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# Integrated Multi-Parameter Exploration Footprints of the Canadian Malartic Disseminated Au, McArthur River-Millennium Unconformity U, and Highland Valley Porphyry Cu Deposits: Preliminary Results from the NSERC-CMIC Mineral Exploration Footprints Research Network

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## ABSTRACT

*Mineral exploration in Canada is increasingly focused on concealed and deeply buried targets, requiring more effective tools to detect large-scale ore-forming systems and to vector from their most distal margins to their high grade cores. A new generation of ore system models is required to achieve this. The Mineral Exploration Footprints Research Network is a consortium of 70 faculty, research associates, and students from 20 Canadian universities working with 30 mining, mineral exploration, and mining service providers to develop new approaches to ore system modelling based on more effective integration and visualization of multi-parameter geological-structural-mineralogical-lithogeochemical-petrophysical-geophysical exploration data. The Network is developing the next generation ore system models and exploration strategies at three sites based on integrated data visualization using self-consistent 3D Common Earth Models and geostatistical/machine learning technologies. Thus far over 60 footprint components and vectors have been identified at the Canadian Malartic stockwork-disseminated Au deposit, 20-30 at the McArthur-Millennium unconformity U deposits, and over 20 in the Highland Valley porphyry Cu system. For the first time, these are being assembled into comprehensive models that will serve as landmark case studies for data integration and analysis in the today's challenging exploration environment.*

## INTRODUCTION

In the last decade, small step-changes in exploration success have occurred in many parts of the mining industry (e.g., Marlatt and Kyser, 2011), but there is a need for fundamental improvements if not disruptive change (Enders and Saunders, 2012) in the way exploration is done to maximize those successes. Despite massive spending on acquisition of new data, the process of exploration has become less effective per dollar spent over time, in large part because of the need to find ever deeper resources (e.g., Witherly, 2012; Schodde, 2014), but also because of many problems related to the difficulties of working with the increasingly large datasets being generated during modern exploration programs:

1) *Volume of data*: New surveys are being conducted faster than ever before, frequently exceeding the capacity to assemble and interpret them. As a result, vast amounts of quantitative information are often left unused.
2) *Subjective data selection*: Conventional methods of handling the data are no longer sufficient to extract their full value and expensive data are regularly dismissed on the basis of subjective evaluations.
3) *Consistency*: Lack of consistency in the quality and resolution of different data sets creates problems in comparing and integrating data.
4) *Incomplete quantitative analysis*: Most exploration models have typically not been populated with quantitative data for more than a few parameters or at the range of scales necessary for effective exploration.
5) *Data interrogation/relationships*: Even where data are abundant, they are often interrogated individually or without qualification that may emphasize their relationship to an economic deposit.

Faced with these challenges, explorers are searching for new and better ways to mine their existing data sets for the most sensitive indicators of ore potential in remote areas and at depth (e.g., Agnew, 2015). A new generation of ore system exploration models[1] is needed to guide that search and to take full advantage of the rapidly expanding volumes of data available in today's exploration environment (Barnett and Williams, 2012).

To address this challenge, a team of 70 faculty, research associates and students at 20 universities across Canada are working with the Natural Sciences and Engineering Research Council of Canada (NSERC), the Canada Mining Innovation Council (CMIC), and 30 mining and mining service companies to develop and test new models that will unlock Canada's future mineral wealth. With $13M in cash and in-kind funding from NSERC and CMIC, the project is the largest of its kind to have been launched in Canada. This contribution describes the network and presents some preliminary results for three integrated study sites.

[1] In the context of this project an "ore system exploration model" is the combination of district- to local-scale geological, structural, mineralogical and mineral chemical, geochemical and isotopic, petrophysical, geophysical, and surficial footprints and vectors that can be used to *directly detect* an ore deposit. It is obviously important to consider the metal source, regional tectonic/stratigraphic/magmatic setting, and complete plumbing system when exploring for ore deposits, but we are focussed here on features that can be detected directly.

## ADDRESSING THE CHALLENGE

The greatest competitive advantage for explorers in the search for mineral resources is to improve the threshold of detection of an ore system at the district scale, to move quickly and effectively from the point of detection to the mineralized portions, and to minimize the sample density required to vector within the deposit footprint (**Fig. 1**). Many exploration programs suffer from incomplete knowledge of the attributes of the ore-deposit footprint coupled with the prevailing hope that a single parameter (the elusive "silver bullet") will guide them to the target. In most cases there is no single data type that will be the unique identifier or vector to ore; different combinations of survey techniques are almost always required. Continuous improvements in geophysical and geochemical techniques applied to mineral exploration have produced large numbers of targets for drilling, but the ability to efficiently discriminate the most prospective anomalies has not been similarly advanced. Even where data are abundant, they are often interrogated individually or without qualification that may emphasize their relationship to an economic deposit.

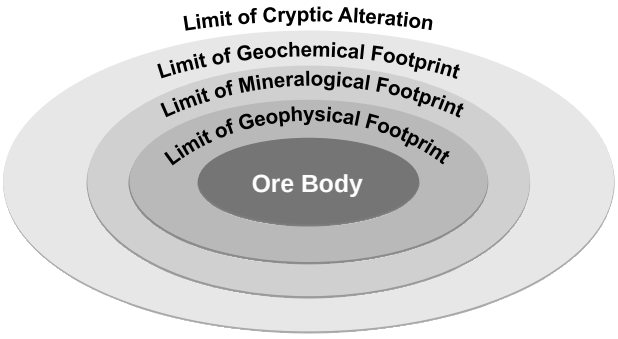



**Figure 1**: Schematic representation of a multi-parameter ore system footprint, each of which may be internally zoned and extend to different distances with a geometry that may vary according to structural controls on magmatic/hydrothermal fluids or deformation, metamorphism, erosion, and glacial cover.

Out of necessity and experience, industry has recognized that vastly better and more sophisticated integration of different data sets is now needed to decrease the size of their search space and more efficiently target their next drill holes. There have been several initiatives across the globe to better assess multi-parameter exploration data. Many of these have focused on complex data sets such as multi-element lithogeochemistry and trace element mineral chemistry for more effective detection of ore systems (e.g., Cooke et al., 2014; Wilkinson et al., 2015), but few have succeeded in comprehensive integration and simultaneous interrogation of the many different types of data available in a modern exploration program. Fewer still have developed the necessary data-driven, non-deterministic

approaches to the analysis of the data using modern geostatistics (e.g., Barnett and Williams, 2012).

Integrating multiple data sets into coherent ore system models for identification and targeting has become a daunting task because of the staggering amount of new data that is being collected. New surveys are being conducted faster than ever before, frequently exceeding the capacity to assemble, level/condition, and interpret them. As a result, vast amounts of quantitative information are left unused, leaving explorers to rely on descriptive models of their targets and mainly qualitative interpretations of the data. In the past, near-surface discoveries were possible at this level of interrogation, commonly employing simple paper maps and static 2D sections. However, to keep up with modern data flows and the need to look deeper and for more subtle footprints, explorers must work with multi-parameter data sets and must use more sophisticated interactive methods to interrogate the data.

The goal of data integration is not new. It has been a major theme in the industry for at least a decade (e.g., Exploration '07, *www.dmec.ca*), but the sheer volume and a lack of consistency between different data sets has always been a problem. Commonly, very detailed geological data, such as core logs, are over-simplified in order to match the coarser scale of geophysical or geochemical data, resulting in the loss of critical information. A major challenge is to integrate the data in such a way that the maximum resolution is achieved in each layer while making the most out of the spatial overlap. Although developments in information technology have had a profound impact on the exploration process, especially in visualization techniques, conventional methods of handling the data are no longer sufficient to extract their full value and expensive data are regularly dismissed on the basis of subjective evaluations (e.g., Broome and Cox, 2007). Rigorous approaches to levelling and integration of geological and geophysical data in self-consistent Common Earth Models (CEM; McGaughey, 2006) have been a mainstay in the petroleum industry, allowing explorers to consistently identify and rank targets. Despite being widely acknowledged as adding value in the exploration process, the mining sector has lagged significantly behind in the implementation of these approaches (McGaughey and Vallée, 1998; McGaughey, 2007; Reeckmann et al., 2007). This stems in part from inadequate knowledge of the right data to collect. These must be guided by the right ore system model, a comprehensive and consistent approach to data integration, and careful validation that the data can be directly or indirectly linked to the actual ore-forming process. The goals are to identify specific combinations of geological, structural, mineralogical, geochemical, petrophysical, and geophysical signatures that best reflect the controls on mineralization and alteration at the greatest possible distance from the deposit. How to tease those relationships out of the volumes of data available in today's exploration environment and discriminate the effects of the hydrothermal system from those of a number of interrelated or competing variables, is the challenge being addressed by the Exploration Footprints project.

## A SOLUTION

A variety of ore deposit and ore system models exist for most mineral deposit types, but are typically not populated with quantitative data for more than a few parameters at the range of scales necessary for effective exploration. For most ore systems, the full range of geochemical, mineralogical, and physical rock properties and their vertical or lateral extents have not been established. Creating the next generation of ore system models requires the basic research that will fill those gaps. An unprecedented new look at different kinds of geological, structural, mineralogical, mineral chemical, lithogeochemical, petrophysical, and geophysical data is required, along with the workflows and the tools to integrate those data. Data from different methods need to be acquired in the same space, at the same scale, and on the same samples, requiring direct collaboration between geologists, mineralogists, geochemists, petrophysicists, and geophysicists. This necessarily involves new and emerging technologies that can test the physical and chemical responses of many different parts of the ore system at the same time, including new analytical tools (e.g., portable X-ray fluorescence spectrometry; shortwave infrared spectroscopy; mineral liberation analysis), more powerful geophysics from airborne to hand-held and down-hole instruments, new types of survey techniques (e.g., hydrogeochemical, soil gas, indicator minerals), and new methods for visualizing the data. New types of targets also need to be developed that may involve unconventional combinations of geological, geochemical, and geophysical measurements.

### The multi-dimensional footprint matrix and data integration workflow

The layers or volumes of data that comprise an ore-system footprint can be viewed as a multi-dimensional matrix. Each attribute, for example a fault or a lithology, has its own mineralogical, geochemical, and geophysical signature at different scales. As the data used to describe these attributes are almost always numerical (or can be encoded numerically), multivariate statistical methods can be used to identify the best combinations of parameters for vectoring towards mineralization. Because the relationships between variables may be complex, the statistical methods must handle non-linear relationships, must be robust to local minima, and must facilitate separation of signal from noise. These techniques must also be tailored to exploration for different deposit types – one of the most challenging parts of the exploration process and the most difficult step in the creation of an integrated footprint model.

Genuine data integration requires a workspace in which the explorationist can visualize how different data accrue to an ore system model. To achieve this, we first developed a workflow in which researchers, students, and industry sponsors could follow how all components of the project come together (**Fig. 2**). The core of the workflow is the collection of new data from field surveys, in conjunction with examination and validation of existing public domain and company data, all of which are captured in a single workspace for integration. Because many data types are imperfectly sampled or sparse, levelling and interpolation in 3D are the first steps in integration. This is facilitated using a variety of statistical and non-statistical approaches to produce a GOCAD® Common Earth Model.

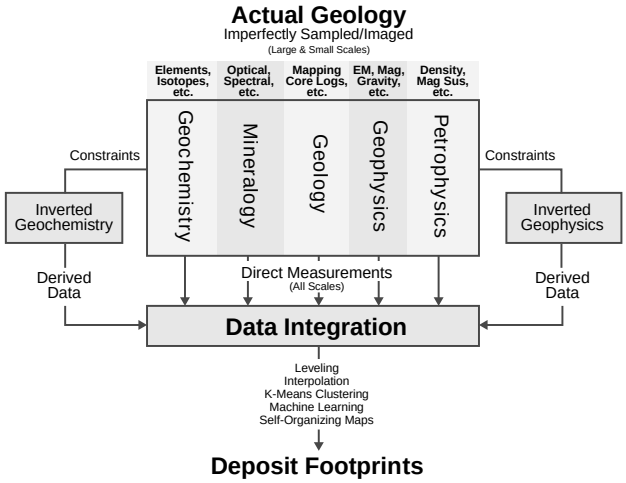



**Figure 2**: Exploration Footprints project workflow. Most direct measurements, regardless of scale, are part of the data integration, but some data are derived from inversions (e.g., large-scale physical properties derived from inversions of geophysical data; normative mineral abundances derived from inversions of geochemical data). These data are then levelled, interpolated to common scales, and then analyzed using a variety of geostatistical and supervised or unsupervised machine learning methods to derive multi-parameter deposit footprints.

### Data management and the Common Earth Model

A Common Earth Model is a platform for assembling unlimited, internally consistent data sets that may be shared at the project level by geologists, mineralogists, geochemists, and geophysicists for the purpose of integrated analysis. It should be editable as the collection of new data proceeds and allow continuous queries by the project participants of all data in the model. CEMs are also an ideal platform on which to translate the results of spatial data integration into coherent 3D images of an ore system footprint.

