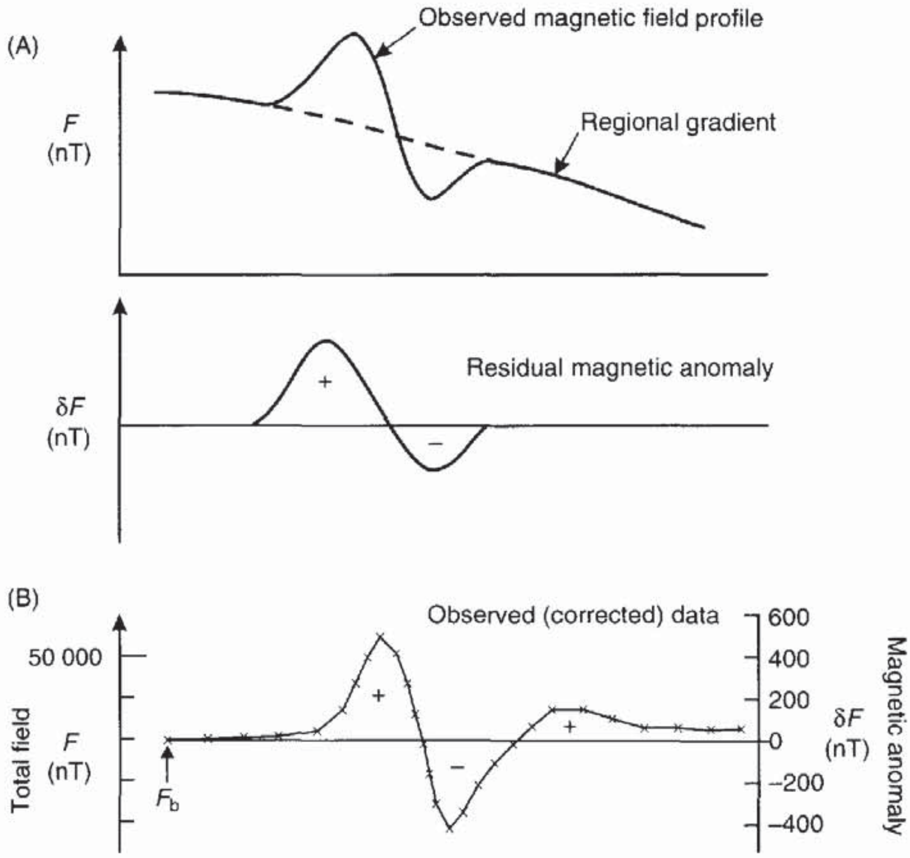


Figure 3.28 Magnetic residuals (A) Subtraction of a regional field gradient, and (B) reference to a local arbitrary base station

3.7 QUALITATIVE INTERPRETATION

Once magnetic data have been fully corrected and reduced to their final form, they are usually displayed either as profiles (Section 3.7.1) or as maps (Section 3.7.2) and the interpretation procedures are different for the two cases. However, it must always be borne in mind that, although the techniques used are similar to those for gravity surveys, there are two important complications. First, the Earth's magnetic field is dipolar, which means that a single anomaly can have the form of a positive peak only, a negative peak only or a doublet consisting of both positive and negative peaks. Secondly, the single largest unknown is whether there is any remanent magnetisation and, if there is, its intensity and direction (J_r) need to be ascertained. It must also be remembered that many geophysical interpretations may fit the observed data and that a given interpretation may not be unique (see Chapter 1, and Figure 1.1 in particular). For this reason, it is always useful to use other geophysical methods in the same area to help constrain the interpretations. If some geological information already exists for the area, then this should be used to help with the geophysical interpretations. However, a word of warning: be careful that some geological information may itself be an interpretation and should not be considered to be the only solution. The geophysics may disprove the geological hypothesis!

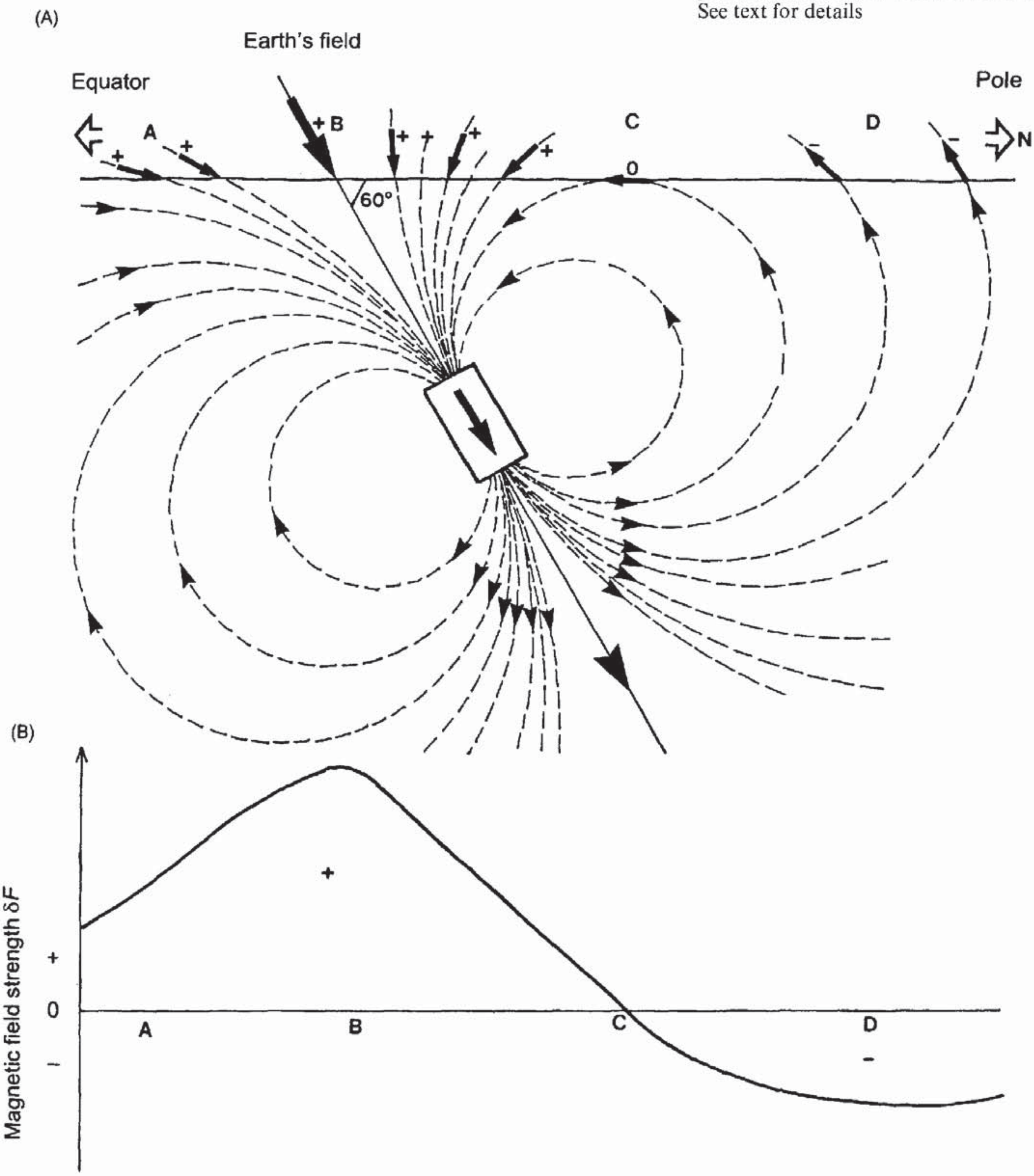


Figure 3.29 The magnetic field generated by a magnetised body inclined at 60° parallel to the Earth's field (A) would produce the magnetic anomaly profile from points A–D shown in (B). See text for details

A magnetisable body will have a magnetisation induced within it by the Earth's magnetic field (Figure 3.29A). As magnetisation is a vector quantity, the anomaly shape will depend on the summation of the vectors of the Earth's field $\boldsymbol{F}$ (with intensity $\boldsymbol{J}$) and the induced field ($\boldsymbol{J}_i$) from the sub-surface body and from any remanent magnetisation ($\boldsymbol{J}_r$). It can be seen from Figure 3.29 (A and B) how any magnetic anomaly is produced. The maximum occurs when the induced field is parallel to the Earth's field; the anomaly goes negative when the induced field vector is orientated upwards as at D. As the magnetic data have been corrected to remove the effect of the Earth's magnetic

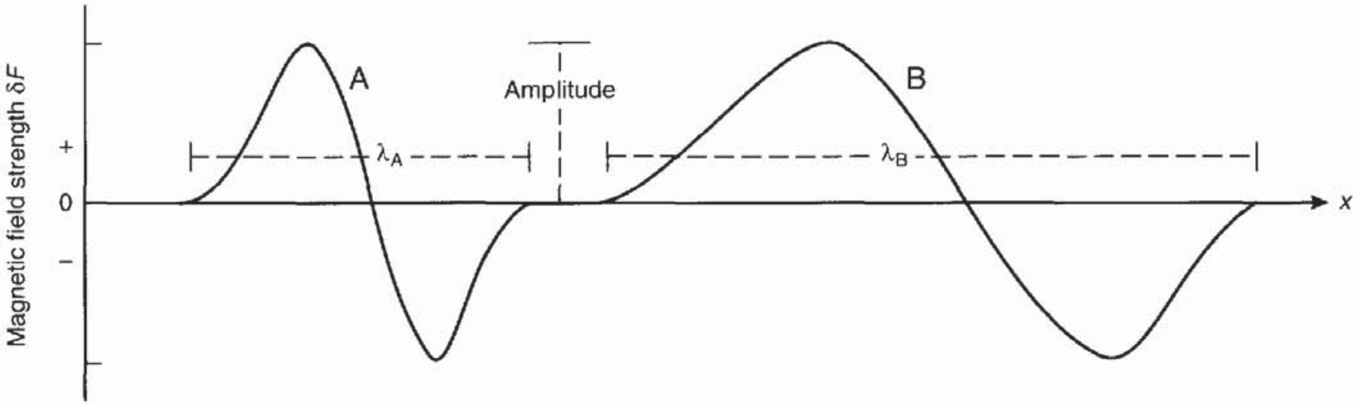


Figure 3.30 Two magnetic anomalies arising from buried magnetised bodies (see text for details)

