Deep reflection seismic imaging of iron-oxide deposits in the Ludvika mining area of central Sweden

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ABSTRACT

Reflection seismic data were acquired within two field campaigns in the Blötberget, Ludvika mining area of central Sweden, for deep imaging of iron-oxide mineralization that were known to extend down to 800–850 m depth. The two surveys conducted in years 2015 and 2016, one employing a seismic landstreamer and geophones connected to wireless recorders, and another one using cabled geophones and wireless recorders, aimed to delineate the geometry and depth extent of the iron-oxide mineralization for when mining commences in the area. Even with minimal and conventional processing approaches, the merged datasets provide encouraging information about the depth continuation of the mineralized horizons and the geological setting of the study area. Multiple sets of strong reflections represent a possible continuation of the known deposits that extend approximately 300 m further down-dip than the known 850 m depth obtained from historical drilling. They show excellent correlation in shape and strength with those of the Blötberget deposits. Furthermore, several reflections in the footwall of the known mineralization can potentially be additional resources underlying the known ones. The results from these seismic surveys are encouraging for mineral exploration purposes given the good quality of the final section and fast seismic surveys employing a simple cost-effective and easily available impact-type seismic source.

Key words: Seismic, Data processing, Imaging.

INTRODUCTION

Reflection seismic methods nowadays are proving their significance in mineral exploration and mine planning, and several published studies (e.g. Milkereit et al. 1996; Salisbury, Milkereit and Bleeker 1996; Eaton, Milkereit and Salisbury 2003; Malehmir and Bellefleur 2010; Malehmir et al. 2012, 2017a; Manzi et al. 2012, 2014; Urosevic, Bhat and Grochau 2012; Urosevic, Ziramov and Moreau 2016) demonstrate their strength for mineral exploration and particularly cost-efficiency for deep targeting. Main advantages of utilizing seismic methods in mineral exploration are their considerably higher resolution (compared to other geophysical methods) at depth, enabling brownfield and near-mine exploration surveys to delineate deeper parts of the mineral deposits (Urosevic and Evans 1998; Bellefleur et al. 2004; Malehmir et al. 2009, 2014; Dehghannejad et al. 2010; Bellefleur, Malehmir and Müller 2012; Cheraghi, Malehmir and Bellefleur 2012; Koivisto et al. 2012; Malinowski, Schetselaar and White 2012; Manzi et al. 2012; Ahmadi et al. 2013) for better exploration drilling programmes and for mine planning purposes. When further combined with other geological, petrophysical and geophysical data, seismic methods help characterize metallic deposits in their often complex geological settings.
and especially in hardrock environments (Milkereit et al. 1996; Eaton et al. 2003; Salisbury, Harvey and Matthews 2003). Many of these targets produce strong seismic contrasts (Eaton et al. 2003 and references therein; Salisbury et al. 2003; Malehmir et al. 2013) due to the high concentrations of sulphides (and to a first order due to the increased density of the target materials), allowing them to generate strong seismic signals (reflection or diffraction). Employing seismic methods is thus increasing for mineral exploration, especially as economic and larger deposits are now targeted at greater depths. After low steel production rates at the end of the twentieth century, a few booming years (2004–2014) of increasing prices due to global demand, especially from China (Wärell 2018), have led to renewed interest worldwide for metallic deposits, and particularly in hardrock environments (e.g. in Europe, Canada, Australia and Central America). This demand greatly pushes research and development towards cost-effective, while retaining quality, seismic mineral exploration methods for deep exploration.

In the present study, we apply the reflection seismic method for imaging the deeper parts of the iron-oxide mineralization in Blötberget in the Ludvika mining area, south-central Sweden. Several complementary studies have been recently carried out within the Ludvika mining area for the same purpose, however focusing mainly on downhole physical property measurements of the mineralized zones and their host rocks (Maries et al. 2017a), drone-based geophysical surveys (Malehmir et al. 2017b), gravity and magnetic modelling (Yehwalashet and Malehmir 2018) and magnetic characterization of the magnetite and hematite deposits (Almqvist et al. 2019). This study focuses on a series of reflection seismic data acquired within two different field campaigns in the area namely (1) a seismic landstreamer survey (acquired in 2015) conducted for a feasibility study of the method for deep targeting and (2) a more conventional seismic survey (acquired in 2016) but using spike-type geophones and denser source and receiver spacing hence higher seismic fold than the 2015 survey. The first study was designed as a pilot test assessing the potential of a digital broadband 240-m-long landstreamer (Brodic et al. 2015) to image the deposit’s seismic signature at depth and in this hardrock environment (Malehmir et al. 2017a), while the second survey (2016) was aimed at providing deeper information on the mineralization and to characterize structures that may be of importance when the mining commences again at the site. The potential of the 2016 and 2015 datasets has been recognized earlier by Maries et al. (2017a) in a conference presentation and is currently used by various research groups for different technical purposes (e.g. Bräunig et al., 2020, for depth imaging; Papadopoulou et al., 2020, for surface-wave imaging; Balestrini et al., 2020, for surface-wave retrieval and attenuation through seismic interferometry approaches; see also Malehmir et al. 2019).

