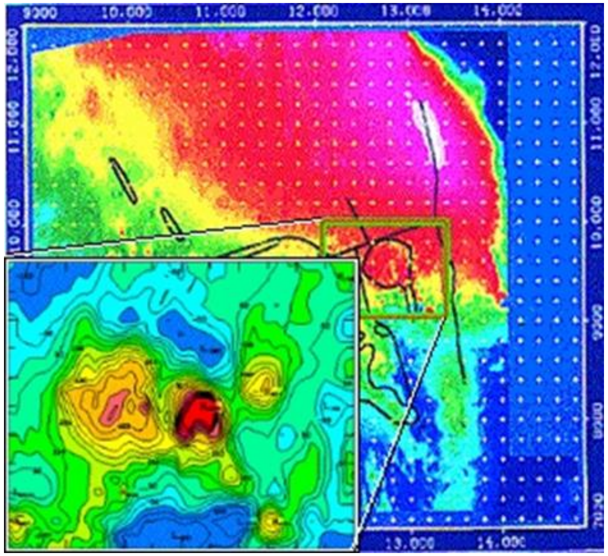
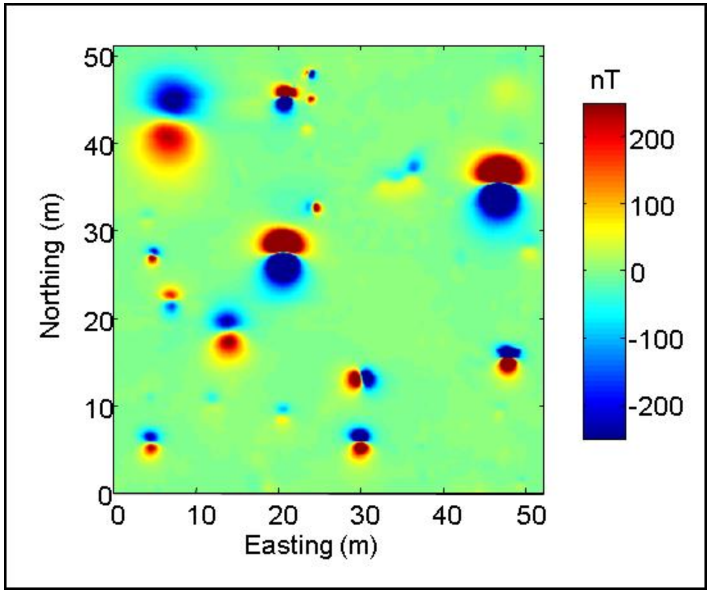
From last time

- Sensors measure total field or sometimes vector components
- Surveys on small or large scale
- Ground, air and borehole surveys
- Optimum spacing determined by size of anomalies

Large-scale data

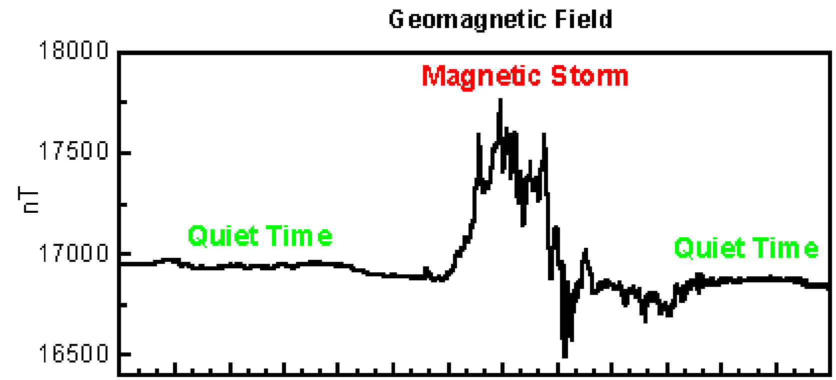


Small-scale data

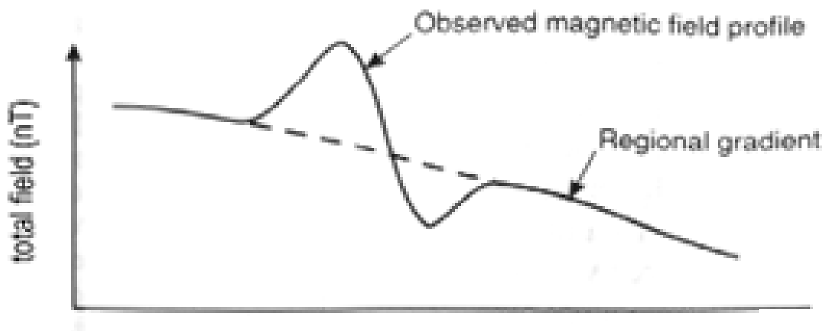


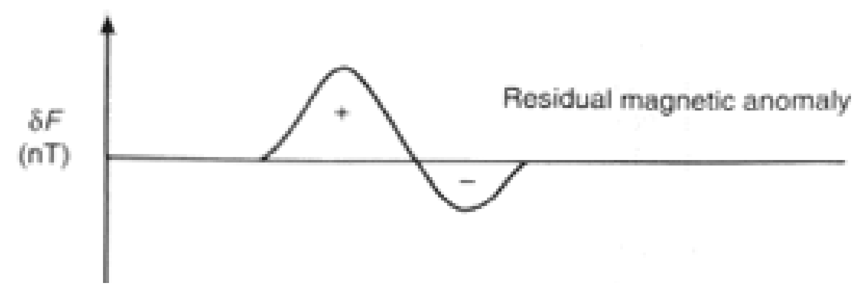
From last time

- Should remove geomagnetic field (base station)

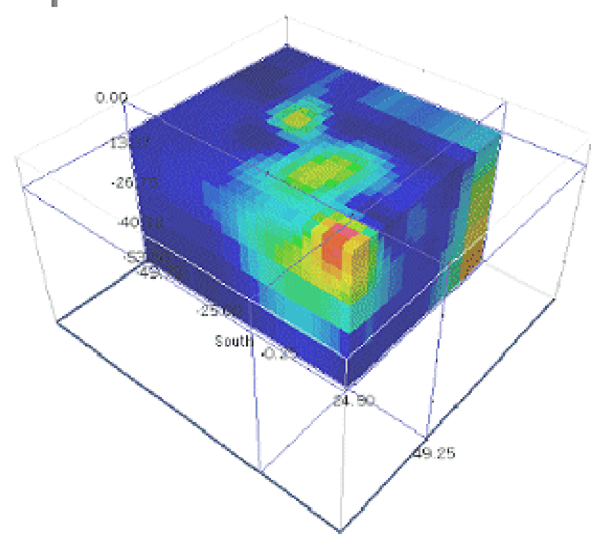


- Remove regional trends





- Other processing:
  - Upward continuation?
  - Derivatives?
  - Reduction to pole?
  - Inversion?



Today’s topics

- Interpretation
  - From data images
  - Using simple models
  - Complicated structures (Inversion)
  - Remanence

- 7-steps example

Interpretation: Data Maps

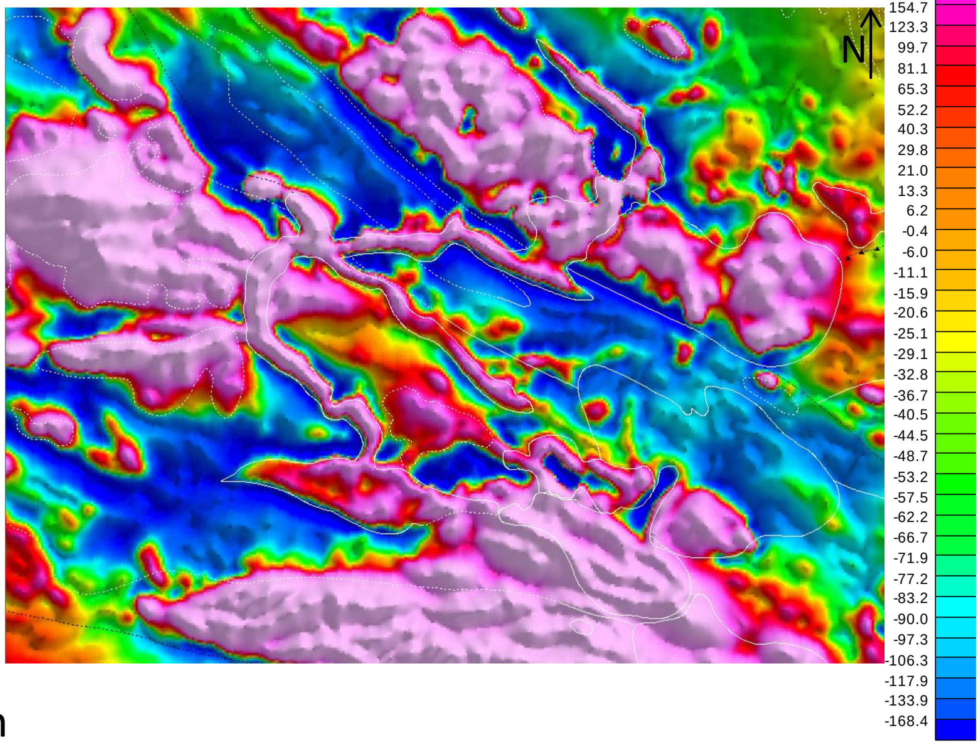
Interpretation from data images

When rock outcrops are sparse we must rely on other available techniques to denote changes in geologic units and/or structures.

Geologic boundaries

Geology map

Magnetic map

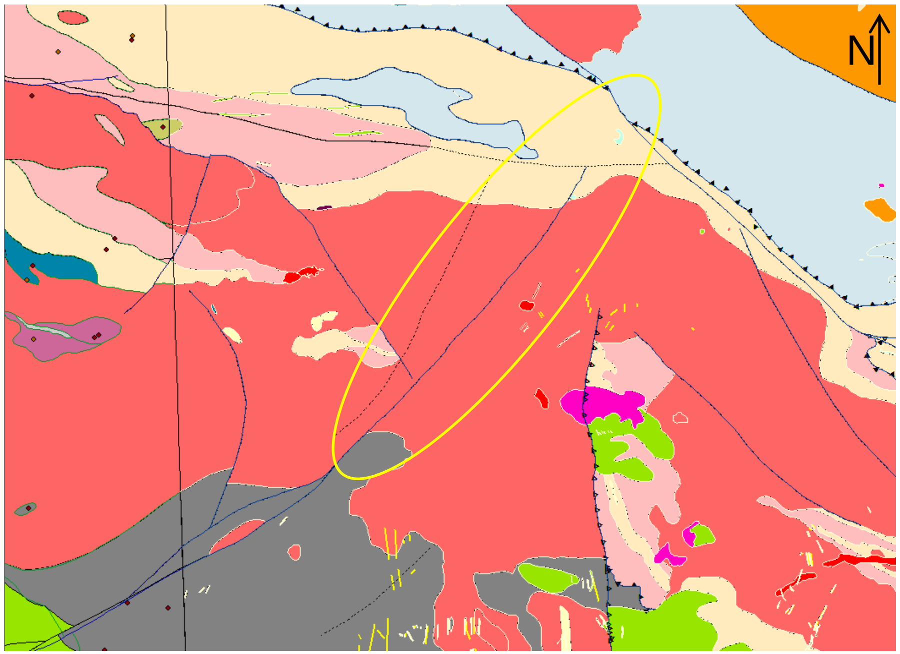


30 km

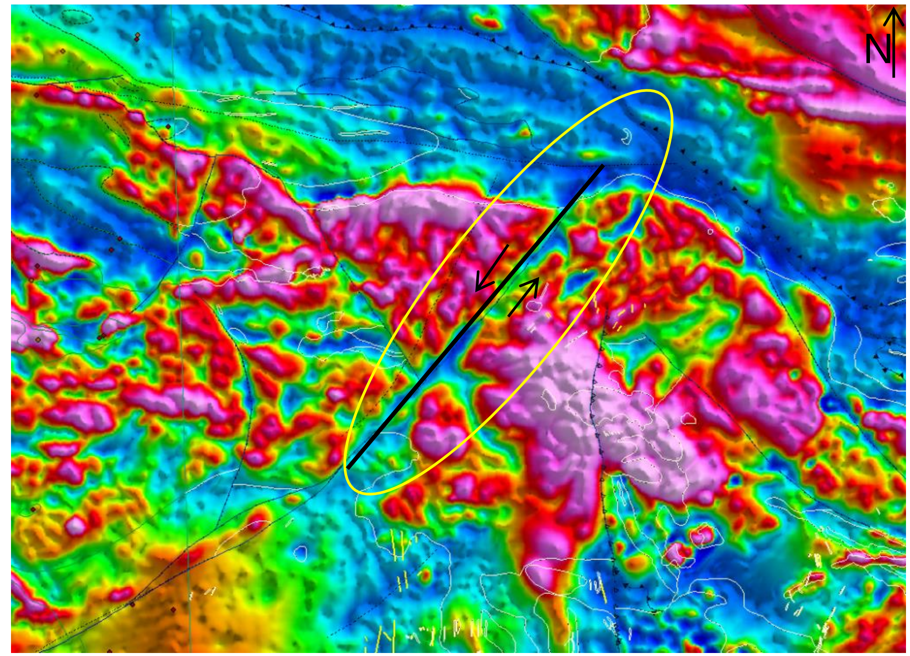
Geology contacts can be inferred from mag maps.

