Perrouty S, NSERC-CMIC Footprint Team, CFREF Metal Earth Team, 2019, Innovations for gold exploration in Precambrian greenstone belts: highlights from the Footprints and Metal Earth programs and potential applications to the Guiana Shield, Extended abstract, XI Interguiana Geological Conference, Paramaribo, Suriname, 4 p.

NSERC-CMIC Mineral Exploration Footprints Project Contribution 200.

Innovations for gold exploration in Precambrian greenstone belts: highlights from the Footprints and Metal Earth programs and potential applications to the Guiana Shield

Stéphane Perrouty*, the NSERC-CMIC Footprint Team and the CFREF Metal Earth Team
MERC, HSES, GSM, Laurentian University
935 Ramsey Lake Road, Sudbury, ON, P3E 2C6

sperrouty@laurentian.ca

SUMMARY

Precambrian greenstone belts are variably endowed with base and precious metal resources despite similarities in rock types and tectono-magmatic evolutions. What are the geological processes contributing to metal endowment and how to identify them are fundamental questions for mineral exploration that are being investigated, at two different scales, by the CFREF Metal Earth and the NSERC-CMIC Footprints research programs. This communication presents on-going crustal-scale investigation in the Superior Province and a district-sale synthesis of the multi-parameter footprint that have been identified for the Canadian Malartic deposit, Canada, with potential applications for exploration in the Guiana Shield.

Key words: Abitibi Subprovince, Canadian Malartic, Footprints

INTRODUCTION

The Superior Province is composed of several variably endowed Archean greenstone belts that host diverse base and precious metal deposits. Main gold deposits include volcanogenic massive sulfide deposits (e.g., Mercier-Langevin et al., 2007), intrusion-related deposits (e.g., Robert, 2001), and fault-hosted gold-bearing quartz – carbonate vein "orogenic" deposits (e.g., Dubé and Gosselin, 2007). The gold resources seem to be heterogeneously distributed between greenstones belts: e.g. the Abitibi Subprovince hosts more than 150 Moz Au whereas the Western Wabigoon Subprovince hosts less than 10 Moz Au (Frieman and Perrouty, in press). Identifying the factors that variably influence mineralization across the Canadian Shield will benefit gold exploration by providing new criteria for prospectivity analysis in greenfield environment and new vectoring tools for mineralized systems at depth. At the scale of the crust, the Metal Earth research program (https://merc.laurentian.ca/research/metal-earth), funded by the Canada First – Research Excellence Fund (CFREF), aims to understand whole mineral systems, from the deep crustal fluid sources to the deposit sites, and to characterize the major structural pathways for mineralization. At the scale of a mining camp, the multidisciplinary Mineral Exploration Footprints research program (https://cmic-footprints.laurentian.ca), funded by the Natural Sciences and Engineering Research Council (NSERC) and the Canadian Mining Innovation Council (CMIC), aims to characterize and expand the size of 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 (Lesher et al., 2017).

METHOD AND RESULTS

Crustal-scale investigations

Crustal-scale investigations require a good knowledge of the surface geology and extensive geophysical datasets. To that end, a series of eleven 100-km long seismic reflection, MT and gravity traverses were conducted across major greenstone belts in the Superior Province. Four of these transects are in the Abitibi greenstone belt, one in the Swayze greenstone belt, two in the Eastern Wabigoon greenstone belt, and four in the Western Wabigoon greenstone belt (Figure 1A). Each of these transects is being mapped by crews of post-doctoral research associate and graduate students to document the stratigraphic relationship, the nature of the lithological contacts (e.g., unconformities), the tectonic setting and the structural control on various type of base and precious metal mineralization. Objectives are to characterize and model the 3D geometry of the main geological features (e.g., crustal-scale deformation zones, terrane boundaries) that could be potential pathways for hydrothermal fluids. These new datasets will help to determine the key characteristics of gold-mineralized and barren geological setting, and ultimately provide new guidelines for greenfield exploration in Precambrian greenstone belts. Preliminary observations suggest that the relative timing between the hydrothermal activity, the metamorphism and the kinematic along crustal-scale deformation zones could be critical to control orogenic gold endowment in the Superior Province.

