3D reflection seismic imaging of the Zinkgruvan mineral-bearing structures in the south-eastern Bergslagen mineral district (Sweden)

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Abstract

Mineral exploration is facing greater challenges nowadays because of the increasing demand for raw materials and the lesser chance of finding large deposits at shallow depths. To be efficient and address new exploration challenges, high-resolution and sensitive methods that are cost-effective and environmentally friendly are required. In this work, we present the results of a sparse 3D seismic survey that was conducted in the Zinkgruvan mining area, in the Bergslagen mineral district of central Sweden. The survey covers an area of 10.5 km² for deep targeting of massive sulphides in a polyphasic tectonic setting. A total of 1311 receivers and 950 shot points in a fixed 3D geometry setup were employed for the survey. Nine 2D profiles and a smaller 3D mesh were used. Shots were generated at every 10 m, and receivers were placed at every 10–20 m, along the 2D profiles, and 40–80 m in the mesh area. An analysis of the seismic fold coverage at depth was used to determine the potential resolving power of this sparse 3D setup. The data processing had to account for cultural noise from the operating mine and strong source-generated surface waves, which were attenuated during both pre- and post-stack processing steps. The processing workflow employed a combination of 2D and 3D refraction static corrections, and post-stack FK filters along inlines and crosslines. The resulting 3D seismic volume is correlated with downhole data (density and P-wave, acoustic impedance, reflection coefficient), synthetic seismograms, surface geology and a 3D model of mineral-bearing horizons in order to suggest new exploration targets at depth. The overall geological architecture at Zinkgruvan is interpreted as two EW overturn folds, an antiform and a synform, affected by later NS-trending folding. Two strong sets of shallow reflections, associated with the Zn–Pb mineralization, are located at the hinge of an EW-trending antiform, while a strong set of reflections, associated with the main mineralization, is located at the overturned apex of the EW synform. The NS Knalla fault that crosses the study area terminates the continuation of the mineral-bearing deposits at depth towards the west, a conclusion solely based on the reflectivity character of the seismic volume. This study illustrates that sparse
INTRODUCTION

Reflection seismic methods have become one of the most used techniques for imaging the subsurface because they can provide high-resolution images of geological structures and lithological boundaries. Over the last few decades, reflection seismic methods have been developed and improved for mineral exploration and mine planning, mainly 2D seismic surveys, due to their lower cost and footprints compared to 3D surveys (Wright et al., 1994; Milkereit et al., 1996; Eaton et al., 2003a, 2003b; Chen et al., 2004; Malehmir & Bellefleur, 2009; Dehghannejad et al., 2010; Cheraghi et al., 2011, 2013; Koivistoo et al., 2012; Ahmadi et al., 2013; Malehmir et al., 2014, 2017a; Donoso et al., 2019; Heinonen et al., 2019; Bräunig et al., 2020; Gil et al., 2021). Recently, however, there has been an increased use of 3D seismic surveys for this purpose in Canada (Adam et al., 2003; Cheraghi et al., 2015; Bellefleur et al., 2015), South Africa (Manzi et al., 2012, 2013, 2019), Australia (Urosevic et al., 2012), Finland (Malehmir et al., 2012, 2018; Singh et al., 2019) and Sweden (Malehmir et al., 2021). Here, we present the first 3D seismic survey in the mineral-endowed Bergslagen region for massive sulphides targeting in the Zinkgruvan mining area (Fig. 1). Aside from this study, there is only one 3D seismic survey reported from the region, but for iron-oxide deep targeting (Malehmir et al., 2021); hence, this study should be considered pilot and for the proof-of-concept that using a well-planned acquisition setup and processing workflow, a sparse 3D seismic dataset can provide valuable information for optimized deep exploration even in a geologically complex setting such as Bergslagen.

Zinkgruvan, in south-central Sweden, is the largest and most important tabular-shaped Zn–Pb–Ag–(Cu) deposit in the Bergslagen mineral district. It is owned by Zinkgruvan Mining AB, a subsidiary of Lundin Mining, and has been in continuous operation since 1857. The current annual production is approximately 1.2 Mt of zinc and 0.2 copper crude ore, and up to date, 47 Mt of ores have been mined out. It is currently the southernmost underground mine in Sweden and produces mineral concentrates of Zn, Pb, and Cu. Like most metallic deposits in the Bergslagen district, it occurs within an inlier of volcanic rocks intercalated with carbonate (marble) and metasedimentary rocks.

Deep-probing reflection seismic profiles, except for the one reported recently by Gil et al. (2021), are not available from the site, and it has generally been believed that these methods have little success within the complex, overturned, faulted and folded structures of the Bergslagen district (Ahmadi et al., 2013). Within a larger-scale research-innovation project, Gil et al. (2021) recently reported three of the nine 2D seismic profiles (P1, P2 and P8; Fig. 1) that were acquired as part of a sparse 3D dataset in the Zinkgruvan area. In their study, the origin of the most pronounced reflections associated with the host rocks was speculated. It was possible to associate some of the reflections to mineral-bearing horizons through a combination with downhole logging data and 3D reflection traveltime modelling. However, the assumption of the 2D geology retrieved from the 2D profiles is rarely valid, especially in the complex geology of Bergslagen. The main issue with 2D profiles is the mapping of apparent depth and dip due to out-of-plane nature of structures and that a straight profile usually is impossible in the northern regions without extensive forest cuttings and clearance. Even when a straight profile is possible, geology is usually 3D; hence, 3D surveys are ideal solutions and should be used prior to any deep targeting. 2D profiles should be used only for studying reflectivity response of the geology and not for targeting and exploration (Malehmir et al., 2009, 2017b). Therefore, in this study, we merged the entire seismic dataset of the nine profiles and additional stations setup for a passive experiment to form a sparse 3D dataset to image 3D structures of the site. This enabled us to shed light on the applicability of 3D reflection seismic studies in the Bergslagen region for massive sulphide targeting, and on deeper geological structures that are difficult to infer in high-resolution using any other methods. The main objectives of this study are (1) to delineate depth and lateral continuation of the mineral-bearing horizon and its host rock, (2) to determine the 3D geological structures at depth, and (3) to support mineral exploration in the area, in terms of risk and prospect assessment.