Identifying regional scale faults

Geology map



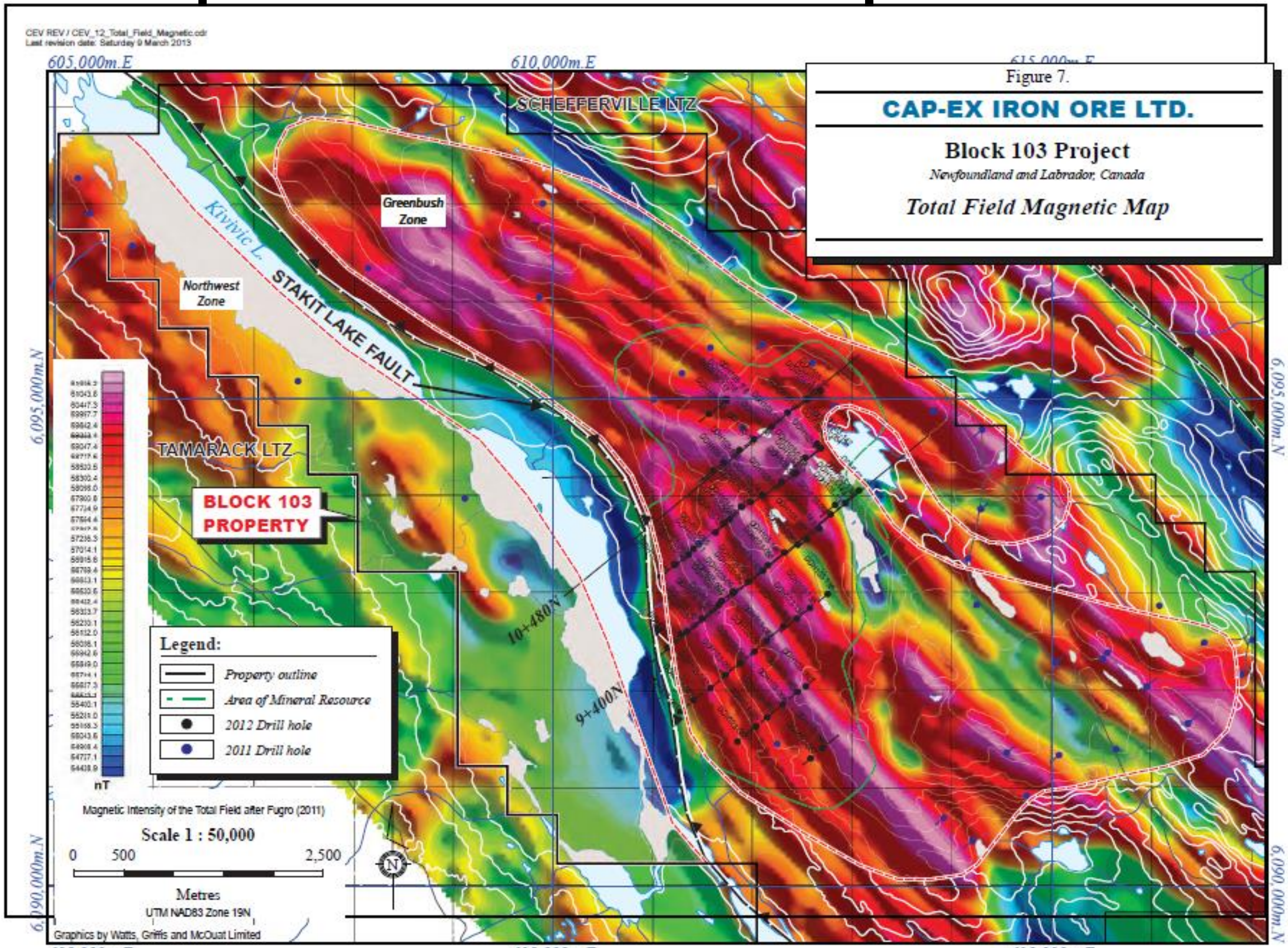
Magnetic map



55 km

Mag map highlights faults within known gold bearing plutonic body (red) in west-central Yukon.

Example - Iron ore deposit

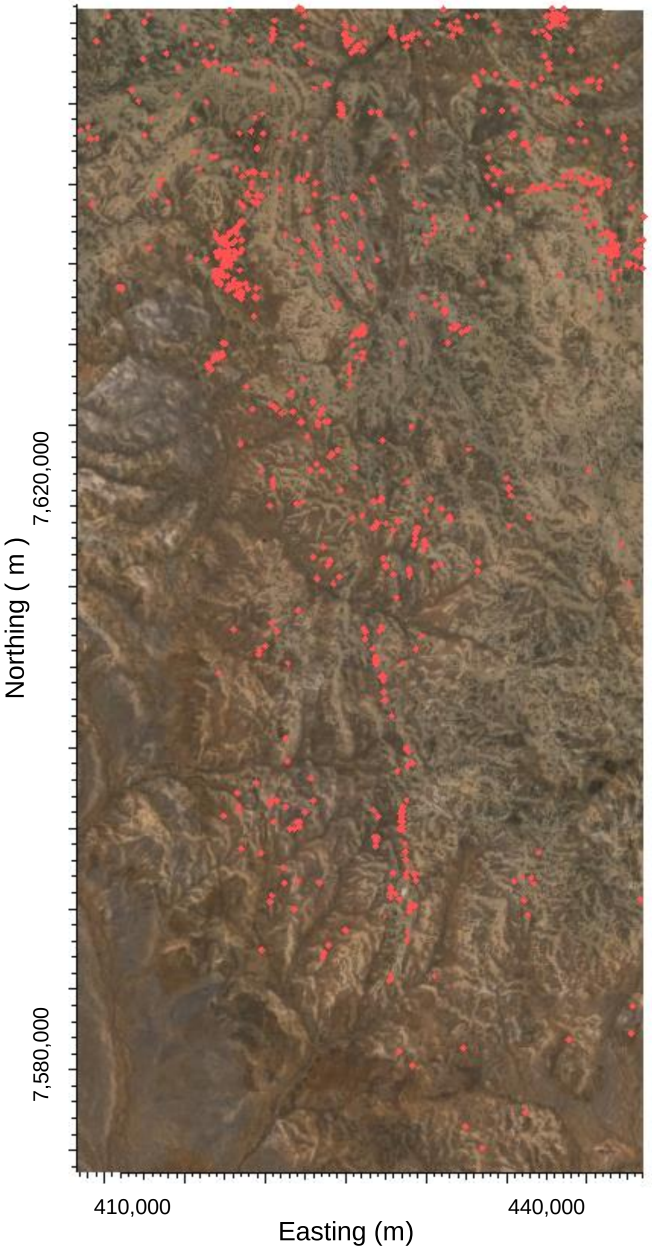


Magnetite rich rock shows as mag high anomaly

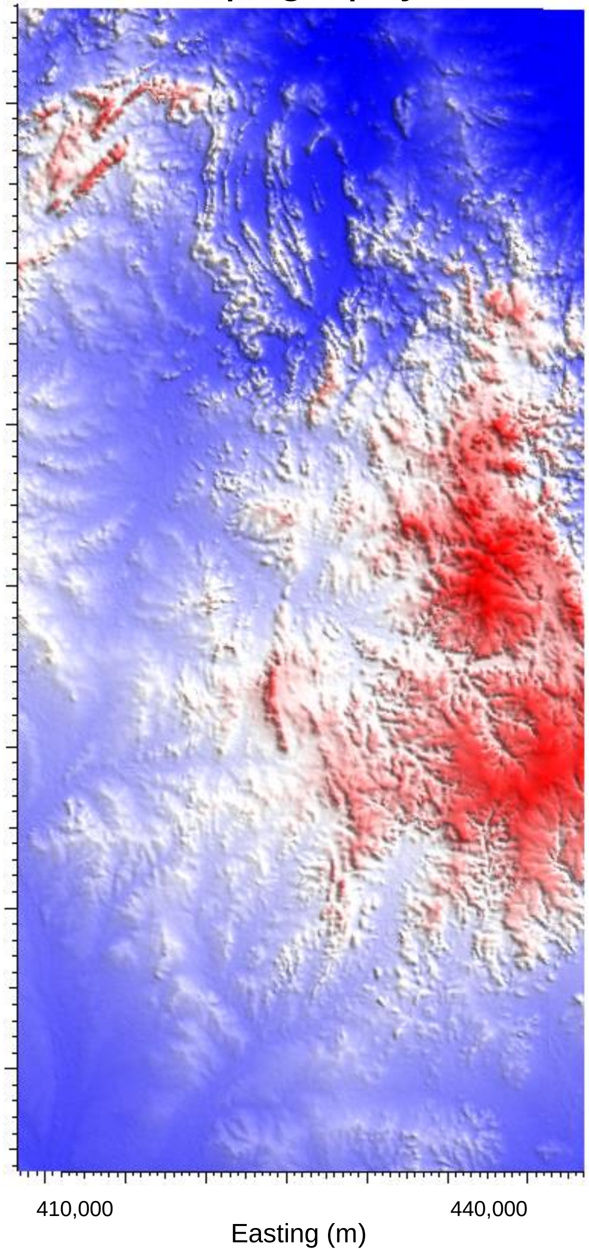
Example: Mount Dore, Queensland, Australia

