Smart Exploration: from legacy data to state-of-the-art data acquisition and imaging

A. Malehmir[1*], G. Donoso[1], M. Markovic[1], G. Maries[1], L. Dynesius[1], B. Brodic[1], N. Pecheco[2], P. Marsden[3], E. Bäckström[3], M. Penney[4] and Vitor Araujo[2] present two legacy datasets from the Neves-Corvo massive sulphide mine in Portugal and the Blötberget iron-oxide deposits in Sweden and demonstrate how both are capable of imaging mineralization and their host rocks.

Introduction

During the last decade, and possibly in years to come, mineral exploration geophysics has strongly pushed itself towards developing new instruments and hardware solutions capable of addressing the ever challenging near-mine and brownfield exploration issues. New data will be acquired but higher noise levels and restricted access due to mining activities and infrastructure increase the challenge of acquiring data of sufficient quality to answer key geologic questions and define additional resources. Companies that value their existing data and reassess them rigorously and continuously are likely to benefit.

However, new generations of geophysicists and mineral explorationists tend to prefer modern data from new instruments than the so-called 'legacy data'. Legacy data by definition are those that have been acquired in the past, but their revival requires a significant amount of time and money, and still it may not always be possible to yield rewarding results. These data often suffer from bad documentation, inaccurate co-ordinates, and are stored on devices (e.g., tapes or hard copies) that makes it difficult to access or they may have partly been corrupted. However, legacy data are still valuable, especially if they are from brownfield or near-mine exploration sites and can be revived and reworked.

Legacy data have the advantage of:
- being less contaminated by noise from mining activities and infrastructures,
- being acquired in places that now might be inaccessible (i.e., logistical challenges),
- being cheaper to reprocess and reinterpret than to collect new data as data acquisition often makes up the bulk of a survey's cost.

Legacy data can also provide a first assessment if new and advanced data acquisition would lead to new knowledge and discoveries.

Smart Exploration, an H2020-funded project involving 27 partners from nine European countries and six exploration sites was launched in late 2017. Its goal is to address some of these challenges concerning legacy data, to develop new geophysical instruments for a wide range of applications and to generate new targets at the exploration sites while training new generations of young professionals for these purposes. Here, we focus on re-evaluating the potential of some of the legacy data available from the exploration sites and together with new instruments developed during the project present how in-mine and brownfield mineral exploration can advance utilizing existing mining infrastructure. For example, we show the

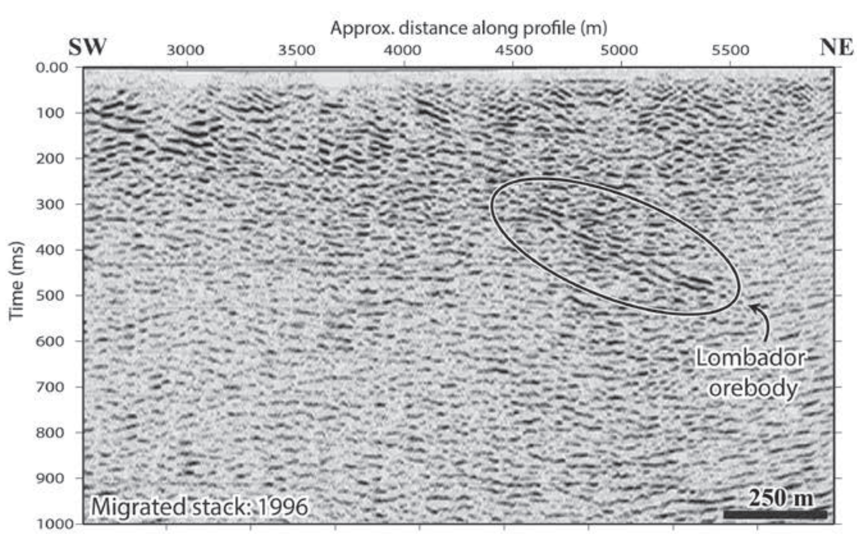

Figure 1 Processing result (1996) from a portion of one of the seismic profiles crossing over the world-class Lombador deposit showing a moderately dipping reflection that is likely to have originated from it. No other clear reflections can be observed from this work other than a very noisy looking shallow (top 200 ms) seismic section.