GEOLOGICAL SETTING

The Zinkgruvan mine is in south-central Sweden (Fig. 1). It is in the southwest corner of the Paleoproterozoic Bergslagen greenstone belt, which hosts volcanogenic massive sulphides (VMS) rich in zinc-lead, copper and silver sulphides and banded iron formations (Allen et al., 1996; Jansson et al., 2017). Strong deformation that affected the area
and consequently create a complex history of the post-ore modification, has made the classification of the Zinkgruvan deposit difficult, with candidates including a sediment-hosted Zn (SEDEX) deposit (Cooke et al., 2000), a VMS-SEDEX hybrid (Hedström et al., 1989), or even a Broken Hill-type deposit (Plimer, 1988; Walters, 1996). In this work, we will follow the classification made by Allen et al. (1996), where Zinkgruvan is described as a ‘stratiform ash-siltstone-hosted Zn–Pb–Ag sulphide deposit (SAS-type)’ with subordinate copper belonging to the Bergslagen mineral endowment of central Sweden. The tabular-shaped Zn–Pb–Ag deposit is hosted by felsic ash-siltstone volcanic rock, skarn, chemical sediment and mafic rocks, all affected by upper amphibolite facies metamorphism (Hedström et al., 1989; Allen et al., 1996, 2013; Stephens et al., 2009). The carbonate rocks host veins of dissemination of Cu mineralization (Allen et al., 2013; Jansson et al., 2017, 2018). The Zinkgruvan deposit is located on the upper part of the Emme Group (Kumpulainen et al., 1996, and references therein). The Emme Group is 10-km thick and comprises eight lithostratigraphic units. From lowermost to uppermost, these are the Mösjön and Gökberget units, the Igelfors and Närkesberg Formations, the Mariedamm volcanic rocks, the Höksjön limestone, the metatuffite unit and the Vintergölen Formation. The Emme Group and their lithological units have been described in detail by Allen et al. (1996) and Kumpulainen et al. (1996). At the bottom of the Emme Group, in the Gökbeget unit, the Marketorp Zn–Pb deposit is hosted (Kumpulainen et al., 1996; Fig. 2). In this work, we refer to the Höksjön limestone and metatuffite unit as Zinkgruvan Formation (Fm), previously defined by Jansson et al. (2017; Fig. 2). The Zinkgruvan Formation is the main host of the stratiform Zn–Pb–Ag mineralization (Jansson et al., 2017, 2018).

The Zinkgruvan deposit is situated in an EW-striking synformal structure (Daffern et al., 2017) because of repeated deformation during the Svecofennian orogeny that includes NS folding and overturn stratigraphy (Beunk & Kuipers, 2012; Daffern et al., 2017; Jansson et al., 2017). Later, the area was affected by a subvertical N–NE trending fault system dividing the mining area into large exploration and mining blocks, including Knalla and Nygruvan areas (Beunk & Kuipers, 2012; Fig. 1). The Zinkgruvan deposit, tabular-shaped, is approximately 5000 m long and is known to extend down to a depth of 1600 m (Daffern et al., 2017). Zinkgruvan...
FIGURE 2 Regional stratigraphic column of the Emme Group and the Zinkgruvan mining area (modified from Kumpulainen et al., 1996 and Gil et al., 2021). The Metatuffite and Höksjön limestone units will be referred to as the Zinkgruvan Formation (Fm) following Jansson et al. (2017). The Zn–Pb–(Cu) Marketorp deposit is located within the Gökberget unit, at the lowermost part of the Emme Group, while the Zn–Pb–Ag–(Cu) Zinkgruvan deposit is located at the uppermost part of the group, within the Zinkgruvan Fm.

is an underground mine that has been in operation by Zinkgruvan Mining AB since 2004 and earlier than that by others.

DOWNHOLE LOGGING

Downhole logging measurements of P-wave velocity and density of host rocks and mineralized zones were carried out by Zinkgruvan Mining AB. Results indicated that the volcanic rocks and the interbedded marble and skarn have large acoustic impedance contrast with respect to the metatuffite (Zinkgruvan Formation) and the pink-red microcline-quartz rocks (Mariedamm volcanic unit) and can seismically be reflective (Fig. 3). The interbedded marble and skarn units form part of the Zinkgruvan Formation, which is known to be the host of the stratiform mineralization (Jansson et al., 2017, 2018). In Figure 3, borehole BH4321 is shown that crosses the Zn–Pb mineralization. From the 1D-convolutional synthetic seismogram, it is possible to envisage that the Zn and Pb mineralized rocks present a strong seismic signature when hosted within the volcanic rocks or the interbedded marble and skarn unit. Earlier successful surveys elsewhere also suggested that massive sulphides are seismically easy to identify because of their high-density contrast, making them good targets for seismic exploration (Malehmir & Bellefleur, 2009; Cheraghi et al., 2011, 2013; White et al., 2016; Maries et al., 2017; Donoso et al., 2019, 2021; Brodic et al., 2021), even if the area presents a strong deformation and geologically complex (Wanstedt, 1992).

ZINKGRUVAN 3D SEISMIC SURVEY

Seismic data acquisition

A consortium from academia and industry and for up-scaling purposes designed the survey for future mining-exploration operation management in major mineral-endowed regions
in Europe. Within this characterization phase, an extensive sparse 3D active-source seismic acquisition programme was carried out. In November 2018, a dense array of 2D profiles in an area of approximately 10.5 km$^2$ (3.5 by 3 km) was acquired in the Zinkgruvan mining area using a 32t seismic vibrator source from TU Bergakademie Freiberg (Fig. 4).

