What do we know so far?

- Geophysical surveys measure the Earth's response to physical input(s)
- Geophysics is viable if there is sufficient contrast in one or more physical properties
- For each physical property contrast there is one or more geophysical methods
- We have a 7-step framework for using geophysics to answer geoscientific questions

Today’s topics

- Magnetism fundamentals
- Physical properties
- Magnetic fields and fluxes
- Remanent magnetization
- Magnetic methods (basic idea)
- Examples of applications

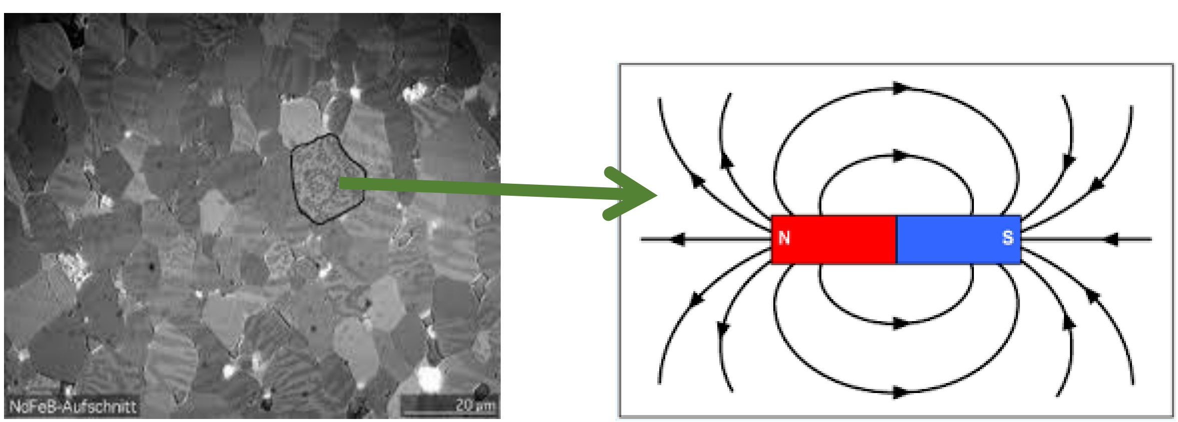
Magnetism Fundamentals

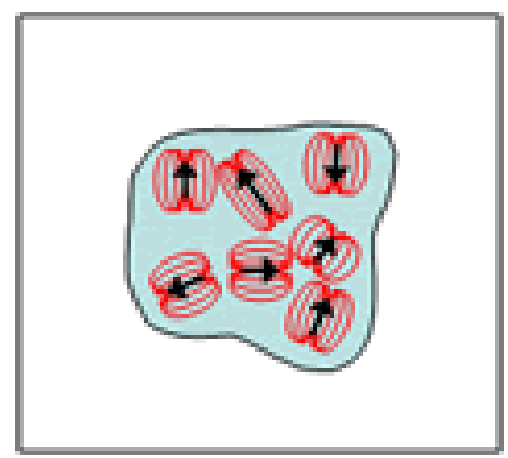
Magnetic materials and magnetization

- Mineral grains contain **magnetic domains** that behave like small bar magnets

- Bar magnets have a North and a South pole
  → **magnetic dipole**

- Each magnetic domain (dipole) contributes towards the overall magnetization of a material

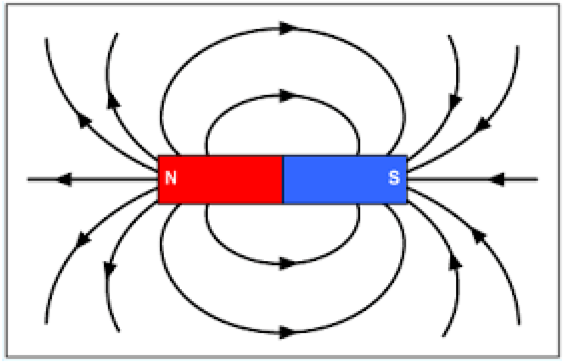




Magnetization and magnetic fields

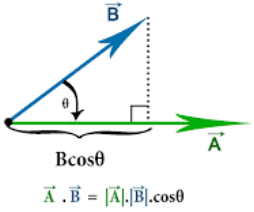
- Magnetization produces a magnetic field

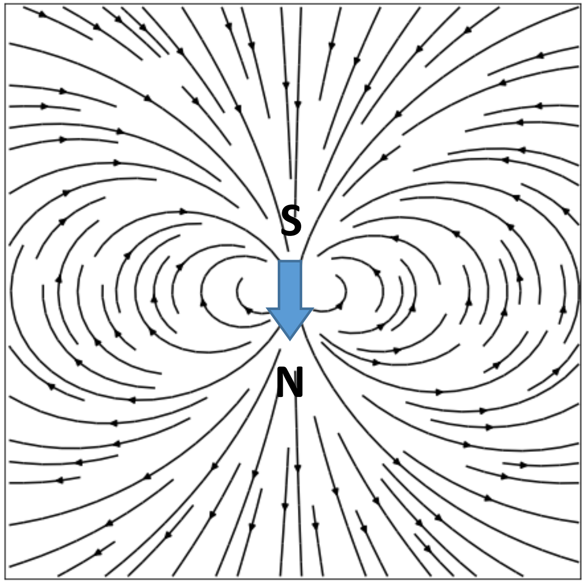
- Magnetic field lines extend from North pole to South pole



- Field due to a single dipole →

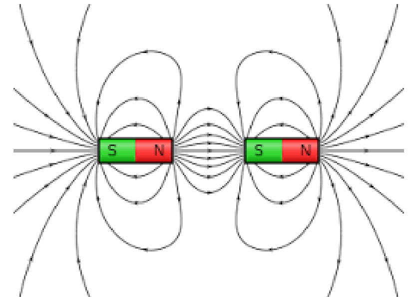
$$\vec{B} = \frac{\mu_0}{4\pi}\left(\frac{3\vec{r}(\vec{m}\cdot\vec{r})}{r^5} - \frac{\vec{m}}{r^3}\right)$$



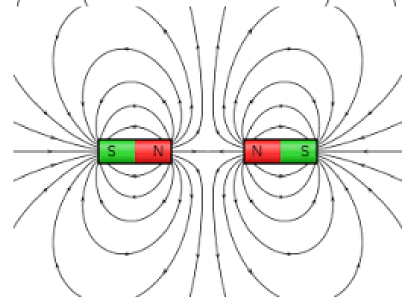


How do bar magnets (dipoles) interact?

