# Proceedings of Exploration' 17

# Seismic Methods & Exploration Workshop

## Seismic Methods & Exploration Workshop

In many parts of the world, exploration for mineral deposits is moving progressively but persistently to greater depths, relying on knowledge gained from previous exploration campaigns but also on new exploration tools and techniques to efficiently guide deep and costly boreholes. With encouraging results recently obtained in various mining camps, seismic methods continue to make valuable contributions to deep mineral exploration worldwide. This workshop will build from successful seismic case studies presented during Exploration 17 and will address technical aspects of the seismic workflow with a particular focus on state-of-the-art methods that have proven impacts and/or open new frontiers in mineral exploration. Four general topics will be covered including:

- New trends in seismic data acquisition and processing
- Seismic methods in ongoing exploration programs
- Rock physics and quantitative analysis
- Ambient noise and seismic interferometry

The workshop will include keynote presentations covering those topics and most importantly, plenty of time for discussion. The aim of the workshop is to bring together industry, academia, and research funding agencies to discuss novel developments, share experiences, and generate new way-forward ideas. Please join us in the morning of Thursday October 26, 2017, for an exciting half-day workshop on seismic methods for mineral exploration.

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Paper 1

# Seismic for mineral resources – a mainstream method of the future

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## ABSTRACT

The seismic reflection method is the only geophysical method that can image deep structures with a precision required for targeting extensions of the existing mineralization and discovering new resources. However, mineral prospecting using seismic methods is not straightforward and is very expensive. While the seismic exploration practice is improving, to make seismic widely acceptable to the mining community, a step change is needed to transform seismic into a standard method for exploration of mineral resources. Significant changes in acquisition, processing and data analysis are required that can only be achieved by introducing new technologies into the application of seismic for mineral exploration. One of the possible approaches is DAS instrumented fields that would incorporate simultaneous recording of multiple VSP and/or cross-hole data and/or surface seismic followed by comprehensive pre-stack depth imaging and inversion. This approach has the potential for providing the highest resolution images needed for mapping complex mineral deposits. Utilizing FWI and automated analysis on such data sets will turn seismic into a mainstream method in exploration of mineral resources.

## INTRODUCTION

The need to see deeper below the existing ore shoots, in order to find their extensions and to discover new, deep economic mineralization, is ever present in the mining industry. The only geophysical method that can detect and delineate deep and complex geological features is seismic. However, seismic has not been established yet as the primary exploration method for mineral prospecting. Seismic data are expensive to acquire, difficult to process and the resulting images are hard to “transform” into meaningful geology.

Development of wireless seismic, implementation of a single geophone in combination with a single broadband sweep reduced the acquisition cost, yet increased the resolution of seismic images. Introduction of the Distributed Acoustic Sensors (DAS) is likely to make a step change in both borehole and surface seismic acquisition practices. Onshore implementation of DAS is of particular interest to mineral seismic studies (Daley, et al., 2013). Further technological advances are aimed at the minimization of human involvement (e.g. passive seismic, airborne seismic) in the data acquisition process which will bring the cost further down.

Recent advances in seismic processing mainly occurred through the implementation of Common-reflection surface (CRS) and/or Multi-focusing (Landa and Keydar, 1998; Berkovitch et al., 2008), diffraction imaging followed by steered migration (Tertyshnikov et al., 2013), pre-stack time (PSTM) and most recently depth imaging (PSDM).

The non-uniqueness of the process of inversion, from seismic response to the geology that caused it, to the presentation of the Inverted images is one of the main obstacles to a geologist. Hence in the arena of seismic interpretation, the wiggle representation of geology seems only acceptable to geophysicists. How can we improve? One way is to conduct a joint interpretation in a team comprised of geologists, geophysicists and mining engineers. This is usually leads to the verification of existing targets, generation of new targets, creation of new exploration strategies, etc. An alternative is to utilize new technologies such as Full Waveform Inversion (FWI) and image processing to help both geologists and geophysicists understand complex seismic images and relate them to host rocks and mineralized bodies. Implementation of these new technologies into all stages of seismic data acquisition, processing and interpretation will turn seismic into a mainstream method for the exploration of mineral resources.

### Seismic – state of the art

In the 1970s and 80s, many tests of high-resolution seismic imaging methods had been conducted in western countries for mineral exploration. It has been quickly recognized that a highly complex hard rock environment cannot be properly imaged with seismic profiling,three-dimensional (3D) seismic was needed. A very successful application of using seismic for mineral exploration and mine development came from South Africa (Pretorius et al., 2000). The application of 3D seismic in Australia

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for mineral exploration came later. It started with several small-scale 3D surveys conducted over the nickel deposit in Kambalda, Western Australia, in 2006 and 2007. All 3D surveys were conducted by the Department of Exploration Geophysics (DEG), Curtin University. The most significant and successful survey was the Beta Hunt 3D acquired in 2007 that led to several new discoveries (Urosevic et al., 2012). Since that time the application of using seismic for mineral exploration in Australia has seen an exponential rise. Consequently, in 2009 a company specialized in hard rock seismic exploration (HiSeis P/L) was formed by the Department of Exploration Geophysics to meet industry demands. Since then, numerous 3D surveys were conducted by the company (Table 1). A brief description of the mineralization, commodity type and seismic survey area are shown in Table 2. It is clear from Table 2 that most of the seismic investigations were conducted over gold deposits. This is expected as these deposits are structurally controlled, making the interpretation of seismic images relatively straightforward.

| Region | Seismic Project | | |
|---|---|---|---|
| | 2D | 3D | Downhole |
| Western Australia | | | |
| Goldfields | 14 | 7 | 6 |
| Pilbara | 3 | 1 | |
| Mid-west | 4 | 1 | 1 |
| Other | 4 | | |
| South Australia | | 1 | 1 |
| Queensland | 2 | 2 | 2 |
| Norhern Territory | 3 | | 1 |
| Tasmania | | 1 | 1 |
| Europe | 2 | 5 | 2 |
| Africa | 1 | 1 | 1 |
| North America | | 1 | |
| *total* | *33* | *20* | *15* |

*Table 1. Seismic surveys conducted by HiSeis P/L in the last 6 years (from late to the beginning of 2017) sorted by the region.*

| Project & Location | High-resolution 3D Survey Size | Year Acquired | Primary Commodity | Deposit Type |
|---|---|---|---|---|
| Gwalia Gold Mine, Western Australia (WA) | 18 km$^2$ | 2017 | Gold | Foliated parallel lodes within moderately east dipping strongly potassic altered mafic rocks |
| Darlot Gold Mine, WA | 25 km$^2$ | 2016 | Gold | Quartz veins and alteration halos controlled by major structures or secondary splays |
| Jundee Gold Mine, WA | 9 km$^2$ | 2016 | Gold | Orogenic gold system; mineralisation hosted in complex quartz and carbonate veins within fractures |
| Geita Gold Mine, Tanzania | 20 km$^2$ | 2016 | Gold | Archaean mesothermal orebody, largely hosted in a banded ironstone formation |
| Tropicana Gold Mine, WA | 12 km$^2$ + 12 km$^2$ | 2015 & 2014 | Gold | Archaean aged high grade quartzofeldspathic gneiss rocks |
| Cracow Gold Mine, Queensland (QLD), Australia | 6 km$^2$ | 2014 | Gold | Steeply dipping low sulphidation epithermal veins |
| Pajingo Gold Mine, QLD, Australia | 9 km$^2$ | 2014 | Gold | Structurally controlled epithermal quartz veins |
| Eagle Mine, Michigan, USA | 8 km$^2$ | 2014 | Nickel & Copper | Ultramafic-intrusive-hosted |
| Plutonic Gold Mine, WA | 9 km$^2$ | 2014 | Gold | Archaean mafic and ultramafic volcanics and sediments |
| Bullabulling Gold Project, WA | 1.5 km$^2$ | 2012 | Gold | Orogenic gold |
| Kilbricken Mine, Ireland | 26 km$^2$ | 2012 | Zinc-Lead-Silver | Volcanogenic massive sulphide |
| Neves Corvo Mine, Portugal | 20 km$^2$ + 50 km$^2$ | 2011 & 2012 | Copper-Zinc | Volcanogenic massive sulphide |
| O'Callaghan's Mine, WA | 2.2 km$^2$ | 2011 | Copper-Lead-Tungsten-Zinc | Polymetalic skarn deposit |

*Table 2. Seismic surveys conducted by HiSeis P/L in the last 6 years sorted by the region.*

In most of the cases a very high image quality is obtained using typically high data density (over 600 receivers and shots per Km$^2$), a single source-receiver position and broad band sweeps.
Direct targeting from seismic is possible for massive ore that has elastic properties quite different from the host rock (Milkereit et al., 1992; Urosevic et al., 2012). An example from a deep VMS deposit in Portugal is shown in Figure 1. Extracted inline from a 3D volume shows a very distinct amplitude anomaly related to a massive ore body. The correlation of seismic anomalies with boreholes shows a very good agreement. The sudden diminishing of reflection amplitudes coincides with the termination of the ore body. The value of seismic as a tool was verified shortly after the acquisition was finished. It was apparent that the seismic amplitude anomalies may be directly related to mineralized zones. Consequently further extensions of the initial 3D area followed (Table 2).

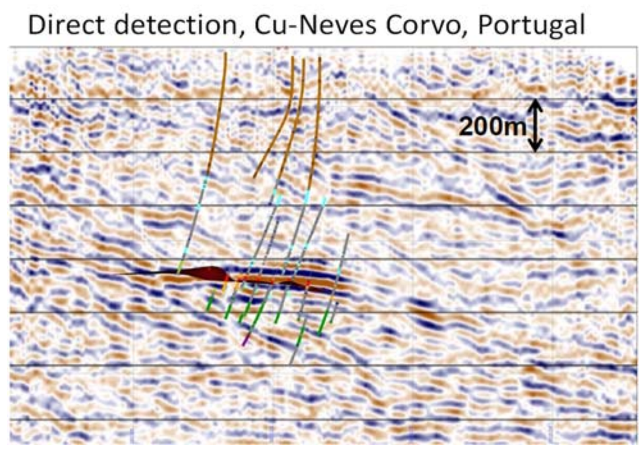


*Figure 1. VMS deposit in Portugal. Massive ore is characterized by very high impedance and stands out in the seismic image (www.Lundinmining.com).*

The second example comes from Cracow, a gold mine in Queensland (table 2). Opposite to the Neves Corvo case, the target here is not a continuous reflective package, rather, it shows discontinuities with an otherwise reflective package. Tracing discontinuities can be a very subjective process. Consequently an automated fault detection process called ant tracking is also deployed (Hossain et al., 2015). Inferred fault traces are overlain onto a lithological model inferred from seismic and borehole markers (Figure 2).

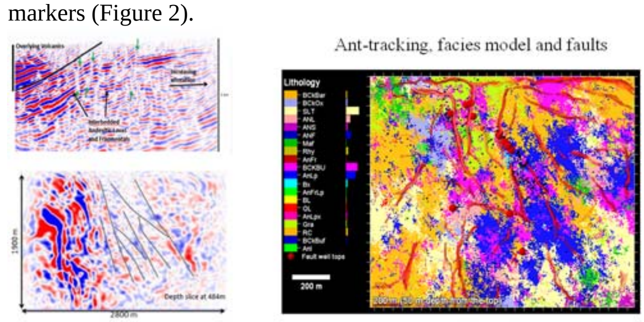


*Figure 2. Cracow gold deposit in QLD: Selected cross section (top left), a depth slice showing three distinct zones (bottom left) and the final ant-tracking and lithology identification product (right).*

These two cases are examples where interpretation is conducted by a team of geologists and geophysicists. The final product for Cracow is a type of output that is more desirable than a wiggle section shown for Neves Corvo 3D (Figure 1). However, clear amplitude anomalies are easily adopted by specialists of a diverse background. In most of the cases seismic amplitudes cannot be directly related to a presence of mineralization. There are however novel methods such as FWI that would be most desirable for interpretation and characterization of mineralized zones. This and other approaches are discussed below.

## Recent developments in seismic exploration in Australia

Complex hard rock environments requires very high data density to resolve steeply dipping structures and "piece-wise" lithology. In brown fields the data density per $km^2$ is typically 10 fold of the one used in conventional soft rock exploration. The cost increases exponentially with data density and pushes seismic to be too expensive for a widespread application in hard rock environments, particularly the green field exploration. Hence the research objective here is to reduce the cost of seismic acquisition while keeping the image quality intact.

This can only be achieved by introducing new technologies and changing the seismic exploration practice.

## Passive seismology

Utilization of ambient noise in brown fields for passive seismic imaging is an attractive option that has been only lightly investigated so far. Currently the utilization of single station recordings and the H/V method (horizontal to vertical component spectral ratio, like offered by Tromino) is used to help map the fresh rock by utilizing surface waves. Reconstruction of deeper sections is difficult and unlikely. The other way is to use large passive receiver arrays. The DEG has recently conducted a large-array passive seismic trial for imaging of mineral deposits in South Australia by utilizing a drill-bit and drilling noise. Reconstructed virtual shots using such noise are similar but below the quality of active seismic shots (Figure 3). This lower quality of the reconstructed seismic 3D shot record is due to the noisy environment of the surface receivers. Moving the receivers to drill holes would greatly improve the ability to utilize passive body waves (as opposed to surface waves used in most passive methods) for subsurface imaging.

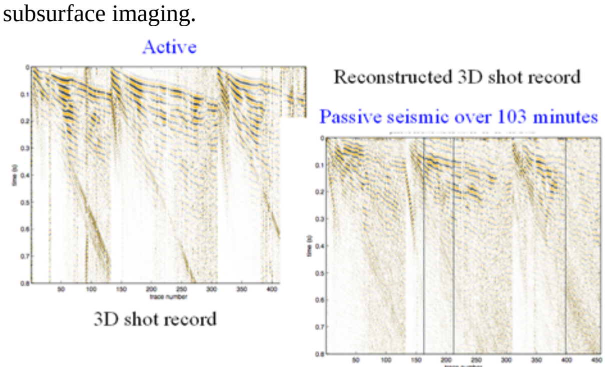


*Figure 3. Active seismic record along three parallel receiver lines (left) and reconstructed record from drill bit noise (right).*

## FWI

The current rapid pace of evolution of computing power has led to the feasibility of inverting the full recorded wavefield for elastic properties by minimizing the difference between forward modelling and field data. Such an optimization problem is still difficult in the presence of surface waves and the lack of a good initial model of the subsurface. These issues are overcome if we try to invert borehole data since there are no surface waves and the data provides the velocity profiles along the borehole, these act as a good starting point for the inversion process. We have performed several feasibility studies by using this approach of inverting borehole data with very promising results as demonstrated in Figures 3-4. A geological model of Sunrise Dam, Yilgarn Craton, is used for this study.

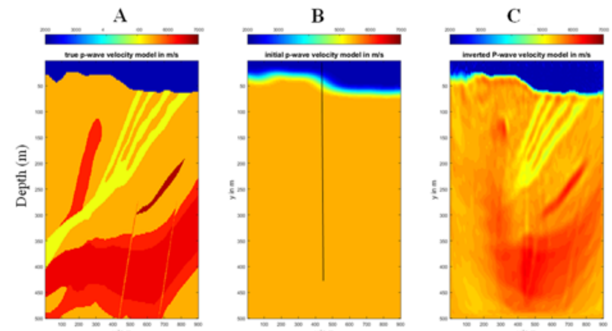


*Figure 4. FWI using 20 surface shots and a single borehole: A) geology, B) starting model and C) Inverted velocity field.*

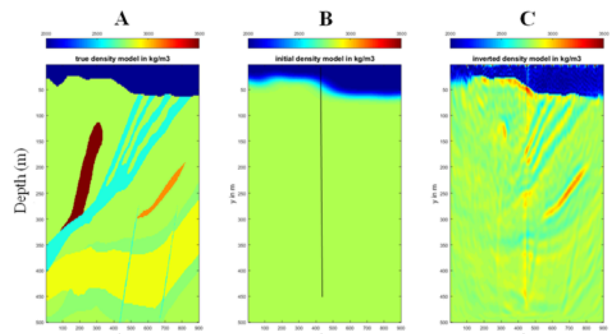


*Figure 5. FWI using 20 surface shots and a single borehole: A) geology, B) starting model and C) Inverted density field.*

A nearly continuous receiver space (0.5 m sampling) allows for accurate reconstruction of velocity and, more importantly, density field. DAS surveys may incorporate simultaneous recording of multiple VSP and/or cross-hole data and/or surface seismic followed by comprehensive pre-stack depth imaging. This approach has the potential for providing the highest resolution images often needed for mapping complex mineral deposits. This can be particularly effective for the cases of thick regolith, oxidized zones and multi-basalt flows, effectively reducing their devastating effect to the wavefield. Considering that a single DAS interrogator can record information from many kilometers of fiber optic cable, a multi well acquisition or borehole instrumented drill-site becomes feasible and inexpensive. Moreover fiber optic cables could be entrenched to replace surface receivers, producing very efficient and excessively high density 3D seismic data cubes (Figure 6).

In summary, DAS surveys incorporate simultaneous recording of multiple VSP and/or cross-hole data and/or surface seismic followed by comprehensive pre-stack depth imaging. This approach has the potential for providing the highest resolution images needed for mapping complex mineral deposits. A recent VSP experiment with DAS was conducted in South Australia. The results obtained are highly promising. A free-fall (375 Kg from 1.2m height) was used to generate a DAS-VSP data (Figure 7). The derived interval velocity profile is shown above the data so we can clearly identify zones where tube waves are generated. These zones correspond to a rapid change in P-wave velocity which, in hard rocks, is likely to be mimicked by S-wave velocity changes, resulting in generation of tube waves with amplitudes roughly proportional to the contrast in rock elasticity.

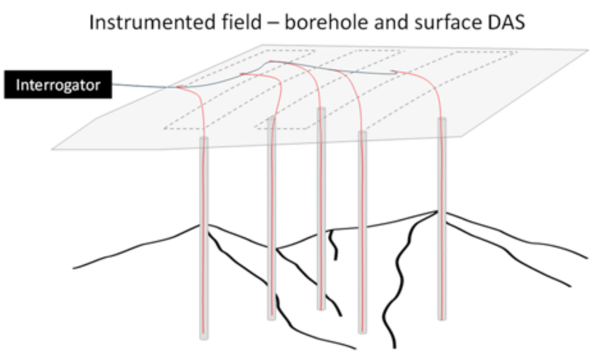


*Figure 6. An instrumented field: DAS is placed in boreholes and entrenched along arbitrary lines allowing for 3D VSP, 3D surface or a combined borehole-surface 3D imaging.*

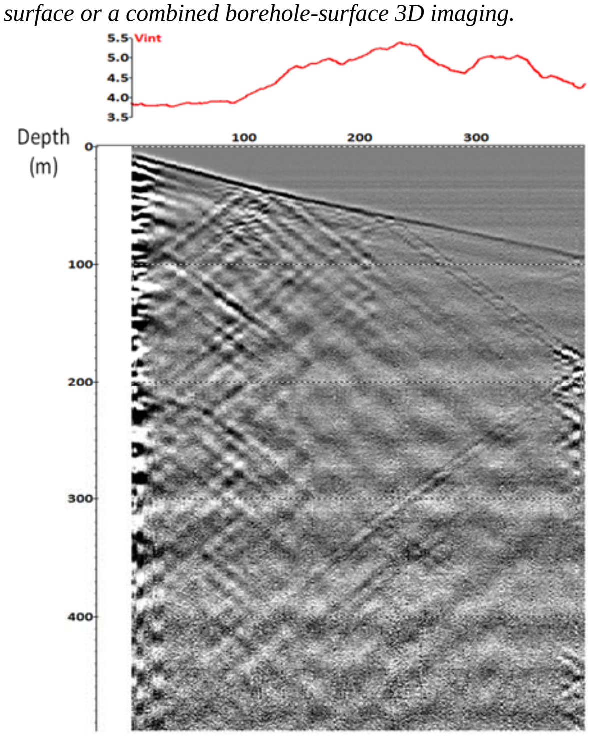


*Figure 7. Example of zero offset VSP data acquired by DAS. The red curve shows the measured P-wave velocity along the borehole (in km/s).*

The application of surface fiber optic recordings could be done in the form of a drag-along system. The technical implementation would need to be thoroughly investigated to overcome issues of coupling and directivity of such a system. Such a system would be a breakthrough in covering large areas at a fraction of a cost. It would be particularly useful for targeting depths of 0-500 m. The DEG has already made some advances and first tests in this direction.

## CONCLUSIONS

The application of seismic methods for mineral exploration has achieved numerous incremental changes over the last three decades. It has managed to overcome an intrinsically low signal to noise ratio by introducing changes into data acquisition practices. The utilization of single source/receiver surveys combined with a single broad band sweep enabled an increase in the data density for the same cost. Such practices allowed for proper sampling of steep dips and all body waves which in turn made the application of multi-channel filters more effective. To make seismic a method of choice for the exploration of mineral resources, a series of step changes are needed within data acquisition, data processing and data analysis approaches. The implementation of DAS technology (or equivalent inexpensive system) offers a possibility for high resolution imaging of brown fields in an inexpensive and efficient way. Extrapolation of the technology to the green fields could be envisaged through the drag-along systems and automated acquisition practices. Introduction of these new technologies could transform seismic into a mainstream method of the future!

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Paper 2

# Setting the Foundation – Integrating Seismic Reflection into Zinc Exploration Workflows

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## ABSTRACT

*This study presents the application of seismic reflection surveys within exploration programs for Irish-type zinc-lead deposits. The search space for Irish-type deposits throughout the Irish Midlands is becoming increasing deeper as a paucity of drilling has been undertaken beneath cover rocks adjacent to significant zinc-lead deposits. In order to locate deep drill holes, it is critical to understand major criteria fundamental to emplacement of Irish-type deposits. Mineral systems analysis (e.g. McCuaig & Hronsky, 2014) and Irish-type specific studies (e.g. Wilkinson & Hitzman, 2014) both suggest that proximity to major deep seated crustal faults is critical but that the geometry and interplay of these fault systems at shallower levels is likely a major factor in localizing mineralization. In this study, we present the case for employing seismic reflection as an early stage tool within Irish-type exploration programs with the goal of generating a complete structural-stratigraphic characterization of a project area prior to undertaking specific drill target testing. A general workflow is outlined starting with physical property analysis and touching on aspects of planning, budgeting, acquisition, and interpretation.*

## INTRODUCTION

For many decades, seismic methods have commonly been used in the petroleum industry due to their ability to image key sedimentary structures which are critical to the localization of oil and gas. Despite this ubiquitous application of seismic methods in the petroleum industry, the mining industry has not widely adopted the seismic toolkit at the early stages of exploration. Within the last 20 years, an increased number of case studies of near-mine applications of seismic reflection toward the detection of anomalies related to massive sulfide (e.g Malehmir, 2010, Eaton, 2003) and or localization of gold bearing fault systems (Pretorius, 2000) have been published. These applications are excellent examples of using seismic methods as a direct targeting tool for economic mineralization (usually within or near an operating mine) or for mine planning. In this paper, we explore the application of the seismic reflection method within an early stage greenfield exploration project. Specifically, we focus on the use of seismic reflection as an indirect targeting tool in the search for Irish-type zinc deposits.

In the Republic of Ireland, exploration for Irish-type zinc-lead (Zn-Pb) deposits has been active in the Irish Midlands since the discovery of the Tynagh deposit (Clifford, 1986) in 1961. Figure 1a shows the location of significant Zn-Pb deposits throughout the Irish Midlands. There have been numerous economic and sub-economic discoveries most of which lie proximal to basement sub-cropping (or near surface) locations (as horsts, anti-forms etc.) which represent the shallowest exploration opportunity. The potential to make additional discoveries in the Irish Midlands is still significant in the case that fertile zones lie under significant amount of post-mineral cover which can mask signals detected by traditional exploration methodologies. In these cases, potential deeply buried deposits are assumed to have similar characteristics to their shallower analogues. We present the major deposit characteristics within this paper.

Figure 2 shows the current state of all effective (test of potential host rock for a Zn-Pb mineralization) drill tests contained within the proprietary database owned by Teck Resources Ltd ('Teck'). At this country wide scale, it is clear there is significant potential to conduct exploration under cover rock throughout the Irish Midlands. However, due to uncertainty of the target depth and lack of corresponding information available, it is often difficult to generate quality targets under cover. The application of seismic methods at an early stage of exploration can help to identify prospective target areas which, in turn, would narrow the focus and timelines of exploration programs. However, seismic reflection is often not employed by the mineral exploration industry due to its high cost compared with other traditional geophysical methods. In this paper, we explore how the relationship between increased target depths and cost of drilling changes this perspective and presents a value proposition for seismic reflection. Once

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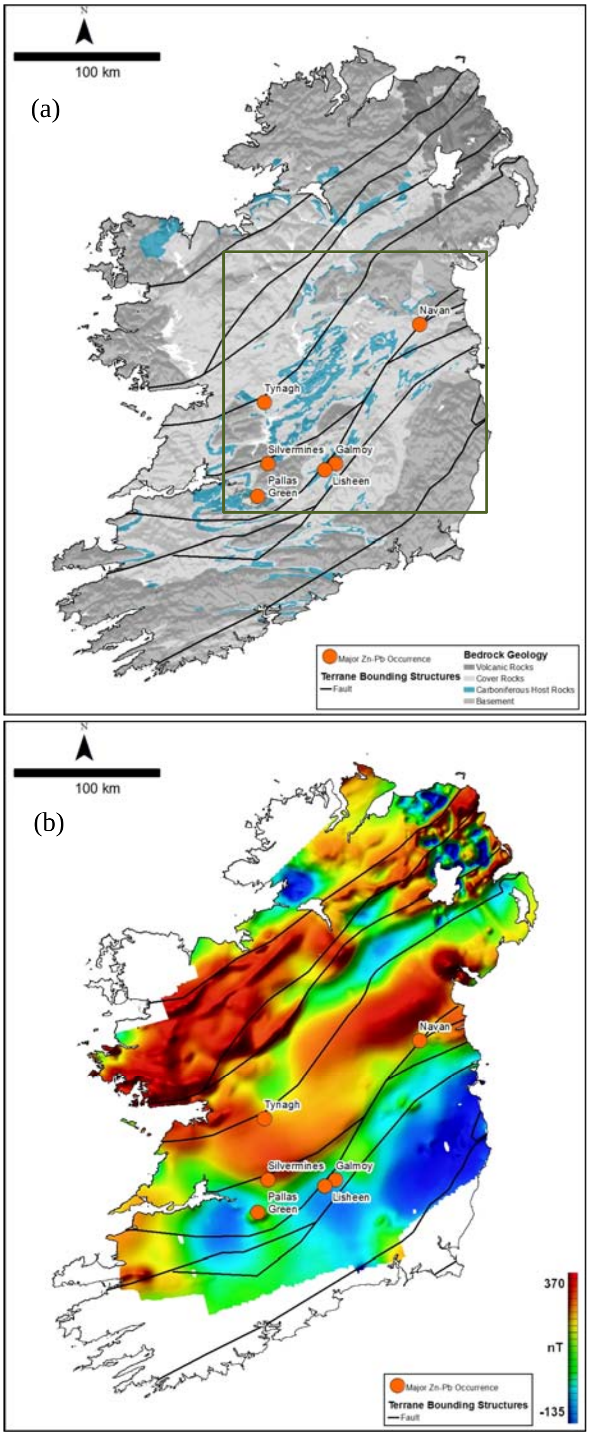


*Figure 1. (a) Simplified Geological Survey of Ireland (GSI) bedrock geology including major Lower Palaeozoic basement terrane bounding structures (Modified after Todd et al., 1991). Orange symbols show locations of major Zn-Pb occurrences. (b) Regional RTP magnetic image. Data merged from multiple GSI Open-File surveys. The general northeast structural trend and orientation of magnetic domains are observed to continue beneath covered areas in (a).*

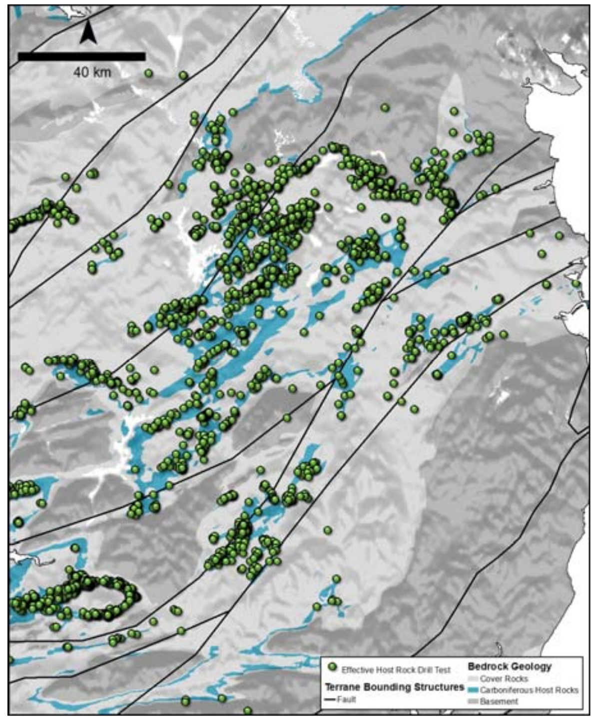


*Figure 2. Close-up of rectangle from Figure 1a. Irish Midlands scale GSI bedrock geology and basement terrane bounding structures. Green circles indicate drill holes that have effectively tested the Zn-Pb host stratigraphy. The majority of remaining untested host stratigraphy is located beneath cover rocks.*

data has been acquired, developing a workflow for interpreting the data and integrating with other geoscience data is important. It is critical to stress that the quality of on-shore seismic data can be extremely variable and much effort must go into considering preferred and alternative interpretations. We present examples of data from various project areas in Ireland and discuss strategies for interpretation and generation of an ultimate final product.

## IRISH-TYPE ZN-PB DEPOSITS

### General Characteristics

Irish-type Zn-Pb deposits are considered to have characteristics that set them apart from the typical sedimentary exhalative (SEDEX) and Mississippi Valley Type (MVT) end-members. Empirical aspects of Irish type mineralization are well documented (e.g. Ashton et al., 2015; Wilkinson & Hitzman, 2014; McCusker & Reed, 2013 Wilkinson, 2003; Hitzman et al., 2002; Reed & Wallace, 2001; Johnston et al., 1996) with major characteristics including:

- Relatively simple mineral assemblages consisting of sphalerite, galena, and pyrite/marcasite +/- tennantite, chalcopyrite, bornite, arsenopyrite with gangue phases of dolomite, calcite +/- barite, fluorite, quartz.

- Hosted by clean carbonate rocks of Lower Carboniferous (Tournasian-Visean) age and occurring in stratiform and stratabound bodies.
- Mineralization typically occurs proximal to extensional faults in either hanging-wall or foot-wall blocks.
- Mineralization is formed by a fluid mixing process: 1) cool, descending, hyper-saline seawater derived S-rich brine; 2) up-welling, hotter, S-poor, metal-rich hydrothermal fluid.

Because of the latter two points in particular, definition of major fault corridors is a key early stage objective in most exploration programs for Irish-type deposits.

## Stratigraphy

The rocks referred to in this paper are of Ordovician-Silurian, Devonian, and Carboniferous age. The north-west and south-east parts of the island of Ireland were sutured during the Caledonian Orogenic Cycle (Chew & Stillman, 2009; Todd et al, 1991). The geodynamic processes associated with these events created the basement foundation to the Carboniferous Basins that host the Zn-Pb Orefield.

Basement rocks are primarily of Ordovician-Silurian age and are characterized by volcano-sedimentary packages, and deep-sea turbidites. Unconformably overlying the basement is the Old Red Sandstone (ORS), or its facies equivalents. This unit is generally Upper Devonian in age in the south of Ireland but the diachronous nature of sedimentation means that the facies equivalents in the northern Irish Midlands are of Lower Carboniferous age. Lithologies here consist of red siliciclastic sandstones and green mudstones representing a fluctuating redox boundary in the sedimentary pile.

A northerly directed marine transgression during the Lower Carboniferous induced the onset of marine carbonate sedimentation. The Navan Group rocks (referred to as the Pale Beds or PB), host to the Navan Zn-Pb deposit, are characterized by flaser bedded siliciclastic rocks at the base which pass up-section to bioclastic, variably oolitic, packstones with intercalations of peritidal micrites with birdseye textures indicative of shallow marine deposition. The Moathill formation (referred to as Shaley Pales or SP) represents an overall deepening of the depositional environment, with lithologies becoming increasingly shale rich up-section to the base of the Ballysteen Limestone Formation (referred to as Lower Argillaceous Bioclastic Limestone or LABL). De Morton et al. (2015) consider black mudstones at the top of the Moathill Formation to represent a phase of extension in the basin inducing a phase of syn-rift deposition, particularly associated with northeast trending, reactivated, basement faults. Such faults are an important feature of Irish-type Zn-Pb deposits (Johnston et al., 1996). The Ballysteen Formation is characterized by nodular textured clean and argillaceous bioclastic limestones that are interpreted as toe-of-slope deposits. The Ballysteen passes up-section into clean, massively bedded mud-boundstones of the Waulsortian limestone, host to the Lisheen, Galmoy, and Pallas Green Zn-Pb deposits. The Waulsortian forms mound-like geometries reflecting the nature of sedimentation. This topography leads to lateral facies variations. Thus in certain areas, the Waulsortian is inter-digitated with nodular, argillaceous lithologies of the Ballysteen Limestone formation and in certain cases, is overlain by such lithologies. Where the latter is the case, these lithologies are assigned their own formation – the Upper Argillaceous Bioclastic Limestone (UABL).

Another significant tectonic event is marked by the base of the Tober Colleen, which overlies the Waulsortian/UABL (de Morton et al., 2015). Lithologies here are characterized by massively bedded black mudstones and burrowed mudstones. The Tober Colleen passes up-section to turbiditic packages reflecting sedimentation in a deep basin. Isolating the tectonic controls on host rock deposition is critical in assessing Zn-Pb potential in a given basin.

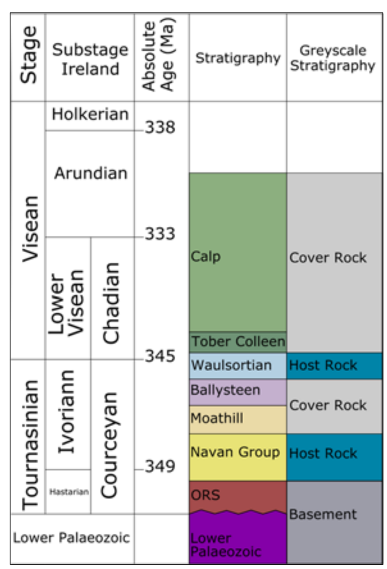


*Figure 3. Summary of regional stratigraphy modified after De Morton et al., 2015. Greyscale bedrock geology shown adjacent to detailed stratigraphy. ORS=Old Red Sandstone. For the purposes of later figures, the following terminology is considered equivalent: Ballysteen Fm = LABL, Moathill Fm = SP, Navan*

*Group = PB, Lower Palaezoic = Basement. The stratigraphic colour scheme from this figure is used in subsequent figures.*

### Discovery History

The onset of modern Irish exploration came in the early 1960s with the discoveries at Tynagh and Silvermines, which are both Waulsortian limestone-hosted deposits. Subsequently, the discovery of the giant Navan Zn-Pb deposit in the late 1960's generated significant interest in the Irish Orefield. Mineralization at Navan is hosted within the Pale Beds, part of the Navan Group – the lowest clean carbonate unit overlying the Ordovician-Devonian basement rocks. The current resources plus past production comprise 124.2Mt @ 8% Zn, 2% Pb (Ashton et al., 2016; New Boliden, 2017), hosted within a series of complexly faulted, tilted horst blocks foot-wall to a major sub-basin controlling normal fault (Ashton et al., 2015). Navan is currently the only known economic deposit hosted within Pale Beds rocks. Two previously operating mines at Lisheen and Galmoy, both Waulsortian limestone-hosted, had pre-mining resources of 22.3 Mt of 11.7% Zn, 2.61% Pb and 10 Mt of 12.7% Zn, 1.27% Pb respectively (Vedanta, 2015; Lowther et al., 2004) respectively. The largest known Waulsortian-hosted deposit is at Pallas Green in the Limerick District (44 Mt of 7% Zn + 1% Pb: Glencore, 2017).

Until recently, exploration in Ireland was focused on a relatively shallow search space (<500 m) and most of the effective drilling was concentrated around the edge of the cover rocks where direct detection methods are viable (e.g. gravity, pole-dipole IP, EM surveys). Exploration at depths >500 m challenges the efficacy of direct detection geophysical methods but opens an under-explored search space.

