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MAGNETIC EXPLORATION

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Definition of magnetic survey

- *Magnetic survey:* ***Measurements*** *of the magnetic field or* its components at a series of different locations over an area of interest and locating **anomalies** in the Earth's magnetic field.

- The objective is **locating** concentrations of magnetic materials or determining depth to basement.

- Most rocks are nonmagnetic, however certain rock types contain sufficient magnetic minerals to produce significant magnetic anomalies.

Magnetic survey

- Magnetic methods can be performed on **land**, at **sea** and in the **air**.

- The technique is **widely employed**, especially the speed of operation makes the method very attractive.

Magnetic survey

Magnetic survey

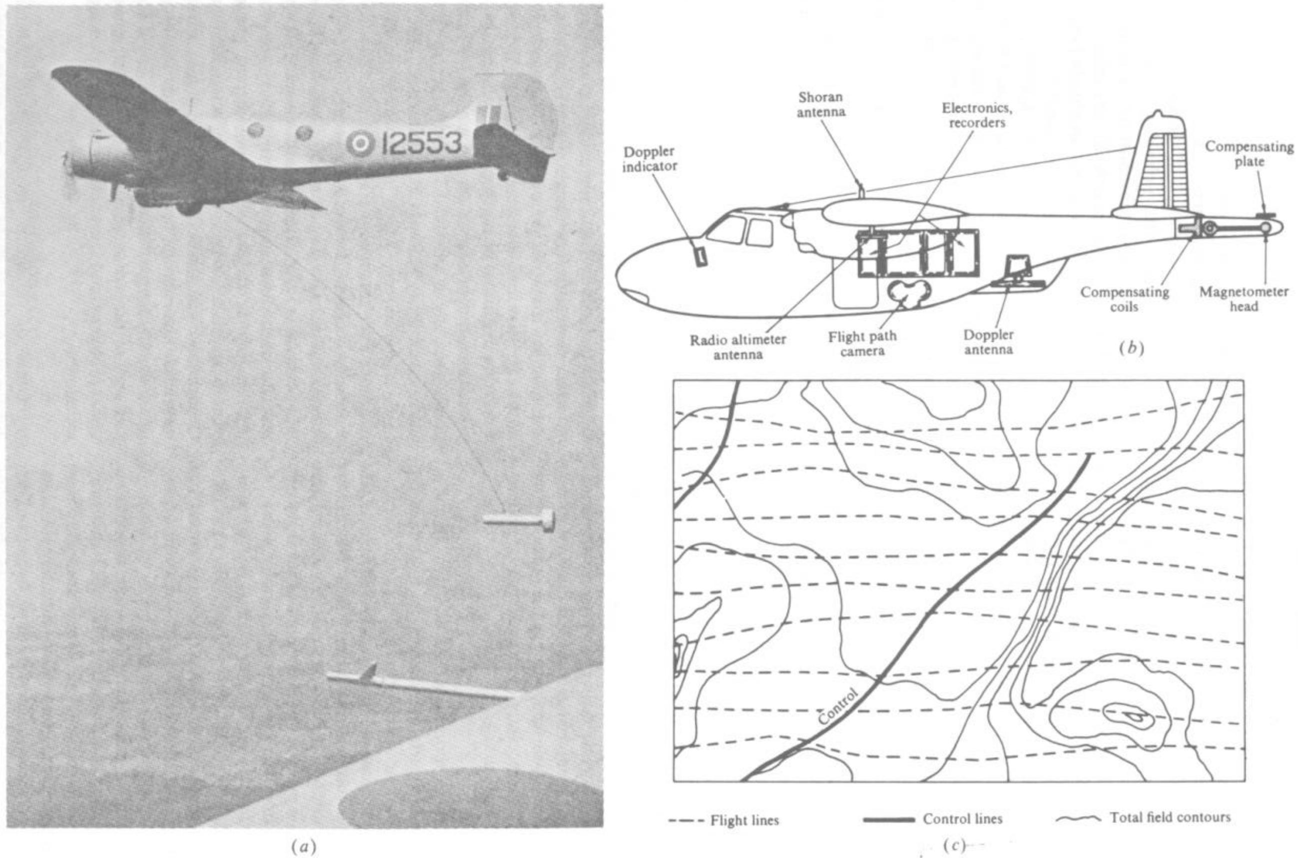
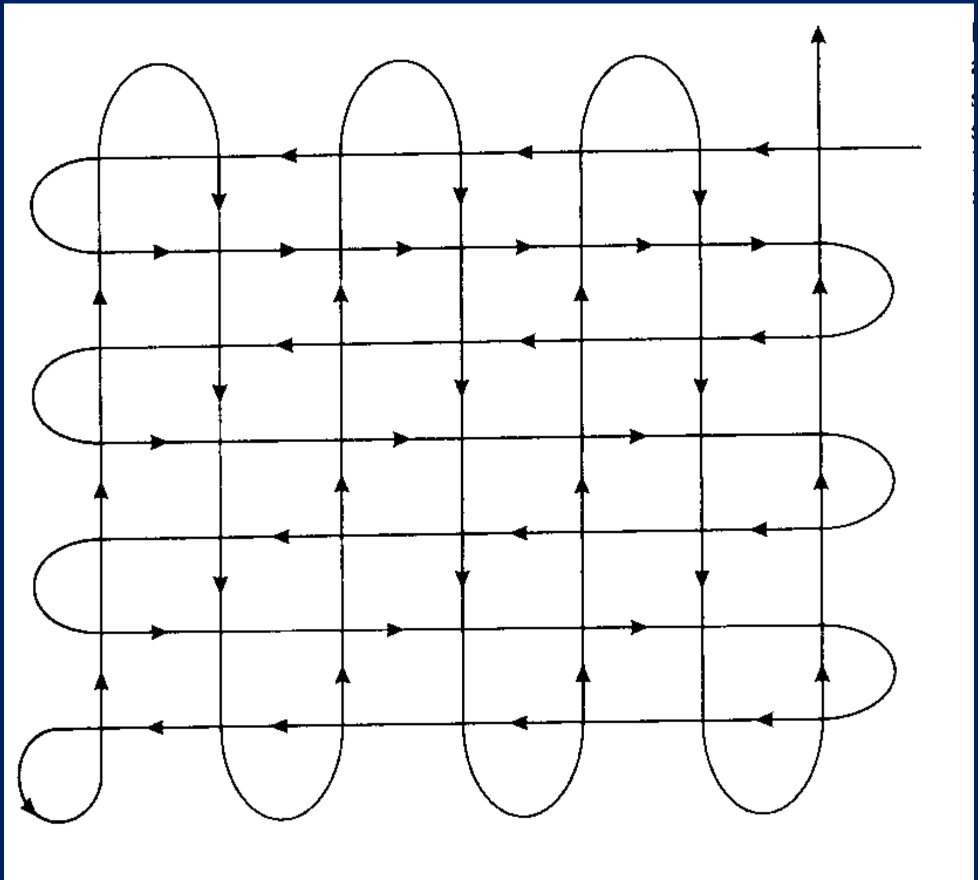


Figure 3.13. Airborne magnetics. (a) Magnetometer in a bird. (b) Magnetometer in a tail mounting. (c) Flight pattern and magnetic map.

Magnetic survey



Applications of magnetic survey

- **Locating**

– Pipes, cables and metallic objects
– Buried military ordnance (shells, bombs, etc.)
– Buried metal drums of contaminated or toxic waste
– Concealed mineshafts and adits

- **Mapping**

– Archaeological remains
– Concealed basic igneous dykes
– Metalliferous mineral lodes
– Geological boundaries between magnetically contrasting lithologies, including faults
– Largescale geological structures

Basic concepts and units

Recall that the gravitational force exerted between two point masses of mass *m1 and m2 separated by a* distance *r is given by Newton's law of gravitation, which is written as*

$$F_g = \frac{G m_1 m_2}{r^2}$$

where *G is the gravitational constant. This law, in words, simply states that the gravitational force* exerted between two bodies decreases as one over the square of the distance separating the bodies. Since mass, distance, and the gravitational constant are always positive values, the gravitational force is always an attractive force.

Magnetic Force

Charles Augustin de Coulomb, in 1785, showed that the force of attraction or repulsion between electrically charged bodies and between magnetic poles also obey an **inverse square law** like that derived for gravity by Newton.

The mathematical expression for the magnetic force experienced between two magnetic monopoles is given by

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

where μ is a constant of proportionality known as **the magnetic permeability**, p_1 and p_2 are the strengths of the two magnetic monopoles, and r is the distance between the two poles.

Magnetic force

- *In form, the expression of magnetic force* (F_m) *is* identical to the gravitational force expression (F_g). There are, however, two important differences:

- Unlike the gravitational constant, *G, the magnetic permeability, μ, is a property of the material in* which the two monopoles, p_1 *and* p_2, *are located. If they are in a vacuum,* ***μ is called the magnetic*** **permeability of free space.**

- Unlike $\boldsymbol{m_1}$ *and* $\boldsymbol{m_2}$, $\boldsymbol{p_1}$ *and* $\boldsymbol{p_2}$ *can be either* ***positive or negative*** *in sign. If* $\boldsymbol{p_1}$ *and* $\boldsymbol{p_2}$ *have the same* sign, the force between the two monopoles is repulsive. If $\boldsymbol{p_1}$ *and* $\boldsymbol{p_2}$ *have opposite signs, the force* between the two monopoles is attractive.

MAGNETIC FIELD STRENGTH

The *magnetic field strength, H, is* defined as the force per unit pole strength exerted by a magnetic monopole, p_1.

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

The magnetic field strength *H is the magnetic analog to the* gravitational acceleration, *g*.

UNITS

- Given the units associated with force, *N, and magnetic monopoles, Amp -m, the units associated with magnetic field strength are Newtons per* Ampere-meter, *N / (Amp - m).*
- *N / (Amp - m) is referred to as a **Tesla (T)**.*

A nanotesla (nT) is also commonly referred to as a ***gamma .***

$1nT = 10^{-9}\ T = 1gamma$.

- The average strength of the Earth's magnetic field is about 50,000 nT.

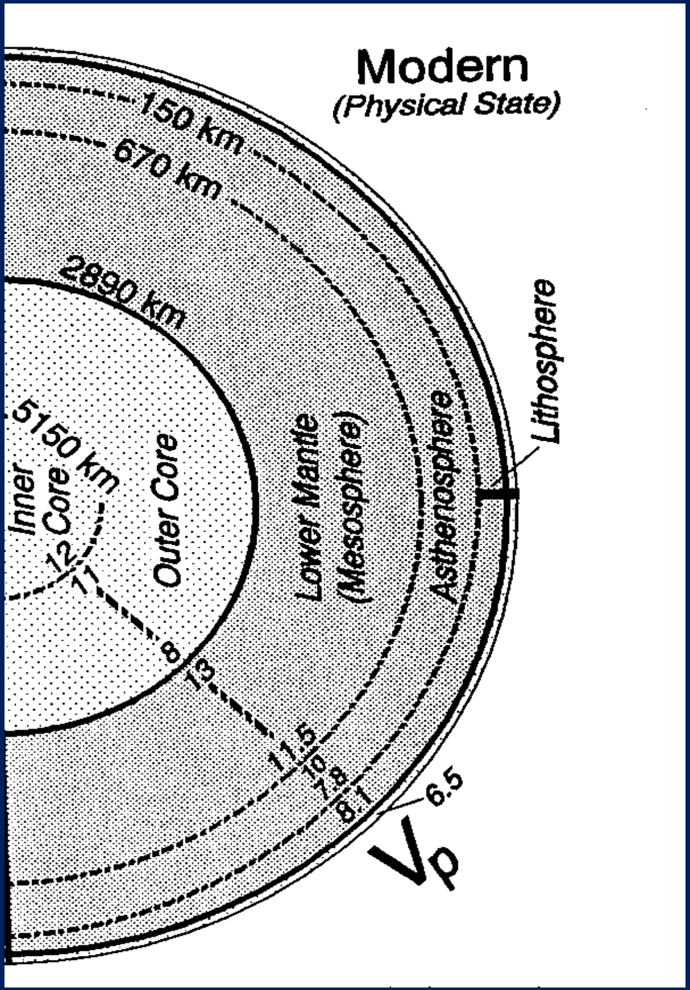
Magnetic induction

- When a magnetic material, say iron, is placed within a magnetic field, *H, the magnetic material will* produce its own magnetization. This phenomena is called ***induced magnetization***.
- In practice, the induced magnetic field (that is, the one produced by the magnetic material) will look like it is being created by a series of magnetic dipoles located within the magnetic material and oriented **parallel to the direction of the inducing field, *H*.**

EARTH'S MAGNETIC FIELD

- The magnetic field at or near the surface of the earth originates largely (98%) from within and around the **Earth's core**. It's thought to be caused by motions of liquid metal in the core.
- The remaining 2% is **external**, of solar origin.
- The magnetic field has secular variations.

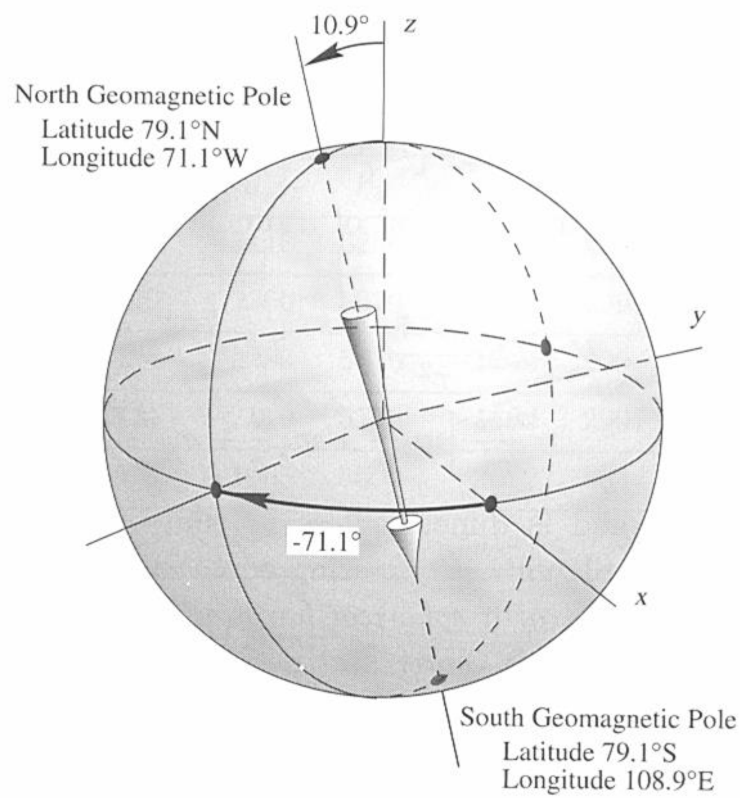
Origin of the Earth's magnetic field



The geomagnetic field is produced by electric currents induced within the conductive liquid outer core as a result of its slow convective mmouvement.

