

GEOPHYSICAL METHODS

FUNDAMENTALS, APPLICATIONS, AND CASE STUDIES

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Geophysical Exploration G405

Lecture-2 Magnetic Methods

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Magnetic Method in Geophysical Exploration

Introduction to Magnetic Exploration

Historical Overview

Magnetic exploration dates back over 500 years, with early contributions from **Sir William Gilbert** (1540–1603), who demonstrated that the Earth behaves like a giant bar magnet.

The first geophysical manuscript on magnetic measurements for iron ore exploration was published by **Thalen (1879)**. **Von Werde (1843)** mapped magnetic variations to locate ore deposits. **Primary applications:** Locating iron ore (especially magnetite), mapping geological structures (faults, contacts, shear zones), and archaeological studies.

Magnetic Theory

Magnetic Monopoles and Dipoles

Magnetic monopoles (theoretical single poles) do not exist; all magnetic sources are **dipoles** (N-S pairs). **Coulomb's Law for Magnetism:**

where:

- F_m = magnetic force,
- μ = magnetic permeability,
- p_1, p_2 = pole strengths,
- r = distance between poles.

$$F_m = \frac{1}{\mu} \frac{p_1 p_2}{r^2}$$

Magnetic Field Lines and Units

Field lines emerge from the **North pole** and enter the **South pole**.

Units:

- **Tesla (T)** = N/(A·m) (Earth's field $\approx 50,000$ nT or gamma).
- **Magnetic field strength (H)** = force per unit pole.

Magnetization of Materials

Types of Magnetization

1. Induced Magnetization:

1. Caused by an external field (Earth's field).
2. Governed by **magnetic susceptibility (k)**: $k=HI$

Susceptibilities of Rocks and Minerals

Material	Susceptibility $\times 10^{-3}(\text{SI})^8$
Air	~0
Quartz	-0.01
Rock salt	-0.01
Calcite	-0.001 to 0.01
Sphalerite	0.4
Pyrite	0.05-5
Hematite	0.5-35
Ilmenite	300-3,500
Magnetite	1,200-19,200
Limestones	0-3
Sandstones	0-20
Shales	0.01-15
Schist	0.3-3
Gneiss	0.1-25
Slate	0-35
Granite	0-50
Gabbro	1-90
Basalt	0.2-175
Peridotite	90-200

2. Remanent Magnetization:

1. Permanent magnetization retained after the external field is removed.
 2. Types: **Thermoremanent (TRM), Chemical (CRM), Detrital (DRM), Viscous (VRM).**
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3. Magnetic Materials

Type	Behavior	Examples
Diamagnetic	Weak, negative susceptibility	Quartz, salt
Paramagnetic	Weak, positive susceptibility	Ca-Ni series
Ferromagnetic	Strong, positive susceptibility	Iron, cobalt, nickel
Antiferromagnetic	Opposing domains, net zero magnetization	Hematite
Ferrimagnetic	Uneven opposing domains, weak net field	Magnetite, ilmenite

Earth's Magnetic Field

Components

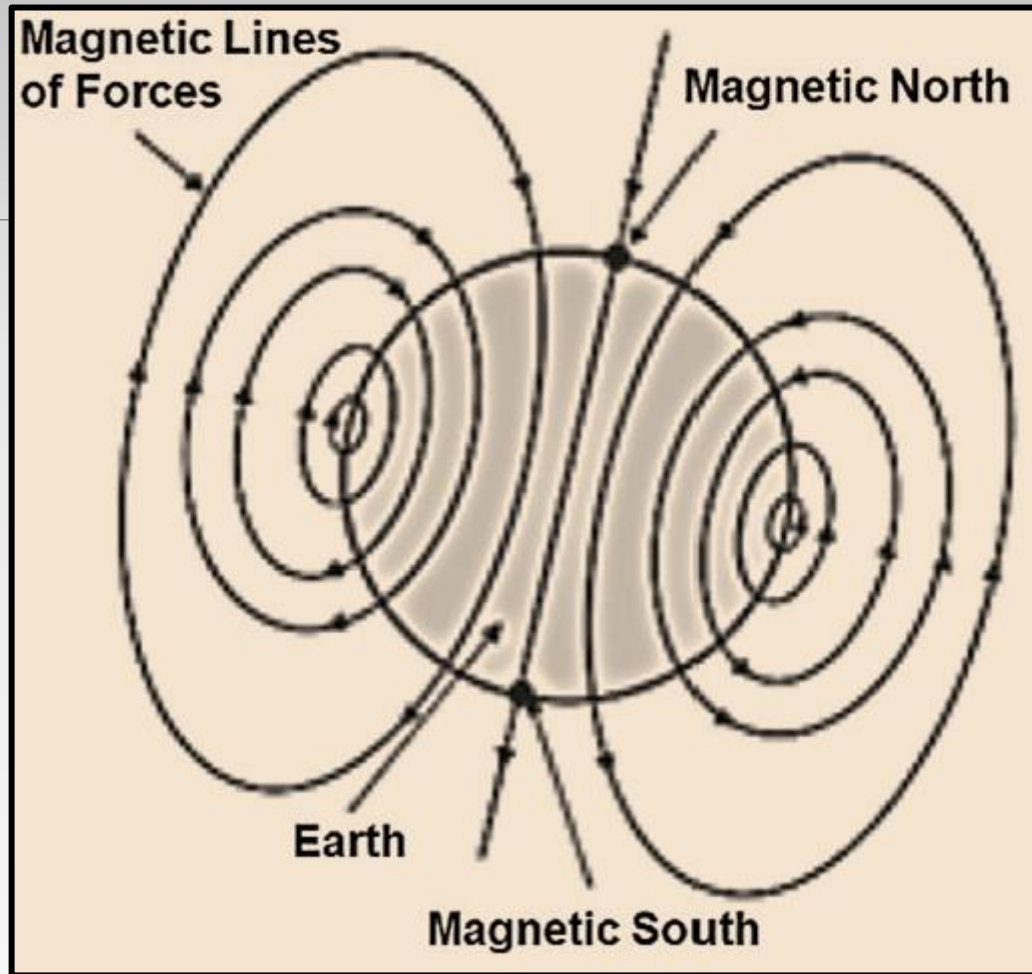
- 1.**Main Field (90%)**: Generated by Earth's outer core (dipolar).
- 2.**External Field**: Ionosphere-solar wind interactions (diurnal variations).
- 3.**Crustal Field**: Local anomalies from magnetized rocks.

