Geomagnetism

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Introduction

• Some basic observations:
  – Compasses point to the (magnetic) North
  – Compasses deviate from North in the presence of serpentine

⇒ The Earth has a magnetic field
⇒ Some rocks are magnetized

• Objectives:
  – Physics of the Earth:
    • Temporal variations of the Earth’s magnetic field
    • Origin (internal and external) of the Earth’s magnetic field
  – Geodynamics: Archeomagnetism, paleomagnetism, and plate motions
  – Magnetic surveying: subsurface investigations
The Earth’s magnetic field

• Gravimetry: fundamental parameter = density

• Magnetism: fundamental parameter = magnetic susceptibility

• Magnetism more complicated than gravity because:
  – Field vector is generally not vertical
  – Varies more rapidly with time
The Earth’s magnetic field

If a compass is placed in the vicinity of a magnet and moved along the direction it is pointing:

⇒ It traces a path from one end of the magnet to the other
⇒ Many such paths (starting at different points)
⇒ These paths = lines of magnetic field
The Earth’s magnetic field

- A compass points to the magnetic North because it aligns with the Earth’s magnetic field lines
- The Earth’s magnetic field can be approximated by a dipole (magnet) tilted about 11.5 degrees from its rotation axis
  - Magnetic North differs from true (= geographic) North
  - Definition of the magnetic equator
The Earth’s magnetic field
The Earth’s magnetic field

- **Declination** = horizontal angle between the direction of the magnetic field and the true North
- The magnetic field lines intersect the Earth’s surface at an angle:
  - A compass needle actually points up or down (in addition to north)
  - Magnetic **inclination** = angle between the direction of the magnetic field and the horizontal
    - -90 at the geomagnetic south pole
    - +90 at the geomagnetic north pole
    - 0 at the equator
The Earth’s magnetic field

- Magnetic field = geocentric axial dipole => \( \tan I = 2 \tan \lambda \)
- Inclinations measured in the modern deep-sea sediments cores agree well with the theory
- Measurement of “paleo-I” in old rocks => estimation of their paleo-latitude
The Earth’s magnetic field

- Isoclinal map:
  - **Geomagnetic** poles:
    - Dipole field, exactly opposite poles
    - North = 79.3N/288.6E (epoch 1995)
  - **Magnetic** poles:
    - Total field, poles not exactly opposite to each other
    - North = 77.3W/258.2E (epoch 1995)
  - Deviations to a perfect dipole:
    - The Earth’s magnetic field is partly due to **external sources** (Sun, ionospheric currents) ~ 1%
    - **Internal sources**:
      - The Earth’s magnetic field is produced by complex electric currents in the liquid outer core (= geodynamo) => dipole field
      - Non-dipole field (~5%), poorly understood
The Earth’s magnetic field

Iso-intensity map

Iso-inclination map

Iso-declination map
The Earth’s magnetic field

- Short term variations:
  - Caused by external factors
  - Very-short period: 1/100 to 1 sec, ionosphere noise, magnetic storms
  - 12 hours, 24 hours, 27 days, 1 year, 11 years, etc.: astronomical effects, Sun, Moon
  - Earthquakes?
The Earth’s magnetic field

- **Secular variations** of the dipole field:
  - Decrease of dipole moment
  - Slow change of the tilt angle of the dipole axis
  - Westward drift of the geomagnetic poles
  - Corrections to compass readings have to be changed very few years
  - Poorly understood, internal causes
- **Principal / transient field**
What have we learned?

• The Earth has a magnetic field that can be approximated by a dipole tilted about 11.5 degrees from its rotation axis
• The Earth’s magnetic field consists of:
  – A principal field, due to internal processes: 95% dipole, 5% non-dipole
  – An external field, due to magnetospheric and ionospheric processes (1%)
• The magnetic field vector is 3-dimensional:
  – Declination
  – Inclination, varies with latitude \( \tan I = 2 \tan \lambda \)
• The magnetic field varies in time:
  – Short-term: mostly external effects
  – Secular variations
The magnetism of rocks

- Source of magnetism in rocks = magnetic atoms (half the chemical elements)
- Direction of atoms randomly oriented
- In a magnetic field, rocks may become magnetized
- Ability of materials to become magnetized = susceptibility
- Rocks may retain that magnetization to the present = remanent magnetization
The magnetism of rocks

Ternary diagram of the iron-titanium oxide magnetic minerals

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Chemical formula</th>
<th>Saturation remanence (kA/m)</th>
<th>Curie temperature (°C)</th>
<th>Susceptibility* (rationalised SI units)</th>
</tr>
</thead>
<tbody>
<tr>
<td>magnetite</td>
<td>Fe₃O₄</td>
<td>5–50†</td>
<td>585</td>
<td>0.07–20</td>
</tr>
<tr>
<td>haematite</td>
<td>Fe₂O₃</td>
<td>1</td>
<td>675</td>
<td>0.0004–0.038</td>
</tr>
<tr>
<td>maghaemite</td>
<td>Fe₃O₄</td>
<td>80–85</td>
<td>c. 740</td>
<td></td>
</tr>
<tr>
<td>goethite</td>
<td>FeO·OH</td>
<td>≤1</td>
<td>c. 120</td>
<td></td>
</tr>
<tr>
<td>pyrrhotite</td>
<td>c. Fe₂O₉</td>
<td>1–20</td>
<td>c. 300</td>
<td>0.001–6.3</td>
</tr>
<tr>
<td>(iron)</td>
<td>Fe</td>
<td>780</td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

