UNIVERSITY OF DIYALA
COLLEGE OF SCIENCE
DEPARTMENT OF PETROLEUM AND MINRAL GEOLOGY

Geophysics and geophysical prospecting

Magnetic method
Lectures

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Magnetic method

Magnetic prospecting, the oldest method of geophysical exploration, is used to explore for oil, minerals, and even archaeological artifacts. In prospecting for oil, it gives information from which one can determine the depth to basement rocks and thus locate and define the extent of sedimentary basins.

Geomagnetic methods can be used in a wide variety of applications and range from small-scale investigations to locate pipes and cables in the very near surface, and engineering site investigations, through to large-scale regional geological mapping to determine gross structure, such as in hydrocarbon exploration.

Commonly in the larger exploration investigations, both magnetic and gravity methods are used to complement each other. Used together prior to seismic surveys,

Both magnetic and gravity methods can provide more information about the sub-surface, particularly the basement rocks, than either technique on its own.

Magnetic surveys can be performed on land, at sea and in the air. Consequently, the technique is widely employed, and the speed of operation of airborne surveys makes the method very attractive in the search for types of ore deposit that contain magnetic minerals.

Similarities and difference between magnetic and gravity methods

- Both gravity and magnetic methods are **passive**, this mean when using these two methods we measure a naturally occurring field of the earth

- The acquisition, reduction, and interpretation of gravity and magnetic observations are very similar.

- The fundamental physical properties that controls gravity variations is **rock density**, while the fundamental parameter (properties) controlling the magnetic field variations is **magnetic susceptibility**

- The gravitational force is always **attractive**, while the magnetic force can be either **attractive** or **repulsive.**

- The basic theory to the gravity method is **Newton's law** which is written as $F_g = \frac{G m_1 m_2}{r^2}$

While the mathematical expression for the magnetic force experienced between two magnetic monopoles is given by Coulomb's law $F_m = \frac{1}{\mu} \frac{p_1 p_2}{r^2}$

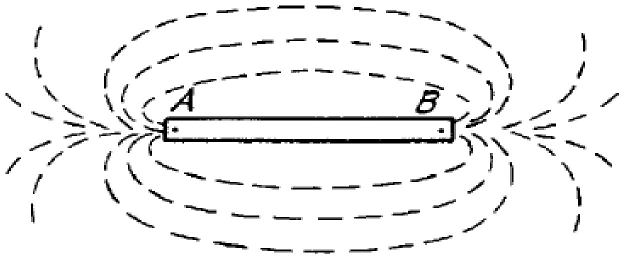
- In gravity survey only **vertical competent** of gravity field is measured while in magnetic survey three competent are measured these are (**H,,Z, F**) horizontal and vertical competent and total field intensity.

Basic theory

If two magnetic poles of strength m_1 and m_2 are separated by a distance r, a force, F, exists between them. If the poles are of the same polarity, the force will push the poles apart, and if they are of opposite polarity, the force is attractive and will draw the poles together. The equation for F is the following:

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

where μ is the magnetic permeability of the medium separating the poles: p_1 and p_2 are pole strengths and r the distance between them.



Magnetic units

The unit used in geomagnetic surveys is the Tesla

- 1 Tesla = 1 T = 1 N/Am
- 1 nT = 10^{-9} T=1 γ = 10^{-5} Oersted
- c.g.s unit:

  1 gauss (G)=10^{-4} T

  1 gamma (γ)=10^{-5} G

Magnetic susceptibility (k)

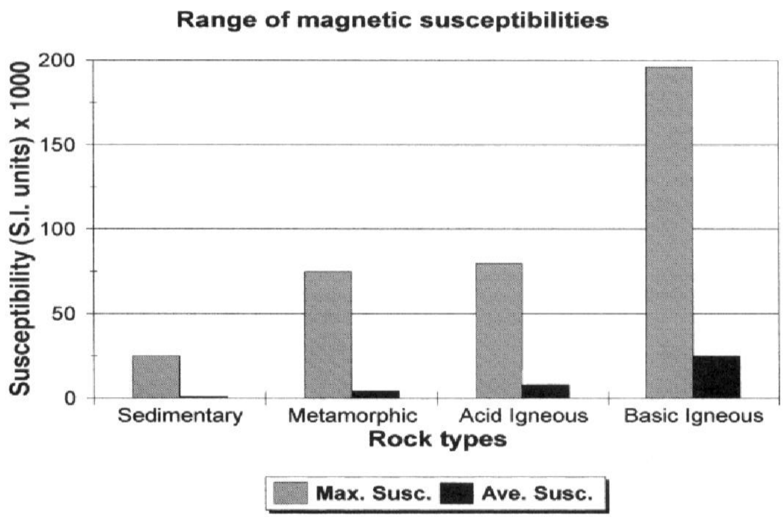
Magnetic susceptibility is a measure of the ability of a material to be magnetized. it is the proportional constant links induced magnetization(I) to the applied magnetic field intensity(H) where is ***I=KH***

- The magnetic susceptibility is a unitless constant that is determined by the physical properties of the magnetic material. It can take on **either** **positive** or **negative** values. **Positive values** imply that the induced magnetic field, (***I***), *is in the **same direction** as the Magnetic field,(* ***H****)*. ***Negative values*** *imply that the* induced magnetic field is in the **opposite direction** as the magnetic field intensity(**H**).

- In magnetic prospecting, the susceptibility is the fundamental material property whose spatial distribution we are attempting to determine. In this sense, **magnetic susceptibility** is analogous to **density** in gravity surveying.

Rocks with significant concentrations of ferri/ferro-magnetic minerals have highest susceptibilities:

- **Ultramafic rocks** highest 95,000 – 200,000
- **Mafic rocks high** 550 – 122,000
- **Felsic rocks** low 40-52,000
- **Metamorphic** low 0-73,000
- **Sedimentary** very low 0-360



Curie Temperature Tc

It is the temperature at which mineral loses its ferromagnetic behavior, and any permanent magnetization is lost.

- Cure temperature varies with mineral:

- Magnetite 550-580^o C
- Hematite 650-680^o C

-**Types of magnetization:-**

The magnetization can be either **remnant** or **induced** magnetization. In most rocks both are present.

1- Induced magnetization (*I*):- is the magnetization acquired by rocks in the direction of applied external magnetic field and it is disappear when the external magnetic field is removed

2- Remnant Magnetization (permanent magnetization):- is the magnetization acquired by rock through geological history (in the past) and remain until after the disappearance of applied external magnetic field

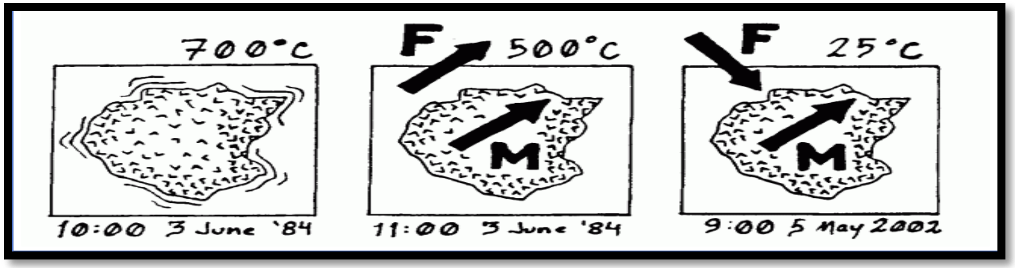
- **Types of remnant (permanent) magnetization:-** There are two types of remnant :-

-Primary magnetization:- forms at the time the rock forms.