Source: Queensland Government, Australia

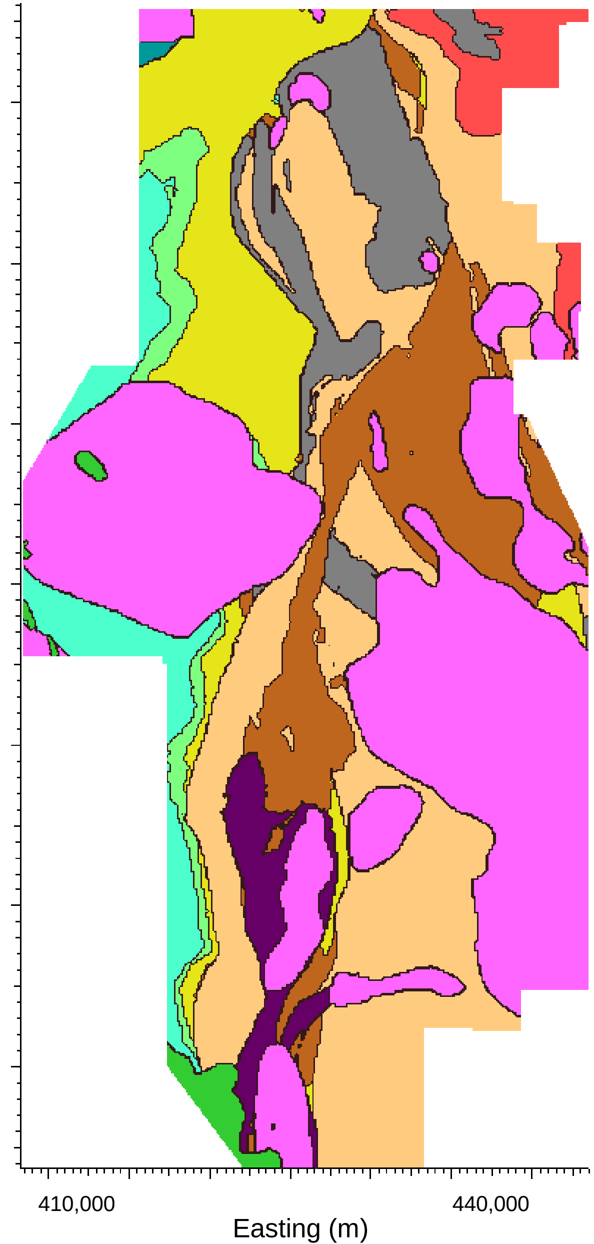
Landsat Image



Topography

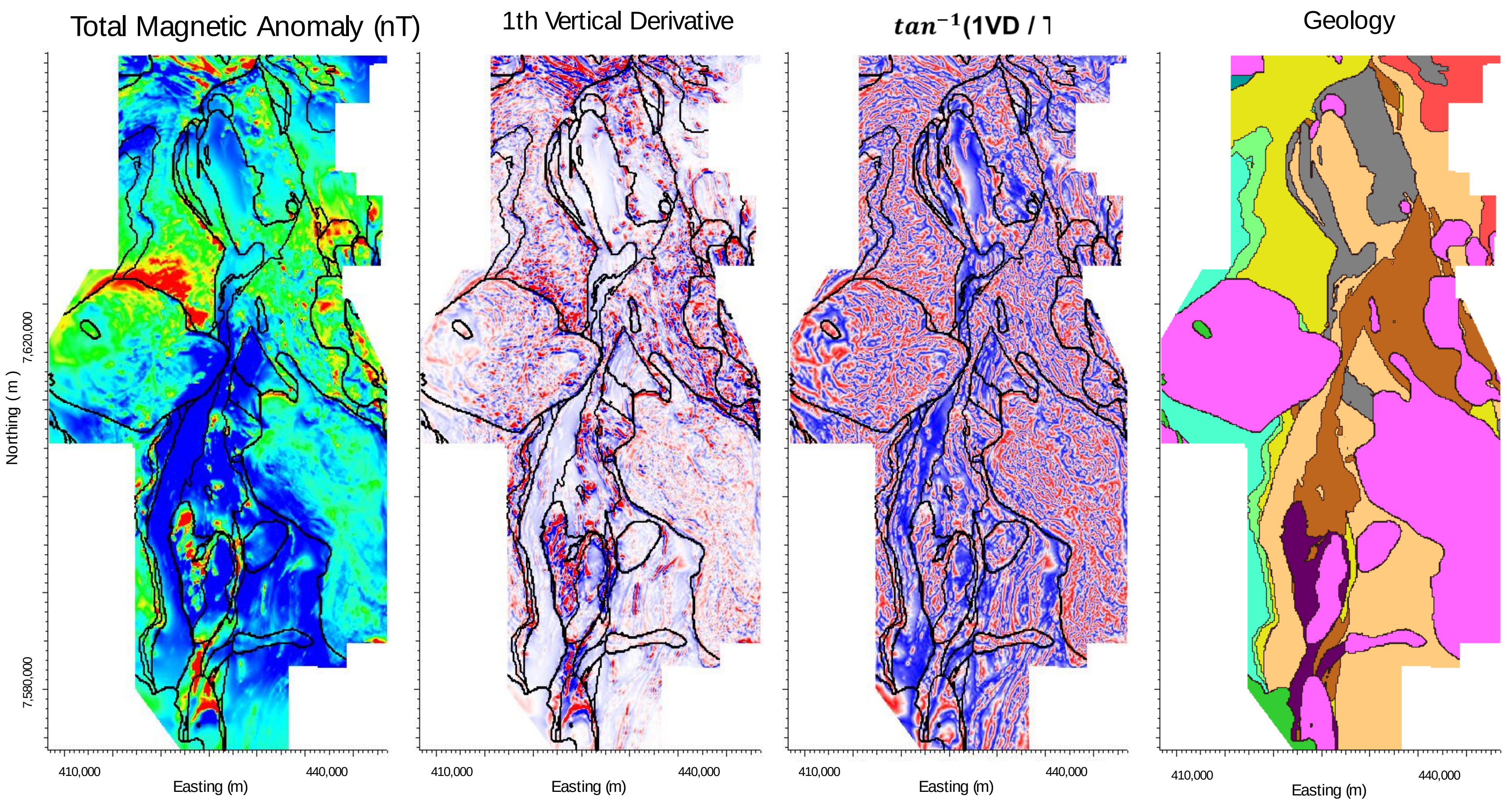


Surface Geology



Magnetic data and derivatives

Source: Queensland Government, Australia

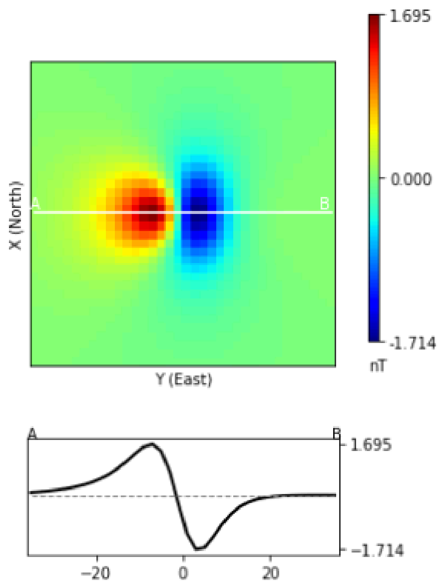


Interpretation: Simple Models

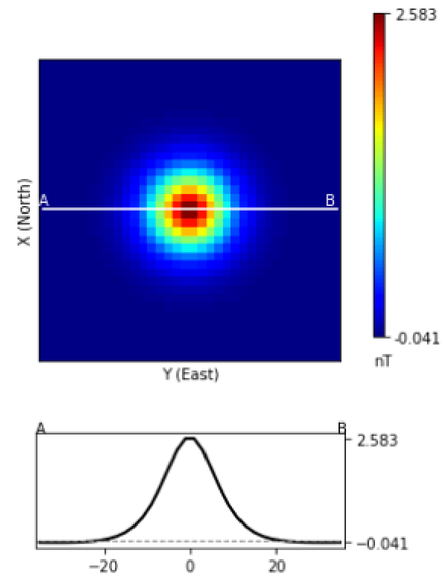
Simple Models

- Simple geometric shapes result in less-complex anomalies
- Use a simplified model to characterize anomaly and extract information
- Assume uniform magnetization

Dipole



Monopole

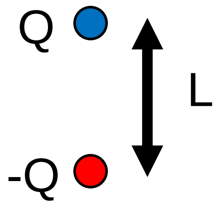


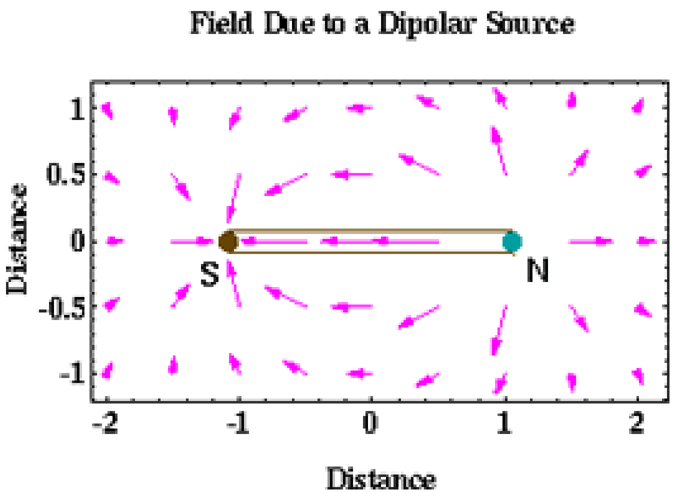
Magnetic Dipole

In nature: magnetic poles always appear in pairs with a positive and negative pole yielding a dipole.

Magnetic Dipole Moment

$$m = \frac{Q\,L}{\mu_0}$$

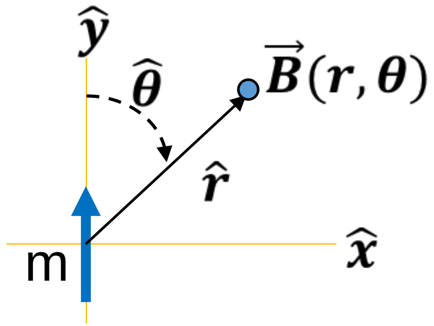




Magnetic field of dipole

$$\vec{\mathbf{B}} = \frac{\mu_0 m}{4\pi r^3}\left(2cos\theta\hat{\mathbf{r}} + sin\theta\hat{\boldsymbol{\vartheta}}\right)$$

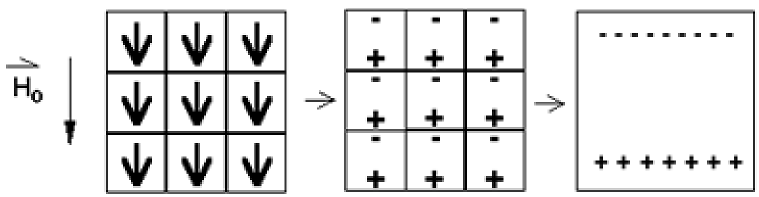
Magnetic field of dipole decays as $1/r^3$.



Objects as dipoles

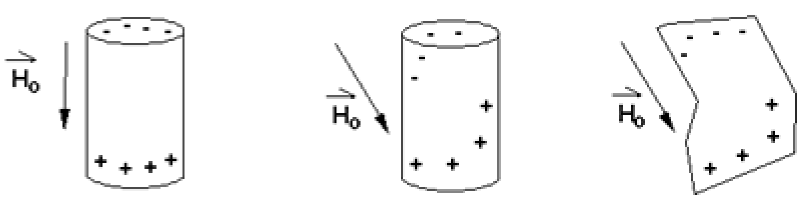
- When is a buried feature like a simple dipole?
  - When it’s diameter is much less than depth to it’s centre.
  - GPG Magnetics: Basic Principles

- Fields from some buried bodies, (cylinders, dykes) can be estimated by using charge concepts.



Charge strength, **T** = $\vec{M} \bullet \hat{n}$

- Magnetized objects have a +ve and –ve end and give rise to dipole-like fields



Magnetic Monopole

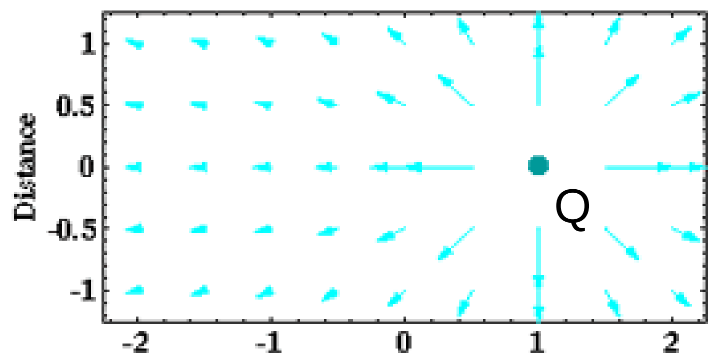
- “Magnetic charges” generate a magnetic field **B**

- Theoretical field from a +ve and –ve magnetic charge

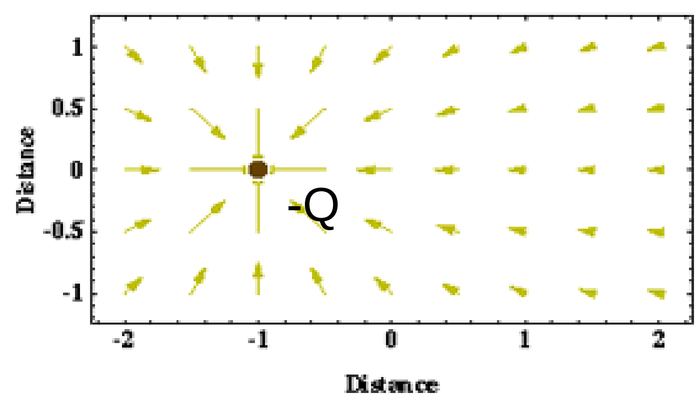
$$\mathbf{B} = \frac{\mu_0 Q}{4\pi r^2}\hat{\mathbf{r}}$$

Q: magnetic charge (monopole)

Positive Pole at (1,0)

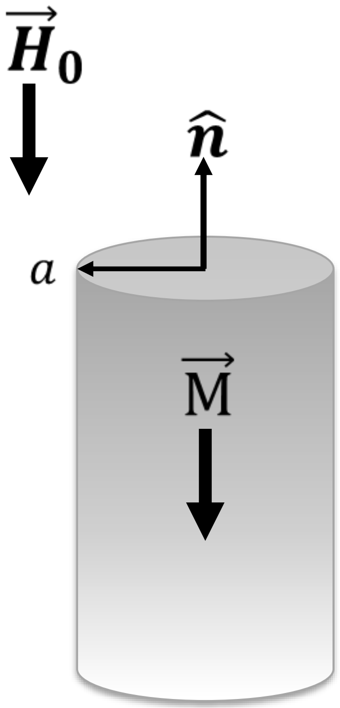


Negative Pole at (-1,0)



Vertical Pipe as a Monopole

- Fields from some buried bodies, (cylinders, dykes) can be estimated by using charge concepts.



