Estimating total and remanent magnetization of geological sources

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Workshop 8: "Improving Exploration with Petrophysics: The Application of Magnetic Remanence and Other Rock Physical Properties to Geophysical Targeting"

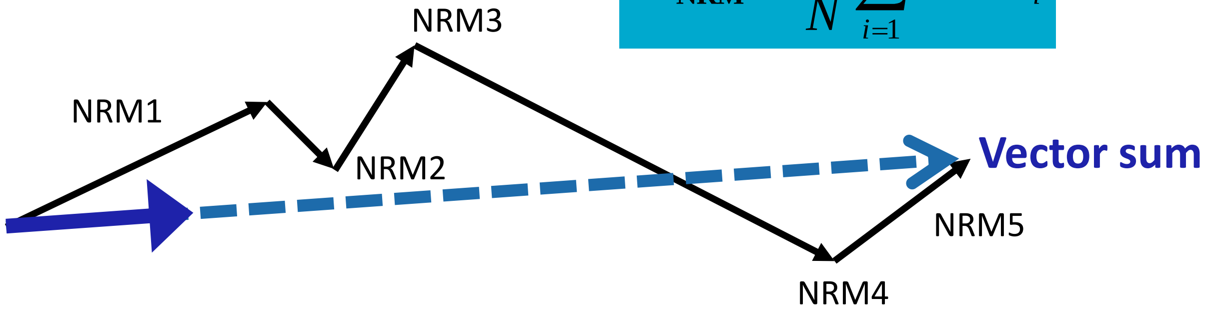
Methods discussed (briefly!)

Clark, 2014. Methods for determining remanent and total magnetisations of magnetic sources - a review. Exploration Geophysics, 45, 271–304.

1. Sample measurements
2. Borehole measurements
3. Constrained modelling/inversion of magnetic sources
4. Simple direct inversions of measured or calculated vector and gradient tensor data for compact sources
5. Helbig-type analysis
6. Dual vector magnetometers or a single combined gradiometer/ magnetometer in base station mode
7. Combined analysis of magnetic and gravity anomalies using Poisson's theorem
8. Active source magnetics
9. Inference from petrography, supplemented by palaeomagnetic databases

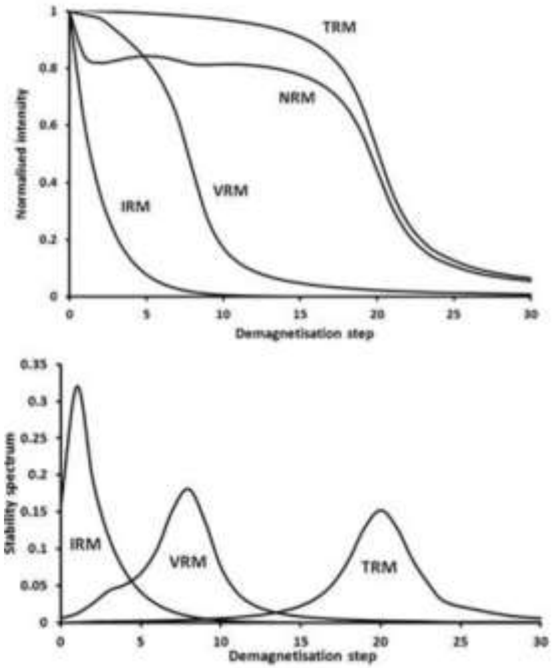
Sample measurements – correct averaging of remanence vectors

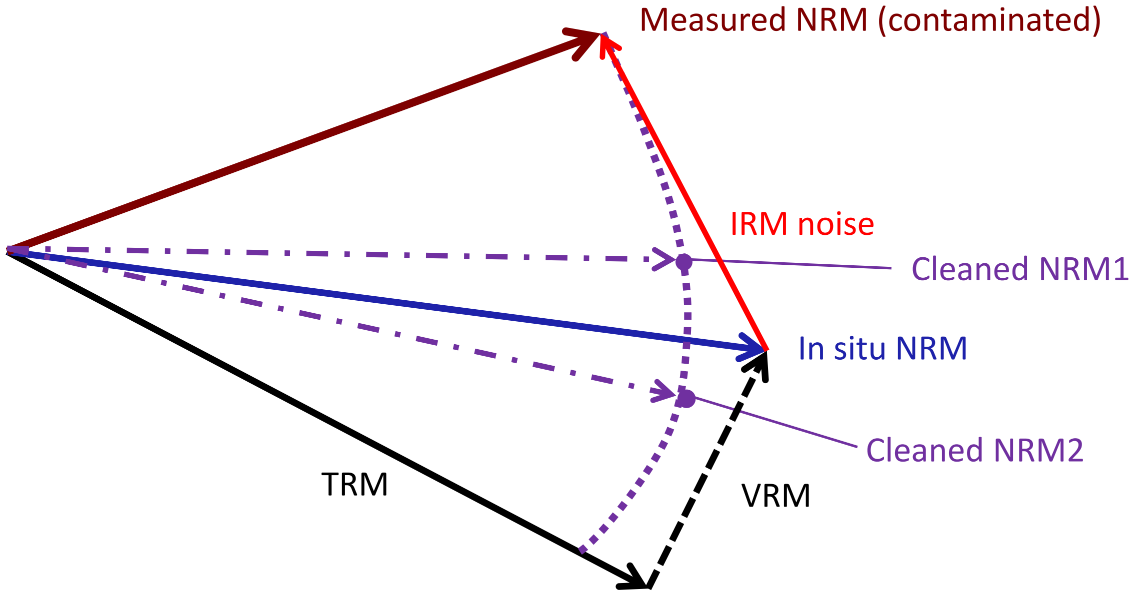
$$\overline{\mathbf{M}}_{\mathbf{NRM}} = \frac{1}{N}\sum_{i=1}^{N}\mathbf{NRM}_i$$