The liquid core behaves as a geodynamo but the precise nature of the process involved has yet to be resolved.

Origin of the Earth’s magnetic field



The orientation of the dipole field as described by IGRF 1990.

90% of the earth's magnetic field can be explained as a dipole at the earth's center, inclined about 10.9° from Earth’s rotational axis dipole with M (العزم المغناطيسي) = 8×10 22 Am2.

Origin of the Earth's magnetic field

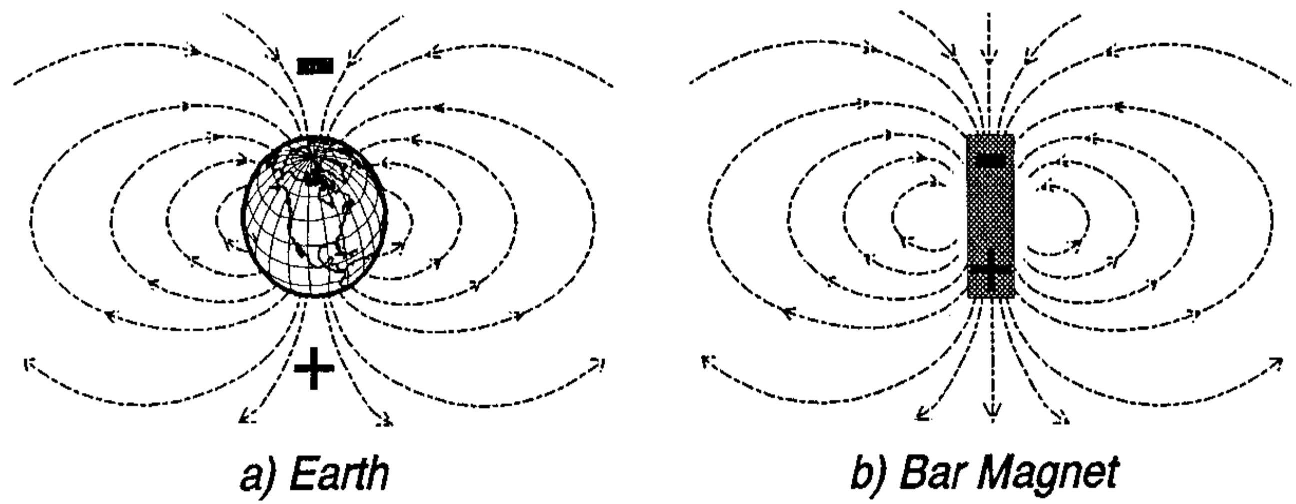


FIGURE 9.2 Earth's magnetic field is similar to that of a bar magnet, with the negative magnetic pole in the northern hemisphere and the positive magnetic pole in the southern hemisphere. The positive end of a compass needle (defined originally as "north-seeking") thus points roughly toward the geographic north pole.

With the model of magnetic dipole at the center of the Earth , Earth's magnetic field is a<u>na</u>logous to that of a bar magnet.

Strength and direction of magnetic field

- A magnetic field is composed of vectors, having both magnitude and diection.
- The orientation of compass needle illustrates the direction of Earth’s magnetic field.

Strength and direction of magnetic field

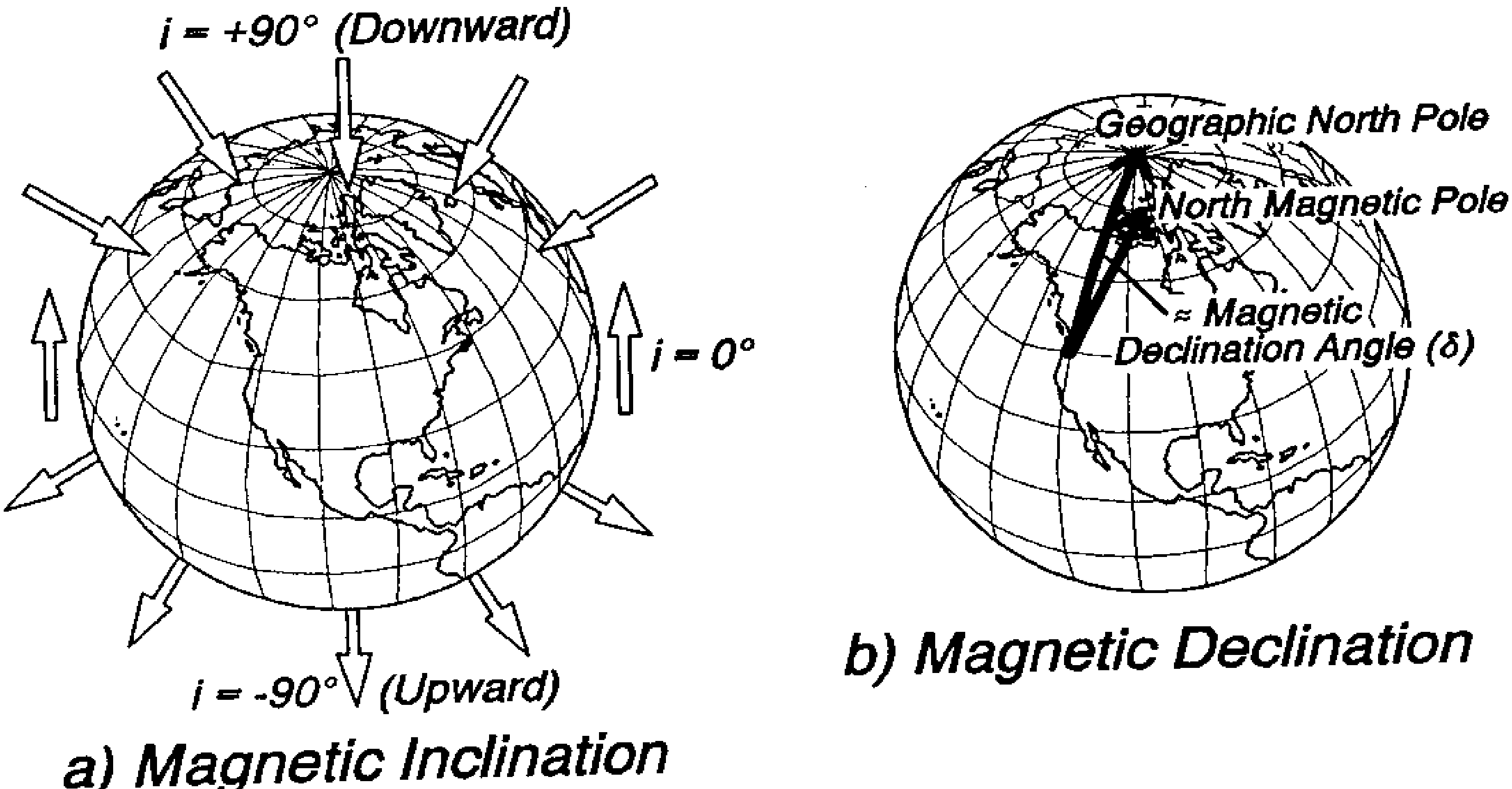
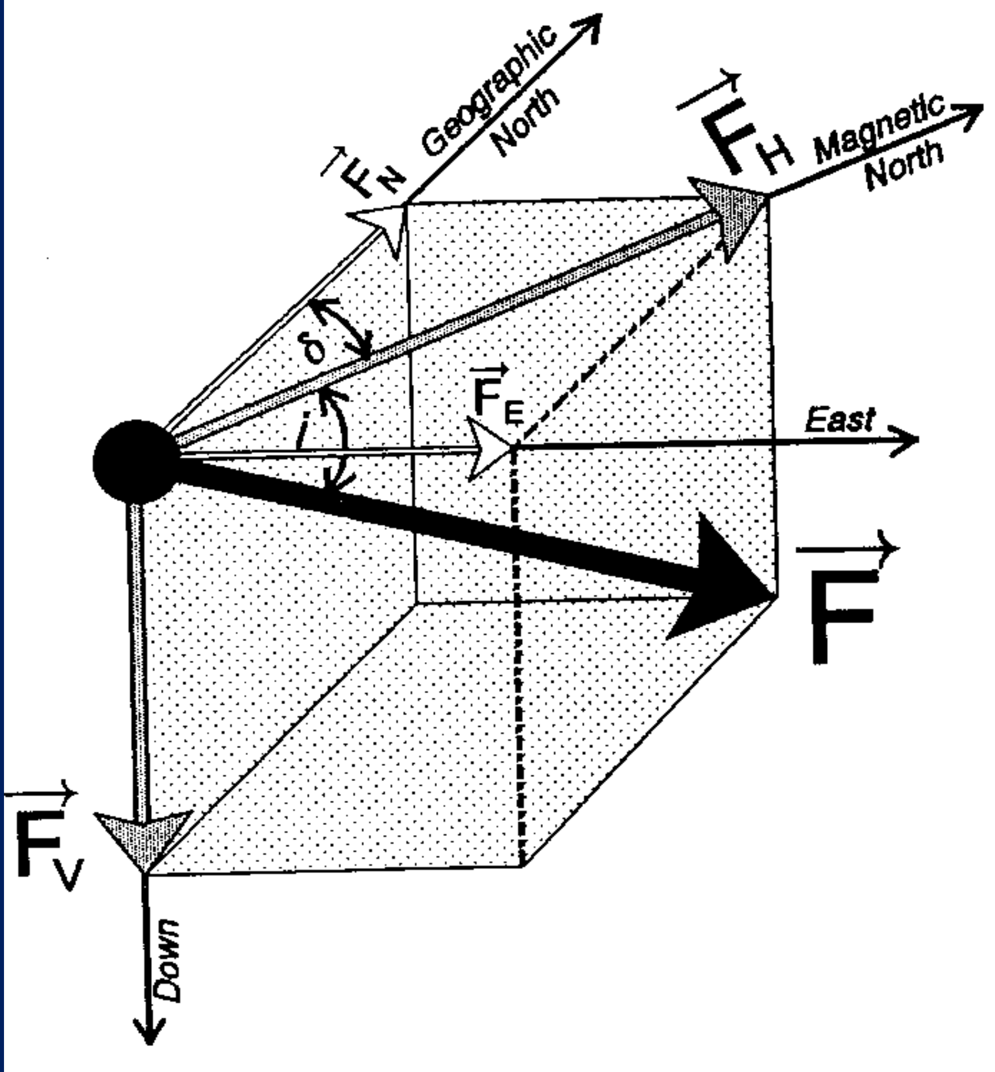


FIGURE 9.4 *Magnetic inclination and declination.* a) The angle between magnetic lines of force (Fig. 9.1b) and a horizontal ground surface is the magnetic inclination (i). b) The magnetic declination (δ) is the angle a compass needle deviates from geographic north.

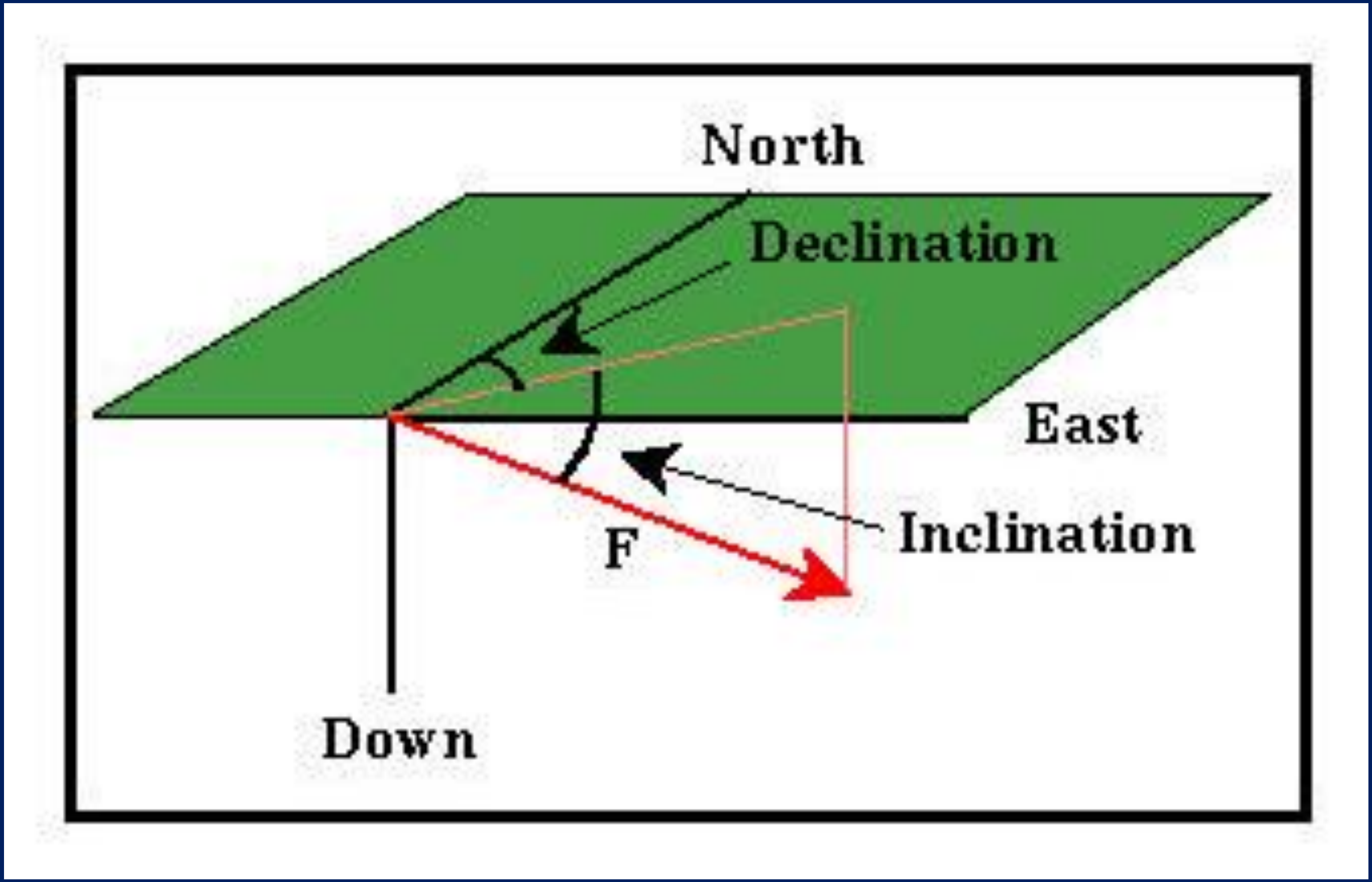
Components of the Geomagnetic field



The geomagnetic field can be described in terms of declination d, inclination I and the total force vector F.

