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Challenges in ground-truthing magnetizations interpreted from magnetic field data

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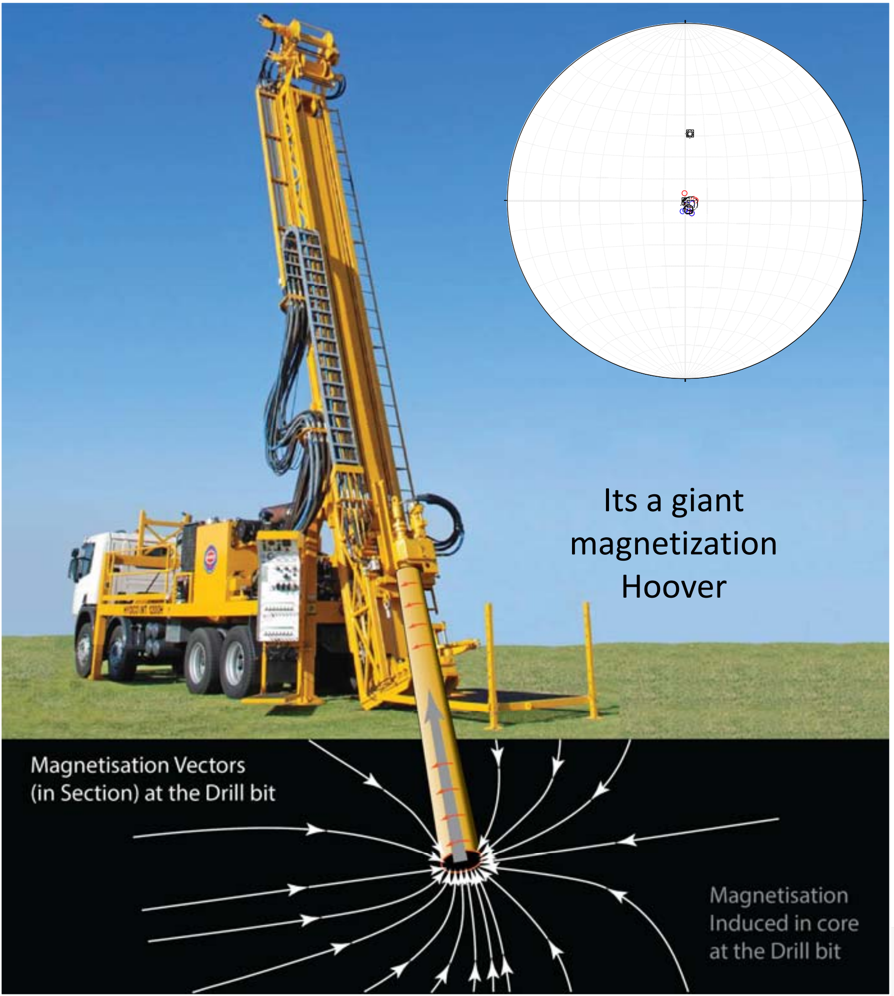
Introduction

- 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

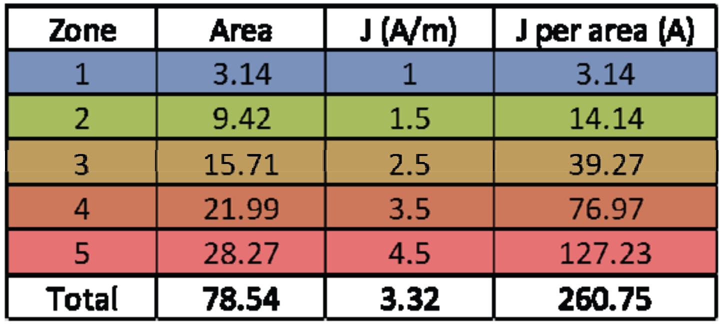


Its a giant
magnetization
Hoover

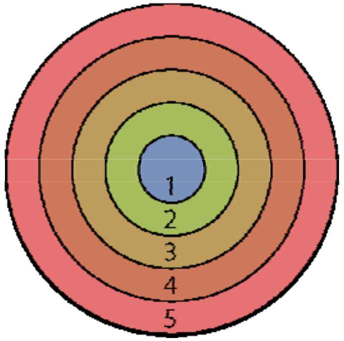
Audunsson and Levi (1989),

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.

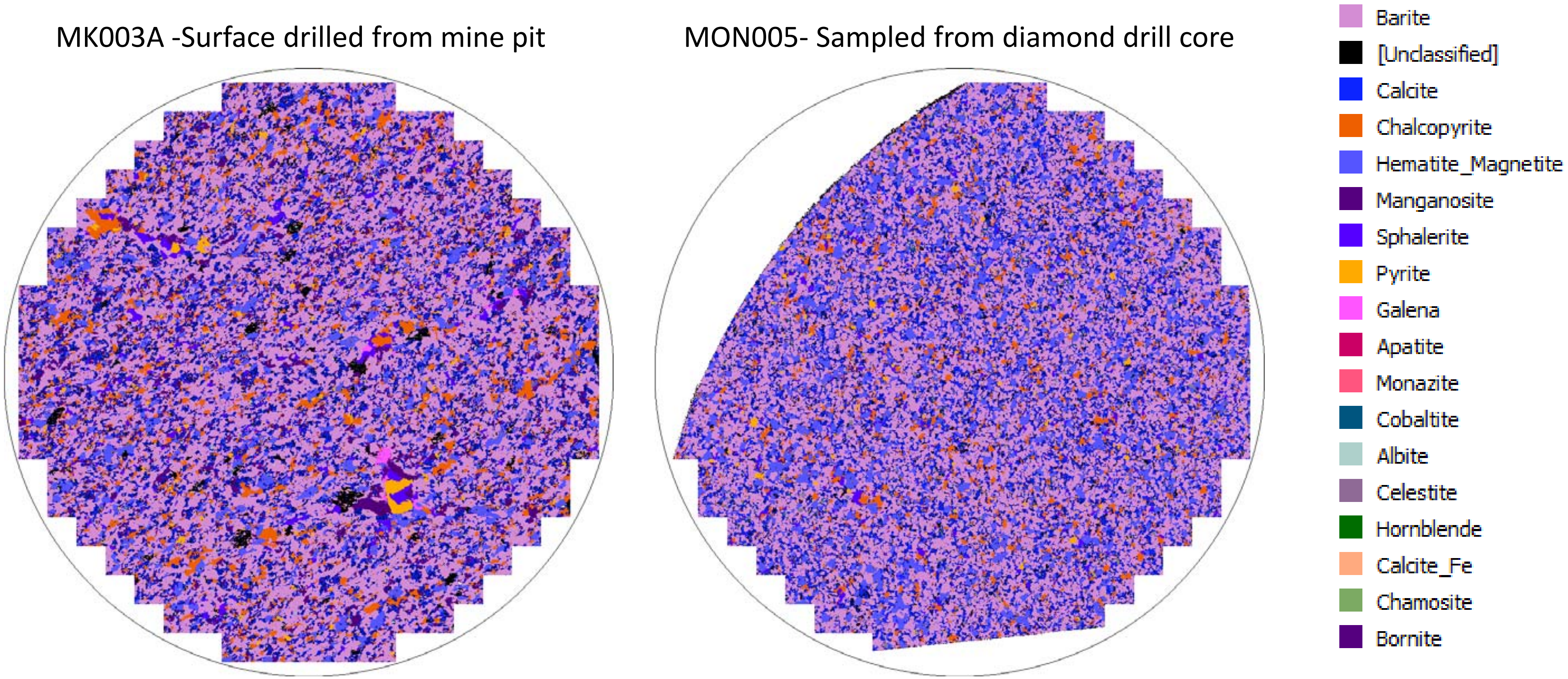
If we use this observation as a starting hypothesis, and assuming a linear decline in the intensity of DIM from the edge of the core to the center (where there is zero enhancement) we can make a rough calculation of the intensity of the DIM relative to the area of the core (in cross-section) as shown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



Zone	Area	J (A/m)	J per area (A)
1	3.14	1	3.14
2	9.42	1.5	14.14
3	15.71	2.5	39.27
4	21.99	3.5	76.97
5	28.27	4.5	127.23
Total	**78.54**	**3.32**	**260.75**