- DON'T average NRM intensities (irrespective of direction, or even polarity!!)
- DON'T average Koenigsberger ratios (calculate Q from correctly averaged NRM and average susceptibility)

Sample measurements





- Only include stable components + VRM in estimated remanent magnetisation of source

Sample measurements

ASSUMPTIONS/RESTRICTIONS /REQUIREMENTS	INFORMATION PROVIDED	LIMITATIONS
• Representative sampling •Sufficient sampling •NRM uncontaminated or cleanable • Adequate statistical analysis and appropriate treatment of vectors	k or **K** $\mathbf{M}_{IND}$ $\mathbf{M}_{NRM}$ **M** Q	•Unavailability of samples •Available samples unrepresentative •Remanence contaminated •Weathering •Heterogeneity, nugget effect •Requires sophisticated equipment for complex NRM

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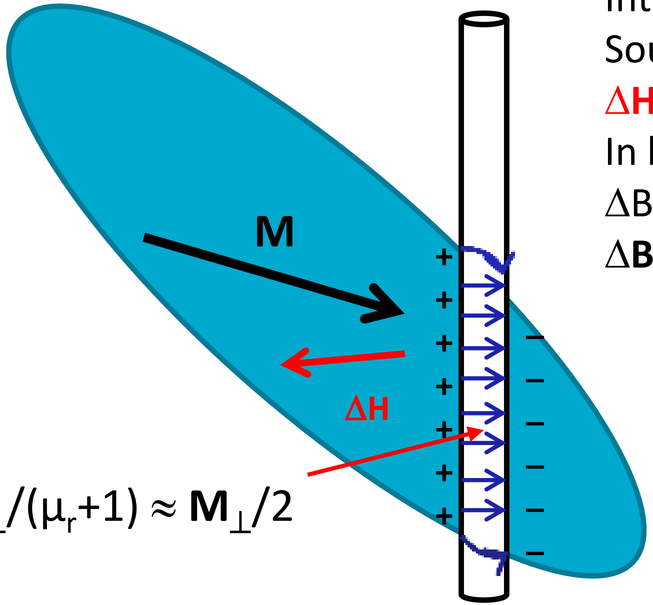
Borehole measurements



$\Delta \mathbf{H}_{cav} = \mathbf{M}_{\perp}/(\mu_r+1) \approx \mathbf{M}_{\perp}/2$

Internal anomalous field of Source = self-demag. field:

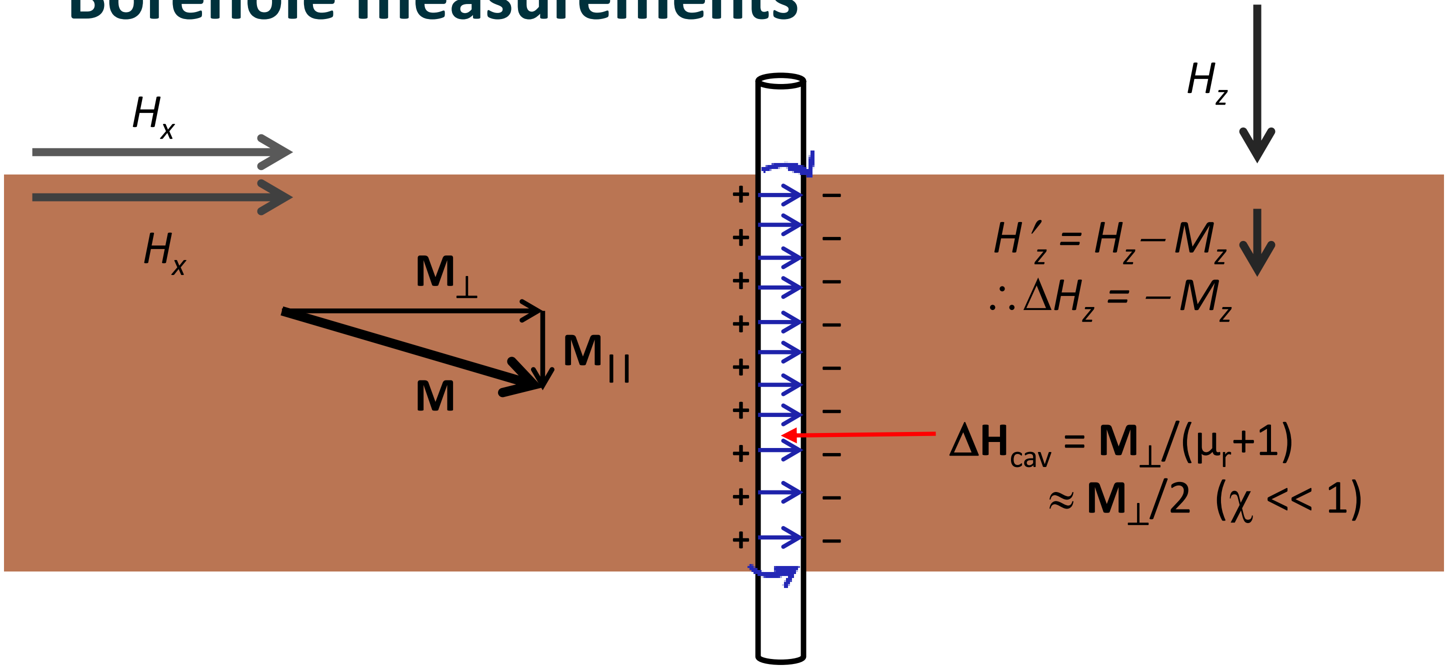
$\color{red}{\Delta \mathbf{H}}$ = – **NM**