### Irish Type Deposits as Mineral Systems

McCuaig and Hronsky, 2014 suggest that mineral deposits are scaled examples of a range of Earth processes occurring over a range of temporal and spatial scales. They consider four critical components of mineral systems: 1) Whole Lithospheric Architecture; 2) Transient Geodynamics; 3) Fertility; 4) Preservation of Primary Depositional Zone. The first two components are relevant at the regional to camp scale. Deep-seated, vertically accretive structures connecting basement rocks to depositional sites are critical. Understanding the continuity and along-strike heterogeneity of deep-seated structures is important in order to target the potential for high-flux fluid conduits, which are a fundamental criterion for overall prospectivity. As such, a greater understanding of the structural continuity, evolution and connectivity between basement faults and overlying basins is absolutely critical in the exploration for Irish-type deposits. Defining this overall architecture, which controls the generation and level of interaction between some of the basic ingredients for Zn-Pb deposit formation

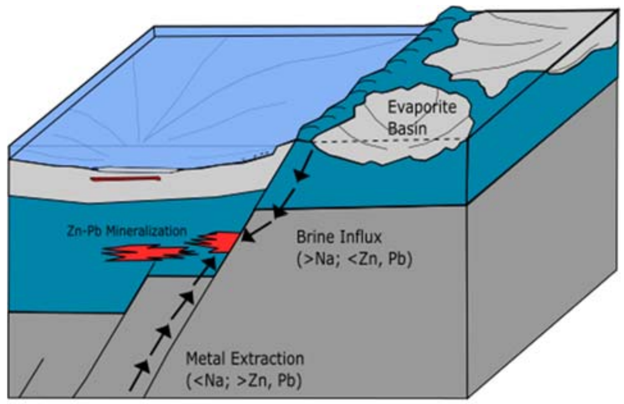


*Figure 4. Schematic fluid flow model modified after Wilkinson & Hitzman, 2014. Dense bittern bines flow down along faults where they are heated, decrease in Na and scavenge metals. Deep-seated, hydrothermal fluids are then expelled along faults where they mix with reduced sulfur-bearing brines at the trap site.*

(reactive host-rock development; brine generation and fluid flow; metal scrubbing; sulfate reduction; heat and energy flux; Figure 4), has been a major goal of Teck's recent exploration programs and has led to the use of seismic reflection as an early-stage program activity.

## TRADITIONAL EXPLORATION METHODOLOGY

### Geological and Geochemical Methods

Exploration for and definition of Irish-type Zn-Pb deposits can be very drill intensive, as the deposits often have a relatively small footprints, complex geometries and can exhibit significant grade variations over short distances. For example, recent exploration at the Pallas Green deposit has required 370 km of drilling in 735 holes to define a resource of 44 Mt of 7% Zn + 1% Pb (Glencore, 2017).

Stratigraphic and structural mapping and logging are critical geologic tools in the exploration of Irish type Zn-Pb deposits; however, in general, the Irish Midlands do not present an opportunity to map on surface due to the lack of outcrop. As a result maximizing stratigraphic knowledge from re-logging of historic drill core is an important element of developing 3-dimensional geological knowledge.

Historic exploration for shallowly buried deposits in Ireland relied heavily on soil geochemical methods. These methods have had variable success rates due to various factors including soil type, depth of cover and target depth. More recent exploration has employed other geochemical techniques including litho-geochemical and micro-analytical methods; however, these require drill testing of permissive stratigraphic units. Specific case studies can be found in Marks, 2015. As exploration programs search for deeper economic deposits in Ireland (>500m), geochemical methods can be applied subsequent to obtaining contextual understanding from the mineral systems approach. In this case, subtle anomalies from distal Zn-Pb mineralization and characterization of fertile fault systems will more likely be recognized.

### Geophysical Methods

The majority of the rocks of interest in the Irish Midlands are sedimentary and, as a result, have subtle physical property differences. Figure 5 shows the physical property contrast for common surface methods (gravity, magnetics, resistivity, induced polarization) with respect to major stratigraphic units. These values have been collected by successive exploration programs by Teck and have been acquired using industry-standard downhole and drill core methods. Important comments with respect to each method are outlined below:

- Gravity: Downhole density values (Figure 5a) surveyed indicate that most stratigraphic units have virtually no density contrast between them (with a median around 2.67 g/cc). In this dataset basement values also do not record significant contrast although it is expected that density of the basement rocks would increase with depth. One of the potential host units for Zn-Pb mineralization (Waulsortian limestone) is generally more dense (being extremely calcareous and massive in nature). Outliers in this unit represent mineralized samples and can approach 3.2 g/cc (not shown on the plot).
- Generally, all units are relatively non-magnetic and demonstrate significant overlap in magnetic susceptibility (Figure 5b). Basement samples are higher in magnetic susceptibility in general and it would be expected that variably aged magnetic intrusions would be present within basement units.
- Resistivity (Figure 5c) of most units is around 1000 ohm-m. Fresh Waulsortian limestone can be very resistive in a small sample measurement due to its high carbonate content coupled with textural considerations (e.g. calcite-filled cavities). Outlying low resistivity values from Waulsortian limestone represent mineralized samples.
- Chargeability (Figure 5d) values reflect the clean nature of the sedimentary units with most units having medians close to or less than 10 msec. Some units are pyrite rich in general (i.e. SP) and outlying values occur in other units including cover and LABL. This reflects the occurrence of diagenetic pyrite formation in these units. Mineralized samples in the Waulsortian limestone are extremely chargeable.

The observations above present some challenges in using traditional surface based techniques for deeper exploration purposes. Firstly, potential fields techniques will present very subtle (or below noise level) anomalies as the distance between the source and the sensor increases. Although strong potential field anomalies that define basement zones can be detected near surface, these become more diffuse and less coherent sub-cover. Direct detection methods such as induced polarization will struggle to penetrate current to deeper target levels and will encounter false positives from diagenetic pyrite responses nearer surface. In addition, surface surveying in Ireland encounters many anthropogenic obstacles and can be prone to significant noise levels.

## SEISMIC REFLECTION APPLICATION

The need to model a structural-stratigraphic architecture from a mineral systems perspective coupled with the limitations of traditional exploration techniques provide a technical basis for the application of seismic reflection surveys in Irish-type exploration programs.

### Seismic Stratigraphy

De Morton et al (2015) provide a comprehensive summary of the stratigraphy of the North Irish Midlands from a seismic reflection perspective. Here, we present well logging data collected using a standard sonic velocity tool (slim line, triple receiver) and processed for formation velocity in metres per second. Figure 6 shows the compressional velocity (p-wave) data from fifteen Teck drill holes (over 9,000m of logging) throughout the Irish Midlands. Contrary to other methods, the median p-wave velocity shows adequate contrast between units suggesting that seismic reflection would be able to discriminate stratigraphic units (maximum reflection coefficients up to 10%, assuming constant density of 2.67 g/cc). Some particular points of note from the data set are:

- Although there may some internal reflections within the cover sequences, the first major reflection is likely to occur at the base of the cover units (either at the top of the Waulsortian limestone if present, or toward the top of the Shaley Pales or Pale Beds.
- Limited sampling of the basement rocks is available, but seismic reflection should distinguish the base of the prospective (Courceyan aged; see Figure 3) sediments.

- When present in sufficient thickness, Waulsortian limestone should produce high amplitude reflections.

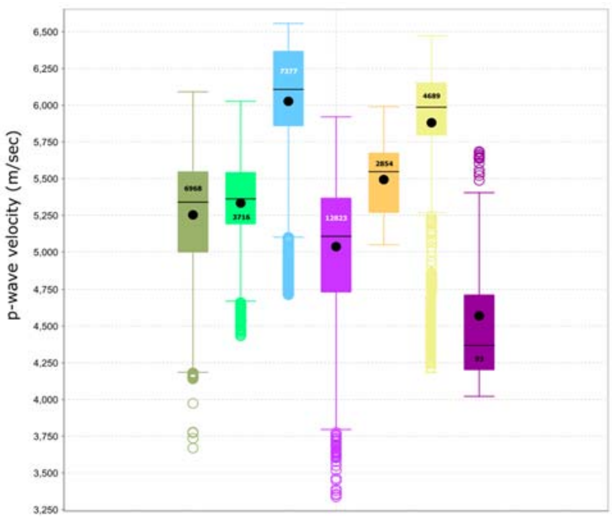


*Figure 6. Compressional sonic velocity logs from fifteen in-situ well logs grouped by formation. The data is presented as box and whisker plots with the inner quartiles defined as a solid box and the outer quartiles as lines extending from the box. Medians are presented as a solid line within the box and mean values as a dot. The number of samples in each dataset is plotted in each box. Outliers are shown as individual plot points. Contrast between the cover (green units) and Waulsortian (blue) and between Pale Beds (yellow) and basement (deep purple) is very significant and would yield reflection coefficients up to 10 percent. The colour table is from Figure 3 - light green values denote Upper ABL and are part of the cover sequences.*

### Cost Benefit

The application of 2D reflection on shore surveys can be perceived as a high-cost proposition for early stage exploration. However, as depths of investigation increase the cost benefit of the seismic surveys is supported by analysis of the offset in drilling costs. Recent Teck exploration programs in Ireland have been conducted on packages of contiguous licenses along key structural trends with significant untested potential. Typically, these tenure packages measured about 20km x 20km. In Figure 7, we consider average costs of 2D reflection surveys from Teck surveys from 2011-2017 against typical drilling costs in the Irish Midlands. The data is presented as the number of drill holes which could be completed for the equivalent seismic program. For the considered tenure package, 120km of seismic reflection would permit a full structural-stratigraphic interpretation (5 lines + 1 tie line). Other cases are shown for consideration of smaller seismic programs. Each case is considered against an average drill target depth of 250, 500, 750 and 1000m. For shallow 250m depth drilling, almost sixty holes could be completed for the cost of 120km of seismic. However, for 1000m target depths less than fifteen drill holes could be completed. Also, the cost of one 20km seismic line would offset only five 1000m

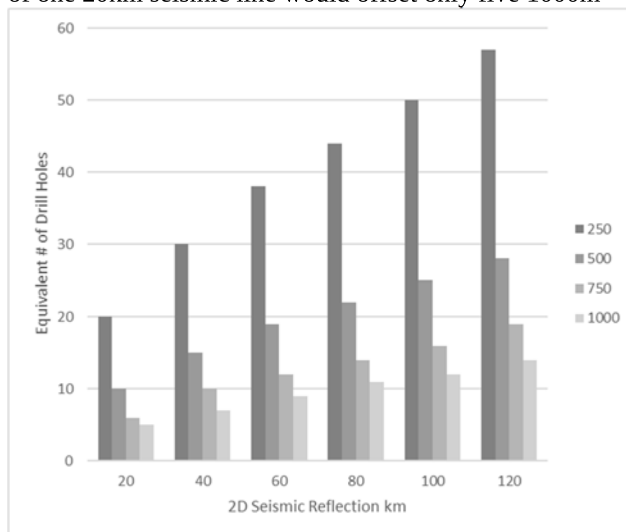


*Figure 7. Number of drill holes which could be completed for the cost of a variable amount of seismic reflection. The drill holes and seismic data are calculated based on average all-in costs of Teck programs and are shown for 4 different average target depths (250, 500, 750 and 1000 m). As depth of target increases, the cost benefit of acquiring seismic data increases as the equivalent number of drill holes is much smaller.*

holes. Considering that the tenure package is 400 $km^2$, it is unlikely that fifteen holes (or less) would adequately locate and test the best deep targets. It is clear that the investment in early stage seismic reflection data would deliver a clear cost benefit to a project exploring at deep levels. This would be accomplished by ensuring any drilling is (a) targeted in the most prospective structural and stratigraphic target areas and (b) returns useful and contextual information to guide further exploration targeting beneath cover.

### Acquisition Considerations

There have been previous attempts at using seismic methods for both direct detection and stratigraphic modelling (i.e. European Union, 1993; Vermeulen, 2000) but the data was typically of low fold. In contrast, recent Teck 2D reflection surveys were designed to have high fold at the depths of interest (typically > 500m). The survey data was collected with a 6km spread with sources every 20m and receiver groups (typically up to 12 receivers per group) every 10m. The resultant nominal fold of the survey data was 150 (ignoring any gaps due to cultural installations and permitting refusals). A cabled system was preferred to ensure adequate onsite QA/QC to monitor signal quality (specifically due to ground conditions), and the ambient noise field (due to weather and/or cultural interference). Sources were generated by sixty ton vibrators which were limited to drive levels as low as 15% depending on infrastructure. At times two vibrators were used simultaneously to ensure an adequate source for signal at long offsets. Sweep lengths and stacks were changed as the program progressed to find the best tradeoff between signal quality and program cost. Careful acquisition of the data was the most important part of the program and yielded interpretable data products for the majority of the lines. Teck has collected over 400 line km of seismic reflection data on 25-30 lines (some lines were merged over multiple programs).

## Data Quality & Interpretation

It should be emphasized that the application of on-shore seismic reflection does not guarantee unambiguous results. In Figure 8, we present a sample of different data qualities, which we term high, medium, and low quality. All data presented is depth converted and post-stack migrated. Dip move-out was performed on all sections prior to migration. Depth conversion was applied using smoothed interval stacking velocities from the processing and has been verified against known drill holes for accuracy. Generally, depth errors are less than 10m. The goal of the interpretation step is to identify major syn-sedimentary faults across the seismic lines, and to identify key stratigraphic surfaces which are consistently present. In general, this includes the base of the cover sequences (all stratigraphy above the Waulsortian), the top of the Pale Beds (or more carbonate rich units near the Pale Beds) and the top of the crystalline basement. Interpretation in Ireland is aided by two main factors: (1) a strong stratigraphic understanding due to the history of work in the district, which allows for a reasonable expectation of seismo-stratigraphic response, and (2) a plethora of historic drilling which is generally shallow in nature but defines sub-cropping units.

### High Quality Data

In general, high quality data is obtained over normal overburden (lower peat content) conditions where the sub-cropping unit is generally well-bedded and a minimum thickness. These conditions form a buffer (in time) for signals from deeper reflections to be recorded without interference from ground roll, distortion, other surface waves or arrivals from shallower, steeply dipping stratigraphy. Figure 8a shows an excellent example of high quality data. In this section the base of the cover is well imaged as a major reflection across the line, and the Pale Beds unit is imaged as a series of reflections sitting above a featureless, incoherent basement (consistent with its steeply dipping nature). Faults are easily identifiable and analyzed for their growth history. One major syn-sedimentary fault is evident on this line and its growth, throw, geometry and other characteristics can be compared analytically with adjacent lines to determine whether a target zone exists. It should be noted that the section presented is over 5 km long and no drilling would be required to confirm any of the interpretation. Given that this high quality seismic data permits a full interpretation, follow-up work to assess the prospectivity of the region can be extremely focused and conducted with contextual understanding. From an exploration prioritisation perspective, decisions on projects and land tenure can be accelerated with this data in hand.

Even on this high quality section, the importance of the shallow cover can be seen. On the right hand side of Figure 8a, a well bedded unit is seen to be thinning out to the centre of the section. Once this well bedded sub-unit of the cover thins out, the upper section is imaged less clearly on the left hand side of the section.

### Medium Quality Data

Medium quality data is often obtained over more variable overburden conditions and when the sub-crop may be more complexly bedded (with overlapping or reefal textures). Both high quality and medium quality data are usually representative of a predominantly 2-D structural environment. Figure 8b shows a typical example of medium quality data. In contrast to Figure 8a, it is not possible to interpret this entire line without a significant degree of uncertainty. Basement depths and the Pale Beds unit are generally interpretable across most of the section but cannot be linked across an inferred major fault. Two minor faults are inferred on the section but their timing cannot be determined. The major growth fault on the section is recognizable by the change in dip of the stratigraphy on either side. However, on the hanging wall side the depth to the stratigraphy of interest is not clear. Medium quality data such as Figure 8b gives good insight into the sedimentary section but generally requires additional drilling information to complete the interpretation. In this example, two drill holes to the centre and left of the section would be required to complete the interpretation (Figure 8b star symbols). In Ireland, there is a wealth of old drill hole information available which also can be leveraged in the interpretation step.

### Low Quality Data

Low quality data is often obtained due a combination of overburden variation (depth, composition, presence of peat bogs) and rapid variation in stratigraphy and structure over short distances. These environments are often complicated in 3-D and may be most favorable settings for Zn-Pb deposits due the potential for increased fracturing of the sedimentary column resulting in increased permeability. Figure 8c shows an example of low quality data. It is difficult to interpret any significant stratigraphic unit or fault across the section although small segments of consistent reflections are imaged. Two drill holes are shown on the section (Figure 8c, D-1 and D-2), both of which were drilled pre-seismic. Drill hole D-1 was drilled into a thin cover unit followed by ~150m of Waulsortian limestone. There was evidence of minor mineralization (sphalerite, galena) in this drill hole. Subsequently, drill hole D-2 was drilled as an offset to D-1 following up the minor mineralized interval. This drill hole encountered almost 1000m of cover, followed by a short <50 m interval of Waulsortian limestone. A fault was encountered near the base of this drill hole. These two drill holes can be used to infer the presence of a major fault. The seismic data does support this interpretation; however, it is difficult to precisely draw the location and geometry of the fault. It is possible that this major fault is trending oblique to the azimuth of the seismic section. In areas of extreme complexity such as Figure 8c, significant drilling and other corollary information (gravity, magnetics, etc.) must be used to assist in building an interpretation. In areas of specific interest, 3-D seismic surveying would be an excellent tool to image the complex fault systems. This example illustrates how difficult it would be to undertake exploration in these settings without seismic data. Drill hole D-2 was sited without an understanding of the scale and geometry of the major fault.

### Final Products

Once the interpretation stage is complete, the generation of a full 3-D model of various stratigraphic surfaces, constrained to fault interpretations, is created. This is accomplished by digitizing all stratigraphic horizons and fault traces into the Kingdom® seismic software. Specialty seismic software packages offer a multitude of features to assist with the 3-D modelling process. Significant time must be invested to train staff on the use of the software to ensure full value of the dataset is unlocked.

Figure 9 is an example of one finished 3D product for a Teck project in Ireland. In this image, the top of the Pale Beds unit is displayed and is constrained to a complex fault network. Several major basin bounding faults have been identified as well as several areas where fault displacement is relaying from one fault strand to another. These types of observations allow subsequent target definition work and drill testing to focus on areas with the highest potential to host a Zn-Pb mineral deposit.

## SUMMARY

In this study, we have shown that deep, sub-cover exploration for Irish-type Zn-Pb deposits in the Irish Midlands can be assisted by new exploration approaches to manage increased technical risk. Beneath cover rocks little information exists about the depth to potential target stratigraphy and location of key structural elements required for deposit formation. In these cases, a value proposition can be made to employ early stage seismic

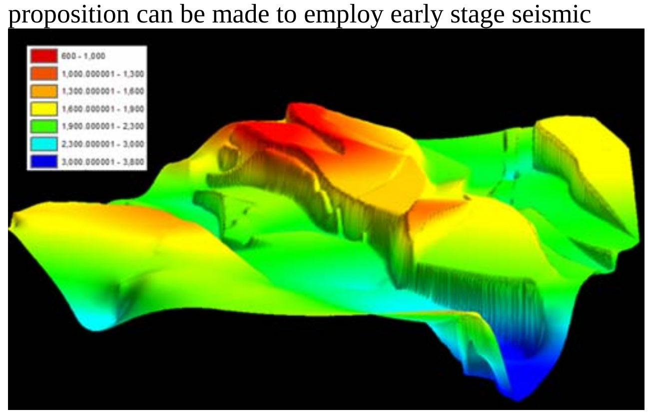


*Figure 9: Example of final product from structural – stratigraphic modelling process. Shown is the top of the Pale Beds coloured by depth (in metres) from surface. The area shown is approximately 20x20km and the interpretation was generated by five 2-D seismic reflection lines traversing the project. A drill hole dataset consisting of historic drilling across the project was also used but the majority of the drilling was shallow in nature.*

reflection programs to focus costly deep drilling. Significant effort must go into planning and executing a seismic program properly to ensure that data quality is adequate. Interpretation of the data can range from easy to difficult. In the latter case, an integrated approach may be necessary to extract the most appropriate interpretation for the project. Available drilling and other geophysical methods can be helpful in guiding interpretations. Ultimately, targeted drilling can assist in unlocking the value from the seismic dataset.

The ultimate product from the seismic survey is a full 3-D rendering of the major stratigraphic units constrained to fault geometries. As predictive studies for deposit localization emerge, this approach will lay a foundation for exploration, which could not have been generated in equivalent detail or quality by any other geophysical method.

## ACKNOWLEDGEMENTS

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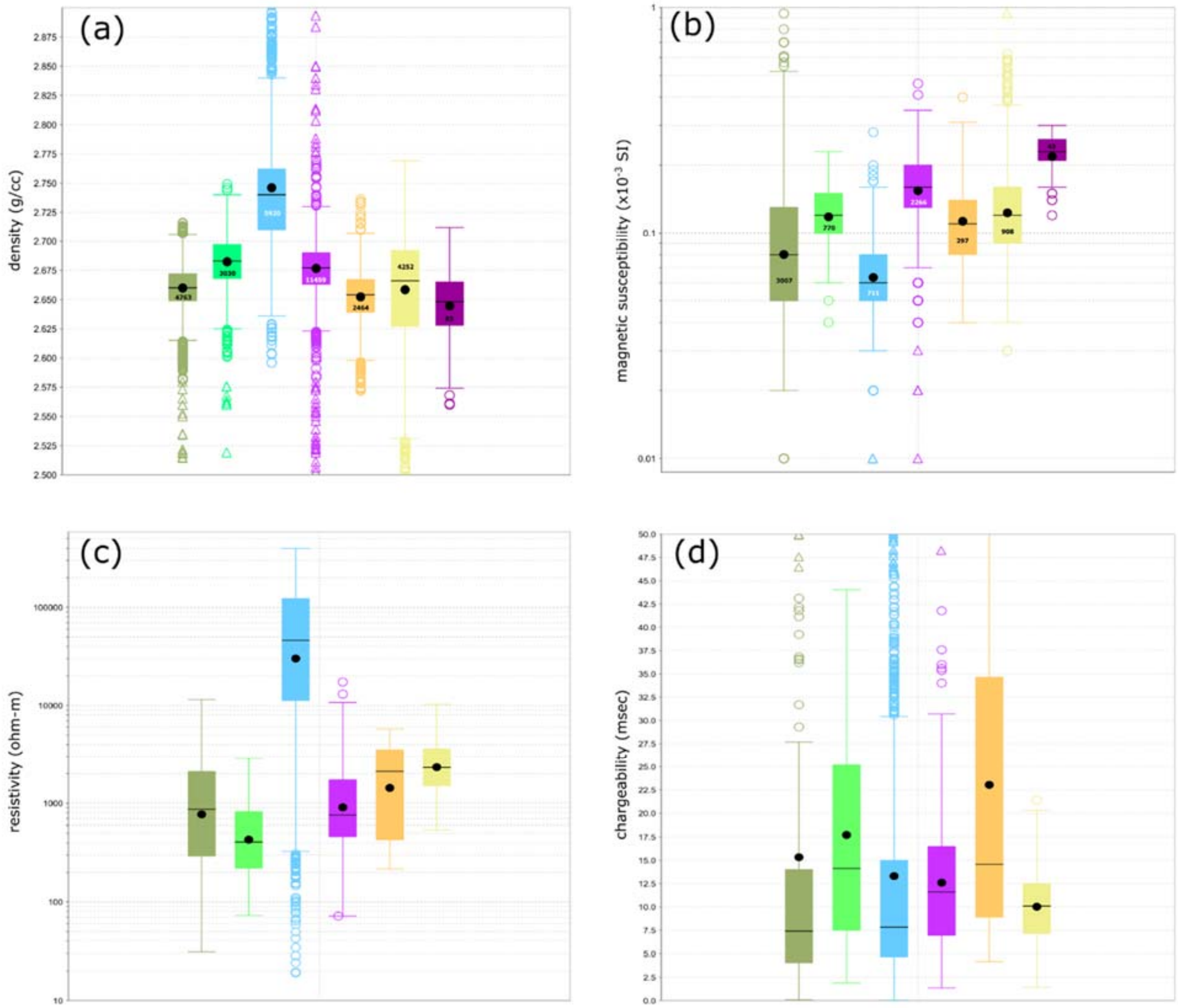


*Figure 5. Physical property analysis of Irish stratigraphy. Colour table is taken from Figure 3. Light green values denote Upper ABL and are part of the cover sequences. The data is presented as box and whisker plots with the inner quartiles defined as a solid box and the outer quartiles as lines extending from the box. Medians are presented as a solid line within the box and mean values as a dot. The number of samples in each dataset is plotted in each box. Outliers are shown as individual plot points. (a) Density dataset collected from well logging fifteen drillholes using a Cs-137 source. (b) Magnetic susceptibility taken from hand sample measurements using a KT-10 metre. (c) Resistivity data from a downhole probe with a 4m pole-dipole configuration. (d) Chargeability measurements taken from downhole probe with a 4m pole-dipole configuration. See main text for a detailed discussion of the results.*

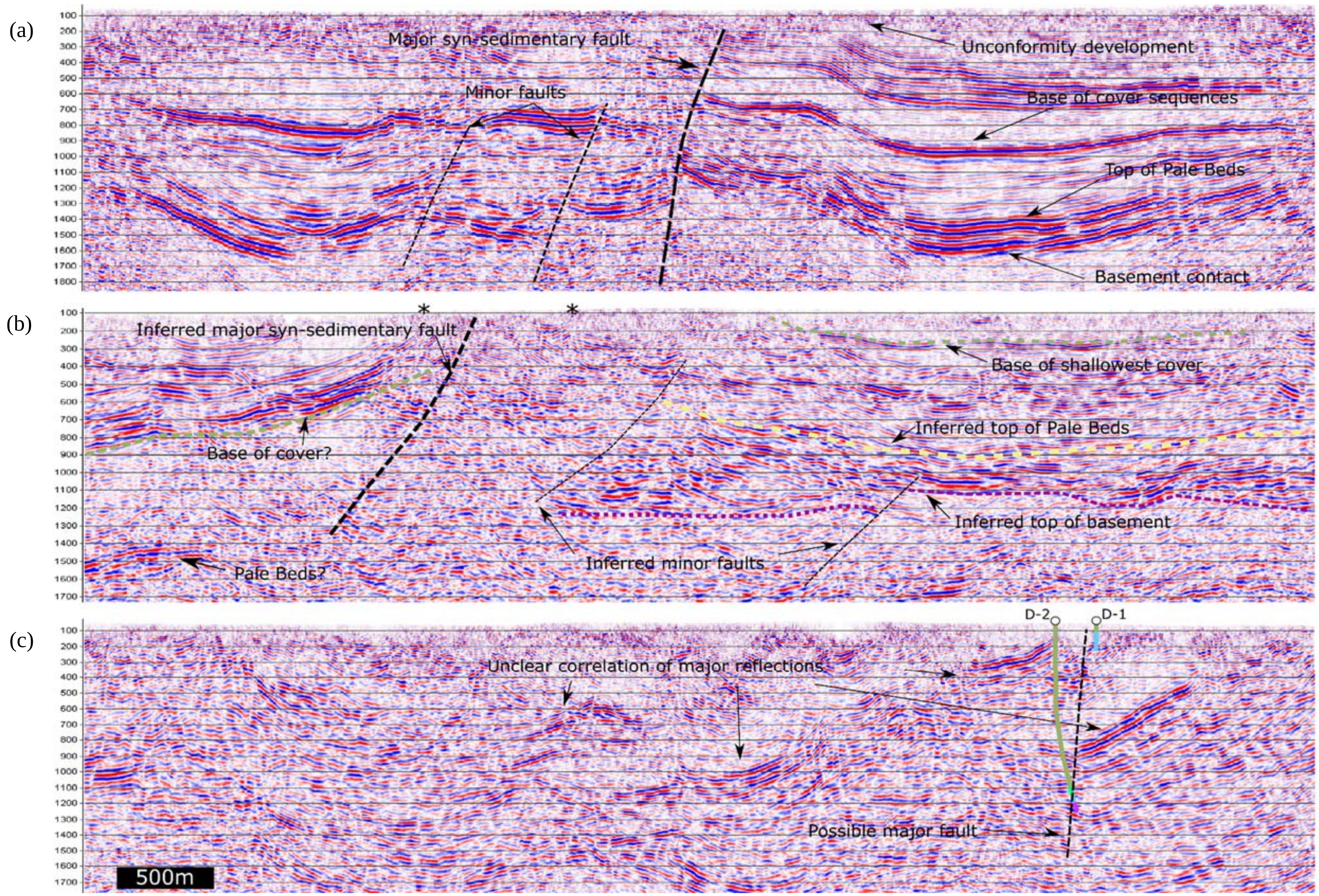


*Figure 8: Examples of seismic data quality. All data is depth converted with depth from datum on the vertical axis. Sections are depth exaggerated at 140%. (a) High quality data with major stratigraphic and structural interpretations noted. (b) Medium quality data with main stratigraphic interpretations annotated. The location of two drill holes required to complete the interpretation is denoted by stars at the top of the section. (c) Low quality data with drill holes D-1 and D-2 annotated and coloured by major formation (colour table from Figure 3). See main text for a more detailed explanation.*

Paper 3

# APPLICATIONS OF SEISMIC METHODS AS A TOOL FOR URANIUM EXPLORATION AND MINE PLANNING

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## ABSTRACT

*Seismic applications in the Athabasca Basin have become more common in uranium exploration over the last decade and have been highlighted with a number of challenges, failures, and successes. This paper reviews some of these methods as they have been applied to various stages of uranium exploration and mine planning at Cameco Corporation.*

## INTRODUCTION

The Athabasca Basin, in northern Saskatchewan, Canada, has been the site of over five decades of uranium exploration; this basin is still considered to be the foremost exploration ground in the world for unconformity related uranium deposits. As exploration advances to deeper parts of the basin, there are increasing challenges related to both exploration targeting and and mine development requiring closer attention. Deeper penetrating geophysical techniques are more frequently being sought to assist in solving some of these challenges. Seismic methods are an obvious choice, but have had a slower acceptance due to financial, logistical, and technical challenges inherent to the local geology and the relatively long turn-around times needed for data processing and interpretation. Despite these challenges a number of seismic surveys have been undertaken by companies in the basin, and there is a growing understanding on how and when they can be applied to explore for unconformity uranium deposits and assist in mine development. To date, the application of seismic methods at Cameco has focused on later stage exploration and geotechnical, mine-related projects within the eastern Athabasca Basin (Figure 1).

## GEOLOGY

The Athabasca Basin straddles the Rae and Hearne provinces of the Canadian Shield and is filled by flat lying, late Paleoproterozoic to Mesoproterozoic Athabasca Group sedimentary rocks occupying an easterly elongated basin approximately 400 km by 200 km (Figure 1). In the eastern portion of the basin, quartz-rich sandstones and conglomerates comprise the Manitou Falls Formation at the base of the Athabasca Group. They unconformably overlie steeply-dipping Paleoproterozoic and Archean rocks of the Wollaston and Mudjatik lithostructural domains within the western portion of the Hearne Province. The majority of known uranium deposits of the eastern Athabasca Basin are situated within the Wollaston – Mudjatik transition zone, comprised mainly of metasedimentary rocks and granitoid gneisses. The metasedimentary sequence includes graphitic and non-graphitic pelitic and semipelitic gneisses, quartzofeldspathic gneisses, metaquartzite and calcsilicate gneisses (McGill *et al*., 1993).


*Figure 1: Athabasca Basin, Saskatchewan Canada.*

### General Athabasca Unconformity Exploration Model

Uranium deposits in the Athabasca Basin are genetically associated with graphitic basement faults initially formed under ductile to brittle-ductile conditions during the Trans-Hudson Orogeny, reactivated after the deposition of the Athabasca Group (Jefferson *et al*., 2007). Currently, there are no proven geophysical methods for directly detecting uranium mineralization at depth. Thus, innovative exploration tools are needed to supplement traditional prospecting (Powell *et al*., 2007). Traditional methods of geophysical exploration also suffer from a decrease in resolution with increased depth (>500 m). Given their relatively small size (10-50 m wide by 100-1000 m long), the challenges in targeting uranium deposits increase significantly at large depths (O'Dowd *et al*., 2007).

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Figure 2 presents a general schematic of the unconformity exploration model in the eastern Athabasca Basin highlighting the areas of focus for seismic applications presented in this paper. Seismic methods, depending on their design, have the ability to map (in detail): 1) glacial overburden thickness, 2) unconformity topography, 3) post-Athabasca structures, and 4) potential alteration zones surrounding the deposits, all of which can greatly impact various stages of exploration and mine development strategy.

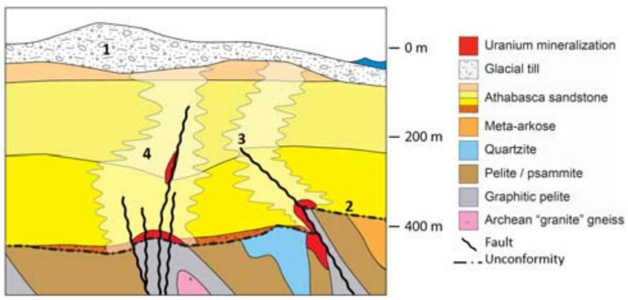


*Figure 2: Unconformity exploration model schematic. 1) Glacial overburden; 2) unconformity topography (offset); 3) Post-Athabasca structure; 4) alteration zone*

## SEISMIC METHODS APPLIED IN THE ATHABASCA BASIN

The following sections are divided up by technique as applied to the various areas identified in Figure 2, moving from mapping shallow overburden with passive seismic methods, mapping of the unconformity using 2D seismic survey profiles, directly imaging sub-vertical post-Athabasca sandstone structures using borehole seismic techniques to mapping large spans of unconformity topography and deep alteration cells around deposits using full 3D seismic programs.

### Passive Seismic: Glacial Overburden Mapping

The majority of the Athabasca Basin is covered by glacial till deposited by the late Wisconsian glaciation event (Campbell, 2007). Thicker accumulations of glacial outwash influence many types of geophysical data and pose significant logistical difficulties during diamond drill programs, increasing cost. Due to the presence of drumlins and overburden troughs the till can vary in depth between 0 to 200 m (Figure 2, #1).

Drilling through significant overburden thickness (>30 m) can be timely and costly, thus having a good understanding of the glacial cover in an area of exploration can be useful prior to finalizing the location of drillhole collars. In addition, the amplitude and wavelength of gravity signatures due to alteration in the underlying sandstone are comparable with that of variable thickness of glacial sediments, rendering the gravity signature of the overburden indistinguishable from potential underlying alteration cells. Passive seismic is used as a method for mapping the thickness of the overburden to mitigate some of these challenges (Fitzpatrick and Keller, 2016).

Traditionally regarded as a nuisance by seismologists, seismic noise has been shown from physical acoustics to be rich in information on the local structure of the subsoil. Since noise is always present and exists everywhere, it acts as a convenient exploration tool to map the overburden thickness variations. The horizontal-to-vertical (H/V) ambient-noise seismic method is a novel, non-invasive technique that can be used to rapidly estimate the depth to bedrock (Lane et al., 2008). The method assumes a strong ($\geq$ 2:1) contrast in the acoustic impedance (product of material density and seismic velocity) of the bedrock and the overlying layer of sediments. Any errors are directly proportional to the estimation of thickness and existing drilling should be used, when available to calculate layer velocities. The method becomes ineffective in geologic settings where the assumption does not hold, such as sites where there is gradational cementation, deep weathering, or strong heterogeneity. Assumptions are the geological materials have consistent velocities. Figure 3 presents the interpretation of passive seismic data with the geological interpretation from drillholes, which were used to estimate a constant velocity for the overburden. The methodology is cheap to deploy and requires minimal training for field acquisition, keeping impact on program budget at a minimum. Besides, optimizing collar locations for pre-season planning in areas with variable overburden thickness, passive seismic results also provides geometric constraints for modelling of other geophysical data.

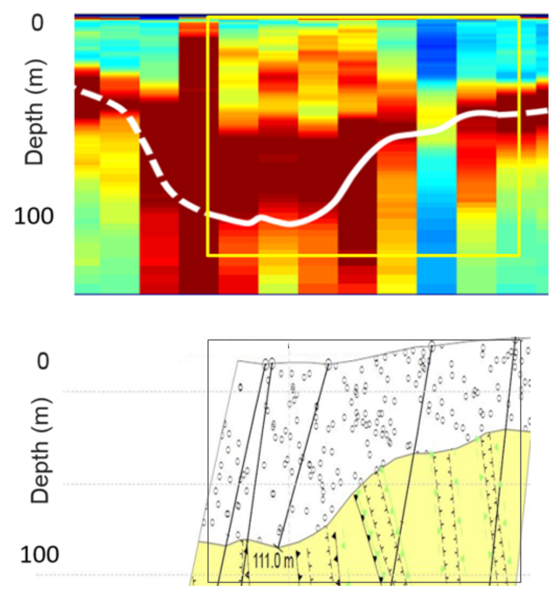


*Figure 3: H/V curves converted to depth along with bottom of overburden interpretation (top) and geological cross-section of glacial overburden overlying the bedrock sandstone, as defined by drilling (bottom) on L3800N on the Mann Lake project.*

### 2D Seismic Profiles: Unconformity Mapping

A number of 2D seismic profiles have been completed by exploration companies and government sponsored scientific initiatives (i.e. Hajnal, 2008 and White *et al*., 2005), with the main objective of characterizing the sandstone – basement unconformity contact and possible offset associated with exploration relevant post-Athabasca sandstone structures. (Figure 2, #2). Obtaining a detailed understanding of the location and nature of the unconformity contact is significant to uranium exploration given that a majority of the uranium deposits in the Athabasca Basin have an unconformity expression of some type.

