Case History

Innovative seismic imaging of volcanogenic massive sulfide deposits, Neves-Corvo, Portugal — Part 1: In-mine array

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ABSTRACT

To evaluate and upscale the feasibility of using exploration tunnels in an operating mine for active-source seismic imaging, a seismic experiment was conducted at the Neves-Corvo mine, in southern Portugal. Four seismic profiles were deployed in exploration drifts approximately 650 m beneath the ground surface, above the world-class Lombador volcanogenic massive sulfide deposit. In addition to the tunnel profiles, two perpendicular surface seismic profiles were deployed above the exploration tunnels. The survey was possible due to a newly developed prototype global positioning system (GPS) time transmitter enabling accurate GPS synchronization of cabled and nodal seismic recorders, below and on the surface. Another innovative acquisition aspect was a 1.65 t broadband, linear synchronous motor (LSM) driven — electric seismic vibrator (e-vib) used as the seismic source along two of the exploration tunnels. We have evaluated the challenges and innovations necessary for active-source tunnel seismic acquisition, characterized by high levels of vibrational noise from the mining activities. In addition, we evaluated the LSM vibrator’s signal and overall seismic-data quality in this hard rock mining environment. Our processing results from the tunnel data and 3D reflection imaging of the Lombador deposit below the exploration tunnels were checked for consistency through constant-velocity 3D ray-tracing traveltime forward modeling. For imaging purposes, 3D Kirchhoff prestack depth and poststack time-migration algorithms were used, with both successfully imaging the targeted deposit. The results obtained show that active-source seismic imaging using subsurface mining infrastructure of operational mines is possible. However, it requires innovative exploration strategies, a broadband seismic source, an accurate GPS-time system capable of transmitting GPS-time hundreds of meters below the surface, and careful processing. The results obtained open up possibilities for similar studies in different mining or tunneling projects.

INTRODUCTION

Geophysical methods have successfully been used for mineral exploration and prospecting on mining camps and regional scales, in green and/or brownfield areas, for more than half a century (Reid et al., 1979; Reed, 1993; Eaton et al., 2003; Dentith and Mudge, 2014; Malehmir et al., 2014, 2020; Buske et al., 2015; Haldar, 2018; Essa and Munschy, 2019). Although the combination of field...
geology, geochemistry, drilling, and different geophysical methods (ground or airborne) has led to numerous discoveries, there is still a great need for innovation and improvement of the present exploration strategies, especially for in-mine purposes. This need is largely driven by an overall increasing demand for metals and increased requirements for sustainability of the raw materials chain to sustain the developing economies and a shift toward green technologies (Arndt et al., 2017; Malehmir et al., 2019a, 2020). Another factor requiring innovative exploration is the need to refocus on exploration depths below 800 m and deeper, given that shallow-seated mineral deposits are considered to have been mostly explored and exploited (Milkereit and Eaton, 1998; Cheraghi et al., 2012; Arndt et al., 2017; Schodde, 2019a, 2019b, 2020; Malehmir et al., 2020). Seismic methods maintain a good vertical resolution with depth and, therefore, have been used more routinely for localizing mineral deposits and mine planning in the past few decades. They are now gaining even more attention with exploration targeting at greater depths and due to the advances in processing algorithms and computing power (Eaton et al., 2003; Urosevic et al., 2007; Malehmir et al., 2012; Bellefleur et al., 2019).

Considering that a vast number of the planet’s mineral wealth is hosted in crystalline or hardrock environments with often complex geologic and tectonic settings, seismic exploration in such areas is a challenging task. Exploration targets in these terrains are frequently found in dipping, or even steeply dipping, structures in which low impedance contrasts to the surrounding rocks are common. Seismic imaging of such targets is characterized by poor lateral coherency of reflections or effects such as diffractions, scattering, or mode conversions related to different geologic units and geometries (Bellefleur et al., 2004, 2019; Malehmir and Bellefleur, 2010; Ahmadi et al., 2013; Buske et al., 2015). In addition to the aforementioned, seismic exploration is commonly conducted in brownfield areas, where mining and anthropogenic noise can significantly reduce the data quality. Further complexities and restrictions are introduced if underground spaces (e.g., exploration galleries and drifts, mining stopes) are used for seismic or other exploration purposes. The nature of these spaces imposes numerous limitations, resulting in conventional active-source seismic imaging being rather difficult, size-limited (small scale), or even an impossible task. Logistical challenges related to active mining operations, strong vibrational noise, combined with GPS-denied nature of underground spaces preventing accurate time synchronization, are just some factors that have restricted in-mine exploration primarily to drilling. Most in-mine seismic exploration has been connected to petrophysical studies or vertical seismic profiling (VSP) surveys inside or in the near vicinity of boreholes (seismic side scans), or more recently with fiber-optic systems (Greenhalgh et al., 2000, 2003; Cosma et al., 2005, 2007; Enescu et al., 2011; Wood et al., 2012; Riedel et al., 2018). From the perspective of in-mine seismic studies, a limited number of publications can be found in which the mine tunnels and galleries have been used for passive seismic purposes (Olivier et al., 2015a, 2015b; Olivier and Brenguier, 2016) or crosshole/cross-drift seismic tomography studies with a limited number of receivers (Gustavsson et al., 1984; Sinadinovski, 1994; Sinadinovski et al., 1995; Greenhalgh et al., 2003; McDowell et al., 2007). However, the aforementioned restrictions have thus far limited the use of conventional 2D/3D reflection seismic methods beneath the surface of active mines to similar scales as those used in surface surveys.