- F: magnitude of total magnetic field vector
-Fv: magnitude of vertical component of total field vector
- F_H: magnitude of horizontal component of total field vector
- F_N: magnitude of North component of total field vector
- F_E: magnitude of East component of total field vector
- δ: declination
- i: inclination

Components of the Geomagnetic field



Components of the Geomagnetic field

- $\tan(i) = F_V / F_H$
- $\tan(d) = F_E / F_N$
- Note:
- Magnetic Inclination: الميل المغناطيسي
- Magnetic Declination: انحراف مغناطيسي
- Magnetic Field Strenth: قوة المجال المغناطيسي

Magnetic field strength

- Magnetic field at:

  geomagnetic pole: 60,000 nT

  equator: 30,000 nT

  Riyadh: 42,000 nT ?
- ➔ It varies with latitude

Magnetic field strength

The axial dipole model simplifies discussion of Earth's overall field because equations can be developed to describe the strength and direction of the field. With such a model the magnitudes of the horizontal, vertical, and total field vectors are (Butler, 1992):

$$F_H = \frac{M \cos \phi}{R^3}$$

$$F_V = \frac{2M \sin \phi}{R^3}$$

$$F = \frac{M\sqrt{1 + 3 \sin^2 \phi}}{R^3}$$

where:

R = radius of the Earth
M/R^3 = total field intensity at the magnetic equator
ϕ = magnetic latitude (for axis inclined 10.9° from the true rotational axis; Fig. 9.3a)

The magnetic inclination for an axial dipole also varies systematically with magnetic latitude as:

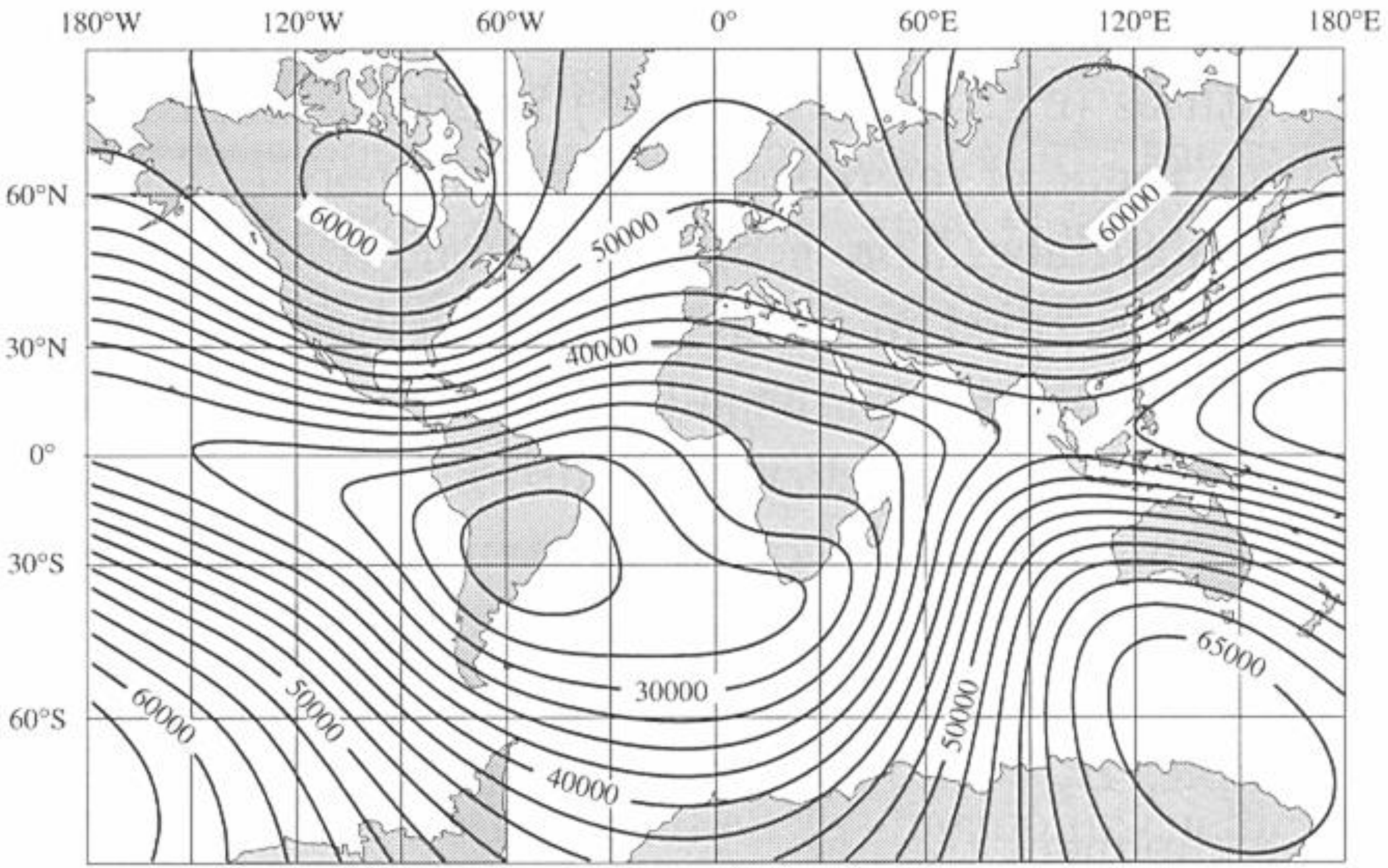
$$\tan i = 2 \tan \phi$$

Magnetic field strength

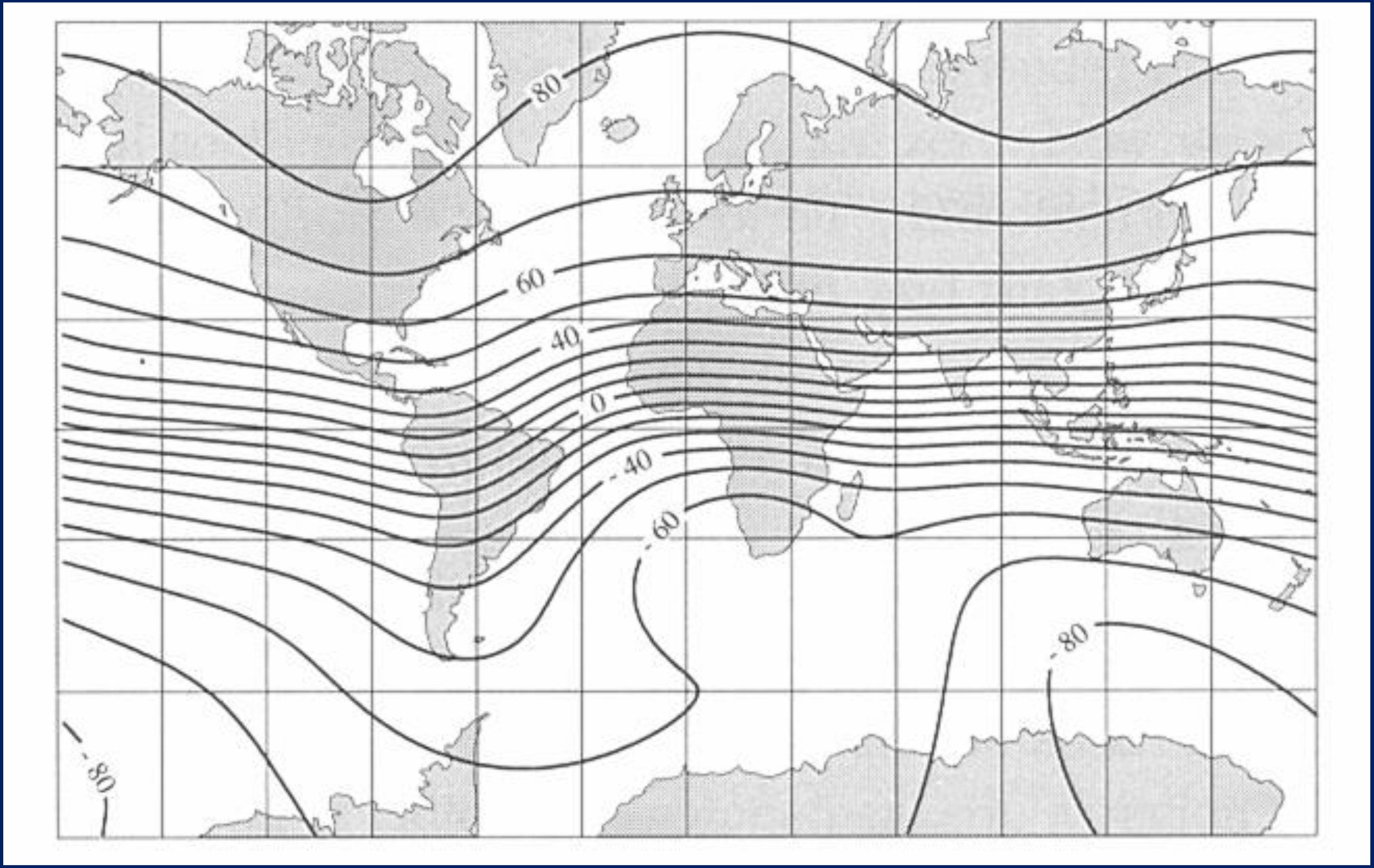
- The equation expressing the total field intensity (F) illustrates that unlike gravity field, which decreases by $1/R^2$, the magnetic intensity falls off by $1/R^3$.

1. For a value of $F=M/R^3 = 30{,}000nT$ at the magnetic equator (Latitude=0), the total field intensity doubles to about 60,000nT at the magnetic pole (Latitude=90).

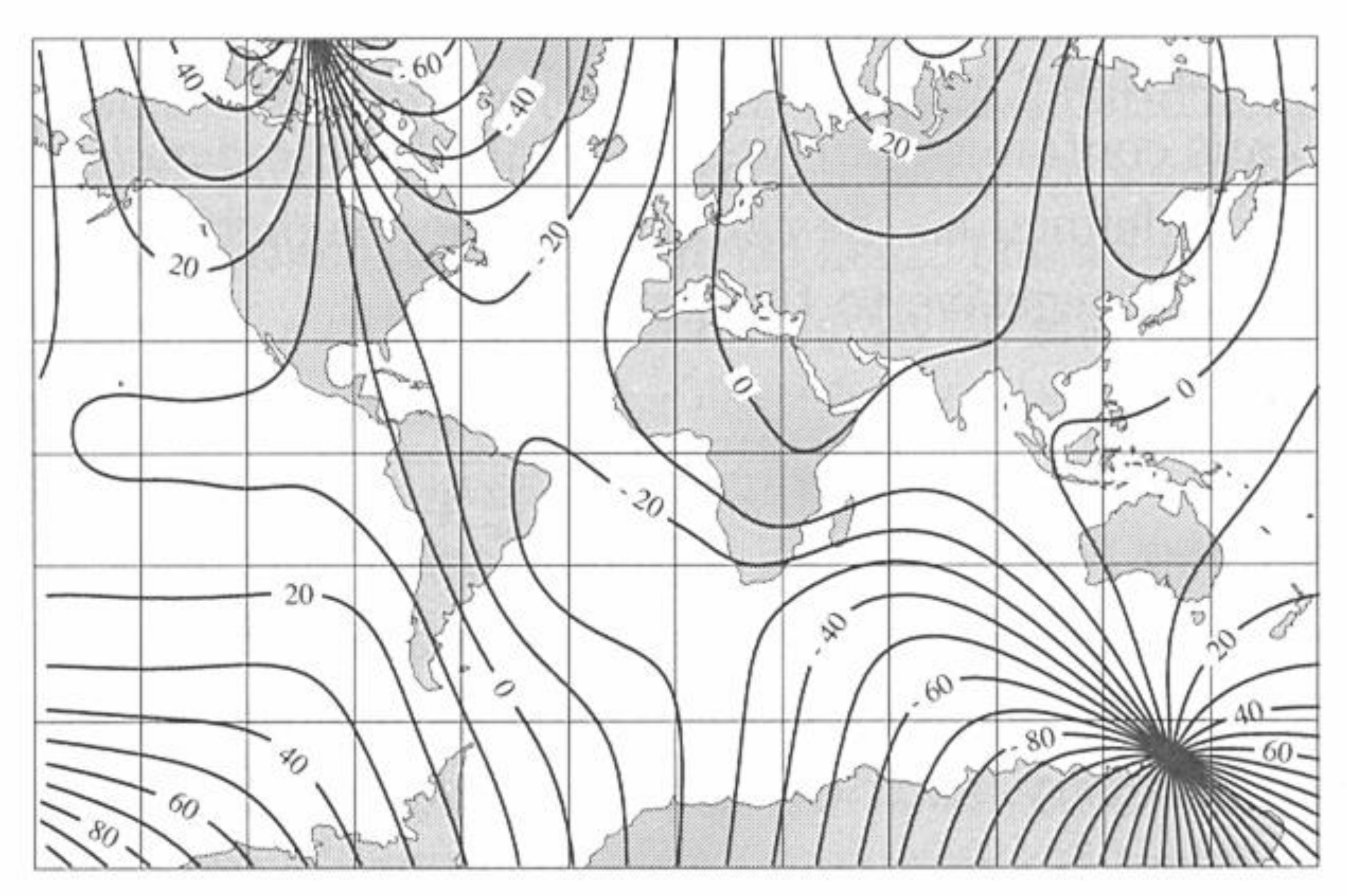
Map of total intensity of Earth's magnetic map based on IGRF 1990, contour: 2,500nT



