sub-vertical shear zones intersecting the tunnel. Imaging such structures in an open pit environment with the usage of the pre-existing mine infrastructure creates a new method of seismic data acquisition. This method is especially applicable when data cannot be acquired on mine benches or inside the open pit due to ongoing mining operations and therefore makes such a survey cost and time efficient. It also helps to understand wave-propagation within such a complex geological environment.

Securing sustainable ore extraction would not be possible without consideration of the economic, technical and environmental aspects. Seismic investigation of the mine wall affected by shear zones and dikes can contribute to the mine planning and mapping the slope stability. Gently dipping structures such as dikes, which are crosscutting the tunnel might be problematic during the mine excavation and may create block wedges leading to rock failures when conditions are suitable. Introducing an innovative survey approach might be therefore advantageous in comparison to the traditional data acquisition design. Note also that imaging sub-vertical feature is nearly impossible using surface seismic data and this study helps to obtain results that points to other features that can be used as a proxy for interpreting sub-vertical structures (i.e., surface-wave backscattered reflection).

Recommendations for future studies could include analysing the two remaining components of the seismic data (horizontal components) as they were prepared through this study and investigating further the relevant particle motions to confirm the nature of reflections and whether they are indeed shear/surface-wave arrivals. Tomography work could be continued for a better understanding of the low-velocity zones and imaging the area between the surface and the tunnel. This would especially be pertinent when dealing with the possible rock failure zones in an open-pit mine. In the future, it might be additionally appropriate to consider a longer acquisition line and investigate the dip and direction of the target structures prior to the survey design. This could be carried out simultaneously alongside preparation of expected seismic response models.
8 Acknowledgments

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9 References


Appendix - EAGE-Near Surface Geoscience Conference 2019 – Extended Abstract

Title: Mine bench-tunnel seismic data acquisition for characterizing shear zones in the Siilinjärvi phosphate mine, Finland

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Summary

Siilinjärvi in central Finland, is currently the only phosphate mine with significant phosphorus production in western Europe. Phosphate rock and phosphorus are critical for the EU because of their supply risks and economic importance. The phosphate bearing rocks in Siilinjärvi are within a major Archean alkaline and carbonatite complex deformed and intruded by several shear and dyke systems. By understanding their spatial and temporal relationships an improved exploration and extraction of this critical ore would be possible. The objective of the study was to employ a novel seismic survey using the existing mine infrastructure for better planning and geological understanding. An innovative in-tunnel seismic survey was conducted in the Siilinjärvi open-pit mine in October 2018. A water-drainage tunnel nearly in the bottom of the pit intersecting two major shear zones was used to enable bench-tunnel seismic data acquisition. High-quality data were acquired using 144 receivers inside the tunnel, with the sources located both inside the tunnel (Bobcat-mounted vertical drop hammer) and on the surface (combined explosives and Bobcat). Two reflections interpreted to originate from subvertical shear zones intersecting the tunnel were observed illustrating the importance of such surveys for shear-zone imaging and site characterization.

Introduction

Siilinjärvi mine in central eastern Finland is currently the only phosphate mine with significant phosphorus production in the European Union. Phosphate rocks and phosphorus are listed as critical raw materials for the EU (European Commission, 2017) because of their supply risks and economic importance for a sustainable growth of the union, in particular because of the significance of phosphate fertilizers in the food supply chain. Securing exploration as well as extraction of phosphate rocks is important for the EU.

At Siilinjärvi, the phosphate rocks are hosted by a major Archean alkaline and carbonatite system. Several post-mineralization shear and dyke systems have complicated the geometry and extraction of the ore in the mine. In the eastern part of the main pit, these shear zones sometimes cause wall stability issues particularly in combination with gently dipping units including dykes. The shear zones striking dominantly in N-S orientation also control the shape of mineralization running in the same direction. Understanding their spatial and temporal relationships would improve exploration and extraction of the ore. A sustainable supply of apatite requires a good understanding of rock quality conditions and geometry, and how mining can be done cost effectively and safely.

Based on the successful implementation of the newly developed landstreamer seismics in noisy urban and challenging mining environments (Brodic et al., 2015 and 2017; Malehmir et al., 2017), an innovative in-tunnel seismic survey was conducted in the Siilinjärvi open-pit mine during October 2018 as part of a larger seismic survey. The objective of the study was to employ the in-tunnel seismic survey using the existing mine infrastructure (water-drainage tunnel) for mapping several shear zones (S1, S2
and S3) intersecting the tunnel in the eastern part of the main pit (Figure 1). The use of this water-drainage-pumping tunnel for the data acquisition is a novel approach in open-pit mines.

**Figure 1** (a) General geological map of the Siilinjärvi complex showing the two open pits, Särkijärvi and Saarinen. (b) Aerial photo showing the location of the tunnel, seismic sources, and receivers in the Särkijärvi (main pit) open-pit mine. Several shear zones (e.g., S1, S2 and S3) intersecting the tunnel (yellow colour) perpendicularly are also marked. These shear zones are speculated to have controlled the geometry of the deposits. Includes edited material from the Digital bedrock map 1:200,000 © Geological Survey of Finland 2012 and Ortophoto Database of the National Land Survey of Finland 06/2018.