To cope with imaging challenges in mineral exploration and mining, the EU-funded Smart Exploration project was established with the aim of advancing innovative geophysical imaging techniques and instrumentation (Malehmir et al., 2019a). Within the project, a pioneering seismic survey was conducted at the active Neves-Corvo mining area in Portugal where two developed prototypes were tested: a GPS-time transmitter providing GPS-time signal in GPS-denied environments, i.e., tunnels, underground spaces (Malehmir et al., 2019b), and a seismic vibrator driven by linear synchronous motors (LSMs) (Noorlandt et al., 2015; Brodic et al., 2019, 2021). Together with seismic receivers deployed along exploration tunnels approximately 650 m below the surface and along two perpendicular profiles at the surface, the two were taken underground, enabling simultaneous data acquisition in a tunnel-to-surface survey setup. Although the nature of the data allows for various approaches to data handling, here we primarily focus on the acquisition challenges and innovation aspects required to acquire the data set. In addition, we analyze the data set’s potential for 3D in-mine seismic imaging of the Lombador deposit below the exploration tunnels, focusing only on the tunnel portion of the seismic spread.

GEOLOGIC SETTING

The seismic experiment was conducted at the Neves-Corvo mine seated in the Iberian Pyrite Belt near Castro Verde, southern Portugal, hosting world-class volcanogenic massive sulfide (VMS) deposits. The VMS deposits of the Neves-Corvo mine are considered Tier-1 (>100 Mt or a deposit that is large, long-life, low cost, and expandable) and presently comprise seven known deposits (Neves, Corvo, Graca, Lombador, Zambujal, Semblana, and Monte Branco; Carvalho et al., 2013; Figure 1). The stratigraphy of the Neves-Corvo region (e.g., Oliveira et al., 2004, 2013, 2016, 2019) includes the three following main geologic formations, from bottom to top: the middle Givetian to late Famennian age Phyllite-Quartzite (PQ) Group, with the base unknown (see Mendes et al., 2020), the Famennian-Visean volcanic-sedimentary complex (VSC) hosting the VMS deposits, and the middle-late Visean Mértola Formation. The PQ basement is characterized by quartz sandstones, shales, and conglomerates capped by thin carbonate shelf deposits representing the basement unit. The VSC is classically divided into an allochthonous (upper) and an autochthonous (lower) sequences separated by the so-called Neves-Corvo main thrust. The former Upper VSC is composed from the top to bottom by the Brancanes Formation (black shales with disseminated pyrite), the Godinho Formation (volcanogenic sediments and gray siliceous shales), the “Borra de Vinho” Formation (purple and green shales), the Grandas Formation (black shales with carbonate lenses and nodules), and the Graça Formation (black graphic shales and gray siliceous shales) with basic intrusive rocks and interbedded felsic volcanic rocks (Oliveira et al., 2013). The autochthonous Lower VSC includes a jaspers and carbonates unit that represents the massive sulfide horizon’s hanging wall, followed by the Neves Formation (black pyritic shales) that is ultimately underlain by the Corvo Formation (black shales with tuffs and breccias) that conformably lies on the top of the PQ basement.

The Mértola Formation is a thick Flysch sequence composed mostly of intercalations of graywackes and dark gray shales (Oliveira et al., 2004, 2013). The study area is characterized by two VSC antiform structures (Rosário-Neves Corvo and São Pedro das Cabeças; e.g., Oliveira et al., 2013, 2016) surrounded by vast
areas of outcropping Mértola Formation flysch sediments. The area is tectonically characterized by southwest-verging thrust sheets (e.g., Inverno et al., 2015), such as, for example, the Neves-Corvo main thrust that separates the VSCs, and all are affected by Late Variscan near-vertical strike-slip faults with a predominant southwest–northeast and north–south strike (Figure 1).

The primary target of our study is the lens-shaped 30°–35° northward-dipping Lombador deposit, above which the tunnel seismic profiles were positioned. The Lombador (approximately 150 Mt) is essentially represented by Zn-rich massive sulfides underlain by Cu-rich stockwork, with the last being mostly hosted by PQ quartzites and shales. Of all the deposits at the Neves-Corvo, Lombador is the one that shows less developed footwall VSC, being that the massive sulfides are almost in direct contact with PQ rocks stratigraphically below. Chalcopyrite and sphalerite are the main productive minerals within the locally up to 140 m thick deposit (Carvalho et al., 2013). Details on the broader scale geologic and tectonic setting of the Lombador and other deposits can be found in, e.g., Carvalho et al. (2013), Oliveira et al. (2013), Yavuz et al. (2015), West and Penney (2017), and Donoso et al. (2020).

INNOVATIVE DATA ACQUISITION

Seismic data used in this study were acquired using a dual-element seismic spread involving GPS-time-dependent cabled and nodal seismic receivers. The first parts of the spread were 453 seismic receivers deployed along four exploration tunnels (or drifts) approximately 650 m below the surface. Given that Neves-Corvo is an active mine, operating seven days a week, 24 h a day in three shifts and with three blasts daily, all activities inside the mine have to be well synchronized, controlled, and approved by the head mining office. To minimize interference with the mining operations, the seismic profiles were positioned 650 m below the surface in the ventilation tunnels located directly above the Lombador deposit. These tunnels are also used for down-dip drilling; hence, they are sometimes referred to as exploration tunnels. During two deployment days, seismic receivers were distributed along four profiles in the exploration tunnels, namely, GP2, GP3, GP4, and GV5. The tunnel seismic spread consisted of cabled seismic receivers, a 3C microelectromechanical system (MEMS)-based seismic landstreamer (Brodic et al., 2015, 2018; Malehmir et al., 2017; Kammann et al., 2019), and 1C wireless seismic receivers — nodes. Cabled receivers were connected to 10 Hz, and nodal receivers were connected to 4.5 Hz vertical geophones. Similar to an earlier study reported in Brodic et al. (2017), geophones were vertically planted in holes made on the side walls of the tunnels, whereas the landstreamer was deployed along the tunnel floor. Seismic profiles GP2, GP3, and GV5 were acquired using cabled geophones spaced 5–6 m. Data acquisition along GP4 involved 70 cabled geophones 5 m apart on the northern side, the MEMS-based landstreamer (100 MEMS sensors with 2 m and 20 with 4 m spacing) in the middle, and 30 nodal receivers 5 m spaced on the southern portion of the profile. The second part of the seismic spread consisted of two crossing seismic profiles (oriented north–south — SP6 and east–west — SP7), deployed at the surface above the tunnel profiles using nodal receivers connected to 4.5 Hz vertical component (1C) or 3C geophones. Apart from the main prototype seismic vibrator source evaluated in this study and used underground, a 250 kg accelerated weight drop (AWD) was activated and recorded on only the surface seismic profiles. The details of the surface source data acquisition are reported in the accompanying paper by Donoso et al. (2021). A 3D overview