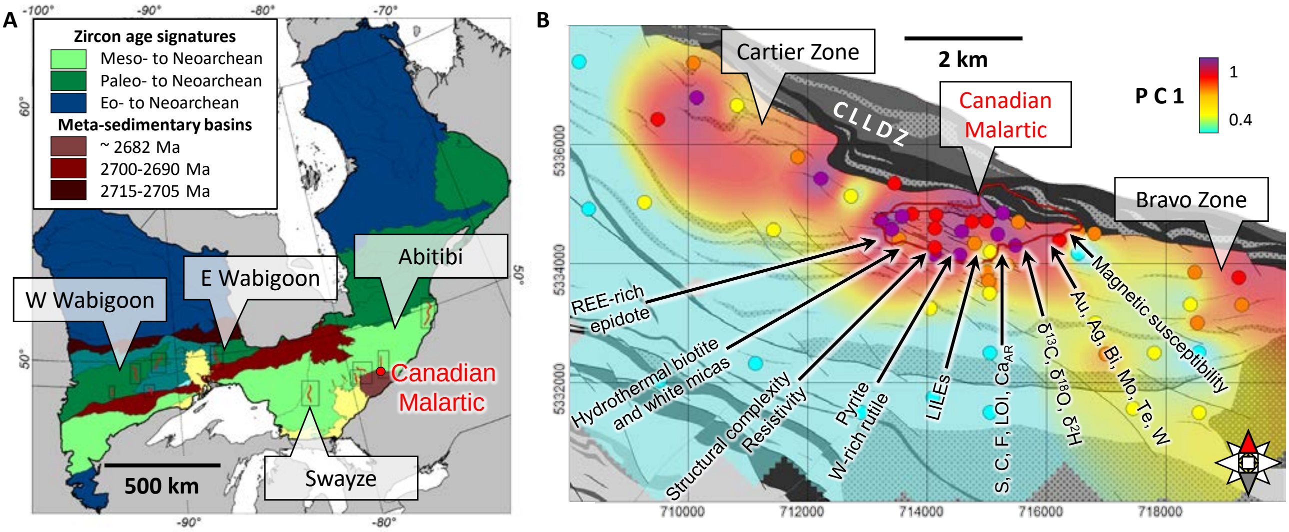

Figure 1: A) Geological sub-provinces of the Superior Province and location of the CFREF Metal Earth transects (red lines) across four Archean greenstone belts (modified after Frieman et al., 2017 and Montsion et al., 2018). The Canadian Malartic deposit is located south of the contact between the Abitibi (light green) and Pontiac (brown) subprovinces. B) Schematic footprint of the Canadian Malartic deposit (modified after Perrouty et al., in press). The color grid represents a metasomatic halo based on principal component analysis of lithogeochemical, mineralogical and petrophysical variables in mafic dykes. Several alteration centers can be seen (Cartier, Canadian Malartic and Bravo). The red line represents the open-pit mine (as designed in 2013). The coordinate system is NAD83-UTM17N.

District-scale investigations

The district-scale studies aim to identify key vectors toward mineralization. Over the last five years, the multi-parameter metasomatic footprint of the Canadian Malartic gold deposit has been extensively using and integrating multiple geological and geophysical datasets. Over one hundred structural, lithogeochemical, mineralogical, petrophysical and geophysical variables were identified, and they outline the spatial distribution of the alteration zones at the periphery of the deposit. The geometries of these metasomatic haloes are both structurally and lithologically controlled along progressive metasomatic fronts from the core to the periphery of the mineralized system.

