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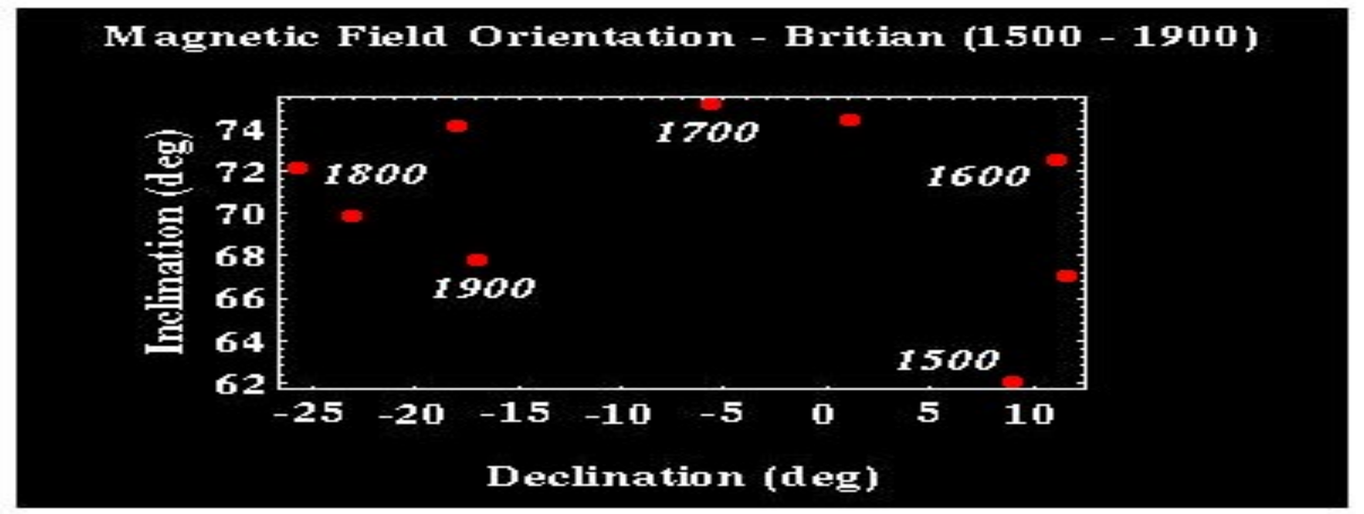
Temporal Variations of the Earth's Magnetic Field - Overview

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. Please note explicitly that the temporal variations in the magnetic field that we will be discussing are those that have been observed directly during human history. As such, the most well-known temporal variation, magnetic polarity reversals, while important in the study of earth history, will not be considered in this discussion. We will, however, consider the following three .temporal variations

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



At this one location, you can see that over the past 400 years, the declination has varied by almost 37 degrees while the inclination has varied by as much as 13 degrees. These changes are generally assumed to be associated with the Earth's main magnetic field. That is, these are changes associated with that portion of the magnetic field believed to be generated in the Earth's core. As such, solid earth geophysicists are very interested in studying these secular variations, because .they can be used to understand the dynamics of the Earth's core

To understand these temporal variations and to quantify the rate of variability over time, standard reference models are constructed from magnetic observatory observations about every five years. One commonly used set of reference models is known as the International Geomagnetic Reference Field. Based on these models, it is possible to predict the portion of the observed magnetic field associated with the Earth's main magnetic field at any point on the Earth's .surface, both now and for several decades in the past

Because the main magnetic field as described by these secular variations changes slowly with respect to the time it takes us to complete our exploration magnetic .survey, this type of temporal variation is of little importance to us

IGRF equation (Macmillan and Maus, 2005

The main field is the negative gradient of the scalar potential V

$V(r,\theta,\lambda,t) = R \quad (R/r)n+1 \quad (gm(t) \cos m\lambda +$
$hm(t)$

r, θ, λ, are geocentric coordinates (r is the distance from the centre of the Earth, θ is the co-latitude, *i.e.* 90∘-latitude, and λ is the longitude), R is a reference radius (6371.2 km);

(t)) and hn (t)) are the coefficients at a time t, and Pn (θ) are the Schmidt semi-normalised associated Legendre functions of degree n and order m.

readers are strongly advised to read the IGRF 'health warning' to be found at www.ngdc.noaa.gov/IAGA/vmod/igrfhw.html about the numerical accuracy with which the IGRF calculates values for the main magnetic field. It can be seen from this figure that instead of the anticipated two maxima consistent with a truly dipolar field, there are in fact four maxima.