Temporal Variations

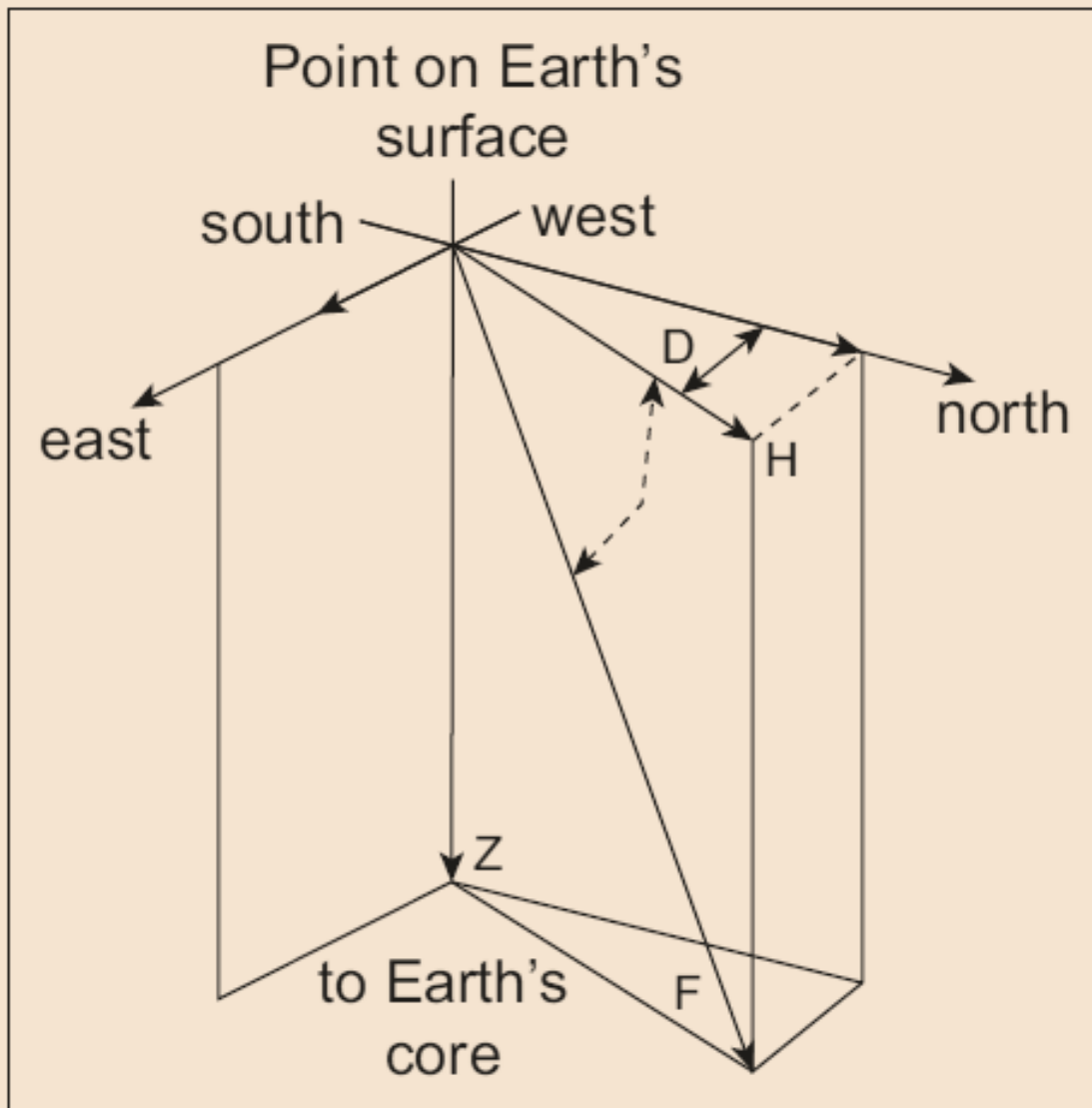
- 1.**Secular Variations**: Slow changes (years) due to core dynamics.
- 2.**Diurnal Variations**: Daily fluctuations (20–30 nT).
- 3.**Magnetic Storms**: Sudden, large disturbances (up to 1,000 nT).

Magnetic Nomenclature

- **Declination (D)**: Angle between magnetic and geographic north.
- **Inclination (I)**: Angle of field lines relative to horizontal.
- **Magnetic Poles**: Where inclination = $\pm 90^\circ$ (not aligned with geographic poles).



Geomagnetic field of the Earth.



In addition to F , I , and D , there are Z , the vertical component reckoned positive downward; H , the horizontal component always positive; and X and Y , components of H to the north and east, respectively. From the diagram:

$$F^2 = H^2 + Z^2 = X^2 + Y^2 + Z^2$$

$$Z = F \sin I$$

where $\sin I = \frac{Z}{F}$, $X = H \cos D$,
 $Y = H \sin D$.

$$\tan D = \frac{Y}{X}.$$

Magnetic elements.

Measuring the Earth's Magnetic Field

Purpose of Measurement

•Detect spatial/temporal variations caused by: **Core dynamics** (main field). **Crustal rocks** (minerals, structures). **External sources** (solar wind, ionosphere).

Instruments Used

Instrument	Measures	Precision	Applications
Fluxgate Magnetometer	Vector components (X, Y, Z)	0.5–1 nT	Ground surveys, archaeology.
Proton Precession Magnetometer	Total field (F)	0.1 nT	Airborne/ground surveys.
Optical Pumping (Cesium/Rubidium)	High-resolution F	0.01 nT	High-precision mapping.
Compass	Declination (D)	~1°	Basic orientation.

Magnetic Surveying

Instruments

1. Fluxgate Magnetometer:

1. Measures field components (0.5–1 nT precision).
2. Used in boreholes, airborne surveys.

Uses **ferromagnetic cores** wound with primary and secondary coils. An alternating current (AC) in the primary coil drives the cores into saturation. External magnetic fields disrupt symmetry, inducing a voltage in the secondary coil proportional to the field strength. Measures **vector components (X, Y, Z)** of the field. Precision: **0.5–1 nT**.

•**Applications:** Ground surveys, archaeological studies, space missions.

2. Proton Precession Magnetometer:

-
1. Measures total field (0.1 nT precision).
 2. No drift, easy to use.

A fluid (e.g., water, kerosene) rich in hydrogen protons is polarized by a DC current in a coil. Current is cut off; protons precession around Earth's field at the **Larmor frequency** (~ 2 kHz for 50,000 nT). Precession induces an AC signal in the coil, with frequency directly proportional to field strength.

Measures **total field (F)**, not direction. Precision: **0.1 nT**.

•**Applications:** Airborne/ground mineral exploration, marine surveys.

3. Optically Pumped Magnetometer (Cesium/Rubidium)

Alkali vapor (e.g., cesium) is excited by polarized light, aligning electron spins. Earth's field causes spin precession, altering light absorption. A photodetector measures absorption changes to calculate field strength. Ultra-high precision: **0.01 nT**.

Measures **total field** or **vector components**.

•**Applications:** High-resolution surveys, space magnetometry.

4. SQUID Magnetometer (Superconducting Quantum Interference Device)

Uses superconducting loops with Josephson junctions. Tiny magnetic fields induce measurable current changes via quantum interference. Extreme sensitivity: **0.0001 nT**.

Requires cryogenic cooling (liquid helium).

•**Applications:** Lab analysis of rock samples, biomedical research.

5. Compass (Magnetic Declinometer)

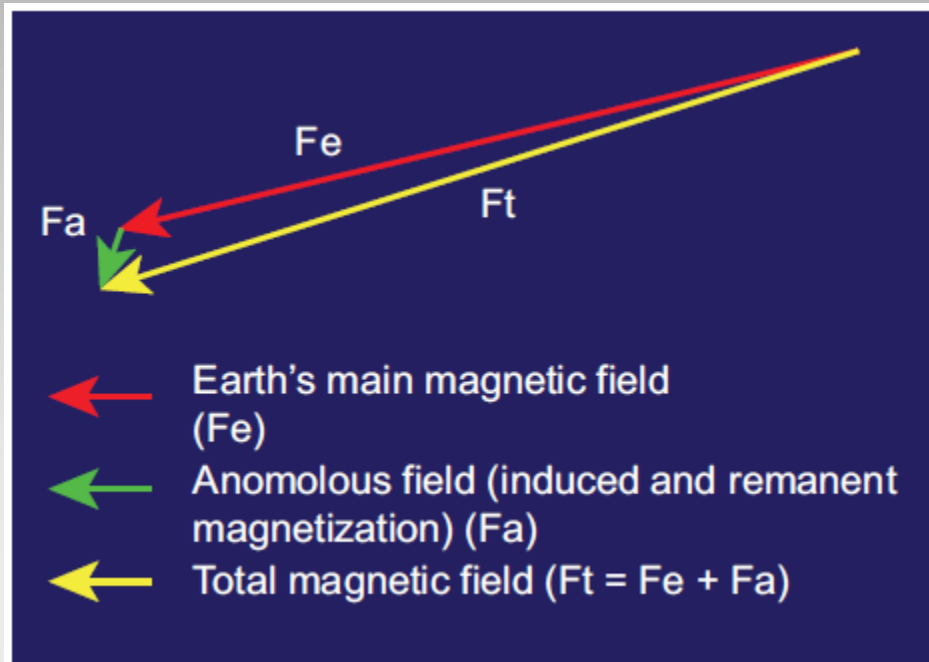
A magnetized needle aligns with Earth's horizontal field component.

