Mitigating the effects of remanance in magnetic data processing and inversion

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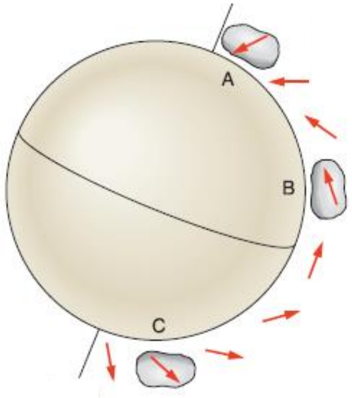
28/04/2023

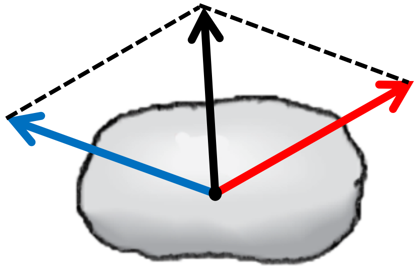
Natural remanence in magnetic exploration



induced magnetization

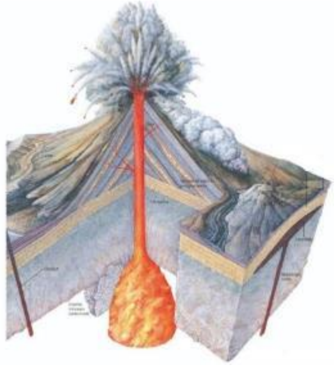
rock is magnetized by current dynamo.(Carlson et al, 2009)

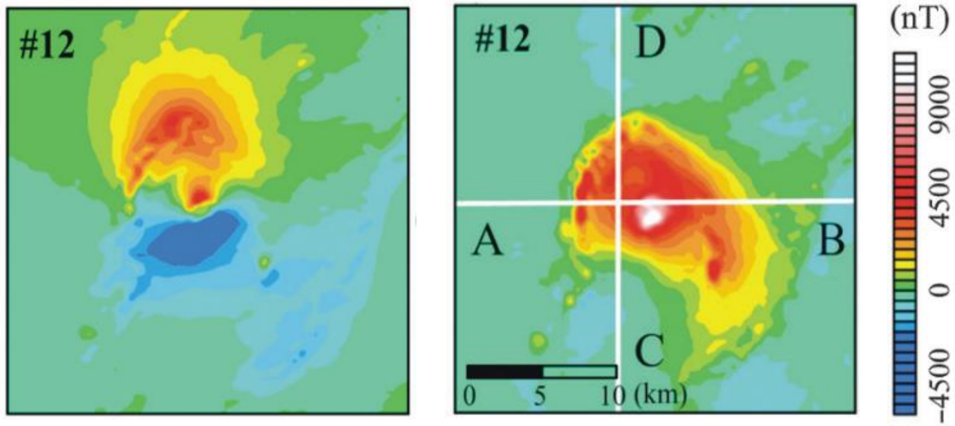
total magnetization



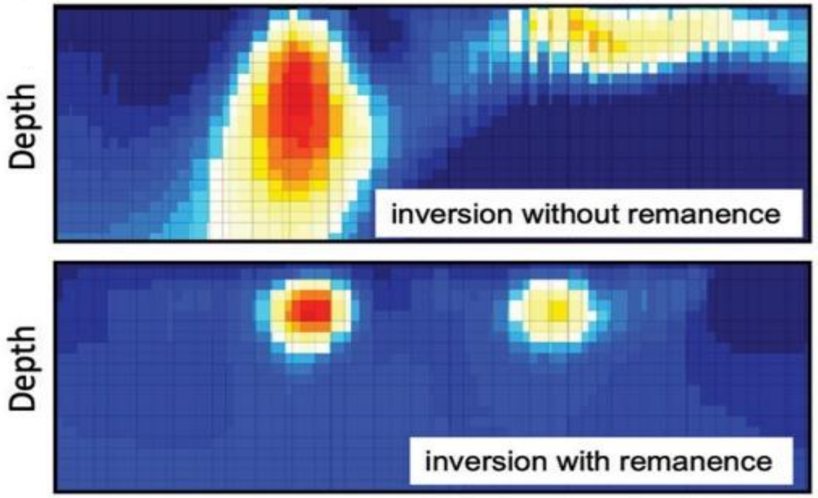
natural remanence

thermal remanence was obtained in diagenetic period.(Marshak, 2019)





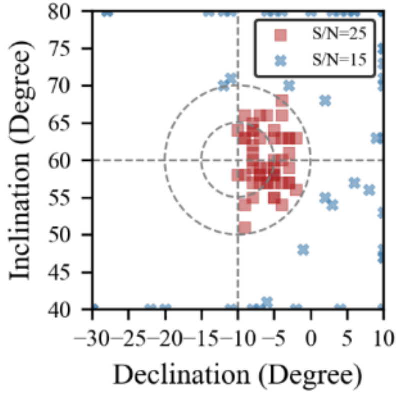
RTP field calculated in inducing magnetization direction (left) and total magnetization direction (right).(Zhang et al., 2018)

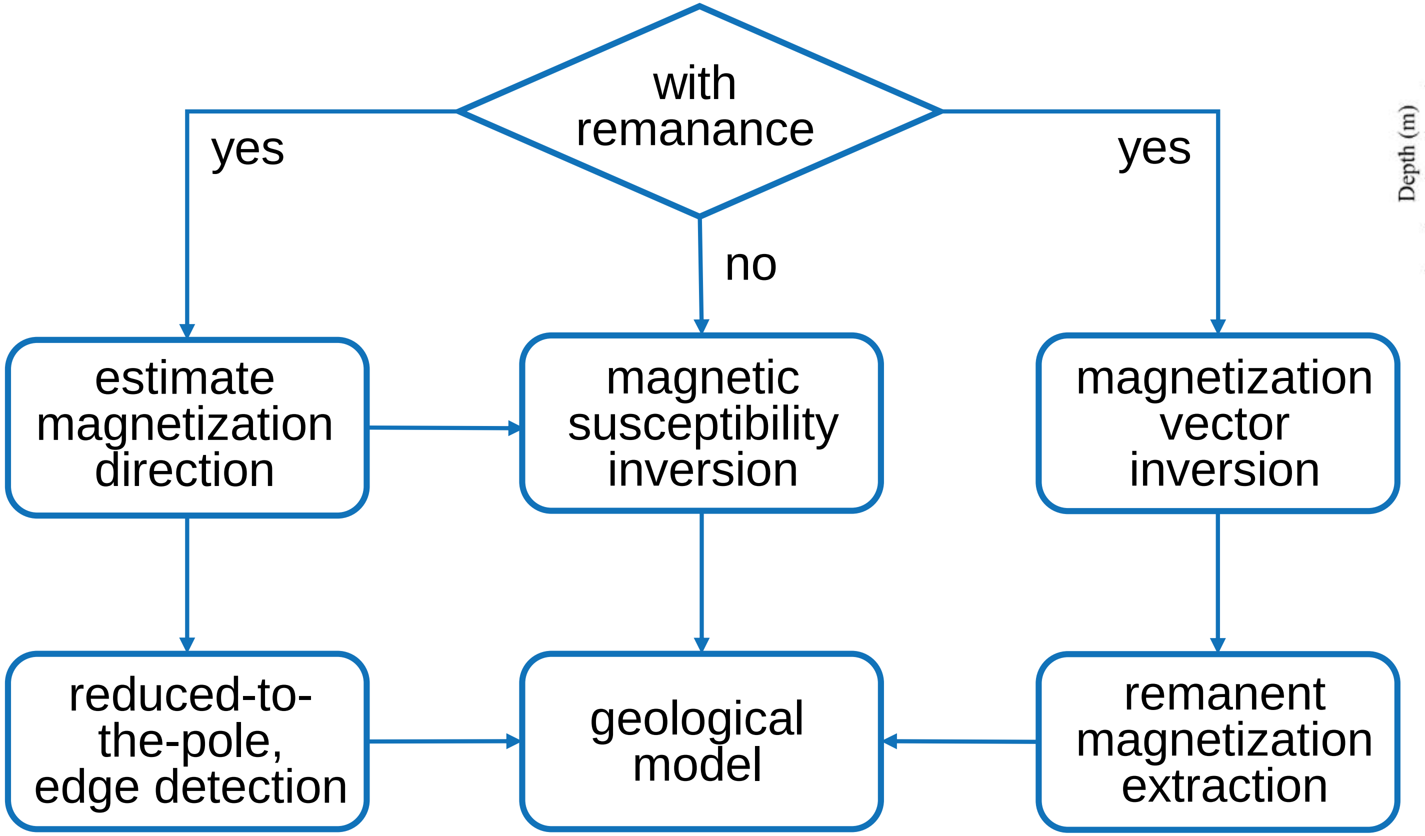


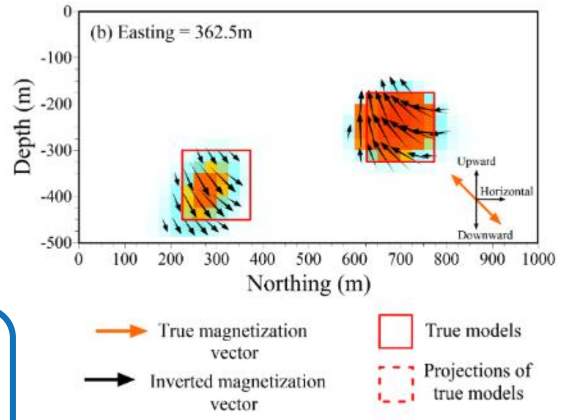
Two magnetic inversion models without (top) and with (button) remanance. (Li et al., 2021)

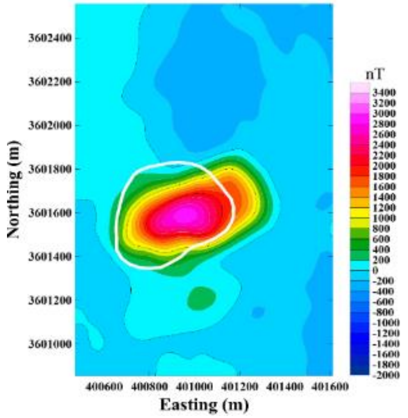
Sharing is encouraged

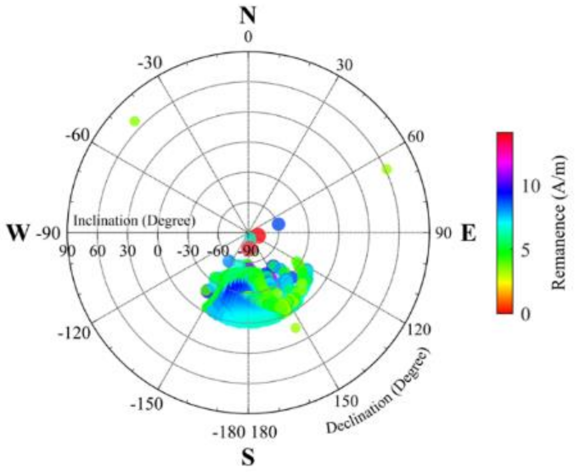
Processing and inversion with remanance









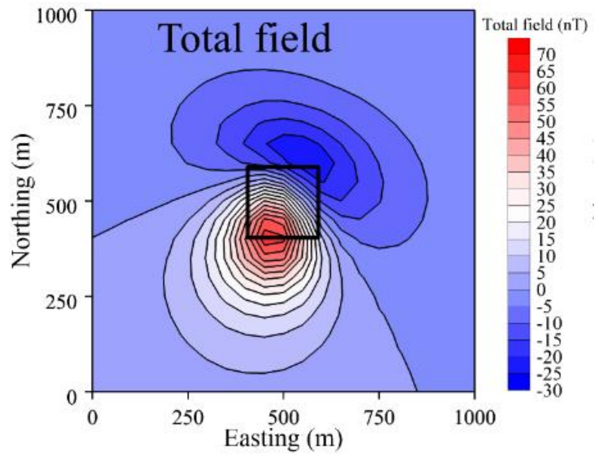


- Total magnetization direction estimation by multiple correlation (Jian et al., 2022).
- Magnetization direction estimated by comparing the correlation between RTP field and total gradient of magnetic potential (Jian et al., 2023).
- High-precision magnetization vector inversion with sparse constraints (Li et al., 2022).