Some time after a given epoch for the IGRF, a definitive version is derived for a given time period and is known as the *Definitive* Ge- omagnetic Reference Field (DGRF). For example, IGRF-10 (2005)

In-Field Referencing

?What is it

In-Field Referencing (IFR) is the provision of magnetic field estimates at a series of locations and dates along a planned well-path which include .estimates of the crustal field from local observations

The magnetic field estimates are derived from a global model, the BGS Global Geomagnetic Model (BGGM), and from local absolute observations of the geomagnetic field collected during an aeromagnetic or marine survey, or .sometimes a ground-based survey

If the local data are measurements of the strength of the field, as is usually the case with aeromagnetic and marine surveys, BGS has developed a method of estimating the direction of the field, important for directional .drilling, from this type of data. This is reported in SPE paper 49061

BGS has been providing IFR services since the mid-1990s and the following map shows all locations where IFR services are readily available from the BGS (restrictions may apply). If your field is not present BGS can source .suitable local magnetic data and set the field up for IFR services

?What is it for

Table 3.1 *Low-field magnetic susceptibilities of rocks and minerals.*

Mineral or rock type	Magnetic susceptibility ($\kappa \times 10^{-6}$ SI)[a]
Granite (with magnetite)	20–40,000
Slates	0–1200
Gabbro	800–76,000
Basalt	500–80,000
Oceanic basalts	300–36,000
Limestone (with magnetite)	10–25,000
Gneiss	0–3000
Sandstone	35–950
Pyrite (ore)	100–5000
Hematite (ore)	420–10,000
Magnetite (ore)	7×10^4–14×10^6
Magnetite (crystal)	150×10^6
Serpentinite	3100–75,000
Graphite (diamagnetic)[b]	−80 to −200
Quartz (diamagnetic)	−15
Gypsum (diamagnetic)	−13
Rocksalt (diamagnetic)	−10
Ice (diamagnetic)	−9

Notes:
[a] To convert the above values to unrationalized electromagnetic c.g.s. units divide by 4π.
[b] In diamagnetic substances the direction of induced magnetization is observed to be antiparallel to that of the inducing field and, hence, the magnetic susceptibility values are negative.

Sedimentary rocks have typically low remanent intensities ($J_r < J_i$). The intensity J_r is particularly large in igneous and thermally metamorphosed rocks, often far exceeding J_i. Hence magnetic interpretation, especially in areas where such rocks occur, must take into account the influence of remanent magnetization on the magnetic anomalies. The same applies when the object of investigation is an iron or steel body.

3.3.3 Total magnetization and effective susceptibility

In general the total magnetization of a rock *in situ* is expressed as a vector sum

$$\mathbf{J} = \mathbf{J}_i + \mathbf{J}_r \quad (3.14)$$

where $\mathbf{J}_i$ is in the direction of the earth's present field and $\mathbf{J}_r$ can have any arbitrary direction. The magnitude of the resultant vector, J, controls the amplitude of the magnetic anomaly caused by a rock body and the orientation of J influences the anomaly shape. If J is constant and has the same direction throughout, a rock body is said to be *uniformly magnetized*.

The intensity of the total (resultant) magnetization, J, can be expressed in terms of an 'effective' susceptibility, κ_e (often referred to as 'apparent' susceptibility, κ_a, in exploration geophysics literature) by the following relationship

$$\kappa_e \text{ or } \kappa_a = (J_i + J_r)/(F/\mu_0) \tag{3.15}$$

where F is the intensity of the earth's field at the rock site.

3.3.4 Magnetic effects of soils and iron objects

In shallow-depth investigations (e.g., of engineering, environmental, or archaeological interest), the local anomalies can be strongly influenced by magnetic effects of soils and buried iron objects. The magnetic susceptibilities of soils reflect their parentage. Soils derived from igneous and metamorphic rocks (particularly the more mafic components of these lithologies) are likely to be relatively rich in magnetite, which also reflects the resistance of magnetite to alteration. Magnetite may also concentrate in sediments where the streams carrying magnetite and other heavy minerals lose velocity and thus deposit these mineral grains. As a result, magnetite tends to concentrate in the alluvial fans at the base of mountains, and in terranes covered by glacial deposits, in beach sands and in outwash deposits.

High-organic soils often contain locally produced maghemite, a relatively stronger magnetic form of hematite. Surface soils often acquire J_r of magnitude greater than J_i, by thermal effects due to fires or simply by isothermal 'viscous' remanent magnetization acquired over a long period of time due to the earth's ambient field.

Typical iron or steel objects such as pipes, drums, etc., have a total magnetic moment ($M = VJ$) of 10^3 to 10^4 A m^2, including the contribution of remanent magnetization (J_r), which may have intensities of 10 or more times the induced component (J_i). The effective magnetic susceptibility (κ_e) of iron and steel objects, which includes both induced and remanent effects according to Breiner (1973), is between 1 and 10 e.m.u. (~10–100 SI units). The magnetic moment of an object, located at a site where the earth's field intensity is F (tesla), can be calculated by using the following formula:

$$M = VJ = V\kappa_e(F/\mu_0) \tag{3.16}$$

where V is the volume (m^3), and κ_e the effective susceptibility (SI units).

