3
MAGNETIC METHOD

Compasses and dip needles were used in the Middle Ages to find magnetite ores in Sweden, making the magnetic method the oldest of all applied geophysical techniques. It is still one of the most widely used, even though significant magnetic effects are produced by only a very small number of minerals.

Magnetic field strengths are now usually measured in *nanoTesla* (nT). The pre-SI unit, the gamma, originally defined as 10^{-5} gauss but numerically equal to the nT, is still often used.

3.1 Magnetic Properties

Although governed by the same fundamental equations, magnetic and gravity surveys are very different. The magnetic properties of adjacent rock masses may differ by several orders of magnitude rather than a few percent.

3.1.1 Poles, dipoles and magnetization

An isolated magnetic pole would, if it existed, produce a field obeying the inverse-square law. In reality, the fundamental magnetic source is the dipole (Section 1.1.5) but, since a line of dipoles end-to-end produces the same effect as positive and negative poles isolated at opposite ends of the line (Figure 3.1), the pole concept is often useful.

A dipole placed in a magnetic field tends to rotate, and so is said to have a *magnetic moment.* The moment of the simple magnet of Figure 3.1, which is effectively a positive pole, strength m, at a distance $2L$ from a negative pole $-m$, is equal to $2Lm$. The magnetization of a solid body is defined by

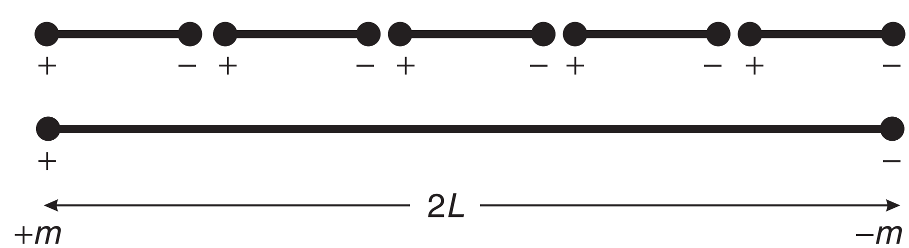

Figure 3.1 *Combination of magnetic dipoles to form an extended magnet. The positive and negative poles at the ends of adjacent dipoles cancel each other out. The pole strength of the magnet is the same as that of the constituent dipoles, but its magnetic moment is equal to its length multiplied by that pole strength.*

its magnetic moment per unit volume and is a vector, having direction as well as magnitude.

3.1.2 Susceptibility

A body placed in a magnetic field acquires a magnetization which, if small, is proportional to the field:

$$M = kH$$

The *susceptibility*, k, is very small for most natural materials, and may be either negative (diamagnetism) or positive (paramagnetism). The fields produced by dia- and paramagnetic materials are usually considered to be too small to affect survey magnetometers, but modern high-sensitivity magnetometers are creating exceptions to this rule. Most observed magnetic anomalies are due to the small number of *ferro-* or *ferri-magnetic* substances in which the molecular magnets are held parallel by intermolecular *exchange forces*. Below the *Curie temperature*, these forces are strong enough to overcome the effects of thermal agitation. Magnetite, pyrrhotite and maghemite, all of which have Curie temperatures of about 600 °C, are the only important naturally occurring magnetic minerals and, of the three, magnetite is by far the most common. Hematite, the most abundant iron mineral, has a very small susceptibility and many iron ore deposits do not produce significant magnetic anomalies.

The magnetic properties of highly magnetic rocks tend to be extremely variable and their magnetization is not strictly proportional to the applied field. Quoted susceptibilities are for Earth-average field strengths.

3.1.3 Remanence

Ferro- and ferri-magnetic materials may have permanent as well as induced magnetic moments, so that their magnetization is not necessarily in the direction of the Earth's field. The *Konigsberger ratio* of the permanent moment to the moment that would be induced in an Earth-standard field of 50 000 nT, is generally large in highly magnetic rocks and small in weakly magnetic ones, but is occasionally extraordinarily high (>10 000) in hematite. Magnetic anomalies due entirely to remanence are sometimes produced by hematitic ores.

3.1.4 Susceptibilities of rocks and minerals

The *susceptibility* of a rock usually depends on its magnetite content. Sediments and acid igneous rocks have small susceptibilities whereas basalts, dolerites, gabbros and serpentinites are usually strongly magnetic. Weathering generally reduces susceptibility because magnetite is oxidized to hematite, but some laterites are magnetic because of the presence of maghemite and

Table 3.1 Magnetic susceptibilities of common rocks and ores

Common rocks	
Slate	0–0.002
Dolerite	0.01–0.15
Greenstone	0.0005–0.001
Basalt	0.001–0.1
Granulite	0.0001–0.05
Rhyolite	0.00025–0.01
Salt	0.0–0.001
Gabbro	0.001–0.1
Limestone	0.00001–0.0001
Ores	
Hematite	0.001–0.0001
Magnetite	0.1–20.0
Chromite	0.0075–1.5
Pyrrhotite	0.001–1.0
Pyrite	0.0001–0.005

remanently magnetized hematite. The susceptibilities, in rationalized SI units, of some common rocks and minerals are given in Table 3.1.

3.2 The Magnetic Field of the Earth

The magnetic fields of geological bodies are superimposed on the background of the Earth's main field. Variations in magnitude and direction of this field influence both the magnitudes and shapes of local anomalies.

In geophysics, the terms *north* and *south* used to describe polarity are replaced by positive and negative. The direction of a magnetic field is conventionally defined as the direction in which a unit positive pole would move but, since all things are relative, geophysicists give little thought to whether it is the north or south magnetic pole that is positive.

3.2.1 The main field of the Earth

The Earth's main magnetic field originates in electric currents circulating in the liquid outer core, but can be largely modelled by a dipole source at the Earth's centre. Distortions in the dipole field extending over regions thousands of kilometres across can be thought of as caused by a relatively small number of subsidiary dipoles at the core–mantle boundary.

The variations with latitude of the magnitude and direction of an ideal dipole field aligned along the Earth's spin axis are shown in Figure 3.2. Note that near the equator the dip angles change almost twice as fast as