Table 3.7 Guidelines to qualitative interpretation of magnetic profiles and maps

Applies to:	Magnetic character	Possible cause
Segments of a profile and areas of maps	Magnetically quiet Magnetically noisy	Low κ rocks near surface Moderate–high κ rocks near surface
Anomaly	Wavelength	Short ⇒ near-surface feature Long ⇒ deep-seated feature
	± 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

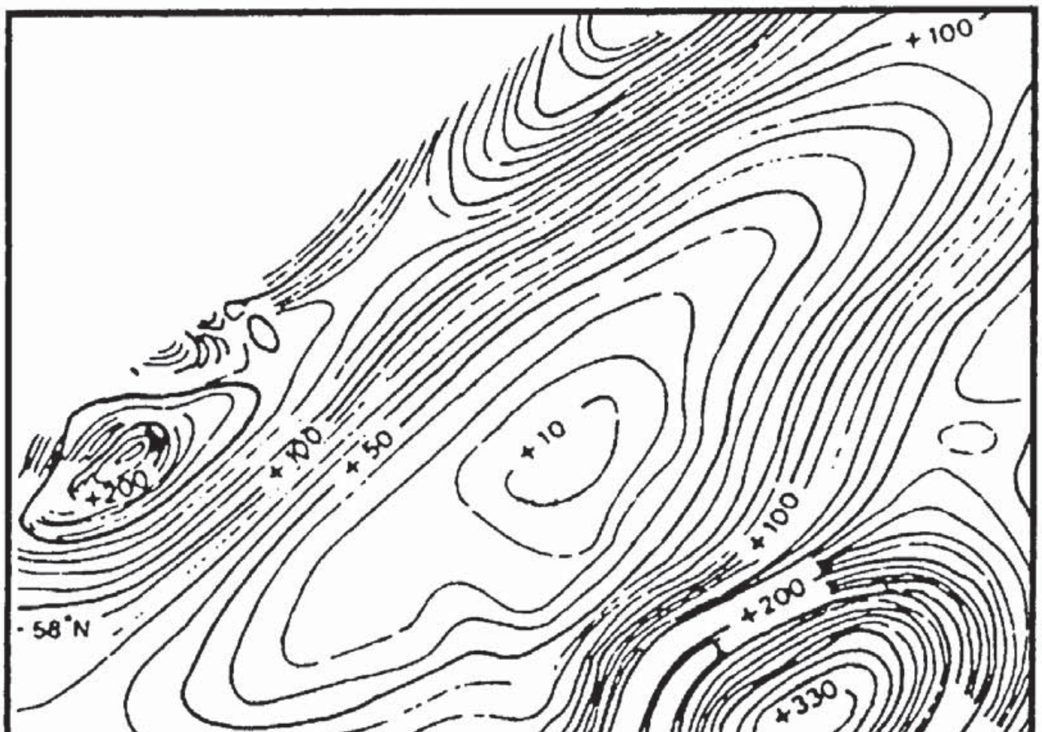
* Can be determined from maps also; [†] Structure = composition of anomaly, i.e. positive peak only, negative peak only or doublet of positive and negative peaks; κ = magnetic susceptibility

field, the anomaly will be due to the vectors associated with the source body. The sign convention is positive downwards, negative upwards. Where there is no remanent magnetisation, a magnetised body in the northern hemisphere will always have a negative anomaly on its northern side and a positive anomaly on its southern side. The opposite is true for the southern hemisphere.

For the two anomalies shown in Figure 3.30, anomaly A has a short wavelength compared with anomaly B, indicating that the magnetic body causing anomaly A is shallower than the body causing B. As the amplitude of anomaly B is identical to that of anomaly A, despite the causative body being deeper, this must suggest that the magnetisation of body B is much greater than for body A, as amplitude decreases with increasing separation of the sensor from the magnetised object.

Some general guidelines for the qualitative interpretation of magnetic profiles and maps are listed in Table 3.7, and an example in Figure 3.31. The list of guidelines should be used like a menu from which various combinations of parameters apply to specific anomalies. For instance, a short-wavelength high-amplitude doublet anomaly with negative to the north, and positive to the south, with an

Figure 3.31 Magnetic anomaly map associated with a fault-bounded sedimentary basin with upthrown horst block to south-east – Inner Moray Firth, Scotland. After McQuillin *et al.* (1984), by permission

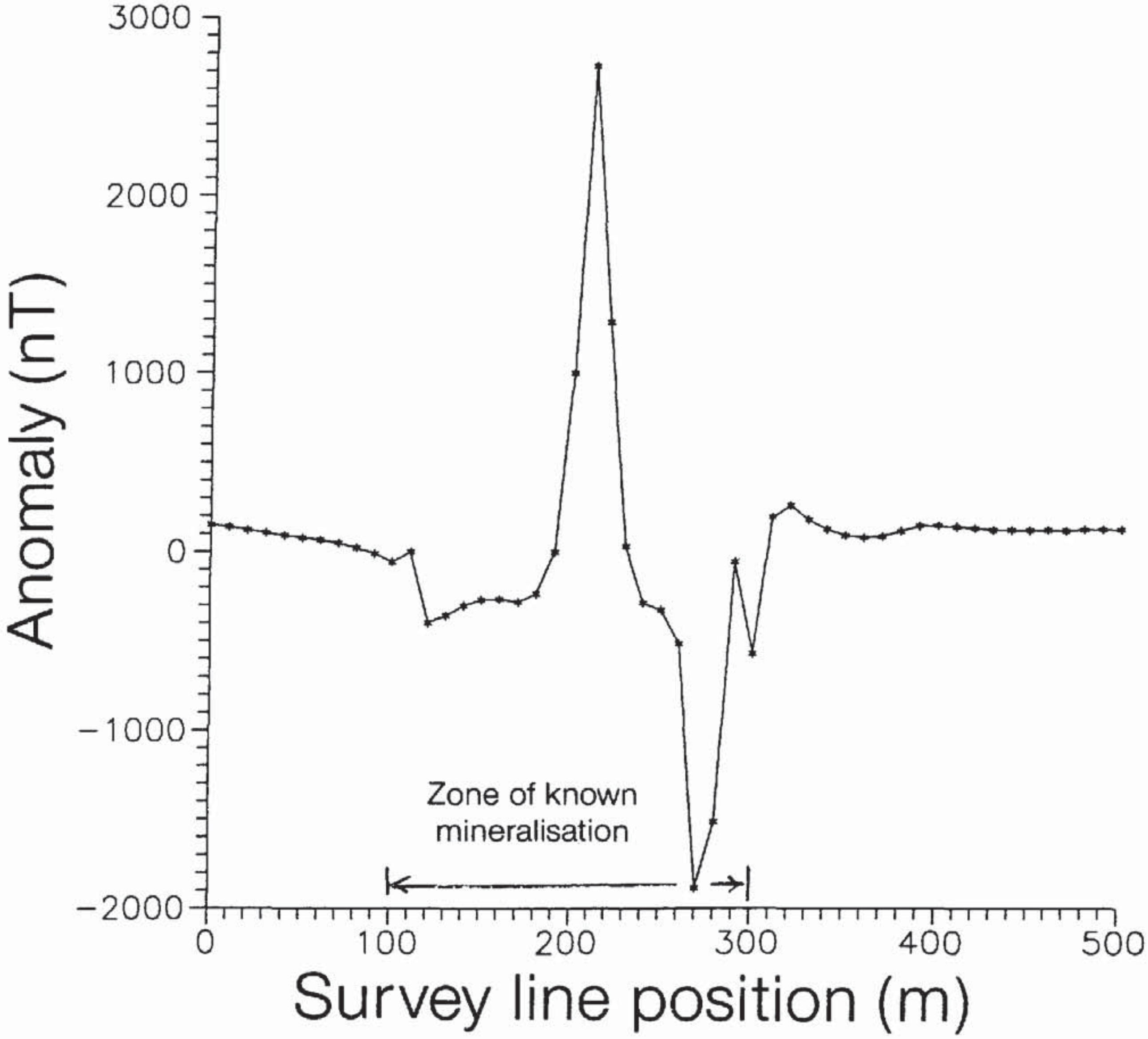


elongation in the east–west direction in the mid-latitudes of the northern hemisphere, suggests a near-surface, moderate-to-high susceptibility magnetic feature with induced magnetisation in a sheet-like body with an east–west strike and northerly dip.

3.7.1 Profiles

The simplest interpretation technique is to identify zones with different magnetic characteristics. Segments of the profile with little variation are termed magnetically 'quiet' and are associated with rocks with low susceptibilities. Segments showing considerable variation are called magnetically 'noisy' and indicate magnetic sources in the sub-surface. The relative amplitudes of any magnetic anomalies (both

Figure 3.32 Magnetic zonation of a proton magnetiometer profile across Sourton Common, north Dartmoor, England

