Call for candidates for research projects on

The metallogeny of orogenic gold deposits

The Agnico Eagle – Eldorado - MRNF Alliance Team

The Agnico Eagle – Eldorado - MRNF Alliance Team is a 5-year major research initiative funded by NSERC and partners Agnico Eagle, Eldorado Gold and Ministère des Ressources Naturelles et des Forêts (MRNF)to study the metallogeny of orogenic gold deposits. The team comprises researchers from Université Laval (Profs G. Beaudoin, C. Guilmette, C. LaFlamme, and B. Rottier), and INRS-ETE (Prof. R. Soucy La Roche). The Alliance Team offers a dynamic and collaborative training environment comprising more than thirty graduate students and research associates. Université Laval is amongst the top-ranked universities in Canada. Recognized for its leadership and high achievements in education and research, it offers a welcoming and diverse environment in the heart of Quebec City, a UNESCO World Heritage City (http://www.quebecregion.com/en/). The university community comprises over 50,000 students and offers an engaging work environment in an outstanding quality of life setting.

We are calling for applications to undertake **seven** PhD projects and **one** 2.5 years post-doctoral fellowship (PDF). The projects comprise **1)** regional scale studies of orogenic gold districts, **2)** studies to date and determine the origin of auriferous fluid events in important orogenic gold deposits, **3)** development of new indicator mineral methodologies to fingerprint the origin, vector towards ore and assess metal endowment of orogenic gold deposits, **4)** investigation of geomechanical modeling of fluid flow and deformation in relationship to gold deposition, and **5)** development of exploration methodologies for orogenic gold deposits using portable instruments. The project titles are listed below, and detailed descriptions are appended.

1. **Regional scale studies** – Understanding the regional geological setting of gold deposits is a critical component for targeting of regions with higher potential to host orogenic gold deposits.
   a. **Bonnefond corridor (PhD1)** – The Bonnefond corridor is a sector of the Val-d'Or orogenic gold vein field, in the Neoarchean Abitibi sub-province (Québec), south and southwest of the Bourlamaque batholith.
   b. **Hope Bay (PhD2)** – Hope Bay is a strongly deformed, 100 km long greenstone belt in the Neoarchean Slave Province (Nunavut), that contains several gold deposits.
2. **Dating gold mineralization events and source of fluids** – deposit scale studies to date fluid flow events and to understand the source and flow of hydrothermal fluids forming gold deposits.
   a. **Meliadine (PhD3):** Meliadine (Nunavut) hosts a series of orogenic gold deposits located along the Pyke Fault, with a complex history.
3. **Indicator minerals** – The projects will continue to develop fingerprinting provenance, vectoring and fertility exploration tools.
   a. **Arsenopyrite (PhD4):** arsenopyrite is a common gold associated mineral for which trace element data are scarce.

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b. **Ormaque (PhD5):** a case-study at Ormaque (Val-d'Or) quartz-tourmaline-carbonate veins to devise innovative indicator mineral vectoring and fertility assessment tools to target gold oreshoots.
c. **Nunavik (PhD6):** this case study will integrate the indicator mineral fingerprinting methodologies in a large regional survey in Nunavik (northern Québec) carried by the MRNF.

4. **Geomechanical modeling of deformation/fluid flow (PDF)** – a common feature in orogenic gold deposits is strain partitioning within and/or between competent intrusive rocks and less competent volcanic country rocks. The study will investigate variations in shear and dilatational strain localization between the intrusive bodies and their host rocks, which are a major control on the distribution of gold mineralization.
5. **Field-Based Methodologies** – develop application of portable instruments for in-field results enabling fast decision making in exploration workflows.
   a. **pSWIR Bonnefond corridor (PhD7):** this study will field test application of portable Short Wave InfraRed (pSWIR) for detection of gold fertile alteration in both granodioritic rocks of the Bourlamaque batholith and in mafic to felsic volcanic rocks of the Bonnefond corridor, which also host volcanogenic massive sulfide (VMS) deposits and related alteration zones.