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

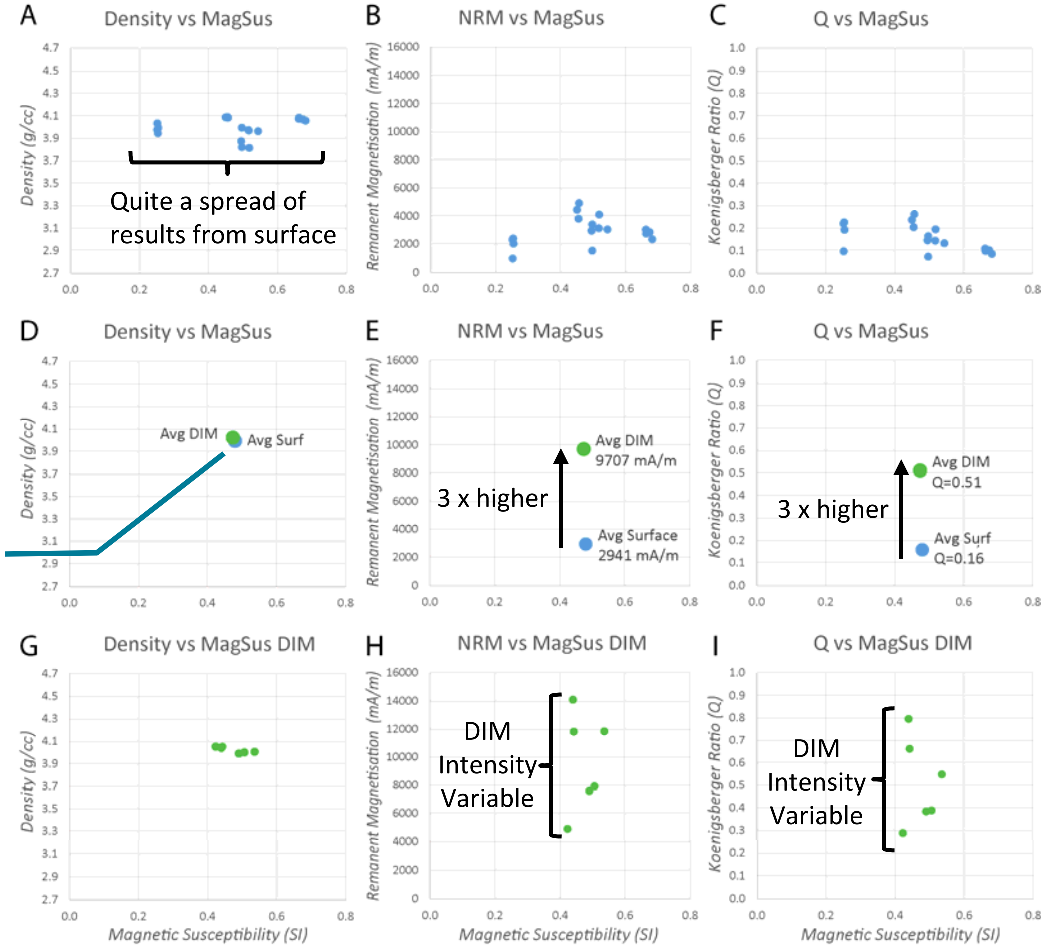
Drilling Induced Magnetisation

Surface drilled from mine pit

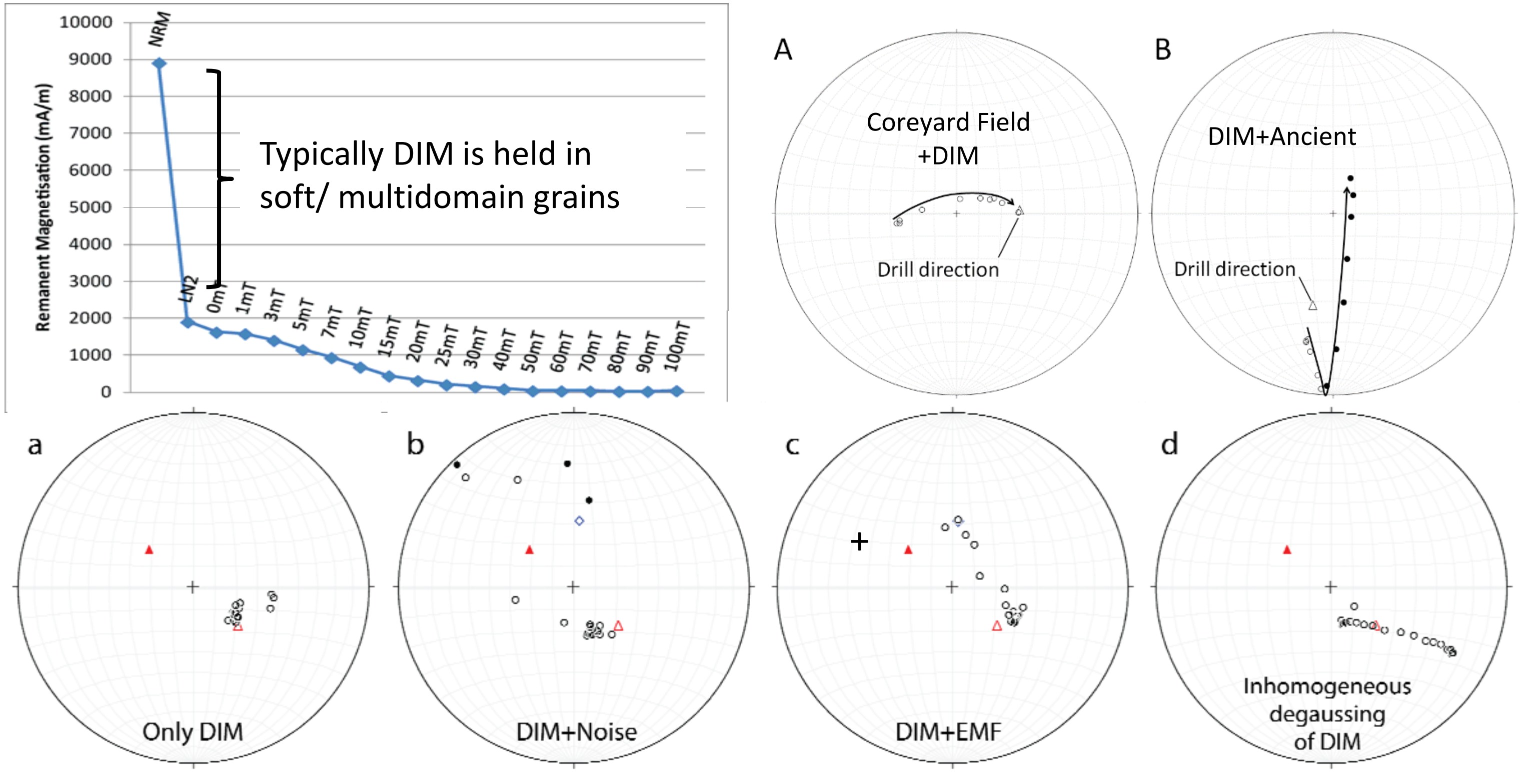
Mean Values

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

Sampled from diamond drill core



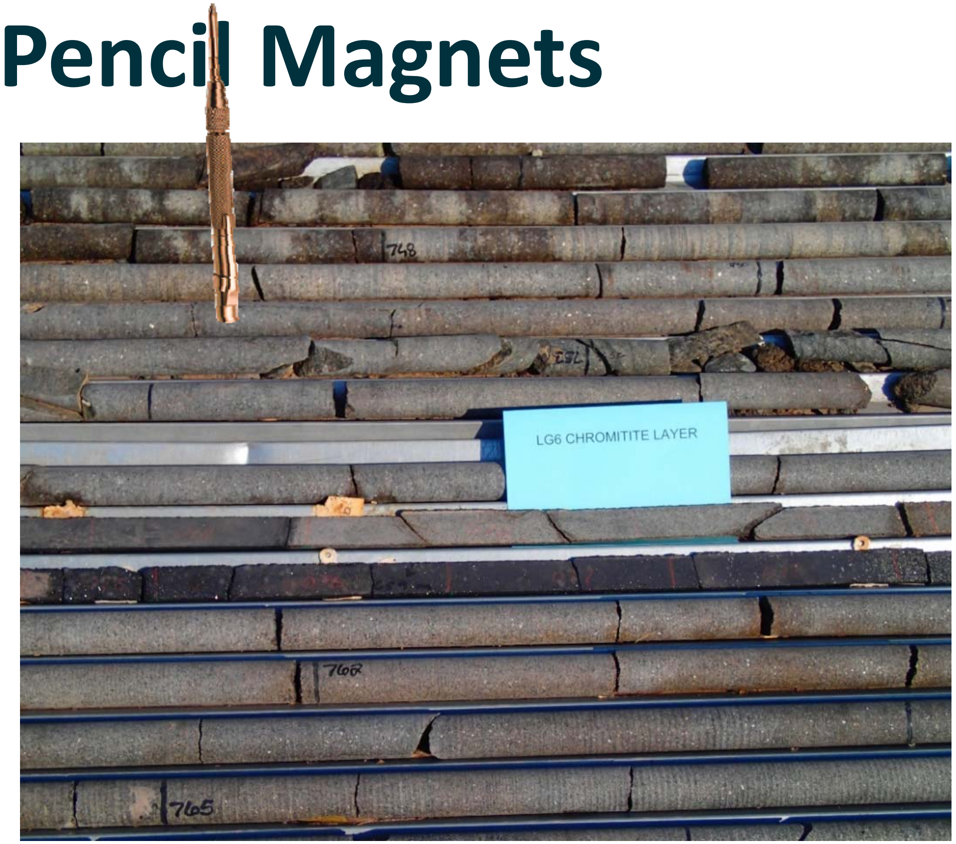
Palaeomagnetic Properties


Typically DIM is held in soft/ multidomain grains

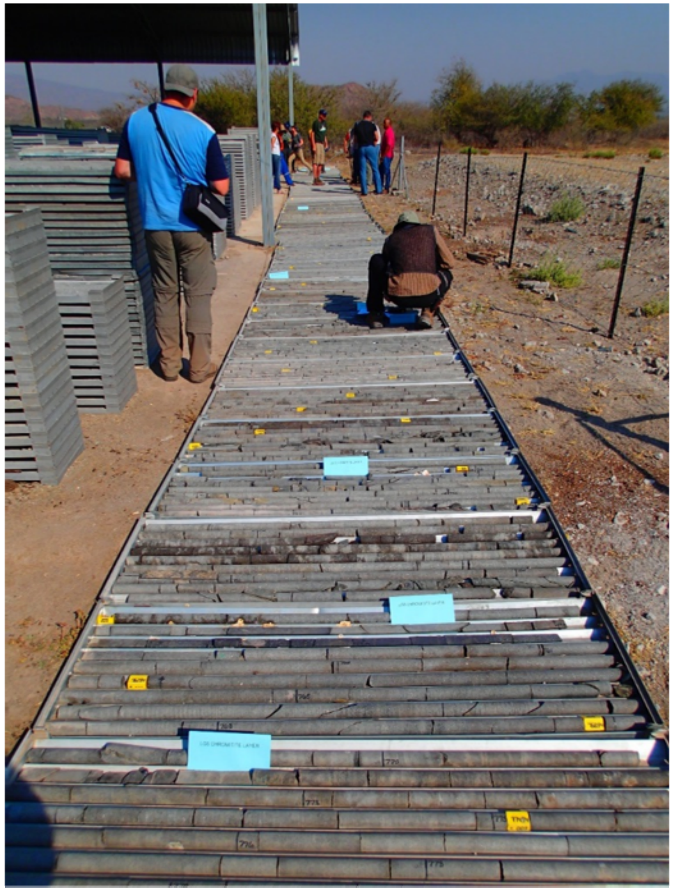
Why does understanding DIM matter

- 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

