SUSTech Southern University of Science and Technology
南方科技大学 SOUTHERN UNIVERSITY OF SCIENCE AND TECHNOLOGY
地球与空间科学系 DEPARTMENT OF EARTH AND SPACE SCIENCES

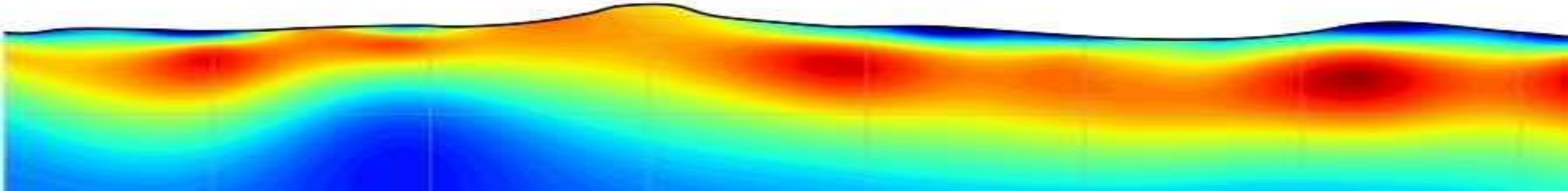
ESS302 Applied Geophysics II

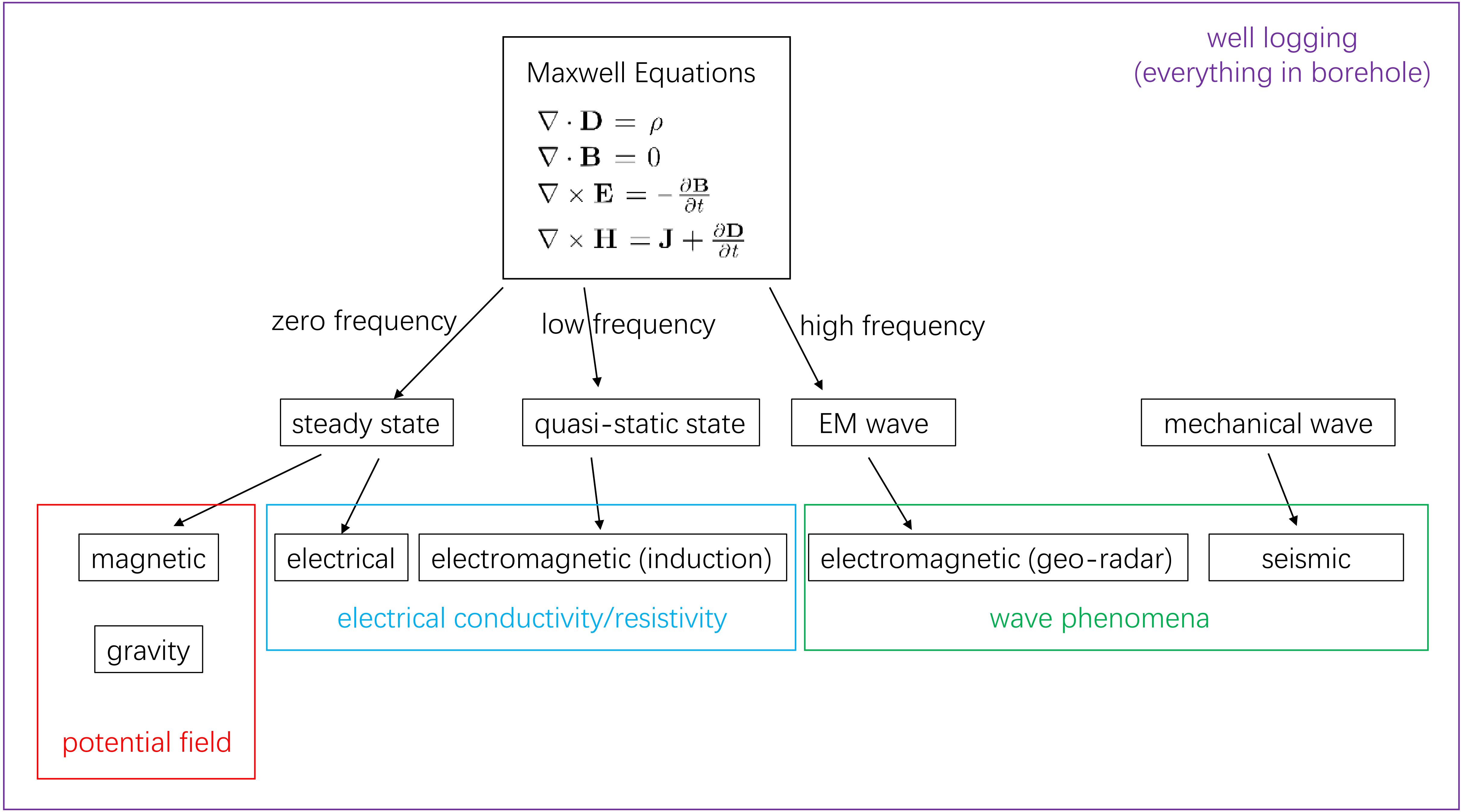
Gravity, Magnetic, Electrical, Electromagnetic and Well Logging

Magnetic Wrap-up

Instructor: Dikun Yang

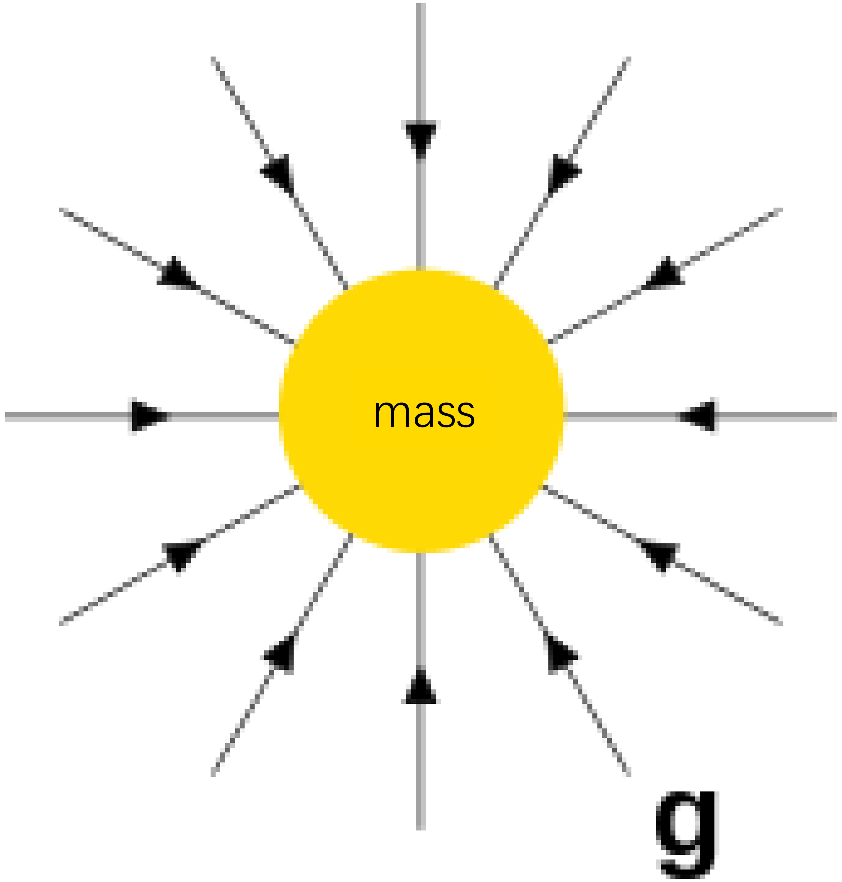
Feb – May, 2020

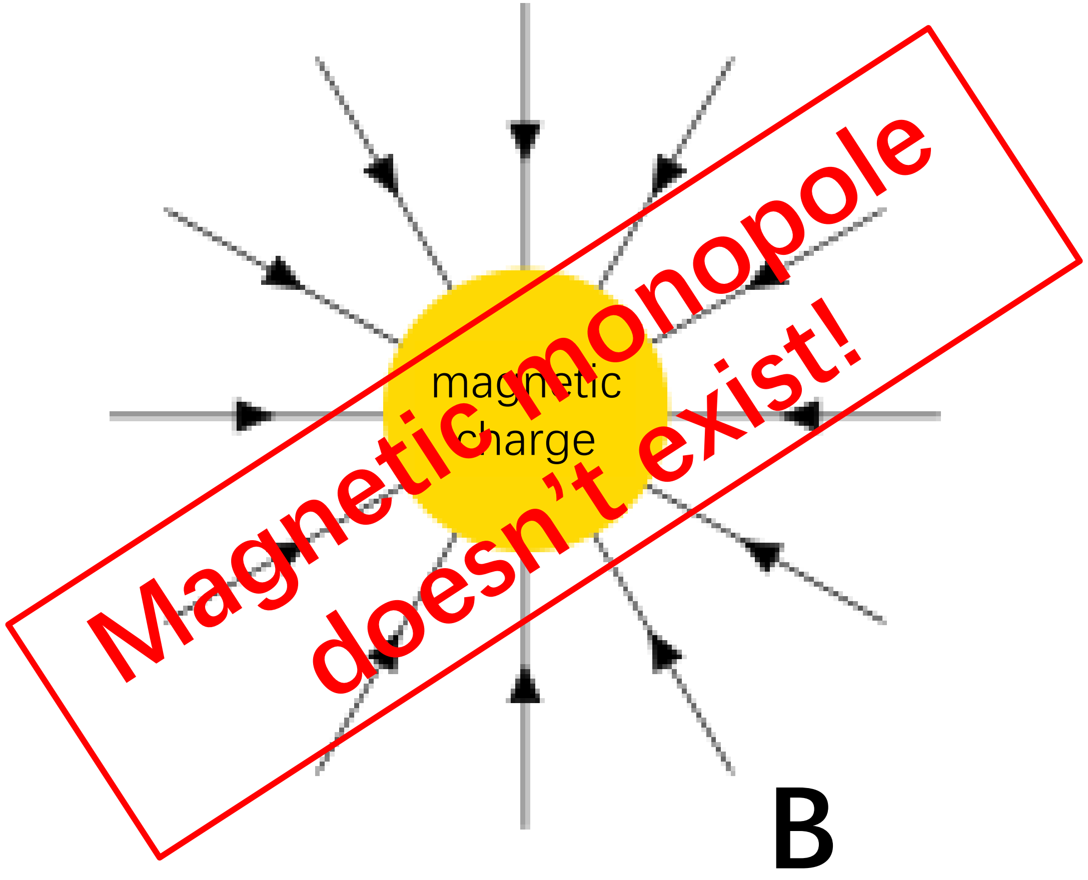




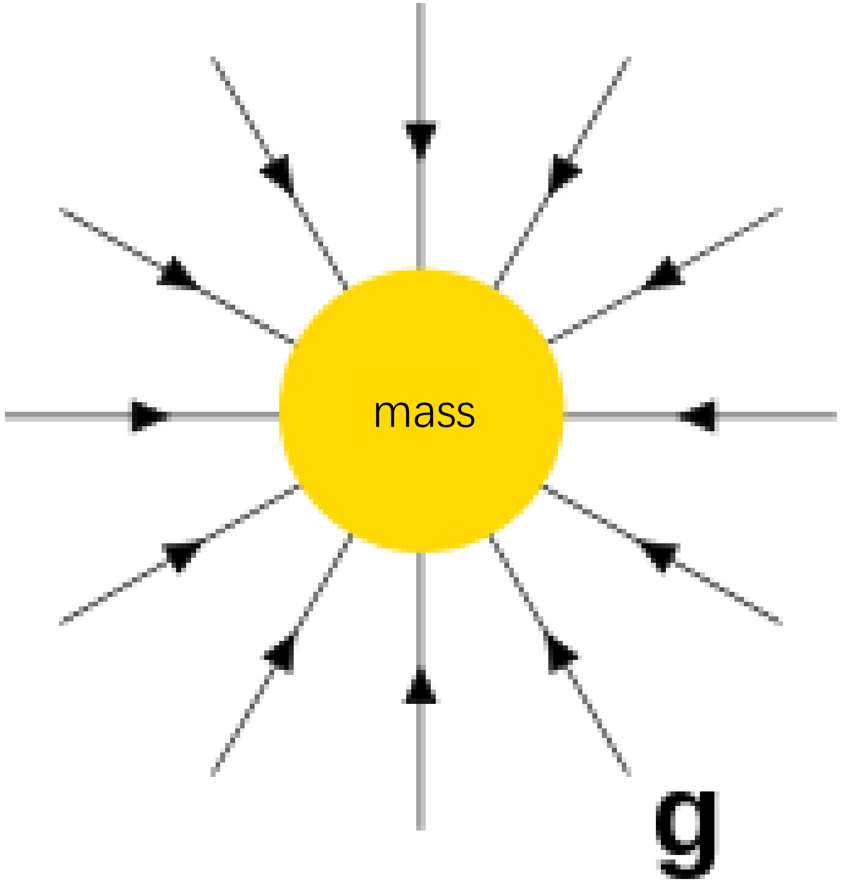
well logging
(everything in borehole)
Maxwell Equations
$\nabla \cdot \mathbf{D} = \rho$
$\nabla \cdot \mathbf{B} = 0$
$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
$\nabla \times \mathbf{H} = \mathbf{J} + \frac{\partial \mathbf{D}}{\partial t}$
zero frequency
low frequency
high frequency
steady state
quasi-static state
EM wave
mechanical wave
magnetic
gravity
potential field
electrical
electromagnetic (induction)
electrical conductivity/resistivity
electromagnetic (geo-radar)
seismic
wave phenomena

