Broadband seismic source data acquisition and processing to delineate iron oxide deposits in the Blötberget mine-central Sweden

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ABSTRACT
A prototype electromagnetic vibrator, referred to here as E-Vib, was upgraded and developed for broadband hardrock and mineral exploration seismic surveys. We selected the iron oxide mine in Blötberget, central Sweden, for a test site in 2019 for the newly developed E-Vib because of the availability of earlier seismic datasets (from 2015 to 2016) for verification of its performance for hardrock imaging purposes. The two-dimensional data acquisition consisted of a fixed geometry with 550 receiver locations spaced at every 5 m, employing both cabled and wireless seismic recorders, along an approximately 2.7 km long profile. The E-Vib operated at every second receiver station (i.e. 10 m spacing) with a linear sweep of 2–180 Hz and with a peak force of 7 kN. The processing workflow took advantage of the broadband signal generated by the E-Vib in this challenging hardrock environment with varying ground conditions. The processed seismic section shows a set of reflections associated with the known iron oxide mineralization and a major crosscutting reflection interpreted to be from a fault system likely to be crosscutting the mineralization. The broadband source data acquisition and subsequent processing helped to improve signal quality and resolution in comparison with the earlier workflows and data where a drophammer seismic source was used as the seismic source. These results suggest new possibilities for the E-Vib source for improved targeting in hardrock geological settings.

Key words: Broadband, Mineral exploration, Processing, Seismic source.

INTRODUCTION
The mineral exploration industry constantly requires developing solutions that allow the exploration and exploitation of targets in various complex geological settings. A number of internal and external factors (e.g. the public perception, mineral demand, governments, among others) plunged the necessity of improving current deep exploration technologies despite its good progress and developments (Haldar, 2018; Essa and Munsch, 2019). The increasing demand worldwide for the so-called critical raw materials and base and ferrous materials, such as copper, zinc and iron, adds extra pressure to provide new primary resources to the whole value chain. In addition, their presently high demand as input materials for green technologies will continue to grow in the foreseeable near future. Therefore, to meet the increasing need, improved exploration strategies are necessary (Malehmir et al., 2014, 2020). According to the projections by OECD (Organization for Economic Cooperation and Development), raw material use is expected to increase from 90 to 167 Gt by 2060, suggesting an accelerated demand in the next decades (Agrawala et al., 2018). Moreover, the fast drive towards a neutral carbon emission world implies increased use of raw materials (e.g. copper, zinc, iron) to allow a smooth transition. Iron, given its

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significance in the construction and infrastructure industries, will remain as the largest production commodity per capita (Fizaine, 2018).

Most metallic mineral deposits have contrasting physical properties compared to their host rocks making their direct targeting possible, using geophysical methods, even within a complex three-dimensional (3D) geological setting (Eaton et al., 2003). Seismic and electromagnetic methods, for instance, are ideal for this purpose with the latter mapping conductivity and the former, essentially, acoustic impedances (Juhlin et al., 1991; Milkereit et al., 1996; Adam et al., 1998; Salisbury et al., 2003; Chen et al., 2004; Malehmir et al., 2012 and references therein). Seismic methods have recently opened up new possibilities in the mineral exploration industry with promising examples reported worldwide, especially during the past 10 years (e.g. Koivisto et al., 2012; Manzi et al., 2012, 2015; Buske et al., 2015 and references therein; Malehmir et al., 2017, 2018; Balestrini et al., 2020; Malehmir et al., 2020 and references therein; Papadopoulou et al., 2020, Polychronopoulou et al., 2020). Given the commonly complex nature and small target size of deposits hosted within hardrock environments, seismic exploration in such settings may benefit from high-resolution imaging provided by broadband data acquisition and processing workflows (ten Kroode et al., 2013; Cordery, 2020). Broadband seismic data acquisition is beneficial for recognition and delineation of smaller geological targets in hardrock environments due to the deeper penetration available by low frequencies and improved resolution provided by the wide bandwidth and small side lobes in the wavelet (ten Kroode et al., 2013). However, the majority of developments have so far focused on methodologies while there is still research to do on hardware solutions. On the receiver side, improvements have been great with the introduction of digital sensors such as micro-electromechanical sensors (MEMS) and distributed acoustic sensing technologies (Campman et al., 2016; Malehmir et al., 2016). On the source side, innovative broadband seismic source technologies are still being developed for land-based hardrock data acquisition with the aim of addressing the challenges that seismic methods face in mineral exploration.

In this study, we present first-hand results from a prototype linear-synchronous-motor-based (electrically driven) broadband seismic source (Noorlandt et al., 2015; Brodic et al., 2019a, 2019b and 2021a, 2021b), used as a surface seismic source for mineral exploration. The source provides a flat amplitude response capable of a 2–200-Hz bandwidth at a peak force of approximately 7 kN. Earlier tests with the source were done at a sedimentary rock setting and inside mining tunnels (Brodic et al., 2021a, 2021b; Donoso et al., 2021), while in this study we validated the source on the surface at a hardrock site, more specifically, an iron oxide deposit located near Blötberget in central Sweden (Fig. 1). The Blötberget mining site was selected to verify the performance of the electromagnetic vibrator (E-Vib) for deep targeting in a real hardrock geological setting. Several existing two-dimensional surface lines are available in the study site, and borehole observations as well as downhole logging studies provide good control on the 3D geometry of the deposits (Malehmir et al., 2017; Maries et al., 2017, 2020; Markovic et al., 2020). Furthermore, several research topics such as depth imaging algorithms (Bräuning et al., 2020; Ding and Malehmir, 2021), surface wave imaging workflows (Papadopoulou et al., 2020) and data-driven surface wave attenuation workflows (Balestrini et al., 2020) are also available from this site. In this study, we evaluate the source signal and benefits of broadband signal excitation and processing in this hardrock setting and compare it with an available seismic dataset in the area. Although we could not employ fully broadband seismic recorders (such as MEMs), as a proof-of-concept and demonstration work, we show how the E-Vib and the processing workflow helped to image the known mineralization and its potential down-dip continuation as well as a clear oppositely dipping reflection that may have geological implications on how the deposits are emplaced and terminated at depth. Our goal is to illustrate that the E-Vib is a viable source for deep-deposit targeting, rather than make this study a comparative work among various types of seismic sources and setups.

