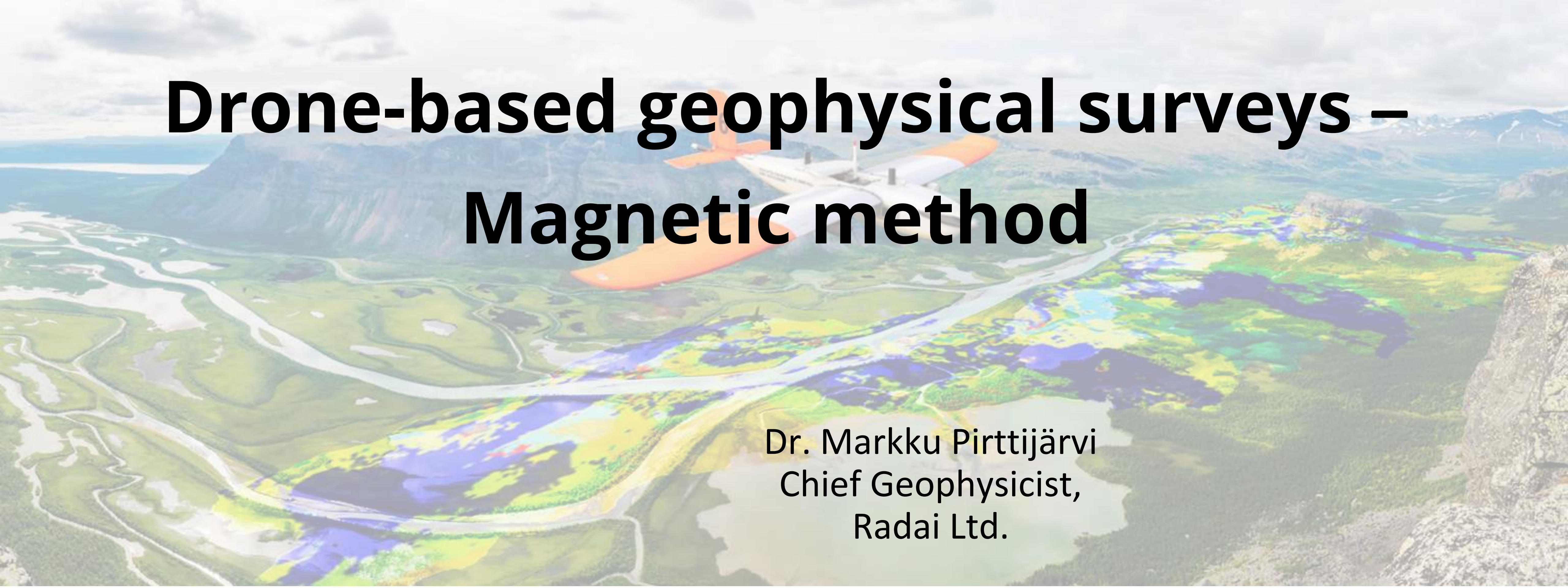

Drone-based geophysical surveys – Magnetic method

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Chief Geophysicist,
Radai Ltd.

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- Earth’s magnetic field
- Magnetization
- Radai’s magnetic survey system
- Survey example
- Fourier transform
- Derivatives and their use
- Summary

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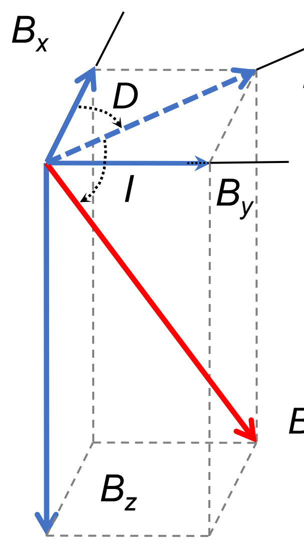
Geomagnetic field components

- When talking about magnetic field we actually mean the *magnetic flux density* **B** [Vs/m^2 = T (Tesla)].
- It is a vector field having both direction and amplitude
  - $\mathbf{B} = B_x\mathbf{i}+B_y\mathbf{j}+B_z\mathbf{k}$, where **i,j,k** are unit vectors along XYZ axes
- Intensity of magnetic flux density (TMI) is
  - $B_t = |\mathbf{B}| = [B_x^2+B_y^2+B_z^2]^{(1/2)}$.
- Declination is the angle from geographic north towards magnetic north (where compass points to).
- Inclination is the angle from horizontal plane towards total field (down-wards here in northern hemisphere).



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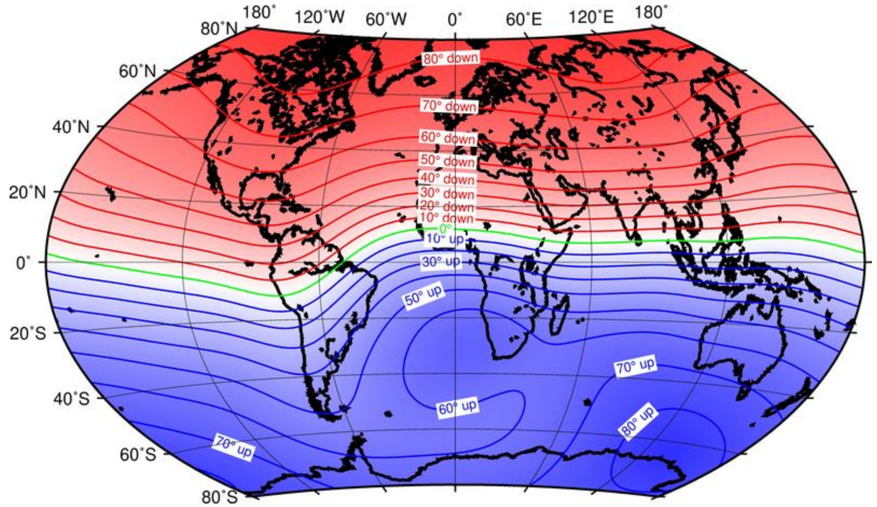
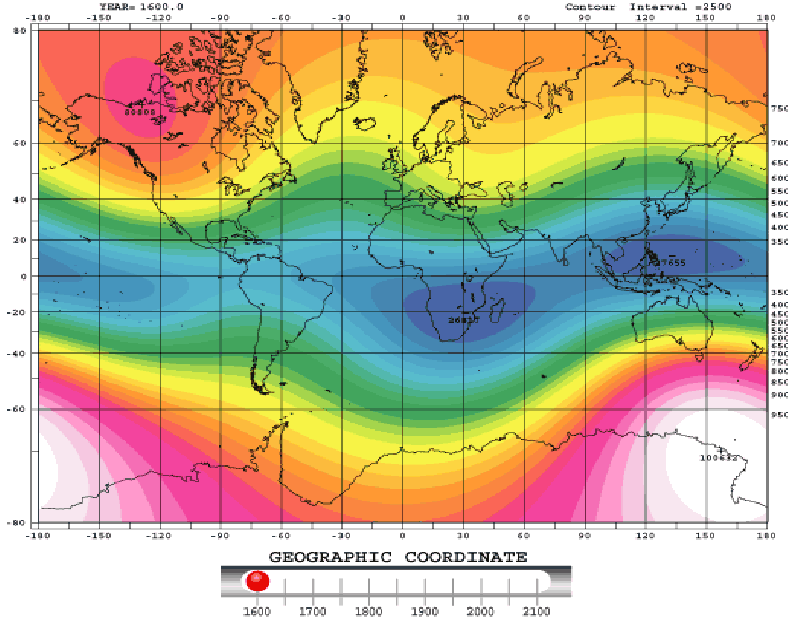
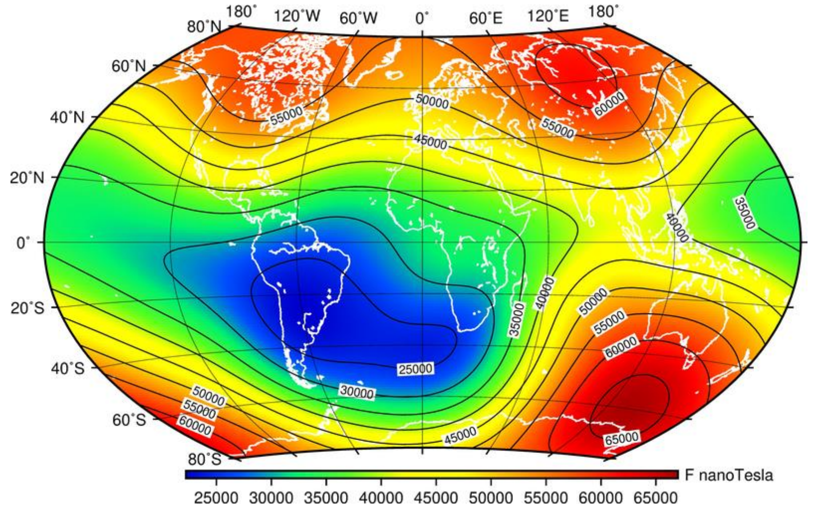
Earth's magnetic field

- The global magnetic field and its long-term changes are described by a mathematical models.
- IGRF describes historical field and predicts the future for the next 5 years.







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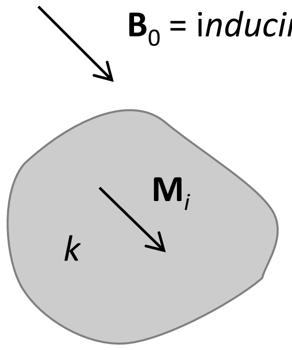
(https://geomag.bgs.ac.uk/; https://wdc.kugi.kyoto-u.ac.jp/)

Magnetization

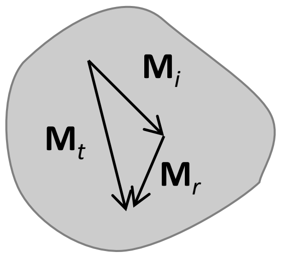
- <u>Induced magnetization</u>:
  - Earth's magnetic field polarizes iron-bearing minerals (eg. magnetite & pyrrhotite)
  - $\mathbf{M}_i = k\mathbf{H}_0 = \mathbf{B}_0 k/\mu_0$
- k= magnetic susceptibility, a material property, that varies between 10^{-5} and 10 (SI) and can be even negative
- **Magnetization is a vector quantity**
- <u>Remanent magnetization</u>:
  - Minerals can have a permanent magnetic component of fixed direction that may differ from that of earth's inducing field.
- Total magnetization:
  - $\mathbf{M}_t = \mathbf{M}_i + \mathbf{M}_r = \mathbf{M}_i(1+Q)$
  - Köningsberger's ratio $Q = \mathbf{M}_r/\mathbf{M}_i$

a) Induced magnetization



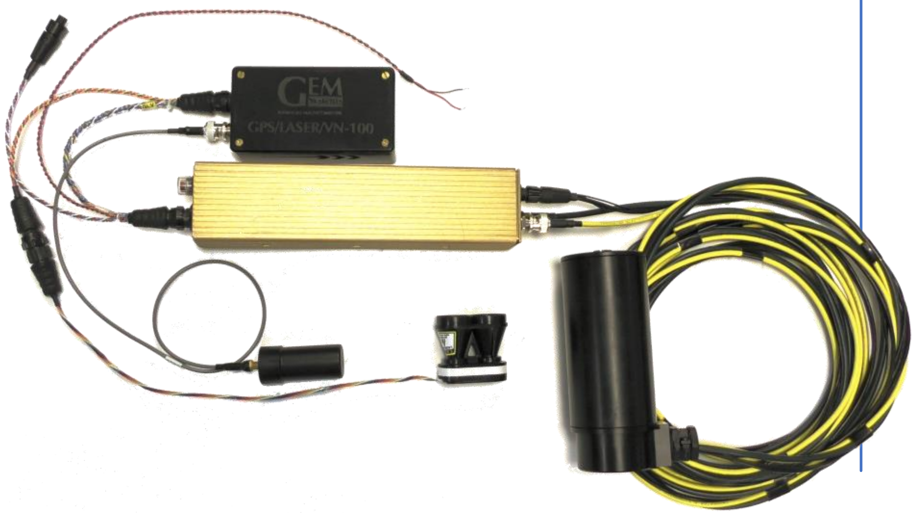
Non-magnetic host, $k_h = 0$, $M = 0$

b) Total magnetization



Direction of total magnetization ≠ direction of inducing field

Magnetometers



- Fluxgate magnetometers
  - Vector field (Bx,By,Bz)
  - Resolution 0.1 nT, noise ±1 nT
  - Fast (100Hz), small and lightweight
  - Suffer from temperature drift (0.1nT/C°)
- Proton precession magnetometers
  - Total field (Bt)
  - Resolution 0.1 nT, noise level ±1 nT
- Optically pumped magnetometers
  - Total field (Bt)
  - Accurate, noise ±0.1nT, suffer from a blind spot
- SQUID magnetometers (supra-conductivity)
  - Vector field (Bx,By,Bz)
  - Highly sensitive, require cooling (heavy)

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Radai's magnetic survey system