3.4 Acquisition of magnetic data

3.4.1 Magnetic survey instruments

In recent decades there has been considerable improvement in magnetic survey instrumentation by the extensive use of integrated circuit devices. This has led to

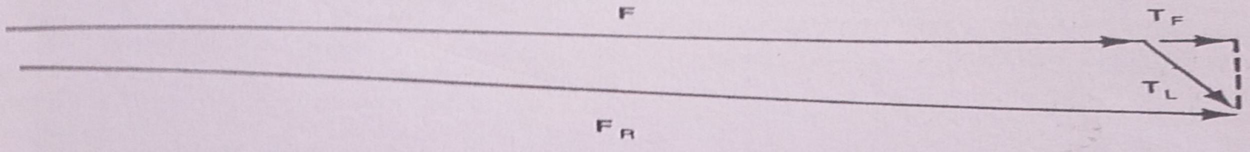


Fig. 3.7 Definition of the total-field magnetic anomaly. F, geomagnetic field (undisturbed); T_L, local disturbance (anomaly field); F_R, resultant of F and T_L vectors; T_F, the total-field anomaly in the direction of the earth's field for the case $F \gg T_L$.

sensor is a critical requirement for precise measurement of the field. Most of the available designs for use in ground surveys measure the vertical component of the field and provide the facility of a digital read-out with a sensitivity of 1 nT. For some survey operations, rough leveling of the instrument is adequate which in practice yields an accuracy of 5–10 nT.

Proton-precession magnetometers. By far the most commonly used magnetometers in both stationary and mobile modes are proton magnetometers. In these instruments, the sensor element is water (or some other liquid containing a large number of hydrogen nuclei) in a small bottle surrounded by a suitable coil. A strong magnetic field ('polarizing field'), oriented at a large angle to the earth's field direction, is applied by sending a direct current in the coil to displace the protons out of the earth's field. When the polarizing field is switched off, the protons, while returning to their original alignment, precess for a short time around the direction of the earth's ambient field. The frequency of this precession is related to the absolute earth's field through a well-known constant, the gyromagnetic ratio of the proton (γ_p). The measured frequency divided by γ_p gives the value of the earth's total field.

An important advantage of this instrument is that orientation of the sensor is not critical; the only requirement is that the polarizing field should make a sufficiently great angle with the direction of the earth's field. In contrast to the fluxgate magnetometer, which can measure the field continuously, the proton magnetometer gives a series of discrete measurements at intervals of a few seconds because of the polarizing and relaxing time taken by protons. This disadvantage of the lower sampling rate is particularly felt in airborne surveys where a choice must be made between data interval and data sensitivity. However, sampling rates can be increased with an Overhauser-effect proton magnetometer that enables measurements at intervals of about 0.5 s. Another point of difference is that the instrument measures the scalar magnitude of the total field and not its direction (Fig. 3.7). Furthermore, the instrument is subject to malfunction in areas of large magnetic gradients. Gradients of the order of 500 nT/m, which may occur very near iron or steel objects, will cause erroneous readings.

