rics Inc.'s G-858 instrument. These instruments can sample at up to 10 readings per second with a sensitivity of 0.05 nT. An additional feature of this particular instrument is that it can be connected to a Differential Global Positioning System for the simultaneous logging of position and magnetic data. The system was first tested at Stanford University, USA, in March 1993. As with any geophysical instruments, it is always best to check with equipment manufacturers for the latest technical specifications.

3.6 MAGNETIC SURVEYING

3.6.1 Field survey procedures

As with every geophysical survey, the keeping of detailed and accurate field notes cannot be emphasised too strongly, even if dataloggers or memory-magnetometers are used. Orderly record-keeping permits more efficient and accurate data processing. Practical details of how magnetic surveys should be undertaken have been given by Milsom (1989).

In the vast majority of cases where the magnetic targets have a substantial strike length, survey profiles should, where possible, be conducted across strike with tie-lines along strike. In cases such as some archeological and engineering site investigations where the targets are more equidimensional, such as the ruins of a Roman villa or a brick-lined mineshaft, north–south and east–west orientations are commonly used.

In ground-based surveys, it is important to establish a local base station in an area away from suspected magnetic targets or magnetic noise and where the local field gradient is relatively flat. A base station should be quick and easy to relocate and re-occupy. The precise approach to the survey will depend on the type of equipment. If a manual push-button proton magnetometer is deployed, the exact time of occupation of each station is needed and at least three readings of the total field strength should be recorded. Each of the three values should be within ±1 or 2 nanoteslas; an average of these three readings is then calculated. As the survey progresses, the base station must be re-occupied every half or three-quarters of an hour in order to compile a diurnal variation curve for later correction (see next section). Next to each data entry, where required, should be any comments about the terrain or other factors that may be considered to be important or relevant to subsequent data processing and interpretation.

If a continuous-reading base-station magnetometer is used to measure the diurnal variation, it is still worth returning to base every 2–3 hours, just in case the base magnetometer fails.

When dataloggers or memory magnetometers are used, regular checks on the recording of data are vital. It is all very well occupying hundreds of stations and taking perhaps several thousand measurements only to find that the logger is not functioning or the memory has been corrupted.

One golden rule is always to check your data as they are collected and at the end of each survey day. This serves two purposes. First, it provides a data quality check and allows the operator to alter the survey in response to the magnetic values measured. For example, if a 50 m station interval was selected at the outset and the field values indicate a rapid change over a much shorter interval, the separation between stations must be reduced in order to collect enough data to image the magnetic anomaly. Secondly, it provides a check on the consistency of the data. Odd anomalous values may indicate something of geologic interest which may need to be followed up, or may highlight human error. In either case, the next day's survey can take this into account and measurements can be made to check out the oddball values.

In the case of aeromagnetic or ship-borne surveys, the specifications are often agreed contractually before an investigation begins. Even so, there are guidelines as to what constitutes an adequate line separation or flying height, orientation of survey line, and so on. As an example, Reid (1980) compiled a set of criteria based on avoidance of spatial aliasing (Tables 3.5 and 3.6). For example, if a mean flying height over magnetic basement (h) of 500 m is used with a flight line spacing (δx) of 2 km, then $h/\delta x = 0.5/2 = 0.25$, which would indicate that 21% aliasing would occur in measurements of the total field and

Table 3.5 Degree of aliasing (Reid 1980)

$h/\delta x$	F_T	F_G
0.25	21	79
0.5	4.3	39
1	0.19	5
2	0.0003	0.03
4	0	0

F_T and F_G are the aliased power fraction (per cent) expected from surveys of total field and vertical gradient respectively

Table 3.6 Maximum line spacings (Reid 1980)