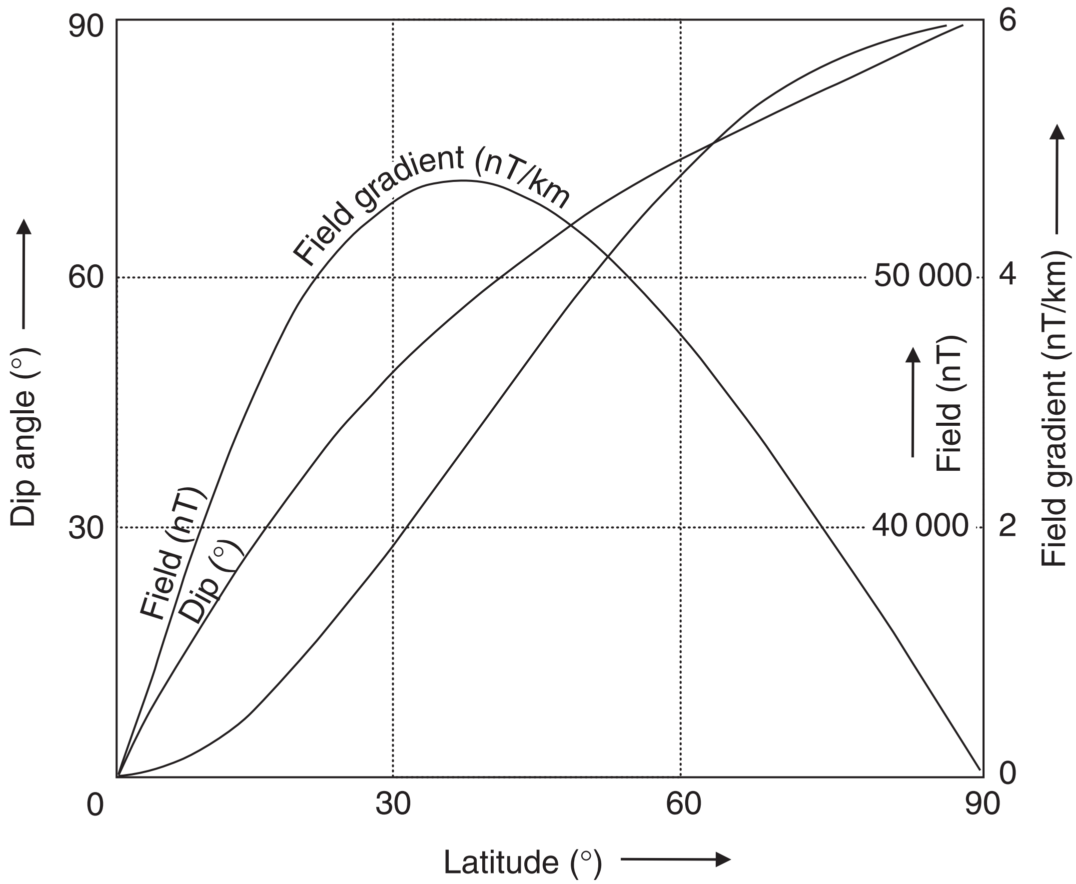

Figure 3.2 *Variation in intensity, dip and gradient for an ideal dipole aligned along the Earth's spin axis and producing a polar field of 60 000 nT.*

the latitude angles. To explain the Earth's actual field, the main dipole would have to be inclined at about 11° to the spin axis, and thus neither the magnetic equator, which links points of zero magnetic dip on the Earth's surface, nor the magnetic poles coincide with their geographic equivalents (Figure 3.3). The North Magnetic Pole is in northern Canada and the South Magnetic Pole is not even on the Antarctic continent, but in the Southern Ocean at about 65°S, 138°E. Differences between the directions of true and magnetic North are known as declinations, presumably because a compass needle *ought* to point north but *declines* to do so.

Dip angles estimated from the global map (Figure 3.3) can be used to obtain rough estimates of magnetic latitudes and hence (using Figure 3.2) of regional gradients. This approach is useful in determining whether a regional gradient is likely to be significant but gives only approximate correction factors, because of the existence of very considerable local variations. Gradients are roughly parallel to the local *magnetic* north arrow, so that corrections have E–W as well as N–S components. In ground surveys where anomalies of many tens of nT are being mapped, regional corrections, which generally amount to only a few nT per km, are often neglected.

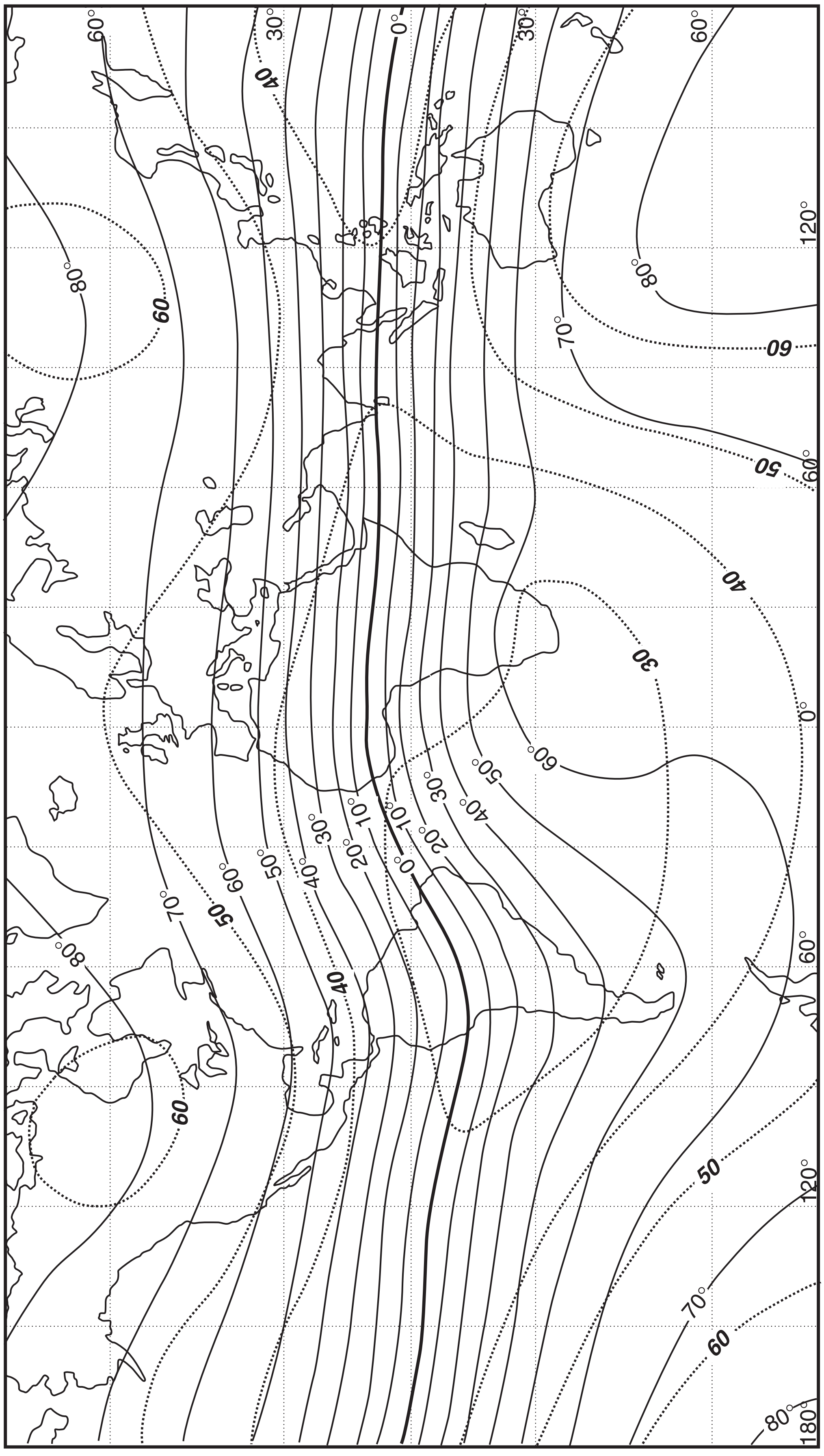

Figure 3.3 *Dip (continuous lines, values in degrees) and intensity (dotted lines, values in thousands of nT) of the Earth's magnetic field. The thick continuous line is the magnetic equator.*

3.2.2 The International Geomagnetic Reference Field (IGRF)

The variations of the Earth's main field with latitude, longitude and time are described by experimentally determined International Geomagnetic Reference Field (IGRF) equations, defined by 120 spherical harmonic coefficients, to order $N = 10$, supplemented by a predictive secular variation model to order $N = 8$. The shortest wavelength present is about 4000 km. IGRFs provide reasonable representations of the actual regional fields in well-surveyed areas, where they can be used to calculate regional corrections, but discrepancies of as much as 250 nT can occur in areas from which little information was available at the time of formulation.

