Challenges in ground-truthing magnetizations interpreted from magnetic field data

Jim Austin | Clive Foss
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Introduction

• In theory, it is optimal to constrain potential field modelling procedures using measured petrophysical data.
• However, it is not always possible or feasible to do so.
• Where possible several artificial overprints can cause confusion – drilling-induced magnetisation, – overprinting by pencil magnets, and – lightning-induced magnetisation.

• Even with reliable petrophysical measurements, the calculation bulk properties from limited samples is problematic.
• In this study we explore some of the challenges in ground-truthing magnetizations.
Drilling Induced Magnetisation

- Drilling induced magnetisation is a type of isothermal remanent magnetisation.
- Usually only overprints VRM (viscous remanent magnetisation).
- The upward magnetic field is deflected into the orientation of the drill rod.
- Small vibrations and or heat associated with grinding the rock at the drill bit demagnetise the rock.
- It then remagnetises in the field inside the rod, and acquires remanence in the rod orientation.

Theory: from Pinto and McWilliams 1990
Audunsson and Levi (1989), showed that the DIM intensity within a single sample increased by at least a factor of five from the center of the drill core to the drill string's cutting surface, where it appears to have been produced.

If we use this observation as a starting hypothesis, and assuming a linear decline in the intensity of DIM from the edge of the core to the center (where there is zero enhancement) we can make a rough calculation of the intensity of the DIM relative to the area of the core (in cross-section) as shown in Figure 2.

<table>
<thead>
<tr>
<th>Zone</th>
<th>Area</th>
<th>J (A/m)</th>
<th>J per area (A)</th>
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<tr>
<td>1</td>
<td>3.14</td>
<td>1</td>
<td>3.14</td>
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<tr>
<td>2</td>
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<td>3</td>
<td>15.71</td>
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<td>39.27</td>
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<td>4</td>
<td>21.99</td>
<td>3.5</td>
<td>76.97</td>
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<tr>
<td>5</td>
<td>28.27</td>
<td>4.5</td>
<td>127.23</td>
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<tr>
<td>Total</td>
<td>78.54</td>
<td>3.32</td>
<td>260.75</td>
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</tbody>
</table>
Drilling Induced Magnetization - Test

MK003A - Surface drilled from mine pit
MON005 - Sampled from diamond drill core

Barite-calcite-magnetite-chalcopyrite-sphalerite-galena ore – Monakoff Mine
Surface drilled from mine pit

Mean Values

Sampled from diamond drill core

Quite a spread of results from surface

On average, very similar density and Mag Sus, and hence same Mt-content
Palaeomagnetic Properties

Typically DIM is held in soft/multidomain grains

- A: Coreyard Field + DIM
- B: DIM + Ancient

Graph showing magnetic field strength (µT) against distance (km):

- Only DIM
- DIM + Noise
- DIM + EMF
- Inhomogeneous degaussing of DIM
Why does understanding DIM matter

- Brumby case study
- If you measure the NRM and assume that the DIM is genuine remanent magnetisation
- You might think it’s a good idea to constrain a magnetic model using the Drilling magnetization

- The magnetization will be a soft remanence
- *In situ* magnetisation will be Oriented in the Earth’s field
- You will get you model wrong
- And then people like me will publicly ridicule you...
- A decade later
Pencil Magnets

You can tell when a good geo has been over the core
What is the field generated by a pencil magnet

- Not easy to quantify because we can’t get one close to a fluxgate
- However if we predict the data based on the inverse cube attenuation
- We estimate a field of approx 550 nT close to the end of the magnet.
  - 10x the Earth’s field
- That will only remagnetize low coercivity grains
Pencil Magnet test on Multidomain Pyrrhotite

Why the mis-match?

• Stable Remanence still in rock
• Anisotropy
• Misalignment of the magnetic field within the magnet
Coarse Pyrrhotite MT2A – Cormorant Prospect

<table>
<thead>
<tr>
<th>MT2A</th>
<th>field corrected step</th>
<th>dec</th>
<th>inc</th>
<th>int</th>
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<td>974987.3</td>
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<td>708279.9</td>
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<td>139.9</td>
<td>-22.9</td>
<td>6282.583</td>
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</table>
Characteristic PIM

- In rig-drilled samples PIM will display a large variation in the declination.
- But magnetisation directions will typically be approximately normal to the drill orientation.
- E.g., Pyrrhotite-rich samples from the Artemis prospect have magnetisations approximately normal to the drill orientation, indicating pencil magnet contamination.
- Again,... If you measure NRM from contaminated samples and use it in your modelling:
  - you will bugger up the model, miss the target
  - your company will go bust and you will seek employment as a taxi driver.
Lightning
Lightning - Magnetic Effect

Lightning Induced Magnetisation

- Strikes usually Only Affect Radius of 10-30 m
- Starfish shaped anomaly
- Can induce magnetic fields of ~ 0.002 T
  - 2 mT
  - 40 x Earth’s Field
Lightning Induced Magnetisation

- Manifested by uncharacteristically high remanent magnetisation in lithologically similar samples
Lightning Induced Magnetisation

• NRM s might consist of
  • Steep up
  • Steep down
  • Mostly flat in one (general) direction
• Remanent magnetisation will often:
  • Start in several orientations
  • Migrate towards a common orientation
Rover 3 Case History