1) Digital 3-component fluxgate (FG) magnetometer
   - Sensitivity ±0.5 nT, dynamic range ±100 000 nT
   - Radai's multi-purpose (RMP) datalogger (135 Hz)
   - Decimation & averaging of raw data → 27 Hz (0.8 m)
2) Fixed-wing VTOL (Vertical Take-Off and Landing) drones
3) Data processing using in-house software (*RadaiView /RadaiPros*) & Equivalent Layer Modelling (ELM)
   - Pre-processing and QC: FG calibration, map coordinates, barometric height, geoid correction, visual inspection, cutting/joining, noise analysis, base station correction, clipping, filtering
   - ELM = numerical inversion using a single-layer susceptibility model composed of vertical prisms
   - Tie-line levelling + trend removal, heading correction, micro-levelling
   - Compute gridded data and derivative results at constant height (+height correction)

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Puffin VTOL – Vertical Take-off and Landing drone

- Based on a Chinese Foxtech Loong VTOL drone
- Modified for magnetic surveys by Radai
- Wingspan 2.16 m
- FG located in the tail boom, ca. 1.4 m away from the flight engine
- Pixhawk 4 autopilot (ArduPilot)
- Endurance < 1.5 hours

Photo by A.Pylväs, 2021

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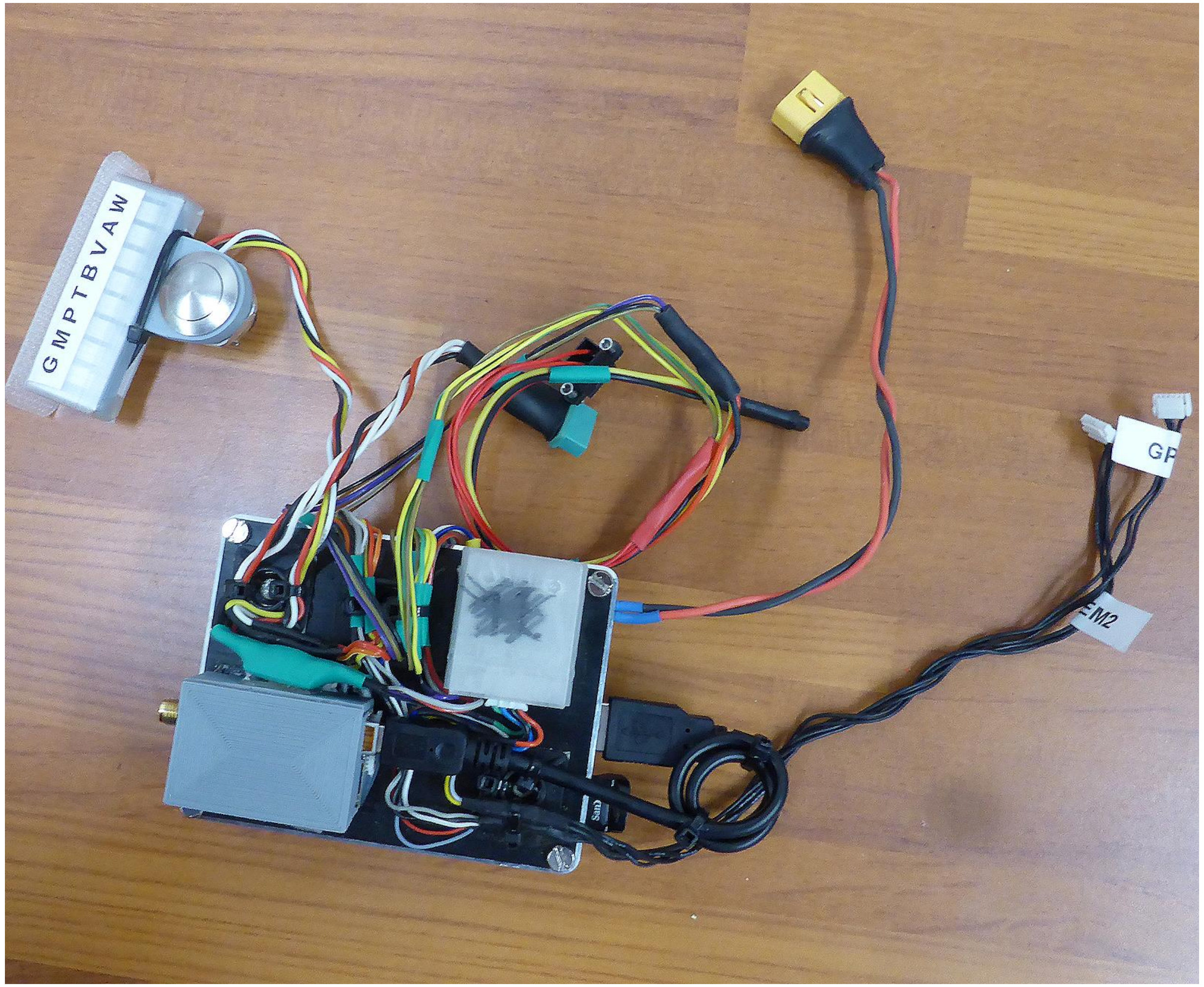
Radai’s multi-purpose datalogger

- Build on Raspberry Pi4 mini-PC
- Records multiple digital sensors
- Fluxgate magnetometer (135 Hz)
- Zed9 GNSS (GPS, Glonass, Beidou, Galileo) (10 Hz), horiz. accuracy < 0.5 m
- Barometric pressure & temperature (10 Hz)
- IMU orientation (200-100 Hz) (optional)
- Synchronized by GNSS and Pi4 processor time
- Data transfer via Wifi (Lan, 3G/4G) or USB
- Upload to a Google Drive
- Pre-processing and QC made remotely in Oulu



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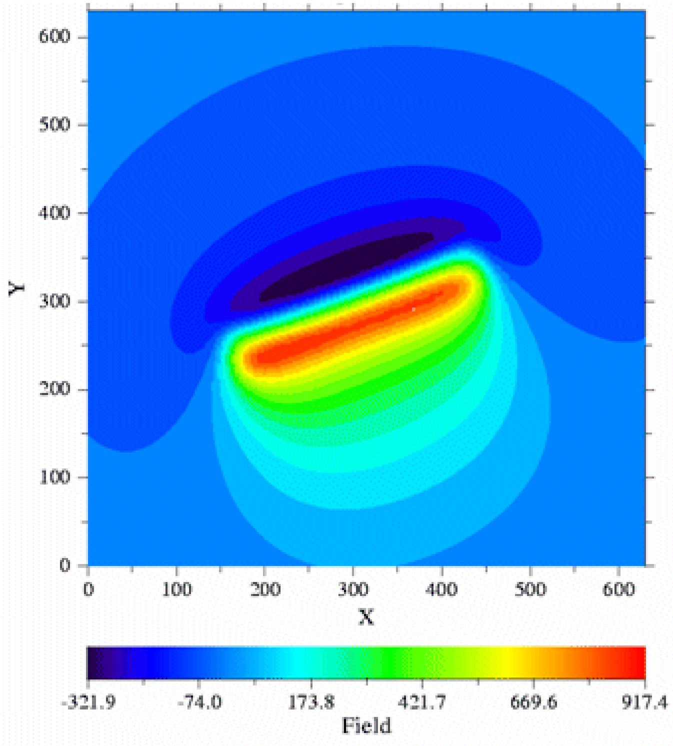
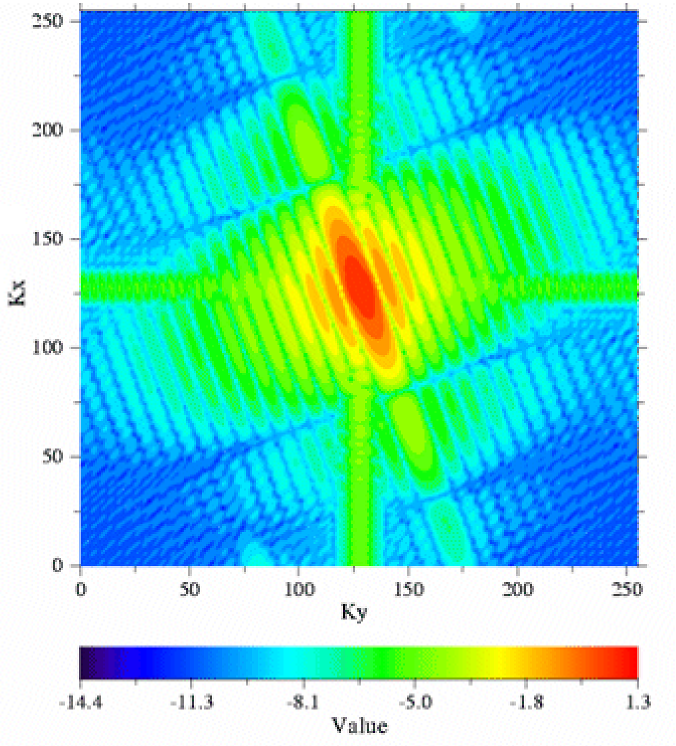
Fourier-transform

- Fourier-transform converts the (potential field) data F(x,y) into a sum of harmonic (sine/exp) functions of frequency f(kx,ky)
- The frequencies vary from zero (in the middle) to 1/2Δ (m^{-1}) (Nyquist at the sides, Δ= sampling)
- Several mathematical operations like low-pass filtering and pole-reduction can be made frequency-domain easily
- The inverse Fourier transform yields the filtered data

$$f_{kl} = \frac{1}{NM}\sum_{n=0}^{N-1}\sum_{m=0}^{M-1} e^{+2\pi i\left(\frac{nk}{N}+\frac{ml}{M}\right)} F_{nm}$$

$$F_{nm} = \sum_{k=1}^{N}\sum_{l=1}^{M} e^{-2\pi i\left(\frac{nk}{N}+\frac{ml}{M}\right)} f_{kl}$$





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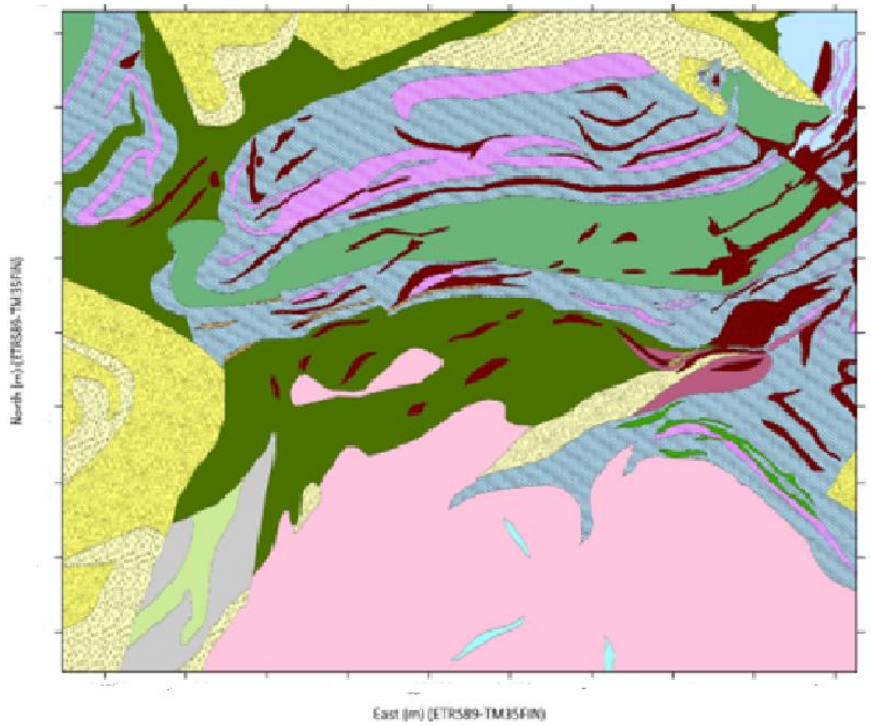
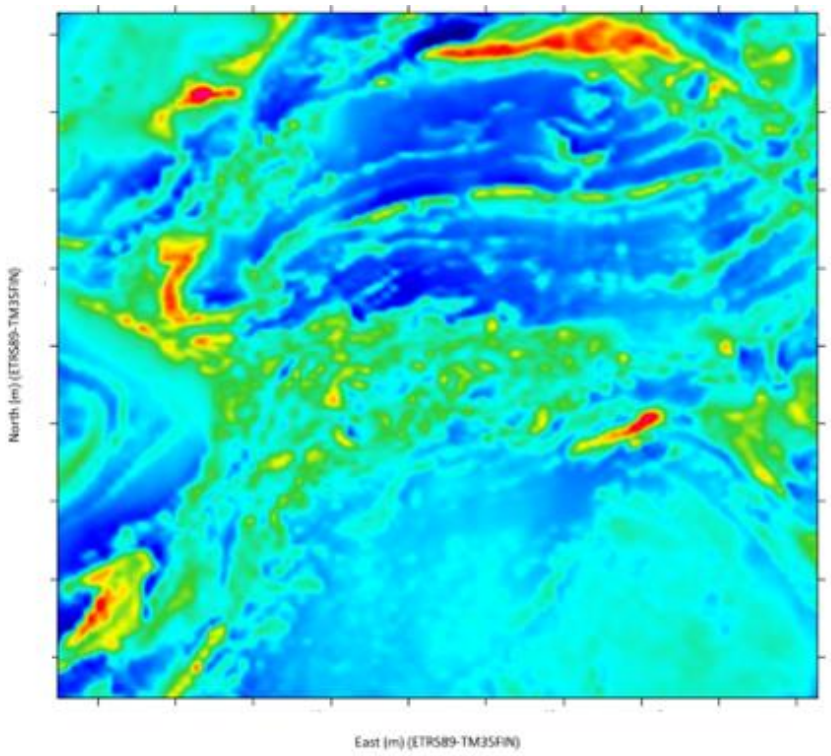
Example: GTK airborne data, Kittilä99 map sheet