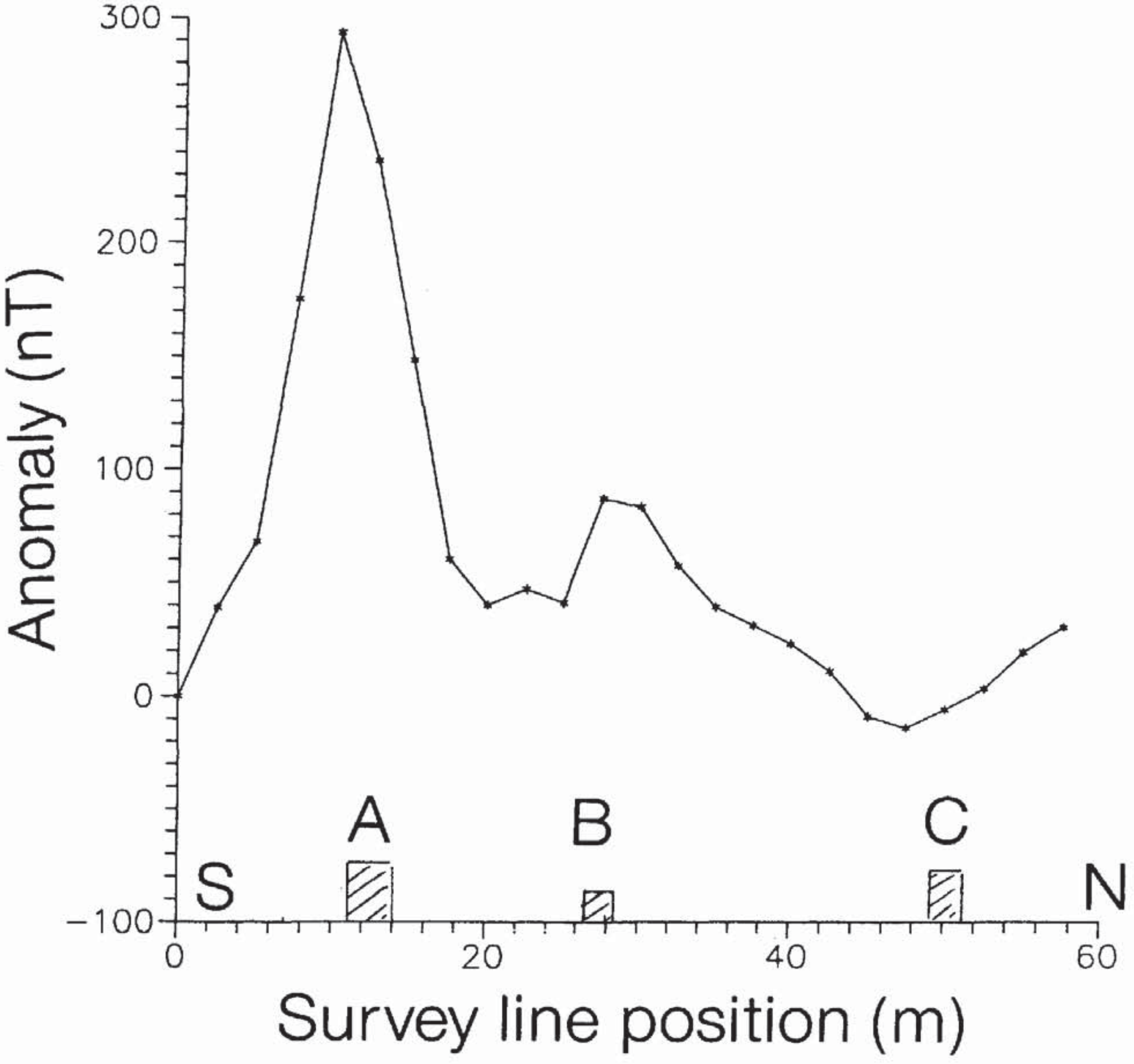


positive and negative) and the local magnetic gradients can all help to provide an indication of the sub-surface.

Figure 3.32 illustrates the differences between noisy and quiet zones in a profile over Sourton Tors, north Dartmoor, England, where the magnetically noisy segments indicate metalliferous mineralisation. The negative occurring as the northern part of the doublet indicates that there is little remanent magnetisation and that the anomaly is due largely to induction ($J_i \gg J_r$).

Figure 3.33 shows a profile measured at Kildonnan, Isle of Arran, Scotland, across a beach section over a series of vertical dolerite dykes. Two of the three dykes (A and B) give rise to large positive anomalies, while a third dyke (C) produces a broader low. All the dykes have virtually identical geochemistry and petrology and hence

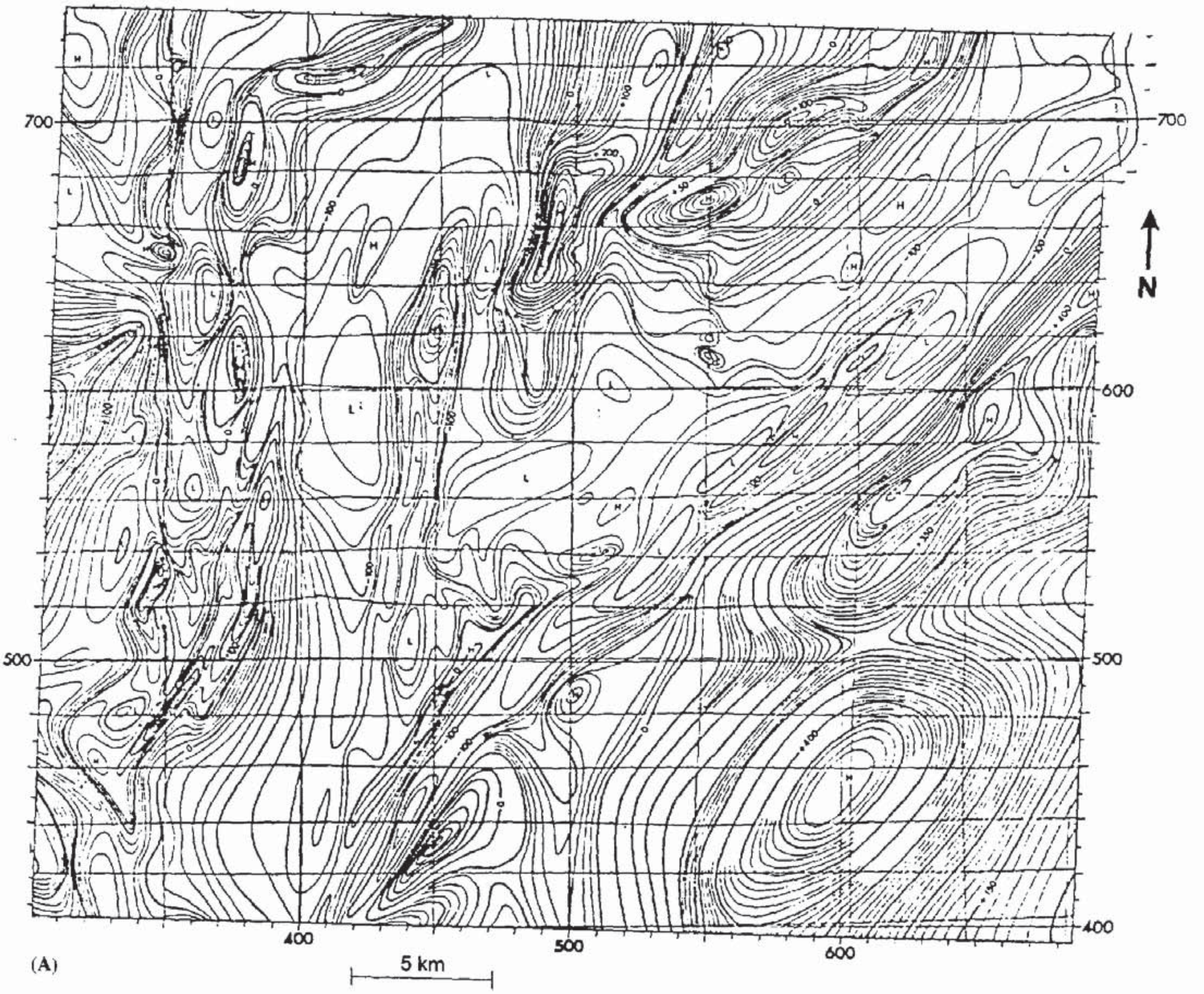
Figure 3.33 Proton magnetometer profile across three vertical dolerite dykes at Kildonnan, Isle of Arran, Scotland, which have been intruded during a period when the Earth's magnetic polarity changed



similar susceptibilities. The difference in magnetic character associated with dyke C compared with dykes A and B is attributed to there having been a magnetic reversal between the intrusion of dyke C relative to the other two. It is well known that in the British Tertiary Igneous Province, which includes the western isles of Scotland, a phase of doleritic intrusion occurred which lasted 10 million years and straddled a magnetic reversal (Dagley *et al.* 1978). Some dykes are normally magnetised and others have a reversed polarity. The different magnetic characters therefore provide a means of identifying which dykes were associated with which phase of the intrusion episode, whereas it is virtually impossible to make such an identification in the field on the basis of rock descriptions.

Having identified zones with magnetic sources, and possibly having gained an indication of direction of dip (if any) of magnetic

Figure 3.34 (A) Aeromagnetic map of the south-east part of the Shetland Islands, Scotland (Flinn 1977); (B) (*opposite*) zonation of (A) in terms of magnetic characteristics

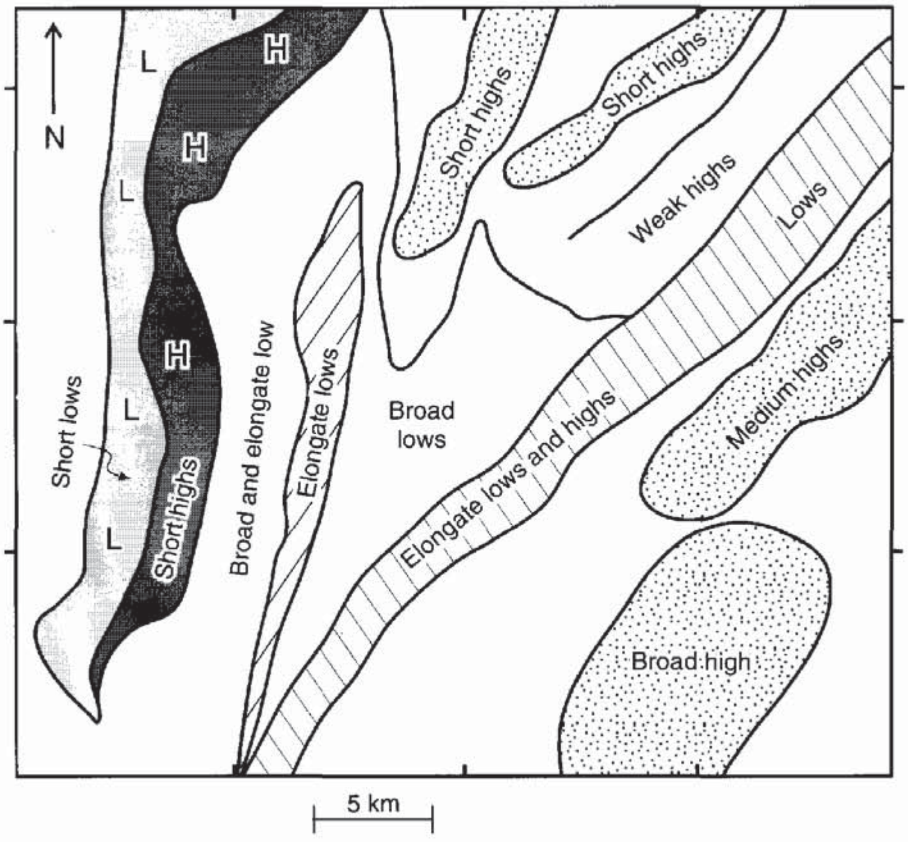


targets and relative intensities, either more detailed fieldwork can be undertaken to obtain more information and/or the existing data can be interpreted using quantitative methods (see Section 3.8).

