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SPECTRAL INDUCED POLARIZATION SIGNATURES OF ALTERED METASEDIMENTARY ROCKS FROM THE CANADIAN MALARTIC GOLD DEPOSIT BRAVO ZONE, QUEBEC, CANADA

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Abstract

At the Canadian Malartic deposit, gold mainly occurs as fine inclusions in 1 μm to 1 mm pyrite grains hosted in altered metagreywacke. Previous time-domain induced polarization surveys conducted over this deposit have, however, failed to delineate known areas of pyrite alteration in the metasedimentary host rocks. To define the petrophysical footprint of the gold mineralization using an alternative approach, spectral induced polarization (SIP) measurements were conducted both on drill core samples in the laboratory and in situ, at a key outcrop zone. Three groups of SIP spectra are identified and interpreted using Mineral Liberation Analysis of polished thin sections and by performing Bayesian inference of SIP parameters using a Debye decomposition model. Values of Debye mean relaxation time ($\bar{\tau}$) and total chargeability (Σm) are used to characterize the respective SIP signatures of ilmenite-rich mudstones and monzodiorite ($\bar{\tau} = 0.10\ s$ and $\Sigma m = 17\%$), mineralized metagreywacke ($\bar{\tau} = 0.05\ s$ and $\Sigma m < 10\%$), and barren metagreywacke ($\bar{\tau} < 0.03\ s$ with variable Σm).

Geological context

The Canadian Malartic deposit is a world class, large tonnage and low-grade Archean gold deposit located in the Pontiac subprovince, Quebec, Canada. It is situated in the proximity of the Cadillac Larder Lake Fault Zone, south of the boundary between metamorphosed siliciclastic metasedimentary rocks of the Pontiac Group and mafic to ultramafic volcanic and intrusive rocks of the Piché Group (Figure 1). The mineralization is hosted mainly (70%) in metasedimentary rocks (greywackes) and partly (30%) in felsic to intermediate porphyry intrusions (monzodiorites) or mafic dykes. Gold occurs as fine-grained native gold grains disseminated in the host rock, included in pyrite grains, or along the contacts between minerals such as pyrite, potassium feldspar, plagioclase, biotite or quartz (Helt et al., 2014). Across the deposit, gold mineralization is spatially and genetically associated with a halo of 1 to 5 % disseminated pyrite.

Spectral induced polarization

Measurement principle

Spectral induced polarization (SIP) measurements describe the complex resistivity of rocks or soils in the frequency domain. Raw data consists of both phase shift and amplitude of the complex-valued resistivity measured at logarithmically-spaced frequencies, typically from 1 mHz to several kHz. With the recent development of high-precision field and laboratory instruments, this geophysical technique has received growing interest for applications in both hydrogeophysics and mineral exploration. In the latter, SIP data is used to describe the polarization in the electrical double layers that form in the pore network and at the interface between electrolyte and metallic grains when rocks are subjected to alternating currents. The SIP response is therefore characteristic of rock porosity, permeability, texture, mineralogy, and grain size distribution (Zisser et al., 2010; Placiencia-Gomez et al., 2013). Per recent models, metallic grains of different nature or size become polarized with different characteristic relaxation times (Gurin et al., 2013). In time-domain induced polarization (TDIP) data, the respective responses of two different types of sulfide grains in a single sample will be superimposed and often become indissociable. In raw SIP data, polarization with specific characteristic relaxation times will appear as phase shift peaks at the corresponding frequencies.