**GEOLOGY AND EARLIER STUDIES**

Blötberget (Fig. 1) belongs to the Ludvika Mines and lies in the Bergslagen mineral district of central Sweden. Bergslagen contains a significant number of iron oxide occurrences and historically has contributed to the Swedish economy and wellbeing for over 800 years (Stephens et al., 2009). Bergslagen is situated in the Fennoscandian Shield, dominated by paleoproterozoic rocks and affected by Svecofennian orogeny that led to ductile deformation and metamorphism of rocks in the district. A complex fold characterizes the area in the Ludvika region, with a strike line direction northeast–southwest (Stephens et al., 2009).

Dominant rock types are of Svecofennian age (1.91–1.89 Ga), felsic meta-volcanics with metallic deposits mostly occurring as inliers. Pegmatite and mafic dykes are also observed post-dating the volcano-sedimentary rocks (Markovic
Figure 1 Study area, Blötberget, Ludvika Mines (Sweden). (a) Aerial photograph showing the seismic profile. (b) The total-field aeromagnetic map shows the pronounced magnetic signature of the Blötberget deposits towards the northern end of the profile (dark blue line). Light blue line: wireless stations and dark blue line: cabled stations.
The deposits usually form sheet-shaped bodies consisting of over 40% magnetite and hematite and vary from apatite-rich to relatively free from apatite and are accompanied by small amounts of quartz and calc-silicate minerals. Mafic dykes and subvolcanic intrusions generally crosscut both the mineralization and the host rock.

At Blötberget, the deposits contain high-quality apatite iron oxide mineralization distributed in four sheet-like horizons, skarn-type iron oxide deposits and apatite-rich iron oxide deposits. The latter deposits contribute to most of the production in the area and become one of the biggest iron sources in Sweden and biggest providers in the European Union (Allen et al., 1996; Williams et al., 2005).

**Earlier studies in Blötberget**

Earlier works at the Blötberget mine, such as ground-based geophysical surveys in the 1950s, airborne geophysical surveys in the 1970s and core drilling between 1942 and 1977, helped to define the location and extent of the shallower deposits. Mining activities focused therefore down to 200–300 m depth until 1979 when, due to low global iron prices (Nordic Iron Ore, 2011), iron oxide mining and exploration stopped not just at Blötberget but also in the entire Bergslagen region. In 2011, Nordic Iron Ore took the lead into exploration activities in the area as a consequence of improved iron ore prices, better mineral processing technologies available and improved prospects for the iron ore market. In recent years, the exploration activities continued by a series of deep-targeting drilling and geophysical surveys, among which were downhole logging of seven boreholes from different depths (Maries et al., 2017), two-dimensional reflection seismic profiles in October 2015 and September 2016 (Malehmir et al., 2017; Maries et al., 2020; Markovic et al., 2020) and a recent sparse threedimensional (3D) seismic survey (Malehmir et al., 2021).

Encouraging outcomes of those recent studies were an implied depth extension of the mineralization down to approximately 1200 m depth (known earlier to be only 800 m from boreholes), knowledge of host structures such as fault and fracture systems and potentially additional resources beneath the known deposits (Malehmir et al., 2017; Maries et al., 2017, 2020; Markovic et al., 2020). The 3D dataset (Malehmir et al., 2021) suggests an additional 300 m lateral extent for the deposits towards the west worth drilling for resource evaluation. These extensive datasets and good control on the depth extent of the mineralization were also additional motivations to validate the electromagnetic vibrator source at the Blötberget site.

**The Electromagnetic Vibrator**

Hydraulic seismic vibrators have successfully been serving the seismic industry for over 50 years (Meunier, 2011). However, with recent increased interest in broadband data acquisition, the intrinsic limitations of both hydraulic and mechanic aspects of their design impose certain restrictions on fully fulfilling this broadband criterion (Bagaini, 2008; Meunier, 2011; Sallas, 2010; Rowse and Tinkle, 2016). It is challenging for vibrators to generate low frequencies at full drive power although it might be possible by designing complicated nonlinear sweeps that shake longer for the low frequencies. To cope with the broadband signal excitation challenge, Noorlandt et al. (2015) proposed the use of an alternative vibroseis seismic source based on linear synchronous motor – LSM technology – electromagnetic vibrator (E-Vib), which is schematically depicted in Figure 2. The E-Vib source is a vertical electrically driven electromagnetic vibrator that can provide a flat amplitude response in the frequency range of 2–200 Hz. The source weighs approximately 1650 kg, operates at a constant drive level with a peak force of 7 kN and requires 14 kW of power to operate. The absence of hydraulics, combined with the frictionless guidance system of the LSMS behind the E-Vib overcome some of the intrinsic limitations of the hydraulic vibrators (Sallas, 2010; Bagaini et al., 2014; Brodic et al., 2021a). To support this, in studies conducted by Sallas (2010) it was found that more than two third of the power produced by a hydraulic vibrator engine is transferred as heat, thus not usable. The flow pump and reaction mass in hydraulic vibrators limit the output frequency. On the one hand, heavy reaction masses usually decrease the dwell-time and produce the low-frequency end of the spectrum but introduce harmonic distortions. On the other hand, the compressibility of hydraulic fluid limits high-frequency output, and increasing the dimension of the vibrator causes a higher flow demand and hence an overpressure condition (Sallas, 2010).