GTK lithological map 1:200k
(Geological Survey of Finland)



Original magnetic data (TMI, nT)
200 m line separation, 30 m flight height, 100x100 m grid



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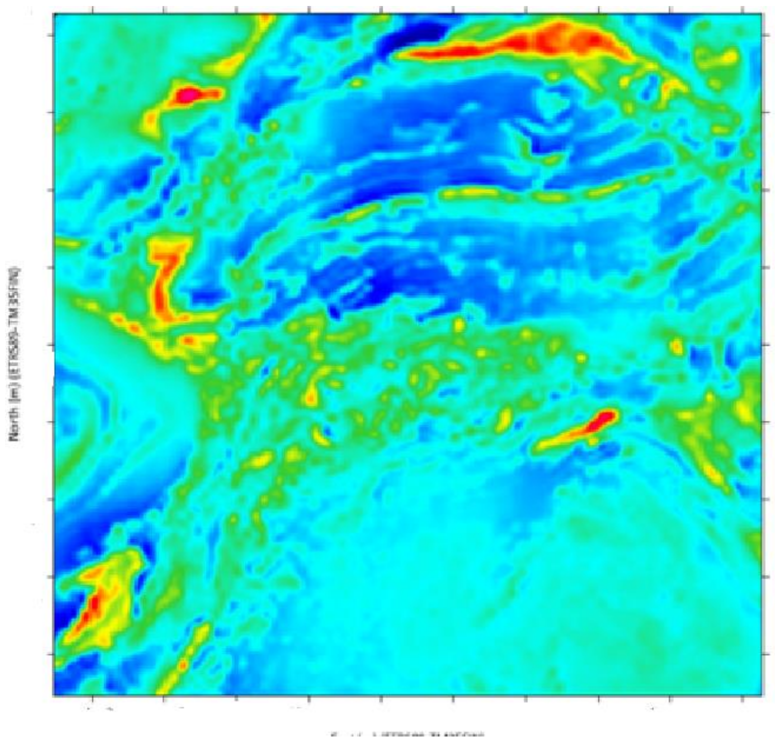
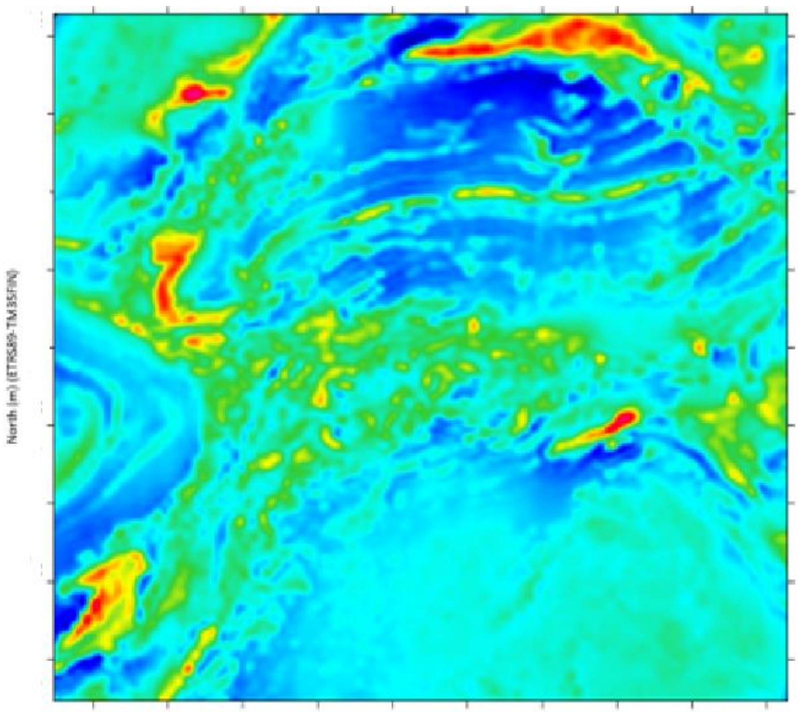
Low-pass filtering, RTP, and upward continuation

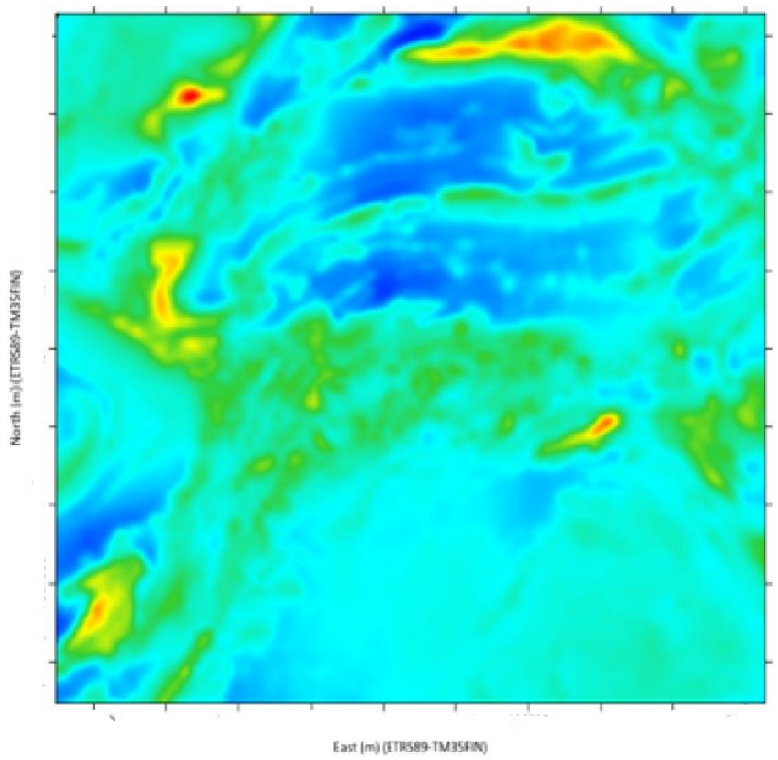
Low-pass filtered TMI map (LP, nT) (D= 250 m). Smoothens data and removes “noise”



Pole-reduced data (RTP, nT) (year 1999, I= 77°, D= 17°). Corrects inclined field effect

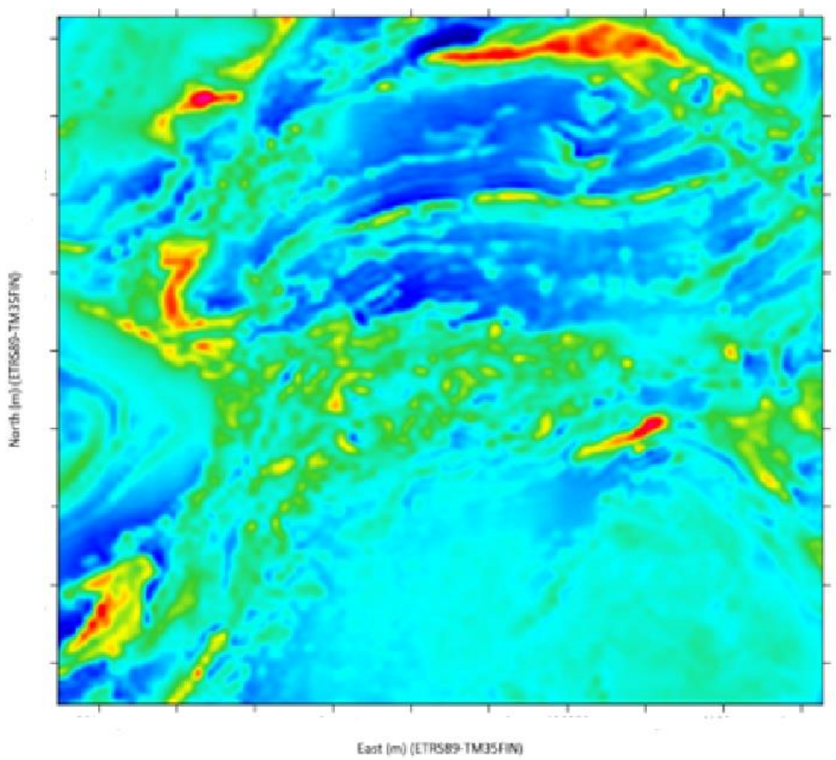


Upward continuation (UP, nT) (h= 100 m). Acts like a low-pass filter

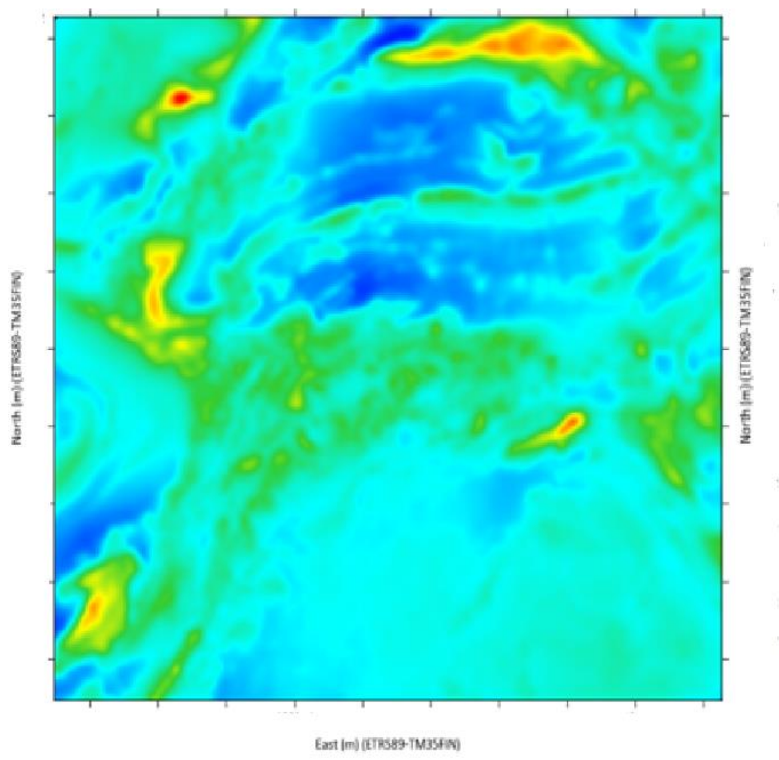


Residual field

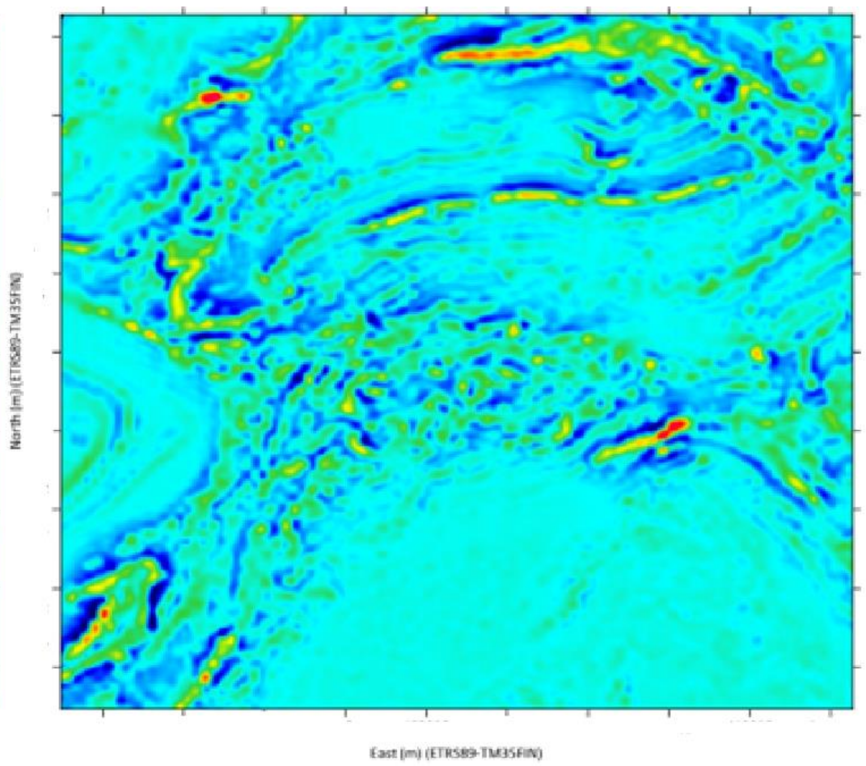
Original LP TMI map



Upward continued field (UP, nT) (h= 100 m)