Measures **declination (D)** relative to geographic north. Low precision ($\pm 1^\circ$).

•**Applications:** Basic navigation, field reconnaissance.

Comparison Table

Instrument	Measures	Precision	Pros	Cons
Fluxgate	Vector (X,Y,Z)	0.5–1 nT	Directional data, rugged.	Sensitive to orientation.
Proton Precession	Total field (F)	0.1 nT	No drift, easy to use.	No directional data.
Optically Pumped	Total/Vector	0.01 nT	Ultra-sensitive, fast sampling.	Expensive, complex operation.
SQUID	Ultra-weak fields	0.0001 nT	Best sensitivity.	Cryogenic cooling required.
Compass	Declination (D)	$\sim 1^\circ$	Simple, portable.	Low precision, no intensity data.



Direction and component of the Earth's magnetic field.

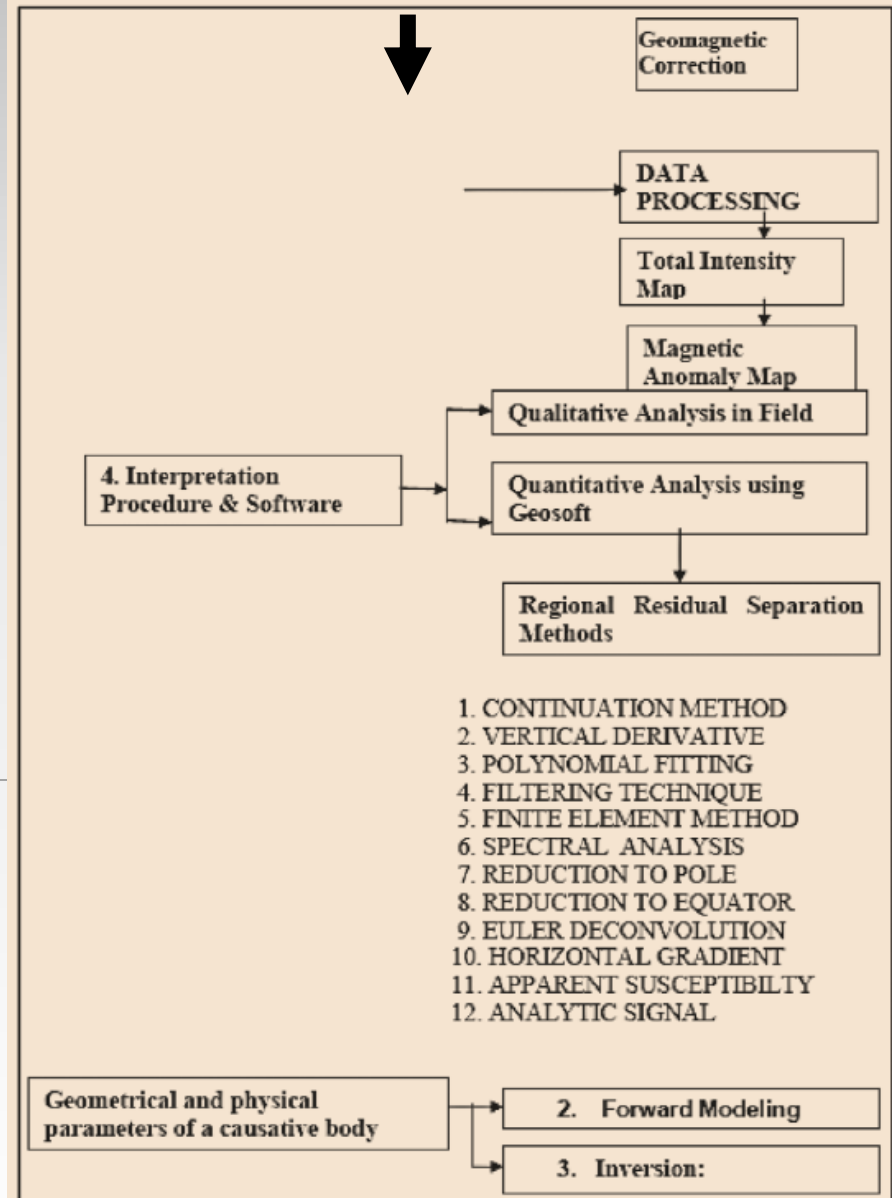
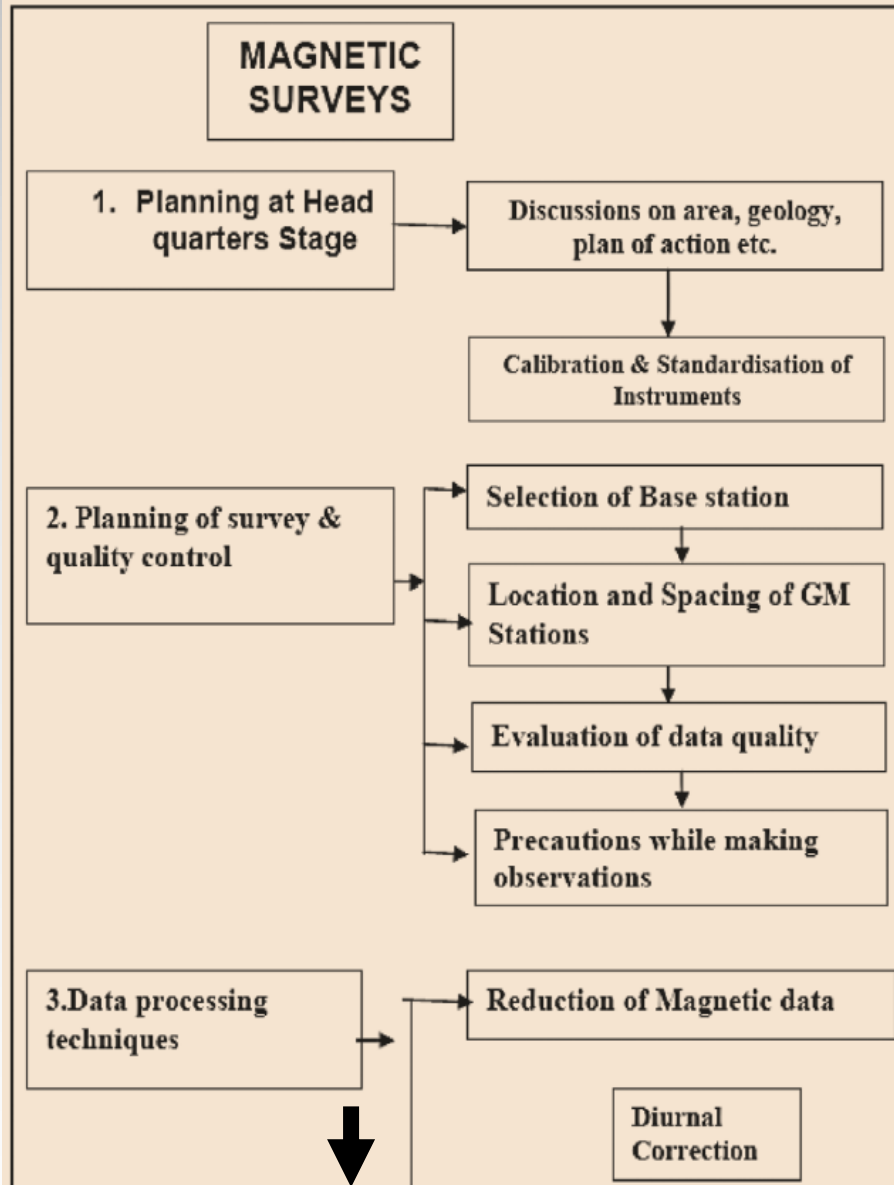
Survey Types

- **Airborne:** Fast, cost-effective for large areas.
- **Ground-Based:** High resolution for detailed studies.
- **Shipborne:** Used in marine surveys.

Corrections

- **Diurnal Correction:** Base station monitoring.
- **IGRF Correction:** Removes main field variations.
- **No Bouguer Correction:** Susceptibility variations make it unreliable.