There are a number of logistical and technical challenges when conducting surveys in the Athabasca basin including:

1. Variable thickness of glacial overburden, hindering the collection of high quality, high frequency seismic data
2. Much of the surface is covered with lakes and swamps, dictating that data collection occurs during the winter season
3. Extreme cold weather conditions during winter months

In addition to the logistical challenges, technical ones such as the inherent character of the sandstone units provide imaging and interpretation challenges. The Athabasca group sandstones in the eastern portion of the basin are comprised of interbedded quartz-rich units deposited in a fluvial environment. Few continuous horizontal reflectors have been preserved in the sandstone, thus the ability to interpret offset and structures is limited.

The EXTECH IV Athabasca uranium multidisciplinary study (Jefferson, 2007) of northern Saskatchewan and Alberta included seismic studies at the McArthur River Mine site, a joint venture between Cameco Corporation (69.805%) and AREVA Resources Canada Inc. (30.195%) (Hajnal et al., 2002, Mwenifumbo et al., 2004, White et al., 2005, and Gyorfi, 2007). This included two regional seismic profiles, 2 high-resolution lines and a 2.5D seismic survey. The survey specifications and results of the high-resolution 2D seismic survey are described in White et al. (2005).

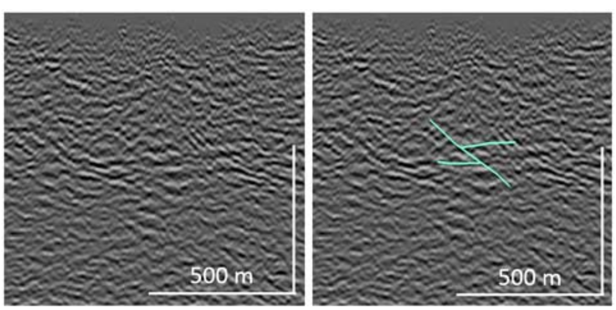


*Figure 4: Segment of high resolution line 12, from EXTECH IV shot south of the McArthur River Mine. The same section is presented on the left and right. The right image identifies the location of the P2 fault and the unconformity on either side of the fault, as defined by drilling.*

Figure 4 displays an example extracted from high resolution Line 12 which transects the P2 fault, the host structure of the McArthur River deposit, which has over 80 m of offset proximal to the deposit. This image highlights the lack of coherent reflectivity observed in the sandstone which provides a significant challenge to interpretation of relevant exploration features, particularly when attempting to map the unconformity or even sub-vertical structures, as significant as the P2 fault, with any amount of detail. Without drillhole (or other geophysical) information it would be difficult to identify or target the P2 structure from this data.

In 2013 a feature interpreted to have potential to resemble the P2 fault on high-resolution line 12 was drilled to a) confirm the presence of post-Athabasca structure, and b) identify if the potential feature was prospective for uranium mineralization. Given the proximity to the McArthur River mine, hopes were high that there would be some degree of elevated radioactivity associated with the interpreted unconformity offset.

Unfortunately, the lack of geological or geophysical constraints used in the original interpretation resulted in an incorrect model. The information collected in the drillholes provide a significantly different picture as displayed in Figure 6, which presents the original interpretation alongside the drill supported results . No unconformity offset nor significant P2 parallel structure was identified, and the region was designated as un-prospective. Seismic velocity information from logs collected in drillholes targeting the structure indicated that the acoustic impedance contrast between the bottom of the paleoweathering profile and the basement rocks was stronger than that observed at the unconformity interface, resulting in a misinterpretation of the unconformity offset. The lack of detail that can be extracted from the sandstone, complicated with the variability of the reflectivity of the sandstone-basement unconformity, emphasizes the need for drillhole constraints when interpreting seismic data in this environment.

At a similar time, an exploration based seismic program was undertaken on the Read Lake project, a joint venture between Cameco Corporation (78.241%) and AREVA Resources Canada Ltd. (21.759%). This program consisted of four camp scale 2D seismic profiles to confirm the geological model of a strike-slip dominant system with little to no unconformity offset. Two vertical seismic profile (VSP) surveys were also completed to directly image post-Athabasca Sandstone structure. The VSP surveys will be discussed in a later section.

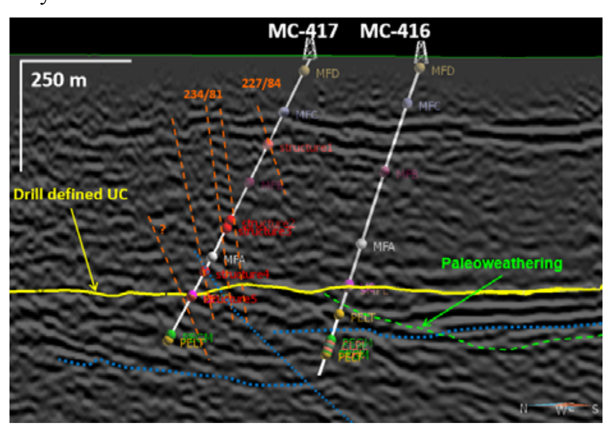


*Figure 5: EXTECH Line 12, with drilling results and interpretations: blue traces – interpretation prior to drill program; yellow trace - unconformity interpretation after drill program; orange traces - drill-defined structures; green trace – interpreted paleoweathering profile.*

The 2D data were collected in late winter/early spring. The survey was designed to obtain high frequency data focused at the unconformity using lessons learned from previous seismic programs. The unconformity in the Read Lake area was interpreted to have good reflectivity based on velocity contrasts observed in numerous full-wave sonic logs[1] that had been collected in drillholes prior to executing the seismic program.

The images of the unconformity and sandstone column obtained during the Read Lake survey (Figure 6) are improved over those from the EXTECH IV survey, largely attributed to survey design and a higher frequency source. The resultant migrated 2D sections confirm that there is no significant unconformity offset within the area of interest; however, there once again are areas where the unconformity is not associated with the strongest reflection, likely indicating variability in either the paleoweathering or basement lithology. The primary exploration target (C10 Fault at the unconformity) is more apparent in this profile; however, inferring sub-vertical structures from the data remains challenging without continuous, coherent sandstone reflections to base the interpretation on.

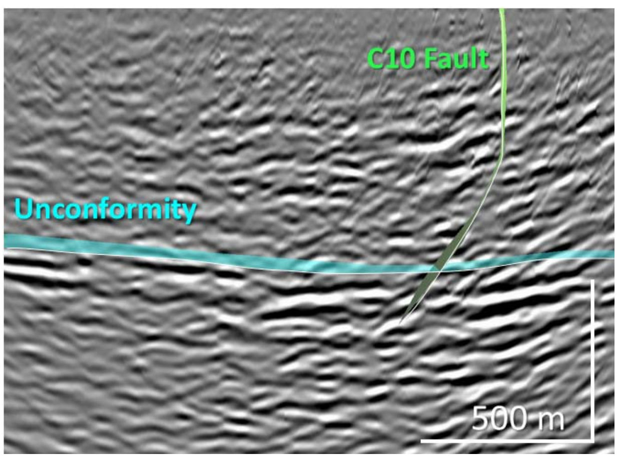


*Figure 6: Fox Lake 2D Line 4, looking west. Blue trace – unconformity surface interpreted from drilling; green trace – C10 Fault interpreted from drilling.*

## Downhole seismic applications: Imaging Post-Athabasca structures

In 2004, a series of multi-azimuth (Side-scan) surveys were undertaken at McArthur River to test the method for its ability to directly image post-Athabasca sandstone structure with high resolution (Figure 2, #3). The technique involves placing a high-frequency source below a receiver chain and surveying the geology by moving the source and receiver chains incrementally up and down the borehole (O'Dowd et al., 2006). The result of the survey is an image of the multi-azimuthal reflectivity surrounding the hole, with sub-metre accuracy. Side-Scan surveys can image geology between 80 to 300 metres away from the borehole depending on borehole conditions and the velocity characteristics of the geology. A limitation of the Side-scan method is the presence of reflectors from 360° around the borehole represented on a single 2D image; thus requiring a number of holes to be surveyed in order to triangulate where the reflections are located in 3D space.

Given that the test was successful, Cameco subsequently used Side-scan survey techniques to map potential sub-vertical structures near shaft pilot holes in an attempt to reduce the risk around geotechnical problems related to shaft sinking (Wood et al. 2010, Enescu *et al*., 2011).

Cameco has also employed a number of variations on the vertical seismic profile (VSP) survey technique, which utilizes an impact source at surface and a string of three component geophones in the borehole (Cosma ***et al.,*** 2003, Cosma *et al*., 2006, Enescu *et al*., 2011). Survey designs have ranged from pseudo-random shot points surrounding a single borehole repeated so that every shot point has been recorded at 5 m intervals downhole, to continual measurements recorded by geophones fixed in the hole while shooting a 3D survey on surface, referred to as moving source profile (MSP) (Wood *et al*., 2012). Advantages in utilizing borehole seismic techniques include the ability to mitigate data quality issues related to the glacial overburden, an increase in resolution realized by the borehole receiver chains ability to collect higher frequency seismic data in close proximity of the target of interest, and the ability to directly image sub-vertical structures and contacts.

Both of these survey designs utilize a surface source shot from a known location and can therefore be used to provide a unique location and a direct image of the of the reflectors (both vertical and horizontal) in 3D space through the application of the Image Point Transform (IPT) (Cosma *et al*., 2010).

This innovative processing application results in the retention of higher frequency data compared to traditional processing and rotation generally applied to VSP data. The IPT is used on all Cameco VSP data to produce 3D volumes similar to that created during a 3D seismic program, with the primary reflections being sourced from a vertical orientation rather than horizontally. This is ideal for uranium exploration, given the importance of targeting post-Athabasca structure as part of the unconformity uranium model.

A number of VSP surveys have been run at Cameco with varying degrees of success. The Read Lake exploration program utilized 2 VSP surveys in conjunction with the 2D surface profiles discussed above to map the structural environment surrounding the C10 Fault, a significant exploration target and host to the Fox Lake deposit (Yackulic, *et al*., 2014). Each VSP cube was created from 40 shot points and receivers positioned at 5 m intervals from 207 m to 847 m within the drillholes. The source used was the same impact source used for the 2D profiles.

[1] *Full-wave sonic logs have proven invaluable on a number of seismic projects undertaken by Cameco, the information is not only used to develop the velocity model used in processing, but also for better understanding what to expect with regards to the acoustic expression of the unconformity or other sources of potential reflectivity within an area of interest.*

The survey was successful in imaging over 600 m away from each hole, to a depth of 700 m imaging the structural environment within the area of interest including the C10 Fault, the host structure associated with the deposit (Yackulic, *et al*., 2014). The interpretation of the data was completed using drillhole constraints. Unfortunately, in the VSP data, the C10 fault structure did not appear to be unique from other reflections observed in the 3D cubes, even after re-processing (Figure 7).

The Read Lake exploration project completed an aggressive three-drill program concurrent with the seismic processing; therefore, the amount of time spent processing and re-processing the data meant that the area was well defined from drilling by the time the seismic model was finalized. Lessons learned from this experiment is that significant lead-time is required to fit in a seismic program into an exploration program to provide timely results that can influence targeting decisions for the drilling program.

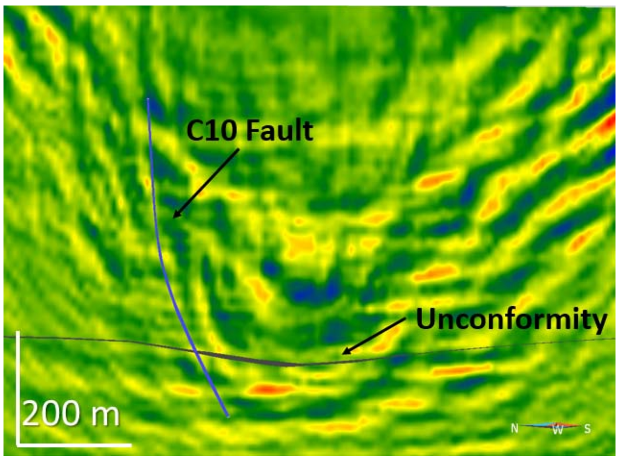


*Figure 7: Profile from 3D VSP cube REA-172 looking East survey, drill defined unconformity – black trace; drill defined C10 Fault – blue trace.*

Previous to the Read Lake exploration application, the primary force for promoting the VSP method in exploration was the successful application of the method as part of a prefeasibility study for the Millennium deposit (Cosma *et al*., 2009, Wood *et al*., 2010 and Juhojuntti *et al*., 2012). The VSP program was part of a larger seismic program consisting of a 3D surface survey, VSP, MSP, and Side-scan surveys which was undertaken to map the sandstone-basement unconformity topography, the complex geology and post-Athabasca structure surrounding the Millennium deposit for geotechnical purposes (Wood *et al*., 2012).

The Millennium 3D VSP cube was created from data collected from 28 shot points positioned radially around a proposed shaft pilot hole. Receivers were positioned and re-positioned so as to achieve complete coverage at 5 m intervals throughout drillhole CX-61. Ultimately the final VSP data was combined with MSP data collected during the 3D surface program (Wood *et al*., 2009, and Wood *et al*., 2012), resulting in a high resolution seismic cube encompassing the Millennium deposit.

The cube imaged significant sandstone structures associated with the deposit, previously unconfirmed but interpreted cross-structures, and also imaged what were later identified as lithological changes in the moderately dipping basement stratigraphy hosting the deposit.

Figure 8 presents two orthogonal views of the VSP cube, focused on the upper basement, displayed with some of the lithological contacts extracted from the geological model. This geological model was created from drillhole information only, and has good correlation with the seismic cube providing confirmation that the various units, particularly the Upper Calcsilicate assemblage (U), Heterogeneous assemblage (H), and the Marker unit (M) have sufficient impedance contrasts to be imaged (given the appropriate survey design). The quality of this VSP cube, when compared to the VSP cubes at Fox Lake, is significantly better. It is thought that the inclusion of the MSP data and the geological setting specific to Millennium was better attuned to obtaining strong reflections from both the sandstone (sub-vertical) structures and basement lithologies, while the lack of significant acoustic impedance contrast and unconformity offset may have been a limiting factor for the Read Lake VSP.

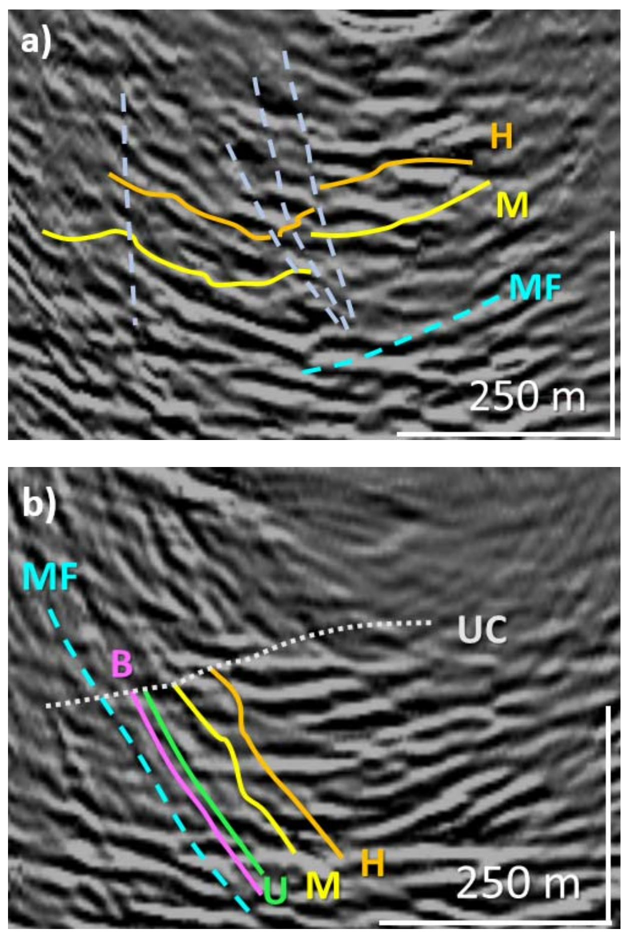


*Figure 8: Millennium 3D VSP cube view from a) west and b) south of the seismic cube with geological interpretation from drillholes. The VSP cube appears to be imaging the lithological contrasts between the highlighted lithologies: H – Heterogeneous*

*assemblage; M – Marker unit; U – Upper Calc-silicate assemblage; B – Bracketed assemblage; MF – Mother Fault; UC – unconformity. Additional faults interpreted from the seismic data are presented in Figure 8 a), these appear to fit with the geological model, and could explain some of the geometries therein.*

## 3D Seismic: Mapping Camp Scale Unconformity and Alteration

The main objectives of the 3D survey shot at Millennium, were to provide a detailed map of the location of the unconformity map and to image the acoustic properties of the basement rocks and overlying sandstones located above, and in proximity to, the deposit (Figure 2, #4). This information was used to assist in mine planning, specifically mine shaft and infrastructure locations (Wood *et al*., 2010 and Juhojuntti *et al*., 2012). At the time, the highest technical risk of pre-production development was identified as shaft sinking. Therefore, the ideal location for the shaft is at an unconformity topographic high within competent rocks that are a reasonable distance to the mineralization, and development into the basement rocks below the unconformity is technically less challenging. CX-062 and CX-063 in Figure 9 highlight the two proposed shaft locations located in a local UC topographic high proximal to the deposit.

The amount of time and effort put into the planning and execution of the surface 3D seismic program resulted in a high resolution 3D cube from which the unconformity surface could be interpreted in detail (Figure 9). This unconformity surface is well constrained surrounding the deposit; however, the accuracy of the unconformity model outside of the main deposit area is reduced due to fewer geophysical and geological constraints. Significant insights into the reflectivity of the unconformity in the Athabasca Basin arose from this survey. The reflectivity of the unconformity throughout the survey area was found to be variable (Figure 10). The variability can be attributed to the combination of the paleoweathering profile, the complexity of the basement lithologies hosting the deposit, and the presence of pre- and post-Athabasca structure, all of which were overprinted by intense hydrothermal alteration associated with the depositional event.

The clay alteration associated with some uranium deposits is a product of focused hydrothermal fluids related to the mineralization event (Halaburda and Roy, 2006). The structure and associated alteration reduces rock quality, raising geotechnical concerns of ground failure and water inflow during development and mining. The unconformity and the seismic patterns observed in the 3D seismic cube are muted in the vicinity of the Millennium deposit. Drilling information confirms that the source of this lack of signal is related to alteration. This characteristic signal can be mapped within the 3D cube data, constrained by drillhole information. Figure 11 presents the shape of the interpreted clay alteration zone associated with the Millennium deposit from a) the interpolation of drilling and geochemistry data, and b) from the 3D seismic cube (Wood *et al*., 2012). The ability to develop an understanding of the extent of post-Athabasca structure and alteration provides valuable geotechnical information for mine planning and development.

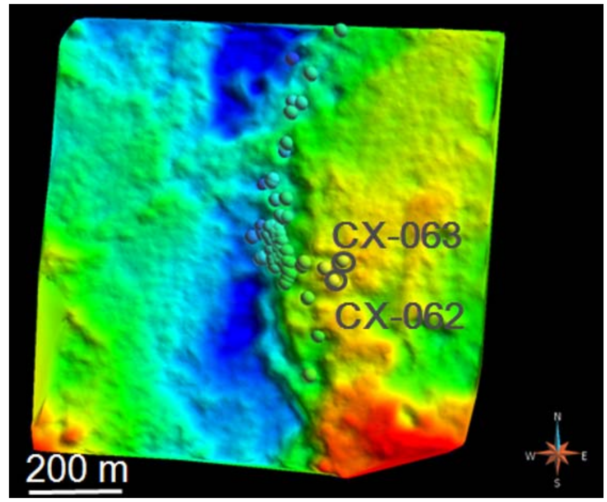


*Figure 9: Unconformity topography as interpreted from 3D surface seismic cube with drillhole pierce points (warm colours – higher elevations, cool colours – lower elevations).*

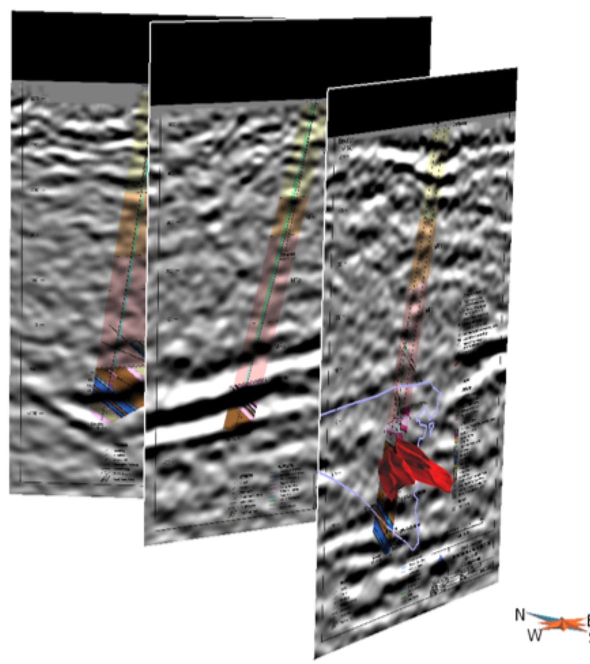


*Figure 10: 3D perspective of three drillhole fences draped with 3D seismic cube data. The unconformity reflectivity can vary significantly as observed on these three closely spaced fences (from Wood et al., 2012).*

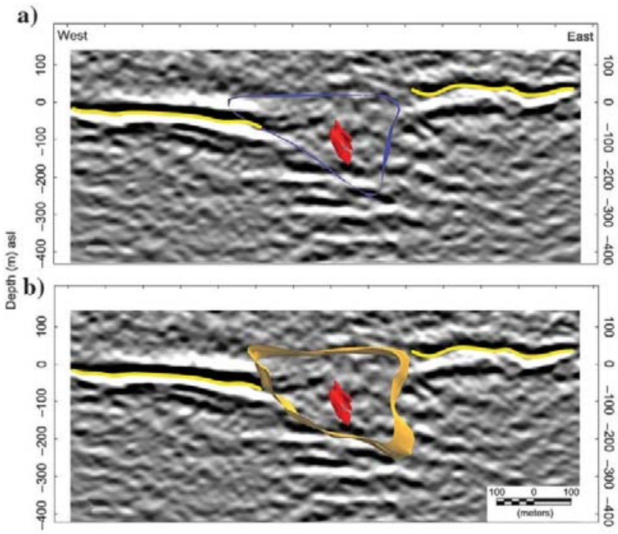


*Figure 11: a) alteration halo as defined from drilling, and b) alteration halo as interpreted from seismic data (from Wood et al., 2012).*

## SUMMARY AND CONCLUSIONS

Seismic applications in the Athabasca Basin have become more common in uranium exploration over the last decade. In total, Cameco has completed 15 separate seismic surveys, some of which have been more successful than others. The application of these surveys has mainly focused on later stage exploration and geotechnical studies relate to mine development located within the eastern portion of the basin.

The use of passive seismic data for the purpose of determining appropriate drilling techniques and collar locations for pre-season planning is the latest application being employed at Cameo. 2D seismic lines have been used in early stages of exploration to quickly evaluate portions basins for non-conductive structures and unconformity topography that may be of significant exploration potential (i.e. Roughrider; Hajnal, 2008). 3D seismic programs have produced high resolution data from which the unconformity surface could be interpreted in detail. Borehole seismic methods have been employed to directly image vertical to sub-vertical structure. However, inferring sub-vertical structures from the data remains a challenge without coherent sandstone reflections to base the interpretation on.

The innovation of the IPT technique has resulted in elevating the ability to directly image and interpret vertical structures in VSP data while retaining high frequency data which is often lost during traditional processing and rotation applied to VSP data. This is ideal for uranium exploration, given the lack of coherent sandstone and variability in the UC reflectivity. And finally, the extent of intense alteration zones associated with hydrothermal alteration surrounding some deposits (specifically millennium) can be imaged and mapped outside of drilling information using the 3D surface seismic data.

From a practical standpoint it is critical that the capabilities of the applied seismic techniques, the timelines involved and the data integration required to get full value out of the datasets needs to be understood by all parties for successful application. In complex geological environments seismic datasets need to be revisited if new geological or geophysical information becomes available that was not included in the original processing. It has been shown that initial processing and interpretation of any type of seismic data will not result in a true picture of the subsurface in complex geological environments. The more that is known about the acoustic properties of the geology being investigated, the more accurate the final seismic image will be.

## ACKNOWLEDGMENTS

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Paper 4

# Enhancing bandwidth in Seismic Data Acquisition for Mineral Exploration

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## ABSTRACT

*Innovative technology for conducting seismic exploration historically derives from petroleum exploration in soft rock environments. Mineral exploration in hard rock environments requires different emphasis so that simple porting of methods from soft to hard-rock settings seldom works well. Nevertheless, seismic data acquisition planned for the early stages of the Metal Earth project will benefit greatly from recent advances in the petroleum sector as well as those in mineral exploration. Vibroseis® methods now have both sources and receivers that are rated down to 5 Hz frequencies and are known to generate records with 1.5 Hz signal while continuing to sweep up to 150–200 Hz. Not only will this enhance reflections from the deep crust, it also enables the use of full waveform inversion and related techniques. Regional-scale transects will target mineralizing fluid pathways throughout the crust, whereas higher spatial-resolution reflection and full-waveform surveys will target structures at mine camp scales using over 5000 active sensors. A second phase of acquisition will work in remote areas and attempt passive (source-less) surveys at relatively high resolution. Because Metal Earth was proposed to map and compare entire Archean ore and geologically similar non-ore systems, teleseismic data acquired with sparse, 3-component broadband sensors that record distant earthquakes will also be analyzed to map layers and major seismic discontinuities within the lithospheric mantle, but with resolution of several kilometers. Such teleseismic studies have been used for decades in diamond exploration. Mapping structures controlling deep carbon concentration appears increasingly relevant to both diamond and metals exploration.*

## STATE-OF-THE-ART

Both major innovations and more incremental technical improvements have occurred within the petroleum (soft rock) seismic exploration industry over the past decade and some of these will be adapted into the upcoming (hard rock) Metal Earth seismic acquisition program. Metal Earth is dedicated to understanding the processes responsible for Earth's differential metal endowment and to do so will, for the first time, map entire ore and non-ore systems at full crust-mantle scale to identify key geological-geochemical-geophysical attributes of metal sources, transport pathways, and economic concentration. This program therefore requires new observations and data over a broad range of scales, from craton- to deposit-scale and plans to integrate information from seismic, magnetotelluric (MT), gravity and traditional geological transect surveys. The primary mode of transect surveying will build upon previous regional-scale surveys conducted as part of the Lithoprobe and Discover Abitibi projects (Calvert and Ludden, 1999; Ludden and Hynes 2000; White et al., 2003; Snyder et al., 2008). Acquisition technology is significantly improved from the early days of Lithoprobe (1990), less so from the time of Discover Abitibi (2005). A few seemingly small improvements may however now enable very significant new approaches to analysis and our understanding of mineralization pathways and processes. Here the focus will be solely on the seismic method advances being adopted, particularly embracing broader bandwidth data and its analysis.

### Improved bandwidth

Perhaps the most straightforward improvement is in the bandwidth of seismic signal now recorded. It has long been known that frequencies higher than 50–70 Hz do not propagate well into the deep crust whereas low frequency propagation appears relatively unlimited. "White noise" spectral sources such as earthquakes and explosions are, in contrast, recorded across all the continents at less than 10 Hz if sufficiently large in magnitude. Local or regional seismic surveys using so-called controlled sources typically were limited to frequencies greater than 10 Hz by the practicalities of the technology and large amount of equipment used to acquire multi-fold data. That has changed recently.

The newest large (61,800 lbs of peak force) vibrator trucks that are typically used as precisely controlled seismic sources by the petroleum industry now attain a bandwidth of 2 to 250 Hz. These AHV-IV 364 Commanders attain a peak force at 6.2 Hz, but useful frequencies have been recorded as low as 1.5 Hz. Metal Earth plans to use an array of four of these vibrator trucks producing an upsweep of 2–120 Hz that is repeated 4 or 5 times at each source location. Based on the relatively fast seismic wave speeds previously encountered near the surface in the proposed

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survey areas, useful P-wave seismic wavelengths of 50–3000 m will be generated. If conditions are similar to those of some Discover Abitibi transects, S-wave conversions can also be expected at the alluvium-basement discontinuity several meters below the surface (Snyder et al., 2009).

Receiver bandwidth has also improved, partly driven by the transition from coils to solid-state vibration sensors. Metal Earth will be using single SG-5 vertical-component 5 Hz geophones within an OYO GSX Wireless nodal recording system. Although these geophones have a 5-Hz natural frequency, recorded signal is down only a few dB at 2–3 Hz (Figure 1). For high-resolution surveying near mines, 10-Hz 3-component geophones may be substituted.

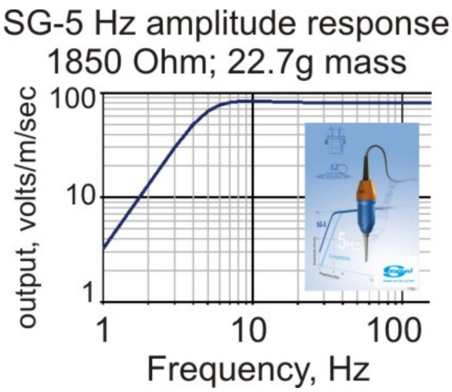


*Figure 1. SG-5 geophone specifications.*

A cable-less recording system will be used. Each sensor with its associated recording box and power pack are harvested when that sensor location is no longer required within the receiver array. Lithoprobe-standard split-spread receiver arrays with 15-km far offsets will be used for longer transects. Regional mode surveying will use 50 m source and 25 m receiver intervals. For shorter transects, the entire spread will remain active throughout the shooting. Long offsets continue to be valuable for deep velocity analysis and in order to capture reflections off steeply dipping in-line structures. Wireless receiver spacing will be 12.5 m for a second mode, high-resolution 2-D transects, but creative vibrator move-ups will make common depth point (CDP) intervals of 5–6 m possible. If frequencies of 120 Hz can be recorded to a few km depths, vertical resolution of several tens of meters is theoretically possible. Recent grid and 3-D surveys in mine camps using explosive sources have recorded useful 80–170 Hz signal that enables the eventual correlation with rock units with 5–10 m resolution (Figure 2).

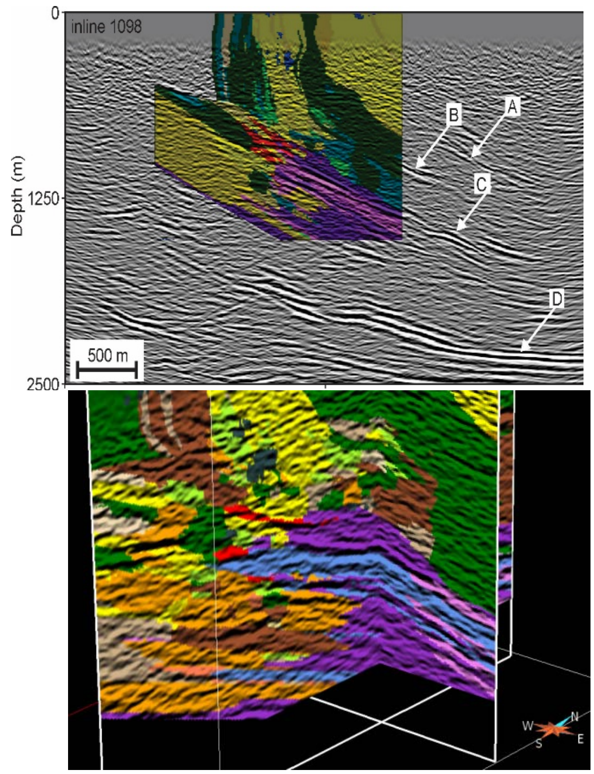


*Figure 2. Example of high-resolution seismic sections in mine camps, here Lalor Lake VMS mining area, Manitoba (Bellefleur et al., 2015).*

## Using full waveforms

In addition to operating at regional and high-resolution modes to create traditional CDP gathers and stacks, some transects will be augmented so as to be analyzed using the full recorded seismic waveforms. More commonly referred to as full waveform inversion (FWI) (Pratt et al., 1998; Kamei et al., 2015), this method requires a receiver array as long and as dense as logistics and budget will allow. Metal Earth plans to acquire data for full waveform inversion along a few 2-D lines, using a 40–50-km long linear receiver array with both vibrator and explosive sources all recorded by the entire active array (Figure 3). The vibrators will work only along the receiver spread, shots will be randomly spaced but some at far offsets from the receiver spread of as much as 100 km.

To our knowledge, full waveform inversion data and analysis has not been used at this scale in hard rock environments to date although related, more traditional near-surface P- and S-wave tomography has shown promising results (Snyder et al. 2009). Inversions of full waveform ensembles are best performed in stages using ever increasing frequency content (e.g., Kamei et al., 2015). Starting frequencies of 1 or 2 Hz are typical in soft-rock settings. High computational costs typically limited inversions to a few stages that reach maximum frequencies of perhaps 10 Hz. These frequencies translate into seismic wave lengths of 500-5000 m with mapping resolution typically assumed to be ¼ wavelength. Additional inversion stages at higher frequencies would greatly enhance the resolution achievable in modelled P-wave sections but are computationally expensive. The primary strength of this FWI method is that it maps P-wave velocity structure at equal resolution vertically and horizontally so that nearly vertical structures will be revealed as clearly as horizontal ones wherever sufficiently distinct changes in rock types exist. Such changes may be related to lithology or degree of alteration/mineralization. By using offsets as great as 100 km, we hope to map structures as deep as 10–12 km and be able to undershoot problem logistical areas such as swamps or towns (Figure 3). At shallower depths of a few kilometers, both the high-resolution CDP and FWI modes are readily mapped against drill core compilations of known rock to extrapolate these know rocks over greater rock volumes in mine camps (Figure 2).

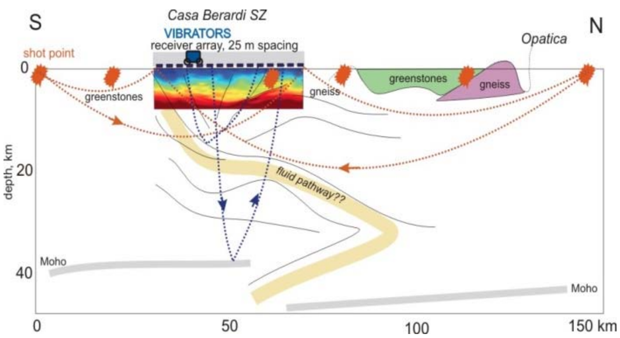


*Figure 3. Schematic cross section of a proposed Metal Earth seismic survey designed to implement full-waveform inversion analysis. Structural form lines are based on the interpretation of nearby Lithoprobe Line 28 where thrust-related, gold-bearing structures were inferred. Moho depths are from Lithoprobe receiver function studies: note clear Moho offset. Colored inset shows a recent Full Waveform Inversion result from Japan as example of achievable resolution; colors are P-wave velocities variations within an accretionary prism sediments.*

## PASSIVE SEISMOLOGY

Exploration programs worldwide are increasingly interested in whole mineral systems: not just where the metal of interest finally was deposited, but also source region where it came from, what pathways it followed, how it became concentrated, and what might have stalled its progress to the surface. Mapping deep structures within the crust and uppermost mantle lithosphere has therefore become ever more appealing as finding ore bodies is more challenging. Controlled source surveys are becoming ever larger in scope, but seldom send sufficient energy to depths of tens or hundreds of kilometers. Deep surveys thus rely on distant, teleseismic sources, most typically large earthquakes. Academics have used such sources to map continent-scale seismic wave velocity variations for decades. Magnetotellurics uses similar methodology to map conductivity to depths of kilometers to hundreds of kilometers. Such surveys typically have resolution of tens of kilometers. More recently, related methods often referred to as "structural seismology" map strong discontinuities in seismic properties to infer deep structures and past tectonic history. The most common example, subduction zones, are considered by many workers to be important features that concentrate fluids and elements important to mineral exploration.

### Deep Surveys

Seismic exploration at mantle depths of 100–400 km typically uses seismic waves converted at major discontinuities to estimate depth and map the lateral extent of such features if sufficient observing stations are available. Relatively dense arrays have only appeared within the past decade on a few continents (Schaeffer and Lebedev, 2014). Maps of surfaces such as the Moho and Mid-lithosphere Discontinuity, where correlated with seismic tomography and conductivity in 3-D, often provide insights into large-scale structure and possible rock types in a few places (Figure 4) (Snyder et al., 2016). If extrapolated sensibly toward the crust and surface structures, whole mineral systems can be tentatively recreated where structures align or appear consistent. This typically involves major regional structures long recognized to control mineralization, so it mostly provides a sounder underpinning of why those structures are so important.

