Perrouty S, Linnen RL, Gaillard N, Clark JR, L-Bérubé CL, Lypaczewski P, Mir R, Olivo GR, Lesher CM, Piercey SJ, Williams-Jones AE, Chouteau M, Rivard B, Enkin RJ, 2017, Integrated multi-parameter footprints of the world-class Canadian Malartic gold deposit, QC, Canada, Extended abstract, Society for Geology Applied to Mineral Deposits (SGA), Québec, QC, 3, 1103-1106

Integrated multi-parameter footprint of the Canadian Malartic gold deposit, Québec, Canada

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Abstract. The metasomatic halo of the Canadian Malartic gold deposit has been investigated using and integrating multiple geological and geophysical methods. Over 50 structural, lithogeochemical, mineralogical, petrophysical and geophysical parameters were identified and they provide the spatial distribution of alteration zones within the deposit footprint as well as vectoring information. This communication highlights the main parameters that define the Canadian Malartic footprint and on-going progress regarding their geological, geospatial and geostatistical integration.

1 Introduction

The NSERC-CMIC Multidisciplinary Mineral Exploration Footprints project (http://cmic-footprints.ca/), aims to characterize the distal signature of major ore systems, to identify new exploration criteria, and to develop exploration methodologies by integrating geological, structural, lithogeochemical, mineralogical, petrophysical and geophysical datasets.

This communication presents a synthesis of some of the multi-parameter footprints and vectors toward the mineralization that have been identified for the world-class Canadian Malartic deposit (>18.6 Moz, Gervais et al. 2014), which is located south of the Cadillac Larder Lake Deformation Zone, Abitibi Subprovince, Canada (Fig. 1).

2 Geological setting

2.1 Host rocks and deformation

The Canadian Malartic gold deposit is hosted by Archean meta-sedimentary rocks (Pontiac Group) and quartz-monzodiorite intrusions of the Pontiac Subprovince, and by meta-volcanic rocks of the Abitibi Subprovince (Piché Group). These lithologies were intruded by basic dykes prior to the mineralization event(s). Upper greenschist metamorphism overprints all host rocks, mineralization and associated alteration.

Three major deformation events have been recognized in the area (Derry 1939; Perrouty et al. 2017) and include: 1) a pre-mineralization and pre-intrusion D_1 deformation event that produced isoclinal F_1 folds and a pressure-solution bedding parallel S_1 cleavage, 2) a syn-mineralization D_2 deformation event that produced open to tight steeply dipping F_2 folds, an east-plunging L_2 stretching lineation and a NW-SE-trending penetrative biotite/amphibole foliation, and 3) a post-mineralization minor D_3 deformation event that produced open F_3 folds, a subtle NE-SW-trending crenulation S_3 cleavage and kinks. The D_3 event postdates the metamorphic peak and may correlate with late dextral transcurrent movement along the Cadillac Larder Lake Deformation Zone (Bedeaux et al. 2017).

2.2 Mineralization

Low grade, large-tonnage gold mineralization in the Canadian Malartic deposit is structurally controlled by the E-W Sladen Fault Zone (which is connected to the Cadillac Larder Lake Deformation Zone) and NW-SE high-strain bands (Derry 1939). Ore zones are spatially associated with quartz monzodiorites intrusions (Helt et al. 2014). The proximal alteration mineralogy consists of biotite, K-feldspar, albite, white mica, quartz, carbonate, pyrite, rutile, scheelite in the meta-sedimentary rocks (Helt et al. 2014, De Souza et al. 2015, 2016) and biotite, quartz, carbonate, chlorite, pyrite, rutile, epidote in the meta-basic dykes (Perrouty et al. 2015).

3 Integrated multi-parameter footprints

3.1 Structural footprint

Orogenic and intrusion-related gold systems are all structurally controlled. At Canadian Malartic, the relationship between the deformation and the mineralization was recently investigated by De Souza et al. (2015, 2016), who demonstrate a syn-D_2 timing for the main gold mineralization event and estimate it to be around 2664 Ma.

Perrouty et al. (2017) showed that gold occurrences in the Canadian Malartic district are systematically associated with structurally complex zones, which are interpreted to be joined F_1 and F_2 fold hinges. They also highlighted spatial variations in the intensity of the S_2 biotite foliation in greywacke and tentatively interpreted it as a consequence of the alteration by mineralizing fluids during the D_2 deformation event.