Survey type	Intended use	δx_{max}
Total field	Contour map	$2h$
Total field	Computation of gradient, etc., maps	h
Vertical gradient	Gradient contour maps	h
Total field	Modelling of single anomalies	$h/2$

as much as 79% if the vertical magnetic gradient were being measured (Table 3.5). Neither value is acceptable. The larger the value of $h/\delta x$, the less aliasing will occur; a survey is considered reasonably designed if $h/\delta x \geqslant 0.5$, depending on survey type. At this minimum value, about 5% maximum aliasing is acceptable if contouring is to be undertaken on total field data. Other maximum flight line spacings are given in Table 3.6. There have been examples of commercially flown surveys in Egypt, for instance, where the flying height was 400 m above ground, but with 1 km thickness of sedimentary cover over magnetic basement (hence $h = 1.4$ km) and the line spacing was 21 km. This gives a value of $h/\delta x \approx 0.07$, resulting in more than 65% aliasing. The contour maps of these surveys, which covered thousands of square kilometers, are virtually useless. To have been contoured adequately, the flight line spacing for data acquired at a flying height of 1.4 km above basement should have been no more than 2.8 km; i.e. from Table 3.6, $\delta x \leqslant 2h$.

The choice of survey parameters will also affect the success (or otherwise) of subsequent computer contouring. These guidelines can also apply to surface surveys using a proton magnetometer where $h = 3$ m (1 m of overburden over a magnetic target, plus 2 m for the magnetometer sensor pole) for example. In this case, an acceptable maximum line spacing would be 6 m if a contour map of the total field were required. Survey design parameters and automated contouring have been described briefly in Chapter 1 and in detail by Hood *et al.* (1979) and by Reid (1980).

3.6.2 Noise and corrections

All magnetic data sets contain elements of noise and will require some form of correction to the raw data to remove all contributions to the observed magnetic field other than those caused by sub-surface magnetic sources. In ground magnetometer surveys, it is always advisable to keep any magnetic objects (keys, penknives, some wristwatches, etc.), which may cause *magnetic noise*, away from the sensor. Geological hammers put next to the sensor bottle of a proton magnetometer will have a significant effect, as demonstrated by students trying to simulate a magnetic storm so that they could abandon the survey and retire to the nearest hostelry! It is also essential to keep the sensor away from obviously magnetic objects such as cars, metal sheds, power lines, metal pipes, electrified railway lines, walls made of mafic rocks, etc.

The most significant correction is for the *diurnal variation* in the Earth's magnetic field. Base station readings taken over the period of a survey facilitate the compilation of the diurnal 'drift' as illustrated in Figure 3.24. Measurements of the total field made at other stations can easily be adjusted by the variation in the diurnal curve. For example, at point A in Figure 3.24, the ambient field has increased by