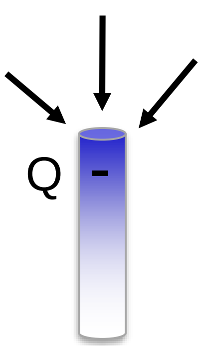
a: radius (m)
$\hat{n}$: outward normal
$\vec{H}_0$: inducing field

$\vec{\mathbf{M}} = \kappa \vec{\mathbf{H}}_0$ (Magnetization)

$\boldsymbol{\tau} = \vec{\mathbf{M}} \cdot \hat{n}$ (charge / m^2)

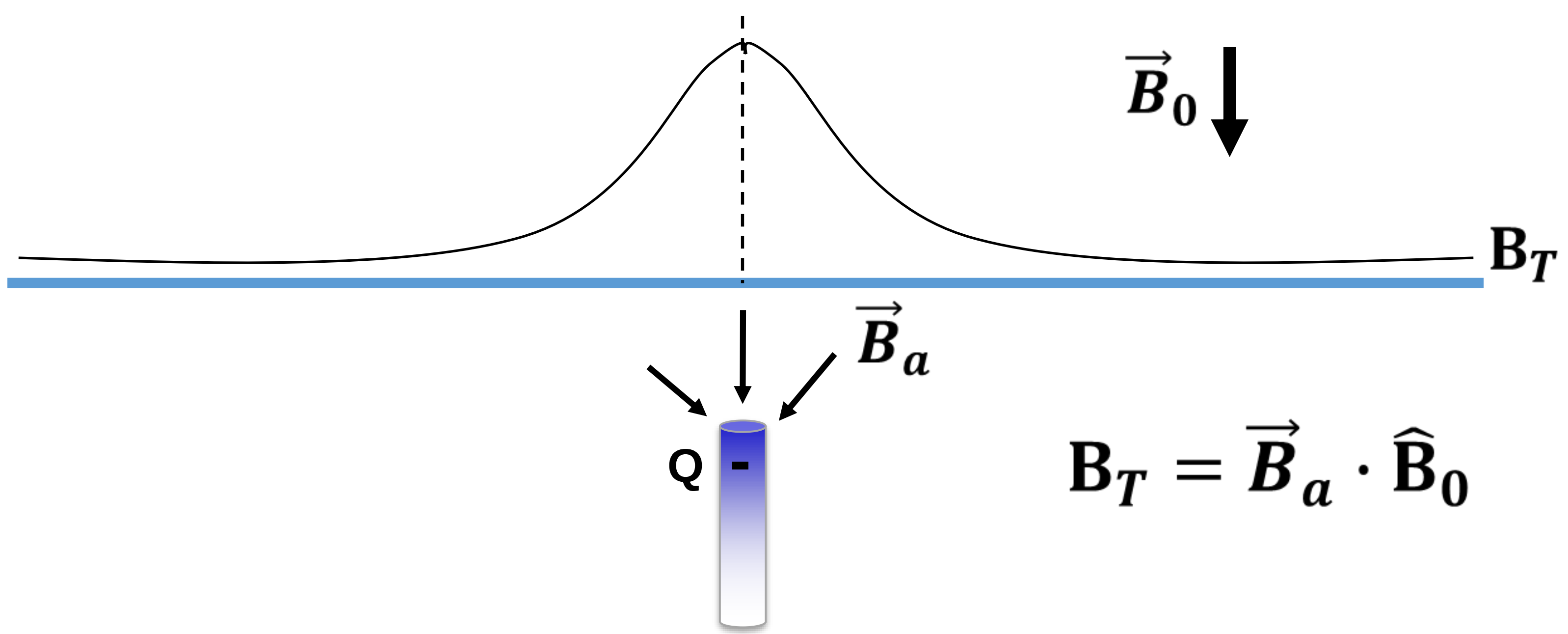
Total charge = $\boldsymbol{\tau} * \text{area}$

Q = $-\kappa \vec{\mathbf{H}}_0 \pi a^2$



Vertical Pipe as a Monopole

- Maybe data at high declination or reduction to pole was used
- Estimate Q if properties and cross-sectional area known
- Use peak anomaly to estimate depth to object $\mathbf{B} = \dfrac{\mu_0 Q}{4\pi r^2}\hat{\mathbf{r}}$



$$\mathbf{B}_T = \vec{B}_a \cdot \hat{\mathbf{B}}_0$$

Half-Width Approximation

- Maybe data at high declination or reduction to pole was used

- Use half-width to estimate depth to object

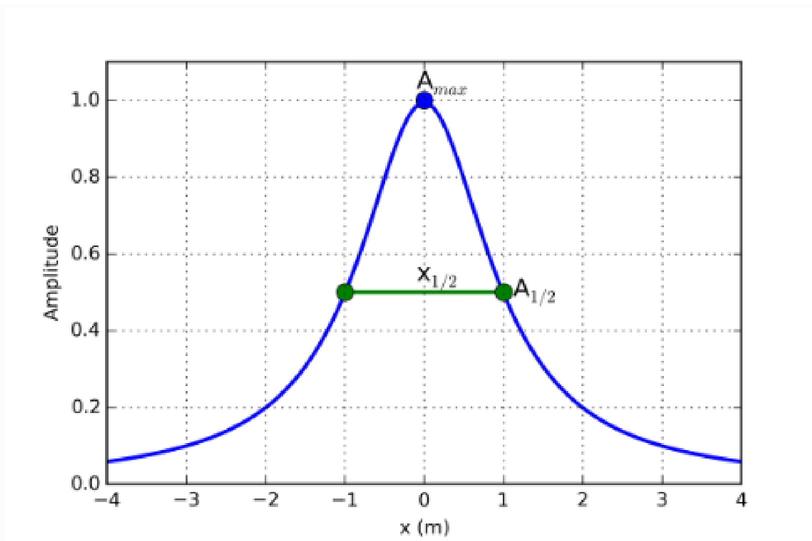
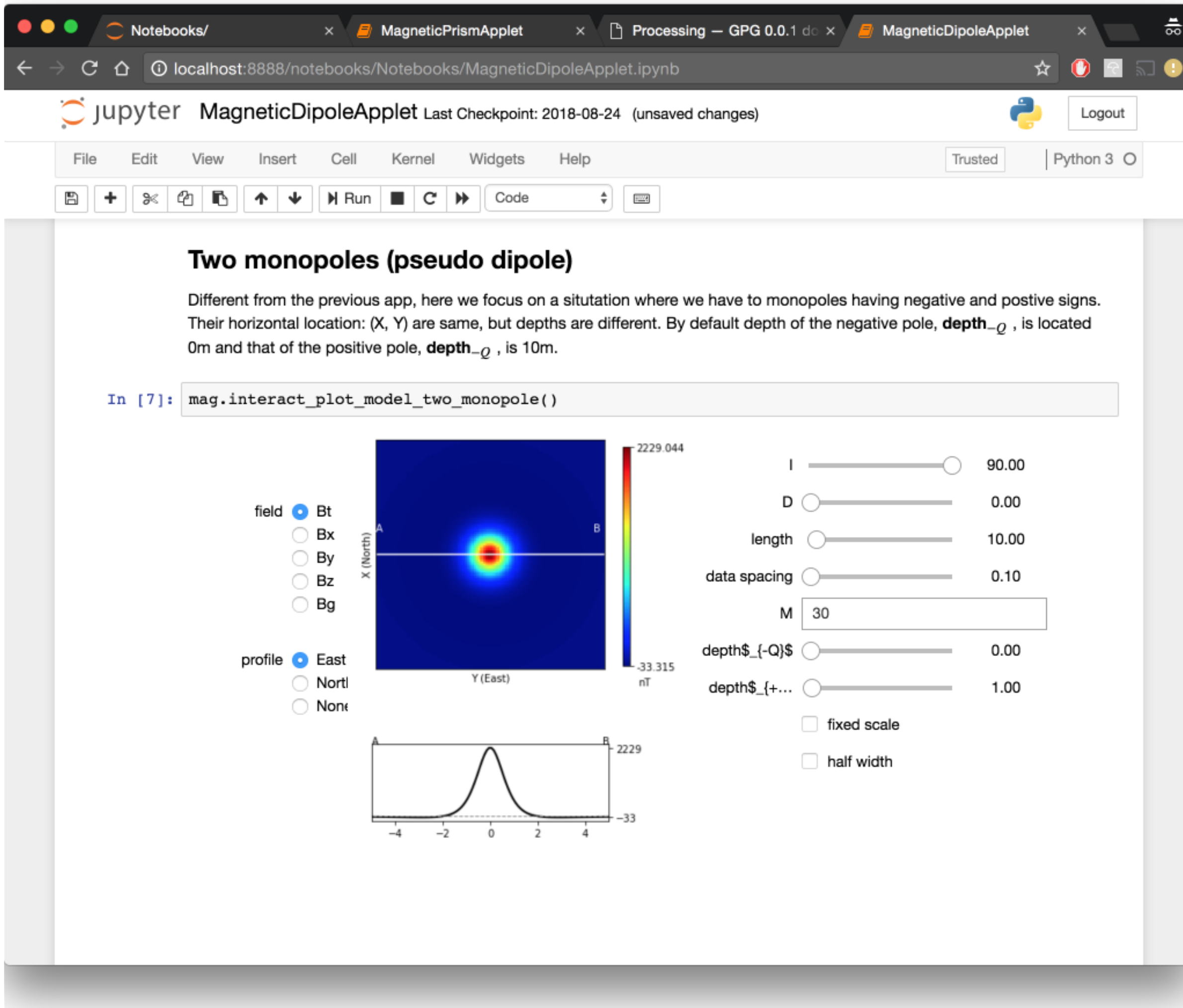


Fig. 44 Definition of half-width.