For exploring the full potential of both of the seismic datasets, we have merged the 2015 and 2016 datasets and processed them together in order to increase the fold and improve resolution for deeper imaging. Besides the conventional seismic processing, we have also tested a new way of attenuating surface waves, using curvelet de-noising methods on the prestack data. The main objectives of the study are (1) to delineate the depth extension of the iron-oxide mineralization beyond the known 800 m depth, (2) to study the seismic signature of new potential deposits and (3) to better understand the geological architecture in which these deposits are found. This study suggests that there are additional iron-oxide resources down-dip beyond the known 800 m depth and provides new targets located a couple of hundreds of meters in the footwall of the known deposits in a cost-effective yet high-resolution manner. Additionally, large-scale geological features can be inferred from the seismic results.

BACKGROUND

Geology

Our area of interest, Blötberget in the Ludvika mining area (Fig. 1) belongs to the Bergslagen mineral district of south-central Sweden. Bergslagen is one of the most important mineral districts in the country, with a history of iron ore mining for several centuries, a commodity that likely formed the foundation of the Swedish mainstream industry (e.g. steel-making industry and high-voltage electrical transmission). Geologically, Bergslagen belongs to the Svecofennian orogen in the Fennoscandian Shield (Fig. 1), with metamorphosed volcanosedimentary host rocks of Palaeoproterozoic age (1.85–1.8 Ga). The mineralization in Bergslagen comprises banded iron formation, skarn-type iron-oxide deposits and apatite-rich iron-oxide deposits (Geijer and Magnusson 1944; Stephens et al. 2000, 2009), among which apatite-rich iron-oxide deposits account for more than 40% of the iron ore produced in the region (Geijer and Magnusson 1944; Stephens et al. 2009). Blötberget area is rich in high-quality iron-oxide deposits (primarily magnetite) and has a history of mining dating back to the sixteenth century up to the end of the twentieth century when dropping steel prices affected mining in Europe, including Bergslagen as a whole and Blötberget in particular.
Deep reflection seismic imaging of iron-oxide deposits

Figures 1 Geological map of the Blöterberget mining area showing the major lithological units and seismic profiles (modified from Maries et al. 2017a). Major tectonic units in the Scandinavia and location of the study site (modified from Malehmir et al. 2015) in Sweden. The bedrock map was reprinted with permission from the Geological Survey of Sweden (SGU). Seismic profiles 15P1 (year 2015, blue colour) and 16P1 (year 2016, red colour) are the focus of this study. Downhole logging data from boreholes BB14004 and BB14005 are shown in the paper.

A renewed interest in mineral exploration in recent years due to high iron ore prices however has led to the re-evaluation of Ludvika historical iron-oxide mines and new assessments of the mining potential in the area given the availability of mining and transportation infrastructures already in place. New exploration and mining permits have been granted to mining company Nordic Iron Ore (NIO) thus there is considerable interest to invest in understanding and then mining the deposits currently known to extend down to at least 800–850 m depth. A wealth of boreholes and historical data are also available from the area, including petrophysical and petrochemical laboratory measurements. Information on the depth extent of the deposits as well as their lateral extent is crucial for planning new mining infrastructure (e.g. tunnels, shafts and ramps), as well as for utilizing the existing ones.

Economic parts of the ore, often found in sheet-like horizons, occur within dacitic to andesitic, feldspar and porphyritic metavolcanic rocks. Metamorphic grades range from medium to upper amphibolite facies. The host rock and the mineralization are cut by several intrusions: coeval dacitic, andesitic and basaltic dykes and subvolcanic intrusions as well as by synvolcanic, granitic to intermediate plutonic rocks. Post-mineralization intrusion of granite–aplite–pegmatite and metamorphism severely deformed these rocks (Allen et al. 1996; Ripa and Kübler 2003).