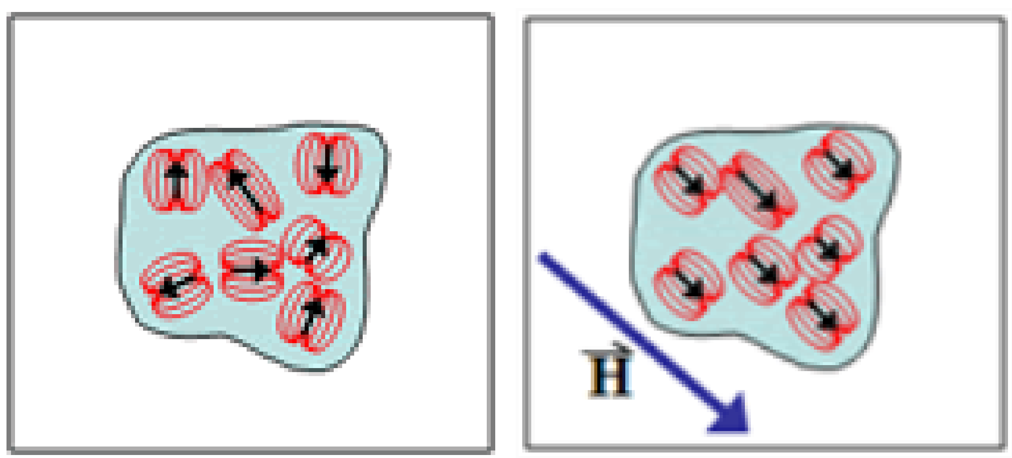
- Opposite poles attract



- Like poles repel



- Small magnets align with fields from stronger magnets

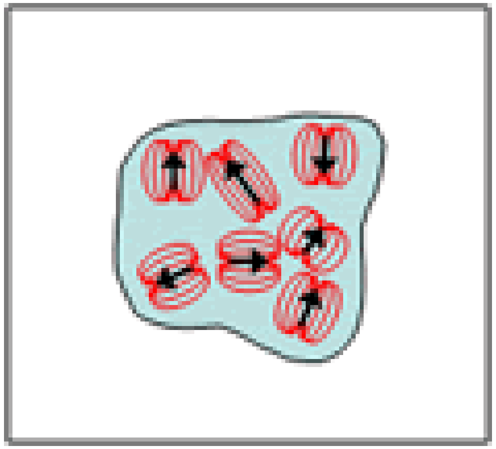


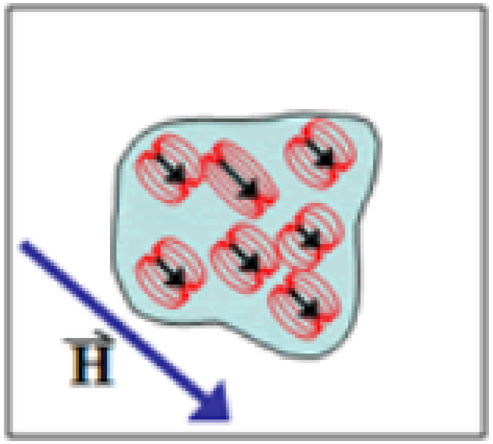
Dipole moment and magnetization

- **Magnetic dipole moment** m_i defines the strength and orientation of a magnetization (domain or rock)
- **Magnetization** is average magnetic moment per unit volume

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

- **Units:** dipole moment per unit volume Ampere/meter (A/m)





More on dipole moments

- **Magnetic dipole moment** m_i defines the strength and orientation of a magnetization
- **Magnetization** is average magnetic moment per unit volume

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

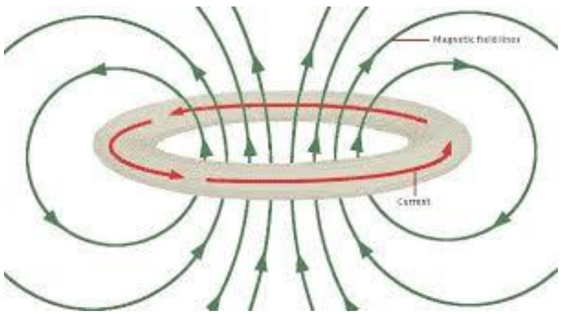
- Integrate magnetism to get dipole moment for a whole sample

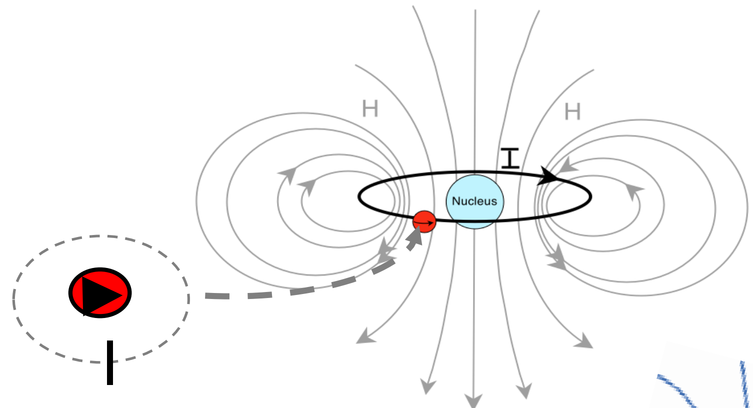
$$m = \int M dV$$

- Dipole moment has units Ampere-m^2

Sources of magnetism

Magnetism results from movement of electric charges

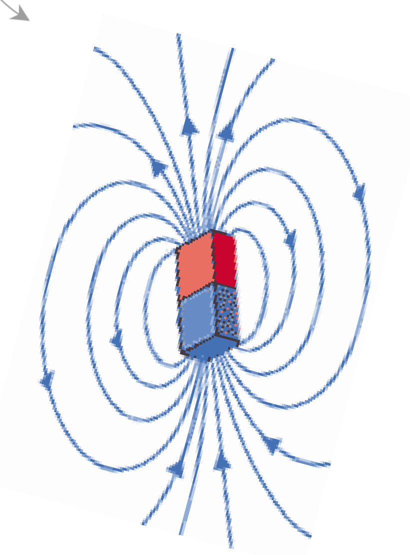




- A current loop produces magnetic fields

- Atoms can have a dipole moment and produce fields:
    - Electrons and protons spin on their axis
    - Electron circulate around the atomic nucleus.