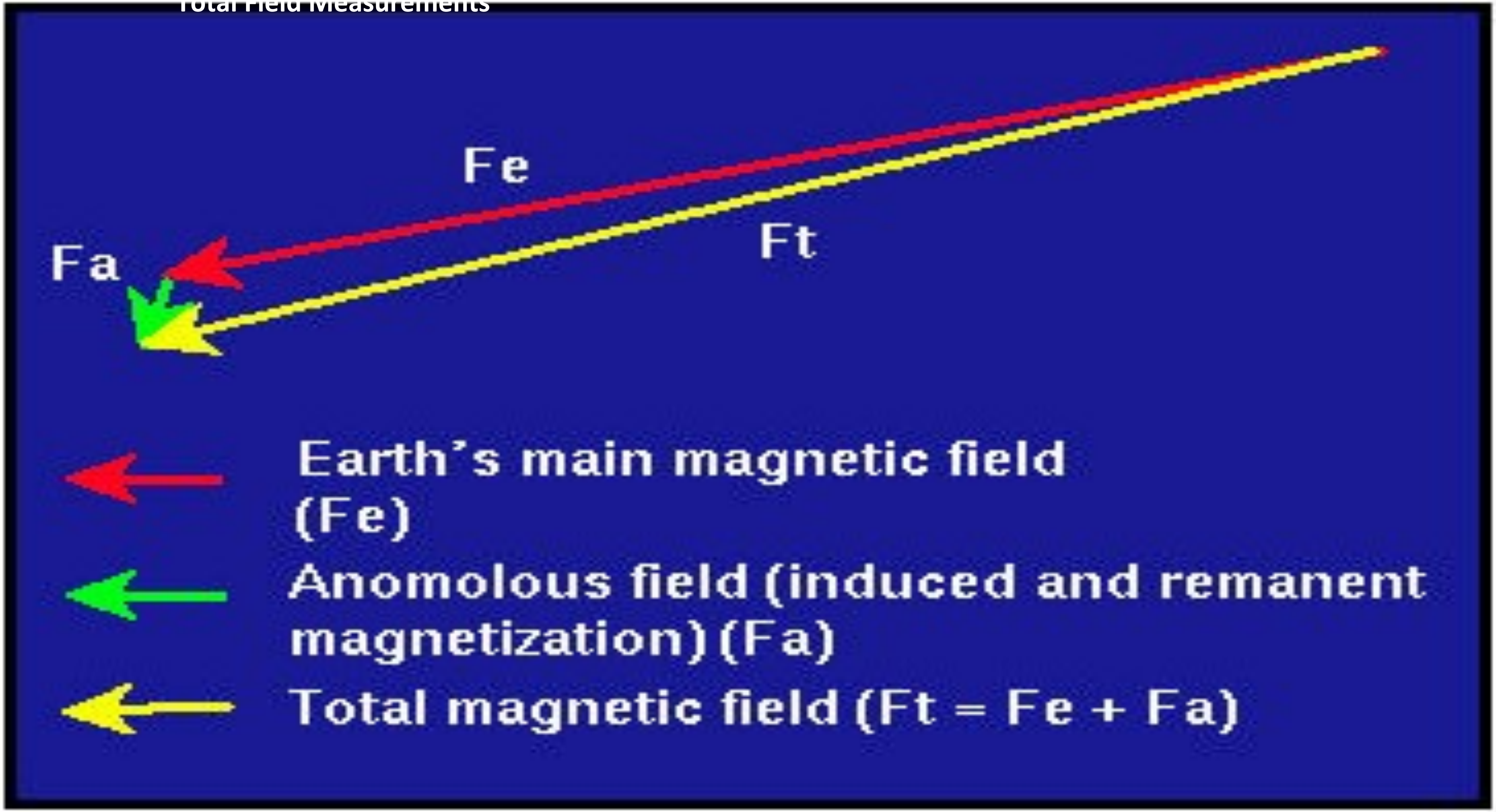
Fig. 3.8 A portable proton magnetometer for ground surveys. By mounting two sensors on the same rod at different heights the instrument can be used as a differential magnetometer (gradiometer). (Courtesy Bison Instruments, Inc.)

Several portable designs for ground surveying are available within the sensitivity range of 1 to 0.1 nT at sampling rates of 0.5 to 2 s, controlled by automatic triggers or manually. One such instrument is shown in Fig. 3.8. Many designs for use in airborne survey are available with a sensitivity of the order of 0.1 nT.

Alkali-vapor magnetometers. These instruments (also called optical absorption magnetometers) operate on the principle of optical pumping, a development in radiofrequency spectroscopy based on irradiating alkali metal (e.g., rubidium, cesium) atoms with spectral beams of appropriate frequency (Bloom, 1962). Like a proton magnetometer, the alkali-vapor magnetometer measures the total ambient field, and orientation of the instrument is not critical. The sampling rate of the instrument is much higher than that of proton magnetometers. As the output frequency (100–300 kHz) can be determined with great accuracy, a high sensitivity of the order of 0.01 nT can be obtained. The high sensitivity makes the instrument ideally suited for using it as part of an airborne gradiometer.

Magnetic gradiometers. A magnetic gradiometer can be considered to be a differential magnetometer where the spacing between two sensors of the same type is fixed and small with respect to the distance to the sources whose fields are measured. The

Total Field Measurements



Ignoring for the moment the temporally varying contribution to the recorded magnetic field caused by the external magnetic field, the magnetic field we record with our proton precession magnetometer has two :components

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 *Fe* in the figure

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 *Fa* in the figure

The total magnetic field we record, labeled *Ft* in the figure, is nothing more than the sum of *Fe* and *Fa*. Typically, *Fe* is much larger than *Fa*, as is shown in the figure (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*.
That is because the anomalous field, *Fa*, is so much smaller than the main field, *Fe*, that the total field , *Ft*, will be almost parallel to the main field.,

Modes of Acquiring Magnetic Observations
Magnetic observations are routinely collected using any one of three different .field operational strategies

Airborne - Both fluxgate and proton precession magnetometers can be mounted within or towed behind aircraft, including helicopters. These so-called *aeromagnetic surveys* are rapid and cost effective. When relatively large areas are involved, the cost of acquiring 1 km of data from an aeromagnetic survey is about 40% less than the cost of acquiring the same data on the ground. In addition, data can be obtained from areas that are otherwise inaccessible. Among the most difficult problems associated with aeromagnetic surveys is fixing the position of the aircraft at any time. With the development of realtime, differential GPS systems, however, this difficulty is rapidly disappearing.

