Alan G. Jones* (Complete MT Solutions Inc.), Stephan Thiel, Kate Robertson, Mike Dentith, and Graham Heinson: Mineral systems mapping using magnetotellurics: Examples from Canada and Australia

Increasingly the search for world-class deposits is using the mineral system concept as a framework to identify the most prospective terrains within which to explore. An important implication of this concept for geophysics is that, in addition to the well-established approach of seeking responses from targets that comprise the immediate mineralised environment, a whole set of new targets are presented. These include source zones for metals and/or metal-bearing fluids (brines or magmas) and also the conduits through which these fluids passed, both before and after precipitation of the deposit-forming metals. Alternatively, geophysics can map lithospheric structures to identify regions likely to concentrate fluid flow.

Electrical conductivity is highly sensitive to a very minor (<1%) content of interconnected low resistivity minerals, and these mineral system processes will alter the electrical properties of the crust and mantle. Electromagnetic imaging, using the natural-source magnetotelluric (MT) technique, maps the spatial variations in electrical conductivity. Given the inherent scalability of MT, zones can be mapped from the near surface to deep in the lithospheric mantle. Thus, MT offers the greatest tool in the geophysical arsenal for mapping mineral systems at all scales.

We will give examples of the application of MT for mineral systems mapping. In Canada the Yellowknife Fault Zone, mapped during Lithoprobe, lies directly above a crust/upper mantle diffuse region of reduced resistivity, suggesting flow through a generally increased permeability region rather than along defined fault zones. Diamondiferous kimberlites in multiple localities across Canada are the correlated with enhanced conductivity in the mantle. Insights from AusLAMP and subsequent infill surveys across the Gawler Craton shows there exists good correlation between conductive zones interpreted as lithospheric scale conduits and expressions of mineral systems in the upper crust. In Western Australia MT has mapped major faults and terrain boundaries, which were probable foci of fluid flow.

Randy Enkin* (GSC-Pacific, NRCan): Petrophysics for Mineral Exploration: Linking Geophysics and Alteration Geology

Mineral exploration expenses are dominated by geophysical surveys and geological sampling. Knowledge of rock physical properties provides the link which makes geological interpretation of geophysical surveys possible. One cannot directly apply the geological tools of lithology, mineralogy, and geochemistry without direct access to rock samples. However the lithology, mineralogy, and geochemistry all control the rock physical properties which in turn control the responses detected by geophysical surveys and measurements. For mineral exploration, it is necessary to know the typical distributions of rock physical properties for different lithologies, and the effects of alteration and mineralization. To this end, we have been compiling the Canadian Rock Physical Property Database, which currently contains petrophysical measurements, along with their associated locations and lithologies on 20k samples. Particular emphasis will be given to the “Henkel Plot”, that is log(Magnetic Susceptibility) vs density, which is well-established in many settings globally and provides great insight on the mineralogy and geological setting of different settings. The results are interpreted using Mike Dentith's conceptual framework for petrophysical data, which places the various rock physical properties on a ternary diagram with end members of "Bulk (Overall Composition), "Grain (Amount, Size, Shape of Minority Mineral Species)", and "Texture (Geometric Relationships Between Grains)". Density is dominated by the bulk composition, whereas magnetic susceptibility is dominated by the concentration of the minor mineral magnetite. Electric resistivity in sedimentary rocks is dominated by the porosity and permeability, which are textural properties. The laboratory and analysis methods of the Canadian Rock Physical Property Database will be presented, followed by case studies of several important Canadian mineral deposits.

Richard Smith*, Reza Mir, Stéphane Perrouty (Laurentian University): Geophysical exploration for mineral systems: highlights from the NSERC-CMIC Footprints Project and CFREF Metal Earth Project

Footprints of mineral systems can be evident at multiple scales. At lithospheric scales, MT and seismic surveys can image major structures (e.g., terrane boundaries, faults) that could act as conduits for mineralizing fluid flow from the deep in the crust. The Metal Earth project aims to map these crustal-scale structures across ten 100-km long traverses in the Superior Province. Some of these traverses are in metal-rich greenstone belts with a long history of mining (e.g., Abitibi), while others are in similar geological environments, that are not as rich in metals (e.g., Wabigoon).