*Defined in Section 10.6
†All ranges, which are from various sources, are approximate.
The magnetism of rocks

• In a magnetic field: magnetic atoms align to a very small degree with the field
  ⇒ Weak magnetization
  ⇒ Magnetization disappears if the field is removed
  ⇒ = paramagnetism

• In some materials: magnetic atoms align quasi-perfectly with the field
  ⇒ Strong magnetization
  ⇒ Magnetization remains if the field is removed
  ⇒ = ferromagnetism (and its various flavors: ferrimagnetism, antiferromagnetism, etc.)
The magnetism of rocks

- Magnetization and demagnetization:
  - Application of magnetic field $\Rightarrow$ magnetization
  - Heating: in the absence of a magnetic field $\Rightarrow$ random thermal oscillations increase $\Rightarrow$ thermal demagnetization and (range of) blocking temperature(s)

- Heating in the presence of a magnetic field:
  - At $T_c =$ Curie temperature, individual atomic magnets cease to align with each other $=$ the material becomes paramagnetic
  - Curie temp. $>$ blocking temp.
  - Above $T_c$: no magnetization even in the presence of a magnetic field
The magnetism of rocks

• Remanent magnetization (= remanence): ability to acquire a permanent magnetization

• Remanence may be acquired:
  – At or close to the time of formation of the rock = primary remanence
  – At a later time = secondary remanence
The magnetism of rocks

- Igneous rocks solidify above 1000°C => grains are solid and fixed in a rigid matrix
- Ferromagnetic grains still above T_c:
  - Hematite (Fe_2O_3) = 675°C
  - Magnetite (Fe_3O_4) = 578°C
- As the rock cools: temperature becomes < T_c => spontaneous magnetization appears
- As cooling continues: temperature becomes < blocking temperature => magnetization is “frozen in”
- Result = thermo-remanent magnetization (TRM)
The magnetism of rocks

• At ambient temperature, during the deposition of a sediment:
  – In water, physical alignment of detrital ferromagnetic particles with ambient field
  – In the sediment, magnetic and mechanical forces compete + compaction => alignment slightly spoiled

⇒ Depositional remanent magnetization (DRM)
The magnetism of rocks

• Growth of a crystal in a magnetic field

Chemical remanent magnetization (CRM):
  – Chemical alteration
  – Precipitating iron oxide from iron-saturated percolating fluids (hematite)

• Usually a secondary form of remanence in rocks
The magnetism of rocks

- Igneous rock reheated above blocking temperature:
  - De-magnetized = loses its primary remanence
  - When the rock cools => re-magnetized in the magnetic field of the time

- Igneous rock reheated below blocking temperature:
  - Primary remanence not completely destroyed
  - When the rock cools:
    - Retains the magnetic field of the time
    - Acquires secondary remanence

- **Natural remanent magnetization** (NRM) = mix of the 2 remanences
The magnetism of rocks

- Progressive reheating in the absence of a magnetic field
- Simultaneous measurement of the magnetization
- Secondary remanence removed first => one measures a linear change in strength and direction (OB to OD)
- Until all secondary remanence removed => then magnetization decreases but does not change direction (OD to OF)
The magnetism of rocks

- Representation in 3D space:
  - Vector component diagram (=Zijderveld diagram)
  - Stereo plot (but changes in strength do not show)
The magnetism of rocks

- Common cause of reheating = intrusion
- Example: Paleozoic lava baked by a 6.2 m wide early Tertiary dyke:
  - D = direction of magnetization of the dyke
  - L = direction of magnetization of the lava where it has not been affected by the dyke
  - Trajectory of a sample 0.75 m from the contact
The magnetism of rocks

- When was the remanence acquired?
- Fold test:
  - Let’s assume that a magnetized layer has been folded: magnetization acquired before folding => scatter in mag. directions
  - Tilt correction accounting for the fold geometry => scatter removed
  - Example: 4 sites in the Himalayas tilted by Late Eocene folding (~38 My)
    - After tilt corrections: single group => rocks magnetized before the folding
    - Average inclination = 55° => paleolatitude ~38°
- Conglomerate test:
  - Magnetized rock eroded into clasts deposited in a conglomerate => mag. direction = random
  - If magnetized after deposition => mag. direction = constant
The magnetism of rocks

- Remanent magnetization can be measured in the laboratory on rock samples => 3D “paleo”-magnetic field direction
- Provides access to paleomagnetic field of the Earth
- Provides information on the location of the rock on Earth
- Provides information on the age of the rock
⇒ Paleomagnetism
What have we learned?

- Some minerals can be magnetized = their magnetic atoms orient in the direction of the magnetic field
  - Susceptibility
  - Paramagnetism / ferromagnetism

- Some rocks can retain their magnetization to the present = remanent magnetization
  - Thermo-remanent magnetization and Curie temperature
  - Depositional-remanent magnetization
  - Primary / secondary magnetization