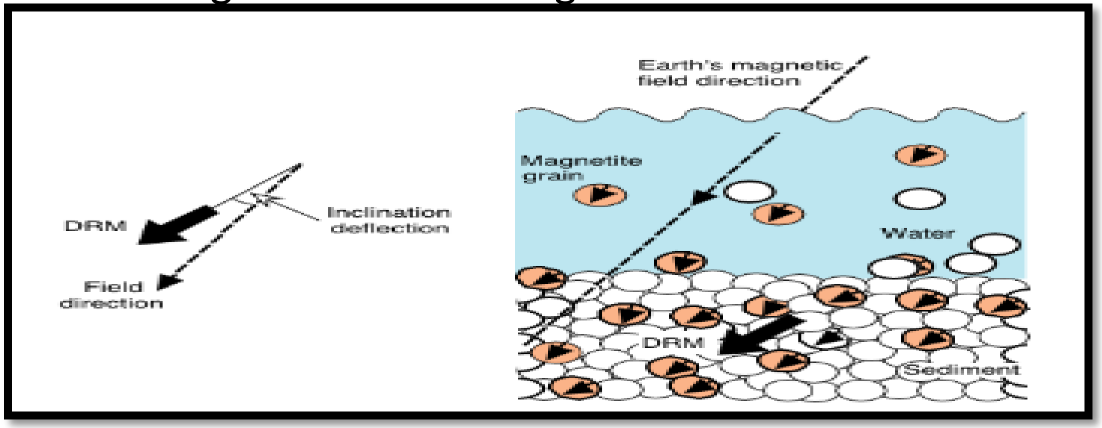
- Secondary magnetization :- occurs when the ferromagnetic mineralogy in a rock is somehow altered

1- Primary remnant consist to:-

- **Thermal remnant magnetization (TRM):-** **This magnetization acquired by a material during cooling from a temperature greater than the curie temperature to room temperature (e.g molten lava cooling after volcanic eruption)**



- **Detrital(Depositional)-remnant magnetization(DRM)** : acquired during accumulation of sedimentary rocks containing detrital ferromagnetic minerals.



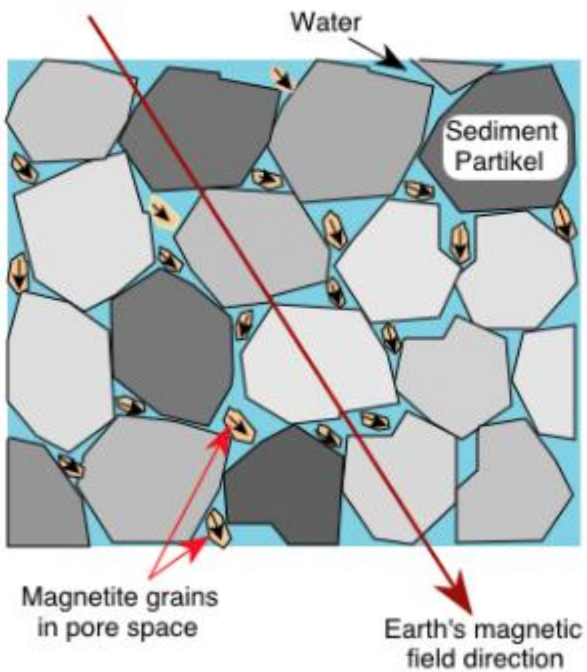
- **Chemical-remnant magnetization(CRM):** Also called crystallization RM : it is acquired at the time of growth or crystallization of fine magnetic grains far below the curie point in an ambient field

2- Secondary remnant magnetization consist to :-

•**Viscous remnant magnetism (VRM):-** acquire after a long exposure to an external magnetic field with all other factors being constant , and it may be important in fine-grained rocks.

•**Isothermal remnant magnetism (IRM) :-** acquired over a short time (order of seconds) when an external field is applied and removed at a constant temperature (e g. Lightning strike)

• **Post – depositional remnant (PDRM):-** acquired by a sediment by physical processes acting upon it after deposition (e g. compaction or cementation)



Geomagnetic Field Elements

The direction and strength of the magnetic field can be measured at the surface of the Earth and plotted. The total magnetic field consist to several elements such as:-

1- Declination (D) :- is the angle between magnetic north and true north

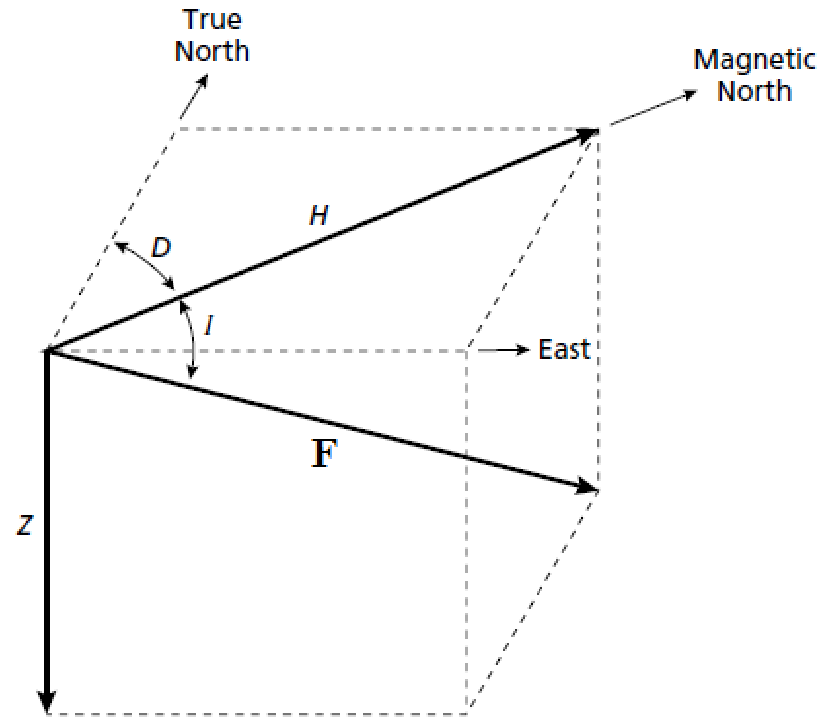
2- Inclination (I) is the angle between the magnetic north and the total intensity field (F)

_ both (D and I) are elements for describing the direction of the magnetic field and both measured by degree

3- Horizontal Intensity (H) defines the horizontal component of the total field intensity.

4- Vertical Intensity (Z) defines the vertical component of the total field intensity.

5- Total Intensity (F) is the strength of the magnetic field, not divided into its component parts.



The geomagnetic elements.

$$H = F\cos I \qquad Z = F\sin I = H\tan I$$

$$X = H\cos D \qquad Y = H\sin D$$

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

The last three Elements (H,Z,F) is used for describing the field intensity and they are generally expressed in units of (nanoTesla)

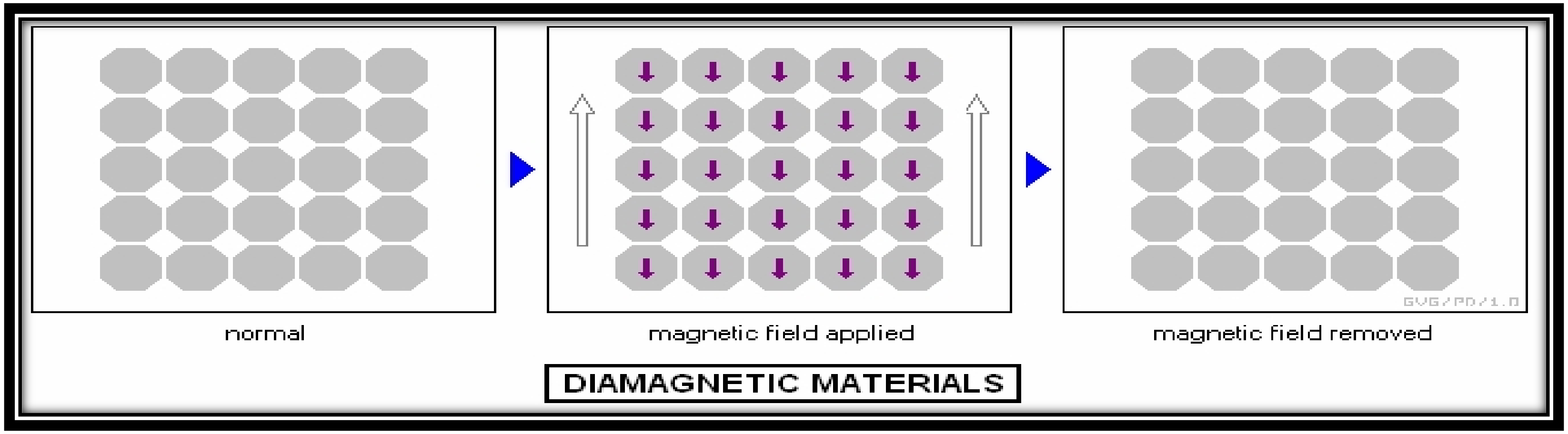
Types s of magnetism in minerals :- There are three types of magnetism in minerals these Are:-

1- Diamagnetic materials

In a diamagnetic material such as halite,quartz,rock salt, calcite and anhydrite all electron shells are complete and no unpaired electrons exist.,

•If an external magnetic field applied , electrons orbit to produce a weak magnetic field that opposes to applied field.