Residual field (RES, nT) obtained by subtracting UP from TMI.
Shows small-scall features by removing large-scale trends



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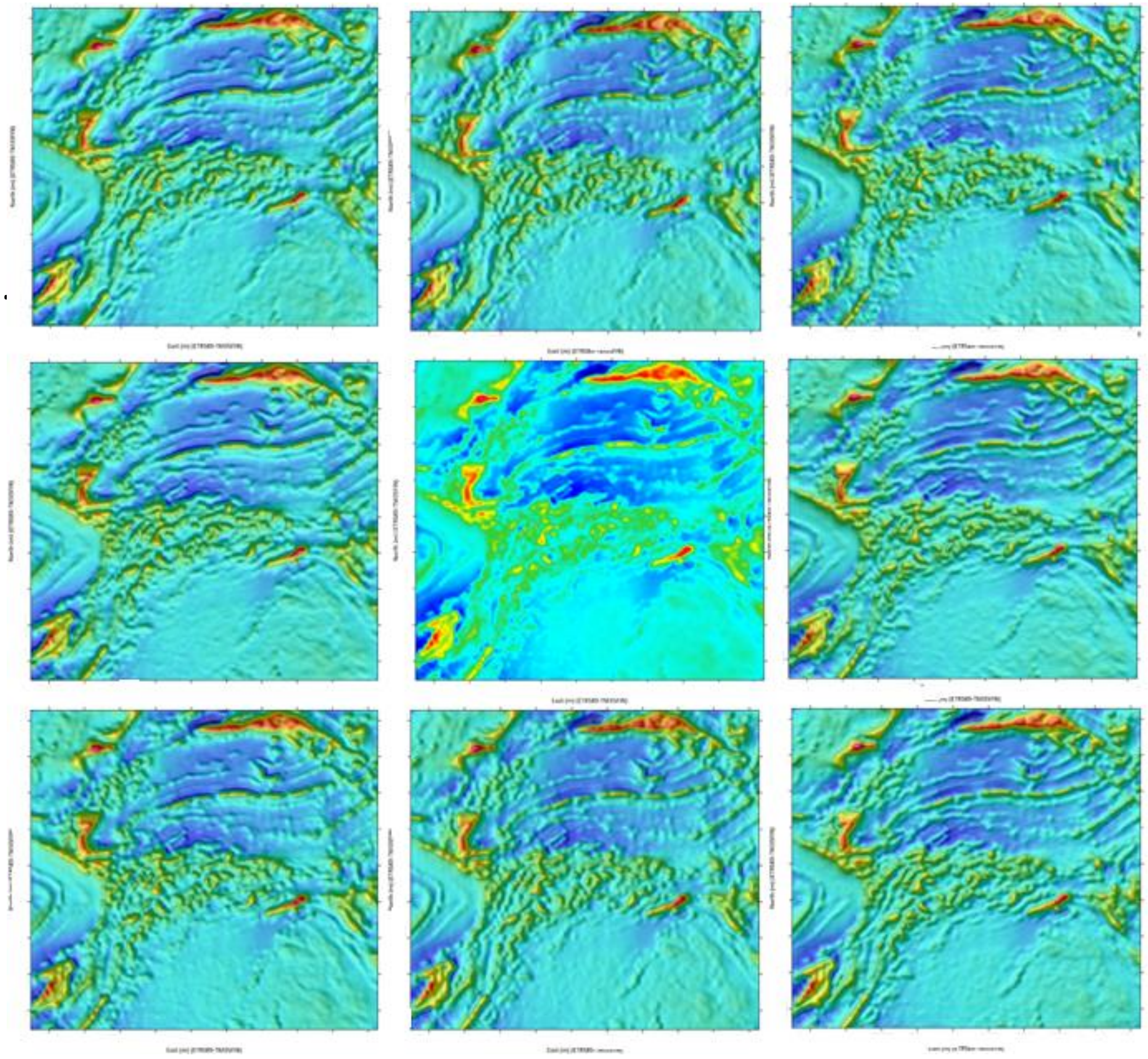
Sun-shading

- Sun-shading enhances (linear) features that are perpendicular to the direction of the sun.
- It diminishes (linear) features that are parallel to the direction of the sun.
- Sun-shading is a great tool for finding lineaments and faults from magnetic maps.
- Shading is made using different **azimuth direction** (from north) and **angle** (from horizontal).
- In the example, the direction of the sun is comparable to the position of the image around the map in the centre (with no sun-shading).



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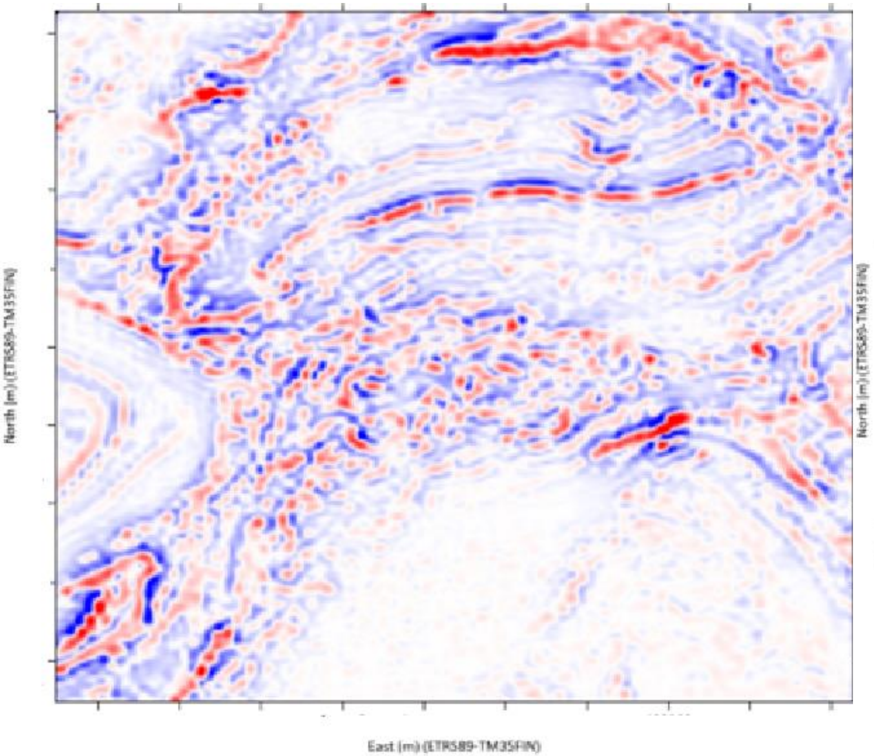
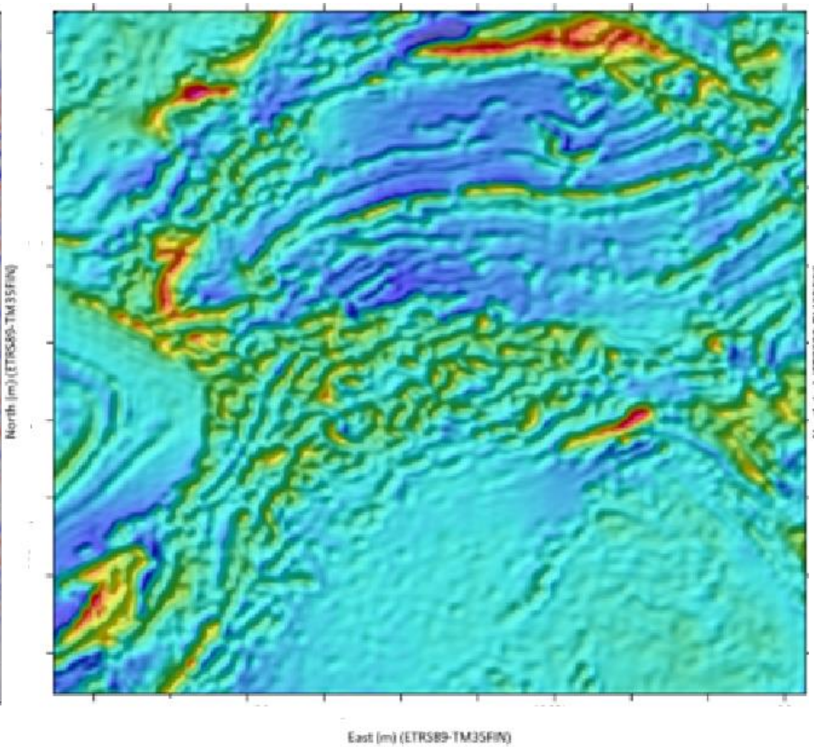
1st vertical derivative

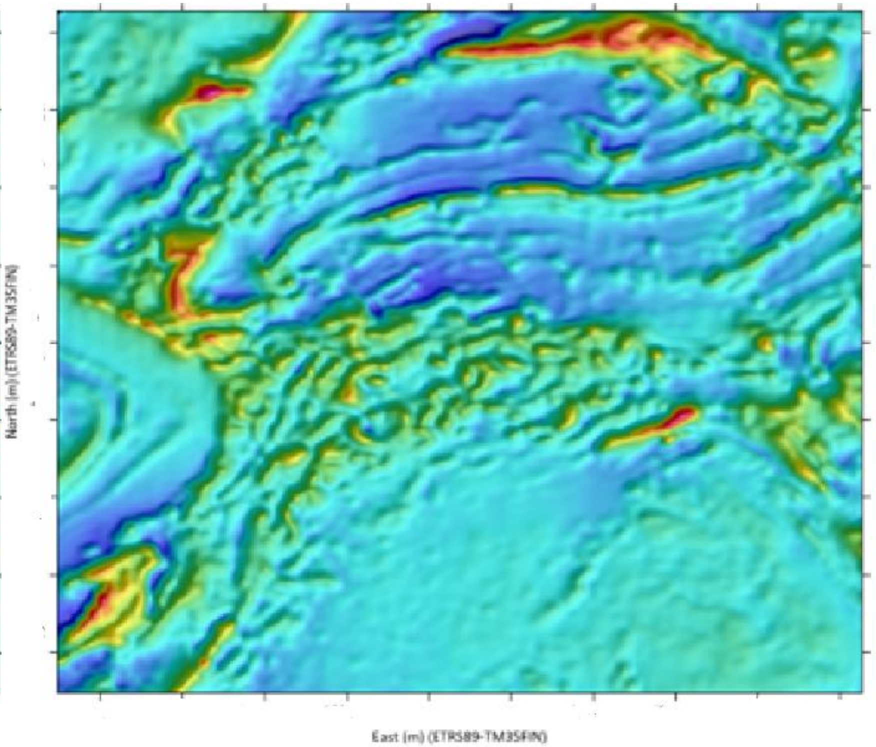
First vertical derivative (1VD, nT/m) focused maximas over the sources (and creates negative minimas around them)



Using sun-shaded 1VD transparently over the magnetic map enhances its details

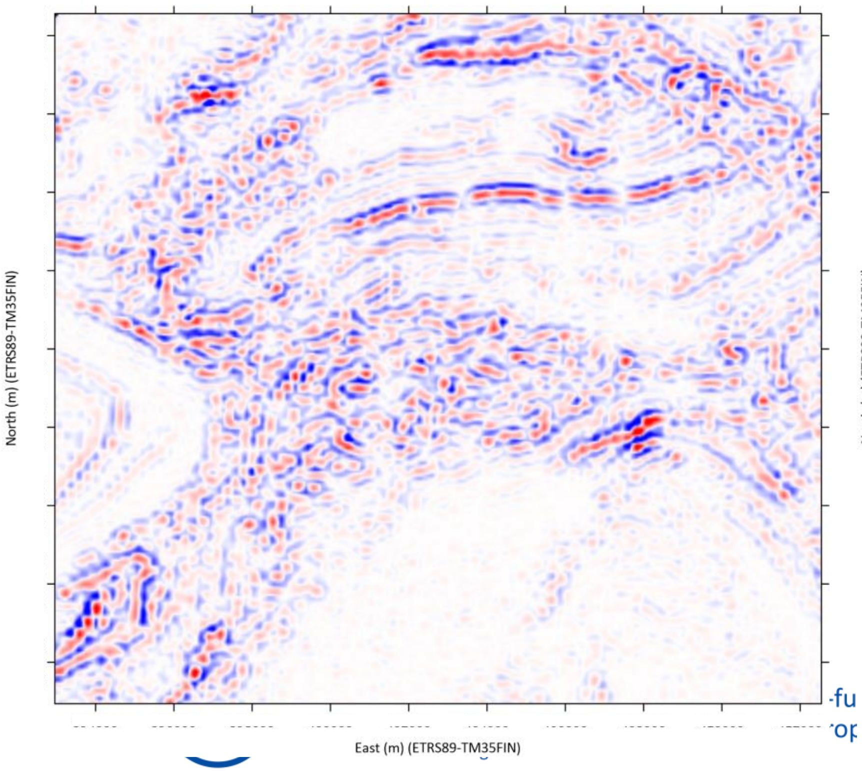


Here's sun-shaded TMI map for comparison (direction NW, azimuth -45°)