For a **dipole** target, the depth of burial(to the top of the target), z, is approximately equal to the half-width

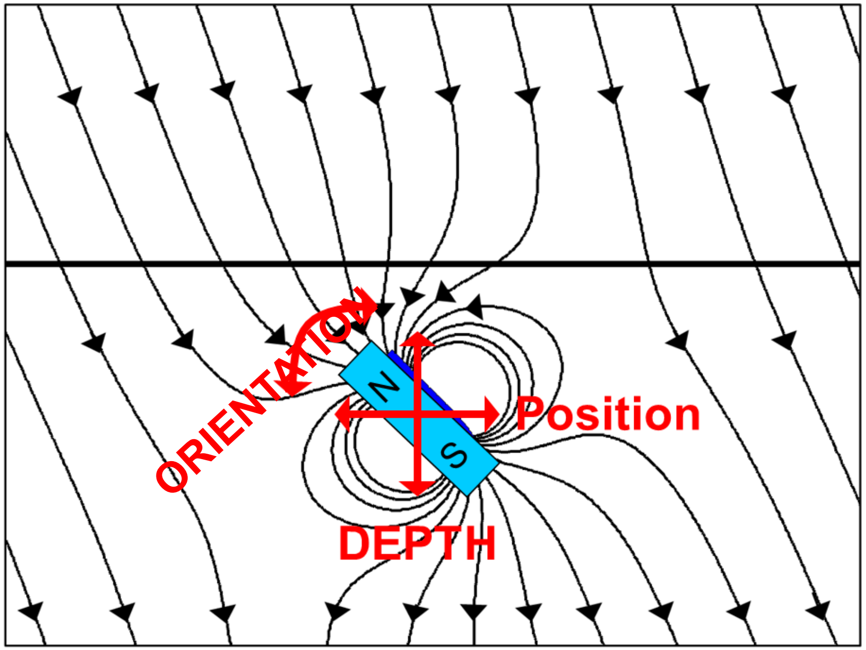
$$z \sim x_{1/2}$$

Fit Anomaly with Modeling



Objects as Dipoles: UXO Example

- We model the response as a dipole (equivalent to a bar-magnet):
  - Location
  - Orientation
  - Magnetization



Parameter extraction

- Six parameters ([x, y, z, m1, m2, m3])

- Inversion or “parameter extraction” is used to estimate the parameters of an underlying model