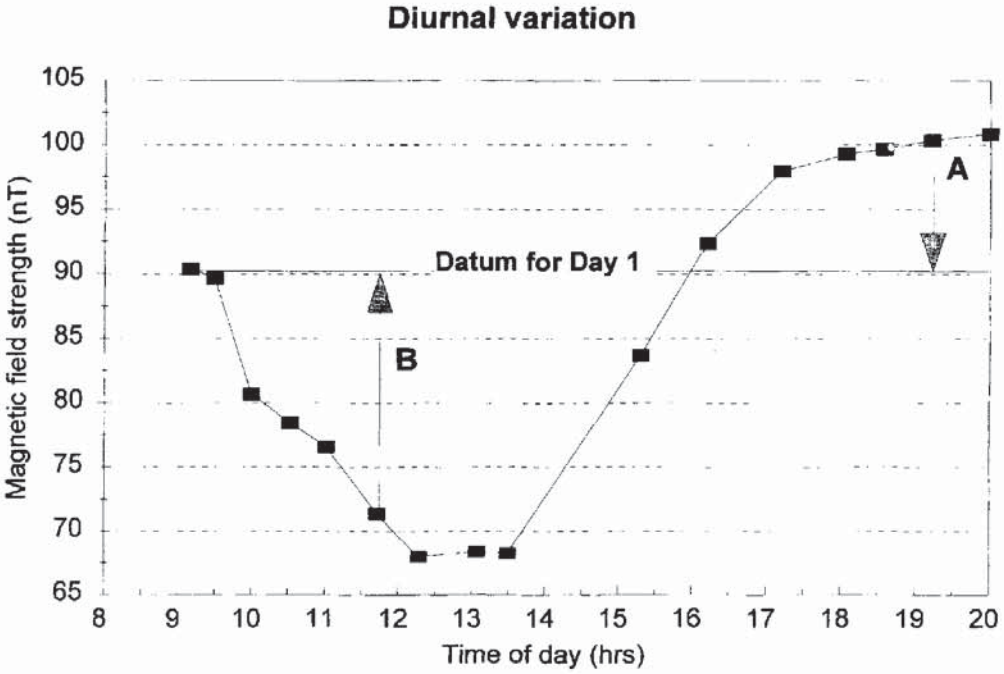


Figure 3.24 Diurnal drift curve measured using a proton magnetometer

10 nT and thus the value measured at A should be reduced by 10 nT. Similarly, at B, the ambient field has fallen by 19 nT and so the value at B should be increased by 19 nT. Further details of diurnal corrections have been given by Milsom (1989). Gradiometer data do not need to be adjusted as both sensors are affected simultaneously and the gradient remains the same between them.

In airborne and shipborne surveys, it is obviously not possible to return to a base station frequently. By designing the survey so that the track lines intersect (Figure 3.25), the dataset can be appropriately corrected. Some surveys use profiles and tie-lines at the same spacing to give a regular grid. Other surveys have tie-lines at 10 times the inter-profile line spacing. In addition to checking on diurnal variations, tie-lines also serve as a useful control on navigational and measurement accuracy. A flow chart depicting the reduction of aeromagnetic data is given in Figure 3.26. In regional surveys, a further tie is to a local Geomagnetic Observatory, if there is one within 150 km, at which all the magnetic components are measured and which can provide diurnal variations. It would then have to be demonstrated that the curve obtained from the observatory applied in the survey area.

The degree of data processing is dependent upon the resolution required in the final dataset. For a broad reconnaissance survey, a coarser survey with lower resolution, say several nanoteslas, may be