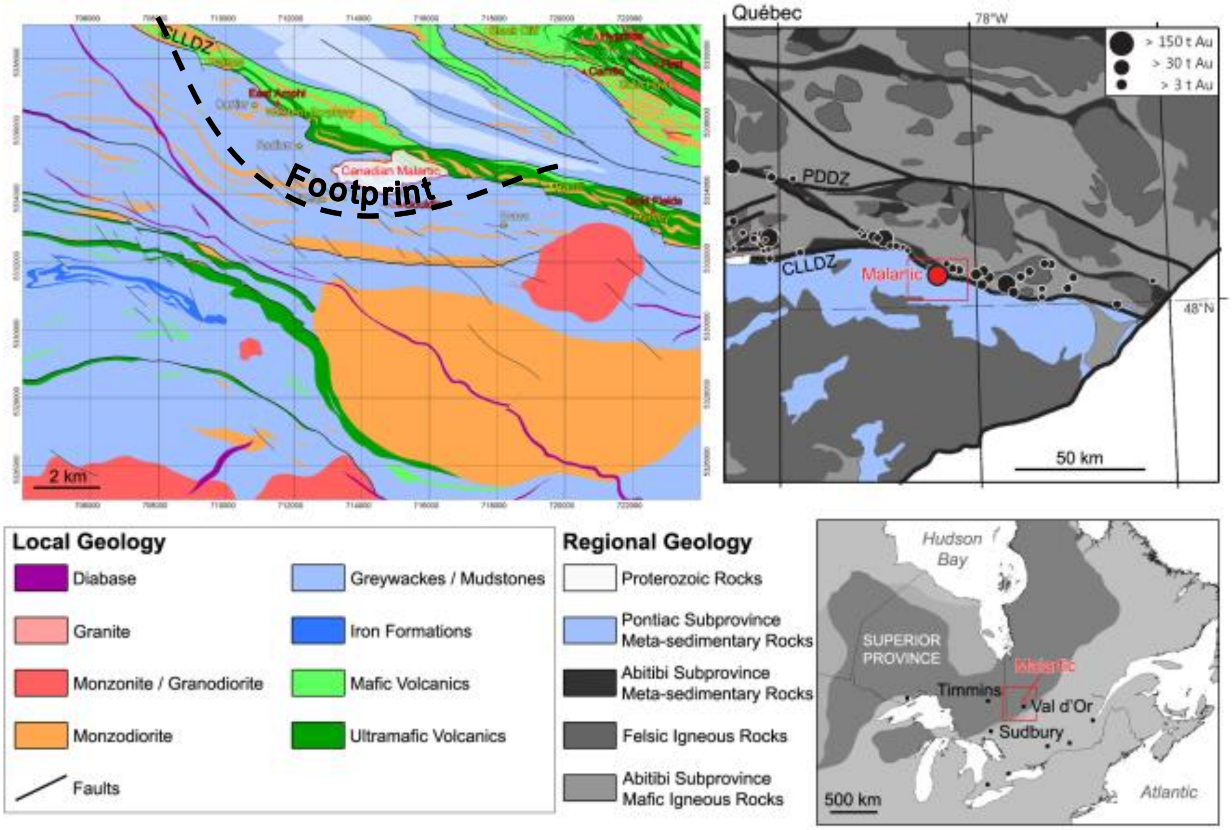


Figure 1. Location of the Canadian Malartic deposit at the contact between the Pontiac and Abitibi sub-provinces (modified after Perrouty et al. 2017). Historical mines (in red) and prospect (in yellow) are indicated. PDDZ: Porcupine Destor Deformation Zone. CLLDZ: Cadillac Larder Lake Deformation Zone.

3.2 Geochemical footprint

Lithogeochemical variations throughout the footprint of the deposit are controlled by the protolith composition and by alteration. Whole-rock geochemical analyses were conducted by ACTLABS, ALS and SGS laboratories and were supplemented by a whole-rock stable isotope study (see Raskevicius et al. 2017).

Mass changes were calculated for meta-sedimentary rocks and meta-basic dykes in order to generate a series of representative mass gain and loss maps. Gold and associated elements (Ag, Te) have the most significant mass gains proximal to the deposit in both rock types. Elements such as S and C are intimately associated with gold mineralization and are enriched in the vicinity of the deposit. Significant mass gains are also observed for large-ion lithophile elements and for light rare-earth elements, but their distributions highlight a more distal alteration signature, which is particularly well recorded in the meta-basic dykes (Fig. 2).