Manipulation of large (terabytes), multi-parameter data sets requires a robust relational database management system. A relational database management system allows interaction between different datasets through one or more relational variables. For geospatial analysis, for example, the relational variables can be the X-Y-Z sample coordinates, along with the sample number. Major mining companies are already moving to centralized databases for their geoscientific and geotechnical data that can be converted to CEMs. Two examples are the GET-IT® database system, implemented by Geosoft Corp. for Cameco Ltd. (Mining Magazine, 21 April 2015), and Geoscience INTEGRATOR® created by Mira Geoscience Ltd., all three of whom project industry sponsors.

The Exploration Footprints project uses Geoscience INTEGRATOR® to store and query all quantifiable data used in its CEMs. These include data as diverse as geological and structural information, mineralogical, textural and mineral chemical data, as well as images such as photos and hyperspectral images, all lithogeochemical and surficial geochemical data, petrophysical data, and geophysical data at all scales. The program also facilitates transfer of data to third-party software packages such as GOCAD® and ioGAS®, which were also provided to the project by its sponsors.

Linked to the relational database management system, are necessary protocols for rigorous and consistent data quality assurance and quality control (QA/QC). A consistent QA/QC workflow followed by all project members has been especially critical when combining legacy data from one or more company files with new data generated by the project. This situation is similar to any evolving exploration program where new data are being combined with old. Data levelling and greater confidence in subsequent analysis also requires that appropriate metadata regarding instrumentation, methodology, precision and accuracy, and data processing procedures are captured in the database management system. Consistent and complete metadata are needed to follow up the many false positives that can arise from analysis and statistical manipulation of data sets collected at different times or by many different methods. A major focus of the Exploration Footprints project is determining which data are valuable, when new data should be acquired, how they should be acquired, what density of data is needed, what level of accuracy/reliability is required, and how to maximize the efficient use of the basic tools of exploration data management in this process (e.g., GOCAD®, ArcGIS®).

### Inversion modeling

Among the most important steps in the identification of the ore-system footprint is the modelling of geophysical data (e.g., magnetic, gravity, electromagnetic, seismic, gamma spectrometric, etc.) to reveal physical properties of the subsurface that can be interpreted in terms of geology (e.g., structure, rock type, alteration) and then directly related to ore. While inversions of potential field data are used to "image" the physical properties in the subsurface (reverse modelling), geological interpretation of those images has been limited to qualitative assessments owing to a lack of knowledge of physical rock properties to constrain the model (density, susceptibility, conductivity, etc. of the target lithologies or structures; e.g., Williams and Dipple, 2007). Because a wide range of processes associated with productive ore-forming systems, such as hydrothermal alteration, directly affect the physical properties of the rocks, combining alteration studies with petrophysics can provide a basis for better constrained and more meaningful geophysical inversions. Joint inversions, for example of total magnetic field, ZTEM™ (Z-Axis Tipper Electromagnetic), and gravity gradiometry, could potentially delineate different rock masses according to covariations in magnetic susceptibility, resistivity, and density. However, in order to interpret these inversions in the context of an ore system, complete datasets on the mineralogy, geochemistry, and physical rock properties of the rock masses are required. Optimizing the fit between the geological data and the attendant geophysical inversion models can reveal a residual difference that represents the effect of an overprinting hydrothermal footprint. However, the details of the alteration systems must be known; for example in the case of strong alteration in Cu-Mo porphyry systems, which involves the oxidation of magnetite and causes a local magnetic anomaly low.

In addition to refining the physical rock property data sets, a major effort is also needed to reconcile field information, which is often collected on a very fine scale (detailed outcrop mapping or drill core sampling), with much coarser inversion models of geophysical data that may be resolved on 20m cells. One approach is to use much more readily available geochemical data as a proxy for more thinly populated rock property data, as demonstrated by Schesstlar et al. (2014). The whole-rock geochemical data are "inverted" by calculating normative mineralogy and correlating known physical properties of the minerals to measured geophysical signals.

### Geostatistical modeling, machine learning, and data visualization

Identifying novel multiparameter exploration footprints requires that the different data sets "communicate" with each other. This involves a variety of geospatial statistical methods and cross-validation techniques in both supervised and unsupervised modes. "Supervised" approaches to the data analysis are rules based, using known multiparameter ore system criteria and assumptions about their spatial relationships. "Unsupervised" approaches, such as clustering of data, result in new rules or criteria that may not be obvious from a preliminary ore-system model. This essentially data-driven process is the first step in machine learning.

The process might begin, for example, by defining alteration zonation in a preliminary exploratory data analysis and then refining that zonation by identifying parallel or related variability in other parameters. Two unsupervised approaches that are commonly used in this type of analysis are K-Means Clustering and Self-Organizing Maps. The zonation revealed by preliminary, unsupervised clustering can then be investigated by machine learning approaches to determine the root causes of the clustering. Established data analytics software packages, such as HyperCube or Random Forest™, perform this task by defining sets of rules that determine the clustering. The HyperCube algorithm, for example, performs an exhaustive search through the dozens of geological, geochemical, physical property, and geometric variables (discrete, continuous, derived, or combined) that have been assembled at co-located points and tagged as belonging to a specific footprint, based on previous learning steps. Within this space, HyperCube identifies orthogonal subspaces in which a specific footprint is predominant. It then defines "rules" that describe how different combinations of parameter values and ranges (e.g., Variable 1 = yes, B < Variable 2 < C, Variable 3 < D, Variable 4 > E) correspond to that footprint. In practice, to maintain reasonable computer run times and to produce rules that are interpretationally meaningful to geoscientists, the output is restricted to rules that combine only a small number of parameters, although any of the available parameters can be used to create a rule. If the identified footprints are real and robust, their essential nature should be revealed by any of several alternative supervised machine learning approaches and should not depend on whether HyperCube or Random Forest™ or any other platform is used to reveal it.

In order to better visualize the vast array of data, we have utilized a variety of methods, including Clustered Heat Maps (**Fig. 3**), which utilize a clustering procedure to classify samples and variables. The pixels are spatially organized using a double hierarchical sorting procedure (e.g., Ward's distance, which is an agglomerative clustering procedure based on a dissimilarity measure). The clustering method sorts columns and rows to facilitate the visual identification of similar samples/variables and relative cluster demarcation in the data matrix (e.g., see square outlines in **Fig. 3**).

## BUILDING THE RESEARCH NETWORK

Creating the next generation of multiparameter ore-system models was recognized at the start as a massive undertaking. Building the "footprint" of even one complete ore system would require a large multidisciplinary team. Researchers who are experienced in large scientific projects of this size and complexity are all accustomed to working in teams, but this is rarely done in resource exploration project. To achieve the goals of the Exploration Footprints project, it was necessary to break a long tradition of researchers working in isolation or in small groups with individual companies.

Another key factor was that the impetus for the research effort came from the mining companies themselves. They formulated the larger-scale research goals (identifying mineral system footprints from their most distal margins and vectoring toward their high-grade cores), presented the problem to the researchers, and asked them to start organizing into the teams needed to find the solutions. The voice of the industry was the Canadian Mining Innovation Council (www.cmic-ccim.org). CMIC was founded in 2007 with the goal of addressing the emerging innovation challenges in the mining industry (Galley et al., 2014). By the time CMIC was incorporated in March 2009, it had a membership of 70 exploration and mining companies, as well as consulting firms and service providers, federal and provincial government agencies, and industry associations. The first task of the Exploration Innovation Consortium within CMIC (CMIC-EIC) was to identify the critical questions for the project:

1) Can we increase the signal-to-noise ratio or identify new signals where traditional measurements have failed to detect the footprint of the ore system?

2) Can we relate the mineralogy and geochemistry of alteration assemblages to changes in physical rock properties (e.g., density, resistivity, magnetic susceptibility) and then detect these signals remotely with targeted geophysics?

3) Can we better interpret geophysical signals in terms of processes that are demonstrably linked to large-scale ore-forming systems?

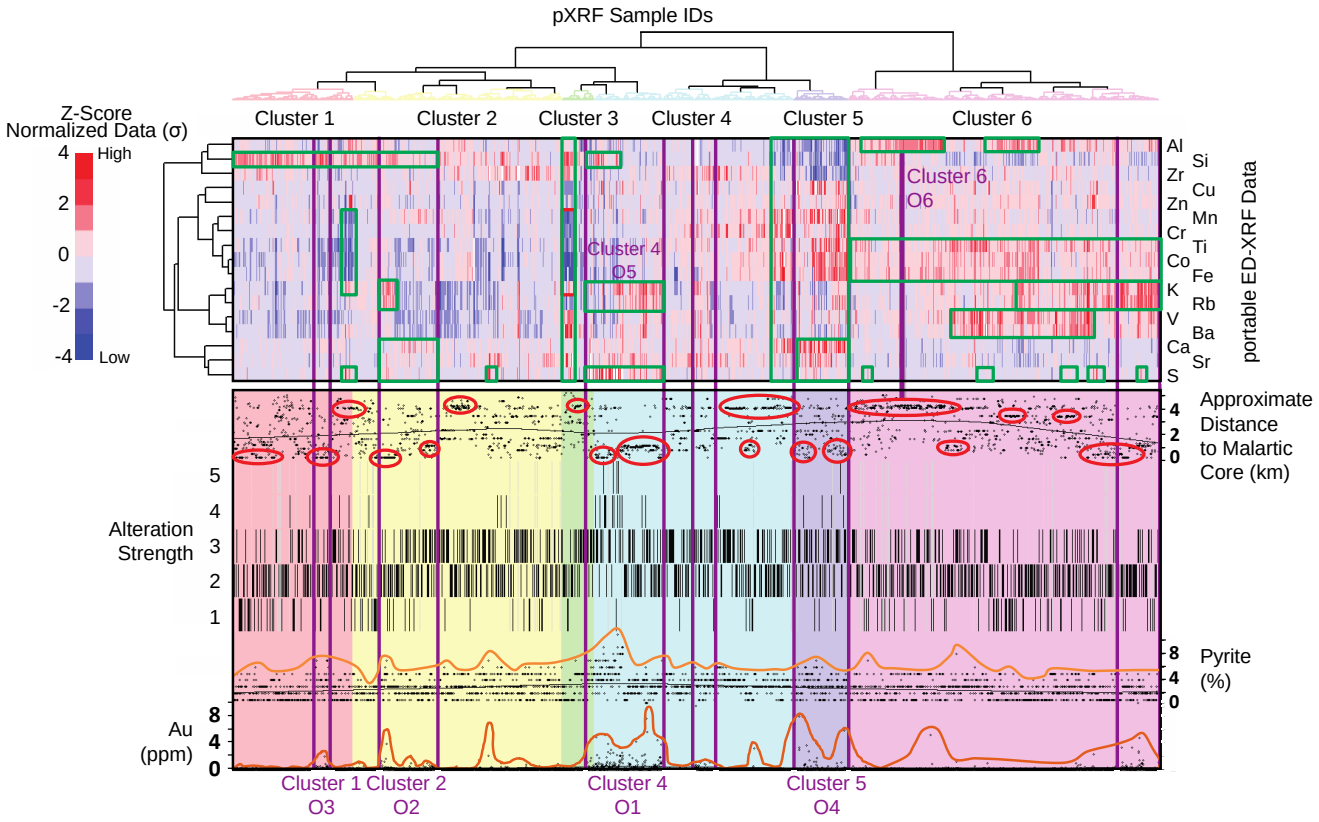



**Figure 3**: Clustered Heat Map visualization for 3787 samples of Pontiac Group metasediments from the Canadian Malartic Mine area (modified after Feltrin et al., 2016). The upper section shows CHM of normalized portable-XRF data with color-scale indicating relative element abundance (warmer colors for higher abundances), broken down into six broad clusters. The lower section shows 1) estimated Euclidean distance from the approximate centre of high-grade Au-mineralization, 2) logged alteration strength (1 lowest, 5 highest), 3) logged pyrite abundance, and 4) analyzed Au abundance (fire assay). *Purple squares* outline additional mineralized subclusters, representing internal heterogeneities in the broad clusters. O1-O6 highlight specific observations within those subclusters. *Red circles* outline subpopulations of samples occurring at the same/similar distance from the deposit hypothetical centre. *Green squares* outline key subclusters (squared rows capture high-abundance groups, squared columns capture particularly distinctive specimen groups). By comparing clusters/subclusters against Au abundance and other alteration indicators it is possible to interpret if a cluster is likely linked to mineralization/alteration. For example, in some cases high Si appears to have a positive relationship with mineralization/alteration (e.g., Cluster 4 – O1), but some samples with elevated Au may have low Si if other alteration phases are dominant (e.g., Cluster 4 – O1 has more K-altered samples, Cluster 2 – O2 has more abundant Ca-altered samples). High Fe is often associated with high S (confirmed by peaks in pyrite abundance), but sometimes also with high Ca-Sr-Mn, likely indicating the presence of Fe-bearing carbonates. High K-Rb correlate well with mineralization/alteration in most cases, except in zones dominated by high Si (Cluster 1 – O3) or carbonate alteration (Cluster 5 – O4). High K-Rb samples occur predominantly in proximal locations (e.g., Cluster 4 – O5), suggesting that K-altered rocks are more likely to represent near-core assemblages. A Clustered Heat Map also allows the detection of enrichments in the relative abundance of elements distal to and unrelated to mineralization (e.g., Cluster 6 – O6 for Al).