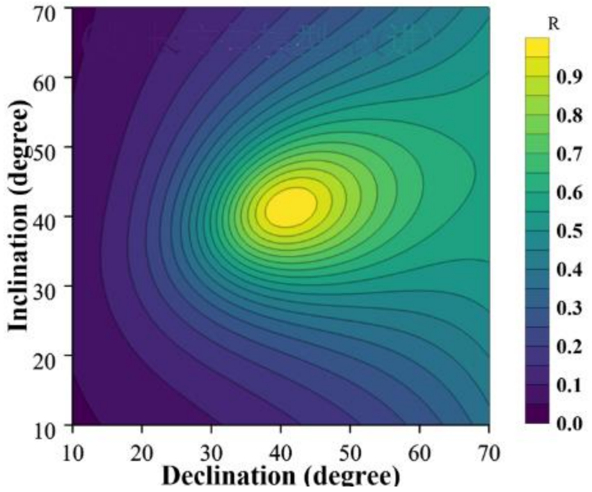
Outline

- Methodology
- Synthetic examples
- Field examples

Magnetization direction estimation use cross-correlation

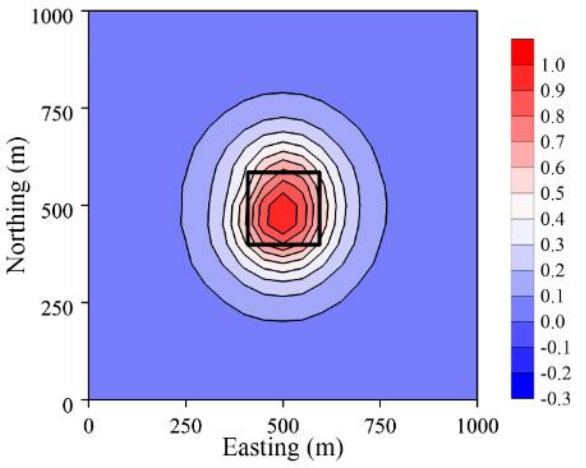


Cross correlation



choose max correlation

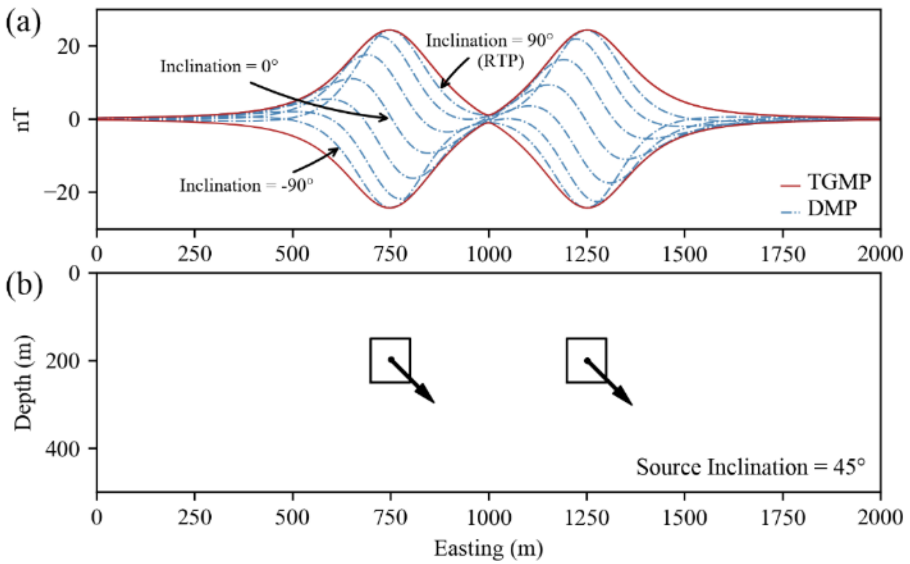
Get total magnetization direction



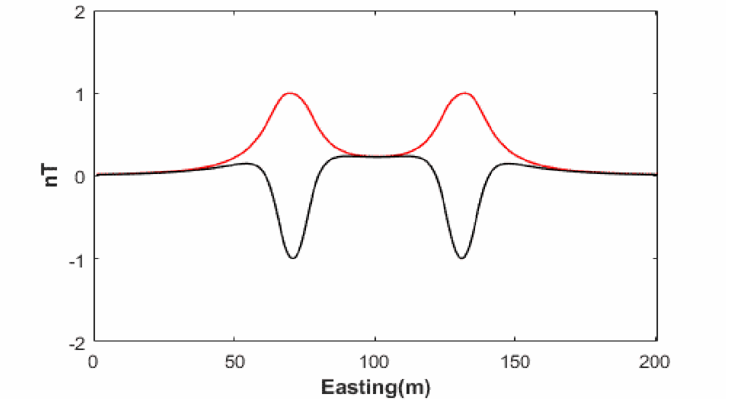
Select one

- **Magnetization direction insensitive field:**
- Analytic signal (Nabighian, 1972, 1984; Keating and Sailhac, 2004)
- Pseudo-gravity (Bilim & Ates, 2004)
- Magnitude magnetic transforms (Stavrev and Gerovska, 2000)
- Normalized source strength (Clark, 2009, 2012; Beiki et al., 2012)
- Anisotropy normalized variance (Zhang et al., 2014)

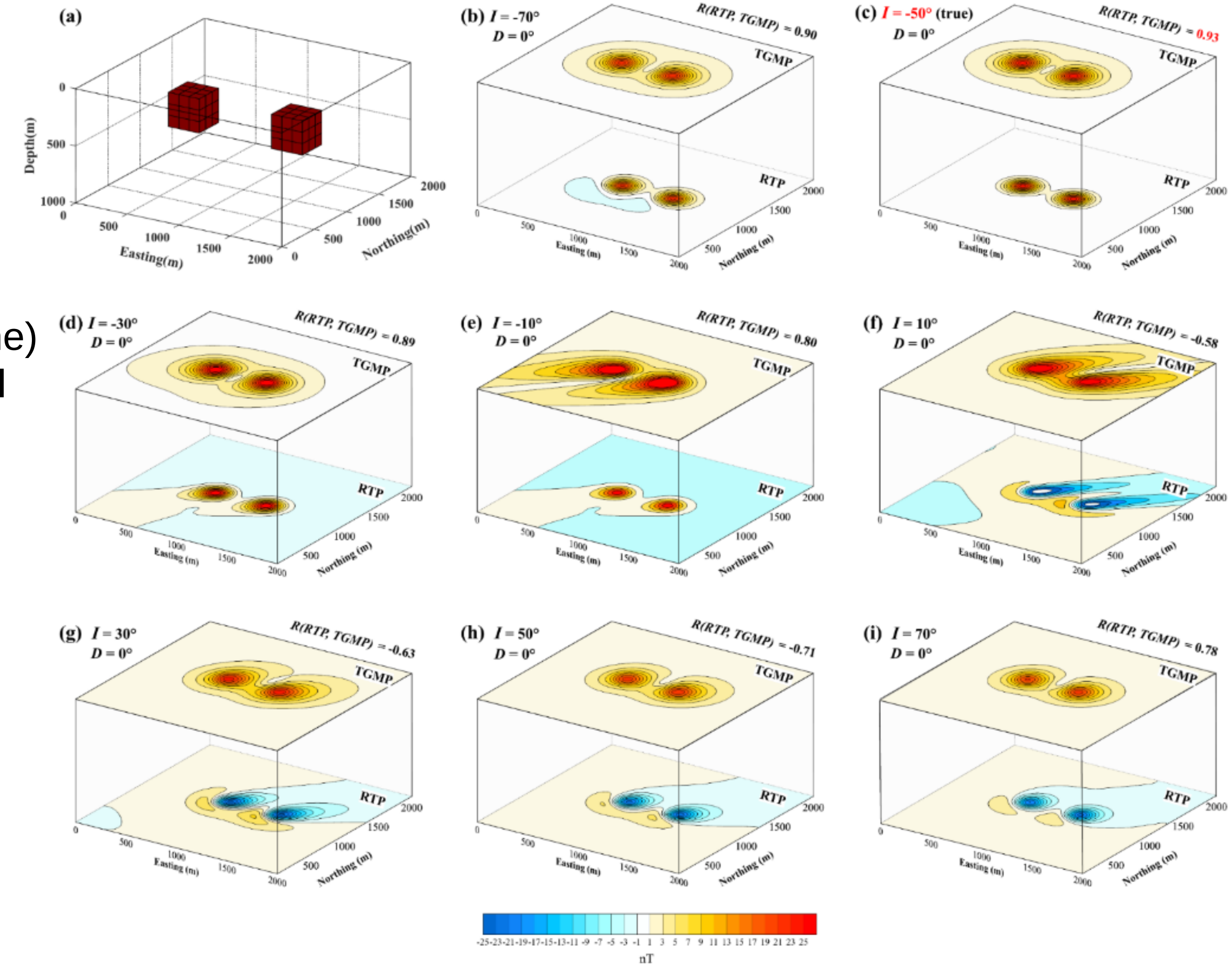
Estimation using cross-relation



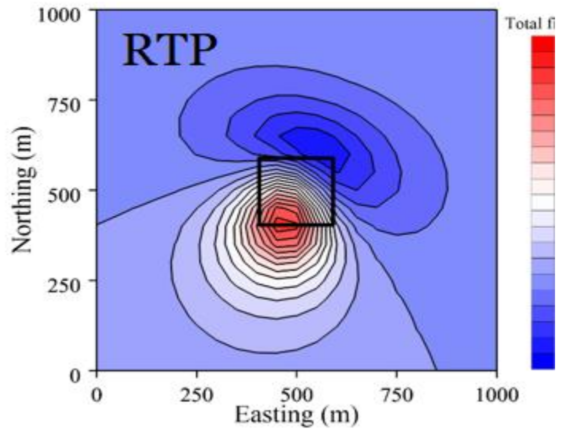
(a) Total gradient of magnetic potential (TGMP, solid red line) is the envelop of vertical derivatives of magnetic potential (DMP, dashed blue lines) of (b) two rectangular sources

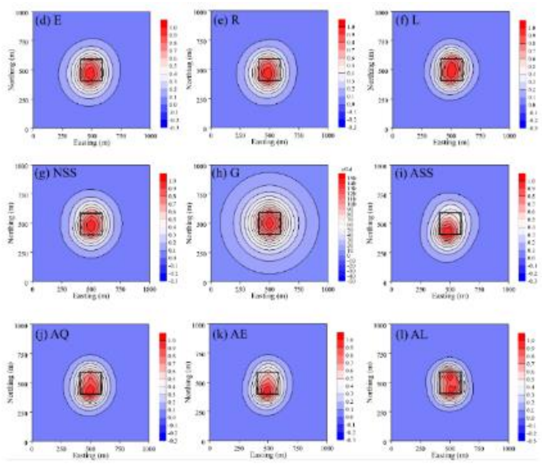


Total gradient of magnetic potential (TGMP, red line) and RTP field (black line) tend to achieve max correlation in the true total magnetization direction.

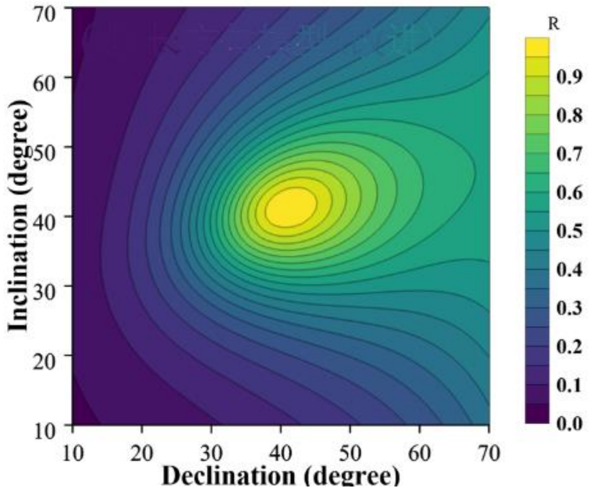


Estimation using multiple correlation





Multiple correlation



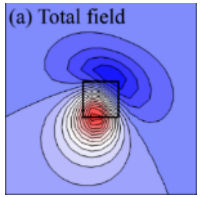
choose max correlation

Get total magnetization direction

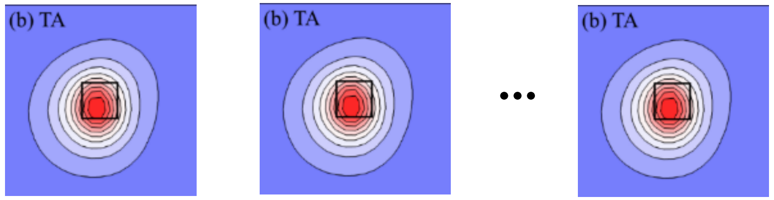
- **Magnetization direction insensitive field:**
- Analytic signal amplitude (Nabighian, 1972, 1984)
- Pseudo-gravity (Bilim & Ates, 2004)
- Magnitude magnetic transforms (Stavrev and Gerovska, 2000)
- Normalized source strength (Clark, 2009, 2012; Beiki et al., 2012)
- Anisotropy normalized variance (Zhang et al., 2014)

Computation of multiple correlation

Total anomaly



p direction insensitive fields: $x_1, x_2, \dots, x_p$



Step 1: select *p* direction insensitive fields.

Step 2 : establish a linear regression between RTP field and these direction insensitive fields. The regression coefficients can be computed through the least squares method.

$$RTP = \alpha + \beta_1 x_1 + \beta_2 x_2 + \dots + \beta_p x_p$$

Step 3 : The multiple correlation coefficient can be written as right.