**Background**

The Siilinjärvi complex is an ultramafic alkaline-carbonatite complex intrusive into the neighbouring granite gneiss area (Puustinen, 1971). The complex can be described as a carbonatite-glimmerite tabular body. The complex is amongst the oldest carbonatite deposits in the world with the estimated age of approximately 2610 Ma (e.g., Kontinen et al., 1992). Yara International operates Siilinjärvi phosphate mine with production in two open pits: Särkijärvi main pit and Saarinen satellite pit.

Seismic reflection data in the Siilinjärvi mine (main pit) were acquired using 144 receivers 2 m apart, out of which 120 were 3C MEMS (micro-electro-mechanical system) sensors mounted on a landstreamer (Figure 2a) and 24 conventional coil-based 1C geophones (7 cm spike). This in total provided a spread of 286 m covering most of the tunnel (Figure 2b). The tunnel is fairly horizontal with elevation only changing a couple of meters along the tunnel, making it ideal for such a survey. A 500-kg Bobcat-mounted drophammer (Place et al., 2015) was used as the seismic source that was activated at every second receiver position (i.e., every 4 m) inside the tunnel. At every shot position, five hits were done within a 30 s window and used later in a shift and stack manner to improve the signal-to-noise ratio. In order to guarantee successful imaging of the shear zones and their geometry, several explosive and Bobcat drophammer shot locations were also generated on benches above and away from the tunnel enabling ray coverage between the benches and the tunnel receivers for traveltome tomography purposes. GPS-time tagging with an accuracy of a few microseconds was used for stamping initiation of impact sequences and explosive charges.
Seismic data quality and processing

Prior to the processing, data had to be inspected rigorously to obtain zero times of every individual hit. The five hits had to be picked manually and later vertically stacked to allow improvement of S/N ratio of shot gathers for travelt ime picking and reflection processing. Figure 3a,b shows a comparison between an example of raw shot record (one hit only) and after vertical stacking of five repeated hits. Following first break picking, refraction static corrections were estimated and applied to the data helping to obtain much more coherent features as evident in the first and secondary arrivals (Figure 3c). A number of steep features (e.g., R1 and R2) were noticed especially in shots generated on the easternmost part of the tunnel. These features had to be preserved using a dedicated workflow. A median filter targeting first and secondary arrivals worked well and helped to preserve these events as intact as possible (Figure 3d). Reflection processing continued using conventional prestack data enhancement and poststack migration, however, this did not produce as convincing results as expected from the events observed in the shot gathers (e.g., Figure 3d). This will be discussed later.

Figure 3 (a) An example of a raw shot gather from the tunnel line (amplitude balancing is applied for display purpose), (b) after vertical stacking of repeated hits, (c) after refraction static corrections, and (d) after removal of source-generated arrivals using a dedicated median filter. Note the steep events marked as R1 and R2.
Results

At this stage, we only present the data and discuss their implications for mapping the shear zones that intersect the tunnel. The shear zones have been observed in the pit and also in a number of boreholes, hence their geometry, being sub-vertical, is reliably accurate. Figure 4 shows 3D visualization of the eastern part of the main pit with the location of the water-drainage tunnel and shots generated on benches above and away from the tunnel. Shear zones S1 and S2 intersect the tunnel exactly at where reflections R1 and R2 are observed in the shot records, respectively (Figure 4b,c). Luckily during the data acquisition, an UAV-based video was recorded showing water leakages exactly at the locations of these events (e.g., around receiver positions 5054 and 5094, respectively). At these locations there are no side tunnels to produce these events, therefore they are judged to be geologically associated and most likely from the shear zones as they are mapped to be at these positions. Shear zone S3 does not occur in this shot gather clearly but has also been weakly observed on receivers near the entrance of the tunnel.

![Figure 4](image)

**Figure 4** 3D visualization of the eastern part of the main pit benches with superimposed (a) models of the three shear zones (S1, S2 and S3) intersecting the tunnel, (b) example processed shot gather showing the steep R1 and R2 reflections and (c) their possible correlation with the shear zones S1 and S2. Location of the explosive sources (red colour) and Bobcat drop hammer sources (green colour) on the mine benches are also shown.

Conclusions

We have presented a novel in-tunnel seismic data acquisition from the Siilinjärvi open-pit mine utilizing the mine infrastructure for mapping sub-vertical shear zones. Given the logistical challenges and high noise levels due to vibrational noise from mine crushers and mining machineries at the site, the data quality is reasonable and clear features associated with the shear zones can be observed. We will present tomography results using the mine-bench-tunnel data, study of particle motions from the 3C data and speculate on the nature of the steep events appearing to originate from the shear/surface-wave arrivals. We currently favour that they are sub-vertical and that these events are surface-wave reflections from vertical shear zones, however these claims are still inconclusive. This innovative survey is quite encouraging and opens up opportunities for similar-type surveys and better understanding of seismic signature of vertical shear zones.

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