- A magnetic domain is a region of uniform atomic spins



Physical Properties

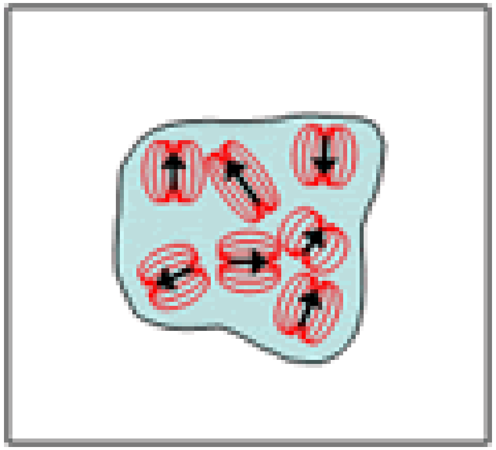
Reading on the GPG:

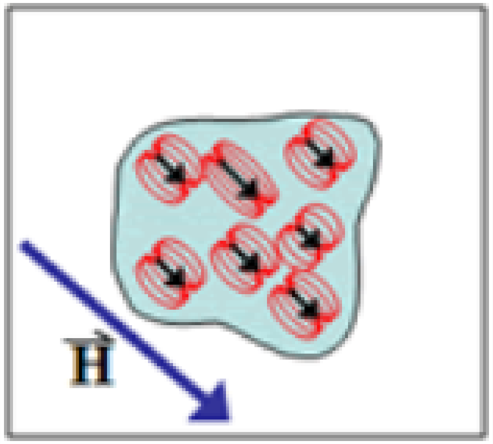
https://gpg.geosci.xyz/content/physical_properties/magnetics_susceptibility_duplicate.html#susceptibility

What we learned

- The magnetization changes when a magnetic field is applied

- **Induced magnetization** lies along direction of the applied field





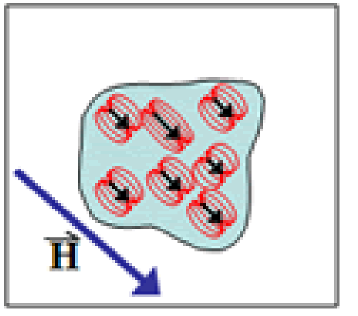
- How do we define the **induced magnetization** due to an applied magnetic field?

Magnetic Susceptibility: κ

- Defines strength of magnetization due to an external field

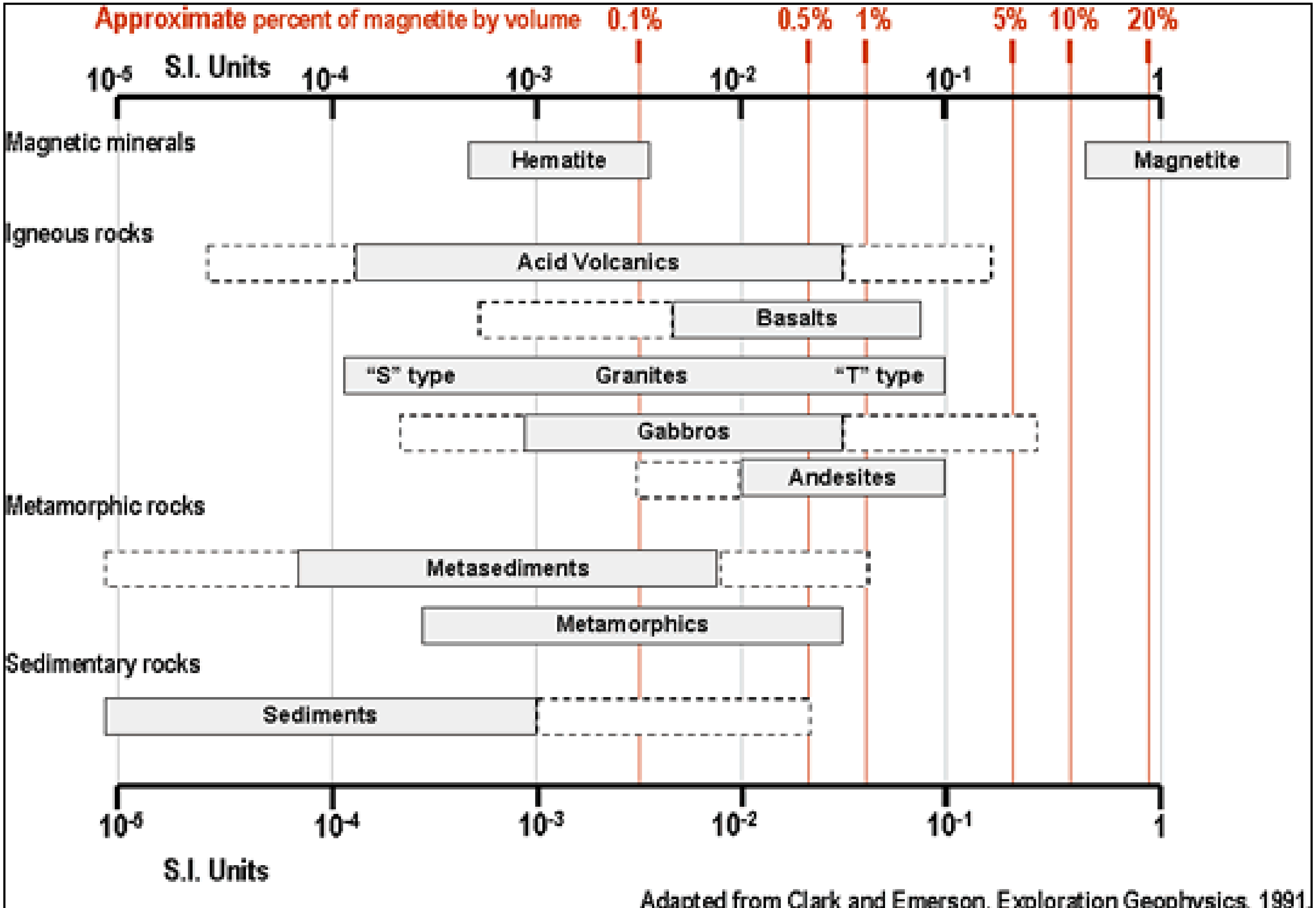
$$\vec{M} = \frac{\Sigma \vec{m}_i}{Volume}$$