![Seismic imaging of VMS deposits — Part 1](image)

Figure 1. A geologic cross section (A–B), constrained by boreholes, through the Lombador and Neves VMS deposits. Different deposits represent different feeder zones that were active within the same paleobasin. Due to several thrust faults, the deposits are displaced to different levels and show various dips and characteristics. Modified from Donoso et al. (2020), courtesy of Somincor. The numbers shown on the left portion of the cross section correspond to the different mining levels (in meters), with 1200 being relative to the mean sea.
of the survey elements, together with the site’s infrastructure and model of our exploration target — the Lombador deposit, is shown in Figure 2. Receiver positions inside the tunnel and on the surface were accurately surveyed using a theodolite system connected to the nearest reference point with an estimated coordinate accuracy of ±25 cm. All tunnel profiles were actively recorded and quality controlled (except for 30 autonomous nodes along GP4), whereas the nodal receivers along the surface profiles operated in an autonomous mode.

Prototype GPS-time transmitter

The entire tunnel data acquisition survey was facilitated by a newly developed prototype GPS-transmitter (Malehmir et al., 2019b) providing accurate GPS time in GPS-denied environments such as tunnels/drifts and/or boreholes. The prototype was designed to transmit simulated microsecond accuracy GPS-time signals to a single recording unit or an array of recorders (seismic and electromagnetic) placed in different tunnels and at different depths. It was built using readily available components (off the shelf) and consists of a primary and a replica unit. The primary unit feeds the main recording system (single point transmission), whereas the replica relays the signal to other GPS-dependent systems (distributed transmission; e.g., nodal receivers and secondary acquisition). The two are interconnected via fiber-optic cable, minimizing the GPS-time signal attenuation for longer sensor arrays or at different mining level depths. The replica is only used if the GPS signal needs further transferring at distances greater than approximately 10 m radius from the primary. The entire primary-replica assembly is ruggedized for harsh conditions, is easy to set up and operate, and has accessories with weights of approximately 30 kg. Figure 3a shows an overview of the individual components of the GPS transmitter. At the beginning of the survey, the primary unit’s base station (used to discipline the internal clock from GPS satellites) is established at the surface. Prior to taking the GPS transmitter underground (at the start of every acquisition day), the primary unit’s internal clock GPS time is updated at the base station using the available satellites. Following this, the unit is taken underground and the GPS signal is transmitted to either a single point using an antenna or is connected to the replica for further distribution.

At the end of every acquisition day, the primary unit is taken back to the base station to update its internal clock and log the GPS-time drift (the difference between the satellite-based and the transmitted GPS time). The procedure is repeated daily until the end of the survey. Figure 3b shows the daily time drifts for the Neves-Corvo site survey. The bar length corresponds to the operation (data acquisition) time in hours, for a specific acquisition day. The bold numbers along the bars show the average GPS-time drift per hour in microseconds, and the numbers on the top of the bars correspond to the total drifts (in microseconds) during data acquisition for a specific day. Considering the sampling rates of active-source field seismic experiments on the ms order, Figure 3b shows that the accuracy achieved within a two-shift operation time (15–18 μs) is more than sufficient for such experiments. By using the GPS time provided by this prototype as a common reference, we were able to simultaneously record data in the tunnel and on the

Figure 2. A 3D overview of the location of the Neves-Corvo seismic spreads and mine drifts, relative to the Lombador and Neves deposits. Key spread features are marked with arrows, along with an aerial photo projected onto the digital elevation model (DEM). The orange color represents nodal receivers inside the tunnel and on the surface. The lightly shaded blue color corresponds to the geophone, and the darker shaded blue corresponds to the MEMS landstreamer portion of the tunnel seismic spread.

Figure 3. (a) Overview of the individual components of the prototype GPS-time transmitter with 1. the primary unit; 2. the laptop controlling the primary unit; 3. the primary unit’s GPS antenna amplifier; and 4. the replica unit with individual components. (b) GPS-time drifts (difference between satellite-based and transmitted GPS time) for individual acquisition days during the Neves-Corvo experiment. The left axis shows the time during the day, and the bottom axis corresponds to the acquisition date and the bar length transmitter’s operation time (acquisition time) for individual acquisition day. The numbers along the bars represent microsecond drifts during the entire operation (top) and on an hourly basis (middle, bold). For a two-shift operation time, a 15–18 μs drift is logged, and these might be regarded as negligible for ms-order seismic sampling/time stamping. Photos by A. Malehmir November 2019.
surface portions of the seismic spread in a tunnel-to-surface survey manner.