These challenges were articulated in a 10-year roadmap for the discovery of new exploration criteria, new exploration technologies, and new ways to transfer data to knowledge. In a series of industry-university workshops in March, April, May, and September 2011, followed by site-specific consultations through November 2011 to June 2012, a comprehensive research plan was developed. There was an unprecedented level of participation in these workshops, involving more than 20 companies and 60 researchers from universities across Canada. Eventually, 17 universities and 24 industry partners participated in the project proposal. Now, 20 universities and 30 companies are partners in the Footprints Research Network.

This powerful approach to research is deriving maximum benefit from the experience and expertise of people from across Canada. Researchers and their students, who are experts at collecting and analyzing different types of information on different parts of ore systems, are now working together at three different integrated study sites. A unique aspect of the network is that teams of researchers are working on all of the sites to ensure a uniform approach to defining the ore-system footprints: working groups coordinate and drive the geological, structural, mineralogical, mineral chemical, lithogeochemical, petrophysical, geophysical, and surficial layers at all three study sites (**Fig. 4**). This workflow ensures that critical data are being collected and

treated in the same way for the entire project and that knowledge gained at one site is transferred more quickly to other sites. Another important aspect is that each Technical Working Group generates data from the same sample sets in order that the multidisciplinary results can be more easily compared and integrated. A dedicated Data Integration Team is exploring the best methods for data integration and guiding the analysis, and is working closely with the Site Leaders, Researchers, and Technical Working Groups.

The success of the project has been largely due to the cooperation of the sponsor companies. Researchers are working closely with the host companies, in some cases working for long periods on site. On-site research is coordinated by Site Leaders, assisted by independent Technology Working Groups with expertise in lithogeochemistry, mineralogy, petrophysics, geophysics, inversion modeling, surficial materials, and data integration. Industry is participating directly in the research effort, assigning subject matter experts (SMEs) to guide geological, geochemical, and geophysical investigations by the university teams.

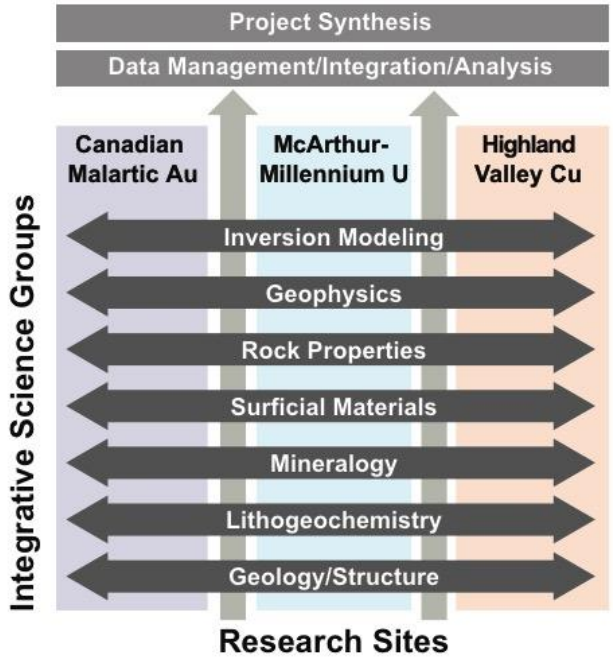



**Figure 4**: Summary of activities in the Exploration Footprints Network, emphasizing similar research and data collection across all three sites with many of the same researchers working at the different locations.

More than 70 researchers have participated in the project thus far, including 13 research associates and post-doctoral fellows, 9 PhD students, 14 MSc students, 3 BSc Honours students, and 33 undergraduate field and laboratory assistants. Some students are focusing their research on one site, but others are conducting research on two or three sites, and all belong to a team with members who are working at all of the sites. Industry geologists are working with the students and researchers at each site and are directly involved in (and in some cases responsible for) on-site research and training. Commercial partners, including analytical companies, geophysical contractors, and consultants are also contributing services and expertise in all parts of program. In particular, the service provider partners are training new people to carry out the data integration and developing procedures for organizing data in an ongoing research and exploration workflow. The companies involved see this as a unique opportunity with unprecedented alignment with their own research and development objectives, and this has been crucial in the establishment of the Network.

The governance structure is much like that of other large Research Networks, with a Board of Directors that includes representatives of the corporate sponsors and government, a Scientific Advisory Board consisting of technical experts from outside the project, and a Secretariat chaired by a Director and Co-Director. A Research Technical Committee, composed of the Site and Working Group Leaders, oversees the performance of specific research tasks and the technology transfer.

## INTEGRATED STUDY SITES

Early in the consultation process, the industry partners and researchers realized that the greatest advances would be made at multiple study sites that encompass a range of ore-forming processes (magmatic vs. hydrothermal vs. basinal), geological environments (deep crustal vs. shallow), and geochemical, mineralogical, and geophysical attributes. The three sites chosen were:

1) Canadian Malartic low-grade Archean stockwork-disseminated Au system in Malartic, Québec
2) McArthur-Millennium unconformity-associated U corridor in the Athabasca Basin, Saskatchewan
3) Highland Valley porphyry Cu-Mo system near Logan Lake, British Columbia

These are among the most important ore deposits in Canada (**Fig. 5**).

The selection criteria were straightforward: 1) the sites had to be accessible to a large number of researchers, 2) they had to be endowed with extensive exploration data, and 3) they had to have a sponsor prepared to provide access to those data and host the researchers. All involved recognized that the workflow and methodology ultimately would have to be exportable to other geological settings and other ore deposit types.

Examination of legacy data provided by the site sponsor(s), as well as regional survey information collected by federal and provincial geological surveys, revealed a number of critical gaps that required collection of new data by project researchers, and in some cases by project sponsors as part of their in-kind contributions. This was a major component of the on-site research. The information that was collected and collated from each site included lithological, structural, mineralogical, whole-rock and mineral geochemical/isotopic, petrophysical, and geophysical data. The data collection has focused almost exclusively on bedrock. Of secondary focus – *in this phase of the project* – was collection of data from the overlying surficial

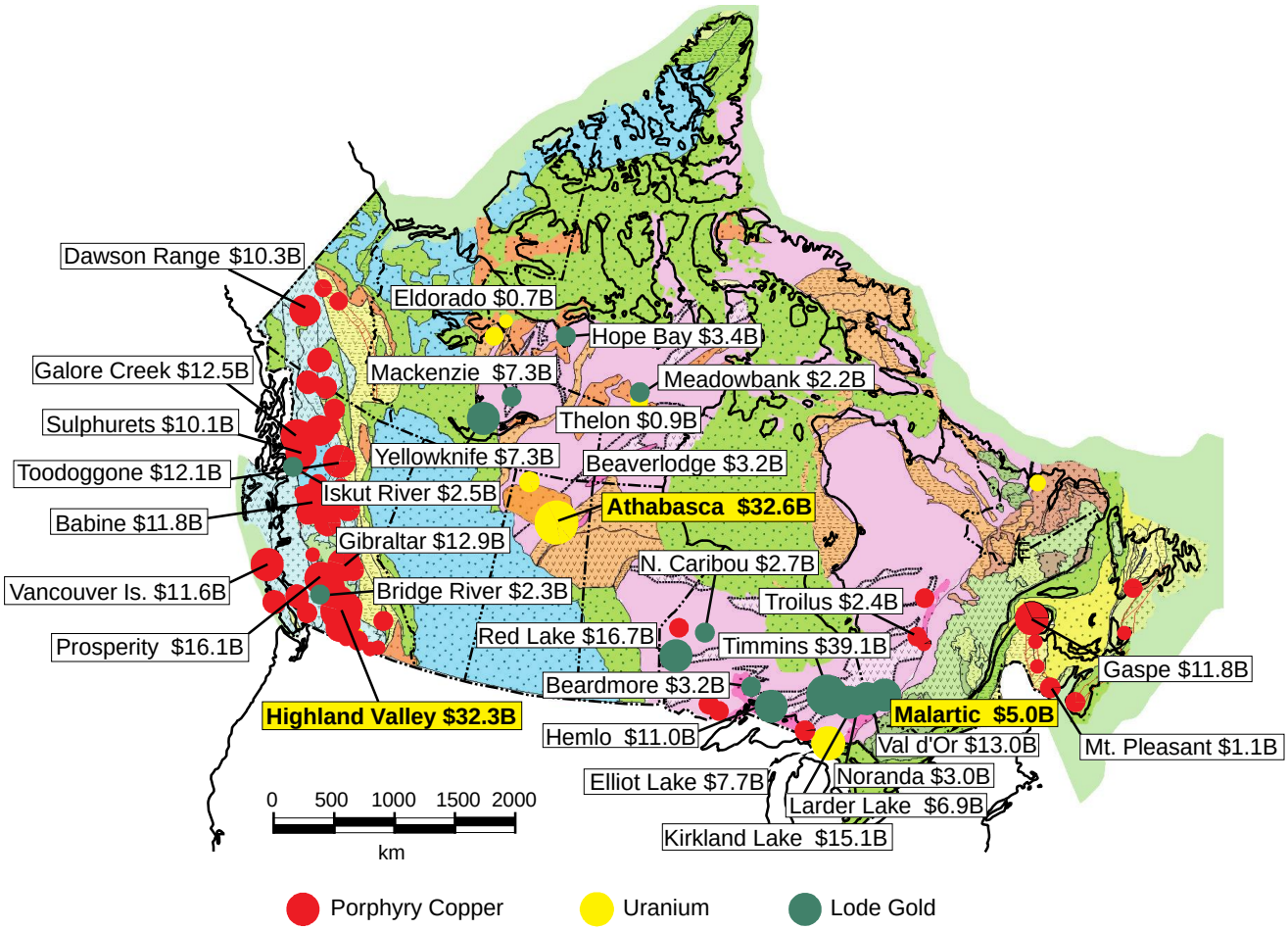



**Figure 5**: Major porphyry Cu, U, and Au deposits in Canada (from Lydon, 2007). The three integrated study sites of the Exploration Footprints project are highlighted in yellow.

environment, consisting primarily of glacial sediments (e.g., till and glaciolacustrine sediments, and overlying soils). Where new data were collected from bedrock, drill core, and surficial materials, the samples were of sufficient size to allow for multi-parameter analysis.

Other research initiatives are running concurrently at several of the sites. For example, the Targeted Geoscience Initiatives (TGI-4 and -5) of the Geological Survey of Canada and its provincial partners in Québec, Saskatchewan, and British Columbia are providing the essential geological framework at these locations, and are in some cases carrying out specific surveys that are beyond the capacity of the university teams (e.g., larger-scale geophysical or surficial geochemical sampling programs).

### Canadian Malartic Disseminated Au System

The Canadian Malartic deposit, located in the Archean southern Abitibi subprovince (**Fig. 6**), is a bulk-tonnage, low-grade Au deposit that encompasses several smaller high-grade vein systems. It has most recently been classified as an oxidized intrusion-related deposit (Helt et al., 2014) and a stockwork-disseminated system (De Souza et al., 2015). Production at Canadian Malartic began in 1935 as underground bulk tonnage mining of a relatively high-grade (>3 g/t) mineralized structure over a strike length of 3.5 km, south of the Cadillac – Larder Lake Deformation Zone. Historical operation included 4 past-producing gold mines (8.7 Moz Au up to 2013: Gervais et al., 2014), two of which are now within the Canadian Malartic open pit. Several major occurrences also occur outside the ore shell.

The present Canadian Malartic mine is exploiting two main mineralized corridors of 1-5% disseminated pyrite with fine native Au: the E-W Sladen fault and the NW-SE high-strain zones (Derry, 1939; Sanfaçon and Hubert, 1990; De Souza et al., 2015; Perrouty et al., 2017). Approximately 2 Moz Au have been produced since 2013. Measured and indicated resources as of June 2013 totalled 314.2 Mt @ 1.07 g/t Au, for a total of 10.8 Moz Au (Gervais et al., 2014). Au is hosted mainly by altered clastic metasedimentary rocks of the Pontiac Group, by quartz-monzodioritic porphyry intrusions, and by mafic-ultramafic rocks of the Piché Group. The low-grade, disseminated Au mineralization is associated with widespread carbonate and

potassic alteration throughout the system (Helt et al., 2014, De Souza et al., 2015). A major question in an ore system of this size is how to distinguish the critical structures that control the mineralization at the camp scale and deposit scale from the many complex structures in the area. What are the signatures of the specific fluid/rock interactions that are crucial to ore formation and transformation; what is the cumulative footprint of highly complex multi-stage orogenic Au systems like Malartic; how do they differ from smaller high-grade vein systems?