•Magnetic susceptibility (*k*) is **weak** and **negative.**

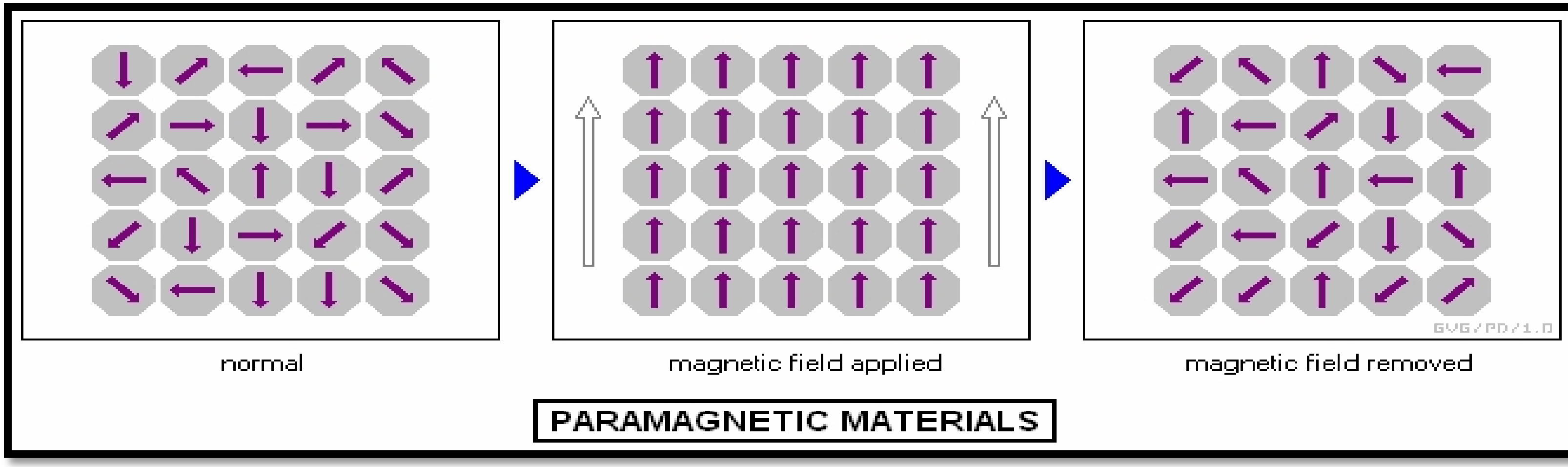


2- Paramagnetic materials

•In paramagnetic materials such as olivine, **clay minerals, pyroxene and amphibole** unpaired electrons in incomplete electron shells produce unbalanced magnetic moments.

•If an external field applied , magnetic moments align themselves in same direction of applied field , producing a weak magnetic field aligned with external.

•Magnetic susceptibility (k) is **weak** and **positive**



Both **diamagnetic** and **paramagnetic** material return to normal situation when magnetic field is removed.

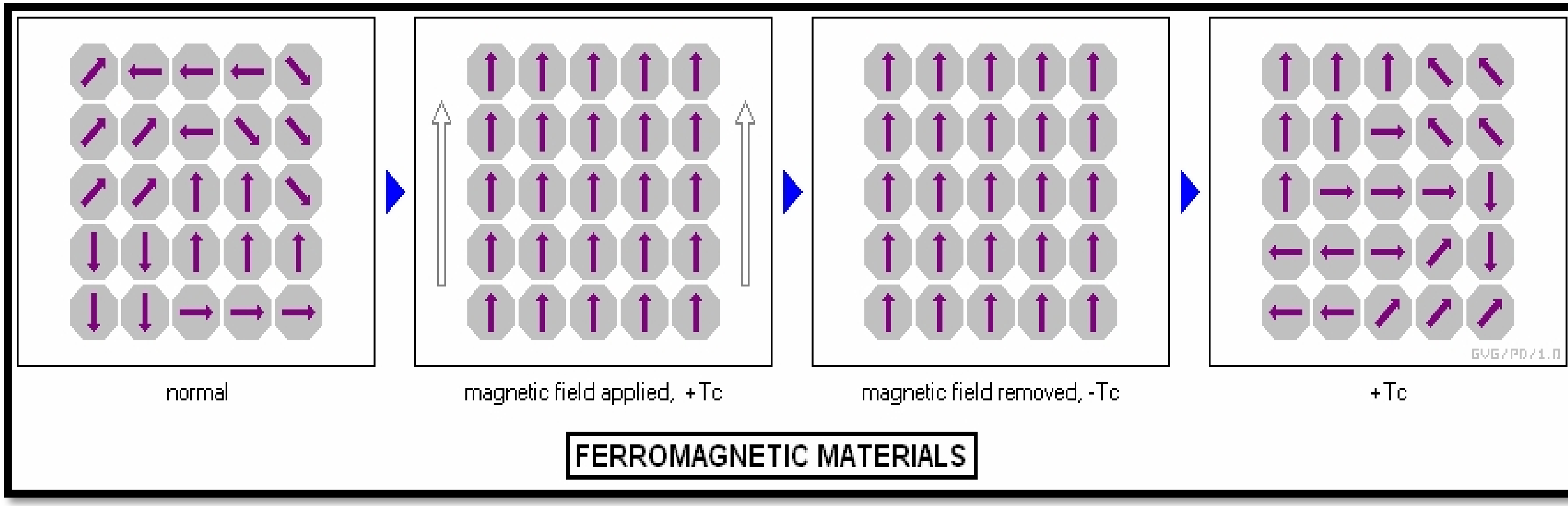
3- Ferromagnetic materials

•In ferromagnetic materials such as cobalt, nickel and iron, unpaired electrons are coupled magnetically due to strong interaction between adjacent atoms .

- If an external field applied , magnetic moments align themselves in same direction of applied field, **as with paramagnetic materials, but actually staying aligned after the magnetic field is removed**.

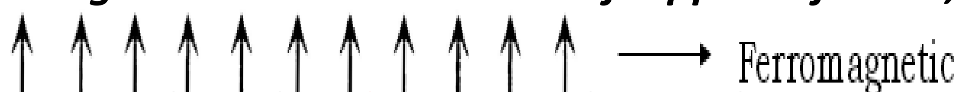
- **Ferromagnetism disappears when the temperature of the material is raised above the Curie Temperature Tc.and the material becomes paramagnetic material as illustrated below**

•Magnetic susceptibility (k) is **strong** and **positive**



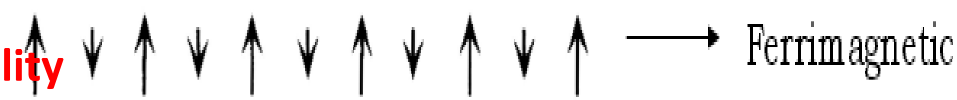
❑ **There are three types of ferromagnetism these are :**

1. ***pure ferromagnetism – all the domains align the same direction of applied field , producing strong magnetism***



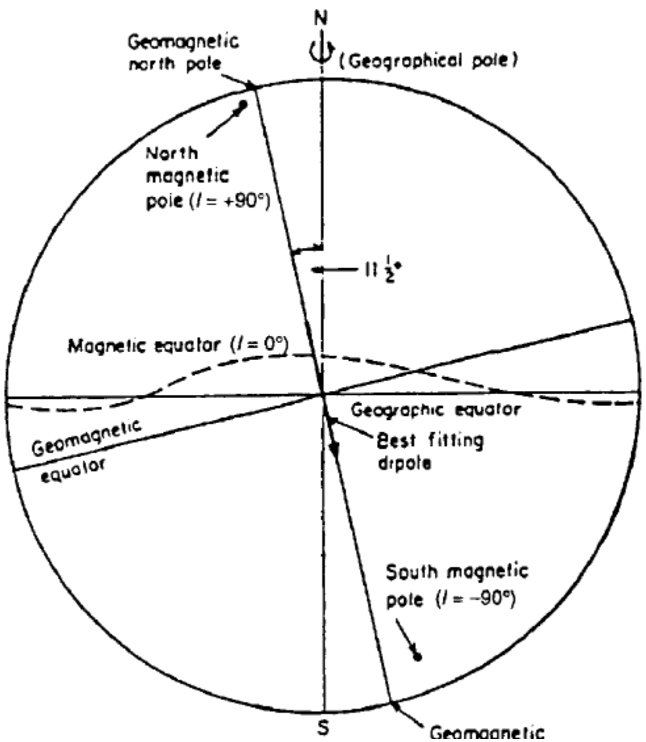
2- **antiferromagnetism**: **In *antiferromagnetic* materials such as hematite, the dipole coupling is antiparallel and the strength of dipoles in each direction is equal, therefore there is no external magnetic effect because of the magnetic field of the dipoles are self cancelling**