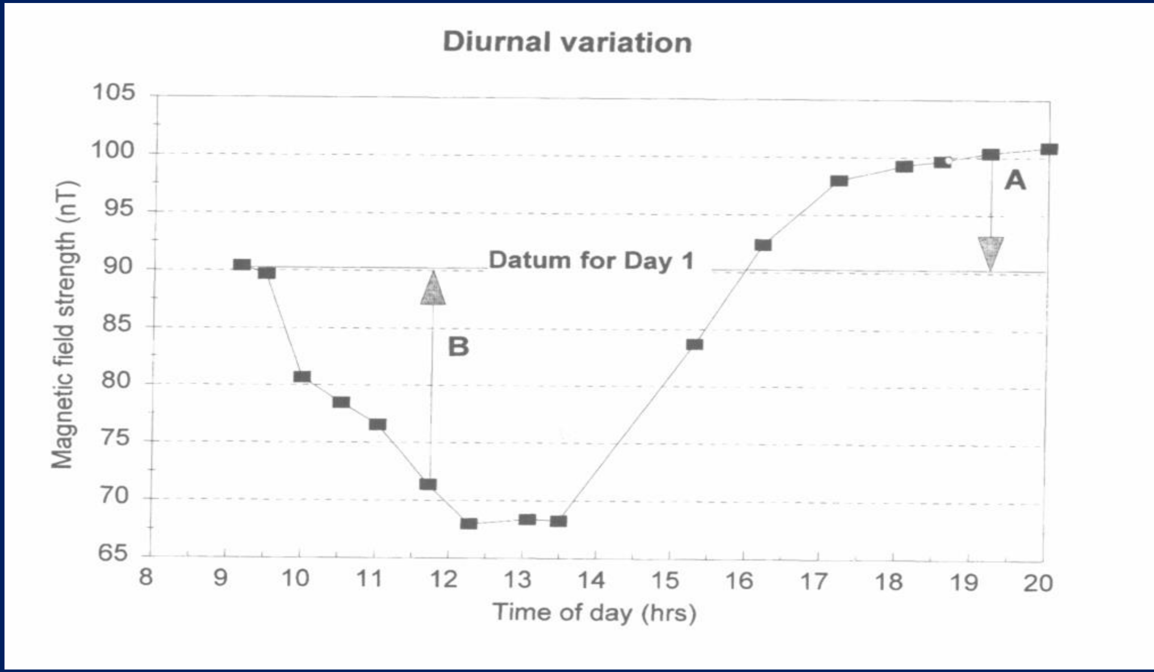
Map showing contant inclination of total magnetic fiels, contour: 10° (based on IGRF 1990)



Map showing constant declination. Contour interval: 10°



THE EXTERNAL MAGNETIC FIELD
Daily variation of the Earth's magnetic field



About 2% of the Earth's Magnetic Field is External, due to solar activity.
This component varies with time.
The earth's magnetic field changes over a daily period, the diurnal variation (10-30 nT)

MAGNETIZATION OF ROCKS

- **Note:**

- Magnetic Field Strength: قوة المجال المغناطيسي
- Intensity of Magnetization: شدة التمغنط
- Magnetic Moment: العزم المغناطيسي
- Remanent Magnetism: مغناطيسية متبقية
- Magnetic Induction: الحث المغناطيسي
- Magnetic Susceptibility: قابلية مغناطيسية
- Diamagnetic: ضعيف النفاذية المغناطيسية
- Ferromagnetic: ضعيف النفاذية المغناطيسية

MAGNETIZATION OF ROCKS

Earth's magnetic field is perturbed locally by materials that are capable of being magnetized.

Perturbations in the direction of the field can be illustrated by moving a magnet around a compass. The inclination and declination of the needle of the compass change in response to the position of the magnet.

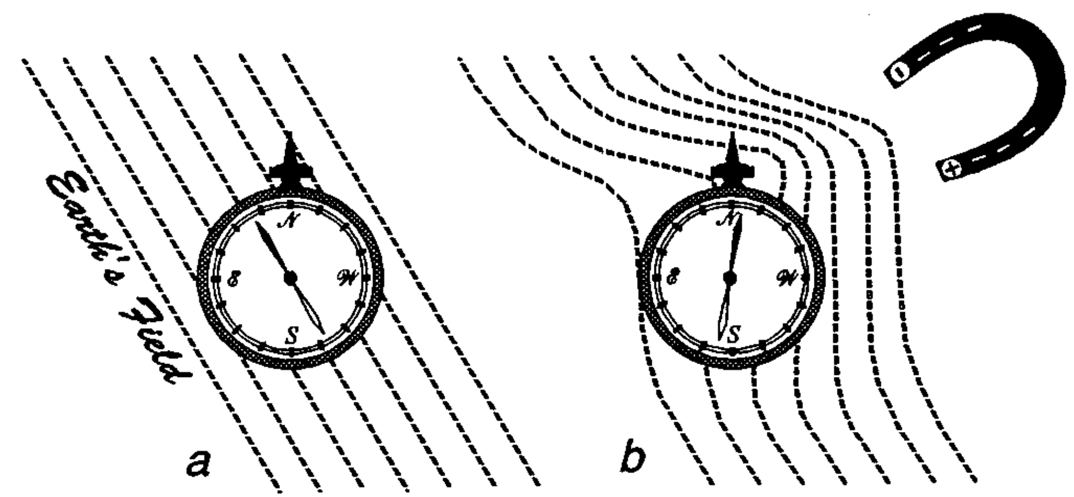


FIGURE 9.7 a) Compass responding to Earth's ambient magnetic field. b) Magnet causes a local deviation of Earth's field.

MAGNETIZATION OF ROCKS

- When magnetized rocks occur at or below Earth's surface, the direction and magnetic of Earth's overall magnetic filed change slightly. It is thus important to understand the predisposition of various type of materials toward magnetization, and how the magnetization locally affects Earth's field.

- $F_{observed} = F_{internal} + F_{external} + F_{local}$

- $F_{observed} = F_{reference} + F_{local}$

MAGNETIZATION OF ROCKS
Type of magnetization

- Magnetization of rock occurs in two ways:
- 1./ It can be induced by Earth's present magnetic field: **Induced magnetization**
- 2./ It could have formed some time in the past: **Remanant magnetization**.

MAGNETIZATION OF ROCKS

- $F_{observed} = F_{reference} + F_{local}$
- $F_{local} = F_{induced} + F_{remanent}$
- **Induced part, $F_{induced}$** : proportional to the ambient magnetic field (present Earth's magnetic field) and depends on the susceptibility.
- **Remanant part, $F_{remanent}$** : remains unchanged if there is no field present and is <u>independent of ambient magnetic field</u>. It has formed some time in the past.
- The magnitude is very variable, on the scale of 1000nT.

MAGNETIZATION OF ROCKS

Induced magnetization

- If a body is placed within an external magnitude field (H), the body acquires a magnetization (I), with intensity proportional to the overall magnetic susceptibility (k) of the body.

MAGNETIZATION OF ROCKS
Intensity of induced magnetization

- The strength of the magnetic field induced by the magnetic material due to the inducing field is called the *intensity of magnetization, I.*
- The magnitude and direction of magnetization induced within a material depends on the magnitude and direction of the external (ambient) field (H) and the ability of the material to be magnetized.

$$I = k\,H$$

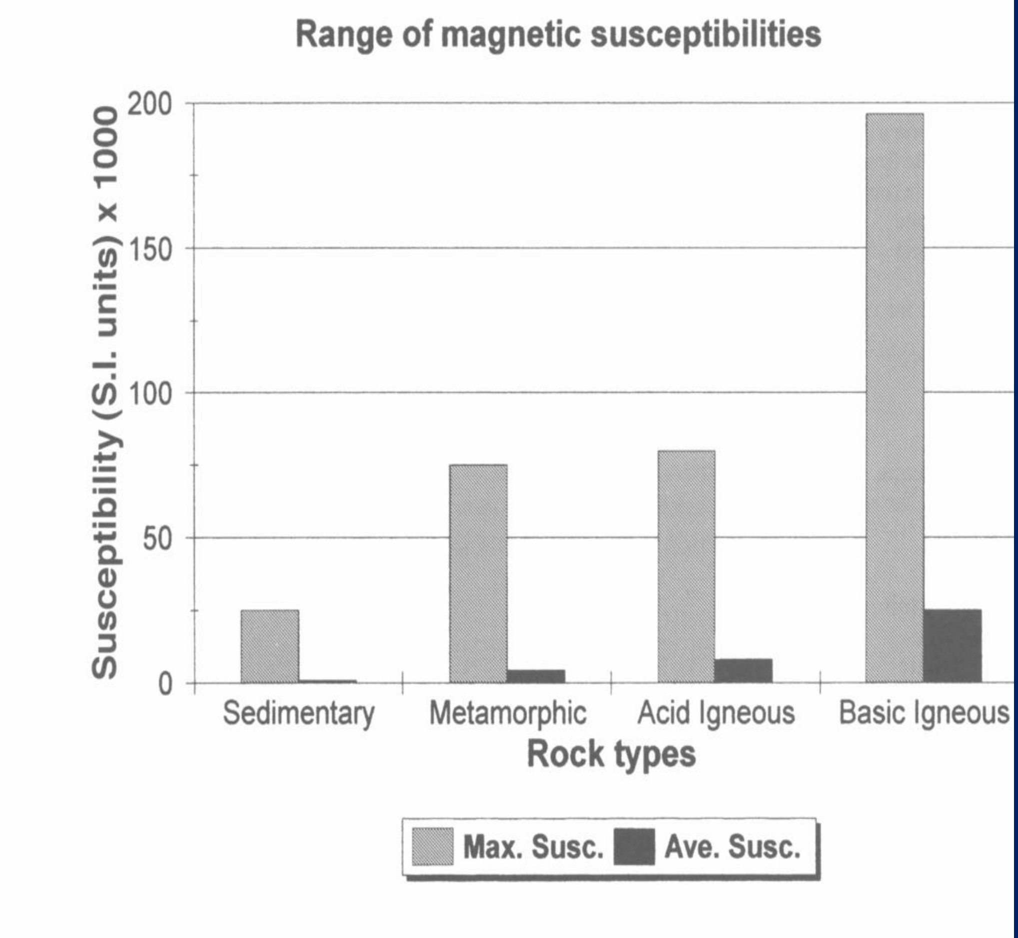
I: Intensity of the magnetization of the material (Induced magnetization).

K: magnetic susceptibility of the material

H: magnitude of the ambient field (Earth's field).

MAGNETIZATION OF ROCKS

Magnetic Suceptibility



The intensity of magnetization, *I, is related to the strength of the inducing* magnetic field, *H, through a constant of proportionality, k, known as the magnetic* susceptibility.

The magnetic susceptibility (k, a dimensionless quantity) is a measure of the degree to which a substance may be magnetized.

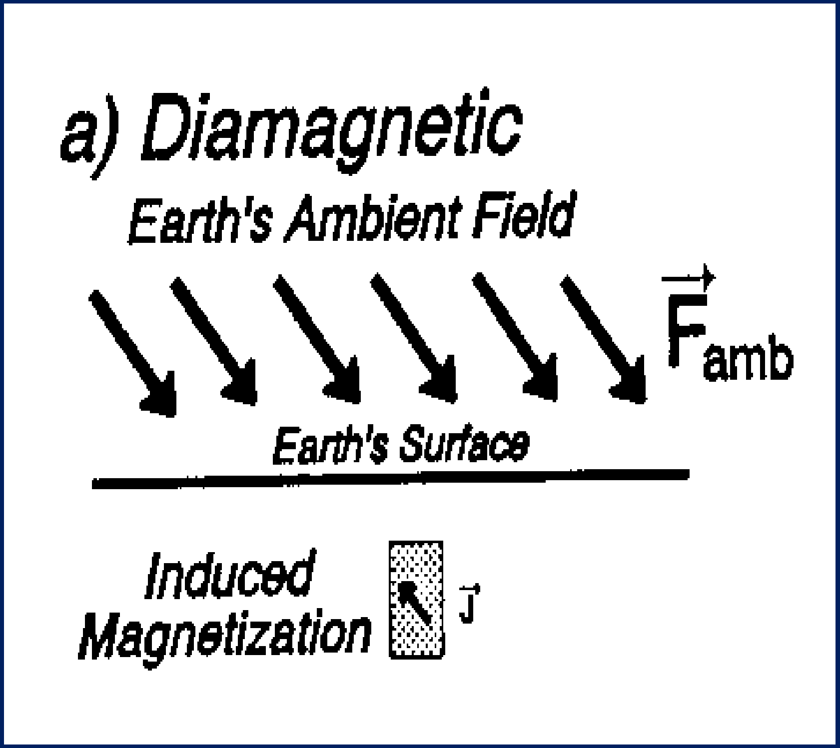
MAGNETIZATION OF ROCKS

Type of Magnetic Behavior

- The type of magnetism exhibited by a body depends on the mineral's magnetic susceptibility.

MAGNETIZATION OF ROCKS

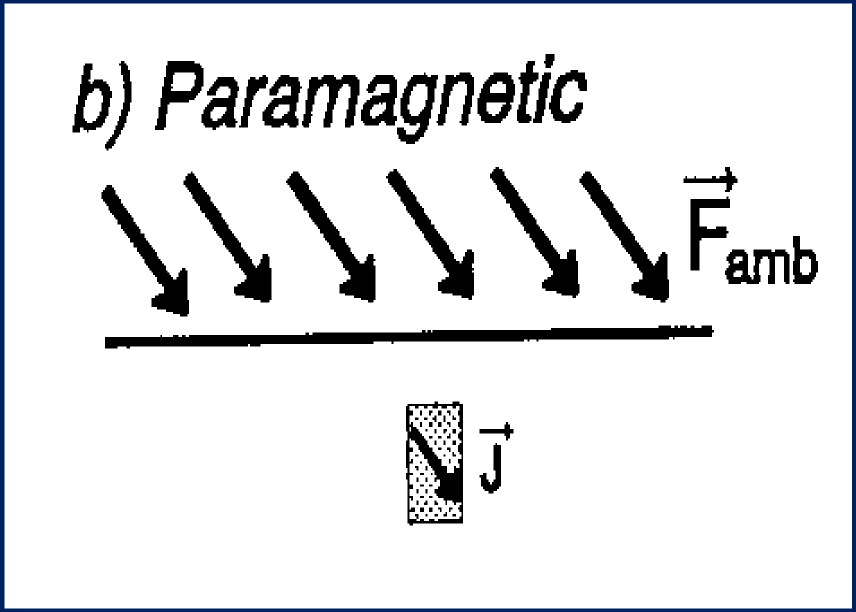
Diamgnetic material, k ~ -10 $^{-4}$



The Diamagnetic mineral, such as halite (rock salt) has negative and low magnetic susceptibility. The body acquires a weak magnetization and opposite to the external Field.