In borehole resultant field is:

$\Delta B_{||}' = \mu_0 \color{red}{\Delta H_{||}}$,

$\Delta \mathbf{B}_{\perp}' = \mu_0(\color{red}{\Delta \mathbf{H}_{\perp}} + \mathbf{M}_{\perp}/2)$

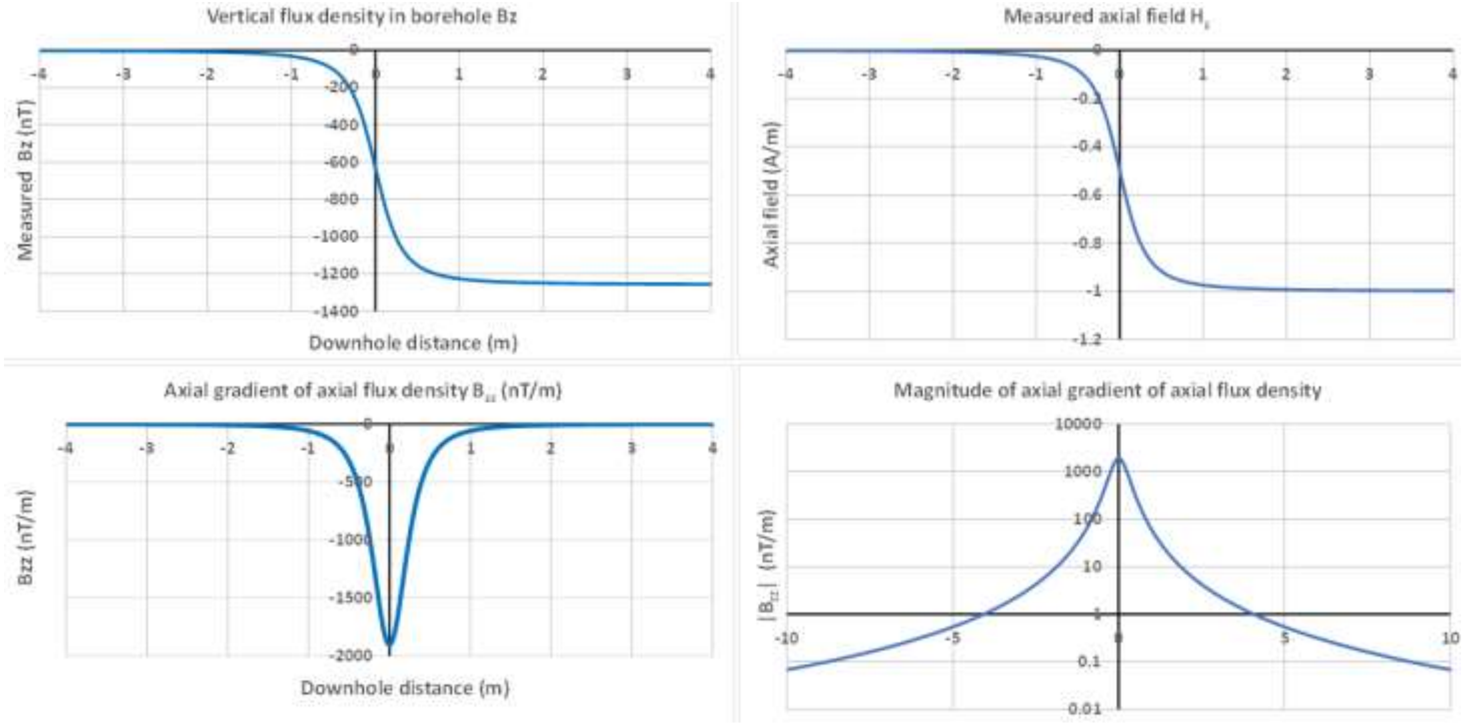
Borehole measurements



Borehole measurements

ASSUMPTIONS/RESTRICTIONS /REQUIREMENTS	INFORMATION PROVIDED	LIMITATIONS
• Uniform properties within intersected source •Layered earth with known dips, or known shape of intersected source •Hole intersects source(s)	*k* * $\mathbf{M}_{IND}$* $\mathbf{M}_{NRM}$ **M** *Q* * *If susceptibility is logged downhole or measured on core*	•Source geometry may be unknown (possibly can be modelled by external measurements) •Orientation noise on vector measurements •Noisy vectors due to heterogeneity and rugosity

Borehole measurements

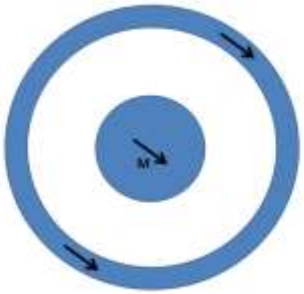


Why inversion often works/what about non-uniqueness?