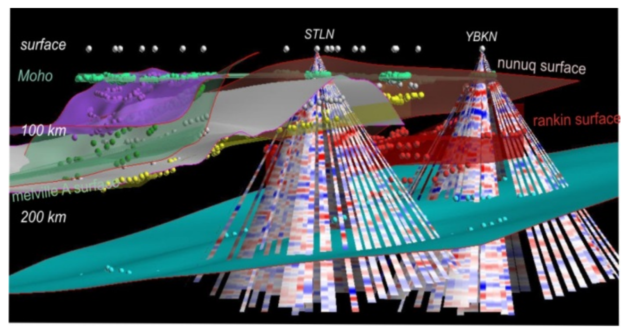


*Figure 4. Example of mapped seismic discontinuities in the mantle, here beneath Bake Lake (YBKN), Nunavut.*

### Shallow surveys

Shallow seismic exploration increasingly attempts source-less surveys as well. The successful correlation of recorded signals that lies at the core of this method requires very dense sensor arrays, both in terms of spacing as well as azimuth. Modern 3-D and large-N surveys can meet this requirement using receiver spacing of several meters in mine camps and tens of meters in petroleum fields. It is the distribution environmental noise sources that remains problematical because some systematic or correlated noise source is theoretically required at every azimuth and inclination within the study volume. Continental-scale arrays have coastlines with ocean wave action (broad peak at 8 s) on all sides, whereas mine camps have roads, trains and generators with narrow-band signals in specific directions (Cheraghi et al., 2015). Magneto-telluric currents from the aurora borealis or thunder storms have better azimuthal distribution, but also suffer similarly during short-term, local surveys.

Despite these limitations, Metal Earth plans to undertake a few trial so-called passive seismic surveys in remote areas where access for vibrator trucks, drill rigs and other source-related equipment is either prohibitive or very costly. These seismic surveys are considered very high risk and will accompany magnetotelluric surveys and may be augmented by a few seismic sources wherever possible in order to continue comparative cost-benefit studies between active and passive seismic surveying.

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Paper 5

# Seismic interferometry: cost-effective solution for mineral exploration?

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## ABSTRACT

*The quality of seismic imaging in hardrock exploration depends on the acquisition parameters, especially regular and dense distribution of sources. With the modern recording systems, especially wireless, it is now possible to deploy a dense grid of surface receivers even in difficult terrain, but maintaining regular shooting pattern remains both costly and often impossible. Recent advances in global and exploration seismology led to establishing a new tool, called seismic interferometry (SI), which allows retrieving the reflection response from the correlation of seismic background noise. In this paper we review the basic principles of SI and present examples of applications related to hardrock exploration including our recent experience with large-scale passive 3D survey over an active mine in Finland.*

## INTRODUCTION

We observe a steady increase in number of applications of the seismic reflection method, both 2D and 3D, to ore exploration in hardrock environment (hardrock seismic exploration) (e.g. Malehmir et al. 2012). The quality of seismic imaging depends on the acquisition parameters, especially regular and dense distribution of sources. With the modern recording systems, especially wireless, it is now possible to deploy a dense grid of surface receivers even in difficult terrain, but maintaining regular shooting pattern remains both costly and often impossible. Recent advances in global and exploration seismology led to establishing a new tool, called seismic interferometry (SI) (Wapenaar et al. 2008, Schuster, 2009), which allows retrieving the reflection response from the correlation of seismic background noise. This background (ambient) noise could be in form of simply random noise as well as transient events coming from a distribution of sources with unknown positions, source signals and time origins (e.g. microseismic events). SI principles are applicable also to normal active-source data. In this case, SI can provide additional information, e.g. create new virtual shot gathers at the receiver positions.

We first review the basic theory of the ambient noise SI, then we discuss few published applications of both active and passive source SI in hardrock seismic exploration. We also present some results from a recent passive seismic survey acquired over an active mine in Kylylahti (Finland) and finish with the recommendation for future surveys.

## THEORY OF PASSIVE SI

In simplest terms, SI is a method of generating new data from the cross-correlation of existing data. It was first introduced by Clearbout (1968), who demonstrated that the reflection response at the free-surface can be obtained from the autocorrelation of the observed transmission response at the free-surface coming from the sources at depth. The underlying principle of the SI is that the reflection response in 3D media between the two receivers is obtained by cross-correlating transmission responses recorded passively at those two receivers (Fig. 1).

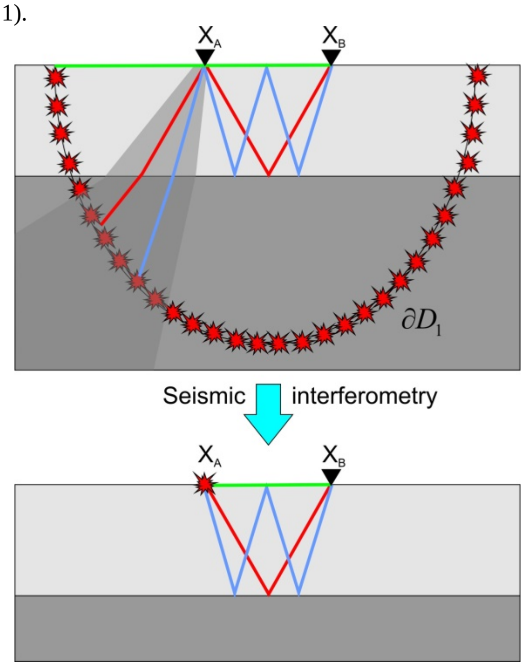


*Figure 1: Input (top) and output (bottom) from SI for a layer over a halfspace model. Two receivers are placed at the free-surface and record wavefield coming from sources in the subsurface (red stars). After SI, the response is obtained as if there were a source at $x_A$ and a receiver at $x_B$. Shaded area represents the stationary-phase region (adapted from Draganov and Ruigrok, 2015).*

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This is equivalent of having an impulse source (also referred to as virtual source) at the location of one of the receivers. This process is also called Green's function retrieval. The Green's functions can be retrieved from cross-correlations of either diffuse or deterministic wavefields. The diffuse wavefield originates from the (i) multiple scattering due to medium heterogeneity (Lobkis and Weaver, 2001; Snieder, 2004) or (ii) due to the random distribution of noise sources acting simultaneously (Shapiro and Campillo, 2004). Deterministic wavefield originates from the transient sources (e.g. active shooting or earthquakes) in a deterministic medium (Schuster, 2001, Bakulin and Calvert, 2004).

Following Wapenaar and Fokkema (2006) for the general 3D acoustic/elastic medium the approximate Green's function G between receivers at $x_A$ and $x_B$ located at the free-surface arising from the impulse sources located along the boundary $D_1$ (Fig. 1) can be written in the frequency domain as:

$$2\Re\left\{\hat{G}(\mathbf{x}_B, \mathbf{x}_A, \omega)\right\} \approx \frac{2}{\rho c}\oint_{\partial D_1} \hat{G}^*(\mathbf{x}_A, \mathbf{x}, \omega)\hat{G}(\mathbf{x}_B, \mathbf{x}, \omega)d^2\mathbf{x} \quad (1)$$

Where R denotes real part, * indicates complex conjugate, c is medium velocity and ρ is medium density. Not every source located along the $D_1$ is contributing to the Green's function – only those located in so-called stationary-phase region (Snieder, 2004) (Fig. 1). The following assumptions are made to derive eq. 1: (i) the boundary sources are in the far-field of the receivers, (ii) the medium outside the boundary $D_1$ is not causing scattering, (iii) medium properties vary smoothly across the $D_1$, (iv) medium properties along the $D_1$ are constant. The above assumptions are almost impossible to fulfill in reality, therefore the amplitudes of the retrieved Green's functions are incorrect. There could be also some non-physical (ghost) events that can originate from non-perfect wavefield separation (presence of mode-conversion) or from the attenuation (the above derivation is valid for lossless medium). In the latter case, ghosts can be used for Q estimation (Draganov et al. 2010). In case of non-impulse sources, the Green's function on the left hand side of eq. 1 is multiplied by the source signature.

### Extracting body-wave energy

Theory predicts that the cross-correlation retrieves the complete wavefield including body-wave reflections (Wapenaar, 2004). However, sources close to the surface (one-sided illumination) contribute mostly to surface waves retrieval. Interaction of free-surface multiples can lead to retrieval of body waves in such a case (Nakata et al. 2011), but one-sided illumination result in non-physical events that can be interpreted as physical reflections. As a remedy, using distant surface sources is advised. However, body waves will originate primarily from either the deeper or distant transient sources emitting body-wave energy (Draganov et al. 2009). In order to capture such sources, relatively longer recordings are needed as compared to those required for surface waves retrieval.

Recorded ambient noise panels will be always dominated by surface waves, therefore surface waves suppression is a crucial step in SI aimed at obtaining reflection response. Surface waves can be suppressed either at the acquisition stage by using groups of geophones or during pre-processing step with the application of (i) bandpass filters, (ii) automatic or semi-automatic illumination analysis to select non-surface-waves dominated panels (Draganov et al. 2013). It is worth to note that in the hardrock environment there is usually a good separation between surface waves (peaking at 20-30 Hz) and reflections (above 35-40 Hz) observed, however ambient noise sources are considered as emitting energy primarily lower than 30 Hz. Contribution of the body-wave energy can be further enhanced on the correlated panels by either the illumination analysis including slowness (Panea et al. 2014) or specially designed filters (Nakata et al. 2015). It might be also useful to locate the noise sources using, e.g. methods proposed by Dales et al. (2017) or Roots (2016) and perform selective stacking, considering only those sources located in the stationary-phase region After the surface-wave suppression, in case of using cross-correlation, the essential step is to apply trace-by-trace energy normalization in the recorded noise panels in order to equalize non-even source/receiver contributions. This step is not necessary when using cross-coherence (Nakata et al. 2011). Another advantage of the cross-coherence is that the correlated panels do not need to be deconvolved for the source signature. However, it can also boost the noise due to the prewhitening.

## SI IN HARDROCK EXPLORATION

### Ambient noise SI

The first ambient noise SI experiment in the hardrock exploration context was performed at Lalor Lake, Manitoba, Canada (Cheraghi et al. 2015) before an active source 3D seismic survey. 336 receivers were deployed along a net of 16 receiver lines (100 m receiver spacing, 360 to 400 m line spacing) forming a small 3D patch (4 km$^2$) located close to the operating mine. 300 hours of data were recorded and processed using cross-correlation in the 2-35 Hz frequency band, however power spectral density plots indicate some energy as high as 100-150 Hz. Beamforming analysis suggested that the mine was a source of the body-wave signals. Resulting virtual shot gathers were processed similarly to the active source data. Comparison of the 3D DMO volumes from processing active/passive data indicates similarities, but noticeably passive data exhibit flatter dips as expected for the imaged geology. As demonstrated by Roots (2016) using synthetic modelling this can be a result of one-sided source distribution (Fig. 2). In case of dipping strata, sources should be located down-dip for a proper imaging. If sources are located up-dip from the receiver array, reflectors are not properly focused or their dips seem to be flatter. However, scattering occurring in the hardrock environment can act as secondary sources at depth, therefore relaxing the above conditions. To circumvent the biased source distribution, Roots (2016) used beamforming analysis to select the correlated panels before stacking that fall into given source azimuth bin. Subsequently, only the panels with the azimuths corresponding approximately to the stationary phase regions for the analyzed receiver lines (pretty much in-line azimuths) were kept. Finally, selected bins were energy-normalized to equalize contribution of each azimuth. Beamforming was also used to apply time-shifts and flatten dominant coherent energy coming from the ventilation shafts before application of the F-K rejection filter. Comparison of the results of Cheraghi et al. (2015) with Roots (2016), Roots et al. (2017) suggests that this revised workflow improved imaging of the deeper reflectors (Fig. 3). Girard and Shragge (2016) also used Lalor Lake data and demonstrated the potential of using 3D beamsteering to create plane-wave dip spectra of the data to isolate body-wave energy.

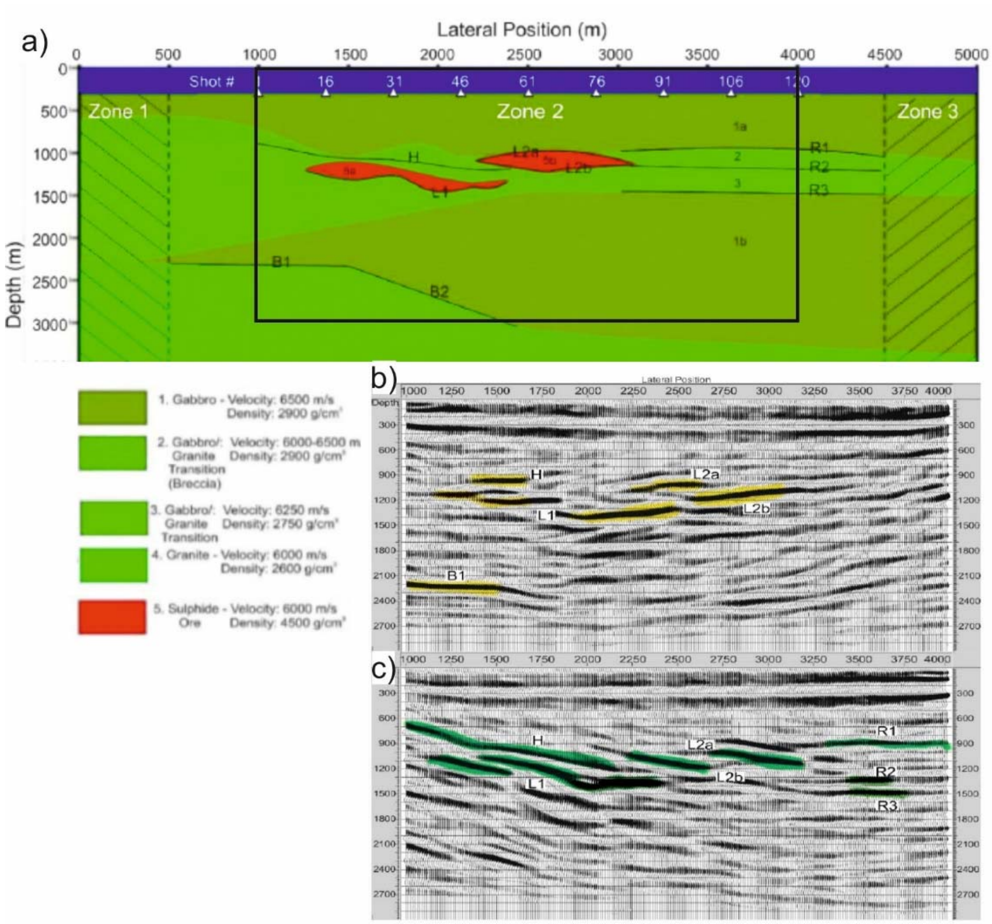


*Figure 2: (a) Model of the Lalor Lake VMS deposit used to generate synthetic data simulating active and passive survey. (b) Migrated stack of the passive noise data with the noise sources located in Zone 1 (left). (c) Migrated stack of the passive noise data with the noise sources located in Zone 3 (right). Modified from Roots (2016).*

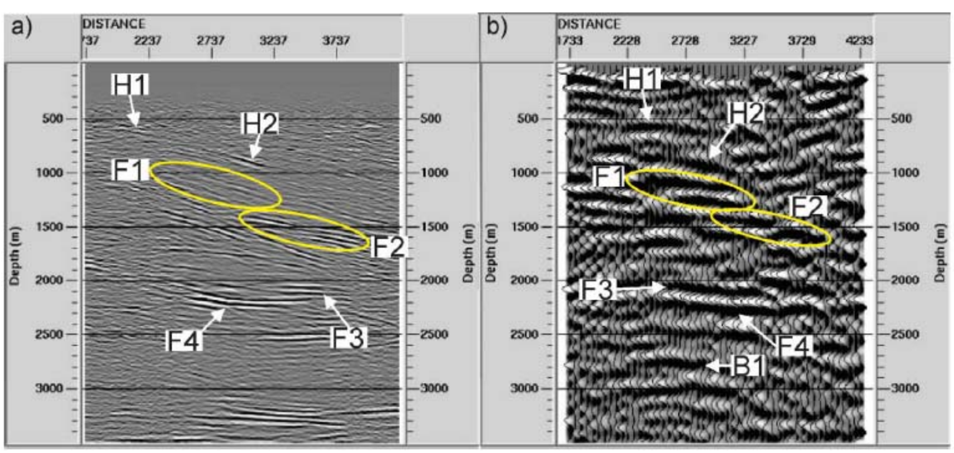


*Figure 3: Stacked DMO sections along line 133 from the Lalor Lake survey: a) active source data; b) ambient noise data. From Roots (2016).*

SI can be also applied to the data acquired directly in the mine as recently shown by Olivier et al. (2015). Authors process 30-day long passive data acquired in the Garpenberg iron ore mine in Sweden using 18 sensors. Retrieved Green's functions are characterized by a broadband frequency range (20-400 Hz) thanks to the broadband characteristics of the noise sources and careful noise panels selection. Similarly to the conclusions derived from the Lalor Lake case, strong scattering of waves due to the mine infrastructure is helping in reconstruction of Green's functions despite the non-perfect source illumination. A 3D S-wave tomography attempted from the retrieved Green's function in the lower frequency limit (<100 Hz) has shown some velocity anomalies correlating with the know ore bodies.

## Active source SI

There is a large potential in SI methods applied to active-source data in the ore exploration context. One can think of potentially regularizing seismic surveys by creating new virtual shot gathers. However, the biggest challenge is how to merge the SI data with the original active source data? Active source SI can be also used e.g. to improve the first break picking, and in consequence, refraction static solution, as recently demonstrated by Place and Malehmir (2016) for 2D data. Authors used the method of virtual and supervirtual refraction (Bharadwaj et al. 2012) to enhance long-offset refracted arrivals. Potentially, the virtual refraction method could be used in combination with the LMO + residual statics method to produce a refraction-based static solution without first break picking.

Active source SI is especially applicable to transform/redatum borehole/VSP data (e.g. Bakulin and Calvert, 2004). Potential applications in the hardrock exploration context were studied by Brand et al. (2013) and Hurich and Deemer (2013). Brand et al. (2013) demonstrated that using SI, surface shots used in walkaway VSP could be redatumed to the borehole receivers. The whole survey can be then reoriented in such way that the new virtual shot gathers can be processed like a standard surface reflection seismic to image the subvertical reflections. Hurich and Deemer (2013) further verified this methodology using real VSP data acquired in the Voisey Bay mine site in northern Labrador, Canada. Redatumed VSP data imaged confidently a sulfide-bearing dike.

## PASSIVE SEISMIC EXPERIMENT IN KYLYLAHTI, FINLAND

Passive 3D seismic survey was recently acquired in the vicinity of the Kylylahti Cu-Au-Zn mine in Polvijärvi, eastern Finland between early August to late September 2016 as a part of the COGITO-MIN project. Following conclusions derived from the Lalor Lake experiment, we used shorter receiver/line spacing (50/200 m), bigger array (~1000 receivers) and longer recording time (~30 days). Detailed description of the experiment and data treatment can be found in Chamarczuk et al. (this volume). Initial processing results suggest that there is a potential in extracting body-wave energy in the high-frequency range (> 30 Hz), where the surface waves are significantly attenuated. It looks like, in this case, the environment is generally more noisy than in case of Lalor Lake, but the dominant body-wave sources associated with the mine activity are also not illuminating the target from all directions. Fig. 4 shows a comparison of a virtual shot gather obtained for receiver 1012 (Fig. 4, red star in the inset) with a co-located dynamite shot.

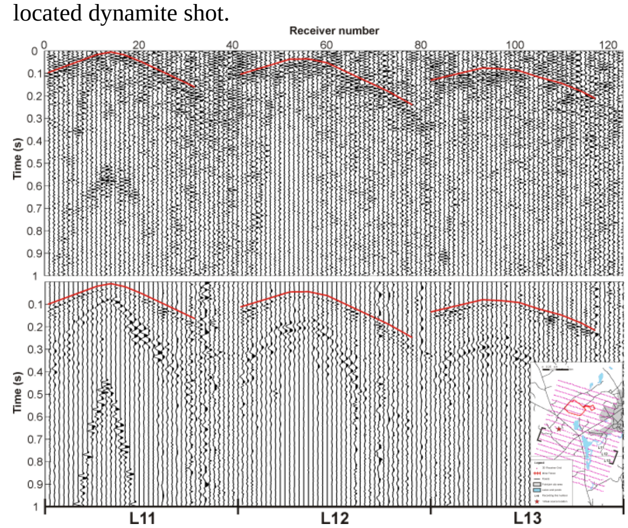


*Figure 4: Comparison of virtual (top) and active (bottom) shot gathers along lines L11, L12 and L13 with shot point located in the direct vicinity of receiver 1012. Red lines indicate the theoretical lines of first arrivals. Inset shows the survey area with the master trace (denoted as red star) and mine location (denoted with red line) indicated. Black thick lines indicate receiver lines L11, L12 and L13.*

To produce virtual shot we used 10 days of ambient noise recordings bandpass filtered in range 35-95 Hz. For comparison purposes active shot is presented in the same frequency range. Generally more coherent events are observed in the active data, however P-wave first arrivals are clearly visible on both shot gathers. Traces visible in virtual data exhibit lower S/N ratio. This could be the effect of applying cross-coherence algorithm (Nakata et al. 2011), which discards the amplitude information, retaining only phase of signals. Events visible in virtual data before the theoretical lines of first arrivals are artifacts caused by aforementioned directional bias of mine sources. Note that receiver lines presented in Fig. 4 are located south of the master trace and the mine, therefore we suspect that the noise sources related to mining activities generate sufficient body-wave energy to retrieve first arrivals and potentially reflections. However, to acquire the 3-D image of subsurface with SI, illumination from ambient noise sources should be omni-directional. Thus, virtual shot gathers produced for receiver lines located in direction going from the master trace towards the mine site (not shown here) exhibit much poorer quality. Beamforming indicates that there are also noise sources coming from directions other than the mine site, however to evaluate the possibility of SI to retrieve reflections from these recordings the illumination diagnosis needs to be implemented to confirm presence of body waves.

## CONCLUSIONS

Seismic interferometry finds a range of applications in the hardrock seismic exploration context, both in case of ambient noise/passive and active-source surveys. In the first case though, first field-scale tests shown images with lower resolution (frequencies < 30 Hz) and with less confidence as derived from active-source data (which are still necessary to ground-truth SI outcomes). However, our recent experience from Finland, suggests that it is possible to extract body waves from surface recordings in the higher frequency range (35-95 Hz). The optimal design of the ambient noise SI experiment should be preceded by a modeling study with a simple geological model and expected noise distributions (following e.g. Roots, 2016 or Girard and Shragge, 2016). However, strong scattering of seismic waves occurring in hardrock environment makes the assumptions about omni-directional noise sources less restrictive. It might be also highly beneficial to use dense receiver arrays also in the crossline direction (i.e. shorter receiver line spacing) for a confident separation of surface/body-waves arrivals. Clearly, a lot of care is required in selection of the noise panels that are cross-correlated, which should be devoid of surface wave contamination as much as possible. We see also a large potential in the active source SI – to solve statics issues as well as in direct imaging from redatumed VSP data. Regularizing/densifying active seismic surveys using SI remains largely underexplored, but this direction of research seems very promising as it can be applied to the already acquired data.

## ACKNOWLEDGEMENTS

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Paper 5

# Seismic interferometry: cost-effective solution for mineral exploration?

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## ABSTRACT

*The quality of seismic imaging in hardrock exploration depends on the acquisition parameters, especially regular and dense distribution of sources. With the modern recording systems, especially wireless, it is now possible to deploy a dense grid of surface receivers even in difficult terrain, but maintaining regular shooting pattern remains both costly and often impossible. Recent advances in global and exploration seismology led to establishing a new tool, called seismic interferometry (SI), which allows retrieving the reflection response from the correlation of seismic background noise. In this paper we review the basic principles of SI and present examples of applications related to hardrock exploration including our recent experience with large-scale passive 3D survey over an active mine in Finland.*

## INTRODUCTION

We observe a steady increase in number of applications of the seismic reflection method, both 2D and 3D, to ore exploration in hardrock environment (hardrock seismic exploration) (e.g. Malehmir et al. 2012). The quality of seismic imaging depends on the acquisition parameters, especially regular and dense distribution of sources. With the modern recording systems, especially wireless, it is now possible to deploy a dense grid of surface receivers even in difficult terrain, but maintaining regular shooting pattern remains both costly and often impossible. Recent advances in global and exploration seismology led to establishing a new tool, called seismic interferometry (SI) (Wapenaar et al. 2008, Schuster, 2009), which allows retrieving the reflection response from the correlation of seismic background noise. This background (ambient) noise could be in form of simply random noise as well as transient events coming from a distribution of sources with unknown positions, source signals and time origins (e.g. microseismic events). SI principles are applicable also to normal active-source data. In this case, SI can provide additional information, e.g. create new virtual shot gathers at the receiver positions.

We first review the basic theory of the ambient noise SI, then we discuss few published applications of both active and passive source SI in hardrock seismic exploration. We also present some results from a recent passive seismic survey acquired over an active mine in Kylylahti (Finland) and finish with the recommendation for future surveys.

## THEORY OF PASSIVE SI

In simplest terms, SI is a method of generating new data from the cross-correlation of existing data. It was first introduced by Clearbout (1968), who demonstrated that the reflection response at the free-surface can be obtained from the autocorrelation of the observed transmission response at the free-surface coming from the sources at depth. The underlying principle of the SI is that the reflection response in 3D media between the two receivers is obtained by cross-correlating transmission responses recorded passively at those two receivers (Fig. 1).

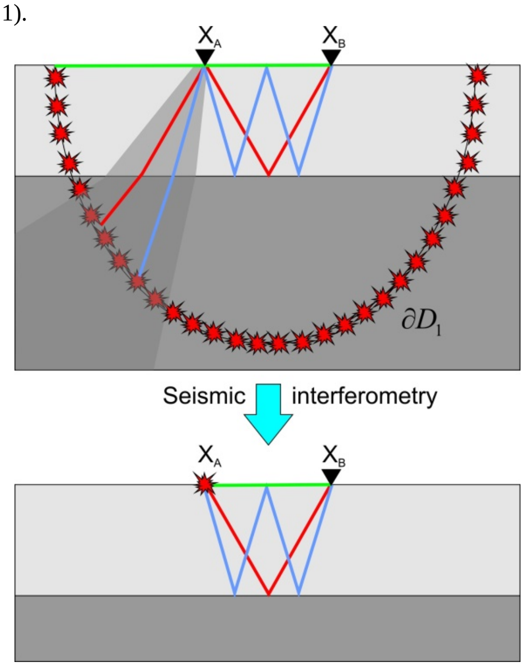


*Figure 1: Input (top) and output (bottom) from SI for a layer over a halfspace model. Two receivers are placed at the free-surface and record wavefield coming from sources in the subsurface (red stars). After SI, the response is obtained as if there were a source at $x_A$ and a receiver at $x_B$. Shaded area represents the stationary-phase region (adapted from Draganov and Ruigrok, 2015).*

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This is equivalent of having an impulse source (also referred to as virtual source) at the location of one of the receivers. This process is also called Green's function retrieval. The Green's functions can be retrieved from cross-correlations of either diffuse or deterministic wavefields. The diffuse wavefield originates from the (i) multiple scattering due to medium heterogeneity (Lobkis and Weaver, 2001; Snieder, 2004) or (ii) due to the random distribution of noise sources acting simultaneously (Shapiro and Campillo, 2004). Deterministic wavefield originates from the transient sources (e.g. active shooting or earthquakes) in a deterministic medium (Schuster, 2001, Bakulin and Calvert, 2004).

Following Wapenaar and Fokkema (2006) for the general 3D acoustic/elastic medium the approximate Green's function G between receivers at $x_A$ and $x_B$ located at the free-surface arising from the impulse sources located along the boundary $D_1$ (Fig. 1) can be written in the frequency domain as:

$$2\Re\left\{\hat{G}\left(\mathbf{x}_B,\mathbf{x}_A,\omega\right)\right\}\approx\frac{2}{\rho c}\oint_{\partial D_1}\hat{G}^*\left(\mathbf{x}_A,\mathbf{x},\omega\right)\hat{G}\left(\mathbf{x}_B,\mathbf{x},\omega\right)d^2\mathbf{x} \quad (1)$$

Where R denotes real part, * indicates complex conjugate, c is medium velocity and ρ is medium density. Not every source located along the $D_1$ is contributing to the Green's function – only those located in so-called stationary-phase region (Snieder, 2004) (Fig. 1). The following assumptions are made to derive eq. 1: (i) the boundary sources are in the far-field of the receivers, (ii) the medium outside the boundary $D_1$ is not causing scattering, (iii) medium properties vary smoothly across the $D_1$, (iv) medium properties along the $D_1$ are constant. The above assumptions are almost impossible to fulfill in reality, therefore the amplitudes of the retrieved Green's functions are incorrect. There could be also some non-physical (ghost) events that can originate from non-perfect wavefield separation (presence of mode-conversion) or from the attenuation (the above derivation is valid for lossless medium). In the latter case, ghosts can be used for Q estimation (Draganov et al. 2010). In case of non-impulse sources, the Green's function on the left hand side of eq. 1 is multiplied by the source signature.

### Extracting body-wave energy

Theory predicts that the cross-correlation retrieves the complete wavefield including body-wave reflections (Wapenaar, 2004). However, sources close to the surface (one-sided illumination) contribute mostly to surface waves retrieval. Interaction of free-surface multiples can lead to retrieval of body waves in such a case (Nakata et al. 2011), but one-sided illumination result in non-physical events that can be interpreted as physical reflections. As a remedy, using distant surface sources is advised. However, body waves will originate primarily from either the deeper or distant transient sources emitting body-wave energy (Draganov et al. 2009). In order to capture such sources, relatively longer recordings are needed as compared to those required for surface waves retrieval.

Recorded ambient noise panels will be always dominated by surface waves, therefore surface waves suppression is a crucial step in SI aimed at obtaining reflection response. Surface waves can be suppressed either at the acquisition stage by using groups of geophones or during pre-processing step with the application of (i) bandpass filters, (ii) automatic or semi-automatic illumination analysis to select non-surface-waves dominated panels (Draganov et al. 2013). It is worth to note that in the hardrock environment there is usually a good separation between surface waves (peaking at 20-30 Hz) and reflections (above 35-40 Hz) observed, however ambient noise sources are considered as emitting energy primarily lower than 30 Hz. Contribution of the body-wave energy can be further enhanced on the correlated panels by either the illumination analysis including slowness (Panea et al. 2014) or specially designed filters (Nakata et al. 2015). It might be also useful to locate the noise sources using, e.g. methods proposed by Dales et al. (2017) or Roots (2016) and perform selective stacking, considering only those sources located in the stationary-phase region After the surface-wave suppression, in case of using cross-correlation, the essential step is to apply trace-by-trace energy normalization in the recorded noise panels in order to equalize non-even source/receiver contributions. This step is not necessary when using cross-coherence (Nakata et al. 2011). Another advantage of the cross-coherence is that the correlated panels do not need to be deconvolved for the source signature. However, it can also boost the noise due to the prewhitening.

## SI IN HARDROCK EXPLORATION

### Ambient noise SI

The first ambient noise SI experiment in the hardrock exploration context was performed at Lalor Lake, Manitoba, Canada (Cheraghi et al. 2015) before an active source 3D seismic survey. 336 receivers were deployed along a net of 16 receiver lines (100 m receiver spacing, 360 to 400 m line spacing) forming a small 3D patch (4 $km^2$) located close to the operating mine. 300 hours of data were recorded and processed using cross-correlation in the 2-35 Hz frequency band, however power spectral density plots indicate some energy as high as 100-150 Hz. Beamforming analysis suggested that the mine was a source of the body-wave signals. Resulting virtual shot gathers were processed similarly to the active source data. Comparison of the 3D DMO volumes from processing active/passive data indicates similarities, but noticeably passive data exhibit flatter dips as expected for the imaged geology. As demonstrated by Roots (2016) using synthetic modelling this can be a result of one-sided source distribution (Fig. 2). In case of dipping strata, sources should be located down-dip for a proper imaging. If sources are located up-dip from the receiver array, reflectors are not properly focused or their dips seem to be flatter. However, scattering occurring in the hardrock environment can act as secondary sources at depth, therefore relaxing the above conditions. To circumvent the biased source distribution, Roots (2016) used beamforming analysis to select the correlated panels before stacking that fall into given source azimuth bin. Subsequently, only the panels with the azimuths corresponding approximately to the stationary phase regions for the analyzed receiver lines (pretty much in-line azimuths) were kept. Finally, selected bins were energy-normalized to equalize contribution of each azimuth. Beamforming was also used to apply time-shifts and flatten dominant coherent energy coming from the ventilation shafts before application of the F-K rejection filter. Comparison of the results of Cheraghi et al. (2015) with Roots (2016), Roots et al. (2017) suggests that this revised workflow improved imaging of the deeper reflectors (Fig. 3). Girard and Shragge (2016) also used Lalor Lake data and demonstrated the potential of using 3D beamsteering to create plane-wave dip spectra of the data to isolate body-wave energy.

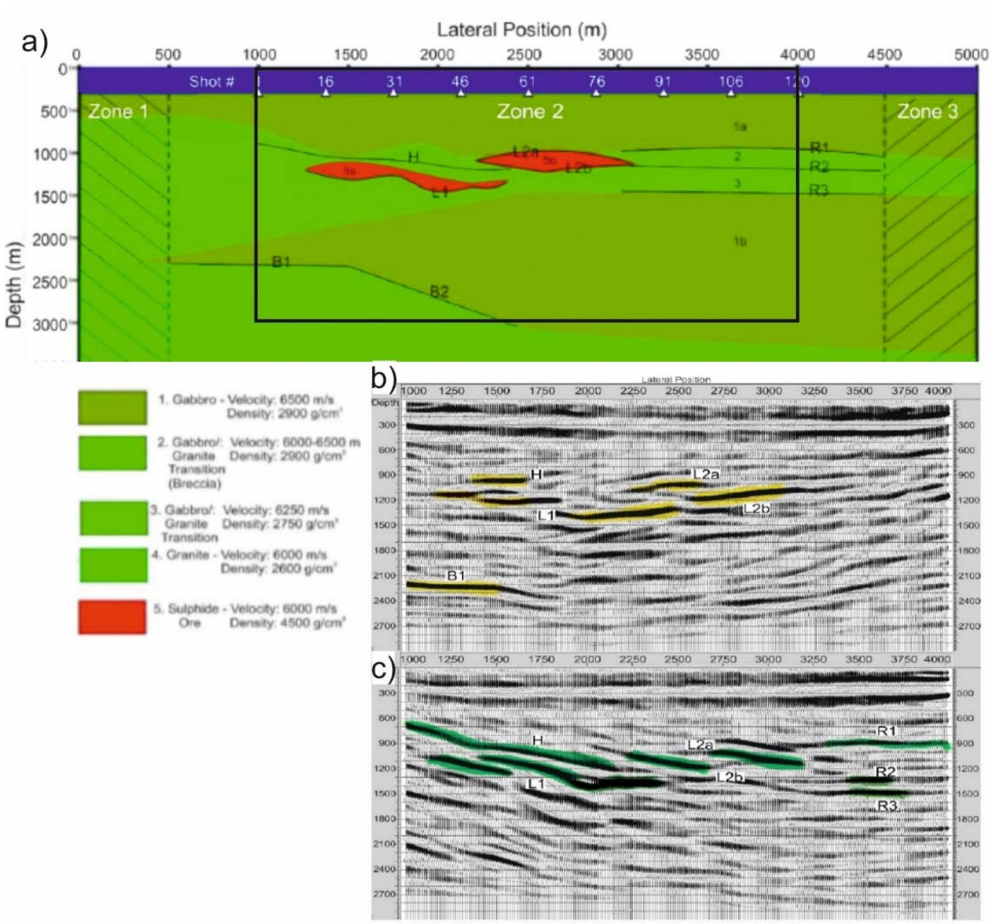



*Figure 2: (a) Model of the Lalor Lake VMS deposit used to generate synthetic data simulating active and passive survey. (b) Migrated stack of the passive noise data with the noise sources located in Zone 1 (left). (c) Migrated stack of the passive noise data with the noise sources located in Zone 3 (right). Modified from Roots (2016).*

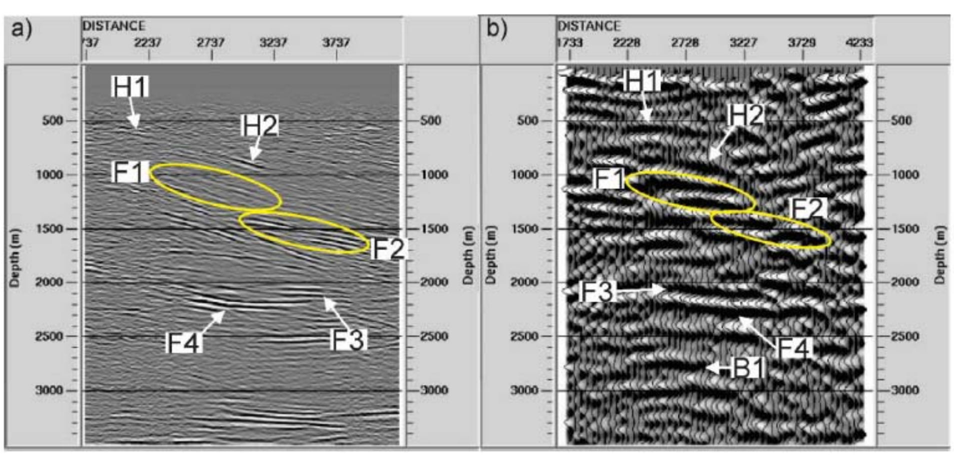



*Figure 3: Stacked DMO sections along line 133 from the Lalor Lake survey: a) active source data; b) ambient noise data. From Roots (2016).*

SI can be also applied to the data acquired directly in the mine as recently shown by Olivier et al. (2015). Authors process 30-day long passive data acquired in the Garpenberg iron ore mine in Sweden using 18 sensors. Retrieved Green's functions are characterized by a broadband frequency range (20-400 Hz) thanks to the broadband characteristics of the noise sources and careful noise panels selection. Similarly to the conclusions derived from the Lalor Lake case, strong scattering of waves due to the mine infrastructure is helping in reconstruction of Green's functions despite the non-perfect source illumination. A 3D S-wave tomography attempted from the retrieved Green's function in the lower frequency limit (<100 Hz) has shown some velocity anomalies correlating with the know ore bodies.