3.7.2 Pattern analysis on aeromagnetic maps

Magnetic data acquired over a grid with no spatial aliasing are displayed as contoured maps, as three-dimensional isometric projections, or as image-processed displays (see Section 3.8.3). The various displays can be interpreted in terms of the guidelines in Table 3.7. Commonly, even such a basic level of interpretation can yield important information about the sub-surface geology very quickly. One major advantage of airborne surveys is that they can provide information about the geology in areas covered by water.

An aeromagnetic survey was acquired over the south-eastern part of the Shetland Islands, north-east Scotland, and described in detail by Flinn (1977). The original aeromagnetic data were extracted from part of a British Geological Survey map and are shown in Figure 3.34A. The corresponding pattern analysis for the same area is shown in Figure 3.34B and compares very well with Flinn's



(B)

interpretation (Figure 3.35). Magnetic lows in band A are associated with psammites and migmatised psammites which have been heavily injected by pegmatite. The lows in band B correspond to gneissified semipelites and psammites intruded by granites and pegmatites. The short-wavelength but large-amplitude highs just east of band A are attributed to the magnetic pelitic schist and gneiss. In the central part of Figure 3.34A, truncation of NE–SW trending contours can be seen to be associated with the Whalsay Sound Fault. Other faults, such as the Lunning Sound Fault and the Nesting Fault, separate zones of differing magnetic character and lie parallel to the local aeromagnetic contours. A series of three localised positive highs in the south-east corner (h, i and j along the thrust beneath the Quarff Nappe;

Figure 3.35 Geological interpretation of the aeromagnetic map shown in Figure 3.34 of the south-east part of the Shetland Islands, Scotland. From Flinn (1977), by permission

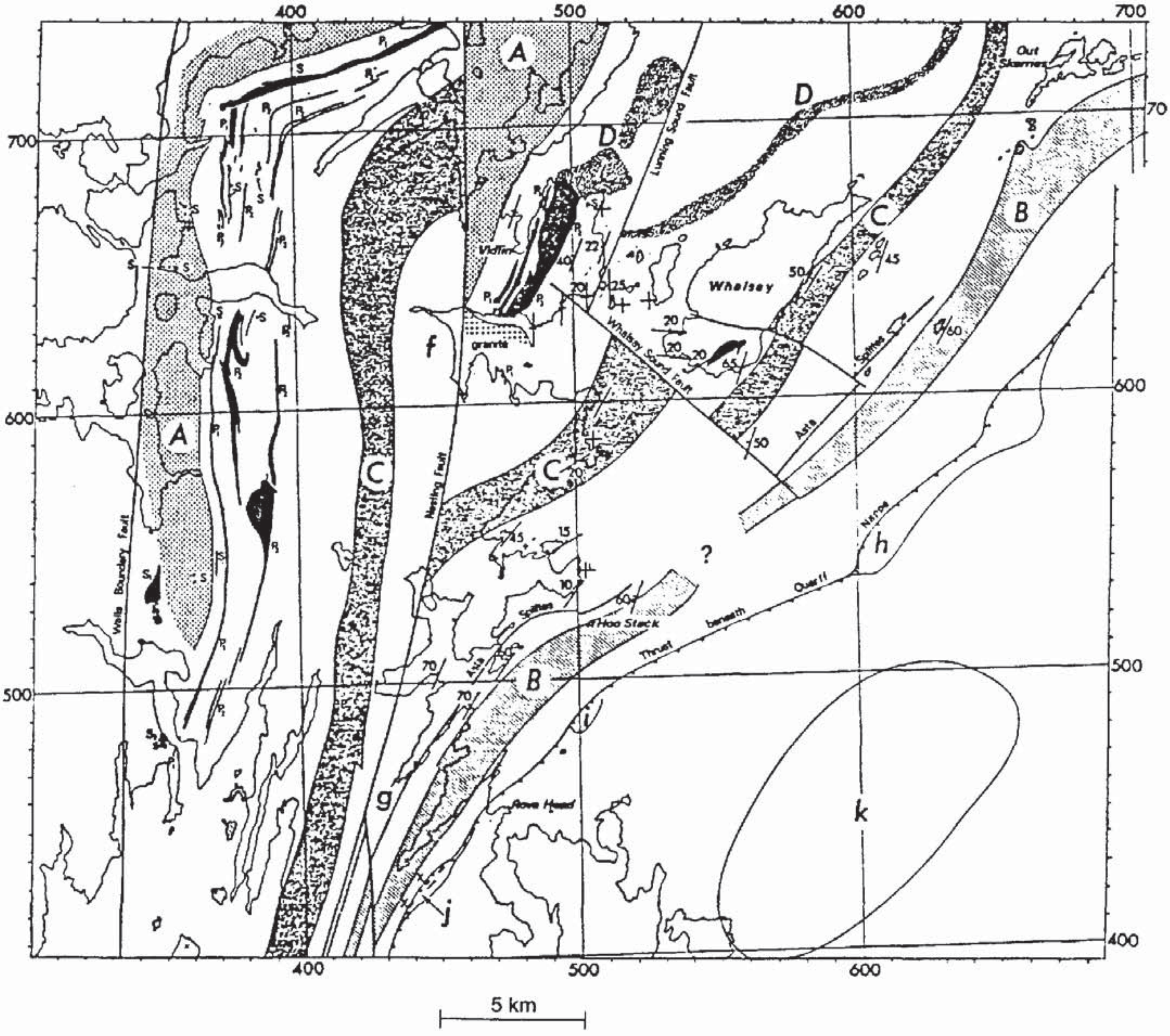


Figure 3.35) is thought to be due to phyllites with 4% hematite which in itself cannot explain the anomaly amplitudes. However, suitably orientated remanent magnetisation could account for these magnetic features. The large-amplitude anomaly (k) in the south-east corner is attributed to a large buried intrusive which is also evident on gravity data. However, this and similar anomalies in the vicinity with similar character all occur over sea and have not been sampled and so the exact nature of the rock remains unknown.

More detailed discussions on the interpretation of aeromagnetic maps have been given, for example, by Vacquier *et al.* (1951), Nettleton (1976) and Hinze (1985).

3.8 QUANTITATIVE INTERPRETATION

The essence of quantitative interpretation is to obtain information about the depth to a particular magnetic body, its shape and size, and details about its magnetisation in two possible ways. One is direct, where the field data are interpreted to yield a physical model. The other is the inverse method, where models are generated from which synthetic magnetic anomalies are generated and fitted statistically against the observed data. The degree of detail is limited by the quality and amount of available data and by the sophistication of either the manual methods or the computer software that can be used.

3.8.1 Anomalies due to different geometric forms

Just as with gravity data, magnetic data can be interpreted in terms of specific geometric forms which approximate to the shapes of subsurface magnetised bodies. This tends to be true where profiles are to be interpreted only in terms of two dimensions. Three-dimensional models are far more complex and can be used to approximate to irregularly shaped bodies (see Section 3.8.3). Detailed mathematical treatments of the interpretation of magnetic data have been given by Grant and West (1965), Telford *et al.* (1990) and Parasnis (1986), among others.

The commonest shapes used are the sphere and the dipping sheet, both of which are assumed to be uniformly magnetised and, in the simplest cases, have no remanence. Total field anomalies (δF) for various types of model are illustrated in Figures 3.36–3.39; except where otherwise stated, the field strength is 50 000 nT, inclination $I = 60°$, declination $D = 0°$, and susceptibility $\kappa = 0.05$ (SI).

In the example of a uniformly magnetised sphere (Figure 3.36), the horizontal and vertical components are shown in addition to the total field anomaly. The anomalies associated with vertical bodies of various thicknesses are shown in Figure 3.37. The anomaly produced by a 50 m thick vertical dyke (Figure 3.37A) is both wider and has

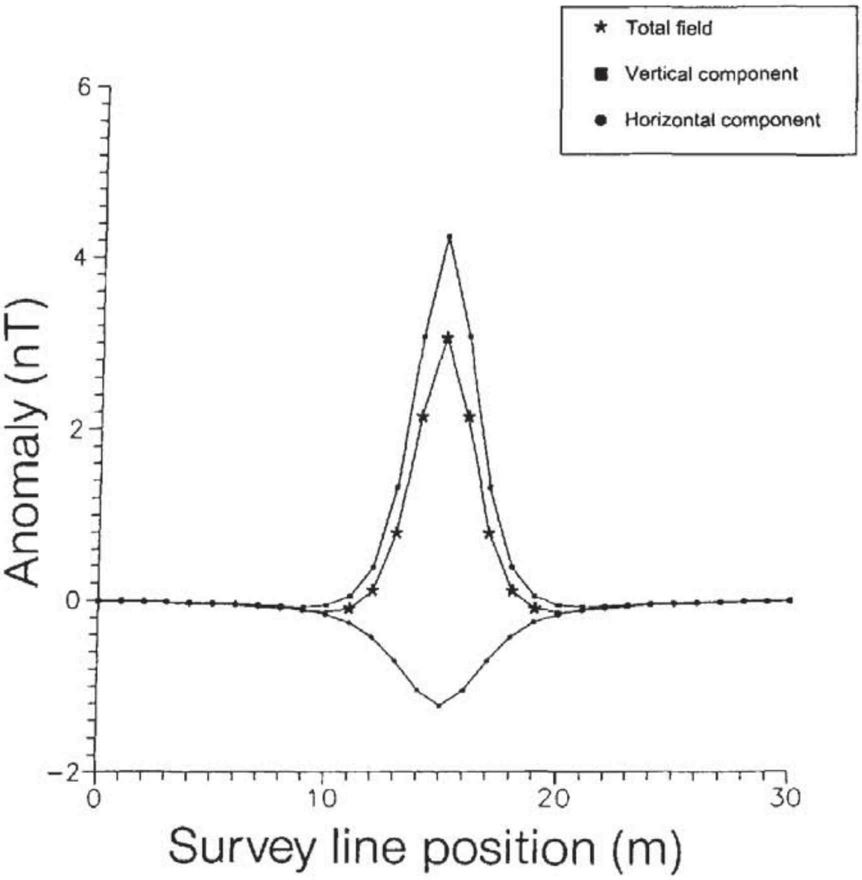


Figure 3.36 Horizontal and vertical components and the total field over a uniformly magnetised sphere with a radius of 1 m and whose centre lies at 3 m depth at position $x = 15$ m