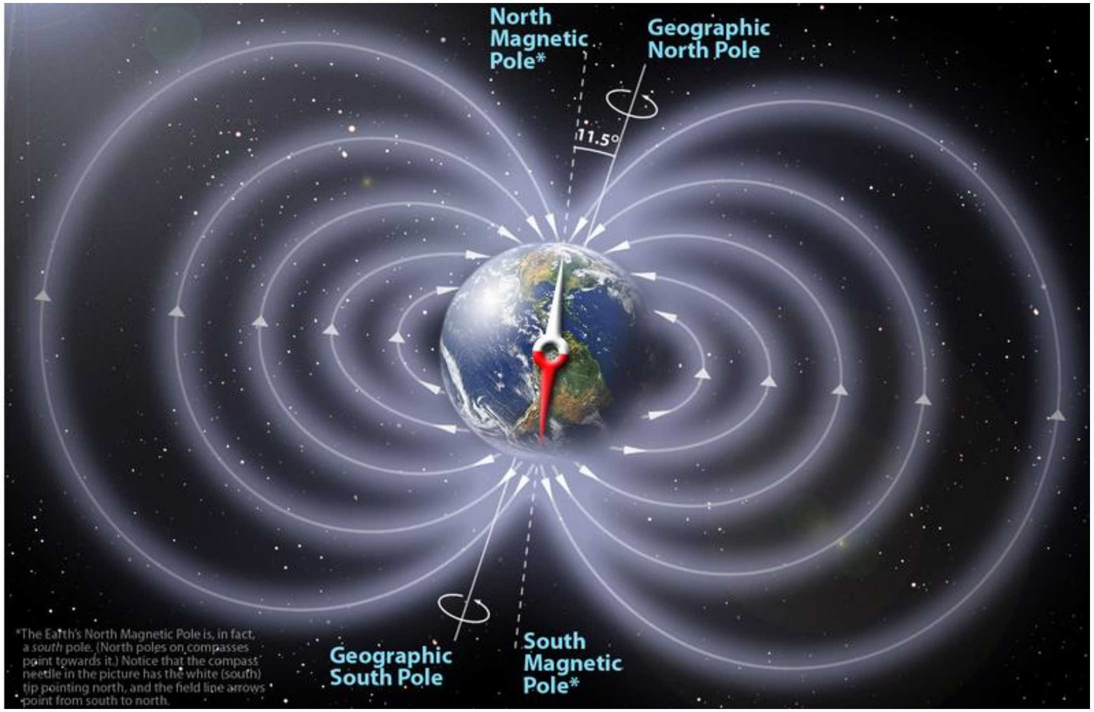
3- ferrimagnetisim:-In *ferrimagnetic* materials such as magnetite, the dipole coupling .is antiparallel, but the strength of dipoles in each direction are unequal. Consequently ferrimagnetic materials can exhibit a strong magnetization and a high susceptibility



Geomagnetic Field

The geomagnetic field is very similar to that of a large bar magnet placed at the center of the Earth, with its south end oriented toward the north magnetic pole. The field is dipolar, vertically downward at the north magnetic pole, vertically upward at the south magnetic pole, and horizontal at the (magnetic) equator. It has a strength of roughly 30,000 gammas at the equator, 70,000 gammas at the poles. In the United States, it is acceptable for the purposes of simple modeling to assume that a field declination of about 60 degrees has a strength of 55,000 gammas. Figure 1 illustrates the magnetic field around the earth as well as the difference in geographic loaction between the magnetic north pole and geographic north poles.

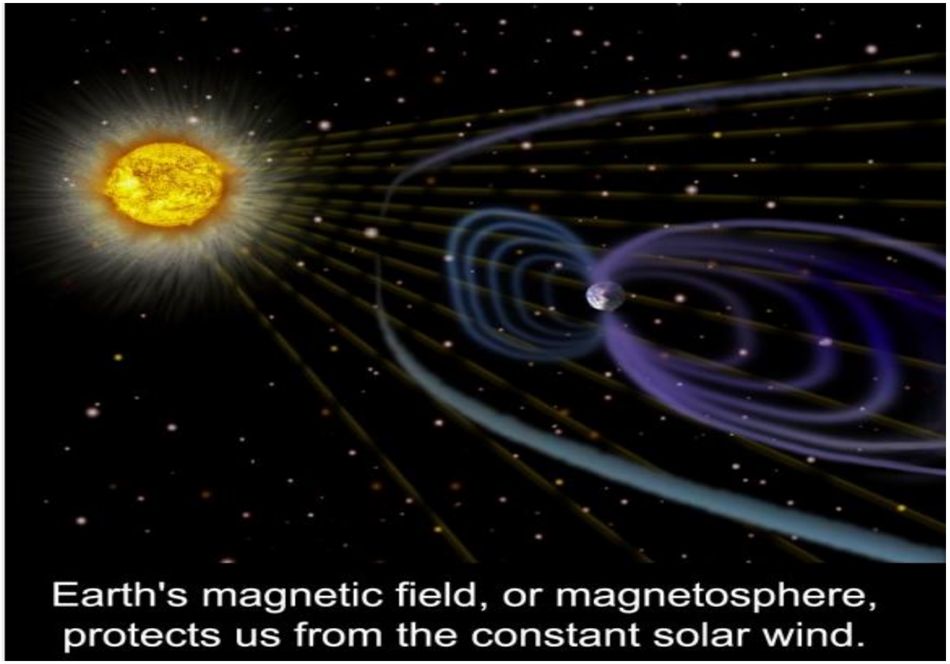




Why Is the Earths Magnetic Field Important to Life on Earth?

Answer

The earth's magnetic field acts as a shield against the harmful particles that come from the solar wind. The absence of a magnetic field in planets such as earth would render them inhabitable, especially by humans.



What is the Difference between dipole and monopole?

dipoles, are pairs of opposite polarity, poles.(positive and negative)

If one pole sufficiently distant so does not affect other, it is said to be a **monopole.**

Theories on the origin of the Earth's magnetic field

There are many theories were discussed to explain the origin of the magnetic field some of which are:-

1- In about 1600 W. Gilbert absolved the pole star of responsibility for the Earth's magnetic field.

2- The second theory say that the origin of magnetic field is due to magnetized surface rocks , but this not true because the magnetic field changes with time and also the magnetic field producing from surface rocks represent 1-2 % from current observed field

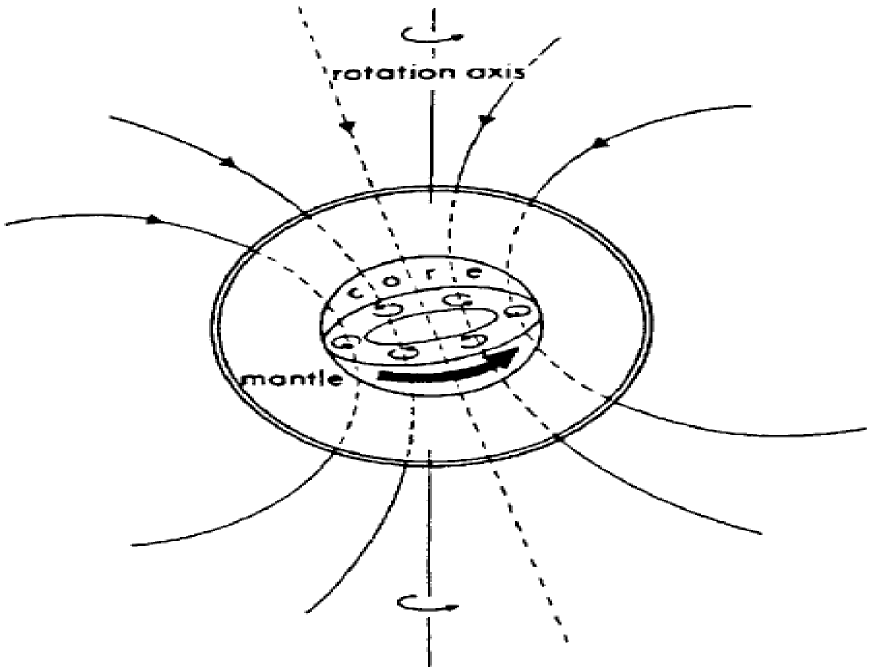
3- The other theory assumed that the source of magnetic field is due to magnetised rocks from which the core of earth is forming, but this not true also because the magnetised rocks must be deep, and rocks lose all magnetisation above the Curie temperature. The Curie temperature for magnetite is about 578°C, whereas the temperature of the core is probably ~ 5,000°C