Geological setting of the Canadian Malartic district

The world-class Canadian Malartic deposit (>18.6 Moz Au, Gervais et al., 2014) is hosted by metamorphosed (upper greenschist to lower amphibolite facies, Piette-Lauzière et al., submitted; protolith name are being used for simplicity) Archean sedimentary rocks and quartz-monzodiorite intrusions of the Pontiac Subprovince, south of the Cadillac Larder Lake Deformation Zone (CLLDZ, Figure 1B), and volcanic rocks of the Abitibi Subprovince. These lithologies were intruded by mafic dykes prior to the mineralization event(s). Volumetrically these mafic dykes are not significant, but they provide key information to characterize the distal 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. Low grade, large-tonnage, gold mineralization is early to syn-metamorphic peak, and is structurally controlled by the CLLDZ, by faulted contacts between intermediate-felsic intrusive and sedimentary host rocks, and by NW-SE high-strain structural corridors within fold hinges. Ore zones are spatially associated with quartz monzodiorites intrusions (Helt et al., 2014, De Souza et al., 2015). The proximal alteration mineralogy consists mainly of biotite, white mica, microcline, albite, quartz, calcite, ferroan-dolomite, rutile and pyrite in the sedimentary rocks (Gaillard et al., 2018) and biotite, albite, quartz, calcite, rutile, and pyrite in the mafic dykes (Perrouty et al., in press).

Integrated multi-parameter footprint

1) Structurally complex zones are systematically associated with gold occurrences in the Canadian Malartic district. They can be detected by field mapping, statistical processing of structural orientation data (e.g., variance of the bedding, Perrouty et al., 2017) and geophysics (Mir et al., in press). This latter technique can be applied at regional-scale and in area with poor outcrop exposure like in the Guiana Shield.

2) Lithogeochemical variations throughout the footprint of the deposit are controlled by protolith compositions, hydrothermal alteration and analytical methods (i.e., partial versus total digestion). Mass gains and losses were calculated and mapped for sedimentary rocks and mafic dykes. Gold and associated elements (e.g., Ag, Te, W, S, C) are enriched in and at the periphery of the deposit in both rock

types (Gaillard et al., 2018). Large-ion lithophile elements (e.g., K, Cs) outline a distal metasomatic halo, up to 6 km from the deposit using mafic dykes (Perrouty et al., in press). Stable isotopes (e.g., H, O) can also be used to detect the presence of hydrothermal alteration (Raskevicius et al., submitted).

3) Mineralogical changes are linked with major element lithogeochemical changes. In mafic dykes, the mineralogy evolves from a distal amphibole-rich composition to a proximal biotite–albite-calcite-quartz–rutile-pyrite mineral association and can be seen using hand lens or quantify through XRD analysis (Perrouty et al., in press). In sedimentary rocks, the relative abundances of alteration minerals such as microcline, calcite, rutile and pyrite increase toward the deposit and can be detected using felspar or carbonate staining (Gaillard et al., 2018). Mineral chemistry changes in biotite and white mica have been documented (Gaillard et al., 2018) and can be mapped efficiently using hyperspectral (Short-Wave InfraRed, SWIR) imagery techniques (Lypaczewski and Rivard, 2018; Lypaczewski et al., submitted). This technique was also applied to document the surficial dispersion of the footprint in the overlaying quaternary sediments (i.e., glacial till, Taylor et al, 2018).

4) Petrophysical properties and geophysical responses are controlled by multiple parameters including mineralogy, porosity and structures. The strong mineral abundance variations in mafic dykes results in a density decrease toward the mineralization. In the Canadian Malartic district, mafic dykes are not volumetrically significant and cannot produce a detectable gravity anomaly. However, a similar hydrothermal alteration in areas dominated by mafic volcanic rock may result in a negative gravity response. Historical Induced-Polarization surveys in the Canadian Malartic district were not successful to detect hydrothermal alteration and gold mineralization. Petrographic investigations of the ore textures highlighted that the increase of pyrite abundance toward the deposit is associated with encapsulation of the pyrite grains in microcline and albite, diminishing the surface of contact between the sulfide minerals and the porosity, and resulting in a negative chargeability anomaly (Bérubé et al., in press). This result suggests that a good understanding of the mineralization assemblage is critical to correctly interpret the geophysical signal. High resolution (meter-scale) time-domain and spectral induced polarization ground surveys were conducted and succeed to detect mineralized sedimentary rocks.