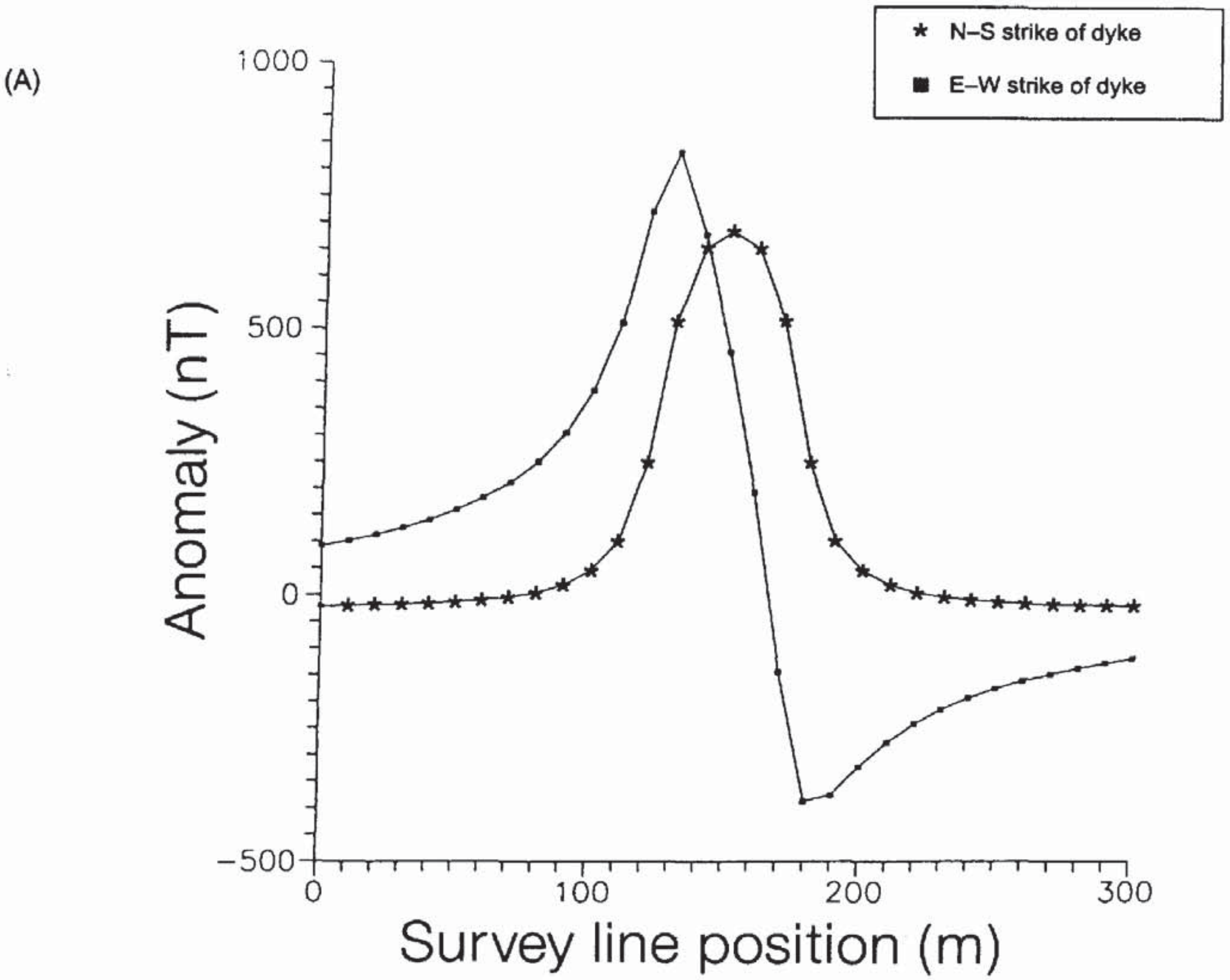
a significantly larger amplitude (830 nT) than that of the 5 m thick dyke (peak amplitude 135 nT). Notice also that the anomaly shape changes considerably with strike direction, from being a positive–negative doublet when the dyke is striking east–west (with the negative on the northern side) to being a single symmetric positive peak when the dyke strikes north–south. In all cases, when an inductively magnetised body of regular shape is orientated north–south, its anomaly is symmetric. For a 70 m thick, 400 m long magnetised slab with its top 30 m below ground, a symmetric M-shaped anomaly is produced with the strike in a north–south direction (Figure 3.37B). When striking east–west, the positive–negative doublet is stretched to form an inflection in the middle; again the negative is on the northern side.

The effects on anomaly shape caused by changing the depth to the top of a vertical magnetised dyke are illustrated in Figure 3.38. With increasing depth, the anomaly decreases in amplitude and widens. At any given latitude, the anomaly shape will also be affected by any dip (α) of a sheet-like body, such as the inductively magnetised sheet (5 m thick) striking east–west (dip direction is towards the north) indicated in Figure 3.39. With zero dip, the body behaves like a thin horizontal slab with its northern edge off the scale of the figure.

If one end of a thick horizontal slab is sufficiently far enough away from the other, the model effectively becomes a vertical boundary separating two contrasting magnetic media (Figure 3.40A). The anomaly produced when the boundary strikes east–west has a significantly larger field strength (peaking around 1870 nT) than when in the other orientation. Furthermore, the single peak is effectively the positive peak of Figure 3.37C isolated from its negative partner.

The direction and degree of dip of a fault plane in a magnetised body also has a distinctive anomaly shape (Figure 3.40B). The negative anomaly is associated with the downthrown side. The anomaly shape is very similar to half of the M-shaped anomaly in Figure 3.37B.

Anomalies produced over a near-semicylindrical low-susceptibility body within magnetised basement, to simulate a buried rock valley



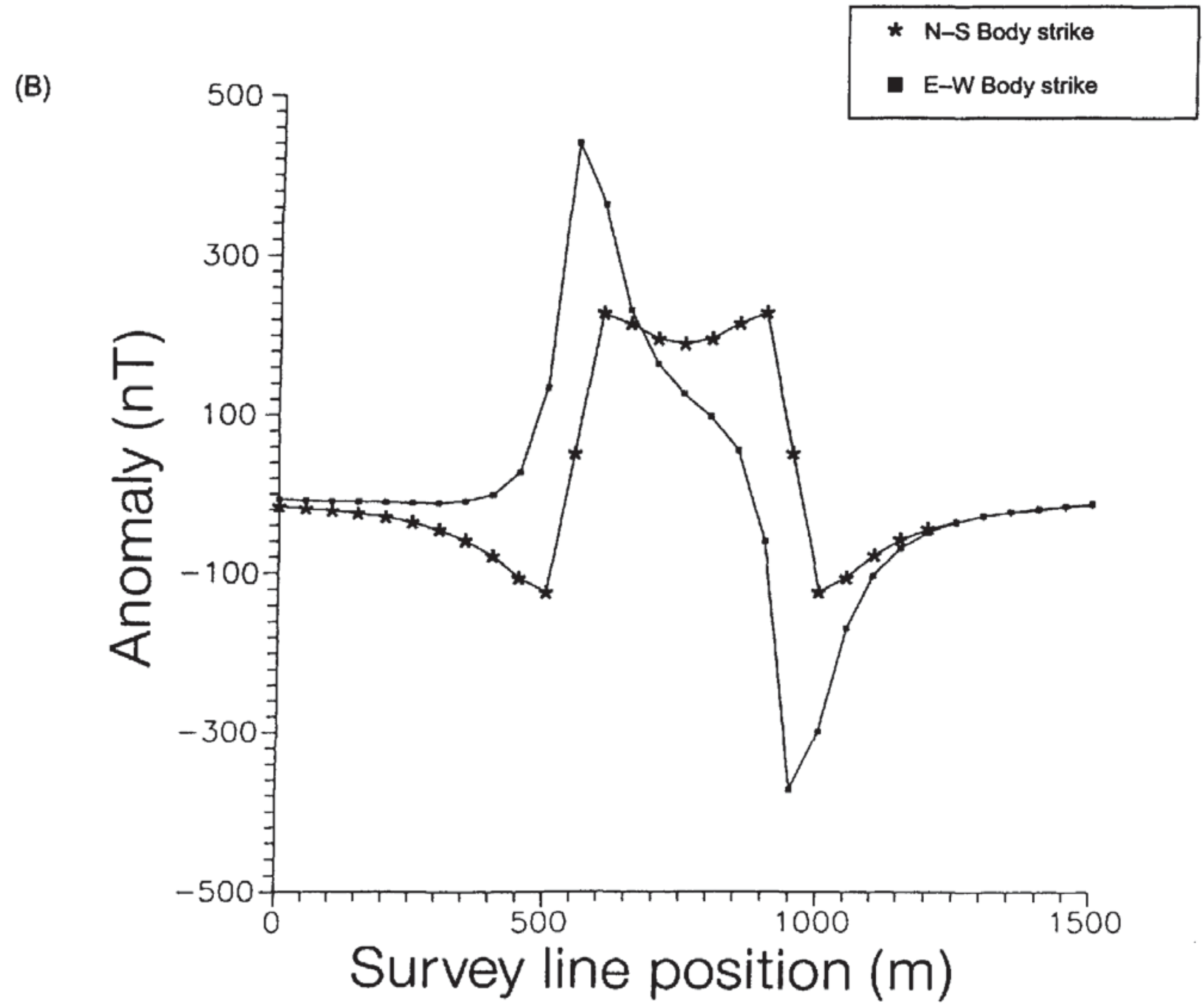


Figure 3.37 Total field anomalies over a vertical sheet-like body. (A) (*previous page*) 50 m and (B) 400 m wide. In (A), the magnetic anomaly arising from a 5 m wide body is given for comparison

infilled by sediments in magnetic bedrock, are shown in Figure 3.41. The symmetric anomaly is obtained when the semicylinder is orientated north–south. When this body is orientated north–south, the negative anomaly is on the southern side and so can be distinguished from the anomaly over a thin vertical dyke. Furthermore, the minimum anomaly amplitude is far greater in the case of the low-susceptibility semicylinder than for a vertical dyke.