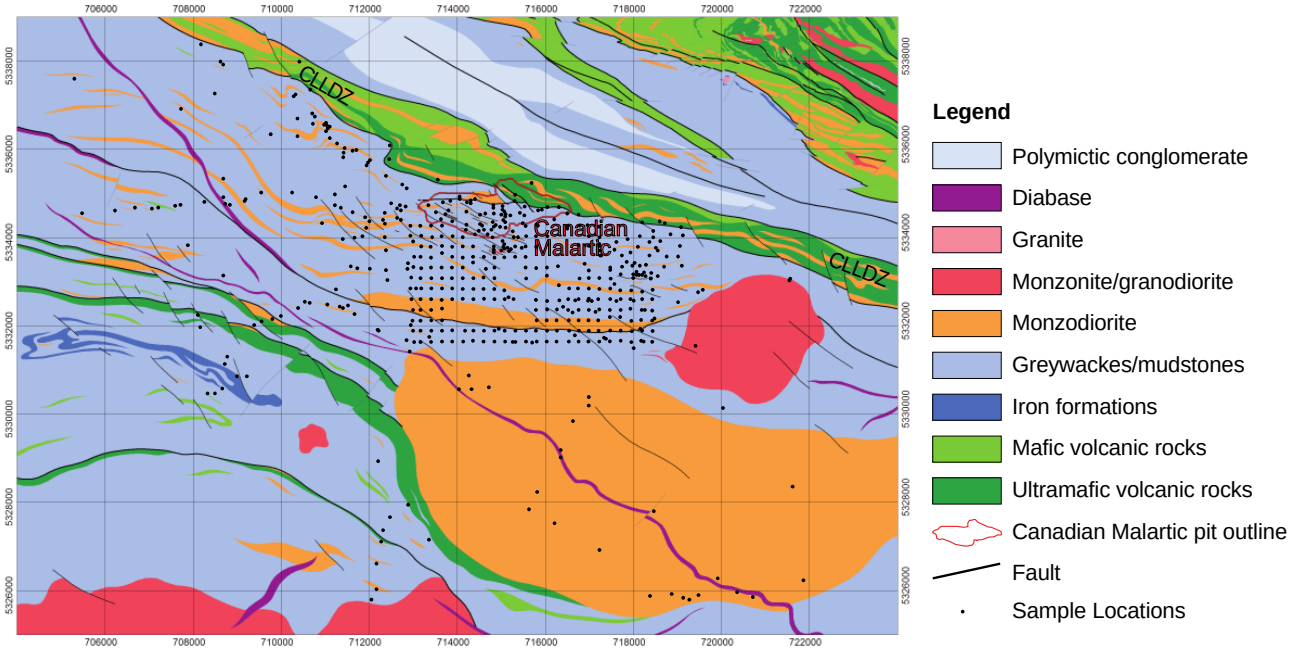



**Figure 6**: Geological map (modified after Perrouty et al., 2017) of the Canadian Malartic area showing the location of the 2013 pit (red line) on the southern margin of the Cadillac-Larder Lake Deformation Zone (CLLDZ). Grid coordinates are WGS84 UTM Zone 13.

### McArthur-Millennium Trend

The McArthur River deposit was discovered in 1988 at a depth of 530 m, at the intersection of the sub-Athabasca unconformity with moderately-dipping reverse faults in graphite-rich pelitic rocks in the immediately underlying basement. It is the richest U deposit in the world (Zaluski et al., 2007). Bronkhorst et al. (2012) report past production of 225 Mlb at an average diluted grade of 13.5% $U_3O_8$, proven and probable reserves of 1062.2 Mt at 16.46% $U_3O_8$ for a total of 385.5 Mlbs $U_3O_8$, measured and indicated resources of 84.1 Kt at 6.35% $U_3O_8$ for a total of 11.8 Mlbs $U_3O_8$, and inferred resources of 325 Kt at 7.86% $U_3O_8$ for a total of 56.3 Mlb $U_3O_8$.

The Millennium deposit, which was discovered in 2000 at a depth of 650m, is located in semipelitic basement rocks ~100 m below the unconformity, footwall to a graphitic pelitic gneiss but in the hanging wall of a strongly altered basement fault zone. The measured and indicated resource at Millennium as of Dec 2016 is 75.9 Mt at 2.39% $U_3O_8$, with an additional inferred resource of 29.0 Mt at 3.19% $U_3O_8$ (*https://www.cameco.com/businesses/uranium-projects/millennium/reserves-resources*).

The Exploration Footprints project is focusing on the structural corridor between the Millennium and McArthur deposits, an area encompassing 40 x 10 km (**Fig. 7**). Previous studies across the trend by Cameco and the EXTECH IV Athabasca Uranium study (Jefferson et al., 2007) have explored electromagnetic conductors in the area (Powell et al., 2007). Geophysical survey data (EM, VLF, gravity, magnetics, resistivity) are most dense along sections where faults are inferred, but it is still difficult to identify the specific structures that are associated with mineralization. The Millennium deposit, in particular, is well covered by closely spaced high-quality geological, geochemical, and geophysical data that are being examined in the Exploration Footprints project. Recent discoveries have been made at depths of up to a kilometer, but due to the very high grades the orebodies themselves are volumetrically very small. Aquifer- or structurally-controlled fluid flow at the basal unconformity of the basin and along major fault systems played a key role in the formation of the deposits. As a result, the emphasis has been on the ability to remotely map prospective structures and to detect the larger subsurface alteration developed during fluid flow within the host basement and sedimentary rocks. The challenge for deep exploration is to distinguish between pre-, syn- and post-mineralization hydrothermal effects, and to isolate the appropriate mineralogical and geochemical (including isotopic) signals that directly vector towards and within the alteration zones.

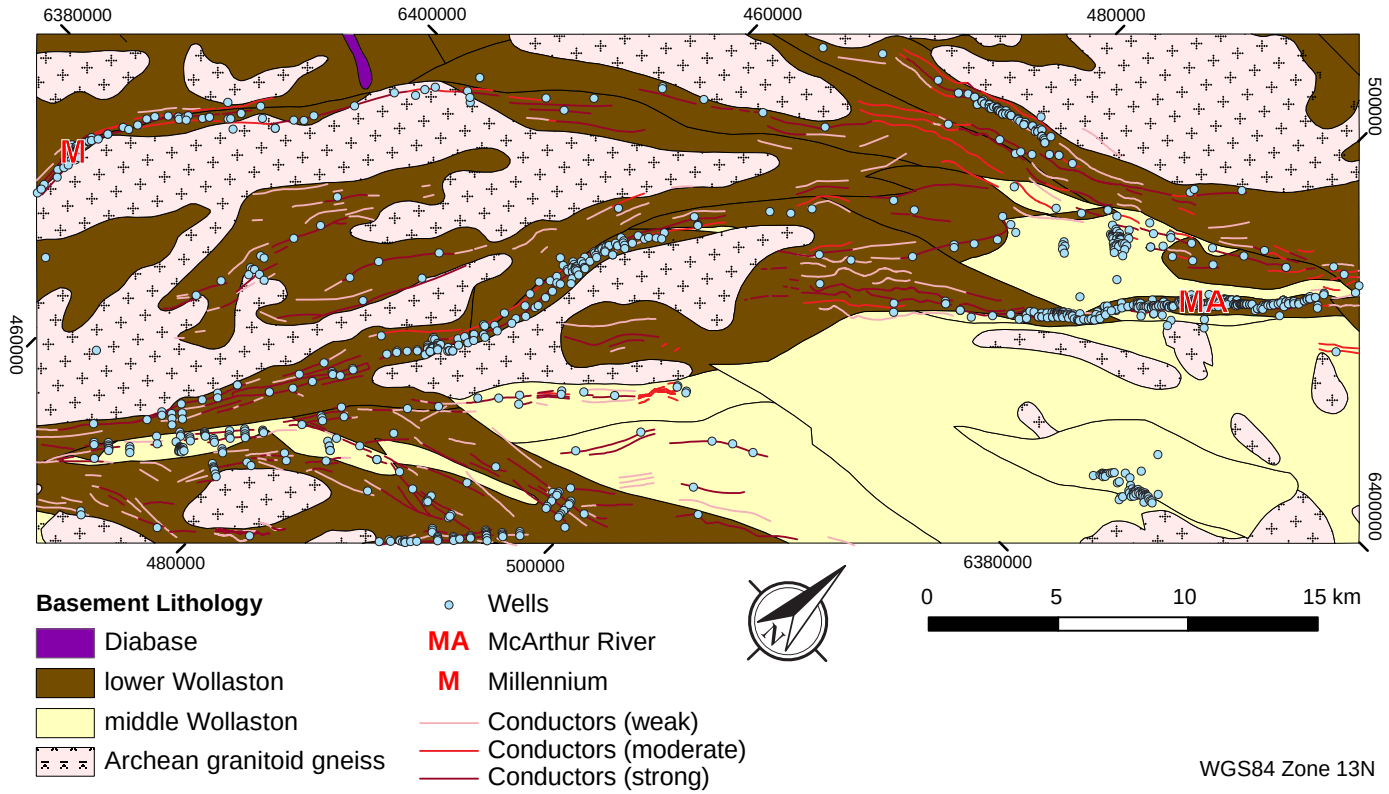



**Figure 7**: Simplified geological map of the SE part of the Athabasca basin showing basement geology (after G. Zaluski, Cameco), electromagnetic conductors, and the locations of wells, the McArthur River mine, and the Millennium deposit.

### Highland Valley Porphyry Cu System

The world-class Highland Valley Copper (HVC) system in south-central British Columbia (**Fig. 8**) is the largest known porphyry system in Canada. The Teck Highland Valley Copper Partnership ('Highland Valley Copper') is wholly owned and operated by Teck Resources Limited. It currently comprises five known porphyry centres (Valley, Lornex, Bethlehem, Highmont, and JA) within a 15 km$^2$ area at the core of the Upper Triassic Guichon Creek batholith (McMillan, 1976; Casselman et al., 1995; Byrne et al., 2013). Production between 1962 and 2013 was 1615 Mt grading 0.40% Cu and 0.010% Mo (Byrne et al., 2013). Proven and probable reserves as of December 2016 are 546.6 Mt at 0.29% Cu and 0.008% Mo, and measured and indicated resources are 1471.1 Mt at 0.26% Cu and 0.009% Mo (*http://www.teck.com/media/2017-AIF.pdf*). Because of the long history of mining, there is abundant legacy data, and HVC is now the focus of increased exploration.

Unlike the other deposits being studied in the Exploration Footprints project, large porphyry Cu systems involve 100s of cubic kilometers of the upper crust and have equally large footprints. Where they crop out, the main parts of the systems are relatively easy to recognize, but in covered areas the discovery of new deposits is particularly difficult. In western Canada, exploration is further complicated by the fact that most of the porphyry systems have been structurally offset at various scales. This presents a challenge but also an opportunity to examine different views of the alteration footprint, both laterally and vertically. The broad-scale alteration is typically a product of at least two fluids: a magmatic fluid exsolved from the ore-related intrusion and groundwater that enters the system by thermal convection above cupolas on the deeper magma body. Magmatic-hydrothermal alteration is easiest to recognize in the central part of the system, but the peripheral alteration is often cryptic and only detectable where subtle gradients can be mapped with large amounts of outcrop. A major challenge is the superposition (in time and space) of a range of alteration mineral assemblages from the different fluids involved.

## SOME PRELIMINARY RESULTS

Data compilation has been completed at all three sites, data generation has been completed at the Au site and is close to completion at the U site and Cu sites. Preliminary results presented here focus on the CEMs, some of the findings related to the large-scale ore-system footprints at all three sites. Results of the data integration will be reported elsewhere.

