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Targeted Geoscience Initiative 4: Contributions to the Understanding of Precambrian Lode Gold Deposits and Implications for Exploration

Petrophysical signature of gold mineralization and alteration assemblages at the Canadian Malartic deposit, Quebec

Najib El Goumi[1], Stéphane De Souza[2], Randolph J. Enkin[1], and Benoît Dubé[2]

[1]Geological Survey of Canada, Sidney, British Columbia
[2]Geological Survey of Canada, Québec, Quebec

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Contribution to the Geological Survey of Canada's Targeted Geoscience Initiative 4 (TGI-4) Program (2010–2015)

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Najib El Goumi[1], Stéphane De Souza[2], Randolph J. Enkin[1]*, and Benoît Dubé[2]

[1]Paleomagnetism and Petrophysics Laboratory, Geological Survey of Canada, P.O. Box 6000, Sidney, British Columbia V8L 4B2
[2]Geological Survey of Canada, 490 rue de la Couronne, Québec, Quebec G1K 9A9
*Corresponding author's e-mail: renkin@nrcan.gc.ca

ABSTRACT

The rock physical properties of samples from the Canadian Malartic gold deposit in the Abitibi greenstone belt of Quebec have been measured to relate lithology and alteration assemblages to physical properties contrasts, and to provide geological interpretation of geophysical survey analyses for this type of ore deposit. Disseminated gold deposits are seldom directly characterized by a clear geophysical signature. However, we propose that a geophysical characterization of such ore deposits can be achieved by combining cost-effective geophysical surveys to identify zones of interest for gold exploration. This study has shown that the metasedimentary rocks and porphyritic intrusions that host the gold mineralization show similar variations in rock physical properties, probably because both rock types have similar geochemical and mineralogical compositions. However, the intrusive rocks show both magnetic and non-magnetic phases, and have a slightly lower density than metasedimentary rocks. Hydrothermal alteration produced continuous trends for magnetic susceptibility, density, and electric chargeability, but with no apparent variation in magnetic remanence and resistivity. These trends of decreasing density and magnetic susceptibility and increasing chargeability are correlated with alteration facies (carbonate saturation index), gold concentration, and proximity to ore. Based on this correlation, a principal component analysis petrophysical proxy has been established to represent this gradual hydrothermal mineralization process. This petrophysical proxy is a valid estimation of the variability of the rock physical properties inside the actual pit area of the Canadian Malartic deposit. Based on composite geophysical surveys (gravity, magnetic, and induced polarization) and inversion of the surface data for rock physical properties at depth, a petrophysical proxy, such as presented here, could help target zones of interest for orebodies similar to that at Canadian Malartic.

INTRODUCTION

Rock physical properties allow integration of geological and geophysical data and constitute an essential element of Common Earth Models (McGaughey, 2006). In the geological environment of a hydrothermal ore system, petrophysical characterization can play a key role for predicting geophysical methods that will be useful in mineral exploration.

The goal of this Geological Survey of Canada – Targeted Geoscience Initiative 4 (TGI-4) study is to define mutual relationships between physical properties (density, porosity, magnetic susceptibility and remanence, electrical resistivity and chargeability) and the local geological setting (lithology, alteration, structures, and metamorphism), to integrate data in geological models, and to constrain geophysical inversions. The project also aims to identify which combination of geophysical methods will give the best exploration results. This contribution presents a suite of rock property measurements from the Canadian Malartic low-grade, bulk-tonnage gold deposit and discusses implications for improvements in the use of geophysical methods in gold exploration.

The Archean Abitibi greenstone belt (700 km by 200 km) is located within the Superior Province and is known to host world-class gold and base metals deposits (Fig. 1; Poulsen et al., 1992, 2000; Robert et al., 2005; Dubé and Gosselin, 2007). The tectonic contact between the Abitibi and Pontiac subprovinces is marked by the Larder Lake - Cadillac Fault Zone, which is delineated by highly strained mafic and ultramafic rock slivers belonging to the Piché Group (Robert, 1989; Card, 1990; Daigneault et al., 2002). The Canadian Malartic gold deposit, which is located immediately to the south of the Larder Lake - Cadillac Fault Zone, is mainly hosted by turbiditic greywacke and mudstone of the Pontiac Group and by Timiskaming (2677–2678 Ma) porphyritic quartz monzodiorite with local granodiorite intrusions (Fig. 2; Sansfaçon and Hubert, 1990; De Souza et al., 2013, in press; Helt et al., 2014). In the mine area, the Pontiac Group was metamorphosed to biotite-chlorite facies

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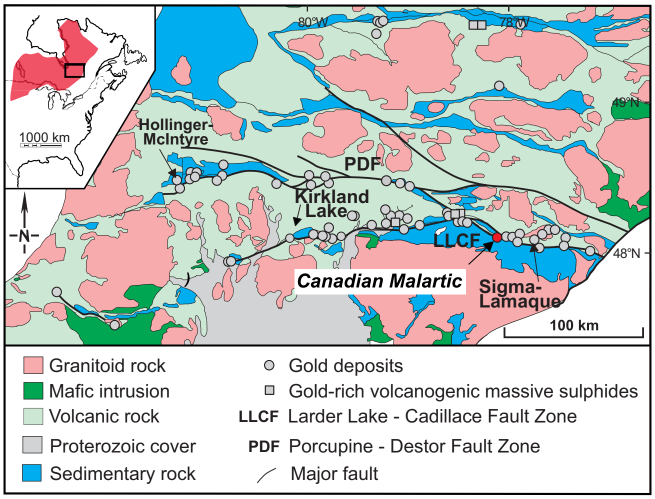

Figure 1. Simplified geological map of the Abitibi greenstone belt. The Canadian Malartic gold deposit is identified by a red dot. The inset shows the location of the Abitibi belt within the Superior Province (red). Map is adapted from Dubé and Gosselin (2007) and Poulson et al. (2000).