The 3D dataset was acquired using a fixed geometry comprising 1311 receiver positions distributed along nine 2D crooked seismic profiles and in a smaller pseudo-3D mesh inside the main 3D survey area (Fig. 1). Considering the limited number of receivers available to the project and to this study, 606 wireless recorders (210 CUBES, 165-1C and 231–3C RAUs; Fig. 4) connected to 10 Hz geophones along profiles P2–P9, with 20 m receiver spacing, were used. Another 425 receiver stations were set up using 28-Hz geophones and with a 10 m spacing along P1 (Figs. 1 and 4). P1 was also used for live data quality control and sweep parameter tests during the data acquisition. Some details of the survey and sweep tests are covered in Gil et al. (2021). All profiles were designed to be mostly perpendicular to the main geological structures so that some key lithological–structural boundaries (e.g., Zinkgruvan Formation; Fig. 2; Gil et al., 2021) could reliably be imaged. With the idea of imaging the depth and lateral extension of key geological structures, another 285-1C wireless recorders connected to 10 Hz geophones were used in a semi-regular grid (Fig. 1) to cover the gaps in-between the 2D seismic profiles. An average of 80 m receiver spacing was considered. Only a small portion of the mesh presents a 40 m receiver spacing near the mine ventilation shaft and at the vertex of the main geological fold in the area.

The selected parameters for the source were three linear 17 s up-sweeps with a 10–150 Hz bandwidth (Gil et al., 2021). The total number of source points is approximately 950, resulting in nearly 1,144,000 traces. All shots were recorded by all the receivers providing a comprehensive dataset for 3D control on deep geological structures. The acquisition parameters of the experiment (Table 1) including position, size and geometry of the survey were chosen after a careful survey planning and numerous visits to the study area to check for the location of the shot and receiver lines given the limitation of the receivers and number of shots (acquisition days) available to the project. In theory, acquiring higher fold and much better source–receiver offset–azimuth distributions was possible but would have involved a higher cost. This sparse 3D dataset should provide a first-hand 3D image of the...
subsurface and a geometry that could bridge the gap between 2D profiles and higher fold, but expensive, 3D setups (Cheraghi et al., 2013; Singh et al., 2019; Malehmir et al., 2021, and references therein).

**Planned versus executed survey**

With the idea of covering a wide area as possible (15 km²), around 1500 stations, in a combination of five crooked 2D seismic lines, with 20 m receiver and shot spacing were considered, together with a mesh comprising 586 stations, and 900 shots along all the 2D profiles (Fig. 5a). However, the planned survey turned out impractical because it considered having access to all main roads and forest tracks and accessibility in the dense forest. Figure 5(a) and (b) shows the planned receiver and shot profiles using common data point (CDP) bins of 10 and 20 m, respectively. The eventual survey employed fewer stations in the mesh region, but more 2D profiles were deployed maintaining an improved source–receiver offset–azimuth coverage (Fig. 5c and d).

In a 2D survey, the fold may be uniform, while in a 3D survey this distribution is often irregular, presenting usually farther offset traces complicating depth imaging and processing workflows (Fig. 5e–g; Chaouch & Mari, 2006). To elaborate on how offset irregularities interfere with shallow and depth imaging potential of the dataset, we assumed a constant velocity medium of 6000 m/s and a horizontal surface target to calculate the fold coverage at various depths (Fig. 6). This helped us later to interpret if the lack of continuity of the reflections is data related or geological, as well as where in the 3D volume to expect this behaviour. Considering that the main objective of the study was to image the key mineralized formations at depth beyond >1.6 km (Jansson et al., 2018),
FIGURE 5 Planned versus executed 3D survey at the Zinkgruvan mining area. Planned survey and fold coverage using (a) 10 m and (b) 20 m regular CDP bins. (c) Executed offset–azimuth coverage and (d) the executed survey fold using 10 m bins (as used during the processing of the dataset). (e–g) Offset–azimuth coverage for some recorders (recorders: 11416, 1296 and 463, respectively). The executed survey ended using fewer stations in the mesh area but more distributed along 2D profiles, keeping the overall offset–azimuth coverage more uniform although narrow for most individual bins.

this exercise also provided some level of confidence in the imaging potential in the central part of the seismic volume. The fold analysis (Fig. 6) indicates how targets shallower than 1000 m will be imaged by the 2D profiles but difficult to image in the 3D dataset. Deeper targets should have enough fold to be imaged in the 3D dataset.

Seismic processing workflow

The sparse 3D survey was designed to cover the Zinkgruvan mining area north of the mineshaft (Fig. 1), where the mineral exploration potential is thought to be higher. All forest tracks and trails that could host source points were used in the survey. Wireless recorders were deployed in all locations accessible by car or on foot. In some cases, this resulted in significant amounts of noise due to their proximity to power lines and/or roads. The data acquired for this pilot study used different receivers with different natural frequencies as detailed in Table 1. Thus, it required careful signal processing to obtain quality images of the subsurface. As a first step, the data recorded by the CUBE recorders, from P2 and P5, were resampled to 1 ms to be able to merge them with the data from other recorders.

The sparse 3D dataset shows remarkable quality with first breaks visible in nearly all shot gathers and offsets, and clear reflections in some raw shot gathers. Despite being in a noisy mining environment (operations inside mining tunnels include two major rock crushers), good quality data were recorded. We present an example of a raw shot gather after cross-correlation and vertical stacking of the three repeated shot records in Figure 7(a), and in Figure 8(a) we show a raw receiver gather from a station within the mesh region. Several reflections within the shallow subsurface plus deeper
FIGURE 6 Fold coverage at different depth levels. The plotted coverage is referred to an average depth assuming a flat surface and an average velocity of 6000 m/s. Black dots represent the receivers and yellow dots the shot locations. The area covered by the mesh receivers shows a fold of around 25–50 starting at around 1500 m or 500 ms two-way traveltime. Shallow targets could be imaged only along the receiver lines where near-offset shots were generated.

reflections at 700–800 and around 1000 ms are visible illustrating the quality of the data.