4- in the 20th century, *Einstein* described the origin of the Earth's magnetic field as one of fundamental unsolved problems in physics

5- Now the most acceptable theory believed that the geomagnetic field is produced by electric currents induced within the conductive liquid outer core as a result of slow convective movements within it. The liquid outer core behaves as a geodynamo. This theory called dynamo theory

<u>What is the dynamo theory ?</u>

dynamo theory, is a geophysical theory that explains the origin of Earth's main magnetic field in terms of a self-generation dynamo. In this dynamo mechanism, fluid motion in Earth's outer core moves conducting material (liquid iron) across an already existing weak magnetic field and generates an electric current. (Heat from radioactive decay in the core is thought to induce the convective motion.) The electric current, in turn, produces a magnetic field that also interacts with the fluid motion to create a secondary magnetic field. Together, the two fields are stronger than the original and lie essentially along the axis of Earth's rotation.



Components of the magnetic field

The magnetic field can be broken into three separate components.

- ***Main Field -This is the largest component of the magnetic field and is believed to be caused by*** **electrical currents in the Earth's fluid outer core . For exploration work, this field acts as the inducing magnetic field**.

- ***External Magnetic Field -This is a relatively small portion of the observed magnetic field that is*** **generated from magnetic sources external to the earth. This field is believed to be produced by interactions of the Earth's ionosphere with the solar wind**

- ***Crustal Field(magnetic anomaly) - This is the portion of the magnetic field associated with the magnetism of crustal rocks.*** **This portion of the field contains both magnetism caused by induction from the Earth's main magnetic field and from remanent magnetization. This portion is the targets of magnetic surveying.**

Temporal variations of magnetic field:

Like the gravitational field, the magnetic field varies with time. When describing temporal variations of the magnetic field, it is useful to classify these variations into one of three types depending on their rate of occurence and source

1- Secular Variations - *These are long-term (changes in the field that occur over years) variations in the* main magnetic field that are presumably caused by fluid motion in the Earth's Outer Core. Because these variations occur slowly with respect to the time of completion of a typical exploration magnetic survey, these variations will not complicate data reduction efforts.

2-Diurnal Variations - *These are variations in the magnetic field that occur over the course of a day and* are related to variations in the Earth's external magnetic field. This variation can be on the order of 20 to 30 nT. per day and should be accounted for when conducting exploration magnetic surveys.

3- Magnetic Storms - *Occasionally, magnetic activity in the ionosphere will abrubtly increase. The* occurrence of such storms correlates with enhanced sunspot activity. The magnetic field observed during such times is highly irregular and unpredictable, having amplitudes as large as 1000 nT. Exploration magnetic surveys <u>should not be conducted </u>during <u>magnetic storms</u>.

. Magnetic surveys

• The base station must be choose in an open area, with hopefully not close to any surface and buried metal objects

•The magnetic surveys are usually done with portable magnetometers.

•Profiles or networks of points are measured in the same way as for gravity survey.

•It is important to survey perpendicular to the strike of an elongate body

•It is necessary to tie back to the base station at 2-3 hour intervals, or to set up a continually-reading base magnetometer. This will give diurnal drift and detect magnetic storms.

The operator must:

- **record the time at which readings were taken, for drift correction,**
- **stay away from interfering objects, e.g., wire fences, railway lines, roads,and car**
- **not carry metal objects *e.g., mobile phones, watch and hammer***
- **take multiple readings at each station to check for repeatability.**

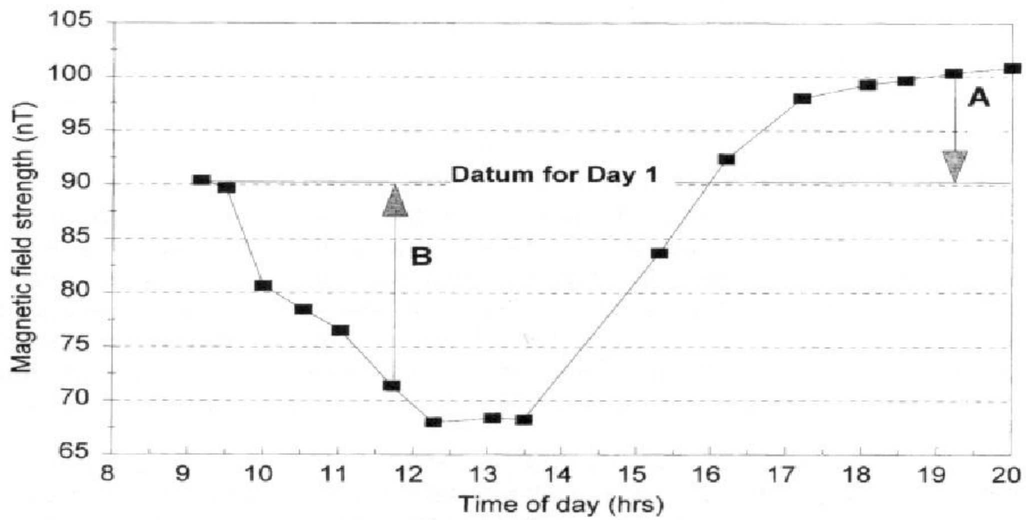
Corrections of Magnetic Survey Data 1

Magnetics data reduction is usually simpler than with gravity, the main correction are :

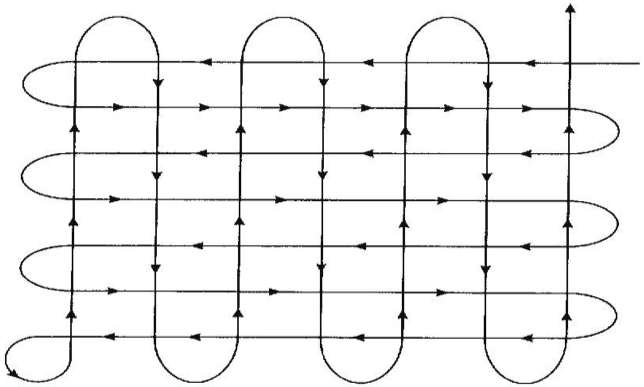
- Diurnal Correction
- Normal Correction (geomagnetic correction)
- Elevation/Terrain Correction (occasionally)

1- Diurnal correction

- **It is the correction to remove the effect of a temporal variation in the measured magnetic field**
- It is similar to drift correction in gravity survey
- Reading is recorded at base station during survey, and then corrections applied to
- survey data.



• in airborne work it is difficult to return to base station , but it is possible to estimate diurnal correction from line intersections especially with additional tie lines



Note : **for gravity survey , the base station reading is taken both to correct for drift and tidal effect while in magnetic survey the base reading is taken only for diurnal effect because the magnetometer do not drift**

2- Normal(geomagnetic) correction:- It is the correction to remove the effect of variation of geomagnetic field with latitude or to remove the effect of a geomagnetic reference field from the magnetic survey data

- **It is similar to latitude correction in gravity survey**

- **Earth's total magnetic field varies from 25,000 nT at equator to 70,000 nT at poles**

- **increasing of magnitude with latitude must be taken in account by using normal or as named geomagnetic correction.**

There are three possible methods for normal correction , these are:-:

a) Subtraction of International Geomagnetic Reference Field (IGRF)

The survey data at any given location can be corrected by subtracting the theoretical field value (F_{th}) obtained from IGRF from the measured value ($F_{obs.}$).
(Normal correction = $F_{th.} - F_{obs.}$)

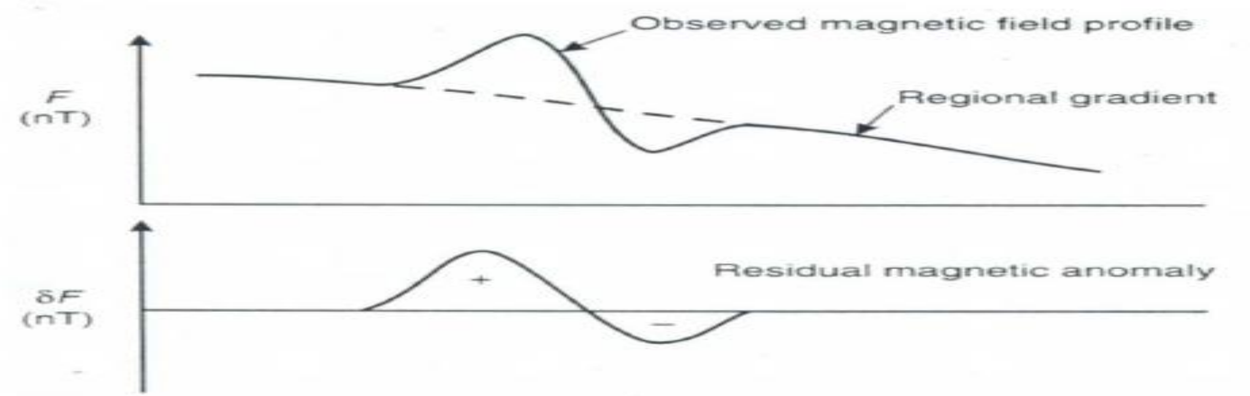
Q/ what IGRF means?