ω is the cross-correlation matrix of these *p+1* quantities and ω_{11} is the algebraic cofactor of the first row and column element of ω.

multiple correlation coefficient

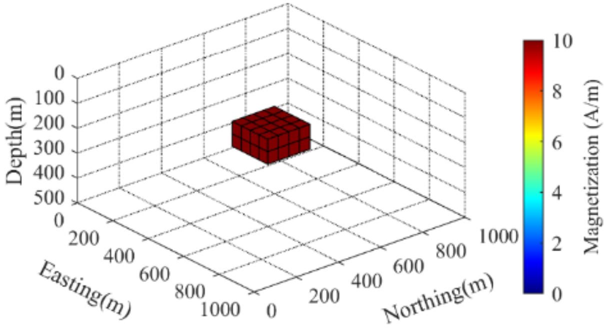
$$R_{1,23\dots p} = \sqrt{1 - \frac{\omega}{\omega_{11}}}$$

Estimation use multiple correlation

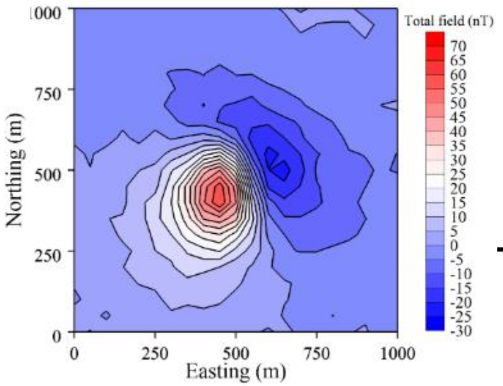
Method abbreviations	Direction insensitive fields
M2	TA, Q
M3	TA, Q, NSS
M4	TA, Q, NSS, DNSS
M5	TA, Q, NSS, DNSS, R
M6	TA, Q, NSS, DNSS, R, L
M7	TA, Q, NSS, DNSS, R, L, Gravity

- Magnitude magnetic transforms: TA, Q, R, L (Stavrev and Gerovska, 2000)
- Normalized source strength (Clark, 2009, 2012; Beiki et al., 2012)
- Derivative of Normalized source strength (Zhang et al., 2018)

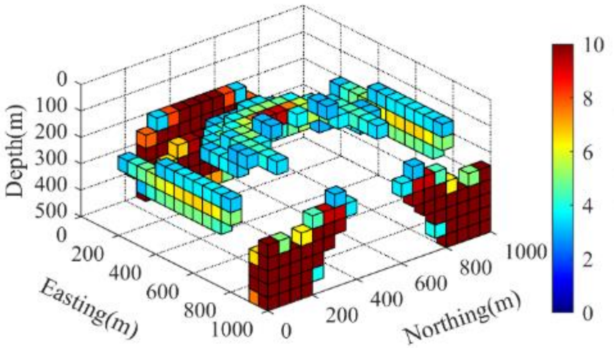
Magnetic susceptibility inversion with remanance



forward



inversion without remanance



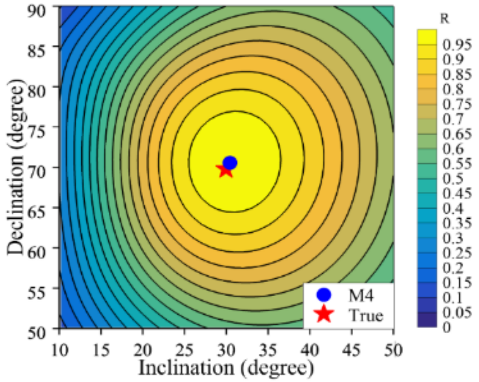
estimation magnetization direction

the objective function in magnetic susceptibility (Liu et al., 2013):

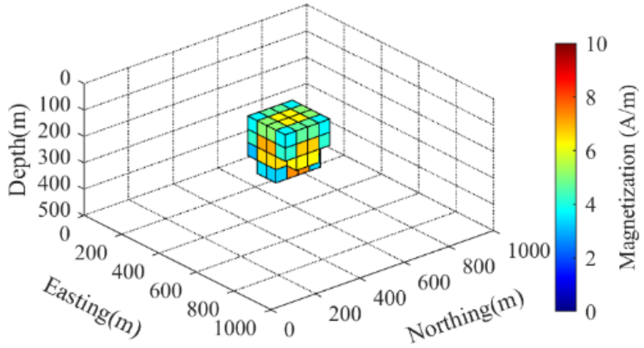
$$\phi = (\mathbf{d} - \mathbf{G}\mathbf{m})^T \mathbf{W} (\mathbf{d} - \mathbf{G}\mathbf{m})$$

solve the inversion problem by preconditioned conjugate gradient method (Liu et al., 2013):

$$\mathbf{P}\mathbf{G}^T \mathbf{W}\mathbf{G}\Delta\mathbf{m} = \mathbf{G}^T \mathbf{W}\Delta\mathbf{d}$$



inversion with remanance



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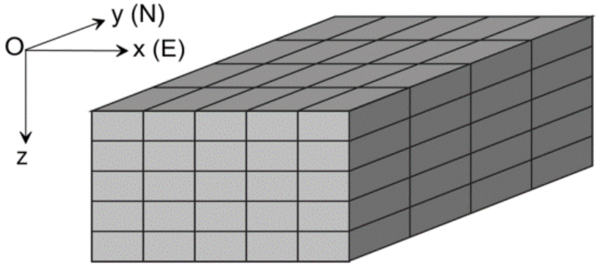
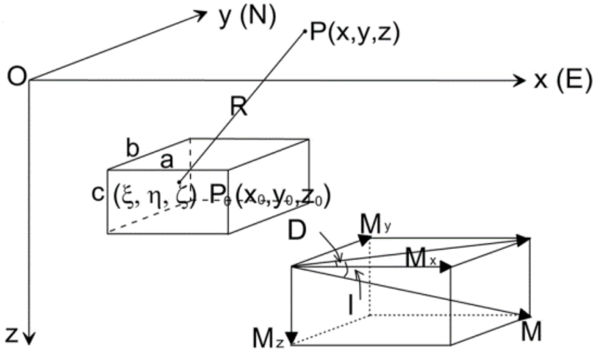
Magnetization vector inversion





The forward of total magnetic intensity in magnetization vector inversion is (Liu et al., 2017):

$$\begin{bmatrix} \mathbf{G}_{M_x} & \mathbf{G}_{M_y} & \mathbf{G}_{M_z} \end{bmatrix} \begin{bmatrix} \Delta\mathbf{M}_x \\ \Delta\mathbf{M}_y \\ \Delta\mathbf{M}_z \end{bmatrix} = \Delta\mathbf{B}$$

- Suitable for non-uniform magnetized situation.
- Inverse the magnitude and directions of magnetization.
- More computation consume and more serious non-uniqueness.

$$\mathbf{m} = \arg\min_{\mathbf{m}}\{P^{\alpha}(\mathbf{m})\}$$

$$= \arg\min_{\mathbf{m}} \left\{ \|\mathbf{W}_d(\mathbf{Gm}-\mathbf{d}_{obs})\|_2^2 + \alpha^2 \|\mathbf{W}(\mathbf{m}-\mathbf{m}_{apr})\|_2^2 \right\}$$

$$\mathbf{W} = \mathbf{W}_{depth}\mathbf{W}_{hard}\mathbf{W}_{L} \quad \begin{cases} \mathbf{W}_{depth} = \begin{bmatrix} z^{-\beta}\mathbf{I} & & \\ & z^{-\beta}\mathbf{I} & \\ & & z^{-\beta}\mathbf{I} \end{bmatrix} \\ \mathbf{W}_{\mathbf{Lp}} = \begin{bmatrix} \mathbf{D}_{\mathbf{Lp}} & 0 & 0 \\ 0 & \mathbf{D}_{\mathbf{Lp}} & 0 \\ 0 & 0 & \mathbf{D}_{\mathbf{Lp}} \end{bmatrix} \\ \mathbf{D}_{\mathbf{Lp}} = \dfrac{1}{\left((\mathbf{J}-\mathbf{J}_{\mathbf{apr}})^2 + \varepsilon^2\right)^{\frac{2-p}{4}}} \end{cases}$$

The model with sharp boundary is obtained by vector inversion based on sparse constraints(Li et al., 2022)

Outline

- **Methodology**
- **Synthetic examples**
- **Field examples**

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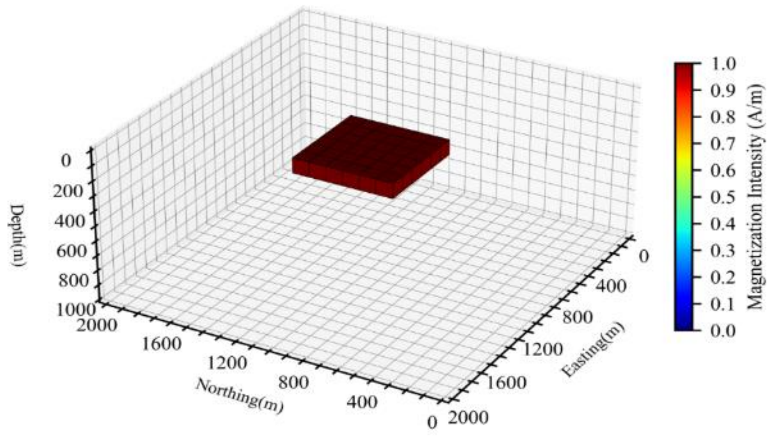
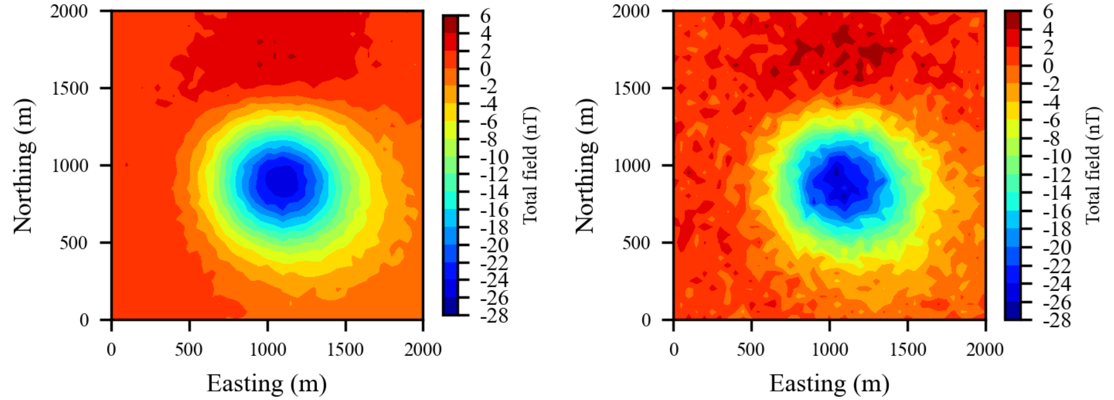
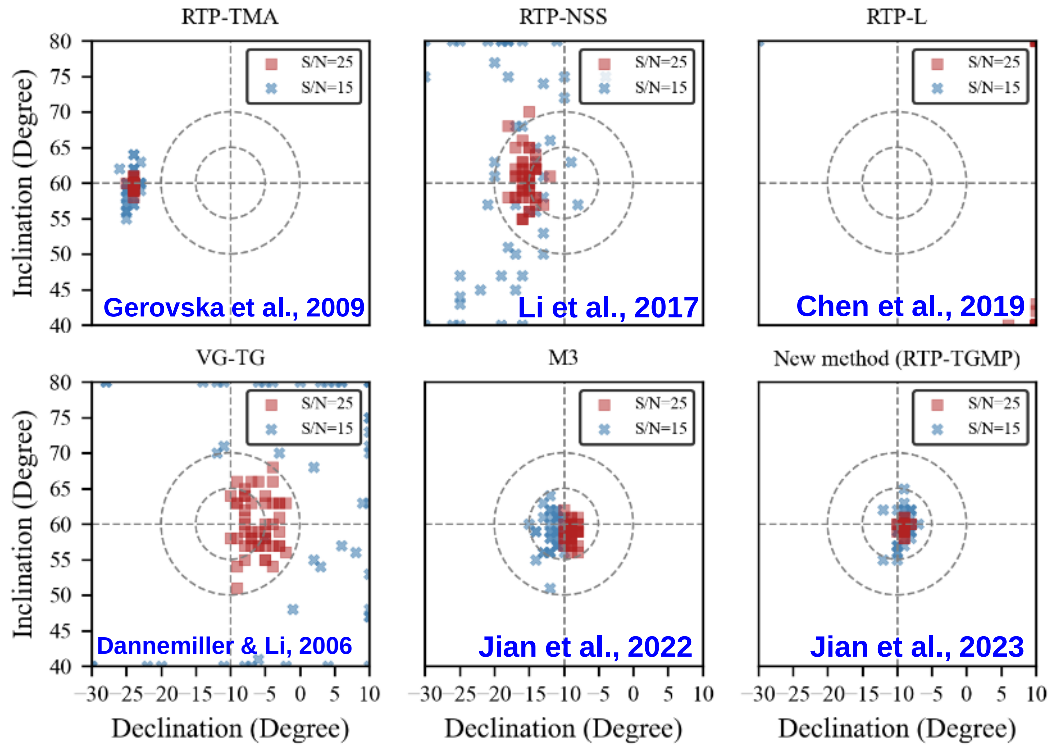
Estimation of magnetization direction

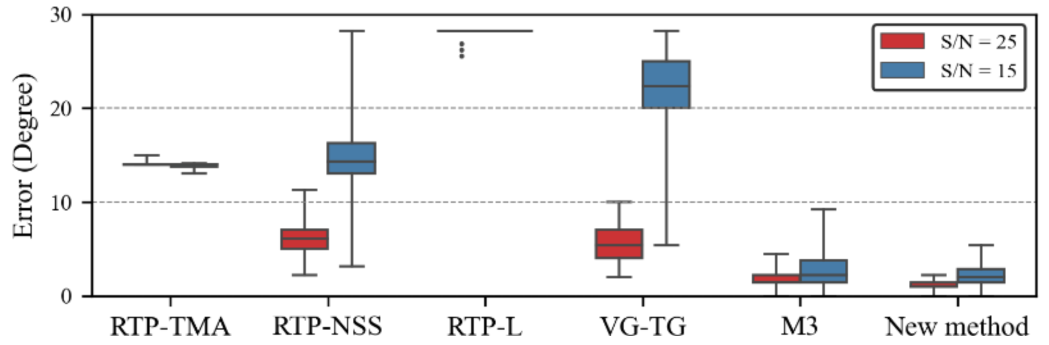


The source magnetization inclination and declination are 60° and -10° , respectively.