Pre-stack data processing workflow

Static corrections

Elevation and refraction statics are key steps for obtaining a high-quality and resolution seismic image in hard rock settings (Juhlin et al., 2007; Malehmir & Juhlin, 2010). In our case, they are essential for improving the final image due to a large number of stations located at far offsets and the great number of stations that only record shots at far offset as it is observed in the azimuth-offset distribution shown in Figure 5.

The entire dataset was referenced to a datum of 120 m above sea level, just above the highest altitude of the survey area. The replacement velocity, based upon apparent velocities in the shot gathers, was set to 5500 m/s. To correct for the effect of near-surface statics, approximately 850,000 first breaks were picked automatically and corrected manually. 3D refraction static corrections using a two-layer generalized reciprocal method were first estimated with an RMS value of 6.5 ms. This was obtained using a moderate smoothing parameter and offsets between 20–1000 m. Three different rounds of iterations using 400, 200 and 100 m cells split into four triangles were consecutively used to obtain the final velocity model of the near surface that narrowed down the RMS from 21 to 6.5 ms.

Later, and due to the sparse nature of the 3D dataset, we decided to follow a similar approach to that presented in Malehmir et al. (2021) for obtaining a much-improved static correction solution. We calculated the 2D refraction static solutions from shots and receivers along the active profiles first, and where this was not possible (i.e. the mesh area),
TABLE 1 Main acquisition parameters of the Zinkgruvan mining area 3D seismic survey, November 2018

<table>
<thead>
<tr>
<th>Survey parameters</th>
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<tbody>
<tr>
<td>No. of shot points</td>
<td>950</td>
</tr>
<tr>
<td>Shot point spacing</td>
<td>10 m</td>
</tr>
<tr>
<td>Source type</td>
<td>Vibroseis (32t)</td>
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<tr>
<td>Sweep length</td>
<td>17 s linear</td>
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<td>No. of sweeps point</td>
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<tr>
<td>Sweep frequency</td>
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</tr>
<tr>
<td>No. of traces</td>
<td>1,144,000</td>
</tr>
<tr>
<td>Sample rate</td>
<td>1 ms (FDU and RAU) and 1.25 ms (CUBES)</td>
</tr>
<tr>
<td>Receiver spacing</td>
<td>10−20 m (10 m along P1), 40−80 m Mesh, otherwise 20 m</td>
</tr>
<tr>
<td>Total no. of receivers</td>
<td>1311</td>
</tr>
<tr>
<td>No. of inline</td>
<td>324 (1000:1323)</td>
</tr>
<tr>
<td>No. of crossline</td>
<td>286 (1000:1285)</td>
</tr>
<tr>
<td>Bin size</td>
<td>10x10 m</td>
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</tbody>
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<table>
<thead>
<tr>
<th>Spread parameters</th>
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<tbody>
<tr>
<td>Receiver spread array</td>
<td>1311 live receivers, fixed geometry</td>
</tr>
<tr>
<td>Receivers</td>
<td>Single spike 10 Hz (only along P1 28 Hz) Triple spike 10 Hz along P3, P4, P6 and P7 profiles</td>
</tr>
<tr>
<td>Recorders</td>
<td>FDU along P1, CUBES along P2+P5 Wireless RAUs 1C/3C along all other profiles and mesh</td>
</tr>
<tr>
<td>Geodetic survey</td>
<td>DGPS (differential global positioning system) combined with national LiDAR</td>
</tr>
</tbody>
</table>

3D refraction statics was used. The quality of 2D and 3D refraction static was examined on key notable reflections in some shot gathers, guaranteeing that the mixed 2D and 3D refraction statics resulted in an improved solution and did not harm the continuity of the reflections. Hence, the best stack volume was obtained using a combination of 2D static corrections for profiles such as P1, P2, P7 and P8 (Fig. 7b) and 3D refraction static corrections along those where only receivers were placed, such as P6, P9 and the mesh area (Fig. 8b). Several runs of brute stacks and quality controls helped to make sure this procedure led to improved results instead of destructively stacking the reflections.

Noise attenuation

As observed in Figures 7(a) and 8(a), the dataset is affected by strong surface waves. Some receivers also show strong 50-Hz power-line noise and its harmonics due to their proximity to a major power grid passing through the survey area. Processing of the data followed an industry-standard workflow (Table 2) to remove this and other noise sources. A band-stop filter was applied to those receivers (selective) affected by the 50-Hz noise, followed by a band-pass filter, a median velocity filter to attenuate the surface waves, a Wiener deconvolution and a front mute (Figs. 7c and 8c), using the first arrivals, as well as trace normalization to suppress the strong surface waves in the data at the expense of also reducing the reflection amplitudes. This allowed us to highlight some reflections that were not visible on the raw shot gathers. Refraction statics and filtering were key steps in the pre-stack processing workflow of this dataset.