MAGNETIZATION OF ROCKS

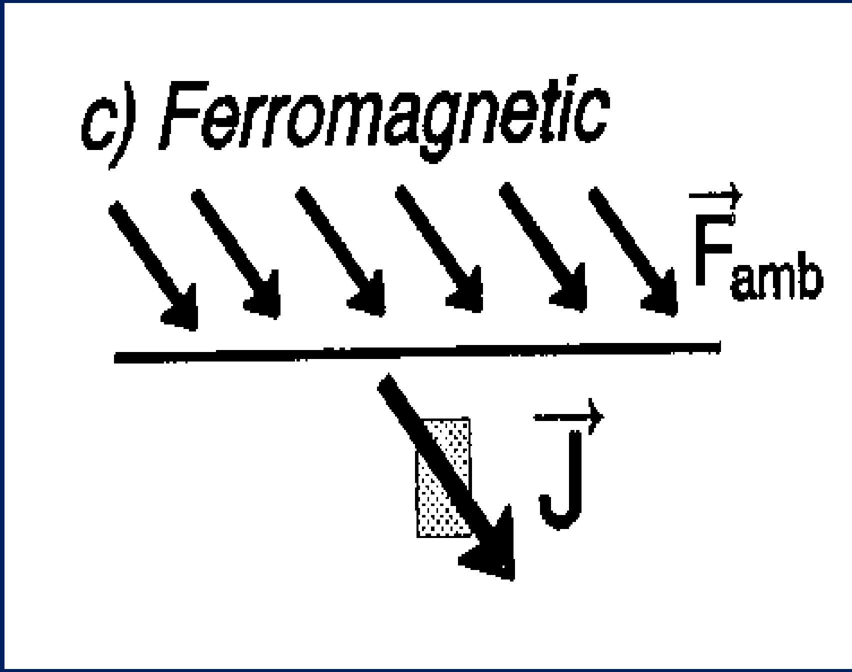
Paramagnetic material, $k \sim +10^{-4}$



The magnetic susceptibility of paramagnetic minerals is positive.

The magnetization in paramagnetic is weak but in the same direction as the external field.

MAGNETIZATION OF ROCKS
Ferromagnetic material, k ~ $+10^{-1}$



In some metallic minerals rich in iron, cobalt, manganese, or nickel, atomic magnetic moments align strongly with external field. Susceptibility on the order of 10-1 indicate that the magnetization in the same direction as, and about 1/10 the magnitude of, the external field. In this case we have a strong magnetization.

Under some circumstums, induced magnetization may remain in ferromagnetic materials, even after the external field is removed (remanent magntisation).

TOTAL FIELD MEASUREMENTS

- Using Proton procession magnetometer, we measure only the magnitude of the total magnetic field as a function of position.
- Surveys conducted using the proton precession magnetometer do not have the ability to determine the direction of the total field as a function of location.

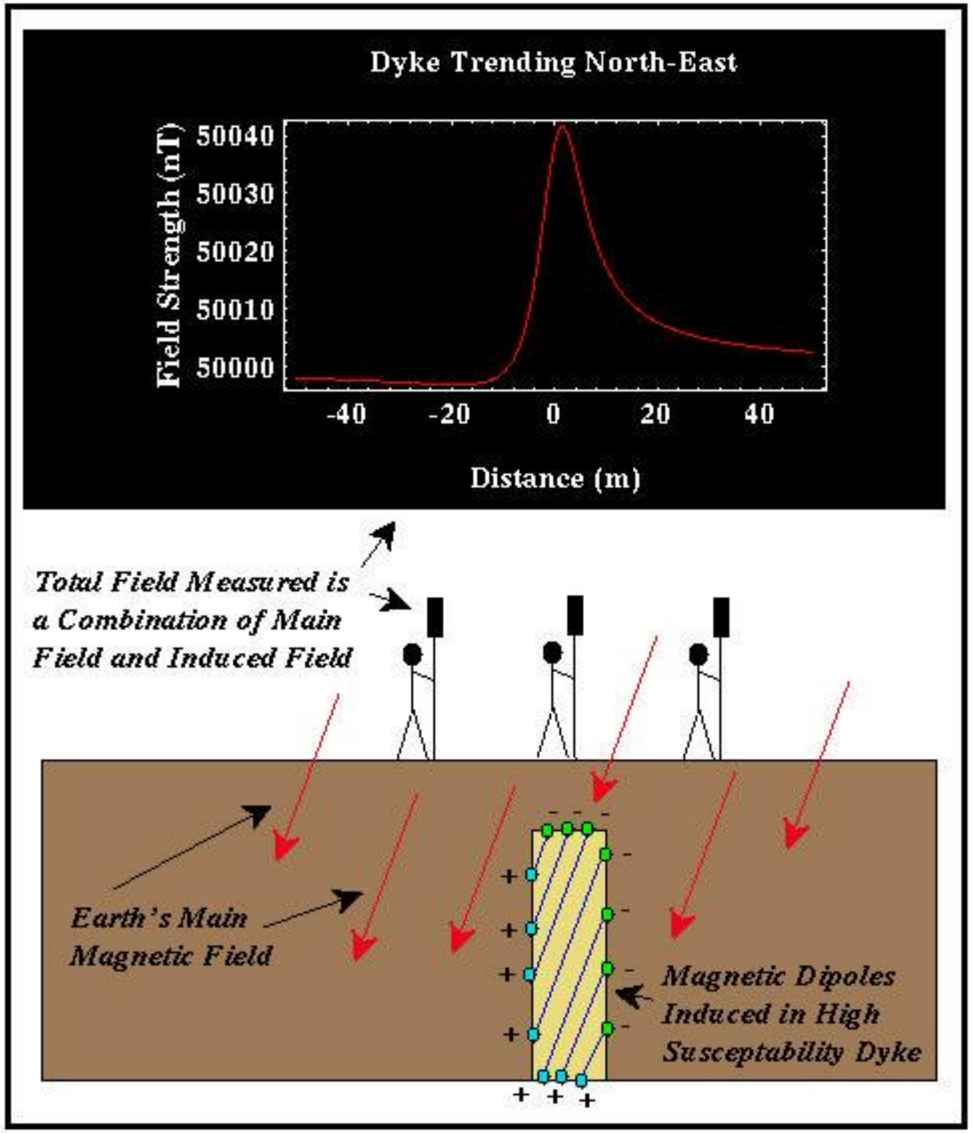
TOTAL FIELD MEASUREMENTS

- After correction of temporally variations (external field caused by the sun), the measured magnetic field has two components:

- 1) The main magnetic field, or that part of the Earth's magnetic field generated by deep (outer core) sources. The direction and size of this component of the magnetic field at some point on the Earth's surface is represented by the vector labeled F_e.
- 2) The anomalous magnetic field, or that part of the Earth's magnetic field caused by magnetic induction of crustal rocks or remanent magnetization of crustal rocks. The direction and size of this component of the magnetic field is represented by the vector labeled F_a.

- The total measured magnetic field F_t, *is the sum of* F_e *and* F_a.

TOTAL FIELD MEASUREMENT

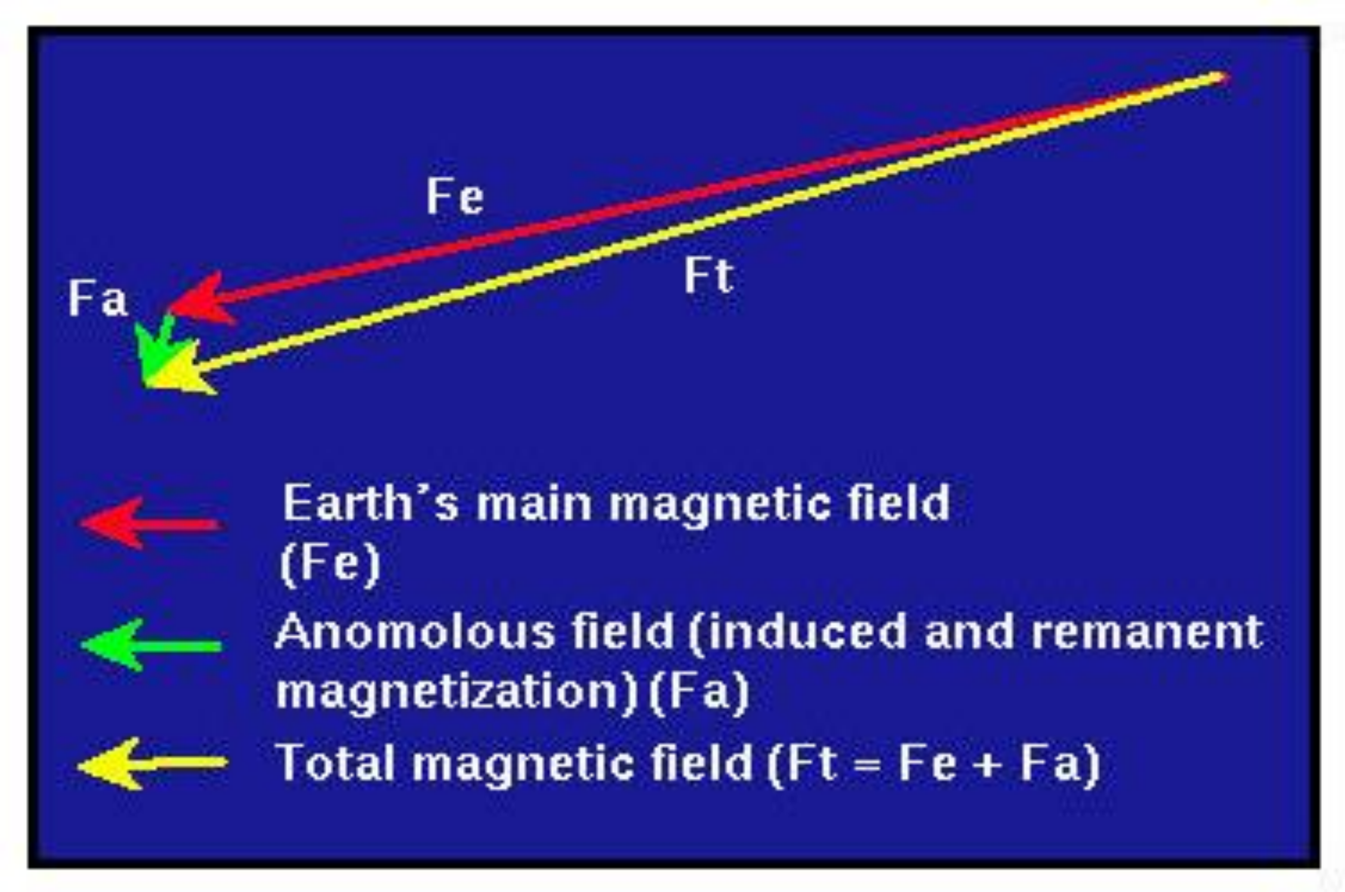


TOTAL FIELD MEASUREMENT

- Like a gravitational anomaly associated with a high-density body, the magnetic anomaly associated with the dyke is localized to the region near the dyke. The size of the anomaly rapidly decays with distance away from the dyke.
- Unlike the gravity anomaly we would expect from a higher-density dyke, the magnetic anomaly is **not symmetric** about the dyke's midpoint which is at a distance of zero in the above example.
- The maximum anomaly is ***not centered*** *at the center of the dyke.*

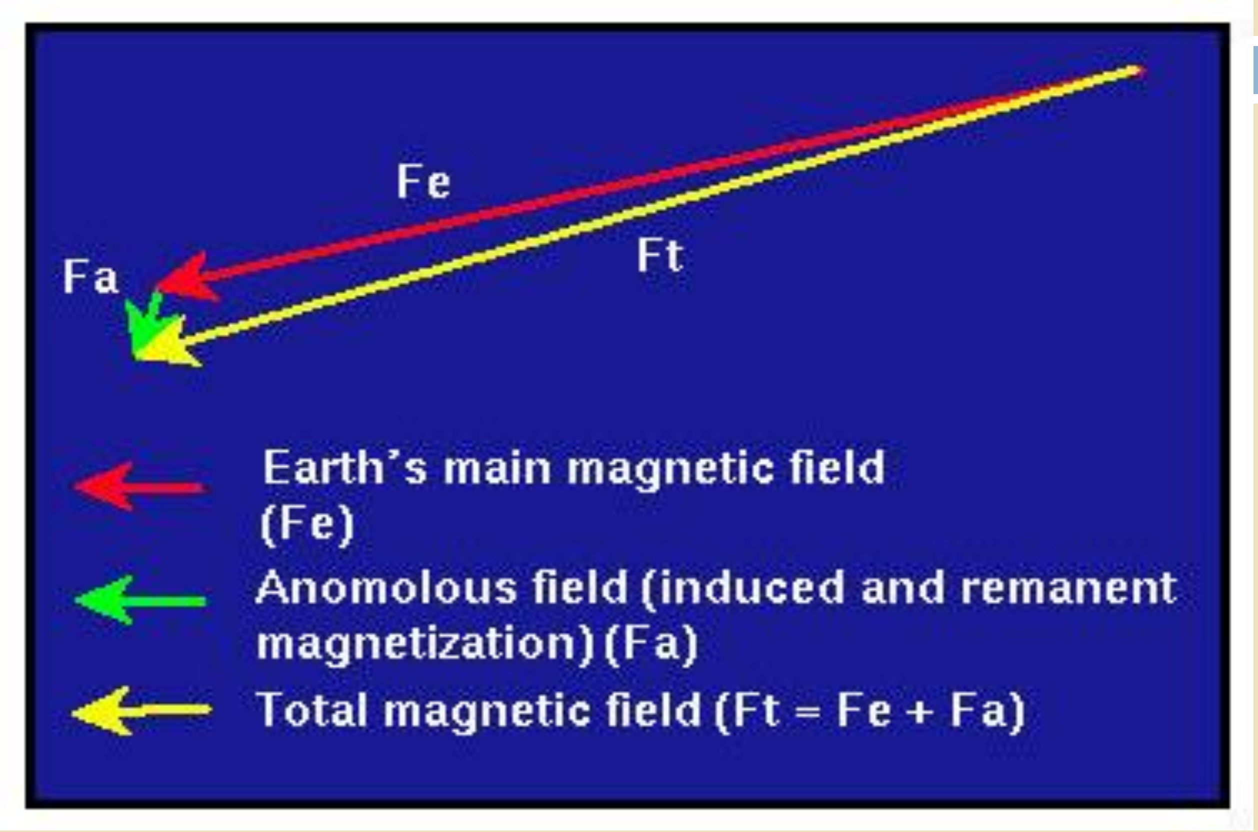
- *These observations are in general true for all* magnetic anomalies. The specifics of this generalization, however, will depend on **the shape** and orientation of the magnetized body, its **location** (bodies of the same shape and size will produce different anomalies when located at different places), and the **direction** in which the profile is taken.
- The size of the anomaly produced by this example is about 40 nT. This is a pretty good- sized anomaly.