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



- Magnetization parallel to inducing field
- Susceptibility units: dimensionless

Magnetic Susceptibility of Rocks



Different mechanisms for induced magnetization

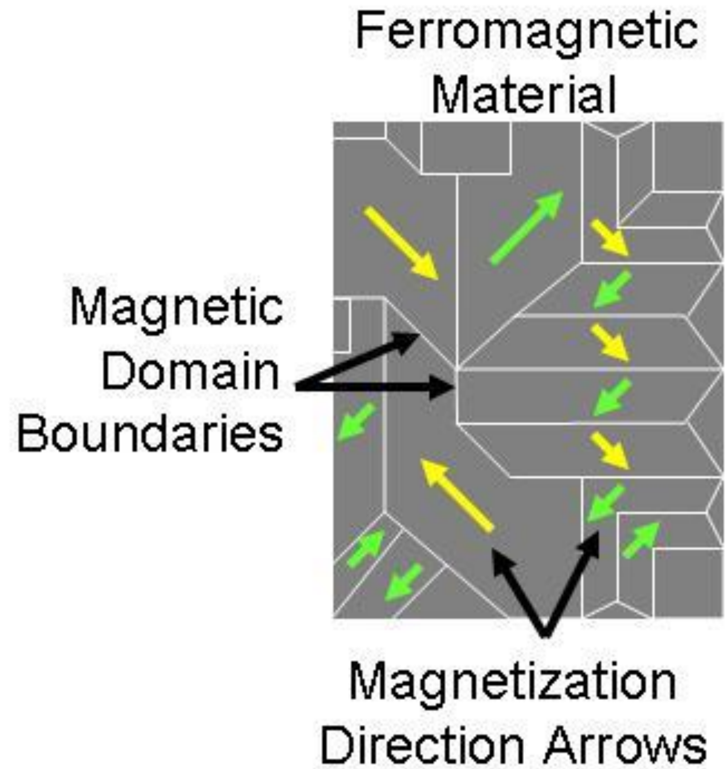
$$\vec{M} = \kappa \vec{H}$$

- Ferromagnetic Materials: $\kappa \sim +1 \rightarrow +10$
- Ferrimagnetic Materials: $\kappa \sim +1 \rightarrow +10$
- Antiferromagnetic Materials: $\kappa \sim +10^{-4} \rightarrow +10^{-3}$
- Paramagnetic Materials: $\kappa \sim +10^{-5} \rightarrow +10^{-2}$
- Diamagnetic Materials: $\kappa \sim -10^{-5}$.

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

Ferromagnetic Materials:
$\kappa \sim +1 \rightarrow +10$

(induced field can be 10× inducing field). Magnetization is organized in domains of many atoms.

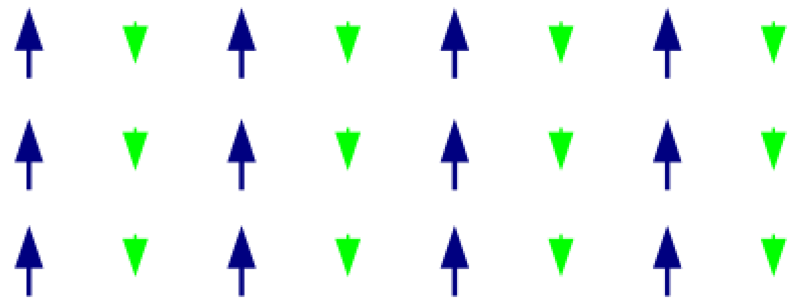


Iron, cobalt and nickel are ferromagnetic.

We place iron cores inside solenoids to make their magnetic fields stronger.

Anthropogenic features made of iron like pipes, rebar and drums are magnetized by Earth's field and show up well on magnetic surveys.

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



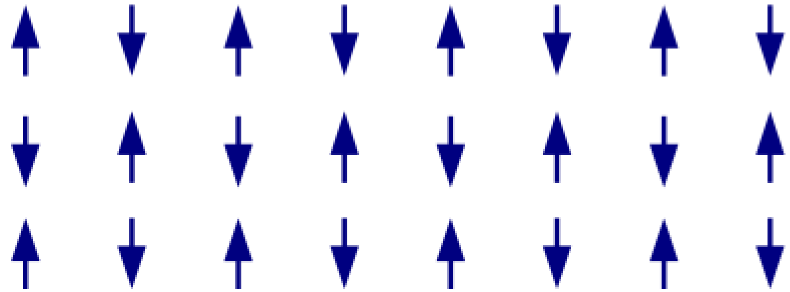
Ferrimagnetic Materials:
$\kappa \sim +1 \rightarrow +10$

are like ferromagnetics, but atoms in different positions in the crystal lattice have opposite and <u>un</u>equal magnetic moments.

Magnetite, ilmenite, titanomagnetite and pyrrhotite are examples

These minerals are responsible for most of the geological anomalies on magnetic surveys.

Antiferromagnetic Materials
$\kappa \sim +10^{-4} \rightarrow +10^{-3}$

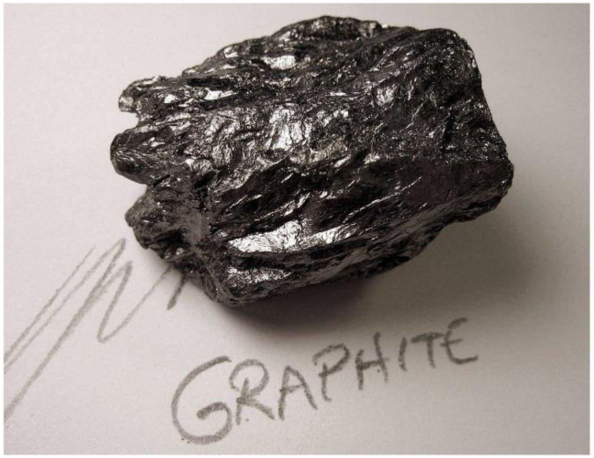


Neighbouring atoms have opposite and nearly equal magnetic moments leading to relatively small susceptibility.

Hematite (Fe_2O_3) is the most common example.

Diamagnetic Materials: negative κ approximately -10^{-5} (induced and inducing fields are in opposite directions).