The LSM itself is a synchronous electric motor composed of a U-shaped magnet track, which consists of permanent magnets that generate a magnetic field perpendicular to the coil track or plane of motion (Fig. 2b). When an electrical current is induced in the coil, linear forces are generated, acting along a line over the full stroke, which results in lower harmonic distortion, thus allowing a wider range of low frequencies to be produced (Li et al., 2019; Noorlandt et al., 2015; Brodic et al., 2021a, 2021b). The forces generated are transferred into the subsurface via a ground-coupled base plate while the suppression mechanism reduces the resonance produced by the mass of the carrier vehicle and
improves ground coupling. The source is described in detail in Noorlandt et al. (2015) and Brodic et al. (2021a). To be better suited for hardrock surveys and within a larger research and innovation project, the source was upgraded and ruggedized to withstand different ground coupling and weather conditions (Fig. 2c).

DATA ACQUISITION

To evaluate the electromagnetic vibrator (E-Vib) in a hardrock setting, a field campaign took place in September 2019. One of the advantages of the E-Vib is its design and dimensions enabling versatility (Malehmir et al., 2019; Brodic et al., 2021a, 2021b) and allowing it to be attached to locally available vehicles such as skid-steers or telehandlers, and the latter was used in this test (Fig. 3a). The data were acquired along a two-dimensional (2D) profile with 553 receiver locations covered by 425 cabled and 128 wireless seismic recorders using a combination of both 4.5 and 10 Hz geophones. At the time of the survey, 200 geophones of 4.5 Hz were planted into the ground at every odd receiver location (in terms of peg numbering) along the cabled portion of the seismic spread, whereas geophones of 10 Hz natural frequency covered the wireless and cable portions along the line spread. All receivers were deployed 5 m apart from each other, in an approximately south–north direction (Fig. 3b), perpendicular to the strike of the mineralization. This allowed an approximately 2.7 km long seismic profile. The northern portion of the profile was located in a major forest, along a swampy gravel road, providing rather mixed good-poor ground-coupling condition with the seismic source, while the southern portion crossed a heavily trafficked asphalted road.

The E-Vib was tested for a range of sweep parameters focused on the sweep length to make sure that surface waves are not dominating the records while allowing enough time for the generation of low-frequency signals. After analysing sweeps of lengths of 14, 16, 18 and 20 s, a 16-s long linear sweep ranging from 2 to 180 Hz was selected; a compromise between the natural and spurious frequency limitations of the geophones used (160 and 200 Hz for 4.5 and 10 Hz, respectively, according to their manufacturers) and honouring the aforesaid criteria. Three repeated sweeps were generated at every source location in order to improve the signal-to-noise ratio through vertical stacking of the repeated shot records.

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Given the relative lightweight of the system, the E-Vib source was permitted to operate on the southern portion of the profile where earlier surveys using heavy hydraulic sources (>10 tons) were not allowed. This meant the current survey benefited from more shot points (also higher fold) in that region, in comparison with the earlier 2D surveys as well as the recent three-dimensional survey (Malehmir et al., 2021). All shot and receiver positions were surveyed using a real-time kinematic differential global positioning system (DGPS) with high accuracy and precision. At positions where this was not possible, national LiDAR data from the study area (2 m cell size, on average, 3–5 cm elevation difference when compared with the DGPS data) were used to obtain missing elevations. High-resolution aerial photographs were used for quality control to make sure the receiver coordinates follow the actual location of the seismic profile. Table 1 summarizes the main acquisition parameters of the E-Vib survey conducted in the year 2019 as well as some of the previous 2D datasets in the area, years 2015 and 2016.

Figure 4 evaluates the amplitude spectra of the seismic signal recorded with the 4.5- and 10-Hz geophones, which are separately estimated and averaged for every 10 shots. It illustrates that even though band limited, both geophone types were able to reasonably successfully record the full bandwidth of the selected source sweep. Additionally, Figure 4 implies that the 4.5-Hz geophones show higher amplitudes at the lower frequencies, as one would expect.
Table 1 The 2D seismic data acquisition parameters of the 2015 and 2016 drop hammer datasets (earlier surveys) and the 2019 E-Vib validation survey in the Blötberget mine

| Field Campaign | 2015                     | 2016                     | 2019                     |
|----------------|--------------------------|--------------------------|--------------------------|
| Acquisition geometry | Fixed receivers (wireless) Roll-along land streamer | Fixed spread | Fixed spread |
| Receiver-line direction | S–N                     | S–N                     | S–N                     |
| Number of receivers | Land streamer: 900 (nine sections by 100 movements) | Land streamer: N/A Cabled: 427 Wireless: 24 | Land streamer: N/A Cabled: 425 Wireless: 128 |
| Receiver interval | Cabled: 2–4 m Wireless: 10 m | Cabled: 5 m Wireless: 10 m | Cabled: 5 m Wireless: 5 m |
| Maximum offset | 2500 m                   | 2200 m                   | 2753 m                   |
| Source | Drophammer | Drophammer | E-Vib |
| Number of shot points | 533                     | 387                     | 553                     |
| Frequency range | 10–400 Hz (Nyquist) | 10–400 Hz (Nyquist) | 2–180 Hz |
| Sweep pattern | N/A                     | N/A                     | Linear                  |
| Sweep length | N/A                     | N/A                     | 16 s                    |
| Recording parameters | Record length 10 s (used only 1 s for processing) | 1 s                     | 3 s                     |
| Sampling rate | 1 ms                    | 1 ms                    | 1 ms                    |

**METHODOLOGY**

The selected sweep parameters provided seismic data of good the signal-to-noise ratio with strongly reflected events that were already noticeable during the quality control of shot gathers and brute stacks. Compression of raw vibrograms, both for the sweep testing phase and the 16 s long selected sweep, was achieved via cross-correlation of the merged cab-

![Figure 5](https://via.placeholder.com/150)

Figure 5 Sweep length tests using a (a) 14 s, (b) 16 s and (c) 18 s sweep length. These tests, in addition to those of 12 and 20 s, led us to decide on a sweep length of 16 s due to better quality first breaks, less surface-wave contamination and clearer reflections as marked by the arrows.
(a) An example of a raw shot gather correlated with a sweep length of 16 s. (b) Same shot gathers with statics corrections. (c) Gapped-deconvolution and (d) median filter were applied in the pre-stack stage as part of the adapted workflow processing, in which noise is removed and thus reflection features become clearer. The surface waves present in the shot gathers is highlighted in blue.

breaks and the expected mineralization reflection. On the southeast portion of the profile where the wireless recorders were located, shot gathers (Fig. 6a), show noisier data quality due to the presence of heavy road traffic.