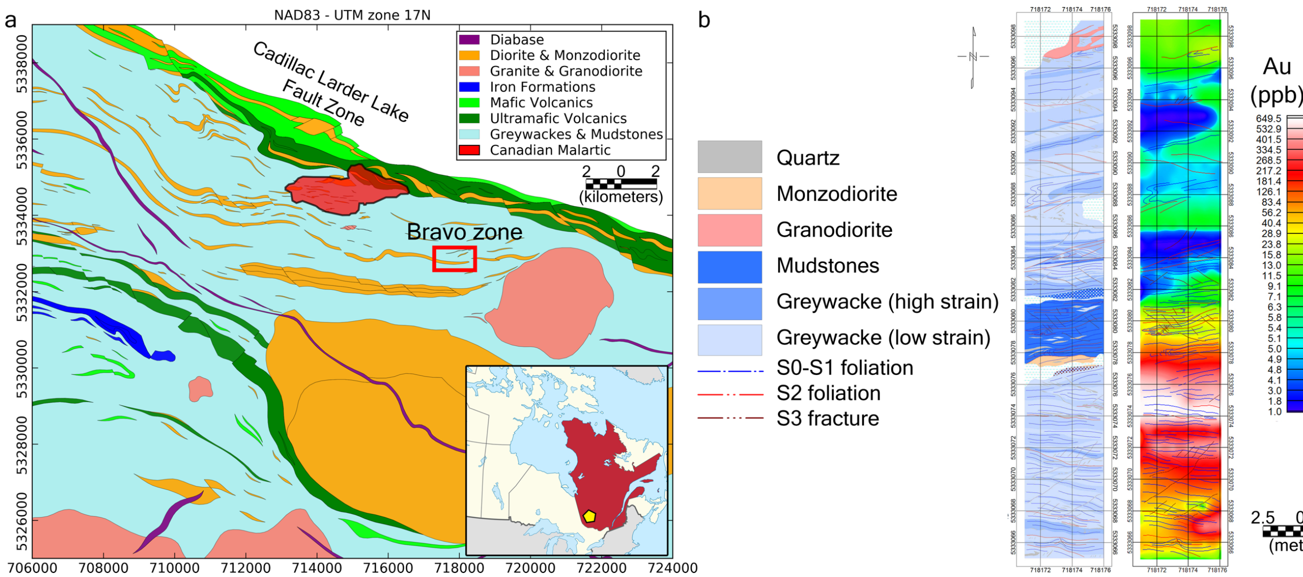

Figure 1: Location of the Canadian Malartic gold deposit in Quebec, Canada and regional geology of the Pontiac subprovince south of the Cadillac Larder Lake Fault Zone (a). Local geology and gold mineralization at the Bravo zone outcrop (b).

The sample holder used for laboratory SIP measurements is shown in Figure 2. Two copper needles (C_1-C_2) are used to inject current from one water-filled cell to another, and two non-polarizable Ag-AgCl point-electrodes (P_1-P_2) are used to measure the voltage in the water on each side of the rock sample. The induced polarization spectra are acquired by measuring the phase shift and amplitude of complex resistivity at 20 frequencies ranging from 11.4 mHz to 10 kHz using the SIP Fuchs-III equipment from Radic Research, Germany.

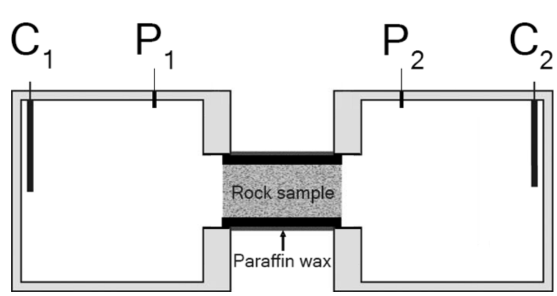

Figure 2: Schematic of the sampler holder for SIP measurements. Modified after Zisser et al. (2010).

Stochastic inversion approach

Several electrochemical and empirical models have been proposed to parametrize the frequency-domain induced polarization spectra. We developed an open-source Python program to perform Bayesian inference of SIP parameters using a Debye or Warburg decomposition approach (Keery et al., 2012) or a generalized Cole-Cole model (Chen et al., 2008). Bayesian inference allows the estimation of a system's optimal parameters and their uncertainties (posterior distribution) from measurements and their errors (observations), and from prior information about the parameters (prior distribution). The posterior distribution of SIP parameters is estimated using an Adaptive Metropolis algorithm for Markov-chain Monte Carlo (MCMC) simulation (Haario et al., 2001).

Results and discussion

We extracted 35 core samples from the BR08-2034 borehole dipping north at 50° below the Bravo zone outcrop and measured their SIP spectra in the laboratory. The borehole intersects the vertically dipping rock units observed on the surface (see Figure 1). Three types of SIP curves are identified (Figure 3). The first type is associated with altered non-mineralized metagreywacke, in which pyrrhotite replaces pyrite as the main sulfide mineral (Figure 4). It displays no obvious phase peaks in the 10 mHz – 10 kHz range. The second type has increasing phase shift with decreasing frequency, with a phase peak below 10 mHz. It corresponds to fine-grained metasedimentary rocks (mudstones with graphitic layers rich in 20 μm ilmenite grains) and monzodiorite intrusives rich in disseminated ilmenite. Lastly, the third type shows a well-defined phase peak between 1 and 10 Hz, and is associated with pyrite-rich metagreywacke.