- Non-uniqueness is an important issue *but* its importance is often exaggerated
- Classic cases of *theoretically* equivalent sources are generally very artificial
- Some parameters are uniquely defined, even if source is ambiguous – *magnetisation direction is generally robust*
- Any constraints from other data or geological plausibility drastically reduce ambiguity

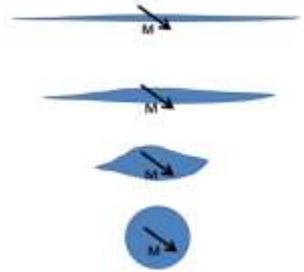
Strictly equivalent sources with unique magnetisation direction and total moment

Equivalent shells – equivalent even when |**M**| specified



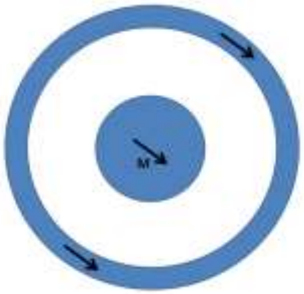
Equivalent confocal ellipsoids – *unique when* |**M**| *specified*

Equivalent lenses – *unique when* |**M**| *specified*

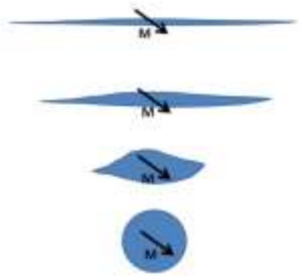


Strictly equivalent sources

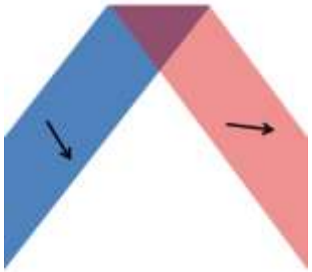
Equivalent shells: 2D or 3D (*even if* |**M**| *specified*)



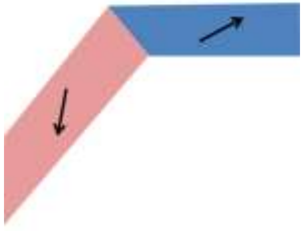
Equivalent lenses : 2D or 3D (*but have different* |**M**|)



Equivalent dipping sheets: 2D (*semi-infinite*)

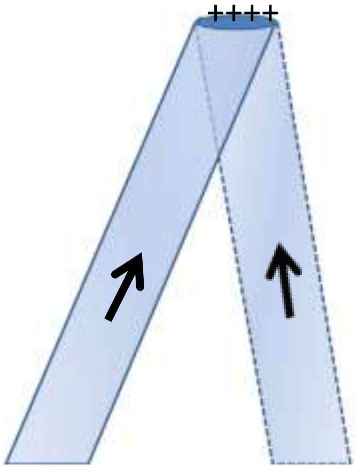


Equivalent sloping step/dipping sheet: 2D (*semi-infinite*)

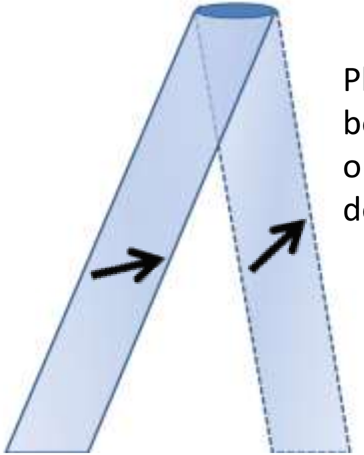


Equivalent and non-equivalent plugs

Axially magnetised:
equivalent



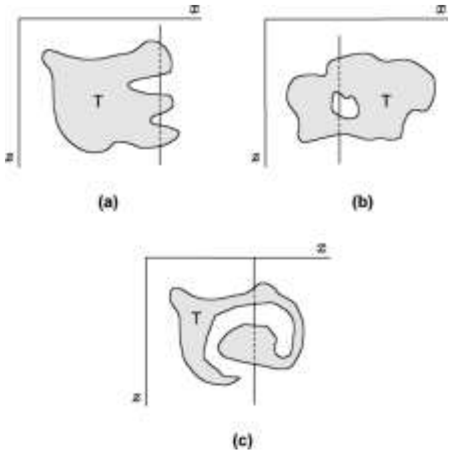
Transversely magnetised:
non-equivalent



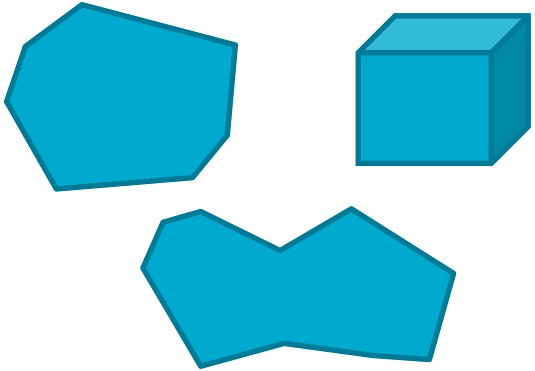
Plunge & **M** [wide body]
or **M***A* [narrow plug]
determinable

Non-uniqueness of pathological sources vs uniqueness of simple polygons/polyhedra

Potentially non-unique, but pathological



Theoretically unique geometry *and* magnetisation

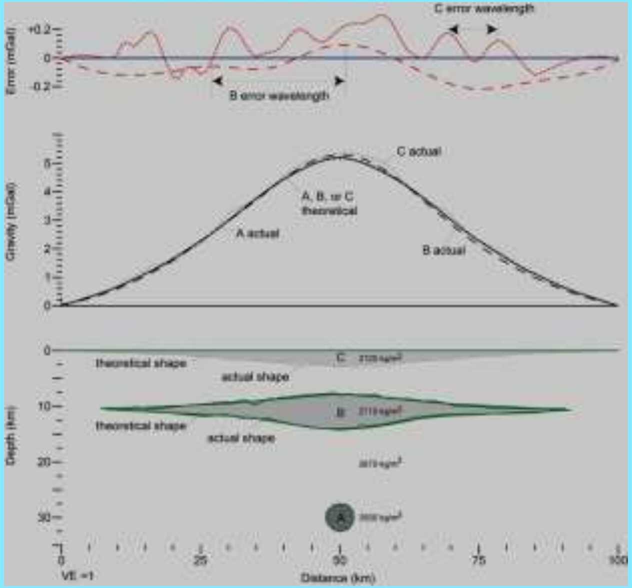


What about non-uniqueness?