To enhance the reflections visible in the shot gathers after the cross-correlation, it was necessary to adapt (here we interchangeable refer to this as broadband processing) dedicated processing workflow than used in the earlier surveys. However, earlier processing flows used at the site were the base to process the E-Vib dataset in order to maintain as much as possible hence to compare with the previous results. The processing workflow while kept simple, permitted preserving the broadband frequency nature of the data, generated by the source primarily, by introducing alternative steps such as gap deconvolution and median filters. This led to attenuate source-generated noise and surface waves while preserving the low-frequency content of reflections and helped to image clear reflected events. Table 2 describes the processing steps followed in this study, roughly subdivided into pre- and post-stack phases. The main objective of the workflow was to attenuate source-generated and ambient (e.g. moving vehicles) noise in the data by having the minimum effect on signal quality. As an initial step in the processing workflow,
Table 2  Adapted for broadband E-Vib source data and conventional processing workflows and parameters used in this study

| Step | Process                          | Processing Workflow          | Conventional                  |
|------|----------------------------------|-----------------------------|--------------------------------|
|      |                                  | Adapted                     | Conventional                  |
| Pre-stack |                                  |                             |                               |
| 1    | Data input                       | SEGData format              | SEGData format                |
| 2    | Merged                           | Cabled system and wireless  | Cabled system and wireless    |
| 3    | Trace edit                       | Kill noisy traces           | Kill noisy traces              |
| 4    | First break picking              | Automatic and manual        | Automatic and manual          |
| 5    | Refraction statics               | Two-layer model and using   | Two-layer model and using     |
|      |                                  | surface elevation shot      | surface elevation shot        |
|      |                                  | positions and first breaks  | positions and first breaks    |
| 6    | Bandpass filter                  | N/A                         | 10-30-110-150 Hz              |
| 7    | Spectral equalization            | N/A                         | 20-40-90-130 Hz               |
| 8    | Gapped deconvolution             | Gap: 13 and 22 ms; Length: 80 and 150 ms | N/A |
| 9    | Median filtering                 | Velocity: 2150 m/s and 2250 m/s Horizontal window length: 12 traces | N/A |
| 10   | Airwave                          | Linear noise attenuation at vel. 330 m/s | Linear noise attenuation at vel. 330 m/s |
| 11   | Trace muting                     | Mute above first breaks     | Mute above first breaks       |
| 12   | Residual statics                 | Surface-consistent (iterative) | Surface-consistent (iterative) |
| 13   | Normal moveout                   | 50% stretch and taper 20 ms | 50% stretch and taper 20 ms |
| 14   | Stack                            | Unity (2.5 m CDP spacing)   | Unity (2.5 m CDP spacing)    |
| Post-stack |                                  |                             |                               |
| 15   | Gapped deconvolution             | N/A                         | Gap: 19 ms; Window: 80 ms     |
| 16   | FX-deconvolution                 | Filter length: 19 msWindow length: 100 ms | Filter length: 19 msWindow length: 100 ms |
| 17   | Frequency-wavenumber filtering   | On selected CDPs and steep dips | On selected CDPs and steep dips |
| 18   | Two-dimensional time migration   | Phase shift velocity: 5900 m/s | Phase shift velocity: 5900 m/s |

First breaks were picked and used to estimate refraction static corrections, which were on the order of 10–20 ms for both shot and receiver gathers (Fig. 6b). To retain the broadband nature of the data, no bandpass filtering or other filters, for example spectral balancing, operating in the frequency range of the sweeps were permitted. Bandpass filters are often used in combination with median- and frequency-wavenumber filters to remove surface waves efficiently. This noise removal is optimal at very low frequencies, whereas the median filter removes remaining surface waves with frequency content considered traditionally as overlapping with reflections. In the current work, noise attenuation was instead based on gapped deconvolution followed by a median filter in the pre-stack domain (Table 2). This was an iterative step as the dataset is strongly contaminated with both source-generated and ambient surface waves (Fig. 6). After a series of tests, enhancement in the resolution of the reflections and partial attenuation of the surface waves was made possible when using the surface-consistent gapped deconvolution filter, which included two gap operators of 13 and 22 ms lengths, respectively, resulting in a reduction of surface-wave contamination as highlighted in Figure 6. A median filter was designed to attenuate the remaining surface waves (appeared as linear features) as well as shear-wave energy from the source and helped to improve the quality of the reflections in the pre-stack data (Fig. 6d). Coupled with velocity analysis and normal moveout corrections, surface-consistent residual static corrections helped to improve the continuity of the reflections and the final resulting seismic section.

Post-stack processing steps included FX-deconvolution (in the frequency-space domain) that was used to improve the coherency of the reflections and attenuate random noise in the data. After this processing sequence, surface-wave energy was still present up to 250 ms in some shots gathers from the southern part of the profile. For this reason, filtering in the frequency–wavenumber domain was applied in the post-stack stage only for a selection of CDPs in that region of the profile. A phase-shift time migration algorithm was employed using a...
constant velocity of 5900 m/s, due to judged lateral-invariant velocity distribution, which was decided based on an average from borehole sonic data and velocities used in earlier studies (Malehmir et al., 2017; Maries et al., 2020; Markovic et al., 2020). Additionally, a range of velocities were tested assuring that the selected velocity provided the best result of the migration algorithm applied. The time-to-depth conversion was done using the identical velocity as used for the migration, that is 5900 m/s. After this step, both unmigrated and migrated stacked sections were exported for 3D visualization purposes and comparisons with other available datasets from the area. To visualize the unmigrated stacked section in 3D with other cultural information, we used a velocity of 5900 m/s to convert time to depth.