Format For Magnetic Surveying



Data Processing and Interpretation

Filtering Techniques

1. **High-Pass Filter:** Enhances shallow anomalies.
2. **Low-Pass Filter:** Enhances deep anomalies.
3. **Upward Continuation:** Smooths data to remove shallow noise.
4. **Downward Continuation:** Enhances shallow features.

Derivatives and Edge Detection

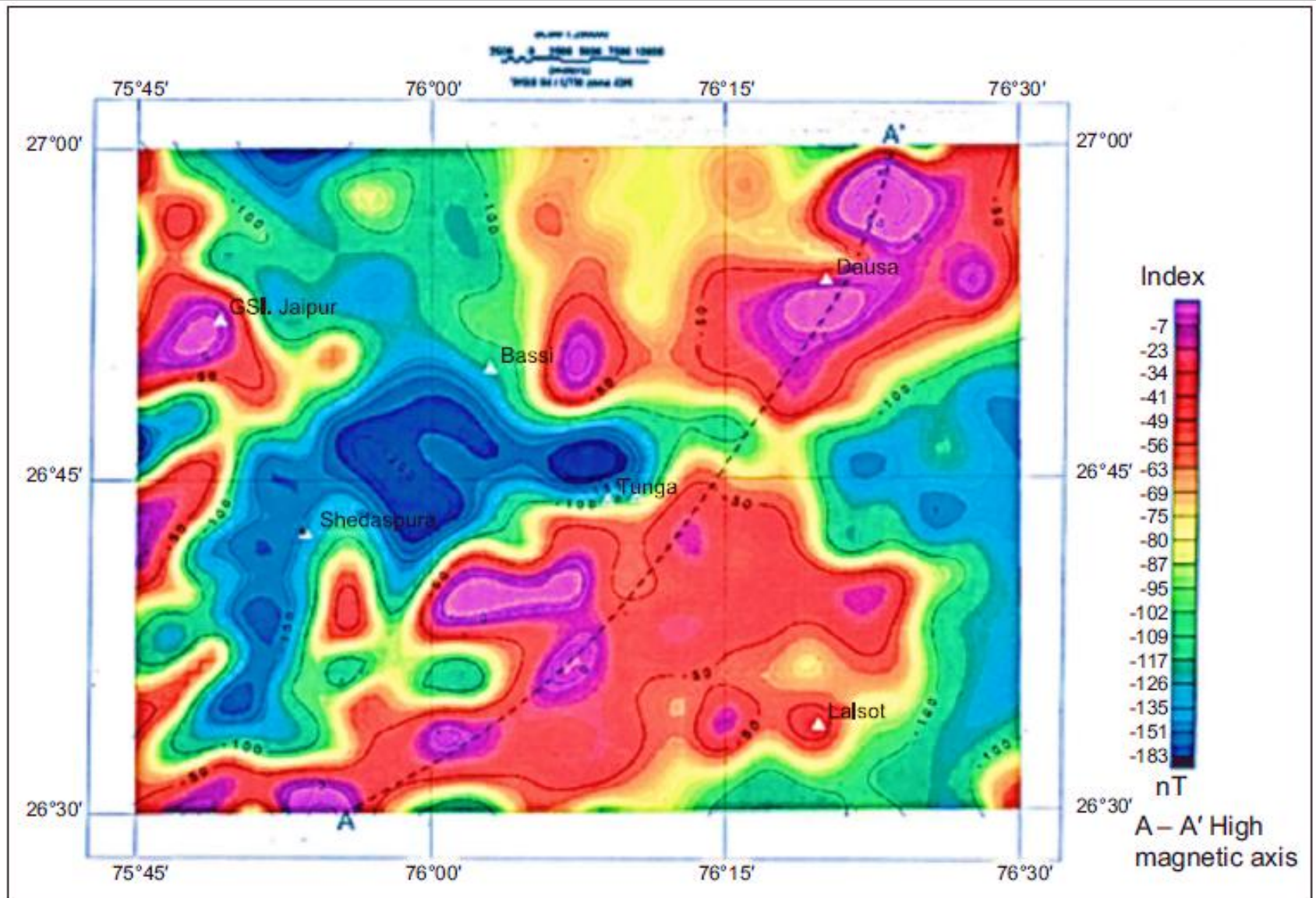
- **Horizontal/Vertical Derivatives:** Highlight contacts/faults.
- **Analytic Signal:** Combines gradients to locate edges.

Reduction to Pole (RTP)

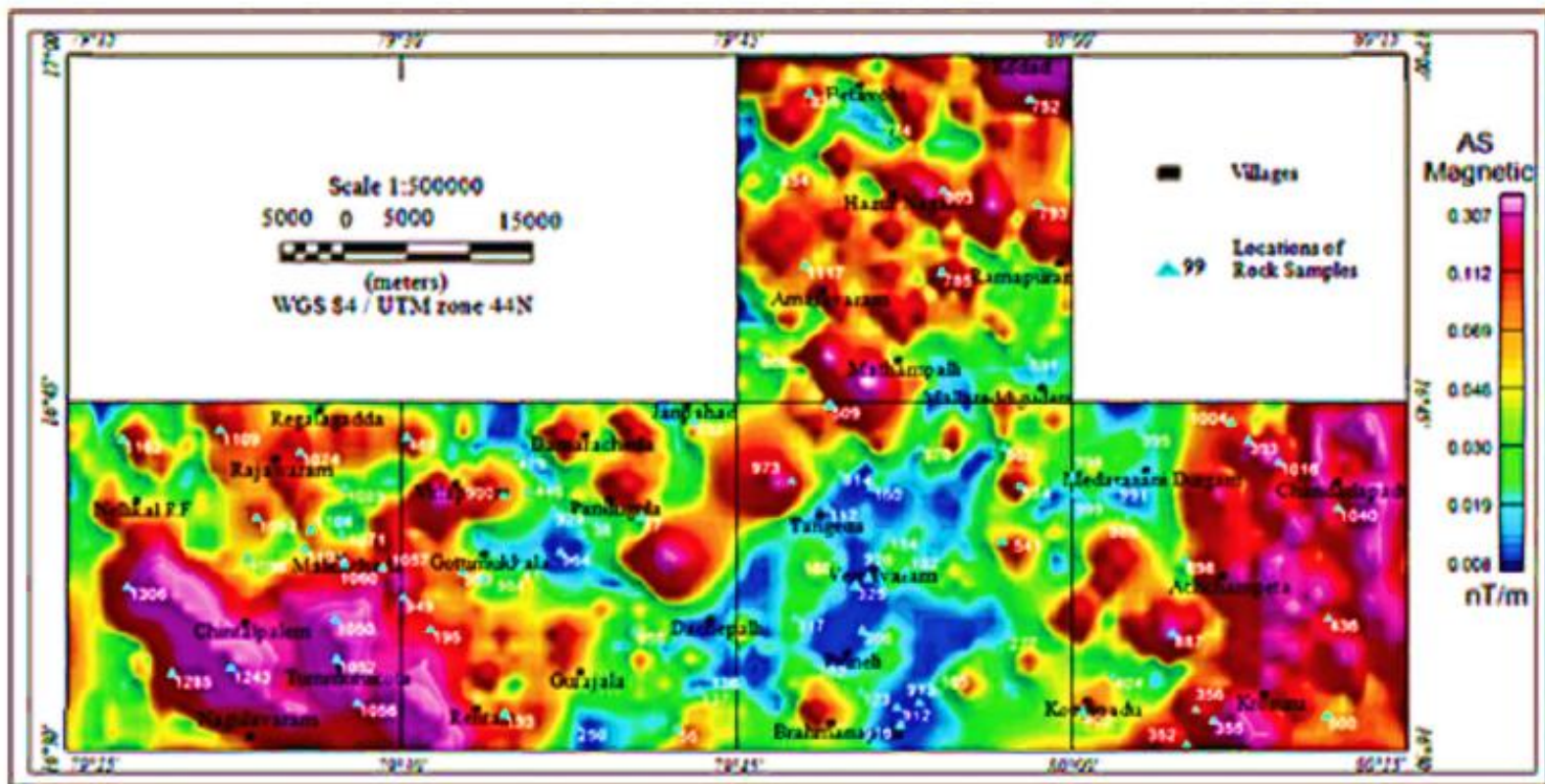
- Converts dipolar anomalies to monopolar (simplifies interpretation).
- Not useful near the equator ($<21^\circ$ latitude) or for remanent magnetization.

