GLE 594: An introduction to applied geophysics

Magnetic Methods

Fall 2004

Instruments and Surveying

Reading
Today : 75-86
Next Lecture : 86 - 111.
Induced magnetization ($J_I$) and magnetic susceptibility

- A magnetizable body acquires magnetization when $H$ field is applied
  - Disappears when field is removed
  - Field ‘induces’ magnetization in material
- The induced magnetization is parallel and proportional to $H$: $J_I = \kappa H$ (due to the earth: $J_I = \kappa F/\mu_o$)
  - $k = \text{susceptibility}$
  - $k = \mu_r^{-1}$
  - Dimensionless, however, $k_{SI} = 4\pi k_{cgs}$

Cause of magnetic susceptibility

- At the atomic level, materials have a net magnetic moment due to:
  - Rotation of electrons in various shells around nucleus
  - The spin of the electrons
  - Number of electrons in each shell
  - That is, it is a quantum effect
- All of above result that each atomic nucleus can be though of as a small magnetic dipole with its own moment
Classifications of magnetic materials

• Diamagnetic
  • All electron shells are full, thus there is no net moment.
  • In the presence of an external field, the net moment opposes the external field, i.e., slightly negative susceptibility.

• Paramagnetic
  • Materials contain unpaired electrons in incomplete electron shells.
  • However magnetic moment of each atom is uncoupled from others so they all behave independently.
  • Results in weakly magnetic materials, i.e. small susceptibility

Classifications of magnetic materials

• Ferromagnetic
  • Materials contain unpaired electrons in incomplete electron shells
  • Magnetic moment of each atom is coupled to others in surrounding ‘domain” such they all become parallel.
  • Caused by overlapping electron orbits
  • Gives rise to a spontaneous magnetization even in absence of an external field
  • Magnets are ferromagnetic
  • Examples: Cobalt, iron and nickel
Classifications of magnetic materials

- **Anti-ferromagnetic**
  - Almost identical to ferromagnetic except that the moments of neighboring sublattices are aligned opposite to each other and cancel out
  - Thus no net magnetization is measured
  - Example: Hematite

- **Ferrimagnetic**
  - Sublattices exhibit ferromagnetically but then couple antiferromagnetically between each other
  - Example: Magnetite and ilmenite

### Magnetic properties

**Table 3.2 Susceptibilities of rocks and minerals**

<table>
<thead>
<tr>
<th>Mineral or rock type</th>
<th>Susceptibility *</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sedimentary</strong></td>
<td></td>
</tr>
<tr>
<td>Dolomite (pure)</td>
<td>12.5 to 14.4</td>
</tr>
<tr>
<td>Dolomite (impure)</td>
<td>20000</td>
</tr>
<tr>
<td>Limestone</td>
<td>10 to 23000</td>
</tr>
<tr>
<td>Sandstone</td>
<td>0 to 35000</td>
</tr>
<tr>
<td>Shales</td>
<td>60 to 18000</td>
</tr>
<tr>
<td>Average for various</td>
<td>0 to 300</td>
</tr>
<tr>
<td><strong>Metamorphic</strong></td>
<td></td>
</tr>
<tr>
<td>Quartz</td>
<td>115 to 9000</td>
</tr>
<tr>
<td>Slate</td>
<td>0 to 38000</td>
</tr>
<tr>
<td>Gneiss</td>
<td>125 to 23000</td>
</tr>
<tr>
<td>Serpentinite</td>
<td>100 to 17000</td>
</tr>
<tr>
<td>Average for various</td>
<td>0 to 73000</td>
</tr>
<tr>
<td><strong>Igneous</strong></td>
<td></td>
</tr>
<tr>
<td>Granite</td>
<td>10 to 60</td>
</tr>
<tr>
<td>Granite (m)</td>
<td>30 to 30000</td>
</tr>
<tr>
<td>Rhyolite</td>
<td>250 to 37700</td>
</tr>
<tr>
<td>Pegmatite</td>
<td>3000 to 79000</td>
</tr>
<tr>
<td>Gabbro</td>
<td>800 to 76000</td>
</tr>
<tr>
<td>Basalt</td>
<td>500 to 182000</td>
</tr>
<tr>
<td>Granitic basalt</td>
<td>300 to 38500</td>
</tr>
<tr>
<td>Peridotite</td>
<td>95 500 to 196 000</td>
</tr>
<tr>
<td>Average for acid igneous</td>
<td>40 to 82 000</td>
</tr>
<tr>
<td>Average for basic igneous</td>
<td>550 to 122 000</td>
</tr>
</tbody>
</table>