Model Parameters: m

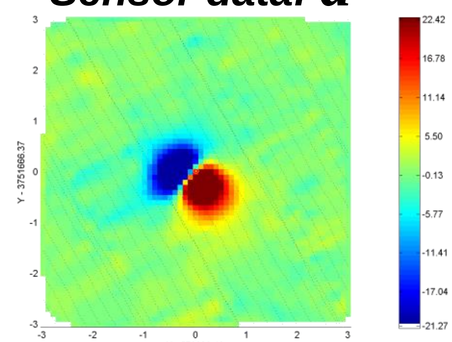
Forward Operator

$$d = g\,[m]$$

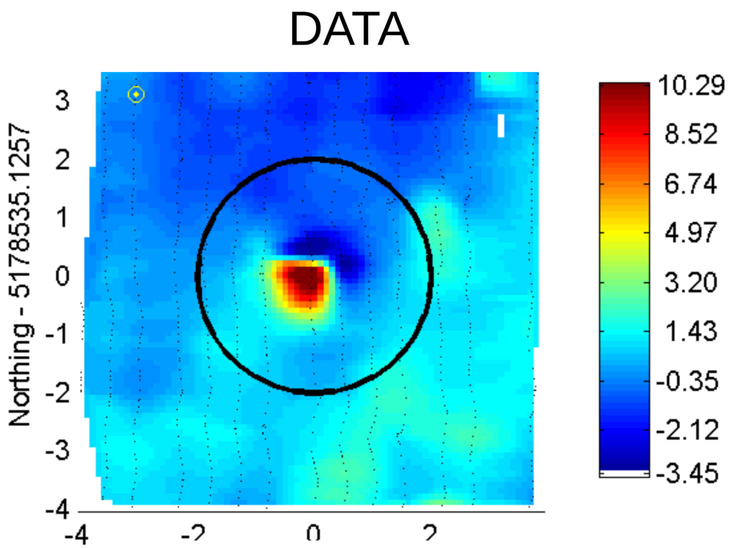
$$m = g^{-1}\,[d\,]$$

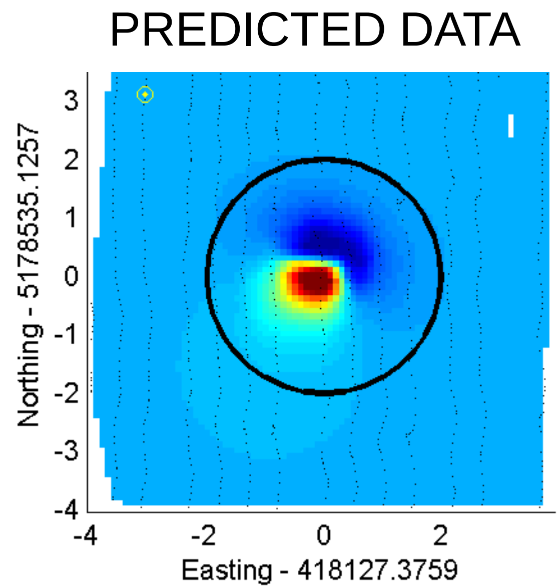
Inverse Operator

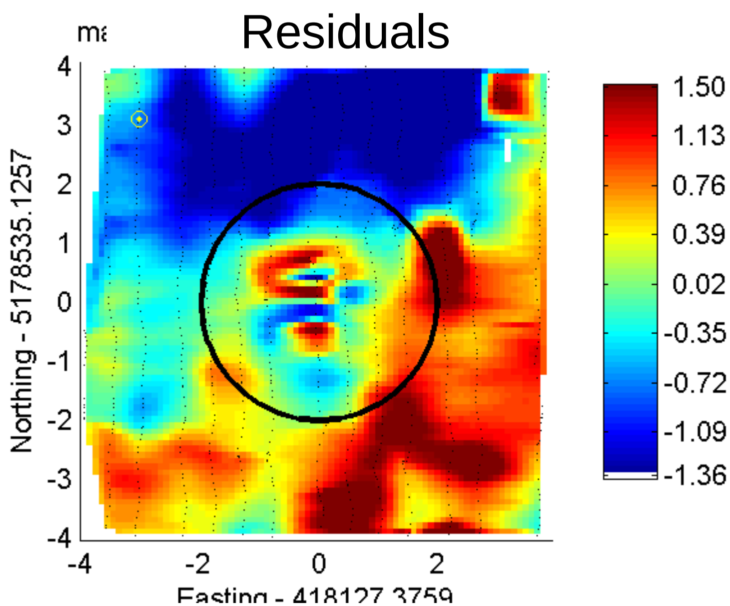
Sensor data: d



Parameter extraction







Easting = -0.13 m

Northing = 0.16 m

Depth = 0.26 m

Moment = 0.0226 Am^2

Azimuth = 37°

Dip = 28.8°

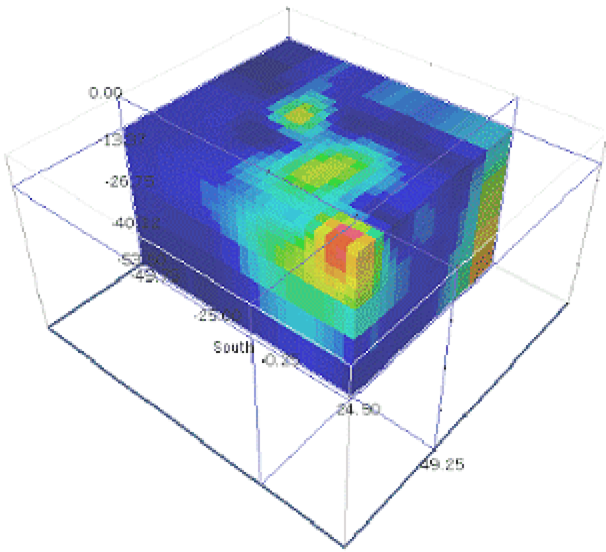
Parameters of interest

Fit quality = 0.95

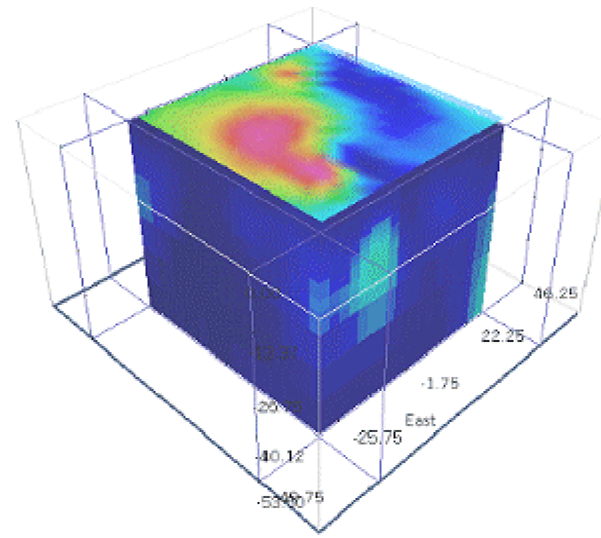
Interpretation: Using Inversion

Earth can be complicated

A complicated earth model

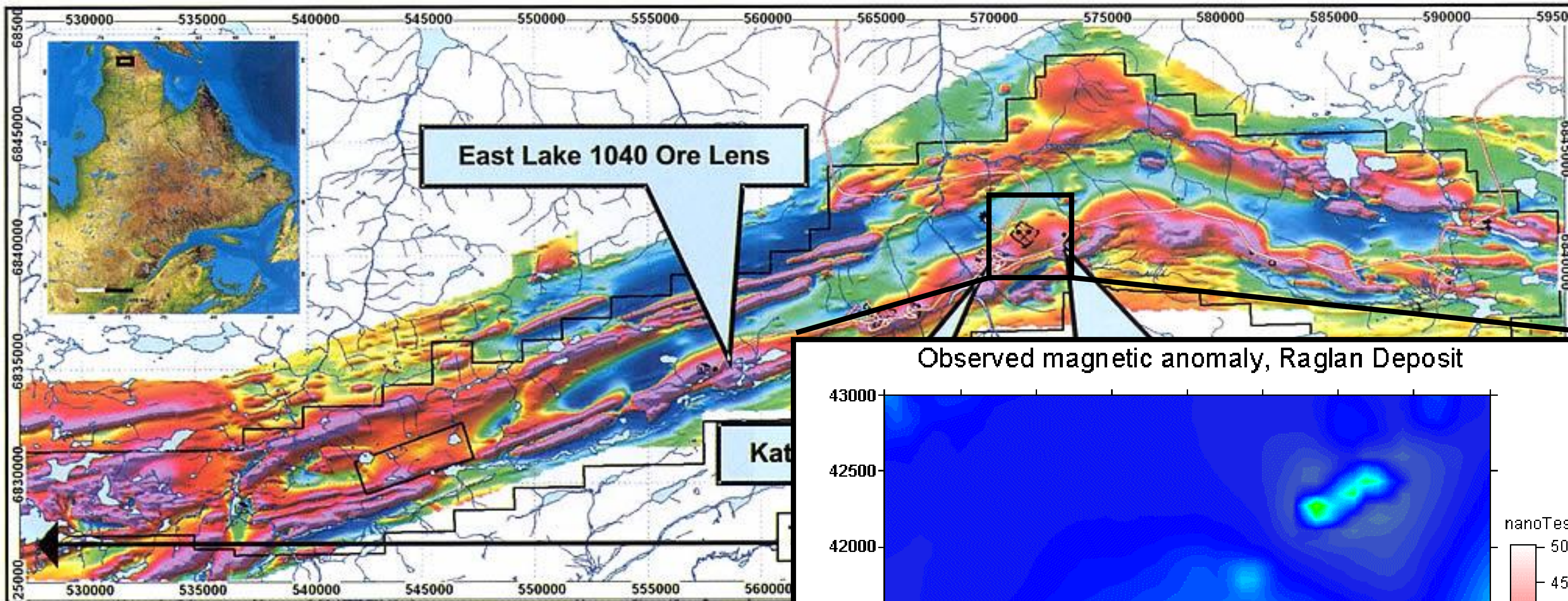


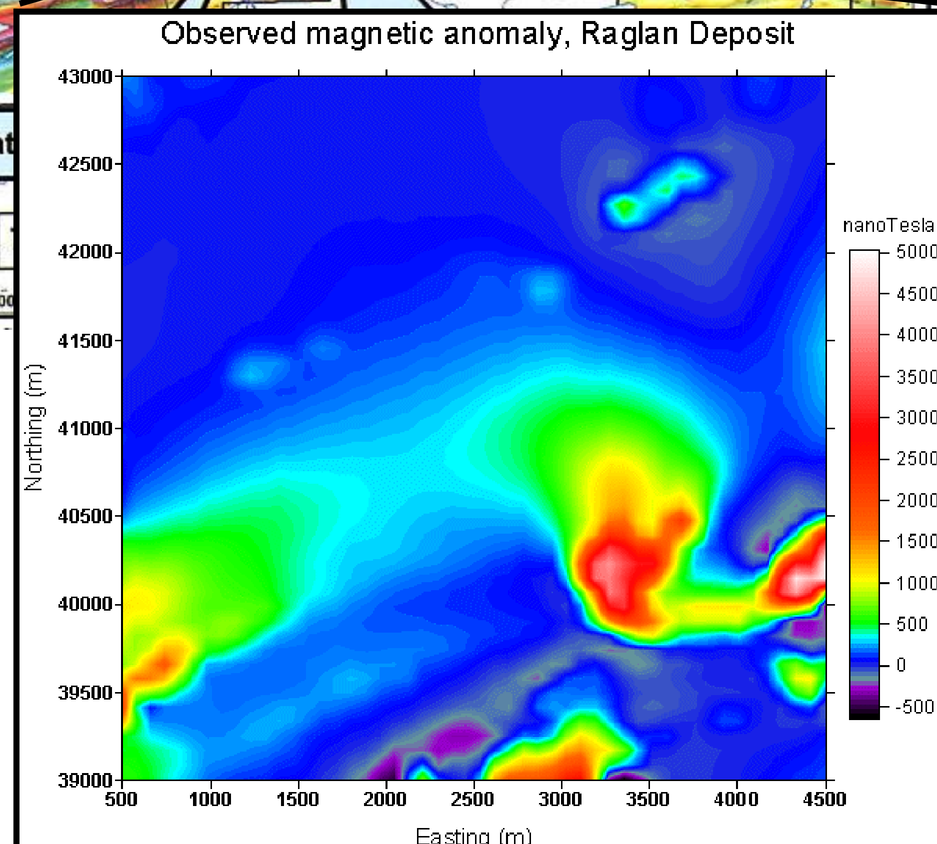
Magnetic data for a complicated earth model.



To interpret field data from a complicated earth we need to have formal inversion procedures that recognize non-uniqueness. Think about finding the causative magnetization of each prism.

Example: Raglan aeromagnetic data





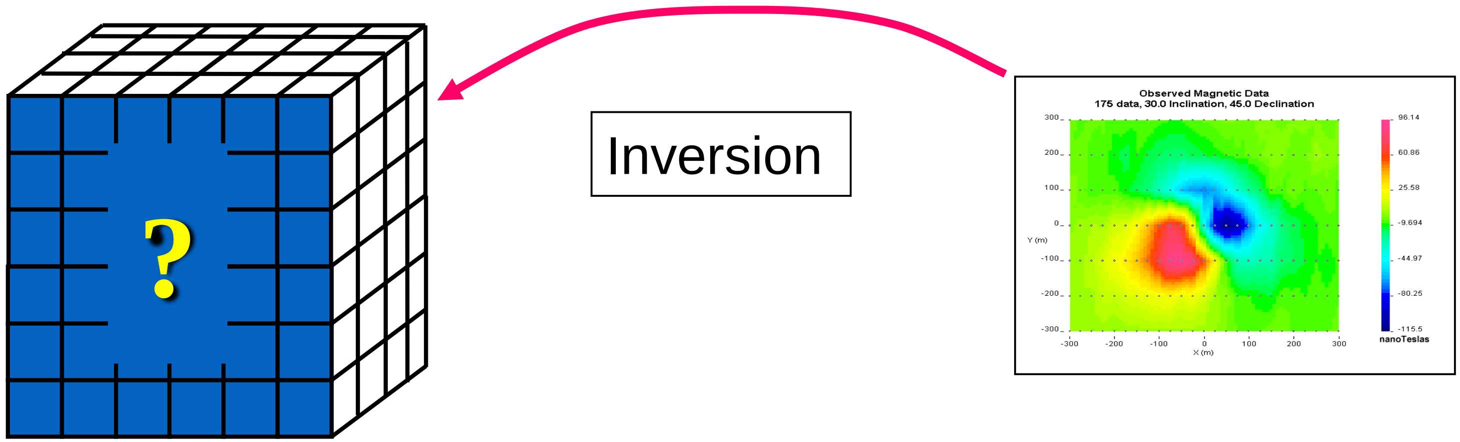
Select a region of interest.

Keep data set size within reason.

Digitized the Earth – up to 10^6 cells.

Inversion

- Finding an Earth model that:
  - Explains the data
  - Is geologically reasonable

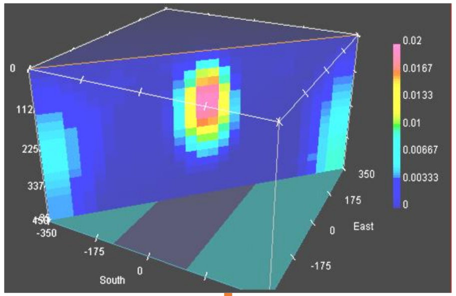


Divide the earth into many cells of constant but unknown susceptibility

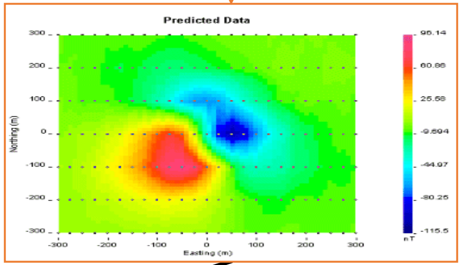
Solve the large inverse problem to estimate the value of each cell

Misfit: Comparing predictions to measurements

Once a model is estimated …



Calculate data caused by that model.



Compare predictions to these measurements.

Is comparison within errors?

Compare

YES

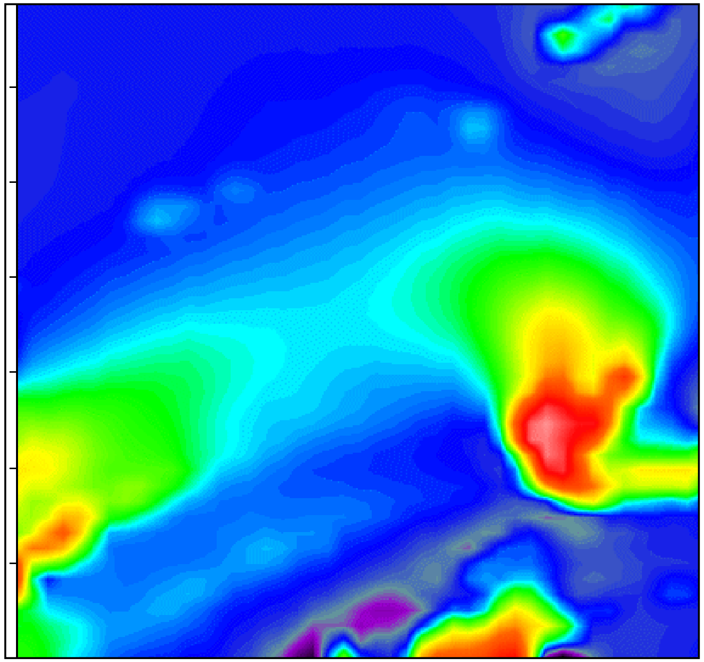
NO

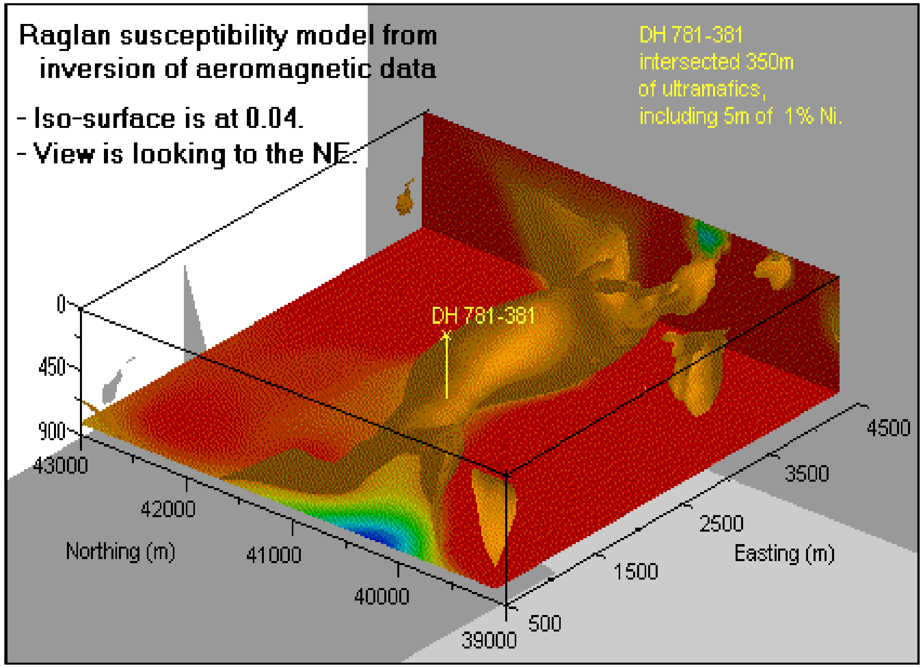
Modify model and try again

Proceed to check for acceptibility

Raglan aeromagnetic data

- Estimate a model for the distribution of subsurface magnetic material.
- Model will be “smooth”, and close to pre-defined reference.
- Display result as cross sections and as isosurfaces.





- Are “sills” connected at depth? Inversion result supports this idea.
- It helped justify a 1050m drill hole.
- 330m of peridotite intersected at 650m 10m were ore grade.
- Image shows all material which has k > 0.04 SI.

Interpretation: Remanence

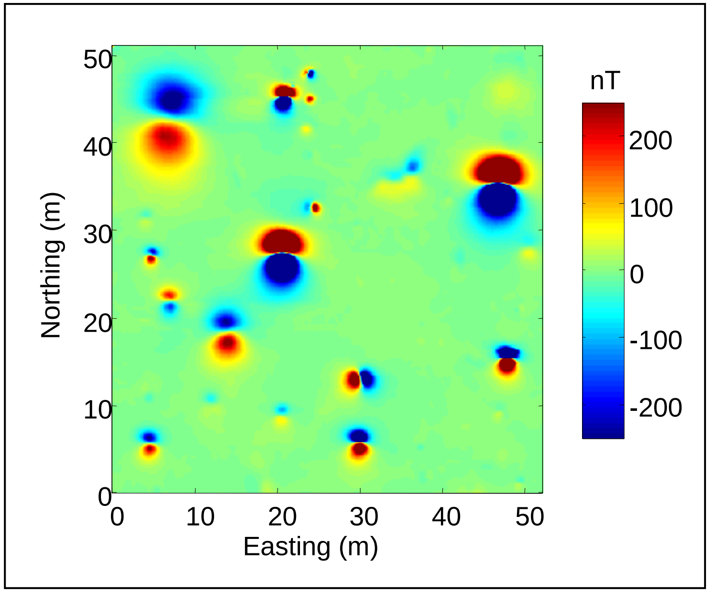
Remanent Magnetization:

Causes problems with interpretation when:

- Our model only assumes induced magnetization
- Remanence changes shape, location and amplitude of anomalies

Recognizing Remanence

- Are there lithologies/objects known to exhibit remanence? (magnetite, rebar, steel etc…)
- Are dipole anomalies oriented same direction?



Dipole anomalies in different orientations due to remanent magnetization in UXO casings.