and has undergone polyphase deformation with a dominant S_2 pressure-solution cleavage that is related to the formation of open to tight F_2 folds and is northwest-striking and north-dipping (Fig. 2; Sansfaçon and Hubert, 1990; De Souza et al., 2015, in press). The orebodies are characterized by the presence of stockwork and disseminated gold mineralization. Ore minerals include disseminated pyrite (~ ≤5%) with traces of telluride, galena, chalcopyrite, sphalerite, and molybdenite. The main orebodies define northwest-southeast and east-west trends that correspond, respectively, to the orientation of the dominant S_2 foliation and to the Sladen Fault. The latter is a south-dipping brittle-ductile structure that controls the distribution of the east-west-trending ore (Sansfaçon and Hubert, 1990; De Souza et al., 2015, in press). The main auriferous hydrothermal alteration types documented at Canadian Malartic are widespread carbonate alteration (calcite+ferroan dolomite), albitization, potassic alteration (biotite+microcline), and local silicification (De Souza et al., 2015). The least altered sedimentary rocks and the quartz monzodiorite are composed of biotite-muscovite-oligoclase-chlorite ± pyrite-epidote-ilmenite-pyrrhotite-magnetite and orthoclase-oligoclase-quartz-biotite-hornblende-epidote-muscovite-magnetite-titanite assemblages, respectively. Distal alteration in the sedimentary rocks comprises biotite, calcite, muscovite, and pyrite, whereas proximal alteration consists of albite and/or microcline, quartz, carbonate (ferroan dolomite+calcite), phlogopite, rutile, and pyrite. Phlogopite is however absent in pervasively altered

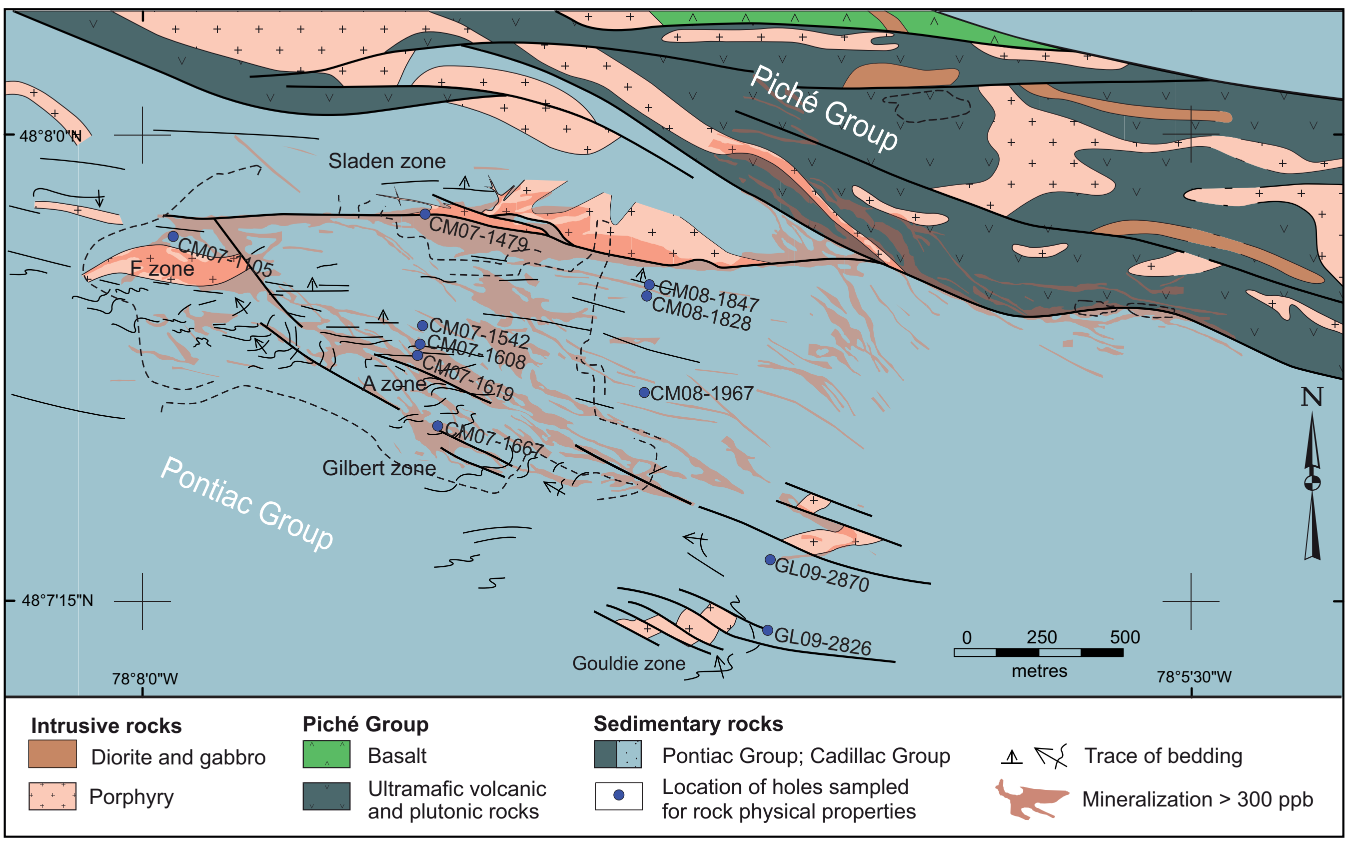

Figure 2. Geological setting of the Canadian Malartic gold deposit hosted by rocks of the Piché and Pontiac groups. Blue circles show the location of the drillholes that were sampled for rock physical properties measurements (adapted from De Souza et al., 2013).