**Minerals**

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Susceptibility *</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iron (d)</td>
<td>9</td>
</tr>
<tr>
<td>Rocksalt (d)</td>
<td>10</td>
</tr>
<tr>
<td>Graphite (d)</td>
<td>12</td>
</tr>
<tr>
<td>Quartz (d)</td>
<td>15</td>
</tr>
<tr>
<td>Chalcopyrite (d)</td>
<td>400</td>
</tr>
<tr>
<td>Pyrite (d)</td>
<td>50 to 5000</td>
</tr>
<tr>
<td>Hematite (d)</td>
<td>420 to 36 000</td>
</tr>
<tr>
<td>Pyrobylthite (d)</td>
<td>1250 to 6.3 x 10^4</td>
</tr>
<tr>
<td>Brucite (d)</td>
<td>3.1 x 10^6 to 3.8 x 10^8</td>
</tr>
<tr>
<td>Magnetite (d)</td>
<td>70 000 to 2 x 10^8</td>
</tr>
</tbody>
</table>

*(d) = diamagnetic material; (m) = mineral; *M* units, or convert to the noninternational c.g.s. units, divide by 4π


**Graph of magnetic susceptibilities**
Concept of hysteresis

• Complex relationship between \( B \) and \( H \) that occurs in ferromagnetic materials.
  – \( B \) flattens off with increasing \( H \) at ‘saturation’
  – When \( H \) is decreased, \( B \) does not follow same curve
  – Will have ‘remanent’ \( B \) value at zero \( H \)

Remanent magnetization (RM)

• Permanent magnetization of rock installed during its formation (\( J_R \)).
• Ferromagnetic materials exhibit this creating spontaneous magnetization.
• Direction of remnant may differ radically from induced field.

<table>
<thead>
<tr>
<th>Type of RM</th>
<th>Process</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural (NRM)</td>
<td>Acquired by a rock or mineral under natural conditions</td>
</tr>
<tr>
<td>Thermal (TRM)</td>
<td>Acquired by a material during cooling from a temperature greater than the Curie temperature to room temperature (e.g. molten lava cooling after a volcanic eruption)</td>
</tr>
<tr>
<td>Isothermal (IRM)</td>
<td>Acquired over a short time of the order of seconds in a strong magnetic field at a constant temperature (e.g. such as by a lightning strike)</td>
</tr>
<tr>
<td>Chemical (CRM)</td>
<td>Also crystallisation RM, acquired at the time of nucleation and growth or crystallisation of fine magnetic grains far below the Curie point in an ambient field</td>
</tr>
<tr>
<td>Thermal-chemical (TCRM)</td>
<td>Acquired during chemical alteration and cooling</td>
</tr>
<tr>
<td>Detrital (DRM)</td>
<td>Also depositional RM, acquired by the settling out of previously magnetised particles to form ultimately consolidated sediments which then have a weak net magnetisation, but prior to any chemical alteration through diagenetic processes</td>
</tr>
<tr>
<td>Post-depositional (PDRM)</td>
<td>Acquired by a sediment by physical processes acting upon it after deposition (e.g. bioturbation and compaction)</td>
</tr>
<tr>
<td>Viscous VMR</td>
<td>Acquired after a lengthy exposure to an ambient field with all other factors being constant (e.g. chemistry and temperature)</td>
</tr>
<tr>
<td>Anhysteretic (ARM)</td>
<td>Acquired when a peak amplitude of an alternating magnetic field is decreased from a large value to zero in the presence of a weak but constant magnetic field</td>
</tr>
</tbody>
</table>
Total magnetization

- Total magnetization:
  \[ \mathbf{J} = \mathbf{J}_i + \mathbf{J}_r \]
- Effective or apparent \( k \):
  \[ k_e \text{ or } k_a = \frac{(\mathbf{J}_i + \mathbf{J}_r)}{\mathbf{F}/\mu_0} \]
- Note: a \( \mathbf{J} \) that is not fully aligned with the natural \( \mathbf{H} \) field at a site will cause a perturbation in \( \mathbf{H} \), and thus \( \mathbf{H} \) local will have a slightly different direction and strength than the natural field.