- Oppose the applied magnetic field because that field changes the magnetic moments of electrons in their orbitals in a systematic way
- All materials are technically diamagnetic, but other forms of magnetization (if present) are much stronger
- Halite, graphite, calcite and quartz are common diamagnetic minerals



Paramagnetic Materials: positive κ in range 10^{-5} to 10^{-2}

- Have unpaired electrons which align in a magnetic field to create an induced magnetic field

- Many metals are paramagnetic.

http://periodictable.com/Elements/074/index.html

Magnetic Fields and Fluxes

Magnetic fields, fluxes and permeability

$\vec{B}$: Magnetic Flux Density (Wb/m^2 = Tesla)
$\vec{H}$: Magnetic Field (A/m)
$\vec{B} = \mu \vec{H}$

μ = magnetic permeability
$\mu = \mu_0(1 + \kappa)$

Magnetic permeability of free space:
$\mu_0 = 4\pi \times 10^{-7}$

Magnetic fields, fluxes and permeability

$\vec{B}$: Magnetic Flux Density $(Wb/m^2 = \text{Tesla})$
$\vec{H}$: Magnetic Field (A/m)

$$\boxed{\vec{B} = \mu\vec{H} = \mu_0(1+\kappa)\vec{H} = \mu_0(\vec{H} + \vec{M})}$$

Inducing field

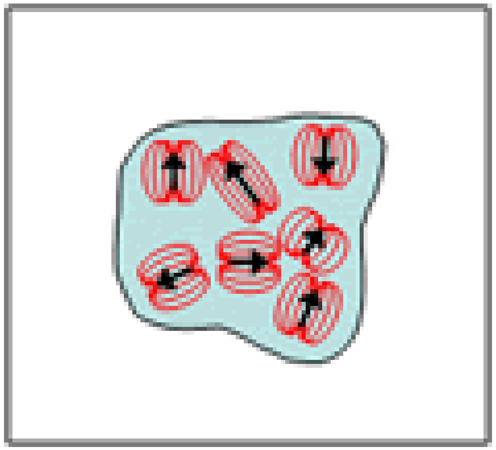
induced

μ = magnetic permeability
$\mu = \mu_0(1+\kappa)$

Magnetic permeability of free space:
$\mu_0 = 4\pi \times 10^{-7}$

Recap

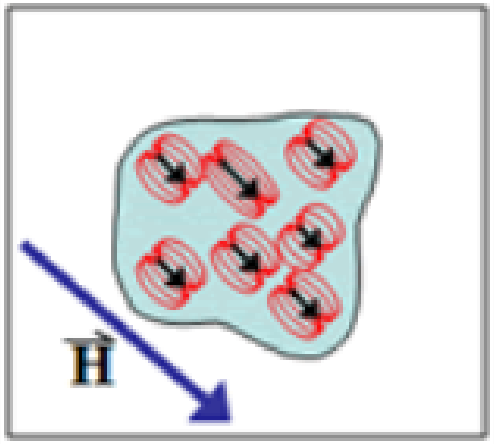
- Earth materials contain magnetic domains that behave like magnetic dipoles



- Magnetization is the total dipole moment per unit volume

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

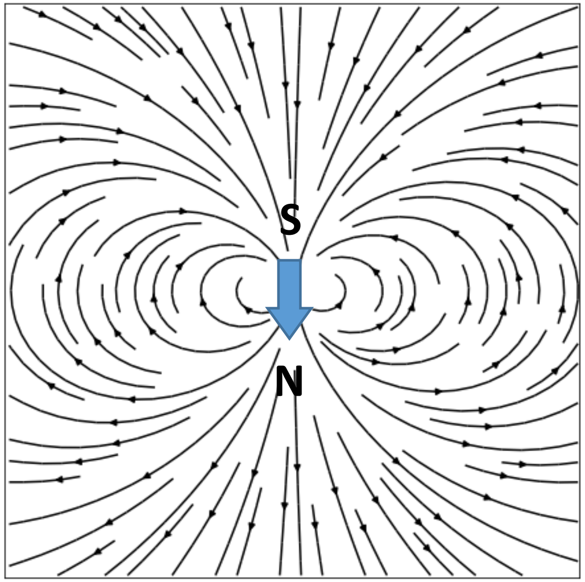
- Magnetic dipoles will re-orient along the direction of an inducing field



- The strength of induced magnetization is defined by the magnetic susceptibility

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

Recap



- Magnetization produces a magnetic field
- Field lines got from North to South pole
- Magnetic fields and fluxes are related by the magnetic permeability

$$\boxed{\vec{B} = \mu\vec{H} = \mu_0(1+\kappa)\vec{H} = \mu_0(\underbrace{\vec{H}}_{\text{inducing}} + \underbrace{\vec{M}}_{\text{induced}})}$$