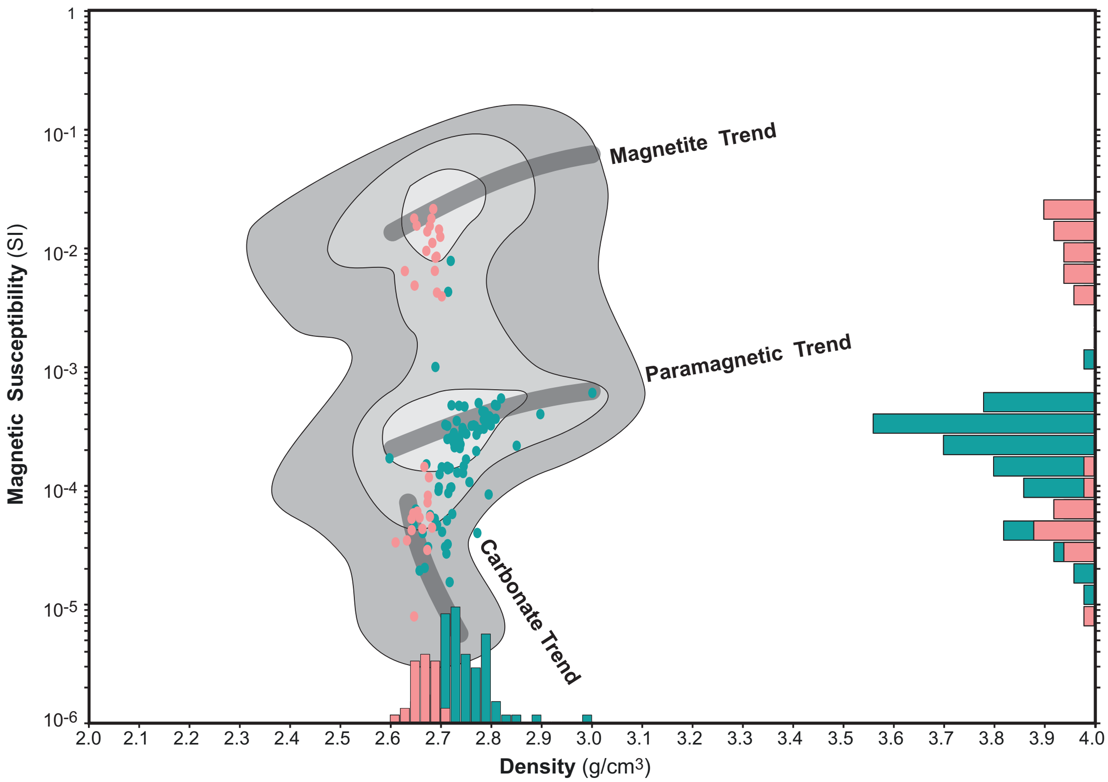

Figure 3. Bivariate plot of the distribution of density versus magnetic susceptibility, with distribution contours, and trends based on the British Columbia Rock Physical Property Database (3388 samples; Enkin, 2014). Density and magnetic susceptibility histograms show variations in metasedimentary (teal-green circles) and intrusive (salmon-pink circles) rocks.

rocks. Distal and proximal alteration assemblages in the quartz monzodiorite are composed of albite-K-feldspar-quartz-biotite-calcite-rutile-magnetite-pyrite-hematite and microcline-albite-ferroan dolomite- calcite-pyrite-rutile, respectively. Field relationships, the nature of the various alteration types, and the geometry of the Au-related veins suggest that gold is largely controlled by syn-D_2 structures and by the Sladen Fault (De Souza et al., 2015, in press). However, the Au-Te-W±Bi-Ag-Mo-Pb geochemical signature of the ore, the presence of stockwork-disseminated Au mineralization, and molybdenite together with potassic alteration, suggest that some of the gold might have been introduced during an early phase of magmatic-hydrothermal alteration that was followed by gold remobilization or a second-stage of gold introduction during D_2 deformation (De Souza et al., 2013, 2015, in press; Helt et al., 2014).

RESULTS AND DATA ANALYSIS

The physical properties were measured for 179 rock samples collected for the TGI-4 project from the Canadian Malartic mine. The collection of core samples was selected from holes drilled within the open pit area (Fig. 2) and is representative of the host lithologies, alteration assemblages, and various ore zones. The rock physical properties summarized in this report are publically accessible in the Canadian Rock Physical Property Database, which is published as a Geological Survey of Canada Open File.

Enkin et al. (2012) describe in detail the measurement protocols and methods. All measurements were conducted on paleomagnetism-size subsamples (2.5 cm diameter, 2.2 cm long cylinders). Samples were saturated with distilled water under vacuum and saturated bulk density was then measured by the weight in air-weight in water method, and porosity was derived from the difference between the dry and water-saturated weights. Magnetic susceptibility was measured using a Sapphire Instruments SI2B susceptibility metre and magnetic remanence was measured with an Agico JR5-A spinner magnetometer. Electrical resistivity and chargeability (Newmont standard time-domain decay) were derived from the complex impedance spectrum measured using a Solartron 1260 Frequency Response Analyser. Gold assays for 139 samples of the collection are also presented.

Magnetic and Density Properties

Metasedimentary rocks are weakly magnetic, with magnetic susceptibilities mostly spanning the range 2×10^{-5} to 5×10^{-4} SI and density varies from 2.65 to 2.85 g/cm^3 (Fig. 3). Unlike typical ore rocks containing high concentrations of sulphide and oxide minerals