• In 2010 Castile Resources drilled the Rover 3 drill-hole to investigate the cause of the Rover 3 anomaly detected in an aeromagnetic survey of the Tennant Creek Area of the Northern Territory.
• They were targeting IOCG mineralization
• They position the hole well and estimate (very reasonably) an intersection depth of 260 metres
• The drill-hole is planned for a depth of 500 metres, but believing the magnetization was not intersected, it is continued to a depth of 750 metres.
• This interpretation was based on magnetic susceptibility measurements only

• In 2013 Jim Austin and Clive Foss sampled the Rover 3 core and measured magnetic susceptibility and remanent magnetization.
• They establish that the cause of the anomaly is in the top 400 metres
• and that the main magnetization has a Koenigsberger ratio of the order of 20
  • (hence the lack of strong magnetic susceptibility measurements).
• The complex sub-surface magnetization is well summarised by the simple, homogeneous model inversion of the magnetic field data.
Relating a Magnetic Field Inversion to Source Magnetization – Rover 3, Tennant Creek

- The Rover 3 TMI anomaly is relatively simple - it only justifies a simple model.
- The Total Gradient (Analytic Signal) enhancement does reveal some complexity – a more diffuse or deeper magnetization in addition to that generating the main total gradient anomaly peak – but this cannot be reliably modelled.
The Preferred Inversion Model for Rover 3

- A simple model (plunging elliptic-section pipe) matches the anomaly well.
- This does not mean that the magnetization in the ground is homogeneous.
- But our model provides estimates of the total magnetization present, its centre, and its direction.
- The extent of magnetization is loosely constrained.
Alternate Inversion Models for Rover 3

- We can produce alternate models which all have consistent values for the meaningful parameters:
  - Centre of magnetization
  - Magnetic moment (volume x intensity)
  - Direction of magnetization
- Factors such as shape and depth to top are details that are not reliably recovered from magnetic field inversion
- We prefer the flat-topped models in expectation that the body terminates at a sub-horizontal unconformity surface
Distribution of magnetization

- The shallowest mafic volcanics
  - highest Mag Sus (up to 0.07 SI)
  - Koenigsberger is up to 10
  - However it low coercivity - soft magnetization
- Very thin units (1-2 m only)
- Can’t explain the anomaly
Distribution of magnetization

- The lower felsic volcanics
- lower Mag Sus (up to 0.1 SI)
- Koenigsberger is up to 25
- High coercivity, very stable magnetization
- Very thick unit (350m)
Litho-stratigraphic Control on Magnetization

- The true distribution of magnetization revealed by direct measurement is highly complex and sharply varying,
- Remanence in the individual layers switches polarity as the volcanic pile builds up
- But can be resolved into representative values for stratigraphic units
- To match the magnetization estimated from the magnetic field inversion requires measurement of both magnetic susceptibility and remanent magnetization to estimate the resultant magnetization which controls the external magnetic field

<table>
<thead>
<tr>
<th>Geological Unit as modelled</th>
<th>Top - m (b.d.l.)</th>
<th>Thickness (m)</th>
<th>MagSus ($\times 10^6$)</th>
<th>RemMag (mA/m)</th>
<th>Dec</th>
<th>Inc</th>
<th>Q</th>
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<tbody>
<tr>
<td>Rhyolite Upper - 1</td>
<td>-146</td>
<td>34</td>
<td>630</td>
<td>170</td>
<td>243</td>
<td>-53</td>
<td>6.7</td>
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<tr>
<td>Mafic Upper +</td>
<td>-112</td>
<td>13</td>
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<td>400</td>
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<td>267.2</td>
<td>-59.3</td>
<td>8.5</td>
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</table>
Agreement between measured magnetization and magnetic field inversion results

• Variation of magnetic susceptibility and remanent magnetization from sample to sample is sufficient that estimation of mean values for litho-stratigraphic units is challenging
• The weighted mean measured magnetization direction is however in good agreement with the homogeneous inversion mean magnetization direction
The Model

- A Vertically Zoned Source Model based on Mag Sus and Remanent Magnetization Measurements
- We have a single bore-hole and can therefore only use a simple horizontal layer model for the distribution of the measured litho-stratigraphic magnetization units
- These horizontal units were extended out to the shell of the magnetic field inversion model
- The computed magnetic field from the sum of the layer magnetization models closely matches the observed magnetic anomaly – confirming that we have resolved the source of the anomaly, and that the homogeneous model from the magnetic field inversion is a valid (though highly simplified) representation of the sub-surface magnetization
Conclusions from the Rover 3 Study

• The inversion of the magnetic field data is shown to produce a valid but highly simplified model of the sub-surface magnetization

• These inversion results are useful to establish the depth of the magnetization, its total intensity and direction, but do not provide any insights to the internal distribution of that magnetization

• Inversion of magnetic field data measured at considerable distance from a magnetization cannot resolve its details, or detail the litho-stratigraphic control on magnetization values. This requires direct measurement

• Rapid measurement of magnetic susceptibility and remanent magnetization, with rapid computation of the results, could have established that the anomaly had been explained at a depth of no more than 400 metres.

• This could have saved considerable $$,$$

• But instead they drilled another 350 m
I hope to see some of you in Sydney next year:

Thanks to my Mentors: Clive Foss, Phil Schmidt, Dave Clark, Dave Pratt, et al.,