Charge and Field

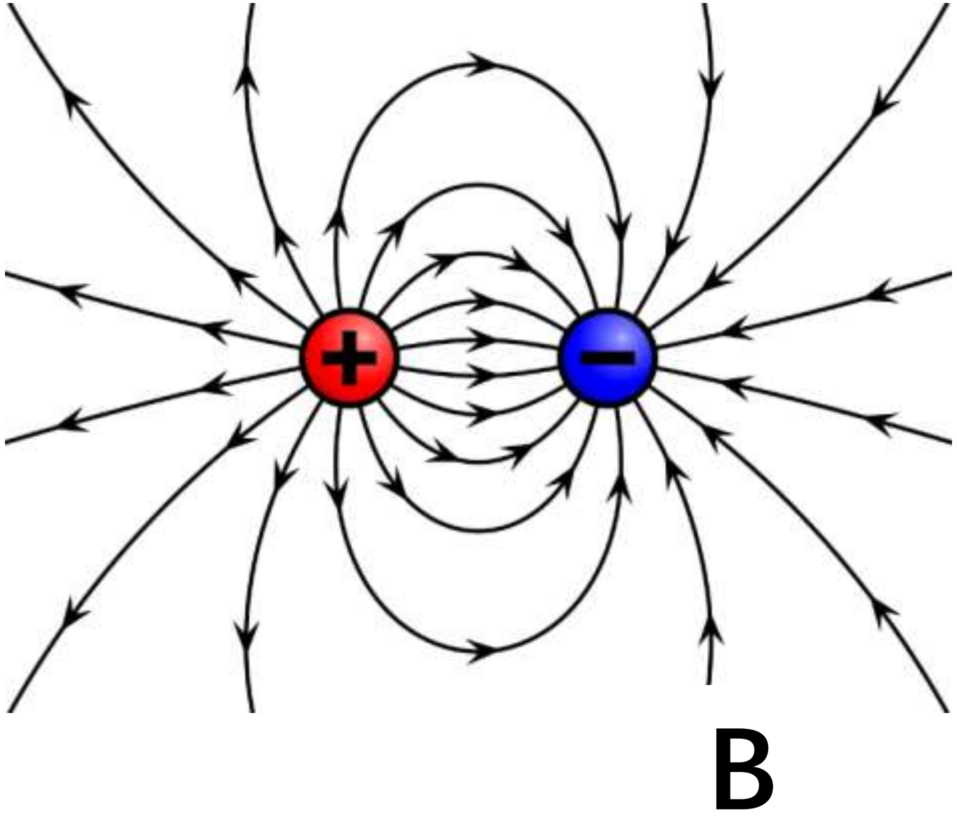




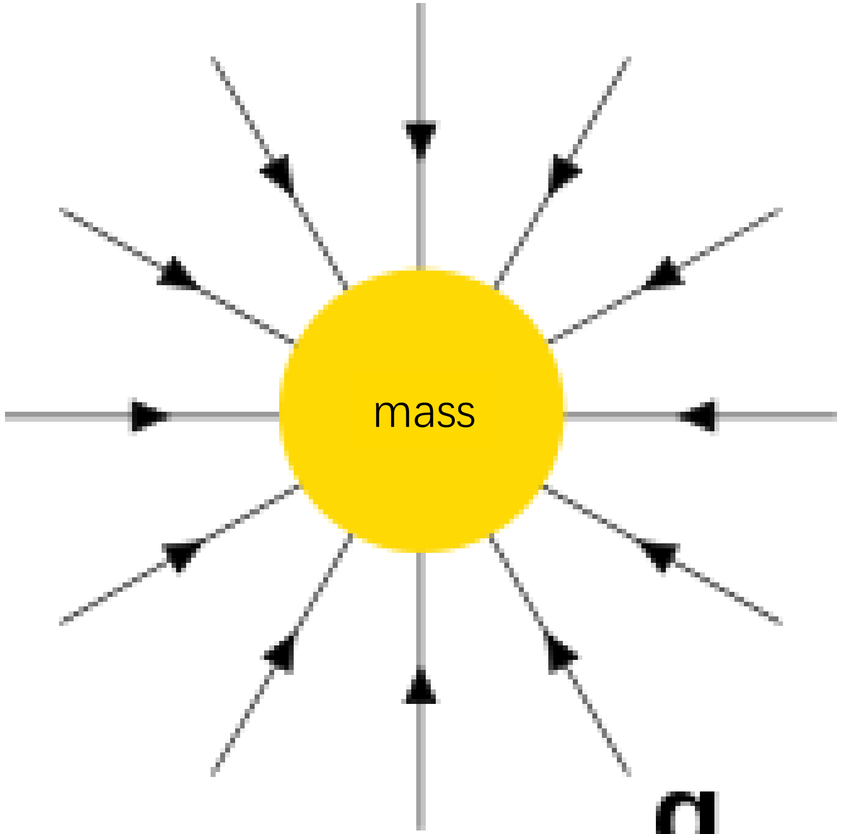
Charge and Field



Magnetic dipole

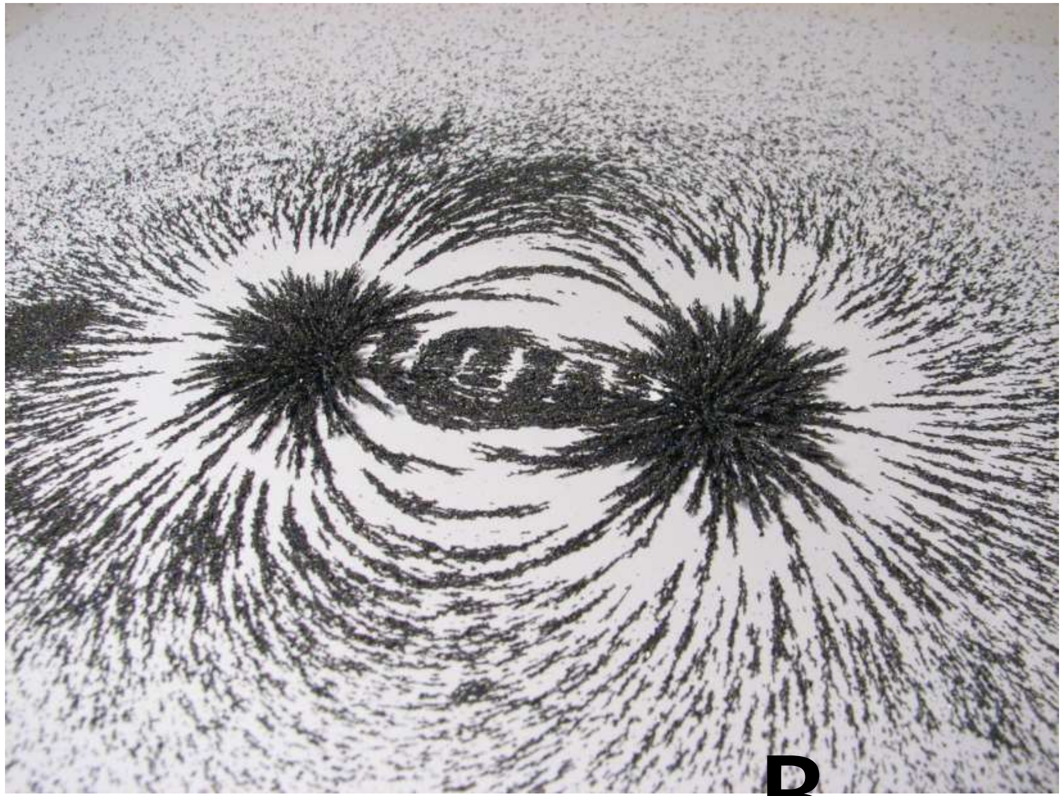


Charge and Field



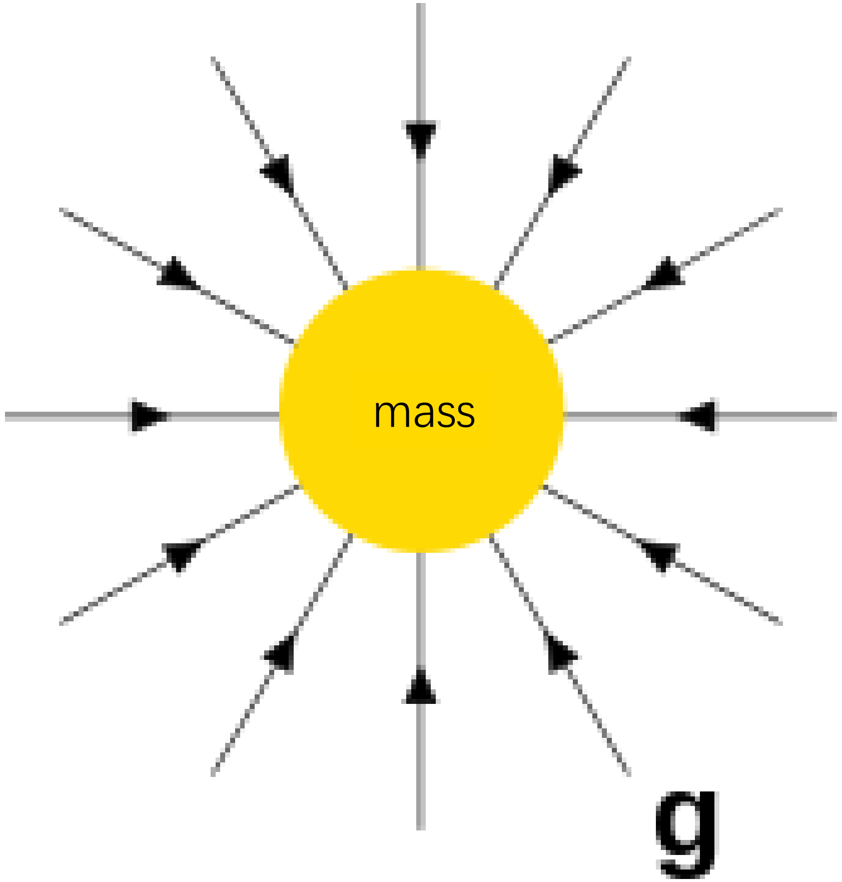
g

Magnetic field lines

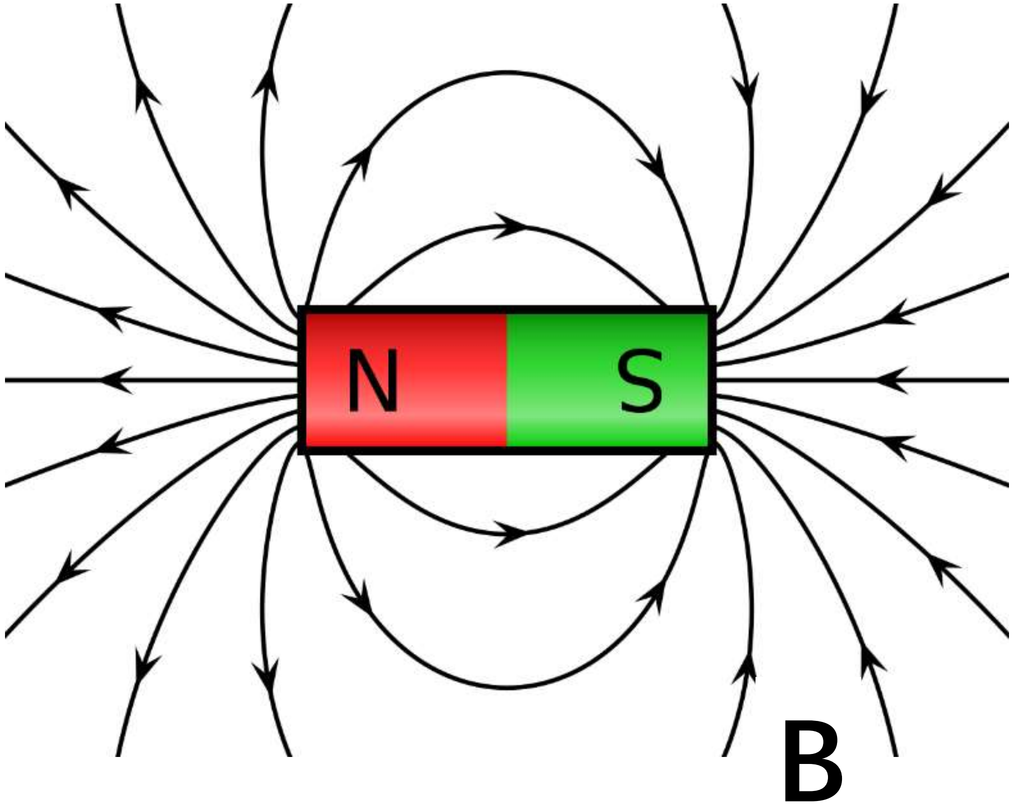


B

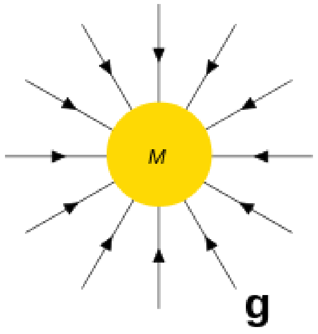
Charge and Field



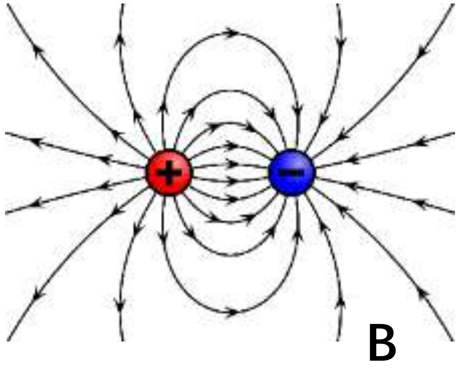
Bar magnet



Charge and Field



$$\boldsymbol{g} = \frac{GM}{r^2}$$



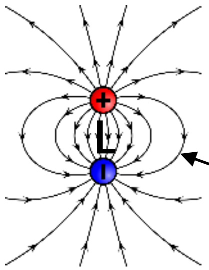
$$\mathbf{B} = \frac{\mu_0 Q}{4\pi r^2}$$

- Mass generates gravity potential and field
- Only positive mass*
- Field lines from infinity to mass (open path)
- Unit of acceleration g: m/s^2

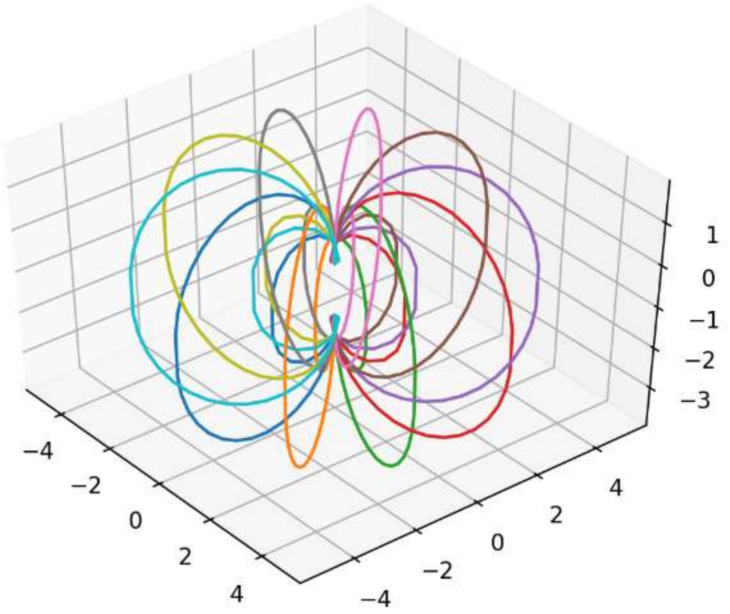
- Magnetic charges generate magnetic potential and field
- Positive charge and negative charge (stick together)
- Field lines from negative charge to positive charge (loop)
- Unit of B: Tesla

* Can be negative in relative sense

Magnetic Dipole



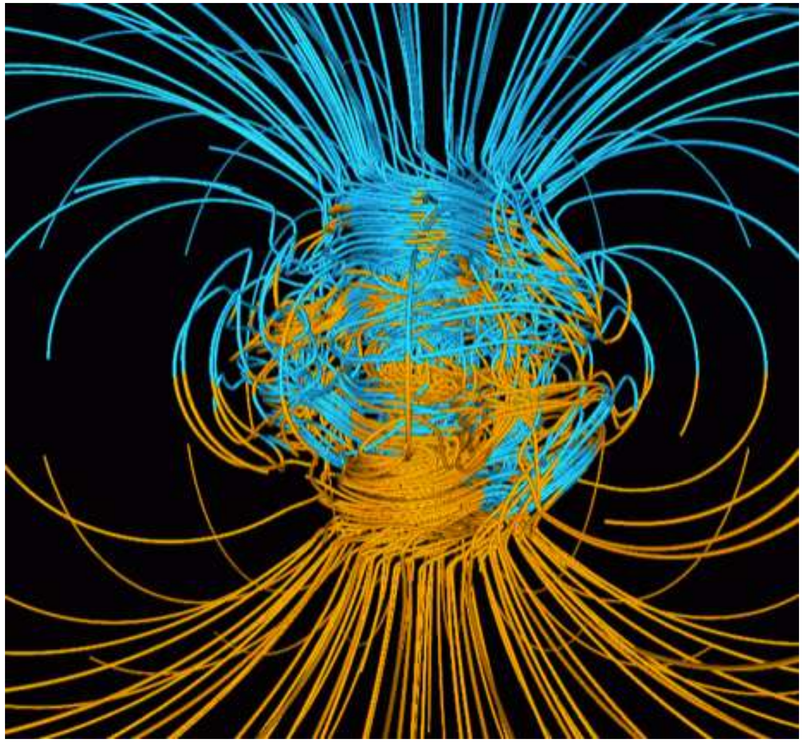
A vertical dipole and field lines

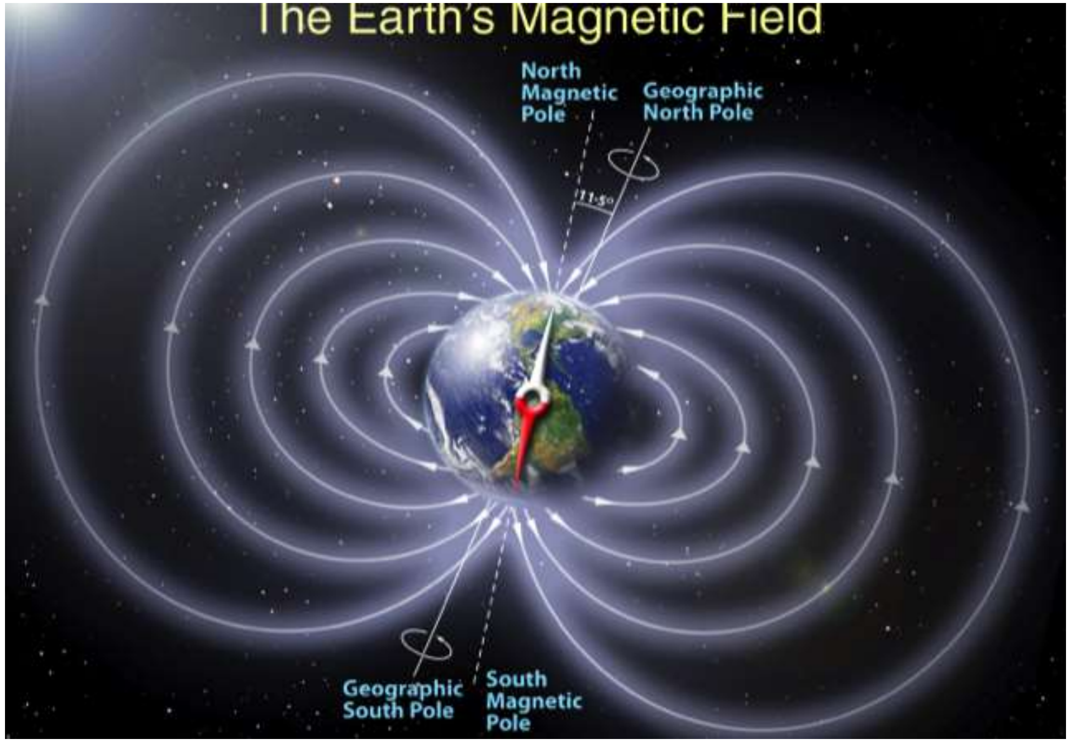


R

R >> L

Earth’s Magnetic Field



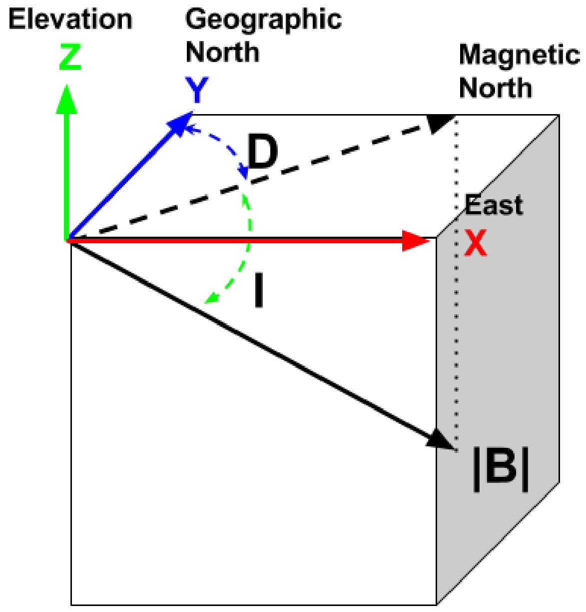


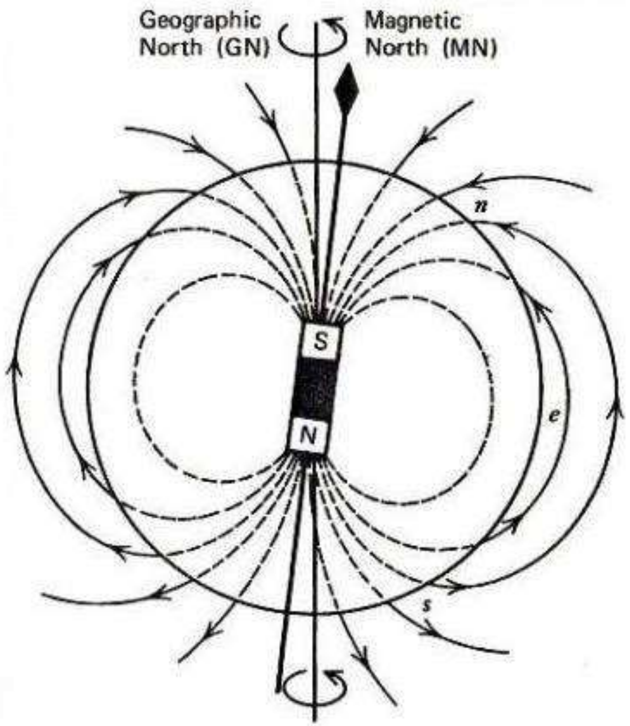
Complicated inside the earth near the core.

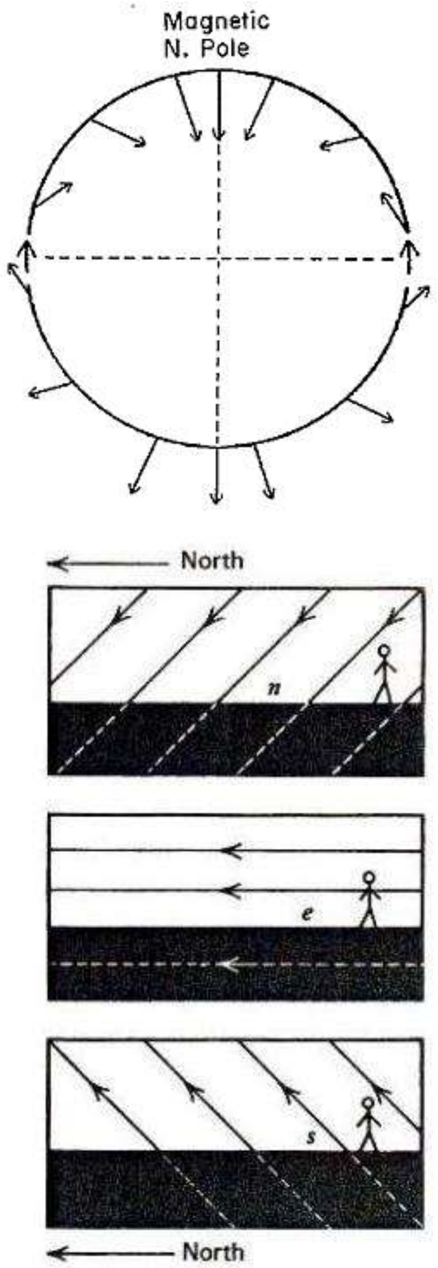
Outside the earth it looks like a magnetic field due to a dipole (bar magnet).

Earth's Magnetic Field

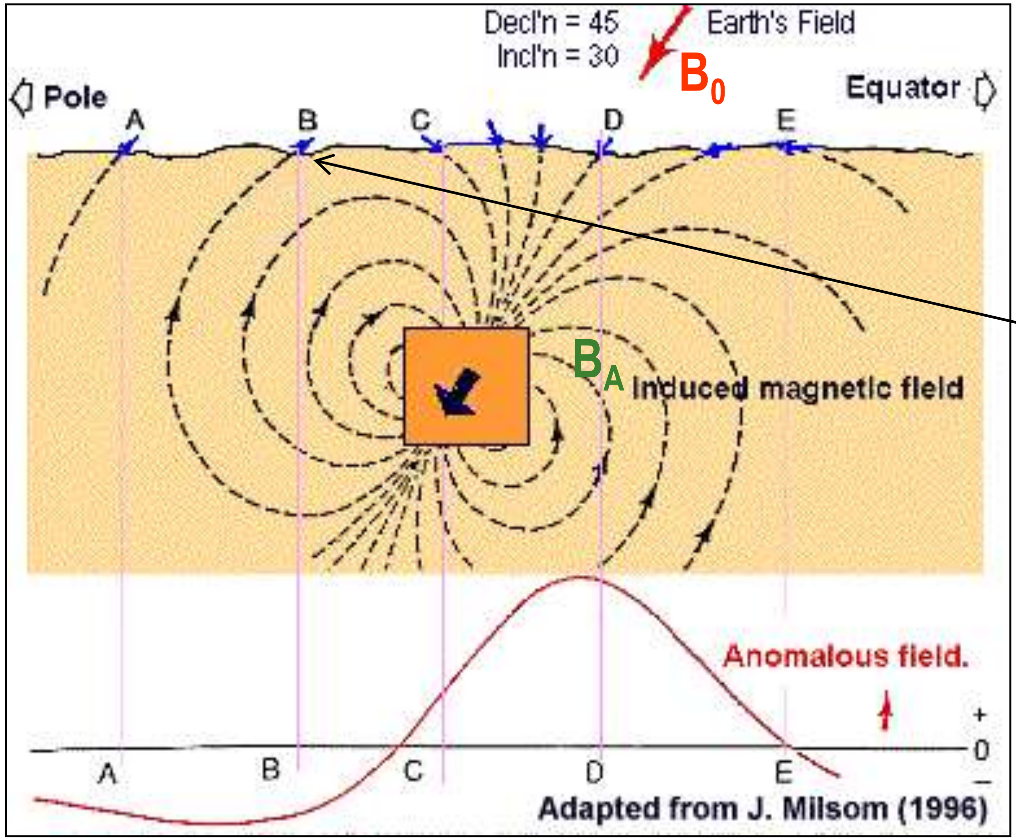
- A vector field
- How is the field described anywhere?
  - Orthogonal decomposition: X, Y, Z
  - Inclination, Declination, Magnitude

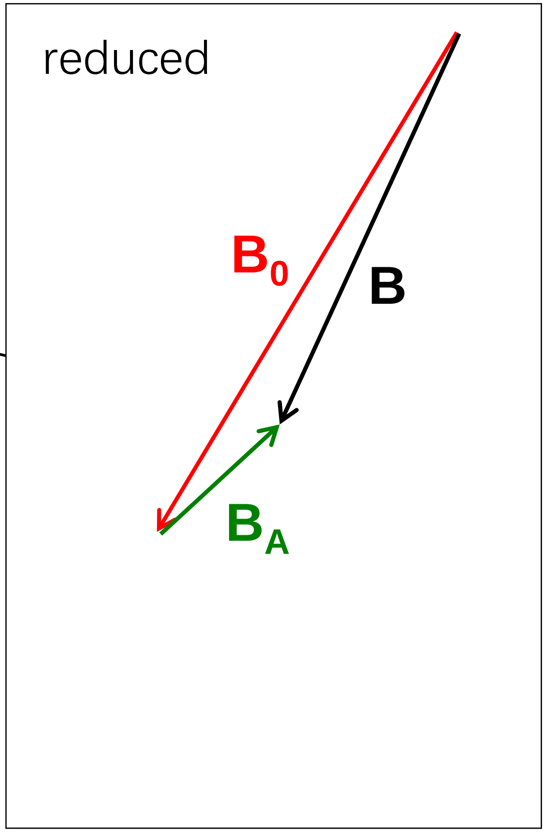






A Buried Dipole





Composite field:

$\mathbf{B} = \mathbf{B}_0 + \mathbf{B}_A$

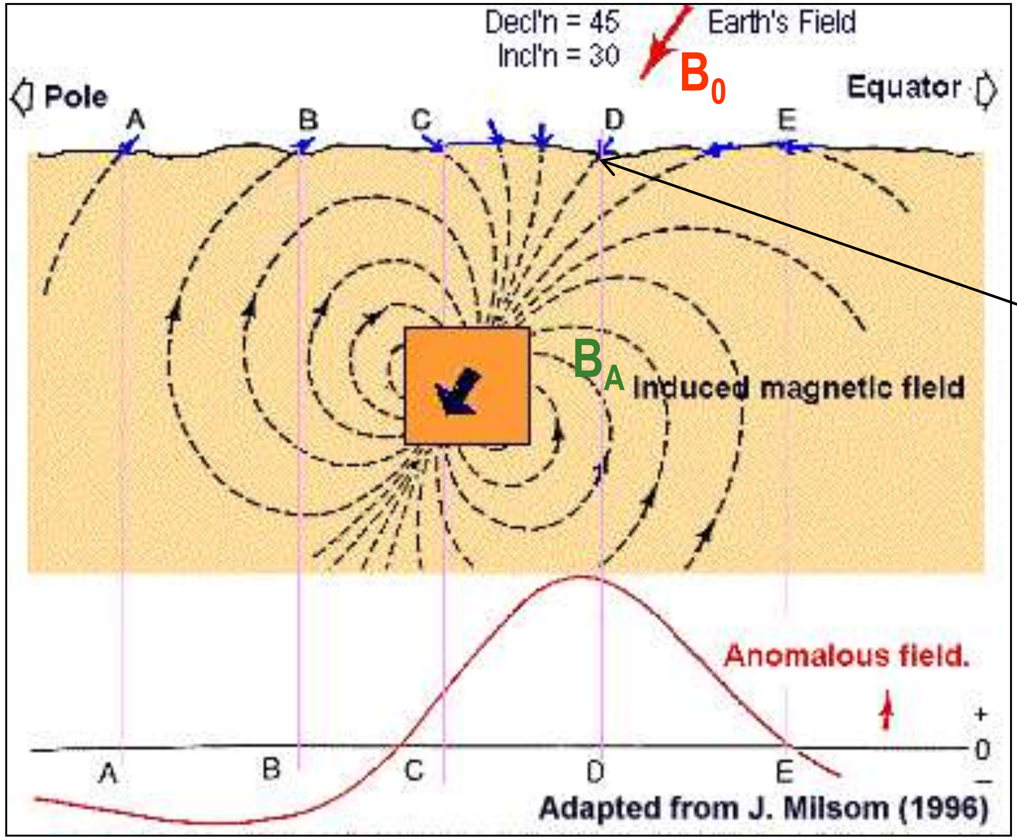
B is a vector:

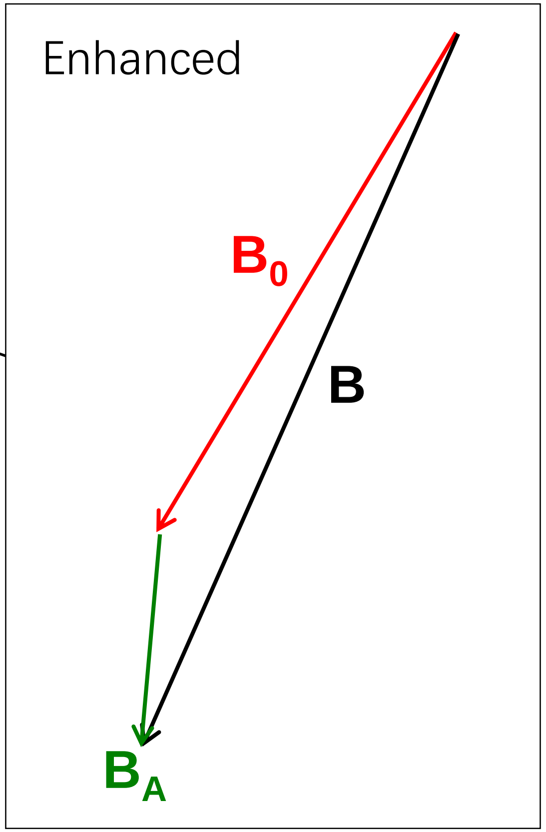
$\mathbf{B} = \{\mathbf{B}_x, \mathbf{B}_y, \mathbf{B}_z\}$

Total field:

$|\mathbf{B}| = |\mathbf{B}_0 + \mathbf{B}_A|$

A Buried Dipole





Composite field:

$$\mathbf{B} = \mathbf{B_0} + \mathbf{B_A}$$

B is a vector:

$$\mathbf{B} = \{B_x, B_y, B_z\}$$

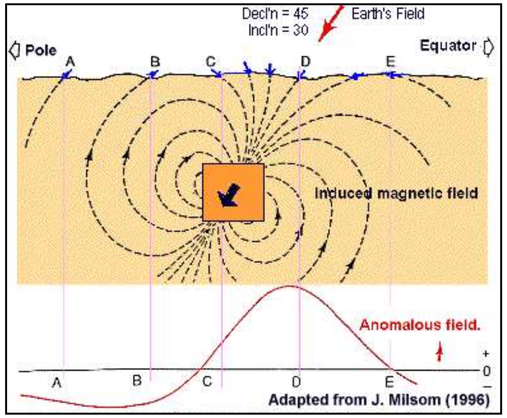
Total field:

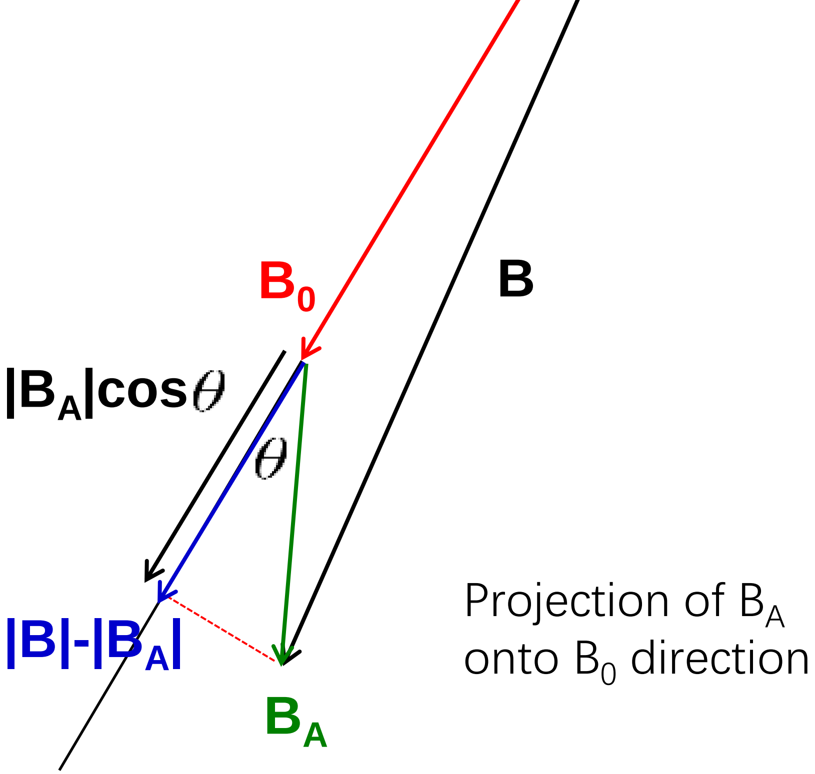
$$|\mathbf{B}| = |\mathbf{B_0} + \mathbf{B_A}|$$

Anomalous Field

- Measured data **|B|** = | **B_0** + **B_A** **|**
- Remove the influence of **B_0**
- The *total* field *anomaly*:
- **$|\Delta B| = |B| - |B_0|$**
- If **$|B_A|$ << $|B_0|$** then

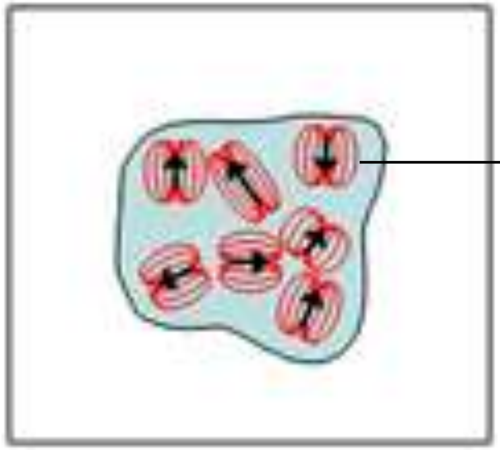
$$
\begin{aligned}
|\triangle\vec{B}| &= |\vec{B}_0 + \vec{B}_A| - |\vec{B}_0| \\
&\simeq \vec{B}_A \cdot \hat{B}_0 \\
&= |\vec{B}_A| cos\theta
\end{aligned}
$$

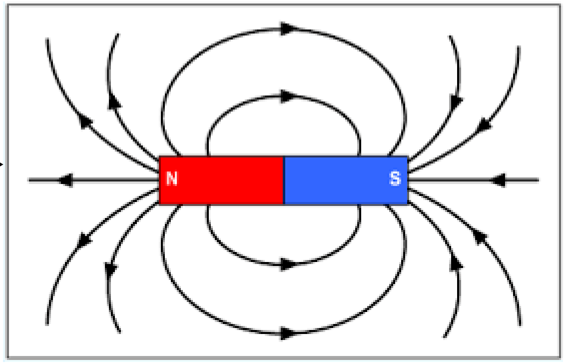


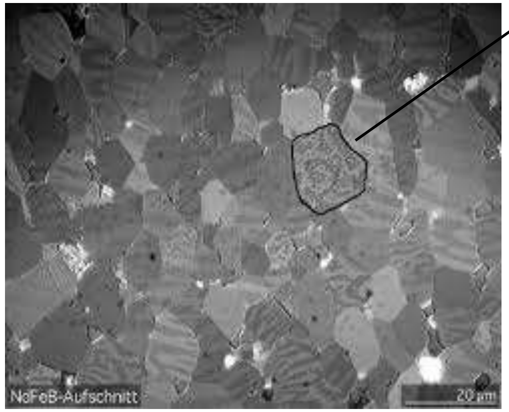


Induced Magnetization

- Earth materials are built up of minerals that behave as small bar magnets





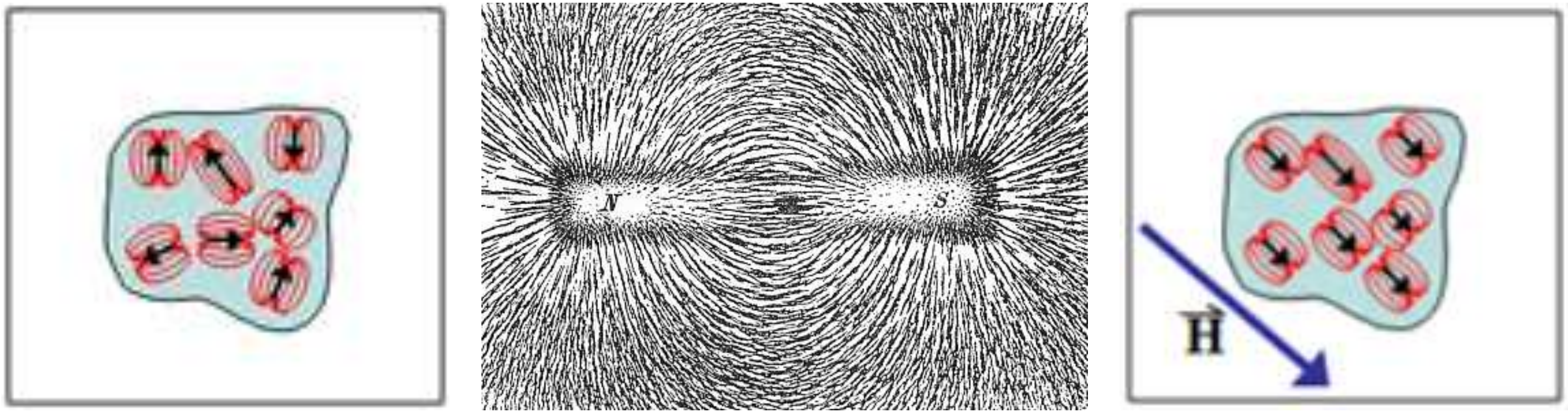


- Dipole: North pole and South pole (dipole)
- Dipole moment **m** is related to the strength of the magnet
- Magnetic field lines extend from N to S

Induced Magnetization

- Strength of each magnet: the magnetic dipole moment m_i
- Magnetization: net "density" of small bar magnets
- Note: every m_i has its own direction, so M can be zero when the magnets are randomly oriented

$$\vec{M} = \frac{\Sigma \vec{m}_i}{Volume}$$



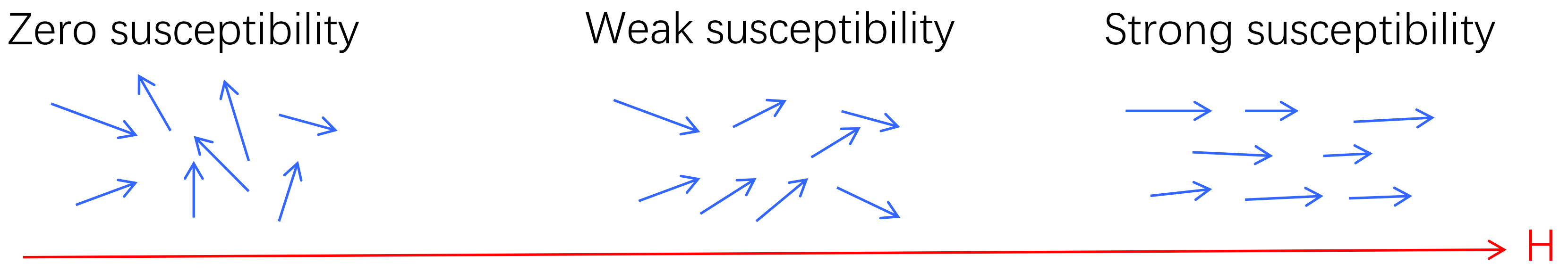
Small magnets align with fields of a larger magnet to have a non-zero total magnetic moment.

Susceptibility

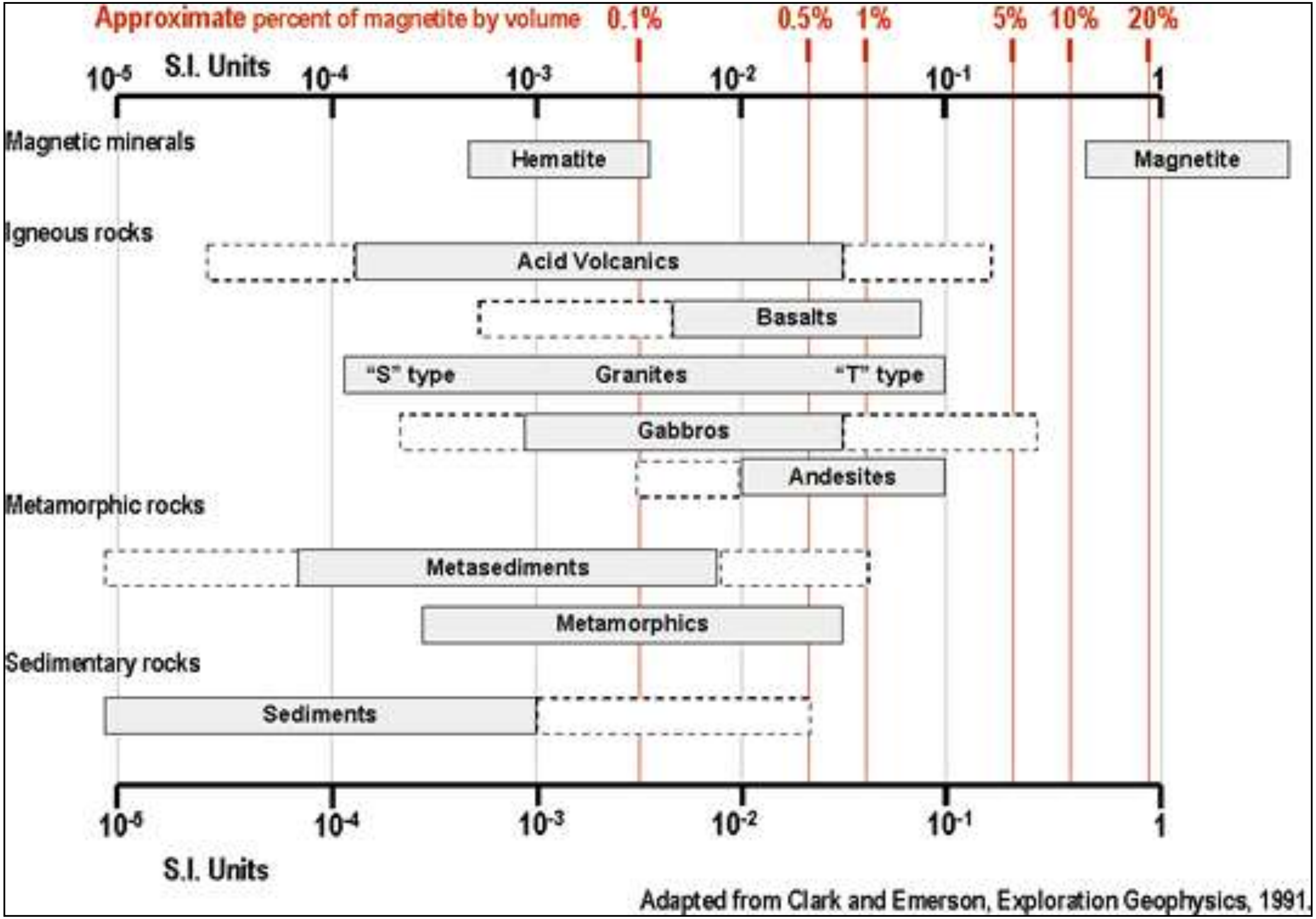
- Physical understanding
  - Microscopic: ability for the small bar magnets in a rock to re-orient to form a large magnet when an external magnetic field is applied.
  - Macroscopic: how much additional magnetic field can be excited (a dimensionless factor)?

$$\vec{M} = \frac{\Sigma \vec{m}_i}{Volume}$$

$$\vec{M} = \kappa \vec{H}$$



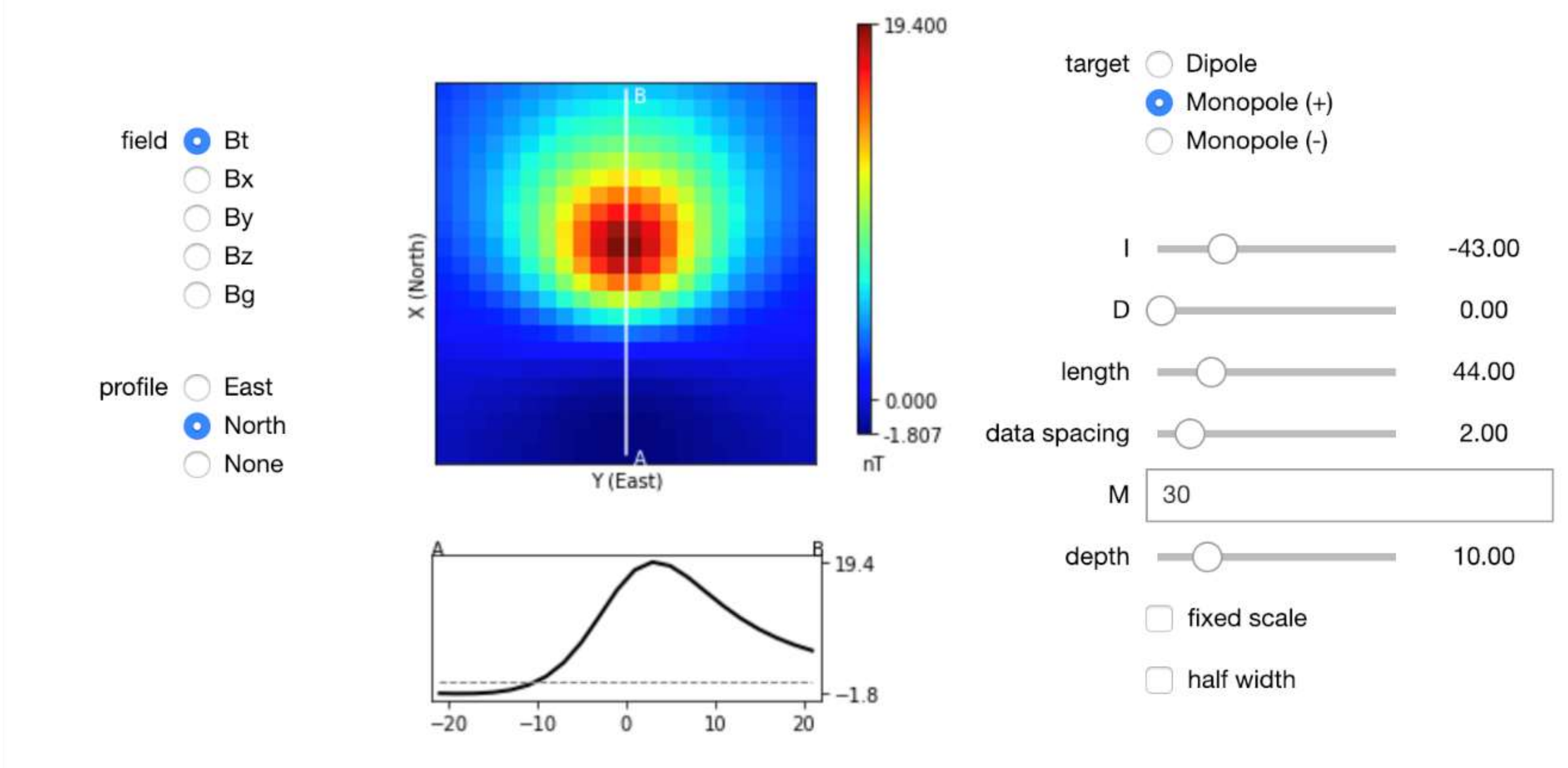
Magnetic Susceptibility



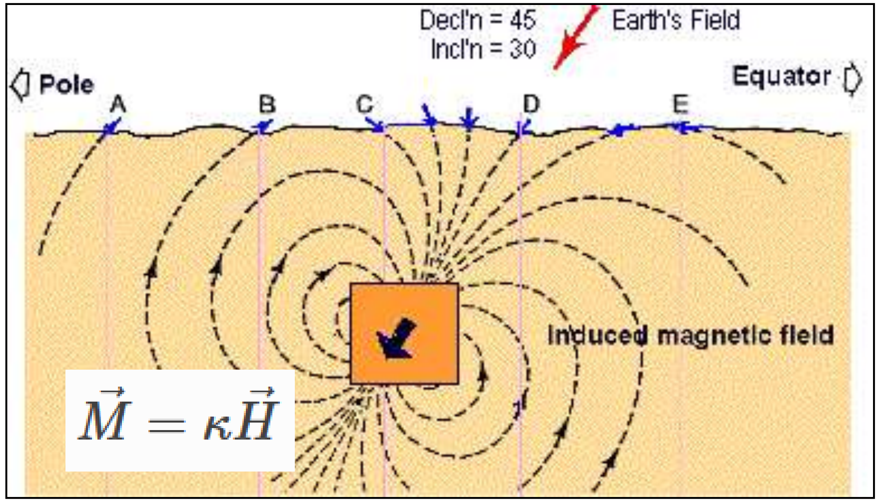
Induced Magnetic Dipole Applet

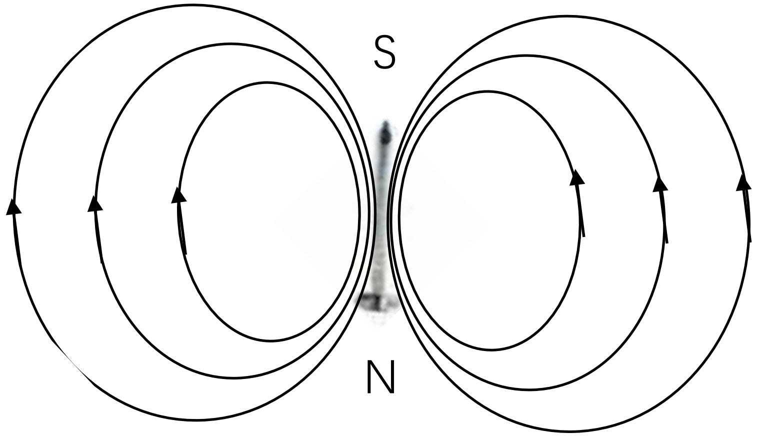
geosci-labs/
MagneticDipoleApplet.ipynb

```
mag = MagneticDipoleApp()
mag.interact_plot_model_dipole()
```