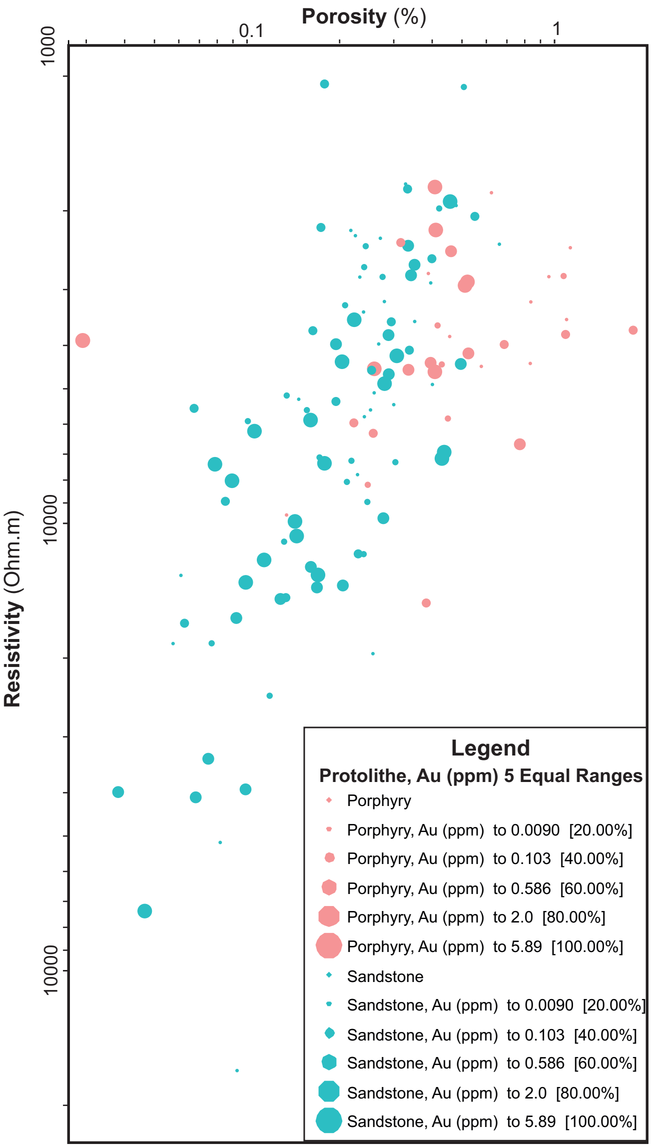

Figure 4. Bivariate diagram of porosity (log scale) and electric resistivity (log scale) revealing their negative correlation. Symbol size related to gold concentration is not correlated with neither porosity nor resistivity for metasedimentary (teal-blue) and intrusive (salmon-pink) rocks.

with densities well above 3.0 g/cm3, disseminated ore zones in the Canadian Malartic deposit have densities that rarely deviate from those of felsic minerals. The biplot of density against magnetic susceptibility does not align along the paramagnetic trend (Henkel, 1994) typical for sedimentary rocks (Fig. 3). Rather, the lower density samples (<2.7 g/cm^3) have magnetic susceptibilities that are anomalously lower by an order of magnitude.

The porphyritic intrusive rocks, mostly least altered quartz monzodiorite or altered quartz monzodiorite, display the typical bimodal magnetic susceptibility distribution of rocks belonging to Henkel's (1994) magnetic and paramagnetic trends, around 10^{-2} and 10^{-4} SI, respectively (Fig. 3). The densities have a restricted range of value of between 2.63 and 2.71 g/cm^3. The porosity was seldom above 1%, which is typical of metamorphosed environments, but we note that the median porosity of porphyries, 0.46%, is more than twice that of the sedimentary rocks, 0.22% (Fig. 4), and density increases with decreasing porosity.

The samples are unoriented, so we can only describe the magnitude rather than direction of the magnetic remanence. The Koenigsberger ratio, K_N, which describes the relative magnitude of magnetic remanence to induced magnetism, is almost always below unity for the higher susceptibility ferromagnetic-trend of the intrusive rock samples. The implication is that the rocks that dominate aeromagnetic survey map anomalies can be modelled accurately using the magnetic susceptibility without regard to the remanence. For the weakly magnetic paramagnetic-trend samples, 30% have K_N above unity but are too weak to markedly affect aeromagnetic results.

Electrical Properties

While porosity does not contribute much to variations in density, it does show a clear inverse correlation with the electrical resistivity (Fig. 4). Such porosity control indicates that these rocks conduct electricity dominantly by ionic conduction through their porosity-permeability rather than by galvanic conduction though networks of sulphide and oxide minerals.

Measurement of electric chargeability is important in disseminated ore systems because induced polarization methods can, in principle, detect the unconnected sulphide (conductive) and oxide (semi-conductive) minerals, as they play the role of electric capacitors interrupting the flow of ions through the rock permeability. In the Canadian Malartic deposit, chargeability has a unimodal distribution with a rather low median Newmont chargeability of 5 ms. The 15% of samples with relatively high chargeability (>10 ms) tend to have lower magnetic susceptibilities (<4×10^{-4} SI), but are otherwise unrelated to the other measured physical properties (Fig. 5).

DISCUSSION AND MODELS

Linking Rock Physical Properties to Hydrothermal Alteration

Native gold and sulphide concentrations are low at the Canadian Malartic deposit and the rock physical properties of the mineralized zones are largely controlled by the mineralogy and texture of the auriferous alterations. Geophysical targeting of such disseminated gold deposits can thus be achieved indirectly by examining rock physical properties of disseminated sulphide alteration and ore zones.

Whole-rock geochemical data give limited information about mineralogy, but can be used to estimate mineral and alteration behaviour based on simple geochemical combinations, geochemical ratios, indexes, and assumptions. We make the initial assumption that sulphur concentration is dominated by pyrite. Gold in the Canadian Malartic deposit is hosted as free gold grains and inclusions in pyrite. Fieldwork and core logging indicate that increasing sulphur and gold contents follow the alteration pathway, from distal to proximal alteration zones.

Atypical of most geological environments, both density and porosity become lower with increasing sulphur and gold concentration. The increase in dense minerals, including pyrite, is apparently offset by an increase in less dense silicate and carbonate minerals. Along with the reduction in porosity, there is a slight increase in electrical resistivity of a factor 2 (Fig. 4). A small proportion (15%) of samples has Newmont chargeabilities above 10 ms, a threshold above which they can usually be imaged using induced polarization surveys. Most of the high-chargeability samples contain relatively high Au and S concentrations.