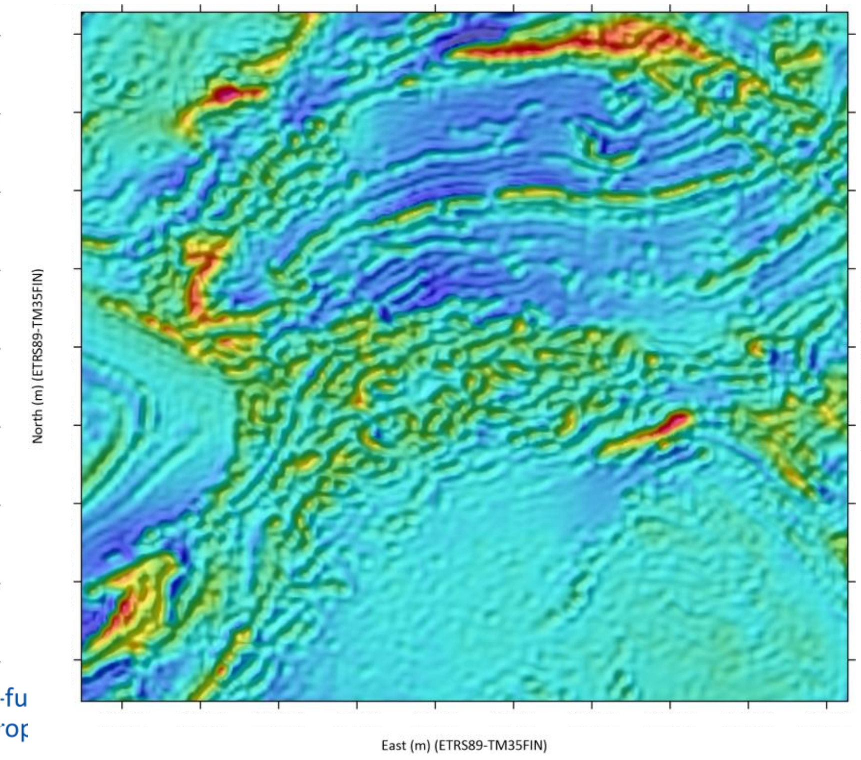


2nd vertical derivative

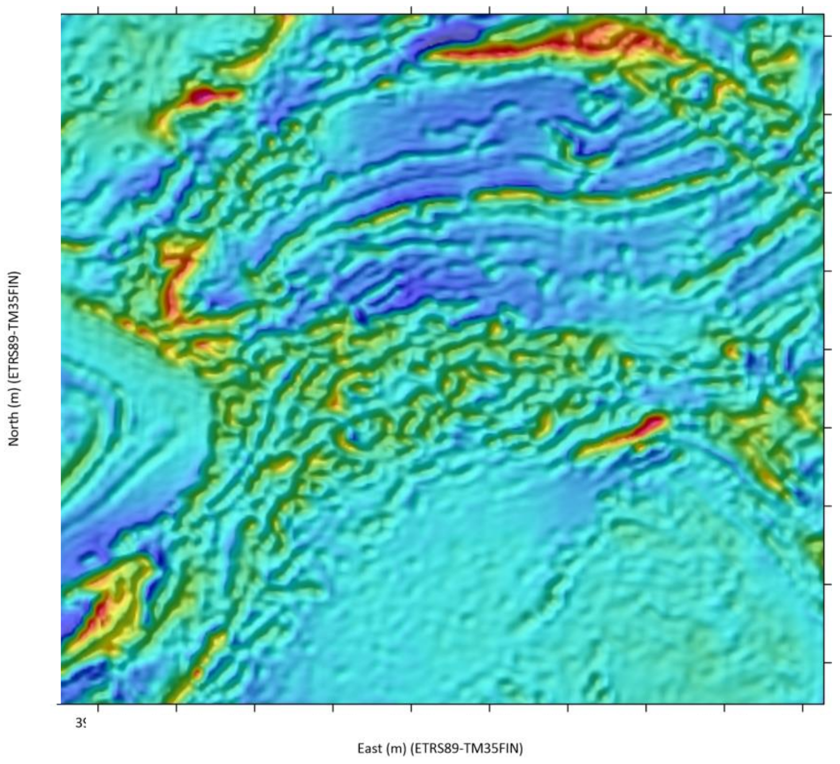
Second vertical derivative (2VD, nT/m^2) focuses the anomalies even more



Using sun-shaded 2VD transparently over the magnetic map enhances its details



Here's similarly sun-shaded 1VD map for comparison (azimuth -45°)

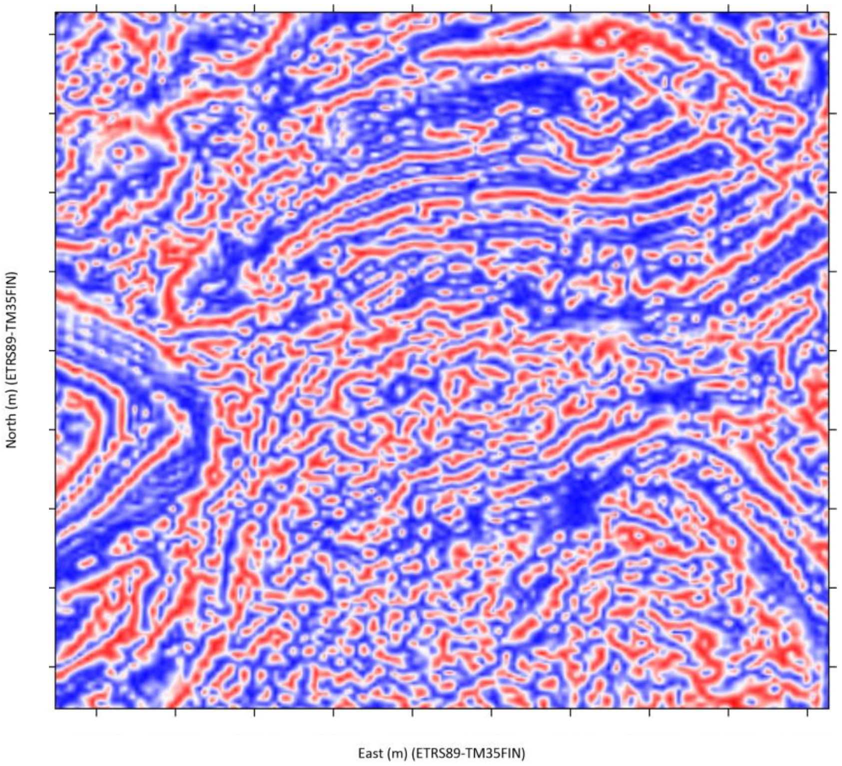


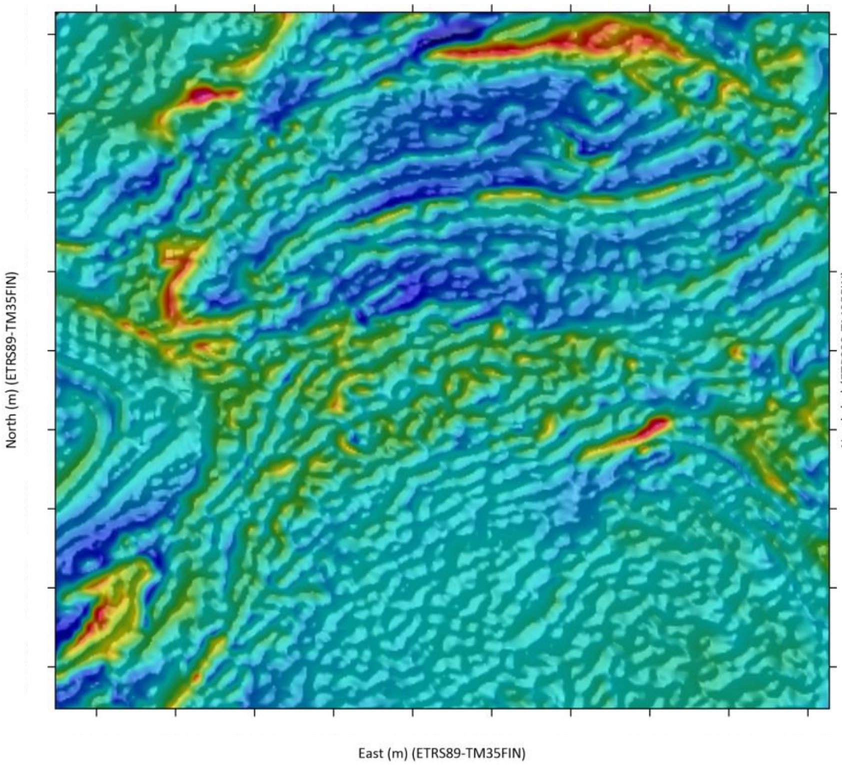
Tilt gradient

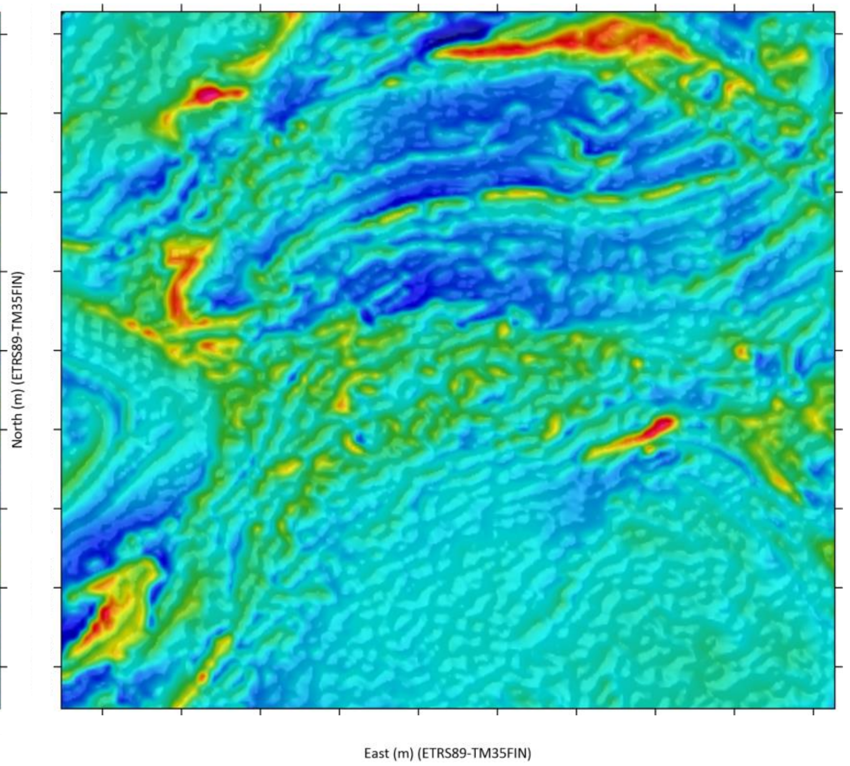
Tilt gradient (TDR= $\tan^{-1}$(1VD/HG), deg) enhances weak anomalies and helps identifying structural geology

Using sun-shaded TDR transparently over the magnetic enhances its details (azimuth -45°)

Adjusting the transparency (alpha channel) of the sun-shading clarifies the colours of TMI map