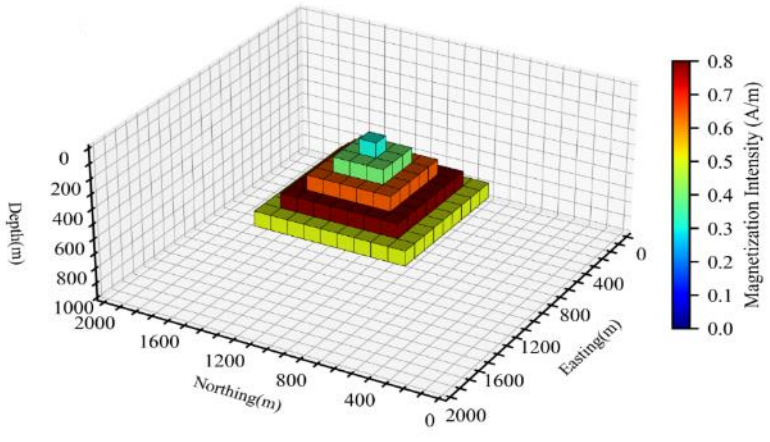


Synthetic total field anomalies with signal-to-noise ratios (S/N) of (left) 25 dB and (fight) 15 dB. The tests are repeated 50 times to assess the robustness of the different methods.

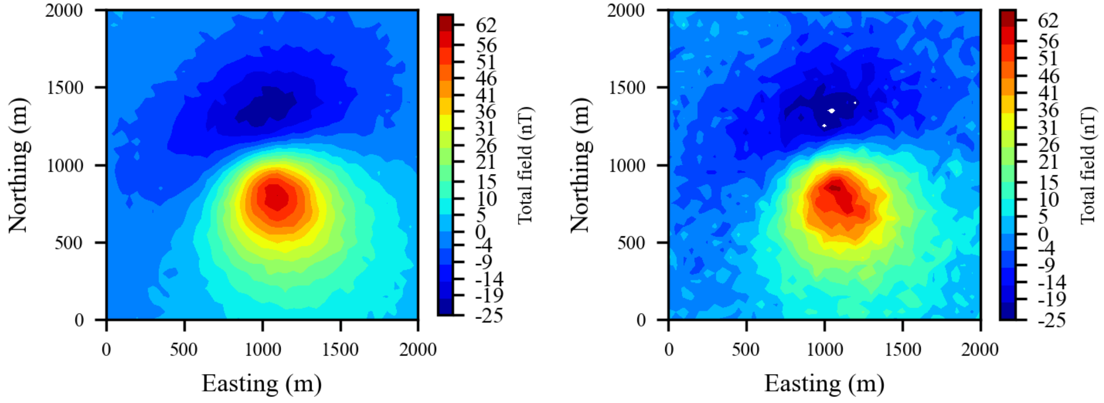




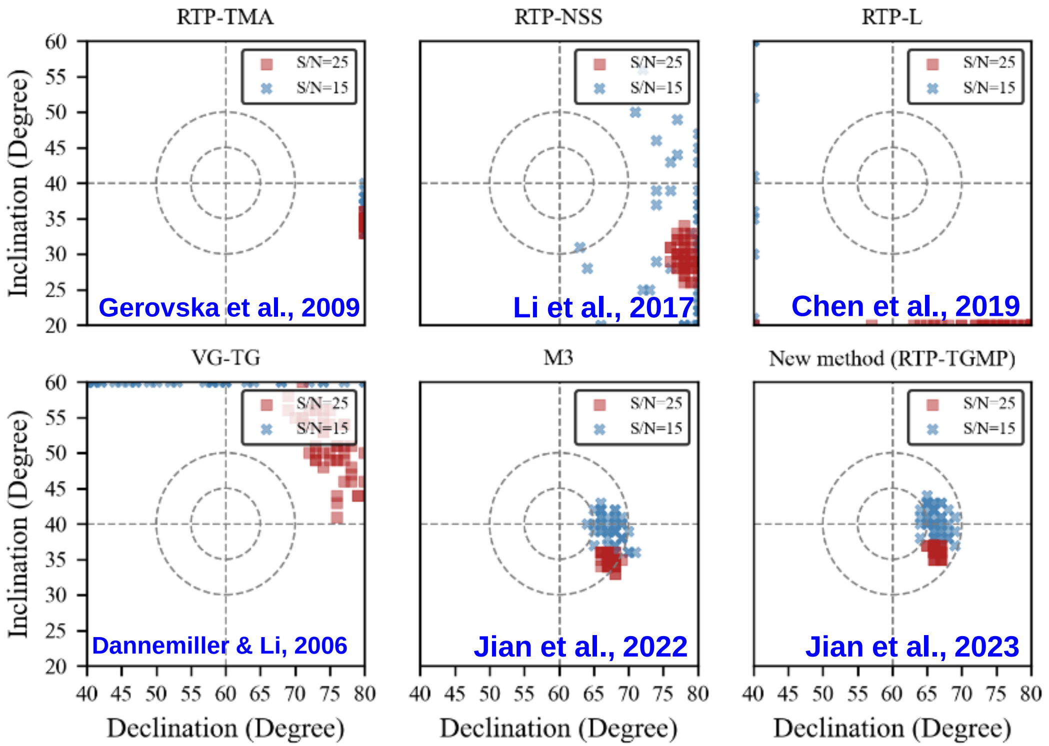
Estimation of magnetization direction

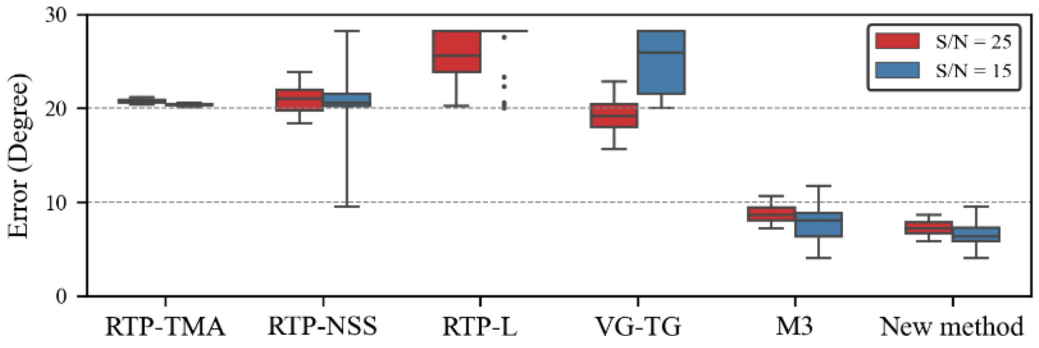


the source magnetization inclination and declination are 40° and 60°, respectively.

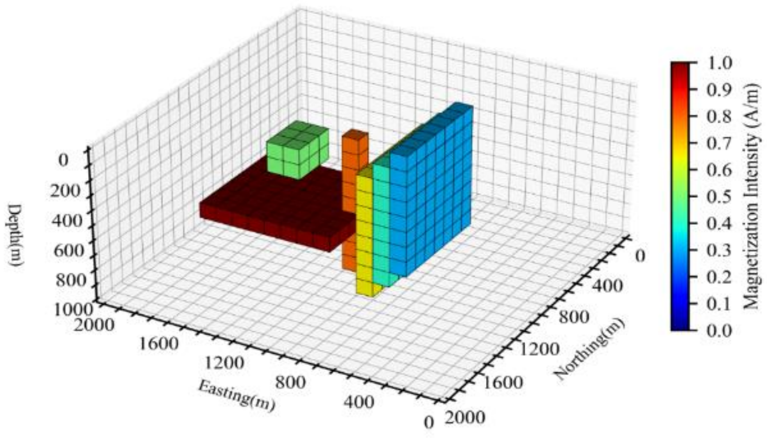


Synthetic total field anomalies with signal-to-noise ratios (S/N) of (left) 25 dB and (fight) 15 dB. The tests are repeated 50 times to assess the robustness of the different methods.

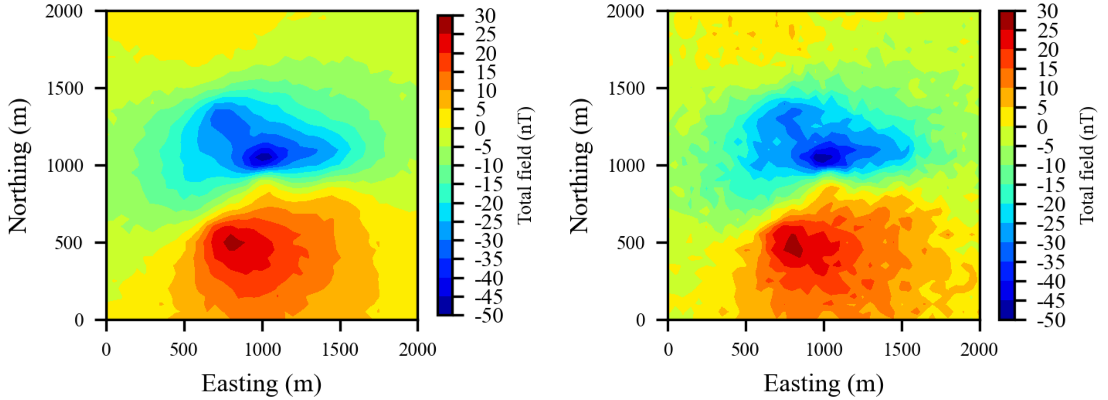




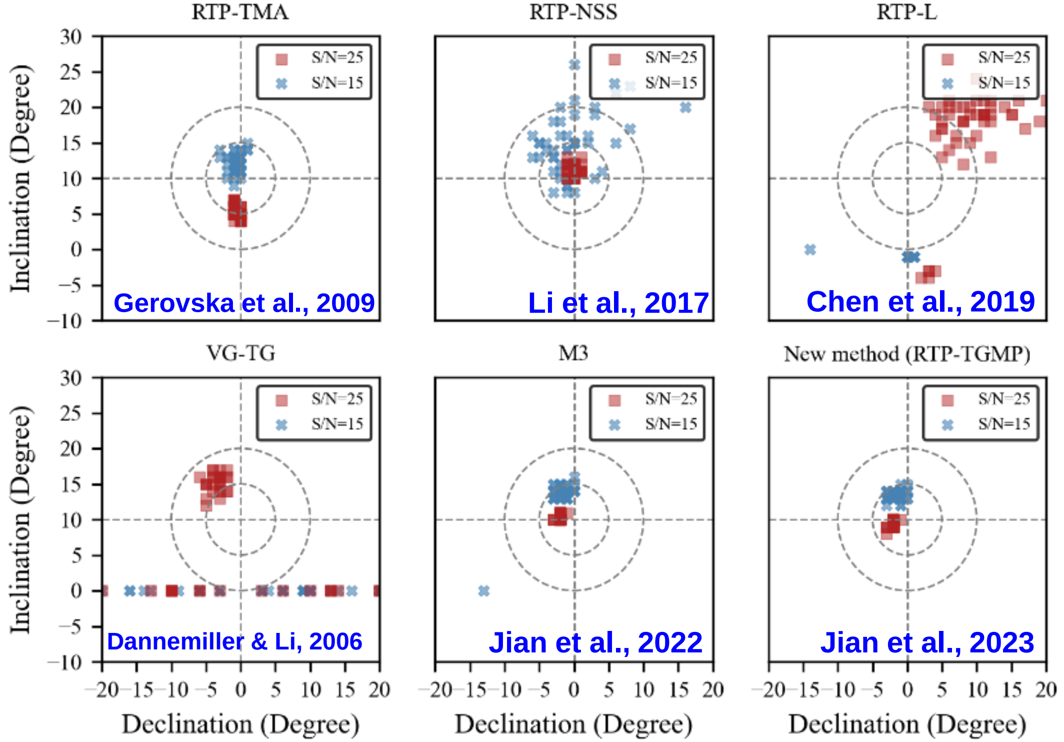
Estimation of magnetization direction

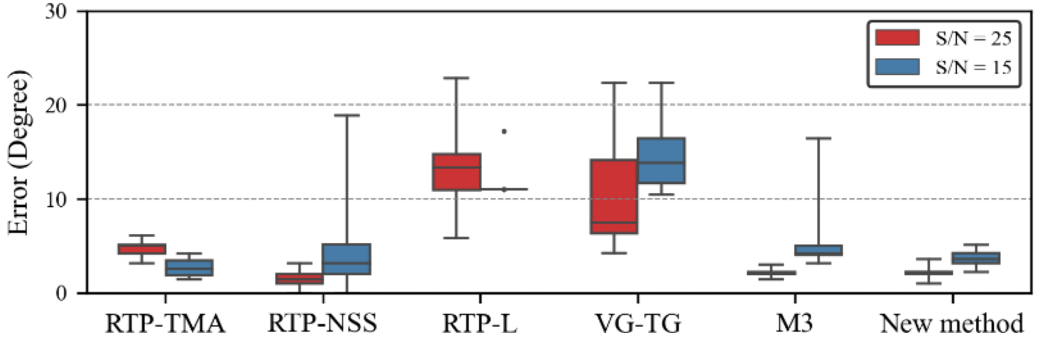


the source magnetization inclination and declination are 10° and 0°, respectively.