Answer / the International Geomagnetic Reference Field(IGRF) defines as the theoretical undisturbed magnetic field at any point of the earth surface , IGRF updated every 5 years because of secular variation. Year of calculation is called the epoch.

Note:- This method well in area where the IGRF is tied in at or near to geomagnetic observatories , but in area remote from observatories can be in substantially in error

b) Linear approximation to IGRF: Earth's field is approximated by linear variation across survey area, and subtracted: **For example, in UK(united Kingdome) gradients is approximated by 2.13 nT/km north, and 0.26 nT/km** west.

c) Regional correction: With large surveys, regional trend can be estimated and removed to leave local anomaly as negative and Positive residual, as with gravity data.



3- Elevation and Terrain Corrections

- **Elevation correction** (F.A.C and B.C) is not applied in magnetic survey , because the Vertical gradient of geomagnetic field is only 0.035nt/m at the poles and 0.015nt/m at the equator

•**Terrain correction** can be applied, but is complicated. Require estimate of ground susceptibility, and topography.

•**By applying diurnal and normal correction , all remaining magnetic field variations should be caused by variation in the magnetic properties of the subsurface and are referred to as magnetic anomalies.**

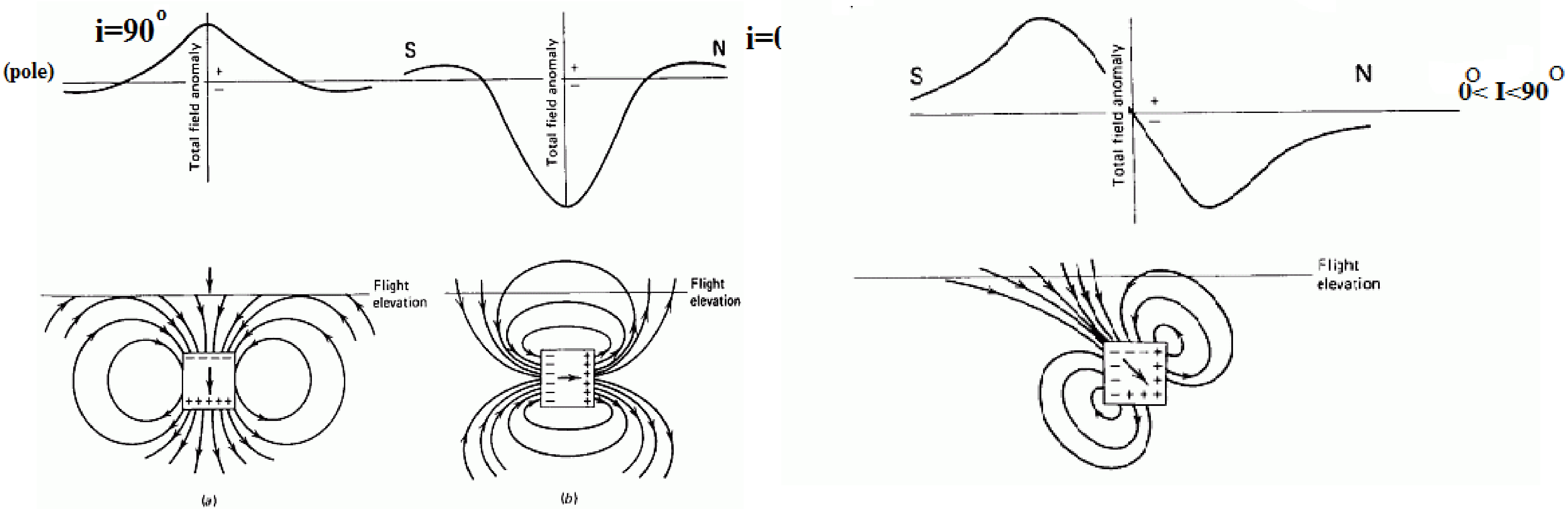
- Factors influence magnetic anomaly shape

There are many factors influence magnetic anomaly shape ,some of which are:-

1. **Inclination (i)(latitude)2- Depth of burial 3- Remnant magnetization 4 -Strike of the body**

1. Inclination (i):-

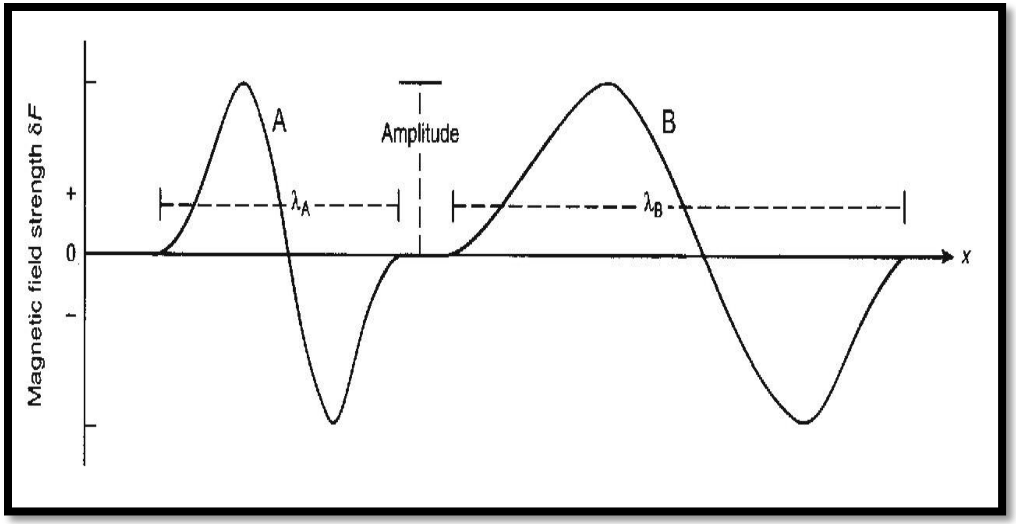
magnetic anomaly shape changes with inclination , because orientation and magnitude of Earth's total field varies. Induced magnetisation indicated by negative to north and positive to south in northern hemisphere and vice versa in southern hemisphere . If the guideline does not hold, it implies significant remanent magnetisation present.

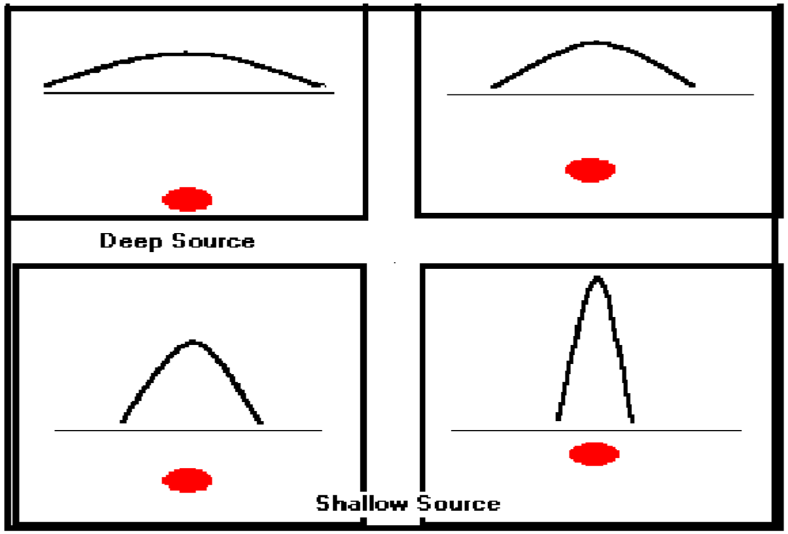


Figures above illustrate the shape of magnetic anomaly **northern hemisphere** Which magnetisation **by induction only** (no remnant magnetisation) .