The **PhD projects** are supported with a scholarship of 27 500$ per year for 3 years. PhD candidates can receive up to $8,500 from the University for achieving milestones in their training program in addition to their scholarship. Foreign PhD students receive a waiver of international tuition fees to the level of students residing in Québec. This scholarship can be cumulated with another excellence award. The **PDF** will receive a salary commensurate with qualifications. The candidates will have the opportunity to conduct original research and to present it at national and international conferences. Projects will start in January or May 2023. Positions are open until filled. Fluency in spoken and written English is mandatory whereas proficiency in French is beneficial, but not required. The team will supervise students in their preferred language (English or French).

Valuing equity, diversity and excellence, Université Laval is strongly committed to provide an inclusive work and living environment for all its members. **We subscribe to equal access and encourage qualified individuals** of all origins, sexes, sexual orientations, gender identities or expressions, as well as persons with disabilities, to apply.

Candidates should send their curriculum vitae, a letter of motivation indicating which project(s) are of interest, and the names of 3 references to:

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Appendix – Detailed description of projects

1. **Regional scale studies** – Understanding the regional geological setting of gold deposits is a critical component for targeting of regions with higher potential to host orogenic gold deposits.

a. **Bonnefond corridor (PhD1)** – The Bonnefond corridor is a sector of the Val-d'Or orogenic gold vein field, in the Neoarchean Abitibi sub-province (Québec), south and southwest of the Bourlamaque batholith. The volcanic country rocks are intruded by several intrusive bodies, both syn- and post-volcanic, including the Bonnefond South tonalitic to dioritic complex and the New Louvre tonalite sill. The intrusions and their immediate host rocks are cut by second- and third-order shallow-dipping (15 and 45º) shear zones that host gold-bearing quartz-carbonate-tourmaline veins. Efficient exploration requires a better understanding of the relations between the intrusion age, petrology and geochemistry, and that of the volcanic host rocks and the overlapping VMS (e.g., Louvicourt) and orogenic gold mineralized systems. **Objectives**: i) characterize the petrological and geochemical evolution of the volcanic and intrusive rocks; ii) constrain the chronology of intrusive activity; iii) establish the paragenetic sequence of mineralization and alteration; iv) define the structural framework of the shear zones and veins; v) compare with other gold deposits hosted in tonalitic and dioritic intrusions. **Activities:** detailed field mapping and core logging, followed by petrography, microstructural analysis, lithogeochemistry, mineral chemistry and geochronology of intrusions. **Anticipated results:** i) a framework explaining the petrochronologic evolution of the intrusions, their geochemical affinity and conditions during emplacement; ii) the structural evolution of the vein-hosting shear zones; iii) the paragenetic evolution on mineralization and alteration; iv) constraints on the timing and role of the intrusions for gold mineralization; v) improved map of the Bonnefond corridor and new exploration guides.

b. **Hope Bay (PhD2)** – Hope Bay is a strongly deformed, 100 km long greenstone belt in the Neoarchean Slave Province (Nunavut), that contains several gold deposits formed during the main D_2 deformation event (Sherlock et al. 2012). It is metamorphosed to lower greenschist facies, with higher metamorphic grade (lower amphibolite) at the contact with surrounding granite/gneiss. Several smaller zones of higher metamorphic grade are recognized proximal to gold mineralization suggesting localized higher thermal regime or carbonic fluid flux as in Timmins/Kirkland Lake (Thompson 2005). This relationship need to be documented in detail to assess its control on localization of gold mineralization and to develop innovative exploration guides. **Objectives**: i) map the structural patterns and distribution of metamorphic facies with emphasis on metamorphic "hot spots"; ii) estimate rock/fluid thermobarometric conditions; iii) establish the geodynamic setting of volcanism, metamorphism/deformation, and gold mineralization; iv) constrain the chronology of deformation, metamorphism, and gold mineralization.