I recommend:

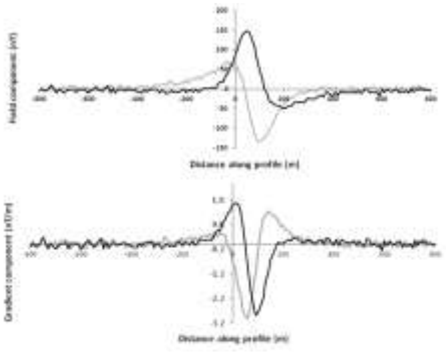
Saltus, R.W. and Blakely, R.J., 2011, Unique geologic insights from “non-unique” gravity and magnetic interpretation: GSA Today, 21(12), 4-11

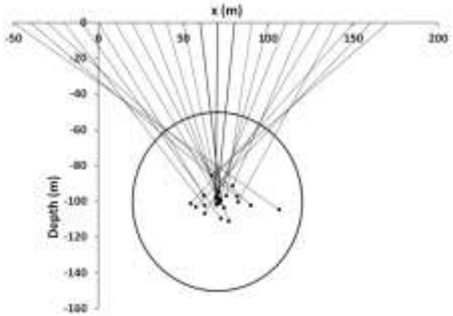
for a common-sense view.



Simple direct inversions of vector or tensor data

Clark , EG, 2012





Located compact source:
moment from field vectors

$$\mathbf{m} = \frac{r^3}{C}\left[\frac{3\mathbf{b.r}}{2r^2}\mathbf{r} - \mathbf{b}\right],$$

Located compact source:
moment from tensors

$$\mathbf{m} = \frac{r^4}{3C}\left[\mathbf{B\hat{r}} - \frac{3}{2}(\mathbf{\hat{r}}^T\mathbf{B\hat{r}})\mathbf{\hat{r}}\right].$$

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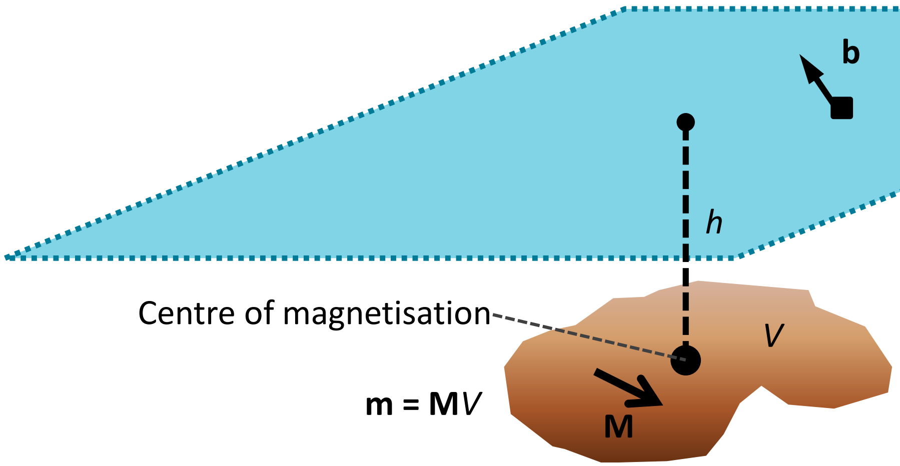
Helbig analysis – what is it?

- Based on integral moments of magnetic vector components over observation plane



Helbig, 1963
Andersen & Pedersen,1979
Schmidt & Clark, 1998
Phillips, 2005
Foss, 2006
Phillips et al., 2007
Caratori Tontini & Pedersen, 2008

Helbig analysis – for *finite isolated source*

- Can be applied to gradient tensor components *and to invariants derived from the tensor*
- *Provided regional trends are removed and correct base levels are known*,

Helbig analysis $\Rightarrow$ magnetic moment vector

$$\mathbf{m} = \overline{\mathbf{M}}V = \int_V \mathbf{M}dV$$

Helbig analysis $\Rightarrow$ average direction of magnetisation

$$\hat{\mathbf{M}} = \hat{\mathbf{m}} = \mathbf{m} / m$$

Helbig analysis $\Rightarrow$ location of centre of magnetisation

These parameters are determined uniquely, *independently of the source geometry*

Helbig Analysis

CAVEATS/LIMITATIONS	MITIGATION
Source cannot extend beyond survey area or to great depth	Select relatively isolated sources, with dipolar character (or do analysis on vertical derivatives)
Requires measurements over whole extent of anomaly to determine moment magnitude	Correct finite integrals for missing tails (requires depth estimate)
Interference from neighbouring sources can invalidate the method	Restrict window and correct for missing tails; analyse gradient components and tensor invariants
Regional trends bias results	Remove regional trends prior to analysis
Base levels must be known	Remove average values of components across integration area

Helbig Analysis – vector components

- Base levels from: $$\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} B_x dxdy = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} B_y dxdy = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} B_z dxdy = 0$$