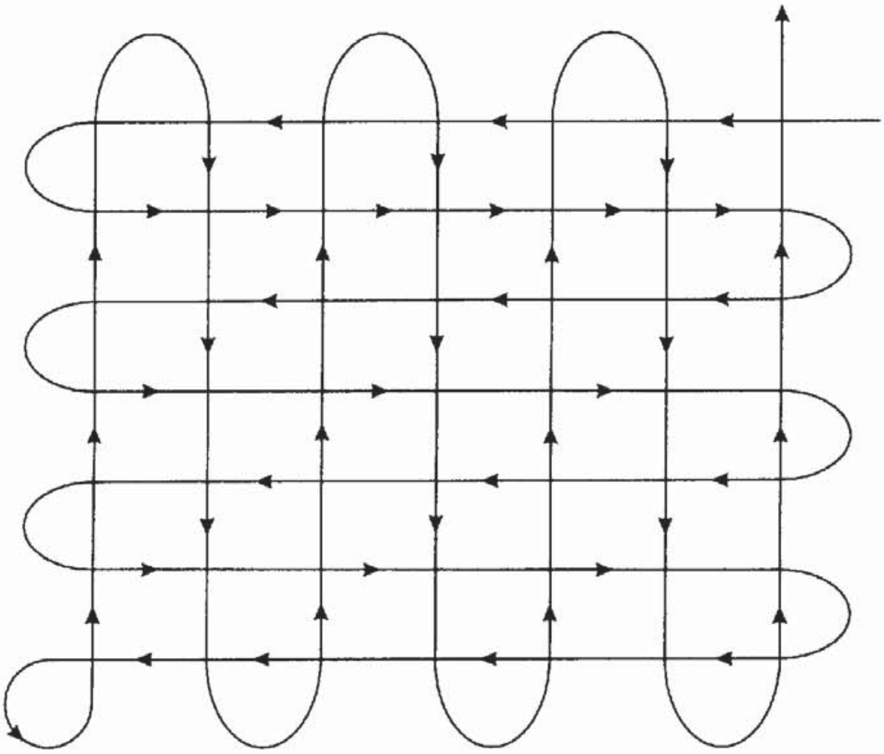


Figure 3.25 Tracks of a shipborne or airborne magnetic survey. Some surveys, rather than having equal spacings between all tracks, have tie-lines at 10 times the normal interline spacing

all that is required. In detailed surveys, however, an accuracy to within 0.1 nT will need a finer survey grid, more accurate position-fixing and diurnal drift corrections.

Rarely, a *terrain correction* may need to be applied when the ground over which a survey is conducted is both magnetic and topographically rough. Unlike the gravity case where terrain corrections, though laborious, are relatively easy to calculate, corrections for terrain for magnetic data are extremely complex. If the rough terrain is made up largely of low-susceptibility sedimentary rocks, there will be little or no distortion of the Earth's magnetic field. However, if the rocks have a significant susceptibility, a terrain factor may have to be applied. Anomalous readings as large as 700 nT have been reported by Gupta and Fitzpatrick (1971) for a 10 m high ridge of material with susceptibility $\kappa \approx 0.01$ (SI). Furthermore, magnetic readings taken in a gulley whose walls are made of basic igneous rocks will be anomalous owing to the magnetic effects of the rocks above the magnetic sensor. Considerable computational effort (see Sharma, 1986, appendix C) then has to be applied to correct the data so that they are interpretable. Similar geometric effects can also occur in radiometric surveys.

Another way of correcting for the effect of topography, or of reducing the data to a different reference plane, is by *upward continuation*. This permits data acquired at a lower level (e.g. on the ground) to be processed so that they can be compared with airborne surveys. The effect of this is to lessen the effects of short-wavelength high-