**Prototype LSM-driven seismic vibrator**

Using the underground mine infrastructure for active-source seismic surveys implies working in restricted spaces, inevitably imposing limits on the selection of the seismic source. From one perspective, the seismic source selected must be versatile, and it must be easy to transport, operate, and move in different mine tunnels and drifts at the desired depth. This poses a lot of restrictions to the sources that can be used inside the mine, given the need to comply with established mine safety protocols. For example, sources that use gasoline engines, such as some accelerated weight-drop sources, cannot be used inside the mine. Considering the high ambient noise levels of active mines, a desirable feature of the seismic source is the energy excitation in a controllable and repeatable manner across a broad bandwidth with sufficient signal-to-noise ratios (S/N). To address the aforementioned issue, the second prototype used and evaluated was a broadband, LSM-based seismic vibrator — e-vib (Noorlandt et al., 2015; Brodic et al., 2019, 2021). The LSM principle behind the prototype seismic source enables the induction of large forces in a highly controllable manner, particularly in the low-frequency portion of the bandwidth (Noorlandt et al., 2015). The system uses a 14 kW generator to power six synchronized LSMSMs, providing a peak force of 6.7 kN in the vertical direction (P-wave excitation) within a 2–200 Hz frequency bandwidth. A detailed overview of the different characteristics of the LSM-based seismic vibrator can be found in Noorlandt et al. (2015). The source weighs approximately 1.65 t, and its design enables easy attachment to locally available vehicles such as telehandlers. In this survey, a skid steer loader provided by the mine was used as the source carrier. Figure 4a shows an overview of the internal design of the prototype seismic vibrator evaluated, and Figure 4b shows the source attached to the carrier vehicle positioned at one of the source points along a profile of our tunnel seismic spread. The source was used along the entire GP4 profile and a portion of GV5 with source points spaced 5–6 m collocated with the nearest receiver. After a series of tests, a 2–200 Hz, 20 s linear sweep with an additional 8 s of recording time was used for the entire survey. For every source location, four repeated sweeps were made to improve the S/N. Compared with earlier studies dealing with the e-vib evaluation (e.g., Noorlandt et al., 2015; Brodic et al., 2019, 2021), this is the first study in which the e-vib was tested in a hardrock environment, particularly beneath the surface. The prototype GPS-time transmitter enabled a common time reference for downloading data segments corresponding to the individual sweeps from the autonomous wireless nodes, inside the GP4 tunnel and on the surface. The survey parameters and details for every single seismic profile deployed and seismic sources used are summarized in Table 1.

![Prototype LSM-driven seismic vibrator](image)

**Figure 4.** (a) Sketch illustrating the internal design of the prototype LSM-driven seismic vibrator — e-vib used in this study (modified from Noorlandt et al., 2015). (b) Field photo showing a view from the GP4 tunnel toward the north (the northern end of GP4) with the e-vib seismic source and its carrier vehicle at one source location next to the seismic landstreamer. Photo by A. Malehmir February 2019.

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<th>GV5</th>
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**Table 1.** Neves-Corvo tunnel-surface seismic survey acquisition details (February 2019).
TUNNEL-TO-SURFACE AND TUNNEL SEISMIC DATA

The exploration tunnels are usually free from mining activities. However, they are equipped with very strong jet-ventilation systems that serve as air exchangers and fresh-air intakes for the mining levels at different depths. The former and the ongoing mining operations contribute to data quality reduction. In addition to these, there are two massive (100 m³) crushers built inside the mine at two different mining levels, and raise boring started toward the end of the seismic experiment in the GP4 tunnel. Although all of these noise sources are rather strong, the raw seismic data (after crosscorrelation) show relatively good S/N with the first breaks clearly distinguishable on approximately 75% of the tunnel and surface portions of the seismic spread. Figure 5 shows an example of a crosscorrelated shot gather, with the accompanying amplitude spectra for individual spreads inside the tunnels and on the surface. The amplitude spectra of all of the spreads show a bimodal distribution with mostly noise dominating the portions below 50 Hz and the seismic signal, particularly possible reflections, above this frequency. Apart from the clear direct P-wave arrivals shown in Figure 5, the tunnel profiles additionally show clear direct S-wave arrivals, along with other events as marked by the arrows and in the enlarged view. Because the primary interest of the survey was the Lombador deposit located beneath the tunnel profiles, we focus on a detailed analysis of only the tunnel data, excluding the surface-recorded profiles SP6 and SP7.

Identifying the origin of the events marked in Figure 5 or other events in different shot gathers is, however, rather challenging. Numerous side tunnels and corridors along the four exploration tunnels where the seismic receivers were located influenced the recorded seismic wavefield. The geologically complex rocks hosting the tunnels may result in energy contributions coming either from the sides or from above the mining level where the tunnel profiles are located, including wavefield complexities due to the existing infrastructure. Figure 6 illustrates the effect that some of the site’s infrastructural features have on the recorded seismic wavefield on the tunnel seismic profiles. For illustration purposes, the shot gathers are plotted with every trace corresponding to its actual receiver position along individual tunnels in a 3D mine infrastructure model. Only the infrastructure at approximately 650 m depth where the profiles were located is shown, and the depth axis is set equal to the time axis of the corresponding gather. For the particular shot gather shown in Figure 6, the source was located along the GP4 tunnel. Numerous diffractions or back-scattered energy (D1–D4) can be noted and interpreted to correspond to different side drifts. In addition to a clear direct P-wave, the GP4 profile shows strong S-wave arrivals (S1 and S2). Another interesting feature in Figure 6 is the hyperbolic event marked with H1. This event, according to available geologic information, does not originate from any known feature beneath the tunnels. The nature of this event will be discussed further.