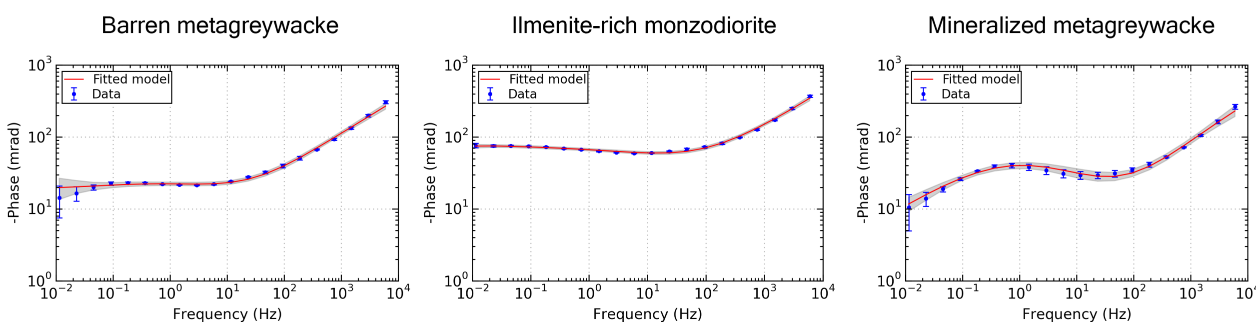

Figure 3: Phase shift of the complex resistivity measured on core samples extracted from the BR08-2034 borehole at the Bravo zone outcrop. The fitted Debye decomposition model is drawn in red, with the grey area corresponding to the 95% highest posterior density interval.

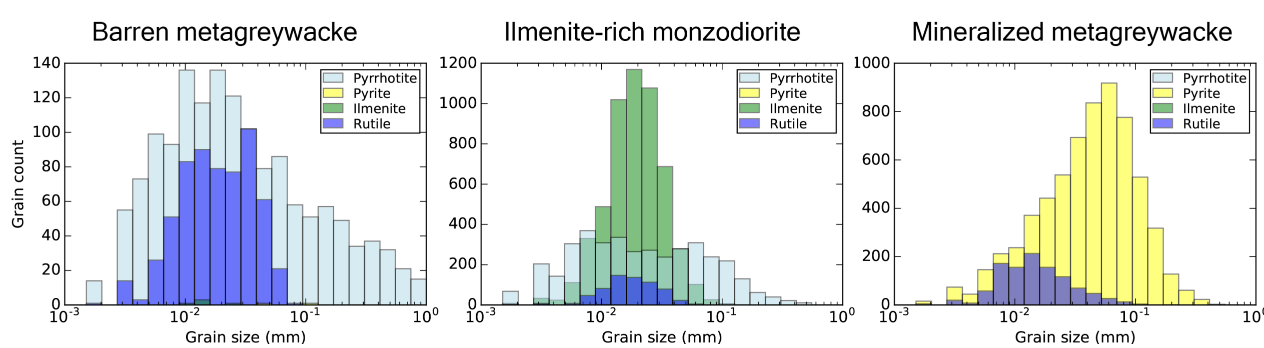

Figure 4: Grain size histograms of metallic grains obtained with Mineral Liberation Analysis for the three identified types of SIP spectra. Pyrrhotite replaces pyrite as the main sulfide in barren metagreywacke.

Field TDIP and SIP measurements were then conducted at the Bravo zone outcrop. A gradient electrode configuration was employed on a regular 50 cm spacing grid for the TDIP survey. SIP measurements were conducted along a North-South profile using a Wenner electrode configuration with 1 m spacing. The resistivity and chargeability obtained with the TDIP survey as well as the Debye mean relaxation time and total chargeability extracted from the SIP data are presented in Figure 5.

