7:00 – 8:00 **Breakfast**

8:00 **Welcome**

8:15--9:00 **The Value of Seismics in Mineral Exploration and Mine Safety** *M. Manzi*[*1] *and A. Malehmir*[2] *(*[1] *University of the Witwatersrand, South Africa;* [2] *Uppsala University, Sweden)*

9:00--9:45 **Deep seismic targeting using exploration tunnels** *Alireza Malehmir (Uppsala University, Sweden)*

9:45--10:30 **Seismic Imaging Challenges along crooked-line surveys of Metal Earth project in Abitibi Greenstone belt** *Saeid Cheraghi (Laurentian University, Canada)*

10:30 --10:45 **Coffee**

10:45--11:30 **Surface-wave methods in mineral exploration** *Myrto Papadopoulou (Polito, Italy)*

11:30--12:15 **Seismic Full Waveform Inversion of subsurface structures at Larder Lake** *Brian Villamizar*[*1]*, Gerhard Pratt*[1]*, Mostafa Naghizadeh*[2] *(*[1]*Western University &* [2]*Laurentian University, Canada)*

12:15--13:00 **Lunch**

13:00--13:45 **Towards the integration of borehole geophysics and petrophysics in mineral exploration** *J.C. Dupuis*[*1]*, S. Tirdad*[2]*, A. Greenwood*[3]*, E. Gloaguen*[2]*, B. Giroux*[2]*, Farnaz Ghoraishi*[1] *(*[1]*Université Laval,* [2] *INRS,* [3] *UNIL)*

13:45--14:30 **Smart Exploration and SkyTEM validation survey at Blötberget Mine Site in Sweden** *Per Gisseloe (SkyTEM Surveys, Denmark)*

14:30--15:15 **Modeling the Cratonic- to Deposit-Scale Resistivity Structure of the Archean Superior Province** *E.A. Roots*[*1,2]*, G.J. Hill*[3,4]*, B.M. Frieman*[1]*, J. Craven*[2]*, R. Smith*[1]*, R. Haugaard*[1]*, & A. Adetunji*[1] *(*[1]*Mineral Exploration Research Centre, Laurentian University, Sudbury, Canada;* [2] *Geologic Survey of Canada, Ottawa, Canada;* [3] *Institute of Geophysics, Czech Academy of Science, Prague, Czech Republic;* [4] *Gateway Antarctica, University of Canterbury, Christchurch, New Zealand)*

15:15--15:30 **Tea**

15:30--16:15 **Seismic and Magnetotelluric signatures of melt/fluid flux through Australian crust** *Tom Wise*[*1]*, Stephan Thiel*[1] *(Geological Survey of South Australia, Australia)*

16:15--17:00 **Integrated Geophysical Imaging of Canada's Superior Province using Metal Earth and Lithoprobe data** *Mostafa Naghizadeh*[*1]*, Christopher Mancuso*[1]*, Alan King*[1]*, and Eric Roots*[1] *(*[1]*Laurentian University, Canada)*

17:00 **End**

The Value of Seismics in Mineral Exploration and Mine Safety

M. Manzi[*1] and A. Malehmir*[2] ([1] University of the Witwatersrand, South Africa; [2] Uppsala University, Sweden)*

Reflection Seismic method has become, and will continue to be, an important tool to help with the exploration and discovery of deep-seated giant mineral and metal deposits needed to sustain long-term global growth. Over the last few years, there has been a proliferation of smart seismic solutions that employ various combinations of equipment, acquisition, and processing techniques, which have been applied in greenfield and brownfield situations for direct deposit targeting. The best surface seismic acquisition solutions to date have come from the deployment of high-density receiver and source arrays which the extension of the seismic bandwidth to six octaves using broadband sources. Another area has focused on seismic acquisition using 3C microelectro-mechanical (MEMS-based) seismic landstreamers, coupled with wireless seismic recorders, and surface-tunnel-seismic surveys. However, numerous difficulties have been encountered by mining industries, even with these innovative seismic approaches. For example, seismic surveys acquired in the mining regions suffer from noise and new data cannot be acquired due to mine infrastructure and new environmental regulations. In addressing these, there have been innovative initiatives worldwide (e.g., Wits Seismic Research Centre in South Africa and Smart Exploration in the EU) trying to tackle some of these challenges by (1) developing new seismic tools for brownfield and in-mine exploration, and (2) extracting valuable information from legacy seismic data. This paper demonstrates, through case studies, how these seismic solutions have been successfully used by the mining industry to explore deep-seated mineral deposits, support mine planning, and contribute to safety.