Because the long-term *secular* changes are not predictable except by extrapolation from past observations, the IGRF is updated every five years on the basis of observations at fixed observatories and is also revised retrospectively to give a definitive model (DGRF). GRF corrections are vital when airborne or marine surveys carried out months or years apart are being compared or combined but are less important in ground surveys, where base stations can be reoccupied.

3.2.3 Diurnal variations

The Earth's magnetic field also varies because of changes in the strength and direction of currents circulating in the ionosphere. In the normal *solar-quiet* (Sq) pattern, the background field is almost constant during the night but decreases between dawn and about 11 a.m., increases again until about

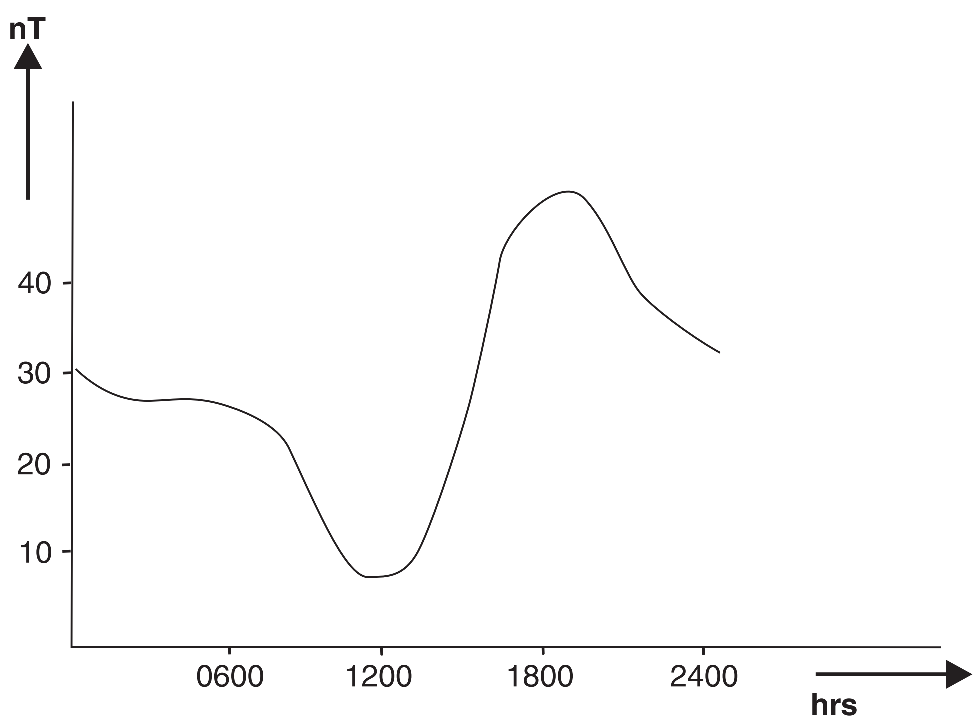

Figure 3.4 *Typical 'quiet day' magnetic field variation at mid-latitudes.*

4 p.m. and then slowly declines to the overnight value (Figure 3.4). Peak-to-trough amplitudes in mid-latitudes are of the order of a few tens of nanoTesla. Since upper atmosphere ionization is caused by solar radiation, diurnal curves tend to be directly related to local solar time but amplitude differences of more than 20% due to differences in crustal conductivity may be more important than time dependency for points up to a few hundred kilometers apart. Short period, horizontally polarized and roughly sinusoidal *micropulsations* are significant only in surveys that are to be contoured at less than 5 nT.

Within about 5° of the magnetic equator the diurnal variation is strongly influenced by the *equatorial electrojet*, a band of high conductivity in the ionosphere about 600 km (5° of latitude) wide. The amplitudes of the diurnal curves in the affected regions may be well in excess of 100 nT and may differ by 10 to 20 nT at points only a few tens of kilometres apart.

Many of the magnetic phenomena observed in polar regions can be explained by an *auroral electrojet* subject to severe short-period fluctuations. In both equatorial and polar regions it is particularly important that background variations be monitored continuously. Returning to a base station at intervals of one or two hours may be quite insufficient.

3.2.4 Magnetic storms

Short-term auroral effects are special cases of the irregular disturbances (Ds and Dst) known as *magnetic storms*. These are produced by sunspot and solar flare activity and, despite the name, are not meteorological, often occurring on clear, cloudless days. There is usually a sudden onset, during which the field may change by hundreds of nT, followed by a slower, erratic return to normality. Time scales vary widely but the effects can persist for hours and sometimes days. Micropulsations are generally at their strongest in the days immediately following a storm, when components with periods of a few tens of seconds can have amplitudes of as much as 5 nT.

Ionospheric prediction services in many countries give advance warning of the general probability of storms but not of their detailed patterns, and the field changes in both time and space are too rapid for corrections to be applied. Survey work must stop until a storm is over. Aeromagnetic data are severely affected by quite small irregularities and for contract purposes *technical magnetic storms* may be defined, sometimes as departures from linearity in the diurnal curve of as little as 2 nT in an hour. Similar criteria may have to be applied in archaeological surveys when only a single sensor is being used (rather than a two-sensor gradiometer).

3.2.5 Geological effects

The Curie points for all geologically important magnetic materials are in the range 500–600 °C. Such temperatures are reached in the lower part of normal continental crust but below the Moho under the oceans. The upper mantle is only weakly magnetic, so that the effective base of local magnetic sources is the Curie isotherm beneath continents and the Moho beneath the oceans.

Massive magnetite deposits can produce magnetic fields of as much as 200 000 nT, which is several times the magnitude of the Earth's normal field. Because of the dipolar nature of magnetic sources these, and all other, magnetic anomalies have positive and negative parts and in extreme cases directional magnetometers may even record negative fields. Anomalies of this size are unusual, but basalt dykes and flows and some larger basic intrusions can produce fields of thousands and occasionally tens of thousands of nT. Anomalous fields of more than 1000 nT are otherwise rare, even in areas of outcropping crystalline basement. Sedimentary rocks generally produce changes of less than 10 nT, as do the changes in soil magnetization important in archaeology.

In some tropical areas, magnetic fields of tens of nT are produced by maghemite formed as nodular growths in laterites. The nodules may later weather out to form ironstone gravels which give rise to high noise levels in ground surveys. The factors that control the formation of maghemite rather than the commoner, non-magnetic form of hematite are not yet fully understood.