Challenges of limited 3D underground seismic acquisition and seismic response of the targeted deposit

Subsurface seismic data acquisition constrained by existing mining infrastructure inherently limits the source and receiver offset-azimuthal coverage, hence affecting the target illumination and the resulting midpoint distribution. The tunnel profiles with source and receivers nominally spaced 5 m and primarily in GP4 resulted in a limited 3D coverage and an imperfect distribution of midpoints. The acquisition limitations restrict target illumination direction, introduce a certain acquisition footprint, and cause an uneven fold distribution. Although the source was used mainly in GP4, the reflection points still fall within a 3D volume than just along a 2D plane following GP4. In addition, with the moderately dipping and folded nature of the target, out-of-the-plane reflections

Figure 5. Example of a raw shot gather and corresponding amplitude spectra (after crosscorrelation and vertical stacking of the four repeated sweeps), recorded on (a) surface and (b) tunnel seismic profiles. The source was located along the GV5 exploration gallery. Apart from direct P- and S-wave arrivals, additional events (possible reflections) can be seen on the tunnel profiles, as indicated by the arrows and in the enlarged view of these events marked with the dashed rectangle in the GP2 profile. For display purposes, a 250 ms long automatic gain control (AGC) window was applied.
Seismic imaging of VMS deposits — Part 1

Guided seismic processing

Table 2 details the processing steps used in this study. Removal of the mining-induced noise along with P- and S-wave direct arrivals’ suppression in the shot gather domain are rather standard steps when dealing with hardrock seismic data in the mining environment. Deconvolution and trace normalization followed the removal of noise, enhancing the coherency of the reflected arrivals that were initially obscured in the shot gathers. Refraction (short- and long-wavelength) and residual and elevation static corrections were applied, but because the first one caused no significant improvements, only the elevation and residual statics were kept in the final processing workflow. A constant velocity of 6.0 km/s was used for the final stacking and afterward migration and time-to-depth conversion.

Prior to stacking and migration, further suppression of the remaining portion of the direct S-wave was made via surgical mute. Special care was taken during the design of the surgical mute to avoid removing significant portions of the reflected energy. The modeling results provided a rough guideline of where the Lombador deposit’s reflection could be expected and were used to validate the images. Figure 8 compares a raw versus processed shot gather (until step 12 in Table 2) with the modeled P- and S-wave direct arrivals, the Lombador deposit P- and S-wave reflections, and the accompanying mode conversions overlaid. The source was located along the GP4 exploration tunnel. Strong direct S-waves entirely mask the Lombador deposit reflection in all of the profiles. The deposit’s reflection becomes prominent only after the suppression of the two direct S-wave arrivals and is mostly visible along the GP4 profile as a dipping event at approximately 100 ms, following the modeled P-P reflection traveltimes (indicated by the arrows in Figure 8b and the dashed blue line in Figure 8c). As previously shown by, e.g., Bellefleur et al. (2004, 2012) and Malehmir et al. (2009), the seismic signature of massive sulfide deposits is often characterized by P-P and strong S-S-wave reflections and their mode conversions connected to either the top or the bottom of the deposit. Figure 8b and 8c is consistent with these studies, indicating the possible presence of mode-converted events, based on the coherent energy around the modeled Lombador response. Considering the nature of the modeling used (a planar reflector versus a true complex-
shaped deposit), an “exact” match between the modeled and the true reflection response cannot be expected.

**CONVENTIONAL NMO STACK AND MIGRATION**

Following the enhancement of reflections in the shot gather domain, two different approaches were used to obtain migrated images (Table 2). The first one involved conventional CDP stacking using a constant-velocity model (6.0 km/s). The velocity was obtained by analysis of a range of different velocities and selecting the one showing the highest coherency of the deposit’s P-P reflection. An important step for quality control of this step were the CDP time-domain-modeled responses used as an approximation for where and what type of event might be expected from the targeted deposit. Detailed velocity analysis did not improve the final image. An attempt to improve the NMO-corrected stacked cube was also made by applying a 3D dip moveout (DMO) correction. Application of this correction decreased the overall quality and coherency of the Lombador reflection and introduced numerous artifacts, especially in the early times; hence, it was excluded. The poor behavior of the 3D DMO correction is likely due to the irregular data sampling and narrow-azimuth, nonuniform offset distribution of the data (Cheraghi et al., 2012; Hedin et al., 2016). Figure 9 shows a series of 2D inline slices extracted from the unmigrated NMO stack seismic cube. Different slices show a strong signature corresponding to the Lombador deposit, as can be seen by comparison with the modeled response.

**Pre- and poststack migration results**

The Lombador deposit dips approximately 30°–35° and appears to have a complex seismic signature. Considering this, the rock volume where the tunnels, hence the seismic spread, is located, along with numerous diffractions seen in the raw data, migration was necessary to correctly reposition different seismic events to their true location. Nonuniform and low-fold sampling with source located dominantly along GP4 were also problematic for different migration algorithms. After testing different algorithms, 3D Kirchhoff prestack depth and poststack time migration were selected. For 3D prestack depth migration, we used a straight ray approach that considers the actual coordinates of the sources and receivers. Such an approach is valid for this study area because the velocity is nearly constant. Figure 10 shows an example inline and depth slices extracted from the 3D prestack migrated cube plotted together with the spread elements, mine infrastructure, and Lombador deposit. The 2D inline slice shown in Figure 10a shows a relatively strong northerly dipping reflector (the solid S arrows — L1) and a weaker, deeper seated, parallel reflector (the dashed arrows — L2). Judging from the Lombador deposit model overlaid (Figure 10b), the L1 reflector corresponds to the top and the L2 likely to the bottom of the deposit. The depth slices shown in Figure 10c and 10d also show coherent energy in accordance with the Lombador deposit. Although the S/N of the results after migration is rather low, coherent reflections that originate from the deposit are clearly visible.