CDP binning

After several tests, a CDP bin size of 10 × 10 m was chosen for CDPs inline following an E-W orientation, the main direction of the receivers (Fig. 4d), and for CDPs crossline perpendicular to the CDPs inline. Following Yilmaz (2001), the minimum CDP bin size, $\Delta x$, can be calculated using

$$\Delta x = \frac{u_{rms}}{4f_{max} \sin \alpha},$$

where $u_{rms}$ is the RMS velocity down to the target reflector, $f_{max}$ is the maximum non-aliased frequency required to resolve the target reflector, and $\alpha$ is the structural dip. Assuming $u_{rms}$ of 5800−6100 m/s (estimated from available logs and Gil et al., 2021), maximum target dips of 60°−70° (obtained from Jansson et al., 2017, 2018) and a 10x10 m bin size (Fig. 5d), we estimate that the maximum non-aliased frequency would be 170 Hz. This is comparable with the sweep frequencies used in the survey (10−150 Hz) and the maximum frequencies (140 Hz) kept in the data after band-pass filtering (Table 2). Given also an average shot spacing of 10 m, we intended to maintain this resolution at the expense of having lower folds, especially for receivers where no co-located shots were possible, like in the mesh area.

Stack, post-stack and migration processing workflow

Velocity analysis was done in several iterations to find the optimal root mean square velocity for the stacking. The initial focus was on shallow reflections and deeper continuous reflections so that accurate reflection residual static corrections could be calculated. Normal moveout (NMO)-corrected gathers were used iteratively, at every five CDPs inline, to obtain surface-consistent reflection residual statics.
FIGURE 7  (a) Example of a raw shot gather along P2 after (b) mixed 2D and 3D static corrections, and (c) band-pass, band-stop, median filters, surface-consistent deconvolution and top mute. Note the increase in the quality and especially the coherency of reflections R1, R2 and T1, marked with black arrows. The 50-Hz harmonic noise is quite notable in the raw data and especially along P8 where the profile is entirely under the power line.

statics (two rounds) before stacking the data. After generating the unmigrated stacked volume, a coherency filter (FXY-Deconvolution) was applied to suppress uncorrelated noise and improve the continuity of the reflections. This filtering can introduce artefacts given the sparsity of the dataset, especially in regions of low fold. To limit this, a post-stack band-pass filter was applied to the data, and an FK filter (45° dip) was applied in those CDPs in the inline direction, highlighting reflections in the first 200 ms, but also some surface waves. Therefore, to attenuate them, the data were resorted to crossline and the remaining surface-wave noise was FK filtered (Fig. 9). We used a finite-difference algorithm.
FIGURE 8  (a) Example of a raw receiver gather at station 11221 in the mesh area (Fig. 1), (b) after mixed 2D and 3D static corrections, and (c) band-pass, median filters, surface-consistent deconvolution and top-mute. Note the increase in the quality and especially the coherency of the reflections T1, R1 and R2, marked with black arrows. The inset map shows the receiver (grey dot) and shots (red dots) locations.

for the migration followed by a time-to-depth conversion (Fig. 10) using a constant velocity of 6000 m/s, which corresponds to the average velocity of the sonic logs as reported in Gil et al. (2021) and shown in Figure 3. Given the sparse nature of the 3D survey and irregular fold and offset–azimuth coverage, we observe reduced reflectivity amplitude after the migration that is a major drawback of 3D sparse datasets and not a problem with migration or velocity used.

RESULTS AND INTERPRETATION

To interpret reflection seismic data, it is essential to have an idea of the size of the structures that can be resolved with the acquisition parameters used in the survey. The dominant frequency of the Zinkgruvan 3D seismic data is about 60–80 Hz. Using the Rayleigh quarter-wavelength criterion (Widess, 1973) for an assumed average P-wave velocity of
Subsurface structures are well imaged in the unmigrated and migrated stacked volumes from ∼150 ms down to 1000 ms. The unmigrated 3D volume reveals several steeply-dipping reflections, some of which are possible to relate to known geology. For this purpose, the available borehole data (density and P-wave logs; Gil et al., 2021) together with their calculated synthetic seismograms (Fig. 3) were used to identify key geological events on the seismic volume. To be consistent with the previous seismic studies in the area, we use the same reflection nomenclature.

**Unmigrated 3D seismic volume analysis**

For a better interpretation of the reflections avoiding potential artefacts due to the sparsity of the data, it is useful to first analyse the unmigrated stacked volume. In Figure 9, we present a series of slices through the unmigrated cube: a crossline section (1103) and an inline section (1060), together with a time slice (260 ms). The crossline section (Fig. 9a) shows some horizontal and sub-horizontal reflections. The first set of high-amplitude reflections are in the first 200-CDP inline, between 140 and 200 ms (R1). It dips to the east between CDPs inline 1050 and 1150 and then to the west between the CDPs inline 1150 and 1225. This first reflection is observed as discontinuous due to the low fold at the first 500 m depth (∼165 ms) in the eastern part of the study area (Fig. 6). The same strong amplitude reflection is observed in the inline section (Fig. 9b). The R1 reflection appears sub-horizontal in the first 125-CDP crossline, between 140 and 200 ms, with a gentle dip towards the north after the 1100 CDP crossline. Deeper down, one can observe the R2 reflection, which consists of two shorter segments previously labelled as R2 and R2′ by Gil et al. (2021). R2 is more continuous along the crossline section (Fig. 9a) and clearer in the first 125-CDP inline (200–300 ms). R2 can also be observed between 1175 and 1250 CDP inline (300–400 ms) presenting a gentle dip towards the east defining an overturned synformal structure. The low fold in the middle of the survey in the first 1250 m depth (∼420 ms) could explain why the R2 reflection is not clearly observed between 1125 and 1175 CDP inline (Fig. 6). In the inline section (Fig. 9b), the R2 reflection is observed as slightly concave-upwards or synformal reflection with the apex/hinge around the CDP 1150 crossline. This could indicate that the shallower R1 reflection presents a similar response, but due to the low fold, it is not possible to observe it in the first 300 ms. In Figure 9(c), we present a time slice at 260 ms, where R2 is observed striking NW–SE between CDP inline 1025 and 1060, and CDP crossline 1080 and 1120. A more diffuse reflection, striking SW–NE is observed between 1150–1200 CDP inline and 1140–1160

