Bayesian inference of Spectral Induced Polarization parameters

Case study at the Canadian Malartic disseminated gold deposit

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Outline

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  - Implications for mineral exploration
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Research team
Introduction

• Research problem:
  - No geophysical signature has yet been identified at the Canadian Malartic gold deposit

• Objectives:
  - Measure rock physical properties in the laboratory
  - Develop a protocol for SIP measurements on core samples
  - Develop a fast and robust SIP curve-fitting platform
  - Interpret SIP parameters with quantitative mineralogy

• Questions:
  - Do rock physical properties vary with the intensity of hydrothermal alteration?
  - Are there any SIP responses associated to the mineralization?
Laboratory SIP measurements

• **Instrument**
  - SIP-Fuchs III (Radic Research, Germany)
  - 17 frequencies from 1000 Hz to 11 mHz

• **Sample holder**
  - $I$: Copper electrodes
    $(C_1, C_2)$
  - $\Delta V$: Ag-AgCl electrodes
    Harvard Apparatus
    $(P_1, P_2)$

```
C_1  P_1
Rock sample
Paraffin wax
30 \Omega \cdot m
```

Modified from Zisser et al. (2010)
Markov chain Monte Carlo simulation

- Code developed at Polytechnique Montréal
- Fast and open source
  - Python language and C extensions to compute forward models
  - Imported as module or can be used with a GUI
- Based on publications by:
  - Ghorbani et al. (2007), Chen et al. (2008), Keery et al. (2012)
- Why this method?
  - Fast global optimization
  - Influence of initial estimates diminishes
  - Full propagation of data uncertainty
  - Study parameter correlation and sensitivity
**MCMC simulation**

- Prior distributions are uniform and uninformative (ex: $0 < m < 1$)
- Metropolis – Hastings algorithm
  - First set of parameters randomly drawn from prior distributions
  - Compute the probability of the set with likelihood function
  - Draw new set from Normal distributions
  - Is the new model more probable than last one ($P_{i+1} > P_i$)?
    - If yes:
      - Move to it
    - If no:
      - Move to it if you win a “dice roll” with probability $P_{i+1} / P_i$

→ Bayes’ theorem ←
MCMC simulation

- Assumption: Errors on the data follow a Normal distribution (random errors)

- 2-D Likelihood $L$ (2-D Gaussian):

$$L = [L', L'']$$

$$L'_k = \frac{1}{\sqrt{2\pi}\sigma'_k} \exp \left[ -\frac{1}{2\sigma'_k^2} \left( \frac{\rho'_k - \hat{\rho}'_k}{\rho'_k} \right)^2 \right]$$

$$L''_k = \frac{1}{\sqrt{2\pi}\sigma''_k} \exp \left[ -\frac{1}{2\sigma''_k^2} \left( \frac{\rho''_k - \hat{\rho}''_k}{\rho''_k} \right)^2 \right]$$

- $\sigma_k$: Error on measurement at frequency $k$
- $\rho_k$: Measured resistivity at frequency $k$
- $\hat{\rho}_k$: Proposed resistivity at frequency $k$
- $N$: Total number of frequencies
SIP models

- Pelton et al. (1978)
  - $\rho_0, m_i, \tau_i, c_i \quad i = 1, 2, 3$

- Debye decomposition
  - $\rho_0, \Sigma m, \bar{\tau}$

- Dias (2000)
  - $\rho_0, m, \tau, \delta, \eta$

- Shin et al. (2015)
  - $\rho_0, m, \tau$
Inversion program

- Simple use

```python
from BISIP_models import mcmcSIPinv

rslt = mcmcSIPinv('ColeCole', 'file.dat', iterations=10000, cc_modes=2, headers=1, units='mrad')

rslt = mcmcSIPinv('Debye', 'file.dat', iterations=50000, burn=40000, polynom=4, units='deg')

Output is a self-explanatory dictionary

rslt = {'fit': ..., 'data': ..., 'opt_params': ...}
```
Convergence of MCMC simulation

- Double Cole-Cole model
  - Iterations: 100 000
  - Burn-in period: 90 000
  - Tune interval: 10 000
  - Computation time: 23 seconds
Case study

• The Canadian Malartic gold mine

Photo by Nicolas Gaillard
Canadian Malartic gold deposit

- 70% in metamorphic sedimentary rocks
- 30% in metasomatized granites, diorites, and other mafic intrusive rocks
- Structurally controlled
- Inclusions in pyrite
Ore distribution

- **Gold content (ppm):**
  - Aqua regia dissolution
  - > 0.3 ppm is mined and processed

- **Whole-rock sulfur (%):**
  - LECO (IR combustion)
  - Pyrite alteration in deposit (1 - 5% pyrite)
  - Halo of hydrothermal pyrite footprint around the deposit (up to 1% S)
Rock properties

- **Gold content (ppm):**
- **Porosity (%):**
  - Generally low (< 2 %)
  - Lowest porosity values (< 0.3%) found in mineralized areas
  - Concern for SIP?
Examples of high phase response

- **Altered greywacke (Sandstone)**
  - Pyrite grains aligned with foliation
  - Pyrite grains formed at boundaries between biotite, plagioclase or carbonates
  - 0.33% porosity
  - 1.52 ppm Au
  - 3.57% Pyrite

1500 μm 1500 μm
Examples of high phase response

- **Altered mudstone**
  - Pyrite grains aligned with foliation
  - Pyrite grains formed at boundaries between biotite, plagioclase or carbonates
  - 0.18% porosity
  - 0.47 ppm Au
  - 0.95% Pyrite
Examples of low phase response

- Altered porphyry and greywacke
  - Foliation obliterated by potassic alteration or silicification
  - Pyrite grains “encapsulated” in K-feldspar, Na/Ca-plagioclase, or Quartz
  - 4.1 ppm Au
  - 1.8% Pyrite
Chargeability (m) + frequency dependence (c)

- 143 sedimentary rock samples

\[
R^2 = 0.596
\]

\[
c + m
\]
Chargeability (m) + frequency dependence (c)

- 143 sedimentary rock samples
Correlation between m and c (Cole-Cole)

- Parameter traces of 10,000 iterations in a Markov-chain
Parameter correlation of SIP models

- Parameter traces of 10,000 iterations in a Markov-chain

Double Cole-Cole

Dias (2000)
Parameter correlation of SIP models

- Parameter traces of 10,000 iterations in a Markov-chain

Shin et al. (2015)

Debye decomposition (Keery et al. 2012)
Cole-Cole parameters

- $m_1$ is correlated with:
  - Other parameters describing the sample ($c_1, \tau_1$)
  - AND parameters describing the high frequency response ($c_2, \tau_2$)

- The high frequency response is laboratory specific
  - EM coupling, capacitive coupling
  - Depends on cables, contact impedance, sample holder, geometry
  - Reciprocal electrode configuration

- Does $m_1$ depend on the laboratory setup?
- Debye $\Sigma m$ more lab-independent than Cole-Cole $m_1$?
  - Inter-laboratory comparisons
Summary / Conclusions

- Developed an open-source program to perform Bayesian inference of SIP parameters
- Inferred the Cole-Cole, Dias, Debye and Shin parameters from rock complex resistivity measurements
  - A double Cole-Cole model fits all data sets
  - There are no advantages in using the Warburg impedance model of Dias (2000) or the R-CPE circuit model of Shin et. al (2015)
  - Cole-Cole m and c are related to total sulfur (pyrite) content
  - Correlation between low and high frequency Cole-Cole parameters
  - Lower correlation for the Debye decomposition approach
Thank you