The mineralization in Blöterberget consists of magnetite and hematite, with additional apatite and small amounts of quartz and calc-silicate minerals present. The ore contains more than 50% of iron dominantly from magnetite but also hematite at distinct horizons. Less massive than the magnetite ones, hematite ores have slightly different host rock mineralogy, containing more quartz and feldspar. The origin of the apatite-rich iron-oxide deposits is considered to be synvolcanic; however, a new study indicates a
magnatic-hydrothermal (hot temperature) origin (Jonsson et al. 2013). The mineralized sheet-like units dip moderately (about 45°) towards the south-southwest down to 500 m depth where they become gently dipping until the currently known from boreholes, depth of approximately 800–850 m. The economic mineral reserves in Blötberget are estimated approximately 45 million tonnes with a cut-off grade of 41.7% iron. The inferred resources are however much more and the site has a potential to yield much more reserves subject to additional drilling programmes and feasibility studies. Most of the mineral extraction from the Blötberget operation, before its closure in 1979, was above the 240-m level. NIO plans to restart mining operations at 280-m level in 2021, subject to a good outcome of the feasibility study and financing of the project (Nordic Iron Ore, personal communication, 2018).

Downhole logging

Maries et al. (2017b) analysed downhole logging physical property measurements in several boreholes that intersect the iron-oxide mineralization and its hanging wall from surface down to 600 m borehole length. The downhole data suggested mechanically poor competent mineralized rock, due to fracturing, by correlating attenuation of seismic waves (seismic Q) with rock quality designation assessments done on core samples. Apart from the distinct magnetic susceptibility signature at depth, acoustic impedances derived from density and seismic velocity suggested a strong seismic response from the mineralized zone. For completeness, we present the downhole logging data from two of the seven analysed boreholes indicating that the mineralization is expected to produce a strong seismic signature on surface seismic data (Fig. 2). Repeated occurrences of the mineralized zones within a short interval (e.g. 520–560 m depth in Fig. 2a and 300–380 m depth in Fig. 2b) imply repeated reflectivity within these certain depth intervals, rather than a single strong reflection. This is illustrated in the synthetic seismograms generated using a 90-Hz central frequency Ricker wavelet (corresponding to the dominant frequency of the data) and the reflection series derived from physical properties data. A 70-Hz Ricker wavelet (not shown here) did not produce much different results than the

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Figure 2  Examples of physical properties and synthetic seismograms obtained from sonic logging derived compressional velocity and laboratory density measurements for two boreholes (BB14004 and BB14005 in Fig. 1) in Blötberget area (modified form Maries et al. 2017a). Magnetite and hematite occur in sheet-like horizons varying from a few meters to about 35 m thicknesses (current example) or more. Synthetic seismogram suggests they may appear in a repeated sequence (short period reflections), as if the reflectivity would be ringy at these depth intervals.
Table 1 Summary of the main acquisition parameters for the 15P1 (year 2015) and 16P1 (year 2016) surveys in the Blötberget mining area, Sweden

<table>
<thead>
<tr>
<th>Field campaigns</th>
<th>October 2015</th>
<th>September 2016</th>
</tr>
</thead>
<tbody>
<tr>
<td>Survey parameters</td>
<td>Acquisition type</td>
<td>Move along using landstreamer and fixed wireless recorders</td>
</tr>
<tr>
<td>Acquisition system</td>
<td>Sercel Lite 428</td>
<td>Sercel Lite 428</td>
</tr>
<tr>
<td>Number of profiles</td>
<td>One (15P1)</td>
<td>Two: 16P1 &amp; 16P2 (16P1 is not in the scope of this paper)</td>
</tr>
<tr>
<td>Receivers</td>
<td>DSU3 (3C MEMS) 10 Hz geophones</td>
<td>10 Hz geophones</td>
</tr>
<tr>
<td>Number of receiver locations</td>
<td></td>
<td></td>
</tr>
<tr>
<td>–Landstreamer</td>
<td>900 (nine times x 100 moving)</td>
<td>N/A</td>
</tr>
<tr>
<td>–Wireless recorders</td>
<td>149 (SE: 75 and NW: 74)</td>
<td>24</td>
</tr>
<tr>
<td>–Cabled</td>
<td>N/A</td>
<td>427</td>
</tr>
<tr>
<td>Number of shot points</td>
<td>533</td>
<td>387</td>
</tr>
<tr>
<td>Receiver interval</td>
<td>2–4 m (10 m for wireless receiver location)</td>
<td>5 m (10 m for wireless receiver location)</td>
</tr>
<tr>
<td>Shot interval</td>
<td>4 m</td>
<td>5 m</td>
</tr>
<tr>
<td>Maximum source–receiver offset</td>
<td>~2500 m</td>
<td>~2200 m</td>
</tr>
<tr>
<td>Source</td>
<td>500-kg Bobcat mounted drophammer and explosives (charges ranging from 50–100 g)</td>
<td>500-kg Bobcat mounted drophammer</td>
</tr>
<tr>
<td>Profile length</td>
<td>~3.5 km</td>
<td>~2.2 km</td>
</tr>
<tr>
<td>Recording parameters</td>
<td>Record length</td>
<td>10 s (reduced to 1 s for processing)</td>
</tr>
<tr>
<td>Sampling rate</td>
<td>1 ms</td>
<td>1 ms</td>
</tr>
<tr>
<td>Receiver and source parameters</td>
<td>Streamer length</td>
<td>240 m</td>
</tr>
<tr>
<td>Nominal fold</td>
<td>88</td>
<td>208</td>
</tr>
<tr>
<td>Source pattern</td>
<td>3 records/point</td>
<td>3 records/point</td>
</tr>
</tbody>
</table>