- Magnetic moment: $$\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} xB_x dxdy = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} yB_y dxdy = -2\pi C m_z,$$

$$\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} xB_z dxdy = -2\pi C m_x; \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} yB_z dxdy = -2\pi C m_y,$$

Helbig Analysis – tensor components

- Base levels from:

$$\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} B_{ij}\,dxdy = 0, \quad i, j = x, y, z$$

- Magnetic moment:

$$\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} x^2 B_{xx}\,dxdy = \int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} y^2 B_{yy}\,dxdy = 2\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} xyB_{xy}\,dxdy = 4\pi C m_z,$$

$$\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} x^2 B_{xz}\,dxdy = 2\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} xyB_{yz}\,dxdy = 4\pi C m_x,$$

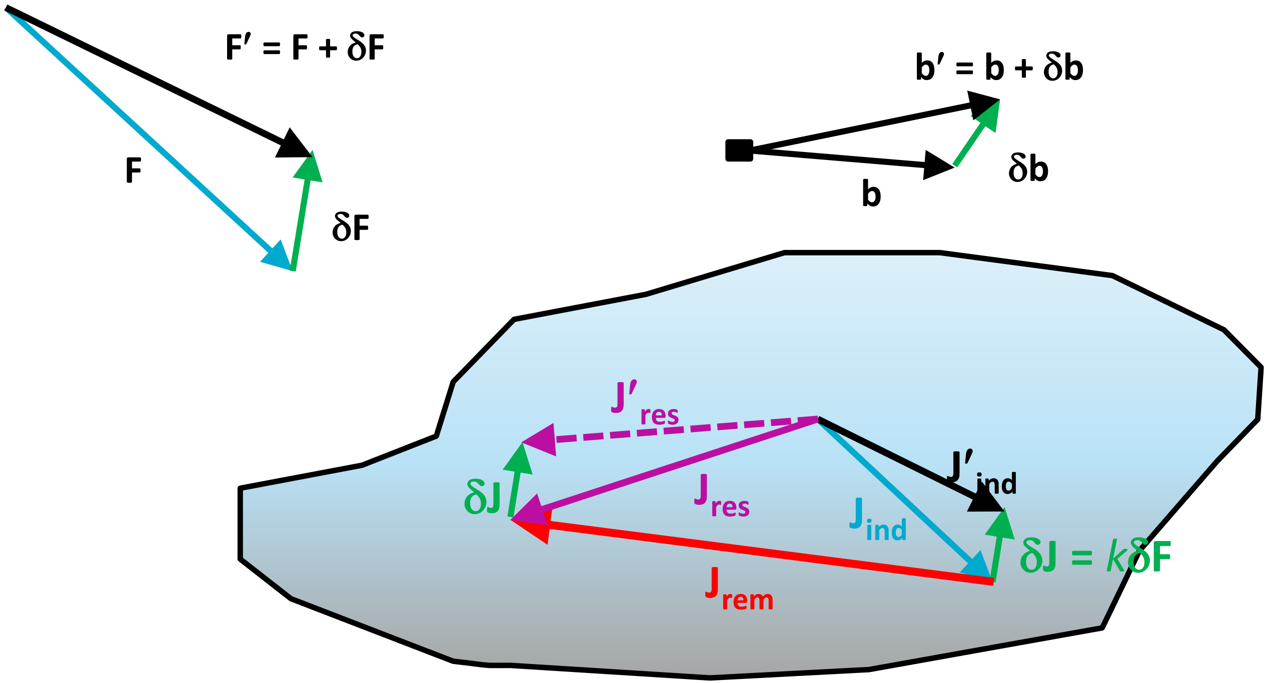
$$\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} y^2 B_{yz}\,dxdy = 2\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty} xyB_{xz}\,dxdy = 4\pi C m_y.$$

Properties and strengths of Helbig Analysis

- Independent of *finite* source shape and heterogeneity
- Uses all data within anomaly $\Rightarrow$ averages noise
- Total moment $\Rightarrow$ indication of source size (if $|M|$ assumed)
- Total moment $\Rightarrow$ indication of magnetisation intensity $\Rightarrow$ lithology (if source size constrained)
- Magnetisation direction is robust, even for small integration windows
- Magnetisation direction can provide indication of strong remanence $\Rightarrow$ indication of mineralogy/lithology

  $\Rightarrow$ possible age of magnetisation

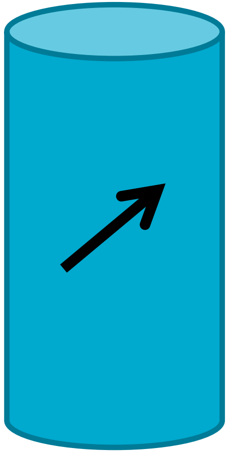
Base station DVM/magnetometry-gradiometry



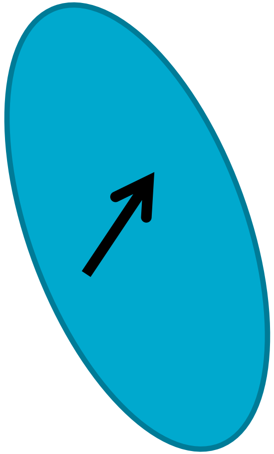
Base station DVM/magnetometry-gradiometry

Discrimination of geologically different targets with similar magnetic signatures