Differences in analytical methods (partial vs total leaches) can also be used to detect alteration.

3.3 Mineralogical footprint

Mineralogical changes within the footprint of the Canadian Malartic gold deposit are linked with lithogeochemical changes during the hydrothermal alteration process. Major mineral proportions are highly dependent on the protolith in the meta-sedimentary rocks (greywacke vs siltstone vs mudstone) and the resultant variations can therefore be difficult to interpret. However, the relative abundances of minor minerals such as carbonates, pyrite, and rutile increase in the vicinity of the mineralized zones.

The meta-basic dykes are more reactive to the hydrothermal fluids than the Pontiac meta-sedimentary rocks. Their mineralogy evolves from a distal amphibole-rich composition to a proximal biotite–carbonate–quartz–pyrite–rutile mineral association (Perrouty et al. 2015).

Mineral chemical variations were also evaluated. Biotite and white mica compositions are highly dependent on the protolith and metamorphic conditions (Gaillard et al., 2015), but a distinct “hydrothermal” signature can nevertheless be identified around the Canadian Malartic deposit. Hyperspectral (SWIR) methods have also been shown to efficiently detect and map mineral compositional changes (see Lypaczewski et al. 2017).

Glacial dispersion from the Canadian Malartic deposit in the surficial till is also being investigated (Taylor et al. 2017).

3.4 Petrophysical footprint

Rock physical properties are controlled by multiple parameters including mineralogy and structures. Measurements were acquired at the Geological Survey of Canada Paleomagnetism and Petrophysics Laboratory and at École Polytechnique de Montréal.

Density is highly dependent on the mineralogy and porosity. Major mineralogical changes during alteration result in density variations across the Canadian Malartic footprint, which are particularly strong for meta-basic dykes.

Magnetic susceptibility and remanence are mainly controlled by minerals such as magnetite and pyrrhotite. The spatial distributions of these minerals in the footprint is complex. Pyrite is the most common sulfide mineral in the deposit and is commonly associated with destruction of magnetite. It is, however, progressively replaced by pyrrhotite towards the south, which is tentatively interpreted to be a metamorphic overprint on the alteration assemblage. The anisotropy of the magnetic properties along geological structures is also being investigated and correlated with structures.

Low-frequency electrical properties were also measured and interpreted based on rock texture, sulfide mineral proportions and grain size distribution (Bérubé et al. 2017).

3.5 Geophysical footprint

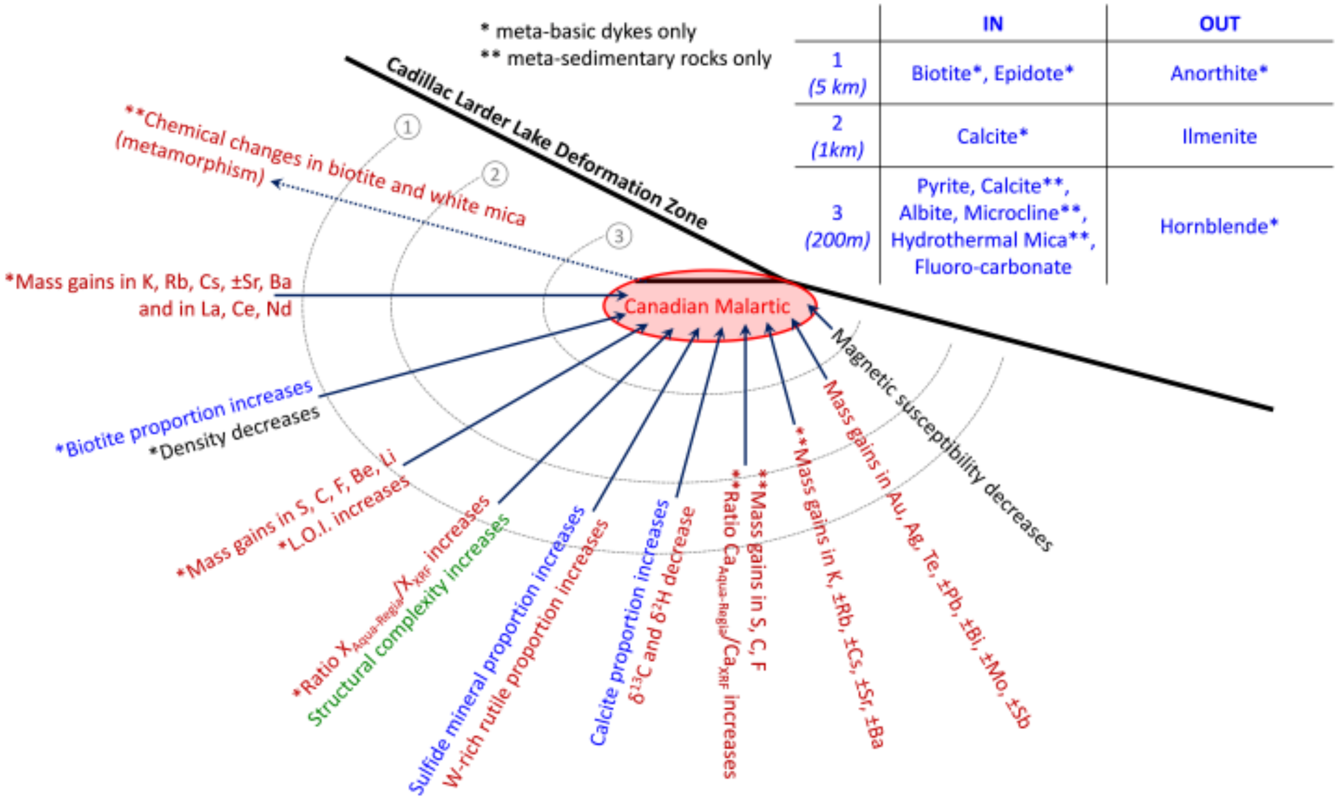
The detection of orogenic intrusion-related disseminated gold deposits by geophysical methods is very challenging because the petrophysical contrasts are often not sufficient to provide a perceptible geophysical signature.