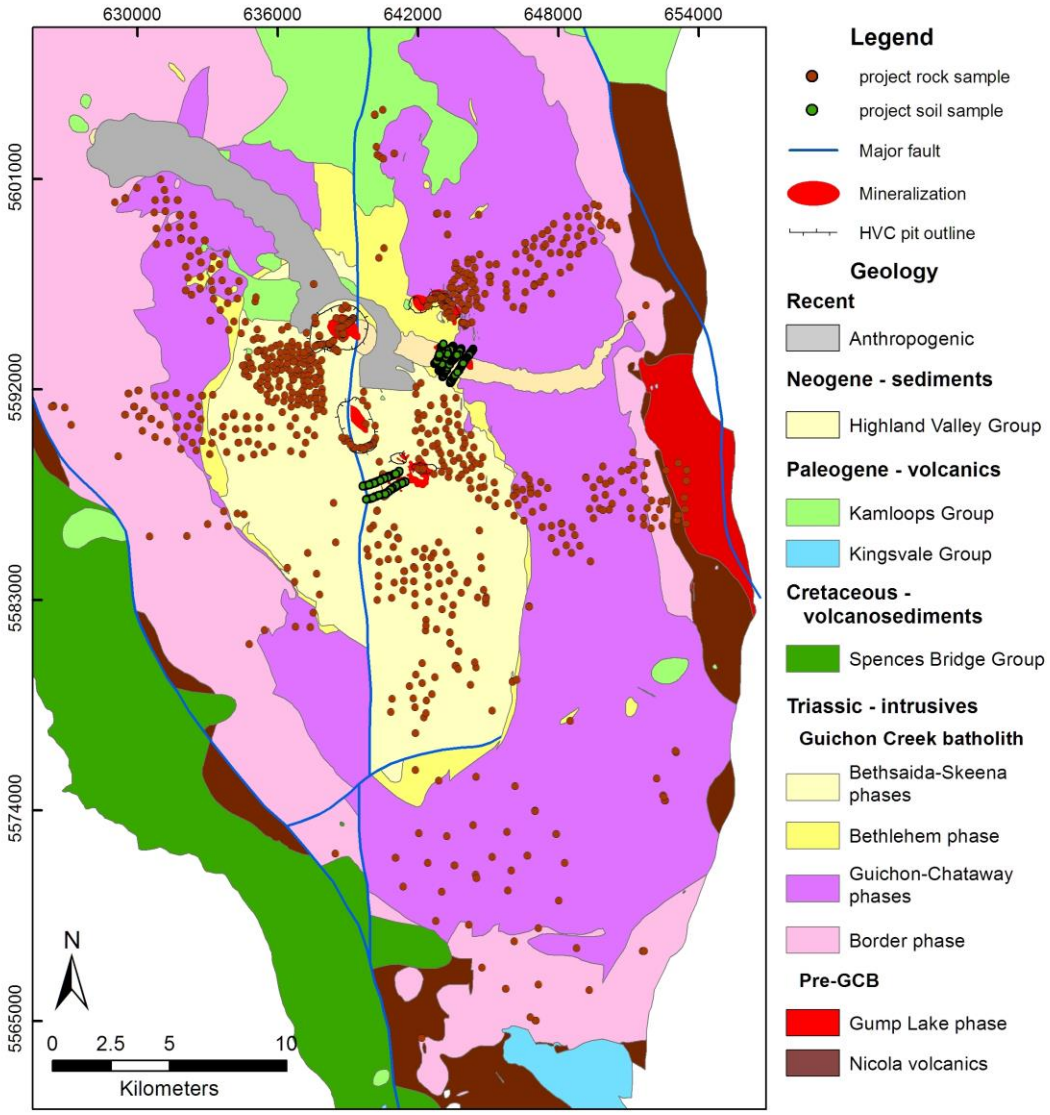



**Figure 8**: Geological map of the Highland Valley area showing the location of the Bethlehem (B), Highmont (H), Lornex (L), and Valley (V) open pits and the JA target (compiled from data provided by Teck Resources Ltd. and generated in this project) and the locations of samples being studied in the Exploration Footprints project to February 2017.

**Gold Site**

The database for Canadian Malartic presently contains 5 local (40 cm resolution) and 1 regional (90 m resolution) digital elevation models; an overburden thickness model; a regional till map; a regional geological model; 14 local outcrop geology maps; 2322 structural measurements; 2888 regional mineral occurrences; 2 airborne magnetic and electromagnetic surveys; 19 induced polarization surveys; 3 satellite and ground gravity surveys; 863 petrophysical measurements; 1011 gamma-ray spectrometric measurements, 4382 portable XRF analyses; 1103 whole-rock lithogeochemical analyses, 272 H-O-C-S stable isotope analyses; 347 XRD mineralogy determinations; 7539 wavelength-dispersive X-ray emission spectrometric (EPMA) mineral analyses; and hyperspectral data for 1639 samples and over 1000m of drill core, as well as a variety of derivative products including stitched 1D inversions of airborne EM data for resistivity and susceptibility at different frequencies, forward magnetic models, inversions for IP resistivity and chargeability, and gridded geochemistry, mineralogy, petrophysics, and a wide range of supporting data including over 2000 photographs, photomicrographs, backscattered electron SEM maps, hyperspectral mineral chemistry maps, WDS-EPMA and LA-ICP-MS elemental maps, and mineral liberation analytical maps. We also have access to 161 historic mine sections, 6045 diamond drill core logs, and 14 downhole petrophysical logs. The image from the Common Earth Model in **Figure 9** shows

the geology and the locations of IP surveys, faults, and some of the samples analyzed for geochemistry, mineralogy, and petrophysical properties.

A schematic footprint map in **Figure 10** shows how some of the geochemical, mineralogical, and petrophysical parameters vary abruptly with distance, representing footprint components, and some increase or decrease toward the deposit, representing vectors to mineralization. A more detailed summary of footprint components and vectors in **Figure 11** shows which are present in which lithology and how they were measured.

The abundances of alteration minerals increase toward the core of the Canadian Malartic system. Such changes are exemplified in metabasic dikes, which evolve from distal (> 1 km) amphibole-rich compositions to proximal (<100 m) biotite–carbonate–quartz–pyrite–rutile-rich compositions (Perrouty et al., 2015). Whole-rock lithogeochemistry provide similar trends (Gaillard et al., 2015): low mass gains in large-ion lithophile elements within distal the potassic alteration zone, intermediate mass gains in C and S within the medial carbonate and pyrite alteration zone, and large mass gains in Au and Au-related elements within the proximal alteration zone. Whole-rock H isotope composition shows a wide alteration footprint up to 2 km outside the pit, characterized by lower $\delta^2H$ and $\delta^{13}C$ values. Mineral chemistry is highly dependent on protolith and metamorphic conditions, but a distinct "hydrothermal" signature, with phengitic white micas and Mg-rich biotite, can be identified proximal to the Canadian Malartic deposit (Gaillard et al., 2015), and can be mapped on drill core and outcrop using hyperspectral methods (Lypaczewski et al., 2017). Proximal alteration is also spatially associated with quartz-monzodiorite intrusions and with complex structural settings such as joined $F_1$ and $F_2$ fold hinges (Perrouty et al., 2017). At the outcrop scale, mineralized corridors present a subtle decrease of magnetic susceptibility ($10^{-4}$ - $10^{-5}$ SI) and spectral IP variations, which are related to rock texture, sulfide mineral proportions, and grain-size distribution (Bérubé et al., 2017).

Many parameters are obviously related: e.g., elements with similar behaviours, elements occuring in specific alteration phases, and effects of changing mineralogy on physical properties. These redundancies provide opportunities to develop proxies utilizing parameters that can be measured less expensively but still provide robust guides to mineralization. Integrating parameters (not discussed in this contribution) using geostatistical and machine learning methods has increased the sharpness, resolution, and robustness of the footprint components and vectors, especially at the distal margins, which is the ultimate aim of the project.

Elements with similar geochemical behaviours or physical properties that vary with alteration mineralogy underlie many of the same footprints and vectors. This is important for identifying multiple proxies (including less expensive alternatives) for the detection of different footprints. Ongoing data integration and statistical analysis shows that combinations of these variables provide greater sensitivity and extend the footprint and that more than one combination can be associated with mineralization. It is clear from these data that multiple processes may be involved in generating a single footprint.

**Uranium Site**

The database for the McArthur-Millennium corridor presently contains 50m-spaced digital elevation map; overburden thickness map; basin and basement geology with fault traces; regional radiometrics; seismic; 1 km-spaced ground gravity and gravity forward model; 100m (Millennium) and 300m (McArthur River) spaced airborne gravity gradiometry and inversions; 300m-spaced aeromagnetic survey and magnetic inversion; AMT survey; electromagnetic conductor traces; airborne electromagnetic surveys, 3D resistivity inversion, and 1D resistivity inversion of all survey lines; diamond drill core lithologies, geochemistry, SWIR, and structural data (12 with new lithogeochemistry, mineralogy, and petrophysics); 5 ground-penetrating radar lines; 74 till samples (geochemistry and pebble counts); surficial geochemistry (~2140 soil horizons, ~580 tree cores, ~270 boulders), and ~250 petrophysical measurements (saturated bulk density, porosity, magnetic susceptibility, resistivity, chargeability). The image from the Common Earth Model in **Figure 12** shows basin and basement geology, a TEMPEST® inversion at Millennium (greens-yellow-red volume in lower left), a VTEM® survey over and north of McArthur River (multicolour lines in upper right), and the locations of some of the many drill core samples analyzed for geochemistry, SWIR mineralogy, and petrophysical properties.

~20 individual footprint components and vectors have been identified in the compiled data at McArthur River and ~30 at Millennium (**Figs. 13-14**). Some are similar at both sites, but some are different, highlighting multiple factors/processes involved in the mineralizing systems in the Athabasca Basin. For example, geochemical investigations utilizing legacy and new lithogeochemical data from the sandstones in the Athabasca Basin has confirmed previously identified "footprint' pathfinders, but the use of Mg/K, Mg/Al and K/Al molar ratios appears to have broadened the signature of the footprint in the sandstones surrounding the Millennium uranium deposit (Guffey et al., 2015). Extension of the footprint to surface is complicated by the presence of distal and proximal tills overlying the sandstone, and the identification of the former, which contains locally derived altered sandstone clasts and elevated As-B-Cr-Cu in finer till fractions, has been achieved using airborne radiometrics (Scott et al., 2017). New sampling has confirmed radiogenic Pb isotopic and uranium anomalies in the various media (soils, tree cores and boulders) directly above the McArthur River Mine (Beyer et al., 2017), and investigations of fractures in the sandstones (Valentino et al., 2017) may be providing evidence of pathways for isotopic and elemental enrichment in the various media of the overburden.

Identifying geophysical footprints in the sandstones of the Athabasca Basin has proven to be challenging due to: 1) subtle but varying physical property changes related to alteration surrounding the unconformity U deposits; and 2) masking of the subtle geophysical responses in the sandstone due to complex overlying overburden and underlying basement geology. Q values (anelastic attenuation factors) derived from seismic surveys at the Millennium deposit are perhaps providing the most promising footprint signature. Nonetheless, establishing best practice methodologies for future inversion and geophysical surveys will provide useful practical approaches for future exploration in the geological complex Athabasca Basin.

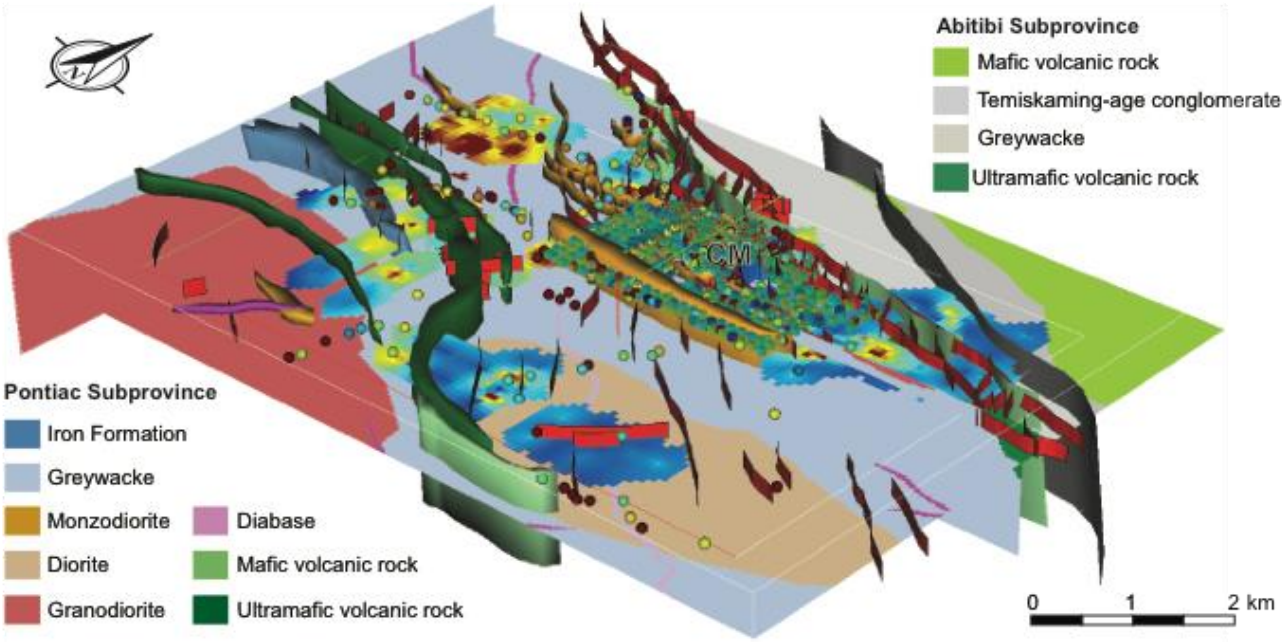
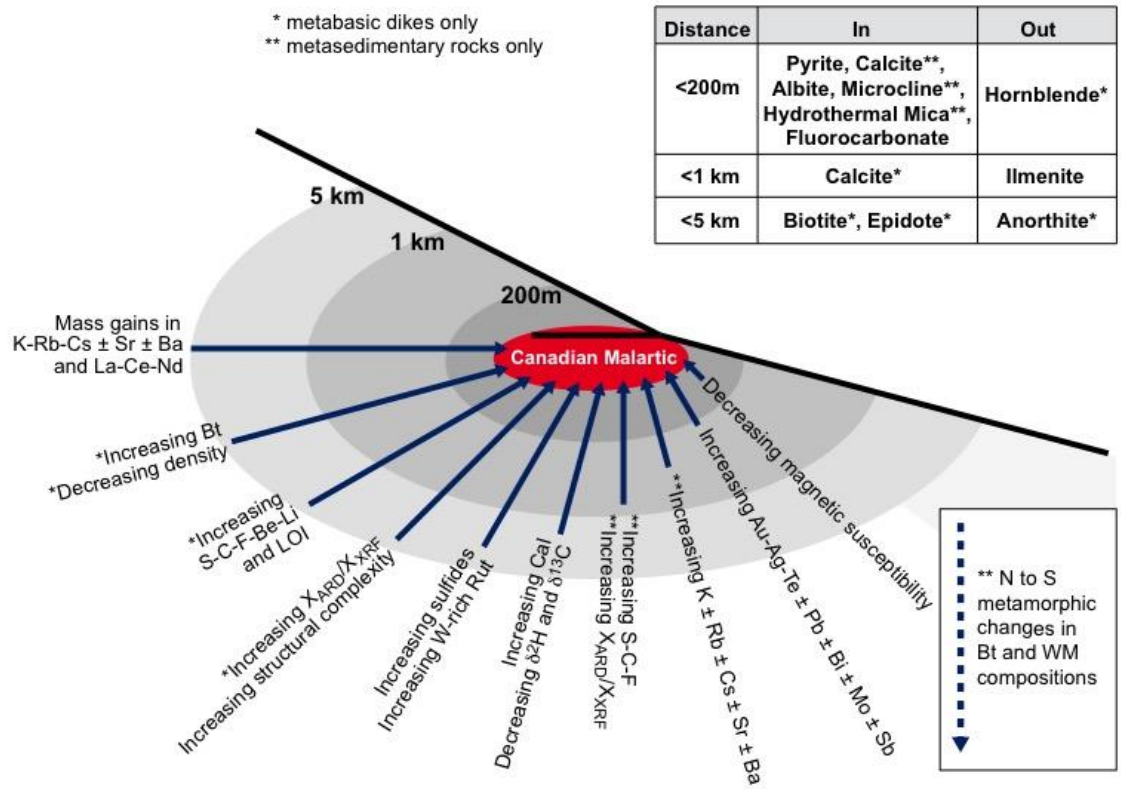