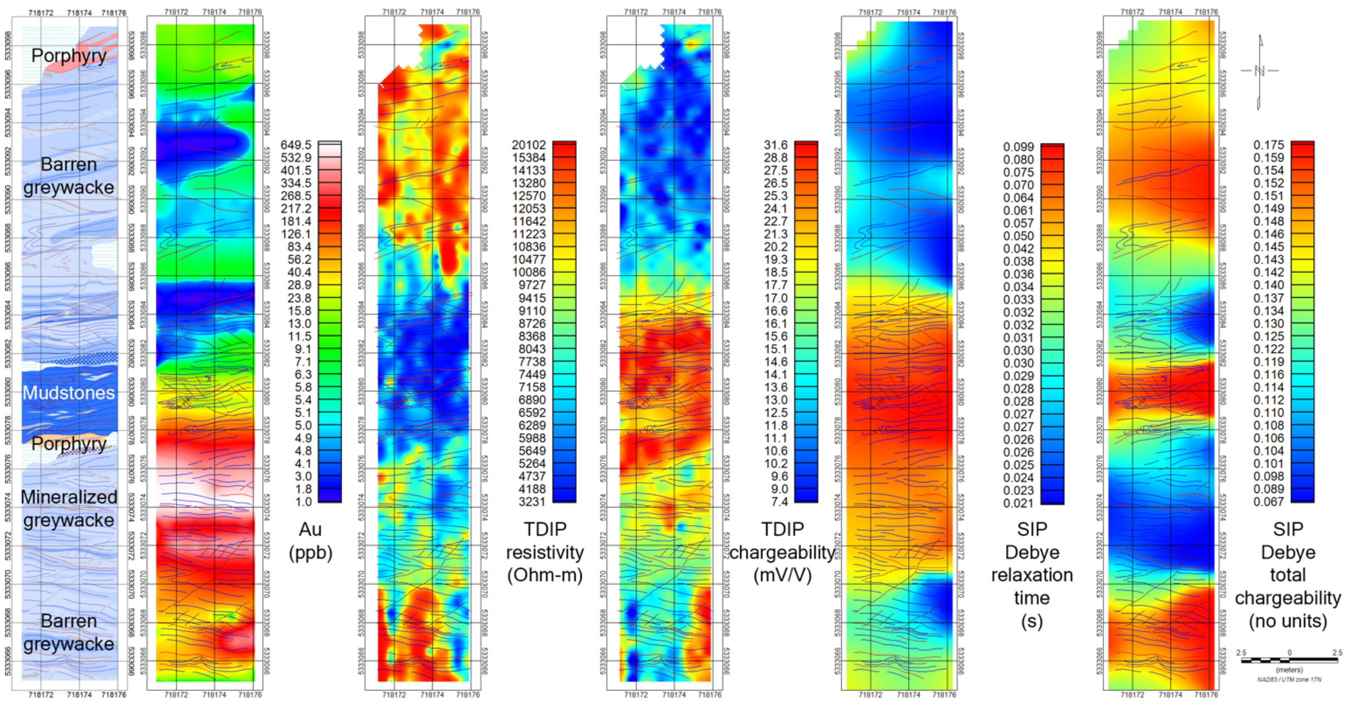

Figure 5: From left to right: local geology, gold content (ppb), time-domain resistivity (Ohm-m), time-domain chargeability (mV/V), frequency-domain Debye mean relaxation time (s), and frequency-domain Debye total chargeability (no units) measured on the Bravo zone outcrop.

Resistivity is minimal (< 5 000 Ohm-m) in areas of strong foliation and fine-grained, graphitic mudstones, whereas it is maximal (> 10 000 Ohm-m) over the barren greywacke units on the northern and southern edges of the outcrop. Changes in resistivity are interpreted as being related to the changes in the texture of metasedimentary rocks, and mainly with the intensity of the main foliation, which provides additional paths for the electrical current to circulate. Next, a time-domain chargeability anomaly up to 30 mV/V is observed directly above the altered mudstones and monzodiorite, which are both rich in fine ilmenite grains. Intermediate values of chargeability (15 - 20 mV/V) are obtained over the mineralized area and the lowest chargeabilities are measured over barren greywacke, where the small amounts of pyrrhotite (see Figure 4) produce little to no polarization in the metasedimentary rocks. The mean relaxation time obtained by Debye decomposition of the SIP data shows a similar trend to the time-domain chargeability. In fact, the longest relaxation times (0.1 s) are obtained directly above altered mudstones and monzodiorite. Intermediate relaxation times around 0.05 s are measured over the mineralized area, and short relaxation times below 0.03 s are obtained over barren greywacke. Finally, the Debye total chargeability parameter offers precious information that refines the electrical signature of the mineralized greywacke. A low total chargeability anomaly (< 10%) is spatially associated with the gold mineralization. This low Debye chargeability is bounded by higher values around 15% in the barren greywackes to the south, and by a peak Debye chargeability of 17% above the ilmenite-rich mudstones and monzodiorite. The low chargeability of gold-bearing metagreywacke may be explained by silicification of sedimentary rocks in areas of pervasive hydrothermal alteration. Some pyrite grains may become encapsulated in silica, therefore preventing an electrical double layer from forming at the electrolyte-grain interface and reducing the total intensity of the polarization effect.

Conclusions

Laboratory and field SIP measurements were conducted on drill core samples and an outcrop zone at the Canadian Malartic gold deposit, where previous TDIP surveys had failed to clearly outline areas of pyrite alteration. Debye decomposition of the complex resistivity spectra into parameters allowed us to define part of the petrophysical footprint of Canadian Malartic. Graphitic mudstones and ilmenite-rich monzodiorites have the longest characteristic relaxation times (0.10 s), followed by the mineralized greywacke (0.05 s) and finally the barren greywacke (< 0.03 s). The mineralized greywacke has well-defined phase peak between 1 and 10 Hz, but also the lowest total chargeability (< 10%). The next step in this study is an attempt to extract the same SIP parameters from full waveform time-domain induced polarization data, combining the rapidity of TDIP measurements with the additional information provided by the frequency-domain measurements. The stochastic inversion program used to process the SIP data in this study is freely available and actively maintained at https://github.com/clberube/bisip.

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