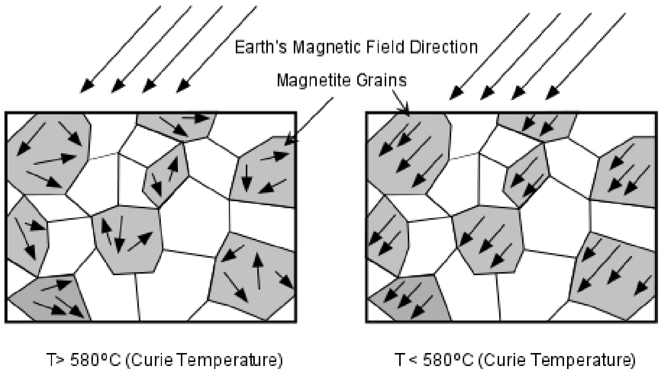
Remanent Magnetization

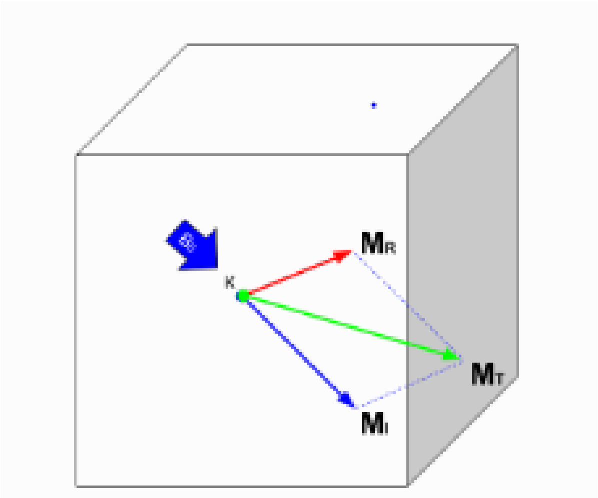
Remanent magnetization

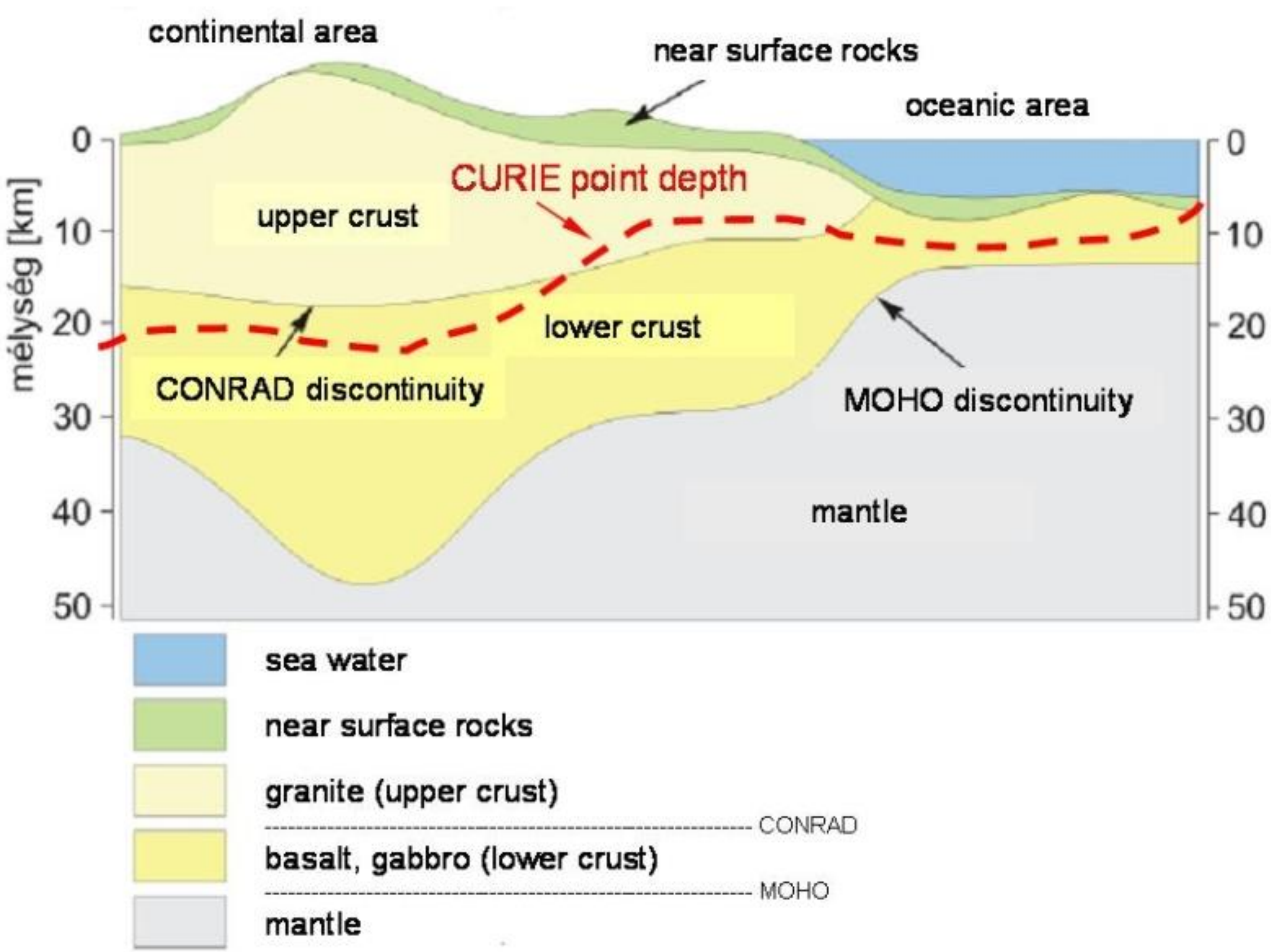
- A permanent magnetization contribution which is **not** supported by an external field
- Magma cools below Curie temperature → Magnetic dipoles align along Earth's field and leave permanent imprint
- Total magnetization is vector sum:

$$\vec{M}_T = \vec{M}_I + \vec{M}_R$$

- Only significant in ferromagnetic materials!!! (magnetite, steel etc…)







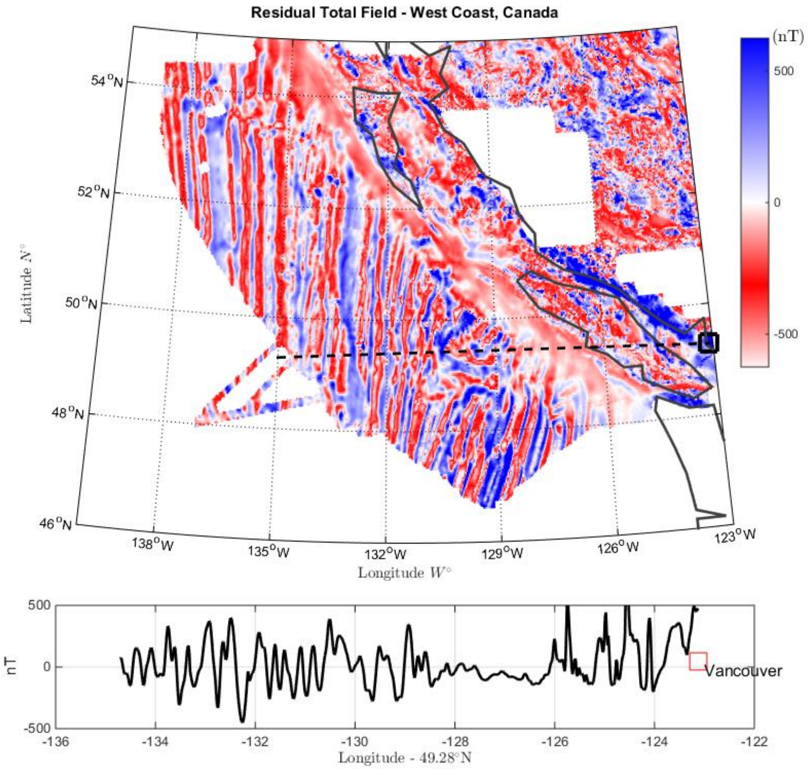
Geotherms ensure magnetization is restricted mostly to the upper crust. The mantle and core are too hot.

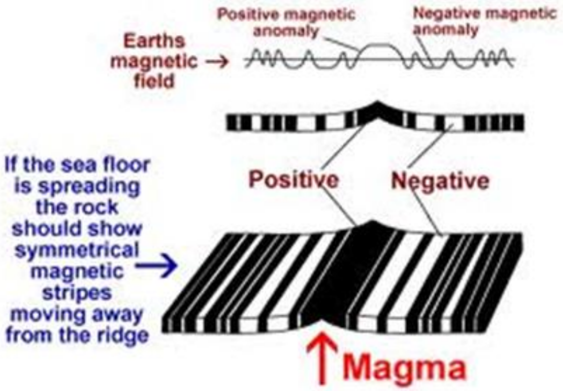
Remanent Magnetism at different scales

- Small scale: UXO, rebar, drums

- Large scale: geologic units.