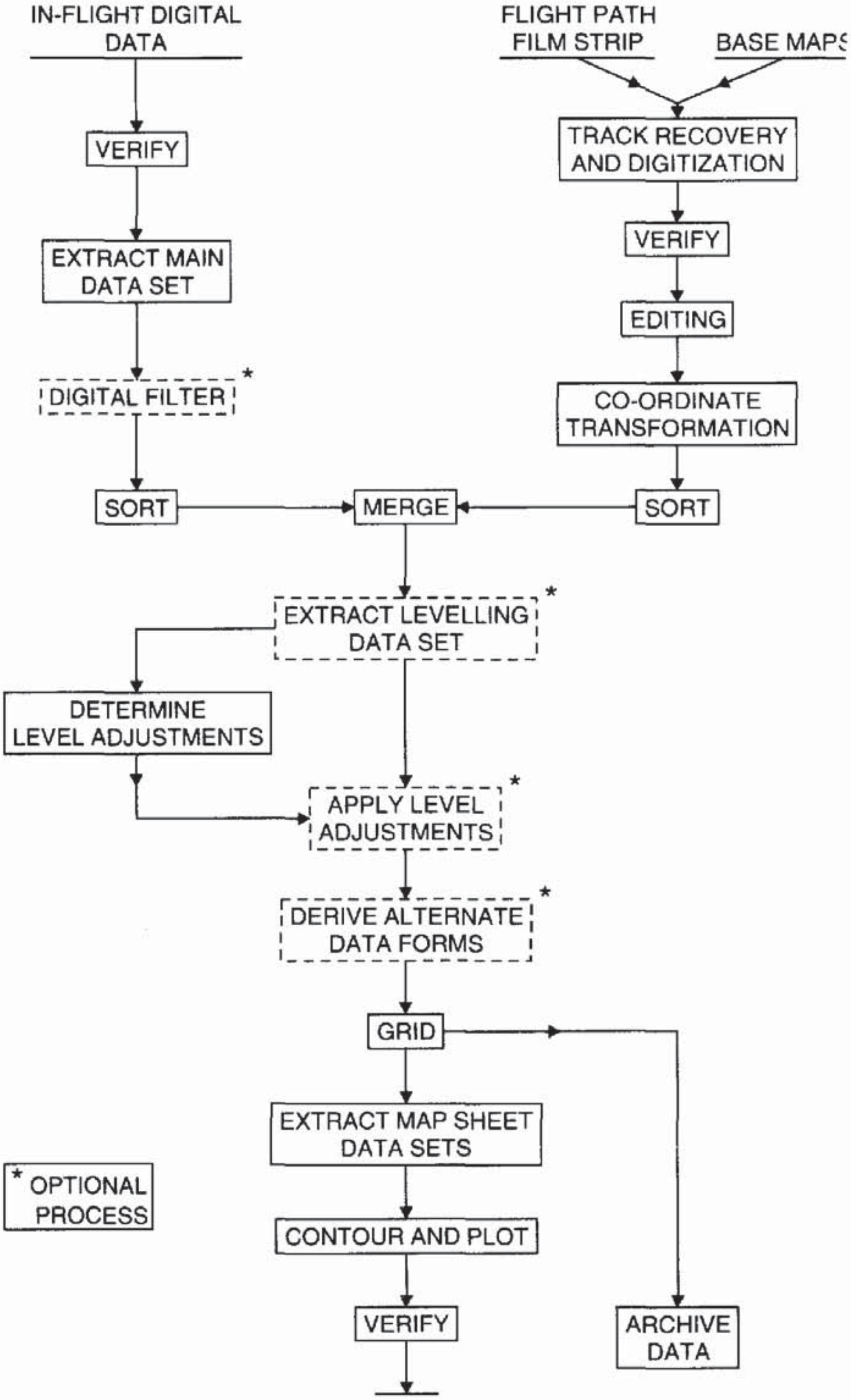
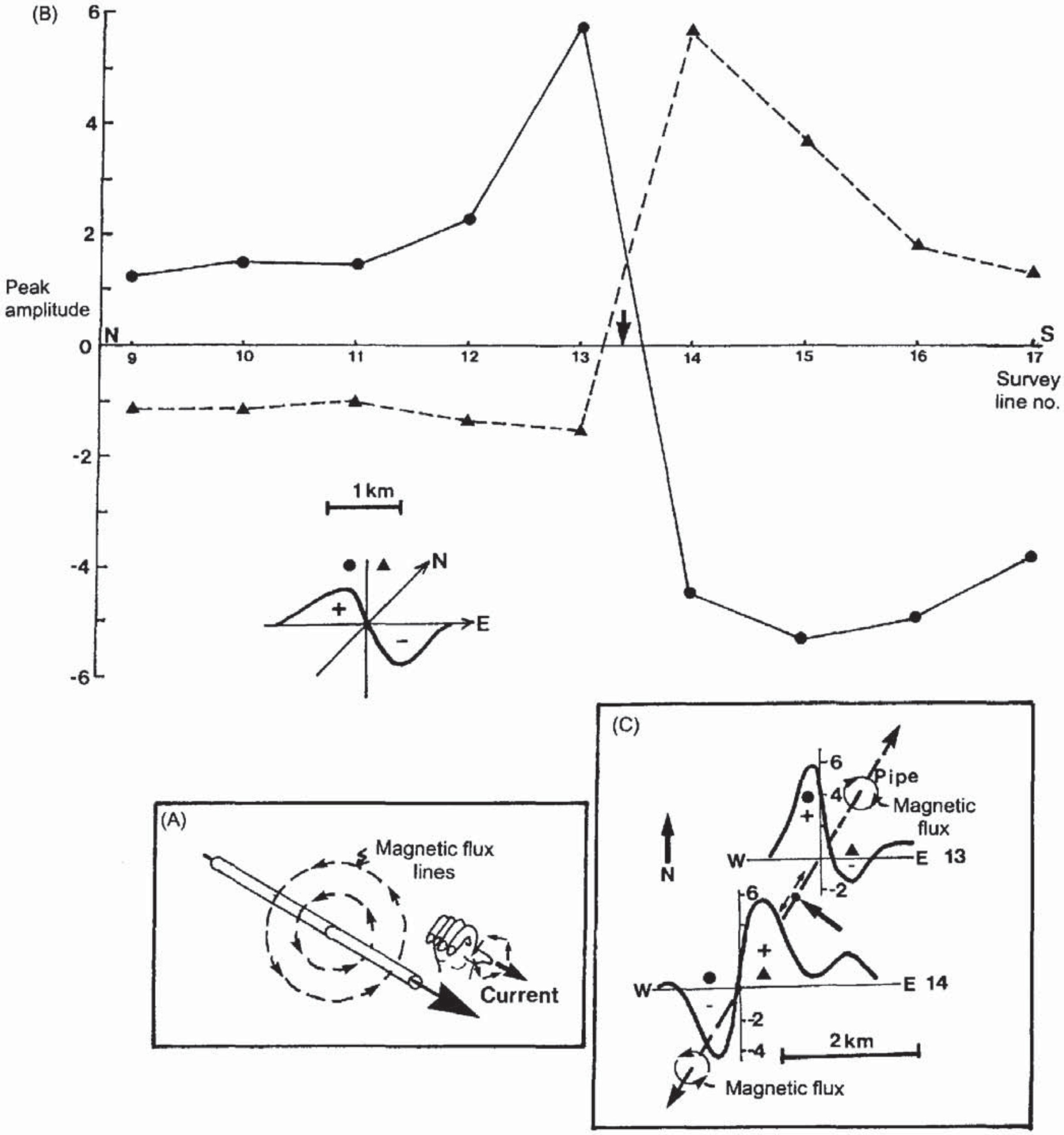