RESULTS AND INTERPRETATION

The processing was largely focused on the top 500 ms (approximately 1.5 km depth) because the main deposit’s reflections (M1, M2 and M3, known from previous studies) and newly detected crosscutting reflections (F1) are within this time window (Fig. 7). This depth range is also important for future mining and exploration at the site and is currently considered a feasible mining depth target.

Major reflections that we interpret to originate from the iron oxide mineralization are M1 and M2, and possibly a deeper one, M3, consistent with the earlier reported two-dimensional (2D) and three-dimensional (3D) surveys (Maries et al., 2020; Markovic et al., 2020; Malehmir et al., 2021). The main mineralization reflection dips towards the southeast, positioned from about 150 to 500 ms in the unmigrated stacked section and 400 to 1000 m in the migrated stacked section (Fig. 7). A clear crosscutting reflection to those interpreted from the mineralization, labelled here F1, dipping towards the northwest is also observed in this study. This reflection is evident on both the unmigrated and migrated stacked sections (Fig. 7a, b) and appears to cut through at where the reflectivity from the mineralization terminates. None of the earlier 2D studies could image this crosscutting feature so clearly although they all provided arguments for its presence. The recent 3D seismic dataset did image this crosscutting feature so clearly although they all provided arguments for its presence. The recent 3D seismic dataset did image this feature, but, due to the lack of shots and near-offsets, it was not possible neither to link it to the surface geology nor to project it onto the surface for verifications.

For comparison purposes, the the signal-to-noise (S/N) ratio was estimated in the amplitude spectra for a single raw shot gather of the E-Vib dataset, at approximately 500 m distance from the northern portion of the profile, but for a different time window of the data (i.e. over the reflection signal corresponding to the mineralization and the noise) and when processed using conventional (earlier workflows) and adapted processing workflows (Table 2). The S/N ratio of the raw shot was estimated to be 1.175, when applying conventional processing increases to 2.376 and with the adapted processing it reaches 2.556. This implies that using the adapted processing on the E-Vib data enhanced the mineralization reflection amplitude approximately 19% and 36.5% for the processed shot shown in Figure 8 compared to the raw shot (Fig. 8a).

In addition, the electromagnetic vibrator (E-Vib) unmigrated stacked section was compared in terms of amplitude spectrum (Fig. 8b) with that of the earlier surveys conducted via a 500-kg drophammer (2016 and merged 2015–2016). We recall that the E-Vib data were never bandpass filtered; however, the earlier surveys used frequency filtering methods as is evident in their amplitude spectra (Fig. 8b). Those filters rejected very low and high frequencies and aimed the removal of noise and attenuation of strong surface waves that covered up main reflection events related to the mineralization. The E-Vib
section shows a relatively broadband nature; however, there is a slow decay in the amplitudes towards the high frequencies (above 120 Hz) when compared with the drophammer unmigrated stacked section. Additionally, the stacked E-Vib spectrum presents 10 dB more than the drophammer in high frequencies (80–180 Hz). The drophammer amplitude spectra with conventional processing show a drastic decrease in the low frequencies associated with bandpass filters and an increase in the high frequencies because of the use of spectral equalization filter to boost amplitudes, both only used in the conventional processing workflow. This is corroborated with the drophammer 2016 amplitude spectra, which were reprocessed with the adapted processing flow for reference purposes in Figure 8(b). The spectrum retains the data frequency composition due to the processing flow highlighting the effect of filters applied in the conventional processing.

**DISCUSSION**

An advantage of testing the electromagnetic vibrator (E-Vib) seismic source at Blötberget is the vast number of seismic datasets available at the site and the good knowledge of the mineralization and downhole physical properties (Malehmir et al., 2017, 2021; Maries et al., 2017, 2020; Markovic et al., 2020). Based on these earlier data, it was possible to compare the data quality from different surveys in which a rather industry-standard processing was applied with the newly acquired E-Vib dataset. Details of the earlier two-dimensional (2D) surveys can be found in Markovic et al. (2020) but also for completeness in Table 1. In comparison to the E-Vib dataset, the two 2D surveys (2015 and 2016) were conducted along the same profile line, but using a 500-kg drophammer as the seismic source. While a fair comparison is not possible due to variable conditions of the 2D surveys, we aim here only to illustrate that the E-Vib performed well and can be considered as a reliable source for seismic mineral exploration surveys. The 2015 dataset was acquired using a combination of a 240-m-long (2–4 m sensor spacing) MEM-based land streamer (Micro Electro-Mechanical system) and 10 m spaced wireless recorders (Malehmir et al., 2017). To acquire the same profile in 2016, similar to the E-Vib survey, 10 m spaced wireless recorders were placed on a portion of the southern extension of the 5-m spaced cabled recorders deployed along the same forest road (Markovic et al., 2020) as the 2019 E-Vib survey. Unmigrated stacked sections (merged 2015 and 2016, as well as 2016 alone) are compared in Figure 9 with that of the E-Vib seismic survey. They are visualized in three dimensions using a velocity of 5900 m/s used for time-to-depth conversion. It is evident that similar features are observed on these sections, for example the southeast- and northwest-dipping reflections interpreted to be from the mineralization and fault system, respectively. The interpreted northwest-dipping fault system by a different time window of the data (noise and reflection signal) and when processed using conventional and dedicated processing workflows. (b) Amplitude spectra of the unmigrated stacked sections from the merged 2015 + 2016 drophammer (continuous black line) and the 2016 drophammer (dashed black line) processed with an industry-standard workflow (Markovic et al., 2020), the 2016 drophammer (red line) and the 2019 E-Vib (green line) when using a tailored broadband processing workflow.