CONCLUSIONS

These innovative and multidisciplinary approaches to investigate mineralized systems revealed over one hundred field- and laboratory-based factors for gold exploration in Precambrian greenstone belt of the Superior Province. Combining these parameters using principal component analysis (Perrouty et al., in press), support vector machine (Bérubé et al., 2018) or other data integration solutions enhance their capacity to vector toward a deposit and decrease the possibility of false positive results. On-going 3D modeling, data integration work and prospectivity analysis at the scale of a greenstone belt (Montsion et al., in press) will contribute explaining the difference in gold endowment between greenstone belts and will provide a new perspective for greenfield exploration. Several vectors that were used to define the footprint Canadian Malartic are also applicable in other geological settings and could be developed further to enhance exploration success in challenging sub-tropical environment, with rare and highly weathered rock exposures, like in the Guiana Shield.

ACKNOWLEDGMENTS

Thanks to all my research colleague of the Metal Earth and Footprints programs for their contribution and thanks to the Canadian Malartic Mine, exploration and production departments for their logistical support during field work. Funding for Metal Earth and Footprints research programs was provided by Canada First – Research Excellence Fund, the Natural Sciences and Engineering Research Council of Canada and the Canada Mining Innovation Council through the NSERC Collaborative Research and Development Program. NSERC-CMIC Mineral Exploration Footprints Project Contribution 200. CFREF Metal Earth Project Contribution MERC-ME-2018-079.

REFERENCES

Bérubé, C.L., Olivo, G.R., Chouteau, M., Perrouty, S., Shamsipour, P., Enkin, R.J., Morris, W.A., Feltrin, L., Thiémonge, R., 2018, Predicting rock type and detecting hydrothermal alteration using machine learning and petrophysical properties of the Canadian Malartic ore and host rocks, Pontiac Subprovince, Quebec, Canada. Ore Geology Reviews, 96, 130–145.

Bérubé, C.L., Olivo, G.R., Chouteau, M., Perrouty, S. Mineralogical and textural controls on spectral induced polarization signatures of the Canadian Malartic gold deposit: applications to mineral exploration. Geophysics, in press.

Derry, D.R., 1939. The geology of the Canadian Malartic gold mine, N. Quebec. Economic Geology, 34, 495–523.

De Souza, S., Dubé, B., McNicoll, V.J., Dupuis, C., Mercier-Langevin, P., Creaser, R.A., Kjarsgaard, I.M., 2015. Geology, hydrothermal alteration, and genesis of the world-class Canadian Malartic stockwork-disseminated Archean gold deposit, Abitibi, Quebec. In: Dubé, B., Mercier-Langevin, P., (Eds), Targeted Geoscience Initiative 4: Contributions to the Understanding of Precambrian Lode Gold Deposits and Implications for Exploration. Geological Survey of Canada, Open File 7852, 113–126.

Dubé, B., Gosselin, P., 2007. Greenstone-hosted quartz-carbonate vein deposits. In: Goodfellow, W.D. (Ed.), Mineral Deposits of Canada: A Synthesis of Major Deposit Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods. Geological Association of Canada, Mineral Deposits Division, pp. 49–73. Special Publication 5.

Frieman, B.M., Kuiper, Y.D., Kelly, N.M., Monecke, T., Kylander-Clark, A., 2017. Constraints on the geodynamic evolution of the southern Superior Province: U-Pb LAICP-MS analysis of detrital zircon in successor basins of the Archean Abitibi and Pontiac subprovinces of Ontario and Quebec, Canada. Precambrian Research, 292, 398–416.

Frieman, B.M., Perrouty, S., 2018. Preliminary structural and stratigraphic investigations along the Metal Earth Dryden-Stormy Lake transect. Open-File Report, Ontario Geological Survey, in press.

Gaillard, N., Williams-Jones, A.E., Clark, J.R., Lypaczewski, P., Salvi, S., Perrouty, S., Piette-Lauzière, N., Guilmette, C., Linnen, R.L., 2018. Mica composition as a vector to gold mineralization: deciphering hydrothermal and metamorphic effects in the Malartic district, Quebec. Ore Geology Reviews, 95, 789–820.

Gervais, D., Roy, C., Thibault, A., Pednault, C., Doucet, D., 2014. Technical Report on the Mineral Resource and Mineral Reserve Estimates for the Canadian Malartic Property. Mine Canadian Malartic, 460 p.

Helt, K.M., Williams-Jones, A.E., Clark, J.R., Wing, B.A., Wares, R.P., 2014. Constraints on the Genesis of the Archean Oxidized, Intrusion-Related Canadian Malartic Gold Deposit, Quebec, Canada. Economic Geology, 109, 713–735.