Figure 11 shows the results after applying the entire processing flow shown in Table 2 and using Kirchhoff 3D poststack time migration and time-to-depth conversion. Compared with the prestack results, the poststack results are noisier but show an additional shallow-seated (650–750 m depth) dipping reflector above the depth where Lombador is located (the solid S arrows). Whether these reflectors are migration artifacts (Hertweck et al., 2003) or related to some of the thrust faults remains inconclusive (Figure 1). Interpreting the reflector corresponding to the Lombador on the poststack time migration results is more challenging compared with the prestack depth migration results. The southern portion of Figure 11a shows strong events whose

Figure 7. (a) Source-receiver azimuthal offset coverage of the tunnel data set showing a dominant northwest–southeast illumination on medium to far offsets, and the northwest and northeast direction, for near offsets. (b) Processing geometry showing the fold distribution with the rectangular midpoint binning into the inline and crossline bins of 3.5 m. The highest fold follows acquisition profile GP4, and an acquisition footprint can be observed by the mostly north–south-directed linear features. (c) Depth-domain P-wave reflection points of the plane used to approximate the Lombador deposit for all shots and receivers (red) and CDPs (blue) plotted together with mine infrastructure, Neves and Lombador deposits, surface and tunnel profiles, and an aerial photo projected onto the DEM model.
The overall geologic dip direction can be expected if the event originates above the exploration tunnels where the seismic spread is located. The low apparent moveout velocity may also suggest a mode-converted origin. Analyzing Figure 1, one can note that a spay of the Neves-Corvo main thrust is placed above the tunnels and might be a good candidate explaining the origin of this reflection. However, more investigations are necessary to confirm this.

The tunnel seismic acquisition strategy used results in a nonuniform target illumination and uneven 3D fold distribution. Both of these may produce a significant acquisition footprint, affecting lateral resolution, the capability to resolve dipping reflections and the selection of processing parameters (Cheraghi et al., 2012). To address these problems, different inline and crossline bin sizes, grid orientations, and their resulting fold distributions were evaluated. All the parameters tested were cross-validated versus the NMO-corrected seismic cube obtained using the parameters from Table 2 and as shown in Figure 9. In addition to the perpendicular grid orientation with inline direction north–south oriented, two additional scenarios also with perpendicular inline-crossline directions were evaluated. The first one involved a grid aligned with the Lombador strike and the second one aligned with the dominant northwest–southeast illumination. For both of these trial scenarios, including

**DISCUSSION**

MEMS-based accelerometers are broadband seismic receivers for which the recorded signal is proportional to ground acceleration. Geophones record signals proportional to ground velocity; hence, a discrepancy between the two exist. To correct for this, the MEMS data were integrated, followed by a cosine tapered low-cut (5–10 Hz) filter during the preprocessing stage. Selection of the low-cut filter frequencies was based on obtaining a similar amplitude response as for the 10 Hz geophones used. Although the source sweep starting at 2 Hz aimed at broadband signal excitation, subsequent data analysis after crosscorrelation shows strong mining-related noise below approximately 50 Hz (Figure 5). To suppress this noise and enhance the seismic signals related to the targeted deposit, frequencies below 50 Hz were removed during the processing from the geophone and integrated MEMS data. In doing so, any given advantage of using a broadband source and MEMS-based accelerometers is lost. Future studies should aim at preserving the full-source bandwidth via curvelet denoising or adaptive or interference noise attenuation (Gulunay et al., 2004; Lu, 2006; Górszczyk et al., 2014; von Ketelhodt et al., 2019; Markovic et al., 2020). Such studies may allow the full bandwidth of the acquisition instrumentation to be preserved.

A particularly interesting feature in the data is the hyperbolic event labeled H1 in Figure 6. According to the available geologic information, there are no geologic structures that this event can be associated with, beneath the GP4 tunnel. Given the apparent moveout velocity of approximately 2.4 km/s and the apex at 65 ms, this event originates somewhere within a 75–100 m radius around the northern end of GP4. Because the event is only visible on GP4 receiver gathers, whereas the source is located close to the northern end, its nature is unclear. A closer look at it reveals a displaced apex of the hyperbola and an apparent southward dip, opposite to the northward-dipping geologic formations and the Lombador massive sulfide deposit. An opposite dip to the overall geologic dip direction can be expected if the event originates above the exploration tunnels where the seismic spread is located. The low apparent moveout velocity may also suggest a mode-converted origin. Analyzing Figure 1, one can note that a spay of the Neves-Corvo main thrust is placed above the tunnels and might be a good candidate explaining the origin of this reflection. However, more investigations are necessary to confirm this.