TOTAL FIELD MEASUREMENT



Fe is much larger than Fa, (ex. 50,000 nT versus 100 nT). If Fe is much larger than *Fa, then Ft will point almost in the same direction as Fe regardless of the direction of Fa. Therefore, the measured total field, Ft, will be almost parallel to the main field.*

Magnetic Anomaly

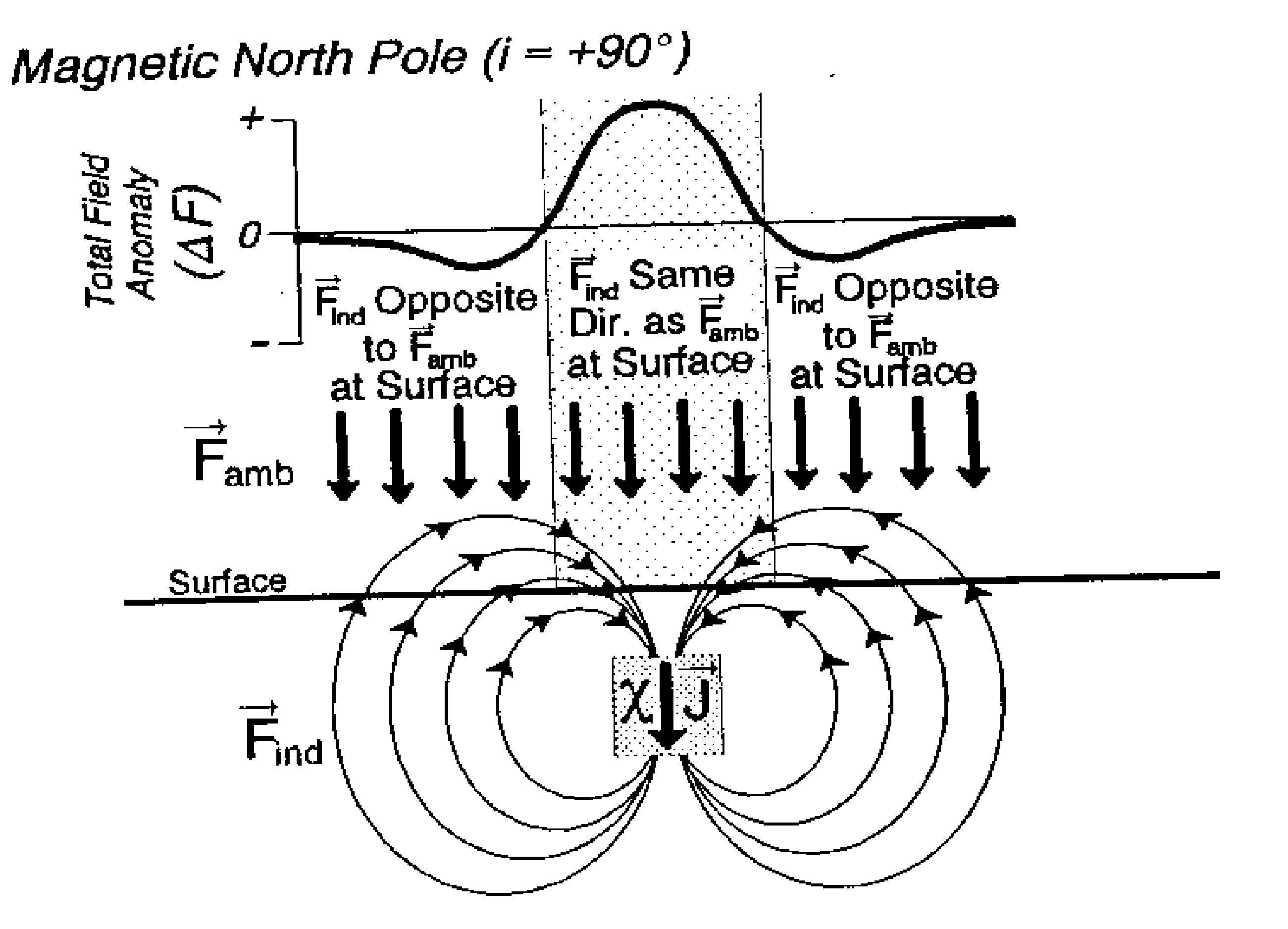


As Ft, is almost parallel to Fe, the observed magnetic anomaly is approximated as follow:

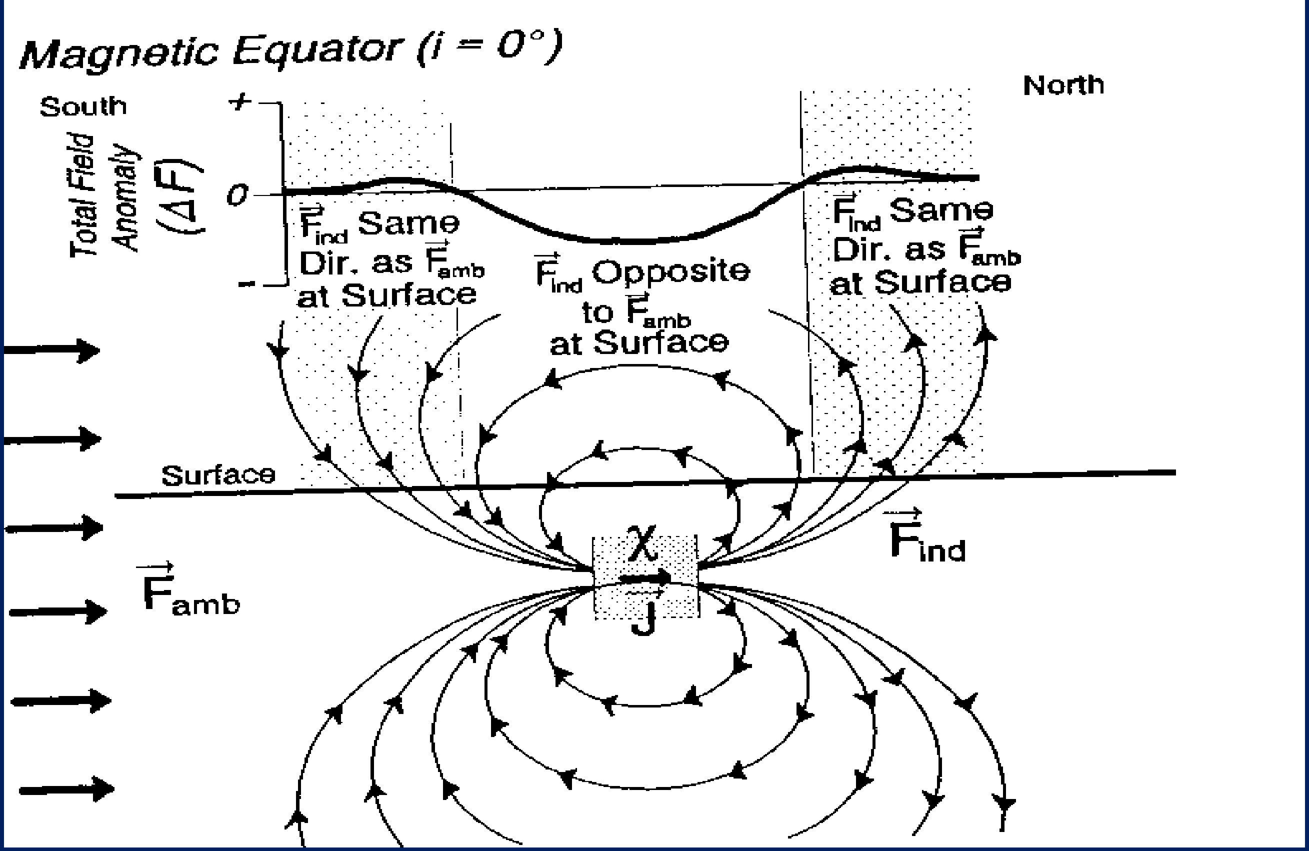
Observed Anomaly $\Delta F = F_t - F_e$

ΔF = the component of F_a parallel to F_e

INDUCED MAGNETIC ANOMALY (ΔF)
Magnetized body at the North Pole



INDUCED MAGNETIC ANOMALY (ΔF)
Magnetized body at the Equator



At equator, the anomaly is symmetrically distributed about the center of the sphere. In this case, the prominent central anomaly is negative and is surrounded by two smaller positive anomalies.

INDUCED MAGNETIC ANOMALY
Magnetized Sphere in the Northern Hemisphere

- As in the previous examples, the Earth's main magnetic field **induces** an anomalous field in surrounding the sphere. The anomalous field is now oriented at some angle, in this case 45 degrees, from the horizontal.

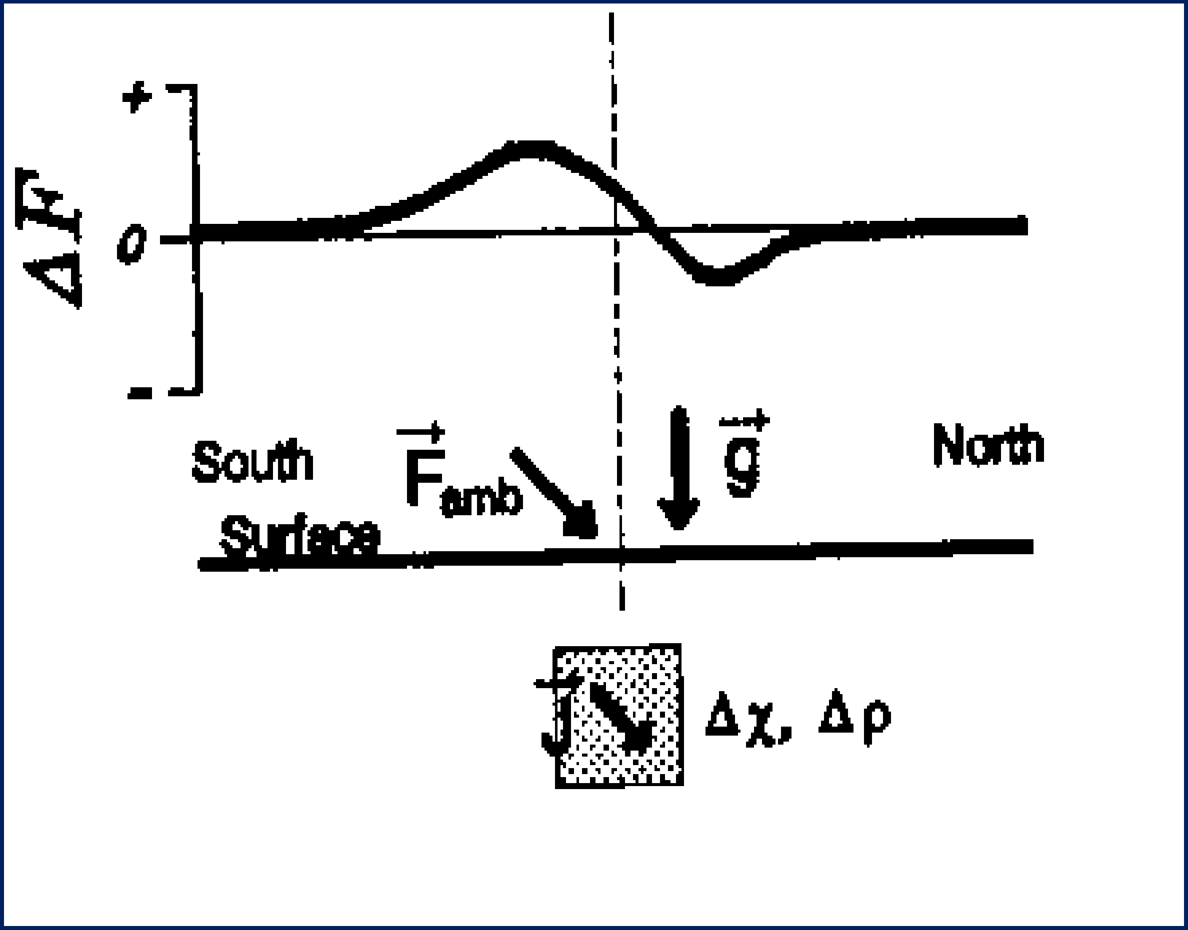
- By looking at the direction of the anomalous field, *Fa, in comparison with the Earth's main* field, *Fe, you can see that there will be a* ***small negative anomaly*** *far to the south of the sphere, a large* postive anomaly just south of the sphere, and a small, broad, negative anomaly north of the sphere.

- Notice that the magnetic anomaly produced is **no longer symmetric** about the sphere. Unless you are working in one of those special places, like at the magnetic poles or equator, this will always be true.

- From this simple set of examples, it is indeed **more difficult** to visually interpret magnetic anomalies than gravity anomalies. These visual problems, however, present no problem for the computer modeling alogrithms used to model magnetic anomalies. You simply need to incorporate the location of your survey into the modeling algorithm to generate an appropriate magnetic model.