Types of Magnetization



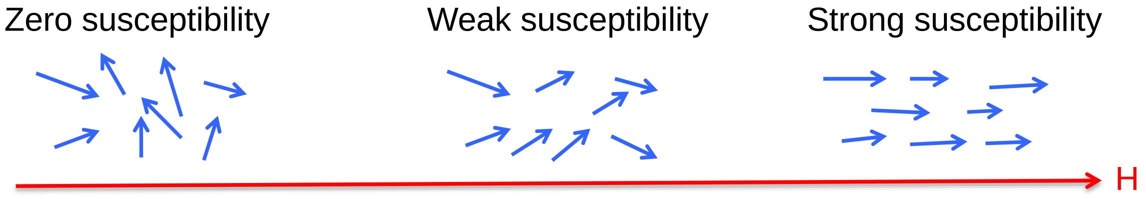


Induced:

- Same direction as B_0
- Depend on inducing field and susceptibility

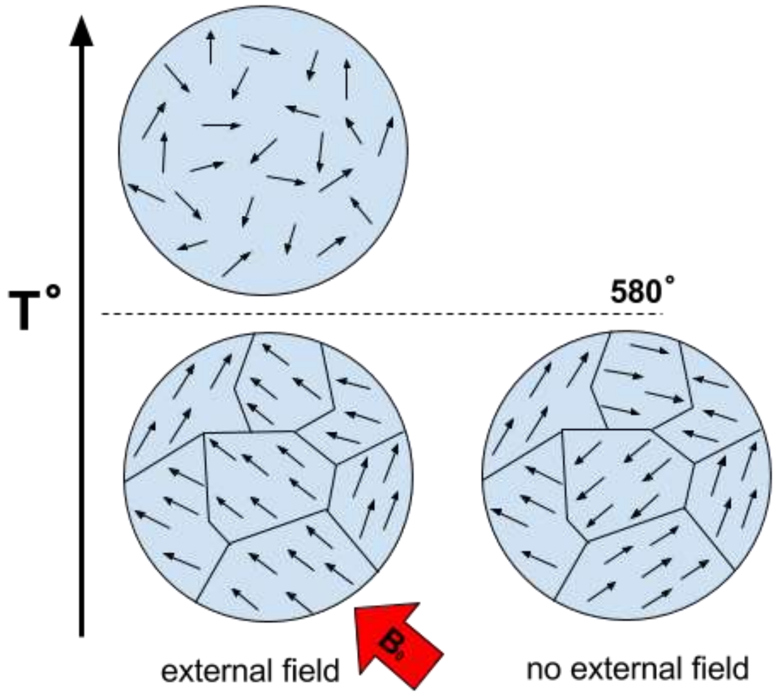
Remanent :

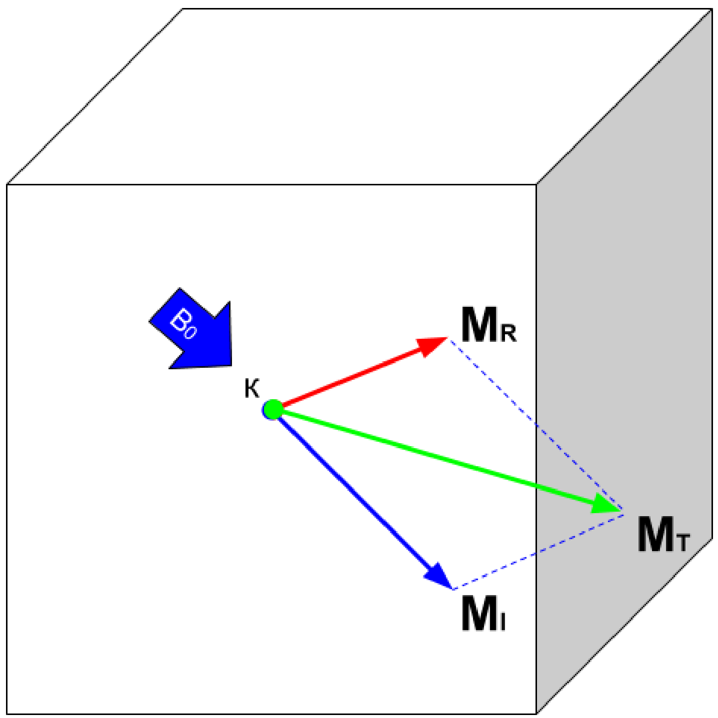
- Memorize external field direction when cooled down



Remanent Magnetization

- Magnetic material cooling through Curie temperature (~550 °C) acquires a magnetic field in the direction of the earth's field.
- Final magnetization sum of induced and remnant magnetizati $\vec{m} = \vec{m}_I + \vec{m}_R$



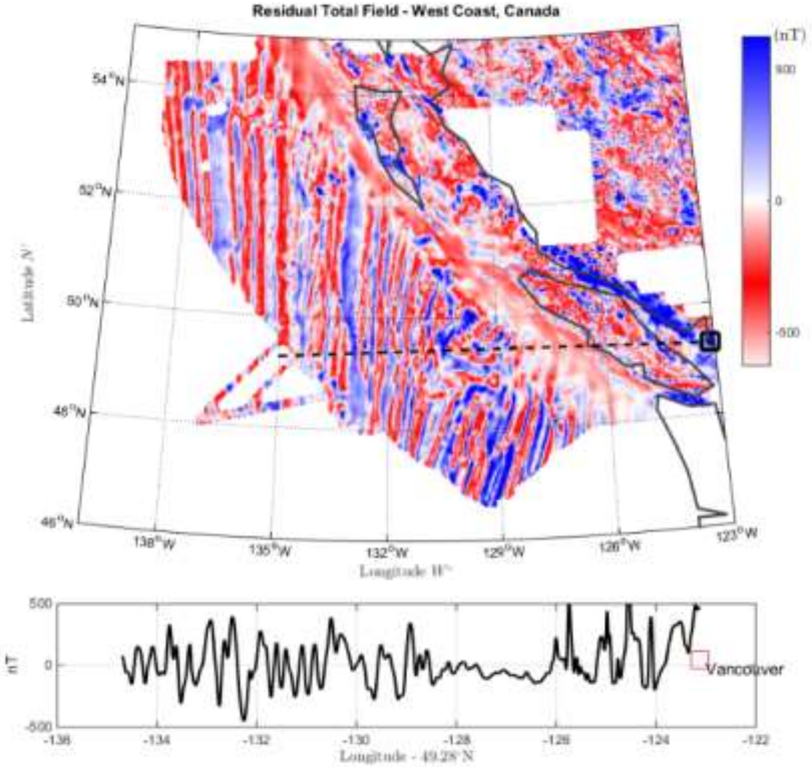


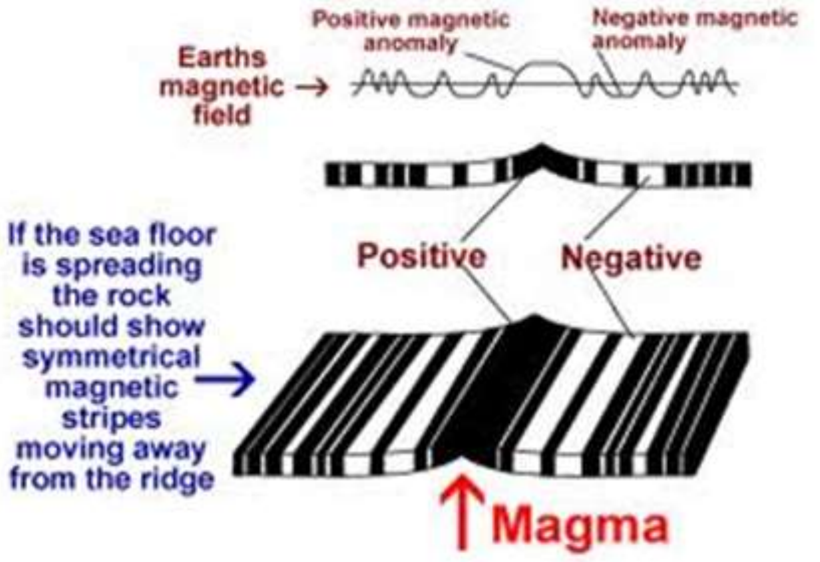
Remanent Magnetism

- Small scale: UXO, rebar, drums

- Large scale: geologic units.

  Sea floor spreading



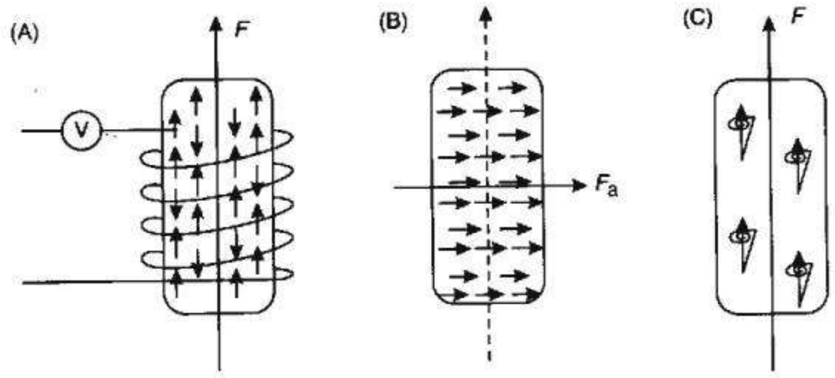


Three Ingredients in Magnetic

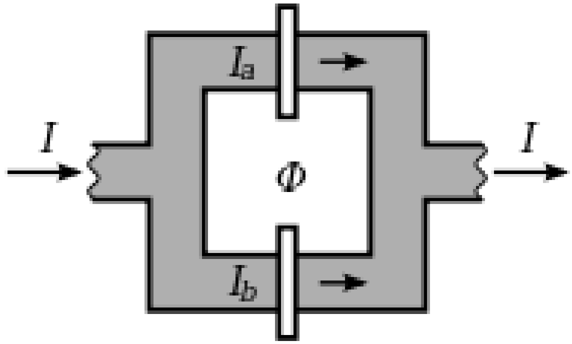
- Inducing field (B_0)
  - Uniform and strong
- Induced field
  - From present-day magnetization
  - Small object behaves like a dipole
  - Induced magnetization in the same direction as B_0
  - Field (usually small) proportional to B_0
  - A linear relation - susceptibility
- Remanent field
  - From ancient magnetization
  - Independent of B_0 (can be large)

Magnetometers

- Total field |B|
  - Proton precession (NMR)
  - Cesium vapour magnetometer



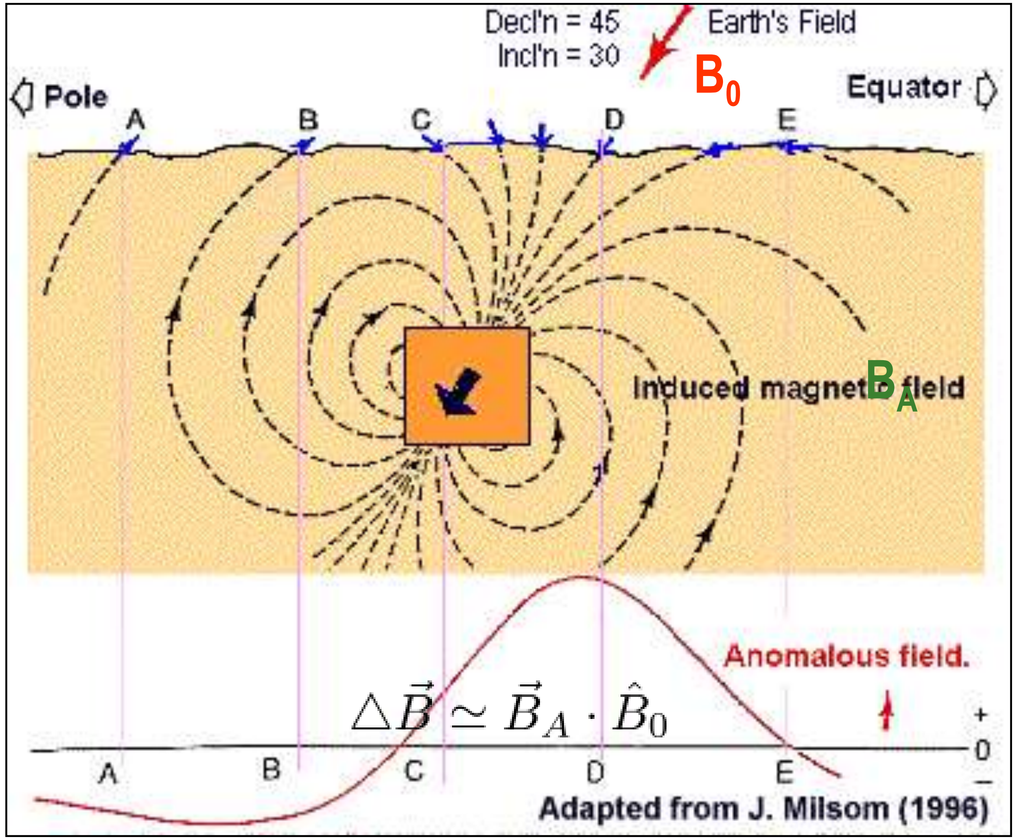
- Vector field B_x, B_y, B_z
  - Fluxgate
  - Hall effect
  - SQUID: superconducting quantum interference devices



Magnetic sensors to acquire data

Multi-scale Nature of Magnetic Field

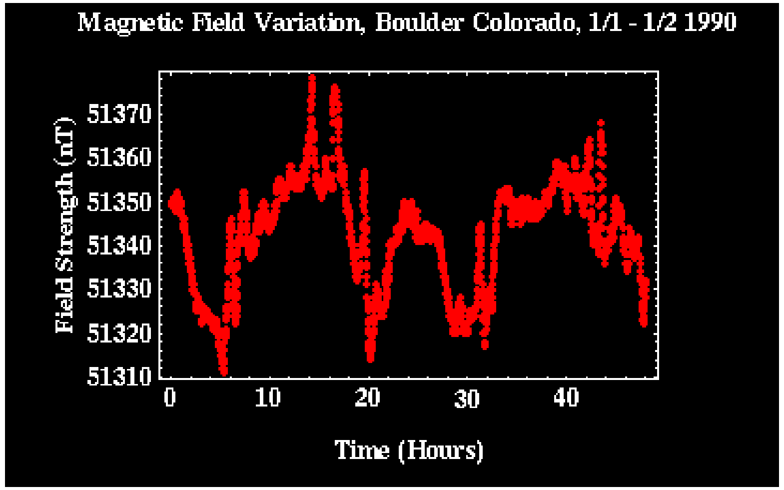
- Assumptions used in this conceptual model?

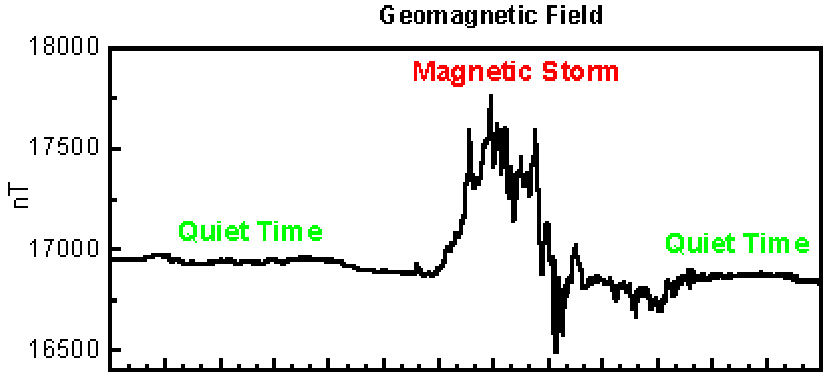


- B_0 is constant in space
- B_0 is constant in time
- A single magnetized body sufficiently small for dipole approximation
- Non-magnetic outside of the body

Time Variations of the Earth's Field

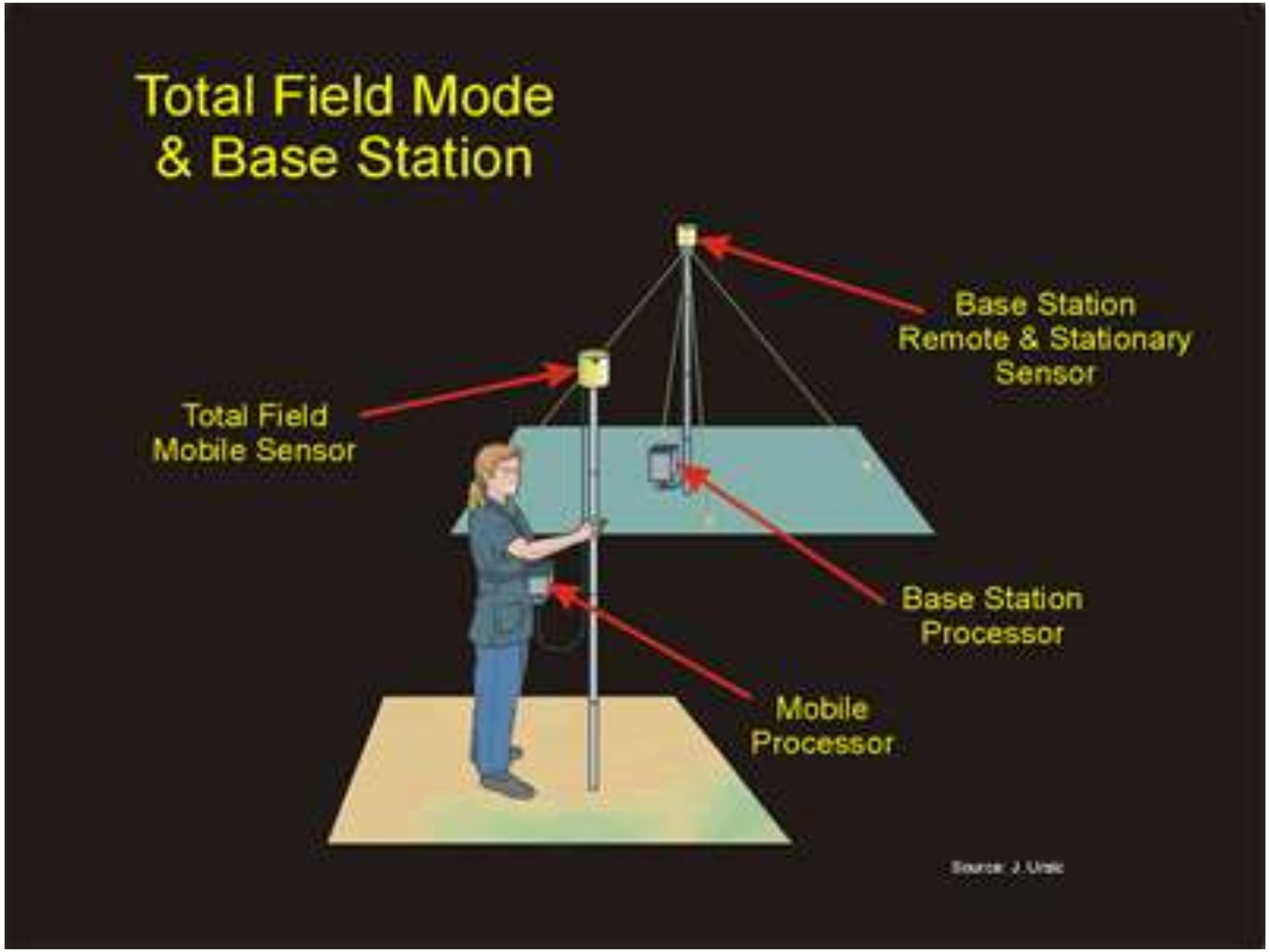
- External sources
  - Solar wind (micro-seconds, minutes, hours)
  - Solar storms (hours, days, months)
- Man made sources
  - Power lines (50/60 Hz plus harmonics) DC
  - Motors, generators, electronic equipment
- Internal sources
  - Fluctuations in core (days – millions of years)





Base station correction

- Set out another magnetometer (base station)
- Assume time-dependent variations at the base stations are the same as at the observation location
- Synchronize the times
- Perform a correction by subtraction



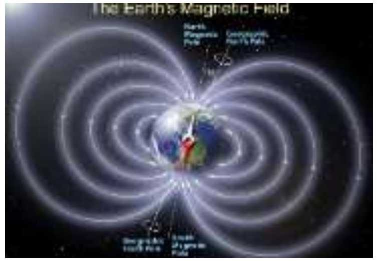
Regional Removal

- Any magnetic measurement is superposition of fields from many objects at different scales
- Example: magnetic data for UXO could include