One of the largest effects on anomaly shape for a given geological structure is latitude. Anomalies in the northern hemisphere over a 5 m thick dyke dipping at 45° to the north decrease in amplitude (partly a function of the reduced field strength towards the magnetic equator) and the negative minimum becomes more pronounced (Figure 3.42A). If the same geological structure exists at different latitudes in the southern hemisphere, this trend continues (Figure 3.42B) but with the slight growth of the now northern positive anomaly. These curves

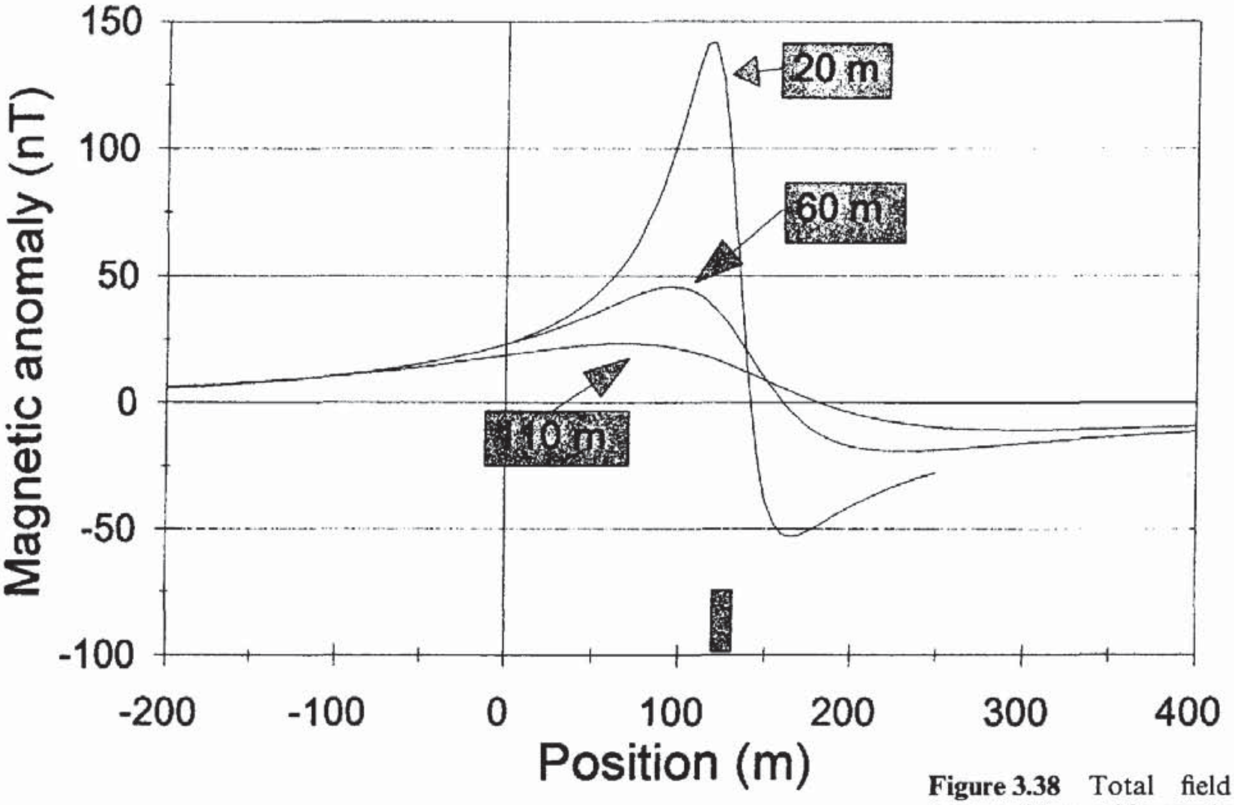


Figure 3.38 Total field anomalies over a 10 m wide vertical sheet-like body orientated east–west and buried at depths of 20 m, 60 m and 110 m; the position of the magnetised body is indicated

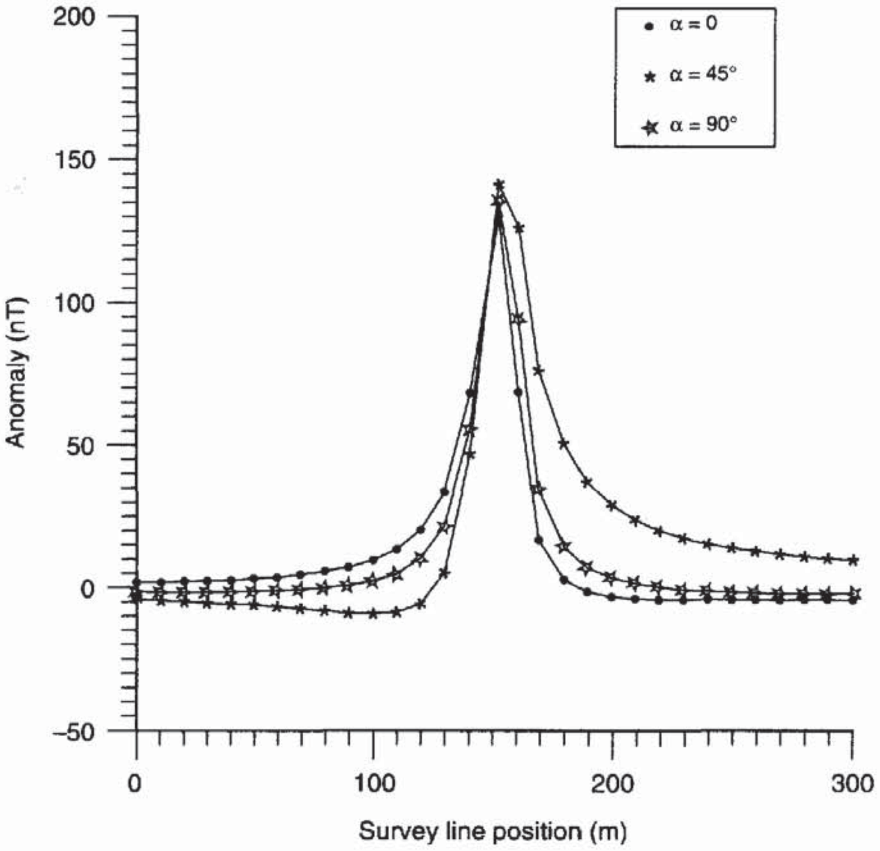


Figure 3.39 Total field anomalies over a thin dyke (5 m wide) dipping to the north at angles from $\alpha = 90°$ to $\alpha = 0°$; body strike is east–west

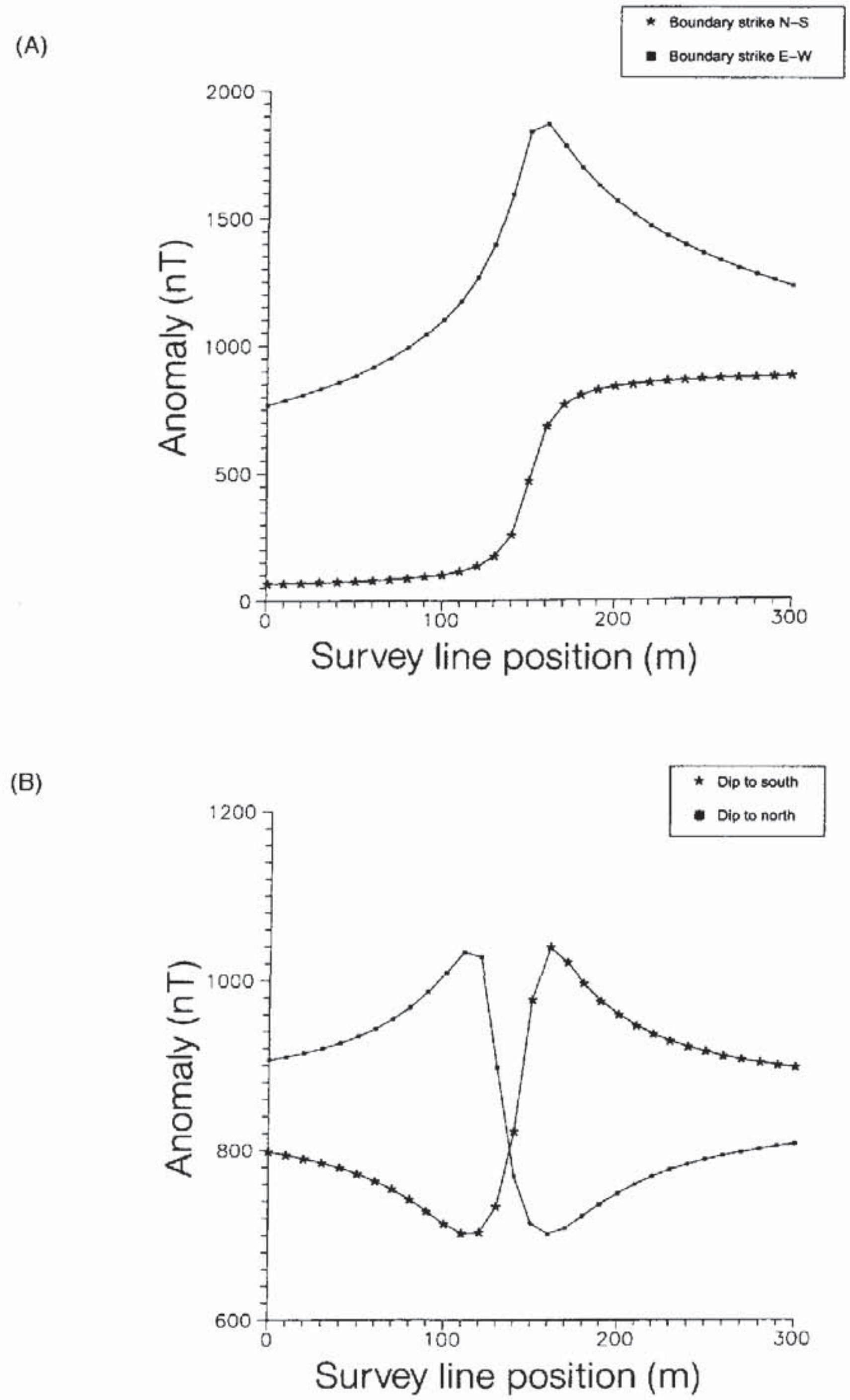
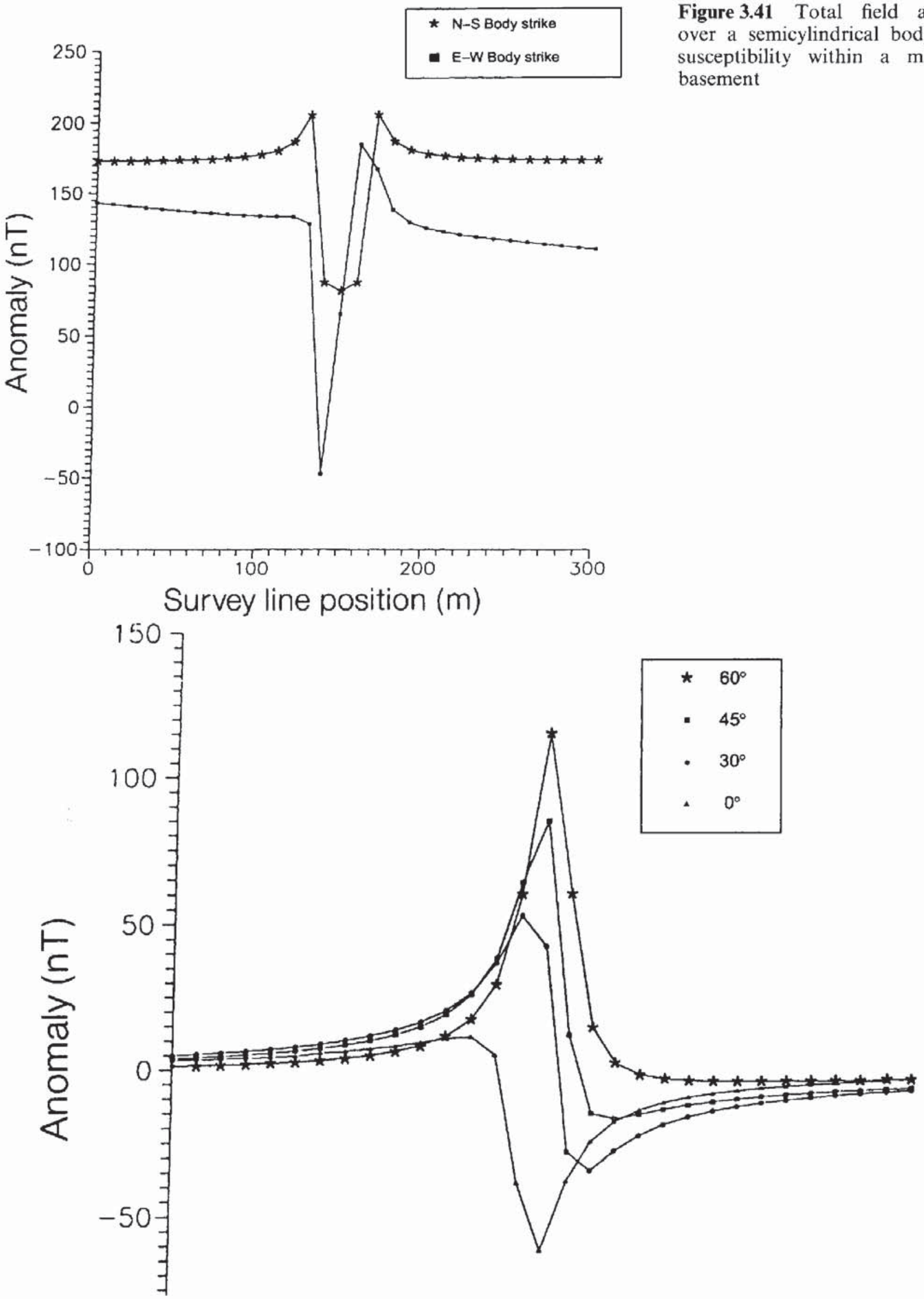