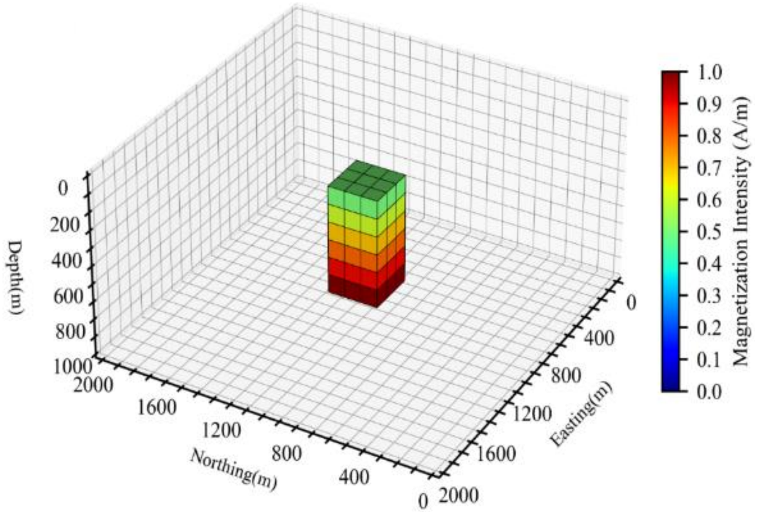


Synthetic total field anomalies with signal-to-noise ratios (S/N) of (left) 25 dB and (fight) 15 dB. The tests are repeated 50 times to assess the robustness of the different methods.

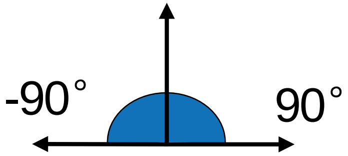




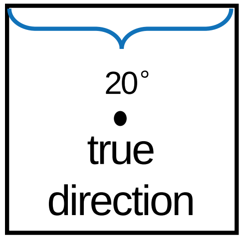
Estimation of magnetization direction



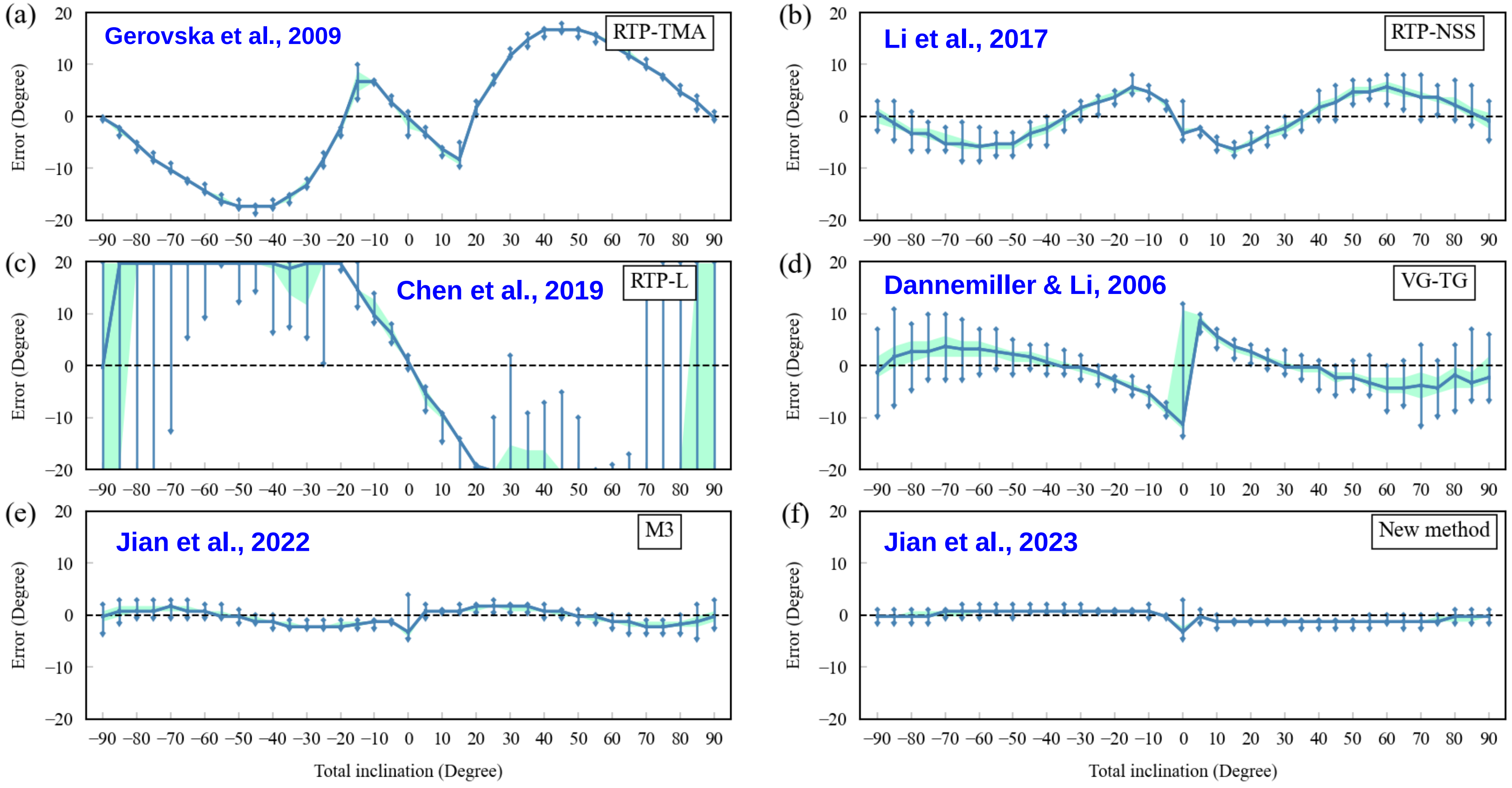
The magnetization distribution of the magnetic source



source inclination

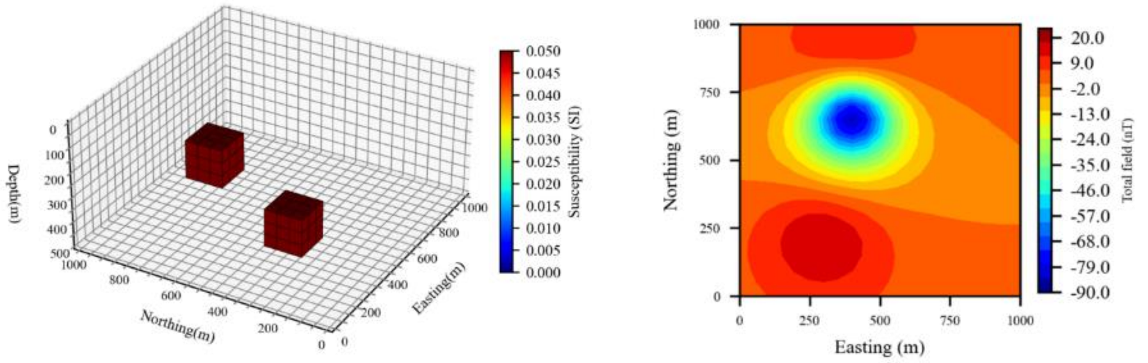


sample area

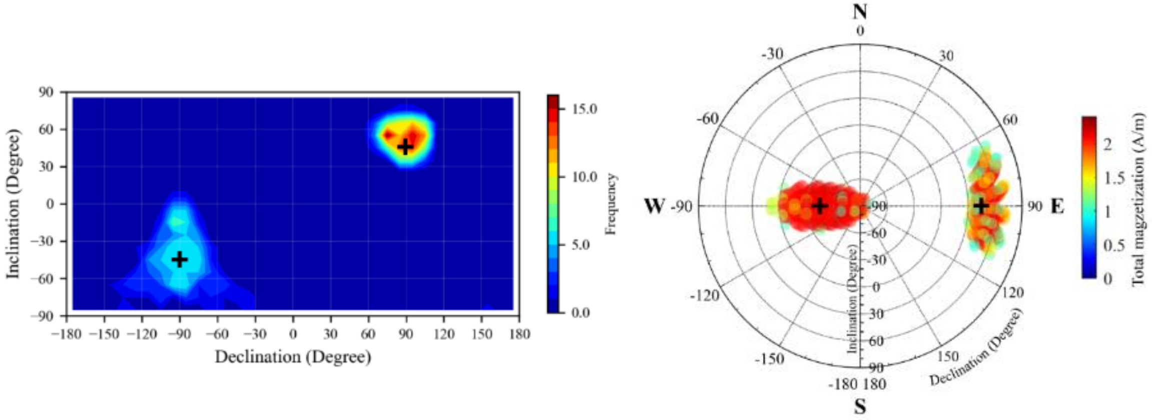


The source magnetization inclination of model D varies from −90° to 90° at 5° intervals. The experiment was repeated 50 times for each source magnetization direction.

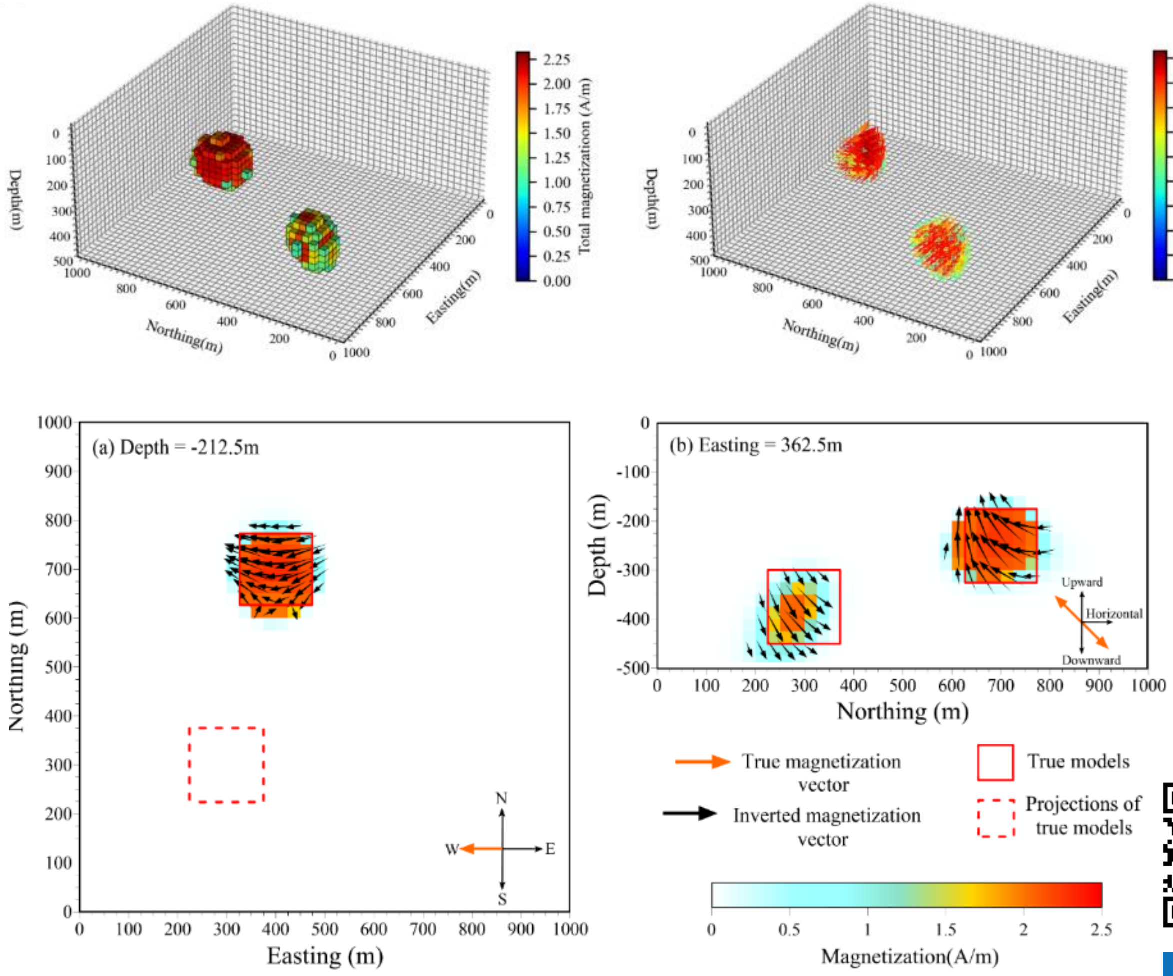
Magnetization vector inversion



(left) The source magnetization distribution and (right) the total magnetic intensity (Li et al., 2022).