[1] Uppsala University, Sweden | [2] Somincor, Portugal | [3] Nordic Iron Ore Ab, Sweden | [4] Lundin Mining Corp., Canada
[*] Corresponding author, E-mail: alireza.malehmir@geo.uu.se

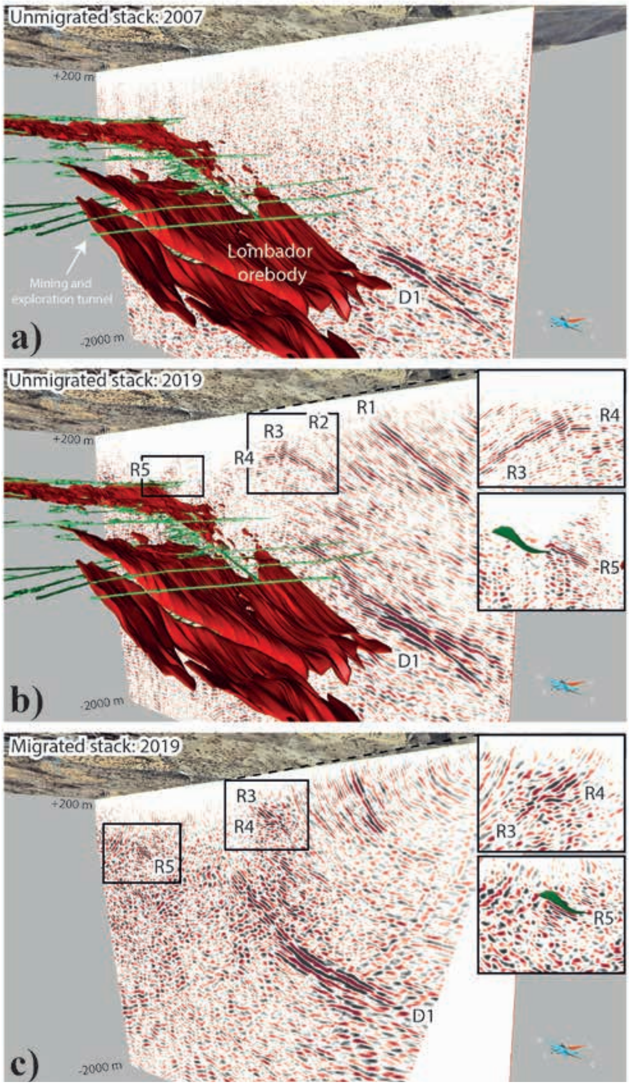

Figure 2 Example of the reprocessing work done on the seismic data shown in Figure 1 (a) from 2007 (unmigrated), (b) this study (unmigrated), and (c) this study migrated. Note improvements obtained in the recent reprocessing work from those of the original processing workflow as well as the reprocessing work conducted in 2007. Lombador orebody generates strong reflection notable in all the processing works (e.g., 1996, 2007 and 2019). However, other reflections such as R1-R5 are only unravelled in the recent processing work. Reflection R5 is associated with mineralization (green surface) and quite notable in the recent reprocessing work as well as some of the raw shot gathers (not shown here). Modified from Donoso et al. (2019).