3.3 Magnetic Instruments

Early *torsion magnetometers* used compass needles mounted on horizontal axes (dip needles) to measure vertical fields. These were in use until about 1960, when they began to be replaced by fluxgate, proton precession and alkali vapour magnetometers. Instruments of all these three types are now marketed with built-in data loggers and can often be set to record automatically at fixed time intervals at base stations. All three can be used singly or in tandem as *gradiometers*, although care must then be taken with precession instruments to ensure that the polarizing field from one sensor does not affect the measurement at the other. Gradient measurements emphasize near surface sources (Figure 3.5) and are particularly useful in archaeological and environmental work.

3.3.1 Proton precession magnetometer

The proton precession magnetometer makes use of the small magnetic moment of the hydrogen nucleus (proton). The sensing element consists of a bottle containing a low freezing-point hydrocarbon fluid about which is wound a coil of copper wire. Although many fluids *can* be used, the manufacturer's recommendation, usually for high-purity decane, should always be followed if the bottle has to be topped up. A *polarizing* current of the order of an amp or more is passed through the coil, creating a strong magnetic

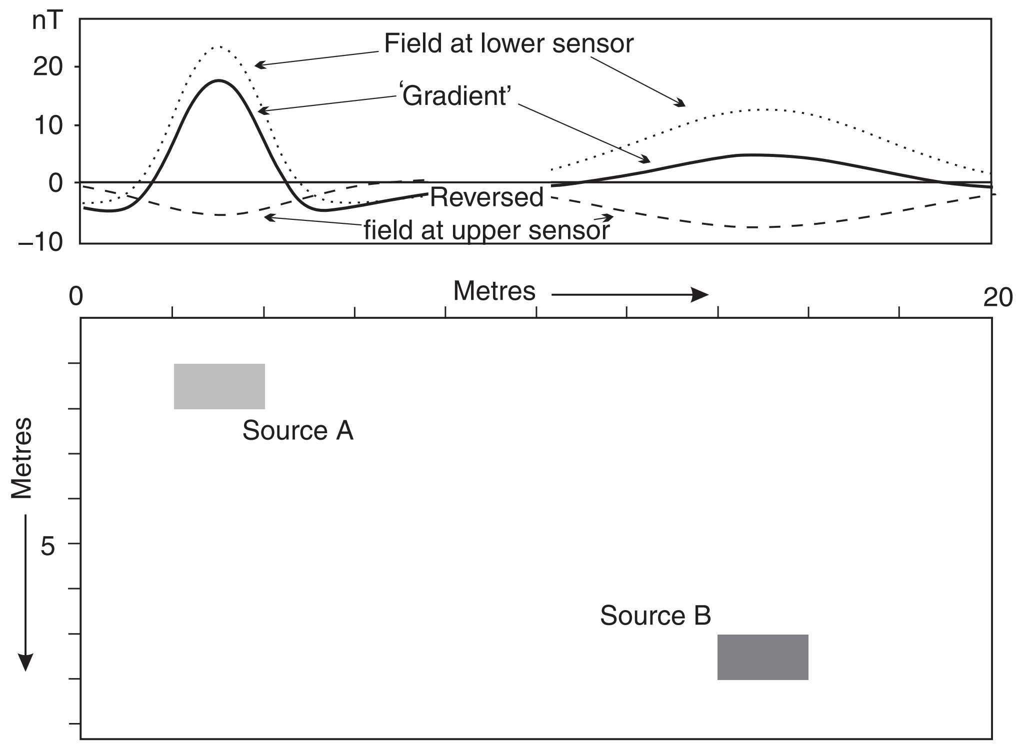

Figure 3.5 *Inverse-cube law effects in magnetic gradiometry. The dotted curves show the magnetic effects of the two bodies measured at the ground surface, the dashed curves show the effects (reversed) as measured one metre above the surface. The solid curves show the differential effect. In the case of Source A, the difference (gradient) anomaly has almost the same amplitude as the anomaly measured at ground level. In the case of the deep Source B, the total field anomaly amplitudes at the two sensors are similar and the gradient anomaly is correspondingly small.*

field, along which the moments of the protons in the hydrogen atoms will tend to become aligned.

When the current is switched off, the protons realign to the direction of the Earth's field. Quantum theory describes this reorientation as occuring as an abrupt 'flip', with the emission of a quantum of electromagnetic energy. In classical mechanics, the protons are described as *precessing* about the field direction, as a gyroscope precesses about the Earth's gravity field, at a frequency proportional to the field strength, emitting an electromagnetic wave as they do so. Both theories relate the electromagnetic frequency to the external field via two of the most accurately known of all physical quantities, Planck's constant and the proton magnetic moment. In the Earth's field of about 50 000 nT, the precession frequency is about 2000 Hz. Sophisticated phase-sensitive circuitry is needed to measure such frequencies to the accuracies of one part in 50 000 (i.e. 1 nT) in the half or one second which is all that modern geophysicists will tolerate. Ultra-portable instruments are available which read to only 10 nT, but these are only marginally easier to use and have not become popular.

In theory the proton magnetometer is capable of almost any desired accuracy, but in practice the need for short reading times and reasonable polarization currents sets the limit at about 0.1 nT.

Proton magnetometers may give erratic readings in strong field gradients and also because of interference from power lines and radio transmitters and even from eddy currents induced in nearby conductors by the termination of the polarizing current. Also, they can only measure total fields, which may cause problems in interpreting large anomalies where the direction of the field changes rapidly from place to place. However, these are only minor drawbacks and the 1 nT or 0.1 nT proton magnetometer is now the most widely used instrument in ground surveys. The self-orientating property allows the sensor to be supported on a staff well away from both the observer and from small magnetic sources at ground level (Figure 1.6). It is also an advantage that readings are obtained as drift-free absolute values in nT, even though corrections must still be made for diurnal variations.

3.3.2 High sensitivity (alkali vapour) magnetometers

Proton magnetometers can be made more sensitive using the Overhauser effect, in which a VHF radio wave acts on paramagnetic material added to the bottle fluid. This increases the precession signal by several orders of magnitude, considerably improving the signal/noise ratio. However, high sensitivity is now more commonly achieved using electrons, which have magnetic moments about 2000 times greater than those of protons. Effectively isolated electrons are provided by vapours of alkali metals (usually caesium), since the outer electron ‘shell’ of an atom of one of these elements contains only a single electron. The principle is similar to that of the proton magnetometer, in that transitions between energy states are observed, but the much higher energy differences imply much higher frequencies, which can be measured with much smaller percentage errors. The actual measurement process is quite complicated, involving the raising of electrons to a high energy state by a laser beam (‘optical pumping’) and then determining the frequency of the high frequency radio signal that will trigger the transition to a lower state. This is all, however, invisible to the user. Measurements are in principle discontinuous but measuring times are very small and 10 readings can routinely be taken every second. The effects of electrical interference and high field gradients are less serious than with proton precession instruments.