Qualitative vs. Quantitative Interpretation

- **Qualitative:** Mapping trends, faults, anomalies.
- **Quantitative:** Depth estimation (Euler deconvolution, modeling).



Upward continuation of magnetic anomaly map (2,000 m) of Toposheets 45 N/13, 14 and 54 B/1, 2, 5, 6 in Tonk and Dausa Districts, Rajasthan.



Analytic signal map of magnetic (TF) anomaly, parts of Khammam and Nalgonda Districts, Telangana.

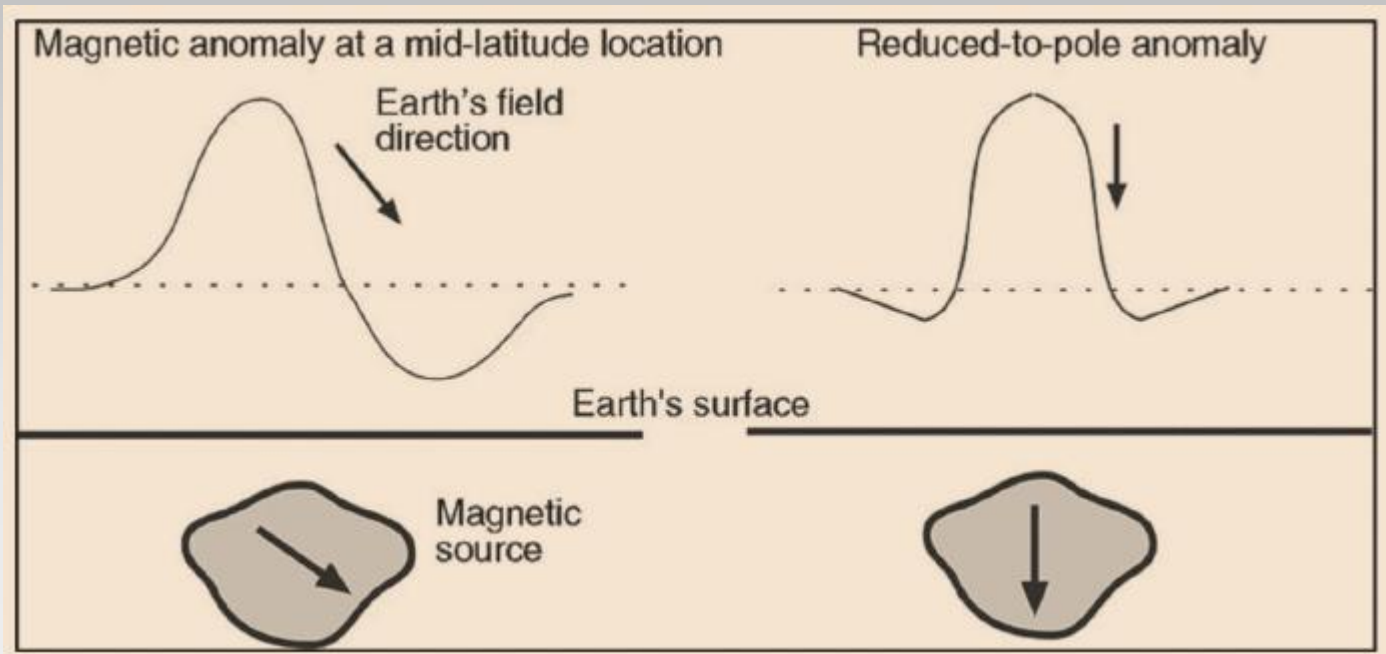


Image shows the effects of using reduction-to-pole correction.

Data Interpretation

1. Qualitative Interpretation

The first stage involves visually analyzing magnetic anomaly maps to identify patterns and trends.

Anomaly Characterization

1. **Bipolar anomalies:** Indicate dipolar sources (e.g., magnetized bodies at mid-latitudes).
2. **Monopolar anomalies:** Seen after **Reduction-to-Pole (RTP)**, where anomalies align directly over sources.
3. **Linear gradients:** Suggest faults, contacts, or shear zones.

Trend Analysis

1. Dominant NE-SW or NW-SE trends may reflect regional tectonic structures.
 2. Circular anomalies may indicate intrusive bodies (e.g., kimberlite pipes).
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Amplitude Variations

1. High amplitudes → Strongly magnetic rocks (e.g., magnetite-rich ores, basalt).
2. Low amplitudes → Sedimentary rocks or weakly magnetic formations.

Contour Patterns

1. **Closed highs/lows:** Isolated magnetic bodies.
2. **Elongated anomalies:** Dykes, faults, or folded structures.

Data Interpretation

2. Quantitative Interpretation

After qualitative assessment, quantitative methods estimate depth, geometry, and susceptibility of sources.

A. Depth Estimation Methods

1. Euler Deconvolution

1. Estimates depth, location, and structural index (shape) of magnetic sources.
2. Works best for isolated anomalies.

2. Slope-Based Methods (e.g., Peters' Half-Slope)

Measures anomaly width to estimate depth.

3. Spectral Analysis

1. Determines depth to top of magnetic basement.
 2. Shallow sources → High-frequency anomalies.
 3. Deep sources → Low-frequency anomalies.
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B. Forward and Inverse Modeling

1. Forward Modeling

1. Tests hypothetical subsurface models (e.g., dykes, spheres, sheets).
2. Adjusts parameters (depth, susceptibility, geometry) to match observed data.

2. Inverse Modeling

1. Computes 3D susceptibility distribution from magnetic data.
2. Non-unique solutions require geological constraints.

3. Data Enhancement Techniques

To improve interpretation,:

A. Reduction-to-Pole (RTP)

Converts dipolar anomalies into monopolar ones centered over sources. **Limitations:**

- Unreliable near the equator (low inclinations).
- Distorted if remanent magnetization is strong.

B. Derivatives and Edge Detection

1.First Vertical Derivative: Enhances shallow features and Sharpens contacts between rock units.

2.Analytic Signal: Combines horizontal and vertical gradients and Locates edges of magnetic bodies effectively.

3.Tilt Derivative: Normalizes amplitude variations, improving subtle anomaly detection.

C. Filtering

1.High-Pass Filtering: Retains high-frequency (shallow) anomalies. Removes regional trends.

2.Low-Pass Filtering: Smooths data to emphasize deep structures.

3.Upward Continuation Simulates data at higher elevations to suppress shallow noise.