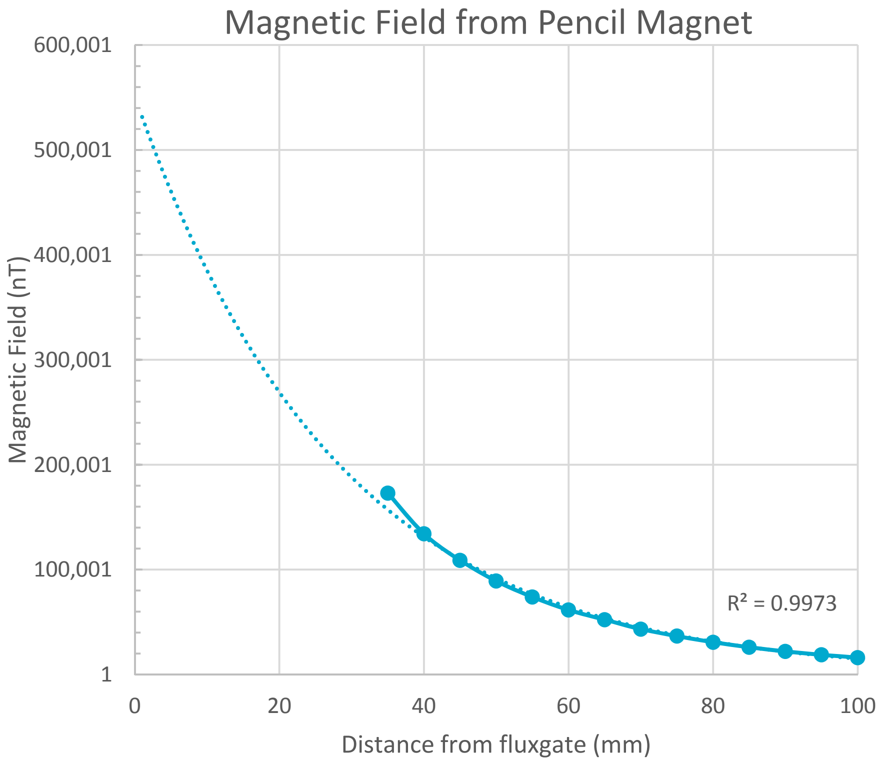


You can tell when a good geo has been over the core



What is the field generated by a pencil magnet

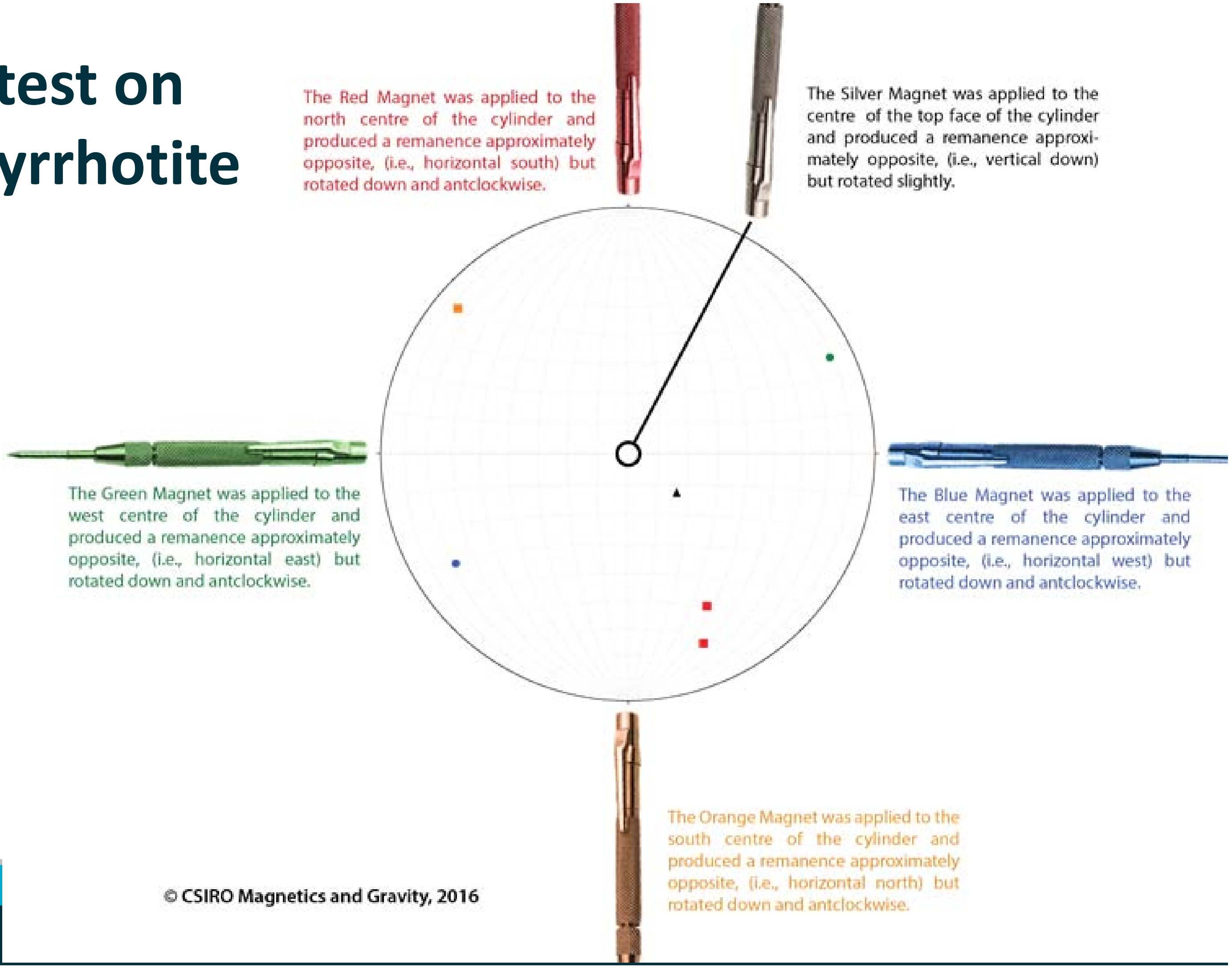
- Not easy to quantify because we can’t get one close to a fluxgate
- However if we predict the data based on the inverse cube attenuation
- We estimate a field of approx 550 nT close to the end of the magnet.
  - 10x the Earth’s field
- That will only remagnetize low coercivity grains



Pencil Magnet test on Multidomain Pyrrhotite

Why the mis-match?