<table>
<thead>
<tr>
<th>TABLE 2</th>
<th>Main processing steps and parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Read 30 s uncorrelated SEG data resample to 1 ms</td>
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<tr>
<td>2</td>
<td>Cross-correlate with the theoretical sweep</td>
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<tr>
<td>3</td>
<td>Vertical stacking of the repeated 3 shot records (2 s output for processing)</td>
</tr>
<tr>
<td>4</td>
<td>Extract and apply geometry (CDP bin size of 10 by 10 m after several tests)</td>
</tr>
<tr>
<td>5</td>
<td>Inspect data quality and inconsistency, correct for bad positions and elevations using LiDAR data</td>
</tr>
<tr>
<td>6</td>
<td>Trace editing: remove dead and noisy traces</td>
</tr>
<tr>
<td>7</td>
<td>Pick first breaks</td>
</tr>
<tr>
<td>8</td>
<td>Refraction static corrections: (mix of 2D and 3D used), datum 120 m and replaced velocity of 5500 m/s</td>
</tr>
<tr>
<td>9</td>
<td>Remove 50-Hz noise (only selected receivers)</td>
</tr>
<tr>
<td>10</td>
<td>Band-stop filter: 47–49–51–53 Hz</td>
</tr>
<tr>
<td>11</td>
<td>Band-pass filter: 25–40–110–140 Hz</td>
</tr>
<tr>
<td>12</td>
<td>Median filter (3000 m/s, 2000 m/s)</td>
</tr>
<tr>
<td>13</td>
<td>Wiener gapped deconvolution (Filter length: 200 ms; gap length: 16 ms)</td>
</tr>
<tr>
<td>14</td>
<td>Top front mute using first arrivals</td>
</tr>
<tr>
<td>15</td>
<td>Trace balance and AGC (250 ms)</td>
</tr>
<tr>
<td>16</td>
<td>Velocity analysis (iterative): every fifth inline</td>
</tr>
<tr>
<td>17</td>
<td>Residual reflection static corrections: two rounds</td>
</tr>
<tr>
<td>18</td>
<td>Normal moveout corrections (NMO): 40% stretch mute</td>
</tr>
<tr>
<td>19</td>
<td>Stack (normal)</td>
</tr>
<tr>
<td>20</td>
<td>Post-stack coherency enhancement (FXY_Deconvolution)</td>
</tr>
<tr>
<td>21</td>
<td>Trace balancing</td>
</tr>
<tr>
<td>23</td>
<td>FK (frequency–wavenumber) filter (one dip of 45°) targeting strong surface waves remained in the inline direction</td>
</tr>
<tr>
<td>24</td>
<td>Migration: Finite difference using a constant velocity 6000 m/s</td>
</tr>
<tr>
<td>25</td>
<td>Time-to-depth conversion using 6000 m/s</td>
</tr>
</tbody>
</table>

6000 m/s, the vertical resolution is estimated to be on the order of 20–25 m. On the other hand, the lateral resolution depends on the target depth (Chopra et al., 2006). At 500 m depth, the lateral resolution for the Zinkgruvan dataset is approximately 160 m, while at 1000 m depth it will be of 225 m length. This frequency range will allow us to interpret the host rock of the mineral deposit, and in some cases the mineralization zones, as shown in Figure 3. After applying the processing workflow specified in Table 2, the unmigrated stacked volume was interpreted. It is, however, important to note that smaller features with sufficient seismic contrast can still be detected as reflections but unresolved (thickness and lateral extent).
Figure 9 A series of slices extracted from the unmigrated stacked volume. (a) Crossline 1103, (b) inline 1060, (c) time slice at 260 ms and (d) CDP fold plot showing the locations of the slices. Several horizontal and sub-horizontal (in the crossline) and north dipping (in the inline) reflections are notable. In the crossline section, all the observed reflections are sub-horizontal or synform-shaped. On the other hand, in the inline section, almost all the reflections present a dip towards the north, apart from R2, that is observed as a concave-upward reflection. R1 and R2 are also observed in the time slice (a) CDP crossline, which corresponds to R1 reflection. These observations led us to assume that R1 and R2 reflections tend to dip towards the east.

T1, a sub-horizontal to slightly antiformal reflection in the crossline section (Fig. 9a), is observed in the first 175-CDP inline at 600–800 ms, while in the inline section (Fig. 9b) T1 presents a dip towards the north, between 600 and 900 ms. This agrees with previous observations and travelt ime forward modelling results from Gil et al. (2021), where T1 and T2 (not shown in this work) have slightly different strike and dip than R1 and R2 reflections. Those observations led them to assume that R1–R2 and T1 reflections present a different origin, something that we will disprove next thanks to the 3D dataset allowing this. Finally, in the inline section, some reflections are observed between R2 and T1. Those correspond to the R4 reflection, previously identified and described by Gil et al. (2021).

3D analysis of the geological structures from time-depth sections

Figure 10 presents the same slices as Figure 9 but extracted from the migrated and time-depth-converted stacked volume. In the migrated slices, it is possible to observe the same three main reflections, namely R1, R2 and T1. They show a gentle to strong dip towards the north–northeast, although they also depict a synformal geometry in the crossline section (Fig. 10a). The hinge of that synform is located at CDP1150 inline for R1, CDP1200 inline for R2 and CDP1110 inline for T1.

The character of reflections R1, R2 and T1 is similar. Assuming they are imaging the impedance contrasts between the Zinkgruvan Formation and the layers on its top (Vintergölen Fm) and bottom (Mariedamm volcanic unit), their geometry could represent that of a couple of E-vent...
isoclinal folds later deformed by a mild N-S synform. In the NS (inline) section, these reflections dip to the N, suggesting that yet another deformation stage affected the area and an EW recumbent antiform controls the observed dip of reflections. This geometry is depicted in Figure 10(d) and coincides with that suggested by the map in Figure 1 where folding interference is key. Although the dip of reflections R1, R2 and T1 is different, as already suggested by Gil et al. (2021), the overlapping of deformation phases shifts the hinge of the fold depending on the limb of the previous fold, something that can also be observed in Figure 10(d). In fact, the location of the hinge for the synform defined by reflections R1 and T1 is located around CDP1150 inline, whereas that of reflection R2 is shifted to the east (CDP1250 inline).