Lesher, C.M, Hannington, M.D., Galley, A.G., and the Mineral Exploration Research Network , 2017. 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, Exploration '17, Toronto, ON, 23 p.

Lypaczewski, P., Rivard, B., 2018. Shortwave infrared reflectance spectroscopy of white mica, biotite and chlorite with variable mineral chemistries. International Journal for Earth Observation and Geoinformation, 68, 116–126.

Lypaczewski, P., Rivard, B., Gaillard, N., Perrouty, S., Piette-Lauzière, N., Bérubé, C.L., Linnen, R.L. Hyperspectral imaging as a tool for vectoring towards mineralization; study of the Canadian Malartic gold deposit, Quebec, Canada. Ore Geology Reviews, submitted.

Mercier-Langevin, P., Dubé, B., Lafrance, B., Hannington, M., Galley, A., Moorhead, J., Gosselin, P., 2007. Metallogeny of the Doyon-Bousquet-LaRonde mining camp, Abitibi Greenstone Belt, Quebec. In: Goodfellow, W.D. (Ed.), Mineral Deposits of Canada: A Synthesis of Major Deposit-Types, District Metallogeny, the Evolution of Geological Provinces, and Exploration Methods. Geological Association of Canada, Mineral Deposits Division, pp. 673–701. Special Publication 5.

Mir, R., Perrouty, S., Astic, T., Bérubé, C.L., Smith, R.S. Identification of structurally complex gold-mineralized zones using airborne EM and ground IP in the Canadian Malartic district, Quebec, Canada. Geophysics, in press.

Montsion, R.M., Thurston, P., Ayer, J., 2018. 1:2,000,000 scale geological compilation of the Superior Craton, Metal Earth, Mineral Exploration Research Center, Laurentian University. 1 p.

Montsion, R.M., Perrouty, S., Frieman, B.M. Preliminary regional interpretation and sampling program for modeling and prospectivity analysis of the Western Wabigoon subprovince. Open-File Report, Ontario Geological Survey, in press.

Perrouty, S., Gaillard, N., Piette-Lauzière, N., Mir, R., Bardoux, M., Olivo, G.R., Linnen, R.L., Bérubé, C.L., Lypaczewski, P., Guilmette, C., Feltrin, L., Morris, W.A., 2017. Structural setting for Canadian Malartic style of gold mineralization in the Pontiac Subprovince, south of the Cadillac Larder Lake Deformation Zone, Québec, Canada. Ore Geol Reviews, 84, 185–201.

Perrouty, S., Linnen, R.L., Lesher, C.M., Olivo, G.R., Piercey, S.J., Gaillard, N., Clark, J.R., Enkin, R.J. Expanding the size of multi-parameter metasomatic footprints in gold exploration: utilization of mafic dykes in the Canadian Malartic district, Quebec, Canada, Mineralium Deposita, in press.

Piette-Lauziere, N., Guilmette, C., Bouvier, A., Perrouty, S., Pilote, P., Gaillard, N., Lypaczewski, P., Linnen, R.L., Olivo, G.R. The timing and extent of prograde metamorphism in the Pontiac subprovince, Superior Craton: implications for Archean geodynamics and gold mineralization. Precambrian Research, submitted.

Raskevicius, T., Beaudoin, G., Kyser, T.K., Perrouty, S., Gaillard, N. Whole-rock $d^{18}O$ and $d^{2}H$ footprint of the Canadian Malartic Gold deposit, Pontiac subprovince, Quebec, Canada. Mineralium Deposita, submitted.

Robert, F., 2001. Syenite-associated disseminated gold deposits in the Abitibi greenstone belt, Canada. Mineralium Deposita 36, 503–516.

Taylor, C.E., Ross, M., Perrouty, S., Lypaczewski, P., Rivard, B., Clark, J.R., Linnen, R.L., Taves, R., 2017. Detecting increasingly larger exploration footprints of a world-class stockwork-disseminated Au deposit: integration of hyperspectral imaging and petrography of glacial clasts in surficial sediments. Abstract, CIM-GAC-MAC, Vancouver, BC, 1 p.