It is hoped that deep geophysics will help us identify and understand the key differences between these settings, so that future exploration campaigns for metal-rich zones in greenfields can be designed more effectively. At camp scale, geochemistry, mineralogy and petrophysics can map the metasomatic halo around mineral systems, thus acting as mineralization vectors. The Footprints project has characterized several such parameters that can be considered vectors to mineralization.

At Canadian Malartic, gold mineralization in meta-sedimentary rocks is commonly hosted within zones of structural complexity (e.g., fold hinges). The physical property changes that are associated with mineralization were measured from drill core and hand samples. The challenge is to detect these subtle changes or a suitable proxy for structural complexity from geophysical measurements taken at or above the ground surface. Helicopter-borne electromagnetic data at Canadian Malartic shows some high resistivity zones correlating with low structural complexity, but the presence of a discontinuous resistive Quaternary sediment cover (i.e., glacial till) limits the possible interpretations.

To overcome this difficulty, fifteen ground resistivity and IP surveys have been compiled and inverted to estimate the properties below this cover. The high chargeability zones correlate with pyrite-pyrrhotite-rich areas close to felsic-intermediate intrusive bodies and/or mineralized structures like fold hinges and faults. The low resistivity zones correlate with areas of variable bedding orientation (or high structural complexity). The anisotropy of resistivity is important at Canadian Malartic, being greater where the bedding is sub-vertical. This has implications for survey design, specifically when choosing the line direction. This work demonstrates that geophysics can be used to infer structural orientation and complexity at depth, and ultimately be used to outline prospective areas for gold mineralization.

NSERC-CMIC Mineral Exploration Footprints Project Contribution 195.

Henry Lyatsky* (Geoscience Consultant): Exploration Uses of Regional Gravity and Magnetic Data: Examples from Province-Scale Work in Alberta

Delineation of regional fault networks and anomaly domains is a vital part of oil and mineral exploration. Gravity and magnetic data are a central part of this work. I previously worked with the Alberta Geological Survey to create a public-domain gravity and magnetic atlas of central and southern Alberta and some neighboring areas of Saskatchewan and BC (2005, AGS Special Report 072, https://ags.aer.ca/publications/SPE_072.html).

Brittle faults and fractures in the crystalline basement commonly propagate up into the overlying sedimentary section, including in the Alberta and Williston basins. Ubiquitous in the continental crust, this phenomenon of pervasive, high-angle block-faulting ("Germanotype tectonics") was described in Europe in the 1920s, and the same concept has been applied in Alberta since the 1947 Leduc oil discovery set off the oil boom. With or without big vertical offsets, basement faults and fractures affect patterns of deposition, erosion, compaction, alteration, salt dissolution and local mineralization, as well as the development of primary and secondary porosity including fracture porosity.

Basement faults and fractures in western Canada commonly have too little vertical offset to be resolvable with seismic data: offsets less than 10 m may be very hard to resolve, and the seismic signature of the basement surface in Alberta is commonly ambiguous. Fortunately, many brittle basement faults appear as subtle linear anomalies in gravity and magnetic maps. Major gravity and magnetic anomalies, by contrast, tend to be associated with ancient, orogenic basement structures which are typically ductile and thus of far less influence on the overlying sedimentary basins.

In much of western Canada, adequate magnetic and gravity data are available in the public domain at zero cost from government agencies. A responsible and budget-conscious explorer owes it to himself to examine these free data before committing capital to performing a more detailed survey.

These data are processed to highlight the hard-to-detect, subtle lineaments that could be related to brittle fault and fracture networks. The most fruitful techniques tend to be the most intuitive and the simplest: horizontal and vertical derivatives, shadow grams, amplitude gain, third-order residuals. Complex processing methods are best avoided in order to: 1/ maintain a clear connection between derivative anomalies and original raw ones, 2/ prevent the suspicious appearance of a mathematically baffling and dodgy "black box", and 3/ avoid creating lineament-like processing artifacts.

Because it may be hard to know in advance which processing steps and parameters would be the most fruitful for subtle-lineament enhancement, a great deal of experimentation is commonly required along the way. I strongly prefer to avoid the magnetic reduction to pole because it dubiously assumes that all magnetization is induced and remanence is negligible.