In the northern hemisphere, the magnetic field generally dips downward the north and becomes vertical at the north magnetic pole. In the south hemisphere the dip is generally upward toward the north. The line of zero inclination approximates the geographic equator, and is know as the magnetic equator.

2- Depth of burial :- **deeper sources producing broader shaped anomalies than the anomalies produced by shallower sources .The deeper magnetic bodies produce anomalies of a longer wavelength than shallower ones.**





•Anomaly B is same form as A, but has longer wavelength, so must be deeper.

Anomaly will broaden and decrease in amplitude with increase in depth.

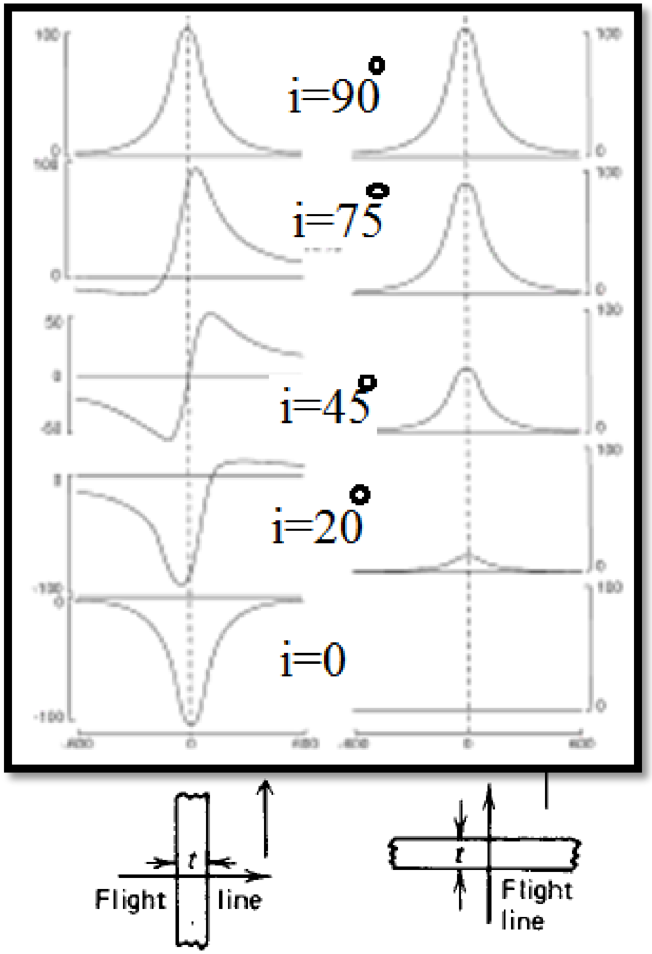
3- Remnant magnetization (jr):- **The presence of remnant magnetisation can distore anomaly Shape .**

4- Strike of the body

- Anomaly is symmetric when strike is N-S. True for all regular bodies.
- Typical peak-trough anomaly arises when dyke strikes E-W

- **For the N-S** striking dyke , the anomaly shape remains the same but the amplitude is reduced

- **For the E-W** striking dyke, the amplitude remains the same across all magnetic latitudes but the shape changes



Interpretation of Magnetic Data

The interpretation of magnetic anomalies is similar in its procedures and limitations to gravity interpretation but there are several differences, which increase the complexity of magnetic interpretation these are:-

A – Because the earth magnetic field is dipolar , the magnetic anomaly of a finite body can have the form of a positive peak only, a negative peak only or **both positive and negative peak** depending on the location of magnetic field , while **the gravity** anomaly of a causative body is entirely positive or negative, depending on whether the body is more or less dense than its surroundings(see figure below).

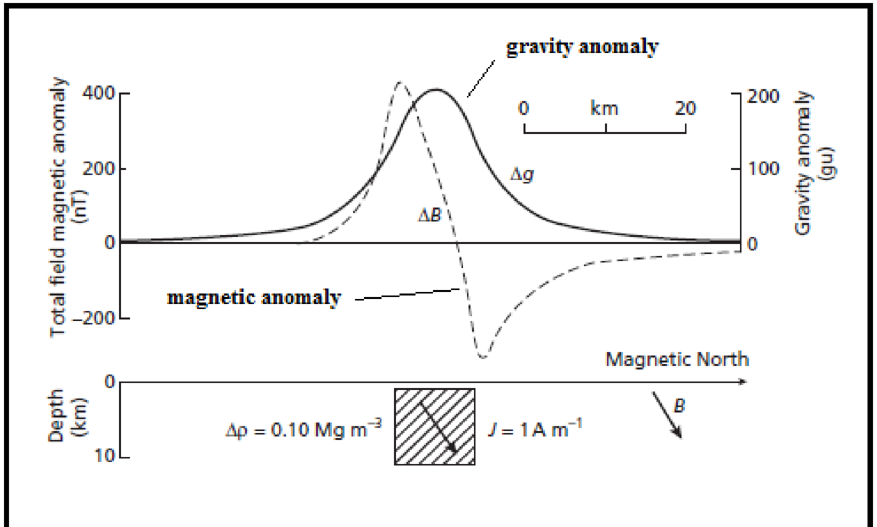
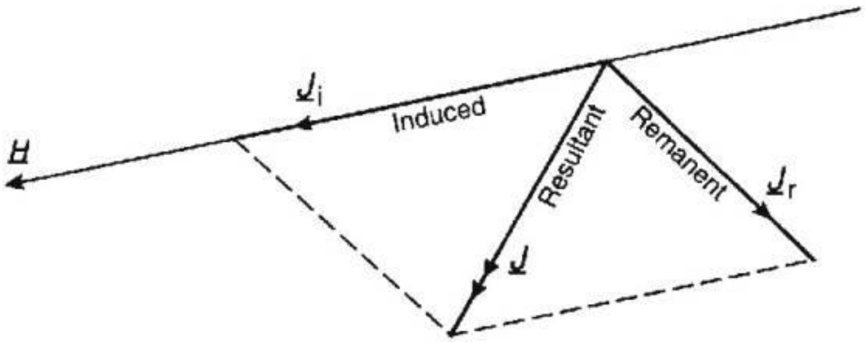


Fig. Gravity (Δg) and magnetic (ΔB) anomalies over the same two-dimensional body.

B- Interpretation of **magnetic data** complicated as magnetic field due to a subsurface body results from combined effect of two vector magnetisations that may have different magnitudes and directions(**induced and remnant magnetisation**)



prepared by Dr. munther Al-Awsi

C-magnetic anomalies are often much less closely related to the shape of the causative body than are gravity anomalies.

-When magnetic data have been fully corrected and reduced to their final form , they are displayed either as **profiles** or as **maps** and then the procedures of interpretation begin .

- The objective of magnetic interpretation is to translate magnetic data to geological terms to give the features of the subsurface structures.

- The interpretation of magnetic data involves qualitative and quantitative interpretation.

1- qualitative interpretation

-This method of interpretation involves to visual description to the magnetic anomalies such as determine the wavelength of anomalies , the extending of anomaly (amplitude) , shapes of anomalies, quiet or noisy magnetically in case of profiles or linearity , dislocation in contour line ,broadening of contour intervals in case of contour maps.

Some general guidelines for the qualitative interpretation of magnetic profiles and maps are listed in Table below

Applies to:	Magnetic character	Possible cause
Segments of a profile and areas of maps	Magnetically quiet	Low κ rocks near surface
	Magnetically noisy	Moderate–high κ rocks near surface
Anomaly	Wavelength	Short $\Rightarrow$ near-surface feature Long $\Rightarrow$ deep-seated feature
	$\pm$ amplitude	Indicative of intensity of magnetisation
Profile*	Anomaly structure† and shape	Indicates possible dip and dip direction 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 remanent magnetisation present
Profile and maps	Magnetic gradient	Possible contrast in κ and/or magnetisation direction
Maps	Linearity in anomaly	Indicates possible strike of magnetic feature
Maps	Dislocation of contours	Lateral offset by fault
Maps	Broadening of contour interval	Downthrow of magnetic rocks

*Can be determined from maps also; † Structure = composition of anomaly, i.e. positive peak only, negative peak only or doublet of positive and negative peaks; κ = magnetic susceptibility

2- quantitative interpretation.