The porphyries display a bimodal magnetic susceptibility. The highly magnetic samples show low-sulphur content, and therefore pyrite content, and have chargeabilities mostly below 10 ms (median below 5 ms), which could be due to low pyrite and high magnetite content (Fig. 5). The low-magnetic samples contain higher sulphur, and therefore higher pyrite content. Chargeabilities are medium but trend toward higher values with increasing sulphur. The trend for magnetic to non-magnetic samples showing increasing values for chargeability is most likely linked to the destruction of primary magnetite and the increasing pyrite content.

In the sedimentary rocks, the distal to proximal alteration assemblages exhibit a trend from low-chargeability + medium-magnetic susceptibility to high-chargeability + low-magnetic susceptibility, which is related to increasing pyrite and gold content. The drop in magnetic susceptibility and increase in chargeability is possibly related to sulphidation, with destruction of magnetite and precipitation of pyrite. Further mineralogical and petrographic analyses should be undertaken to test this interpretation.

A Physical Properties Proxy for Gold Concentration and Hydrothermal Alteration

One of the major goals of the petrophysical study of rocks from a mineral deposit is to delineate rock properties of the ore zones that can be detected from surface geophysical surveys. It has long been noted that geophysical methods have been unsuccessful in delineating the Malartic deposit (Wares and Burzynski, 2011). Indeed the results of the current study reveal that the petrophysical contrasts in this collection are quite subtle.

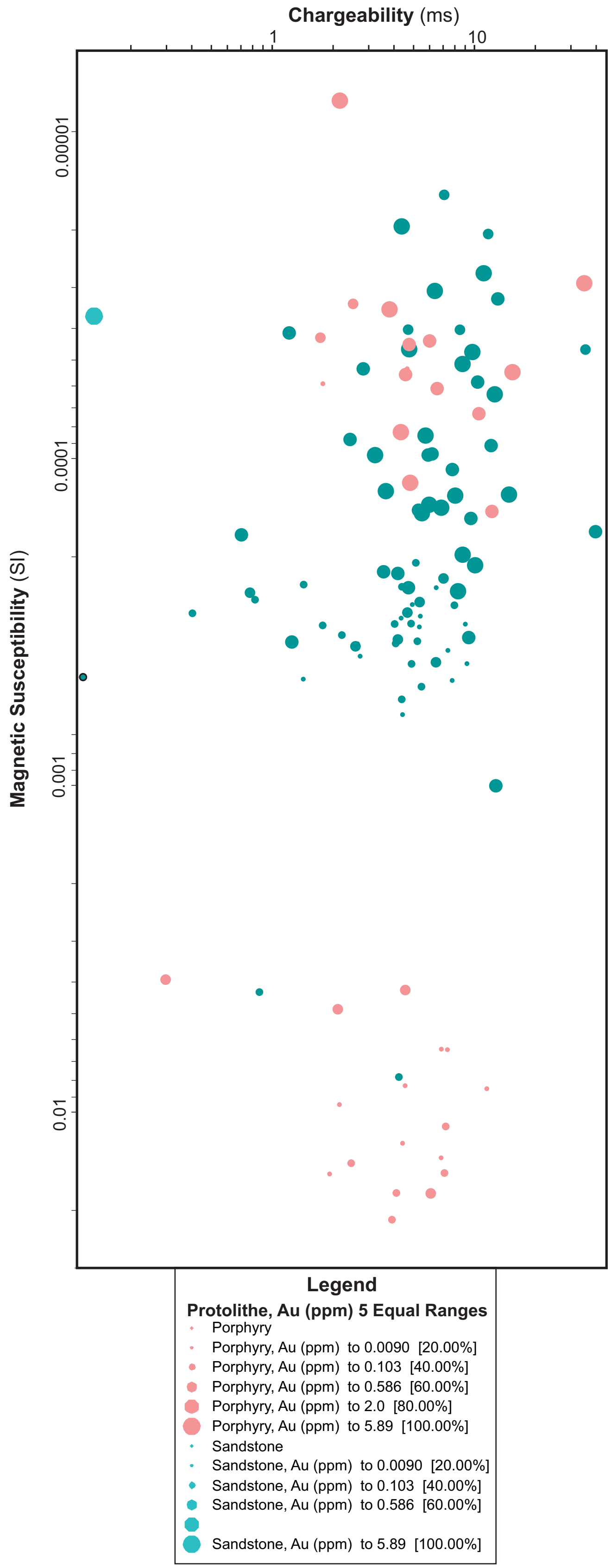

Figure 5. Bivariate diagram of chargeability versus magnetic susceptibility illustrates that highly auriferous samples have physical properties of higher chargeability and low magnetic susceptibility.

We propose that a more useful petrophysical proxy for gold mineralization is obtained by combining multiple physical rock properties, including density, magnetic susceptibility, and chargeability, rather than focusing individually on a single rock physical property.

As gold concentration in the metasedimentary rocks is roughly correlated with the electric chargeability and anti-correlated to the density and magnetic susceptibility, we performed principal component analysis (PCA) on these three physical properties. Since electric resistivity is largely independent of gold concentration, and there was no advantage to including that extra variable. Although gold concentrations are not used in the calculation, they will be used to test the validity of the result. Specifically, we used a robust principal component analysis (Campbell, 1980), with a "low outlier rejection" criterion, as enabled in the geochemical analysis program ioGAS®, which was developed by Reflex. Logarithmic transforms were first applied to the magnetic susceptibility and electric chargeability. The maximum eigenvector, or first PCA component, corresponds to the least-squares line that best fits the data. The proposed proxy is the projection of the measured (density, LOG(susceptibility), LOG(chargeability)) values along that axis:

(1) $$PCA = -0.6268*(dens-2.74)-0.622*LOG(susc/1.64\times10^{-4}) +1.26*LOG(chrg/5.42)$$

where density (dens) is measured in g/cm^3, magnetic susceptibility (susc) in SI units, and Newmont convention electric chargeability (chrg) in ms.