Deep seismic targeting using exploration tunnels

Alireza Malehmir (Uppsala University, Sweden)

Mineral exploration industry while is challenged to provide fresh mineral resources to the society in order to accelerate the energy transition towards decarbonization would in the short term focus on in-mine and near-mine potential resources to benefit from existing infrastructures and great geological knowledge gained. Geophysical exploration in underground mines is an option however also challenged because of logistical issues and extreme noise from mining operation. Within the Smart Exploration project, we have developed a GPS-time system to allow an array of receivers commonly used on the surface to be synchronized with microsecond accuracy for in-mine seismic applications. The system has been lab tested and validated in a unique semi-3D underground semi-3D surface seismic experiment at the world-class Neves-Corvo VMS mine (Portugal) allowing over 1000 seismic recorders (wireless and caballed) to be synchronized. Along with the GPS-time system, a broadband electromagnetic seismic source was also developed in the project and used in the experiment. In this presentation after revisiting existing legacy seismic data from the Neves-Corvo mine, the experiment will be explained and results presented. We demonstrate how such an experiment can open up for possibilities for deep targeting and optimized drilling utilizing mining and exploration tunnels.

Seismic Imaging Challenges along crooked-line surveys of Metal Earth project in Abitibi Greenstone belt

Saeid Cheraghi (Laurentian University, Canada)

Demand for deeper mineral resources has increased during past decades as most of near surface deposits depleted and the trend is set to continue. Reflection seismic method has proven to be as an efficient method to image subsurface architecture for both sedimentary and hard rock environments. Although the method presents more success rate in sedimentary rocks, it is also practiced with relative success in hard rack setting. One major issue in the hard tock terrains is the acquisition of seismic surveys along available roads while taking into account the economical and environmental considerations. The acquired 2D crooked surveys image structures out of the plane of survey line and provide information about 3D earth structures. In the year 2017, Metal Earth acquired regional and high resolution surveys in Greenstone belt of Canadian shield in Abitibi and Wabigoon sub-provinces. Evaluation of the earth evolution causing the metal endowment in Greenstone belt is the main goal of theses surveys. We present our research results from several sites located in Abitibi sup-province. Along with conventional 2D processing, 3D swath processing and evaluation of cross-dip term of the surveys are the most proficient methods to deal with crooked surveys. We show examples from the application of the methods and discuss the advantages/ shortcomings of each method/solution. In a specific case, we present the results from a survey that acquired along two parallel profiles. Each profile is considered as a 2D survey and together they present a 3D parallel geometry which is a unique acquisition layout for hard rock environment.

Surface-wave methods in mineral exploration

Myrto Papadopoulou (Polito, Italy)

As seismic methods become more popular in mineral exploration, the development of fast and effective data processing methods is critical. An important aspect is the use of surface waves, which are typically dominant in seismic records, but have been traditionally treated as coherent noise to be removed, since exploration targets mainly in body waves. Nonetheless, the sensitivity of surface waves to the near-surface properties makes them ideal candidates for the estimation of static corrections, which is a critical step of the seismic processing workflow, necessary to improve the imaging of the deeper mineralization targets. Moreover, the higher seismic velocities of the typical mineral exploration sites, provide longer wavelengths of surface waves, making them suitable also for the characterization of the deeper mineralized bodies, in both 2D and 3D schemes. The use of passive-source seismic data is also possible and can provide a high-quality surface waves, of increased investigation depth, while eliminating the need of an active seismic source. A joint use of active- and passive-source data can increase the investigation depth, while maintaining high resolution and data coverage at shallow depths.

Several surface-wave methods and workflows are proposed. They are highly automated and computationally less intensive than typical surface-wave methods and, therefore, suitable for large-scale applications. Successful examples from legacy and newly acquired, 2D and 3D, active- and passive-source seismic data, shows the value of including surface-wave analysis in mineral exploration.

Seismic Full Waveform Inversion of subsurface structures at Larder Lake

Brian Villamizar[*1], *Gerhard Pratt*[1], *Mostafa Naghizadeh*[2] *([1]Western University & [2]Laurentian University, Canada)*

Seismic methods are playing a more active role in the quest for deeper and more reliable mining resources. When compared with other geophysical methods, seismic images can potentially yield a superior resolving power while maintaining penetration depth. One state-of-the-art seismic technique that is widely used in the oil and gas industry is Full Waveform Inversion (FWI), provides quantitative images of the subsurface by iteratively optimizing a subsurface model of elastic rock properties. The FWI technique has been successful in sedimentary environments (especially with marine data), but it has not been extensively applied in crystalline environments due to the inherent challenges. These challenges include variable surface conditions and topography, strong velocity variations, complex structures, steeply dipping interfaces, anisotropy, etc. We present a number of pre-processing strategies to overcome such challenges, resulting in a successful reconstruction of the near-surface velocity structure. These quantitative models are vital not only for the continuation of surface geology into the first few hundred meters of the subsurface, but also for improving seismic imaging at depth.