• **It is the interpretation of magnetic data to yield the numerical characteristics of the body being studied (depth and dimensions).**

• **The quantitative interpretation of magnetic data involves:**

1- Direct interpretation

2- Indirect interpretation and automatic inversion

1- Direct interpretation

Direct interpretation method for magnetic data consist to :-

A- Calculation of depth to causative bodies.

B- Calculation of magnetic effects of causative bodies.

C- Anomaly separation and filtration.

D- Reduction to the pole.

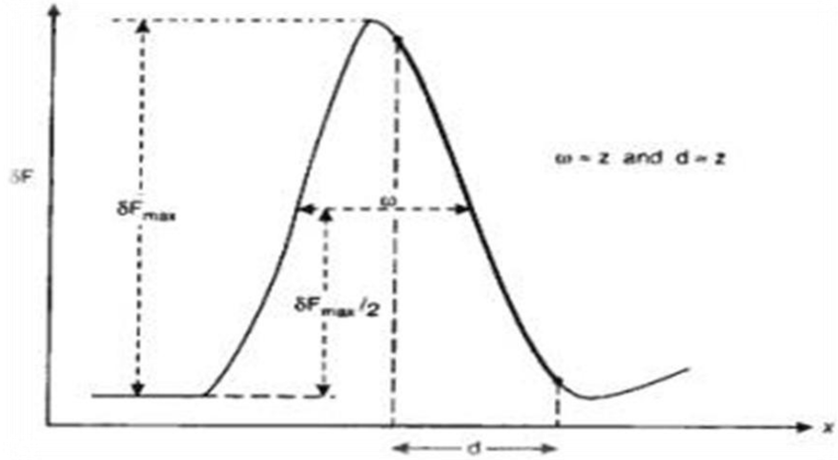
Depth of Causative Bodies Estimations

1-Simple method for depth estimation.

•**It is possible to obtain a very approximate estimate of depth to a magnetic body using the shape of the anomaly.**

•**By referring to either a simple sphere or horizontal cylinder:** the width of the main peak at half its maximum value (δ Fmax/2) is crudely equal to the depth to the center of the magnetic body(figure below)

•**By referring to Dipping Sheet or Prism**: Depth to centre of body is roughly width of linear segment of anomaly (d) (figure below).



2- Peters` Half-Slop method.

To determine depth by using this method the following steps must be done

•**Locate the maximum slope on the magnetic intensity profile.(The maximum slope is the most steep part of the magnetic anomaly line on the graph).**

•Draw a straight line through the maximum slope, extending beyond the slope's top and bottom end and intersecting with the x-axis beyond the bottom end; this is the "slope line.“(line -1-)

•Draw a vertical line, connecting the maximum slope's top end with the chart's x-axis. Measure the vertical line's height with the ruler and mark its middle point.

•Draw a straight line connecting the slope line's intersection with the x-axis and the middle point of the vertical line; this is the "half-slope line.“(line -2-)

• Add two straight lines parallel to the half-slope line and tangent to the magnetic intensity line, touching the curve, but not intersecting it(lines 3 and 4).

• Draw two new vertical lines, starting from the two points were the tangent lines touch the curve and ending at the x-axis.The horizontal distance “d” between these two tangents is a measure of the depth to the magnetic body.

•The depth “z” to the top of the magnetized body is: $z = d / n$
Where “n” varies between 1.2 for narrow bodies and 2 for wide bodies (usually taken as 1.6).

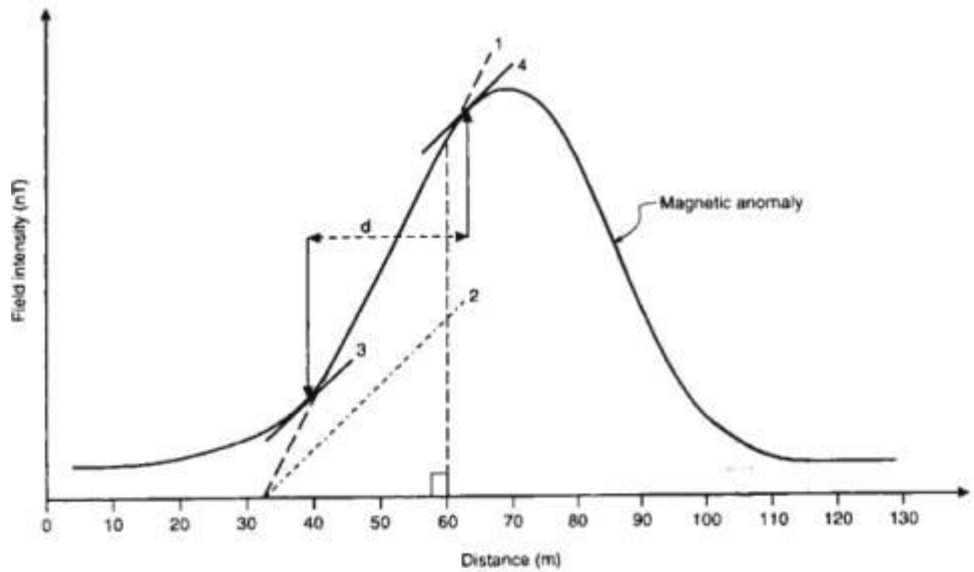


Figure illustrate Peters` Half-Slope method to estimate the depth to a magnetized dyke.

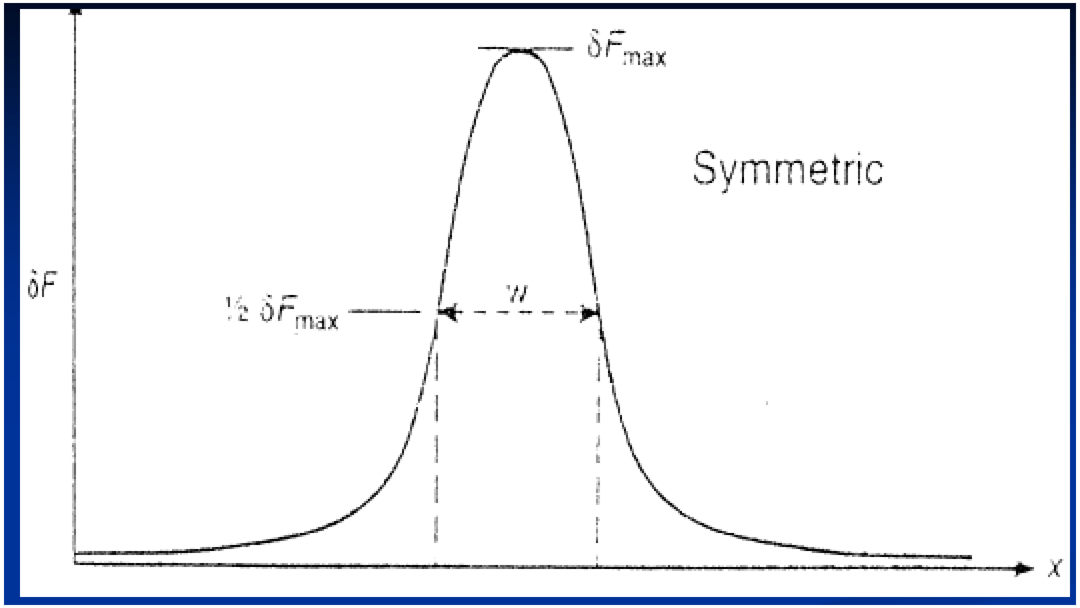
3- Parasnis method for depth calculation:

Parasnis (1986), derived methods of depth determination for a magnetized sheet of various thicknesses and dips using the anomaly shape and amplitude.

•For symmetrical magnetic anomaly curves (Fig. below), the depth of the body "z" is approximately equal to half the width of the anomaly curve at "Fmax/2" as follows,

$$z = w / 2$$

Where, w = anomaly width at fmax/2.



•Other methods for depth determination of different causative bodies have been given in Nettleton (1976).

Indirect interpretation

- Same approach than in gravimetry (improvement of a initial model, see picture)
- Automatic inversion useful since anomalies are complex
- Model built using a series of dipoles (sum of positive and negative poles)