**Figure 9**: Parts of the Common Earth Model for the Canadian Malartic area showing geology, locations of faults (irregular subvertical red-rust-black planes), geochemical-mineralogical-petrophysical samples (small coloured spheres), pXRF lithogeochemistry-hyperspectral mineralogy samples (small coloured cubes in mine area), and IP surveys (blue-yellow-brown coloured horizontal grids).




| Distance | In | Out |
|---|---|---|
| <200m | Pyrite, Calcite**, Albite, Microcline**, Hydrothermal Mica**, Fluorocarbonate | Hornblende* |
| <1 km | Calcite* | Ilmenite |
| <5 km | Biotite*, Epidote* | Anorthite* |

**Figure 10**: Schematic map of Canadian Malartic area summarizing some of the footprint components (upper right) and vectors in the Pontiac Group. Bt: biotite, Cal: calcite, LOI: loss on ignition, Rut: rutile, WM: white mica, $X_{ARD}$: abundance in aqua regia-digested sample, $X_{SPF}$: abundance in sodium peroxide fused sample, where X is Fe-Mn-Mg-Al-Ti-K housed mainly in biotite (dissolved by aqua regia).

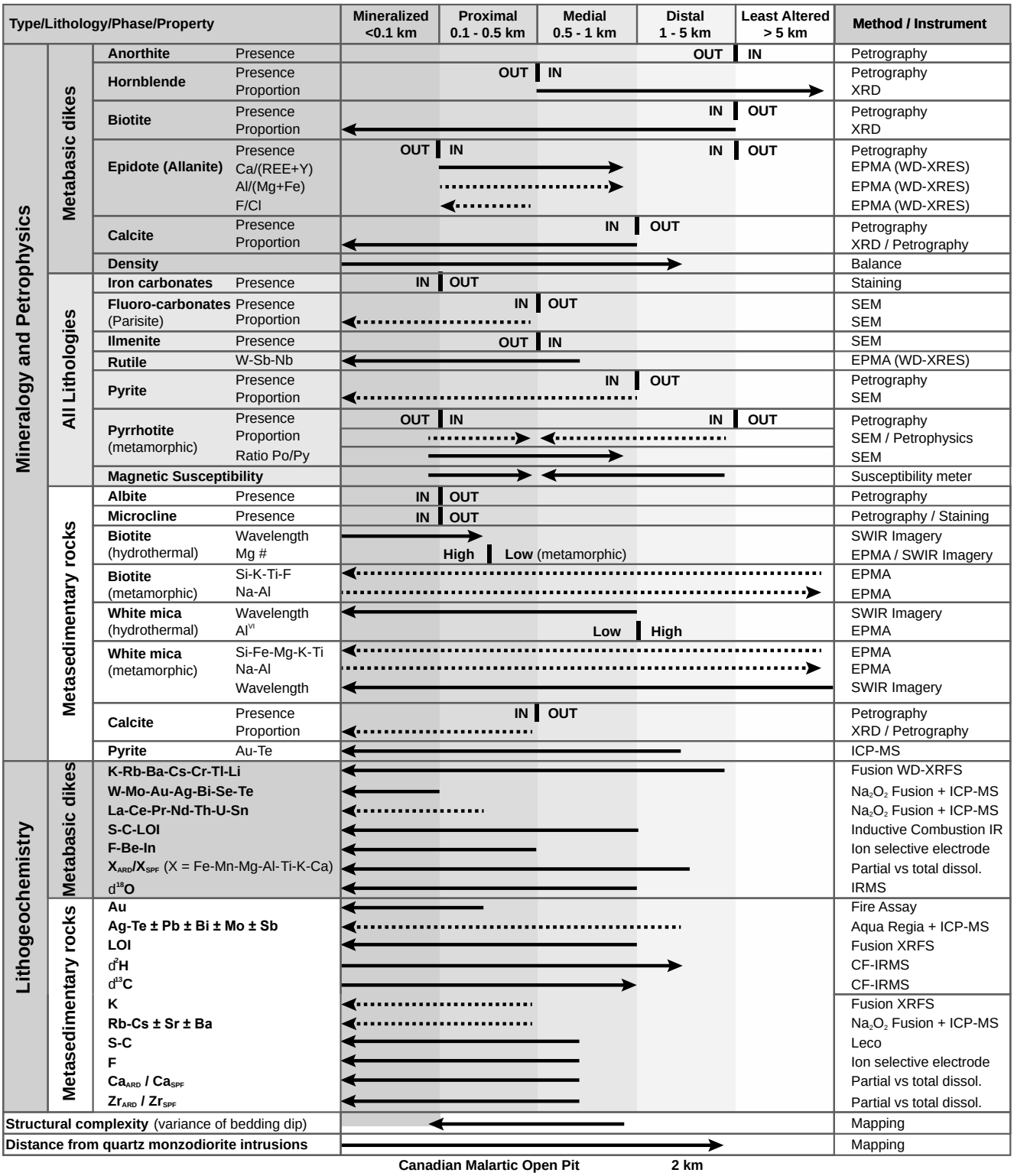



**Figure 11**. Preliminary footprint components and vectors for the Canadian Malartic deposit. ARD: aqua-regia digest, CF: continuous-flow, EPMA: electron probe microanalysis, ICP-MS: inductively-coupled MS, IRMS: isotope ratio mass spectrometry, SEM: scanning electron microscopy, SPF: sodium peroxide fusion, WD: wavelength-dispersive, XRES: X-ray emission spectrometry, XRFS: X-ray fluorescence spectrometry. Arrows indicate increasing in that direction.

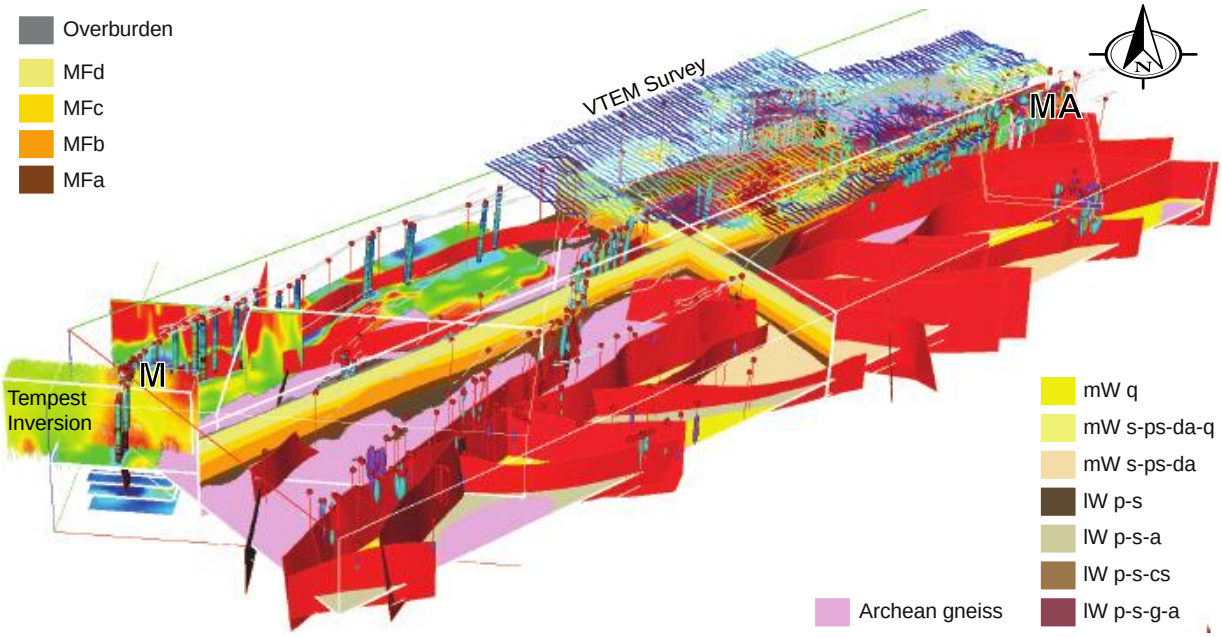



**Figure 12.** Parts of the Common Earth Model for the McArthur River – Millennium area showing basement and basin geology, faults (subvertical red planes), locations of diamond drill cores (lithology, whole-rock geochemistry, hyperspectral mineralogy, and petrophysics), a VTEM® survey over the NE part, and a Tempest® inversion around Millennium. M: Millennium, MA: McArthur River; MFa, MFb, MFc, MFd: members of the Manitou Falls Formation, uW, mW, lW: upper, middle, and lower parts of the Wollaston Group, a: arkose, da: dirty arkose, cs: calc-silicate, g: graphitic sections, p: pelite, ps: psammite, q: quartzite, s: semipelite.

| Method | Indicator/Vector | Notes | Stratigraphic Unit | Distribution | Extent |
|---|---|---|---|---|---|
| **McArthur River** | | | | | |
| Lithogeochem | molar Mg/K | indicative of clay mineralogy | MFa, MFd | above economic mineralization | 1-5 km |
| Lithogeochem | chlorite, kaolinite | | MFa, MFd | above economic mineralization | 1-5 km |
| Lithogeochem | Ba-Sr-P | | MFa, MFb, MFc | above economic mineralization | 1-5 km |
| Lithogeochem | Ga-Cs | | MFa, MFd | above economic mineralization | 1-5 km |
| Lithogeochem | Bi-Co-Cu-Ni-Mo-Pb | traditional pathfinders | MFa | restricted to lower sandstone above all mineralization | <1 km |
| Lithogeochem | $^{207}Pb/^{206}Pb$ | | MFa | restricted to lower sandstone above all mineralization | <1 km |
| Lithogeochem | $^{206}Pb/^{204}Pb$ | | MFd | fractures | <1 km |
| Surfical geochem | $^{207}Pb/^{206}Pb$ | | trees, boulders in A-horizon soils | most radiogenic Pb above ore | <0.1 km |
| Surfical geochem | U | | trees, boulders in A-horizon soils | highest U conc. above ore | <0.1 km |
| Surficial geochem | B, dravite (norm) | dispersal pattern in locally-derived till | altered sandstone clasts in till (various size fractions) | | up to 5 km |

**Figure 13a.** Preliminary footprint components and vectors for McArthur River.

| Method | Indicator/Vector | Notes | Stratigraphic Unit | Distribution | Extent |
|---|---|---|---|---|---|
| Lithogeochem | molar Mg/K | indicative of clay mineralogy | MFa, MFc, MFd | | up to 10 km |
| Lithogeochem | Mo-Co-Ga-Rb | | MFa, MFb, MFc, MFd | | <1 km |
| Lithogeochem | HREE-Y | | MFa, MFb, MFc | | 1-2 km |
| Lithogeochem | LREE | | MFb | | <1 km |
| Lithogeochem | $^{206}Pb/^{204}Pb$, $^{207}Pb/^{206}Pb$ | | MFa | possibly in fractures | <1 km |
| Machine Learning | High Th-Ba, low base metals | | MFc | background? | >1 km |
| Machine Learning | High Zn-Mn-Ca | | MFd | | <1 km |
| Machine Learning | High LREE | | MFb, MFc, MFd | | <1 km |
| Machine Learning | High Ni-Co-V-Mo-Bi-B | | MFc | | <1 km |
| Machine Learning | late Carb, epigentic Chl | | MFb | | <1 km |
| Isotopes | high $^{206}Pb/^{204}Pb$, low $^{207}Pb/^{206}Pb$ | | MFa, MFb | | >1 km |
| Geophysics | Seismic Q | anelastic attenuation factor | | may detect alteration in sandstone in restricted survey | TBD |

**Figure 13b.** Preliminary footprint components and vectors for Millennium. Seismic Q: anelastic attenuation factor. Carb: carbonate, Chl: chlorite.