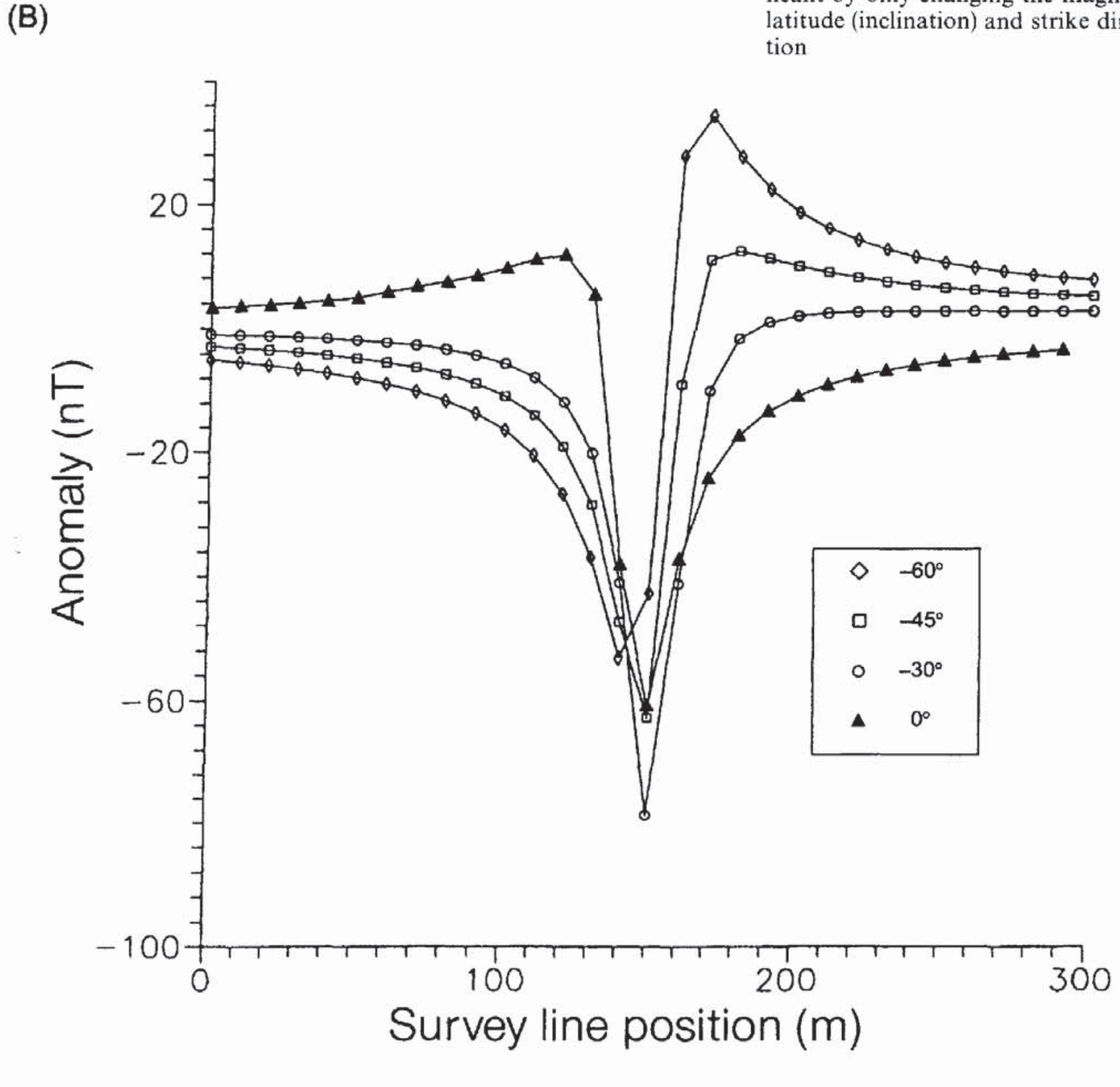
Figure 3.40 Total field anomalies over (A) a vertical contact between contrasting magnetised bodies, and (B) over a fault plane dipping at 45° to the south and to the north for a north–south fault strike direction

Figure 3.41 Total field anomalies over a semicylindrical body of low susceptibility within a magnetised basement

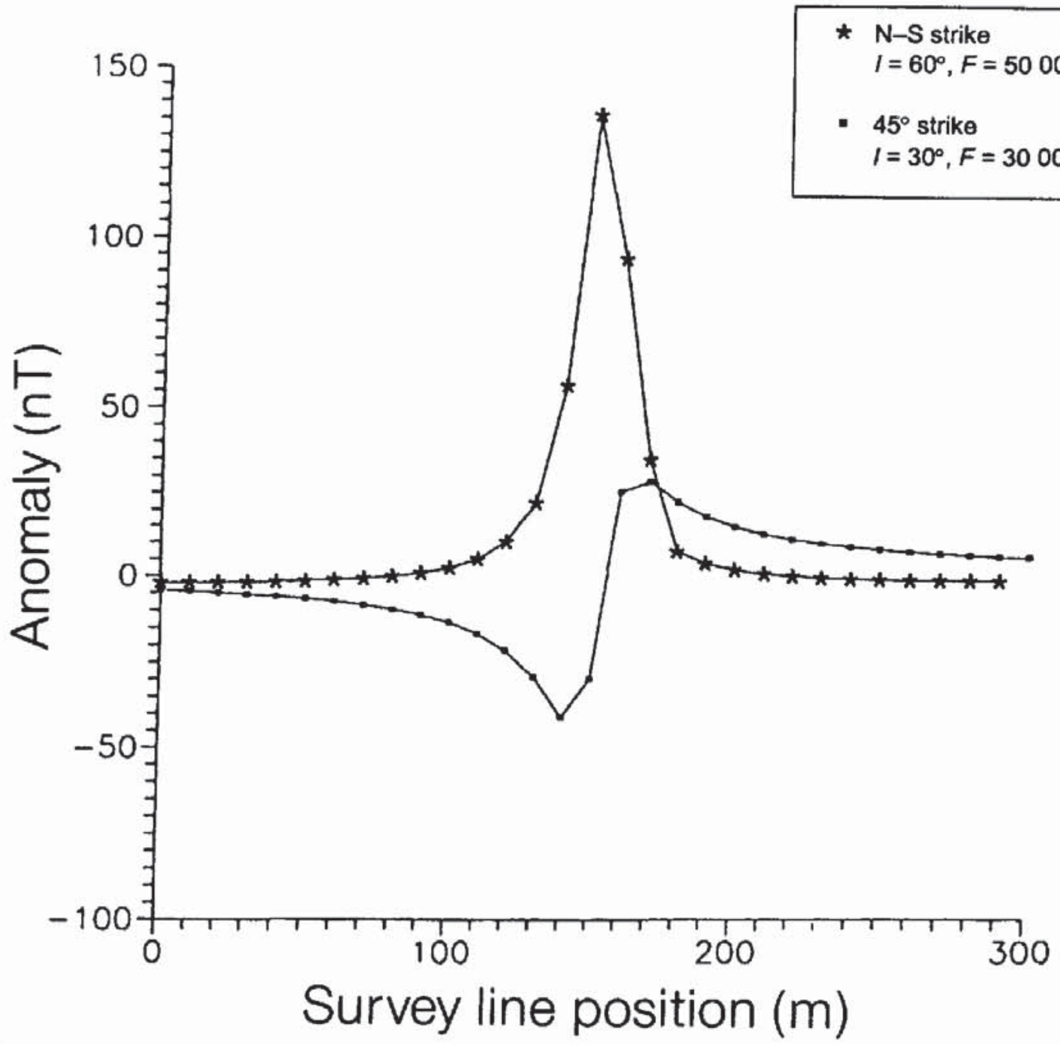


were calculated along the 0° Greenwich meridian where the field strengths in the southern hemisphere are significantly less than at equivalent latitudes in the northern hemisphere. Profiles along other lines of longitude would produce anomalies of similar shapes but with different amplitudes. It is also worth remembering that a given geological model, which produces a significant magnetic anomaly at one latitude and strike direction, may produce only a negligible anomaly at a different latitude and strike (Figure 3.42B) and so could be overlooked.