Geophysical datasets in the area consist of airborne magnetic and EM surveys provided by Canadian Malartic Corporation, and several ground IP lines that were acquired in collaboration with Abitibi Geophysics during this project. Airborne data were used mainly to delineate geological structures and units, and are not sensitive to alteration signature. High resolution (meter-scale) time-domain and spectral induced polarization ground surveys were conducted at the Bravo gold occurrence and appear to detect graphitic mudstone and mineralized greywacke layers (Bérubé et al. 2017).

3.6 Data integration

Three major data integration analyses are being conducted in this project: 1) geological "physical" integration between parameters (e.g., carbonate alteration => density

Figure 2. Schematic diagram summarizing the main parameters that define the footprint of the Canadian Malartic gold deposit from the most distal (left) to the most proximal (right).



	IN	OUT
1 *(5 km)*	Biotite*, Epidote*	Anorthite*
2 *(1km)*	Calcite*	Ilmenite
3 *(200m)*	Pyrite, Calcite**, Albite, Microcline**, Hydrothermal Mica**, Fluoro-carbonate	Hornblende*

decrease), 2) geospatial integration (e.g., gold, quartz-monzodiorite intrusions and F_1-F_2 fold hinges are spatially associated), and 3) geostatistical integration (e.g., principal component analysis, K-means clustering, machine learning), which are still in progress.

Over 50 individual vector and footprint parameters can be used to characterize the proximal, medial, and distal alteration zones. Combinations of these parameters enhance their capacity to vector toward the deposit and decrease the possibility of false positive results. The identification of a minimum set of parameters that best describe the footprint and that are applicable to exploration is a critical goal of this project.

4 Summary and conclusion

Many individual mineralogical, lithogeochemical and petrophysical parameters vary across the Canadian Malartic footprint (Fig. 2), and therefore define the footprint of the deposit. However, some of these parameters are physically linked together (e.g., mass gain in potassium => biotite formation => density decrease in meta-basic dykes.). Extensive data integration will be used to identifying the best combination of variable that define the Canadian Malartic footprint and permit vectoring from the periphery toward the high grade core, which can then potentially be used to target similar ore systems.

Acknowledgements

The research team is deeply grateful to the Canadian Malartic Corporation, exploration and production departments for their logistical support during field work, and to Abitibi Geophysics, ACTLABS, ALS and SGS for providing in-kind services. Funding was provided by the Natural Sciences and Engineering Research Council of Canada and the Canada Mining Innovation Council through the NSERC Collaborative Research and Development Program. CMIC-NSERC Exploration Footprints Network Contribution 136.

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