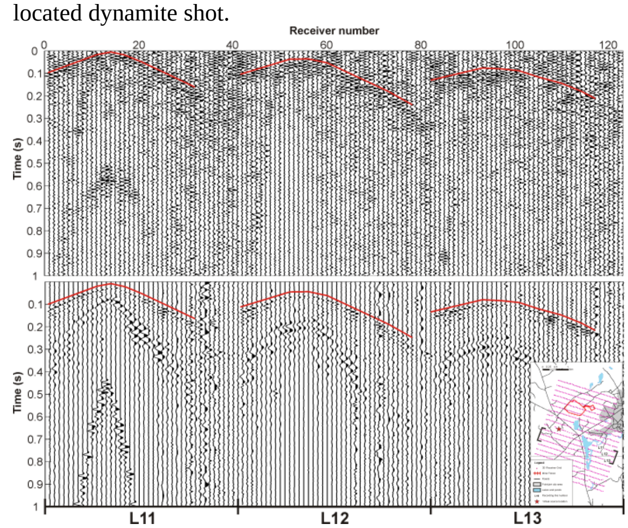
## Active source SI

There is a large potential in SI methods applied to active-source data in the ore exploration context. One can think of potentially regularizing seismic surveys by creating new virtual shot gathers. However, the biggest challenge is how to merge the SI data with the original active source data? Active source SI can be also used e.g. to improve the first break picking, and in consequence, refraction static solution, as recently demonstrated by Place and Malehmir (2016) for 2D data. Authors used the method of virtual and supervirtual refraction (Bharadwaj et al. 2012) to enhance long-offset refracted arrivals. Potentially, the virtual refraction method could be used in combination with the LMO + residual statics method to produce a refraction-based static solution without first break picking.

Active source SI is especially applicable to transform/redatum borehole/VSP data (e.g. Bakulin and Calvert, 2004). Potential applications in the hardrock exploration context were studied by Brand et al. (2013) and Hurich and Deemer (2013). Brand et al. (2013) demonstrated that using SI, surface shots used in walkaway VSP could be redatumed to the borehole receivers. The whole survey can be then reoriented in such way that the new virtual shot gathers can be processed like a standard surface reflection seismic to image the subvertical reflections. Hurich and Deemer (2013) further verified this methodology using real VSP data acquired in the Voisey Bay mine site in northern Labrador, Canada. Redatumed VSP data imaged confidently a sulfide-bearing dike.

## PASSIVE SEISMIC EXPERIMENT IN KYLYLAHTI, FINLAND

Passive 3D seismic survey was recently acquired in the vicinity of the Kylylahti Cu-Au-Zn mine in Polvijärvi, eastern Finland between early August to late September 2016 as a part of the COGITO-MIN project. Following conclusions derived from the Lalor Lake experiment, we used shorter receiver/line spacing (50/200 m), bigger array (~1000 receivers) and longer recording time (~30 days). Detailed description of the experiment and data treatment can be found in Chamarczuk et al. (this volume). Initial processing results suggest that there is a potential in extracting body-wave energy in the high-frequency range (> 30 Hz), where the surface waves are significantly attenuated. It looks like, in this case, the environment is generally more noisy than in case of Lalor Lake, but the dominant body-wave sources associated with the mine activity are also not illuminating the target from all directions. Fig. 4 shows a comparison of a virtual shot gather obtained for receiver 1012 (Fig. 4, red star in the inset) with a co-located dynamite shot.

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Paper 6

# Developing cost-effective seismic mineral exploration methods

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## ABSTRACT

*To be fully embraced into mineral exploration, seismic data require to be acquired faster, cheaper and with minimum environmental impacts addressing also the often brown-field highly noisy environment where these surveys are employed. Since 2013 and through a number of case studies, we have been testing a newly developed, for urban environment digital-based 240 m long, seismic landstreamer for mine planning and mineral exploration purposes. Here, we present a pilot study examining the potential of the streamer for deep targeting a known, down to approximately 850 m depth, iron-oxide mineralization in the historical Blötberget-Ludvika mining area of central Sweden. Combined streamer (100-3C-MEMS, 2-4 m spacing) and 75 wireless recorders (mixed 10 Hz and MEMS, 10 m spacing) were used. A Bobcat-mounted drop hammer, 500 kg, was used to generate the seismic signal. Within 4 days, about 3.5 km of seismic data using 2-10 m source and receiver spacing were acquired. At each source location 3 records were made and stacked vertically to improve the signal-to-noise ratio. The streamer moved 9 times, each time 200 m forward, and wireless recorders were kept at both ends of the profile, moved once, to provide long offsets in the data. While in a swampy and challenging near-surface environment, reflection data processing results clearly image the mineralization as a set of strong high-amplitude reflections and likely slightly extending beyond the known depth. This is encouraging and suggests such a cost-effective exploration method can be used in the area to delineate similar range depth deposits and their depth and lateral extents. Further tests elsewhere should be done to fully recognize the potential of this surveying approach.*

## INTRODCUTION

Economic metallic deposits have usually strong seismic contrast (Eaton et al., 2003 and references therein; Malehmir et al., 2012 and references therein), product of velocity and density, with their host rocks. Therefore, at the presence of favourable geometry, size and signal-to-noise ratio, they should be detectable using reflection seismic methods. While seismic methods have considerably better resolution and penetration depths than other geophysical methods, the high acquisition and processing cost poses a restriction in using them routinely for mineral exploration purposes. There is therefore a high demand in reducing this cost in order the method to be established in the mineral exploration sector similar to a variety of other geophysical methods. Decrease in receiver cost and higher quality sensors have allowed some contributions but in the source side this is still a challenge.

Within an on-going project involving petrophysical, geological and geophysical studies, we have examined the potential of a newly developed, for urban environment, MEMS-based seismic landstreamer (Brodic et al., 2015) for cost-effective mine planning and mineral exploration in two sites in Finland (Malehmir et al., 2017a) and Sweden (this study publihse recently by Malehmir et al., 2017b; Figure 1), respectively. The choice of the streamer was justified in this study due to the road accessibility, and the possibility of high-voltage power cables, railroad and noise contamination if the conventional geophone-type sensors were used instead (Bordic et al., 2015). Earlier seismic studies (Malehmir et al., 2011; Place and Malehmir, 2016) targeting similar types of commodities (iron-oxide mineralization) in the region, Bergslagen ore district, as the one in this study further encouraged us to take this initiative. Downhole logging investigations including full-waveform sonic and laboratory density measurements were conducted (Maries et al., 2016) prior to this study suggesting the iron-oxide deposits (magnetite and hematite) in the study area should seismically be detectable. Therefore, with the main objectives of (1) delineating the known mineralization using the seismic landstreamer and (2) checking the penetration depth provided by a readily accessible and cheap Bobcat-mounted drop hammer, we conducted a pilot seismic survey in October 2015 within 4 days and using 4 persons only. Here, we present how the data acquisition was carried out and encouraging results obtained.

## BLÖTBERGET IRON-OXIDE DEPOSIT

The study area, Blötberget, hosting iron-oxide apatite-bearing ore bodies, is the target of a number of innovative exploration experiments currently on-going (e.g., Maries et al., 2016; Malehmir et al., 2017b,c). We have a great level of knowledge on the mineralization and its 3D geometry, also a wealth of geophysical and downhole logging data (e.g., Maries et al., 2016). Important for this study are: (1) there is currently no mining operation although there are plans to reopen the mine, (2) the

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mineralization is dominantly magnetite but there are horizons where hematite is rich or present notably, and (3) the estimated intact ore is about 45 Mt and is known to extend at least to 850 m depth. The mining operation stopped in 1979 with most of the mining taking place at approximately 240 m depth.

magnetic susceptibility, formation resistivity, fluid conductivity and temperature. The two deepest holes, BB70-001 and BB73-001 are too slim (32 mm) to be logged. In addition to these, density measurements were conducted on core samples at every 1-3 m allowing studying seismic response of the mineralization using synthetic 1D seismograms. Figure 2 shows two examples

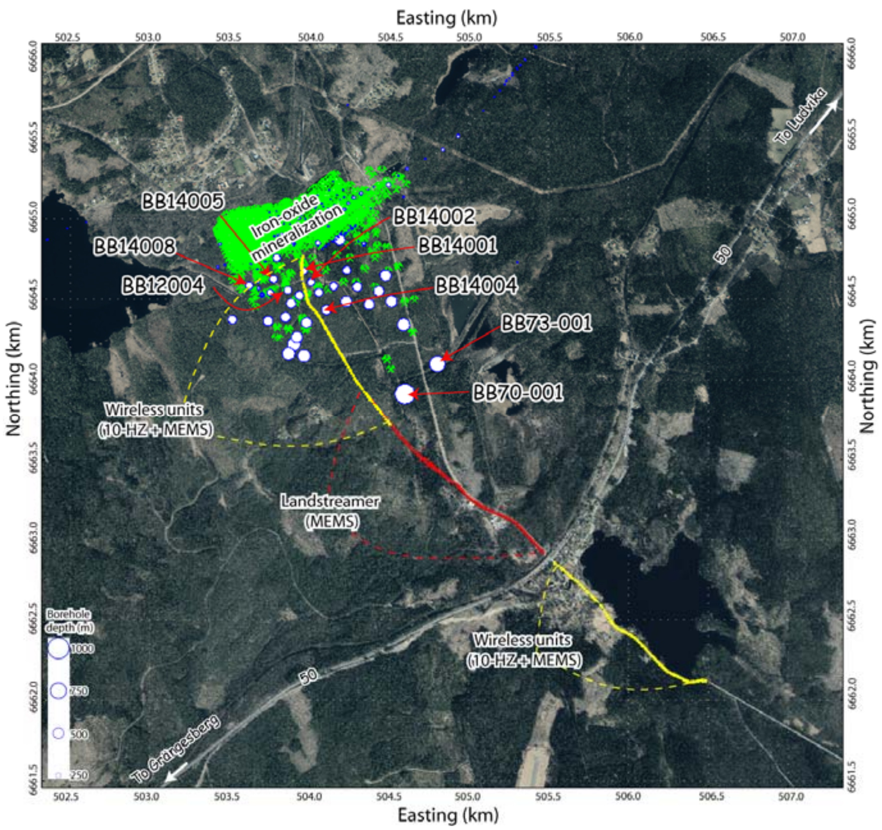


*Figure 1. Aerial photo of the Blötberget-Ludvika mining area in central Sweden, and the location of the seismic profile (yellow and red lines). The profile was acquired using a combination of wireless recorders (purple points) at its both ends and the landstreamer (red points) in between. Green symbols show vertical projection (to the surface) of the known mineralization, two distinct hematite and magnetite mineralized zones dipping at about 40 to the southeast and striking NE-SW. Various size circles show existing boreholes six of which (e.g., BB12004) have so far been downhole logged.*

The mineralization occurs within inliers of volcano-sedimentary rocks as sheet-like bodies moderately dipping towards southwest down to 850 m depth after which it is unclear if continues deeper or stops due to faulting of folding, or simply dies out. Two sets of district mineralization occurs, on average approximately 30-40 m apart, with thicknesses varying from a few meters to sometimes over 30 m of magnetite-hematite. Sequences of granitic-pegmatitic rocks occur within the mineralization (likely concordant with the foliation).

## DOWNHOLE PHYSICAL PROPERTY LOGGING

Since 2015, we have downhole logged six boreholes (Figure 1, BB12004, BB14001, BB14002, BB14004, BB14005 and BB14008) using full-waveform triple sonic, natural gamma,

and why we anticipate reflection seismic method to be suitable for deep targeting the iron-oxide mineralization at the site. Hematite and magnetite in fact showed low resistivities and only on the order of 500-1000 ohm-m, which is not so significant to justify electric- or electromagnetic-based methods to be superior even when ignoring their limited depth resolution. Maries et al. (2017) details the physical property studies and how the results can be correlated with RQD and other types of measurements.

## SEISMIC DATA

### Seismic data acquisition

The seismic data acquisition started after a quick site reconnaissance upon our arrival. Because of a major and high-traffic road running in the southern part of the profile (Figure 1), it was decided to cover the southern part of the road using 51 wireless recorders connected to 10 Hz geophones and 24 recorders connected to MEMS sensors near the road (also railroad) and at where a small village is present. The streamer, totally 240 m long, comprising of 5 segments each containing 20 MEMS-based sensors were used right after the road on the northern side of the wireless segment (Figure 3a). One of the streamer segments contained 20 sensors 4 m apart and the remaining four segments had 2 m sensor spacing. A Bobcat-

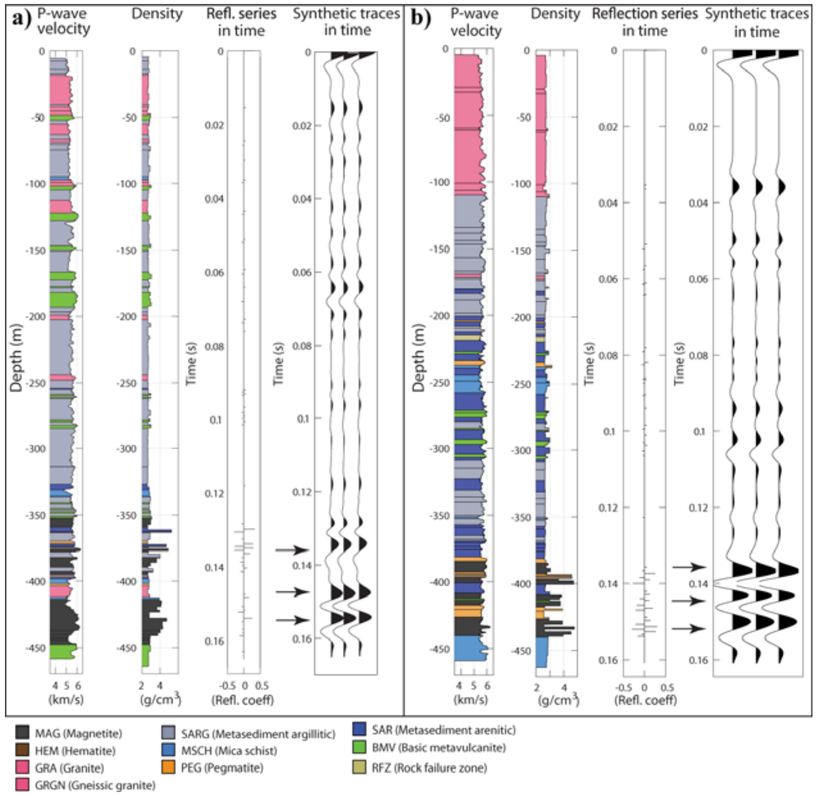


*Figure 2. Example downhole sonic logging and laboratory density measurements from two boreholes (a) BB14005 and (b) BB14002 (for locations see Figure 1) intersecting the mineralization at 400-450 m depth suggesting, based on 1D synthetic seismograms, a strong seismic signal can be expected form the iron-oxide deposits. From Maries et al. (2017).*

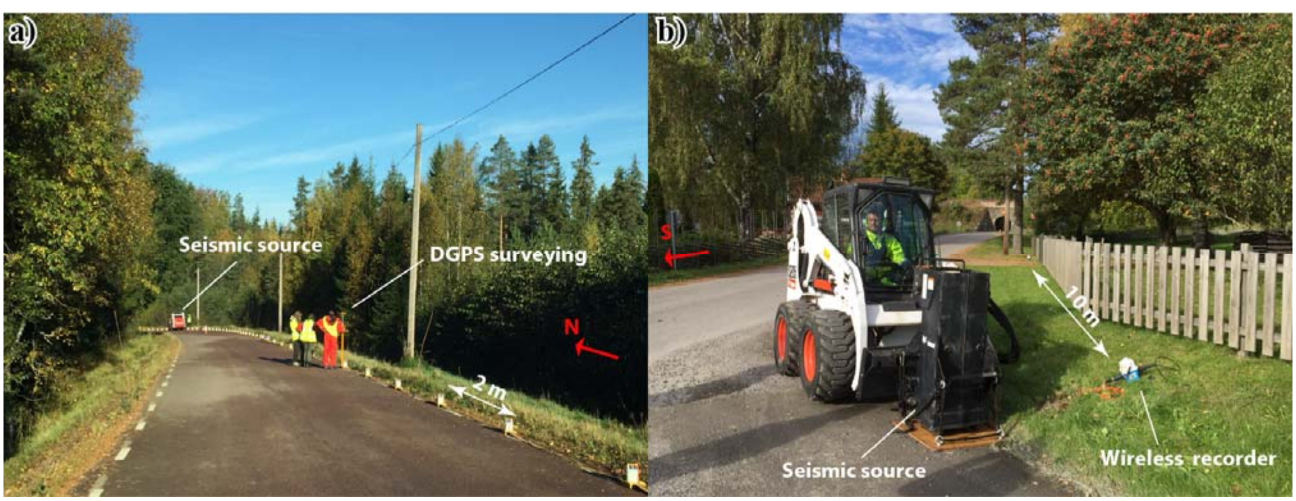


*Figure 3. Example field photos taken during the data acquisition (October 2015) from (a) the seismic landstreamer, and (b) the Bobcat-mounted drop hammer (500 kg) used in combination with 75 wireless recorders. Fixed array geometry was used while recording the data along the streamer. The streamer then moved to a new position (200 m forward) with 40 m overlap from the previous position. Main portion of the profile was on forest's gravel roads. Photos by Alireza Malehmir.*

mounted drop hammer (500 kg) was used as the seismic source (Figure 3b). The acquisition started from the southern-end of the profile with 3 shot records made at each receiver location and then progressed towards the streamer part on the northern side of the road. When shots were made at the last sensor of the streamer, the streamer was moved about 200 m towards the north to a new position while the wireless recorders south of the road kept fixed. The shooting-recording at every new streamer receiver position was then done and again the streamer was moved 200 m forward. The streamer was moved seven times after which the wireless recorders placed south of the road were then moved to the northern-end of the profile (Figure 1). Data recording then continued with the streamer moved twice more towards the north and then shots were made at the new position of the wireless recorders while the streamer then kept fixed at its last position.

Wireless recorders were placed at every 10 m and partly overlapped the last position of the streamer (Figure 1). GPS times of the hits registered on the streamer data were used to extract the data from the wireless recorders operating in an autonomous mode during the whole survey. These data were then merged together and the three repeated shot records vertically stacked to improve the signal-to-noise ratio. To avoid a total failure, 23 explosive shots (charges ranging from 50-100 g) hand drilled into the glacial tills down to 50-80 cm were also recorded in the middle of the profile. All receiver positions were surveyed using an accurate DGPS system to provide high-precision geodetic positioning. In the middle of the profile, accurate DGPS data could not be obtained because of the dense forests therefore some of the coordinates had to be interpolated thanks to the fixed and known spacing of the sensors in the streamer. For the quality control and further corrections, LiDAR elevation data publically available were used. Overall we anticipate some inaccurate geodetic positioning on the order of 50 cm in some part of the profile. The whole data acquisition including mob/demob and geodetic surveying took 4 days. In total 533 shots and 90,587 traces (after the vertical stacking) were generated. Also in total, 1049 receiver locations/pegs (900 from the streamer, 75 wireless recorders south of the road and 74 recorders on the northern-end of the profile) were used.

## Seismic data processing

The data processing followed a conventional poststack approach

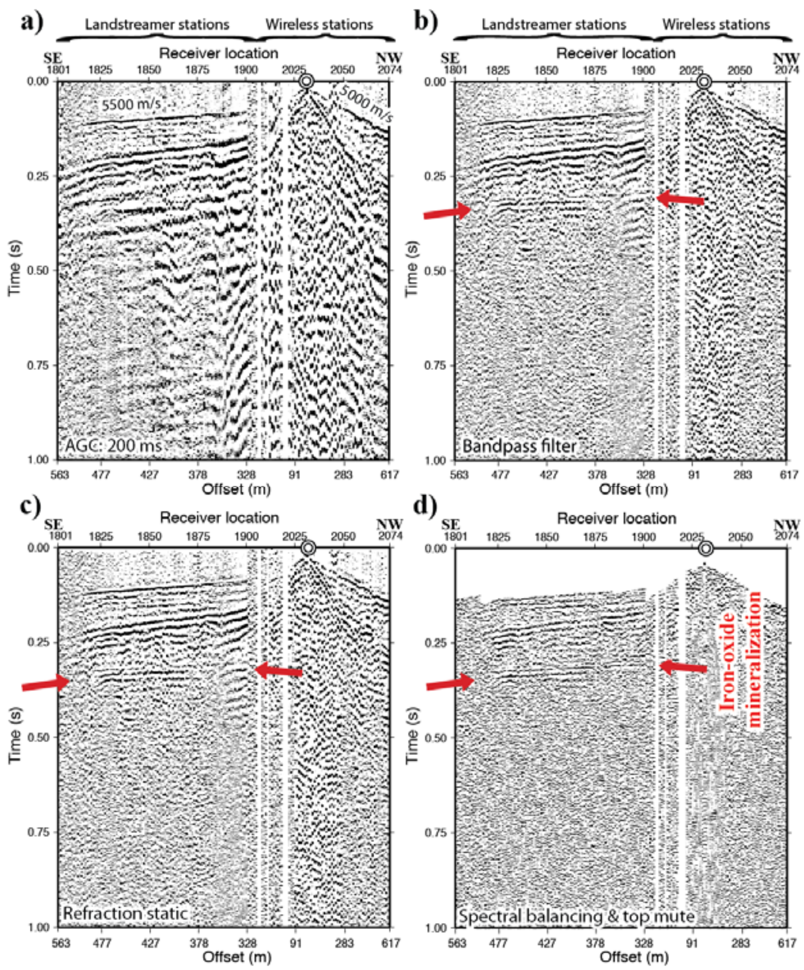


*Figure 4. (a) Example raw shot gather from a shot fired near one of the northern wireless stations and after (b) bandpass filtering, (c) refraction static corrections, and (d) spectral balancing and top mute. Note the reflection marked by the red arrow and interpreted to originate from the mineralization clearly recorded in the streamer sensors.*

giving a focus to refraction static corrections, differentiating geophone data (to be in the acceleration domain as the MEMS data), coherent and random noise attenuation prior and after stacking, velocity analysis and NMO corrections. Figure 4 shows an example shot gather and how a shot fired near one of the wireless recorders on the northern part of the profile generated a strong reflection from the mineralization in the streamer data. The reflection is quite clear after a few steps of processing.

## RESULTS

Figure 5a shows the six deep boreholes downhole logged by Maries et al. (2016) and visualized in 3D. The two distinct sets of mineralized zones (hematite and magnetite) are evident from the density measurements on core samples from these holes. The deepest boreholes in the area (BB70-001 and BB73-001 in Figure 5a) intersect the mineralization at about 850 m depth. Figure 5b shows the reflection seismic result visualized in 3D with the known mineralized horizons. The most striking feature in the section is a set of high-amplitude reflections associated with the known mineralization. It is so noticeable and bright-spot looking that it cannot be anything than from the mineralization.
Results are encouraging and the reflections are most likely generated from the mineralized horizons. This may also suggest a deeper continuation of the mineralization from the known depth of 850 m. It is however unclear why the mineralization stops and whether this is a problem of depth penetration or if it reflects the actual geology remained to be further investigated.

## CONCLUSIONS

We have carried out a novel and pilot test to check deep targeting iron-oxide mineralization using a MEMS-based seismic landstreamer and a Bobcat-mounted drop hammer in an exploration and mining site in central Sweden. Such a set-up

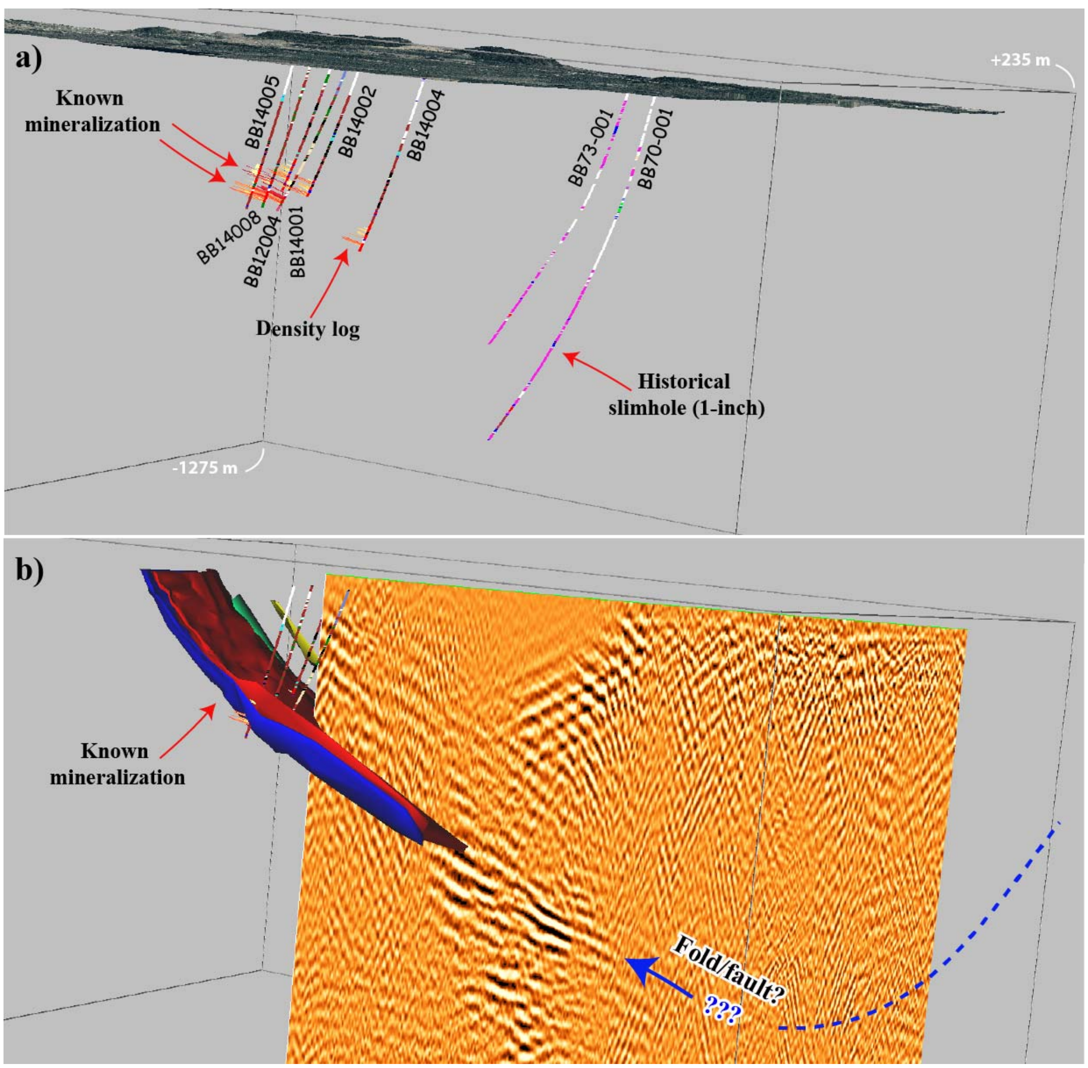


*Figure 5. (a) 3D visualization of some of the boreholes downhole logged prior to the seismic survey, and (b) reflection seismic section of a portion of the profile and known ore bodies. A series of strong reflections associated with the mineralization is evident down to about 900 m depth. It is unclear why the reflections stop at this depth and if this has any exploration or geological implications.*

appears to be sufficient for this type of deposit and depth range and is highly cost-effective (50% cheaper than convectional ones) using also an affordable source; it does not require extensive reconnaissance and site planning. Only a minimum set-up was required to set up the drop hammer as the seismic source and a minivan to place the acquisition system (for QC-ing). The streamer system has been used in various test sites in the Nordic countries but none of those studies have shown such a deep potential. This test therefore places its potential highly also for deep targeting (750-1000 m) as illustrated here. Future studies should aim at comparing the streamer data with conventional plant type sensors, checking the lateral extent of the mineralization and if the abrupt stop in the mineralization is due to geology or depth penetration problems.

## ACKNOWLEDGEMENTS

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Paper 7

# Wireline logging and distributed acoustic sensing VSP to characterize host rocks and alteration of porphyry deposits: preliminary results from the New Afton mine

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## ABSTRACT

*Wireline logs and vertical seismic profile (VSP) data were acquired in two boreholes intersecting the New Afton Cu-Au porphyry deposit located near Kamloops, BC. The wireline logs and VSP data are components of an integrated geophysical imaging and 3D geological modelling study that aims to improve knowledge of the role of magmatic hydrothermal processes and structural controls in concentrating metals in porphyry deposits. Log data provide physical rock properties for the propylitic, phyllic, and potassic alteration zones. Both propylitic and phyllic zones are characterized by a broad distribution of density and P-wave velocities whereas the feldspar-dominant potassic alteration zone has generally high velocities. The VSP survey was conducted with a distributed acoustic sensing (DAS) system which utilized fibre-optic cables cemented in two boreholes at the New Afton mine. Fibre-optic cables comprised standard and Constellation™ fibres in both straight and helically-wound configurations for comparison purposes. Seismic sources consisted of fifty shot points each loaded with one kilogram of pentolite explosive placed in a 20 m deep shot hole. VSP data from both types of fibre show clear downgoing waves and reflections although signal-to-noise ratio is significantly higher on the Constellation™ fibre-optic cable. A preliminary analysis of VSP data from one shot point shows reflections possibly associated with the potassic zone and the picrite unit located just below the bottom of the borehole.*

## INTRODUCTION

The Geological Survey of Canada's Targeted Geoscience Initiative is developing an integrated geophysical imaging and 3D geological modelling research study of the New Afton porphyry deposit located in the Canadian Cordillera of south-central BC. This alkaline Cu-Au porphyry deposit previously supported an open pit operation and is currently being mined at deeper levels through underground workings, providing geological constraints extending beyond 1.5 km in depth. The study intends to combine new vertical seismic profile (VSP) and 3D magneto-telluric (MT) surveys, along with multi-parameter deep drillhole geophysical logs, and 3D modelling to elucidate the magmatic hydrothermal processes and structural controls responsible for concentrating metals in porphyry deposits. Here, we present acoustic and elastic rock properties from wireline logs and show preliminary results from a VSP survey acquired with a distributed acoustic sensing (DAS) system deployed in two boreholes that intersect the main mineralized zone. The two boreholes are intersecting the porphyry alteration halo with a gradual but not necessarily homogeneous increase of alteration intensity towards the mineralized zone. The wireline logs and DAS data also provide information on lithology and fault zones.

## GEOLOGY

This summary of the local mine geology is based on drillcore logging, 3D geological modelling and surface mapping recently conducted by New Gold (Lipske, J., and Wade, D. 2014; Bergen et al. 2015). Figure 1 summarizes this description of the geology by showing a plan view of the main lithologies and alteration zones. The Cu-Au New Afton porphyry deposit is dominantly hosted by fragmental and crystalline volcanic rocks (BXF) of the Late Triassic Nicola Formation and to a lesser extent by the 204 Ma Cherry Creek monzonite of the Iron Mask batholith, the latter interpreted as the heat source that caused alteration and mineralization in this alkalic porphyry (Lipske and Wade, 2014). A subvertical SW-plunging zone of primary hypogene mineralization, largely coincident with the potassic alteration zone, contains disseminated chalcopyrite and bornite (Lipske and Wade, 2014). This hypogene ore zone is controlled structurally by two subvertical NE-SW striking fault zones, known as the footwall and hanging wall faults. The hanging wall fault, juxtaposes BXF with a subvertical body of serpentinized picrite (Lipske and Wade, 2014). This tectonic contact is within the incompetent serpentinized picrite defined by a high strain zone of ductile deformation rich in magnetite and locally confines a zone of calcic alteration composed of magnetite, epidote, actinolite and apatite (Lipske and Wade, 2014). The primary hypogene ore zone is cut by numerous moderately to steeply dipping fault zones that controlled secondary hypogene mineralization of tetrahedrite and tennanite. Supergene mineralization of native copper and chalcocite in hematite-rich oxidation zones is more abundant at higher structural levels in the vicinity of the open pit but native copper extends to 700 m below surface beneath the pit along older, long-lived structures (Lipske and Wade, 2014; Bergen et al. 2015).

## WIRELINE LOGGING

Wireline logs were acquired in June and July 2017 in two boreholes (EA16-171 and EA17-197) located underground approximately 650 m below the surface. The two boreholes start

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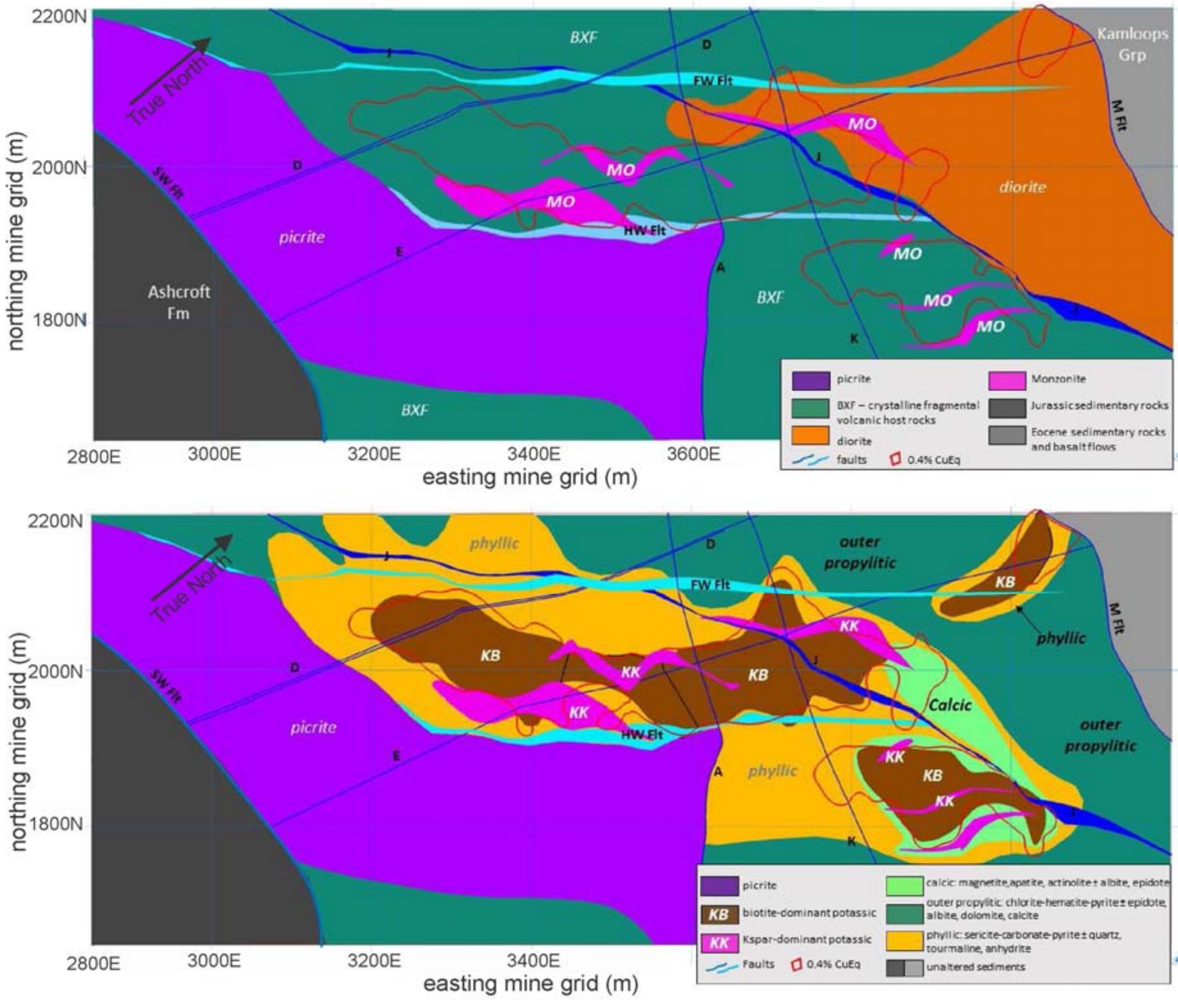


*Figure 1. plan view of (top) the main lithological units and (bottom) main alteration zones at New Afton. The main hypogene mineralized zone is outlined in red with no color fill and is associated with the biotite-dominant and feldspar-dominant potassic alteration zone. Units are in mine grid coordinates (from Lipske and Wade, 2014).*

from the same drill bay but have different dip and azimuth. Borehole EA1-197 has a length of 701 m whereas EA16-171 is 870 m long. Both boreholes intersect numerous faults that tend to cave in open drill holes that significantly complicated acquisition of the wireline logs. A drill rig was used to ream out and maintain boreholes open for the entire duration of the logging program. Logging was conducted in short open-hole sections starting from the bottom of the borehole while drill rods covered unstable areas above the interval being measured. Drill rods were then lifted to uncover the next interval of stable open hole for logging. Probes were not deployed over larger fault zones or caved sections. Logging measurements included calliper, density, natural and spectral gamma-ray spectrometry, magnetic susceptibility, resistivity, induced polarization, induction conductivity, and full-waveform sonic logs. All wireline logs will be calibrated with petrophysical measurements on drill core samples (ongoing). Density measurements were conducted through drill rods and subsequently calibrated with values measured over a short section of stable open hole. This approach minimized the risk of having the radioactive source used for density measurements stuck in a borehole.