90 Hz in terms of cyclic reflectivity within the ore zone. Ricker wavelet was chosen primarily because it is conventional to use but also for better visual matching of reflection series with the one-dimensional synthetic reflections.

DATA ACQUISITION

Acquired during two field campaigns (2015 and 2016), the Blötberget seismic data consist of three seismic profiles in total: profile 15P1 from year 2015 and profiles 16P1 and 16P2 from year 2016, respectively (Fig. 1). Key acquisition parameters for both surveys are summarized in Table 1. The first survey, using the seismic landstreamer (Malehmir et al. 2017a) and a 500-kg Bobcat-mounted drophammer (Urosevic et al. 2009; Place et al. 2015; Place and Malehmir 2016) consisted of an approximately 3500 m long seismic profile along the available roads and forest trails, including passage over a high traffic road on the southern part of the profile. Profile 15P1 (Fig. 1) deployed 100 MEMS (micro-electromechanical system) sensors spaced at 2–4 m moved along the profile and 75 fixed wireless recorders connected to 10-Hz geophones, spaced at 10 m at both ends of the landstreamer final spread. Shots were generated at 4 m spacing along the MEMS sensors and at 10 m spacing along the 10-Hz geophone spread (Fig. 3), using three repeated records to help improve signal-to-noise ratio by vertical stacking. For a better depth penetration and source comparison and to avoid failure in case the seismic signal was attenuated by the swampy terrain when using the drophammer only (Malehmir et al. 2017a), part of profile 15P1 employed 23 explosive shots (50–100 g of dynamite fired at a depth of 50–80 cm, hand drilled). The 2016 seismic survey consisted of two profiles in the same area, 16P1 and 16P2 (Fig. 1), aimed at better imaging the extent of the mineralization at depth already delineated from profile 15P1. Profile
16P1 (approximately 2200 m length) followed a similar geometry and was largely collocated with 15P1 on the northern part of the main road. Receivers were 10-Hz spike-type cable-connected geophones for nearly the entire profile, with 5 m receiver and shot spacing. Twenty-four wireless recorders connected to 10-Hz geophones were used on the southern portion of profile 16P1. Profile 16P2 (approximately 700 m length), consisting of wireless sensors connected to 10-Hz geophones, was positioned perpendicular to profile 16P1, with the aim of providing information about the lateral extension of the mineralization (not the scope of this paper). The seismic energy was generated with the same Bobcat-mounted drophammer as for 15P1 (Fig. 3). Seismic data were acquired within 5 days for each of the two field campaigns including line setup, geodetic surveying and pickup, a remarkable speed for such a survey in the challenging Swedish logistical landscape.

**DATA PROCESSING**

Seismic data processing followed a conventional prestack data enhancement (Malehmir et al. 2013a) and poststack migration to better control the processing workflow and parameters ensuring that reflections observed on shot records are preserved in the final section. However, given the complexity of the datasets, to enable successful imaging of the mineralization and its host rock, the two datasets (with different equipment setup and background noise) from profiles 15P1 and 16P1 were merged, with the goal of increasing the resolution of the data along the main profile.

Processing of the 2015 dataset started with merging of the cabled (and landstreamer) and wireless recorded data using GPS timestamps registered on the active (i.e. cabled line or landstreamer) data. Details are provided in Malehmir et al. (2017a). For the 2015 dataset both geophone and MEMS-recorded data were used. These two types of sensors have similar phase but different frequency bandwidth and amplitude (Malehmir et al. 2017c). The integration of these domain types was embedded in the gapped deconvolution filter as well as balancing spectra (40–60–200–280 Hz) applied to the 2015 dataset, given the source type, that is impact type (Mougenot, Cherepovskiy and Jun Jie 2011; Malehmir et al. 2017c). Figure 4(a) shows a raw shot gather with applied refraction static corrections from the 2015 survey recorded for a shot fired on nearly the north-western end of the profile. After applying bandpass filtering, spectral balancing and top mute, we were able to identify a reflection, likely originating from the mineralization, already in the shot gathers (Fig. 4b). Figure 4(c) shows another shot gather recorded close to the southern end of the profile where a wide-angle reflection is clearly observed in the data from the wireless recorders. After the same processing steps, the shot gather (Fig. 4d) shows the reflection with its apparent NW-dipping character (marked as R1). We infer later that this reflection represents either a fault contact or a weakly mineralized horizon given the apparent velocity increase of the first arrivals associated with the reflection (Fig. 4c).