Figures 11 and 12 present additional slices from the 3D volume to better interpret the 3D geometry of the reflectivity. The setup of reflections R1, R2 and T1 indicates that the hinge of the synform and the layers themselves dip around 25°–70° towards the north–northeast, as observed locally on the surface geology (Fig. 1). However, there is no evidence of any reflection like R1, R2 or T1 to the north of CDP crossline 1200. This could be related to the scarcity of shot points on the eastern part of the survey area (Figs. 1 and 5d) or to the existence of the Knalla fault. From the surface geology and the fold coverage maps (Figs. 1 and 6), we know that the Knalla fault crosses the seismic survey around CDP inline 1180 (Fig. 11a) partly explaining the lack of reflectivity to the east of this CDP in the crossline sections. Previous studies (Jansson et al., 2017) have identified the Knalla fault as a NS strike–slip feature with an E–SE 70° dipping, which occurs near the hinge of a moderately N–NE-plunging fold (Fig. 1). The results presented in Figure 11 agree with Jansson et al. (2017, 2018) observations, although the identified fold is observed as a synform in the centre of the study area. Finally, lack of R1, R2 and T1 reflections north of CDP crossline 1200 might respond to the structure in this area.
FIGURE 11  (a) Several crossline sections, from south to north, and (b) inline sections, from migrated seismic volume showing a multiple set of strong reflections interpreted to be associated with the Zinkgruvan Formation. The crosslines and in-lines mark the length and extension of reflections R1, R2 and T1. Note how reflection R1 becomes more energetic towards the north. R2 is also more energetic towards the north and the east. Reflection T1, however, loses its continuity towards the north. Mark with a small black arrow is the intersection with the Knalla fault. Note that on the east side of the Knalla fault, there is no clear reflectivity.
where the northern limb of a north-vergent isoclinal synform takes Zinkgruvan Fm to the surface, also wedging to the Mariedamm volcanic unit to the west. Furthermore, the mineralization is never continuous, and lack of reflectivity might always respond to an irregular distribution of the mineral zone.

**Constraints from time-depth slices**

For a better interpretation of the continuity of the reflections laterally and at depth, several time-depth converted time slices from the 3D seismic cube were extracted and are shown in Figure 12. R1 reflection is observed in the southwest side of the study area, between 460 and 540 m depth (Fig. 12a–b), and at 730 and 800 m depth (Fig. 12c–d) in the central part of the study area and featuring a gentle change of orientation. These observations were anticipated by the 2D reflection seismic work by Gil et al. (2021) where they determined the R1 reflection between 730 and 800 m and R1’ as an out-of-the-plane reflection.

The R2 reflection is observed as a 70-m thin reflection (Figs. 11 and 12c–d) in the southwest part of the survey while towards the north it becomes thicker, up to 400 m (Figs. 10 and 11). There, R2 reflection is observed between 1000 and 1500 m (Figs. 10 and 11). This feature was previously defined as the R1 reflection by Gil et al. (2021) as they both presented a similar amplitude and reflective character. The acquisition of this sparse seismic dataset has allowed to observe the geometry of the R2 reflection thus constraining the relation between R1 and R2: they represent the same mineralized horizon affected by isoclinal folding and then refolded as a synform (Fig. 10d). T1 is not observed until 1800 m depth (600 ms) and can be followed to 2200 m (approximately 400 m thick). Gil et al. (2021) determined from their forward modelling that T1 dips towards the north. However, the time-depth converted time slices (Fig. 12e–f), help to redefine its dip as northeast, like the R1 and R2 reflections. Furthermore, as aforementioned, the T1 presents similar amplitudes and reflective energy as R1 and R2, which led us to assume that the three reflections (R1, R2 and T1) could represent the same isoclinal folded layer (Fig. 10d).

Again, time slices show that the above-mentioned reflections do not present continuation after the 1200 inline CDPs, as a result of the structure, the position and kinematics of Knalla fault (Fig. 1) or the irregularity of the mineralization. Jansson et al. (2018) analysed some borehole data from the Zinkgruvan mining area, and some of them crossed the Knalla fault at different depths (boreholes 1697, 1341 and 1458; Jansson et al., 2018). From their analysis, they observed that the greatest geological variation and the most important Zb–Pb mineralization is westwards of the Knalla fold, while to the
FIGURE 13 Various 3D views of the migrated crossline and inline sections of the 3D seismic volume, together with the current model of the top of the prospective Zinkgruvan Formation (green), the in-mine structures (yellow), and some boreholes in the Zinkgruvan mining area. Observe how R1 and R2 reflections broadly mark the top of the modelled prospective formation, at shallow and greater depths. It is also possible to observe how the Zn–Pb mineralization on the borehole data (marked in red) matches with the R2 reflection.

east only the migmatites and gneiss of the Vintergölen Formation are observed (Fig. 2), which would explain the decrease in the reflectivity in the eastern part of the crossline sections. The Vintergölen Formation hosts pyrrhotite mineralization (FeS; Jansson et al., 2018; Gil et al., 2021), and, therefore, presents some reflection response, as previous downhole log studies showed (Gil et al., 2021). Therefore, some reflections may be expected given that their size and impedance contrast is visible to the present dataset. Also, the available geological information (Fig. 1) indicates that the Zinkgruvan Fm is observed eastwards of the fault. But, unfortunately, as there are no available boreholes in that area, it is difficult to determine how thick this formation is eastwards of the Knalla fault. Further borehole data and geological analysis east of the Knalla fault could be beneficial for a better understanding of the geological structures of the Zinkgruvan mining area, although the current experiment does not provide an important reflective response in the sampled area.