Recap

- Interpretation with geological mapping:
  - Correlate magnetic patterns to geology

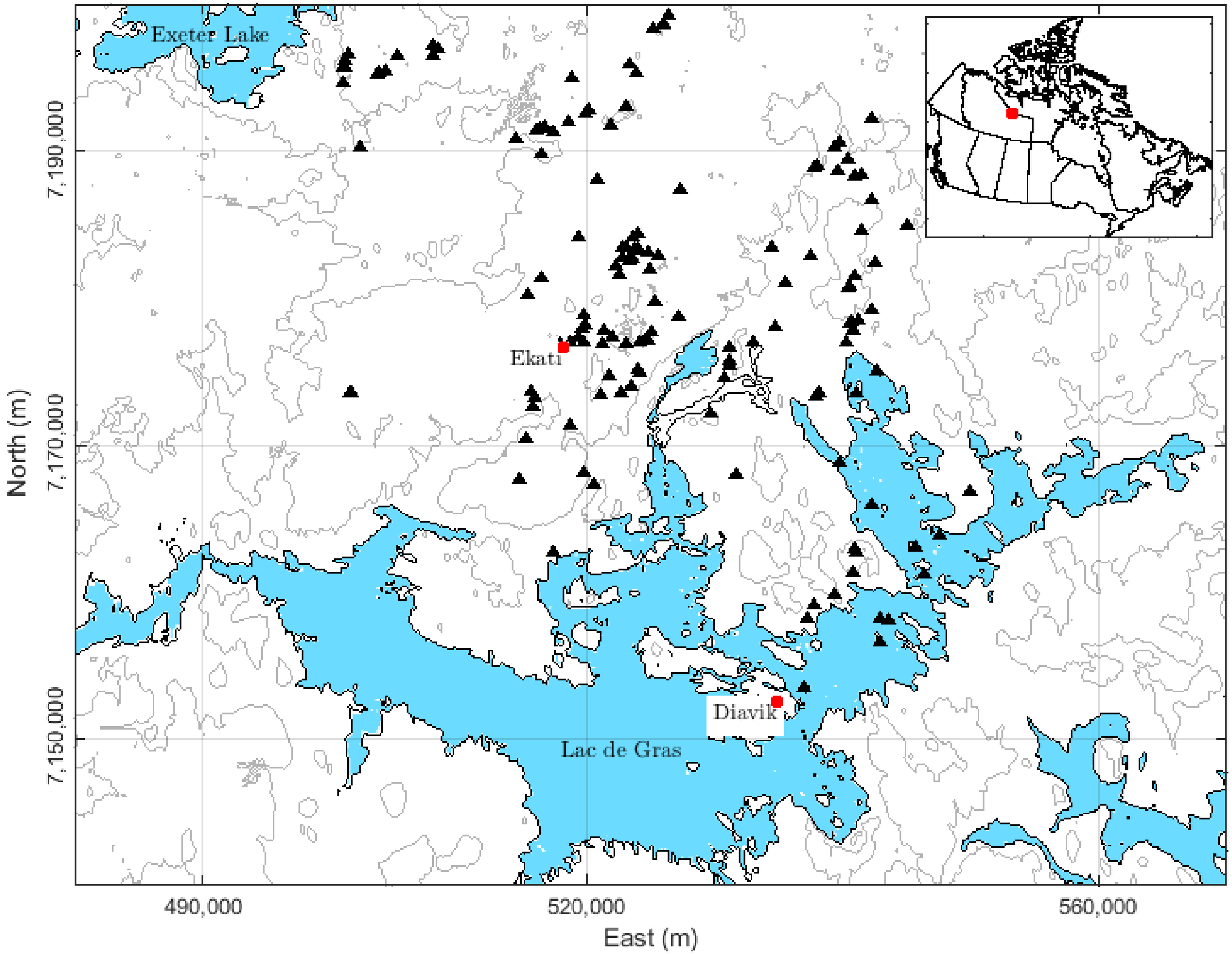
- Interpretation with simple models
  - Monopole or dipole
  - Use model to infer things about target

- Interpretation with forward modelling
  - “Guess” geology
  - Calculate result - Compare to data
  - Iterate.

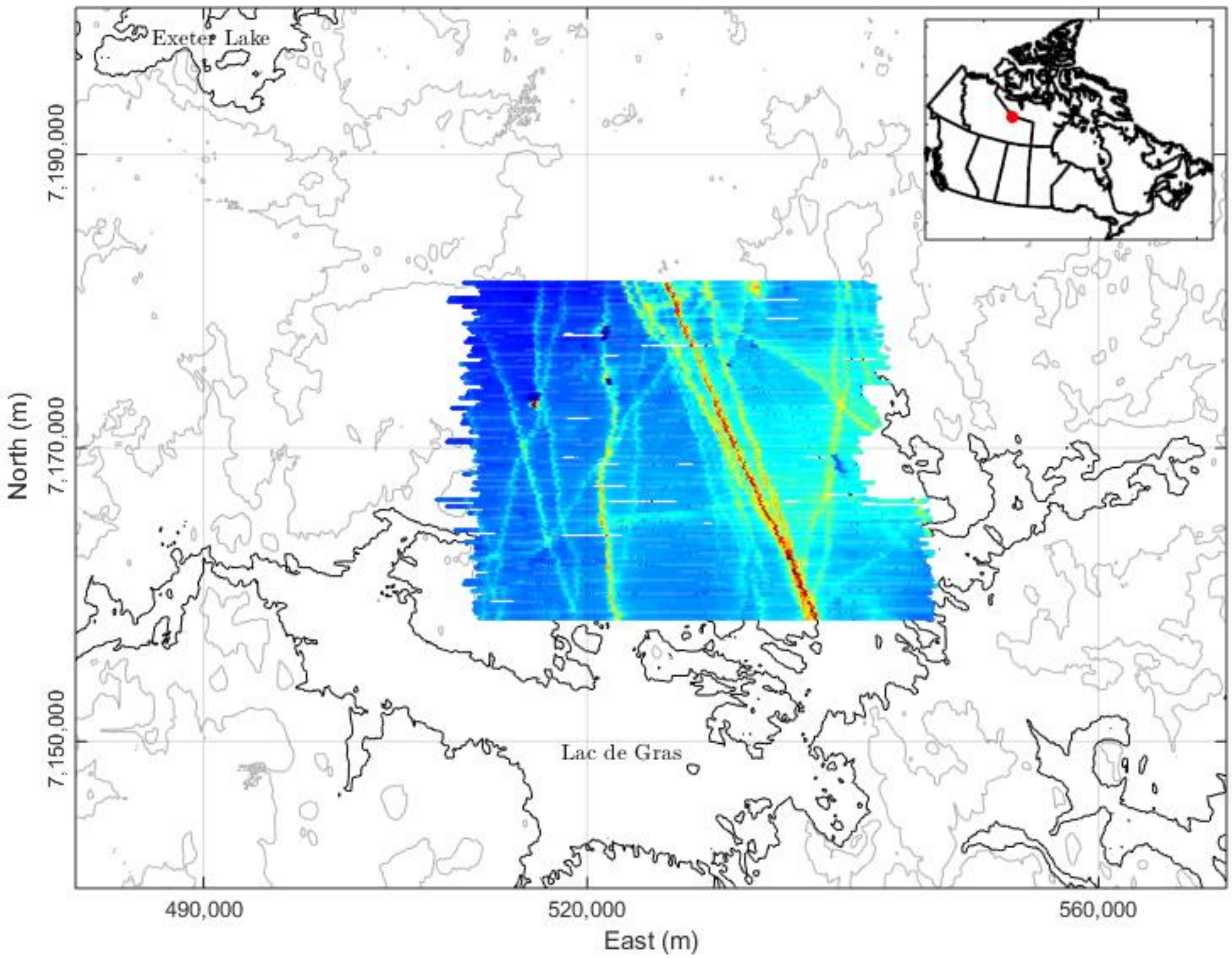
- Interpretation with inversion
  - Recover susceptibility or other model

