Examples of modelling IP in AEM data: synthetic and real data

Andrea Viezzoli  
Vlad Kaminski  
Gianluca Fiandaca  
Aarhus Geophysics Aps  
Aarhus Geophysics Aps  
HGG- Arhus University
What will you hear

• IP effects can be visible and measurable in AEM data
  – Signature is varied, beyond simple sign change
• IP can be modelled from AEM data, both synthetic and real. We can recover corrected resistivities and some IP parameters
  – Large degree of non uniqueness, which can be reduced by constraints and apriori
  – Chargeability can be recovered down to some depth
• Failure to model IP in IP affected AEM datasets produces:
  – Erroneous resistivity sections
  – Loss of extra information about the subsurface that might be relevant for mineral exploration and other applications
IP effect in TEM data

- The evidence
  - Sign changes in central loop* TDEM systems
  - Calls for a frequency dependent resistivity $\rho(\omega)$

- The explanation
  - Presence of chargeable (polarizable) material

- The models
  - Cole Cole (DC or $\infty$ frequency limit)
  - GEMTDIP (more parameters)
  - Others with less parameters
The evidence
The explanation

After Flis et al (1989)

Polarizable, homogeneous half space

Constant current

Ramp down

On time

Early times

Late times

Off time
The model

- **Cole Cole model (DC limit - Flis et al.)**

\[ \sigma(s) = \sigma_0 + \Delta_0 \hat{\sigma}(s), \ s = i\omega \]

\[ \Delta_0 \hat{\sigma}(s) = \frac{\sigma_0 m(s\tau)^c}{1 + (1 - m)(s\tau)^c}. \]

- **Cole Cole model (∞ frequency limit - Smith)**

\[ \sigma(s) = \sigma_\infty + \Delta_\infty \hat{\sigma}(s), \ s = i\omega \]

\[ \Delta_\infty \hat{\sigma}(s) = \frac{-\sigma_\infty m}{1 + (1 - m)(s\tau)^c}. \]
IP effect in TEM data: **BIG FAT WARNING**!

- Even in presence of IP effect measureable by a given AEM system, its transients can be distorted **without ever changing sign**! This can be due to:
  - Noise level
  - Bandwidth
  - Combinations of Cole Cole Parameters within a given layer
  - Combination of layers
Different IP effects: transients from different AEM systems

VTEM (a)

VTEM (b)

VTEM (c)

SkyTEM (g)

VTEM (d)

HeliTEM (e)

Equator (f)
Different IP effects: channels profiles, obvious effects

- **SkyTEM**
  - Copper (Greenland)
  - BIF (Australia)
- **HeliTEM**
  - Base metals (Canada)
Different IP effects: channels profiles: more subtle effects

- VTEM
  - Kimberlites (Russia)
  - Permafrost (Russia)
  - Gold (arabic Peninsula)
Different IP effects: Same target, 2 AEM systems

- Kimberlites
  - VTEM
  - Equator
Different IP effects: Same survey, different geologies
Same survey, different geologies
Same survey, different geologies

Schist
Same survey, different geologies
Same survey, different geologies

All in one line! Distinctive features. Make good use of this info in inversion.
Why is it important to model to model IP in AEM data

• Failure to model IP in IP affected AEM datasets produces
  – Erroneous resistivity sections
  – Loss of extra information about the subsurface that might be relevant for mineral exploration and other applications

• Chargeability can be recovered beyond the near surface (under some conditions)
Why is it important to model it: improved resistivity sections

True model

\[ \tau = 0.001 \text{ s}; \quad c = 0.5 \]

FWD, noise added, inverted without modelling IP

Recovered model

Conductors are gone!
Why is it important to model it: improved resistivity sections

True model

FWD, noise added, inverted modelling IP (no apriori)

Recovered model

Conductors are back!
Why is it important to model it: improved resistivity sections.

BIF project, SkyTEM data affected by IP

Resistivity section obtained from inversion without modelling IP

Resistivity section obtained from inversion modelling IP

Associated chargeability section

Why is it important to model it: improved resistivity sections.

BIF project, SkyTEM data affected by IP

Resistivity section obtained from inversion without modelling IP

Resistivity section obtained from inversion modelling IP

Associated chargeability section
Why is it important to model it:
it can recover $m$ at some depth

True model

FWD, noise added, inverted modelling IP
(no apriori)

Recovered model
Kimberlite exploration: synthetic data

Overburden: \( \rho = 500 \text{ Ohm m} \); \( m_0 = 10 \text{ mV/V} \)
\( \tau = 0.001 \); \( C = 1.0 \)

Crater: \( \rho = 30 \text{ Ohm m} \); \( m_0 = 300 \text{ mV/V} \); \( \tau = 0.001 \); \( C = 0.5 \)

Diatreme: \( \rho = 250 \text{ Ohm m} \)

Host rock: \( \rho = 5000 \text{ Ohm m} \)
Inversion results (no a-priori, loose constraints)

Geometry of the kimberlite fairly resolved. Some artefacts

\( \chi = 0.98 \)
Inversion results (A-priori, tighter constraints)

Geometry of the kimberlite resolved better. Artefacts decreases.

\[ \chi = 0.98 \]
Kimberlite exploration: case study 1, Amakinskaya pipe (VTEM)

**Amakinskaya Kimberlite pipe results:** From the geological standpoint, the area surrounding Amakinskaya kimberlite pipe belongs to a sedimentary basin with widespread outcrops of clays and alerovolites of Jurassic age (J1or), which unconformably overlay Cambrian limestone complex (C3hl). Triassic basalts (βT1kt) are also widespread in the area, especially to the north from the pipe. Amakinskaya Kimberlite pipe shows a great deal of anisotropy in the vertical direction, shifting from weathered, clayish upper facies, affected by permafrost to consolidated hard kimberlite below 30 m depth. This obviously has reflection in the physical properties of the kimberlite. Resistivity and chargeability changes with depth, showing lowering resistivity and increasing chargeability values in the upper facies of the kimberlite, while magnetic susceptibility increases with depth, as kimberlite consolidates (Bondarenko and Zinchuk, 2004).
The data
The workflow when working with actual AEM data