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is observed in all the seismic sections shown in Figure 9; however, because the 2016 profile stops at the major road south of the profile, the interpreted fault (F1) is only partly imaged (Fig. 9b). Merged 2015 and 2016 datasets, as is the case of the E-Vib dataset, do show this feature as the 2015 campaign extended towards the south of the major road. Compared to the earlier surveys, the E-Vib section shows greater resolution, more coherent features and appears less noisy. In order to provide a more comparable section with the E-Vib data, the 2016 dataset was reprocessed using a similar broadband processing flow as used for the E-Vib data. Figure 9(c) shows the stacked section of this processing workflow. Reflection F1 in Figure 9(c) displays an improvement over the conventional processing because this reflection can be identified across the mineralization. The 2016 reprocessed section, however, suffers from the strong low-frequency surface waves that were in the earlier processing works targeted with frequency and spectral balancing filters. The F1 reflection was projected to a place where there is a weak topographic lineament. In addition, there is no magnetic high or low where it was projected.

The E-Vib migrated section shows distinct features, for example, when seeing the image of the fault (F1) on the southern part of the profile, among other features (Fig. 10). The drophammer section appears to contain cyclic features (Fig. 9a) and stronger surface waves in the shot gathers and the stacked sections (discussed also in Balestrini et al., 2020; Papadopoulou et al., 2020; Markovic et al., 2020 due to their significance in the datasets). The adapted processing workflow on the drophammer data did not improve the quality of the stacked section as much as the E-Vib shows and is evident in the signal-to-noise (S/N) plots in Figure 8(b).

In order to provide a quantitative way of comparing the drophammer source with the E-Vib source data, a window of first breaks was selected from only refraction static corrected shot gathers (i.e. no filter applied). After aligning the first breaks horizontally using a linear moveout correction, the traces were then stacked for all offsets and each
shot resulting in only a single trace for each shot. After normalization, we treated this trace as an extracted source wavelet signal for each shot gather. The normalized source wavelet for each shot enables us to compare the performance of the drophammer source with that of E-Vib quantitatively. We then estimated the frequency spectra for each extracted source wavelet due to each shot in order to judge the frequency band and its amplitude variations of the source wavelet recorded in the 2016 (drophammer) and 2019 (E-Vib) datasets. A careful analysis of the frequency spectra suggests that not only higher amplitude signals were recorded using the E-Vib source but also increased frequency range was recorded between 20 and 160 Hz as opposed to the drophammer showing a narrow range between 10 and 80 Hz (Fig. 11). It is also instructive to observe smaller side lobes for the E-Vib data, which essentially means improved resolution than the drophammer data (ten Kroode et al., 2013). Combined with the migrated stacked section mentioned above, this analysis of extracted source wavelets from different source-type data supports the good performance of the E-Vib seismic source for hardrock seismic imaging. Future surveys could benefit from a combination of broadband seismic recorders (such as microelectromechanical sensors) and the E-Vib source, which we could not afford during this validation work, but strongly recommend for advancing this topic for mineral exploration.

CONCLUSIONS
An approximately 2.7-km long reflection seismic profile has been acquired at the Blötberget mine in central Sweden. The survey was performed for the validation of a newly developed broadband electrically driven electromagnetic seismic source, the electromagnetic vibrator (E-Vib), for hardrock seismic imaging applications. Previous seismic studies at the site utilized a drophammer source along the same survey line, which enabled direct comparison with the E-Vib dataset. A tailored processing workflow was employed to retain the broadband frequency data generated with the E-Vib. To suppress the strong surface waves while maintaining the broadband frequency in the dataset, median filter and gapped deconvolution in the pre-stack domain were applied without any bandpass filter. The processing results show that the E-Vib section has higher resolution and bandwidth compared with the earlier studies, illustrating its potential for hardrock seismic imaging applications. The resulting seismic section presents strong reflections originating from a multi-set of mineralized horizons confirmed by borehole data from previous studies and a short but strong reflection underlying these reflections a couple of hundreds of meters deeper. An oppositely dipping reflection, interpreted to be a major fault, crosscuts this set of reflections appearing to terminate the mineralization, which has a great impact on further mine planning and exploitation process. The E-Vib source contributed to both improved imaging of the mineralization and the fault system. We conclude that the E-Vib is not only a reliable source for surface seismic surveys in hardrock settings but also provides broad bandwidth data for high-resolution imaging and other approaches such as full-waveform inversion or reverse time migration. The results and analysis performed in this study are encouraging and should open up possibilities for up-scaling the E-Vib source for larger surface seismic surveys and additional case studies in various hardrock settings.

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Figure 11 A window around the first breaks (refraction static corrected only) is chosen for the E-Vib and drophammer (only 2016) seismic surveys in order to analyse the frequency band of the datasets. (a) Stronger amplitudes and broader bandwidth frequencies are recorded by the E-Vib source, (b) while the dataset acquired with the drophammer presents limited bandwidth. (c and d) Extracted wavelets for different shot gathers displaying also a smaller side-lobe and hence better resolution for the E-Vib source than the drophammer. (e and f) The amplitude spectra for the seismic datasets clearly exhibit wider bandwidth for the E-Vib source.

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DATA AVAILABILITY STATEMENT

Research data will be available after exploiting the potential of the seismic source and the dataset by the team that initiated the project and idea. There is currently an embargo time of 3-years on the data. Contact alireza.malehmir@geo.uu.se for further instructions.