Shipborne - Magnetic surveys can also be completed over water by towing a magnetometer behind a ship. Obviously, marine magnetic surveying is slower than airborne surveying. When other geophysical methods are .being conducted by ship, however, it may make s ense to acquire magnetic data simultaneously

Ground Based - Like gravity surveys, magnetic surveys are also commonly conducted on foot or with a vehicle. Ground-based surveys may be necessary when the target of interest requires more closely-spaced readings than are possible to acquire from the air. In the next discussion we will concentrate on ground-based surveys. .All of this discussion, however, could be applied to air- and shipborne surveys also

Because magnetic surveying is generally far cheaper than other geophysical methods, magnetic observations are commonly used for reconnaissance. These surveys can cover large areas and are used to identify the locations of targets for more detailed investigations. Because of their cost effectiveness, magnetic surveys usually consist of areal distributions of data instead of single lines of data. We will refer to the collection of geophysical observations over a geographic area as *two-dimensional surveys*. Data that is collected along a single line of observations will be .referred to as *one-dimensional surveys* difference in measured field intensity divided by the vertical distance between sensors is taken to be the gradient (in nT/m) at the midpoint of the sensor spacing. Gradient measurements are free from noise coherent in time, such as time variations of the earth's field (diurnal variations). Gradiometers are also used to suppress noise effects from regional (distant) sources to emphasize anomalies from shallow sources. This application can be considered as a distance filter; anomalies vary inversely with distance at a rate one order higher for a gradiometer than for a magnetometer. The practical advantages of such measurements over mathematically derived vertical gradients (derivatives) have been studied. The ability to survey through periods of high temporal magnetic variations (especially in regions of high magnetic latitude) is considered to be a major advantage.

The gradiometers most widely used in airborne surveys employ pairs of sensing elements (usually cesium-vapor cells) which are suspended from a helicopter or fixed-wing aircraft with a fixed spacing of several meters between the sensors (Fig. 3.9). In ground surveys, two proton magnetometers held on the same rod, at different heights above the ground surface (for instance, at 1 m and 2 m), can be used for gradient measurements. Such an arrangement is simple to handle and allows rapid measurements at grid points with small spacings (a couple of meters) that may be required in shallow depth investigations for features of engineering or environmental interest.

3.4.2 Survey procedures and data correction

Magnetic surveying is carried out on land, at sea and in the air. For extensive areas, reconnaissance over both land and sea is conveniently done with the airborne magnetometer. Line spacing for airborne surveys varies widely, from a typical 4 km in the case of surveys over sedimentary basins to as little as 200 m in areas of exposed crystalline basement. The height of the flight path is chosen on the basis of line spacing. Cross-control 'tie lines' are often flown at larger intervals than the line spacing. In helicopter-borne surveys for environmental investigations of hazardous waste dumps, line spacings could be as small as 50–100 m with flying at a constant height of 30–50 m above ground level. The flight height is monitored mostly by radar altimeters, which yield an accuracy of 5% of the flying height. Positions are determined by a combination of photography or video tape, altimeter, and electronic navigational aids. Airborne/helicopter-borne surveying is preferred for most applications except high-resolution studies of limited areas for which detailed ground surveying is necessary.

In land surveys, observations can be made at extremely close intervals which permit high resolution of near-surface sources. Stations are laid out either on a grid or, in mapping linear features, on profiles perpendicular to the strike at an interval of several times the station spacing. Land surveys are time-consuming and expensive if the survey is measured in kilometers. To minimize costs and time, magnetometers

Magnetic Cleanliness and Interference

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When making total field measurements from which * estimates of the subsurface distribution of magnetic susceptibility or the presence of subsurface magnetized bodies are made, it is imperative that factors affecting the recorded field other than these be eliminated or isolated so that they can be removed. We have already discussed several of these added complications, including spatial variations of the Earth's main magnetic field and temporal variations mostly associated with the external magnetic field. In addition to these factors which we can not control, there are other sources of *noise* that we can control

Because any ferromagnetic substance can produce an induced magnetic field in the presence of the Earth's main field and because modern magnetometers are very sensitive (0.1 nT), the field crew running the magnetic survey must divest itself of all ferrous objects. This includes, but is not limited to, belt buckles, knives, wire-rimmed glasses, etc. As a result of this, proton precession magnetometers are typically placed

on two to three meter poles to remove them from potential noise sources .worn by the operators
In addition to noise sources carried by the operators, many sources of magnetic noise may be found in the environment. These can include any ferrous objects such as houses, fences, railroad rails, cars, rebar in concrete foundations, etc. Finally, when using a proton precession magnetometer, reliable readings will be difficult to obtain near sources

Strategies for Dealing with Temporal Variations

In acquiring gravity observations, we accounted for this temporal variability by periodically reoccupying a base station and using the variations in this reading to account for instrument drift and temporal variations of the field. We could use the same strategy in acquiring :magnetic observations but is not routinely done for the following reasons difference in measured field intensity divided by the vertical distance between sensors is taken to be the gradient (in nT/m) at the midpoint of the sensor spacing. Gradient measurements are free from noise coherent in time, such as time variations of the earth's field (diurnal variations). Gradiometers are also used to suppress noise effects from regional (distant) sources to emphasize anomalies from shallow sources. This application can be considered as a distance filter; anomalies vary inversely with distance at a rate one order higher for a gradiometer than for a magnetometer. The practical advantages of such measurements over mathematically derived vertical gradients (derivatives) have been studied. The ability to survey through periods of high temporal magnetic variations (especially in regions of high magnetic latitude) is considered to be a major advantage.