Examples

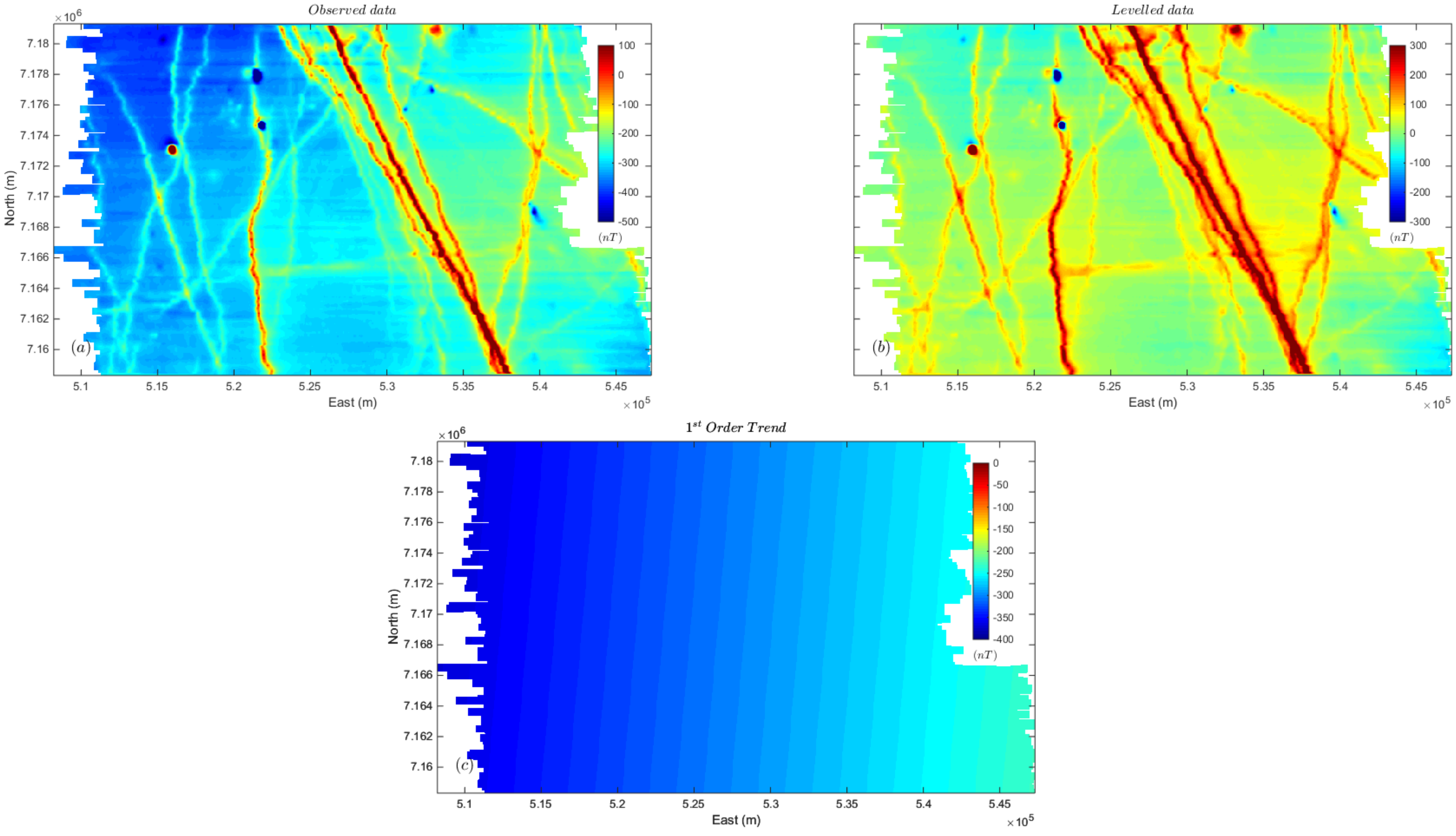
Ekati Property, Northwest Territories



Ekati Property: Airborne TMI Data

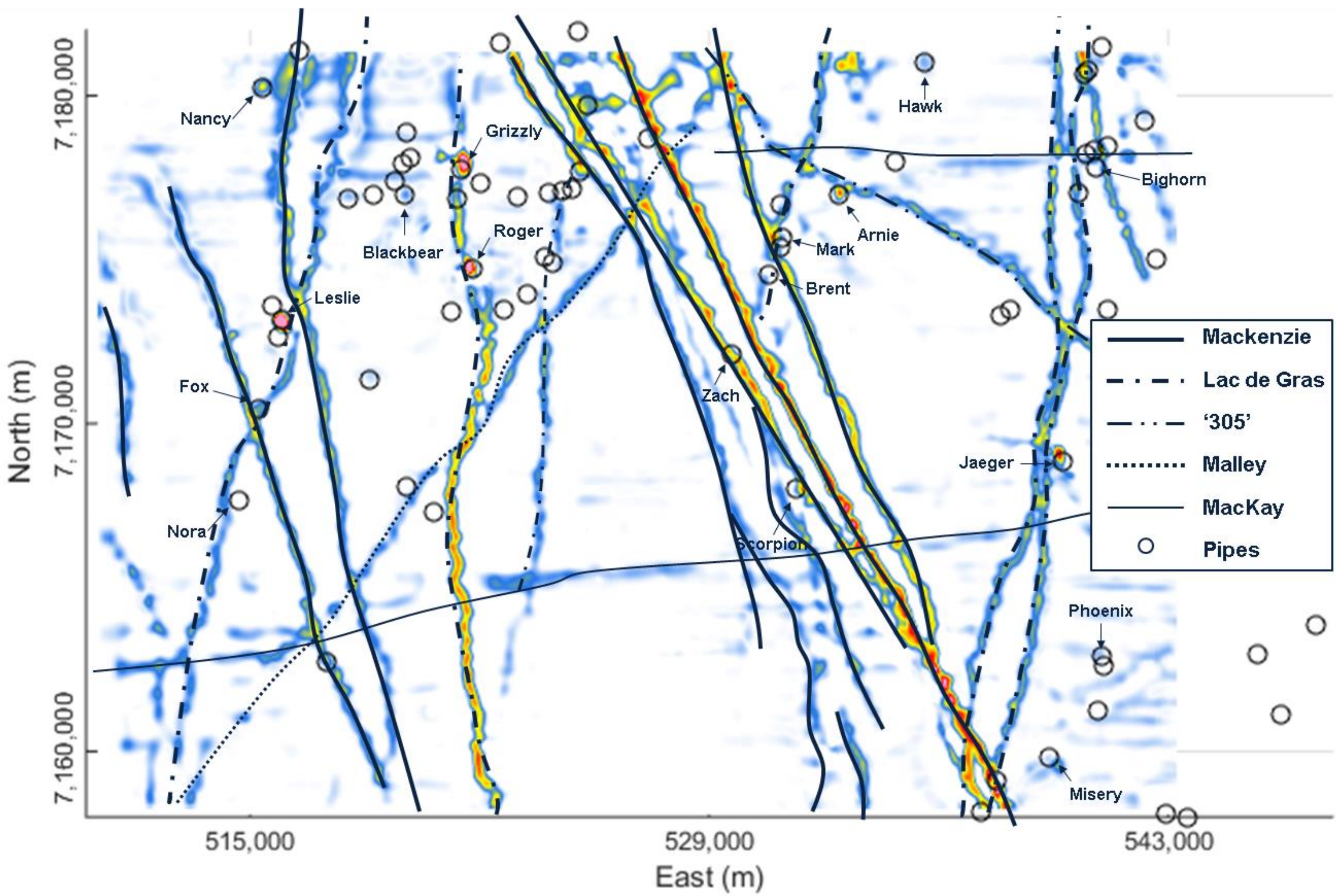


Ekati Property: Regional Removal

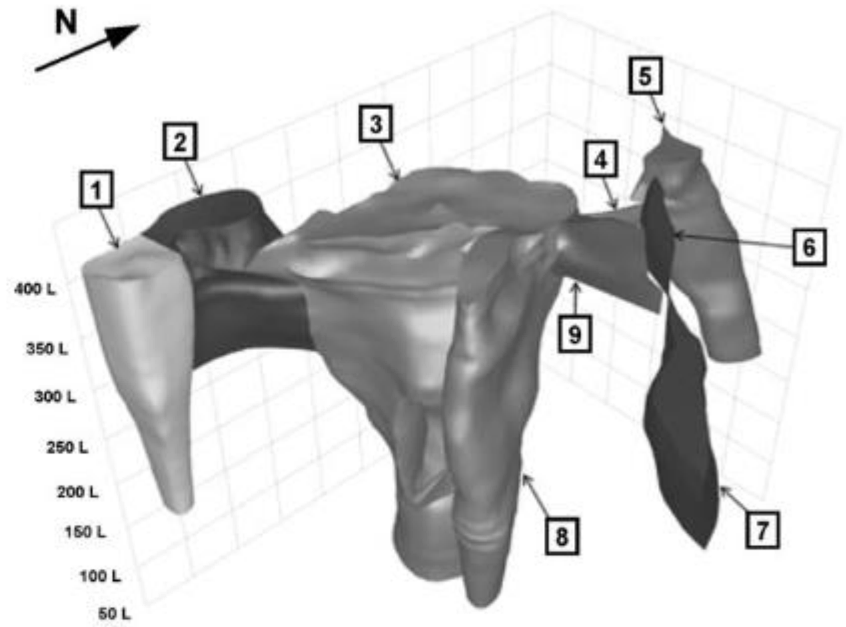


Ekati Property: Data Matches Contacts

- Data lies over known contacts
- Data infers previously unknown contacts



Example: Misery pipe



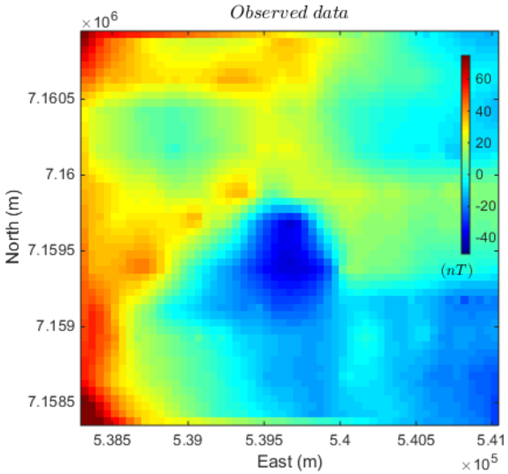
- Property owned by BHP Billiton
- Pre-stripping under way
- Production expected to start in 2016

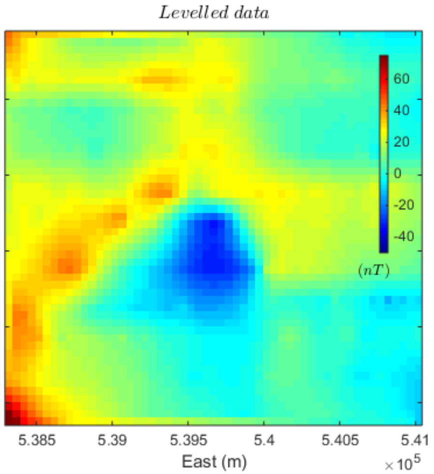
Fig. 4. Three-dimensional model of the Misery kimberlite complex. The Misery Main (3), Misery South (1), Misery Southwest Extension (2) and Misery Northeast (5) pipes are occupied by volcaniclastic kimberlite, whereas the Misery East pipe (7), East and Northeast extensions (9, 4) and Misery Mid-east dyke (6) are hypabyssal intrusions of magmatic kimberlite. Misery Northeast extension (8) contains both magmatic kimberlite and possible tuffistic kimberlite (TK).

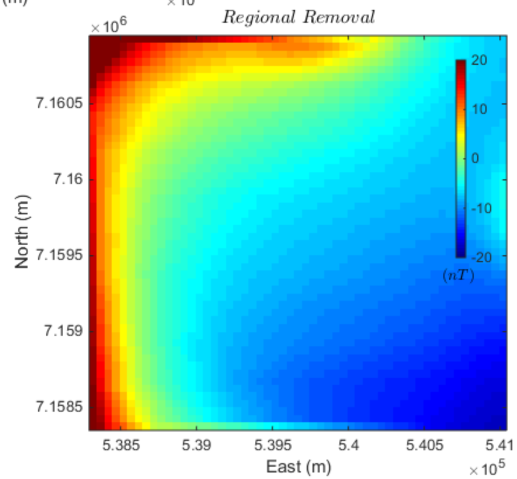
Borrowed from Nowicki et al. (2004)

Misery pipe

- Local anomaly showing reversely magnetized body
  → Remanence
- Removal of the regional field to enhance the target

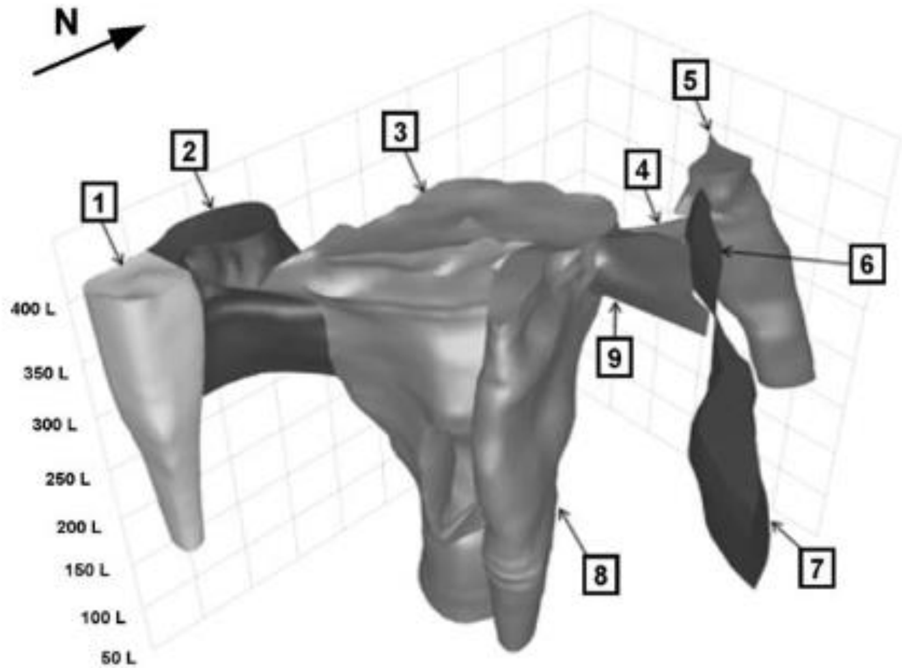




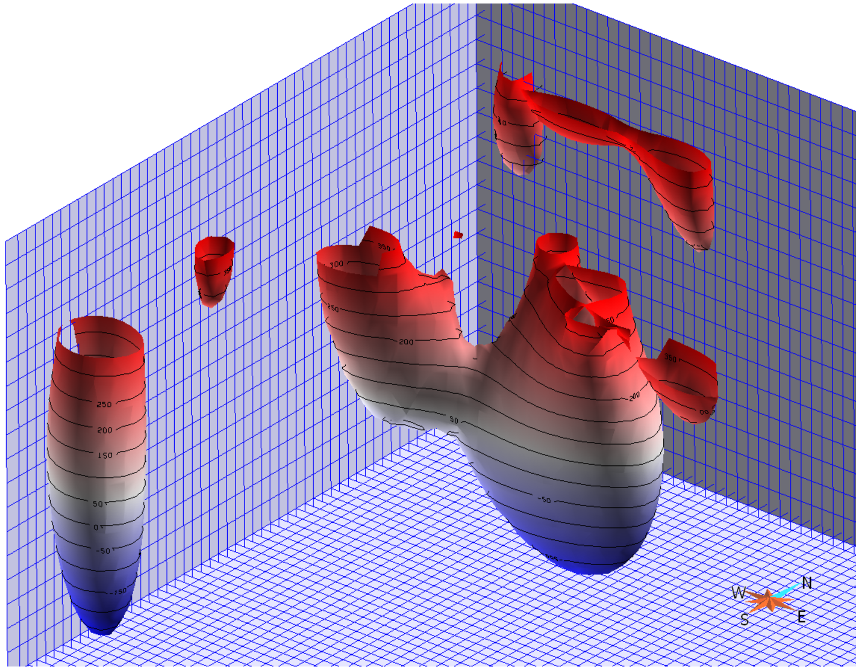


Misery pipe

Geology from drilling



Inverted magnetization amplitude model



Borrowed from Nowicki et al. (2004)

The End of Magnetics

Unit Activities

- **Labs: (Magnetics I)**
  - Monday, September 16th
  - Tuesday, September 17th
- **Labs: (Magnetics II)**
  - Monday, September 23rd
  - Tuesday, September 24th
- **TBL:**
  - Monday, September 23rd
- **Quiz:**
  - Monday, September 23rd