- Stable Remanence still in rock
- Anisotropy
- Misalignment of the magnetic field within the magnet



The Red Magnet was applied to the north centre of the cylinder and produced a remanence approximately opposite, (i.e., horizontal south) but rotated down and antclockwise.

The Silver Magnet was applied to the centre of the top face of the cylinder and produced a remanence approximately opposite, (i.e., vertical down) but rotated slightly.

The Green Magnet was applied to the west centre of the cylinder and produced a remanence approximately opposite, (i.e., horizontal east) but rotated down and antclockwise.

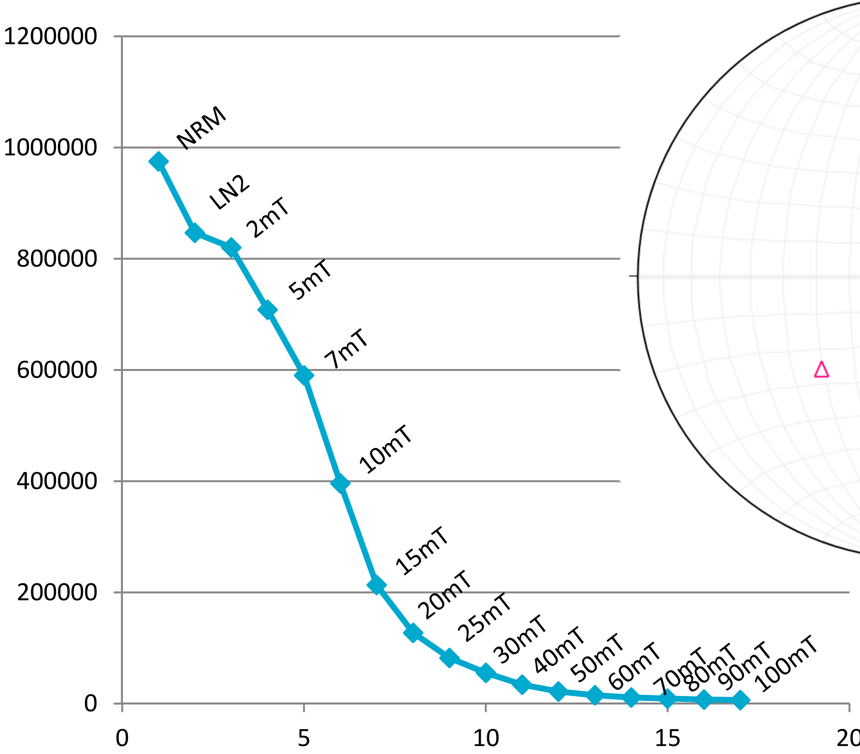
The Blue Magnet was applied to the east centre of the cylinder and produced a remanence approximately opposite, (i.e., horizontal west) but rotated down and antclockwise.

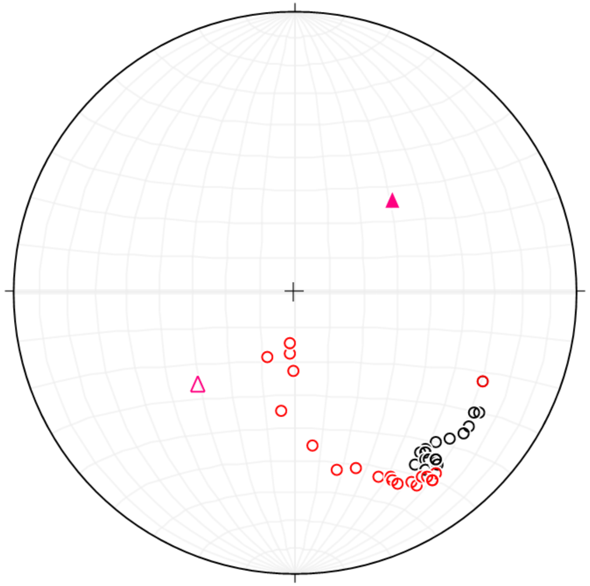
The Orange Magnet was applied to the south centre of the cylinder and produced a remanence approximately opposite, (i.e., horizontal north) but rotated down and antclockwise.

© CSIRO Magnetics and Gravity, 2016

Coarse Pyrrhotite MT2A – Cormorant Prospect

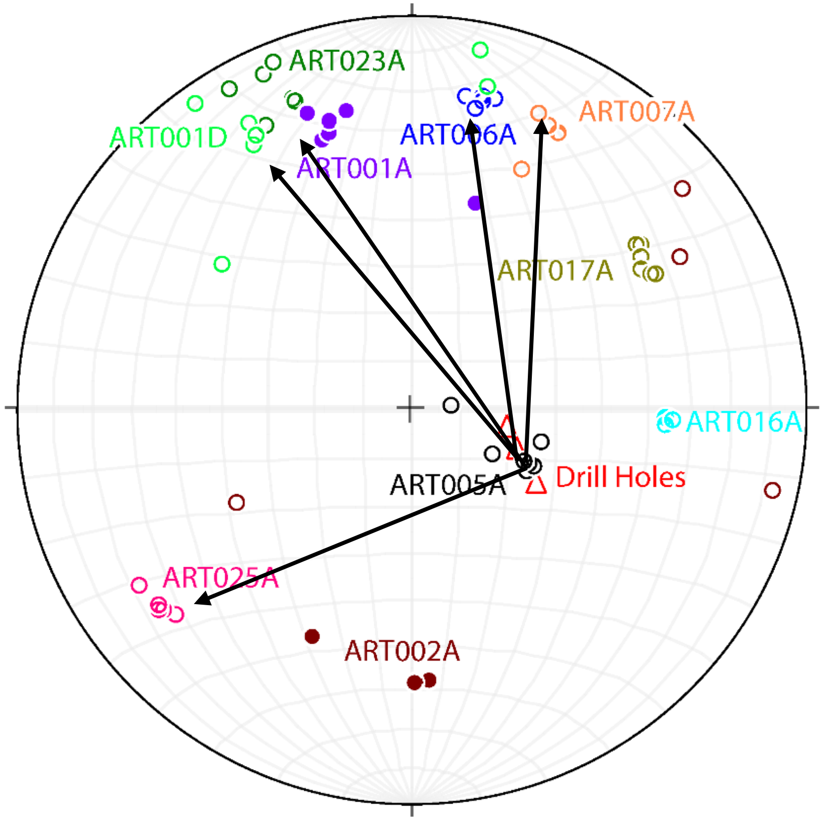
MT2A	field	corrected		
	step	dec	inc	int
NRM	115.3	-26.2	974987.3	1
LN2	123.2	-22.5	846694	1
2mT	124	-23.5	820145.7	1
5mT	127.7	-22.1	708279.9	1
7mT	129.9	-22.1	590219.9	1
10mT	133.4	-24.4	396034.8	1
15mT	136.6	-27	213404.6	1
20mT	140.2	-27.6	127115.7	1
25mT	141.8	-27.5	82034.57	1
30mT	144.9	-25.6	55276.56	1
40mT	140.6	-27	33929.21	1
50mT	142	-25.1	21559.12	1
60mT	141.1	-24.4	15141.99	1
70mT	143.7	-21.9	11072.78	1
80mT	140.4	-21.6	8847.735	1
90mT	140.5	-20.8	7338.543	1
100mT	139.9	-22.9	6282.583	1





Characteristic PIM

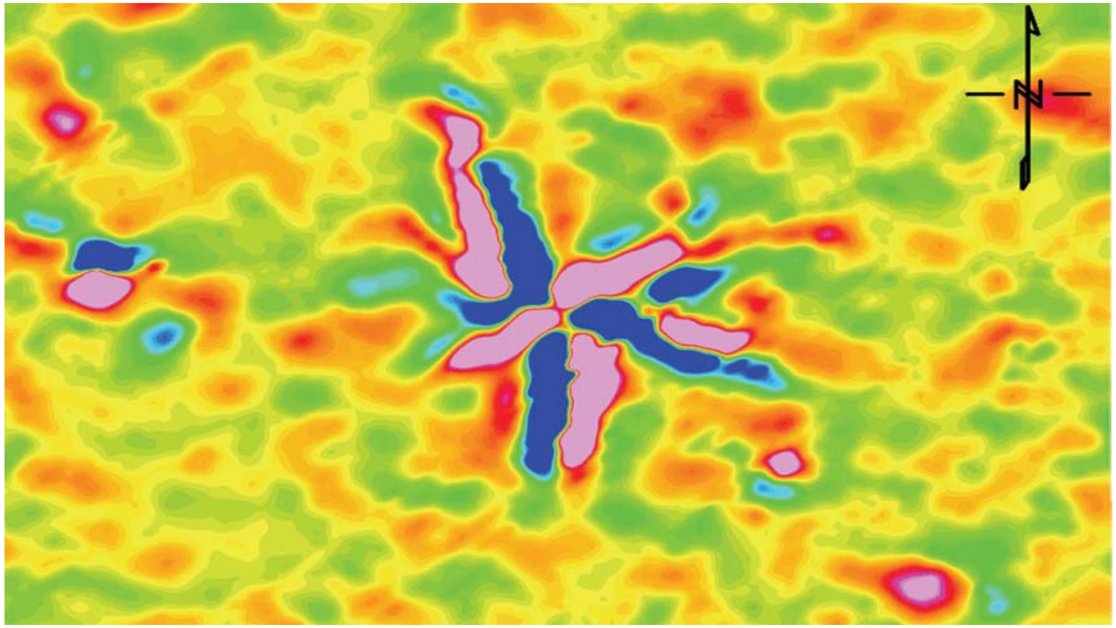
- In rig-drilled samples PIM will display a large variation in the declination
- But magnetisation directions will typically be approximately normal to the drill orientation.
- E.g., Pyrrhotite-rich samples from the Artemis prospect have magnetisations approximately normal to the drill orientation, indicating 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