Activities: detailed field mapping of metamorphic facies, petrography, microstructural analysis and lithogeochemistry, thermobarometric phase diagrams for rock and fluid phase equilibrium, dating of tectonometamorphism. **Anticipated results:** i) improved tectono-metamorphic map of the Hope Bay greenstone belt; ii) metamorphic and deformation history of the belt; iii) relation between tectono-metamorphic evolution and mineralization; iv) new exploration guides.

2. **Dating gold events and source of fluids** – deposit scale studies to date fluid flow events and to understand the source and flow of hydrothermal fluids forming gold deposits.

a. **Meliadine (PhD3):** Meliadine hosts a series of Banded-Iron Formation (BIF) associated orogenic gold deposits located along the Pyke Fault, in Nunavut. Dating of arsenopyrite by Re/Os yields a range of model ages from 2.3 to 1.8 Ga (Lawley et al. 2015). Late xenotime in quartz veins and altered host rocks yielded SHRIMP ages of 1858±10 Ma (Lawley et al. 2015) similar to monazite 1854±6 Ma (Carpenter et al. 2005), but the relationship of the dated phosphate grains with gold mineralization is equivocal. Thus, the age of gold mineralization is uncertain, and the source of fluids has not been investigated, such that the origin of the gold mineralization hosted in Archean rocks, overprinted by Paleoproterozoic events, remains mysterious, thus hampering efficient exploration in similar terranes. **Objectives**: i) date auriferous hydrothermal fluid flow events using phosphate U/Pb geochronology on grains related to gold deposition; ii) establish the source of fluids, gold ligands, and metals; iii) present a framework relating the auriferous fluid events to the tectonometamorphic evolution of the country rocks. **Activities:** detailed paragenetic sequence of gold mineralization and deformation, geochronology of phosphate minerals, stable isotope geochemistry of sulfides and vein minerals (bulk and in situ). **Anticipated results:** i) age of gold mineralization and other hydrothermal events; ii) source and evolution of hydrothermal fluids, gold ligands and metals; iii) improved understanding of potentially polyphased orogenic gold deposits; iv) implications and new guides for gold exploration.

3. **Indicator minerals** – The NSERC-Agnico Eagle Industrial Research Chair in Mineral Exploration as established itself as the international leader in indicator mineral research. The proposed research will continue to develop our leadership in fingerprinting the provenance of indicator minerals, on indicator mineral vectoring and fertility exploration tools.

a. **Arsenopyrite (PhD4):** arsenopyrite is a common gold associated mineral for which trace element data are scarce. This hampers application of indicator minerals for deposits where arsenopyrite is abundant, such as orogenic gold deposits in Nunavut. **Objectives**: i) measure the major and trace element composition of arsenopyrite from a range of geological settings; ii) define chemical criteria to fingerprint arsenopyrite sourced from orogenic gold deposits; iii) carry case studies to test application of arsenopyrite for provenance surveys. **Activities:** acquire a set of representative samples from orogenic gold and other settings, measure the major and trace element composition of arsenopyrite, statistical analysis of chemical composition using

multivariate and machine learning methods. **Anticipated results:** i) a database of arsenopyrite major and trace element composition; ii) chemical criteria to discriminate the source of arsenopyrite; iii) methodology to use arsenopyrite in exploration for orogenic gold deposits.