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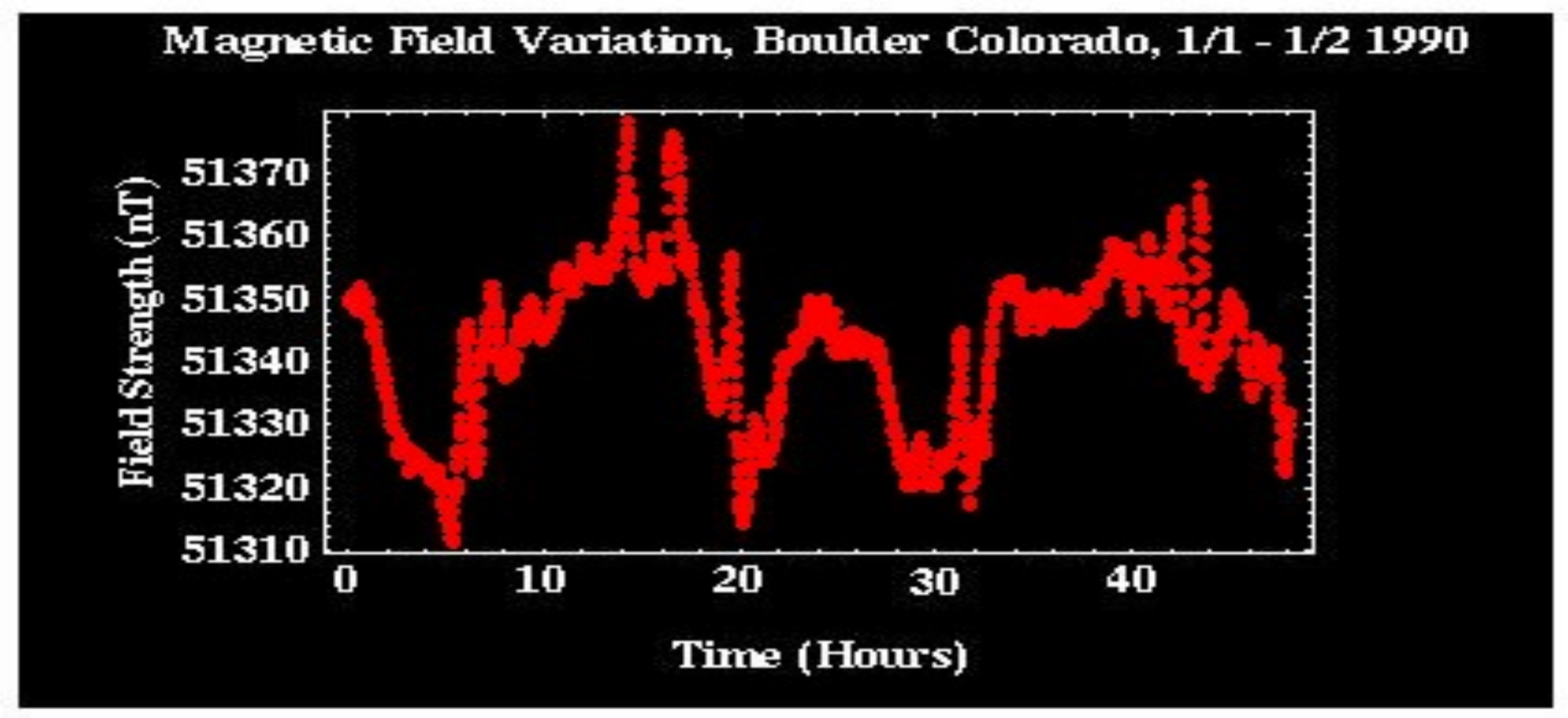
Diurnal Variations - These are variations in the magnetic field that occur over the course of a day and are related to variations in the Earth's external magnetic field. This variation can be on the order of 20 to 30 nT per day and should be accounted for when conducting exploration magnetic surveys. it was also noted .that these daily variations were larger in summer than in winter



Measuring the Earth's Magnetic Field

Instruments for measuring aspects of the Earth's magnetic field are among some of the oldest scientific instruments in existence. Magnetic instruments can be .classified into two types