Lineaments are picked in the derivative gravity and magnetic maps by hand with a crayon, by viewing each map at low angles on a table. A lineament could be a gradient zone, a linear break in the main anomaly pattern, a straight anomaly, an alignment of small local anomalies, or some combination of the above. Without prejudice, anything in a map that seems linear and has some appreciable length is picked as a lineament. Identified geophysical lineaments may not all be caused by brittle fault and fracture zones, and some real faults and fractures may have no discernible gravity and magnetic signatures.

The picked lineaments should be compared with surface topography, drainage patterns and, above all, with surface and subsurface geological and seismic information. Correlations of linear hydrocarbon-reservoir trends and other Phanerozoic geologic features in the Alberta Basin with gravity and magnetic lineaments may point to control by basement fractures and faults, giving our methodology its predictive power.

Fiona Darbyshire * (Université du Québec à Montréal): Regional-Scale Natural-Source Seismology and the Cratonic Lithosphere

In the last ~15 years, significant advances have taken place in our understanding of the regional-scale structure of the crust and upper mantle beneath Canada, thanks to studies using networks of broadband seismometers. These instruments allow us to take full advantage of the seismic waves arriving from large worldwide earthquakes, resulting in an array of complementary information on seismic structure. Using the arrivals from body and surface waves, we can map out wave speed variations throughout the crust and upper mantle, as well as the depths to key boundaries such as the Moho and the lithosphere-asthenosphere boundary. Distributed 2D networks with station spacings of 100-300 km, along with quasi-linear profiles with denser station spacing, have permitted the imaging of the Canadian Shield and its margins in unprecedented detail in recent years. These images have, in turn, advanced our understanding of the processes governing the formation and evolution of continental lithosphere, and the role of plate tectonics in the Precambrian.

This presentation highlights a number of case studies from the northern, eastern and central Canadian Shield, where recent densification of seismograph networks at a regional scale has permitted detailed imaging of the crust and upper mantle. We explore the scope of the natural-source imaging techniques using different parts of the seismic wavefield and the geological information that can be gained from these techniques. In the case studies, we see strong correlations between past tectonic processes and present-day lithospheric structure within and around the oldest cratonic keels. In particular, we note significant similarity between the structures preserved in Proterozoic mobile belts and those observed in the present-day Himalayan collision zone, supporting the idea of plate-tectonic uniformitarianism throughout at least 2 billion years of Earth history.

Andrew Schaeffer*, Pascal Audet, Sergei Lebedev (GSC-Pacific, NRCan): Probing the Diamond Potential of the North American Lithosphere using Seismic Tomography

The North American continent has had a long, eventful tectonic history, the assembly of which is recorded by the stable cratonic core. Since its formation, the North American shield, the stable craton anchoring the North American continent, has undergone numerous collisions and accretion at its boundaries, major rifting episodes within it, as well as the loss of ancient lithosphere beneath parts of it.

In addition, it plays host to numerous ultramafic intrusions and pipes, which themselves contain, in many cases, world-class diamond deposits.

Seismic tomography offers rich evidence on the structure, evolution and architecture of the cratonic lithosphere. With the deployment of the Earthscope USArray over the last decade, in addition to numerous regional targeted deployments, the North American continent is now densely sampled with broadband seismic data, spanning from the west to east coasts, and more recently the north. Utilizing sophisticated and efficient methods capable of handing the massive volumes of available seismic data, new models are available that constrain, in greater detail, the upper mantle underlying the North American continent. Using one of these models, we compute the lithosphere-asthenosphere boundary (LAB) depth in order to resolve the architecture of the craton.

Examination of this `snapshot' of the modern LAB in the context of diamondiferous and non-diamondiferous kimberlites across the continent provides a temporal pinning for the evolution of the cratonic lithospheric root of North America. In particular we note that known kimberlite pipes (diamondiferous or not) dominantly cluster around but not below the deepest parts of the lithospheric root. Assuming a minimal spatial kimberlite sampling bias and minimal changes in lateral LAB depth gradients, the ultra-mafic source magmas for kimberlitic eruptions seem not to penetrate the deepest cratonic lithosphere, imparting limitations on the source, transit and emplacement mechanisms, and therefore diamond potential at the surface.

