“All charged up”

Advances and applications for IP surveys

Douglas Oldenburg and Seogi Kang
Motivation

Minerals

Complex resistivity

Permafrost

Geotechnical

Groundwater
Chargeability

Initially - neutral

Apply electric field, build up charges

Charge polarization, Electric dipole

Input current

Measured voltage
**Chargeability**

**Minerals at 1% Concentration in Samples**

- pyrite: 13.4 ms
- chalcocite: 13.3 ms
- copper: 12.3 ms
- graphite: 11.2 ms
- chalcopyrite: 9.4 ms
- bornite: 6.3 ms
- galena: 3.7 ms
- magnetite: 2.2 ms
- malachite: 0.2 ms
- hematite: 0.0 ms
# Chargeability

## Minerals at 1% Concentration in Samples

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Chargeability (msec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>pyrite</td>
<td>13.4 ms</td>
</tr>
<tr>
<td>chalcopyrite</td>
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</tr>
<tr>
<td>copper</td>
<td>12.3 ms</td>
</tr>
<tr>
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<td>2.2 ms</td>
</tr>
<tr>
<td>hematite</td>
<td>0.2 ms</td>
</tr>
</tbody>
</table>

## Material Type and Chargeability

<table>
<thead>
<tr>
<th>Material type</th>
<th>Chargeability (msec.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20% sulfides</td>
<td>2000 - 3000</td>
</tr>
<tr>
<td>8-20% sulfides</td>
<td>1000 - 2000</td>
</tr>
<tr>
<td>2-8% sulfides</td>
<td>500 - 1000</td>
</tr>
<tr>
<td>volcanic tuffs</td>
<td>300 - 800</td>
</tr>
<tr>
<td>sandstone, siltstone</td>
<td>100 - 500</td>
</tr>
<tr>
<td>dense volcanic rocks</td>
<td>100 - 500</td>
</tr>
<tr>
<td>shale</td>
<td>50 - 100</td>
</tr>
<tr>
<td>granite, granodiorite</td>
<td>10 - 50</td>
</tr>
<tr>
<td>limestone, dolomite</td>
<td>10 - 20</td>
</tr>
<tr>
<td>ground water</td>
<td>0</td>
</tr>
<tr>
<td>alluvium</td>
<td>1 - 4</td>
</tr>
<tr>
<td>gravels</td>
<td>3 - 9</td>
</tr>
<tr>
<td>precambrian volcanics</td>
<td>8 - 20</td>
</tr>
<tr>
<td>precambrian gneisses</td>
<td>6 - 30</td>
</tr>
<tr>
<td>schists</td>
<td>5 - 20</td>
</tr>
<tr>
<td>sandstones</td>
<td>3 - 12</td>
</tr>
</tbody>
</table>
Overvoltage

\[ \Delta V_{IP} = \frac{Z}{t_2 - t_1} V_s(t) dt \]
IP Inversion

DC / IP data collected

Potential (i.e. voltage) data

Invert potentials for conductivity, $\sigma$

Use $\sigma$ model for sensitivity

Invert for chargeability

Conductivity model

Chargeability model
Example DC: prism with geologic noise

- Pole-dipole; $n=1.8$; $a=10m$; $N=316$; $(\alpha_s, \alpha_x, \alpha_z) = (0.001, 1.0, 1.0)$
IP Inversion

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Example IP: prism with geologic noise

- Pole-dipole; \( n=1.8 \); \( a=10\text{m} \); \( N=316 \); \((\alpha_s, \alpha_x, \alpha_z)=(.001, 1.0, 1.0)\)
Challenge: EM coupling, grounded sources

- DC-IP: overvoltage
Challenge: inductive sources

VTEM set-up

At 90 micro-s

Decay curve
Outline

• Background

• Grounded IP
  – How to remove EM contamination?
  – How to extract valuable conductivity?
  – Gradient array example

• Inductive source IP
  – Revisit physics
  – IP inversion workflow
  – Tli Kwi Cho kimberlites
Simulation of TEM data

- Maxwell’s equations:
  
  **Frequency domain**
  
  \[ \nabla \times \vec{E} = -\omega \vec{B} \]
  \[ \nabla \times \mu^{-1} \vec{B} - \vec{J} = \vec{J}_s \]
  
  Ohm’s law in **frequency** domain

  \[ \vec{J} = \sigma \vec{E} \]