Alkali vapour magnetometers are slightly direction sensitive. Readings cannot be obtained if the sensor is oriented within a few degrees of either the direction of the magnetic field or the direction at right angles to it. This is not a significant limitation in most circumstances, and the rather slow acceptance of these instruments for ground surveys has had more to do with their relatively high cost and the fact that in most geological applications the high sensitivity is of little use. Sensitivity is, however, essential in gradiometry (Figure 3.5), and field changes of less than 1 nT may be significant in archaeology, where rapid coverage (sometimes achieved using a non-magnetic trolley with a trigger actuated by the rotations of the wheels) demands virtually continuous readings.

3.3.3 The fluxgate magnetometer

The sensing element of a fluxgate magnetometer consists of one or more cores of magnetic alloy, around which are wound coils through which alternating current can be passed. Variations in the electrical properties of the circuits with magnetization of the cores can be converted into voltages proportional to the external magnetic field along the core axes. Measurements are thus of the magnetic field component in whichever direction the sensor is pointed. Vertical fields are measured in most ground surveys.

Fluxgates do not measure absolute fields and therefore require calibration. They are also subject to thermal drift, because the magnetic properties of the cores and, to a lesser extent, the electrical properties of the circuits vary with temperature. Early ground instruments sacrificed thermal insulation for portability and were often accurate to only 10 or 20 nT. In recognition of this, readings were displayed, rather crudely, by the position of a needle on a graduated dial. Despite claims to the contrary by some manufacturers, such sensitivity is quite inadequate for most ground survey work.

One problem with portable fluxgates is that because they require orientation at each station, the operator must be close to the sensor when the reading is taken. Ensuring the operator is completely non-magnetic is not easy, and most dry batteries now obtainable are steel-jacketed and very magnetic. They can make nonsense of readings if installed in the same housing as the sensor. External battery packs can be used but are clumsy and reduce rather than eliminate the effects. Lead–acid gel rechargeable batteries are not inherently magnetic but need to be checked for the presence of magnetic materials.

Fluxgates are now mainly used, either with internal memory or linked to data loggers, in archaeological surveys where the negligible reading times allow very large numbers of readings to be taken quickly within small areas. A survey of this type may require measurements to be made close to ground level and may not be possible with proton magnetometers because of their sensitivity to field gradients and electrical interference. Subtracting the readings from two similar and rigidly linked fluxgate sensors to obtain gradient information minimizes thermal drift effects, reduces the effect of errors in orientation, emphasizes local sources (Figure 3.5) and virtually eliminates the effects of diurnal variations, including micropulsations.

Three-component fluxgate magnetometers can eliminate the need for precise orientation or, alternatively, can provide information on field direction as well as field strength.

3.4 Magnetic Surveys

Although absolute numerical readings are obtained (and can be repeated) at the touch of a button with proton and caesium magnetometers, faulty magnetic maps can still be produced if simple precautions are ignored. For example, all base locations, whether used for repeat readings or for continuous diurnal monitoring, should be checked for field gradients. A point should not be used as a base if moving the sensor a metre produces a significant change.

3.4.1 Starting a survey

The first stage in any magnetic survey is to check the magnetometers (and the operators). Operators can be potent sources of magnetic noise, although the problems are much less acute when sensors are on 3 m poles than when, as with fluxgates, they must be held close to the body. Errors can also occur when the sensor is carried on a short pole or in a back-pack. Compasses, pocket knives and geological hammers are all detectable at distances below about a metre, and the use of high sensitivity magnetometers may require visits to the tailor (and cobbler) for non-magnetic clothing. Survey vehicles can affect results at distances of up to 20 m. The safe distance should be determined before starting survey work.

All absolute magnetometers should give the same reading at the same time in the same place. Differences were often greater than 10 nT between instruments manufactured prior to 1980 but are now seldom more than 1 or 2 nT. Sensors can be placed very close together and may even touch when checks are being made, but proton magnetometer readings cannot be precisely simultaneous because the two polarizing fields would interfere.

Large discrepancies and very variable readings with a proton magnetometer usually indicate that it is poorly tuned. The correct tuning range can be roughly identified using global maps (Figure 3.3) but final checks should be made in the field. Near-identical readings should be obtained if the setting is varied over a range of about 10 000 nT about its optimum position (e.g. 47 000 in Example 3.1). Manual versions are generally rather coarsely tunable in steps of a few thousand nT, but greater accuracy is possible with microprocessor control. It is partly this finer tuning that allows some proton magnetometers to be routinely read to 0.1 nT. Often, these instruments are programmed to warn of faulty tuning or high gradients by refusing to display the digit beyond the decimal point.

Example 3.1 also shows that repeatability alone is no guarantee of correct tuning. It is the range of settings over which the circuits can lock to the precession signal that provides the crucial evidence.

Example 3.1: Proton magnetometer tuning (manual model)

Tuning setting		*Readings*	
30 000	31 077	31 013	31 118
32 000	32 770	32 788	32 775
34 000	35 055	34 762	34 844
36 000	37 481	37 786	37 305
38 000	42 952	40 973	41 810
41 000	47 151	47 158	47 159
44 000	47 160	47 158	47 159
47 000	47 171	47 169	47 169
50 000	47 168	47 175	47 173
53 000	47 169	47 169	47 169
56 000	53 552	54 602	54 432
60 000	59 036	59 292	58 886
64 000	65 517	65 517	65 517

3.4.2 Monitoring diurnal variation

Diurnal corrections are essential in most field work, unless only gradient data are to be used. If only a single instrument is available, corrections have to rely on repeated visits to a base or sub-base, ideally at intervals of less than one hour. A more complete diurnal curve can be constructed if a second, fixed, magnetometer is used to obtain readings at 3 to 5 minute intervals. This need not be of the same type as the field instrument. A cheaper proton magnetometer can provide adequate diurnal control for surveys with a more expensive caesium vapour instrument.

In principle, it is possible to dispense with frequent base reoccupations when an automatic base station is operating. It is, however, poor practice to rely entirely on the base record, since recovery of field data will then be difficult, if not impossible, if the base instrument fails. Problems are especially likely with unattended automatic instruments because the battery drain is rather high and the transition from operational to unworkable can occur with little warning. Readings already stored are preserved by the action of a separate lithium battery, but diurnal control is lost for the rest of the day.

Obviously, bases should be remote from possible sources of magnetic interference (especially temporary sources such as traffic), and should be describable for future use. Especial vigilance is needed if field and diurnal instruments are later linked by a data-exchange line and corrections are made automatically. Unless the diurnal curve is actually plotted and examined, absurdities in the diurnal data (as might be caused by an inquisitive passer-by driving up to the base) may be overlooked and may appear, in reverse, as anomalies in the field data.

3.4.3 Field procedures – total field surveys

At the start of each survey day the diurnal magnetometer must be set up. The first reading of the field magnetometer should be at a base or sub-base, and should be made at the same time as a reading is being made, either automatically or manually, at the base. This does not necessarily require the two instruments to be adjacent.

All field readings should be taken twice and the two readings should differ by no more than 1 nT. Greater differences may indicate high field gradients, which may need further investigation. Large differences between readings at adjacent stations call for *infill* at intermediate points. It is obviously desirable that the operator notices this, and infills immediately.