  Sea floor spreading





All Together Now!!!

$\vec{B}$: Magnetic Flux Density (Wb/m^2 = Tesla)

$\vec{H}$: Magnetic Field (A/m)

κ: Magnetic susceptibility ($Unitless$)

μ: Magnetic permeability $\mu = \mu_0(1+\kappa)$

Inducing field

Induced magnetization

Remanent magnetization

$$\begin{aligned}\vec{B} &= \mu_0(\vec{H}+\vec{M}) \\ &= \mu_0(\vec{H}+\vec{M}_I+\vec{M}_R) \\ &= \mu_0(1+\kappa)\vec{H}+\mu_0\vec{M}_R \\ &= \mu\vec{H}+\mu_0\vec{M}_R\end{aligned}$$

Inside susceptible material

Inducing field

Anomalous field (due to magnetization)

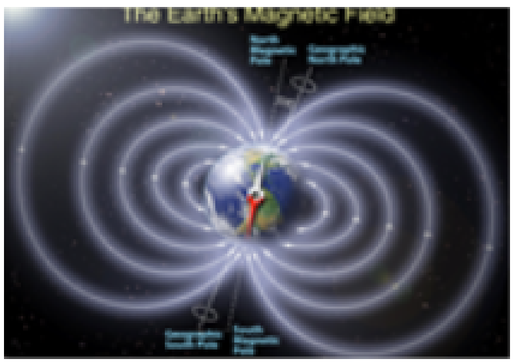
$$\begin{aligned}\vec{B} &= \mu_0(\vec{H}+\vec{H}_A) \\ &= \vec{B}_0+\vec{B}_A\end{aligned}$$

Outside susceptible material

Magnetic methods (basic idea)

Magnetic methods (basic idea)

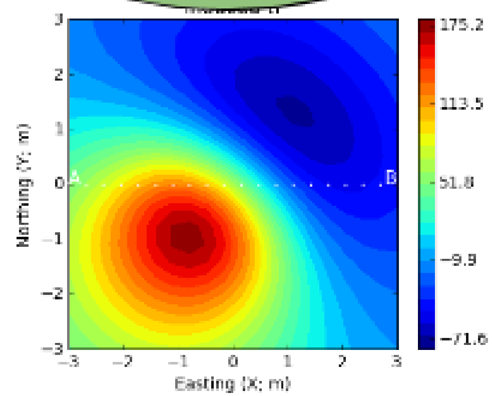
Source



Input energy

Measured response

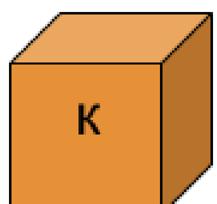
Data

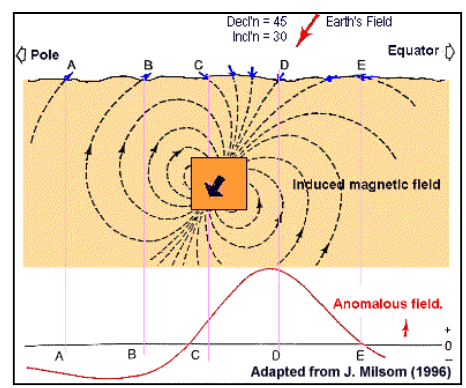


Subsurface

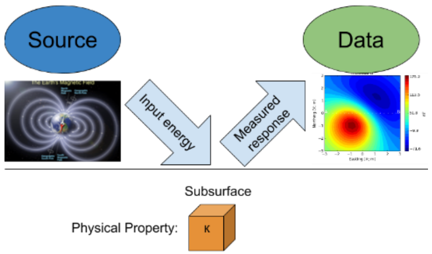
Physical Property:

Magnetic susceptibility

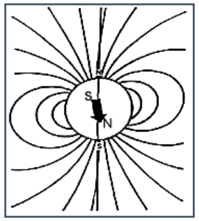




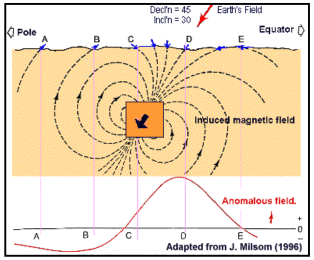
Magnetic surveying



- Earth's magnetic field, B_0, is the source:

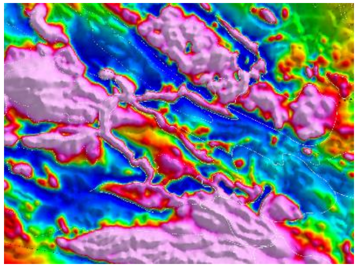


- Induces magnetization
  (may also have remanence):
  → Creates anomalous field B_A