  **Time domain**
  
  \[ \nabla \times \vec{\epsilon} = -\frac{\partial \vec{b}}{\partial t} \]
  \[ \nabla \times \mu^{-1} \vec{b} - \vec{j} = \vec{j}_s \]
  
  Ohm’s law in **time** domain

  \[ \vec{j} = \sigma \vec{\epsilon} \]
Complex conductivity

- Cole-Cole model (Pelton et al., 1978)

**Frequency domain**

\[ \sigma_0 = \sigma_\infty (1 - \eta) \]

\[ f_c = (2\pi \tau)^{-1} \]

**Time domain**

\[ \sigma(\omega) = \sigma_\infty + \sigma_\infty \frac{\eta}{1 + (1 - \eta)(\omega \tau)^c} \]

\[ \mathcal{F}^{-1}[\sigma(\omega)] = \sigma(t) \]

- \( \sigma_\infty \): Conductivity at infinite frequency
- \( \sigma_0 \): Conductivity at zero frequency
- \( \eta \): Chargeability
- \( \tau \): Time constant (s)
- \( c \): Frequency dependency

Inverse Fourier transform
Simulation of TEM data with IP

- Maxwell’s equations:

  **Frequency domain**
  \[
  \vec{\nabla} \times \vec{E} = -\omega \vec{B} \\
  \vec{\nabla} \times \mu^{-1} \vec{B} - \vec{J} = \vec{J}_s
  \]

  Ohm’s law in **frequency** domain

  \[
  \vec{J} = \sigma(\omega) \vec{E}
  \]

  **Time domain**
  \[
  \vec{\nabla} \times \vec{e} = -\frac{\partial \vec{b}}{\partial t} \\
  \vec{\nabla} \times \mu^{-1} \vec{b} - \vec{j} = \vec{j}_s
  \]

  Ohm’s law in **time** domain

  \[
  \vec{j} = \sigma(t) \otimes \vec{\epsilon}'(t) \\
  \otimes: \text{convolution}
  \]

EMTDIP code
(Marchant et al., 2015)
Observed response
Observed response
Define IP datum

- **IP datum:**

\[
\text{IP} = \text{Observation} - \text{Fundamental}
\]

\[
d^{IP}(t) = F[\sigma(t)] - F[\sigma_\infty]
\]

\[
F[\sigma(t)] \quad \text{Observation}
\]

\[
F[\sigma_\infty] \quad \text{Fundamental}
\]

\[
F[\cdot] : \text{Maxwell’s operator}
\]
Define IP datum

- IP datum:

\[ d^I P(t) = F[\sigma(t)] - F[\sigma_\infty] \]

\[ F[\sigma(t)] \] Observation
\[ F[\sigma_\infty] \] Fundamental
\[ F[\cdot] \]: Maxwell’s operator
• **Conductivity at Infinite frequency:**
  - halfspace = 0.01 S/m
  - \( A_1 = 1 \) S/m
  - \( A_2 = 0.01 \) S/m
  - \( A_3 = 0.1 \) S/m
  - \( A_4 = 0.001 \) S/m

• **Chargeable objects:** \( A_2 \) and \( A_3 
  - \( \eta = 0.1 \)
  - \( \tau = 0.5 \) s
  - \( c = 1 \)
Forward modelling set up

- Measure potential difference
  - 200 m bi-pole (625 mid points)

- Step-off waveform:

- Time range: 1 – 600 ms (off-time)
  - Chargeable objects: A2 and A3
Observed DC data

Voltage

Apparent conductivity
Observed data (off-time)

- Decaying curves at A1-A4
Observed data (off-time)

- Decaying curves at A1-A4
Observed data (off-time)

- Decaying curves at A1-A4
Observed data (off-time)

- Decaying curves at A1-A4

![Graphs showing decaying curves at A1-A4 with time (ms) on the x-axis and voltage (mV) on the y-axis, with different lines representing observed (+), observed (-), fundamental (-), and IP (+) with a color code for voltage (V).]
EM decoupling

- Time decaying curves (off-time)

\[ \frac{dIP(t)}{dt} = F[\sigma(t)] - F[\sigma_{\infty}] \]

- \( IP = \text{Observation} - \text{Fundamental} \)

No hope

Can make a difference

No need to do anything
EM decoupling: true $\sigma_{\infty}$

- Off-time at 80 ms

$$d^{IP}(t) = F[\sigma(t)] - F[\sigma_{\infty}]$$
EM decoupling: $\sigma_{\infty}^{half}$

- Off-time at 80 ms

$$d_{raw}^{IP}(t) = F[\sigma(t)] - F[\sigma_{\infty}^{half}] + noise(t)$$
How do we estimate conductivity, $\sigma_\infty$?