At each station the location, time and reading must be recorded, as well as any relevant topographic or geological information and details of any visible or suspected magnetic sources. Unless the grid is already well mapped, the notebook should also contain enough information for the lines to be positioned on maps or air-photos.

At the end of the day, a final reading should be made at the base first occupied. This should again be timed to coincide with a reading of the diurnal magnetometer. If readings in the field are being recorded manually, it is good practice to then transcribe the diurnal data for the times of the field readings into the field notebook, which then contains a complete record of the day's work.

3.4.4 Standard values

Diurnal curves record the way in which field strength has varied at a fixed base, and data processing is simplified if this base is at the same point throughout the survey. A *standard value* (SV) must be allocated to this point, preferably by the end of the first day of survey work. The choice is to some extent arbitrary. If the variation in measured values were to be between 32 340 nT and 32 410 nT, it might be convenient to adopt 32 400 nT as the SV, even though this was neither the mean nor the most common reading.

Unless the survey area is so small that a single reference base can be used, a number of sub-bases will have to be established (Section 1.4) and their SVs determined. The underlying principle is that if, at some given time, the base magnetometer reading is actually equal to the base SV, then identical instruments at all other bases and sub-bases should record the SVs at those points. The field readings are then processed so that this is true of the values assigned to all survey points.

3.4.5 Processing magnetic data

During a survey, bases or sub-bases should be occupied at intervals of not more than two hours, so that data can be processed even if the diurnal record is lost or proves faulty. The way in which such readings might be used to provide diurnal control, with or without an automatically recorded diurnal curve, is shown in Figure 3.6.

The diurnal correction at any time is simply the difference between the SV at the diurnal station and the actual diurnal reading, but magnetic data can be corrected in two different ways using this fact. The most straightforward is to determine, by interpolation when necessary, the diurnal value at the time a given field reading was made and to subtract this from the reading. The

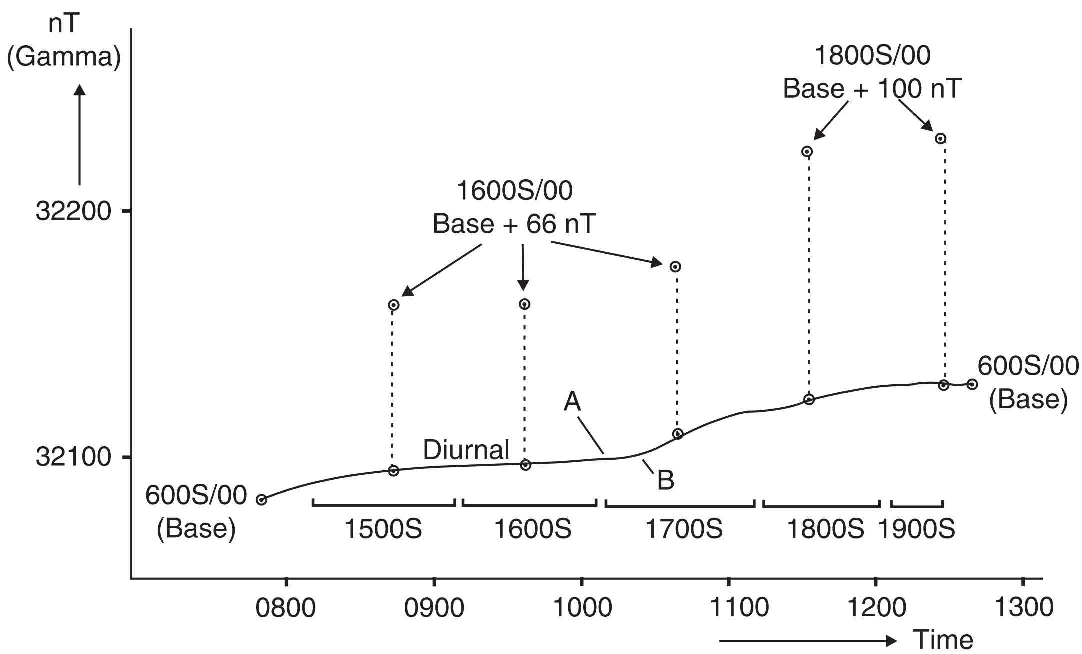

Figure 3.6 *Diurnal control, with variations monitored both by a memory instrument at the diurnal base and by repeat readings at various sub-bases. The greatest error introduced by using straight-line interpolation between diurnal values derived from the sub-bases would have been 5–10 nT and would have affected Line 1700S between points A and B. Interpolation using a smooth curve instead of straight lines would have significantly reduced this error. The shifts needed to make the sets of sub-base values fall on the diurnal curve provide estimates of the differences between the SVs at the diurnal base and at the sub-bases. The time periods during which individual survey lines were being read are also shown.*

diurnal station SV can then be added to give the SV at the field station. If a computer is available, the whole operation can be automated.

This method is simple in principle and provides individual values at all field points but is tedious and error-prone if hundreds of stations have to be processed by hand each evening. If only a contour map is required, this can be based on profiles of uncorrected readings, as shown in Figure 3.7. Fewer calculations are needed and errors and peculiarities in the data are immediately obvious.

Even if no computer is available to do the hard work, plotting magnetic profiles should be a field priority since this provides the best way of assessing the significance, or otherwise, of diurnal effects and noise. For example, the profile in Figure 3.7 shows very clearly that, with 100 nT contours, the 5 nT discrepancy between the diurnal curves based on direct observation and on