MD magnetite-bearing igneous plug Q ~ 0.5



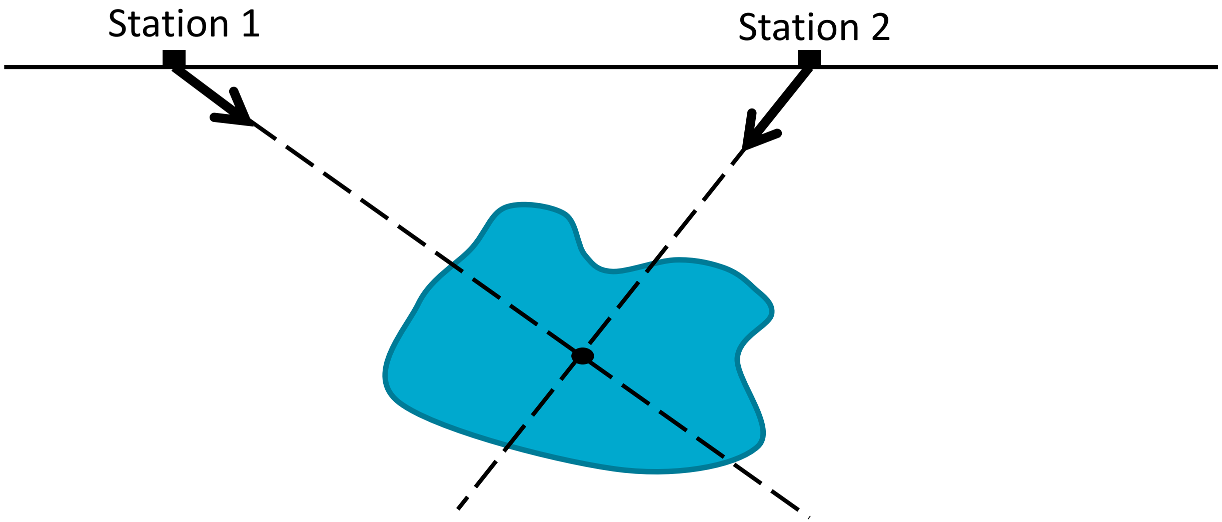
Pyrrhotite-bearing sulphide orebody Q ~ 10



Base station DVM/magnetometry-gradiometry

Drill hole targeting – directions to source from DVM

DVM moved to new location ⇒ source centroid

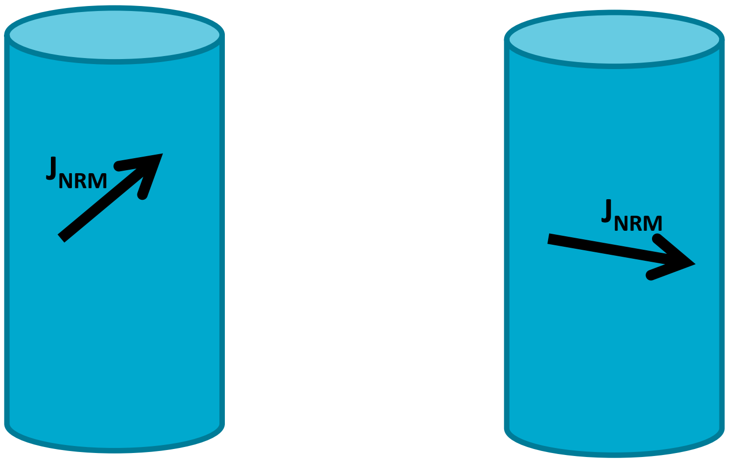


Base station DVM/magnetometry-gradiometry

Discrimination of intrusions (or other magnetic bodies) of different ages

Age 1 –
prospective system

Age 2 –
non-prospective system



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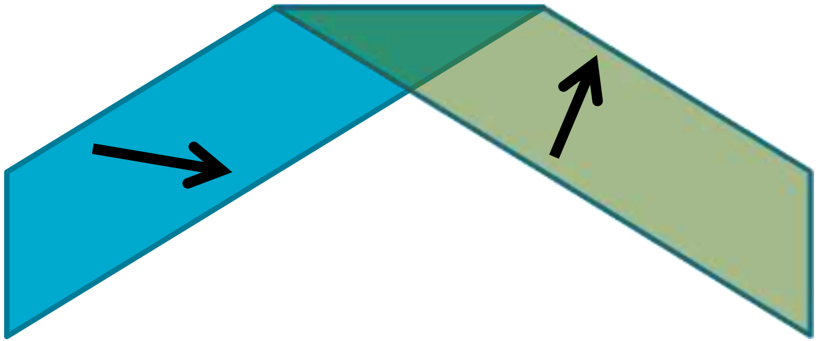
Base station DVM/magnetometry-gradiometry

Disambiguation of non-unique models

- Body 1 and body 2 produce identical anomalies $\Rightarrow$ dip is ambiguous if magnetisation direction is unknown
- DVM $\Rightarrow$ resultant magnetisation direction $\Rightarrow$ resolves dip
- DVM $\Rightarrow$ Q $\Rightarrow$ indicative of magnetic mineralogy
- DVM $\Rightarrow$ remanence direction $\Rightarrow$ indicative of magnetic age