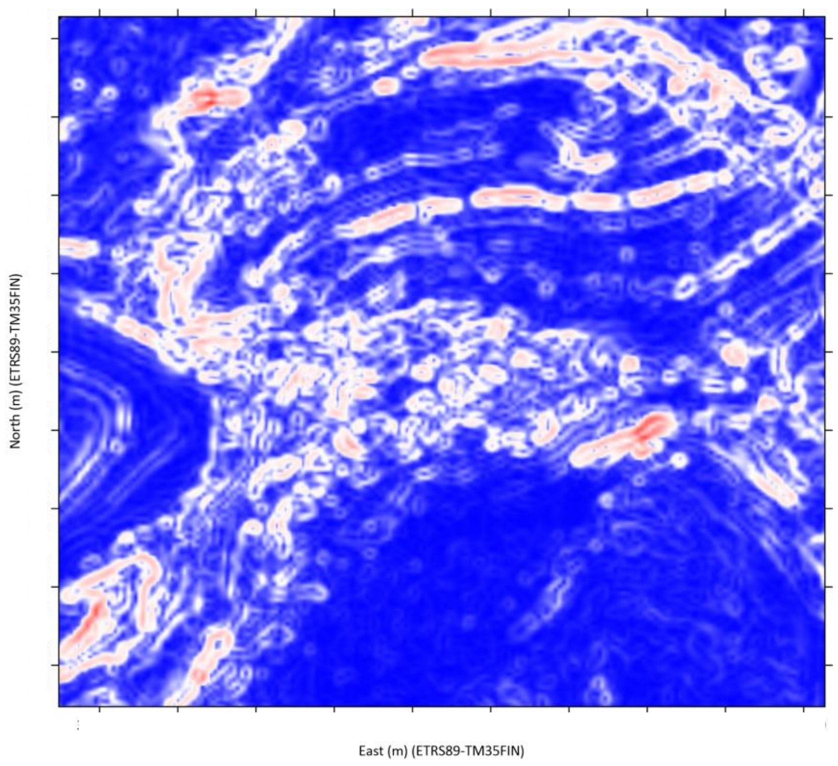


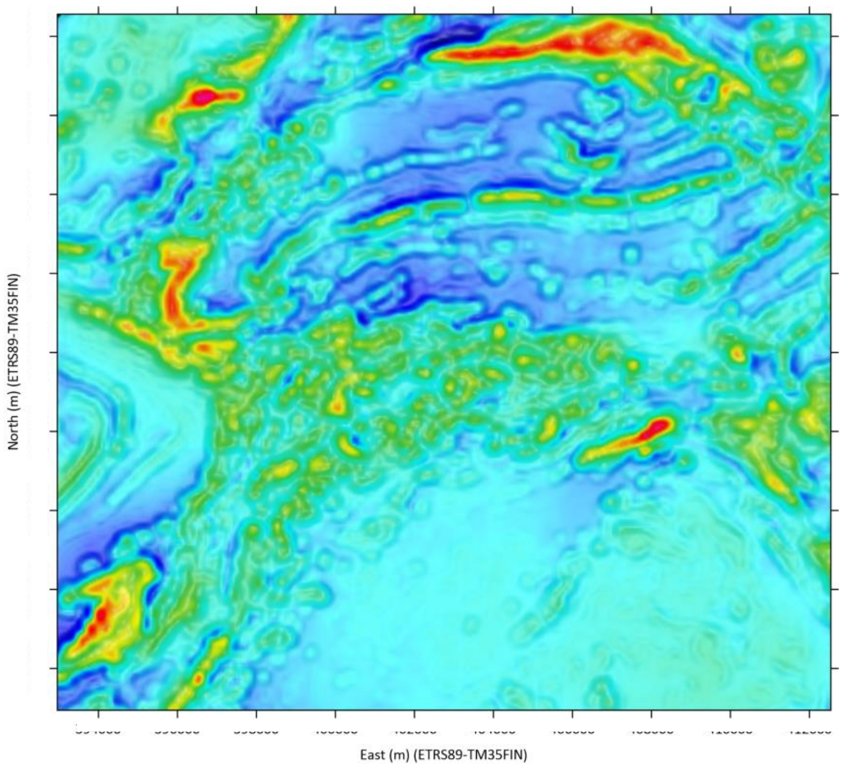
Horizontal gradient

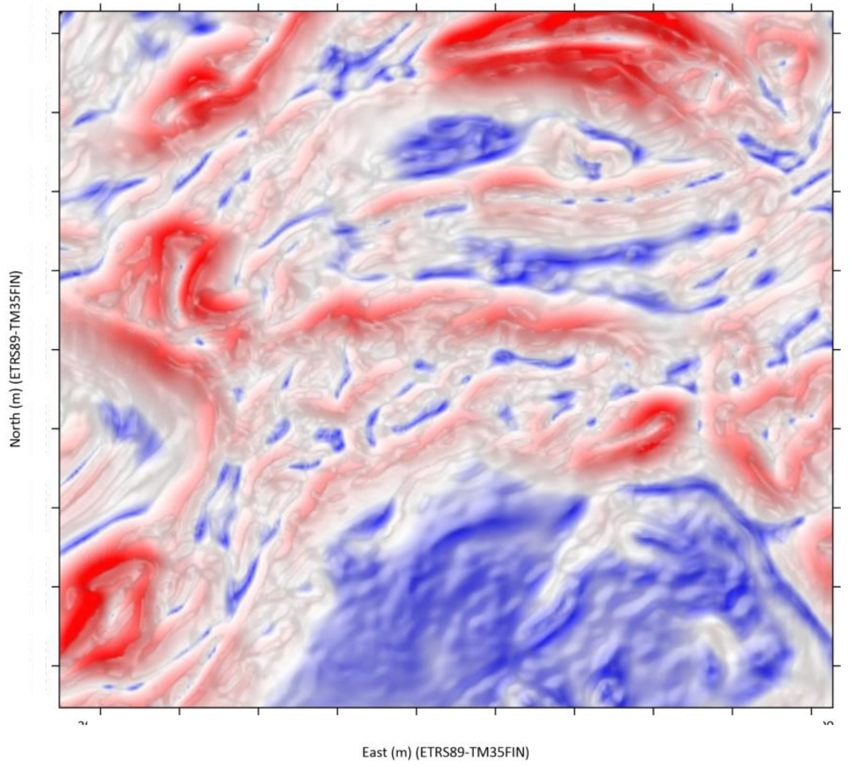
Horizontal gradient (HG, nT/m) creates maximas where the magnetic anomaly is the steepest, thus outlining isolated anomalies

Using sun-shaded HG over the TMI map enhances the side slopes (angle 90°)

Asymmetry of HG side-maximas helps estimating dip angle. When made for upward continued data we can compute so-called “worming”.





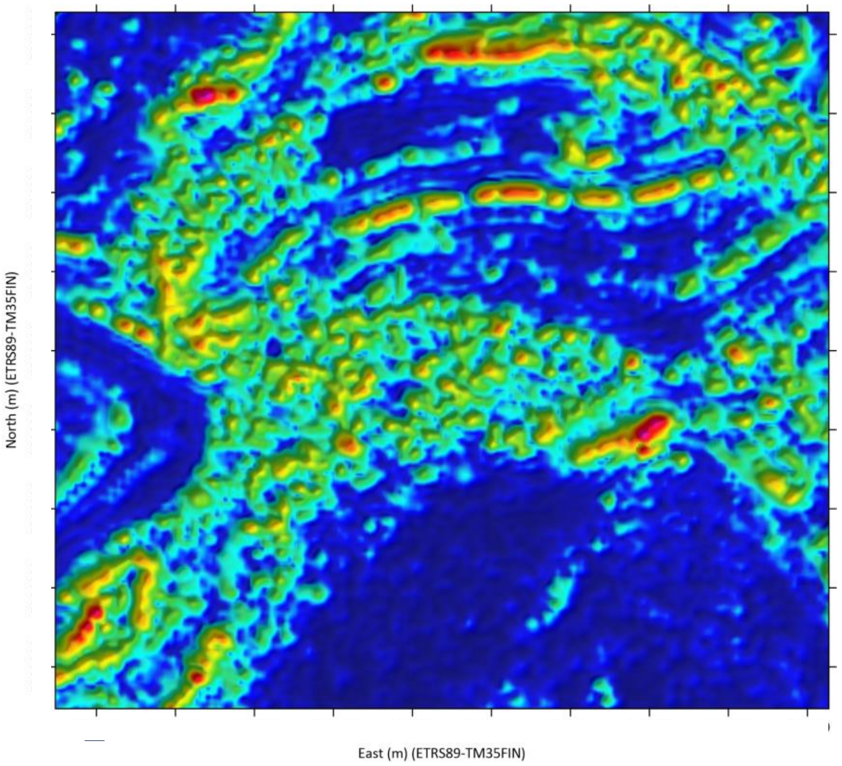


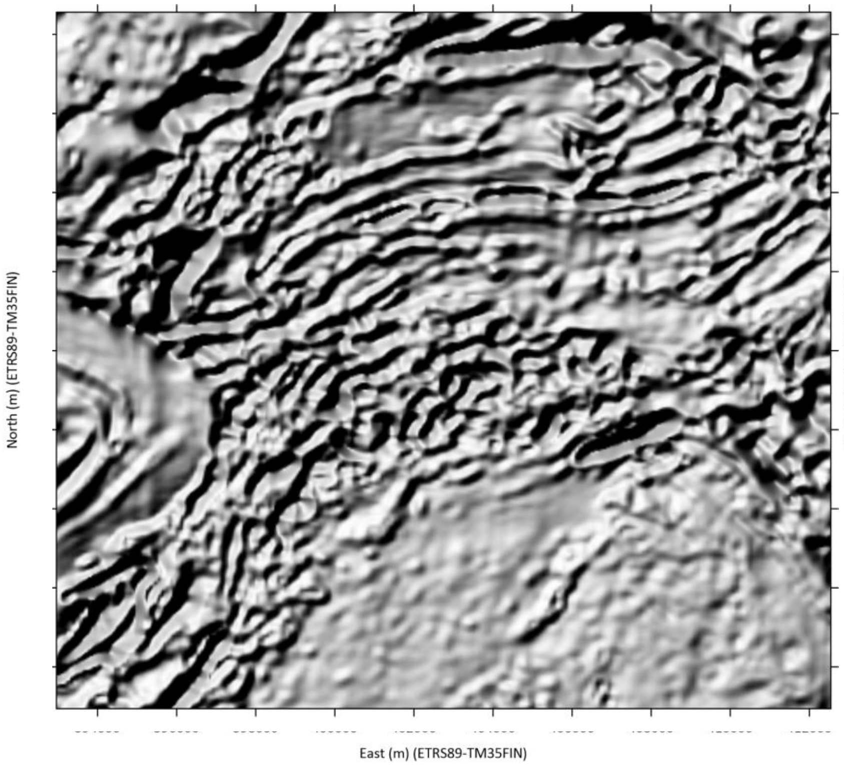
Total gradient & Hilbert transform

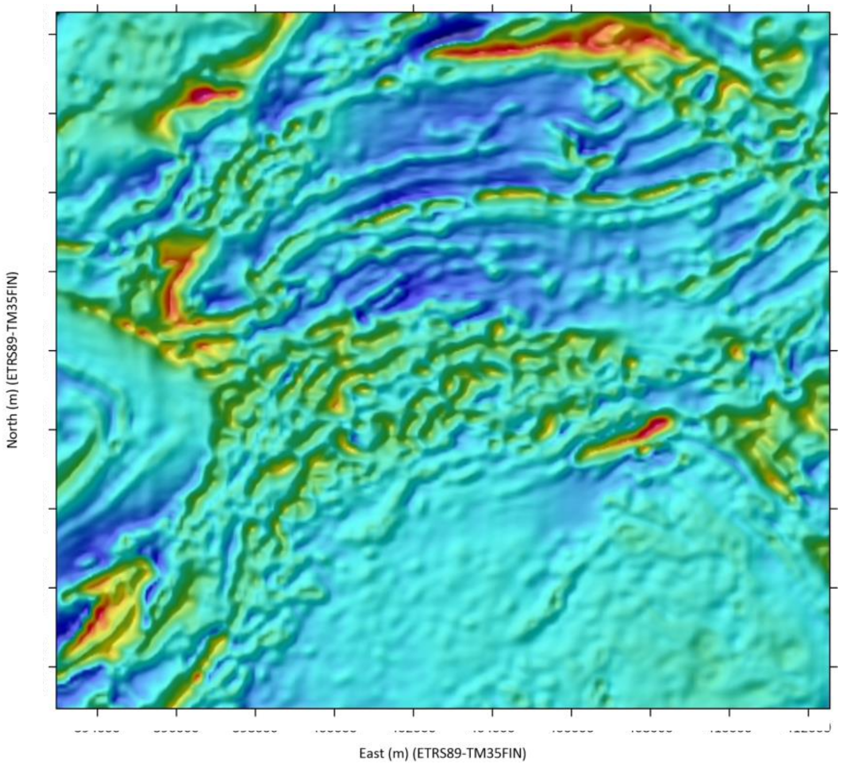
Total gradient a.k.a. analytical signal (TG=AS, nT/m) creates a map that is invariant of inclination (like RTP is)

Hilbert transform can be used to create an envelope field (ENV) that encloses the magnetic anomalies

Using sun-shaded ENV transparently over the magnetic map enhances its details. AS and ENV reflect the texture of magnetic anomalies