- Data processing
  - Recognize and maintain IP effects while increasing S/N and eliminating artefacts
- Inversion with IP modelling (AarhusInv)
  - Cole Cole modelling
  - No apriori
  - Solved for all parameters at once
  - Spatially Constrained Inversion (quasi 3D)
  - Many realizations, scanning the model and regularization space thoroughly
  - Tight spatial constraints on $c$ and $\tau$
- Careful assessment of results
  - General geological settings
  - Comparison with ancillary data
Resistivity slices

Depth 5 м

Depth 23

Depth 48 м

Depth 97 м

Depth 193 м
Chargeability slices

Depth 5 м

Depth 23 м

Depth 48 м

Depth 97 м
Close up on the pipe
Res, m and mag vertical sections

Power line

Saline aquifer

The pipe crater

3D resistivity model

3D chargeability model
Comparing physical properties

<table>
<thead>
<tr>
<th>Rock type</th>
<th>Formation</th>
<th>Electrical resistivity ($\rho$, Ohm m)</th>
<th>Magnetic susceptibility ($10^{-5}$ SI)</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kimberlites</td>
<td>Amakinskaya pipe</td>
<td>30-60</td>
<td>100 - 900</td>
<td>Weathered, clayish</td>
</tr>
<tr>
<td>Kimberlites</td>
<td>Amakinskaya pipe</td>
<td>500 - 1000</td>
<td>100 - 900</td>
<td>Kimberlitic breccia</td>
</tr>
<tr>
<td>Kimberlites</td>
<td>Amakinskaya pipe</td>
<td>290 - 400</td>
<td>100 - 900</td>
<td>Carboniferous kimberlites</td>
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<tr>
<td>Clayish limestones</td>
<td>J1,uk</td>
<td>100 - 400</td>
<td>N/A</td>
<td></td>
</tr>
<tr>
<td>Sandy silts</td>
<td>J1,uk</td>
<td>100 - 400</td>
<td>N/A</td>
<td></td>
</tr>
</tbody>
</table>

Physical properties from ancillary data

Physical properties from airborne geophysics
Kimberlite exploration: case study 2, Drybone pipe (VTEM)
Drybones kimberlite geology

**Kimberlite facies**
- Pyroclastic facies
- Crater facies
- Diatreme facies

**Drill Holes**
- DRY94-1

**Geological Map**
- Granite
- Metasedimentary rocks
- Volcanic rocks
- Great Slave Lake
- Nicholas Lake
- Discovery Con mine
- Palisades Range
- MON

**Sectional View**
- Lake
- Sediments
- Kimberlite
- Granodiorite
Drybones kimberlite geology

Inverted in 3D (Kaminsky et al., 2012), no IP modelling
Drybones kimberlite IP effect

(a) Drybones bay

(b) $\frac{V}{(A \cdot m^4)}$ vs. Time [s]
Drybones kimberlite comparison with previous inversions

(a) Resistivity Inverted in 3D no IP modelling

(b) Resistivity SCI, with IP modelling

(c) Chargeability SCI

(d) Resistivity SCI, with IP modelling
ZTEM is a passive AEM system, very different bandwidth

Resistivity SCI, with IP modelling

Resistivity Inverted in 3D*
....base metal example...
Conclusions

- IP effects can be visible and measurable in AEM data
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- IP can be modelled from AEM data, both synthetic and real. It is possible to recover corrected resistivities and some IP parameters
  - Large degree of non uniqueness, which can be reduced by constraints and a-priori
  - Chargeability can be recovered down to some depth
- Data needs to be understood and properly (pre)processed before attempting recovering IP
- Taking wrong assumptions on parameters (e.g., locking them to a predefined value) can lead to wrong models
Conclusions (continued)

- More research should focus on, e.g.,
  - Exploring IP models (not Cole Cole)?
  - Using B field data
  - Different inversion strategies

- Failure to model IP in IP affected AEM datasets produces:
  - Erroneous resistivity sections
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Conclusions (continued)

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How much existing AEM data out there contains IP effects never looked at properly?
Acknowledgments

- Geotech, Ltd
- Alrosa
IP effect in TEM data: $\infty$ freq. limits

After Smith et al (1989)

\[ \sigma(s) = \sigma_\infty + \Delta_\infty \hat{\sigma}(s), \]
\[ \Delta_\infty \hat{\sigma}(s) = -\sigma_\infty \frac{m}{1 + (1 - m)(s\tau)^c}, \]
\[ s = i\omega \]
The charging up in TEM vs DC

(a) TEM

(b) DC

(c) PRIMARY MAGNETIC FIELD

(d) SECONDARY MAGNETIC FIELD

IN ELECTRICAL EQUILIBRIUM
VORTEX CURRENT
POLARIZATION CURRENT

ROCK
METALLIC MINERAL GRAIN
CLAY

Aarhus Geophysics
Brief investigation into non-uniqueness, and on locking $c$

$$
\Delta \text{Par}_{i,j}^k = \log_{10} \text{Par}_{i,j}^{\text{Out}(k)} - \log_{10} \text{Par}_{i,j}^{\text{true}}
$$

Mode ($\Delta \text{Par}_{i,j}$)
Brief investigation into non-uniqueness, and on locking $c$

**Mode ($\Delta m_{i,j}$)**

- Locking $c$
- Solving for $c$