Base station DVM/magnetometry-gradiometry

ASSUMPTIONS/RESTRICTIONS/ REQUIREMENTS	INFORMATION PROVIDED
• Assumes ~homogeneous source •Assumes induced magnetisation is parallel to inducing field (deflection due to anisotropy or self-demagnetisation requires multiple stations)	*Compact 2D source*: $\mathbf{M}_{\perp}A$, $\mathbf{M}_{\perp}/\lvert\mathbf{M}_{\perp}\rvert$, $\mathbf{M}_{\perp}/k$, $(\mathbf{M}_{\perp})_{NRM}/k$, $(\mathbf{M}_{\perp})_{NRM}/\lvert(\mathbf{M}_{\perp})_{NRM}\rvert$, Q, centroid *Compact 3D source*: $\mathbf{m} = \mathbf{M}V$, $\mathbf{M}/\lvert\mathbf{M}\rvert$, $\mathbf{M}/k$, $\mathbf{M}_{NRM}/k$, $\mathbf{M}_{NRM}/\lvert\mathbf{M}_{NRM}\rvert$, Q, centroid *Arbitrary 2D source*: $\mathbf{M}_{\perp}/k$, $\mathbf{M}_{\perp}/\lvert\mathbf{M}_{\perp}\rvert$, $(\mathbf{M}_{\perp})_{NRM}/k$, $(\mathbf{M}_{\perp})_{NRM}/\lvert(\mathbf{M}_{\perp})_{NRM}\rvert$, Q, centroid *Arbitrary 3D source*: $\mathbf{M}/k$, $\mathbf{M}/\lvert\mathbf{M}\rvert$, $\mathbf{M}_{NRM}/k$, $\mathbf{M}_{NRM}/\lvert\mathbf{M}_{NRM}\rvert$, Q, centroid

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Conclusions

- There are many different approaches to characterising properties of magnetic sources
- These methods are largely complementary
- The practicality of each method depends on access to samples or to geophysical data
- Each method has its strengths and weaknesses
- Even partial information provides useful constraints on interpretation

Thank you

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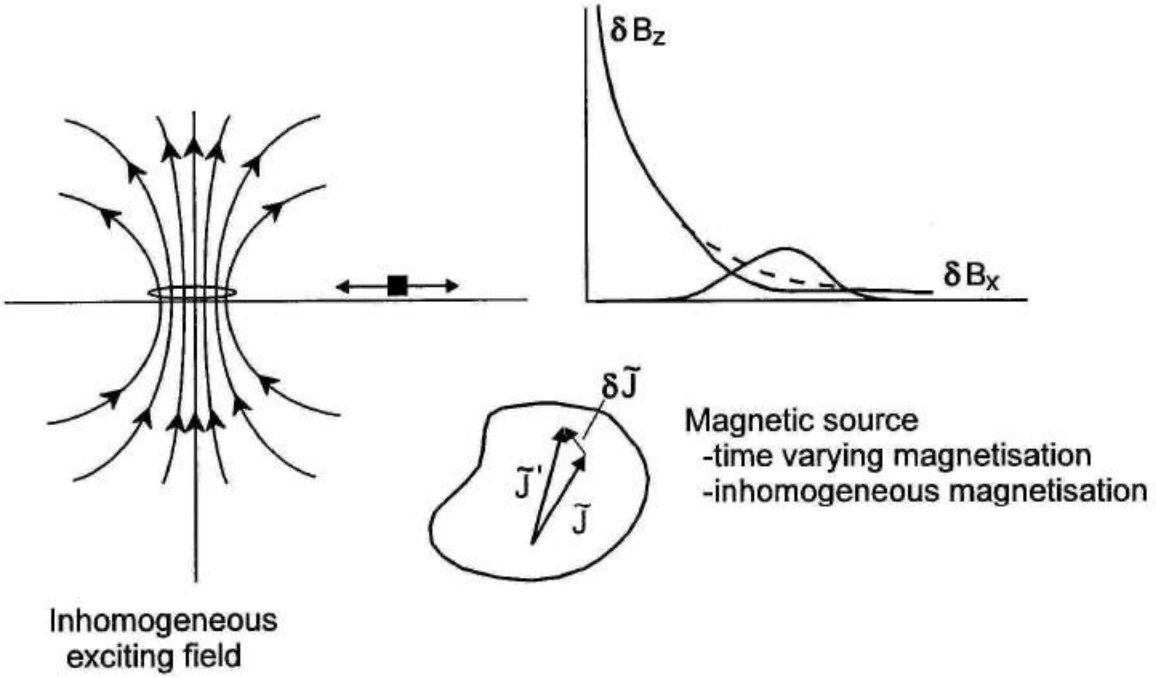
Combined magnetics and gravity

(based on Poisson's relation)

ASSUMPTIONS/RESTRICTIONS/ REQUIREMENTS	INFORMATION PROVIDED	LIMITATIONS
• Assumes common source for magnetic and gravity anomalies (shape does not need to be known) • Assumes homogeneous density and magnetisation, or at least constant $\lvert\mathbf{M}\rvert/\rho$ and constant direction of **M**	$\lvert\mathbf{M}\rvert/\rho$ $\mathbf{M}/\lvert\mathbf{M}\rvert$	• Sources of gravity and magnetic anomalies are often not identical • Density contrast or **M** may be insufficient to generate anomaly that can be accurately separated from background trends and noise

Active source magnetics



Active source magnetics

ASSUMPTIONS/RESTRICTIONS/ REQUIREMENTS	INFORMATION PROVIDED	LIMITATIONS
• Roving primary source field is accurately known across survey area • Measurements are made sufficiently long after switching primary field that eddy currents in subsurface have decayed	k $\mathbf{M}_{IND}$ $\mathbf{M}_{NRM}$ $\mathbf{M}$ Q	• Rapid fall-off restricts method to shallow sources, with tradeoff between depth of penetration and spatial resolution of subsurface magnetisation distribution