- Measure total magnetic field

$$B = B_0 + B_A$$

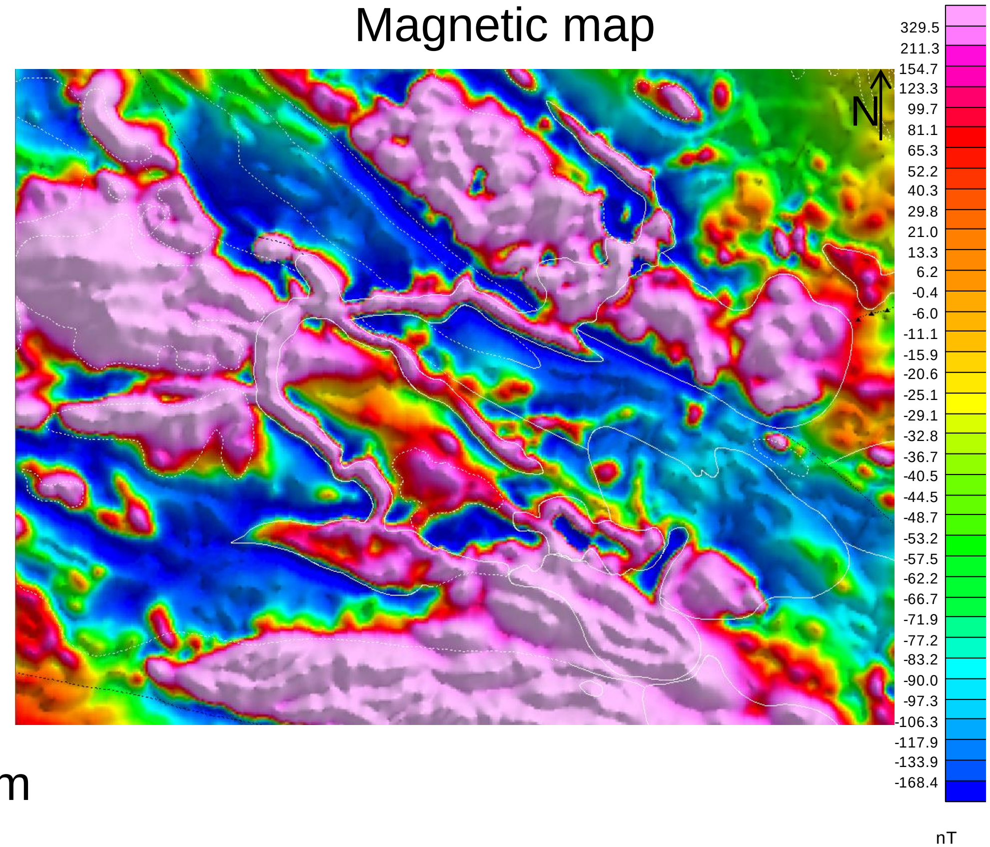


Example Applications

Geologic mapping

Geology map

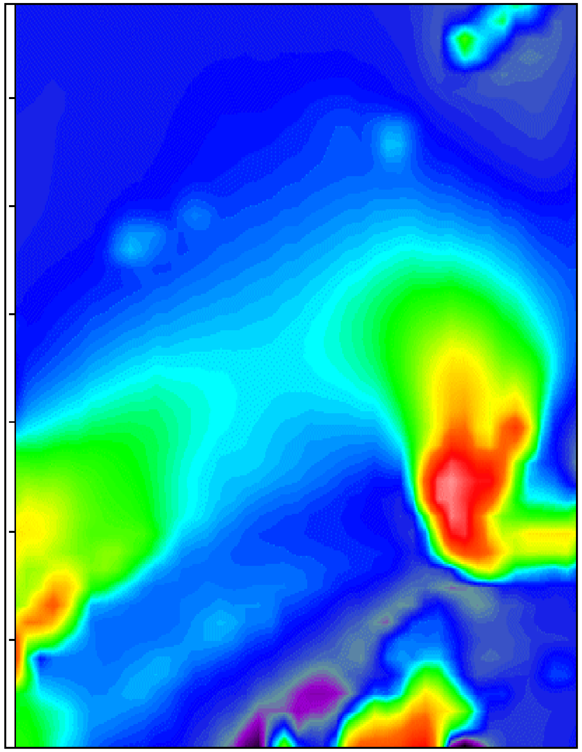
Magnetic map

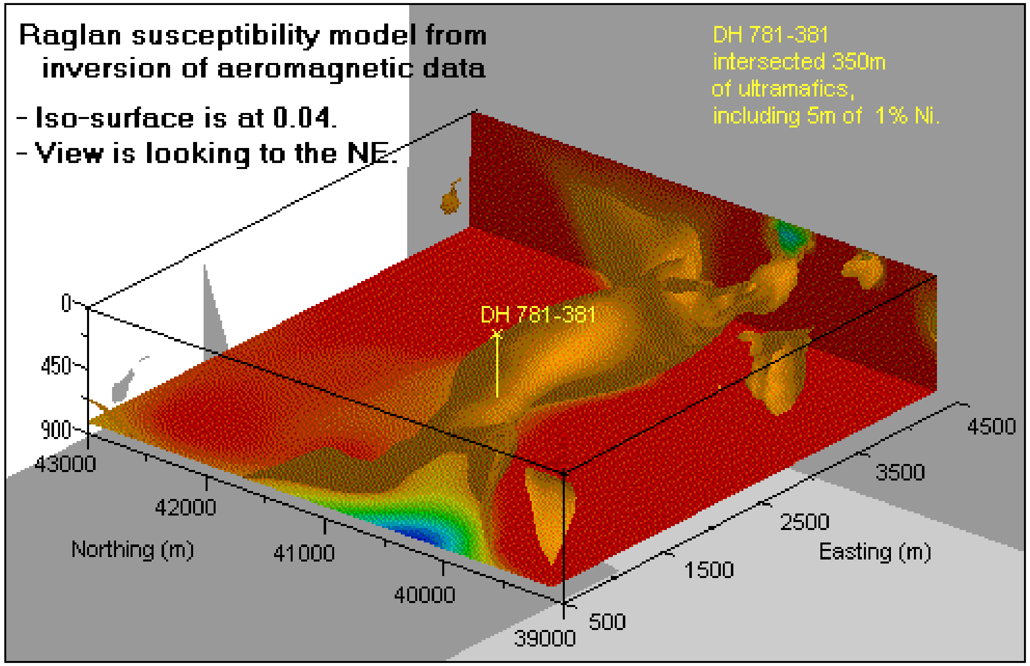


30 km

Geology contacts can be inferred from mag maps.

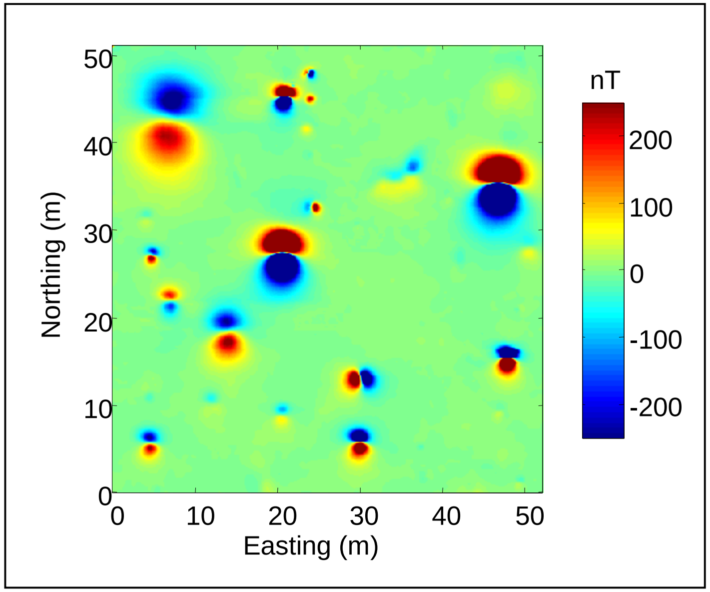
Mineral exploration





Ore-bearing minerals may be significantly more susceptible than host

Environmental Contaminants: UXO



UXOs are very susceptible compared to host

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