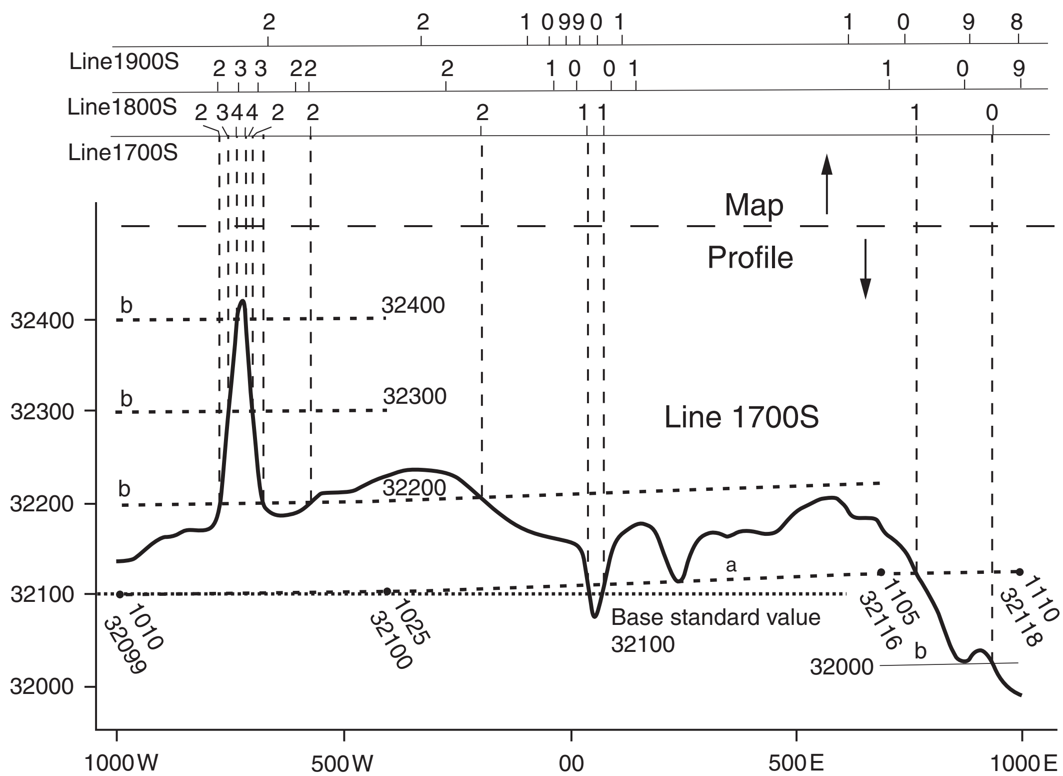

Figure 3.7 *PROFILE: Contour cuts at 100 nT intervals on uncorrected profile 1700S, by diurnal curve and parallel curves. The reference base SV is 32 100 nT and the points at which the diurnal curve (dashed line 'a') intersects the profile therefore correspond to points on the ground where the corrected value of the magnetic field is also 32 100 nT. Parallel curves (dashed lines 'b') identify points at which the SVs differ from those at the diurnal base by integer multiples of 100 nT. MAP: Contour cut plot of 1700S and two adjacent lines. Only these contour cuts need be plotted on the map, and some may be omitted where they are very close together.*

base reoccupations is unimportant. It also shows the extent to which such contours leave significant magnetic features undefined.

If a computer is used to calculate corrected values at each field point, profiles should still be produced but can then be of corrected rather than raw data.

3.4.6 Noise in ground magnetic surveys

Magnetic readings in populated areas are usually affected by stray fields from pieces of iron and steel (*cultural noise*). Even if no such materials are visible, profiles obtained along roads are usually very distorted compared to those obtained on parallel traverses through open fields only 10 or 20 m away. Since the sources are often quite small and may be buried within a metre of the ground surface, the effects are very variable.

One approach to the noise problem is to try to take all readings well away from obvious sources, noting in the field books where this has not been possible. Alternatively, the almost universal presence of ferrous noise can be accepted and the data can be filtered. For this method to be successful, many more readings must be taken than would be needed to define purely geological anomalies. The technique is becoming more popular with the increasing use of data loggers, which discourage note-taking but allow vast numbers of readings to be taken and processed with little extra effort, and is most easily used with alkali vapour and fluxgate instruments which read virtually continuously. The factors discussed in Section 1.3.10 in relation to continuous readings must all be taken into account. It is only safe to dispense with notebooks for comments on individual stations if the survey grid as a whole is well surveyed, well described and accurately located.

3.5 Simple Magnetic Interpretation

Field interpretation of magnetic data allows areas needing infill or checking to be identified and then revisited immediately and at little cost. Good interpretation requires profiles, which preserve all the detail of the original readings, and contour maps, which allow trends and patterns to be identified. Fortunately, the now almost ubiquitous laptop PC has reduced the work involved in contouring (providing the necessary programs have been loaded).

3.5.1 Forms of magnetic anomaly

The shape of a magnetic anomaly varies dramatically with the dip of the Earth's field, as well as with variations in the shape of the source body and its direction of magnetization. Simple sketches can be used to obtain rough visual estimates of the anomaly produced by any magnetized body.

Figure 3.8a shows an irregular mass magnetized by induction in a field dipping at about 60°. Since the field direction defines the direction in which a positive pole would move, the effect of the external field is to produce

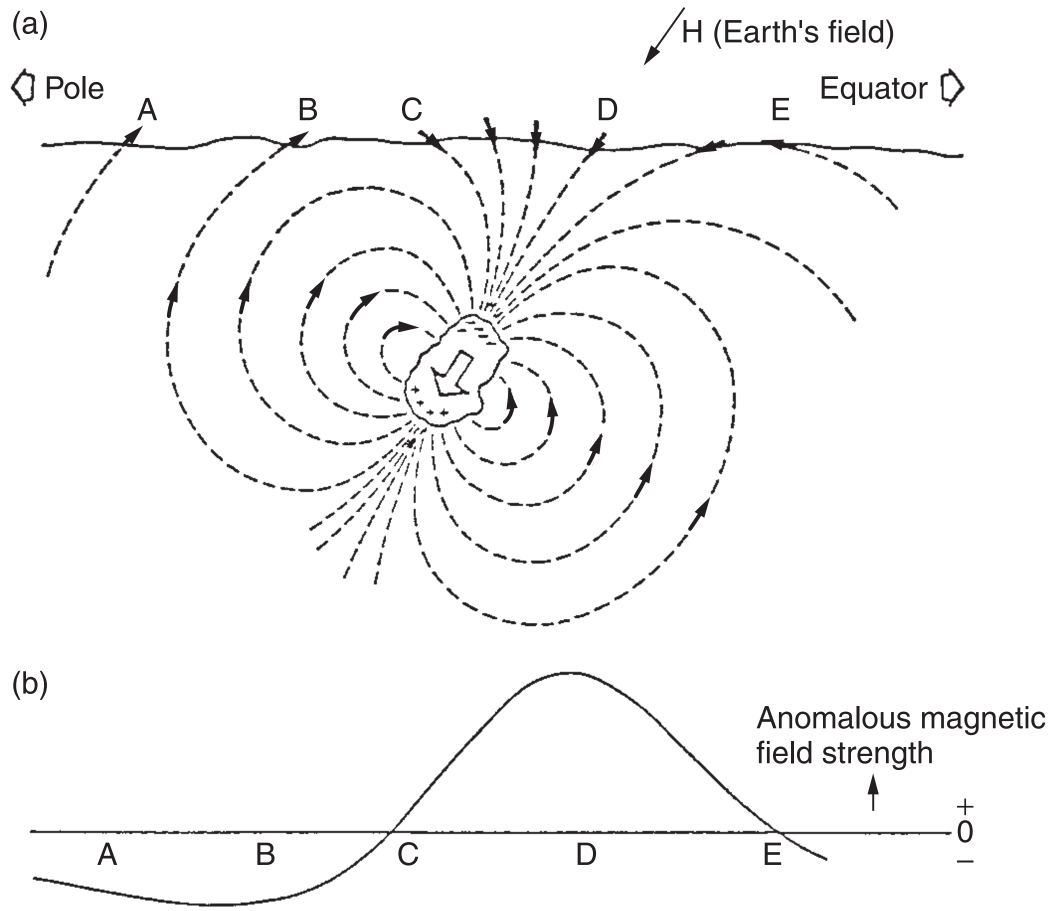

Figure 3.8 *Mid-latitude total field anomaly due to induced magnetization. (a) The induced field. (b) The anomaly profile, derived as described in the text.*

the distribution of poles shown. The secondary field due to these poles is indicated by the dashed lines of force. Field direction is determined by the simple rule that like poles repel.