4. Challenges and Considerations

1. Remanent Magnetization

1. Can distort induced-field anomalies.
2. Requires lab measurements (e.g., spinner magnetometer) to correct.

2. Non-Uniqueness

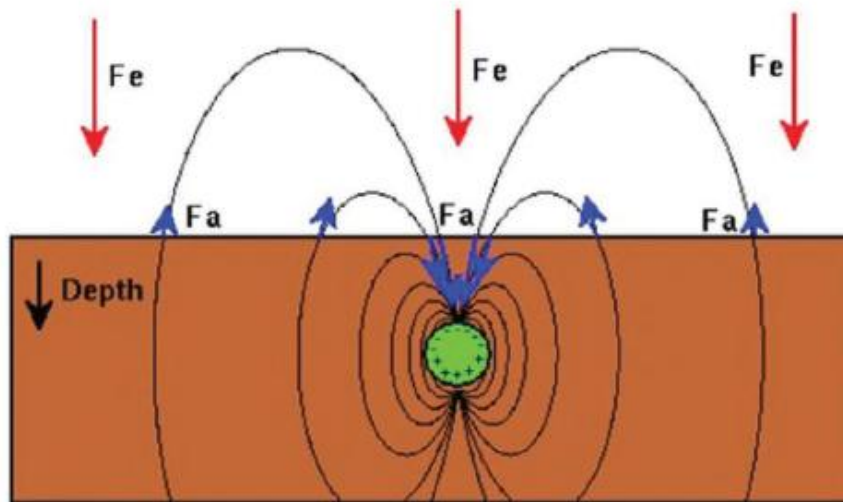
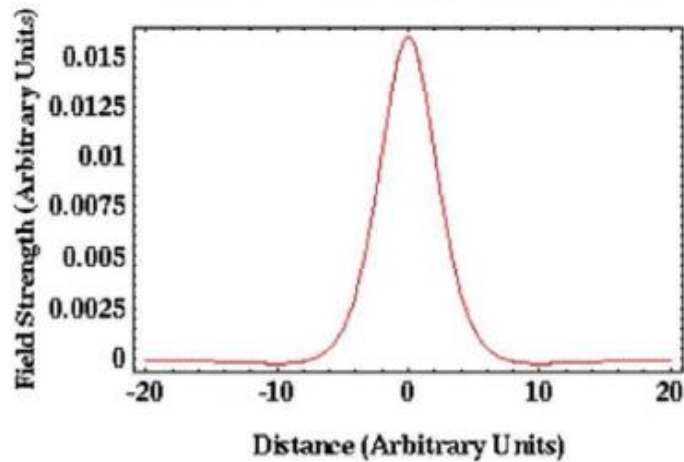
1. Multiple geological models can fit the same magnetic data.
2. Must integrate with geology, gravity, or drilling data.

3. Low-Latitude Effects

1. Near the equator, anomalies are weak and asymmetric.

2. Reduction-to-Equator (RTE) may help but is less effective than RTP.

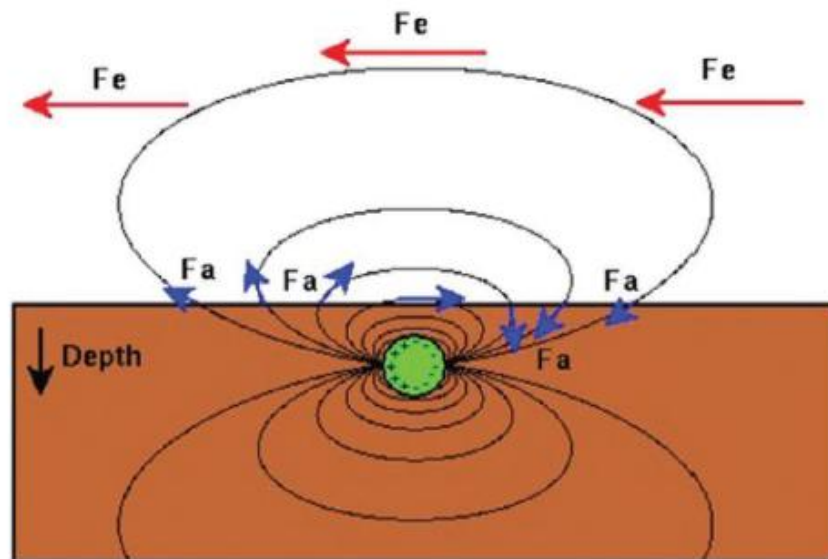
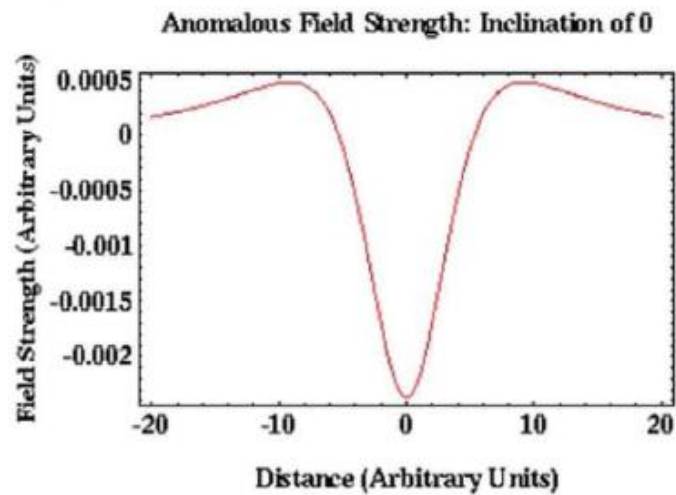
Anomalous Field Strength: Inclination of 90



Fe = Earth's Main Magnetic Field

Fa = Induced Anomalous Magnetic Field

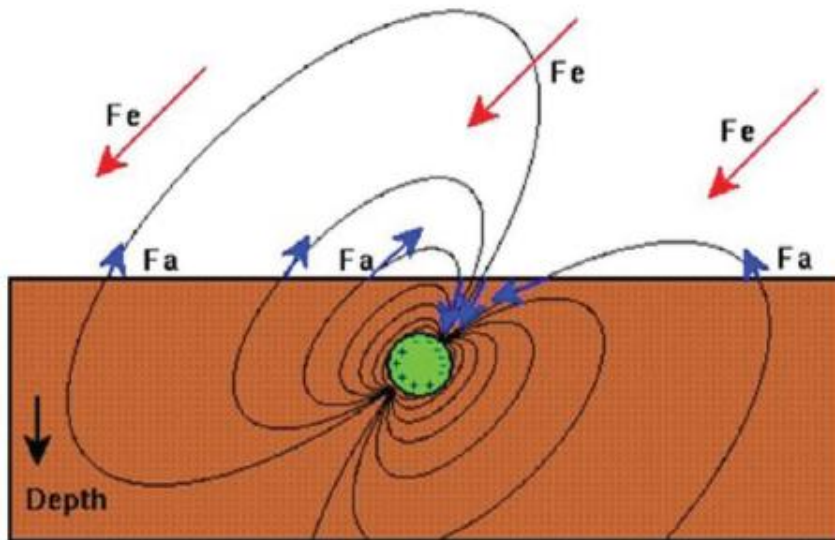
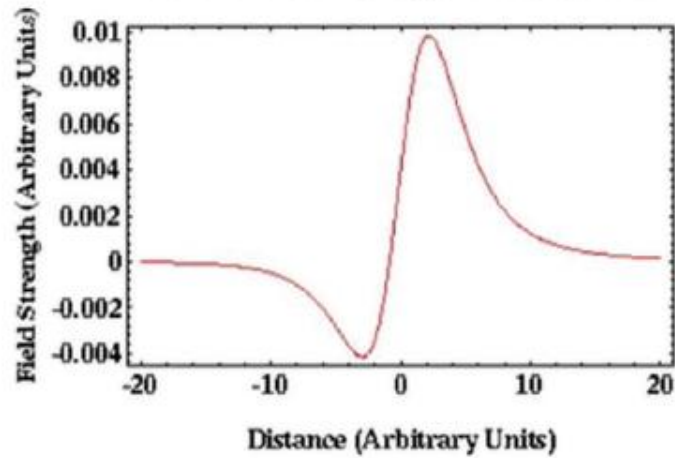
Magnetized sphere at
the Earth's North Pole.



F_e = Earth's Main Magnetic Field
 F_a = Induced Anomalous Magnetic Field

Magnetized sphere at the Earth
Equator

Anomalous Field Strength: Inclination of 45



Fe = Earth's Main Magnetic Field

Fa = Induced Anomalous Magnetic Field

Magnetized sphere in the Northern Hemisphere.