Figure 2 presents some logs for borehole EA17-197 plotted together with the main fault zones, alteration, and lithological units from drill core geological logging conducted by New Gold. In general, density and velocity values vary significantly especially in the upper part of the borehole. Some of this variability is due to faults and caved zones indicated by large values on the calliper log. The large values on the calliper log correlate with low density and to some extent with lower velocity values on P- and S-wave velocity logs. Some variations occur over depth intervals corresponding to one lithology and one type of alteration (for example near 400 m). The cause of those variations still need to be investigated. The lower part of EA17-197 shows fewer faults or caved zones. Latite dikes near 560 m are characterized by lower P- and S-wave velocites. Below 560 m, the sonic logs show higher P- and S-wave velocities with less variability than for rocks above. This deepest interval comprises the potassic alteration zone (KK and KB on figure 2).

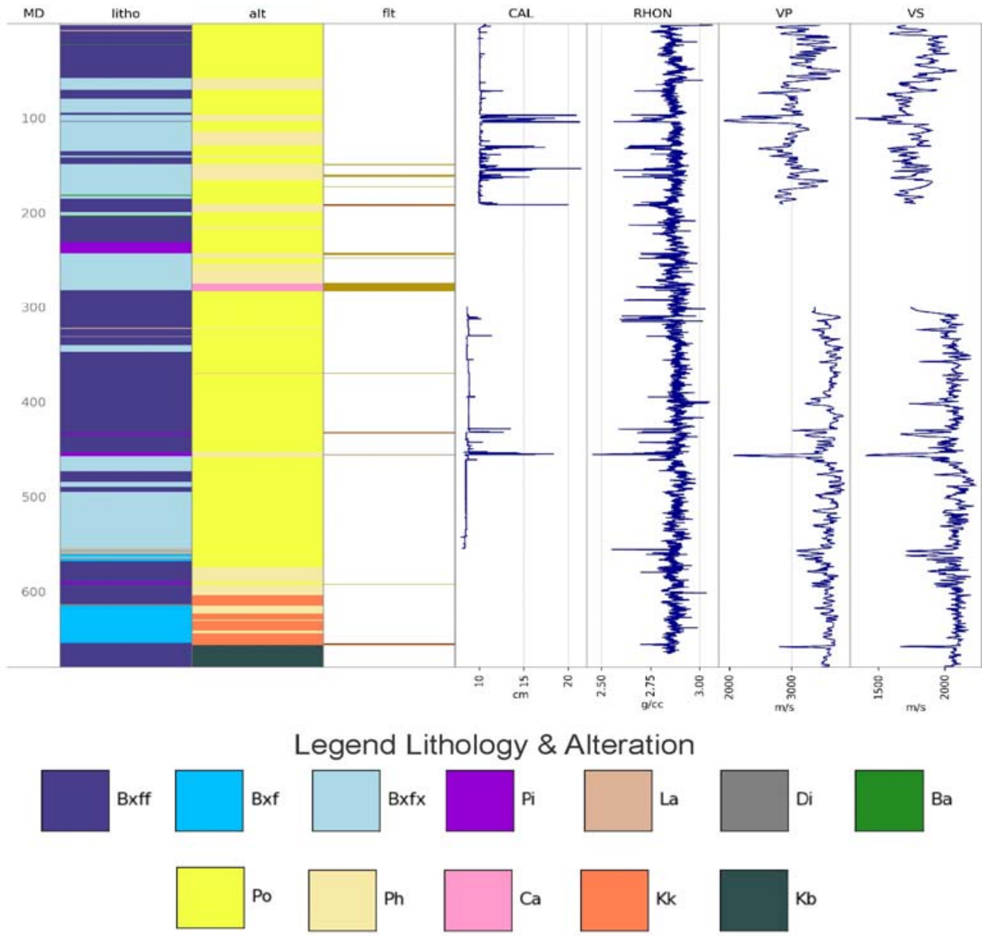


*Figure 2. Wireline logging data in borehole EA17-197. Tracks from left to right show, meters, lithology, alteration, faults, caliper, density, P-wave and S-wave velocity. Bxf: volcanic fragmental; Bxfx: crystalline Bxf; Bxff: fragmental Bxf; Pi: picrite; La: latite; Di: diorite; Ba: basalt; Po: propylitic; Ph: phyllic; Ca: calcic; Kk: feldspar-dominant potassic; Kb: bitotite-dominant potassic.*

Figure 3 shows P-wave velocities and densities for the various alteration types intersected in the borehole. Also shown on this figure are ellipses from principal component analysis representing the mean and scaled eigenvectors of the covariance matrix of the distribution of each alteration type. The major and minor axes of the ellipses correspond to two standard deviations. Both propylitic and phyllic alteration zones have broad distributions of density and velocity values. The feldspar-dominant potassic zone (KK on figure 2) is characterized by higher P-wave velocities and relatively high densities. This suggests that the feldspar-dominant potassic alteration zone may be detectable on VSP data when juxtaposed against rocks characterized with lower acoustic impedances. Logging data presented in figure 2 suggest this is a possibility in EA17-197 as rocks above the potassic zone have similar densities but slightly lower velocities.

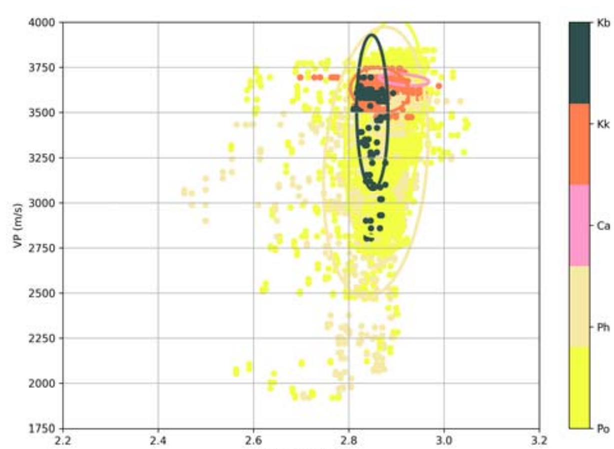


*Figure 3. Velocity versus density for different types of alteration in EA17-197. Main axis of ellipses represent two standard deviations (from principal component analysis).*

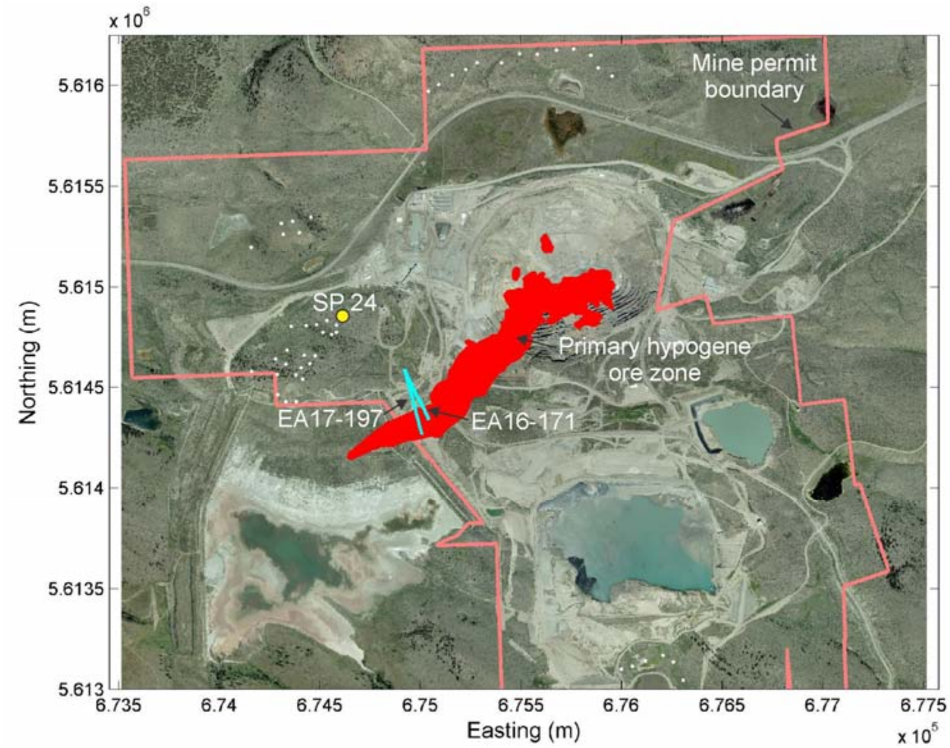


*Figure 4. Map showing surface location of seismic shot points (white dots), surface projection of two boreholes, and surface projection of the hypogene mineralized zone (in red). VSP data from shot point 24 are shown in figure 5.*

## VSP WITH DISTRIBUTED ACOUSTIC SENSING

One technical objective of the survey was to compare VSP results obtained with different types of fibre-optic cables and to assess their benefits for mineral exploration. The two boreholes surveyed with wireline logs were also instrumented with fibre-optic cables for VSP-DAS recording. The fibre-optic cables comprised straight standard single mode fibre and straight Constellation$^{TM}$ single mode fibre (hereafter referred to as Constellation). In addition, a helically-wound single mode fibre-optic cable comprising both types of fibre was installed in borehole EA16-171. Standard fibre-optic cables placed in the two boreholes were "daisy-chained" together to form an approximately 5 km long continuous fibre combining the straight and helically-wound cables. The Constellation fibre-optic cables were also daisy-chained together. All fibre-optic cables were cemented in boreholes to provide optimal coupling with rock formations. DAS technology has been used previously for oil and gas applications (Daley et al., 2014; Harris et al., 2016) and for mineral exploration (Riedel et al., 2017; Urosevic et al., 2017). Results from our survey at New Afton are the first VSP data for mineral exploration obtained with straight and helically-wound Constellation fibre-optic cables. The latter was deployed to ensure omni-directional sensing capability of the various potential wavefield modes and wave propagation directions.

Figure 4 shows a map of the survey area with locations of shot points and surface projection of the two boreholes and the main hypogene mineralized zone. The mine site has a variety of infrastructure including mills, offices, subsidence zones, and tailing pounds that restricted areas where seismic sources could be deployed. The open pit of the old Afton mine was avoided due to slope stability issues. In addition, the trans-Canada highway, two pipelines, numerous power lines, and concerns raised to protect a vulnerable spadefoot toad species were addressed during the planning of the survey. The survey included 50 shot locations located in four clusters. Most shot points are located in a cluster west of the open pit which should contribute to image the extent of lithological units and alteration zones west of the two boreholes. Other shot locations will help define velocities and will also contribute to seismic imaging. At each source location, one kilogram of pentolite explosive with two electronic detonators was placed in a 20 m deep shot hole. Each shot hole was tamped with 90 kg of bentonite mixed with water and drilling sand.

Two different distributed acoustic sensing recording systems were used for the VSP survey; one for the standard fibre-optic cables (hereinafter referred to as V2) and one for the Constellation fibre-optic cables (V3 – also referred to as the Carina® sensing system). Constellation fibre-optic cable combined with the V3 recording unit provides seismic data with higher signal-to-noise ratio whereas the helically-wound fibre-optic cable has enhanced transverse sensitivity relative to straight cable (Kuvshinov, 2016) which is most sensitive to wavefields that exert longitudinal strain on the fibre. Seismic waves generated at each source location were recorded every 0.25 m along the standard fibre-optic cable and every 1 m along the Constellation fibre-optic cable using a sampling rate of 0.5 ms.

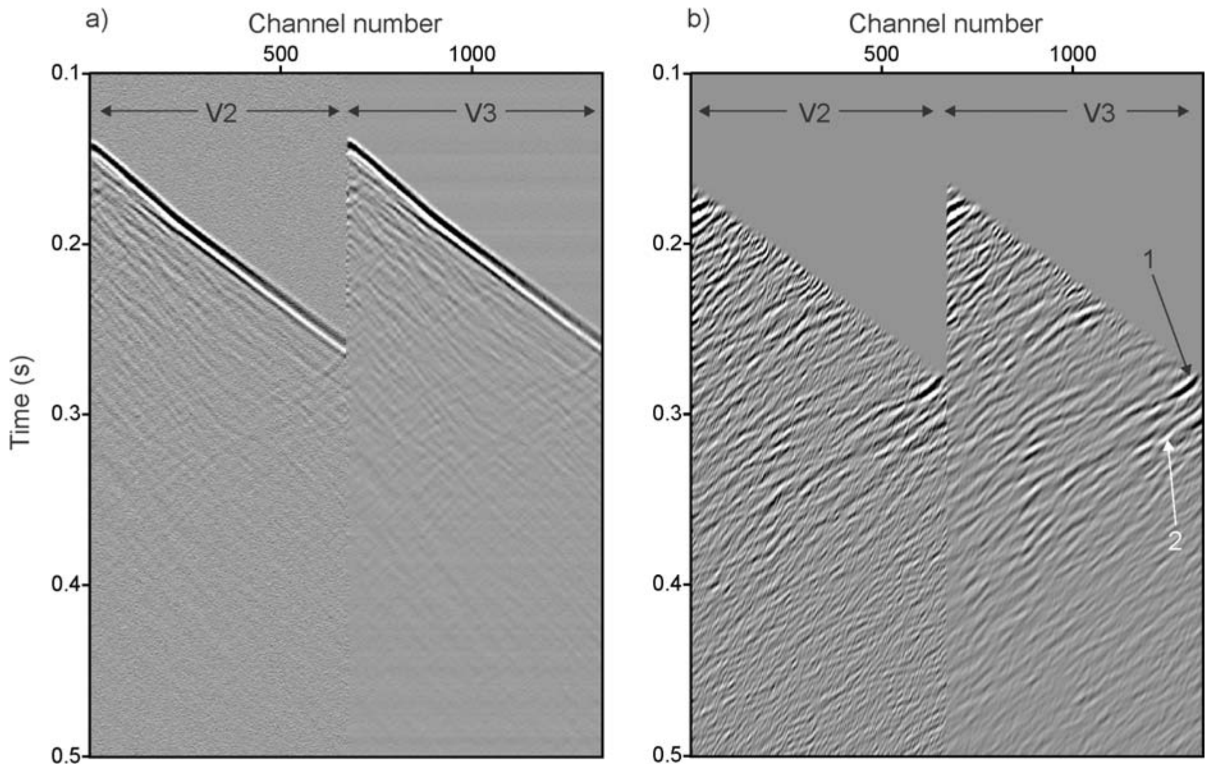


*Figure 5. Comparison of V2 and V3 DAS data in EA17-197. (a) Field data without any processing showing strong downgoing waves and some reflections. Both V2 and V3 data have the same gain for display. Signal-to-noise ratio is lower for the standard fibre-optic cable. (b) Reflections and other upgoing signal after the application of a fk-filter and muting of first breaks. Arrows point to reflections discussed in the text. V2 data on this figure are sampled at 1 m interval (one channel corresponds to 1 m). The first channel is at 116 m above sea level, approximately 600 m below surface.*

Synchronization between surface shots and underground DAS recording units was done with GPS time. A high-precision clock synchronized at surface with GPS time was brought underground and used to keep the time of continuous seismic records. At surface, the GPS time stamp was saved at the firing time of each shot point and served as the basis to extract shot gathers from continuous DAS recording. Three days of ambient noise were also recorded for seismic interferometry analysis prior to the suvey with explosives. All VSP-DAS data were acquired in August 2017.

Figure 5 shows the field data acquired for the straight fibre-optic cable in borehole EA16-171 for shot point 24 (see figure 4 for location of shot point). Figure 5a compares the field records for both V2 and V3 systems (same gain for display). Both V2 and V3 data show clear downgoing waves and some reflections. Signal-to-noise ratio is significantly higher for V3 data. Figure 5b shows the same data after the application of an fk-filter to remove downgoing waves and first break muting. Several reflections are observed on both V2 and V3 data. V3 data show more detail and clearer reflections again due to higher signal-to-noise ratio. Reflections 1 and 2 on figure 5 are possibly associated with the potassic zone and the picrite unit located just below the bottom of the borehole. This is a tentative interpretation of the preliminary data.

## DISCUSSION

Several factors complicated the acquisition of the borehole logging data and VSP-DAS data at New Afton. One of the most important complications was the instability of the boreholes that required the use of a drill rig. Open-hole deployment of any instrument over the entire length of the two boreholes used in this work was simply not possible. The difficult borehole conditions increased the time required to complete the wireline logging program (by about 3 times). A VSP survey with a string of conventional geophones would have also required a significant amount of time. To this end, the utilisation of DAS simplified greatly the logistics and effort required to collect the VSP data. This also includes the use of only one dynamite charge per shot location, which reduced the cost of survey and simplified the permitting process to use explosives for seismic surveying on the mine site. For example, 58 shots per source location would have been required using a conventional wireline system with 12 levels to obtain data with receiver spacing similar to the V3 data shown in figure 5.

## CONCLUSION

Wireline logs and VSP data were acquired in two boreholes intersecting the Cu-Au New Afton porphyry deposit located near Kamloops, BC. Logging data provide physical rock properties for the propylitic, phyllic, and potassic alteration zones. Both propylitic and phyllic zones are characterized by a large distribution of density and P-wave velocities whereas the feldspar-dominant potassic alteration has similar densities but generally higher velocities. The VSP data used distributed acoustic sensing of fibre-optic cables cemented in two boreholes. Fibre-optic cables comprised standard and Constellation fibres in both straight and helically-wound configurations for comparison purposes. Seismic sources consisted of fifty shot points each loaded with one kilogram of pentolite explosive placed in a 20 m deep shot hole. VSP data from both types of fibre show clear downgoing waves and reflections although signal-to-noise ratio is significantly higher on the Constellation fibre-optic cable. A preliminary analysis of VSP data from one shot point shows reflections possibly associated with the potassic zone and the picrite unit located just below the bottom of the borehole.

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Paper 8

# Active source seismic imaging in the Kylylahti Cu-Au-Zn mine area, Finland

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## ABSTRACT

*We have acquired new 2D seismic reflection data at the Kylylahti Cu-Au-Zn mine area, Finland in 2016 as a part of the COGITO-MIN project. The aim of the project is to develop cost-effective mineral exploration methods with special focus on seismic techniques. Seismic reflection profiling was done in two parallel profiles approximately perpendicular to the known Kylylahti massive sulfide deposit and intersecting the HIRE-seismic reflection profiles previously acquired in the area. New data correlate well with the HIRE seismic profiles, yet they have higher frequency content. Ore hosting rock assemblage is expected to be internally highly reflective because of varying acoustic impedances of constituting rocks. Continuous reflections observed in one of the new profiles are likely originating from the contacts between mica schist and sulfide-bearing black schist, the latter typically enveloping the ore-hosting Outokumpu assemblage rocks.*

## INTRODUCTION

The HIRE-project (High Resolution reflection seismics for ore exploration 2007-2010) by Geological Survey of Finland (GTK) introduced seismic reflection surveys to mineral industry in Finland. One of the survey sites of the HIRE-project was the Kylylahti Cu-Au-Zn mine area in the Outokumpu region, eastern Finland. The positive results of the HIRE seismic profiling (Kukkonen et al., 2012) encouraged the further testing and development of seismic methods for mineral exploration in the Kylylahti deposit within the framework of the COGITO-MIN (COst-effective Geophysical Imaging Techniques for supporting Ongoing MINeral exploration in Europe) project coordinated by University of Helsinki and participated by GTK, Institute of Geophysics, Polish Academy of Sciences, and private companies Geopartner from Poland and Boliden FinnEx and Vibrometric from Finland.

The Kylylahti mine is located in Polvijärvi, within the north-eastern extension of the famous Outokumpu mining and exploration district in Eastern Finland. Kylylahti copper mine started production in 2012 and mining is currently taking place at about 700 m depth. Massive sulfide ore of the Kylylahti is hosted by so called Outokumpu assemblage rocks (serpentinites with carbonate, skarn and quartz rocks) enveloped in sulfide-bearing black schists. Ore host rocks are surrounded by mica schist.

During the COGITO-MIN project, two seismic reflection profiles were acquired at the Kylylahti deposit vicinity (Figure 1). These two new profiles are connected to the previously measured HIRE profiles enabling more detailed modeling of the seismic reflectivity characteristics of the subsurface. The most apparent aim of the newly acquired seismic data is to image the continuation of the ore-hosting rock sequence at depth and indicate new deep drilling targets leading to discoveries.

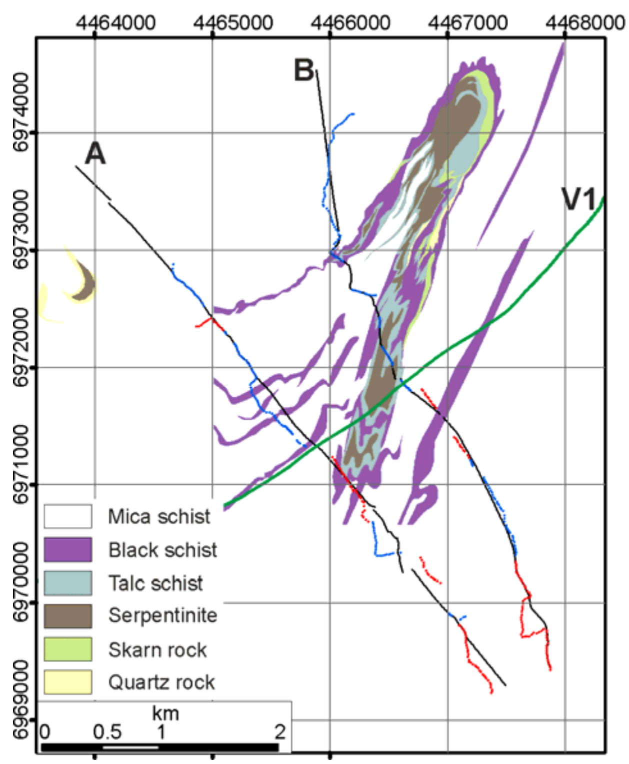


*Figure 1. Seismic reflection profiles acquired in the COGITO-MIN project on geological map. Black dots mark the receiver location and blue and red dots Vibroseis and explosive source positions, respectively. Previously acquired seismic reflection profile V1 is plotted with green. © Geological Survey of Finland*

## GEOLOGY OF THE KYLYLAHTI DEPOSIT

The Outokumpu mineralized region, to which Kylylahti Cu-Au-Zn deposit also belongs, is over 300 km long and covers an area of about 5400 km$^2$ in the eastern part of Finland (Gaal *et al.*,

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1975). It is located within the North Karelia Schist Belt east of the suture zone between Archean Karelian craton in the northeast and the Paleoproterozoic Svecofennian island arc complex in the southwest. The dominant rock type of the area is mica schist that has black schist intercalations. The massive sulfide deposits of the region are associated with variably sized fragments and lenses of serpentinized mantle peridotites tectonically emplaced upon and within younger metasediments (Koistinen, 1981, Park, 1988). This so-called Outokumpu rock assemblage hosting the ore consists of serpentinites, carbonate, skarn and quartz rocks, and is typically enclosed in black schists.

The Kylylahti copper deposit was discovered at 500 m depth in 1984 (Rekola and Hattula, 1995) and later new Cu-Co-Zn lenses were discovered in the up-plunge extension of the previously detected deeper ore. Metaserpentinites enclosing the Kylylahti ore have been substantially altered to talc-carbonate rock along their margins as a result of metamorphic hydrothermal processes. Mineralization is in the near-vertical eastern limb of a tight synform consisting Outokumpu assemblage rocks; serpentinites, talc-carbonate, tremolite skarn and quartz rocks, and sulfide-bearing black schists (Kontinen *et al.* 2006). Amphibolite facies metamorphism and multiple phases of deformation since the formation of deposit 1.97 Ga ago have reshaped the deposit and its surroundings, and its position within a late fault zone also suggest pervasive reworking of the deposit (Peltonen *et al.* 2008).

Earlier seismic data show that the reflectivity is prominent and discontinuous in the Kylylahti area, clearly differing from the surrounding continuous reflections. Kukkonen et al. (2012) suggested that the host rock environment of the Outokumpu-type massive sulfide ore can be identified as strongly reflective packages in the previously acquired seismic profiles. Kukkonen et al. (2012) observed that the reflections originating from the main ore belt are converted into a tectonically disturbed volume in the Kylylahti area. Subvertical structures and lithological contacts, and abundant faults are also expected to produce similar reflectivity pattern in newly acquired 2D seismic data in the Kylylahti mine vicinity.

## SEISMIC DATA ACQUISITION

COGITO-MIN 2D seismic reflection data were acquired in August-September 2016 during two weeks. Both seismic profiles were approximately 6 km long. Nominal receiver/shot spacing was 10/20 m, respectively. Wireless Seismic RT2 recording system was used and receiver stations were equipped with single 10-Hz high-sensitivity geophones. Usage of wireless receivers enabled their deployment in the forestry area, partly difficult terrain, along segmentally straight line. Despite the terrain conditions, the telemetry worked well and it was possible to harvest the data in quasi-real time for QC purposes. Two INOVA UniVib 9.5-ton trucks were used along the roads with 16-s long linear upsweep from 4 to 220 Hz. It was not possible to use Vibroseis along the whole profiles because limited access and where possible, dynamite explosions (125-250g) drilled to about 2 m depth were used to produce source signal. In order to avoid damage for buildings, a 50 m safety distance was kept between seismic sources and any infrastructure. In addition to the natural occurrence of rivers and lakes in the survey area, this caused gaps into the profiles (Figure 1).

## SEISMIC DATA PROCESSING

Small Vibroseis trucks performed very well and clear first-break energy was observed for the whole offset range (up to ~6 km). Despite the manufacturer's specification, that the maximum frequency achievable with this type of Vibe is 400 Hz, we struggled in the field to obtain stable frequencies above 220 Hz with the current configuration (no additional weights were attached that can make the unit weight 12 t). For both profiles we acquired pairs of overlapping dynamite and Vibroseis shots. From Figure 2, showing comparison of the two source types, it is apparent that the Vibroseis record has a better signal-to-noise ratio when compared to the explosive shot gather. The dynamite shot gather shows higher frequency content (Figure 2 c) above 300 Hz, while the Vibroseis record is limited to 220 Hz. A Vibroseis record is actually stack of three records allowing for efficient suppression of noise and thus better S/N ratio. Especially source induced ground roll (velocity ~2300 m/s) is less apparent in the Vibroseis records. Both shot gathers show clear first breaks, indicating good quality of the data along the whole length of 6 km geophone spread. Noticeable reflections at 1800-2500 ms are apparent in the raw shot gathers.

Data processing of the COGITO-MIN 2D seismic reflection data followed standard procedure of hardrock seismic data the processing. The overburden of Kylylahti consists mainly of glacial tills up to 30 m deep and some receivers were also deployed in the swampy forest areas with thick peat cover. Alongside topographic variation, this results in the requirement of careful refraction static corrections in order to compensate for near-surface time delays. In the preliminary processing of the data, automatic gain control with 250 ms window length was used to compensate for the amplitude decay due to geometrical spreading and attenuation. Airwave attenuation and front mute were used to suppress noise in the data. For the removal of surface waves median filtering based on wave velocity and F-K filtering was tested. Combining a median filter with high-cut frequency filter produced superior results. Predictive deconvolution with gap length of 12 ms and operator length of 150 ms and spectral whitening with varying time gates was used to enhance high frequencies, balance the spectrum and improve the signal shape.

The first stacks of the Kylylahti seismic reflection data were done by using velocities obtained from previous HIRE seismic reflection data processing. Velocity increased from 5100 m/s in the surface to 6200 m/s in the two-way travel time of 1000 ms. This velocity field was later modified using constant velocity stack analysis. Prior to constant velocity Stolt migration (5400 m/s), tau-p coherency processing was used to enhance the continuity of reflectivity. Time-to-depth conversion velocity was also chosen to be 5400 m/s in order to make new results directly comparable to the previously acquired HIRE data.

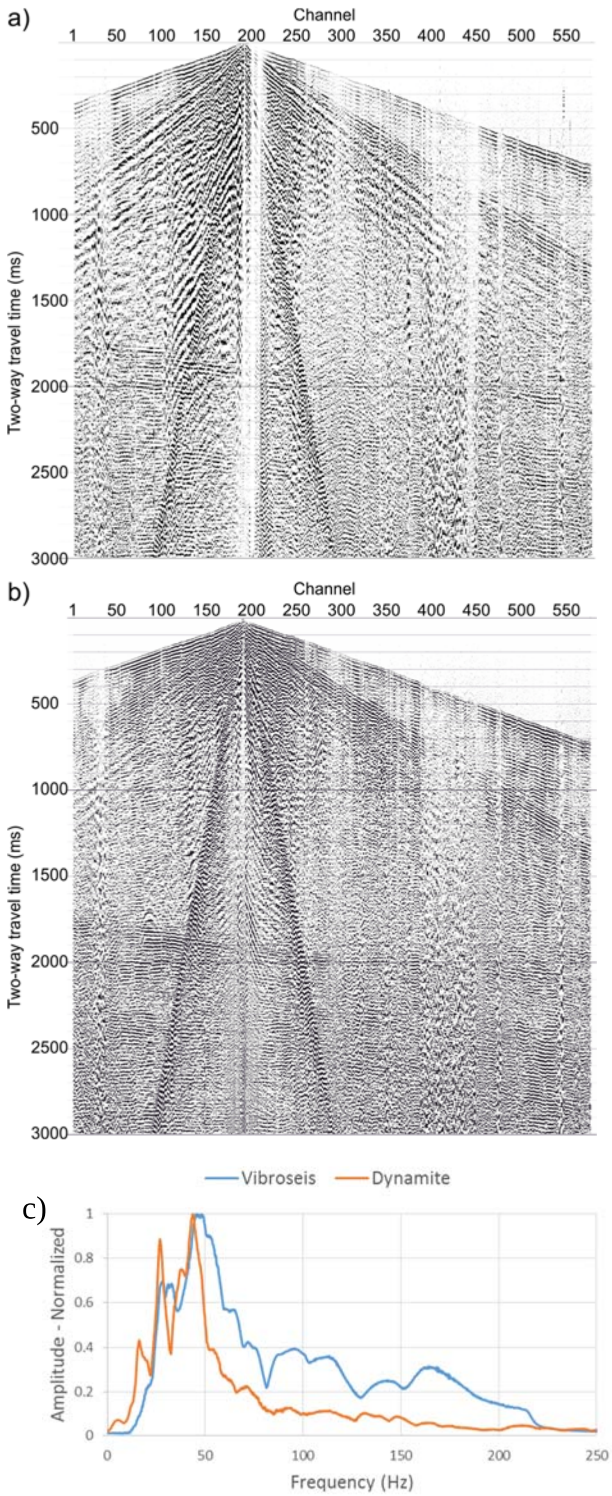


*Figure 2. A dynamite (a) and a Vibroseis (b) shot gather on the same peg location in the Kylylahti seismic reflection survey. Figure (c) shows a comparison of amplitude spectra of the two shot gathers. On the Vibroseis gather, S/N ratio is increased by stacking together three shot gathers measured at the same location. AGC was used to balance amplitudes*

## RESULTS

Migrated and depth converted seismic reflection data were imported to Paradigm GOCAD software for first interpretation and comparison with the previously acquired HIRE seismic reflection data. By visual inspection of the data, it is apparent that the newly acquired COGITO-MIN seismic data have higher frequency content compared to the HIRE data. Prominent reflections at 5 to 8 km depth are observed in both new and old data, and can be mapped all over the Outokumpu area with the network of seismic profiles. These reflectors likely result from amphibolite dykes in the Archean basement (Heinonen et al., 2016).

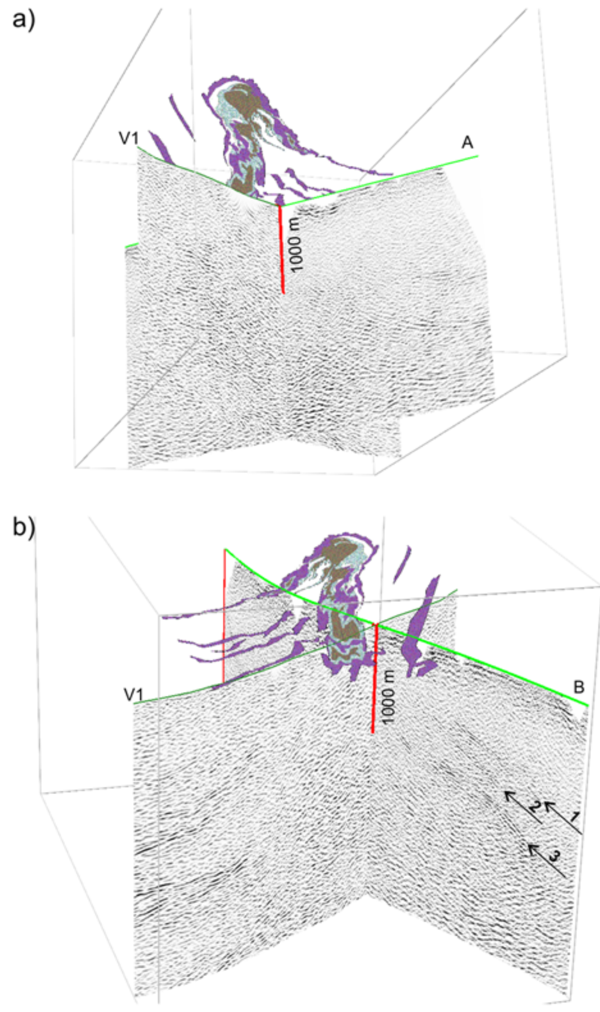


*Figure 3. Comparison of reflectivity observed in the previously acquired HIRE seismic reflection profile V1 and COGITO-MIN (a) profile A viewed from below North-East and (b) profile B viewed from South-East. Red line shows the scale of the figure and reflections discussed in the text are marked with arrows 1, 2 and 3. Color scale of the geological map is the same as in Figure 1, mica schist has been made transparent for plotting purposes.*

Beside the deep reflections, a series of three prominent reflections were observed in the seismic profile B south from the currently mined massive sulfide deposit. A comparison with the surface geological map (Figure 1 and 3) suggest that reflectors are originating from the contacts between mica schist and black schist. Recent drilling in the area has confirmed that black schist contain high levels of sulfide which is likely to increase the seismic velocity of these rocks according to petrophysical study by Luhta et al. (2016) (see also Riedel et al. 2017, this volume). Sulfide-bearing black schist are enveloping the Outokumpu assemblage rocks hosting the Kylylahti massive sulfide deposit and thus these reflectors at 500-1500 m depth are an interesting target for further investigations. If these reflectors are directly linked with the currently known ore deposit and its hosting rocks, lack of continuity of reflections towards to the surface could be attributed to lithological contacts turning to subvertical.

Reflectivity pattern observed in the seismic profile A is consistent with the previously acquired seismic data, showing prominent but very discontinuous reflectivity. This lack of continuity in reflections has already earlier been attributed to the subvertical nature of the lithological contacts and abundant faulting. However, further use of more advanced seismic imaging techniques is expected to improve the current preliminary processing results and provide more detailed information about the subsurface features of interest for exploration.