The plotted LOG (gold concentration) function of PCA (Fig. 6) shows that the proxy tracks most of the variation. The correlation coefficient is not strong (R=0.65), but with the removal of the furthest outliers, the correlation coefficient jumps to (R=0.84). The correlation with LOG (sulphur concentration) is however, less pronounced: R=0.62 and increases to R=0.71 after the furthest outliers are expelled. The suggestion is that a preliminary zonation of gold concentration can be accomplished using only surface geophysical measurements to target exploration drilling.

The direct linkage between geochemical, mineralogical and petrophysical data would be the base for innovative direct, remote, cost-effective methods that could be implemented for gold exploration in greenstone belts. In fact, the intensity and nature of alteration in such environments can be monitored by the combination of the carbonate saturation index (CSI) and the chlorite-carbonate-pyrite index (total Fe) (CCPI). The CSI corresponds to the molar ratio of CO_2/(CaO+ MgO+FeO) and is calculated as

(2) $$CSI=(CO_2/44.0095)/(CaO/56.0774+MgO/40.3044+FeO/71.8444)$$

where C needs to be reported as CO_2, Fe can be expressed either as FeO or Fe_2O_3 (Kishida and Kerrich, 1987). While, the calculation of CCPI (Large et al., 2001; Gemmell, 2007) is determined as

(3) $$CCPI=100*(MgO+FeO)/(MgO+Na_2O+FeO+K_2O)$$

where FeO is total (FeO + Fe_2O_3) content of the rock. The alteration indices (CSI and CCPI) and the petrophysical proxy are completely independent from each other but their correlations demonstrate that they monitor the same hydrothermal alteration processes related to gold mineralization.

Our proposed petrophysical proxy displays a strong positive correlation with CSI with R=0.71, which increases to R=0.73 if furthest outliers are removed. It is, however, negatively correlated with CCPI (R= -0.52), but would be strongly correlated if we reject the magnetic porphyry outliers (R=-0.8) (Fig. 7).

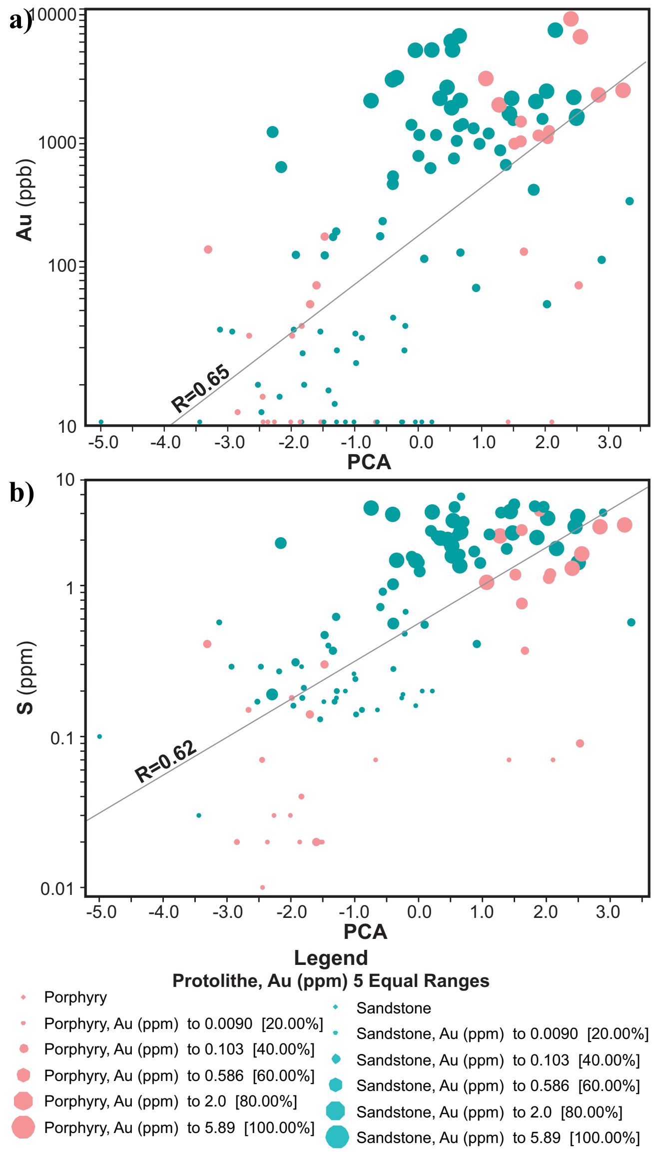

Figure 6. Bivariate diagrams of the petrophysical principal component analysis (CPA) parameter versus **(a)** gold and **(b)** sulphur concentration as a proxy for mineralization.

The implication is that gold and sulphide content are associated with alteration which lowers the density and magnetic susceptibility but increases the electric chargeability. Although pyrite represents the main ore mineral, it is usually present in minor amount (≤5%) and associated with a decrease in Fe of the biotite and breakdown of magnetite in the proximal alteration zones. As a result of hydrothermal alteration and interaction with a CO_2-rich fluid, biotite/phlogopite, plagioclase, epidote, titanite, magnetite, and ilmenite release Fe, Mg, and/or Ca that contribute in part to the formation of carbonate minerals and pyrite, which results in increasing the CSI, whereas increases of K and/or Na are associated with albite and microcline formation, which results in lowering the CCPI. This breakdown of magnetite and Ca-Fe-Mg silicate phases to form pyrite and less dense carbonate, quartz, and feldspar can be linked to the decreasing trends of magnetic susceptibility and density and increasing chargeability in the auriferous hydrothermally altered rocks. Thus petrophysical properties can be used to identify disseminated sulphide gold mineralization and related alteration.

IMPLICATIONS FOR EXPLORATION

Compilation of rock physical properties in national and international databases provides an important tool for mineral exploration. Geological processes that are usually inferred from difficult and costly chemical and mineralogical analyses can be derived from rapid, non-destructive, and inexpensive petrophysical measurements. These measurements contribute to the understanding of the physical change of rocks in ore systems due to alteration, structures, and other geological changes.