(left) 2D histogram of total magnetization and (right) scatter plot of total magnetization (Li et al., 2022).

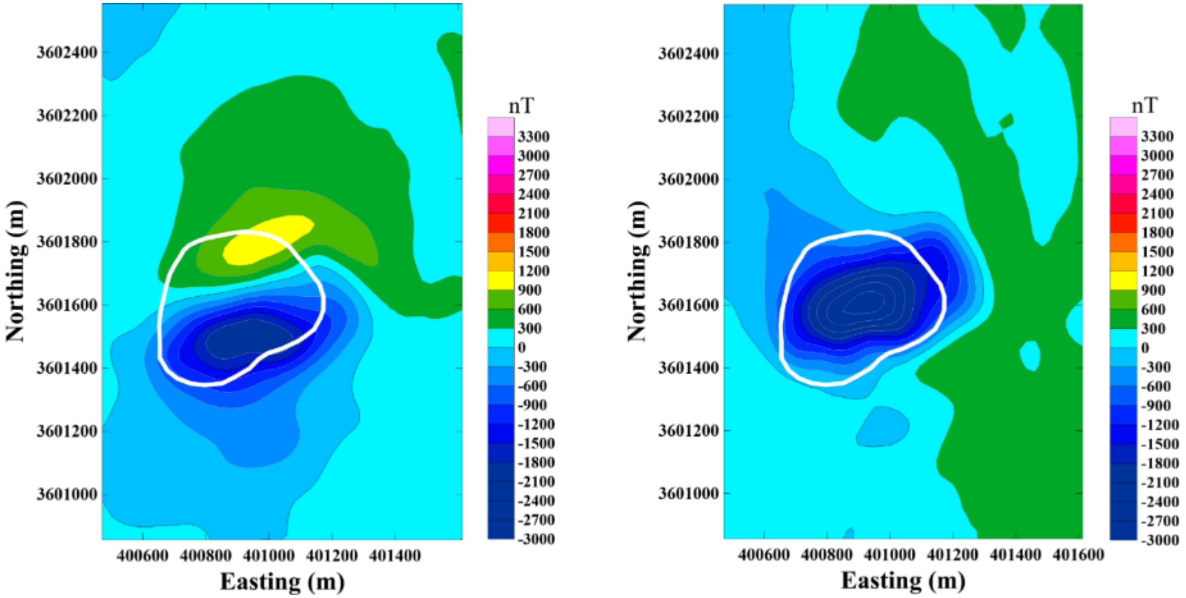


(top) 3D inversion magnetization model and (button) its profiles (Li et al., 2022).

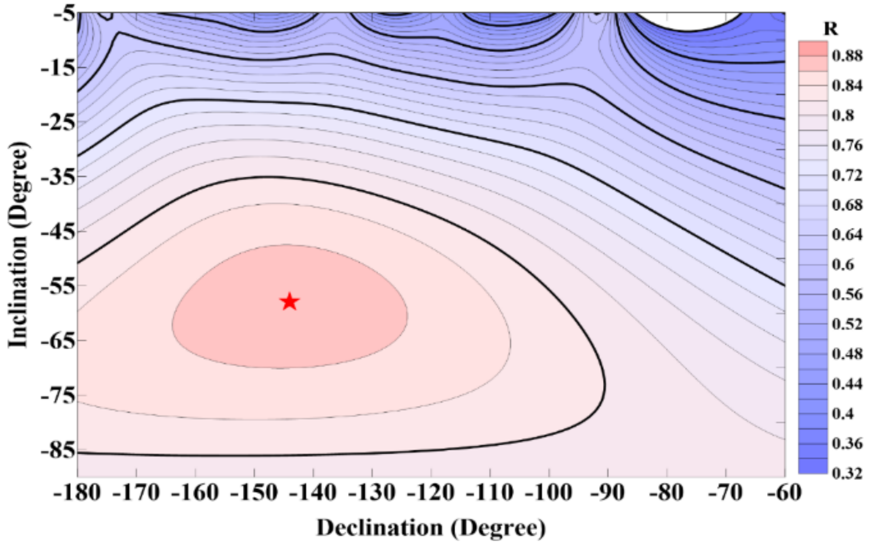
Outline

- Methodology
- Synthetic examples
- Field examples

Field example: Yeshan, East China

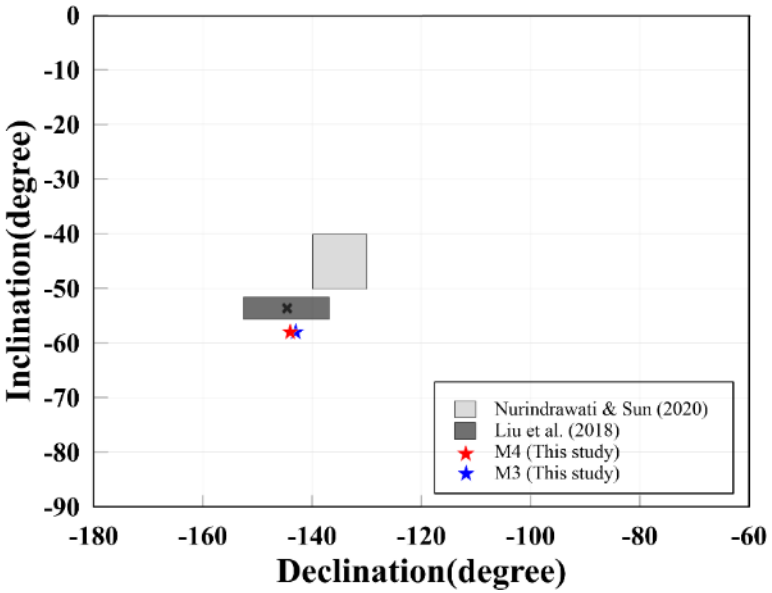


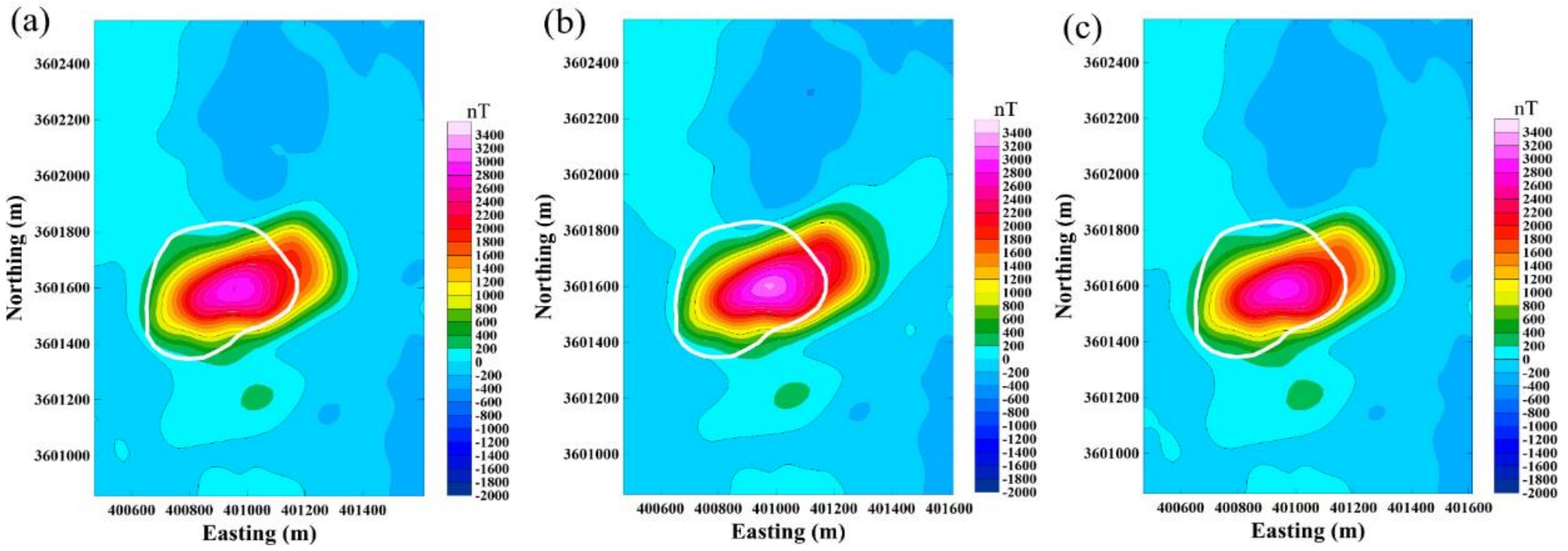
(left) Total field anomaly, (right) RTP anomaly calculated using inducing magnetization direction.
The white line shows the boundary of the basalt rocks outcropping.



Contour map of the multiple correlation coefficient calculated with the multiple correlation method for the Xuezhuang area. The red star represents the position of the maximal coefficient.

Field example: Yeshan, East China

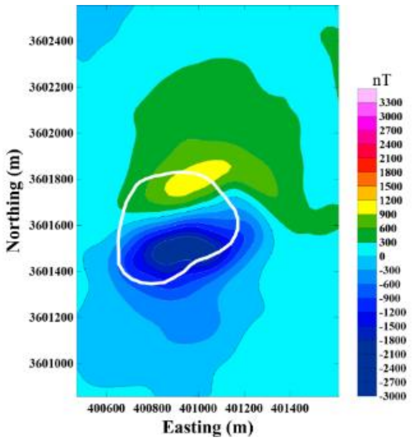




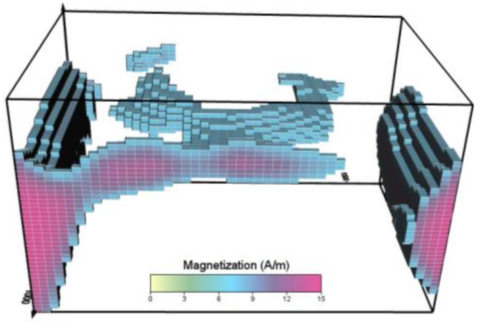
Comparison of the estimated total magnetization direction with previous study results from Liu et al. (2018b) and Nurindrawati and Sun (2020) of the Xuezhuang area, eastern China.

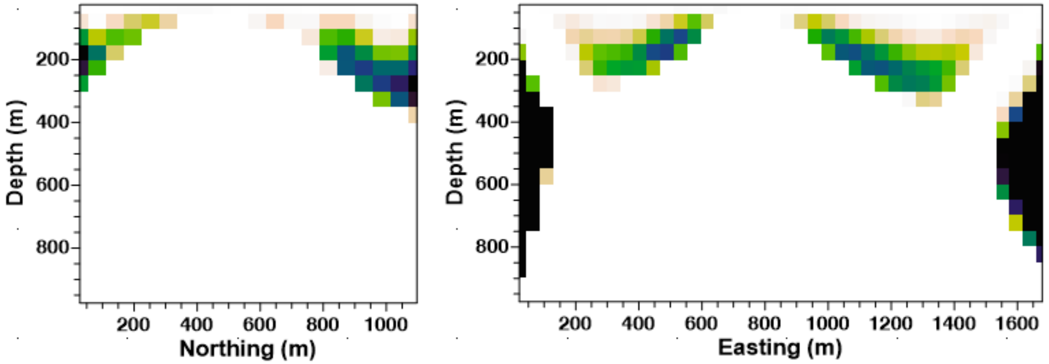
RTP anomaly of Xuezhuang using the magnetization direction from (a) Liu et al. (2018b), (b) Nurindrawati and Sun (2020), and (c) multiple correlation method. The white line shows the boundary of the basalt rocks outcropping.