Magnetic properties of materials of interest

- Basement: tends to be igneous or metamorphic, thus greater magnetic properties.
- Soils and other weathered products: because magnetic minerals tend to weather rather rapidly compared to quartz, will get reduction of magnetic materials with weathering.
- Man-made objects: iron and steel
- Ore deposits: many economic ores are either magnetic, or associated with magnetic minerals.
Acquisition of Magnetic Data

- Magnetic Survey Instrumentation
  - “Fluxgate” Type
  - “Proton-Precession” Type
  - These magnetometers may be used as stationary mode or from moving platforms

- “Alkali-vapor magnetometers” are used for high precision surveys
- Magnetic Gradiometer

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Flux Gate Magnetometer

- Uses electromagnetic induction concepts
- Two permeable coils are wound in opposition opposite directions
  - Coils driven with AC signal
  - Cores are driven to saturation
- A secondary coil is wound around both cores:
  - Detects changes in magnetic field
  - In absence of external magnetic field, signals in primary coils will cancel
  - In presence of external magnetic signal, one primary coil will saturate before the other, creating an imbalance in magnetic field to be detected via EM induction in secondary coil
- It may be aligned in different directions
Flux Gate Magnetometer

- Advantages
  - Can make vector (directional) measurements
  - Can record continuously

- Disadvantages
  - Sensitive to temperature
  - Only measures field in direction of coils.

• With good insulation, 1 nT accuracy can be achieved (typical accuracy 5 to 10 nT)

Proton Precession Magnetometer

- Single proton nuclei exhibit an angular momentum, which yields a net-dipole moment
- Moment of proton will tend to align with an external field
- If external magnetic field changes, proton will ‘precess’ to align with new field
- The precession frequency (Larmor frequency) depends on external field strength
Proton Precession Magnetometer

• Two coils surrounding bottle of water or hydrogen rich fluid.
  • One to induce field in different direction then natural field.
  • One to measure voltage caused by precessing protons.

• Measurement process:
  • Protons originally aligned with natural field (A).
  • External coil is energized with a DC current resulting in a strong B field that aligns protons (B).
  • Current turned off; protons precess back to alignment with external field, generating AC current in receiver coil at Larmor Frequency (C). Larger fields -> higher frequencies

Proton Precession Magnetometer

• Advantages
  • Don’t have to align ‘bottle’ with field.
  • Fairly lightweight yet rugged.

• Disadvantages
  • Can’t record continuously
  • Can’t measure vector field

• Measurement accuracy :
  • 0.1 to 1nT with sampling time of 0.5 to 2s.
  • Can get 0.1 nT accuracy if we have 0.004 Hz frequency resolution.
Alkali Vapor Magnetometer

• Basic Physics:
  • Uses precession frequency of alkali vapor
  • Quantum mechanics

• Magnetometer construction:
  • Bottle filled with cesium or rubidium vapor
  • Polarized light source of same element
  • Coil to generate radio frequency magnetic field
  • Light detector

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Alkali Vapor Magnetometer

• How it works:
  • Polarized light passing through vapor bumps electrons to higher energy shells.
  • AC current flowing in coil through it knocks some electrons down to lower energy states.
  • Light absorbed when electron is ‘re-pumped’ results in flickering light at Larmor frequency.
  • Measurement of frequency via light sensor.
Alkali Vapor Magnetometer

- Advantages
  - Don’t have to align ‘bottle’ with field
  - Very rapid, almost continuous
- Disadvantages
  - Can’t measure vector field
- Measurement accuracy:
  - 0.01 to 1nT

Magnetic Gradiometer

- Takes differences between two measurements that are made close together
- Divides result by distance between sensors
- Advantages
  - Don’t need to be corrected for diurnal variation
  - Provides high resolution of near surface feature
- Disadvantages
  - Won’t measure large scale features
  - Essentially automatic removal of regional
  - Lower signal-to-noise ratio
Ground Surveys

- Lines very close together for higher resolution. Max. line spacing; \( h/\delta x > 1 \)
- Wherever possible, conduct surveys perpendicular to strike
- If 3D survey, use simplest grid
- Establish base station to incorporate drift (should be in flat terrain, away from electromagnetic field sources, and easy to reoccupy)
  - Return to base every at least every hour for reading, or (best) implement continuously recording station
- Position and elevation now routinely recorded with GPS:
  - Continuous
  - Discrete station locations