## CONCLUSIONS

New 2D high-resolution seismic profiles were acquired at the Kylylahti Cu-Au-Zn mine area in the Outokumpu region, Finland in the framework of the COGITO-MIN project. Acquisition was performed along two segmentally straight lines with 10 m receiver spacing and 20 m nominal source point spacing. Both Vibroseis and dynamite were used as seismic sources. Data processing produced seismic images of the subsurface that correlate well with the seismic profiles previously acquired in the area. The discontinuous but prominent reflectivity is characteristic for Kylylahti subsurface due to the complex geology. Continuous reflections observed in one of the new profiles are likely originating from the contacts between mica schist and sulfide-bearing black schist. Black schists are typically enveloping the ore-hosting rock assemblage in the area, and thus these newly observed reflections are of interest for exploration.

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Paper 9

# Passive seismic interferometry for subsurface imaging in an active mine environment: case study from the Kylylahti Cu-Au-Zn mine, Finland

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## ABSTRACT

*Correlations of ambient seismic noise recordings can lead to reconstruction of both surface and body waves. Extraction of body waves is more challenging because noise recordings are usually dominated by surface wave energy. Despite that, a few studies have shown that extraction of body waves is possible. In order to investigate the capability of ambient noise seismic interferometry in ore exploration, a full-scale 3D passive seismic experiment was conducted in Kylylahti mining area, eastern Finland. We used 50 m receiver spacing, array of ~1000 receivers and about 30 days recording time. Presented results indicate that road traffic and mine activities (both surface and underground) have dominant influence on noise characteristics in the survey area and generate omni-direectional noise of broad frequency spectrum. We observe possible body wave arrivals in high frequency range (>35 Hz) potentially related to underground mining activity sources. Such noise panels were used in virtual shot gather retrieval with clear body wave arrivals present.*

## INTRODUCTION

During the past twenty years reflection seismic methods have proved to be very effective for mineral exploration (e.g., Malehmir et al., 2012). However, acquisition of active-source seismic data in the mining camps is challenging and costly. Driven by research within the oil and gas industry, recent studies investigated the possibility of developing cost-effective alternative for active seismic methods by the use of seismic interferometry (SI). SI is a method to retrieve the Earth`s response from ambient noise recordings at both local and global scales (see Malinowski and Chamarczuk, this volume, for an overview of SI and references therein). Using this method we can obtain information about subsurface by correlating noise records between two receivers. Depending on the characteristics of the recorded noise sources, we can extract different parts of seismic wavefield. In most cases surface waves are quite easy to extract because they dominate the ambient noise recordings (Draganov et al., 2009). Retrieving reflection data using SI has proven to be much more difficult than extracting surface waves (Forghani and Snieder, 2010). Inspired by the earlier result of Cheraghi et al. (2015), who used SI to image structure of the Lalor Lake deposit in Canada, we performed a full 3D passive seismic survey in order to further investigate applicability of SI in ore exploration. Our test site was the Kylylahti Cu-Au-Zn mine in Polvijärvi, eastern Finland (Figure 1). Typically, surface seismic surveys are dominated by energy related to the surface sources like road traffic or natural noise. In this case, the presence of an active mine creates a rare opportunity to record seismic arrivals from high energy sources related to routine mining operations.

Here we present the initial results of the Kylylahti passive seismic experiment. First we investigate the spectral content of our data and show the results of array processing techniques to understand the directivity and coherence of dominant noise sources. Combining these results with an *a priori* knowledge about ambient noise sources in the test site (active mine working schedule, road traffic observations) we try to indicate the time periods when energy related to underground sources is stronger than constantly generated surface wave noise. Stacking of carefully selected noise panels results in extraction of virtual shot gathers with clear body wave arrivals as corroborated by the comparison with the active shots.

## DATA ACQUISITION AND SURVEY AREA

Passive 3D seismic data were acquired in the vicinity of the Kylylahti Cu-Au-Zn mine in Polvijärvi, eastern Finland between early August to late September 2016 as a part of the COGITO-MIN (COst-effective Geophysical Imaging Techniques for supporting Ongoing MINeral exploration in Europe) project. We used 994 receiver stations distributed regularly over the 3.5 x 3 km area with 200 m line spacing and 50 m receiver interval (Figure 1). Surface conditions varied between exposed bedrock to swamps. Each receiver station consists of the Geospace GSR recorder and 6 x 10-Hz geophones bunched together and buried whenever possible, recording at a 2 ms sample rate for about 20 hrs/day for about 30 days. As a result we recorded over 600 hours of ambient noise data per each receiver. In addition, the 3D grid recorded irregularly distributed surface shots (both explosives and Vibroseis) specifically designed for the 3D survey as well as those from the 2D seismic profiles crossing the 3D grid (Heinonen et al., this volume). Therefore, a low-fold 3D active-source seismic survey was also acquired to benchmark the results

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of SI. Passive grid recorded also the active shots from the mine tunnels used for the purpose of the VSP imaging (Riedel et al., this volume).

The survey area is located in the direct vicinity of the Polvijärvi town (population of > 4000). Two fairly busy state roads cut through the whole survey area. A roundabout connecting both roads is located in the centre of the array. The Kylylahti mining area is located to the northwest from the roundabout. Access to the mine is along gravel roads, used extensively by hauling trucks. The Kylylahti mine was active during whole recording period. Routine mining activities included: drillings (surface and underground), transporting ore and waste rock (surface and underground), scaling (underground), mine ventilation (surface) among others. Another source generating strong energy are the mine blasts which occurred daily at depths ranging from a few hundred meters down to approximately 800 meters below surface. This abundancy of noise sources may be useful for SI survey and gives us an opportunity to retrieve body wave arrivals from ambient noise recorded in Kylylahti.

## AMBIENT NOISE DATA ANALYSIS

The main prerequisite for retrieving body-wave reflections from ambient noise recordings is to capture the body wave arrivals in the recorded noise (Draganov et al. 2009). In order to determine what type of seismic wave arrivals are buried in our data, some basic noise characteristics should be evaluated prior to the cross-correlation process. Figure 2 shows frequency spectrum plots for five representative regions of the survey area. To calculate each spectrum we took average Fourier transformed response of three receiver stations over the whole recording time. The frequency spectra related to road traffic (Figure 2a,b) exhibit most energetic part up to 50 Hz, with a peak at around 20-30 Hz, which is characteristic for the surface waves observed e.g. in 2D active source data. Amplitude spectra located at some distance from road traffic (Figure 2c-e) indicate presence of ambient noise sources up to 150-200 Hz. Taking into account the possible influence of power lines, we suspect that parts of spectrum in the frequency range above 35 Hz (denoted as green rectangle in Figure 2) can be related to energy generated by potential body wave sources.

To further characterize the noise we performed power spectral density (PSD) and beamforming analyses. PSD plots confirmed the frequency range related to surface waves generated by road traffic and indicated the broader frequency range of energy generated by noise sources related to city and mine activities. Having dense array of receivers enables to use array processing methods to identify the spatio-temporal characteristics of dominant noise sources (Harmon et al. 2008). In this study we decided to use a plane wave frequency domain beamforming, which is one of the classical methods to characterize the directivity of dominant noise sources (Johnson and Dudgeon 1993). Note that theoretical limit on beamforming to avoid aliasing is imposed by the Nyquist wavenumber (Rost and Thomas, 2002), which in case of receiver line spacing of 200 m and velocity of 2 km/s gives $f_{max}=v_{min}/(2\Delta x)=5$ Hz.

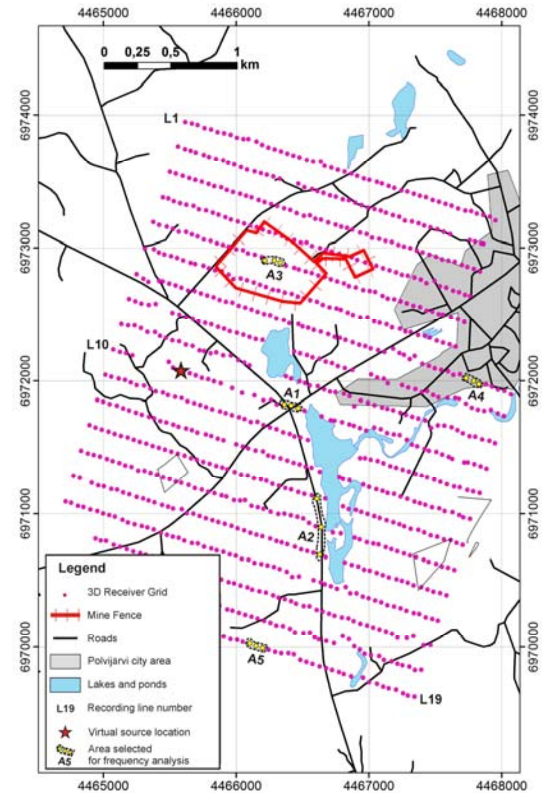


*Figure 1: Location of the 3D passive seismic survey.*

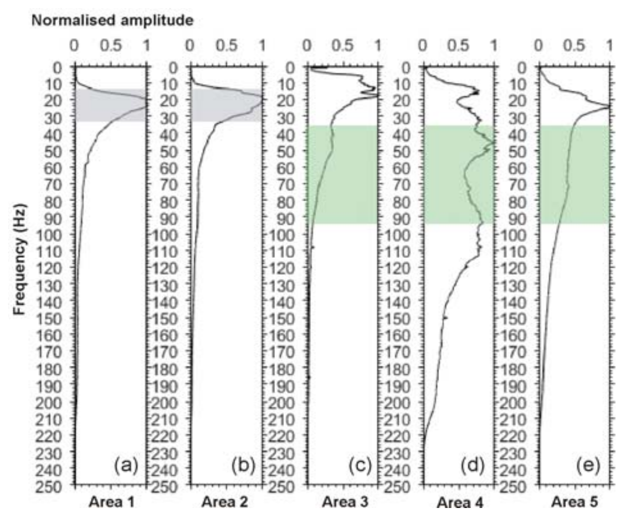


*Figure 2: Amplitude spectra calculated for the representative regions of the survey area marked in Figure 1: (a) roundabout, (b) road, (c) mine, (d) city and (e) 'quiet' area. Each spectrum is calculated by taking average Fourier transform from three adjacent receivers over the whole recording time. Grey rectangle indicates frequency range dominated by road traffic noise. Green rectangle indicates the frequency range where we expect the body wave energy to be present.*

Beamforming analysis calculated for each hourly panel indicated that directions and velocities of dominant noise sources are highly variable and that most energy is related to the mine and city areas. Figure 3 shows an example of the beamforming output calculated and summed over 20 hours recorded on 27th of August in frequency range 3-5 Hz.

The maximum values, represented as bright spots in Figure 3, show dominant propagation of waves coming from the northwest and wide area in the east. These directions are consistent with noise sources located at the mine site and city of Polvijärvi. Observed apparent velocities range from 2.5 to 5 km/s, with the strongest amplitudes at 3-4 km/s. Note that the surface wave velocity observed e.g. in active 2D lines is around 2.5-3 km/s.

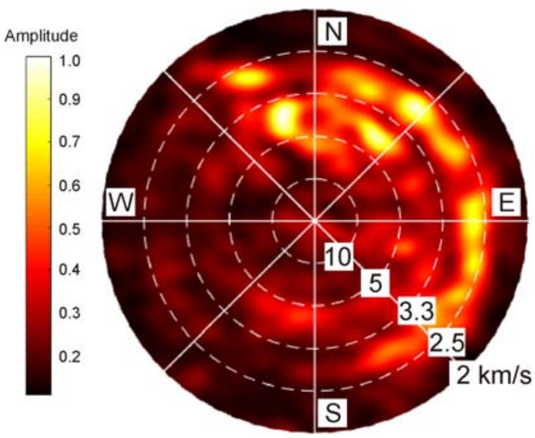


*Figure 3: (a) Beamforming output calculated for 20 hourly panels from 27th of August. Maximum values from each hourly panel are displayed as a function of apparent velocity and azimuth for the frequency range 3-5 Hz.*

## SI PROCESSING WORKFLOW

The choice of processing workflow in body wave retrieval using ambient noise SI is highly case-dependent. However, the following basic steps are usually involved (Draganov et al. 2009, Olivier et al. 2015, Nakata et al. 2015): (i) surface wave removal, (ii) selection of data panels, (iii) cross-correlation process. To remove the surface wave content from our data we applied bandpass filter between 35 and 95 Hz. The lower limit is aimed to suppress the high energetic part of spectrum generated by road traffic (Figure 2a-b). The upper limit is dictated by the lack of useful energy above 100 Hz (Figure 2c,e) and to remove the possible high-energy peaks related to power lines (Figure 2d). The second step of processing usually involves selection of data panels containing body wave arrivals. To evaluate the possibility of retrieving reflections from our data, we visually inspected one week of noise recordings segmented into 10 seconds long windows. Figure 4a shows a part of noise panel recorded along line 11 with mostly incoherent events and low amplitude surface waves. This panel exhibits random noise related to direct vicinity of receiver stations. Figure 4b shows the same part of noise panel after bandpass filtering in the range of 35-95 Hz. Still there is no coherently aligned energy. Such panels shouldn't be used in further processing. Figure 4c shows another bandpass-filtered noise panel with low amplitude hyperbolic event, which can be related either to reflected/transmitted body wave or surface wave propagating not in-line with the receivers. Such events occur intermittently (1-2 times per hour) and appear in noise panels even in the high frequency range (>35 Hz). We link the events with underground mine activities.

As an alternative for visual inspection of noise panels, automatic selection of noise panels containing body wave arrivals can be used (Almagro Vidal et al. 2014, Panea et al. 2014, Nakata et al. 2015, Olivier et al. 2015). We plan to develop an algorithm for searching for dominant ray parameter characterizing the hyperbolic event visible in Figure 4c and comparing it with the same events recorded by few adjacent receiver lines. Events related to underground sources will exhibit slownesses typical for body waves at each scanned receiver line (D. Draganov, personal communication).

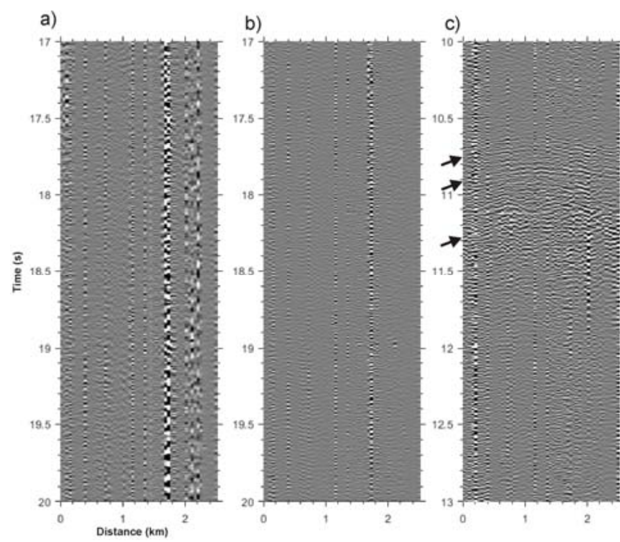


*Figure 4: (a) Arbitrarily chosen noise panel dominated by incoherent noise. (b) The panel in (a) after bandpass filtering between 35-95 Hz. (c) Part of filtered noise panel recorded along line 11. Black arrows indicate hyperbolic events related to potential body waves.*

In order to produce virtual shot gather, we need to choose a receiver at which we want to have a virtual source, and correlate it's trace with all other traces. This step is repeated for every noise panel. Correlated noise panels are then summed together per trace location. In our first approach to create virtual shot gather we used cross-coherence (CCh) relation, utilizing the algorithm applied by Nakata et al. (2011, 2015). CCh involves pre-whitening of signals before correlation and is akin to the standard cross-correlation algorithm with trace energy normalization and source function deconvolution (Prieto et al. 2009, Draganov et al. 2013). As a result of discarding amplitude information, CCh is not prone to inaccuracies caused by differences in receiver sensitivity or weak coupling. However, if noise event useful for retrieval of body waves has low S/N ratio, spectral whitening involved in CCh will mostly boost the noise part not contributing constructively to our result. Despite this phenomena, we decided to use CCh as it does not require prior trace energy normalization nor source function deconvolution of the correlated panels. However, more tests need to be evaluated prior to choosing the optimum algorithm for creating the final virtual shot gathers.

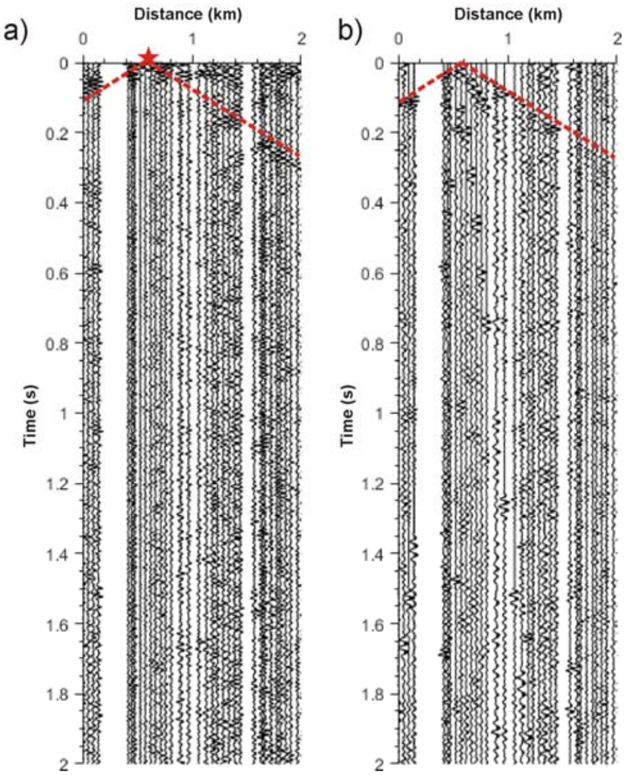


*Figure 5: Comparison of (a) virtual shot gather with (b) dynamite shot fired on line 10, in the direct vicinity of receiver 1012. Red star denotes the location of master trace and red dashed line indicates the theoretical line of first arrivals.*

Figure 5 shows comparison of a virtual shot gather calculated for receiver 1012 (red star in Figure 1) with dynamite shot fired just a few meters apart. For comparison purposes we applied the same bandpass filtering from step 1 to the active shot presented in Figure 5b. Direct P-wave arrival (5 km/s) is observed on active and virtual shot gather. However, virtual shot (Figure 5a) exhibits correct arrivals only to the right of master trace. This can be explained by directional bias of the mine sources, which dominated this record. At times before the theoretical line of first arrivals virtual shot gather contains some noise and artifacts caused probably by insufficient illumination of noise sources. Both active and virtual shot exhibit poor S/N ratio and no clear reflections below the line of first arrivals, however some coherent dipping events can be observed in both gathers. Processing of the retrieved virtual shot gathers similarly to the active source shot gathers can further enhance reflected energy, primarily through CDP stacking.

We should also note that stacking of the noise panels containing body-wave events (like the one from Figure 4c) is beneficial for retrieving reflections in virtual-shot gathers provided that sources of these events are located in stationary-phase regions. Location of sources can be estimated using, e.g. beamforming-like approach, which uses spectrally-whitened cross-correlation functions in maximum likelihood search (InterLoc method of Dales et al. 2017). Therefore the 2-step processing scheme involving (i) selection of the noise panels containing body-wave events and (ii) estimating the location of sources generating these events seems to be adequate processing scheme for successful body wave reflection retrieval. Example of a high-pass filtered (>60 Hz) noise panel with body-wave event, which passed the test run of our two-step approach is presented in Fig. 6.

## CONCLUSIONS

A passive seismic experiment employing regular grid of ca. 1000 receivers recording for about 30 days was conducted in the Kylylahti Cu-Au-Zn mine area, Finland as a part of the COGITO-MIN project. The aim of the experiment is to develop a cost-effective alternative for active seismic methods in hardrock exploration. Initial noise analyses presented in this abstract indicate the possibility of successful body-wave reflection retrieval in the recording area. Most studies applying SI for exploration purposes have concentrated on body waves at frequencies below 40 Hz. By the means of visual inspection we found few noise panels containing possible body wave arrivals in the frequency range not contaminated by surface waves (>35 Hz). We suspect that most of these events are related to routine underground mining activity. Thus, in our first approach to apply SI we created virtual shot gather calculated for ten days of recorded ambient noise in the frequency range above 35 Hz. Comparison with an active shot indicated some similar features, however, it is clealry visible that procedure enhancing the quality of the virtual shots has to be developed. Since the body wave arrivals coming from preasumed underground sources exhibit similar moveout we aim to develop an algortihm which would automatically select noise panels containing these events.

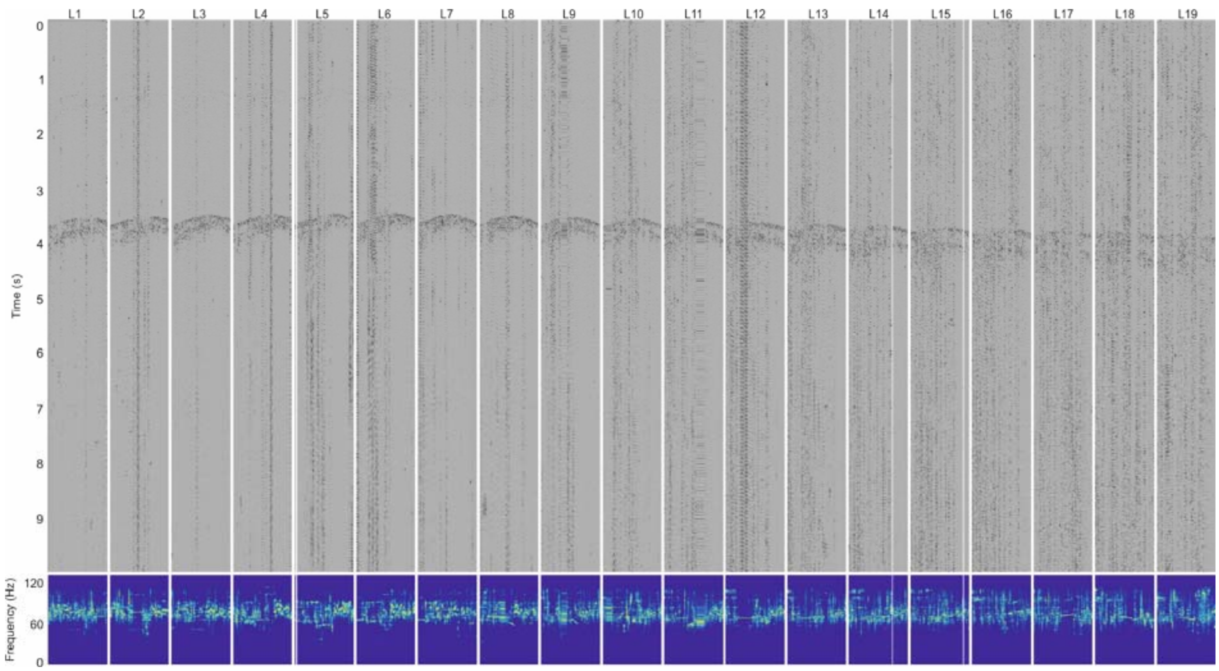


*Figure 6: Noise panel containing body-wave event recorded by all receiver lines and likely related to routine underground mine activity. PSD plots displayed below each panel clearly show high-frequency nature of this event.*

## ACKNOWLEDGEMENTS

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Paper 10

# Seismic imaging of the Kylylahti Cu-Au-Zn ore deposit using conventional and DAS VSP measurements supported by 3D full-waveform seismic modeling

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## ABSTRACT

*The focus of this study is reflection seismic imaging of a massive sulfide ore deposit in the Kylylahti Cu-Au-Zn mine in eastern Finland. The geological environment in the target area is dominated by high-velocity rocks which have been severely folded resulting in a complicated assemblage of various near-vertical structures. In order to image those, we rely on VSP data that were acquired in the Kylylahti mine using conventional three-component geophones in four boreholes as well as a fiber-optic Distributed Acoustic Sensing (DAS) cable in one borehole. The boreholes were located within a few hundreds of meters from the known ore body. The use of high-frequency VSP systems directly within the mine is a fortunate situation which enables very good spatial resolution. Despite this, the processing and interpretation of the acquired data is not straightforward due to the geological complexity of the area. Elastic three-dimensional full-waveform seismic modeling was conducted in order to facilitate the understanding of the acquired data. For this purpose, a realistic geological model of the environment was constructed based on extensive borehole data and petrophysical laboratory measurements. Using this model in combination with the true acquisition geometry, a synthetic dataset was generated which is a very close representation of the acquired field data. Based on the synthetics, target reflection signatures were traced to their geological origins and then linked to similar features in the acquired field data. Both datasets were processed in the same way and then migrated in order to map the recorded reflections in 3D space. The resulting reflectivity sections show the ore signature, as well as other dominant lithological contrasts, with high spatial accuracy. We conclude that the applied conventional and DAS VSP methodologies provide sufficient spatial accuracy to correctly image the sub-vertical ore deposit. However, in order to confidently interpret the acquired data in such a challenging environment, realistic synthetic modeling is required to understand the recorded signals with respect to their geological origins.*

## INTRODUCTION

This work is a part of the COGITO-MIN (COst-effective Geophysical Imaging Techniques for supporting Ongoing MINeral exploration in Europe) research project which aims at the development and testing of new seismic methods for mineral exploration and resource delineation. The project partners include academic and industrial institutions from Finland (University of Helsinki – project coordinator, Geological Survey of Finland, Boliden FinnEx and Vibrometric) and Poland (Institute of Geophysics, Polish Academy of Sciences and Geopartner). The test site of the project is centered at the Kylylahti Cu-Au-Zn mine which is located in the historical Outokumpu mining and exploration district hosting Cu–Co–Zn–Ni–Ag–Au semi-massive to massive sulfide deposits in eastern Finland. The Outokumpu-type sulfide deposits are found in association with ophiolite-derived Outokumpu assemblage rocks containing serpentinite, carbonate, skarn and quartz rocks, which are usually wrapped in black schist and embedded in turbiditic mica schist (e.g., Kontinen et al., 2006). The long history of geological and geophysical studies in the Outokumpu district, also including earlier high-resolution seismic reflection 2D profiling (Kukkonen et al., 2012; Heinonen et al., this volume), makes the site ideal for testing new exploration concepts.

Extensive COGITO-MIN seismic survey campaign was launched at the Kylylahti mine site in summer 2016, during which active-source reflection seismic 2D/3D data and ambient noise surface recordings (Chamarczuk et al., this volume), as well as underground active-source VSP (Vertical Seismic Profiling; e.g. Enescu et al., 2011; Wood et al., 2012) and ambient noise borehole recordings were acquired. The specific goals in relation to the Kylylahti deposit are understanding of the complex 3D geology, resource delineation and near-mine exploration. While ultimately the overall project aims at a joint interpretation of all the collected data including various methods, the essential and most promising source for providing immediate exploration drilling targets are the underground VSP surveys. These were conducted within the underground mine in close vicinity to the known ore bodies and their potential extension at depth.

The underground surveys were carried out in four different boreholes utilizing conventional three-component (3C) VSP technology. Additionally, a fiber-optic Distributed Acoustic Sensing (DAS) cable was deployed in one of the boreholes. To the present knowledge of the authors, this is the first time that this novel technology is utilized in the context of hard-rock mining exploration. The method offers high-resolution (quasi-continuous) and simultaneous measurement along the entire length of the cable. However, the complex arrangement of the predominant geological units inhibits a straightforward interpretation of the acquired VSP data. In order to overcome this problem, 3D full-waveform elastic modeling was conducted using a realistic geological model of the known ore domains and host rocks. In this way, synthetic data which are very close to the measured recordings were created. These facilitate the understanding of the elastic wave propagation in this structurally complex environment and enable the identification of the seismic signatures of the ore deposit.

## SURVEY SETTINGS

The VSP survey design is depicted in Figure 1. The measurements were carried out with conventional 3C geophones in the four boreholes KU-917, KU-919, KU-936B and KU-941 located on the eastern side of the known ore bodies. In addition to the conventional acquisition, a fiber-optic (DAS) cable was installed in borehole KU-917 for most part of the survey, which enabled continuous recording from the top down to a maximum depth of 452 m. The recording parameters are summarized in Table 1.

| Borehole / Recording system | Recording length along borehole | Receiver sampling |
|---|---|---|
| **KU-917 / VSP** | 46 – 364 m | 2.5 m |
| **KU-917 / DAS** | 0 – 452 m | 0.25 m (1 m out) |
| **KU-919 / VSP** | 72 – 142 m | 10 m |
| **KU-936B / VSP** | 2 – 392 m | 5 m |
| **KU-941 / VSP** | 61 – 536 m | 5 m |

*Table 1: Recording parameters of the underground conventional and DAS VSP surveys.*

As an active source, a VIBSIST-200 system was operated in the mine tunnels for the VSP survey. The source emits a rapid sequence of time-coded transient pulses which are stacked for data processing later on. It operates at a dominant frequency of around 200 Hz. The source is particularly well suited for mining environments due to its mobility and its high stack-fold which enables a significant signal-to-noise improvement after the acquisition. In total, 31 distinct shot positions were used at three different depth levels in the mine tunnels (Figure 1).

For the VSP survey, two different geophone strings were used: an 80-m long analogue chain (for boreholes KU-919 and KU-936B) and a 160-m long digital string (for boreholes KU-917 and KU-941). These were lowered into the boreholes successively. All the shots had to be carried out repeatedly for each depth level of the geophone string until the whole borehole was surveyed. In this way, borehole KU-917 was the first one to be measured. After completion, the geophone string in this hole was replaced by the fiber-optic cable. From that point onwards, the DAS system (Silixa`s iDAS$^{TM}$) recorded all repeated shots that were fired also for the conventional VSP measurements. Due to operational reasons, the cable remained uncemented in the borehole.

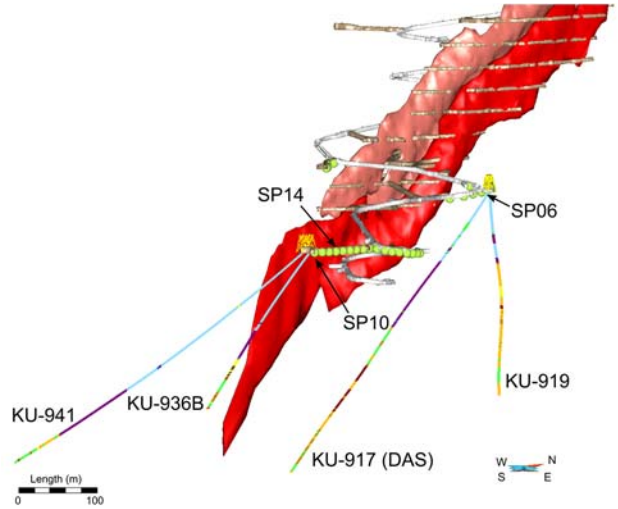


*Figure 1: Layout of the underground VSP surveys. Conventional 3C geophones were used in the four boreholes shown in the figure. These are located on the eastern side of the known ore lenses (red/pink). In addition, a fiber-optic cable (DAS) was used in borehole KU-917. Green spheres indicate the underground VIBSIST-200 shot locations. Borehole traces are color-coded according to the known lithology which is explained in detail in the text and in Figure 2.*

This procedure provided a large amount of DAS data and moreover, enables a direct comparison between the conventional 3C-VSP string and the fiber-optic cable data. The acquired data from both recording systems was found to be challenging to interpret. In particular, the identification of the target primary ore reflection could not be accomplished in a straightforward manner. For this reason, a realistic synthetic modeling experiment was carried out to facilitate proper data understanding and correct interpretation.

## SEISMIC FORWARD MODELING

The goal of the seismic forward modeling was to create a synthetic dataset containing the seismic signatures of the known geological units and therefore being a realistic representation of the acquired field data. A comparison of the two datasets should then provide i) understanding of the complex wave propagation processes within the environment, and ii) identification of the reflection signature of the ore and its host rocks.

### Geological model building

In order to realize these goals, a representative model of the predominant geological units in the mine area and their petrophysical parameters, i.e. the seismic velocities and density, are required. The geological model used in the simulation was provided by Boliden FinnEx and is based on extensive drilling data from the mine area. Therefore, the model provides a very realistic representation of the predominant geology. The seismic velocities of the geological units were determined by laboratory measurements of rock samples from the mine area. The results of this analysis are summarized in Figure 2.

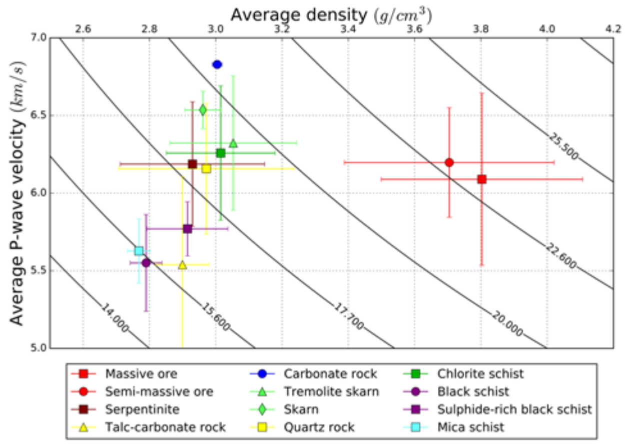


*Figure 2: Average density and P-wave velocity obtained from petrophysical laboratory measurements, with standard deviations presented as error bars. Contours of constant acoustic impedance (m/s × g/cm³) are shown for reference, with a line spacing corresponding to a reflection coefficient of 0.06 (considered to be enough for a detectable reflection; e.g., Salisbury et al., 1996) between two successive lines.*

In general, the predominant geology is structured into four major units (e.g., Kontinen et a., 2006): (1) The first unit contains three massive to semimassive sulfide ore lenses ((S)MS in Figure 3), presently known to be altogether about 1.5 km long, 20-200 m high and 2-30 m wide. According to the laboratory data, the sulfide mineralization exhibits the highest acoustic impedance (Figure 2). (2) The second unit represents the so-called Outokumpu ultramafics (OUM in Figure 3). This unit comprises large serpentinite and talc-carbonate rock bodies which are intercalated by (3) alteration fringes containing carbonate-skarn-quartz rocks (OME in Figure 3). All the fore-mentioned are embedded in (4) the regional Kaleva sedimentary belt (KAL in Figure 3) containing mica schists, black schists and sulfide-bearing black schists. The Kylylahti ore lenses are located along a near-vertical contact between carbonate–skarn–quartz rocks and black schists. The rock samples of all the host rock units show relatively low acoustic impedances when compared to the sulfide mineralization (Figure 2), and hence, if they are large enough, the ore bodies should cause a strong reflection signal when in contact with any of the hosting rocks. Additionally, there should be strong enough acoustic impedance contrasts to produce reflection signals from contacts between the ore-bearing Outokumpu assemblage rocks and the surrounding black schists and mica schists, as well as potentially also from internal contacts within the overall ore-bearing formation (Figure 2). In general, all the units have been severely folded and their contacts are nearly vertical, which is the reason for the complexity of the seismic data.

For the synthetic modeling, the geology was slightly simplified: The units were modeled with the average P-wave velocities of their most representative rock types which are massive sulfide, serpentinite, tremolite skarn, and sulfide-bearing black schist for the units (1)-(4), respectively. The S-wave velocities were scaled by a constant factor of 1/√3 from the P-wave velocities. For the density model, the averaged laboratory values were not used. Instead, the densities were provided independently by Boliden FinnEx based on 3D interpolation of extensive density logging data throughout the mine. Despite the simplifications, the resulting seismic model offers a realistic comparison to the acquired field data.

## Computational setup and modeling results

In the next step, the geological model was passed to the three-dimensional elastic forward modeling software SOFI3D (Bohlen, 2002). The key parameters of the modeling experiment are summarized in Table 2.

| | |
|---|---|
| Computation mode | 3D, elastic |
| Finite difference scheme | Holberg, 8th order |
| Source wavelet | Ricker, 180 Hz peak frequency |
| Spatial model extent | 700 m x 1200 m x 1200 m |
| Grid spacing | 2 m |
| Minimum P-/S-wavelength | 16.11 m / 9.30 m |
| Simulation time | 360 ms |
| Time sampling | 0.05 ms |
| Computation time per shot | 26 minutes on 1008 CPUs |

*Table 2: Parameters used for the full-waveform seismic modeling.*

The synthetic data were computed in the form of VSP shot gathers for all the shot locations in the mine. The resulting synthetic data represent the five different recording systems that were used in the mine boreholes (Table 1). In addition to these data, wavefield snapshots were computed for selected shot positions. This enables tracking of specific wave modes and facilitates targeted identification of reflection signatures from the known ore body in the synthetic data (Figure 3).

The recorded snapshots show the vertical component of the particle velocity. They demonstrate the complicated wave propagation in the model which is due to the geological complexity, although the lithological units were only modeled with constant velocities. Nonetheless, tracking the primary ore reflection is not straightforward, which is also due to the strong presence of shear waves. Moreover, it appears that the high-velocity rocks of the alteration zone (OME) have a shielding effect on the ore causing a large portion of seismic energy to be reflected already at the contact between the sediments (KAL) and the assemblage rocks before reaching the ore body. In the synthetic seismogram sections, these reflections are the first clear ones to be recorded followed by a train of smaller scattered events. The target reflection of the ore (indicated by red arrows) lies within these scattered events, where its appearance and coherency varies for the different boreholes.