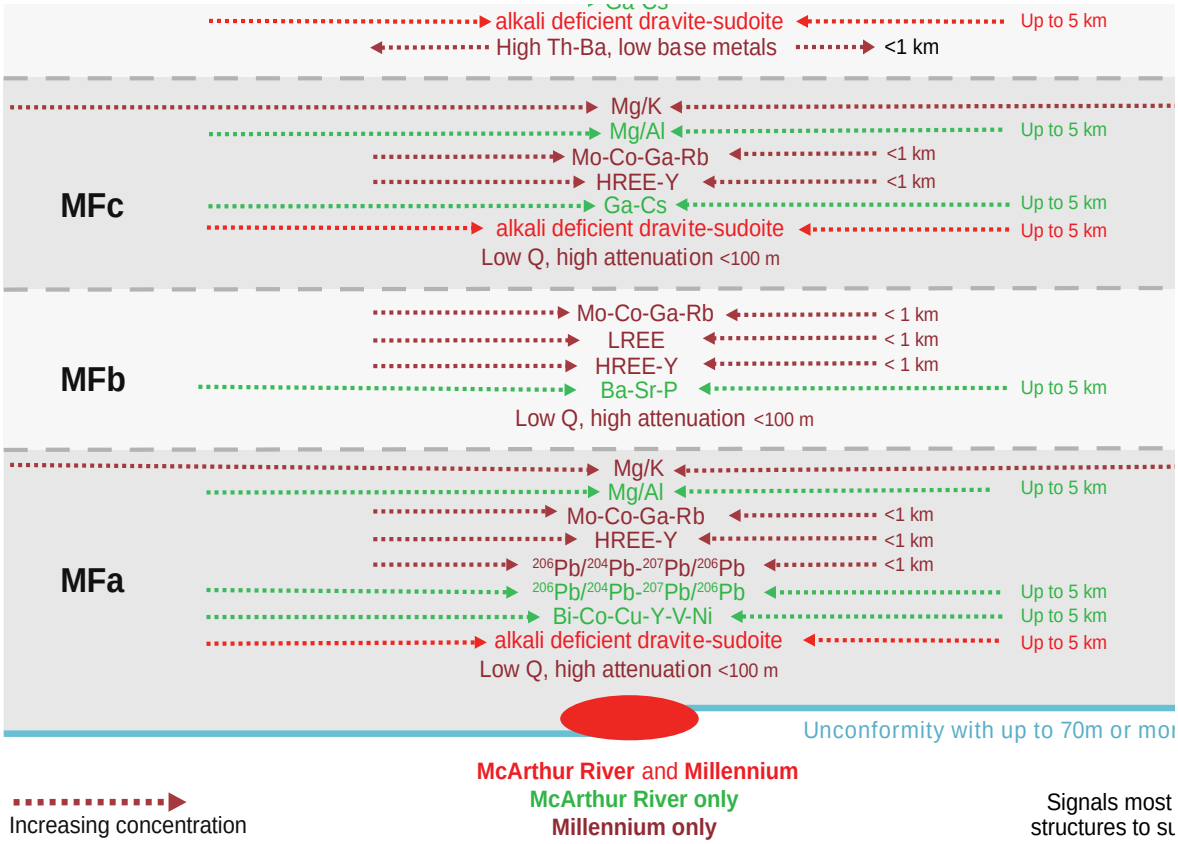



**Figure 14.** Schematic section along the McArthur River – Millennium trend showing preliminary footprint indicators. MFa, MFb, MFc, and MFd: Members of the Manitou Falls Formation; Q: anelastic attenuation factor.

**Copper Site**

The database for the Highland Valley district presently contains a 90m-resolution digital elevation model; a compilation of drill hole overburden thickness; high resolution orthophotography; regional and local geological maps including ~1640 outcrop/DDH stations, ~2350 bedding and structural measurements, ~750 magnetic susceptibility measurements; a compilation of Cu-Au-Ag-Zn-Pb mineral occurrences; a 250m-spacing airborne magnetic and radiometric survey for the entire batholith; a 2 km-spacing airborne gravity survey; a 3D compilation of chargeability and resistivity made up of 20 DCIP surveys, each with a 2D or 3D inverted model; a 2'-resolution satellite gravity survey and a 200-station ground gravity survey; density, porosity, magnetic susceptibility, remanence, and electric measurements on more than 1070 petrophysical samples (GSC) and more than 300 additional samples with density, porosity, magnetic susceptibility, and electric properties (Poly), ~1200 legacy and ~1200 new lithogeochemical, ~235 soil geochemical, and 125 biogeochemical (tree) analyses; ~250 whole-rock and ~180 soil pXRF analyses; ~3200 field and ~700 laboratory hyperspectral analyses; 100 C-O, 70 S, 7 Cu, and 14 Rb-Sr and Sm-Nd isotopic analyses; a wide range of electron probe X-ray emission spectrometric and laser ablation ICP-MS microanalyses of hornblende, plagioclase, epidote, biotite, chlorite, white mica, tourmaline, apatite, zircon, and oxides; and 380 pebble-mineral counts and geochemical analyses of till samples, 80 with petrophysical measurements.

The image from the Common Earth Model for Highland Valley in **Figure 15** shows geology and faults; the locations of samples for analyzed for lithogeochemistry, SWIR mineralogy, and petrophysical properties, a 3D unconstrained IP inversion, a slice through a 3D constrained joint magnetic-gravity inversion, and the location of a Lithoprobe seismic line.

Field mapping in the area has highlighted sodic-calcic (Na-Ca) alteration domains associated with a high density of >0.5 cm/m of epidote veins (Lesage et al., 2016). Sodic-calcic facies in the Guichon batholith consists primarily of light green epidote veins with haloes of albite ± fine-grained white mica ± epidote ± chlorite ± actinolite (Byrne et al., 2017). A key characteristic of the Na-Ca facies is the selective replacement of primary K-feldspar by secondary albite ± fine-grained white mica. Sodic-calcic veins and haloes occur in ~0.5–2 km wide, north-northeast- and northwest-trending domains that extend along trend from the Cu centres for up to 7 km in a non-concentric pattern (Lesage et al., 2016). More pervasive albite alteration, locally accompanied by actinolite and relict garnet (mostly retrograded to pumpellyite and chlorite) formed close (150–1000 m) to the porphyry-Cu centres and stocks (Byrne et al., 2017). These and other footprint components and vectors are shown schematically in **Figure 16** and summarized in more detail in **Figure 17**. As for the other sites, many are obviously related, but provide similar opportunities for selecting less expensive alternatives and/or proxies.

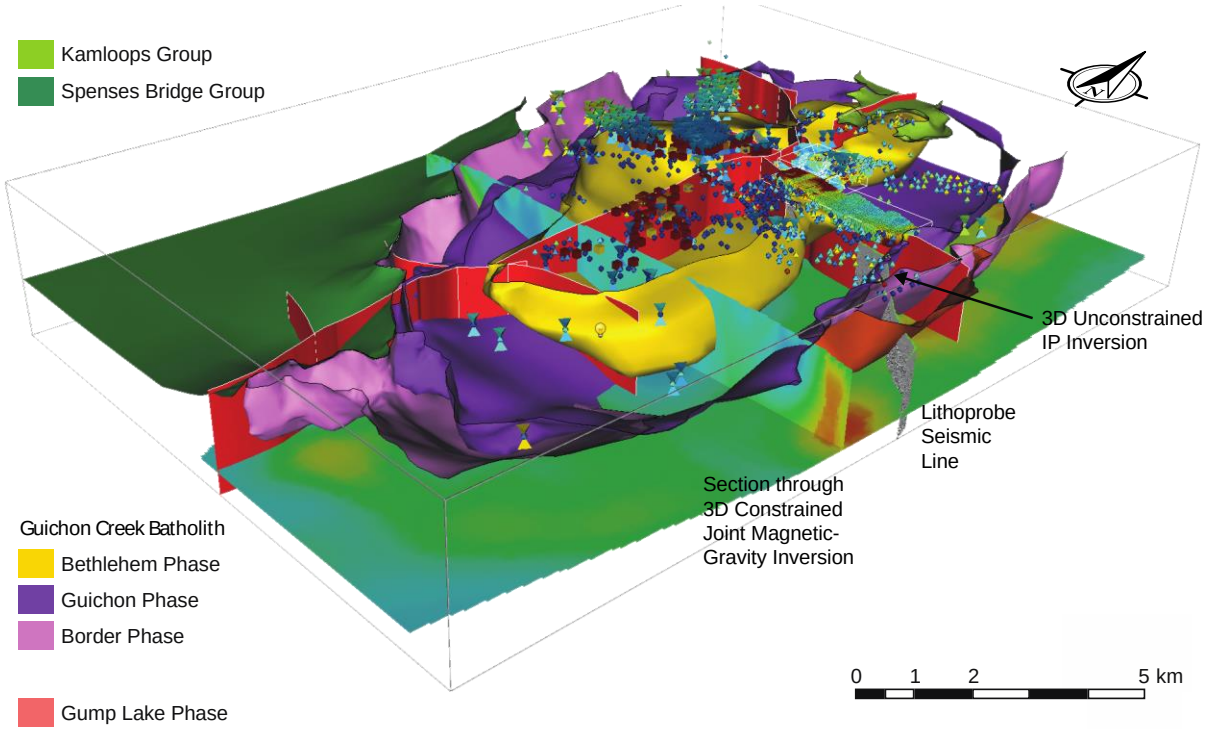



**Figure 15**. Parts of the Common Earth Model for the Highland Valley area showing geology, faults (subvertical red), geochemical samples (small diamonds), SWIR mineralogical samples (small cubes), petrophysical measurements (large hourglasses), a 3D unconstrained IP inversion, a slice through a 3D constrained joint magnetic-gravity inversion, and the location of a Lithoprobe seismic line. Bethsaida, Chataway, and Skeena phases of the batholith are not shown for clarity.

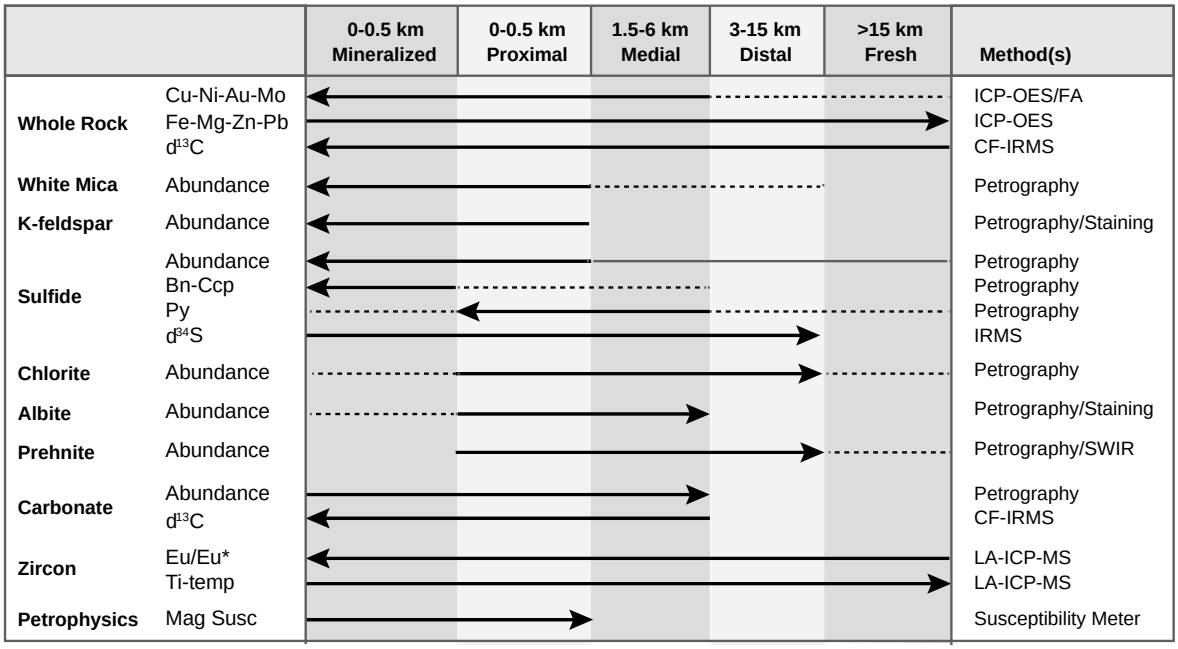



**Figure 16**. Preliminary footprint components and vectors for Highland Valley. Distances vary from location to location and are shown as ranges. CF: continuous-flow, FA: fire assay, ICP: inductively-coupled plasma, IR: isotope ratio, LA: laser ablation, MS: mass spectrometry, OES: optical emission spectrometry, SWIR: shortwave infrared spectroscopy