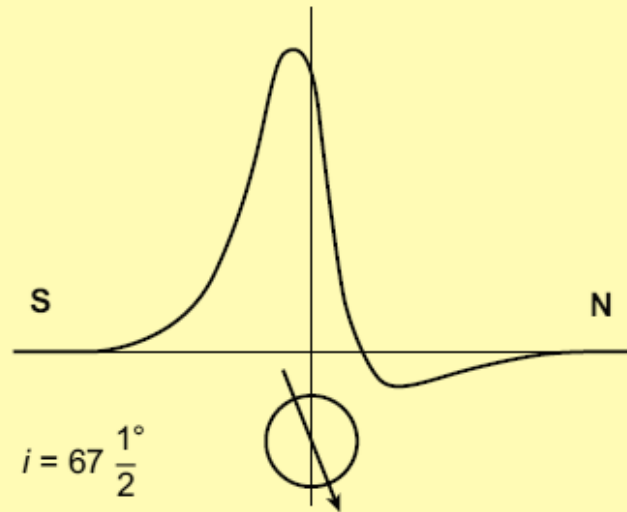


FIGURE 4.13 Magnetized sphere when $i = 67 \frac{1}{2}^\circ$.

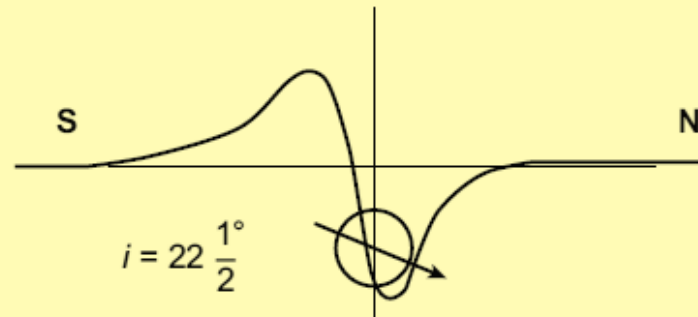


FIGURE 4.14 Magnetized sphere when $i = 22 \frac{1}{2}^\circ$.

Source: Wikipedia.

5. Case Studies:

1.Dyke Detection (Figure 4.3)

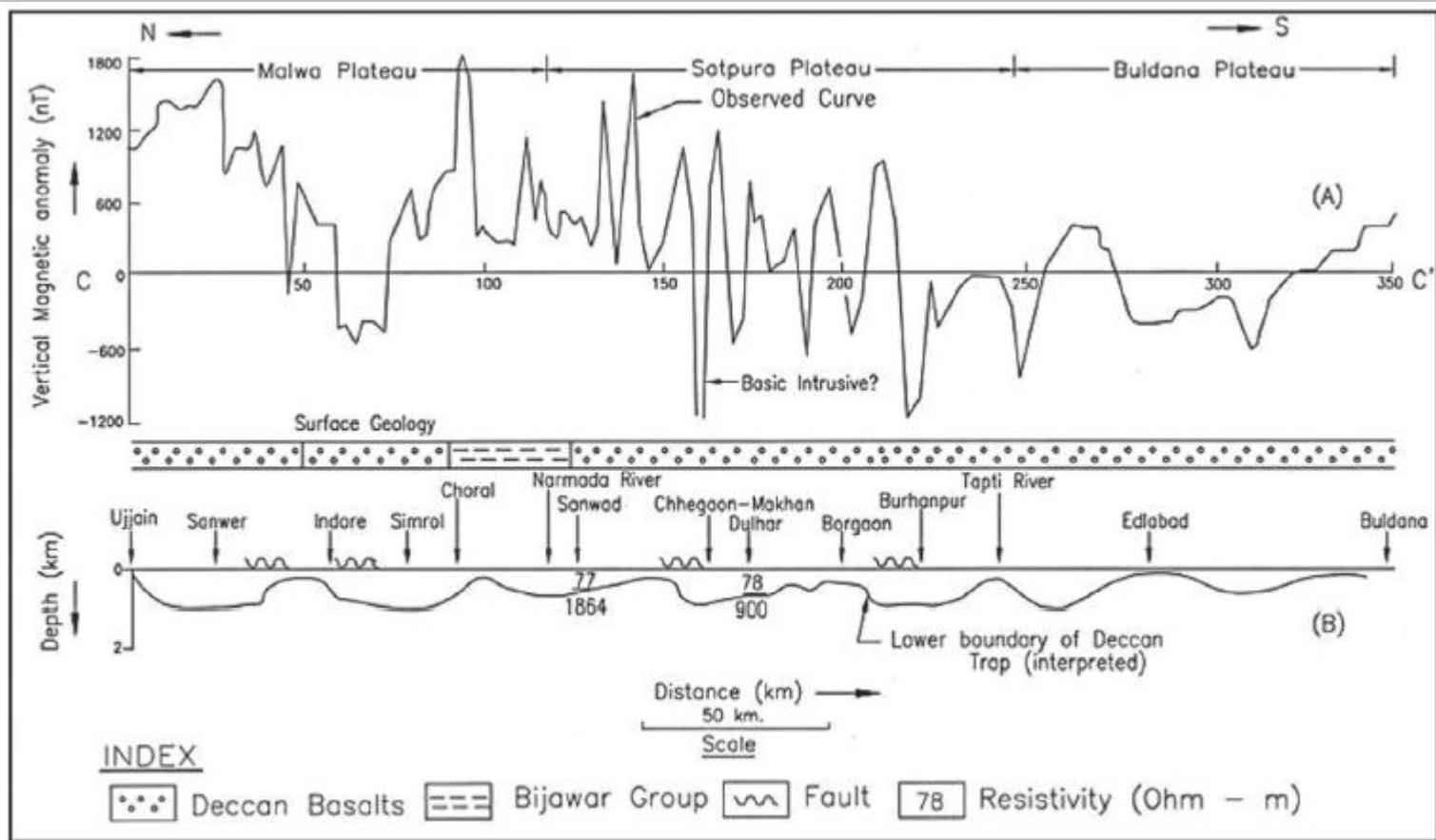
1. A buried dyke (3m wide, 5m deep) produces a 40 nT anomaly.
2. Asymmetric anomaly shape due to inclination (not at pole).

2.Basement Mapping (Figure 4.15)

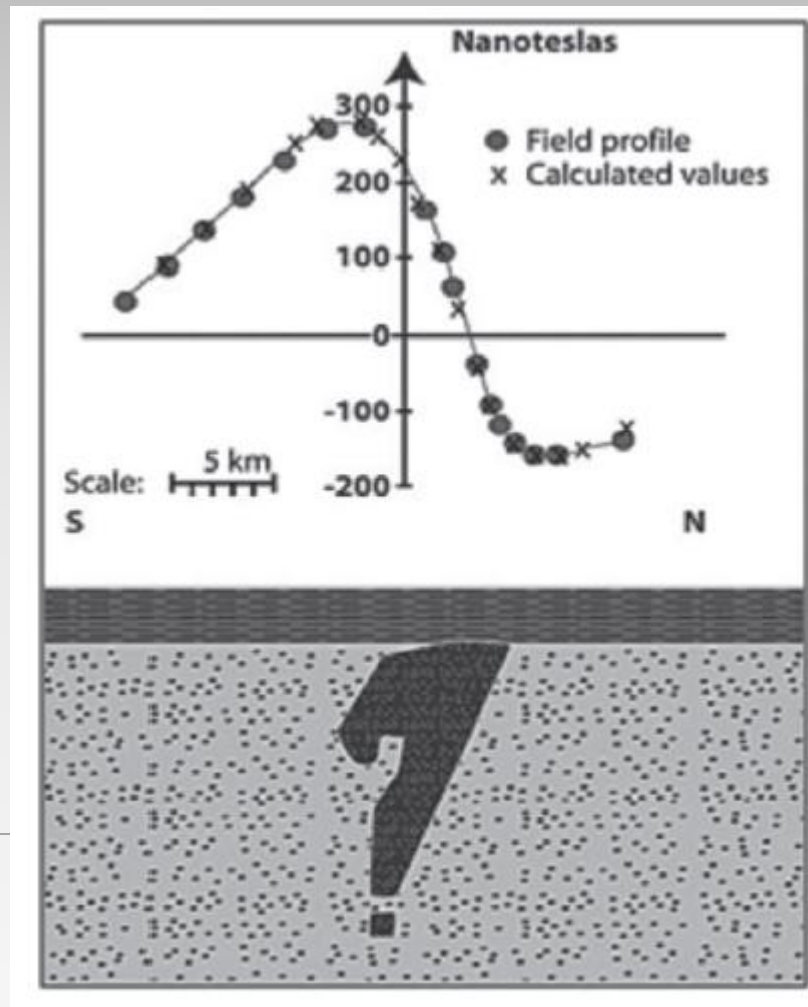
1. Magnetic lows indicate sedimentary basins beneath volcanic traps.
2. 2D modeling reveals basement depth (~600m).