b. **Ormaque (PhD5):** this orogenic gold deposit (Val-d'Or) is mostly formed by a set of extensive sub-horizontal quartz-tourmaline-carbonate veins principally hosted in a porphyry intruded in volcanic rocks, but with a geometry different from the Triangle deposit currently mined by Eldorado Gold Quebec. **Objectives**: i) define the paragenetic sequence of successive gold mineralization events; ii) measure the chemical and isotope composition of minerals associated with gold deposition; iii) identify textural, chemical, isotopic features associated with gold; iv) define vectoring criteria to target gold oreshoots. **Activities:** field, underground mapping and core logging, mineral (ore and gangue) chemical and stable isotope composition (bulk and in situ), petrography of gold mineralization, statistical data analysis. **Anticipated results:** i) characteristic textures, chemical and isotopic composition of minerals intimately associated with gold; ii) discriminating criteria between ore and gangue minerals associated with gold or not; iii) indicator mineral vectoring methodologies to vector towards ore shoots in a deposit.
c. **Nunavik (PhD6):** this case study will integrate the indicator mineral fingerprinting methodologies developed by the previous and proposed research programs in a large regional survey in Nunavik (northern Québec) carried by the MERN. **Objectives**: i) measure the abundance of indicator minerals (scheelite, tourmaline, gold, chalcopyrite, arsenopyrite) in till; ii) measure the major and trace element composition of indicator minerals; iii) assess the provenance of indicator minerals using previous studies fingerprinting criteria; iv) identify deposit types eroded and dispersed in glacial sediments. **Activities:** measure the abundance of indicator minerals in heavy mineral concentrate, measure the major and trace element composition, and mineral association of indicator minerals, apply fingerprinting criteria to assess provenance. **Anticipated results:** i) relative abundance of indicator minerals; ii) database of chemical composition of indicator minerals; iii) classification of potential sources for each indicator mineral, based on chemical criteria.

4. **Geomechanical modeling of deformation/fluid flow (PDF):** a common feature in orogenic gold deposits is strain partitioning within and/or between competent intrusive rocks and less competent volcanic country rocks. Variations in shear and dilatational strain localization between the intrusive bodies and their host rocks is a major control on the distribution of gold mineralization, like in Triangle and several other deposits in the Val-d'Or vein field. A better understanding of the relationships between deforming intrusions, weaker host rocks and fluid flow is crucial. **Objectives**: i) measure rock properties for various lithologies and their alteration products; ii) model rock deformation and fluid flow; iii) establish parameters favorable for localized strain and dilation; iv) compare modeling results to Triangle and other intrusion hosted gold deposits in the Val-d'Or vein field. **Activities:** measure rock

properties, 2D (UDEC) and 3D (FLAC3D) numerical modeling of coupled deformation and fluid flow, compare results to 3D shear and vein, and alteration distribution at Triangle and other deposits. **Anticipated results:** i) relationships between deformation, rock rheology and shear and vein formation; ii) predictive model of gold mineralization localization; iii) key geological features that need to be documented during core logging to predict mechanical behavior; iv) new exploration guides.

5. **Field-Based Methodologies:** field-based methodology projects are designed to develop application of portable instruments for in-field results enabling fast decision making in exploration workflows.

a. **pSWIR Bonnefond corridor (PhD7):** this study will field test application of portable Short Wave InfraRed (pSWIR) for detection of gold fertile alteration in both granodioritic rocks of the Bourlamaque batholith and in mafic to felsic volcanic rocks of the Bonnefond corridor, which also host volcanogenic massive sulfide (VMS) deposits and related alteration zones, building on the alteration facies SWIR spectra database of Eldorado Gold (Québec) Inc. The pSWIR instrument has seen wide adoption for mapping alteration in epithermal and porphyry systems, but less so in exploration for orogenic gold despite promising results obtained by the CMIC-Footprint team at Canadian Malartic (Lypaczewski et al. 2019). **Objectives**: i) measure SWIR absorption spectra in alteration zones related to gold mineralization, in areas devoid of gold, and in VMS alteration zones, in the field and in drill core samples; ii) compare the chemical composition of micas and other alteration mineral to their absorption spectra to identify gold-related alteration; iii) relate the SWIR spectra to geological context (metamorphic, versus hydrothermal VMS or orogenic gold); iv) carry out case studies on outcrops and drill core. **Activities:** acquire SWIR spectra on outcrops and on drill cores, measure in situ the chemical composition of alteration minerals, analyse the relationship between spectral features, chemical composition, and fertility for gold mineralization. **Anticipated results:** i) library of characteristic SWIR absorption spectra of orogenic gold-related, unrelated, and VMS alteration minerals; ii) discriminant criteria for gold-related and unrelated hydrothermal alteration; iii) field-based methodology to integrate pSWIR to exploration survey workflow.