Late on-time data (DC)  
Early off-time data (TEM)
3D inversion methodology

• Data misfit:
\[ \phi_d = \| W_d (A m - d^{obs}) \|_2^2 \]

• Model objective function:
\[ \phi_m = \| W_m (m - m_{ref}) \|_2^2 \]

• Tikhonov inversion: minimize
\[ \phi = \phi_d (m) + \beta \phi_d (m) \]

• Depth weight:
\[ \frac{1}{(z - z_0)^3} \]

DC-IP inversion: SimPEG-DCIP
TEM inversion: UBC-H3DTD code
3D DC inversion

- Recover 3D conductivity

- Depth weighting
  - Compensate for high sensitivity near surface

\[
\frac{1}{(z - z_0)^3}
\]
EM decoupling: $\sigma_{est}^{DC}$

- Off-time at 130 ms

$$d_{raw}^{IP}(t) = F[\sigma(t)] - F[\sigma_{est}^{DC}] + noise(t)$$
EM decoupling: $\sigma_{est}^{DC}$

- Off-time at 130 ms

$$d_{raw}^{IP}(t) = F[\sigma(t)] - F[\sigma_{est}^{DC}] + noise(t)$$
3D TEM inversion

- Recover 3D conductivity

Use uncontaminated EM data

![Graph showing EM induction and IP over time](image)

Time range: 1-6 ms (6 channels)

Estimated $\sigma_{\infty} (= \sigma_{est}^{EM})$

![3D conductivity map](image)

Observed vs. Predicted

- Use uncontaminated EM data
- Time range: 1-6 ms (6 channels)
- Estimated conductivity $\sigma_{\infty} (= \sigma_{est}^{EM})$
EM decoupling: $\sigma_{est}^{EM}$

- Off-time at 80 ms

$$d_{raw}^{IP}(t) = F[\sigma(t)] - F[\sigma_{est}^{EM}] + noise(t)$$
Comparisons of IP

- IP data at 80 ms
IP inversion workflow

Workflow

- Invert TEM data, to recover $\sigma_\infty$
- Compute IP datum, Remove EM responses
- Linearized equations
- Invert $d_{\text{IP}}$ data, recover pseudo-chargeability

Diagram:
- DC / IP data collected
- Potential (i.e. voltage) data
- Invert potentials for conductivity, $\sigma$
- Use $\sigma$ model for sensitivity
- Invert for chargeability

Images:
- Conductivity model
- Chargeability model
3D IP inversion

- Chargeability: recovered by inverting:

![3D IP inversion diagrams](image)
3D cut-off volume

- Pseudo-chargeability > 0.015

True

Half-space

DC

TEM
Take home

Traditionally, early time TEM data has been discarded

By using these discarded TEM signals we can better estimate both 3D conductivity and chargeability
Outline

• Backgrounds

• TEM-IP inversion workflow

• Galvanic source IP
  – Synthetic example: gradient array

• Inductive source IP
  – Field example: Tli Kwi Cho kimberlites
Discovery of Tli Kwi Cho (TKC)

DIGHEM Q7200Hz

Location of TKC, NWT

Kimberlite pipe structure

Devriese et al. (2016)
Time domain EM data

Dighem (1992)  
AeroTEMII (2003)  
VTEM (2004)  
NanoTEM (1993)

Decay curve
Reversed currents

EMTDIP code
(Marchant et al., 2015)
IP inversion workflow

**Workflow**

- Invert TEM data, to recover $\sigma_\infty$
- Compute IP datum, remove EM responses
- Linearized equations
- Invert $d^{IP}$ data, recover pseudo-chargeability
- Estimate intrinsic IP parameters
Step 1: Conductivity inversion

DIGHEM

Positive VTEM (EM-dominant)

Cooperative Inversion

Recovered 3D conductivity

Outline of two pipes
Step 2: EM-decoupling

\[ \text{IP} = \text{Observation} - \text{Fundamental} \]

\[ d^{IP} = F[\sigma(t)] - F[\sigma_{\infty}] \quad F[\cdot] : \text{Maxwell’s operator} \]