INDUCED MAGNETIC ANOMALY

Magnetized Sphere in the Northern Hemisphere



INDUCED MAGNETIC ANOMALY AT DIFFERENT MAGNETIC LATITUDES

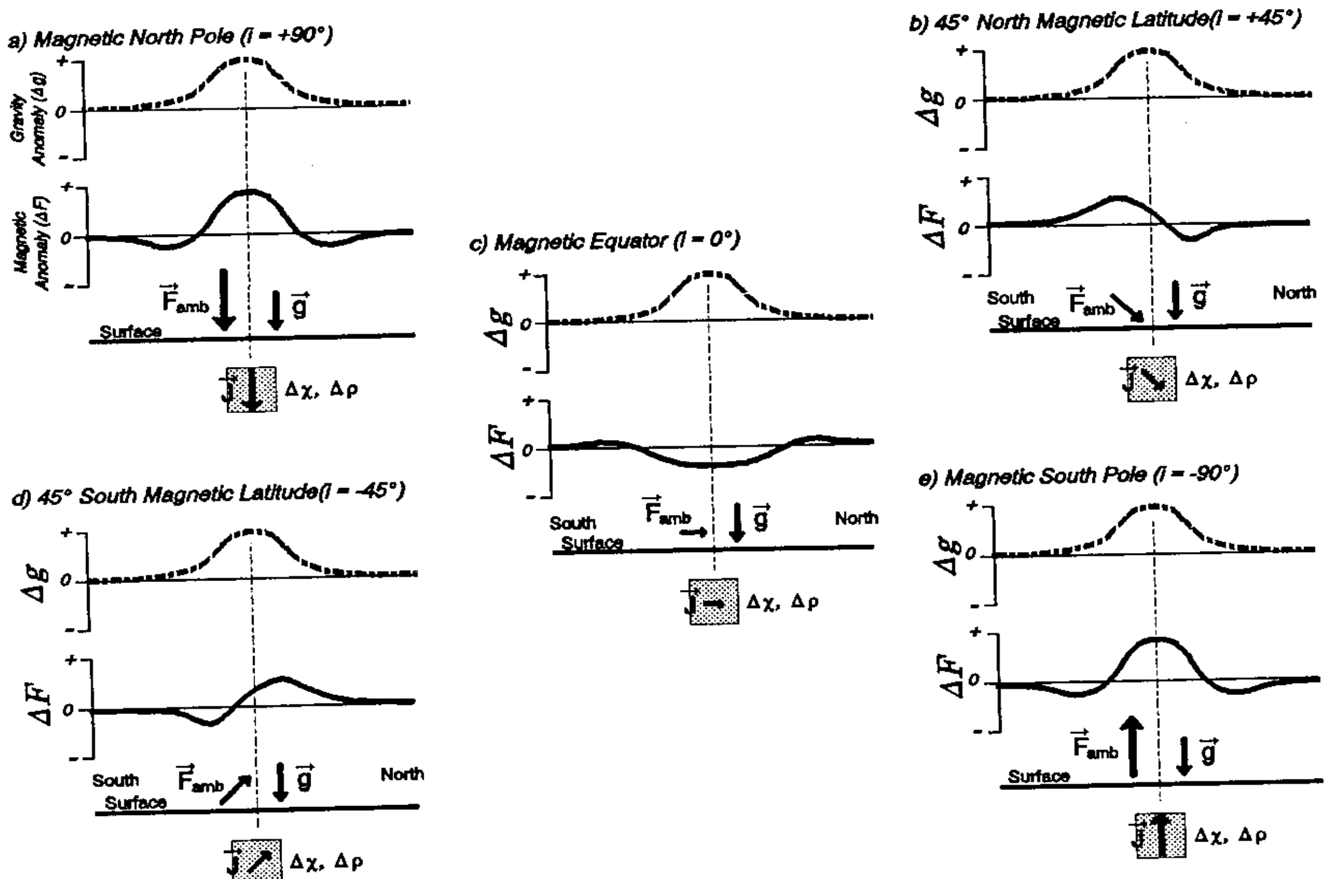
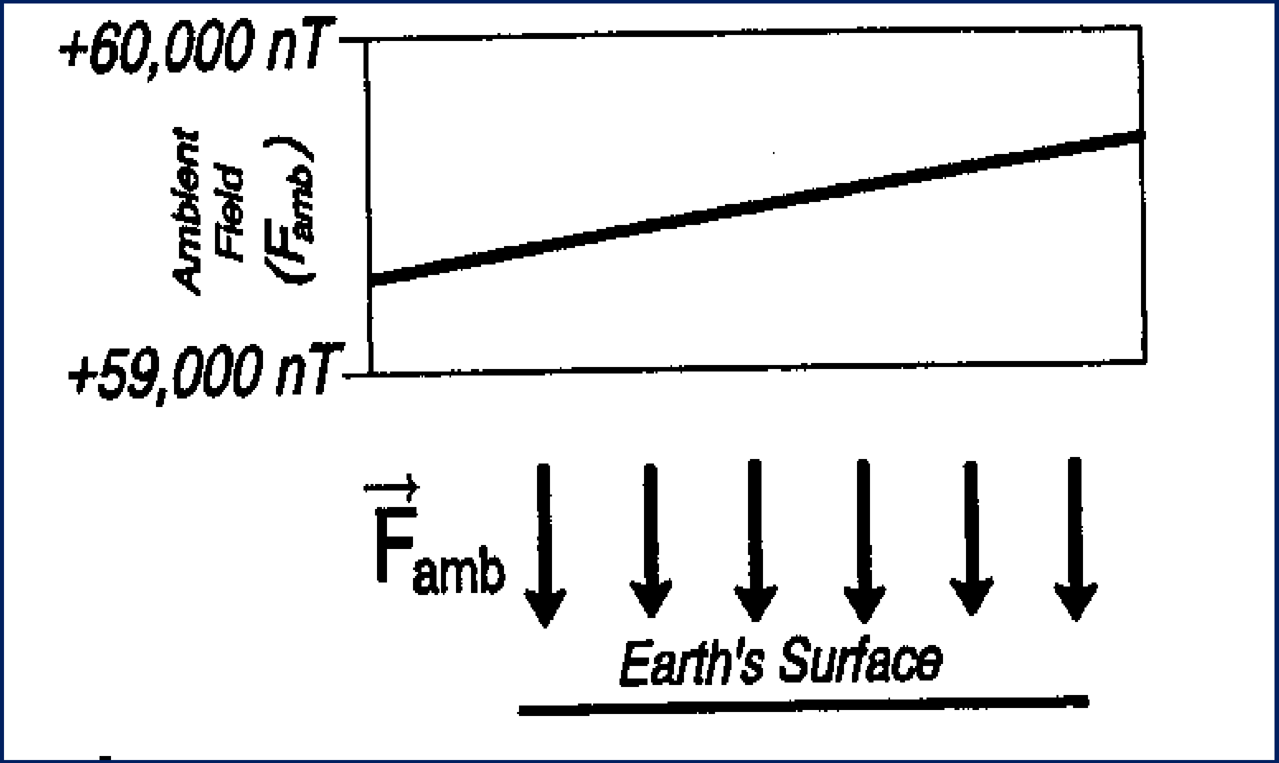


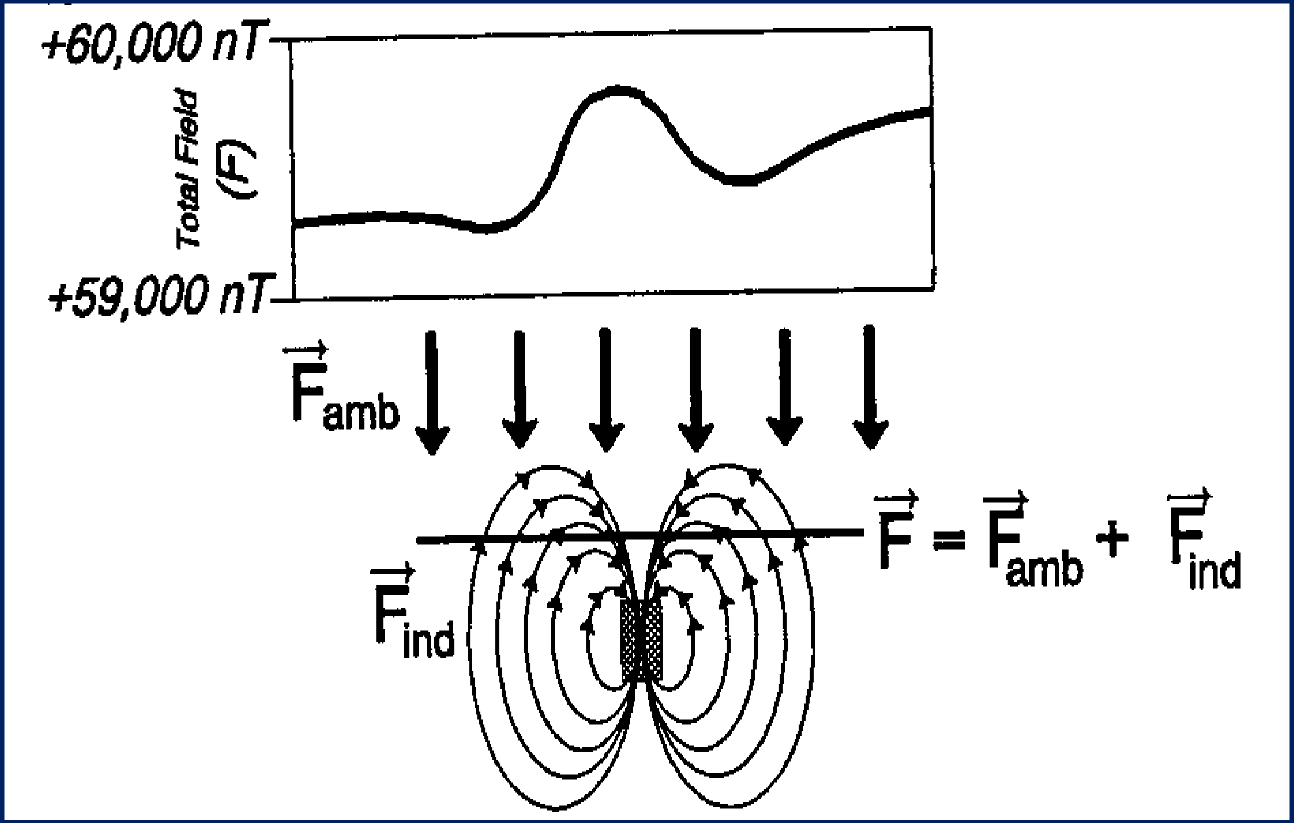
FIGURE 9.12 *Gravity and magnetic anomalies from the same body, at different magnetic latitudes.* At each latitude, the gravity anomaly (Δg) resulting from the body of density contrast (Δρ) is the same. For the same body, with magnetic susceptibility contrast (Δχ), the magnetic anomaly (ΔF) varies. At the magnetic north and south poles (a and e), the anomaly is a central high with flanking lows (Fig. 9.11a); a high magnitude ambient field ($F_{amb} \approx 60{,}000$ nT) induces high magnitude magnetization (J), resulting in high amplitude magnetic anomalies (ΔF). At the magnetic equator (c), the induced field opposes the ambient field at the surface directly over the body, leading to negative magnetic anomalies (Fig. 9.11b); $F_{amb} \approx 30{,}000$ nT leads to low amplitude ΔF. At mid-latitudes (b and d) the anomaly is asymmetric, with intermediate amplitude ΔF.

INTERPRETATION



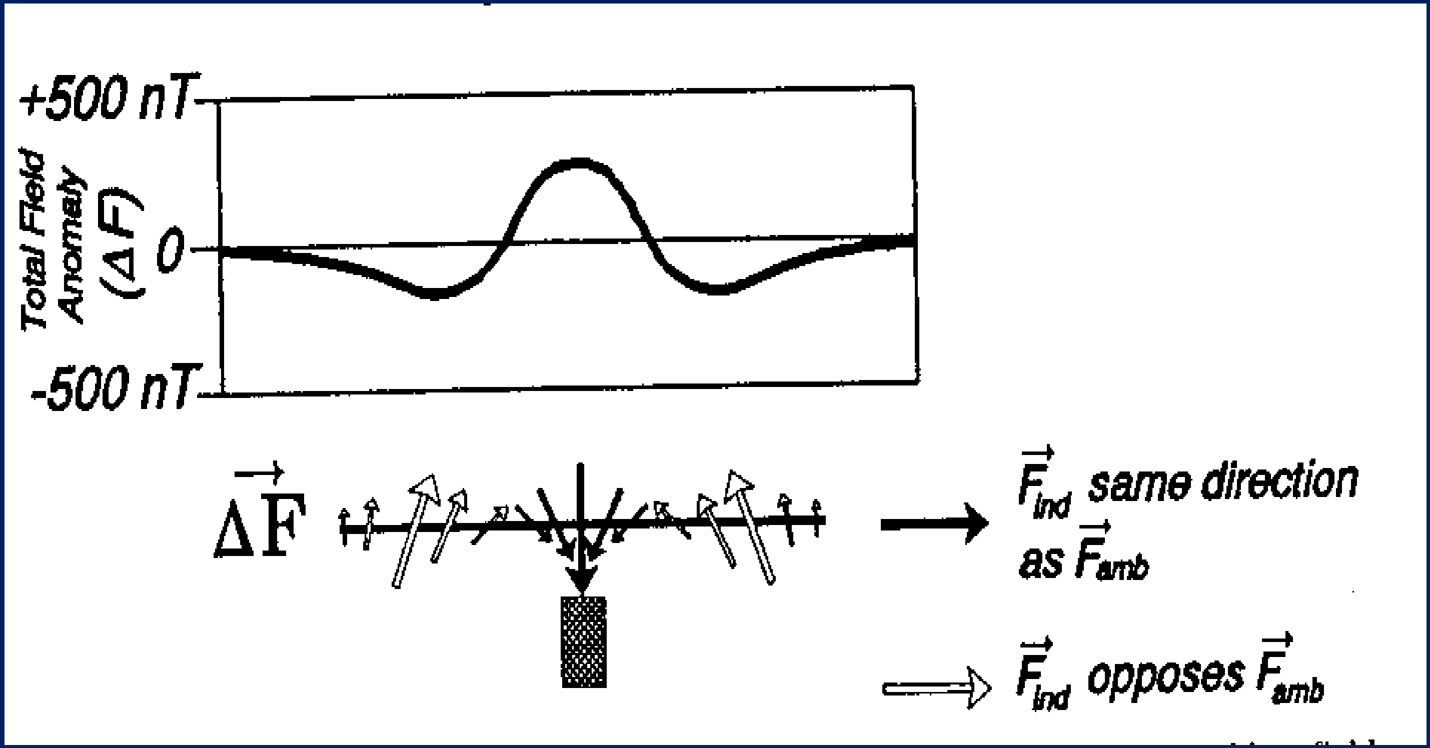
Measured Total magnetic field in polar region. We observe just a long wavelength variation of Earth's magnetic field. There is no observed anomaly and therefore , there is no magnetic buried body in the subsurface.