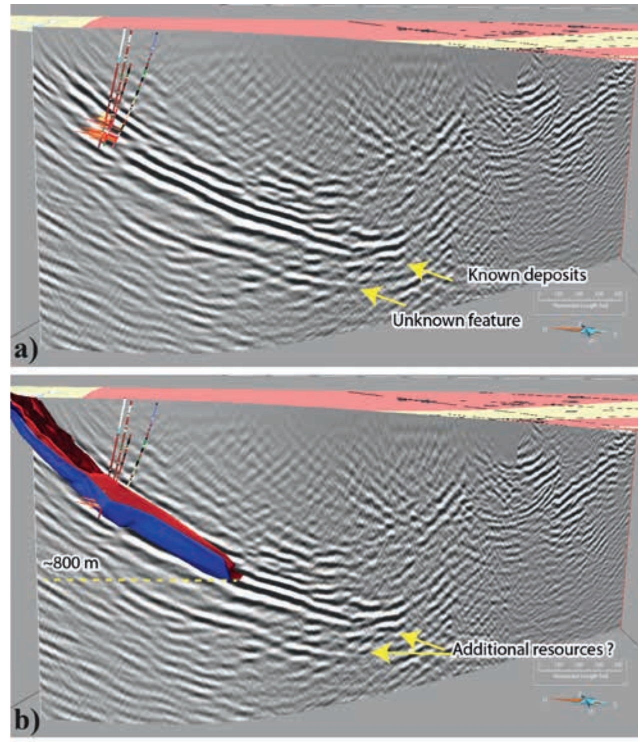

Figure 3 (a) Migrated and time-to-depth converted seismic section of the 2016 survey showing possible depth continuation of the mineralized bodies (b) down to approximately 1200 m depth (beyond the known 800 m depth) suggesting that additional resources might be present in the downdip extension requiring further investigations.

importance of legacy data from a 1996 dataset enabling imaging of a world-class +150 Mt massive sulphide deposit at depth as well as another case study showing that additional iron-oxide resources may be present downdip and under the known mineralized bodies. The development of a GPS-time system and an E-vibrator helped to then acquire a semi-3D tunnel-surface seismic dataset utilizing exploration tunnels in the Neves-Corvo mine.

Examples and results

Neves-Corvo 1996 seismic data, Portugal

The 1996 dataset in Neves-Corvo was acquired and processed by a contractor and the results were presented during that same year in a number of reports. Six rather straight lines (2-6 km long each) were acquired using 96 to 120 channels with a receiver and shot spacing of 15 m providing a high-fold (nominal fold of 48 and 60, respectively) seismic dataset for that time but low fold by today's standard (plus 120 and many more channels) for a hard rock environment. However, the dataset was recoverable and with adequate documentation could be reprocessed. The quality of the dataset is quite remarkable given the explosive used as the seismic source (sharp wavelet and broadband signal), and that the background noise was probably not very high in 1996 compared to recent years when a 3D seismic dataset was acquired at the site.

Figure 1 shows a portion of one of the seismic profiles processed in 1996, which crosses over the well-known Lombador massive sulphide deposit. The processing work, which looks to be poor-quality, does appear to clearly image a reflection associated with the deposit extending down to at least 400 ms or roughly 1000-1200 m depth. Not much information is available from the processing workflow. However, we believe this section is migrated.

Within the Smart Exploration project, the same dataset was reprocessed, this time taking advantage of the experience long gathered in handling hard rock seismic data in complex geological environments such as in the Neves-Corvo mine but also paying attention to the varying quality of the data from one line to another. Figure 2b,c shows the same section as Figure 2a (unmigrated section processed in 2007) but this time from 2019 (Donoso et al., 2019). As evident from a number of shallow but steep reflections (R1-R5), the new reprocessing work is a big improvement on the historic processing, including the 2007 reprocessing work. A small mineralized body known from borehole data probably appears to be generating a short but strong reflection (R5) that was missing in all the processing work done prior to this study.

As illustrated here, the legacy dataset from the Neves-Corvo had much more to offer and it might even be possible to extract more information from it. This would, however, not have been possible without proper archiving of the dataset and adequate documentation allowing for a number of processing workflows to be applied to it. The 1996 dataset was re-evaluated and reprocessed in 2007 in an attempt to check if new follow up seismic data acquisition at the site and different source-receiver combinations could result in new geological knowledge and targets. The reprocessing work was also essential in deciding if a 3D seismic survey should be used to handle the complex geology of the site with several faults and thrusts complicating continuity of the structures and volcanic-bearing rocks for indirect targeting (West and Penney, 2017). Figure 2a shows the result of the reprocessing work from 2007. The only reflection in this line is related to the Lombador deposit suggesting that such a large massive sulphide body should be detectable using reflection seismic method.