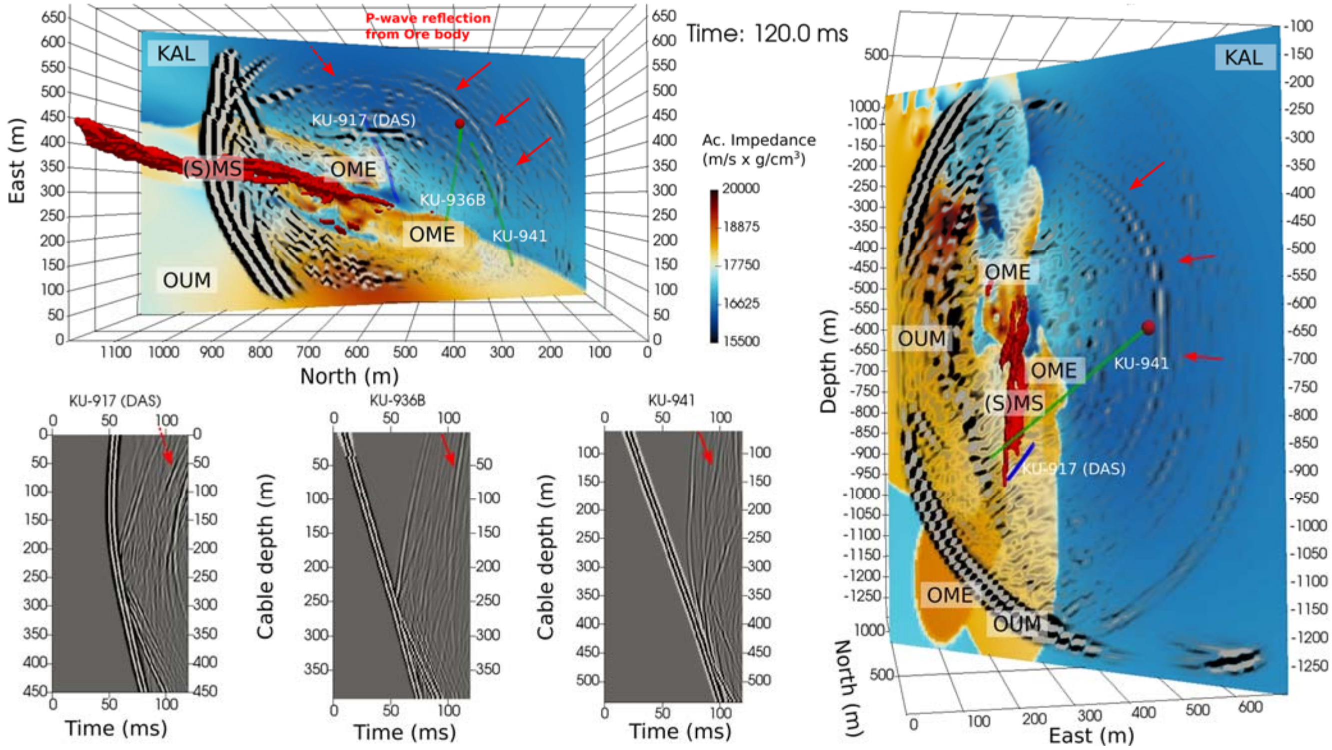


*Figure 3: Elastic wavefield snapshots showing the vertical particle velocity component for shot location SP14 (denoted by red sphere) at 120 ms modeling time. Red arrows denote the identified primary ore reflection. Top left: Plane view of the wavefield over the acoustic impedance model. The red 3D surface represents the known ore body. Right: Front view of the impedance model with the overlaid simulated wavefield. Borehole traces of borehole KU-917 (blue) and KU-941 (green) are depicted as well as the geological unit names. Bottom left: Synthetic seismogram sections for three selected borehole records up to 120 ms.*

## OMPARISON OF MIGRATION RESULTS FOR MODELED AND FIELD DATA

As the final step in the analysis, the synthetic and acquired field data were migrated in order to map the recorded signals in three-dimensional space. At this point, the migration operator was limited to a single plane directed from the respective recording boreholes perpendicular towards the known ore body. To ensure comparability, the synthetic and the measured data were processed in the same manner. The processing included amplitude equalization, suppression of P- and S-wave direct arrivals and multiples, noise suppression, and de-emphasizing of shallow-dipping reflectors. The resulting migrated sections of the modeled and measured data show very similar features which confirms the validity of the synthetic model. Here, the migration results of one selected shot (SP28) are shown for the DAS VSP (Figure 4 & 5) in borehole KU-917 and the conventional VSP in borehole KU-941 (Figure 6 & 7).

Starting with the fiber-optic (DAS) cable in borehole KU-917, the resulting images of the modeled and the field data both show a strong reflection at the point where the ore body intersects the image plain. In the images, this reflection extends a bit deeper than the actual size of the ore, which is a 3D projection effect of the migration. In addition to the ore signature, both datasets also show reflections a few tens of meters east and west of the ore body. The eastern reflection represents a contact between the Kaleva sediments (KAL) and the alteration zone (OME). The reflection west of the ore body probably arises from a contrast of the altered rocks (OME) to the ultramafics (OUM).

The migrated modeled and field data of the conventional VSP chain in borehole KU-941 also reveal similar features with a few differences. First, they also both contain the ore reflection at the correct position. However, in the modeled data, the ore signature seems to overlap with the reflection from the schist (KAL) to skarn (OME) contrast, which is due to the fact that both structures have very similar azimuths with respect to borehole KU-941. Moreover, the ore reflection seems to be more pronounced in the modeled data.

The acquired field data contains at least two further reflections in the upper part of the borehole which are not present in the synthetic data. The first one occurs at a borehole depth of about 130 m and may correspond to a quartz intrusion within the sedimentary unit which is known from the borehole logs. The second reflection coincides nicely with the contrast between the mica schist (light-blue log in Figures 6 & 7) and sulfide-bearing black schist (violet log in Figures 6 & 7). Since the sediments were only modeled with a homogenous velocity, this reflection does not appear in the synthetic data.

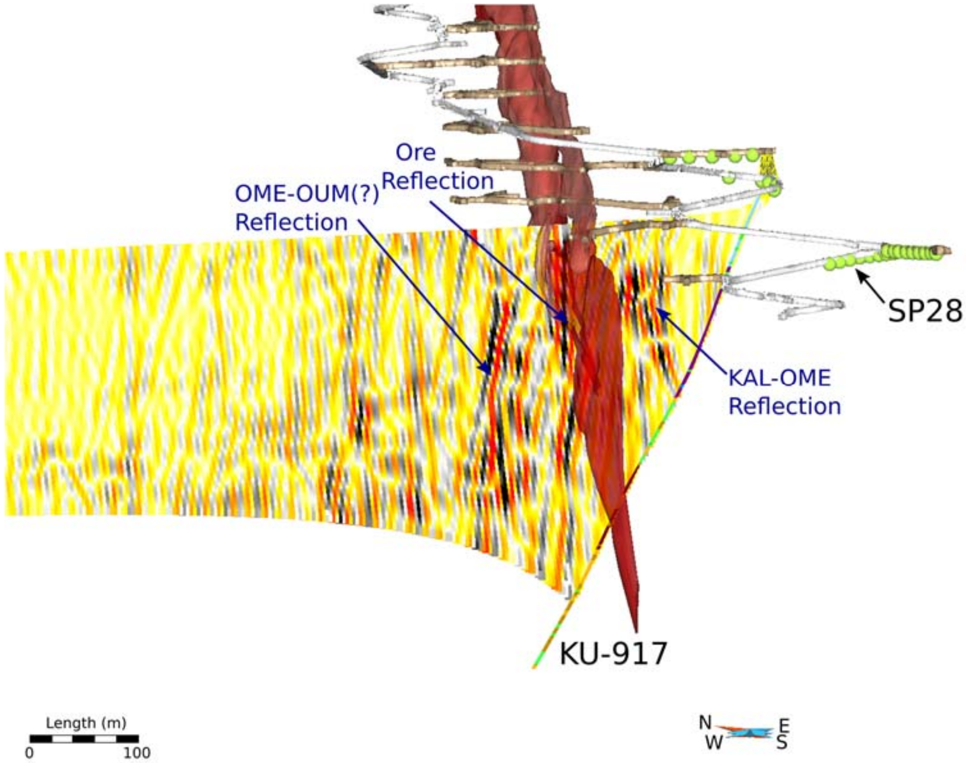


*Figure 4: Migrated section of the synthetic data modeled for shot location SP28 and recorded by virtual DAS chain in the borehole KU-917. Predominant reflections are labeled; more detailed explanation is given in the text.*

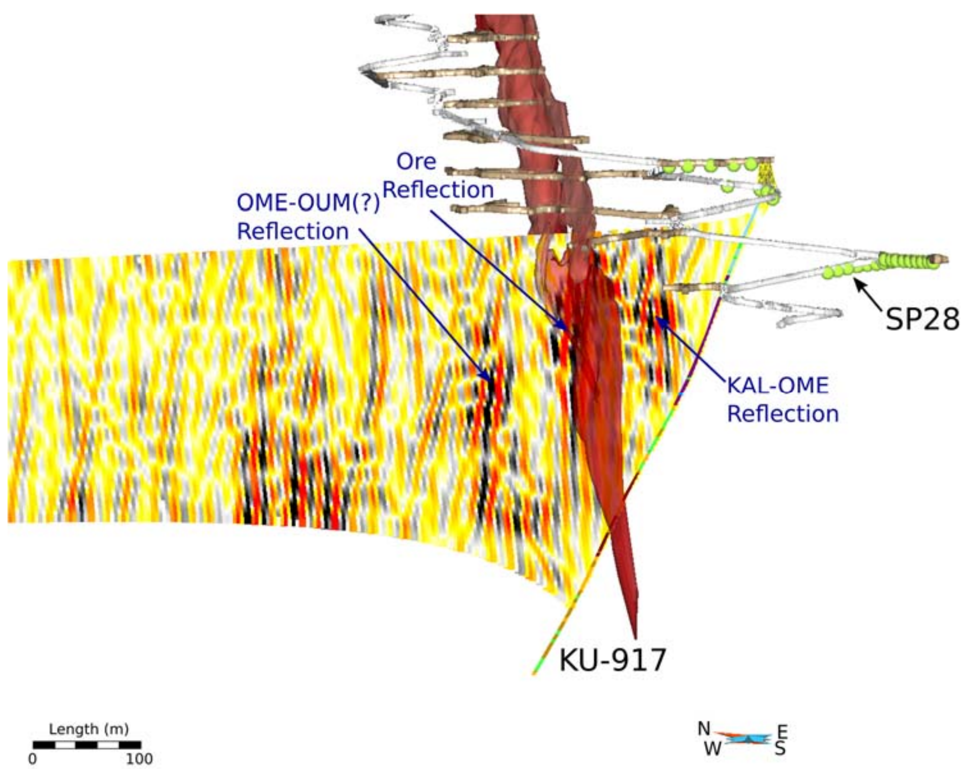


*Figure 5: Migrated section of the acquired field data from shot location SP28 which was recorded by the DAS chain in the borehole KU-917.*

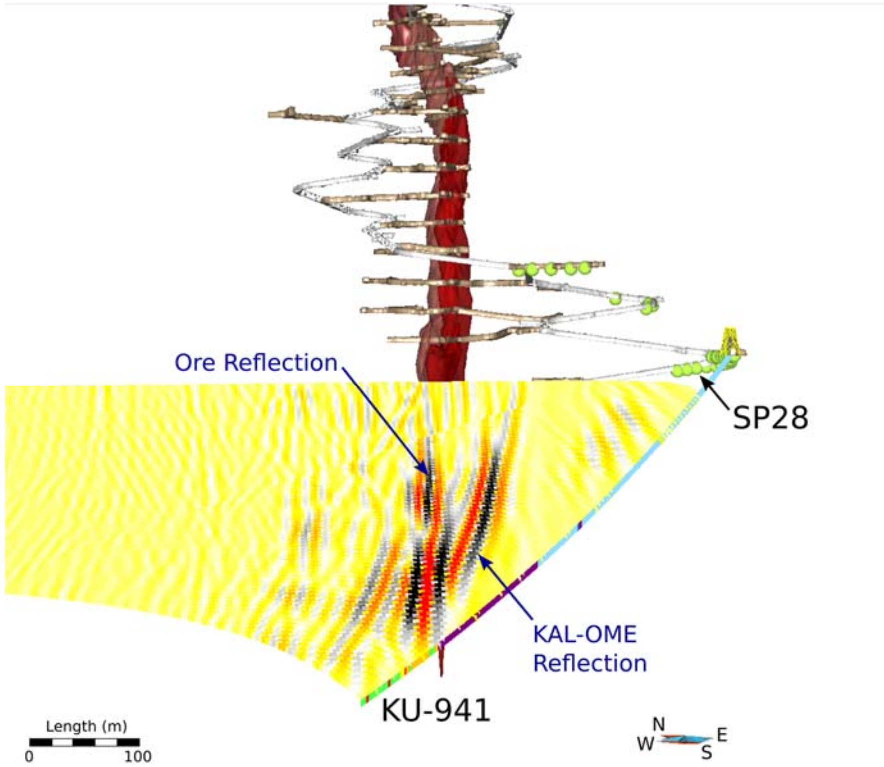

*Figure 6: Migrated section of the synthetic data modeled for shot location SP28 and recorded by virtual conventional 3C chain in the borehole KU-941.*

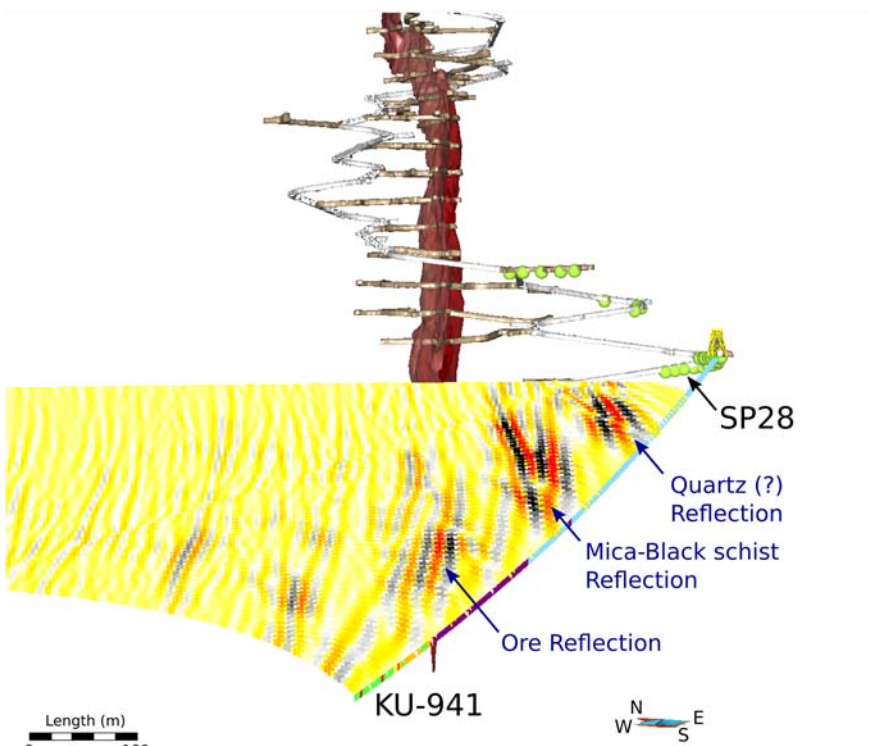

*Figure 7: Migrated section of the acquired field data from shot location SP28 which was recorded by the conventional 3C chain in the borehole KU-941.*

## CONCLUSIONS

From the analysis of the migrated sections, several conclusions can be drawn:

i) The understanding and interpretation of the underground VSP data largely benefits from the use of a realistic synthetic model. In this study, several features in the acquired data are also contained in synthetic records and can therefore be explained with high confidence. In particular, the reflection response of the ore body could be identified.

ii) Both acquisition techniques, the fiber-optic DAS cable as well as the conventional 3C geophones, reveal similar reflection signatures which can be correlated to geological contrasts. In particular, they both are able to image the ore reflection.

iii) Due to the high rock velocities that are predominant in the Kylylahti mining area, high frequencies are required to provide sufficient spatial resolution. This generally makes the application of VSP surveys a beneficial technology for exploration and mining applications in such environments.

The interpretation work of the extensive VSP data will continue with the specific aim to interpret the reflection signals not explained by the current synthetic model and to set new drilling targets.

## ACKNOWLEDGEMENTS

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# Imaging near surface mineral targets with ambient seismic noise

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**ABSTRACT**

*Ambient seismic noise interferometry is a new technique that could provide the mining industry with a cost-effective way to image the subsurface. To test if this method could be used for near-mine exploration, we tested the method as a means to reduce the amount of drilling required to probe the intact high-grade ore amongst the mined-out and back-filled stopes at two Australian mines. These surveys consisted of deploying 100 and 60 geophones for 2 and 5 days respectively. The geophones recorded ambient vibrations from the adjacent highway and mining activities. The data enabled us to image the areas of interest. In both trials low velocity zones were identified in the areas where the mined-out and back-filled stopes were expected. During the first trial, data were recorded for only two days, which wasn't long enough for the cross-correlation functions to converge to the Green's functions. This in turn meant that the dispersion curves were hard to pick and interpret. Nevertheless for frequencies with clear arrivals, dispersion maps were generated that illustrated that the method can be used for this purpose. For the second trial, we were able to produce the dispersion curves and invert for the full 3D velocity model of the sub-surface below the sensors. The results showed the clear existence of low velocity zones in the vicinity of the expected back-filled stopes. The results of the trials were encouraging and it appears as if the method can be useful to image the subsurface over a greater area to reduce the amount of drilling needed to probe the old workings and identify intact rock.*

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## INTRODUCTION

The potential of using seismic methods for mine planning and exploration has been long known (for a good review, see Malehmir et al., 2012), but unlike the oil and gas industry, acceptance by the mining industry started only recently. As is evidenced in several studies (e.g. Pretorius et al., 2003), the overall performance of seismic methods is highly site- and geology-dependent.

The typical procedure for mineral exploration begins with geophysical surveys followed by a drilling program to investigate potential targets. Since the retrieved drill core samples are one-dimensional observations, many holes are needed to interpolate and interpret potential deposits which can lead to very high costs. To reduce the amount of drilling, active seismic imaging is sometimes used as an intermediary, however the active sources (e.g. large vibrating trucks or explosive shots) are expensive and unsuitable for operation in remote or environmentally sensitive areas.

In recent years, passive seismic imaging using ambient noise has emerged as a novel, low-cost and environmentally sensitive approach for exploring the sub-surface. The technique has been used to image the sub-surface on a crustal scale (e.g. Shapiro et al., 2005; Sabra et al., 2005; Moschetti et al., 2007; Young et al., 2011; Poli et al., 2012; Lin et al., 2013) and industrial scale (e.g. Gouedard et al., 2008; Nakata et al., 2011; Olivier et al., 2015) and can even be used to image reflectors (Draganov et al., 2009). This technique dispenses with active seismic sources and instead uses ambient seismic noise such as ocean waves, traffic or minor earthquakes.

In this paper, we will show our recent efforts of using ambient seismic noise to image near-surface targets around active mining operations. Two trial experiments were performed. In both cases, mining operations are commencing close to areas where mining halted more than 100 years ago. In these cases, the locations of the mined-out stopes and remnant zones of high-grade ore are not known to a good degree due to inaccurate and out of date plans.

The goal of the experiments was to find out if passive seismic surveys conducted from surface could be used to delineate mined-out and back-filled stopes amongst remnant zones of high-grade ore. Due to the small scale and relatively shallow nature of the targets, active seismic surveys would be too expensive and are not a suitable replacement for a drilling campaign (although an active survey could be performed in a shorter amount of time).

In "Proceedings of Exploration 17: Seismic Methods & Exploration Workshop" edited by G.Bellefleur and B.Milkereit, p.64-69, 2017

*Figure 1: Locations of the seismic sensors relative to the suspected locations of the old workings.*

### Trial 1

In this trial, we used the ambient seismic noise method to image a portion of a historical gold mine. The goal of the project was to see if the method could be used to identify: old mine workings, mineral deposits, faults or shears and determine the thickness of the slag-heap.

One hundred sensors were installed partly above the old mine workings, partly above the slag-heap and partly above in situ ground. The sensors were buried 5 - 10 cm below the ground to shield them from the wind. The location of the sensors relative to the suspected location of the old mine workings is shown in Figure 1. The locations of the old mine workings were determined from hand drawings.

### Results

The ambient noise recorded on the array was used to produce Raleigh wave dispersion curves. Unfortunately it seems like data were not recorded for long enough to enable the reconstruction of some frequencies in the dispersion curves. As a result, a full depth inversion was not performed. Instead the dispersion curves were only picked at frequencies that showed distinct and clear fundamental modes. We then regionalised the picked group wave velocities by means of a least squares inversion to create dispersion maps.

To approximate the depth of these dispersion maps, we employed the assumption that the surface waves have the highest sensitivity at 1/3 of their wavelength. The dispersion maps are shown in Figure 2 at their estimated depths.

The dispersion maps are able to delineate the slag-heap and old working successfully. The results indicate that the slag-heap is deeper on the southwestern side of the survey area (up to 25 m) compared to the southeastern area. As expected, the tomographic maps also show an increase in

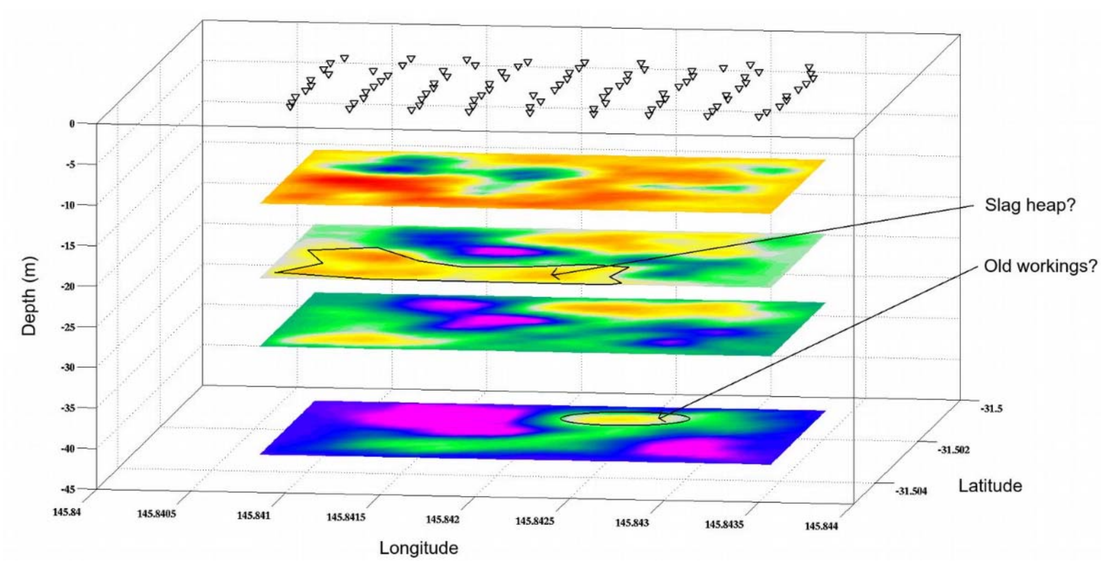


*Figure 2: Dispersion maps represented in 3D. The vertical axis is depth in metres.*

seismic velocity with depth. However, in the northern side of the survey area there is a strong low velocity anomaly in the vicinity of the expected old workings greater than 25 metres below surface. The low velocity anomaly is present (but not as distinct) at shallower depths, indicating that some subsidence could have occurred.

We can create isosurfaces of the low velocity areas to try and aid in interpreting the velocity anomalies. The isosurfaces for one low velocity are shown in Figure 3.

The results from the pilot project were convincing and indicated that a large survey would work well in this environment. The tomographic images appear to clearly delineate the slag heap and old workings, while some other intriguing velocity anomalies can be seen.

Even though the outcomes of the project were positive, the total amount of data recorded was not enough for all the correlation functions to converge to the true Green's functions. This prohibited us from conducting a full 3D shear wave velocity depth inversion. For the pilot project, about one week of data would have been needed to perform the full 3D inversion.

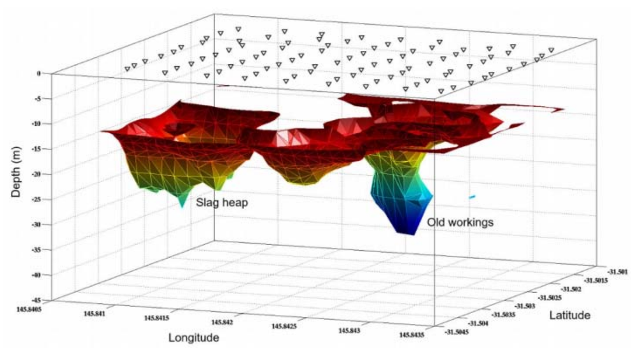


*Figure 3: Isosurfaces of low velocity anomalies. The anomaly in the southwest is interpreted as being the slag heap, while the deeper anomaly in the north is interpreted as the old workings.*

## Trial 2

A second trial was conducted at another historical mine in Australia. Here, the target consists of a known ore-body that has been partially exhausted by mining efforts roughly 100 years ago. In the experiment, we examined whether ambient seismic noise interferometry can be used to image the intact and the exhausted regions of the ore deposit.

A drilling campaign was also conducted in the vicinity. This gives the opportunity to examine whether there would have been any economic benefit if the seismic survey was conducted prior to the drilling campaign. If the accuracy and resolution of passive seismic imaging is adequate to refine drilling efforts, the method could become an inexpensive intermediary step in the exploration process and result in a large decrease in the amount of drilling required to investigate and identify high-grade ore deposits.

Much of the ore body has been exhausted from historical mining, but the mine is still producing from large stopes and from remnant mining areas around very large zones of hydraulic fill. The remnant zones are becoming more and more important as they are very high grade. However, it is difficult to pinpoint the economic remnant zones for a number of reasons.

A total of 60 cable-free seismic data acquisition stations were deployed. Continuous seismic data were recorded for roughly 5 days. The stations were buried in shallow holes to shield the instruments from wind and rain. The use of cable-free stations means that deployment of the stations is relatively quick and easy and took roughly 2 days.

*Figure 4: The locations of the seismic monitoring stations in the first area (in yellow). Two lines with 30 and 15 stations respectively were deployed for 5 days.*

Two areas were selected for the trial. One area was selected to serve as a blind test of the method. A drilling campaign has been conducted over the past few years so that the operator has a general understanding of the subsurface. No subsurface information was given to us prior, during or after the survey was conducted. Two lines of geophones were deployed (see Figure 4) across the area of interest. The first line was orientated in a NW-SE direction and consisted of 30 seismic data acquisition stations with 20 m in-line spacing, whereas the second line was orientated in a W-E direction and consisted of 15 stations with 20 m in-line spacing. The noise generated by the traffic from the adjacent highway and noise from the mining activities likely dominating the ambient seismic noise wavefield.

The second area selected was above an old pit. Here, little subsurface information was available apart from the models of the old mine workings that have been digitised from hand drawings. One line of 15 stations was deployed. The use of a single line of seismic stations means that only a 2D cross-section can be generated in this area, which in turn can mean it is difficult to delineate the subsurface.

Since the target to be imaged in this study is relatively shallow, surface waves provide adequate resolution and depth penetration and were primarily used to image the target. Future work will be to process the body-waves to use diffraction and reflection seismics in conjunction with surface wave tomography to create images of the subsurface with greater resolution.

### Results: Area 1

The ambient background vibrations were used to create virtual seismic sources at each sensor locations. The arrival times of the seismic waves in the virtual source signals are then picked for narrow frequency bands between 5 and 50 Hz. For each frequency band, the seismic velocity is regionalised over a grid encompassing the seismic stations by means of an inversion.

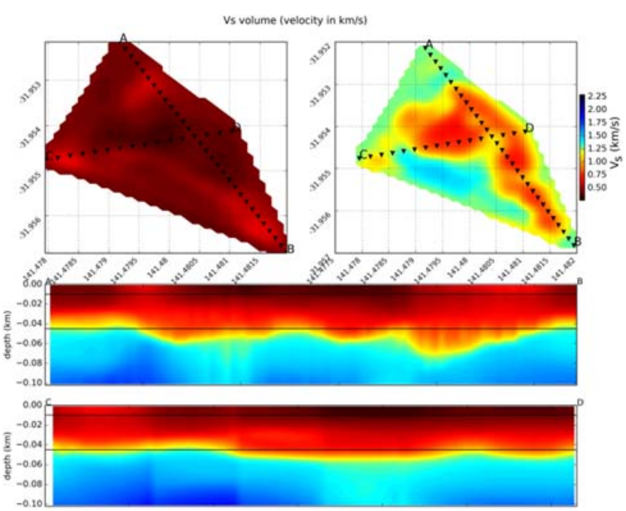


*Figure 5: Plan and section views of the inverted seismic velocity as a function of depth. The two plan views (top) show cross-sections of the shear-wave velocity at two different depths (indicated by the black line in the bottom figures).*

At the request of the operator, the results were converted to local mine coordinates to simplify importing and interpreting the results. The remaining figures in the report will be shown in the local mine coordinate system (note A, B, C and D are marked in Figures 5 and 6 to show the transformation). Please also note the change of colour scheme from crustal seismology (low=red, high=blue) to more common and intuitive geotechnical scheme (low=blue, high=red) from Figure 6 onwards.

After the dispersion maps are created for different frequencies, a depth inversion is performed for each cell in the grid to determine the shear-wave velocity as a function of depth in 3D space.

The two lines of seismic stations used in area 1 enabled us to create a 3D model of the shear wave velocity as a function of depth. In Figure 6 we show plan views of shear wave velocity at two different depths (top) and two cross sections along the geophone lines.

The low velocity zones at 40 m depth (and extending deeper) are candidates for mined-out areas. However, since shear wave velocity increases naturally with depth and confinement, the absolute velocities are not good indicators of near-surface geological areas. Instead it is a good idea to normalise the seismic velocities as a function of depth. The average velocity is calculated for each depth and the percentage difference of each cell is calculated in 3D space. The resulting figure is shown in Figure 7.

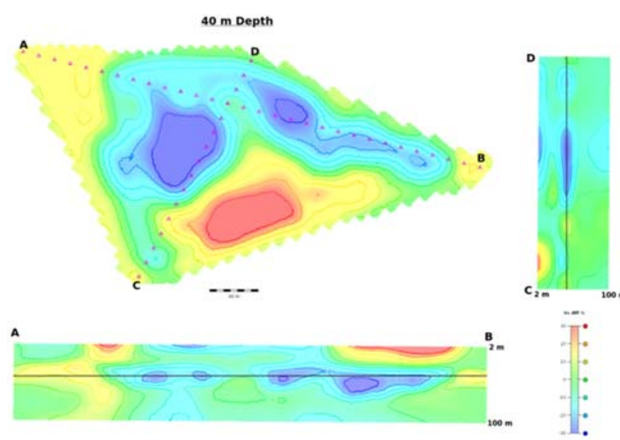


*Figure 6: Plan view of the seismic velocity anomalies at 40 m depth (top left). Cross-sections through the sensor lines are shown at the bottom and to the right.*

Now that the velocity anomalies have been normalised, density isosurfaces of the anomalies might also be useful in building likely models of mined-out stopes and of intact rock. In Figure 7, isosurfaces of velocity anomalies are shown. The low velocity contrasts are likely due to mined-out and back-filled areas where the high velocity areas indicate competent in-tact rock. There is a low-velocity anomaly close to surface just to the southwest of the intersection of the sensor lines that is probably due to the loose gravel and sand at surface in this region.

Not too much weight should be given to the high-velocity isosurfaces presented in Figure 7 as they appear at the same depth as the low velocity anomalies. In other words, the low velocity regions at this particular depth (around - 40 m) decrease the average velocity for this given depth so that the other regions at this depth might appear high, but they might in fact just be unperturbed host rock.

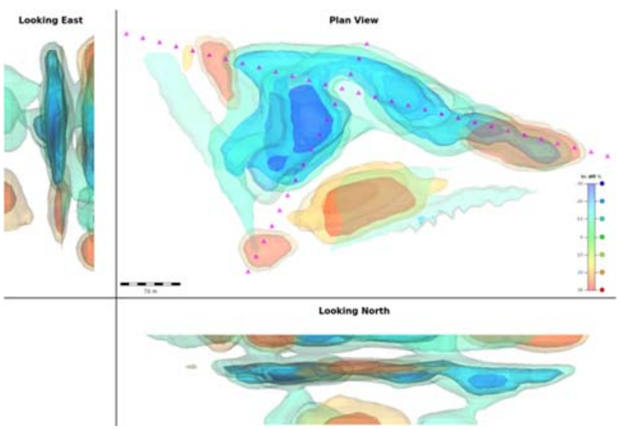


*Figure 7: Isosurfaces of velocity anomalies for different views (plan, looking east and looking north). The blue isosurfaces indicate low velocity anomalies that likely correspond to mined out stopes.*

**Results: Area 2**

A single line of 15 seismic stations was placed above the old pit. The line of receivers was placed above the partially filled in pit and over the road on the southwestern side of the pit. Access was limited in the northeastern section of the pit which prohibited us in extending the line further in this direction.

The use of a single line of geophones makes the imaging and interpretation rather difficult, especially given that the line was placed directly above the suspected mined-out and back-filled stopes.

Similarly as in the first area, the absolute velocities are hard to interpret as the seismic velocity naturally increases with depth and confinement (and the presence of a strong contrast creates problems with a single 2D line, as previously stated). In Figure 8 the velocity anomalies are shown as a function of depth. These anomalies illustrate the lateral variations in velocity at different depths. Here we can see that there are areas within the old mining sections that appear to have significantly higher velocities than the other section. We interpret the high-velocity anomalies to be more likely to be intact compared to the low-velocity anomalies that are more likely to be mined-out.

**CONCLUSIONS**

The passive seismic surveys conducted at the two mines were intended to be trials to determine whether a passive seismic survey can be conducted to delineate and examine remnant in-tact zones of high-grade ore amongst mined-out and back-filled stopes. In theory the method should be able to reduce the drilling needed to delineate the subsurface by 20 – 80 % (depending on the accuracy of the method to detect remnant and mined-out areas that would reduce the amount of drill holes).

Both trials showed clear velocity anomalies at the depths

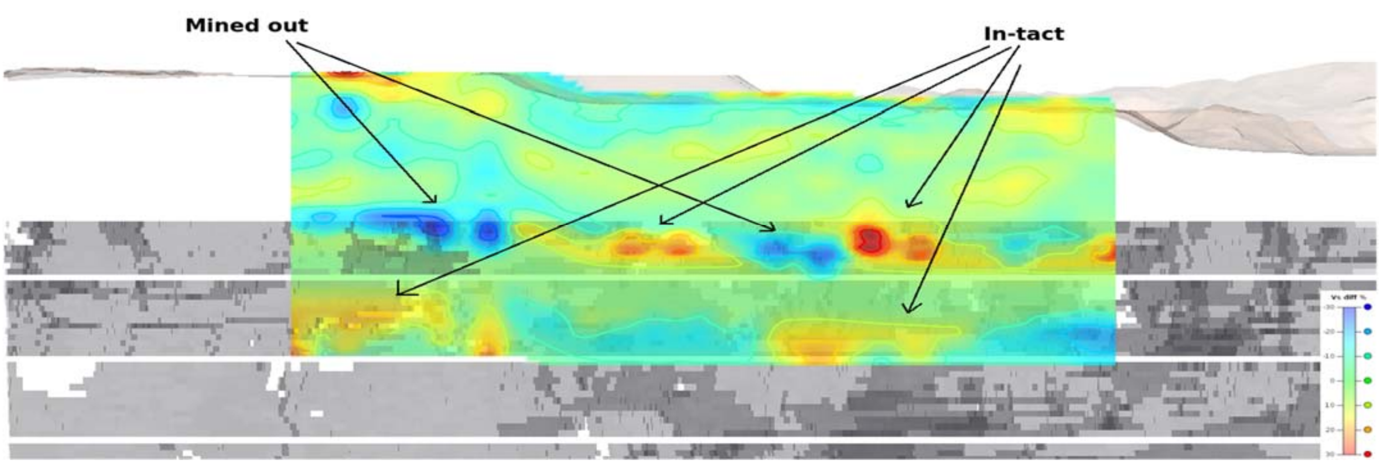


*Figure 8: 2D cross-section of the velocity anomalies below the pit. There are regions with high- and low-velocity anomalies amongst the suspected old mine workings. These are likely to be in-tact and mined out areas respectively.*

where we expect mined-out areas may be located, while the anomalies have sufficiently high contrast to inspire confidence in the results.

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