+

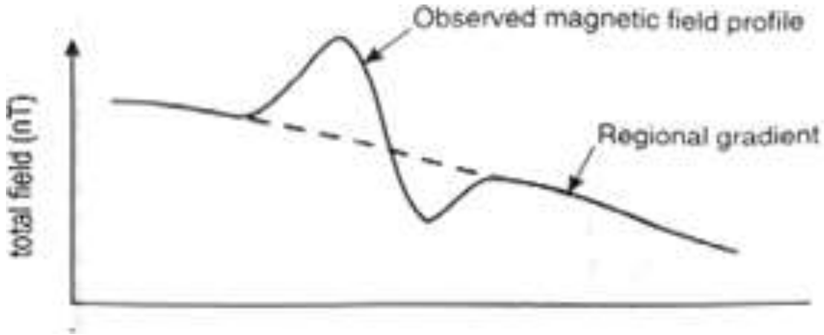
+

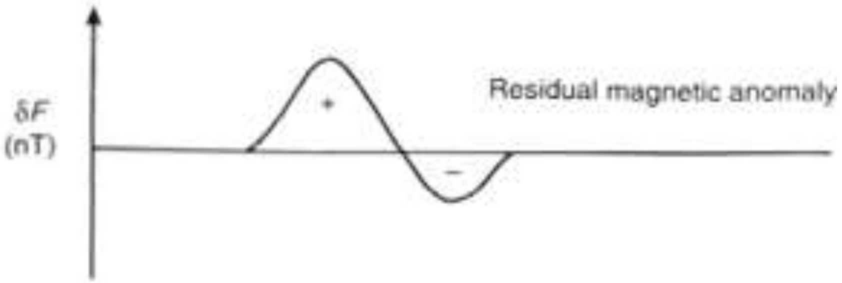
+



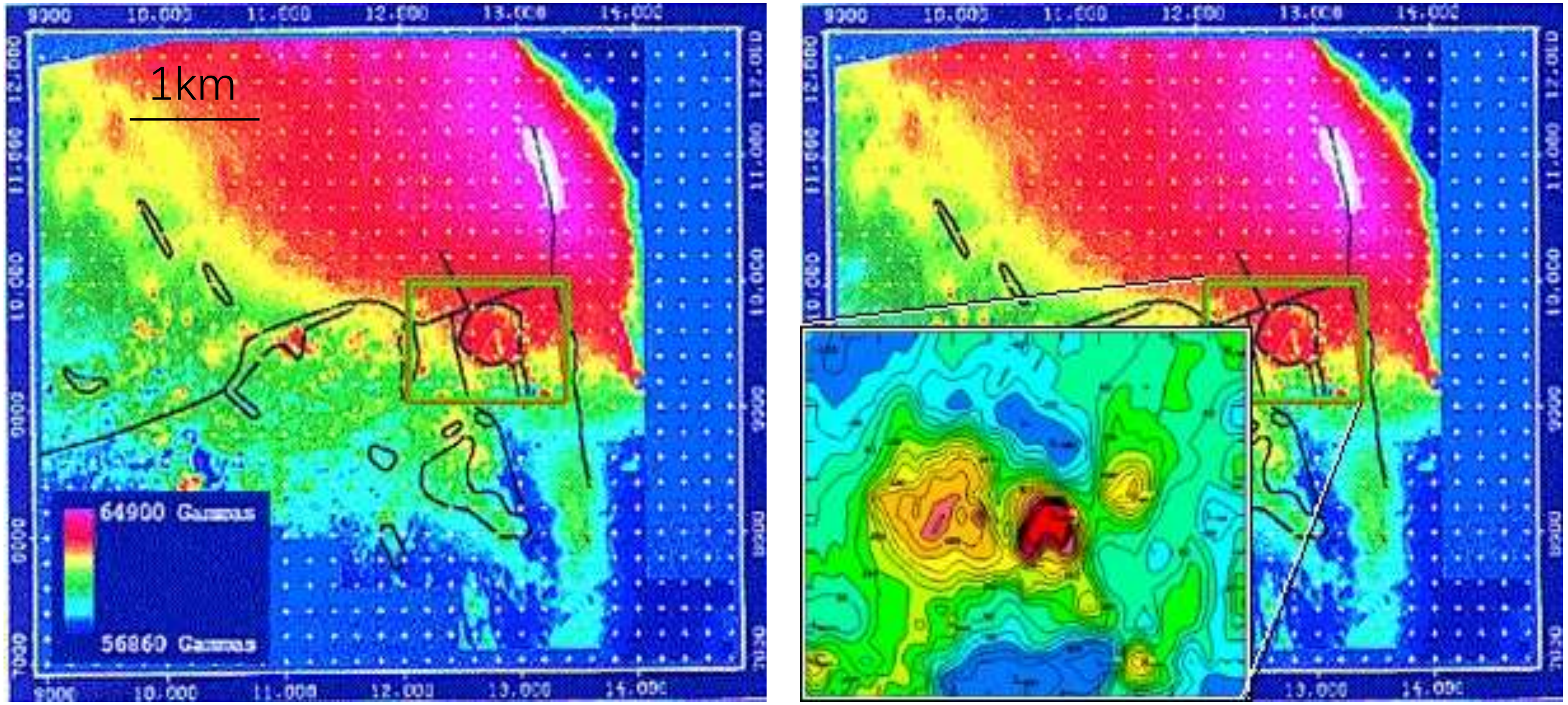
$+\cdots$

- Regional removal (assuming no magnetic objects larger than a certain length scale)





Regional Removal



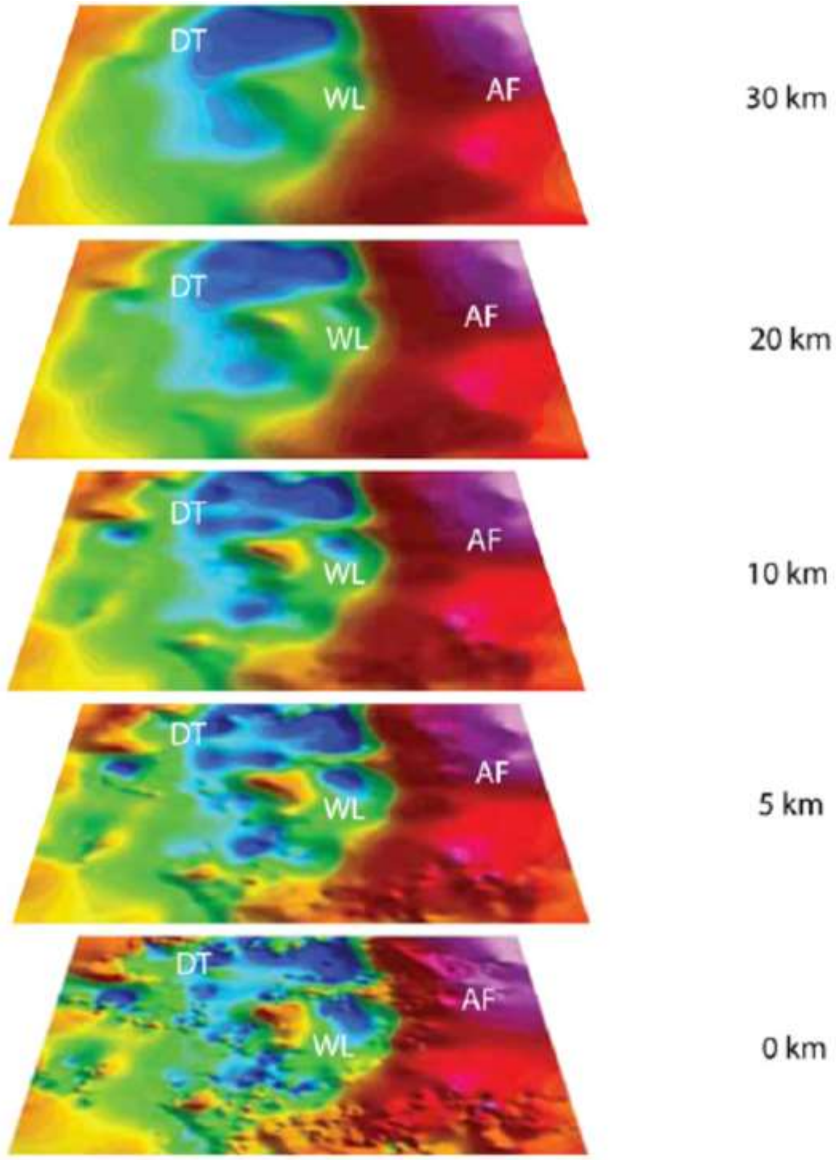
Before: details about the deposit masked by the regional field

After: target of interest better revealed

$$\Delta B = B^{obs} - B^{regional}$$

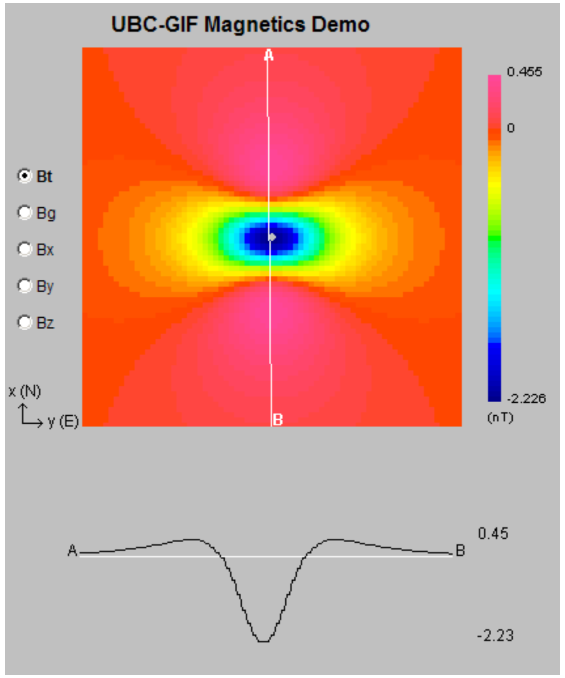
Upward Continuation

- Low-pass filter: remove short-wavelength signals from small near-surface objects
- As if data are measured at higher elevations
- Highlight regional trends

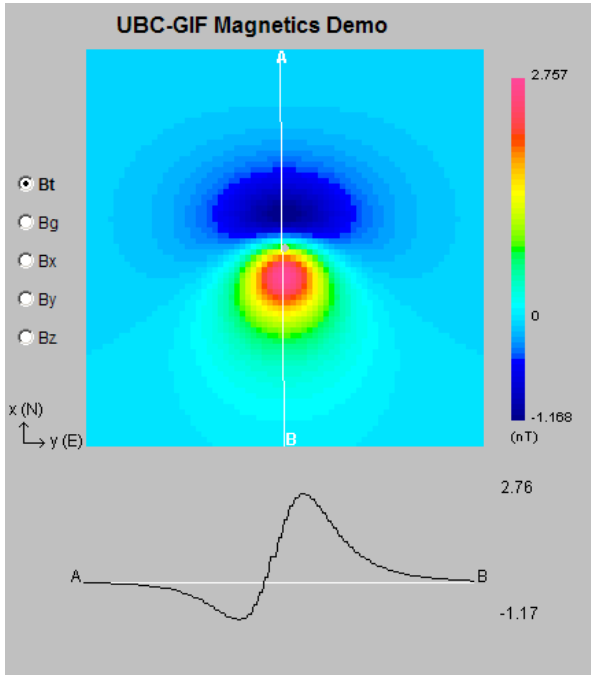


Reduction to Pole (RTP)

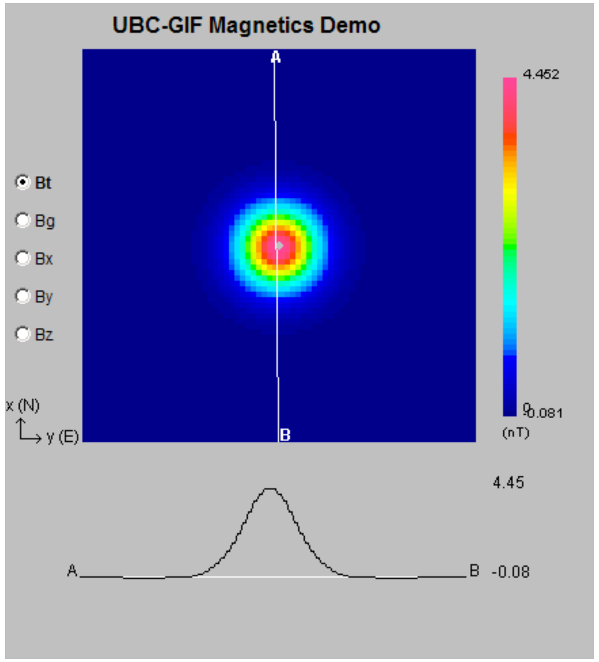
- Same object buried at the center of the map
- Inclination determines the direction of magnetization – we may observe different patterns
- RTP: process the data as if the inducing field (B_0) is purely vertical (at poles)