Figure 3.42 Total field anomalies over a 5 m thick dyke dipping at 45° to the north with an east–west strike direction but with different magnetic inclinations along the 0° Greenwich Meridian, with (A) (*previous page*) the northern hemisphere, and (B) (*below*) the southern hemisphere, taking into account changes in magnetic field strengh with latitude. (C) (*next page*) The total field anomaly for a vertical dyke but at two different magnetic latitudes and directions to illustrate how the magnetic anomaly over a magnetised body can become insignificant by only changing the magnetic latitude (inclination) and strike direction



(C)



In all the above cases, it was assumed that there was no remanent magnetisation, yet if present, it can affect the shape of an anomaly significantly (Green 1960). In Figure 3.43, four profiles are illustrated, one where there is no remanent magnetisation, and three others where the intensity of remanent magnetisation is constant at 0.12 A/m (giving a strength of 150 nT). A schematic vector diagram is shown to illustrate the effects of remanence and the significance of the vertical component in high magnetic latitudes ($>45°$). When the direction of permanent magnetisation is antiparallel to the Earth's field (A), the resultant amplitude is F'_a ($\ll F$), so the anomaly amplitude is substantially reduced. In the case B, where the remanent magnetisation is at right-angles to the Earth's field, the resultant F'_b ($<F$) has a smaller vertical component than F and so the amplitude is slightly reduced. In

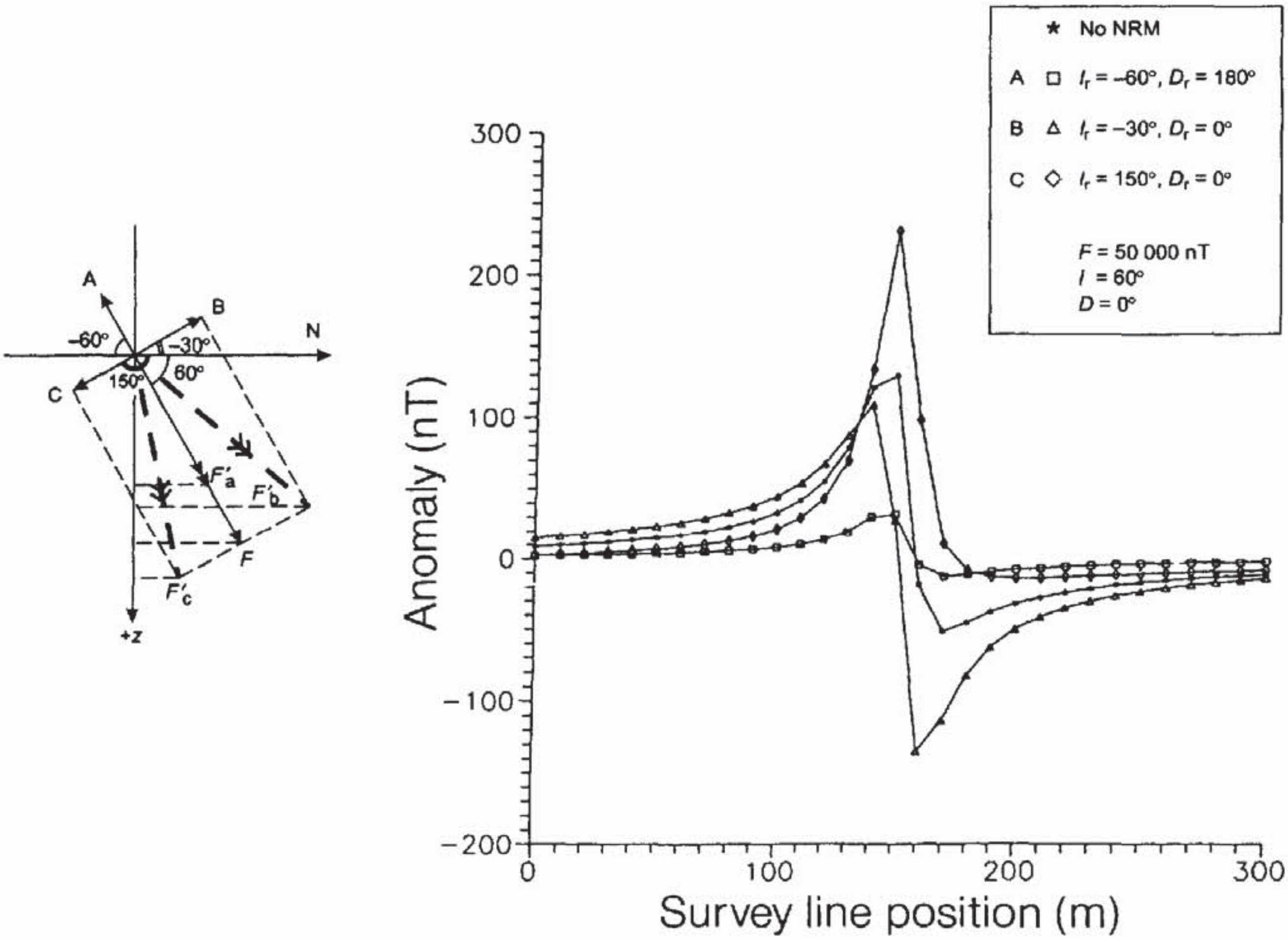


Figure 3.43 Total field anomalies over a vertical dyke striking east-west with either no remanent magnetisation (*), or remanent magnetisation of 150 nT in three directions as indicated by the schematic vector diagram

case C, where the remanent magnetisation is also at right-angles to the Earth's field but has the same positive downwards sense, F'_c, although the same magnitude as F'_b, has a larger vertical component than even the Earth's field and so the anomaly amplitude is increased substantially. In low magnetic latitudes ($<45°$), the horizontal vector component becomes more important than the vertical component when considering remanent magnetisation.

A range of different anomaly shapes demonstrating the effects of strike, latitude, dip, depth and body size has been provided above for comparison. When a field profile is to be interpreted, there is usually some background information available about the local geology (how else was the survey designed?). Consequently, many of the variables can be constrained so that a reasonable interpretation can be produced. The biggest unknown in many cases is the presence or otherwise of any remanance. Commonly it is assumed to have no effect unless found otherwise from measurements of remanence of

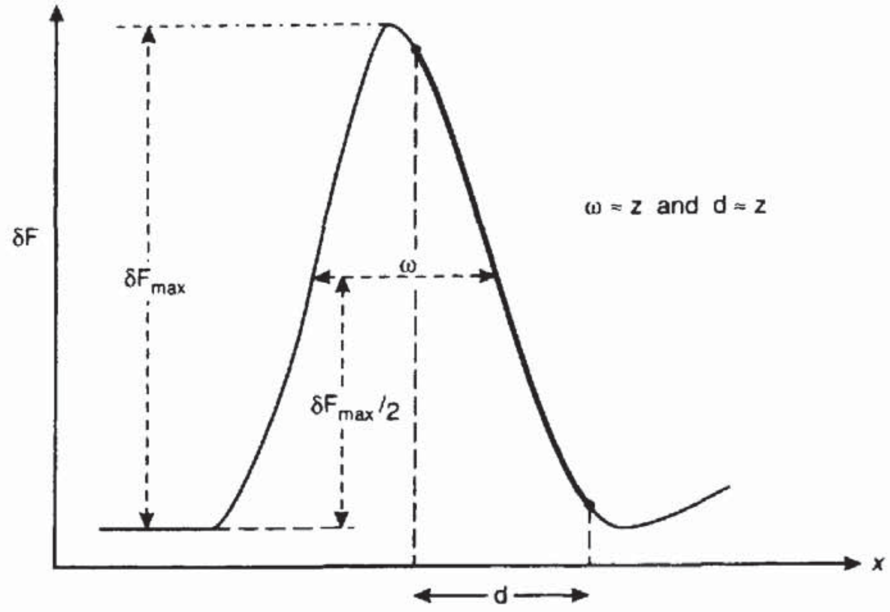


Figure 3.44 Simple graphical methods to estimate the depth to the top of a magnetised body

retrieved rock samples. However, to obtain a more exact interpretation it is necessary to model the observed data using computer methods (see Section 3.8.3).

3.8.2 Simple depth determinations

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 ($\delta F_{\max}/2$) is very crudely equal to the depth to the centre of the magnetic body (Figure 3.44). In the case of a dipping sheet or prism, it is better to use a gradient method where the depth to the top of the body can be estimated. The simplest rule of thumb to determine depth is to measure the horizontal extent, *d*, of the approximately linear segment of the main peak (Figure 3.44). This distance is approximately equal to the depth (to within ±20%).

A more theoretically based graphical method was devised by Peters (1949) and is known as Peters' Half-Slope method (Figure 3.45). A tangent (Line 1) is drawn to the point of maximum slope and, using a right-angled triangle construction, a line (Line 2) with half the slope of the original tangent is constructed. Two further lines with the same slope as Line 2 are then drawn where they form tangents to the anomaly (Lines 3 and 4). The horizontal distance, *d*, between these two tangents is a measure of the depth to the magnetic body (see Box 3.8).