The successful implementation of FWI depends primarily on three factors: the availability of low frequency data, the accuracy of the initial model, and appropriate data pre-conditioning strategies. This preliminary study of the low frequency Larder Lake seismic transect involves the combination of the ray-based refraction traveltime approach for generating the low-wavenumber velocity field, and Laplace-Fourier FWI for the tomographic reconstruction of the velocity structure. We pre-condition the data using band-pass filtering, resampling, muting, removing of out-of-plane traces and near-offset traces, killing of noisy traces, and F-k filtering. We introduce a logarithmic phase-only objective function in order to handle the strong amplitude variations observed in the data. We use a multiscale approach for the inversion of discrete frequencies, starting at from 6 Hz and moving up through the available frequencies. We also use strong time damping and strong filtering in the wavenumber domain, to enhance the early arrivals. These strategies are used to fit the least non-linear parts of the waveform early in the inversions, and to avoid cycle-skipping. The result is a quantitative image of the near-surface velocity down to approximately 3 km in depth. This image reflects structural features associated, for instance, with the Lincoln-Nipissing shear zone. As the inversion frequencies are increased, the resolution of the image improves, leading to a more robust understanding of the shear zone.

Towards the integration of borehole geophysics and petrophysics in mineral exploration

J.C. Dupuis[*1], S. Tirdad[2], A. Greenwood[3], E. Gloaguen[2], B. Giroux[2], Farnaz Ghoraishi[1] ([1]Université Laval, [2] INRS, [3] UNIL)*

Mineral resources underpin all sectors of our society and will continue to play a fundamental role in the development of new technologies that will sustain our future as we adapt to a changing climate. A transition to renewable energy and an increase in global living standards around the world will continue to exert pressure on mineral reserves for the foreseeable future (Kessler 2007). The discovery rate of new mineral resources, however, is faltering.

In order to remain economically viable exploration at depth will require a better understanding of the geological meaning of geophysical responses with fewer geological control from drilling (Dentith et al. 2019). The key to achieve this goal is to understand how geological processes affect the different physical properties of the rock mass. With this insight it becomes possible to model and predict their influence on the measured geophysical response and thus improve our understanding of mineral systems. To reach this goal there is an urgent need for a comprehensive multiple parameter database of physical properties for mineral systems around the world.

This contribution will illustrate how borehole geophysics and petrophysics can enhance our understanding of datasets acquired at surface and improve the earth models that are built from them. Data examples from hard-rock environments will be presented along with strategies for achieving the most value from downhole measurement of physical properties.

Smart Exploration and SkyTEM validation survey at Blötberget Mine Site in Sweden

Per Gisseloe (SkyTEM Surveys, Denmark)

Within the Smart Exploration project SkyTEM has focused on the development of their airborne EM system in order to increase the depth of investigation. The developments for obtaining the increased depth of investigation have been twofold and focused on both the transmitter side and the receiver side.

The developments on the transmitter side have focused on lowering the operational base frequency to 6.25 Hz. This leads to two benefits. Firstly, the on-time can be held for a longer time period inducing a higher signal in the ground. Secondly, it allows for off-time measurements to later times (~60 ms) leading to receival of signal from deeper levels in the ground. In order to measure the EM signal at a 6.25 Hz base frequency the noise level of the receiver system needs to be optimised for this operating condition.

A validation survey was flown in June 2019 at the Blötberget Mine Site in Sweden, that is one of the appointed Smart Exploration project sites. Data was successfully collected to the last gate located at ~60 ms with a high signal to noise ratio. The data collected validated the improvements made to the system in obtaining a higher depth of investigation.

The Smart Exploration project has enabled SkyTEM to make the developments described above to the Airborne EM system. Hereby putting a novel deep penetrating airborne EM system to the market.

Modeling the Cratonic- to Deposit-Scale Resistivity Structure of the Archean Superior Province

E.A. Roots[1,2], G.J. Hill[3,4], B.M. Frieman[1], J. Craven[2], R. Smith[1], R. Haugaard[1], & A. Adetunji[1] ([1]Mineral Exploration Research Centre, Laurentian University, Sudbury, Canada; [2] Geologic Survey of Canada, Ottawa, Canada; [3] Institute of Geophysics, Czech Academy of Science, Prague, Czech Republic; [4] Gateway Antarctica, University of Canterbury, Christchurch, New Zealand)*

