Induced Polarization
Motivation

Minerals

Complex resistivity

Permafrost

Geotechnical

Groundwater

Losing Stream

Gaining Stream

1 – Water table
2 – Unsaturated zone
3 – Saturated zone
4 – Flow direction
Outline

• Sources of IP
• Conceptual model of IP
• Chargeability
• IP data
• Pseudosections
• Two stage DC-IP inversion
• Case history: Mt. Isa
Induced Polarization

- Injected currents cause materials to become polarized
- Microscopic causes $\rightarrow$ macroscopic effect
- Phenomenon is called induced polarization

![Diagram of induced polarization](image)

<table>
<thead>
<tr>
<th>Source (Amps)</th>
<th>Chargeable</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Waveform" /></td>
<td><img src="image" alt="Waveform" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Potential (Volts)</th>
<th>Not chargeable</th>
<th>Chargeable</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image" alt="Waveform" /></td>
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</tr>
</tbody>
</table>
Conceptual Model of IP

Membrane polarization

Electrode polarization

Boundary of fixed layer

Negative charge

Two electrical double layers.
## Chargeability

### Minerals at 1% Concentration in Samples

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Chargeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>pyrite</td>
<td>13.4 ms</td>
</tr>
<tr>
<td>chalcolcite</td>
<td>13.3 ms</td>
</tr>
<tr>
<td>copper</td>
<td>12.3 ms</td>
</tr>
<tr>
<td>graphite</td>
<td>11.2 ms</td>
</tr>
<tr>
<td>chalcopyrite</td>
<td>9.4  ms</td>
</tr>
<tr>
<td>bornite</td>
<td>6.3  ms</td>
</tr>
<tr>
<td>galena</td>
<td>3.7  ms</td>
</tr>
<tr>
<td>magnetite</td>
<td>2.2  ms</td>
</tr>
<tr>
<td>malachite</td>
<td>0.2  ms</td>
</tr>
<tr>
<td>hematite</td>
<td>0.0  ms</td>
</tr>
</tbody>
</table>
Chargeability

Minerals at 1% Concentration in Samples
- pyrite: 13.4 ms
- chalcopyrite: 13.3 ms
- copper: 12.3 ms
- graphite: 11.2 ms
- chalcopite: 9.4 ms
- bornite: 6.3 ms
- galena: 3.7 ms
- magnetite: 2.2 ms
- malachite: 0.2 ms
- hematite: 0.0 ms

### Material type vs Chargeability (msec.)

- **20% sulfides**: 2000 - 3000
- **8-20% sulfides**: 1000 - 2000
- **2-8% sulfides**: 500 - 1000
- **volcanic tuffs**: 300 - 800
- **sandstone, siltstone**: 100 - 500
- **dense volcanic rocks**: 100 - 500
- **shale**: 50 - 100
- **granite, granodiorite**: 10 - 50
- **limestone, dolomite**: 10 - 20

### Material type vs Chargeability (msec.)

- **ground water**: 0
- **alluvium**: 1 - 4
- **gravels**: 3 - 9
- **precambrian volcanics**: 8 - 20
- **precambrian gneisses**: 6 - 30
- **schists**: 5 - 20
- **sandstones**: 3 - 12
Chargeability

Initially - neutral

Apply electric field, build up charges

Charge polarization, Electric dipole

Input current

Measured voltage
IP data

- Seigel (1959):
  - Introduced chargeability: $\eta$
  - Effect reduces conductivity

\[ \sigma_\eta = \sigma_{\text{effective}} = \sigma (1 - \eta) \quad \eta \in [0, 1) \]

- Theoretical chargeability data

\[ dIP = \frac{\dot{\phi}_s}{\dot{\phi}_\eta} = \frac{\phi_\eta - \phi_\sigma}{\phi_\eta} \]

- Not directly measurable
IP data: time domain

- IP decay

Input current

```
<table>
<thead>
<tr>
<th>Input current</th>
<th>Measured voltage</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>phi_s(t)</td>
</tr>
<tr>
<td></td>
<td>phi_\eta</td>
</tr>
</tbody>
</table>
```

- IP datum

**Dimensionless:**

\[ \eta = \frac{\phi_s}{\phi_\eta} \]

**Value at individual time channel:**

\[ \phi_s(t) \]

**Area under decay curve:**

\[ M = \frac{1}{\phi_\eta} \int_{t_1}^{t_2} \phi_s(t) \, dt \]
IP data: frequency domain

- Percent frequency effect:

\[ PFE = 100\left(\frac{\rho_{a2} - \rho_{a1}}{\rho_{a1}}\right) \]

\( \rho_{a1} \): apparent resistivity at \( f_1 \)
\( \rho_{a2} \): apparent resistivity at \( f_2 \)

- Phase

\( \psi \): phase difference between input current and measured potential
Summary of IP data types