For the 2016 dataset, in a similar manner, initial processing steps included merging of the cabled and wireless recorded data using the GPS timestamps registered on the active cabled-line data. After merging and vertical stacking of the repeated shots records, already in the raw shot gathers, high-amplitude reflections were notable. Figure 5(a) shows an example of a shot gather from the 2016 survey with what appears to be two sets of SE-dipping reflections in the data (marked as
Figure 4 An example of shot gather from the 2015 survey (combined wireless and landstreamer). (a) Raw shot gather with refraction static corrections applied and (b) processed shot gather after bandpass filtering, spectral balancing and top mute. Red arrows mark a reflection M2, which likely originates from the mineralization. (c) A different raw shot gather from the 2015 survey with applied refraction static corrections but recorded on its southern end (combined wireless and landstreamer) and (d) the processed shot gather with same processing steps as (b). Red arrows mark a reflection R1 that is interpreted to be associated with a fault system in the area.
Figure 5 An example of shot gather from the 2016 survey and corresponding amplitude spectrum. (a) Raw shot gather, (b) after refraction static corrections, (c) bandpass filtering and (d) FDCT and bandpass filtering after refraction static corrections. Red arrows mark reflections interpreted to be from mineralization. Highlighted blue zones represent gradual attenuation of surface waves. Note how surface waves are more efficiently removed using the FDCT method.

M1 and M2), likely originated from the mineralized zones, given their arrival time and geometry. Such reflections and their preservation and enhancements through the processing work were essential for parameter designs and removal of surface-waves that will be discussed later.

Aiming to improve reflections such as M1 and M2, it was decided only geophone recorded (wirelesses) data from profile 15P1 (2015 dataset) to be merged with the data from profile 16P1 (2016 dataset). This means MEMS data were excluded in the merged data. Before merging the two datasets, surface-consistent refraction static corrections were applied separately to each dataset (15P1 and 16P1) due to different positioning of the receivers and sources (especially elevation-wise). An attempt was made to estimate a common refraction static
model, but this did not result in a suitable model assuming two-dimensional solutions. The difference between elevations (some shots and receivers ended up in ditches with up to 3–5 m elevation differences and different near-surface conditions) from the 2015 and 2016 were handled later through elevation and surface-consistent reflection statics. Figure 5(b) shows the 2016 raw shot gather but after refraction static corrections, where reflections M1 and M2 are seen slightly sharper and more continuous.

The processing applied to the merged datasets focused on attenuation of ground-roll and source-generated noise through bandpass filtering (10–30–150–180 Hz) and amplitude-frequency balancing (i.e. spectral whitening using a 30–50–130–160 Hz frequency range). Figure 5(c) shows the effect of these methods (top mute is also applied) especially for removing surface waves. Reflections M1 and M2 were improved remarkably, suggesting even two slightly different dips (M1 slightly steeper than M2) are present. Nonetheless, some surface-wave energy was still left that could not be removed by conventional CMP stacking (see blue marked region in the shot gather).

In order to further improve reflections M1 and M2, we decided to focus on attenuating the surface-wave energy through other methods. Shots particularly on the northern part of the survey area were generated on thick and swampy landform. This led to a significantly notable surface-wave energy observed on the shot records requiring a better treatment than by just low-frequency filtering and/or spiking deconvolution.

Curvelet de-noising algorithm (FDCT- fast discrete curvelet transform) was chosen for this purpose (von Ketelhodt et al., under review), where we applied de-noising on the prestack seismic data. Curvelet de-noising has been applied for attenuating both incoherent and coherent noise, but not for surface-wave attenuation on the prestack data. Curvelet de-noising has, however, widely been used in structurally complex environments (Neelamani et al. 2008; Górszczyk, Adamczyk and Malinowski 2014; von Ketelhodt et al. under review) and more specifically, for de-noising surface-wave contaminated data in non-steeply dipping reflectivity settings (Naghizadeh and Sacchi 2018). Prior to the curvelet de-noising, data were LMO (linear moveout) corrected, for 5500 m/s, in order to accurately define surface waves in the curvelet de-noising programme. After the LMO correction, the forward curvelet transform was applied, which decomposes the seismic image into different scale and angular curvelet coefficients in the curvelet domain. Subsequently, a threshold is applied, or the curvelet coefficients are modified.