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REFERENCES

Adam, E., Milkereit, B. and Marschal, M. (1998) Seismic reflection and borehole geophysical investigations in the Matagami mining camp. Canada Journal Earth Science, 35, 686–695.
Agrawala, S., Dellink, R., Chateau, J., Bibas, R., Lanzi, E. and Benkovic, M. (2018) Raw materials use to double by 2060 with severe environmental consequences, 2018: online resource. Available at https://www.oecd.org/environment/raw-materials-use-to-double-by-2060-with-severe-environmental-consequences.htm, Accessed 2 April 2020.
Allen, R.L., Lundstrom, I., Ripa, M., Simeonov, A. and Christofferson, H. (1996) Facies analysis of a 1.9 Ga, continental margin, back-arc felsic caldera province with diverse Zn-Ph-Ag-(Cu-Au) sulphide and Fe oxide deposits, Berslagen region, Sweden. Economic Geology, 91, 979–1008.
Bagaini, C. (2008) Low-frequency vibroseis data with maximum displacement sweeps. The Leading Edge, 27(5), 582–591.
Bagaini, C., Laycock, M., Readman, C., Coste, E. and Anderson, C. (2014) Seismo-acoustic characterization of a seismic vibrator. In 84th Annual International Meeting, SEG, Expanded Abstracts. SEG, pp. 25–29.
Balestrini, E., Daganov, D., Malehmir, A., Marsden, P. and Ghose, R. (2020) Improved target illumination at Ludvika mines of Sweden through seismic-interferometric surface-wave suppression. Geophysical Prospecting, 68(1), 200–213.
Boucard, D. and Ollivrin, G. (2010) Developments in vibrator control. Geophysical Prospecting, 58, 33–40.
Bräunig, L., Buske, S., Malehmir, A., Backstrom, E., Schön, M. and Marsden, P. (2020) Seismic depth imaging of iron-oxide deposits and their host rocks in the Ludvika mining area of central Sweden. Geophysical Prospecting, 68(1), 24–43.
Brodic, B., De Kunder, R., Ras, P., Vand den Berg, J. & Malehmir, A. (2019a) Evaluation of signal properties of a prototype electromagnetic vibrator using MEMS-based landstreamer and wireless seismic recorders. In: 16th SAGA Biennial Conference & Exhibition 2019, Durban, South Africa, Extended Abstracts. Conference paper.
Brodic, B., De Kunder, R., Ras, P., Vand den Berg, J. & Malehmir, A. (2019b) Seismic imaging using electromagnetic vibrators-storm versus lightning. In: Near Surface Geoscience Conference & Exhibition EAGE, The Hague, Netherlands, Expanded Abstracts. EAGE, pp. 1–5. Conference paper.
Brodic B., Malehmir A., Pacheco N., Juhlin C., Carvalho J., Dynesius L., van den Berg J., de Kunder R., Donoso G., Sjolund T., Araujo Vitor (2021) Innovative seismic imaging of volcanicogenic massive sulfide deposits, Neves-Corvo, Portugal — Part 1: In-mine array. GEOPHYSICS, 86(3), B165–B179. https://doi.org/10.1190/geo2020-0565.1
Brodic B., Ras P., de Kunder R., Drijkoningen G., Malehmir A. (2021) Seismic imaging using an e-vib — A case study analyzing the signal properties of a seismic vibrator driven by electric linear synchronous motors. GEOPHYSICS, 86(3), B223–B235. https://doi.org/10.1190/geop2020-0181.1
Buske, S., Bellefleur, G., Malehmir, A. (2015) Introduction to special issue on “hard rock seismic imaging”. Geophysical Prospecting, 63, 751–753.
Campman, X., Behn, P. and Faber, K. (2016) Sensor density or sensor sensitivity. The Leading Edge, 35, 578–585.
Chen, G., Liang G., Xu D., Zeng Q., Fu S., Wei X., et al. (2004) Application of a shallow seismic reflection method to the exploration of a gold deposit. Journal of Geophysics and Engineering, 1, 12–16.
Cordingy, S. (2020) An effective data processing workflow for broadband single-sensor single-source land seismic data. The Leading Edge, 39, 401–410.
Ding, Y. and Malehmir, A. (2021) Reverse time migration (RTM) imaging of iron oxide deposits in the Ludvika mining area, Sweden. Solid Earth, 12, 1707–1718.
Donoso, G., Malehmir, A., Brodic, B., Pachecho, N. (2021) Innovative seismic imaging of VMS deposits, Neves-Corvo, Portugal: Part II – surface array. Geophysics, 86, 1–39.
Eaton, D. W., Milkeriet B. and Salisbury M. H. (Eds.). (2003) Hardrock Seismic Exploration. SEG.
Essa, K. and Munschky, M. (2019) Introductory chapter: Mineral exploration from the point of view of geophysicists. In K. Essa (Ed.) Minerals. IntechOpen. 3–8.
Fizaine, F. (2018) Toward generalization of futures contracts for raw materials: A probabilistic answer applied to metal markets. Resources Policy, 59, 379–388.
Ghose, R. (2002) High-frequency shear wave reflections from shallow subsoil layers using a vibrator source: Sweep cross-correlation versus lightning. In: Near Surface Geoscience Conference & Exhibition EAGE, The Hague, Netherlands, Expanded Abstracts. EAGE, pp. 1408–1411.
Halder, S. (2018), Mineral Exploration: Principles and Applications. Elsevier.
Juhlin, C., Lindgren, J. and Collini, B. (1991) Interpretation of seismic reflection and borehole data from Precambrian rocks in the Dala Sandstone area, central Sweden. First Break, 9(1), 24–36.
Kovisto, E., Malehmir, A., Heikkinen, P., Heinonen, S. and Kukkonen, I. (2012) 2D reflection seismic investigations at the Kevitsa Ni-Cu-PGE deposit, northern Finland. Geophysics, 77, WC149–WC162.
Li, G., Qi, W., Ding, Y., Huang, Z., Lian, Z., Tao, Z. and Yang, X. (2019) Method and application of extending seismic vibrator bandwidth toward low frequency. Advances in Mechanical Engineering, 11, 1–13.

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Malehmir, A., Bergman, B., Andersson, B., Sturk, R. and Johansson, M. (2018) Seismic imaging of dyke swarms within the Sorgenfrei-Tornquist zone (Sweden) and implications for thermal energy storage. *Solid Earth*, 9, 1469–1485.