Inclination=0

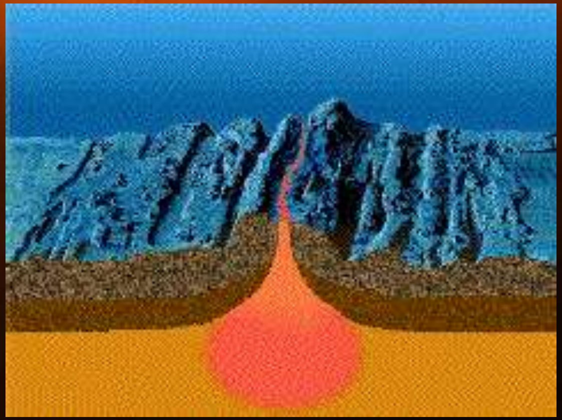


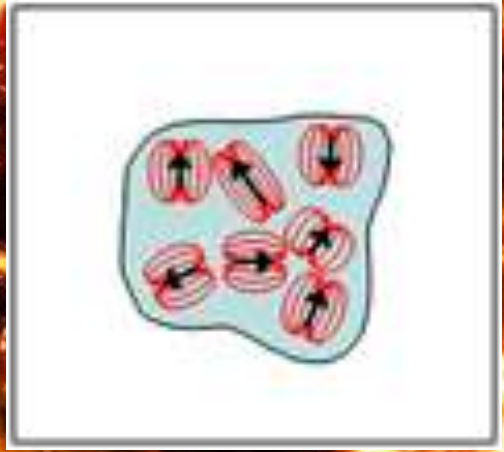
Inclination=45



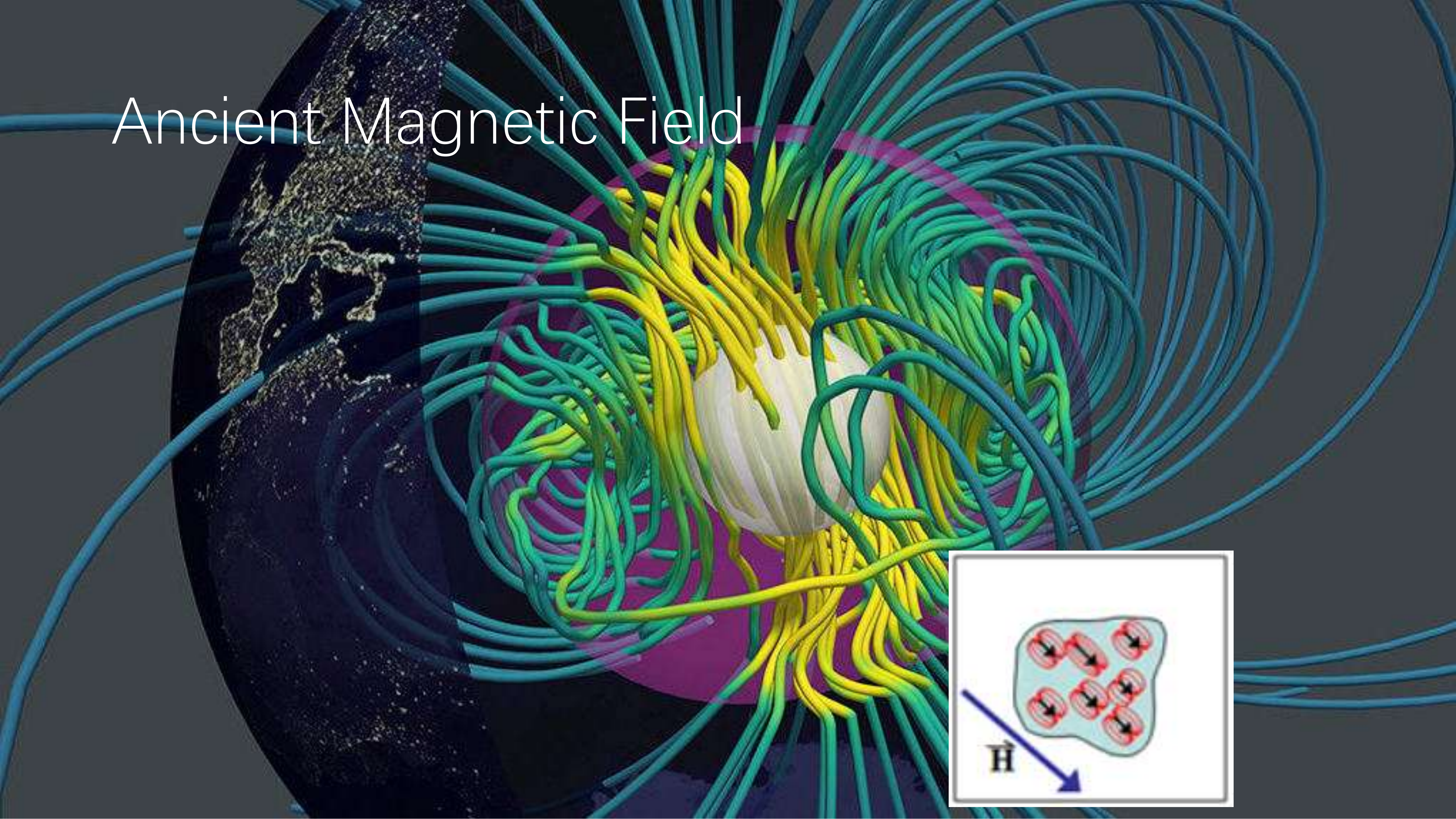
Inclination=90

Heat and Disorientation

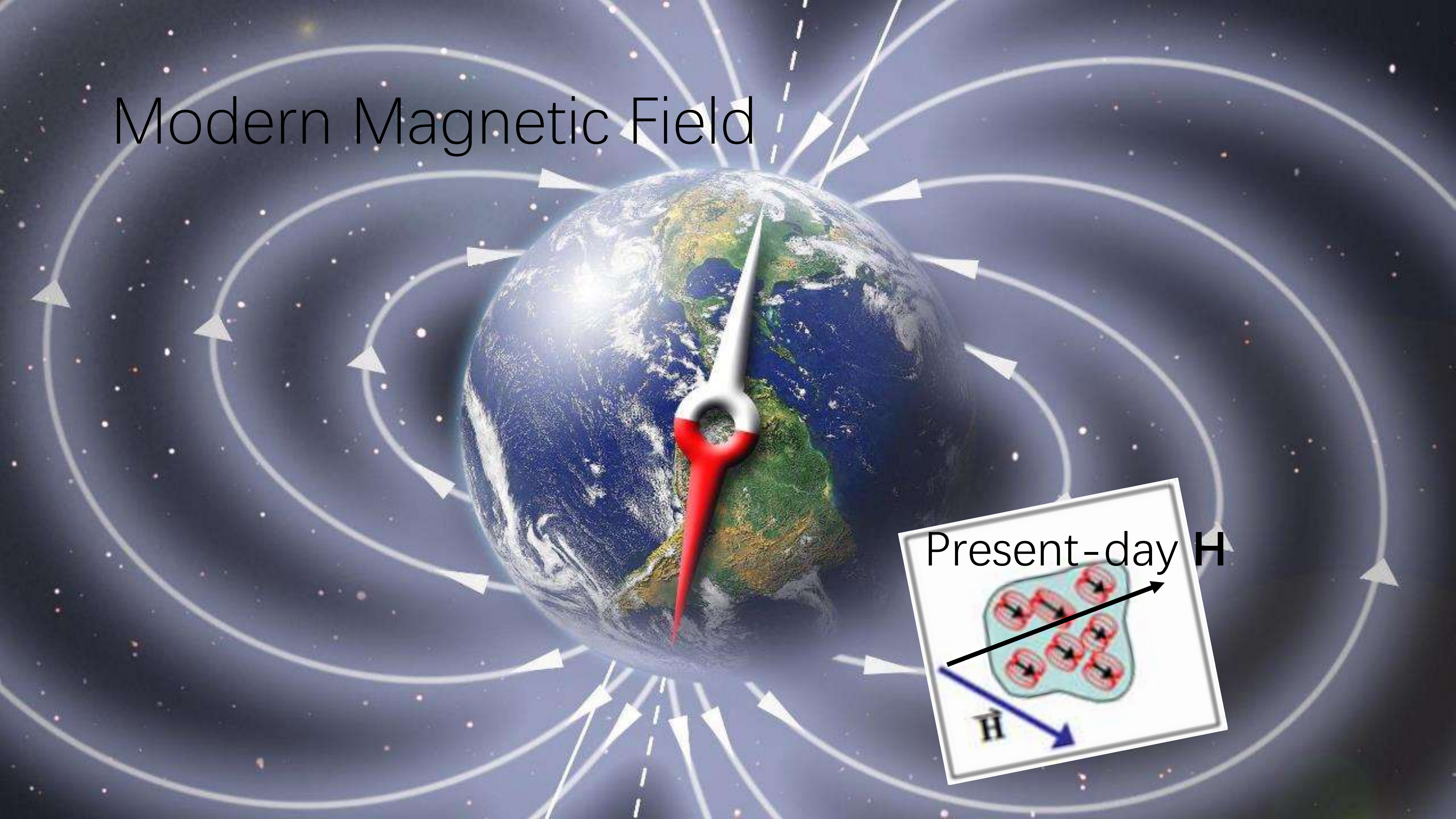




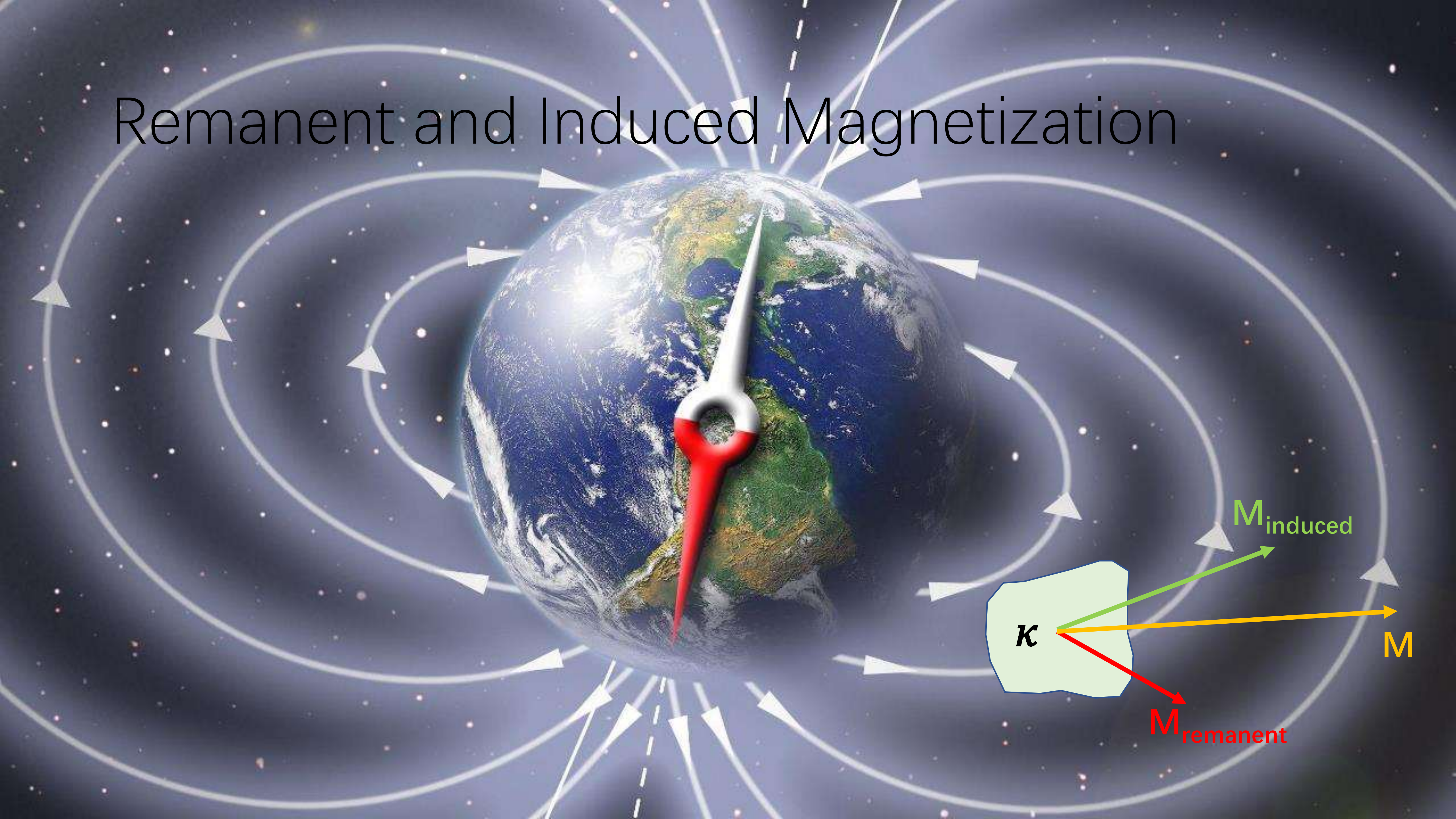
Ancient Magnetic Field



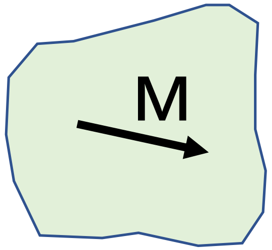
Modern Magnetic Field

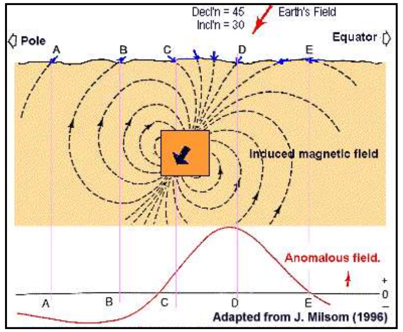


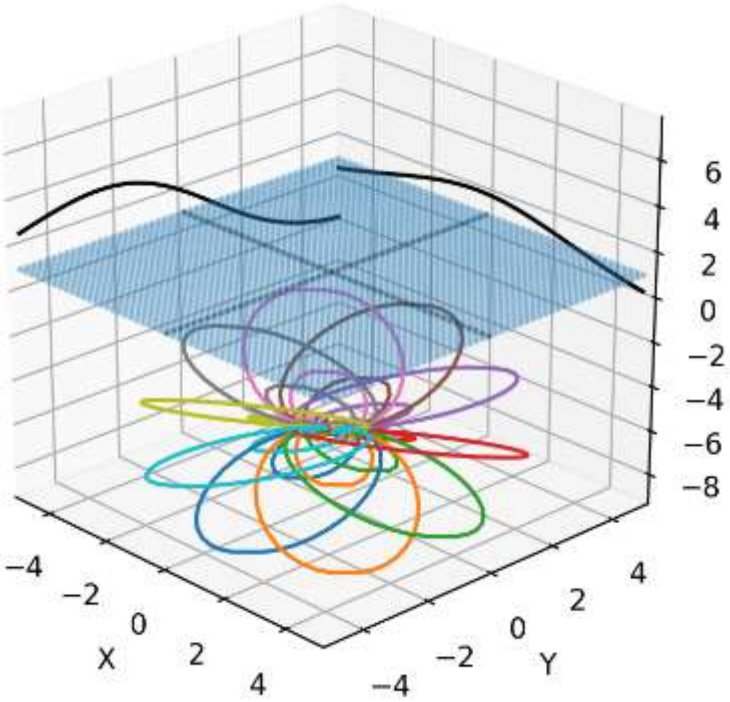
Remanent and Induced Magnetization

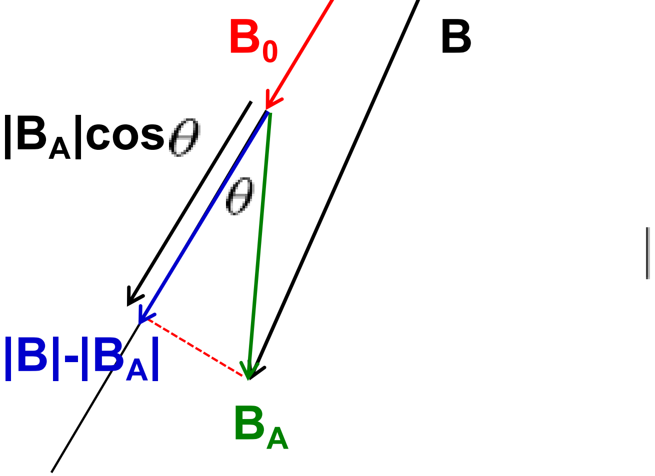


Magnetic Anomaly – Magnetized Objects





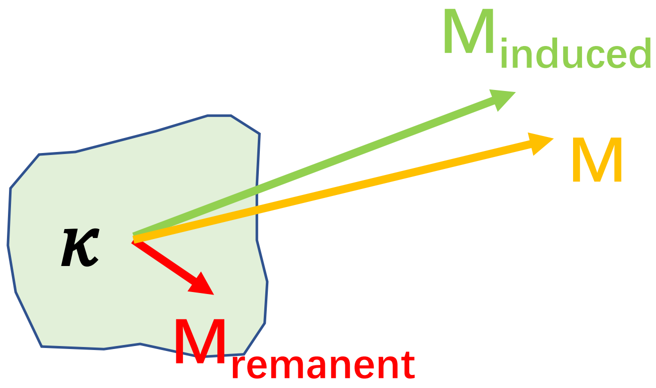




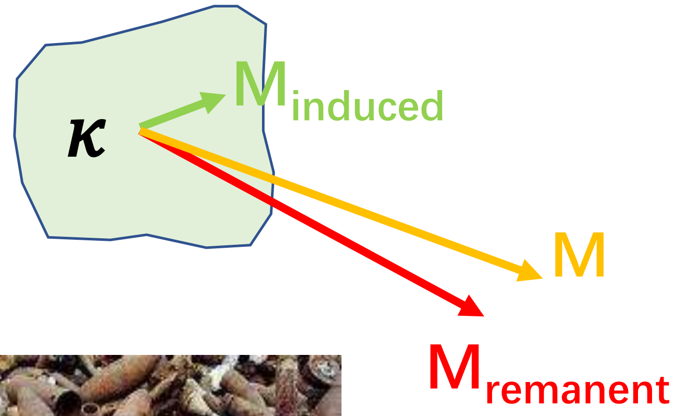
Total-field anomaly

$$\begin{aligned}|\triangle\vec{B}| &= |\vec{B}_0+\vec{B}_A|-|\vec{B}_0| \\ &\simeq \vec{B}_A\cdot\hat{B}_0 \\ &= |\vec{B}_A|cos\theta\end{aligned}$$

Sources of Magnetization



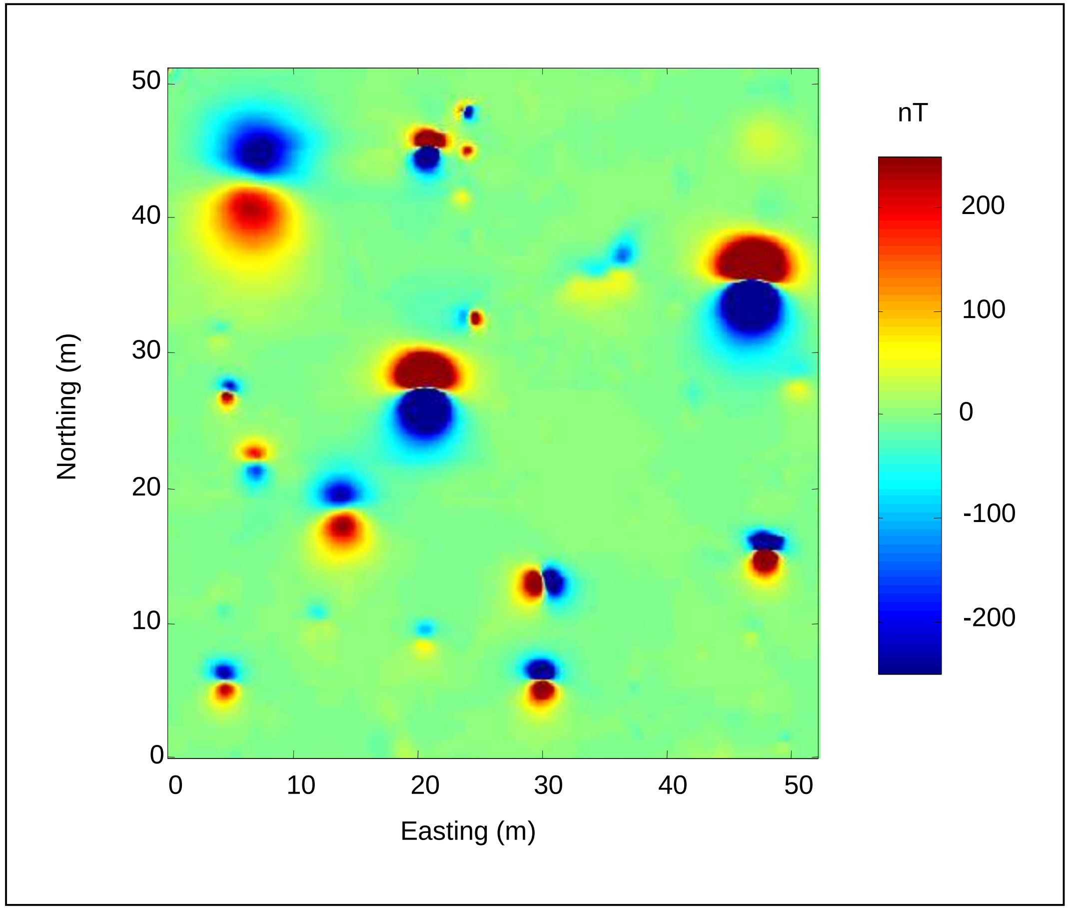
Susceptibility (magnetite)



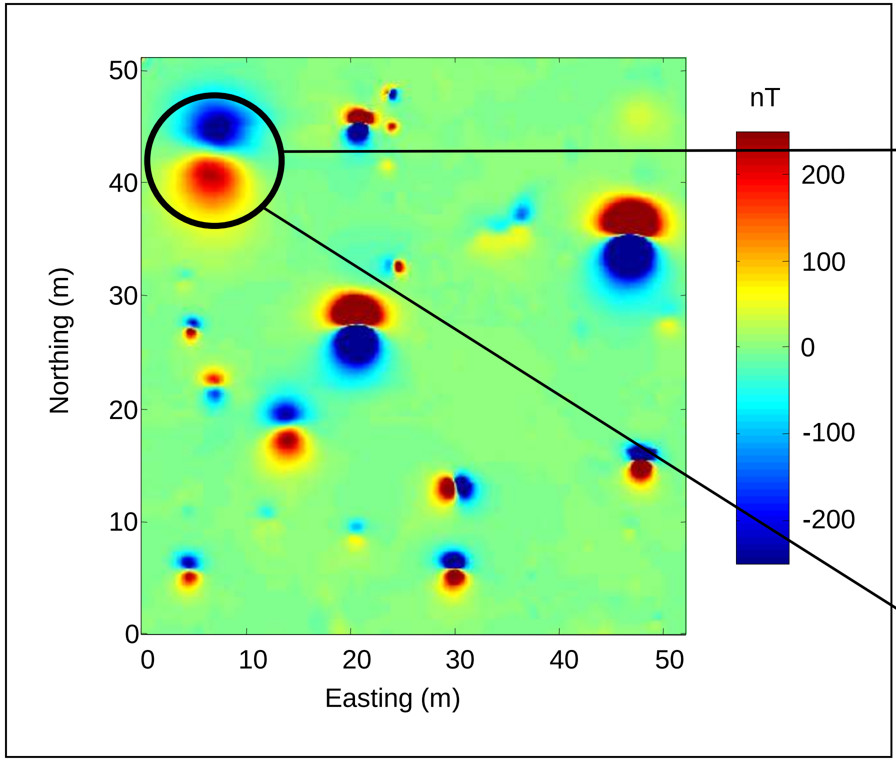
UXO

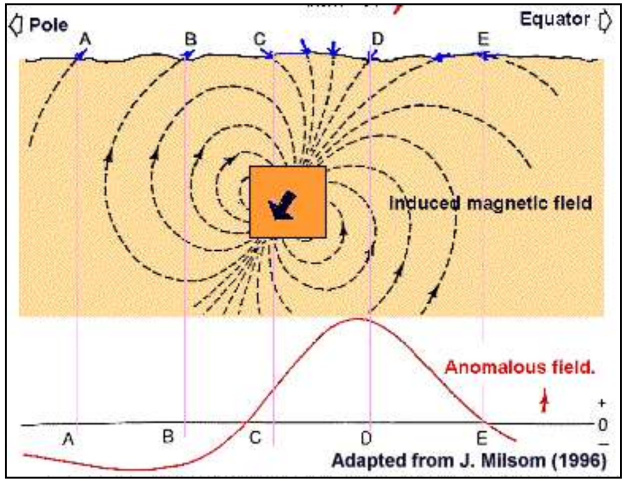
UXO (Unexploded Ordnance)

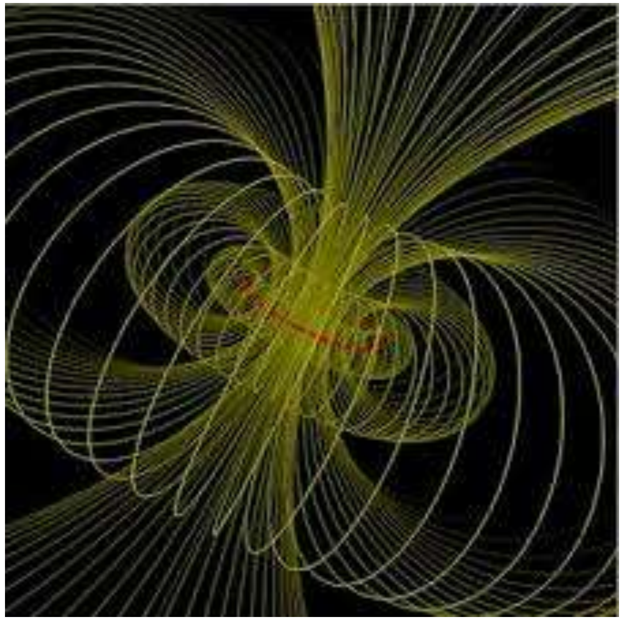
Magnetic Survey



Induced or Remanent?







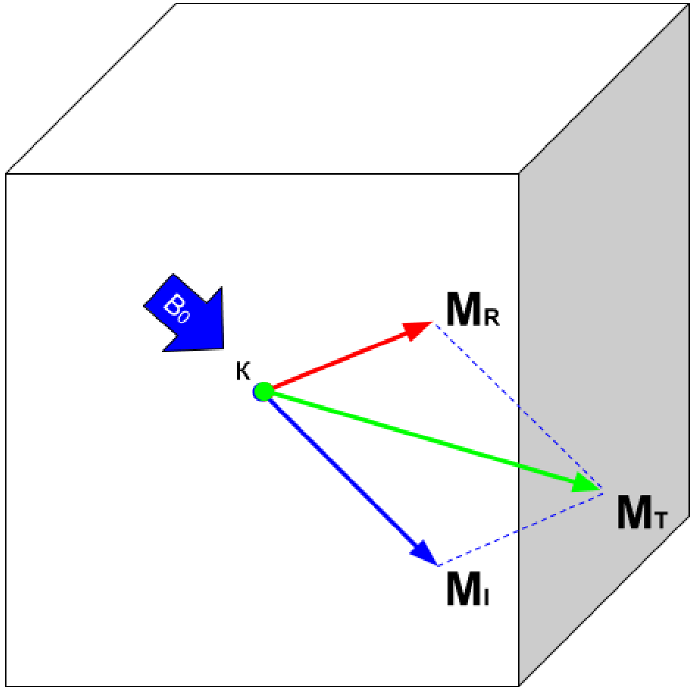
A UXO anomaly map:

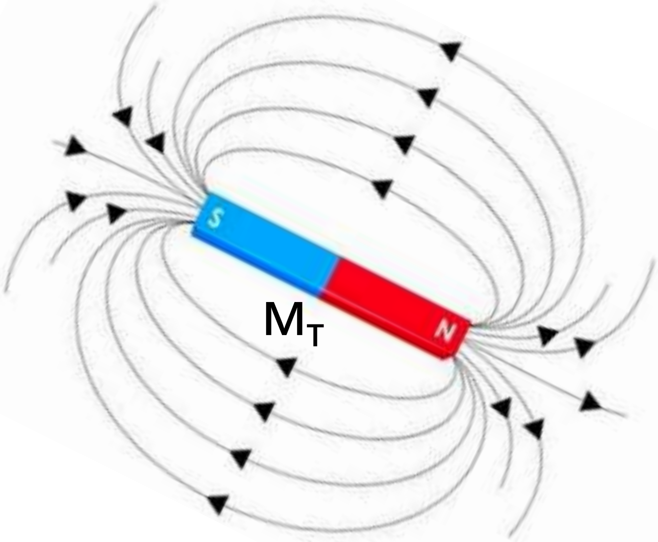
- Dipole field on the surface
- Induced or remanent?
- How can we tell it's a UXO?

Parameterization

Following parameters uniquely define a dipole:

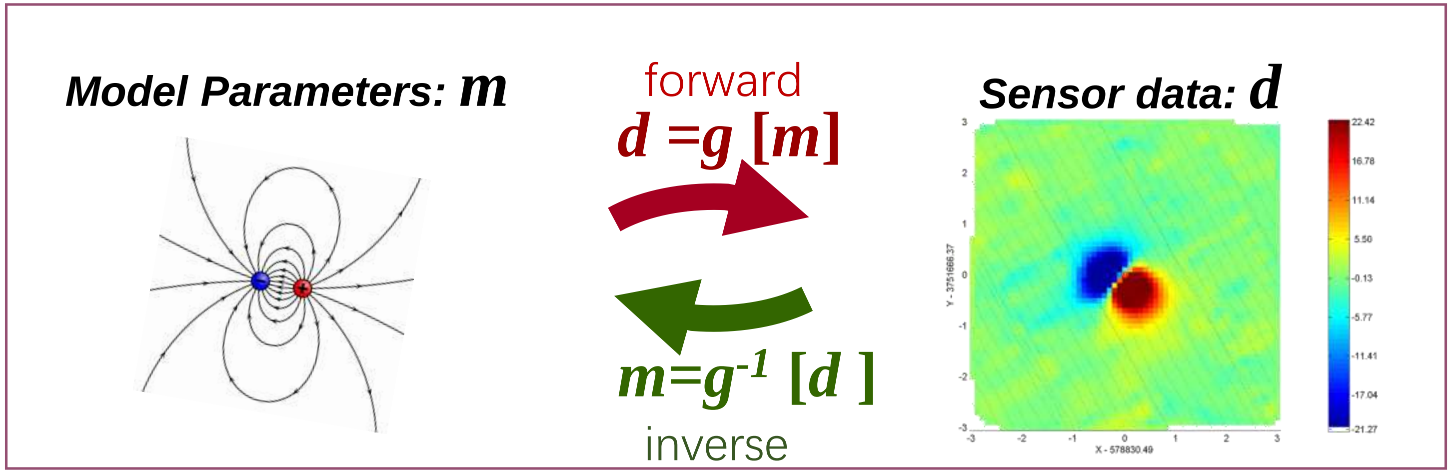
- Position (X, Y, Z)
- Total dipole moment vector (M_T) from induced and remanent (Mx, My, Mz)