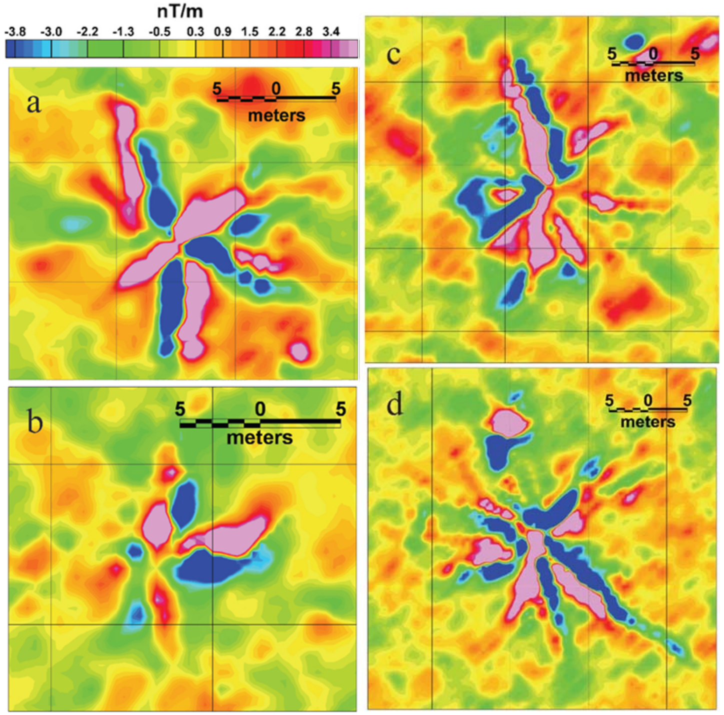



Musgrave Block, Central Australia

Lightning

Lightning - Magnetic Effect

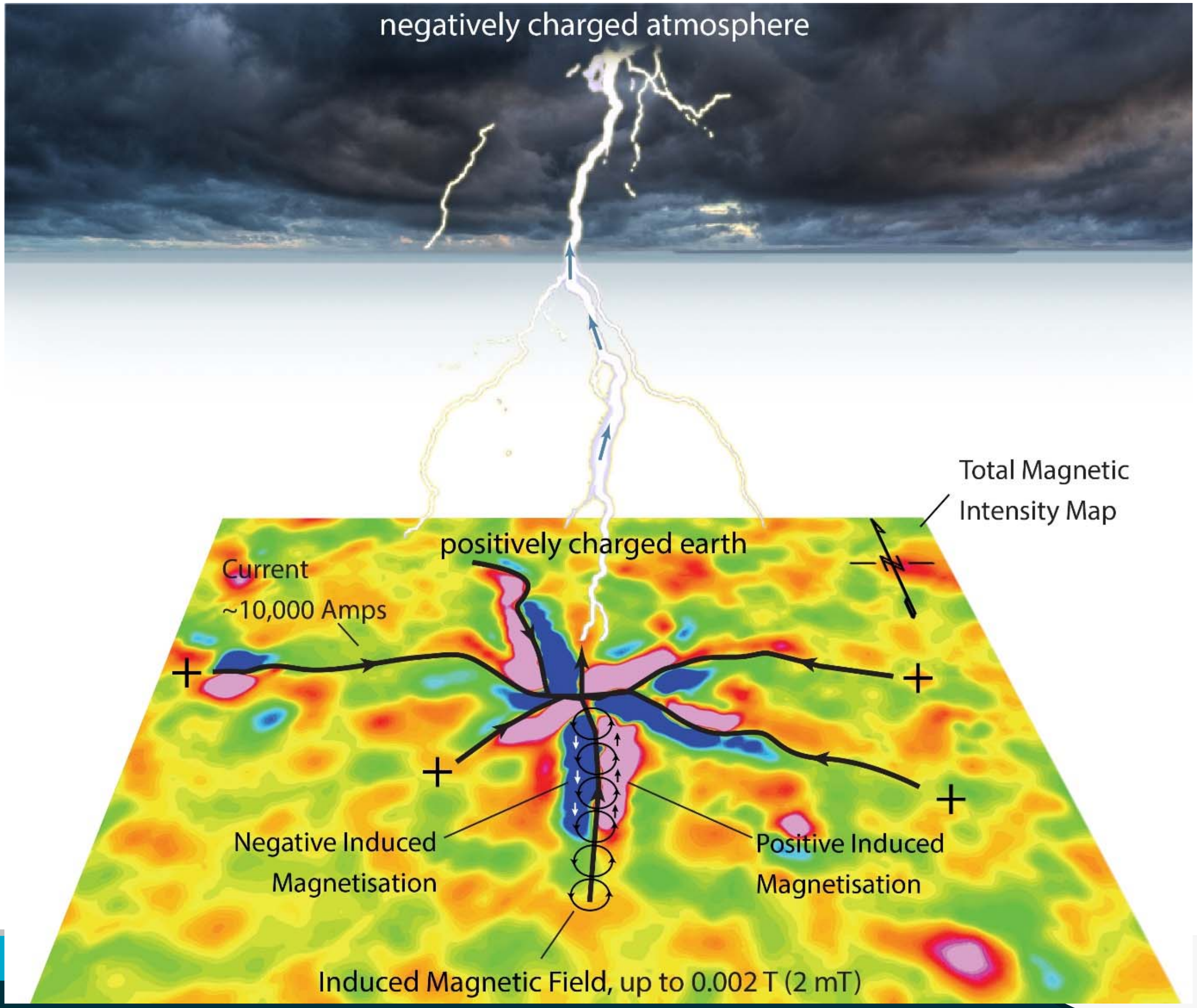




Les P. Beard, Jeannemarie Norton, and Jacob R. Sheehan (2009). "Lightning-Induced Remanent Magnetic Anomalies in Low-Altitude Aeromagnetic Data." Journal of Environmental and Engineering Geophysics, 14(4), 155-161.