Malehmir, A., Brodic, B., Dehghannejad, M., Juhlin, C. and Lundberg, E. (2016) A state-of-the-art MEMS-based 3C seismic landstreamer for various near-surface applications. In: *Near Surface Geoscience Conference & Exhibition EAGE*, Vienna, Austria. EAGE, volume 2016, pp. 1–5.

Malehmir, A., Koivistö, E., Manzi, M., Cheraghí, S., Durrheim, R. J., Bellefleur, G., et al. (2014) A review of reflection seismic investigations in three major metallogenic regions: The Kevitsa Ni-Cu-PGE district (Finland), Witwatersrand goldfields (South Africa), and the Bathurst Mining Camp (Canada): ore. *Geology Reviews*, 56, 423–441.

Malehmir, A., Donoso, G., Markovic, M., Maries, G., Dynesius, L., Brodic, B., et al. (2019) Smart exploration: from legacy data to state-of-the-art data acquisition and imaging. *First Break*, 37(8), 71–74.

Malehmir, A., Durrheim, R., Bellefleur, G., Urosevic, M., Juhlin, C., White, D.J., et al. (2012) Seismic methods in mineral exploration and mine planning: A general overview of past and present case histories and a look into the future. *Geophysics*, 77(5), 173–190.

Malehmir, A., Maries, G., Bäckström, E., Schön, M. and Marsden, P. (2017) Developing cost-effective seismic mineral exploration methods using a landstreamer and a drophammer. *Scientific Reports*, 7, 10325.

Malehmir, A., Manzi, M., Draganov, D., Mark, G., et al. (2005) Iron oxide copper-gold deposits: Geology, frequencies. *Economic Geology*, 100, 371–405.

Sallas, J. J. (2010) How do hydraulic vibrators work? A look inside the black box. *Geophysical Prospecting*, 58, 3–17.

Sallis, J. J. (2010) How do hydraulic vibrators work? A look inside the black box. *Geophysical Prospecting*, 58, 3–17.

Maries, G., Malehmir, A., Backström, E., Schön, M. and Marsden, P. (2017) Downhole physical property logging for iron-oxide exploration, rock quality, and mining: An example from central Sweden. *Ore Geology Reviews*, 90, 1–13. https://doi.org/10.1016/j.oregeorev.2017.10.012

Maries, G., Malehmir, A. and Marsden, P. (2020) Cross-profile seismic data acquisition, imaging and modelling of iron-oxide deposits: A case study from Blötberget, south central Sweden. *Geophysics*, 85, 1ND-Z30.

Manzi, M.S.D., Cooper, G., Malehmir, A., Durrheim, R. and Nkosi, Z. (2015) Integrated interpretation of 3D seismic data to enhance the detection of the gold-bearing reef: Mponeng Gold mine, Witwatersrand Basin (South Africa). *Geophysical Prospecting*, 63, 881–902.

Manzi, M.S.D., Gibson, M.A.S., Hein, K.A.A., King, N. and Durrheim, R.J. (2012) Application of 3D seismic techniques to evaluate ore resources in the West Wits Line goldfield and portions of the West Rand goldfield, South Africa. *Geophysics*, 77, WC163–WC171.

Markovic, M., Maries, G., Malehmir, A., Von Ketelhodt, J., Backström, E., Schön, M. and Marsden, P. (2020) Deep reflection seismic imaging of iron-oxide deposits in the Ludvika mining area of central Sweden. *Geophysical Prospecting*, 68, 7–23.

Meunier, J. (2011) Seismic acquisition from yesterday to tomorrow. SEG, Distinguished Instructor Series. SEG.

Milkereit, B., Eaton, D., Wu, J., Perron, G., Salisbury, M. H., Berrr, E.K. et al. (1996) Seismic imaging of massive sulfide deposits; Part II, reflection seismic profiling. *Economic Geology*, 91, 829–834.

Noorlandt, R., Drijikoning, G., Dams, J. and Jenneskens, R. (2015) A seismic vertical vibrator driven by linear synchronous motors. *Geophysics*, 8, (2), 57–67.

Nordic Iron Ore, (2011) Ludvika mines preliminary economic assessment. Final Report. Rev 3. Ludvika Mines, pp. 1–74.

Papadopoulou, M., Da Col, F., Mi, B., Backström, E., Marsden, P., Brodic, B., et al. (2020) Surface-wave analysis for static corrections in mineral exploration: A case study from central Sweden. *Geophysical Prospecting*, 68(1), 214–231.

Polychronopoulou, K., Lois, A. and Draganov, D. (2020) Body-wave passive seismic interferometry revisited: Mining exploration using the body waves of local microearthquakes. *Geophysical Prospecting*, 68(1), 1–22.

Rowse, S. and Tinkle A. (2016) Vibroseis evolution: may the ground force be with you. *First Break*, 34, 7.

Sallas, J. J. (2010) How do hydraulic vibrators work? A look inside the black box. *Geophysical Prospecting*, 58, 3–17.

Salisbury, M.H., Harvey, C.W. and Matthews, L. (2003) The acoustic properties of ores and host rocks in hardrock terranes. In: Eaton, D.W., Milkereit, B. and Salisbury, M.H. (Eds) *Hardrock Seismic Exploration*. Society of Exploration Geophysicists, pp. 9–19.

Stephens, M., Ripa, M., Lundström, I., Persson, L., Bergman, T., Ahl, M., et al. (2009) *Synthesis of the bedrock geology in the Bergslagen region, Fennoscandian Shield, south-central Sweden*. Geological Survey of Sweden (SGU).

ten Kroode, F., Bergler, S., Corsten, C., de Maag, J., Stribos, F. and Tijhof, H. (2013) Broadband seismic data – the importance of low frequencies. *Geophysics*, 78(2), WA3–WA14.

Williams, P.J, Barton, M. D., Johnson, D.A., Fontbote, L., De Haller, A., Mark, G., et al. (2005) Iron oxide copper-gold deposits: Geology, space-time distribution and possible modes of origin. *Economic Geology*, 100, 371–405.