In order to characterise how crustal architecture influences mineralisation processes, Metal Earth is employing magnetotelluric (MT) surveys in the Archean Superior Province over a variety of scales from the regional- to the deposit-scale. Insight regarding the link between cratonic structures and economic deposits can be gained through modeling and interpretation of deposit-scale datasets within the context of regional studies, however the computational cost of inverting such datasets is prohibitively high. The Metal Earth MT data collected throughout the Superior Province offers the opportunity to refine the workflow needed to integrate MT data at a variety of spatial scales. Broadband data was collected along ~north-south transects with a 5-7 km station spacing ('R1' lines). Embedded within the majority of the R1 lines are high-resolution segments that contain broadband and audio-magnetotelluric stations at a spacing of 330 m ('R2' lines). These data were combined with existing broadband and long-period MT data from prior regional surveys (e.g., Lithoprobe) to provide robust coverage across the Superior Province. To generate mutually consistent models from the transect- to deposit-scales, a sequential inversion workflow was applied to data from the Swayze greenstone belt within the Abitibi subprovince. Broadband data was inverted to image the large scale resistivity structure, and then the embedded R2 lines were inverted using the R1 model as the a priori, resulting in models that are robust across the scales of interest. The resulting models show narrow sub-vertical zones of low resistivity extending from the mid crust to the near surface, representing fluid pathways from depth to the surface. These near vertical low resistivity features correlate spatially with crustal-scale deformation zones, and connect to a lower crustal quasi-horizontal zone of low resistivity. This lower crustal conductor may be the result of graphite generated during large scale lateral crustal flow and strain localisation along discrete quasi-horizontal shear zones in the lower crust.

Seismic and Magnetotelluric signatures of melt/fluid flux through Australian crust

Tom Wise[*1]*, Stephan Thiel*[1] *(Geological Survey of South Australia, Australia)*

In Australia, deep seismic reflection surveys have been used to provide two-dimensional profiles of the whole crust, informing crustal architecture studies and mineral system settings since the 1970's. These programs commonly use seismic reflection profiles to interrogate the crustal component of Precambrian lithosphere, partly under extensive cover sequences. Increasingly acquisition programs incorporate other geophysical techniques, such as magnetotelluric and gravity/magnetics inversion models to compliment the interpreted reflection seismic profiles

A common approach to interpretation of crustal seismic reflection profiles relies on subjective identification of faults, which in most cases are identified as discrete and narrow zones of deformation along which crustal movement was accommodated. However, examples of co-located magnetotelluric and seismic reflection profiles in Australia show that particularly in the mid to lower crust sub-vertical zones of high conductivity cross-cut crustal-scale faults interpreted from seismic sections. There is therefore a need to determine whether or not the results of both techniques can be related to the same geodynamic process, and inform on how different types of interpretation may better link the two data types.

Recent work by Heinson et al. (2018) links electrical and seismic signatures beneath the world class Olympic Dam mine to fluid pathways within a whole-of-lithosphere mineral system. We present co-located profiles in addition to the work of Heinson et al. (2018) to address the wider applicability of the joint interpretation of seismic and MT to mapping melt and fluid ascent processes through the crust. We focus specifically on the spatial association between variations in seismic reflectivity and magnetotelluric low resistivity that cross-cut earlier crustal fabrics, to inform on the nature and controls on the observed geophysical response.

This work has implications for mineral exploration relating to the role of crustal-scale structures in controlling melt and fluid ascent through the crust, and by extension, where could be targeted for subsequent scale-reduced work.

Integrated Geophysical Imaging of Canada's Superior Province using Metal Earth and Lithoprobe data

*Mostafa Naghizadeh[*1], Christopher Mancuso[1], Alan King[1], and Eric Roots[1]*
([1]Laurentian University, Canada)

The Metal Earth project acquired ~1000 km of deep seismic reflection profiles in Canada's Superior Archean province. These surveys cover from Rainy River near the Manitoba-Ontario border in the Wabigoon geological subprovince to Chibougamau in eastern Quebec in the Abitibi geological subprovince. Along the same transects, Gravity and Magnetotelluric (MT) data were also acquired for the purpose of integrated interpretation of geophysical data. Metal Earth regional-scale transects, covering upto 70 km offsets, target mineralizing fluid pathways throughout the crust, whereas higher spatial-resolution reflection surveys target structures at mine camp scales. Because Metal Earth was proposed to map and compare entire Archean ore and geologically similar non-ore systems, regional sections cover the entire crust to the Moho in the Abitibi and Wabigoon greenstone belts. The processing workflow of Metal Earth's crustal-scale seismic data was focused on robust static solutions, detailed velocity analysis, minimal trace smoothing, and high-resolution imaging. Where the new sections overlap with previous Lithoprobe surveys, a clear improvement in reflector detection and definition is observed. Improvements are here attributed to the increased bandwidth of the signal, better estimates of seismic wave speeds used in processing, and especially more accurate migrations of the data. The inverted Gravity, Magnetic, and MT models were integrated into the interpretation of seismic images, revealing possible mineralizing fluid pathways extending to the surface which could be considered as potential mineral prospecting targets. In this talk, I will present the latest integrated geophysical interpretation of the Superior province from the Metal Earth and Lithoprobe data, utilizing electrical resistivity, density, and seismic reflectivity models to identify the nature of anomalies.