INTERPRETATION



Measured Total Magnetic field in polar region. We observe an anomaly (induced magnetization) due to a buried magnetic body.

INTERPRETATION



The Total Field Anomaly (ΔF) obtained by subtraction the magnitude of the ambiant field (F_{amb} or F_e) from the measured Total Magnetic field (F_t).

INTERPRETATION
Mapping of Magnetic bodies

- Magnetics is useful tool for mapping materials that have susceptibilities or remanent magnetizations that contrast with those of surrounding rocks, and for distinguishing between types of intrusive bodies.

- - Igneous rocks often have large amounts of magnetite, inducing high magnetization.

- - Salt exhibits diamagnetic behavior, inducing a weak field opposite in direction to the ambient field.

INTERPRETATION
Depth to Magnetic Basement

- Crystalline basement rocks, which are more mafic than overlying sedimentary deposits, are the main sources of magnetic anomalies in a region.
- Amplitudes and gradients for magnetic anomalies decrease as the sources get farther from the surface observation points.
- The depth to the basement in a region can be estimated, therefore, by studying the pattern of magnetic anomaly amplitudes.
- Short wavelengths and steep gradients suggest shallow basement.
- In case of deep basement, magnetic anomalies are subdued (low amplitude and low gradient).

INTERPRETATION
Depth to Magnetic Basement

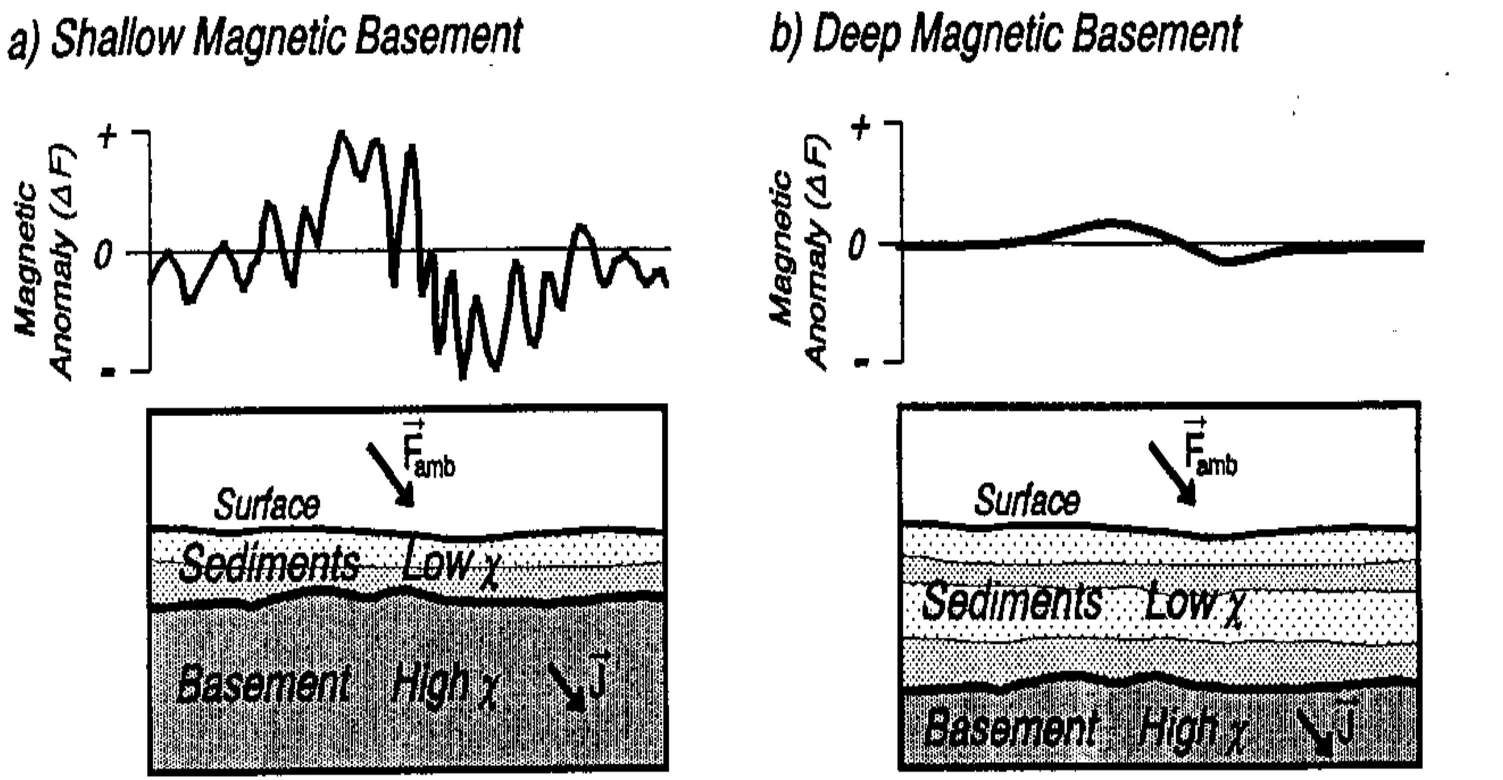
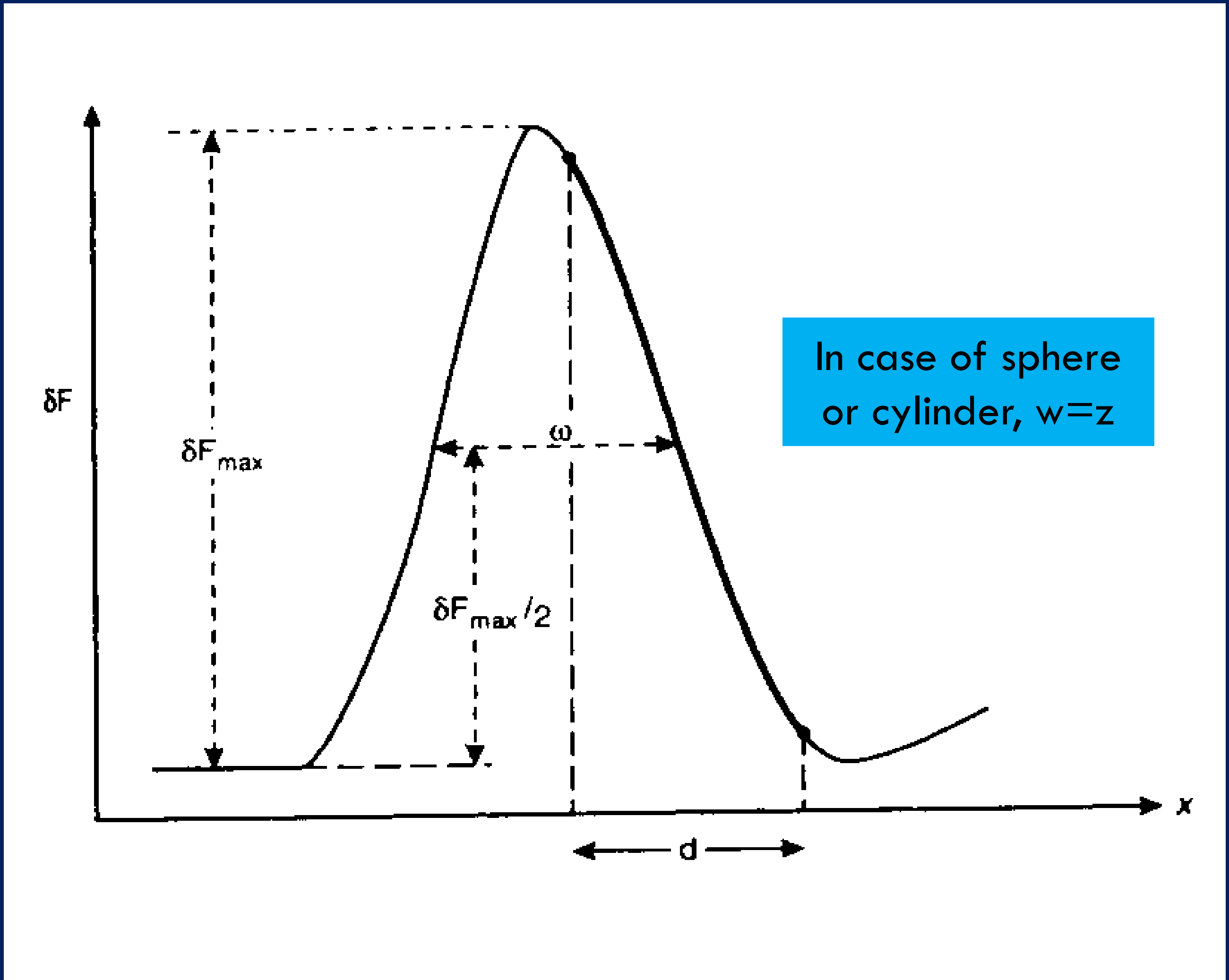
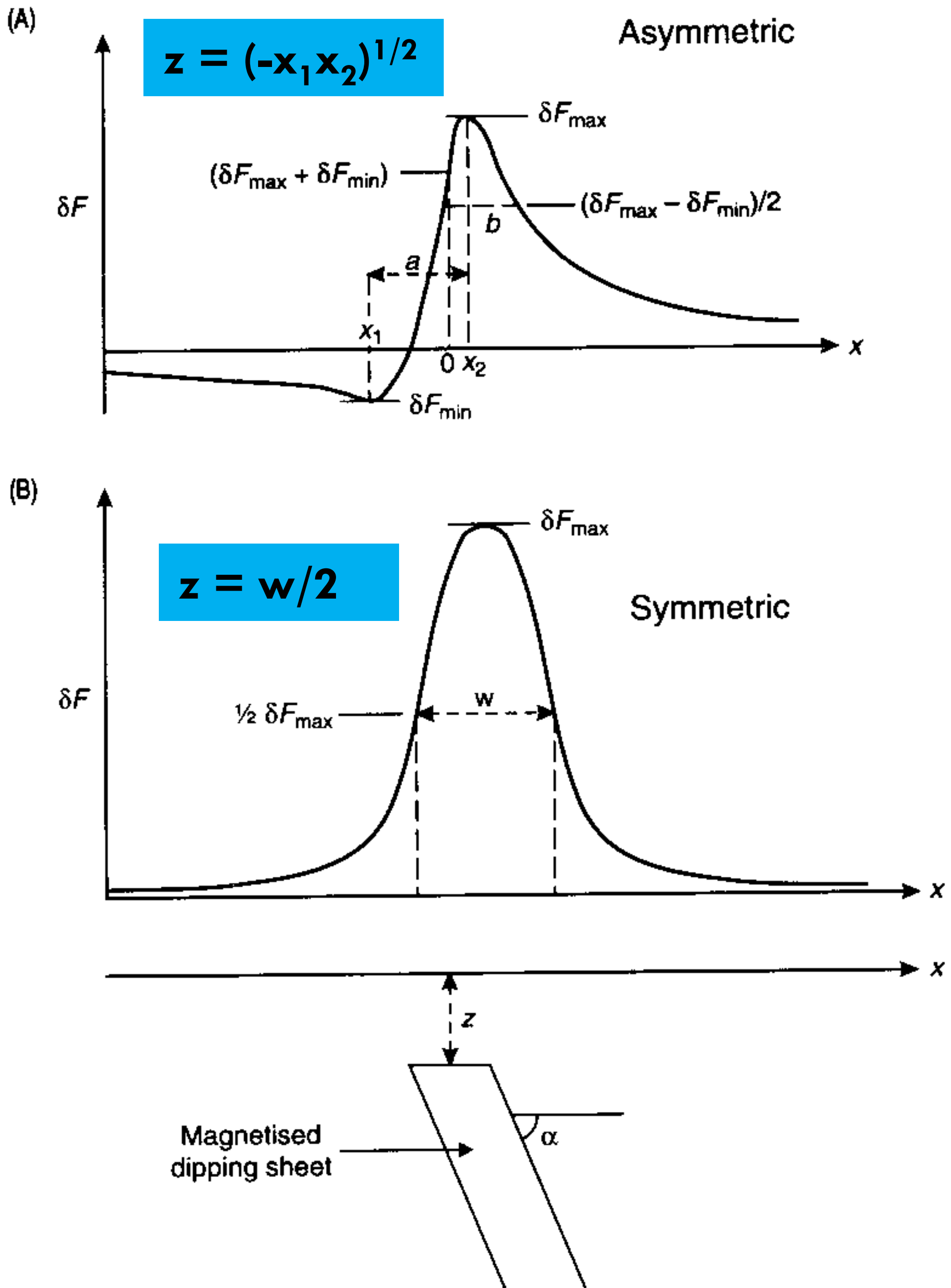


FIGURE 9.14 *Depth to magnetic basement.* Magnetic anomalies measured at Earth's surface depend on the depth of the magnetic sources, commonly located within crystalline basement. a) Where basement rocks are shallow, short-wavelength anomalies, with high amplitudes and steep gradients, occur. b) Basement buried deeply beneath sedimentary cover results in longer wavelength anomalies with smaller amplitudes and gradients.

INTERPRETATION
Depth estimation using graphic method



In case of sphere or cylinder, w=z



(A)
$z = (-x_1 x_2)^{1/2}$
Asymmetric
δF_{max}
$(\delta F_{max} + \delta F_{min})$
$(\delta F_{max} - \delta F_{min})/2$
δF
a
b
x_1
0
x_2
x
δF_{min}
(B)
δF_{max}
$z = w/2$
Symmetric
δF
½ δF_{max}
w
x
x
z
α
Magnetised dipping sheet

REFERENCES

- Reynolds, J.M., 1998. An Introduction to Applied an Environmental Geophysics. Wiley.

- Kearey et al., An Introduction to Geophysical Exploration. Blackwell Science.
- Lillie, R.J., Whole Earth Geophysics.

- www.mines.edu; Exploration Geophysics, Gravity Notes.
- www.mines.edu ; Exploration Geophysics, Magnetic Notes.