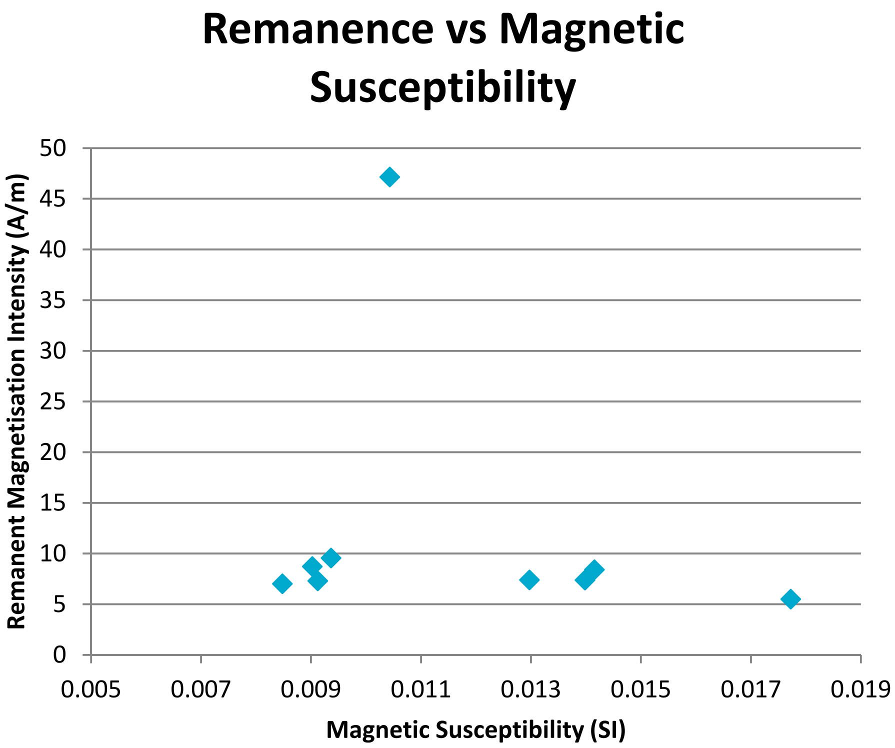
Lightning Induced Magnetisation

- 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



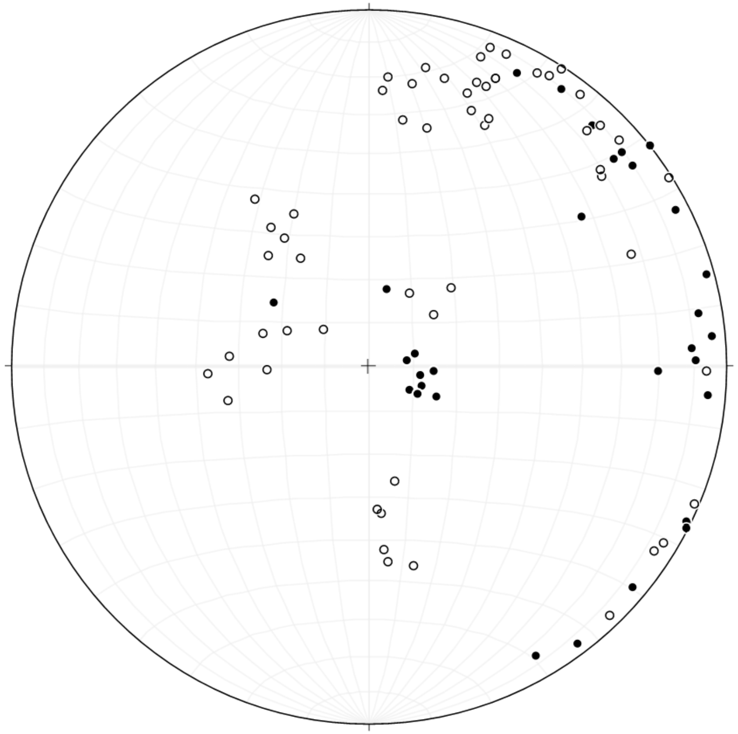
Lightning Induced Magnetisation

- Manifested by uncharacteristically high remanent magnetisation in lithologically similar samples



Lightning Induced Magnetisation

- NRMs 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

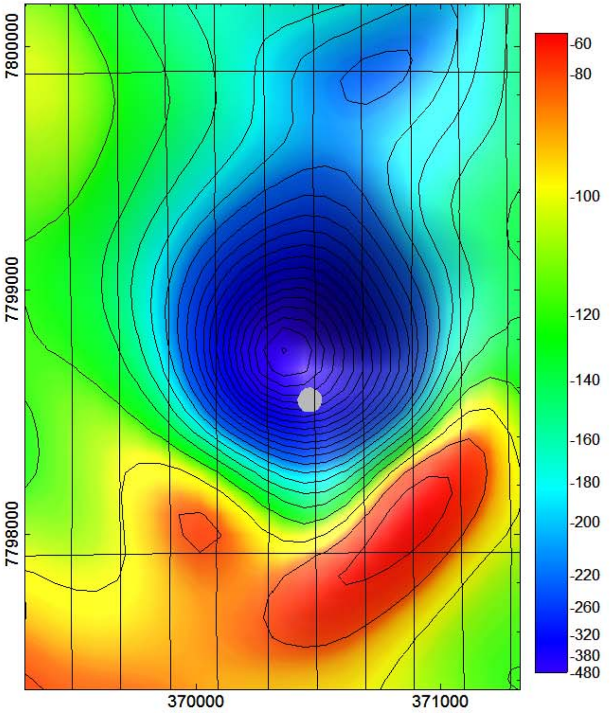


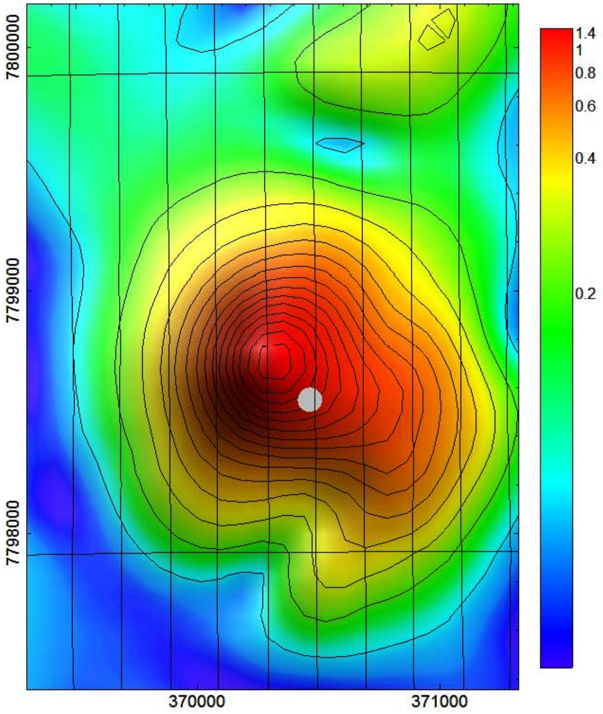
Rover 3 Case History

- 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

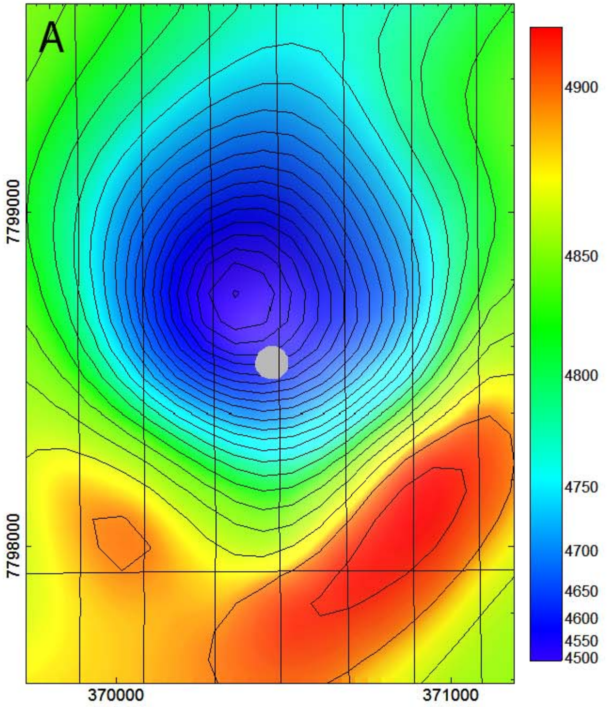
- The Rover 3 TMI anomaly is relatively simple - it only justifies a simple model
- The Total Gradient (Analytic Signal) enhancement does reveal some complexity – a more diffuse or deeper magnetization in addition to that generating the main total gradient anomaly peak – but this cannot be reliably modelled