130 micro-s

Observed

Fundamental
Step 2: EM-decoupling

\[ IP = \text{Observation} - \text{Fundamental} \]

\[ d^{IP} = F[\sigma(t)] - F[\sigma_\infty] \quad F[\cdot] : \text{Maxwell’s operator} \]

130 micro-s

Observed

Fundamental

IP
Step 2: EM-decoupling

\[ IP = Observation - Fundamental \]

\[ d^{IP} = F[\sigma(t)] - F[\sigma_\infty] \]

410 micro-s

Observed  Fundamental
Step 2: EM-decoupling

\[ \text{IP} = \text{Observation} - \text{Fundamental} \]

\[ d^{IP} = F[\sigma(t)] - F[\sigma_\infty] \quad F[\cdot] : \text{Maxwell’s operator} \]

410 micro-s
Step 3: 3D IP inversion

Recovered 3D pseudo-chargeability

130 micro-s

Outline of two pipes

Conductivity contour
Step 3: 3D IP inversion

Recovered 3D pseudo-chargeability

130 micro-s
Elevation (m): 311 m

410 micro-s
Elevation (m): 311 m

Outline of two pipes

Conductivity contour
Step 4: Estimate $\eta$ and $\tau$

Cole-Cole model

\[
\sigma(\omega) = \sigma_\infty + \sigma_\infty \frac{\eta}{1 + (1 - \eta)(\omega \tau)^c}
\]

- $\sigma_\infty$: Conductivity at infinite frequency
- $\sigma_0$: Conductivity at zero frequency
- $\eta$: Chargeability
- $\tau$: Time constant (s)
- $c$: Frequency dependency

Anomaly contours

- A1-A3 has small time constant
- A4 has greater time constant
Impact on kimberlite exploration

- HK, PK, and VK are delineated in 3D
Summary

Workflow

- Invert TEM data, to recover $\sigma_\infty$
- Compute IP datum
- Remove EM responses
- Linearized equations
- Invert $d^{IP}$ data, recover pseudo-chargeability
- Estimate intrinsic IP parameters

Graph and Diagram
Summary

Workflow

**Invert TEM data, to recover** $\sigma_\infty$

- Compute IP datum
- Remove EM responses
- Linearized equations
- Invert $d^{IP}$ data, recover pseudo-chargeability
- Estimate intrinsic IP parameters

![Graph showing Workflow](image)

![Images of data analysis](image)
Summary

Workflow

- Invert TEM data, to recover $\sigma_\infty$
- Compute IP datum, Remove EM responses
- Linearized equations
- Invert $d^{IP}$ data, recover pseudo-chargeability
- Estimate intrinsic IP parameters
Summary

Workflow

Invert TEM data, to recover $\sigma_\infty$

Compute IP datum
Remove EM responses

Linearized equations

Invert $d^{IP}$ data, recover pseudo-chargeability

Estimate intrinsic IP parameters
Workflow

- Invert TEM data, to recover $\sigma_\infty$
- Compute IP datum
- Remove EM responses
- Linearized equations
- Invert $d^{IP}$ data, recover pseudo-chargeability
- Estimate intrinsic IP parameters

Summary

We may distinguish different rock types
Thank you
IP Inversion

DC / IP data collected

IP Data

Invert potentials for conductivity, $\sigma$

Use $\sigma$ model for sensitivity

Invert for chargeability

Potential (i.e. voltage) data

Conductivity model

Chargeability model
TEM-IP inversion workflow

- Kang and Oldenburg (2016)

Invert TEM data, to recover $\sigma_\infty$

Compute IP datum, Remove EM responses

Linearized equations

Invert $d^{IP}$ data, recover pseudo-chargeability

Estimate intrinsic IP parameters

$IP = \text{Observation} - \text{Fundamental}$

$$d^{IP} (t) = F[\sigma(t)] - F[\sigma_\infty]$$

$F[\cdot]$: Maxwell’s operator

$$d^{IP} (t) = G\tilde{\eta}(t)$$

$G(\sigma_\infty)$: Sensitivity function

$\tilde{\eta}$: Pseudo-chargeability
Comparison of 3D conductivities

- Recovered 3D conductivity

![Image showing comparison of true and estimated 3D conductivities at different depths and locations.](image-url)
Comparisons of Fundamental

- Fundamental data at 80 ms