If the secondary field is small, the directions of the total and background fields will be similar and no anomalous field will be detected near C and E. The anomaly will be positive between these points and negative for considerable distances beyond them. The anomaly maximum will be near D, giving a magnetic profile with its peak offset towards the magnetic equator (Figure 3.8b). At the equator the total-field anomaly would be negative and centred over the body and would have positive side lobes to north and south, as can easily be verified by applying the method of Figure 3.8 to a situation in which the inducing field is horizontal.

Because each positive magnetic pole is somewhere balanced by a negative pole, the net flux involved in any anomaly is zero. Over the central parts of a uniform magnetized sheet the fields from positive and negative poles cancel out, and only the edges are detected by magnetic surveys. Strongly magnetized but flat-lying bodies thus sometimes produce little or no anomaly.

3.5.2 'Rule-of-thumb' depth estimation

Depth estimation is one of the main objectives of magnetic interpretation. Simple rules give depths to the tops of source bodies that are usually correct to within about 30%, which is adequate for preliminary assessment of field results.

In Figure 3.9a the part of the anomaly profile, on the side nearest the magnetic equator, over which the variation is almost linear is emphasized by a thickened line. The depths to the abruptly truncated tops of bodies of many shapes are approximately equal to the horizontal extent of the corresponding straight-line sections. This method is effective but is hard to justify since there is actually no straight segment of the curve and the interpretation relies on an optical illusion.

In the slightly more complicated *Peters' method*, a tangent is drawn to the profile at the point of steepest slope, again on the side nearest the equator, and lines with half this slope are drawn using the geometrical construction of Figure 3.9b. The two points at which the half-slope lines are tangents to the anomaly curve are found by eye or with a parallel ruler, and the horizontal distance between them is measured. This distance is divided by 1.6 to give a rough depth to the top of the source body.

Peters' method relies on model studies that show that the true factor generally lies between about 1.2 and 2.0, with values close to 1.6 being common for thin, steeply dipping bodies of considerable strike extent. Results are usually very similar to those obtained using the straight slope. In both cases the profile must either be measured along a line at right angles to the

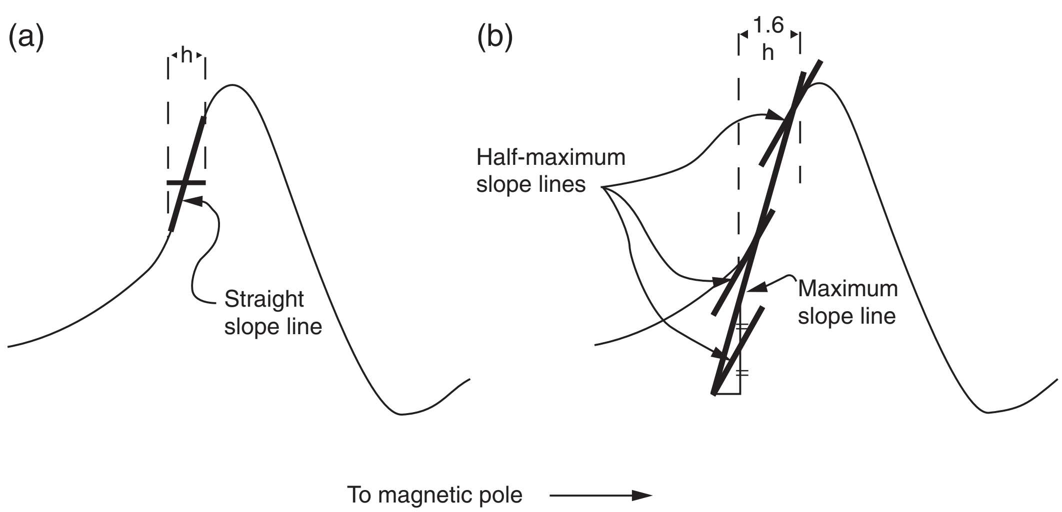

Figure 3.9 *Simple depth estimation: (a) Straight slope method. The distance over which the variation appears linear is (very) roughly equal to the depth to the top of the magnetized body. (b) Peters' method. The distance between the contact points of the half-slope tangents is (very) roughly equal to 1.6 times the depth to the top of the magnetized body.*

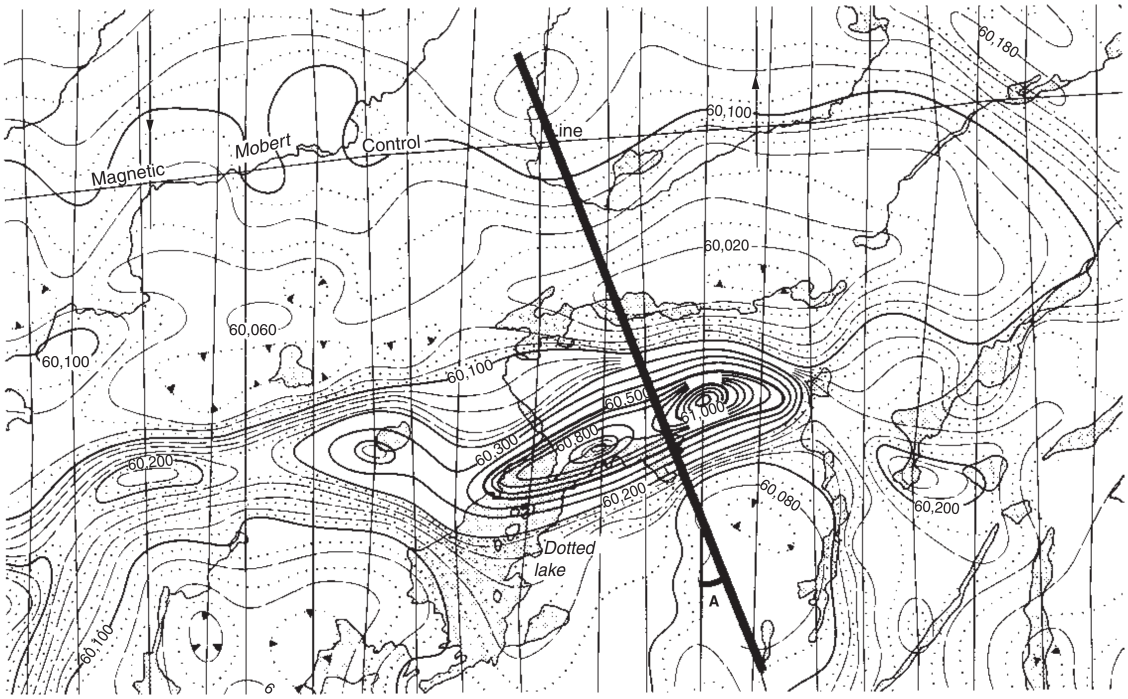

Figure 3.10 *Effect of strike. A depth estimate on a profile recorded along a traverse line (i.e. one of the set of continuous, approximately straight lines) must be multiplied by the cosine of the angle A made with the line drawn at right angles to the magnetic contours. The example is from an aeromagnetic map (from northern Canada) but the same principle applies in ground surveys.*

strike of the anomaly or else the depth estimate must be multiplied by the cosine of the intersection angle (A in Figure 3.10).