**Table 2. Processing steps used for conventional poststack time migration and prestack depth migration workflows.**

<table>
<thead>
<tr>
<th>Step</th>
<th>Parameter</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Read raw SEG data (28 s)</td>
</tr>
<tr>
<td>2</td>
<td>Crosscorrelate raw vibgrams with pilot (5 s)</td>
</tr>
<tr>
<td>3</td>
<td>Vertical stacking of repeated sweeps</td>
</tr>
<tr>
<td>4</td>
<td>Remove all but the vertical components</td>
</tr>
<tr>
<td>5</td>
<td>Convert the MEMS acceleration to velocity (integrate + 5 Hz low-cut filter)</td>
</tr>
<tr>
<td>6</td>
<td>Add geometry (after testing, 3.5 m inline and crossline)</td>
</tr>
<tr>
<td>7</td>
<td>Wiener deconvolution (length 100 ms, gap 5 ms)</td>
</tr>
<tr>
<td>8</td>
<td>Median filter (5.5, 3.5, and 2.8 km/s)</td>
</tr>
<tr>
<td>9</td>
<td>Band-pass filter (50–60–160–180 Hz)</td>
</tr>
<tr>
<td>10</td>
<td>Trace normalization (the entire trace length)</td>
</tr>
<tr>
<td>11</td>
<td>LMO-based P-wave first-break mute</td>
</tr>
<tr>
<td>12</td>
<td>Elevation statics (~400 m, 5.5 km/s)</td>
</tr>
<tr>
<td>13</td>
<td>Surgical mute of remaining S-wave fb’s</td>
</tr>
<tr>
<td>14</td>
<td>NMO (6.0 km/s, 40% mute)</td>
</tr>
<tr>
<td>15</td>
<td>Residual statics</td>
</tr>
<tr>
<td>16</td>
<td>AGC (100 ms)</td>
</tr>
<tr>
<td>17</td>
<td>Stack (normal)</td>
</tr>
<tr>
<td>18</td>
<td>Band-pass filter (60–70–150–160 Hz)</td>
</tr>
<tr>
<td>19</td>
<td>FXY-deconvolution</td>
</tr>
<tr>
<td>20</td>
<td>Trace normalization</td>
</tr>
<tr>
<td>21</td>
<td>Top mute above the Lombador CDP responses (15 ms shifted)</td>
</tr>
<tr>
<td>22</td>
<td>Kirchhoff 3D time migration</td>
</tr>
<tr>
<td>23</td>
<td>Time-to-depth conversion (6.0 km/s)</td>
</tr>
</tbody>
</table>

**Conventional stack**

**Prestack**

- Trace normalization
- Kirchhoff 3D depth migration

The northern portion of the migrated cube is more prone to artifacts due to the lack of receiver coverage. This is notable by strong southward-dipping energy in the northern end of the inline in Figure 11a. Nonetheless, two reflectors can be seen as indicated by the solid and dashed arrows that can be attributed to the top and bottom of the Lombador deposit. After overlaying the Lombador deposit model (Figure 11b), a coherent reflector following the deposit’s top becomes more distinguishable. The inline and depth slice in Figure 11c show coherent energy corresponding to the top and bottom of the deposit (the solid and dashed L1 and L2 arrows). Overlaying the deposit’s model onto inline and depth slices (Figure 11d) indicates that the coherent energy in both of these can be attributed to Lombador.

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the one selected, minimum inline and crossline bin size tested was 2.5 m (half of the nominal receiver spacing) and the maximum size tested was based on the “optimum bin size” formula for a dipping reflector (Yilmaz, 2001; Cheraghi et al., 2012). Using this formula, with 6.0 km/s velocity, maximum usable frequency of 150 Hz and 40° Lombador dip, the optimal bin size is 15 m. The selected bin size of 3.5 m is far lower than the size suggested by the optimum bin size formula, and its selection was largely driven by the highest coherency of the targeted deposit’s reflection in the NMO-corrected seismic cube. Regardless of the bin size, both of the grid orientation scenarios tested showed the lower resolution and poorer coherency of the Lombador reflection compared to the selected grid orientation and parameters. Doubling the bin size in the crossline direction to that in the inline for all three scenarios tested did not improve results either; hence, the same bin size in both directions was kept.

Forward modeling of the seismic response of the Lombador deposit in the unmigrated stack and shot gather domains was crucial for the processing and evaluation of different geometry parameters and their effect on the coherency of the reflection in question. Considering the effect of morphology and surface roughness of the deposit on illumination, traveltimes, and the seismic response (e.g., Clarke and Eaton, 2003), our modeling assumptions (3D planar reflector in a constant velocity media; Ayarza et al., 2000) can only approximate the deposit to a limited degree. Nonetheless, the modeled seismic responses were sufficient to provide a guide for successful enhancement of the reflections of interest. Because our study targeted primarily the Lombador deposit, its enhancement was achieved by applying strong median filters to remove the direct P- and S-waves. These have, in return, attenuated most of the energy of these arrivals and also removed the hyperbolic — H1 event shown in Figure 6. Future studies focusing on data processing for 3D prestack depth migration of all seismic profiles acquired during the experiment will aim at modeling the Lombador response on all of the receivers used. Combined with borehole data (presently unavailable), the modeling can be more constrained and the reflection response of the thrust sheets and formations above and below galleries located at 650 m can be obtained. All forward responses calculated can therefore be used for a more focused processing approach aiming at preserving reflections related to the deposit itself and the geologic structure beneath and above it.

The sparse and nonuniform data sampling was also problematic for the selection of the migration...
strategy resulting in the least amount of migration artifacts. From the prestack perspective, Kirchhoff 3D depth and time migration were attempted, with the former showing better coherency and fewer artifacts compared with the latter (Figure 10). Fresnel volume migration (e.g., Buske et al., 2009) is planned for future studies. On the poststack migration perspective, we attempted 2.5D finite difference, 2.5D Stolt, and 2.5D phase-shift migration, together with Kirchhoff 3D time and depth migration. Except for the limited-aperture Kirchhoff 3D time migration, all of the other algorithms showed poor-quality results with numerous artifacts, and Kirchhoff time migration was selected (Figure 11). The poor behavior of different migration algorithms tested is likely an effect of the sparse and nonuniform data sampling (Körbe et al., 1997; Hertweck et al., 2003; Gray, 2013). As discussed by Hertweck et al. (2003) for Kirchhoff migration, in the case of missing traces, such as the case of our nonuniformly sampled data, a certain degree of “migration smiles” can be beneficial because it can improve reflector continuity. For our sparsely sampled data, a key migration step was the proper selection of a migration aperture that will enhance reflector continuity, and in return limit undesirable artifacts. Limiting the migration artifacts was also dependent on removal of all steeply dipping linear events in the shot gather domain. For prestack migration, in addition to median filters, an

Figure 10. Prestack depth migration result plotted in 3D space together with the seismic spread and mine infrastructure at approximately 650 m beneath the surface. (a) An example inline extracted from the 3D migrated cube without and (b) with the Lombador deposit model (transparent red) overlaid. (c) The same example inline together with a depth slice without and (d) with the Lombador deposit model showing the deposit’s strong signature. The solid arrows marked “L1” correspond to the top and the dashed “L2” arrows likely to the bottom of the targeted deposit.