- *Mechanical Instruments* - These are instruments that are mechanical in nature that usually measure the attitude (its direction or a component of its direction) of the magnetic field. The most common example of this type of instrument is the simple compass. The compass consists of nothing more than a small test magnet that is free to rotate in the horizontal plane. Because the positive pole of the test magnet is attracted to the Earth's negative magnetic pole and the negative pole of the test magnet is attracted to the Earth's positive magnetic pole, the test magnet will align itself along the horizontal direction of the Earth's magnetic field. Thus, it provides measurements of the declination of the magnetic field. The earliest known compass was invented by the Chinese no later than the first century A.D., and more likely as early as the second .century B.C

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Although compasses are the most common type of mechanical device used to measure the horizontal attitude of the magnetic field, other devices have been devised to measure other components of the magnetic field. Most common among these are the *dip needle* and the *torsion magnetometer*. The dip needle, as its name implies, is used to measure the inclination of the magnetic field. The torsion magnetometer is a devise that can measure, through mechanical means, the strength of the vertical component of the magnetic field.

Magnetometers - Magnetometers are instruments, usually operating non-mechanically, that are capable of measuring the strength, or a component of the strength, of the magnetic field. The first advances in designing these instruments were made during WWII when Fluxgate Magnetometers were developed for use .in submarine detection

Since that time, several other magnetometer designs have been developed that include the Proton Precession and Alkali-Vapor magnetometers

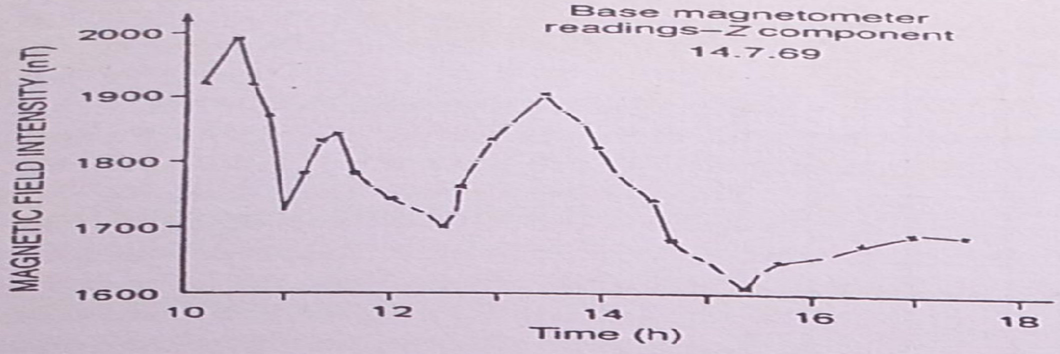

Fig. 3.10 Diurnal variation in the vertical field intensity recorded at the base station in Nûgssuaq, West Greenland, during a magnetic storm. (After Sharma, 1986.)

have been mounted on a surface vehicle (Hildenbrand, 1982). However, for precise measurements great care and effort have to be used to compensate for the field variations caused by the vehicle at the sensor.

Regardless of the type of survey and instrument used, magnetometer observations are affected by a number of sources in addition to the signature of subsurface magnetization contrasts which are of prime interest in mapping. The corrections that are applied to magnetic data of ground surveys are fewer in number and simpler than in the case of gravity data. In contrast, aeromagnetic data (both inflight and the recovered track data) are subject to a great variety of types and degree of severity, of man-made and machine errors. A detailed discussion of these errors and methods for detection and correction can be found in Hood *et al*. (1979). The corrections which are common to ground as well as airborne survey data are described in the following.

Diurnal correction. A correction has to be made to account for the temporal variations of the geomagnetic field which are primarily caused by particle and electromagnetic radiation from the sun perturbing the ionosphere of the earth, and thus the geomagnetic field. The temporal variations have a wide range of period and amplitude. Typical variations are some tens of nanotesla during a normal 'quiet' day. In contrast, the 'disturbed-day' variations are irregular and extreme in magnitude, amounting to several hundreds of nanotesla within an hour or so (Fig. 3.10); they are associated with 'magnetic storms' caused by a strong flux of charged particles from the sun. During 'storm' periods magnetic survey operations have to be discontinued.