In our case, we chose different thresholds based on scale and angular range. Thus, for each scale and angular range, an individual threshold was selected. Finally, the inverse curvelet transform was performed. After de-noising, LMO was removed and the data were stacked with the other gathers. It is important to mention that curvelet de-noising was only applied to the 2016 dataset because of its higher number of channels and regular spacing between the receivers. Figure 5(d) shows the effect of the curvelet de-noising on the same shot gathers and improvements obtained by applying this method. Note how reflections M1 and M2 are better observed in the surface-wave de-noised shot gather. For better follow-up on the processing steps, amplitude spectra of the same shot through different processing steps are also shown in Figure 5. This is particularly important as a quality control if any side lobes are introduced during the frequency filtering of the data, also showing the dominant frequency content of the data and how broad it was kept during the processing work.

Later on, velocity analysis and normal moveout (NMO) corrections (50% stretch mute) were applied in two rounds coupled with residual reflection static corrections, which helped to improve the sharpness and continuity of the dipping reflections. Poststack processing consisted of conventional processing steps, such as gapped deconvolution with gap length of 26 ms (to remove cyclicity in the stacked section). FX-deconvolution assisted in attenuation of random noise and improving the continuity of reflections. This was followed by FK-filtering, applied for gentle dips believed to be the remnant of source-generated noise.

Finally, after padding, migration was done on the stacked section in order to enable imaging steep reflections migrating out of the section. Two hundred zero-amplitude traces were used for the padding. Coordinates were then linearly extrapolated for visualization purposes of the traces. A phase-shift migration using a one-dimensional velocity ranging from 5700 m/s at zero-time increasing to 6300 m/s at 1000 ms was used. In order to reduce the migration artefacts especially at low-fold regions (i.e. south of the main road), strong migration smiles were filtered out using both FK-filtering and bandpass filtering. Reflections were matched to known geological data (about 50 ms shift was needed). Figure 6 sketches the processing workflow applied to the merged datasets.

RESULTS AND INTERPRETATIONS

Figure 7 presents unmigrated seismic sections along a portion of the main profile, 15P1 from 2015 (Fig. 7a), 16P1 from 2016
Dataset 2015

- Refraction static corrections

Merged dataset

- Part of the 2016 data

Dataset 2016

- Refraction static corrections

Figure 6 Processing flowchart, with general processing steps applied to the merged 2015 and 2016 datasets from the Blötberget area. Special care was required to process the two datasets together due to their slightly different positions along the profiles.

(Fig. 7b), merged datasets (only geophones) of 2015 and 2016 with conventional processing (Fig. 7c) and the merged datasets after the curvelet de-noising and residual static corrections (Fig. 7d). Since the two 2015 and 2016 datasets only partly overlap each other (Fig. 1), we first present results along this segment and the corresponding merged data (Fig. 7c,d). We prefer to interpret the sections using unmigrated images to avoid interpreting migration artefacts. We will still consider migrated section when depth and dip are interpreted and it will be presented later.

High-amplitude reflections are visible already in the 2015 dataset (Fig. 7a) and as interpreted by Malehmir et al. (2017) are associated with the iron-oxide mineralization of Blötberget deposits (known to extend down to at least 800–850 m). However, these data only image the deposits to a depth of not more than 800 m due to poor penetration depth (likely due to poor coupling of the landstreamer sensors with the ground) and low-fold data coverage (Table 1). The 2016 dataset (Fig. 7b) while showing essentially similar features as the 2015 dataset, does show the main SE-dipping reflections extending deeper than the 2015 dataset. Blötberget deposits were mined using first open pit and then underground mining methods. Both the 2015 and 2016 surveys began at the edge of the flooded open pit on their northernmost parts (Fig. 1) providing a good proxy for what reflections likely originate from. We interpret the SE-dipping reflections to be from multiple sets of iron-oxide deposits as labelled in the sections and in conjunction with the one-dimensional (1D) synthetic models.