Figure 9. A series of 2D inline slices extracted from the unmigrated NMO stack seismic cube showing the strong signature of the Lombador deposit and its modeled response for P-P (red), P-S and S-P (orange), and S-S reflection traveltimes overlaid. Inline 1148 shows two sets of reflections (indicated by the arrows); the northern one likely originates from the top and the southern one from the bottom of the Lombador deposit. The amplitude spectrum of inline 1148 suggests a dominant frequency of approximately 100–120 Hz. Considering the complex shape of the Lombador deposit and its response modeled as a planar reflector, the modeled traveltimes approximate, to a certain extent, the reflections seen in the different 2D inline slices.
Regarding the lack of uniform and sparse nature of the acquired data imposed by the underground infrastructure hosting the seismic spread and the NMO-corrected seismic cube, it was kept for both processing approaches. To limit the artifacts of the poststack migration, particularly in the shallow part, modeled CDP domain P-P reflection responses (shifted up by 15 ms) were used as a guide for the surgical mute of shallow portions of the NMO-corrected seismic cube (step 21 in Table 2). This enabled a cleaner input data for migration, targeted at Lombador specifically. The pre- and poststack migration results indicate a larger depth extent of the targeted deposit compared to its model as shown in Figures 10b, 10d, 11b, and 11d, which is likely a limited aperture effect smearing the energy further along the Huygens surfaces.

Regardless of the nonuniform and sparse nature of the acquired data imposed by the underground infrastructure hosting the seismic spread, the NMO-corrected stacked seismic cube clearly shows the presence of the targeted deposit (Figure 9). This is also supported by the modeling results shown in the same figure. The prestack (Figure 10) and poststack migration results (Figure 11) show relatively strong reflectors that are in accordance with the borehole constrained deposit model (Figures 10b, 10d, 11b, and 11d). In addition to the data handling strategies used, the unique data nature opens up possibilities for application of other imaging techniques and approaches. By picking first arrivals on the tunnel and surface portions of the seismic spread and using them for 3D traveltime tomography purposes (e.g., Tryggvason et al., 2002), a relatively well-constrained velocity model of the structures between the two can be obtained. This velocity model can be used for tomographic imaging of the formations and local geologic contacts, including steeply dipping structures, above the exploration galleries at 650 m in depth (Gritto et al., 2003, 2004; Daley et al., 2004; Brodic et al., 2017). The tomographically obtained velocity model also provides better control over the medium velocity for imaging and positioning purposes and can be used for detecting zones of weakness (Donoso et al., 2021).

Figure 11. Poststack time-migration result visualized in 3D space, together with the seismic spread and mine infrastructure approximately 650 m beneath the ground surface. (a) An example inline extracted from the 3D migrated cube without and (b) with the Lombador deposit model (transparent red) overlaid. (c) The same example inline together with a depth slice without and (d) with the Lombador deposit model, showing the deposit’s strong signature. The solid arrows marked L1 correspond to the top and the dashed L2 arrows likely to the bottom of the targeted deposit. The “S” arrow marks a shallow event that might originate from some of the existing thrust faults above the Lombador deposit.

CONCLUSION

An active-source seismic survey was conducted at the Neves-Corvo VMS mine, located in southern Portugal. Important aspects of the survey were the testing and evaluation of two prototypes developed for this purpose, namely, a GPS-time transmitter and an electrically driven, LSM-based vibroseis seismic source. The former enabled accurate GPS-time synchronization of the seismic receivers distributed along four tunnel seismic profiles 650 m beneath the surface along with two seismic profiles on the surface. In this paper, we have focused on introducing the survey, the innovations necessary to accomplish it, and the seismic imaging potential of only the tunnel seismic profiles. To the best of our knowledge, this is the first study that uses exploration tunnels, four at the same time, in an operating mine for conventional scale seismic imaging of known mineral deposits in a 3D manner, involving sources and receivers in the subsurface. Considering the strong noise due to the mining operations, the LSM-based electric seismic vibrator was still capable of producing relatively good S/N data, with strong reflections originating from the deposit and other structures. The origin of these reflections was further confirmed by 3D ray tracing to model traveltimes, using the a priori information about the deposit as the input for modeling.
The seismic data were processed using two approaches, 3D Kirchhoff prestack depth and poststack time migration. Both migrated seismic cubes show coherent reflectors that are deemed to correspond to the top and bottom of the Lombador deposit of interest. The borehole-constrained deposit’s surface 3D model is in accordance with the interpreted top of the deposit reflector seen in the 2D vertical sections and depth slices of the seismic cubes. The developed innovations and prototypes prior to the survey were crucial for successful data acquisition, opening up the possibilities for active-source seismic surveys in tunnels or mines worldwide. The reported data handling exploits only a minor part of the full data potential, neglecting the surface-recorded portion of the seismic spread and the combined data sets. By exploiting the full data potential, the rock volume beneath the 650 m exploration depth and the volume between this depth and the surface can be seismically imaged. Such an approach would enable obtaining valuable information on the targeted deposit and the rocks and geologic formation between the deposit and the surface.

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DATA AND MATERIALS AVAILABILITY

Data associated with this research are available and can be obtained by contacting the corresponding author.

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Biographies and photographs of the authors are not available.