The 3D seismic cube shows three main reflections (R1, R2 and R3) that have been interpreted as the limbs of two isoclinal folds affecting the Zinkgruvan Formation. They are further folded by an NS synform also observed in the map of Figure 1. At the southwest of the study area, the R1 and R2 reflections have been observed between 460 and 800 m depth (Figs. 10–12). The same reflections are observed at greater depth towards the central north of the seismic surveyed area (Fig. 11) defining the hinge of the synform. The shallowest reflections, located at the southwest of the study area, seem to represent the apex of an antiform, while towards the north–central part, we observed how all three reflections present a concave-upwards shape, allowing us to determine the hinge of a synform. Further to the east and north, all reflections seem to be terminated, something that has been associated to the deformation patterns, the presence of the Knalla fault and the heterogeneity of the mineralization (Fig. 10d). By analysing the geometry of the different reflections, we can interpret two EW folds that have been affected by a later NS folding event (Beunk & Kuipers, 2012). We hypothesize that east of the Knalla fault is located the Godergård volcanic unit or even the Närkesberg Formation (Fig. 2). Considering that in the Emme Group, there are found the Marketorp deposit and Zinkgruvan deposit (Kumpulainen et al., 1996; Stephens et al., 2009; Jansson et al., 2017), and the deformation stage that affected the area, if such hypothesis were right, then one might consider that at great depth the Zn–Pb mineral lineaments, could be associated with other ore lineament in the middle of the Emme Group.

Zinkgruvan potential mineralization

One of the goals of the survey was to determine the location of further potential mineralized zones to define exploration targets. For an optimal 3D interpretation, we combined the available downhole data (density logs) (Fig. 1), a model of the top of the prospective Zinkgruvan Formation (provided by
Zinkgruvan Mining AB) and the 3D seismic cube (Fig. 13). Gil et al. (2021) correlated the downhole logs BH2710 and BH2726 along P1 and P2 seismic lines, and they determined that the R1 (and R1’) reflection is likely related to the prospective horizon along the Mariedamm volcanic unit and the Zinkgruvan Formation boundary. The Zinkgruvan Formation surface model also correlates R2 (1000–1500 m depth) with the Zn–Pb–Ag–(Cu) mineralization. The downhole log BH4321 (Figs. 1 and 3), obtained in the mine at 600 m below the surface, has provided information of the physical properties of the ore mineralization at 1450 m depth (825–850 m length). This allowed us to convey that the R2 reflection has associated mineralization lineaments. Also, from the analysis of the downhole logging data, and later the calculated synthetic seismograms, we know that the most energetic reflection responses are associated with the Zn–Pb mineralization (Fig. 3). In the R2 case, the tectonic pattern would imply that reflectivity is given by the impedance contrast between the Vintergölen Fm and the Zinkgruvan Fm, although the latter would be in top of the Mariedamm volcanic unit, then providing similar reflections coefficients than those giving R1. Finally, reflection T1 represents the same limb as reflection R1 and, accordingly, would be also associated with the Mariedamm volcanic unit and Zinkgruvan Fm boundary (see Fig. 10d). The R2 reflection, which is associated with the strongest amplitudes and correlates with the prospective horizon (Fig. 13), could be related to a section in the Zinkgruvan Formation with a higher sulphide concentration. In Figure 10(d), it is possible to observe how R2 reflection, and therefore the Zinkgruvan Formation in the overturned limb, is less affected by the Knalla fault, which could explain its strongest amplitudes and penetration along the seismic cube.

As mentioned previously, zones thinner than 25 m will not be resolved in this seismic dataset, while the horizontal resolution would depend on the depth of the target (Chopra et al., 2006). The R1 reflection associated with the Zinkgruvan Formation is likely larger (lateral extent) than 160 m, while the R2 reflection at 1500 m depth is larger than 275 m. The strong reflection at 1500 m depth (R2, Figs 10–13) could be associated with a mineralized zone and its host rock. However, considering the formation of the SAS-type deposits (Allen et al., 1996), one can assume that those thick seismic reflection packages are associated with barren rocks, or with an intercalation of mineral-bearing units in its host rock with different rock types (Figs. 2 and 3).

CONCLUSIONS

This study demonstrates that 3D seismic surveys, even if sparse, with the combination of downhole data and 3D in-mine structures, is useful for the identification and interpretation of prospective horizons, in complex geological settings like in Bergslagen. The combination of the 2D and 3D refraction statics, the median filters, to attenuate surface waves, and the use of the FK filter, on the CDP inline and CDP crossline, were important steps in obtaining good quality final 3D seismic cube. The analysis of the CDP folds at depth, considering a constant velocity of 6000 m/s, like the one applied in the migration and the depth conversion, helped the interpretation of reflections in the stacked volume in low fold regions. We have been able to obtain a subsurface interpretation of the potential mineral-bearing rocks and providing an idea for the geological deformation in the area. The EW overturns folds, affected by the later NS fold, seems to influence the dimension of the mineral deposits (and its host rocks). The Zinkgruvan Fm is over-folded, and the seismic responses appear thicker near the Knalla fault. At the centre of the study area, the reflections present a higher continuity and penetration, because of the overturn synform, and they seem to be terminated by the Knalla fault. Shallow reflections comprising the overturn antiform in the southwest are observed to be narrow. Even so, there are still uncertainties about the formations and geometries east of the Knalla fault, and potential mineral deposits at the middle of the Emme Group.

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DATA AVAILABILITY STATEMENT

The data that support the findings will be available in Swedish National Data Service at https://snd.gu.se/en
following an embargo from the date of publication to allow for the commercialization of research findings.

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