Magnetic Cleanliness

- “You cannot be too obsessed with magnetic cleanliness.” (Burger 1992)
- belt buckles, eyeglasses, pocket knives, spiral-bound notebooks, etc.
- power lines, buildings w/metal beams, wire fences, the field vehicle.
- Keep sensor at least 1 meter from ground, else soil variations might dominate the signal.
Airborne Surveys

• Much the same design as ground based surveys, except larger line spacing.
  • Sedimentary basins (4 km spacing - 1km flight height or greater)
  • Areas of exposed basement (mineral surveys)
    • 200m spacing - 100-500m flight height
  • For rapid environmental surveys,
    • Line spacing of 10-50m - 30-50m flight height

• Have overlapping lines with ‘tie points’;
  • Provides 3D grid;
  • Allows to correct for drift.
• Elevation;
  • Radar or laser altimeter.
  • Differential GPS for some helicopter surveys.
• Position
  • Video tape with maps in older surveys.
  • GPS in modern surveys.
• Max line spacing chosen to make sure that in general, $h/\delta x > 1$. 
Data Processing

• Required to remove ‘noise’ and other errors in data, and correct for other survey parameters.
• Can be broken into ‘corrections’ and ‘data enhancements’

Diurnal Correction

• Time varying magnetic field caused by solar ‘wind’ perturbing ionosphere.
  • Both rapid and long term changes
  • Small corrections during quiet periods, larger during storms

• If too ‘stormy’, survey is discontinued.
• Correction data provided by:
  • Repeat base station measurements or tie lines.
  • Continuously recording base station.
Normal Field Correction

• Essentially a correction for variations in field with latitude and longitude.
• If survey is conducted over a large area, correct for changing magnetic field relative to location:
  • Usually use an IGRF map
  • Between 30 and 60 degrees north or south (North-South gradient is about 2 to 5 nT/km – East-west grad is 0 to 2 nT/km)

Elevation and Terrain Corrections

• Vertical gradient is a maximum of about 0.03nT/m at poles and 0.01 nT/m at equator.
• Elevation correction
  • Generally not required for ground surveys
  • Only in airborne when large elevation changes experienced
• Terrain correction
  • Only comes into play near the base of steep slopes of high k material
Removal of Regional

- Use formula to subtract off IGRF value.

- Filtering processes to get the regional formula (like gravity).

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General Guidelines

<table>
<thead>
<tr>
<th>Table 3.7</th>
<th>Guidelines for qualitative interpretation of magnetic profiles and maps</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applies to</td>
<td>Magnetic character</td>
</tr>
<tr>
<td>Segments of a profile and area of maps</td>
<td>Magnetically quiet</td>
</tr>
<tr>
<td>Anomaly</td>
<td>Magnetically noisy</td>
</tr>
<tr>
<td>Wavelength</td>
<td>Short = near-surface feature</td>
</tr>
<tr>
<td>± amplitude</td>
<td>Indicative of intensity of magnetisation</td>
</tr>
<tr>
<td>Profile*</td>
<td>Anomaly structure and shape</td>
</tr>
<tr>
<td>Induced magnetisation indicated by negative to north and positive to south in northern hemisphere and vice versa in southern hemisphere; if the guideline does not hold, it implies significant remnant magnetisation present</td>
<td></td>
</tr>
<tr>
<td>Profile and maps</td>
<td>Magnetic gradient</td>
</tr>
<tr>
<td>Maps</td>
<td>Linearity in anomaly</td>
</tr>
<tr>
<td>Maps</td>
<td>Dislocation of contours</td>
</tr>
<tr>
<td>Maps</td>
<td>Broadening of contour interval</td>
</tr>
</tbody>
</table>
Derivatives

- Emphasizing shorter wavelength features.
- First vertical derivative emphasizes near surface features. It can be measured with gradiometer, or derived from corrected data.
- Second vertical derivative emphasizes boundaries of target zones.

Reduction to Pole

- Process by which effects of inclination and declination are removed from the data.
- The data are mathematically transformed to measurements over the same geologic structure, but at the magnetic pole where the inducing field is vertical.
Analytic Signal

- Combination of derivatives:

\[ |A(x,y)| = \left[ \left( \frac{\partial F(x,y)}{\partial x} \right)^2 + \left( \frac{\partial F(x,y)}{\partial y} \right)^2 + \left( \frac{\partial F(x,y)}{\partial z} \right)^2 \right]^{1/2} \]

- Shape is independent of inclination/declination of induced field.