When merged datasets are compared (i.e. Fig. 7cd) with any of the individual datasets, a much higher resolution image and less noisy section is obtained particularly against the 2016 dataset alone. The curvelet surface-wave de-noised section shows superior and higher amplitude content with much more continuity in the reflectivity and a short NW-dipping reflection appearing to cut the M1 and M2 reflections. To support this claim, we calculated root-mean-square (RMS) amplitude of a window above (i.e. 0–220 ms) the main zone of the reflectivity and compared this with the reflective (i.e. 220–500 ms) within a common depth point (CDP) range 500–680. Then, we averaged the RMS amplitudes and calculated the ratio between the two. This was done for both with and without curvelet de-noised sections of the merged 2015 and 2016 dataset. As a proxy only, we obtained a signal-to-noise ratio of 2.2 and 2.8 for before and after curvelet de-noised sections, respectively. This implies approximately 30% signal enhancement.

Figure 8 shows the complete seismic section along profile 15P1, merged and processed with profile 16P1 and partly
Figure 7 Unmigrated stacked sections of (a) the 2015 dataset, (b) the 2016 dataset, (c) merged 2015 and 2016 datasets with conventional processing and (d) merged datasets after FDCT and residual static corrections. CMP fold is shown for each dataset. The unusual high fold is due to trace sharing approach used to avoid losing traces during the binning because of the crookedness of the profiles. Black arrows mark how the processing steps affect the resolution of data with the ability to image deeper parts of the mineralization, potential resources below the known ones, as well as interesting features that can be related to other mineralized horizons. Black arrows labelled as M1 and M2 in (d) mark two distinct mineralized horizons, noticed in the shot gathers (Fig. 5).
Figure 8 Unmigrated stacked section along the entire portion of the merged 15P1 and 16P1 datasets after FDCT and residual static corrections. Two sets of NW-dipping reflections are evident on the southernmost portion of the profile (R1 and R2) and a short NW-dipping reflection R3 around CDP 600 appearing to intersect the mineralization. While this is speculative these reflections can either represent, due to their strong amplitudes, new mineralized horizons or faults systems separating two different lithological contacts specially on the southernmost end of the profile (reflection R1).

Figure 9(a) shows migrated and time-to-depth converted seismic section of the profile and its three-dimensional visualization with the recent boreholes downhole logged in the study area. Curves in the boreholes present density measurements (from laboratory on core samples) standing out from the mineralization. Figure 9(b) shows the seismic section visualized with the known ore bodies. It is clear that the SE-dipping reflections (M1 and M2) are generated from the ore bodies, they extend to at least another 300 m depth, and there is a high chance in their footwall that more sets of iron-oxide mineralization can be found. This is encouraging and implies that additional resources may be available down-dip and under the known deposits helping to justify additional drilling and exploration investment in the Blötberget area.

DISCUSSION

Delineating mineral deposits using seismic methods depends not only on their contrasting properties (i.e. density and...
velocity) to those of the surrounding materials but also on
the geometry of the target (Milkereit et al. 1996; Salisbury
et al. 2003). Hematite and magnetite horizons in Blötberget
show considerably high densities compared to their host rocks
and thus a strong seismic response is to be expected, as also
seen in the one-dimensional synthetic seismograms (Fig. 2).
The sheet-like horizons show thicknesses ranging from just a
few meters to about 30–40 m as they extend deeper. Thus, an
issue to discuss is the detection limit of these thin layers. With
an average velocity of 6000 m/s and a dominant frequency of
the seismic data of 90 Hz (estimated by studying amplitude
spectra of a number of shot records), the vertical resolution
(a quarter of a wavelength) is approximately about 15 m,
meaning that many of the thinner layers could not be resolved
(tuning effect). At least the thicker layer (30-40 m) of mag-
netite visible in the magnetic logs (Fig. 2) is likely to generate
high-amplitude reflections in the seismic section (Fig. 7). Ac-
counting for subsurface heterogeneities, it is more likely that
instead, the upper and lower limits of a group of magnetite,
or hematite sheets, are imaged here. This is encouraging
and suggests that the 500-kg Bobcat-mounted drophammer
and the setup used are suitable for such a setting and can
indeed be used for direct targeting. Future surveys, if possible
should aim at comparing these results with other type sources
(e.g. vibrators). Downhole seismic surveys would also be
beneficial to understand the resolving power of the surface
seismic methods in delineating the individual mineralized
horizons as reflection.