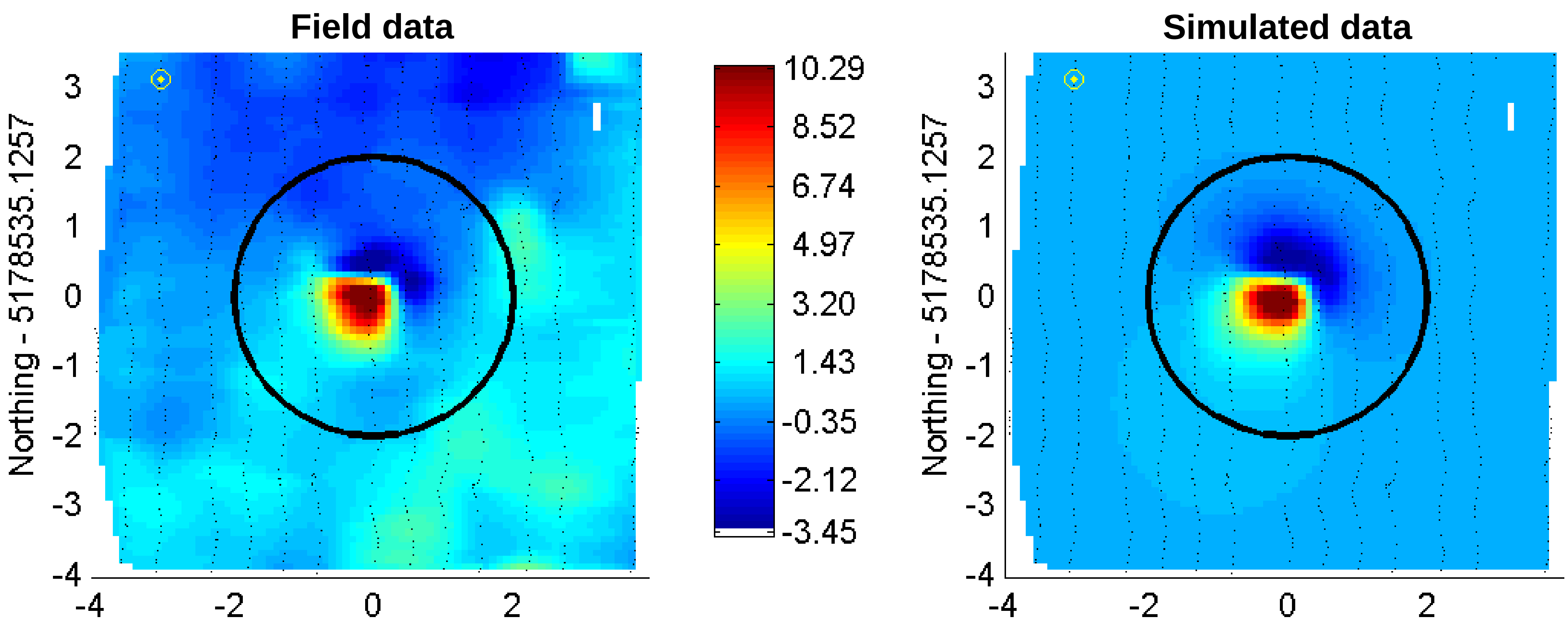




Dipole Model Inversion

- Six parameters *m* = [X, Y, Z, Mx, My, Mz]
- Data inversion: search the parameter space to find a particular combination of [X, Y, Z, Mx, My, Mz] that reproduces the dipole pattern on the map
- Automatic search or manual data fitting





Easting = -0.13 m; Northing = 0.16 m

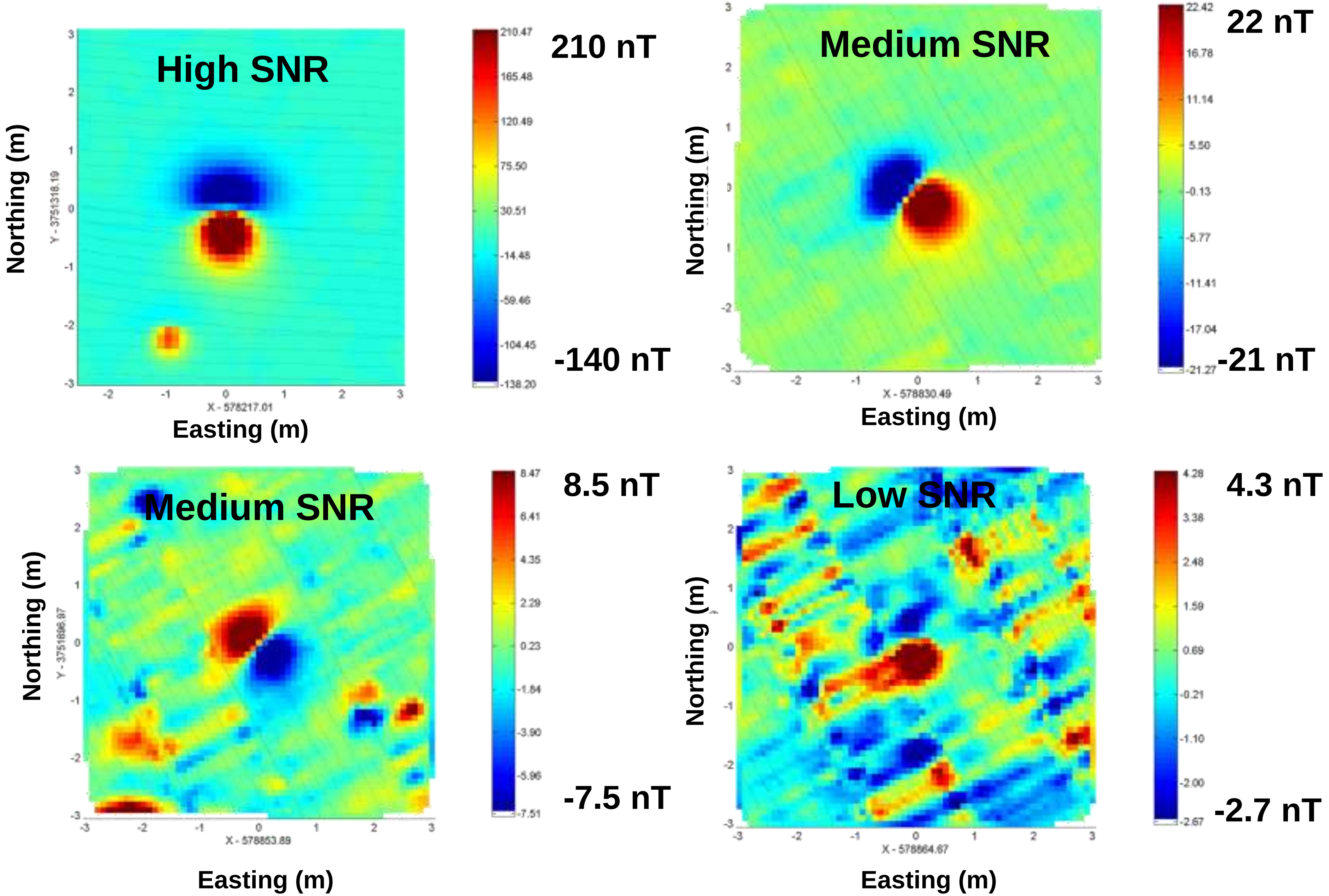
Depth = 0.26 m; Moment = 0.0226 Am^2

Azimuth = 37^o ; Dip = 28.8^o

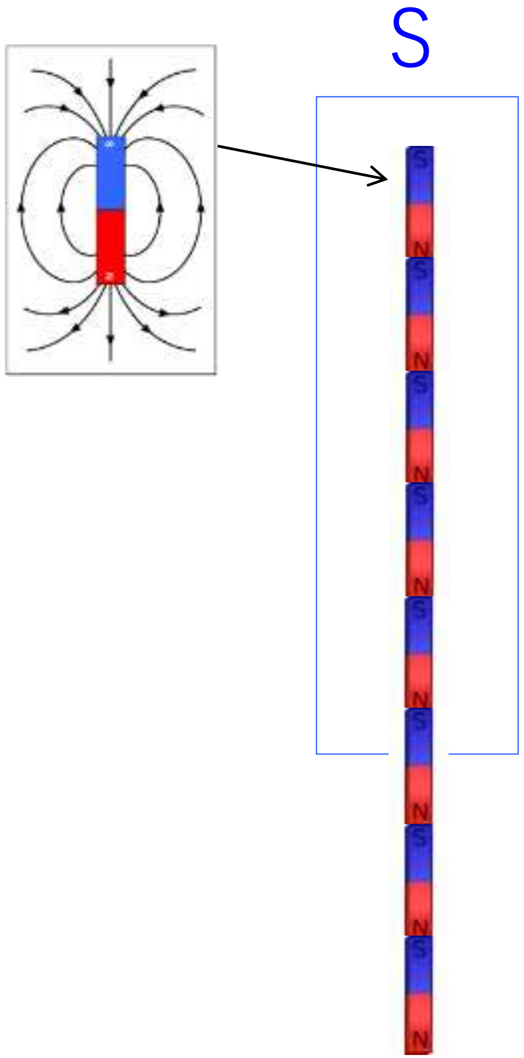
Fit quality = 0.95

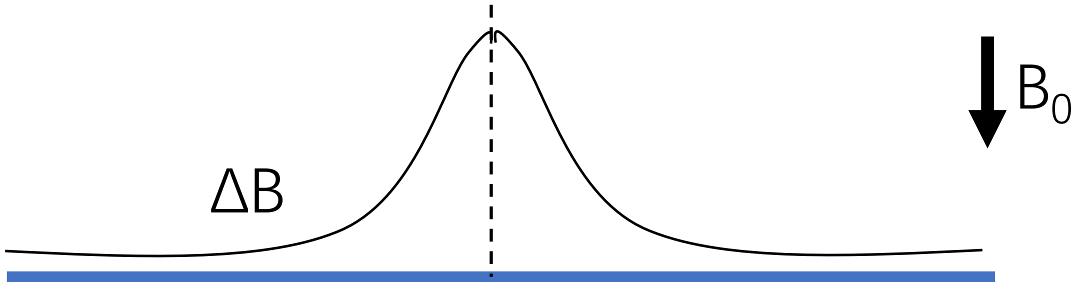
Use the recovered dipole parameters to identify UXO

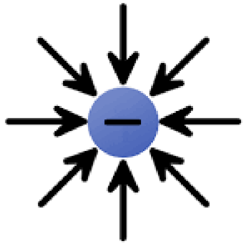
Practical Issues



Build a Long Rod using Dipoles



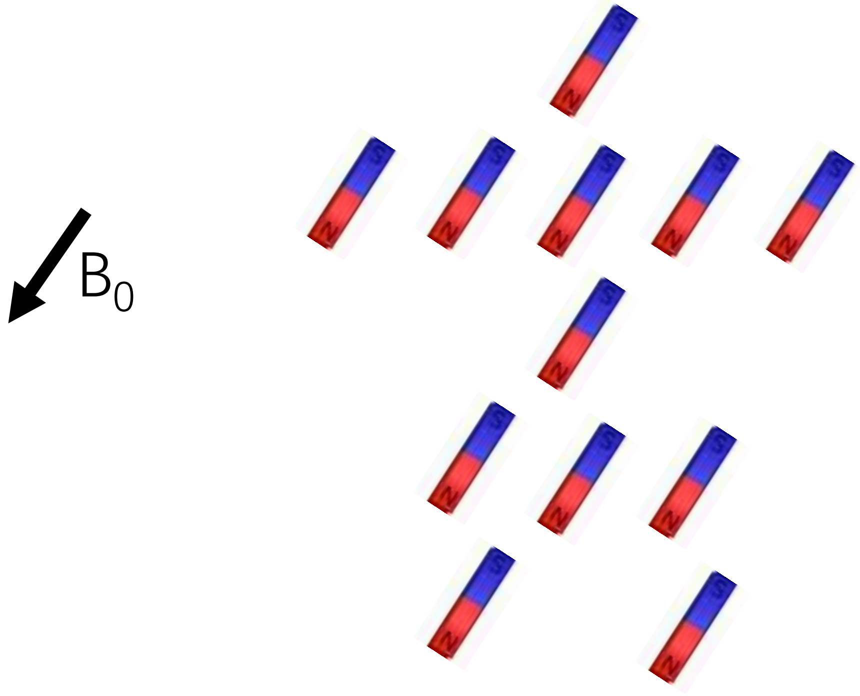


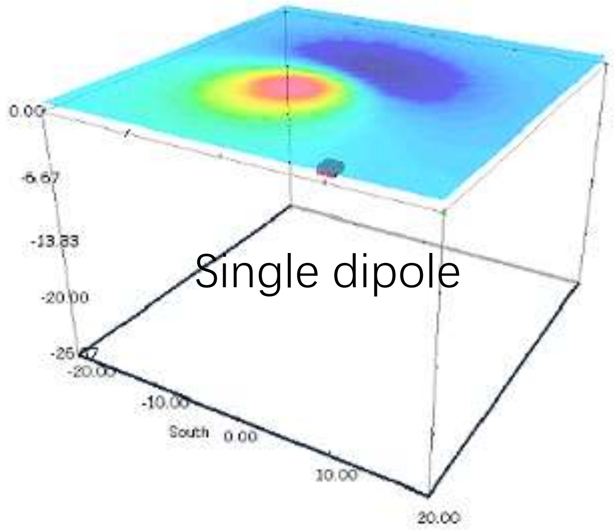


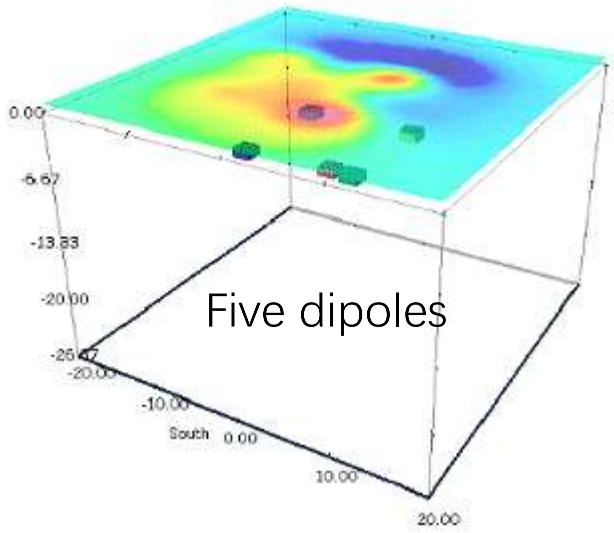
$$\mathbf{B} = \frac{\mu_0 Q}{4\pi r^2}\hat{\mathbf{r}}$$

- N and S inside the rod cancel out
- Net negative and positive charge at two ends
- Only “see” one charge if the rod is vertical and long
- A **monopole** anomaly (field lines determined by a single magnetic charge)

Build a Complex Body







Superposition: Sum up contribution from each dipol

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{r^5} - \frac{\mathbf{m}}{r^3}\right)$$

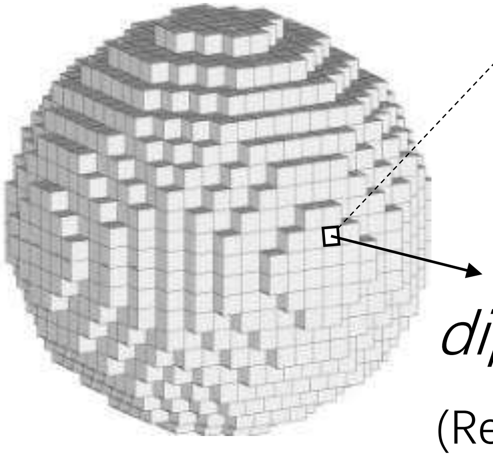
Arbitrarily Shaped Objects

Superposition $\sum_i B_i$

P

r_i

$$\mathbf{B}(\mathbf{r}) = \frac{\mu_0}{4\pi}\left(\frac{3\mathbf{r}(\mathbf{m}\cdot\mathbf{r})}{r^5} - \frac{\mathbf{m}}{r^3}\right)$$



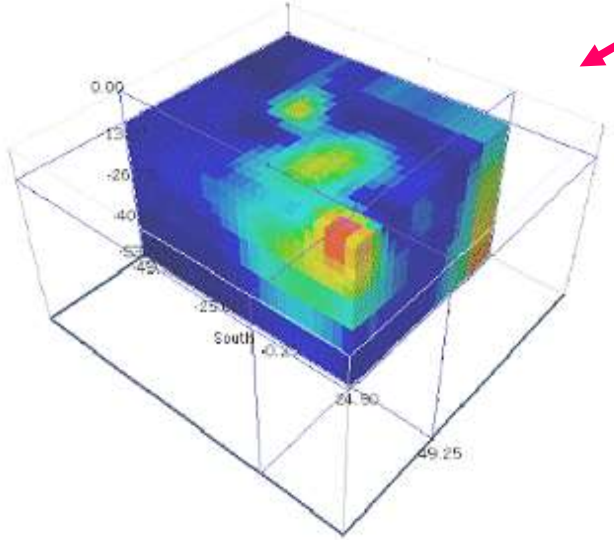
dipole moment: $m_i = \Delta V_i M_i$

(Recall gravity)

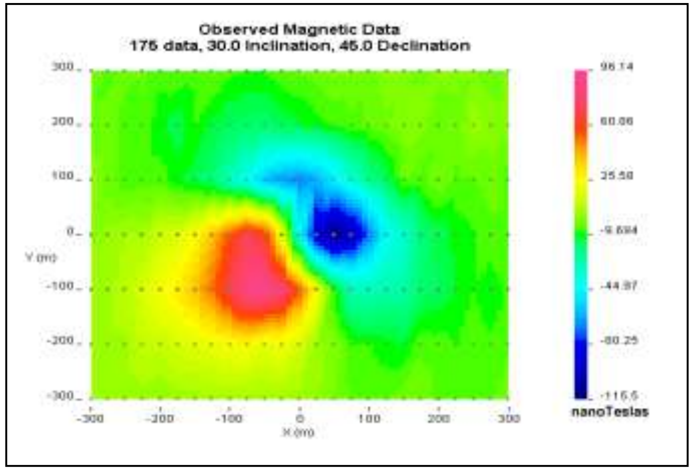
Can you think of any potential problem with this integration approach?

Arbitrary Magnetic Dipole Applet

A complicated earth model of κ
(Induced magnetization)



Inversion

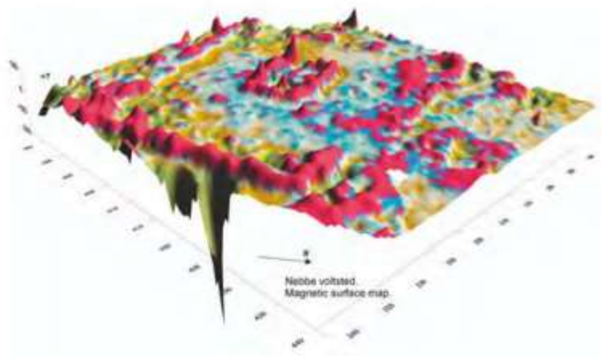


Divide the earth into many cells that contribute to the data on surface

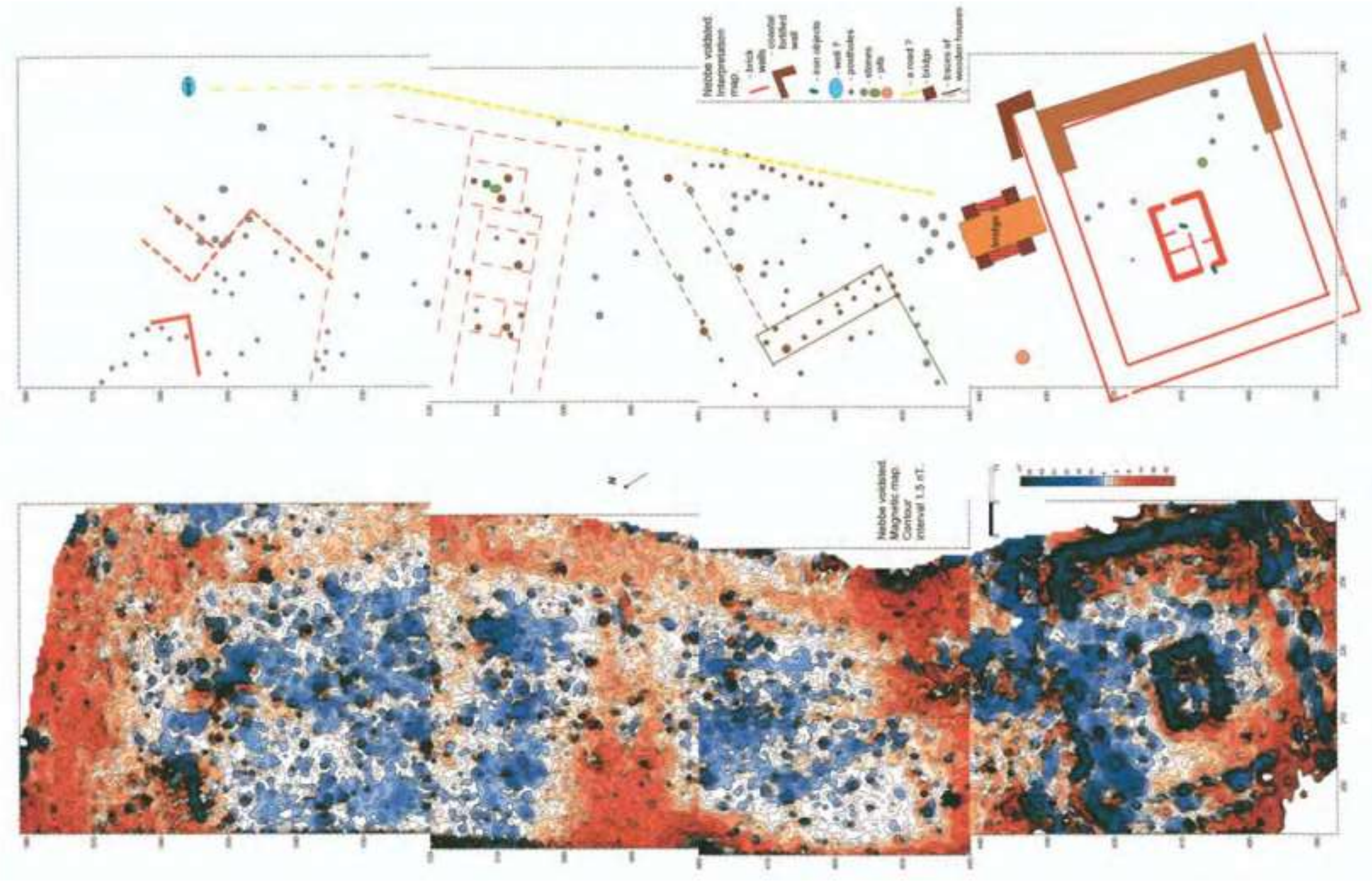
- Each cell has a constant but unknown susceptibility (induced magnetization only)
- Each cell has an unknown magnetization vector (induced and/or remanent magnetization)

Magnetic Survey for Archaeology

The site Nebbe Castle consists of three low hills. Magnetic surveying has been carried out on all of them (view from the north).