For the correction of diurnal variations the method of direct subtraction of base-station magnetometer readings is now a standard procedure in ground surveys and also helicopter-borne surveys of relatively small areal extent. For surveys conducted

With these points in mind, most investigators conduct magnetic surveys using two magnetometers. One is used to monitor temporal variations of the magnetic field continuously at a chosen base station, and the other is used to collect observations related to the survey proper. By recording the times at which each magnetic station readings are made and subtracting the magnetic field strength at the base station recorded at that same time, temporal variations in the magnetic field can be eliminated. The resulting field then represents relative values of the variation in total field strength with respect to the .magnetic base station

.Magnetic susceptibilities vary be orders of magnitude even among samples of the same rock type. So, how can we choose an *average* susceptibility on which to base our c

?Spatially Varying Corrections

When reducing gravity observations, there were a host of spatially varying corrections that were applied to the data. These included latitude corrections, elevation corrections, slab corrections, and topography corrections. In principle, all of these corrections could be applied to magnetic observations also. In practice, the only corrections routinely made for are spatial variations in the Earth's main magnetic field, which would be equivalent to latitude corrections applied to gravity observations. Why aren't the other ?corrections applied

Variations in total field strength as a function of elevation are less than 0.015 nT per meter. This variation is generally considered small enough to ignore. Variations in total field strength caused by excess magnetic material (i.e., a slab correction) and topography could, on the other hand, be quite significant. The problem is the large variation in susceptibilities associated with earth materials even .when those materials are of the same rock type

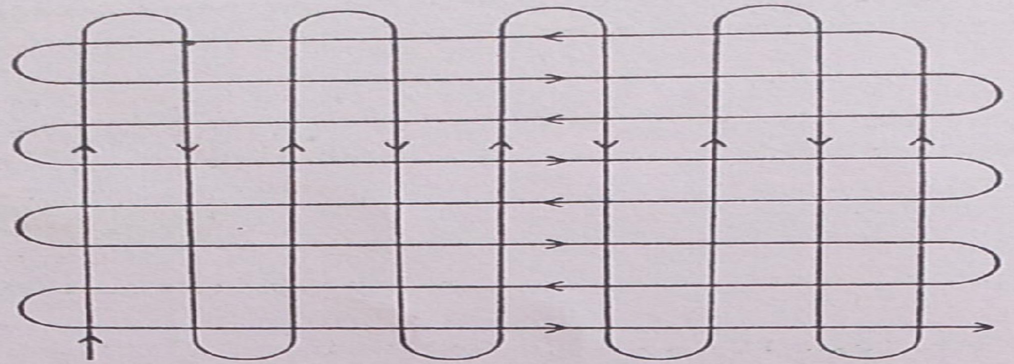

Fig. 3.11 A typical flight pattern for an aeromagnetic survey. Corrections for diurnal variation and misclosures around the loops are made by 'least-squares' adjustment at a number of 'tie points'. (Modified from Kearey and Brooks, 1991.)

within a radius of about 50 km from the base station the temporal variations are essentially synchronous and of sufficiently equal magnitude. In airborne surveys, it is common practice to remove first the base-station variations from the nearest base-recording magnetometer and then apply a final leveling adjustment using traditional 'tie lines' crossing the flight lines at suitable intervals (Fig. 3.11). Gradient measurements (made by magnetic gradiometers) are free from temporal-variation effects.

Normal-field correction. This correction is required to take into account the normal variation of the geomagnetic field intensity with latitude and longitude. The basis of the correction is the IGRF map (see Fig. 3.5) or the tables which are published as grid values of the total field for different epochs. In most local surveys for engineering and environmental investigations, the station locations are relative only and are not defined in latitude and longitude. In these surveys the north–south and east–west gradients of the IGRF are determined from the tables for a central base location and corrections made for the station locations relative to the base. In regions of mid latitudes (between 30 and 60°N), the IGRF gradients typically range from zero to 2 nT/km in an east–west and from 2 to 5 nT/km in a north–south direction. In airborne and shipborne magnetic surveys it may be necessary to use radio navigational devices for locating the positions of measurement points before the normal-field correction can be applied.

Elevation and terrain corrections. The vertical gradient of the geomagnetic field at the surface of the earth can be obtained by differentiating Eq.(3.10a) with respect to r and θ. The gradient is approximately 0.03 nT/m at the poles and only half of this at the geomagnetic equator. Thus, elevation corrections are normally not required in ground surveys. In airborne surveys, the flight altitude may substantially affect the recorded data when the aircraft is flown at a constant terrain clearance in regions of steep topography. In such cases the recorded data must first be reduced to a common altitude.

Terrain effects in ground magnetometer surveys are not considered to be of such importance as in gravity surveys. However, in regions of igneous outcrops, rough terrain may give rise to 'false' negative anomalies at stations near steep hill slopes. Gupta and Fitzpatrick (1971) have reported terrain anomalies as large as −700 nT near slopes of 10-m high formations of susceptibility 0.01 SI. There are no general procedures for applying magnetic terrain corrections, but where necessary the area can be divided into a grid of squares, whose average heights can be estimated from topographic maps. The size of the squares would depend on the intensity of magnetization of surface rocks and on the irregularity of the topography. The anomaly contribution from each block can be calculated by using formulas for the magnetic effect of a right rectangular prism (Appendix C).

3.5 Data enhancement techniques

As in the case of gravity data, various data enhancement processes such as filtering, calculation of vertical derivatives, upward and downward continuation, etc., are commonly used as interpretational aids in magnetics. These