The logged boreholes intersect the deposits in Blötberget
at 300–600 m depth ranges (Fig. 9) after which a possible
continuation down to approximately 1200 m can be inferred
through the SE-dipping reflections in the seismic data; also
Table 2 A sketch cost comparison between the Blötberget seismic and conventional seismic surveys particularly for feasibility studies and pilot seismic surveys. Note also that impact sources usually have sharper signal and broader frequency range. The comparison is only valid for our case study, and in other situations different scenarios should be considered. Note also that a vibrator source is not readily available and requires mobilization hence cost from central Europe

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Blötberget seismic survey</th>
<th>Commercial/conventional survey</th>
</tr>
</thead>
<tbody>
<tr>
<td>Source type</td>
<td>500-kg drophammer</td>
<td>Vibro-truck</td>
</tr>
<tr>
<td>Source cost</td>
<td>100 €/day</td>
<td>2000 €/day</td>
</tr>
<tr>
<td>Source mob/demob</td>
<td>1000 €</td>
<td>5000 €</td>
</tr>
<tr>
<td>Source operation</td>
<td>120–150 shot points/day</td>
<td>120–150 shot points/day</td>
</tr>
<tr>
<td>Fuel consumption</td>
<td>Max 100 l/day</td>
<td>Min 300 l/day</td>
</tr>
<tr>
<td>Source logistics</td>
<td>Small drophammer vehicles permitted on roads</td>
<td>&gt;12 t vehicles are not often permitted on roads or require heavy protections</td>
</tr>
<tr>
<td>Recording</td>
<td>Conventional and comparable</td>
<td>Conventional and comparable</td>
</tr>
</tbody>
</table>

overlying potentially new mineralized horizons in the footwall of the known ones. This is encouraging and should motivate further use of the seismic methods for deep exploration and targeting. The possible extension of the mineralization down to 1200 m depth implies up to 30% increase in mineral resources only in the Blötberget assuming similar thicknesses and lateral extension as those intersected by the boreholes in the higher up in the stratigraphy. The merged datasets helped to improve the fold coverage and further the resolution of the data, a benefit we wish to emphasise.

Despite the increasing resolution of the main reflections by merging the 2016 and 2015 datasets, source-generated noise particularly surface waves made it difficult to spot the two distinguished reflections from the shot gathers and later in the stacked sections. Curvelet de-nosing of the surface-waves proved to be instrumental in obtaining good images from the mineralization as well as structures crosscutting it (Fig. 7d). We therefore suggest its application for other hardrock datasets especially when steep structures are present, as well as simple FK- and/or median filtering may partially remove these wanted reflections.

We consider both the 2015 and 2016 surveys to be cost-effective compared to conventional and commercial ones although the current studies were conducted for research and development purposes to note. Table 2 shows a rough cost comparison to support this claim. Taking into account that before the 2015 survey no seismic survey was conducted at this site, which is known for its soft and swampy ground conditions, the first survey (done in 2015) opened up possibilities for follow-up studies (e.g. a feasibility study). In terms of costs, it is not surprising that both surveys were cost-effective, especially if the cost of mobilization and demobilization of a vibrator is considered. Although the 2016 survey had a receiver setup like those done in commercial and conventional surveys, the 500-kg drophammer was used, allowing to further examine the depth penetration of this source in such ground conditions. Note that some of the roads in the area do not allow heavy vehicle traffic (>12 ton), for example, vibrators, due to the weak ground conditions. We avoid comparing this with any drilling campaign, since they are fundamental for resource estimations and evaluation. Nonetheless, such a survey helps to optimize future drilling programmes, as well as better mine planning (e.g. paying attention to possible resources in the footwall) in the case of mining operation commencement.

In summary, the main cost-reduction comes from avoiding usage of expensive commercial source including its mobilization and demobilization. We however realize that a full comparison and cost estimation versus quality would only be possible when such a comparison is done in reality and are aware of disputing claims by commercial contractors. In a continuation of this study, future surveys are planned at the site to employ vibrators of both commercial characters but also new ones innovated within the same project (Malehmir et al. 2019) that this study has been conducted.

CONCLUSIONS

Two reflection seismic datasets from two different field campaigns using different setups have been merged and processed together for an improved delineation of iron-oxide mineralization in Blötberget, Ludvika mining area of central-south of Sweden. Despite challenges with the source-generated noise, particularly surface waves, the final seismic section shows a number of reflections associated with the mineralization and suggests their depth continuation beyond the known 800-m depth. The strong contrast in acoustic properties, confirmed by borehole logging, from magnetite and hematite
mineralization, produces strong SE-dipping reflections down to at least 1200 m depth. This implies there may be additional resources in the downdip for at least 300–400 m than the known ones worth to be investigated in future studies and through deep boreholes. Oppositely dipping reflections to the mineralization are observed and may suggest a large-scale structural basin responsible for apparent flattening of the mineralization with depth or a major fault system separating two lithological contacts in the southern end of the profile. The present study illustrates the cost-efficiency of seismic methods as a whole and this survey in particular for deep deposit targeting, given the high resolution of the data and the simple and low-cost seismic source used.

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DATA AVAILABILITY STATEMENT

Research data are not shared.

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