In order to assess the subtle change of physical properties in the Canadian Malartic deposit area, a tentative forward modelling of a simple geological model composed of a porphyry body intruded in metasedimentary rocks has been accomplished using the software package Potent®, which provides an interactive framework for 3-D modelling of magnetic and gravity data. A simple 100 m^3 sphere, representing the non-magnetic quartz monzodiorite mineralized body, has been assigned typical rock physical properties of mineralized samples (magnetic susceptibility = 10^{-4} SI and density =2.65 g/cm^3), and the host metasedimentary rocks have been assigned magnetic susceptibility = 8×10^{-4} SI and density = 2.75 g/cm^3. The forward model has taken into account parameters of the geomagnetic field (intensity=57489 nT; inclination = 75.4°; declination=-18.3°) without including magnetic remanence. The results shows that a subtle negative magnetic anomaly of -20 nT and a negative gravity anomaly of -0.17 mgal is to be expected if the top of the body occurs at the surface. If the body is buried (100 m depth), the magnetic anomaly is less than 1 nT and the gravity anomaly is less than -0.02 mgal (Fig. 8).

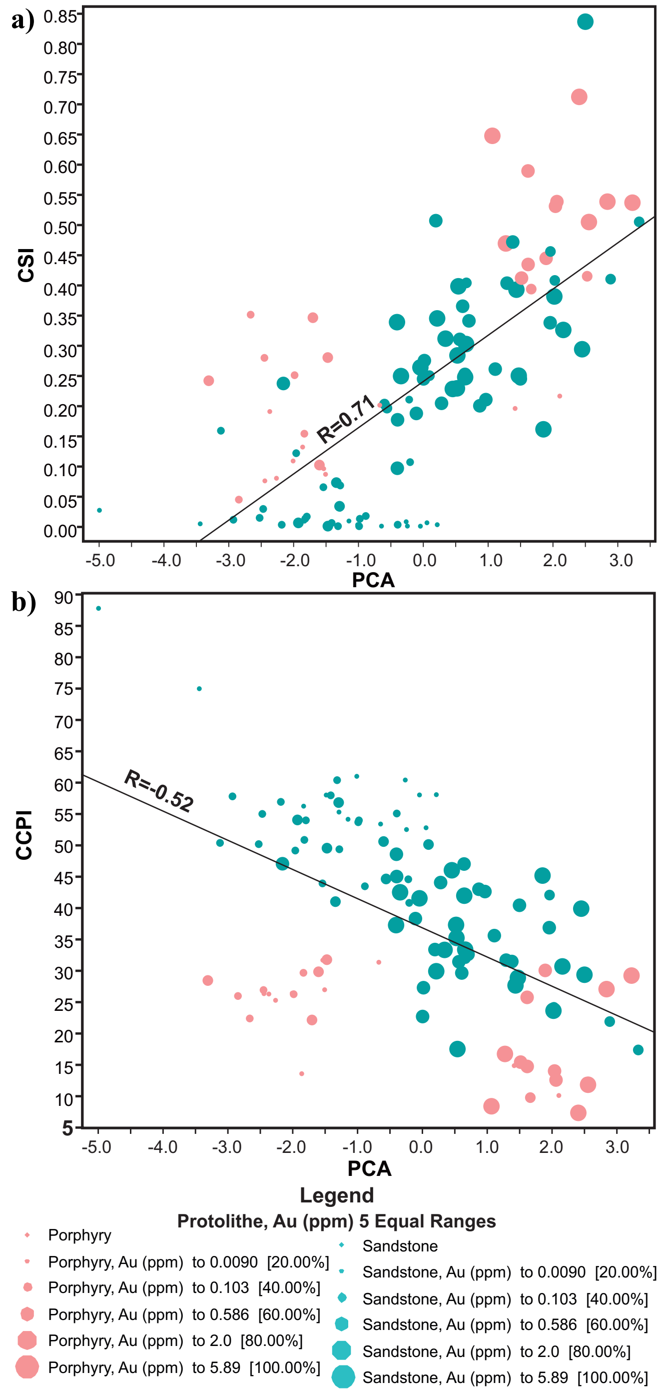

Figure 7. Bivariate diagrams showing the correlation between the principal component analysis (PCA) parameter (petrophysical proxy) versus the alteration indices **(a)** carbonate saturation index (CSI) and **(b)** chlorite-carbonate-pyrite index (CCPI).

Rock physical properties not only allow one to correlate and integrate geology to geophysics, but also can also allow one to optimize geophysical exploration for ore systems by defining the cost-effective geophysical