Field example: Yeshan, East China

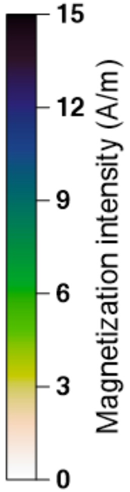


Magnetic susceptibility inversion

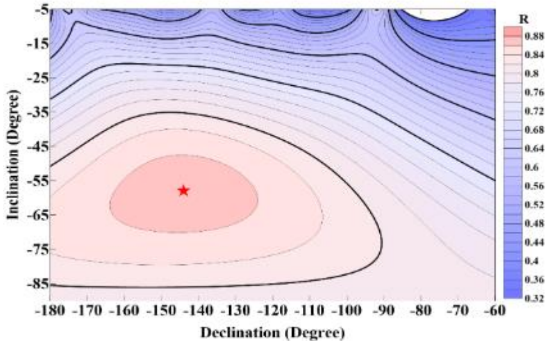




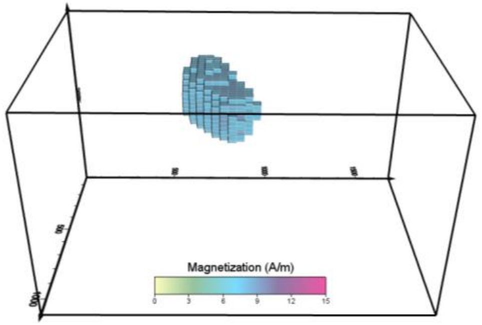
Inversion model without considering remanance

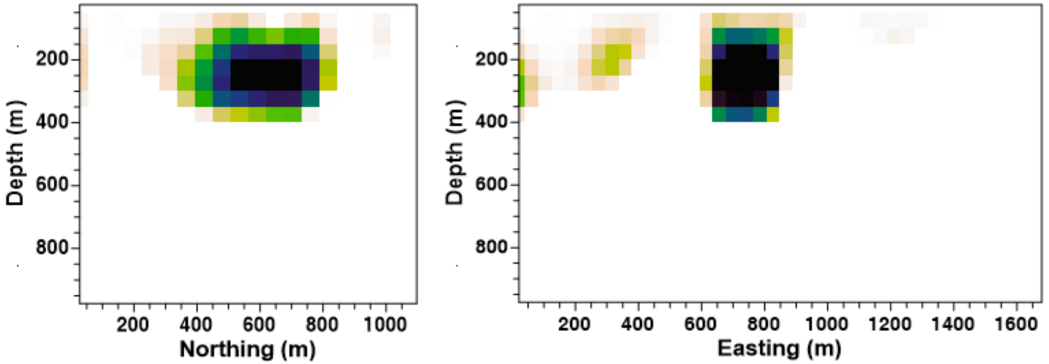


Estimation magnetization direction



Set the estimated total magnetization as prior information

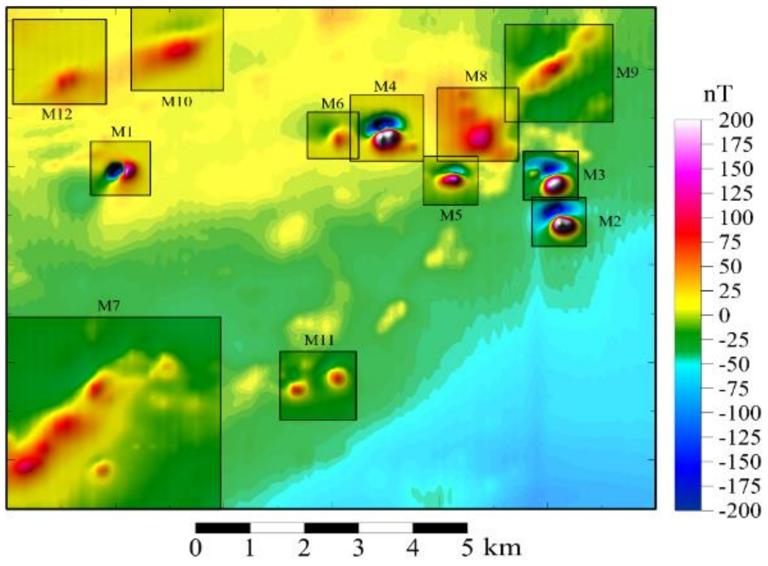




Inversion model with remanance

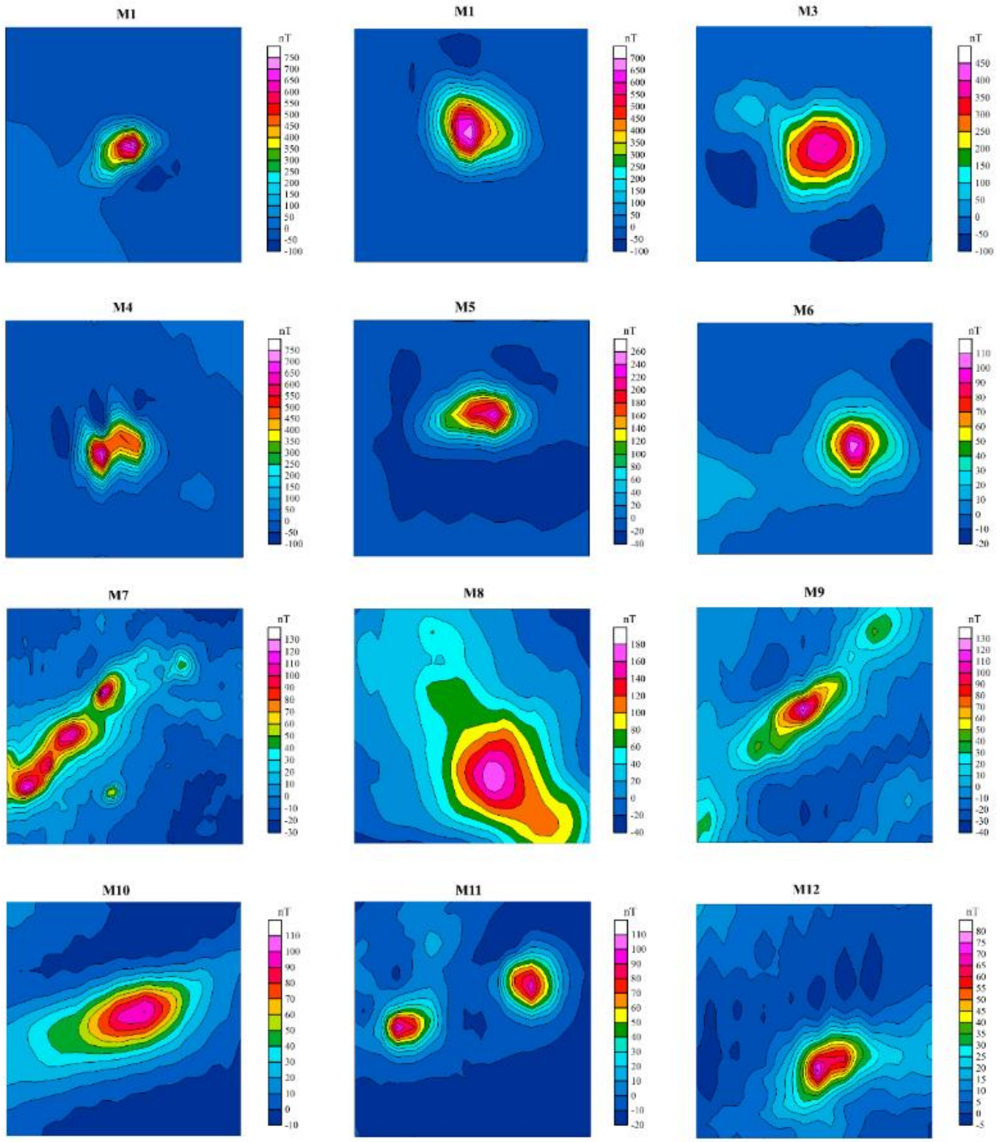
Sharing is encouraged

Field example: Weilasito, North China



Area	Inclination	Declination	Area	Inclination	Declination
M1	–24°	–92°	M7	77°	–10°
M2	33°	–29°	M8	30°	135°
M3	25°	–19°	M9	83°	94°
M4	21°	–12°	M10	65°	91°
M5	40°	21°	M11	81°	–10°
M6	36°	–52°	M12	80°	–64°

Total field anomaly (top) and estimated total magnetization directions in the Weilasito region.



RTP fields obtained using the estimated total directions in the Weilasito region.

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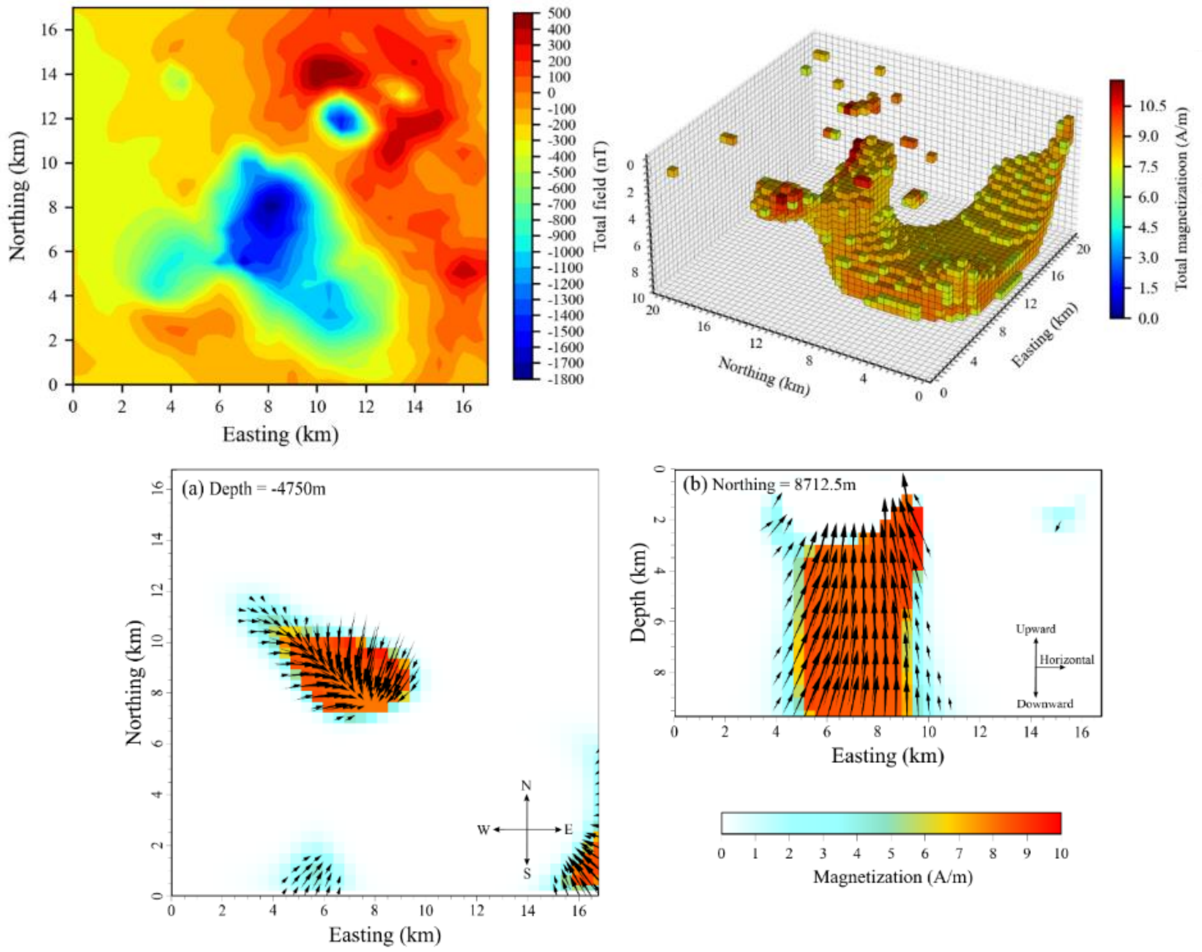
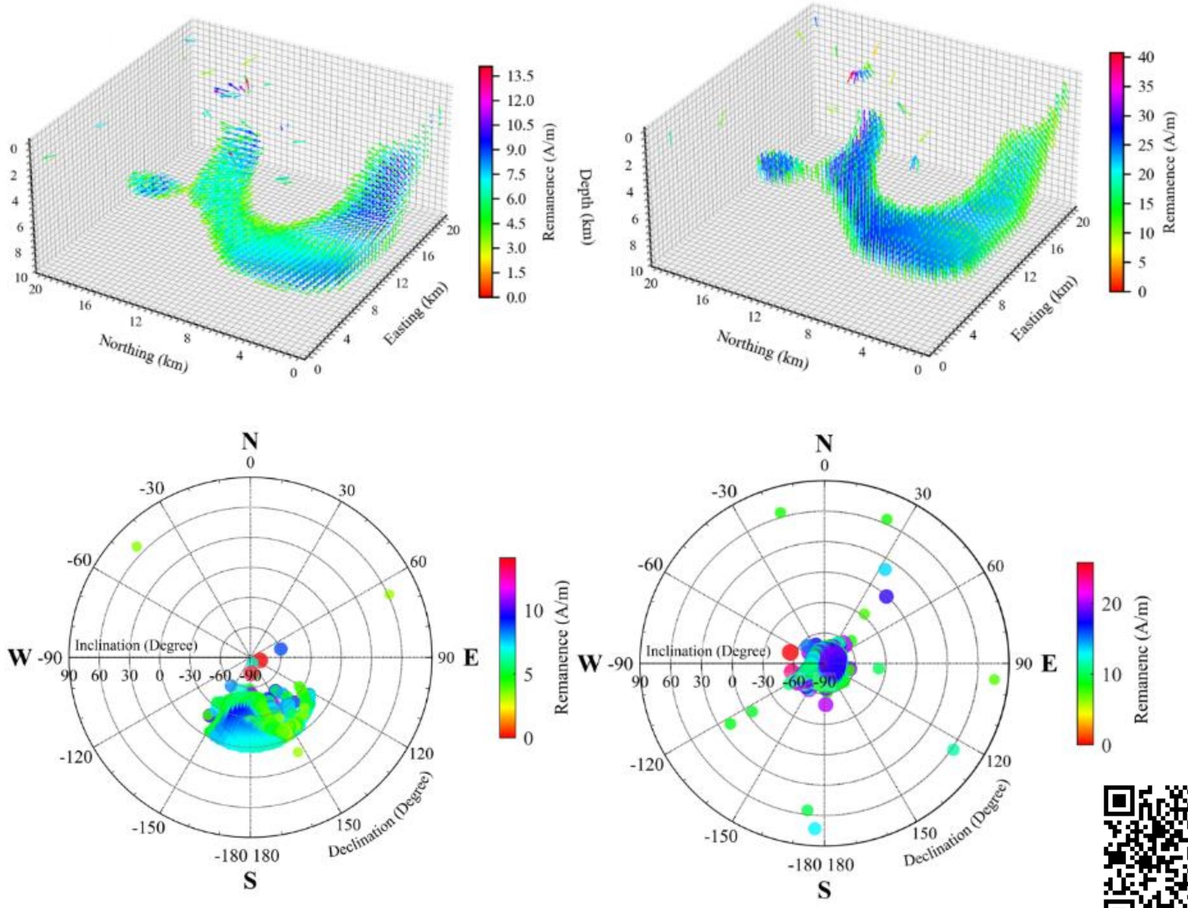
Field example: Haba River, North China