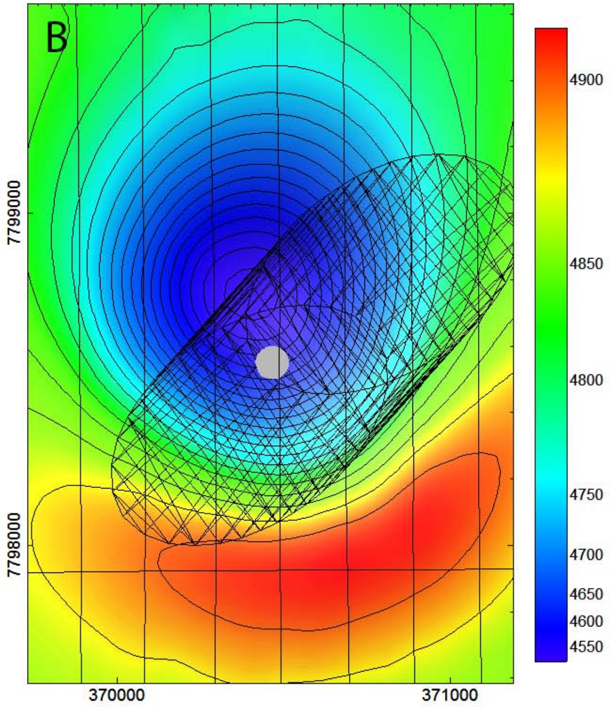


The Preferred Inversion Model for Rover 3

- 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



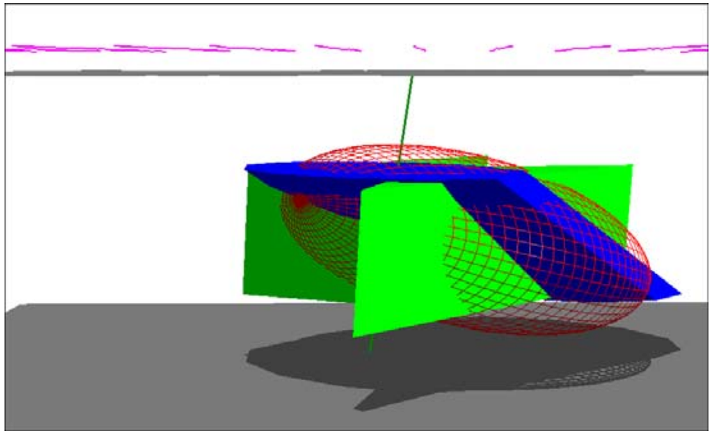
Measured TMI

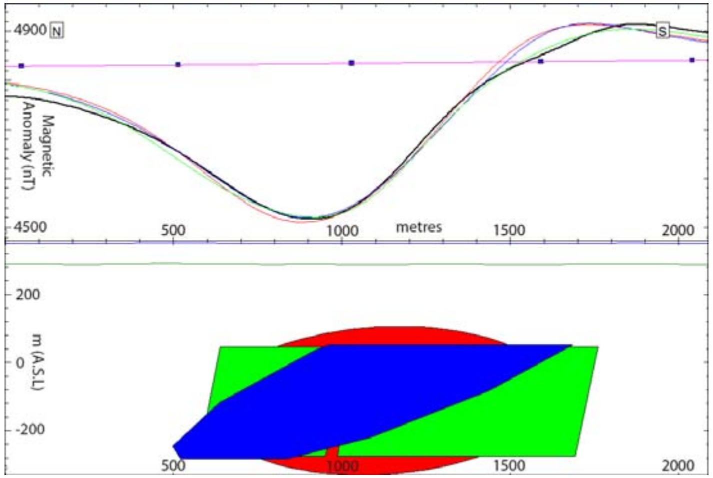


Computed TMI

Alternate Inversion Models for Rover 3

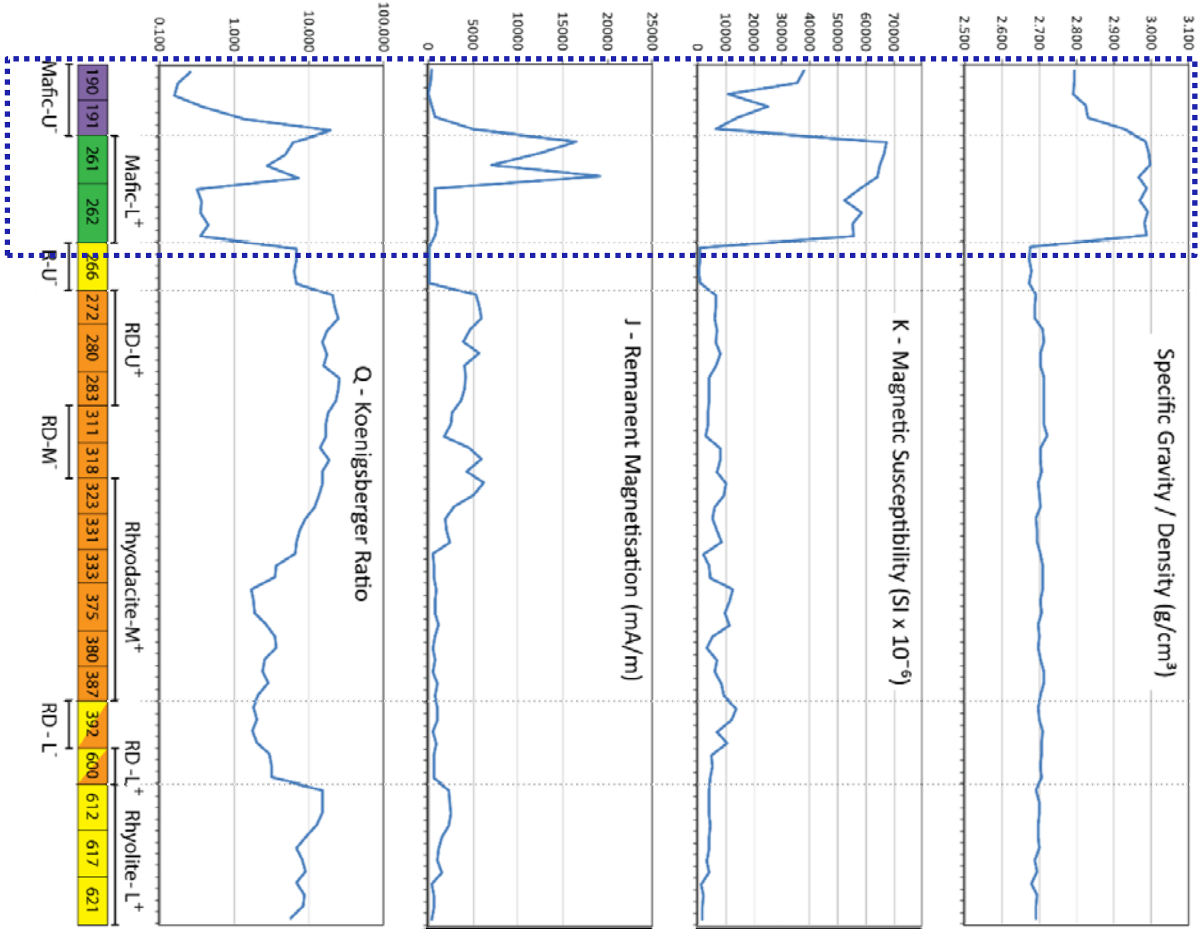
- We can produce alternate models which all have consistent values for the meaningful parameters:
  - Centre of magnetization
  - Magnetic moment (volume x intensity)
  - Direction of magnetization
- Factors such as shape and depth to top are details that are not reliably recovered from magnetic field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