3.Archaeology (Kreuttal, Austria)

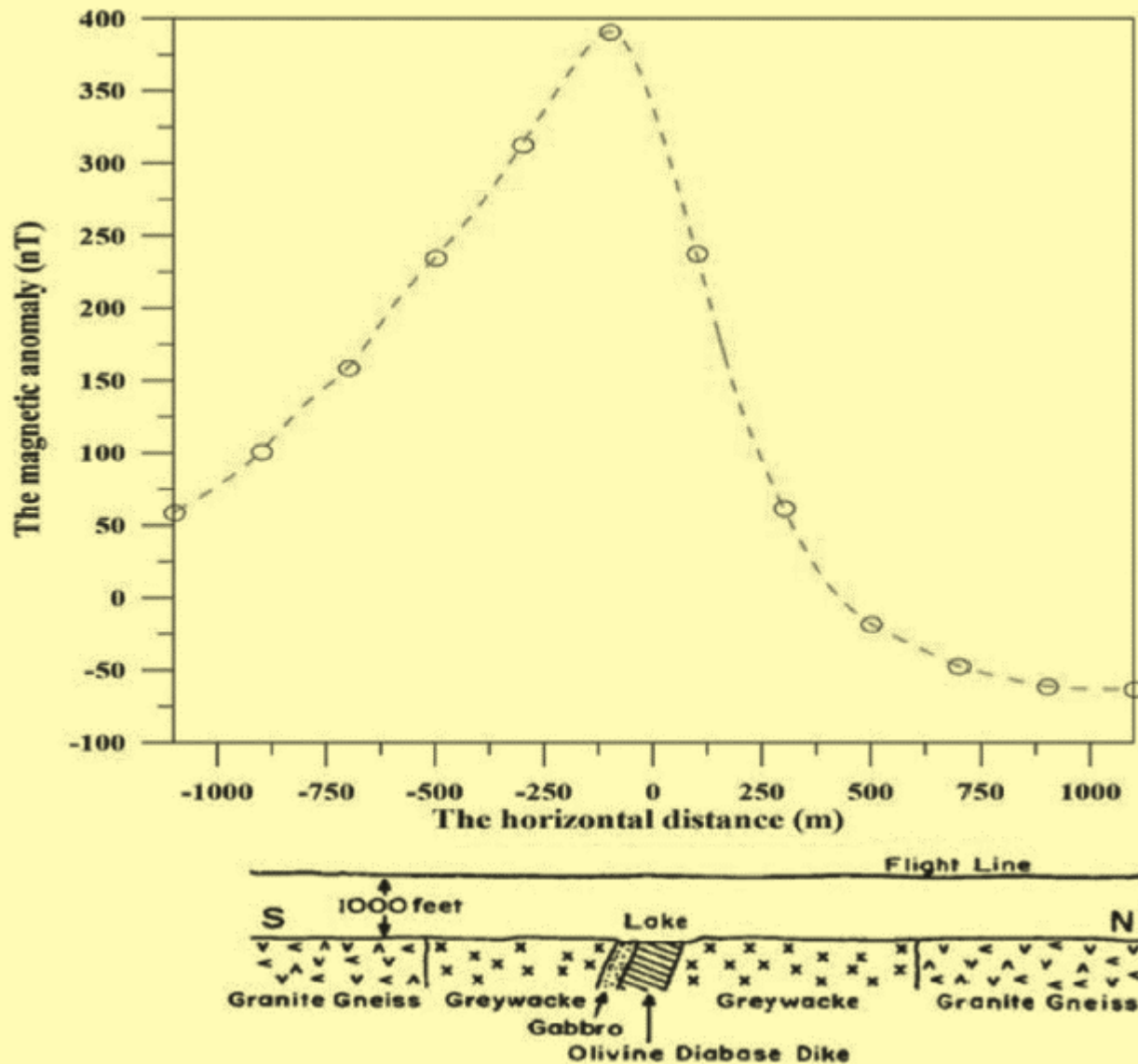
1. Fluxgate surveys detected buried postholes and palisades.
2. Magnetic susceptibility helped confirm anthropogenic features.



Lower boundary of the Deccan trap is delineated by 2-D magnetic modelling.



Magnetic data acquired in Switzerland, and a corresponding subsurface interpretation that is 'theoretically accurate' but geologically absurd.



The magnetic anomaly over an olivine diabase dyke from the Pishabo Lake, Canada.
Source: Adapted from Essa and Munschy (2019).

Similarities and Differences Between Gravity and Magnetic Methods

Both gravity and magnetic methods are **passive geophysical techniques** that measure natural fields of the Earth, but they differ in physical principles, applications, and interpretation challenges. Below is a structured comparison based on the attached book.

Similarities

Aspect	Gravity	Magnetics	Explanation
Field Type	Potential field	Potential field	Both obey Laplace's equation ($\nabla^2\phi=0$) in source-free regions.
Passive Measurements	Yes	Yes	Measure natural fields (no artificial energy source required).
Data Processing	Requires corrections (latitude, elevation, terrain)	Requires corrections (diurnal, IGRF, leveling)	Both need corrections to isolate anomalies of interest.
Anomaly Interpretation	Non-unique solutions	Non-unique solutions	Multiple geological models can fit the same data.
Regional-Residual Separation	Used (e.g., high-pass/low-pass filtering)	Used (e.g., upward continuation)	Both separate shallow/local from deep/regional signals.
Applications	Mineral exploration, oil/gas, tectonics	Mineral exploration, archaeology, tectonics	Used in similar fields but target different properties.

Differences

Aspect	Gravity	Magnetics	Explanation
Physical Property Measured	Density contrasts (ρ)	Magnetic susceptibility (k) & remanence	Gravity responds to mass distribution; magnetics to iron-bearing minerals.
Source Type	Monopole (mass)	Dipole (N-S pair)	Gravity sources are scalar (mass); magnetics require vector treatment (dipoles).
Field Behavior	Always attractive	Can be attractive or repulsive	Magnetic fields depend on dipole orientation.
Time Variations	Minimal (only tidal effects)	Significant (diurnal, magnetic storms)	Magnetic fields are affected by solar activity.
Depth Penetration	Better for deep structures (e.g., Moho)	Better for shallow to mid-crustal features	Gravity anomalies decay more slowly with depth.
Anomaly Shape	Symmetric (for simple bodies)	Asymmetric (depends on latitude & inclination)	Magnetic anomalies distort with magnetic latitude.
Key Minerals Detected	Dense ores (e.g., sulfides, chromite)	Magnetic minerals (e.g., magnetite, pyrrhotite)	Gravity finds high-density bodies; magnetics find Fe-rich rocks.
Remanence Effects	None	Significant (e.g., volcanic rocks)	Remanent magnetization complicates magnetic interpretation.
Correction Challenges	Terrain effects dominate	Diurnal variations & cultural noise dominate	Gravity needs terrain corrections; magnetics need temporal corrections.

Practical Implications

When to Use Gravity

- Mapping **basin architecture** (sediment thickness).
- Detecting **dense ore bodies** (e.g., lead-zinc deposits).
- Studying **deep crustal structures** (e.g., Moho depth).

When to Use Magnetism

- Locating **magnetic ores** (e.g., iron, nickel).
- Mapping **igneous intrusions** (e.g., kimberlite pipes).
- Archaeological surveys (e.g., buried hearths, kilns).

Combined Surveys

- **Gravity + Magnetism** reduces interpretation ambiguity (e.g., distinguishing gabbro vs. granite intrusions).