• Time domain:
  – Theoretical chargeability (dimensionless)
  – Integrated decay time (msec)

• Frequency domain:
  – PFE (dimensionless)
  – Phase (mrad)
IP data

- IP signals due to a perturbation (small change) in the conductivity

\[ \sigma_\eta = \sigma(1 - \eta) \quad \eta \in [0, 1) \]

- An IP datum can be written as

\[ d^{IP}_i = \sum_{j=1}^{M} J_{ij} \eta_j \quad i = 1, \ldots, N \]

\[ J_{ij} = \frac{\partial \log \phi^i}{\partial \log \sigma_j} \]

sensitivities for the DC resistivity problem

- In matrix form

\[ d^{IP} = J \eta \]

\[ J \] is an N×M matrix
Summary of IP data

• **Time domain:**
  – Theoretical chargeability (dimensionless)
  – Integrated decay time (msec)

• **Frequency domain:**
  – PFE (dimensionless)
  – Phase (mrad)

• For all data types: linear problem
  – Same as magnetics or gravity

\[ \mathbf{d}_{IP} = \mathbf{J} \eta \]

\( \mathbf{J} \) is an N×M matrix
IP pseudosections

1) A chargeable block

- Pole-dipole; n=1.8; a=10m; N=316
2) A chargeable block with geologic noise

- Pole-dipole; \( n=1.8 \); \( a=10 \text{m} \); \( N=316 \)
IP pseudosections

3) The “UBC-GIF model”
IP Inversion

DC / IP data collected

Potential (i.e. voltage) data

IP Data

Invert potentials for conductivity, \( \sigma \)

Use \( \sigma \) model for sensitivity

Invert for chargeability

Conductivity model

Chargeability model
Example 1: buried prism

- Pole-dipole; \( n=1.8; \ a=10\text{m}; \ N=316; \ (\alpha_s, \alpha_x, \alpha_z)=(0.001, 1.0, 1.0) \)
Example 2: prism with geologic noise

- Pole-dipole; n=1.8; a=10m; N=316; (α_s, α_x, α_z)=(.001, 1.0, 1.0)
Example 3: UBC-GIF model

- Pole-dipole; $n=1.8$; $a=10m$
Induced Polarization: Summary

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- Questions

- Case history: Mt. Isa
Case history: Mt. Isa

Rutley et al., 2001
Setup

• Mt. Isa (Cluny project)

• Geologic model

Question

• Can conductive, chargeable units, which would be potential targets within the siltstones, be identified with DC / IP data?
Properties

Geologic model

Resistivity and Chargeability

<table>
<thead>
<tr>
<th>Rock Unit</th>
<th>Conductivity</th>
<th>Resistivity ($\Omega \cdot m$)</th>
<th>Chargeability</th>
</tr>
</thead>
<tbody>
<tr>
<td>Native Bee Siltstone</td>
<td>Moderate</td>
<td>Moderate (~10)</td>
<td>Low</td>
</tr>
<tr>
<td>Moondarra Siltstone</td>
<td>Moderate</td>
<td>Moderate (~10)</td>
<td>Low</td>
</tr>
<tr>
<td>Breakaway Shale</td>
<td>Very High</td>
<td>Very Low (~0.1)</td>
<td>Low-None</td>
</tr>
<tr>
<td>Mt Novit Horizon</td>
<td>High</td>
<td>Low (~1)</td>
<td>High</td>
</tr>
<tr>
<td>Surprise Creek Formation</td>
<td>Low</td>
<td>High (~1000)</td>
<td>None</td>
</tr>
<tr>
<td>Eastern Creek Volcanics</td>
<td>Low</td>
<td>High (~1000)</td>
<td>None</td>
</tr>
</tbody>
</table>
Recap: Synthesis from DC

- Identified a major conductor → black shale unit
- Some indication of a moderate conductor

Can a **chargeable**, moderate conductor in the siltstones be identified?
Survey and data

- Eight survey lines
- Two configurations

Surface topography

Apparent chargeability, dipole-pole.
Processing

3D chargeability model

Animation
Interpretation

A: Resistive, Non-chargeable

B: Moderate conductivity; low chargeability

C: Very high conductivity (> 10 S/m)

E and F: High conductivity and high chargeability

G: Other chargeable regions
Synthesis

A: Surprise Creek Formation
   - Resistive, non-chargeable

B: Moondarra and Native Bee siltstones

C: Breakaway Shales
   - Very high conductivity

E and F: Mt Novit Horizon
   - High conductivity and high chargeability

G: Other chargeable regions within siltstone complex

Geologic section

Resistivity section

Resistivity model

Chargeability model
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- Questions
End of IP

- Introduction to EM
- DCR
- EM Fundamentals
- Inductive sources
  - Lunch: Play with apps
- Grounded sources
- Natural sources
- GPR
- Induced polarization
- The Future