Blötberget iron-oxide mine, Sweden

One of the exploration sites of the Smart Exploration project sits within the well-known multi-commodity deposits of Bergslagen mineral district in central Sweden. The Blötberget iron-oxide deposits have been the target of a number of earlier surveys and experiments including downhole logging physical property measurements (Maries et al., 2017), UAV-magnetic surveys (Malehmir et al., 2017a) as well as two surface 2D reflection seismic surveys conducted in 2015 (Malehmir et al., 2017b) and 2016 (Markovic et al., 2019). The 2015 survey used a seismic landstreamer to check its potential for deep-targeting iron-oxide deposits while the 2016 survey used conventional spike-type geophones and a 500-kg Bobcat-mounted drophammer as the seismic source. Both surveys were capable of imaging the known mineralization. However, the 2016 survey allowed much deeper penetration potentially suggesting the presence of additional resources beyond the known 800 m depth and generating targets in the footwall of the known mineralization.

Figure 3 shows a migrated seismic section of the 2016 survey and surfaces representing the ore models. The mineralized bodies are primary magnetite-rich, however at distinct locations some percentage of hematite mineralization can also be observed. These mineralized bodies (tabular in shape) occur with thicknesses varying from 10 to 30 m and sometimes in very close proximity (10-50 m) of each other. Given the dominant wavelength in the data (estimated to be about 60-80 m), we anticipate difficulties in resolving these mineralized bodies as individual reflections and rather see a zone of cyclic-looking reflectivity. The 2016 dataset that was wisely acquired helped to confirm that the known mineralization extends down to 800 m depth, which was previously only known from historical boreholes, and to identify a 300 m extension of the resources downdip. This survey was also fundamental for proposing and approval of a follow-up 3D seismic survey that was conducted during April-May 2019.

A novel semi-3D surface/in-mine seismic survey, Portugal

For a long time now many explorationists have talked about utilizing mining infrastructure for geophysical surveys. While being in a highly challenging noisy mining environment is one of the key limitations for seismic surveys, technical limitations were also a major hindrance. Most geophysical surveys require synchronized in-time array data acquisition to allow time-series analysis. Given that most mining infrastructure, particularly tunnels, are in spaces where GPS signals are denied, such a data acquisition has remained limited to short arrays or only for small mining block investigations. In the Smart Exploration project, we have developed a GPS-time system (Malehmir et al., 2018) allowing us to transmit a GPS-time signal to several 100-1000s receivers on different tunnels and at different levels. This possibility then helped us to acquire a pilot dataset at the Neves-Corvo mine utilizing exploration tunnels used to drill downdip but also simultaneously recording two sets of perpendicular seismic profiles approximately 600 m above the tunnels. More than 1000 receivers of various types (e.g., 1C and 3C), cabled and wireless, were utilized for this survey (Figure 4).

Four exploration tunnels, each about 500-600 m long, were instrumented using a combination of cabled and wireless sensors with an average spacing of 5 m and a new broadband seismic source, an electromagnetic vibrator developed in the project (see Noorlandt et al., 2015; Brodic et al., 2019), used as the main seismic source. On the surface and in the downdip direction, a longer array of wireless receivers (214 receivers) were used while the perpendicular one had a shorter (101 receivers) length. As a result of the development of the GPS-time system, data could be