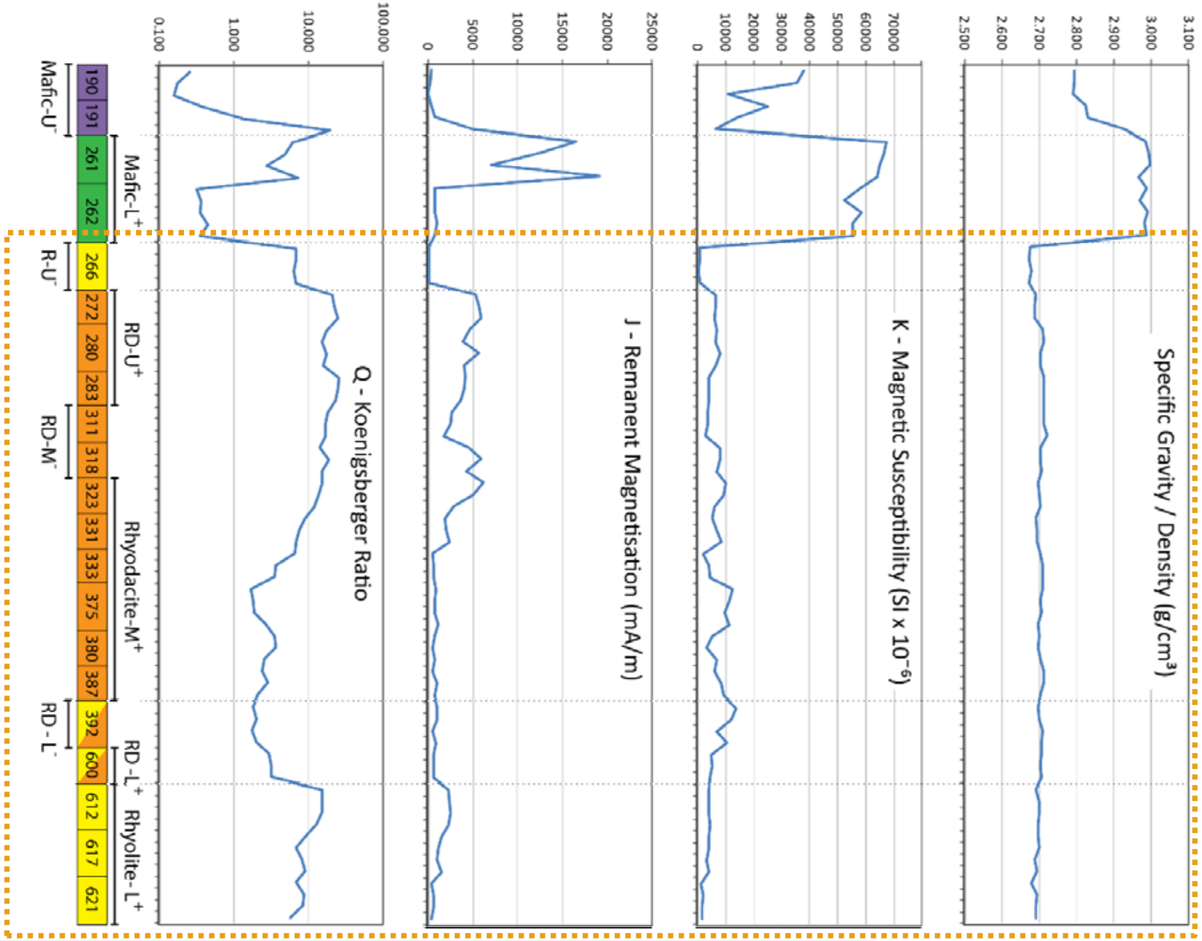
Distribution of magnetization

- 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



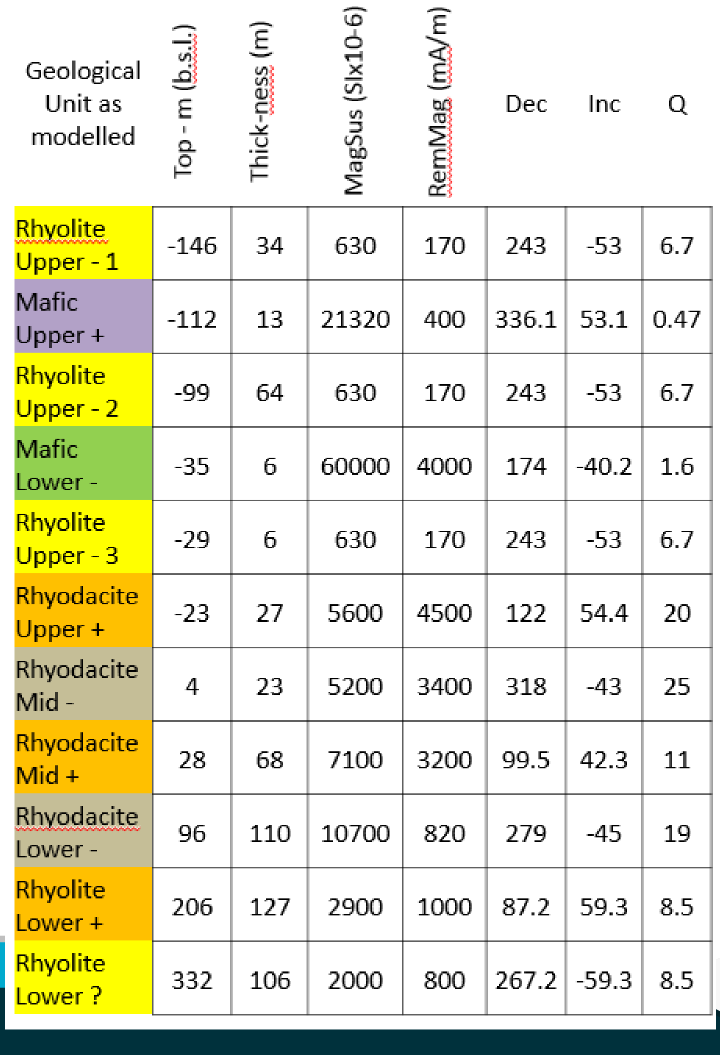
Distribution of magnetization

- 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

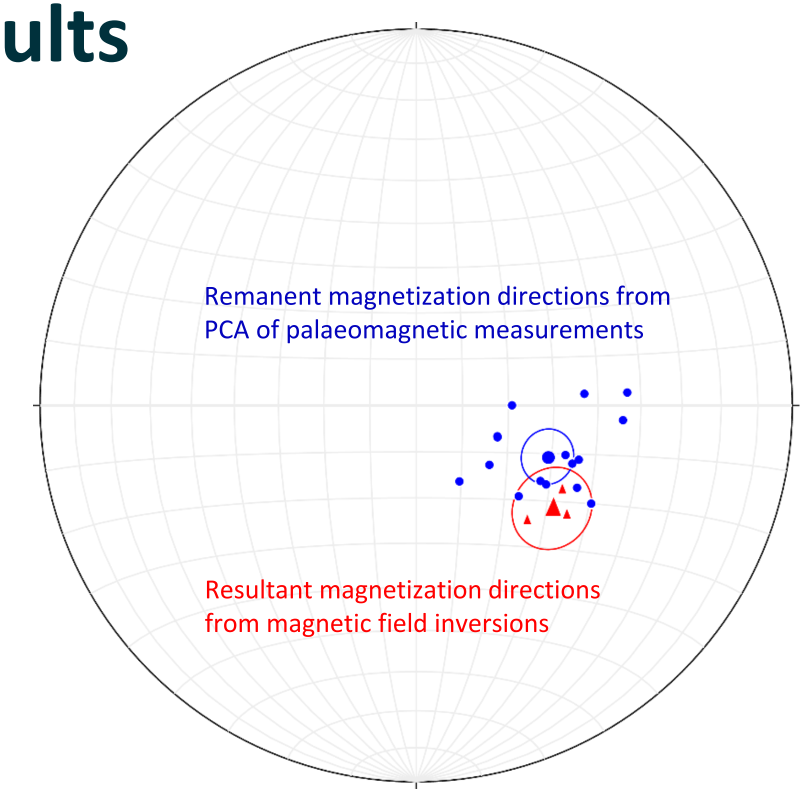
- The true distribution of magnetization revealed by direct measurement is highly complex and sharply varying,
- Remanence in the individual layers switches polarity as the volcanic pile builds up
- But can be resolved into representative values for stratigraphic units
- To match the magnetization estimated 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



Geological Unit as modelled	Top - m (b.s.l.)	Thick-ness (m)	MagSus (SIx10-6)	RemMag (mA/m)	Dec	Inc	Q
Rhyolite Upper - 1	-146	34	630	170	243	-53	6.7
Mafic Upper +	-112	13	21320	400	336.1	53.1	0.47
Rhyolite Upper - 2	-99	64	630	170	243	-53	6.7
Mafic Lower -	-35	6	60000	4000	174	-40.2	1.6
Rhyolite Upper - 3	-29	6	630	170	243	-53	6.7
Rhyodacite Upper +	-23	27	5600	4500	122	54.4	20
Rhyodacite Mid -	4	23	5200	3400	318	-43	25
Rhyodacite Mid +	28	68	7100	3200	99.5	42.3	11
Rhyodacite Lower -	96	110	10700	820	279	-45	19
Rhyolite Lower +	206	127	2900	1000	87.2	59.3	8.5
Rhyolite Lower ?	332	106	2000	800	267.2	-59.3	8.5

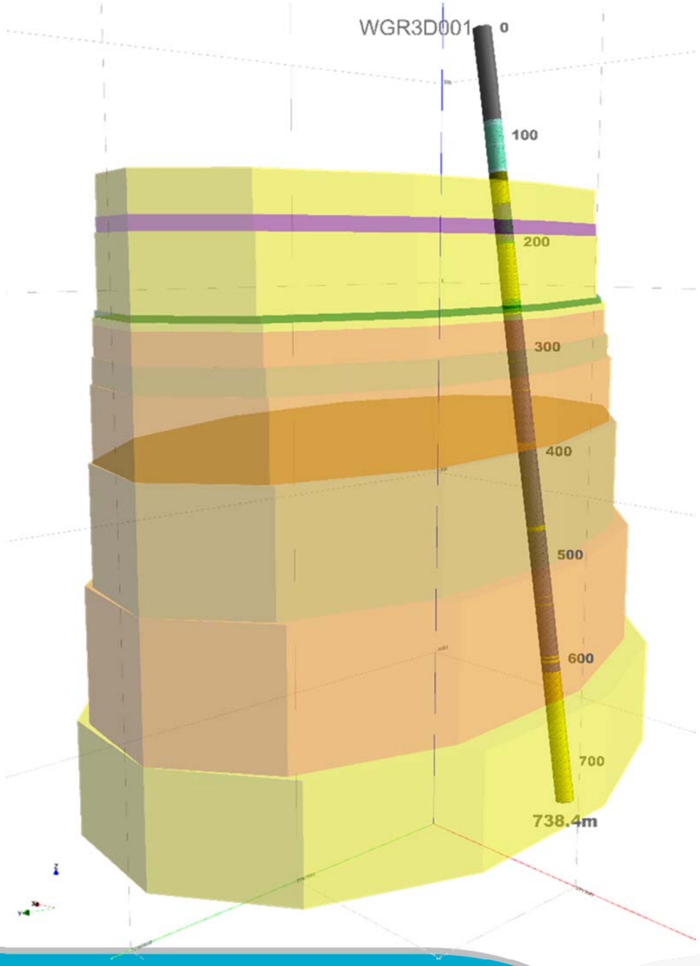
Agreement between measured magnetization and magnetic field inversion results

- 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:

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