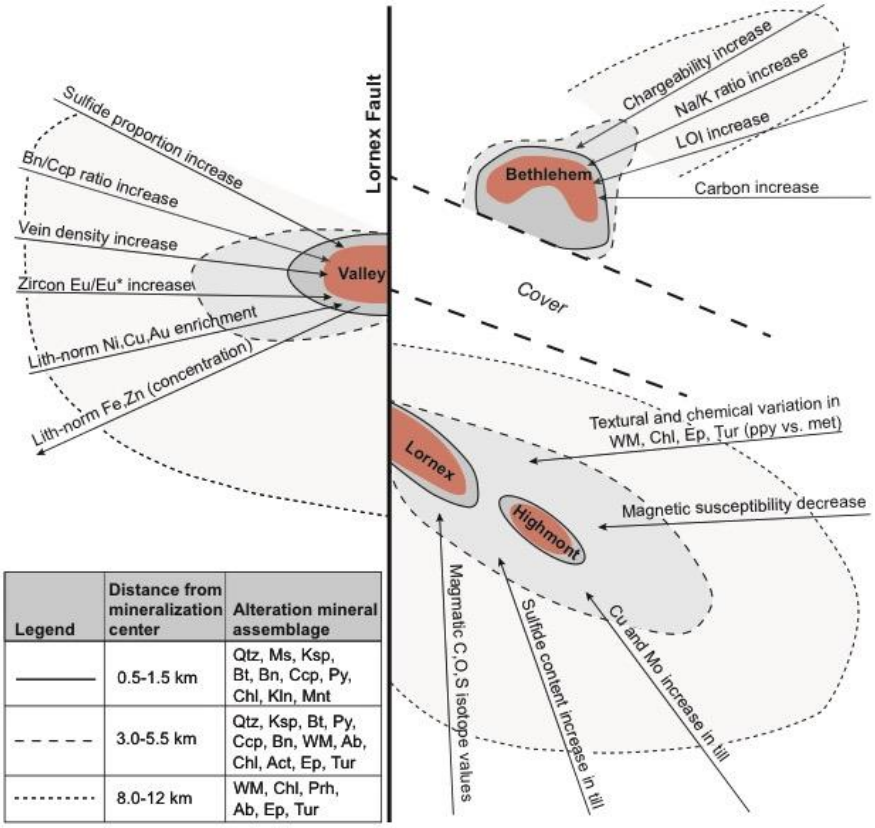



**Figure 17**. Schematic map of Highland Valley area showing preliminary footprint components and vectors observed at all deposits. Ab: albite, Act: actinolite, Bn: bornite, Bt: biotite, Ccp: chalcopyrite, Chl: chlorite, Ep: epidote, Kln: Kaolinite, Ksp: K feldspar, Mnt:

montmorillonite, Ms: muscovite, Prh: prehnite, Py: pyrite, Qtz: quartz, Tur: tourmaline, WM: white mica; ppy: porphyry, met: metamorphic/deuteric alteration.

## TECHNOLOGY TRANSFER

While developing new models of ore-system footprints to guide exploration, technologies and methodologies are also being transferred to industry for the creation of better exploration data. Geophysics is increasingly being used in the project to isolate secondary and tertiary footprints of the ore and alteration systems, rather than just for direct detection of mineralization. New methods for generating physical rock properties and doing geophysical inversions have been tested, advances have been made in the application of lithogeochemistry and mineralogy, and a wide range of data integration methodologies are being utilized. Some of these transfers are summarized below:

### Geophysics

1) Construction of 3D subsurface magnetic field variations at the Au site from borehole navigation logs, including levelling of data using Geosoft® protocols.
2) Estimation of near-surface magnetic susceptibility at the Au site from airborne EM data.
3) First successful application of 3D multi-electrode borehole-to-borehole and borehole-to-surface resistivity and chargeability (IP) imaging for Au exploration.
4) Development of techniques to merge multiple generations of IP and resistivity surveys at the Au site.
5) Use of ground-penetrating radar, high-frequency or resistive-limit electromagnetic methods, and seismic methods to map of Quaternary cover thickness at McArthur-Millennium so that its influence on geophysical signatures can be stripped, aiding recognition of the very subtle geophysical expression of Athabasca-type hydrothermal footprints.
6) Testing use of the seismic anelastic attenuation factor (Q) to define hydrothermal alteration in the Athabasca sandstone overlying the Millennium deposit.
7) Development of new migration noise attenuation software for 3D seismic image enhancement at the Millennium site.
8) Development of processing techniques to extract physical property information from seismic 3-component data to aid in identifying alteration and vertical structures at the Millennium site.
9) Assessment of high frequency magnetic anomalies to define 3D fault geometry and also quantify alteration intensity by comparison with petrophysical and mineralogical data on the same volumes.
10) Use of geostatistical methods to process potential field data, including a) transformation of data by kriging using a gravimetric model of covariance, which has advantages when data are sparse and not on a regular grid, b) factorial kriging for noise reduction and separation of regional and residual components, which has fewer practical limitations than traditional spectral-based methods encounter, and c) interpolation using non-stationary covariances.
11) 3D stochastic magnetic inversion methods have been applied to airborne and borehole magnetic data at the Au site mine at both regional and local scales. Incorporating downhole measurements of either susceptibilities or magnetic data as constraints helps reduce the non-uniqueness characteristic of the magnetic inversion

### Geophysical Inversion

12) Development of a stochastic Python® computer code to model spectral IP data.
13) Development of methods using constrained and joint inversion of complementary geophysical data types for overburden stripping.
14) Determination if detection of the low magnetic susceptibility contrast of the Au mineralization is technically feasible with current instrument and inversion methods.
15) Development of an open-source program that performs fast multi-model inversion of laboratory complex resistivity measurements using Markov-chain Monte Carlo simulation. Using this stochastic method, SIP parameters and their uncertainties may be obtained from the Cole-Cole and Dias models, or from the Debye and Warburg decomposition approaches.

### Petrophysics

16) Petrophysical indicators extracted from modelling the spectral induced polarization response have used to discriminate mineralization (veins and disseminated) from alteration and unmineralized wall rock. Cole-Cole and averaged Debye chargeability and relaxation time constant are particularly useful for targeting Cu and Au mineralization at the HVC and Canadian Malartic deposits, respectively.
17) Multiple magnetic property measurements (e.g., magnetic susceptibility, coercivity, anisotropy of magnetic susceptibility, magnetic remanence) have been used to identify the presence and structural timing of pyrrhotite in large-scale surveys, thereby directly determining the timing and spatial distribution of the Au Site footprint and mineralization.
18) Physical property data have been generated from routinely collected whole-rock geochemistry and used to better constrain geophysical inversions.
19) Joint analysis of physical properties at different scales and sampling distances, including estimation of physical properties from 3D geophysical data and geologically-constrained inversions, is being used to find the physical properties of rock units that best reconcile with the observed geophysical responses
20) Measurements of magnetic susceptibility, resistivity, chargeability, gamma spectrometry in bore holes, on drill cores, and on outcrops is facilitating correlations with geology, foliation, and alteration that allow calculation of average physical properties.

21) Experiments on best practices for measuring complex conductivity in the lab have shown that 1) four-point measurements using non-polarizable electrodes and saturating conditions; measurements on large core samples using Ag-AgCl potential electrodes; wrapping samples in cellophane films to prevent loss of saturation vs. 2) measurement in water-filled sample holders using Ag wire electrodes are both stable and repeatable.
22) Methodologies have been developed to assess the capabilities of and effectiveness of physical property-based joint inversion for mineral exploration, and the application to real-life data to mineral exploration scenarios.

**Structural Geology**

23) Bedding attitude variances have been quantified at both the Au and U sites to detect the complex structural domains that host mineralization.
24) Variogram analysis has been used to identify structural controls on geochemical and petrophysical variations.
25) Orientations, densities, lining compositions, and relative timings of fractures have been used at the U site to identify variations related to mineralization along regional fault systems (e.g., footwall versus hanging wall relationships, proximity to major upflow zones).

**Mineral Assemblage Mapping and Mineral Chemistry**

26) Systematic workflows for integrating mineral chemical data at the 3 sites has permitted exploration of data in conjunction with other measured parameters on the same samples.
27) Hyperspectral mineral mapping is being used in a variety of ways at a wide range of scales, including scanning of field outcrops and open pit walls to map alteration, more efficient use of SWIR in measuring mica compositions, and applications to glacial material to identify the secondary dispersion of the alteration footprint.
28) Mineral chemical data have been used to link pathfinder elements to specific minerals, so that geochemical enrichments can be inferred from field data.
29) Cluster analysis of Rietveld X-ray diffraction data has been used to generate mineralogical data at the same rate and scale as standard whole-rock geochemical data.
30) Traditional field techniques, such as carbonate staining of drill core and feldspar staining in the laboratory, have been modernized by spectral techniques, image analysis, and calibration with mineral-chemical data.

**Lithogeochemistry and Isotope Chemistry**

31) Analysis of field/core rock powders and old assay pulps via fully-calibrated field-portable energy-dispersive X-ray fluorescence spectrometry has provided much more rapid yet sufficiently precise and accurate (fit-for-purpose) data for footprint definition, including both alteration and metal zonation patterns.
32) Element ratio techniques have been used to detect and delineate alteration footprints more reliably, by eliminating closure issues in geochemical data sets.
33) Partial/total leach ratios have been used to map mineral abundance variations.
34) More cost-effective stable (C-O at Highland Valley and Canadian Malartic) and radiogenic (Pb at MacArthur-Millennium) isotope methods have been developed to take advantage of these highly sensitive footprint indicators.

**Surficial Methods**

35) New approaches for handling till samples have been being tested to ensure that "clean" silt and sand-sized fractions are produced consistently for geochemical analysis.
36) Use of multiple media (e.g., fractures, soil fractions, and tree cores) to trace secondary element migration from U ores.
37) A multi-faceted approach has been applied to map the internal glacial stratigraphy of drumlins at McArthur River and to correlate with units exposed at the surface in order to understand the effect of stratigraphy and erosion on the secondary detrital dispersion of mineral indicators and their pathfinder elements.
38) Hyperspectral analysis of pebbles at Malartic and Highland Valley has been used to detect alteration signatures in the glacial sediment cover.
39) Supervised classification of radiometrics and other remotely sensed imagery have been applied to map units of contrasting composition (provenance) in the surficial Quaternary sediment cover at McArthur River, which help constrain the analysis and interpretation of surficial secondary dispersion.
40) Tungsten contents of rutile in tills have been used to map the Au Site footprint dispersion.

**Data Visualization, Integration, and Analysis**

41) The Common Earth Models being developed in this project include a much wider variety of self-consistent geological, structural, mineralogical, mineral chemical, litho-geochemical, surficial, petrophysical, and geophysical data than has been included in the past.
42) K-means clustering, self-organizing maps, and HyperCube have been used to identify patterns in the data that cannot be detected using traditional geostatistical methods.
43) Methods have been developed to better visualize the output from machine learning tools like HyperCube.
44) Geostatistical approaches have been used both to a) combine geological-structural-mineralogical-lithogeochemical-surficial-petrophysical-geophysical variables to expand the outermost limits of footprint detection, and to b) identify smaller combinations of elements that can be analyzed less expensively (e.g., portable energy-dispersive X-ray fluorescence spectrometry vs. fusion or pressed-pellet wavelength-dispersive X-ray fluorescence spectrometry).
45) Workflows for QA/QC of the various types of exploration data have been incorporated into sponsor company exploration workflows.

46) Custom workflows have been developed to clean and import lithogeochemical, mineralogical, mineral chemical, surficial, petrophysical, geophysical, and inversion data for machine learning methods.

47) Integration of lithogeochemical data with geophysical and geochemical data is more clearly defining the footprints and guiding geophysical inversions.

48) Geoscience INTEGRATOR® has been modified for the exploration workflow and public domain elements of the three major data sets generated during the project will be archived in this format and accessible after the end of the project.

49) The relationship between spectral IP response and ore type, grain size, and distribution has been used to determine the impact of these factors on the parameters from the physical models, allowing fine-tuning of the IP method in prospecting for ores.

50) Correlations between co-located petrophysical, geochemical, mineralogical, and hyperspectral data permit statistical analyses of the relationships existing between lithology, alteration, ore, and petrophysical properties.

51) Machine learning algorithms have been used to quantify uncertainties in the classification of petrophysical data.

**Project Management**

52) The Exploration Footprints project is the first of its kind in the minerals industry in Canada, involving an unprecedented number of researchers and industry partners. In addition to the technologies being transferred from the researchers to the companies and from the companies to the researchers, policies and workflows have been developed to facilitate collaboration across the various technological disciplines and across the different research sites. These will be among the longest-lasting of the innovations resulting from the project.

## LOOKING FORWARD

The Project will be completed in March 2018, at which time all relevant data will be in the Common Earth Models and Geoscience INTEGRATOR®, all of the deposit footprints and vectors will be compiled, and a pan-project Data Integration exercise will be completed to capitalize on the many similarities between the three sites (e.g., variations in structural orientations at the Au and U sites, similarities in alteration signatures at the Au and Cu sites).

The results will be available exclusively to the Sponsors for a period of 6 months after which time they will be posted to the public on *cmic-footprints.ca*.

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