Benjamin Murphy* & Gary Egbert (Oregon State University): How Long-Period EarthScope MT Data Might Inform Targeted Mineral Exploration in the Central United States

A growing body of research indicates that regional lithosphere-scale geophysical studies can be valuable in guiding localized mineral exploration. The best examples of this have so far come from Australia, where lithosphere- and crustal-scale electrically conductive anomalies are associated with major mineral deposits. Especially as such deposits are often concealed in the subsurface, this correlation suggests that future exploration efforts could benefit from using regional-scale geophysical imaging techniques. In the U.S., new high-quality, continental-scale geophysical datasets, such as the EarthScope USArray long-period magnetotelluric (MT) dataset, present a scientific resource that can be leveraged for regional mineral exploration. The benefit of such datasets may be greatest in the Central and Eastern U.S., where potentially resource-bearing Precambrian crystalline rocks are generally blanketed by Phanerozoic sedimentary rocks. In the U.S. Midcontinent, three-dimensional electrical resistivity inverse solutions have so far revealed two areas that warrant further exploration. One is demarcated by a northwest-southeast-striking electrically conductive zone in the lower crust and uppermost mantle beneath Missouri that is spatially coincident with a regional Bouguer gravity low. REE-bearing iron oxide-copper-gold (IOCG) deposits have been located along the southeastern margin of this anomaly and are the subject of current resource evaluation efforts by the USGS. The second electrically conductive zone is located in northwestern Ohio and also coincides with a geophysical potential-field anomaly. No economic mineralization has yet been found in the basement rocks of this region, although this is likely due to lack of targeted exploration. Multiple lines of evidence suggest this area may warrant further investigation.

Adam Schultz*, (Oregon State University): Detailed studies of geothermal and volcanic systems by combining EarthScope long-period MT USArray data with higher-resolution wideband MT arrays embedded in the larger array

The widescale deployment of long-period Narod Geophysics (Vancouver, BC) MT systems under the support of the US NSF EarthScope Program (2006-2018) has produced MT data on a regular 70-km grid of temporary stations (the MT Transporable Array, or MT TA) that span 2/3 of the territory of the conterminous US. These data, covering the frequency band of ~10-4 Hz < f < 10-1 Hz, provide information on electrical conductivity structure particularly from mid-crust (~10 km) to upper mantle (~300 km) depths, thus yielding a continental-scale reconnaissance 3-D geoelectric map.

In addition to the MT TA station grid, the NSF EarthScope and related programs such as GeoPRISMS, and the US Department of Energy Geothermal Technologies Office, have supported higher-resolution long-period and wideband MT array installations to obtain additional information in areas where geophysical targets of interest have been identified by analysis of the MT TA array data. Specific projects include the largest amphibious (seafloor and land-based) MT array ever undertaken, along the Oregon continental margin (the MOCHA Project); a very high resolution wideband MT and active/passive seismic project in the southern Washington Cascade volcanic arc designed to image the sources of melt beneath the major volcanoes (the iMUSH Project); detailed wideband MT studies of Yellowstone supervolcano; continuous monitoring of an Enhanced Geothermal Systems stimulation at Newberry Volcano in Central Oregon, and a novel MT study in the interior of Alaska combining a large synchronously operating array of MT instruments operating underneath the footprint of an ionospheric imaging incoherent scattering radar system.

Some of the key findings of analysis of the MT TA data, as well as of the more focused studies just indicated will be presented. These studies have revealed the impact of previously undiscovered deep crustal igneous intrusive bodies (batholiths) on the migration of deep melt and the location of surface volcanic features in the Cascade volcanic arc, as well as the relationship between metasedimentary bands left over from crustal accretion events and the path of melt migration and enhanced seismicity. Images of the electrical conductivity variations immediately above the subducting Juan de Fuca-Gorda plates have been used to infer the fluid content at the plate-mantle wedge interface and the location of upward migration of metamorphic fluids and subduction-derived melts, and studies are underway to understand the relationship between lubrication of the boundary by such fluids and plate locking in this great megathrust seismic zone. MT data have shown evidence for the trace of an ancient (1.1 Ga) deep mantle plume as the source of melt during the incipient continental rifting event that formed the Mid-Continent Rift system, and which is linked to the formation of economically important banded iron formations. The MT TA data set, as well as recently acquired wideband MT data are more clearly illuminating the relationship between deep crustal melt sources that shallow up from the Snake River Plain and serve as the source of melt beneath Yellowstone caldera, and the well-known surface hydrothermal features that are located there. A Multiphysics data set including wideband MT has revealed the source of the most recent eruption at Newberry Volcano, and has constrained the geochemistry of the sub-caldera magma body. Important new information on the evolution of eastern North America has also been revealed by analysis of MT TA data.