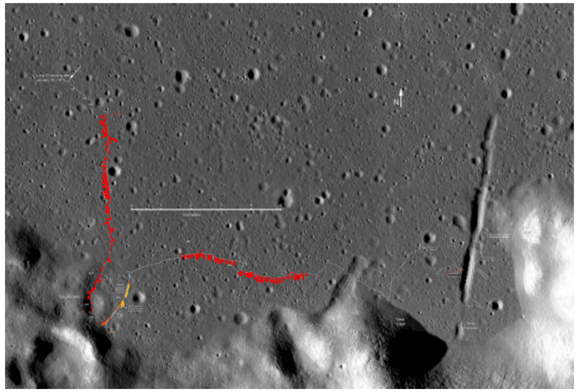
Total magnetic intensity of Haba River and the inverted magnetization model.



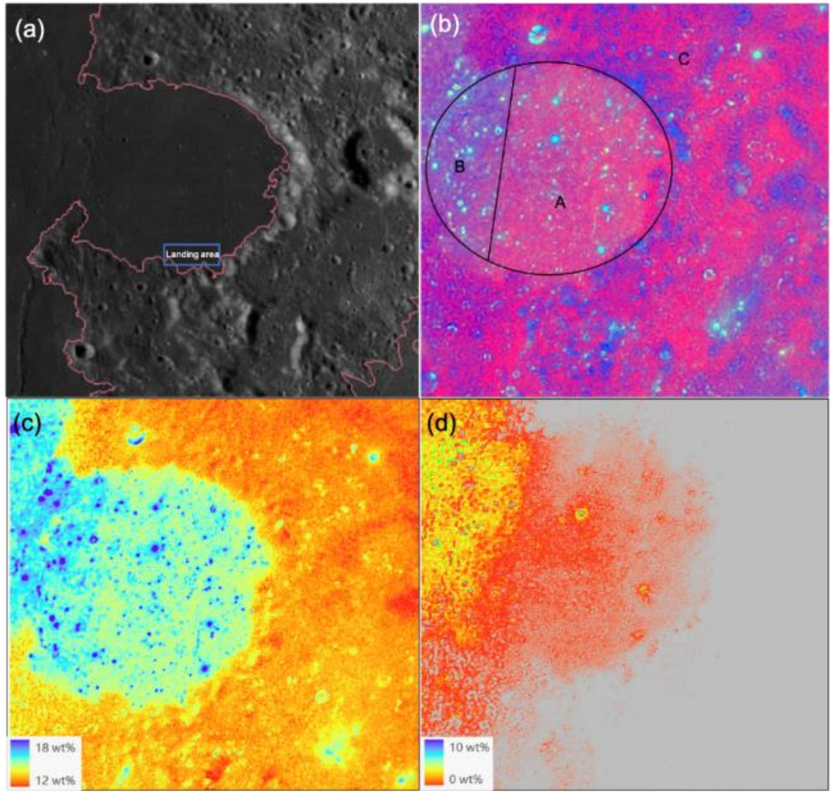
The inverted remanent magnetization vector of Haba River area data with (left column) Q = 0.5 and (right column) Q = 2.

Example: magnetic data inversion of the Lunokhod-2 rover

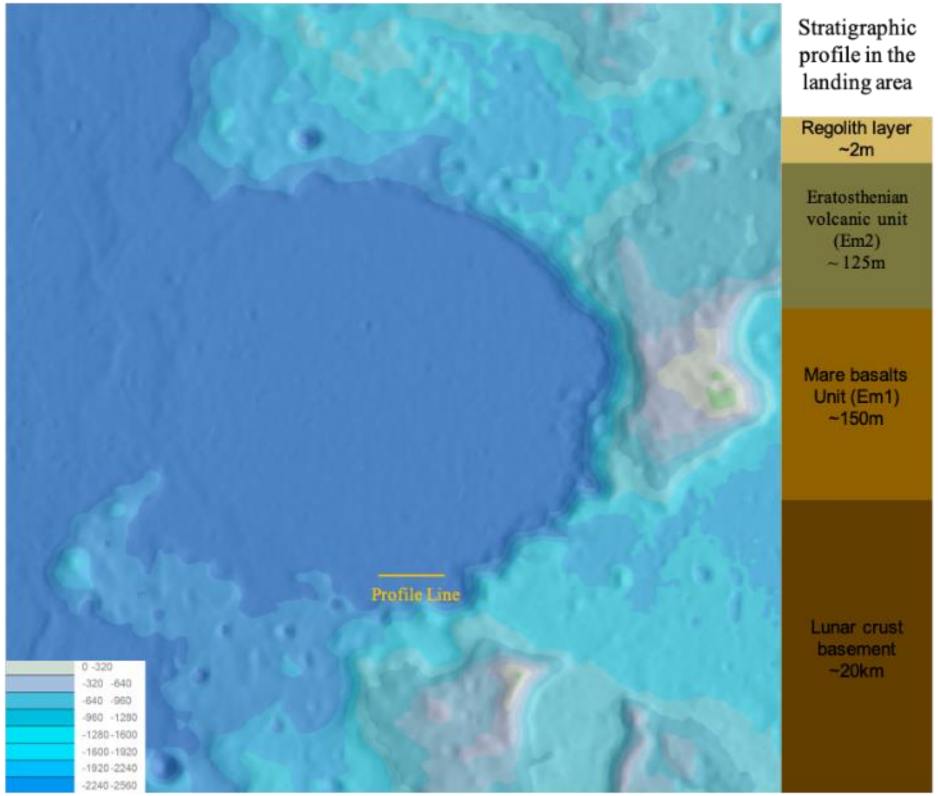
Lunokhod-2 rover



Landing area



(a) High resolution image of Le Monnier crater (b) Color ratio composite based on Clementine spectral data (c) iron abundance (FeO wt%) map based on Clementine UVVIS, and (d) titanium abundance (TiO_2 wt%) map



Le Monnier Bay with Digital Terrain Models (DTM) from Quickmap

Hong et al., 2023

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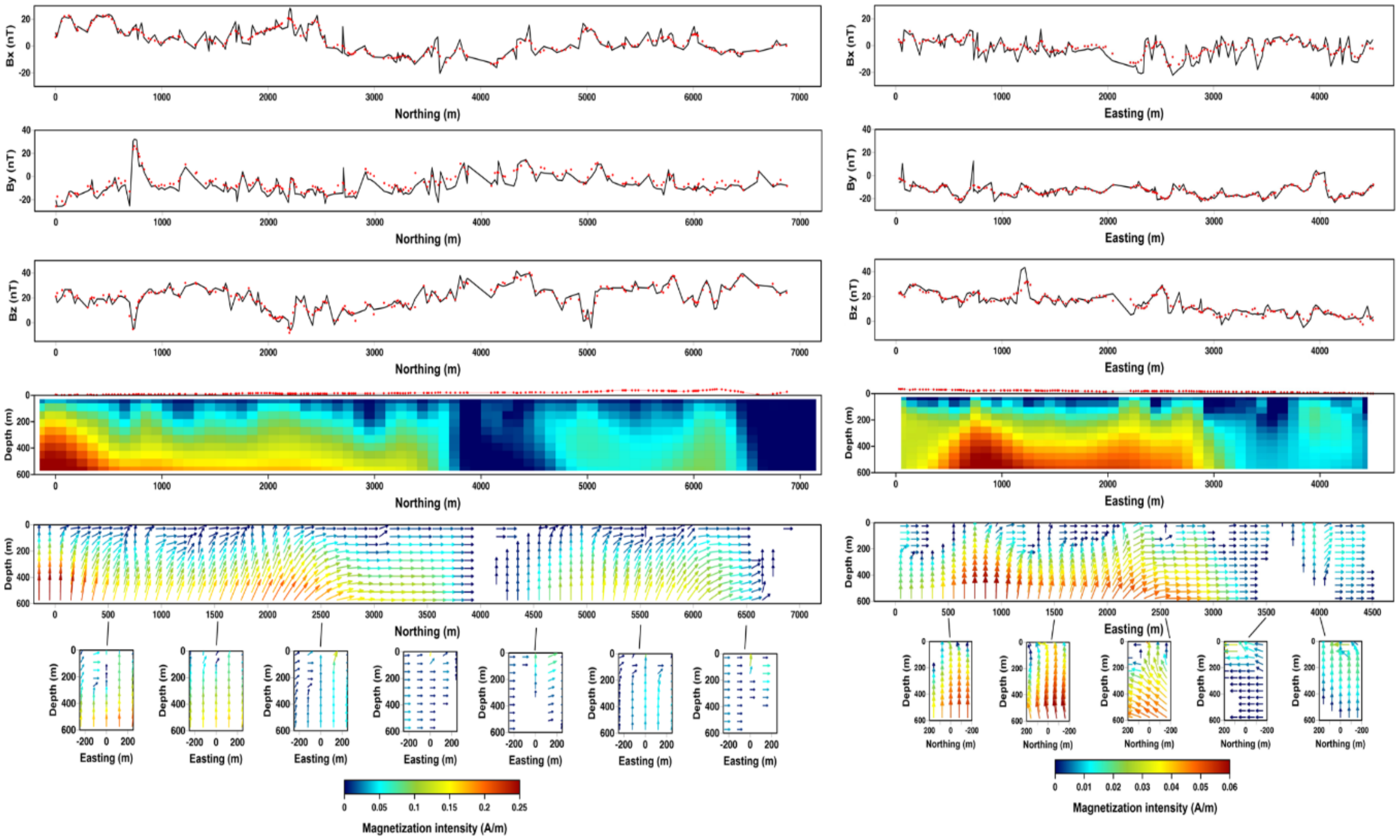

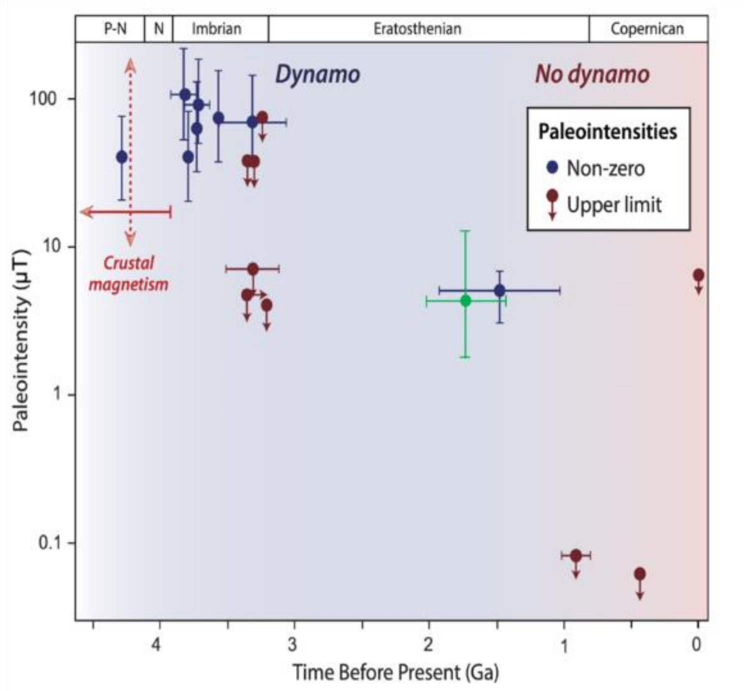

Paleointensity-age map based on Wieczorek et al., (2022), and Lunar sampe data from Lawrence et al., (2008), Cournède et al., (2012), Shea et al., (2012), Tikoo et al., (2012). Our intensity and age results are indicated by the green color.

The thermoremanent magnetization acquired by most rocks is approximately proportional to the magnetizing field for field strengths **less than about 50-100 μT**.

Hong et al., 2023

$$M_{tr} = \chi_{TRM} H$$

$$\chi_{TRM}: 1.58^{+3.14}_{-1.05} \times 10^3$$

Reference

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Thanks for your attention!

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