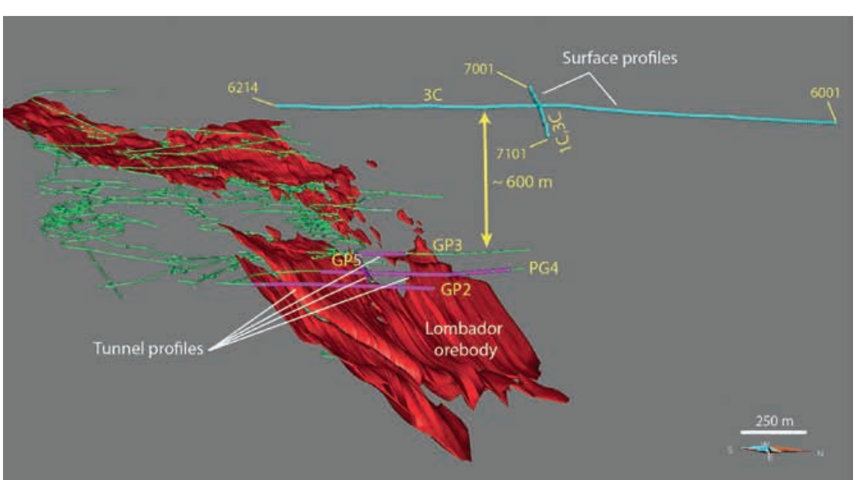

Figure 4 3D visualization of the exploration and mining tunnels with the Lombador orebody model showing how the surface-tunnel seismic experiment was conducted. Four exploration tunnels (GP2-GP5) and two surface seismic profiles were instrumented using receivers spaced at 5-10 m interval and simultaneously recorded for all shots generated regardless of the position (surface or tunnel). The GPS-time system developed within the Smart Exploration project was used to allow array-based accurate time synchronization.

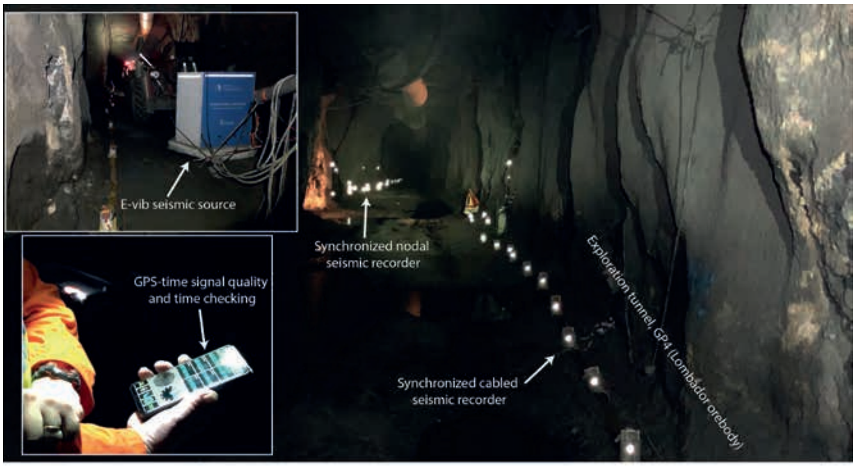

Figure 5 A picture showing receiver set-up in a portion of one of the exploration tunnels (GP4) in the Neves-Corvo mine. Inset pictures show the E-vibrator used as the seismic source and a smart phone application used to check GPS-time signal quality and time from the GPS-time system developed in the project and used in the tunnel for time-synchronized data acquisition.

merged and harvested based on the actual zero-time of the source signal. This development and pilot test should open possibilities beyond surface seismic measurements allowing up-scaled underground seismic investigations but also other types of geophysical surveys requiring accurate GPS time for time-series analysis.

Figure 5 shows a picture from the receiver setup from one of the exploration tunnels (GP4) where a combination of cabled and wireless receivers was used to allow heavy mining machines to pass but also to check the performance of the GPS-time system in real mining conditions. The E-vibrator developed in the project for broadband data acquisition is also shown as an inset picture.

Conclusions

We have shown in this review work the potential of legacy data and their value when carefully documented and reprocessed. In particular the legacy seismic data from the Neves-Corvo help to not only image the world-class Lombador massive sulphide deposit but also steep structures near the surface and smaller mineralized bodies showing the resolution power of the seismic methods at the site. Advancing seismic data acquisition in complex in-mine conditions, we have also managed to acquire a unique seismic dataset utilizing exploration tunnels in the Neves-Corvo mine. Simultaneous surface-tunnel data recording was possible thanks to the GPS-time system that allowed an accurate GPS-time signal to be used for an array of more than 1000 receivers placed in the exploration tunnels and on the surface.

The seismic data in the Blötberget showed clear reflection seismic signature of the iron-oxide deposits and their depth continuation beyond what is known from existing boreholes. Also, the results helped to suggest additional targets in the footwall of the known mineralization and motivated for a follow-up 3D seismic survey that was recently conducted.

This study illustrates that both legacy and modern seismic data have tremendous potential for mineral exploration as long as they are recoverable and contain adequate level of documentation for reprocessing. Modern data acquisition of today will be the legacy data of tomorrow.

Acknowledgments

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