Martyn Unsworth*, Enci Wang, Cedar Hanneson, Sean Bettac (University of Alberta): Lithospheric resistivity structure of Western Canada from long-period magnetotelluric data

Magnetotelluric instrumentation and inversion algorithms have both advanced in recent years, resulting in large datasets that can yield 3-D resistivity models of the crust and upper mantle. Magnetotelluric (MT) studies of Western Canada were an important part of the Lithoprobe project and used a 2-D approach for data modelling and inversion. Since 2000 the University of Alberta has systematically collected long-period data to develop 3-D MT coverage in this area. Using multi-processor clusters, 3-D resistivity models with horizontal cell dimensions of 5 km have been developed for large regions of Alberta and British Columbia. In Alberta the resistivity models have defined a number of low resistivity features associated with crustal boundaries, and also detected variations in upper mantle resistivity. In British Columbia the 3-D inversions have defined the spatial extent of a previous detected mid-crustal conductor beneath the Canadian Cordillera and imaged the geometry of the edge of the North American Craton. The interpretation of these 3-D resistivity models for Alberta and British Columbia will be discussed and implications for resource exploration presented. A 3-D inversion model derived from magnetotelluric data collected in the Slave Craton will also be presented and implications for lithospheric structure and evolution discussed.

David Eaton* (University of Calgary): Tectonic Architecture in the Canadian Cordillera: Potential Insights from CCArray Seismological Studies

As part of the proposed national EON-ROSE initiative, the Canadian Cordillera Array (www.ccarray.org) is a nascent international project that will install a regional network of seismograph stations in western Canada, together with GNSS and other types of monitoring systems. The goal of CCArray is to enable trans-disciplinary research focused on Earth systems processes and boundaries, including tectonic controls on the development of regional mineral systems. Current global and regional models of seismic wavespeed have highlighted the profound influence of large-scale tectonic elements such as the sharp western edge of North American cratonic lithosphere, complex patterns of mantle flow within a mantle window adjacent to the subducting Juan de Fuca slab, and lower-crustal channel flow linked to a widespread flat Moho. Relative to these previous studies, tomographic imaging using passive seismic observations acquired by CCArray will enable significantly improved spatial resolution of these features. Moreover, building upon the legacy of Canada's Lithoprobe program, the large-scale framework derived from CCArray will be enhanced by other geophysical methods such as magnetotelluric (MT) and supporting geoscientific studies. This presentation will provide an update on current plans for CCArray, discuss seismological tools that can be applied for lithospheric imaging, and provide a context for future studies based on previous work in this area.

Katherine Boggs*(Mount Royal University), Dave Eaton (University of Calgary) and Graham Begg (Minerals Targeting International): From LITHOPROBE through EarthScope to the new pan-Canadian EON-ROSE Research Initiatives; Geologic Implications for Mineral Exploration across North America

