Introduction

Mineral exploration industry is challenged to provide fresh resources of the so-called critical raw materials important for green technologies and help accelerate the energy transition towards decarbonization. These critical materials (e.g., rare earth elements) are often found as associated minerals in other deposits. Hence apart from their own significance, other deposits such as base- and precious-metals need to be found and the presence of the critical minerals that are usually beyond the detection limit of geophysical methods studied. What makes discovery of these deposits even more difficult is their presence at depths because most of the shallow deposits are believed to have already been found and exploited. Therefore, deep direct targeting requires a multidisciplinary approach to avoid a costly deep drilling failure also embracing other technologies that hydrocarbon industry have successfully used for deep exploration albeit in a much simpler geological setting with clear and continuous geological markers. Seismic methods particularly reflection seismics after being tested now for over 3 decades in crystalline rock settings are opening their ways into the mineral exploration toolbox as a standard method. A recent number of publications (Malehmir et al., 2020 and references therein) illustrates why the method is so attractive for deep targeting and mineral exploration. In this work, we present a series of seismic surveys conducted at an iron-oxide mining region of central Sweden known as the Ludvika mines (Figure 1). These studies and in particular the recent ones are performed within the H2020-funded Smart Exploration project (Malehmir et al., 2019). Our goal is to illustrate how these studies formed a foundation to advance from 2D to 3D surveys and in future to downhole seismic surveys.

![Figure 1](image1.png)

**Figure 1** (a) Total-field aeromagnetic map and (b) aerial photo of the Blötberget mine a number of profiles surveyed during 2015-2019. P1-11 were surveyed as part of a 3D survey (fixed geometry) with red dots showing the shot locations. 2D profiles were acquired along P1 (landstreamer (Sept. 2015), cabled-plant-geophone (Sept. 2016) and E-vib validation test (Sept. 2019)).

Downhole logging data

A good understanding of reflection seismic response is only possible when physical properties are studied in-situ using downhole logging methods. Through 2015-2016, six boreholes (400-500 m deep) were downhole logged using various probes but more importantly for this study using a full-waveform triple sonic probe. Density measurements could only be done on core samples at a 1-m interval. These studies showed (Figure 2) that at the presence of suitable geometries and reasonably good S/N, direct-targeting iron-oxide deposits (magnetite and hematite) is possible and should be extremely helpful for deep exploration at the site (Maries et al., 2017).

Seismic surveys (2015-2019)

Starting in year 2015, a newly developed MEMS-based seismic landstreamer was tested for a pilot deep-targeting work at the Blötberget site (Figure 3a). Data were acquired using 100-MEMS sensor
placed 2-4 m apart on the streamer (240 m long) and 75 wireless recorders placed north and south of the profile (fixed position, but moved once from the south to the north). A 500-kg Bobcat-mounted drophammer was used as the seismic source. In total, the streamer moved 9 times providing together with the wirelesses a nominal fold of 40. During 4 days, 3.5 km of seismic data along profile 1 (P1) were acquired using 1049 receiver and 533 shot locations (Malehmir et al., 2017).

Figure 2 Example of downhole logging data from borehole (a) BB14004 and (b) BB14005 (Figure 1) showing why a strong seismic response from the iron-oxide mineralization is expected based on the synthetic seismograms generated from the data. Based on Markovic et al. (2020).

In year 2016, a more commercial-type survey using the same seismic source (Figure 3b) but much higher fold (208 using 5 m shot and receiver spacing) and cabled-plant-geophones was conducted (Bräunig et al., 2020; Markovic et al., 2020). A cross-profile recording was also attempted using a fixed geometry along P1 (451 receivers) and a shorter perpendicular profile. Shots were recorded onto both profiles. These data are currently the subject of another study.

As part of the Smart Exploration project, a 3D seismic survey (ca. 2 by 2 km) was acquired during April-May 2019 using a fixed geometry of 1266 receivers (9 receiver lines, P1-P9) and 1052 shots (11 shot lines, P1-P11), and a 32-t vibrator generating three shot records per location with a 20 s long sweep ranging from 10-160 Hz (Figure 3c,e). A mixed receiver spacing of 10 and 20 m was used depending on the profile and after a pre-study of the fold-azimuthal coverage using the equipment available to the project. In this survey both cabled (P1 and P3) and wireless recorders (P1-P2, P4-P9) were used. The seismic profiles were planned so that they would provide best illumination angle, orthogonal to the known strike, to the known mineralization (Figure 1).

Given the vast amount of the seismic data available from the site, it was logical to also validate the performance of a broadband electromagnetic seismic source (E-vib) developed within the project (Figure 3d). Profile 1 where data from 2015, 2016 and an extraction of profiles 1 from the 3D could be used for comparative studies was chosen. This survey was conducted in September 2019 with 3 shot records generated at each shot location using linear sweeps with a bandwidth of 2-180 Hz and 17 s sweep length. A fixed geometry of 553 receivers using a combination of wireless (128) and cabled-plant-geophones (425) 5 m apart was used. Data from this survey are currently being processed and will be presented.

**Results and Conclusions**

All the seismic surveys were capable of imaging the known mineralization including the landstreamer survey (Figure 4). What however makes these surveys more interesting is their ability to provide information about additional resources down-dip and possibly in the footwall of the known deposits.
Preliminary results from the 3D survey shows the greatest resolution and quality, and is capable of providing additional information on host rock structures and lateral continuity of the deposits.

**Figure 3** Field photos from various surveys in the Blötberget mine. (a) In 2015, a combination of a landstreamer and wireless recorders was used and a 500-kg Bobcat drophammer as the source. (b) In 2016, a combination of cabled and wireless recorders was used allowing a high fold coverage to be obtained. (c,e) During April-May 2019, a 3D seismic survey was conducted using a 32-t vibrator, 1266 receivers of which 414 were cabled (P1 and P3). (d) In September 2019, the Strom vibrator was tested along profile 1 using 553 receivers 5 m apart and a fixed acquisition geometry.

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**References**


**Figure 4** Unmigrated seismic sections along profile 1 from (a) the 2015 landstreamer survey, (b) the commercial-type survey in 2016, (c) combined datasets of 2015 and 2016 surveys, (d) a portion of the 3D data along profile 1, and (e) two profiles visualized from the 3D survey imaging the lateral extent of the mineralization. Note these deposits dip approximately 35-40 degrees and will migrate up dip. When migrated they do match the known deposits as shown in the earlier studies.