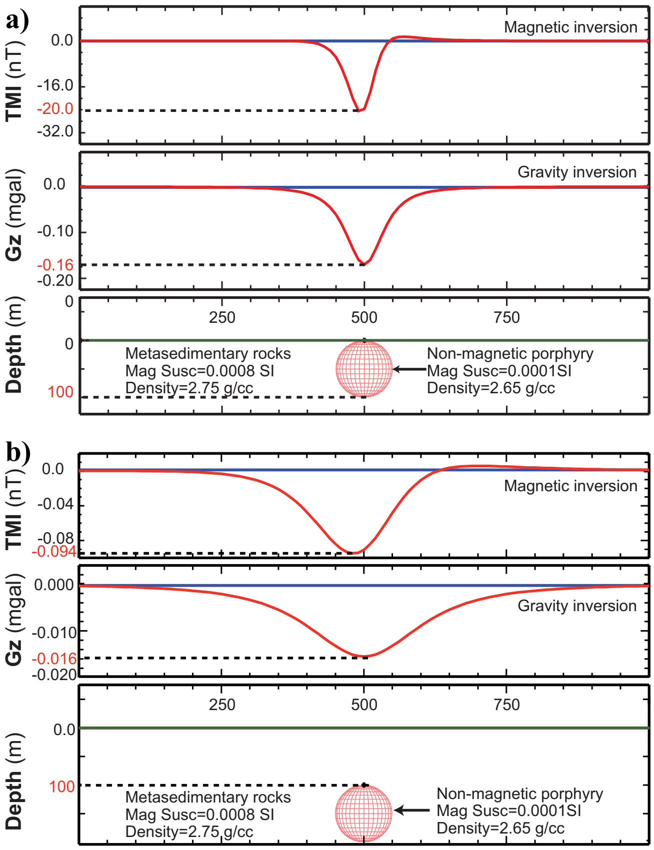

Figure 8. Two-dimensional magnetic and gravity forward modelling of a non-magnetic porphyry (100 m^3) intruded into metasedimentary rocks at depths of **(a)** 0 m and **(b)** 100 m using geomagnetic field parameters of magnetic field intensity of 57489 nT, declination of 18.3°, and inclination of 75.4°.

methods to implement. For the Canadian Malartic deposit area, no single geophysical technique, as demonstrated by forward modelling of gravity and magnetic surveys, can provide anomalies that are a useful measure of mineralization or gold content. However, a proxy can be developed through a combination of gravity, magnetic, and induced polarization survey results. We recommend this combination to define exploration targets over low-density, low-magnetic, and highly chargeable areas. The relationship between the PCA proxy and the different styles of hydrothermal alteration (distal and proximal) with linkage to gold concentration is presented here. Thus, a limit has been established between (1) a background level of gold associated with negative PCA values, including fresh rocks plus distal alteration and (2) a mineralized area with elevated gold concentrations associated with proximal alteration and positive PCA values. Distal alteration has no positive PCA value; petrophysically it is similar to fresh rocks, even if mineralogical differences exist (Fig. 9). The mineralogical and petrophysical border between fertile and non-fertile alteration is most likely the existence of hydrother-

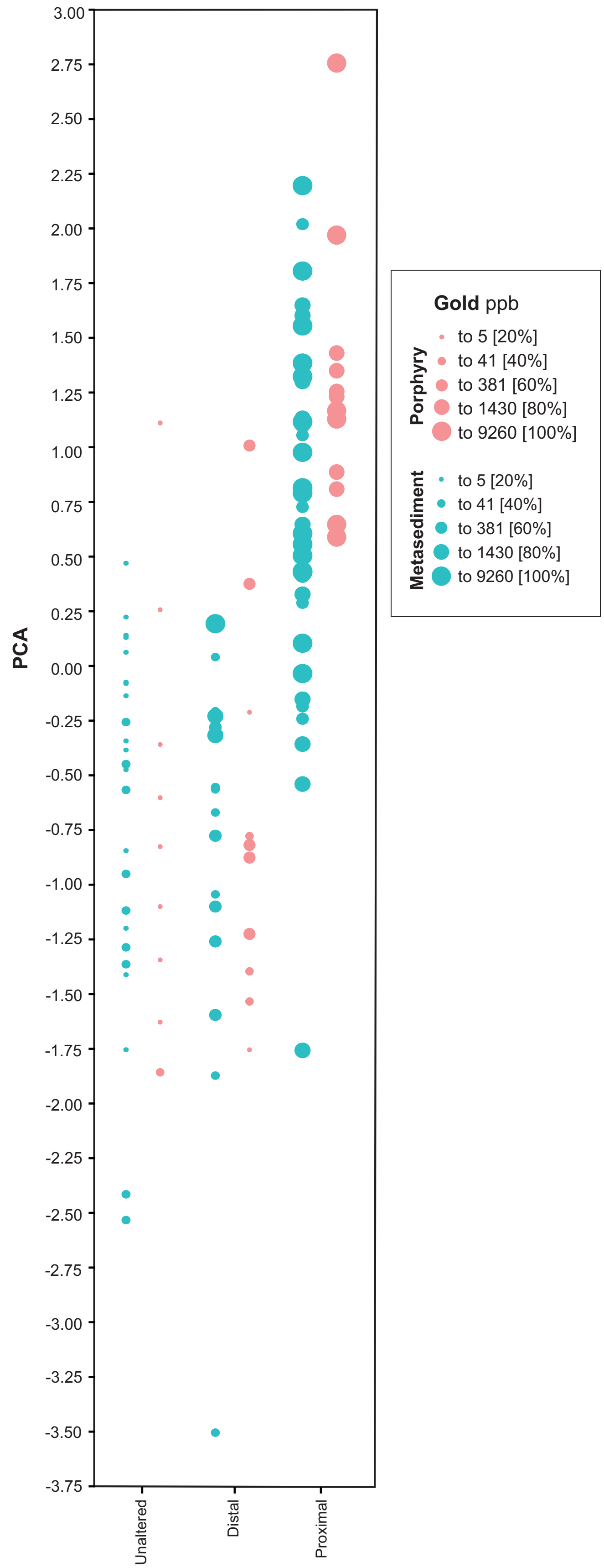

Figure 9. Correlation between the petrophysical proxy and alteration styles in the Canadian Malartic ore system.

mal biotite, as most of the Fe issued from biotite breakdown is going to be a combined with S to form finely disseminated pyrite, which is a good indicator of economic auriferous zones. A good knowledge of rock physical properties is important to constrain inversions, which allows for a better understanding of the correlations between the geological and geophysical data with fewer misleading results. A frequency-domain spectral induced polarization survey is recommended in this setting where time-domain induced polarization fails to discriminate between different conduction modes related to alteration types and mineral assemblages containing gold.

FUTURE WORK

Linking rock physical properties parameters to mineralogical data is our next step in order to refine and clarify integrated interpretations based on geochemical analyses. The integration of mineralogical and petrographic data with rock physical properties could lead to consistent and strong mineral, geochemical proxies for rock physical properties. A rock physical proxy for gold exploration in greenstone belts will also be improved.

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