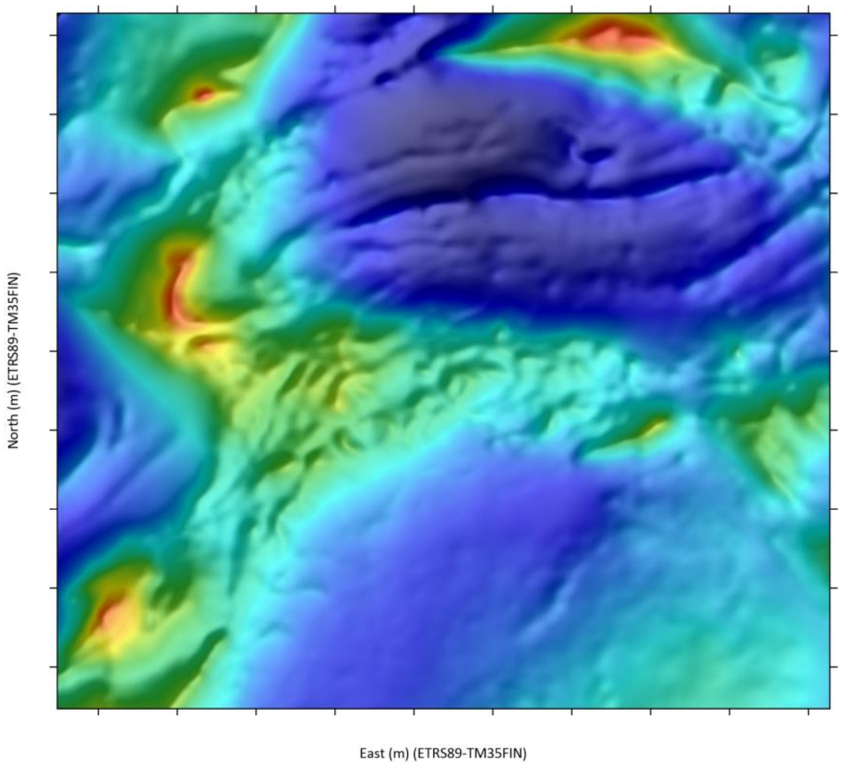


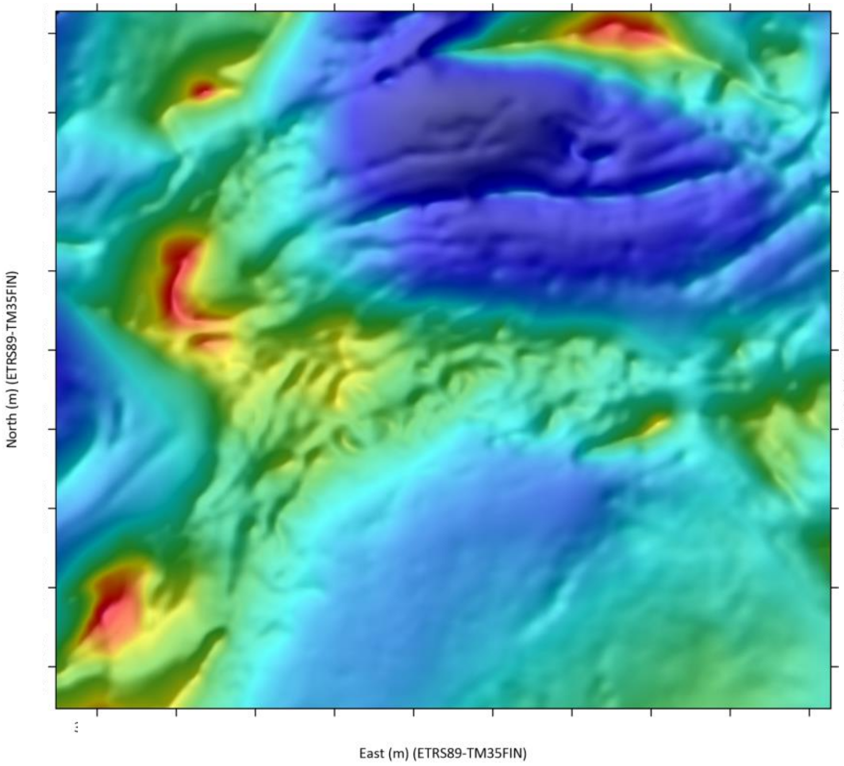
Magnetic potential & pseudo-gravity

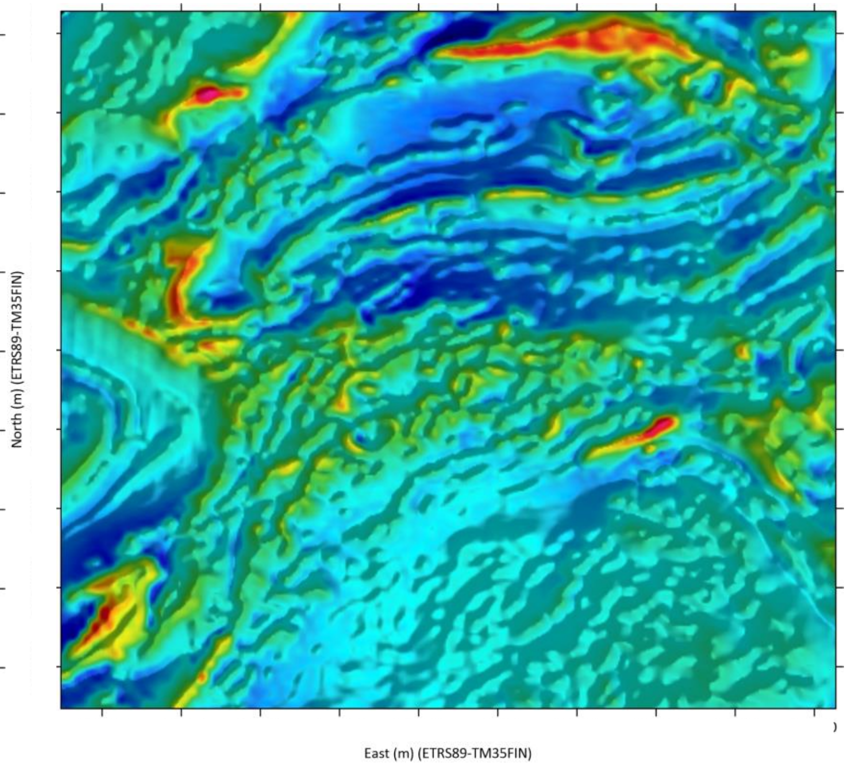
Magnetic field is the gradient of magnetic potential (POT, nTm). Potential shows the large-scale anomaly features.

Pseudo-gravimetric field (PG, mGal) can be computed from POT assuming density contrast and anomalous susceptibility

Computing the above-mentioned derivatives from PG can be used to see the large-scale effects (TDR-PG)

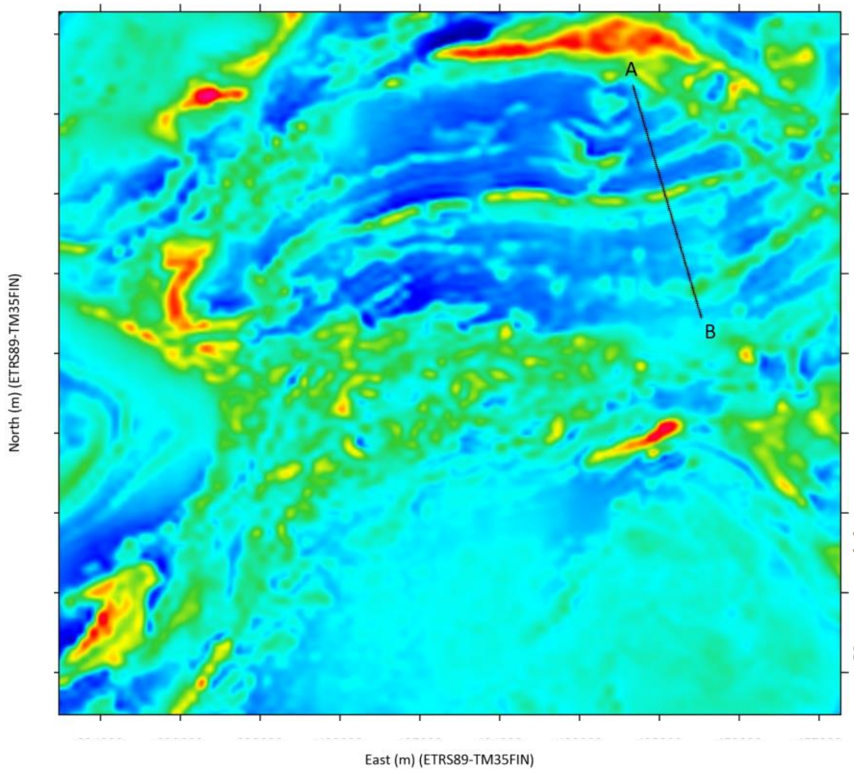




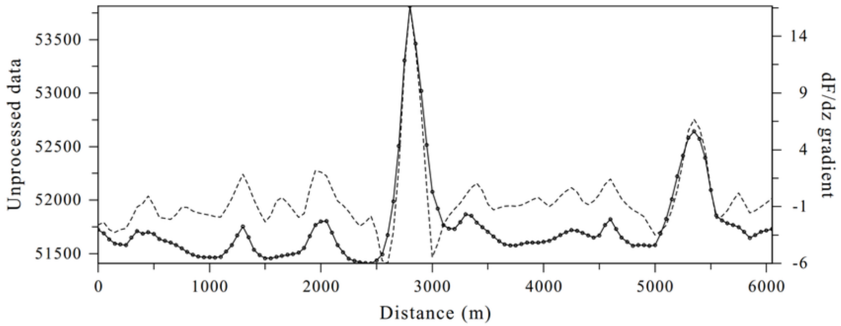


Fourier-operations in 1D

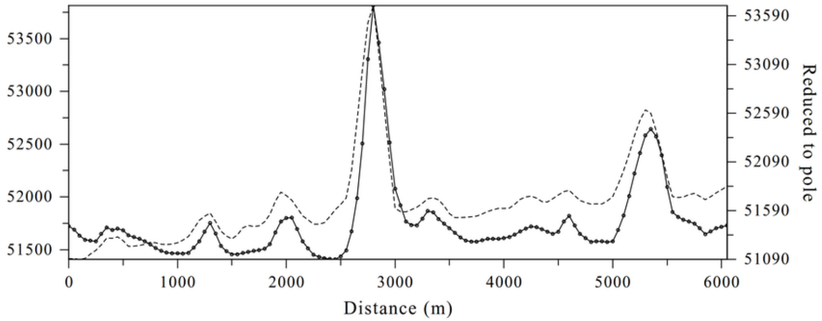
The original LP TMI map and the location of a picked profile (A-B)



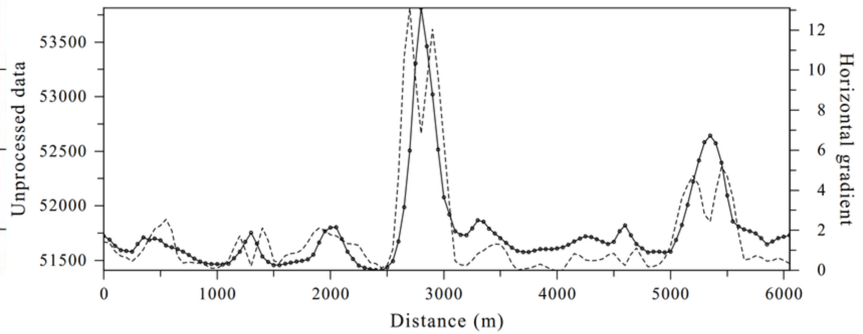
1VD (dashed line) & TMI (solid line)