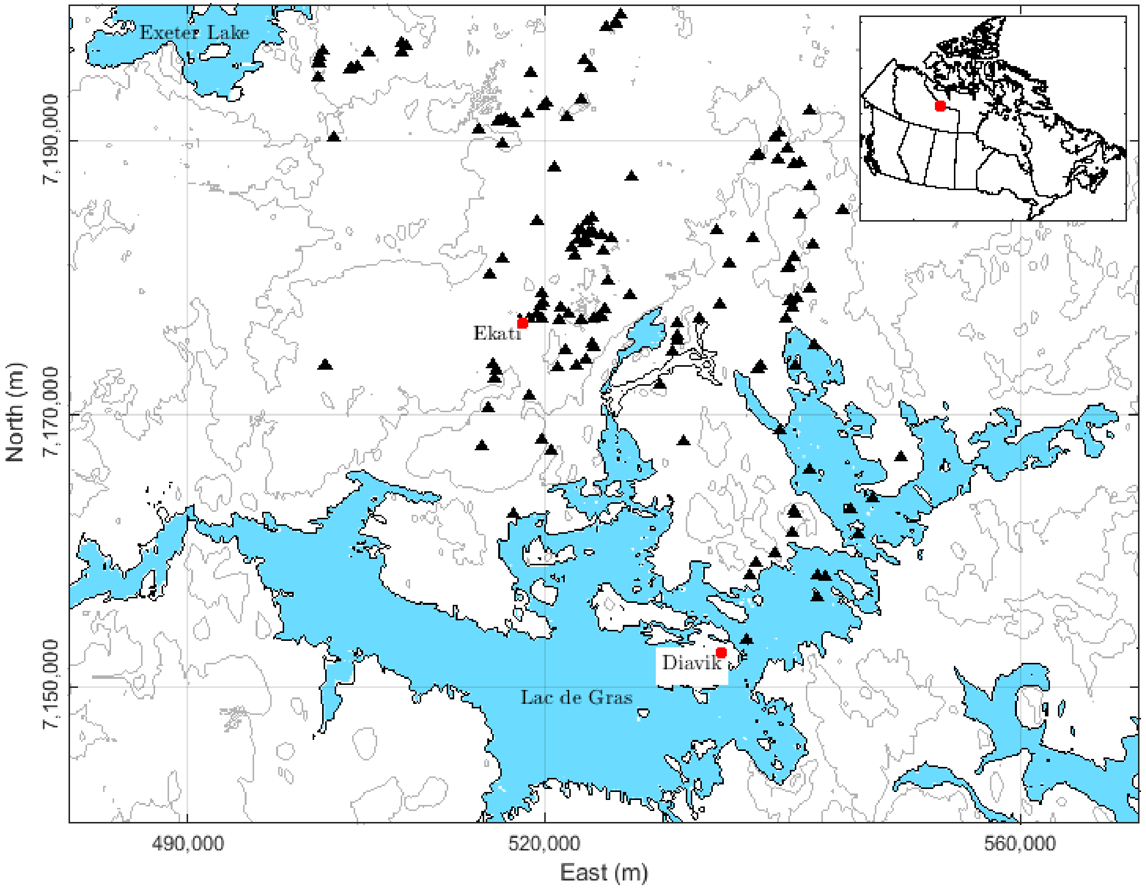


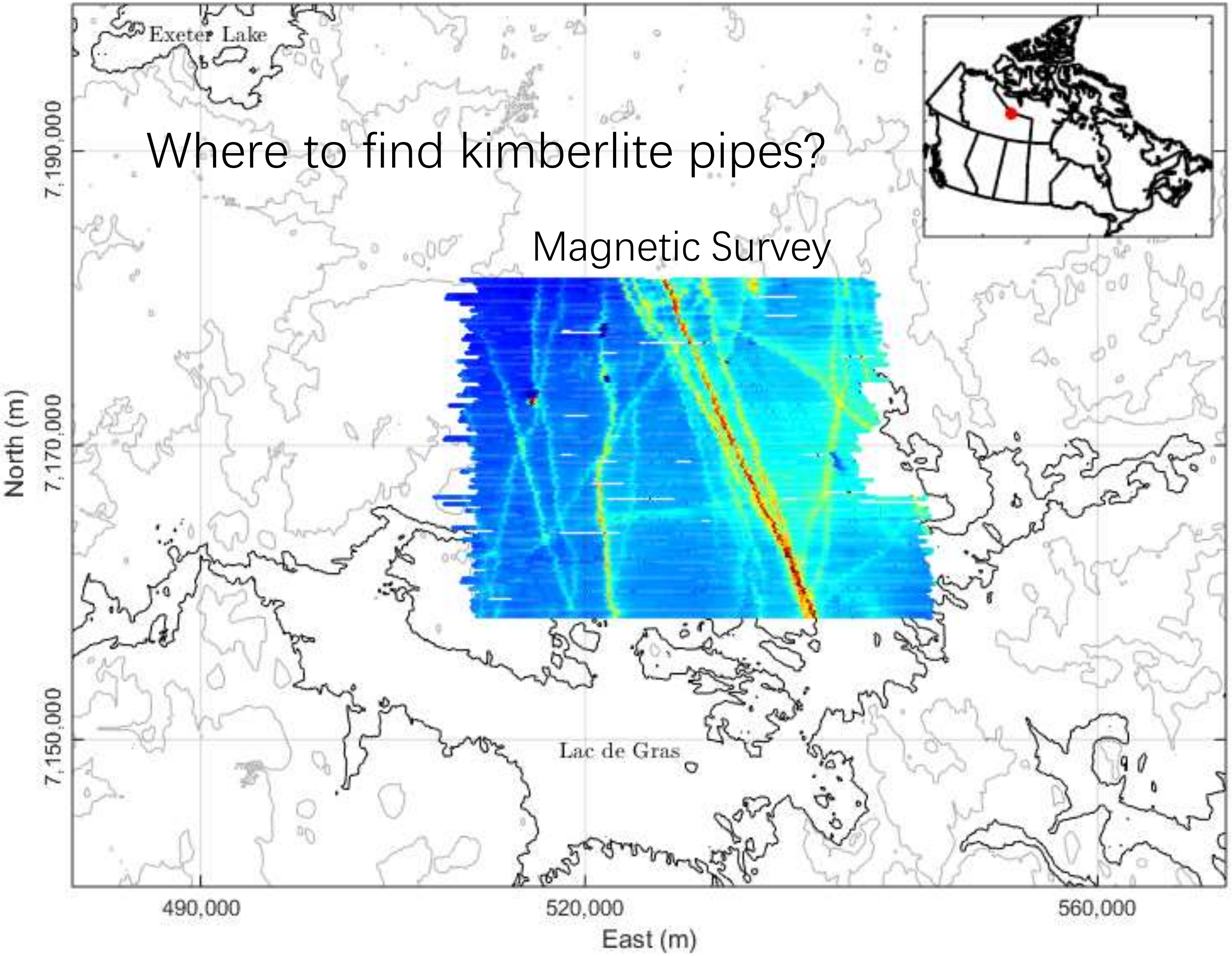
Magnetic perspective map of the Nebbe Castle.



http://www.gemsys.ca/wp-content/uploads/2013/04/10_Years_of_Overhauser_for_Archaeology.pdf

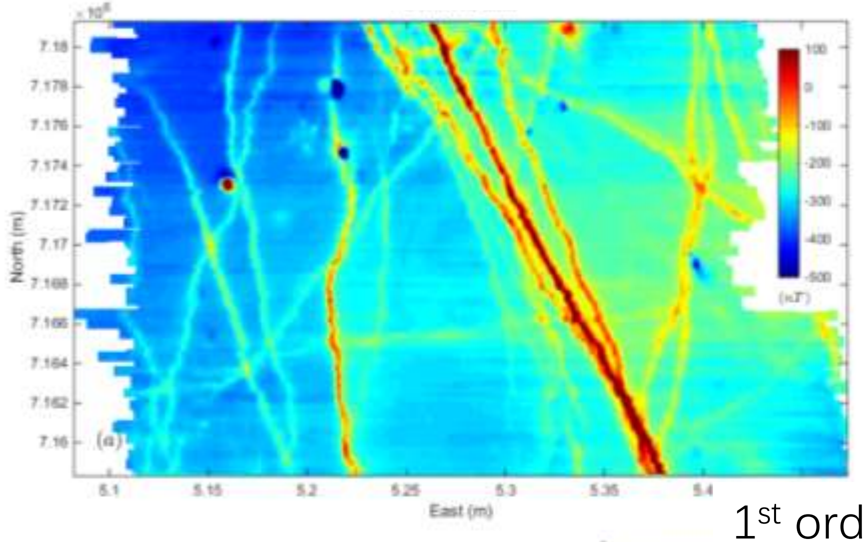
Ekati Diamond Property, Northwest Territories



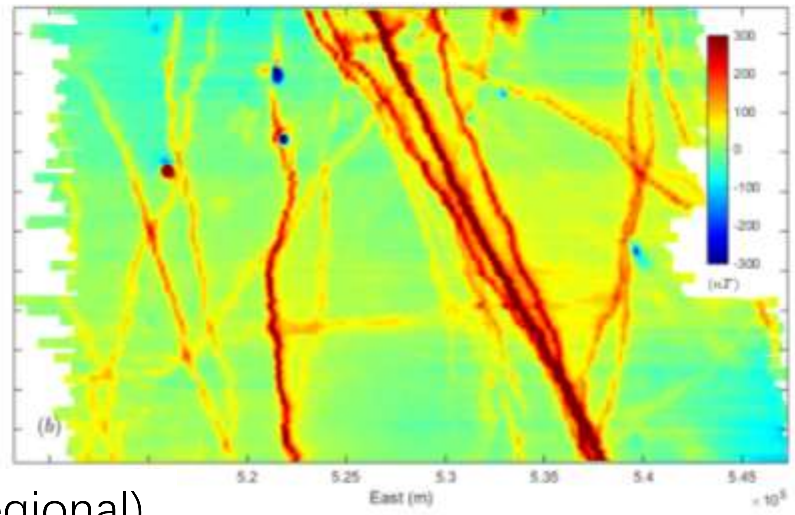

Where to find kimberlite pipes?
Magnetic Survey
Exeter Lake
Lac de Gras
North (m)
7,190,000
7,170,000
7,150,000
East (m)
490,000
520,000
560,000

Data Processing: Regional Removal

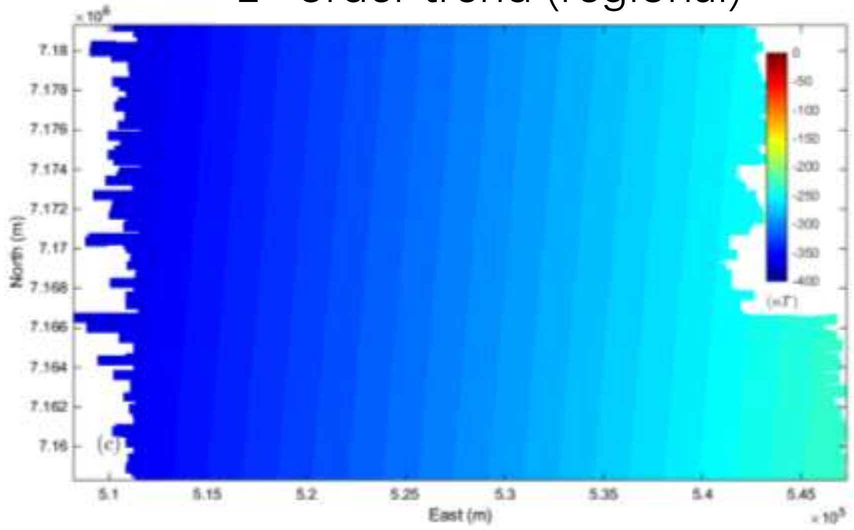
Original data



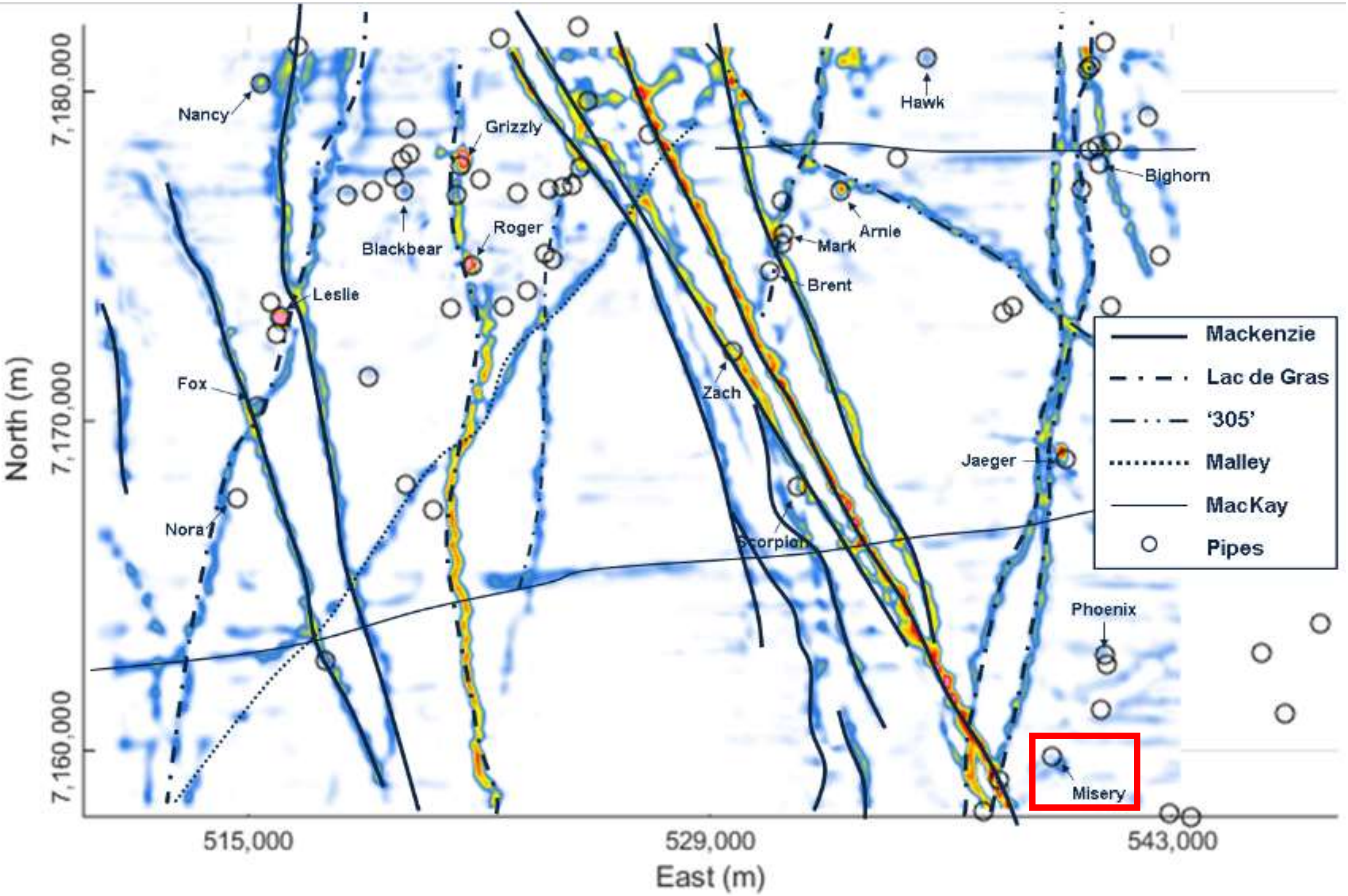
After regional removal



1st order trend (regional)



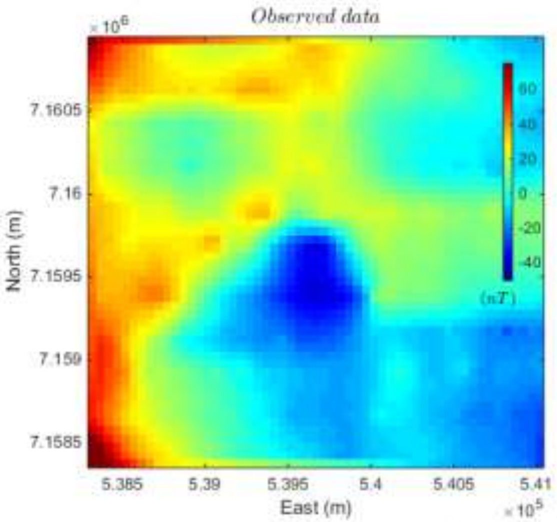
Misery Pipe

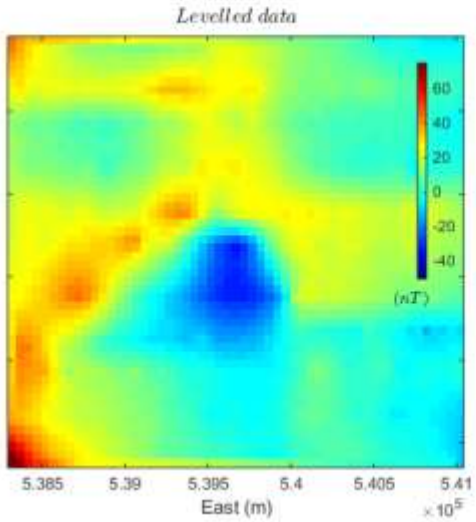


Nancy
Grizzly
Blackbear
Roger
Leslie
Fox
Nora
Hawk
Bighorn
Arnie
Mark
Brent
Zach
Scorpion
Jaeger
Phoenix
Misery
Mackenzie
Lac de Gras
'305'
Malley
MacKay
Pipes
7,180,000
7,170,000
7,160,000
North (m)
515,000
529,000
543,000
East (m)

Data Around Misery Pipe

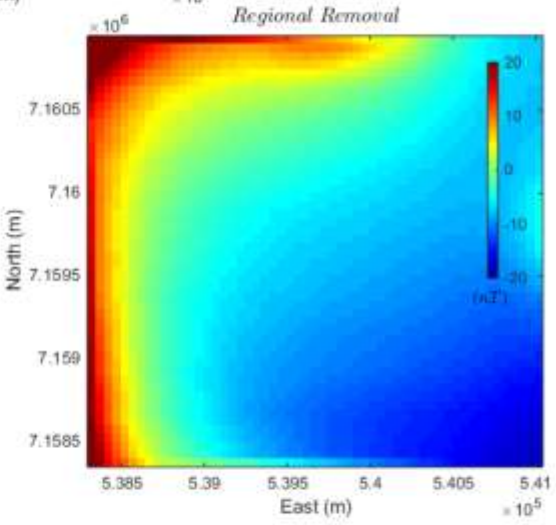
Original





After regional removal

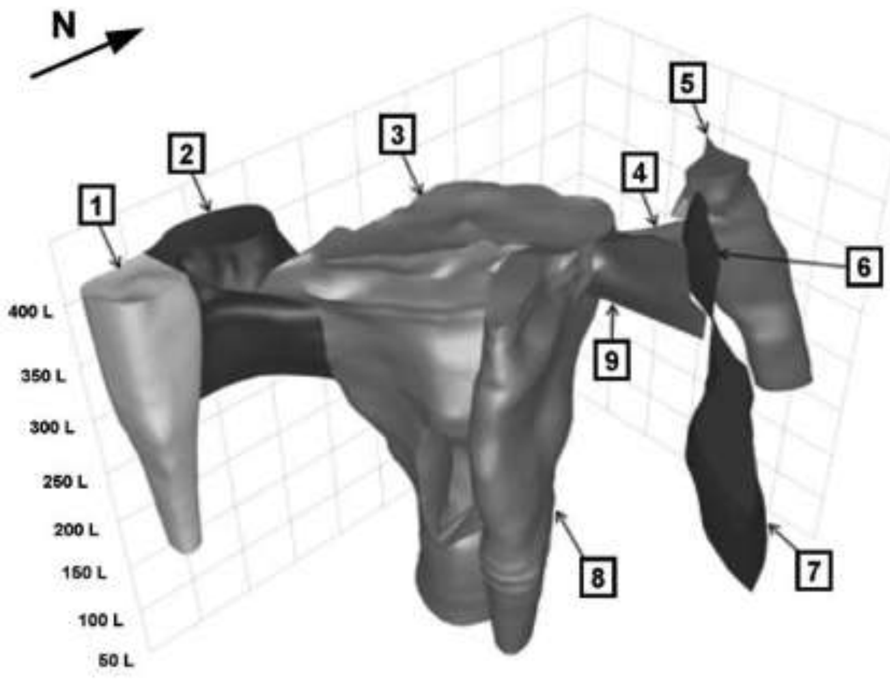
Regional



- Local anomaly showing reversely magnetized body (remanent)
- Removal of the regional field to enhance the target (ready for inversion)

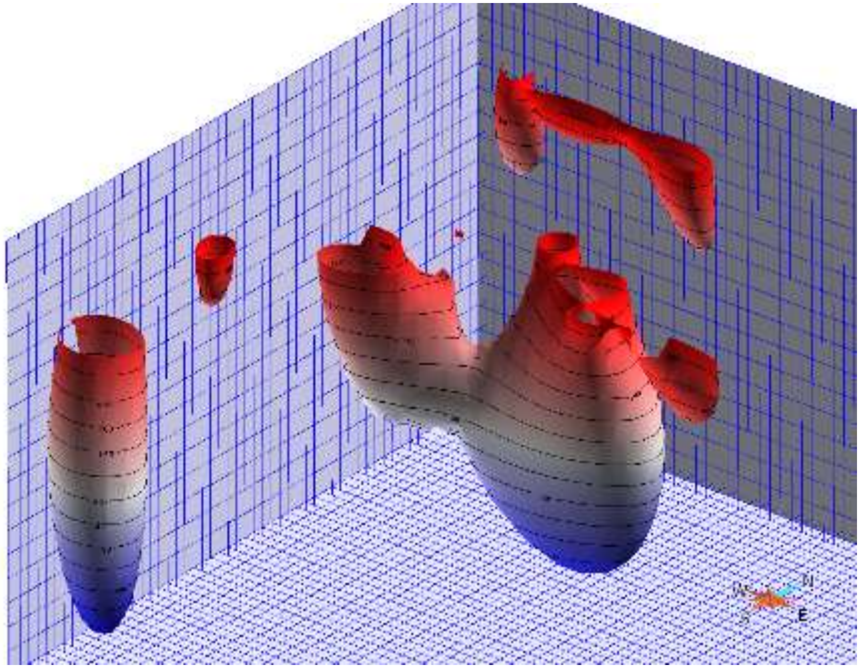
Inversion Result

Geology from drilling



Nowicki et al. (2004)

Inverted model



Summary of Magnetic

- Magnetization: Induced (susceptibility) and remanent (heat)
- Magnetic dipole field
- TMI anomaly data on surface (projection to B_0)
- Superposition
- Applications: military, archaeology, resource, engineering, etc.