Continuing improvements to geophysical imaging methods have enhanced the capacity for geoscientists to test models for the SCLM (subcontinental lithospheric mantle) architecture, with important implications for understanding regional mineral systems. For example, the multi-disciplinary approach of LITHOPROBE (1984 to 2004) was used to refine kimberlite pipe imaging (e.g. A154 pipe at Diavik), enhance base-metal exploration (e.g. Sudbury structure), and was applied to uranium exploration in the Athabasca Basin. Industry support was critical for creating buy-in across the Canadian geoscience community for LITHOPROBE. The US EarthScope program (2004 to 2020) was funded by the US National Sciences Foundation and therefore did not require such industry support. However, the greater resolution possible courtesy of the EarthScope Transportable Array through Vp tomographic images demonstrated that W(-Sn), REE, MO, Cu-Mo-Ag-Au, Cu-Au-Mo and Au deposits are concentrated along major lithospheric structures, particularly on the flanks of highs or in lower-velocity regions in the southwestern USA. Such relationships in the southwestern US, and across Africa (particularly in the Kaapvaal craton) have been used to suggest that these lower velocity zones reflect higher temperatures and/or refertilization of the SCLM (sub-continental lithospheric-mantle). While the influence of SCLM in ore genesis is hotly debated, aside from the architectural control, there is the possibility that some magmas may pick up ore-forming components during their passage through the SCLM to form giant magma-related ore systems. This provides an enticing exploration model to explore with the new pan-Canadian EON-ROSE Earth-System Observing Network – Reseau d'Observation du Systeme terrestrE) research initiative. Whole rock analysis of metasomatized SCLM in China and the US have revealed 10-14 ppb Au, along with up to 100ppm Cu in veins. EON-ROSE will use the multi-discipline approach of LITHOPROBE, combined with the scientific and technological advances of EarthScope, to provide much higher resolution images of the Canadian SCLM. This approach, integrated with geochronology and mantle geochemistry will be used to map the distribution of the Canadian upper-lithospheric domains to depths in excess of 100km.

Fred Cook* (Salt Spring Imaging, Ltd.): Geophysical, Geological and Geochemical Targeting of Potential Mineral Deposits: From Lithospheric Scale to a 5-cm Drill Core

For nearly 30 years, Lithoprobe focused on mapping the structure and physical properties of the North American lithosphere in Canada. An important component of Lithoprobe from its beginning in the early 1980's was an effort to include the mineral exploration industry in defining the objectives and operations within each study (transect) area. Although Lithoprobe ended nearly 10 years ago, some of the implications for mineral exploration continue today. However, a major obstacle in applying the regional findings to more localized exploration is the difference in scale. In other words, how can the regional scale findings (at 10's to 100's of kilometres) be translated to property scale exploration targets that can be tested with 5-cm diameter drill holes?

According to Minex Consulting, between 2007 and 2012 more than 80% of new mineral discoveries in Canada were made by junior exploration companies. Junior companies often acquire large amounts of data (including geophysical), but rarely have sufficient technical personnel for advanced data analyses. Many of these data sets are made available through Assessment Reports. This characteristic of the mineral exploration industry provides opportunities for new exploration concepts, especially where regional perspectives can be merged with property-scale analyses.

In this presentation, some recent studies will be shown to illustrate how large-scale studies may be used to delineate new areas for exploration, to enhance exploration in existing areas, and to develop targets for drill testing. Areas discussed will be: 1) the Nechako Plateau, 2) the western Monashee Complex, and the Purcell anticlinorium.

1) Nechako Plateau: Palinspastic reconstructions of foreland structures in east-central British Columbia lead to the conclusion that Canadian Shield 'basement' and structures within it, such as the Great Slave Lake shear zone, project westward at least as far west as Vanderhoof, BC, and may have significantly influenced the source(s) and chemistry of the igneous rocks responsible for porphyry deposits (e.g., Endako, Mt. Milligan, etc.), as well as for epithermal precious metal deposits (e.g., Blackwater, Capoose, Copley, etc.);

2) Western Monashee Complex: During Lithoprobe activities in the 1990s, a suite of regional seismic profiles across the southern Canadian Cordillera traversed the Monashee complex and provided images of a westward-thickening basin that is older than Windermere (ca. 0.8 Ga), younger than basement (ca. 1.8 Ga) and may be up to 15-20 km deep. Although there have been some significant findings of massive sulphides at the surface (primarily Zn-dominant: Ruddock Creek, Kingfisher, TL), the 'basin' is virtually unexplored;

3) Purcell Anticlinorium: The Purcell basin (now the Purcell anticlinorium) has been heavily explored since the Sullivan deposit was found more than 125 years ago. Enhanced analyses of seismic reflection data have provided images of previously unknown higher-order basins that are similar to the basin that hosts the Sullivan deposit. These 'new' basins are virtually unexplored. In addition, the structural and stratigraphic variations mapped on the seismic data can be combined with techniques such as magnetotellurics to develop new subsurface targets for exploration.