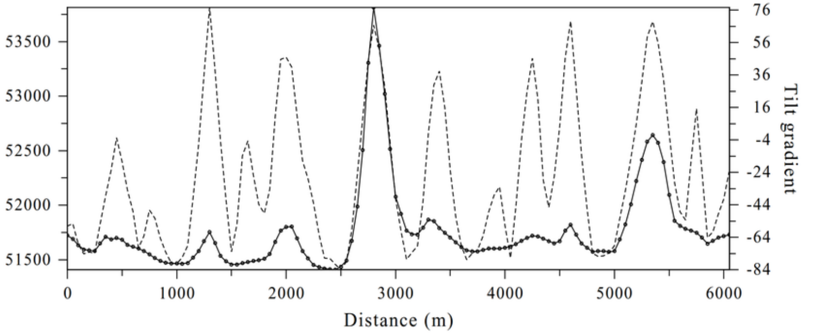
RTP (dashed line) & TMI



HG (dashed line) & TMI



TDR (dashed line) & TMI

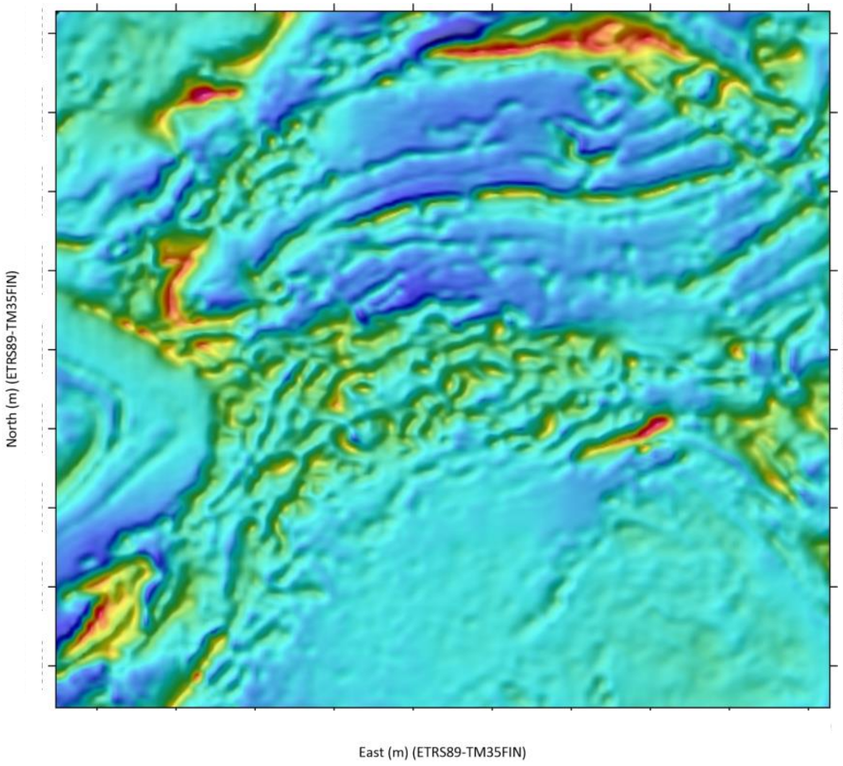


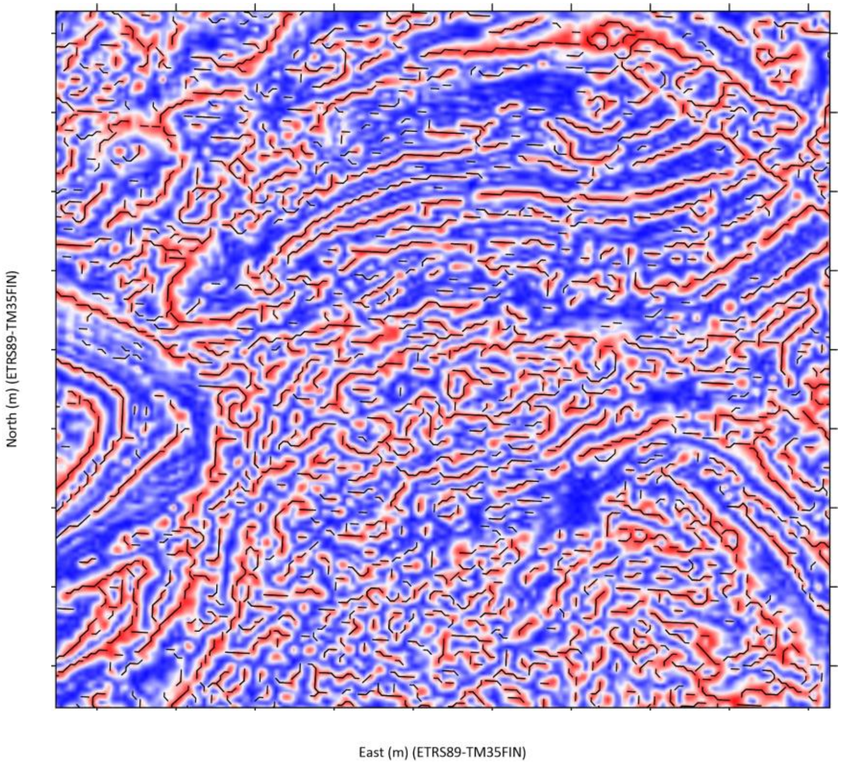
Tilt gradient vectorization

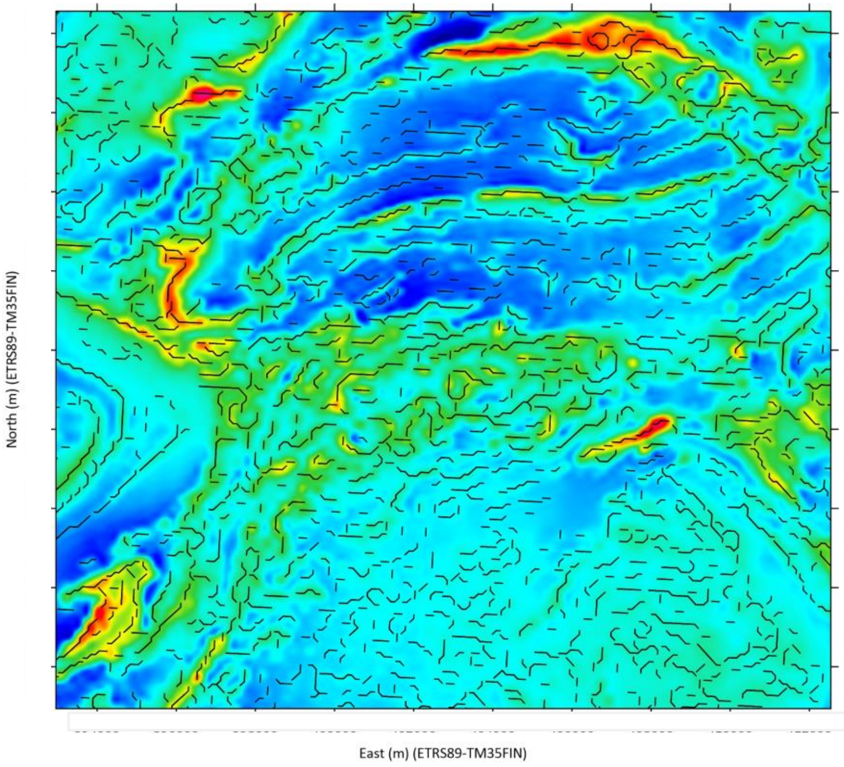
Here's sun-shaded TMI map as a starting point

Using a special vectorization method the peaks/ridges of the TDR are picked up. Data are saved in GIS format (BNA file)

Drawing the ridge (vector) data over TMI helps structural interpretation

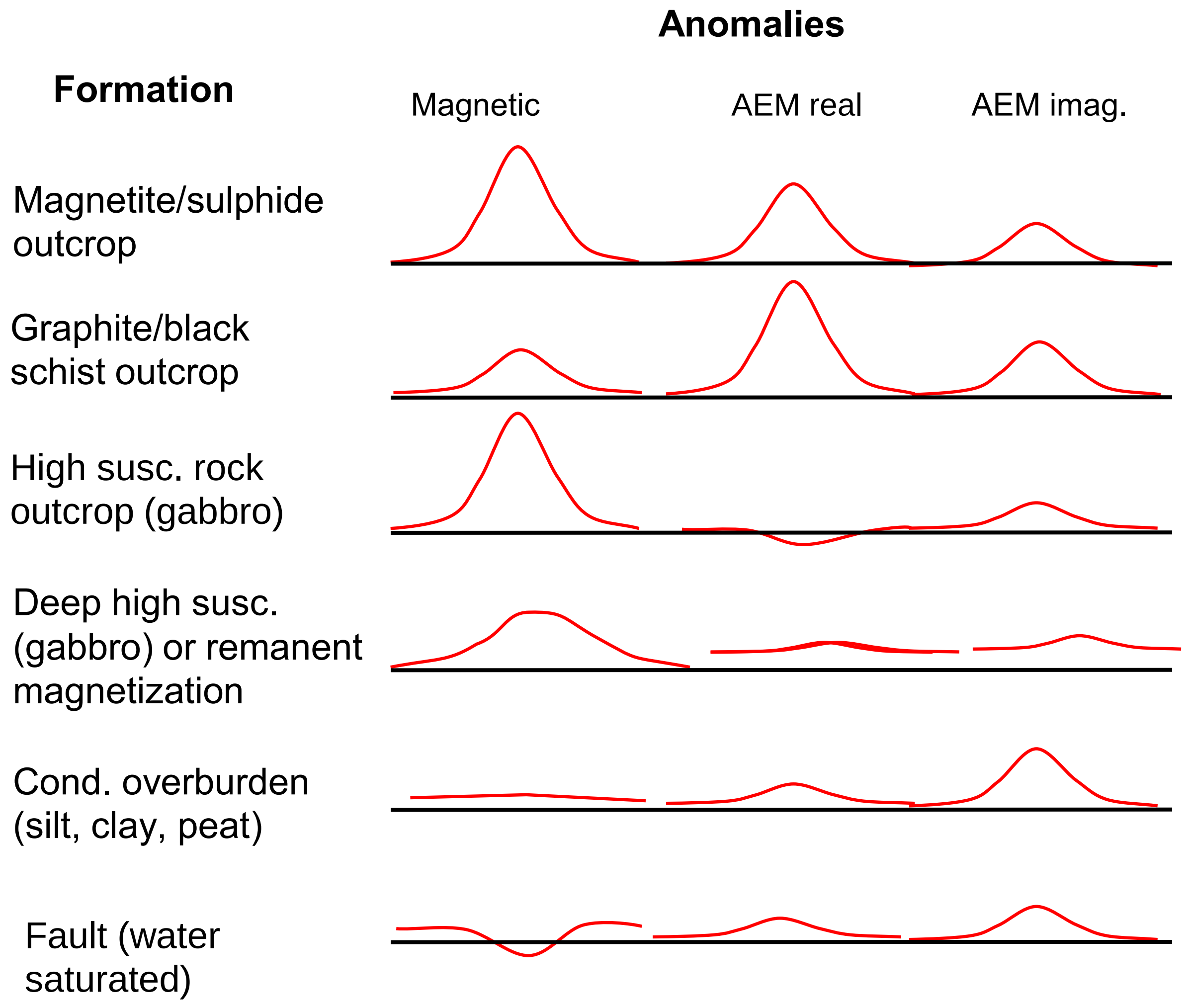






Data integration & interpretation

- For geological interpretation it is better to study the static magnetic field and AEM anomalies together
- Asymmetry → dip direction
- Amplitude width → depth of burial
- In combined (geological) interpretation the gravity data is of great importance → **drone-based gravity by DTU**!
- Mineral prospecting using correlation-based applications and → **advangeo2D and GisSOM**!
- Aim for true 3D joint inversion (**Longying's talk**)



(after Peltoniemi, 1988)

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Summary

- Some iron-bearing minerals (e.g., magnetite, pyrrhotite) get magnetized by Earth's magnetic field
- Individual XYZ components improve 3D inversion and help estimating presence of remanence (Arto's talk)
- Derivative results give additional information about geological structure (ELM and Fourier-methods)
- Tilt gradient, TDR= $\tan^{-1}$(1VD/HG), enhances small anomaly features
- Picking the TDR ridges is useful for structural mapping

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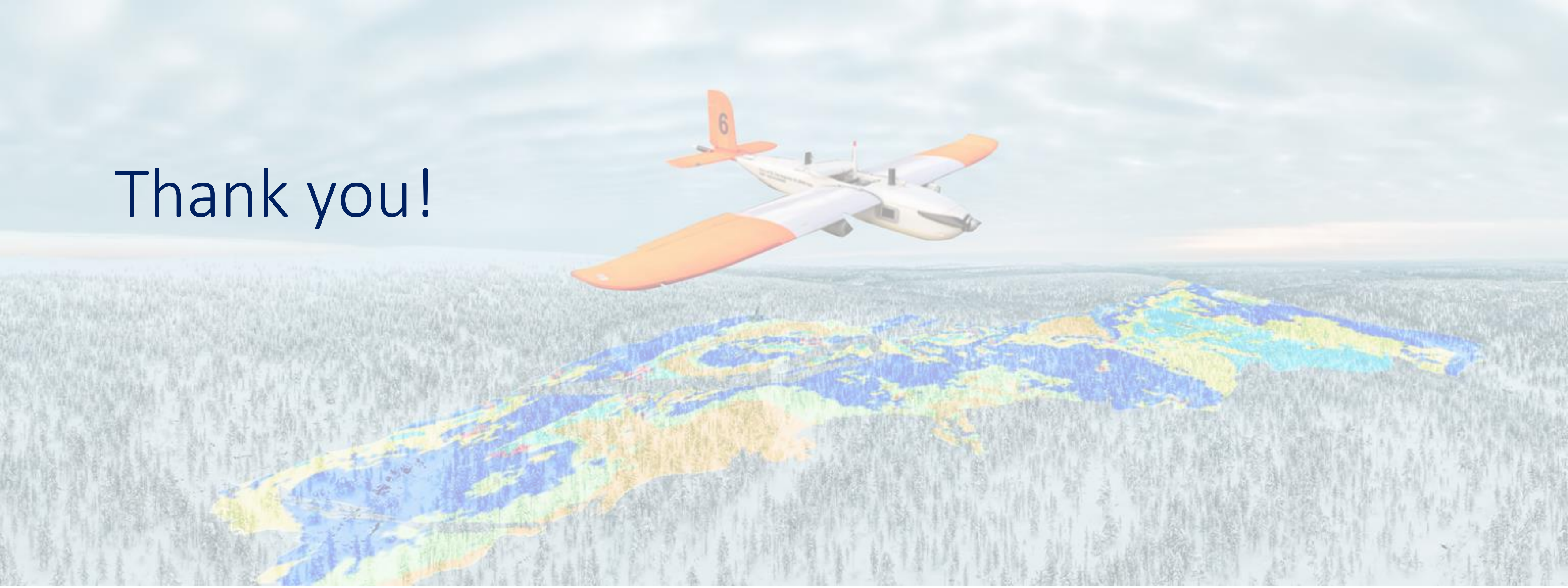

Thank you!

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