Figure 3.26 Flow chart of reduction processes on aeromagnetic data. From Hood *et al.* (1979), by permission

amplitude features as the magnetic force is indirectly proportional to the square of the distance between source and sensor (see Box 3.1). The rate of change of the field with elevation (akin to the gravitational free-air correction) is between 1.5 and 3.5 nT/100 m, with the maximum gradient being at the poles. In areas where the range of elevations of the ground surface is large, such as in the Rockies or Andes, and Himalayas, maintaining a constant terrain clearance is not practicable (or safe!). Indeed, in areas of extreme altitude, airborne surveys are not possible as the ground can be higher than the flying ceiling of available aircraft owing to the rarified atmosphere. Different flying heights can be specified for particular areas within a survey region and the various datasets processed to the same flying height or alternative datum.

In some regions, metal pipes can become inductively magnetised by currents in the atmosphere (Campbell 1986) or are cathodically protected by passing a large direct current (1–7 amps) through them to reduce internal corrosion. The presence of such pipes can contribute a significant anomaly on high-resolution aeromagnetic data (Gay 1986). In hydrocarbon exploration over sedimentary basins up to 6 km depth, basement faulting, which affects basement-controlled traps and reservoirs, can be identified from their respective magnetic anomalies which can have amplitudes of only several nanoteslas. There is then a problem over differentiating between a geologically significant fault and a cathodically protected pipe as their respective magnetic anomalies may appear to be similar.

Iron pipes have a permanent magnetisation acquired at the foundry at the time of manufacture. Being magnetisable, they also acquire a magnetisation induced by the Earth's magnetic field. Current injected into the pipes will also generate a magnetic field according to the right-hand rule. This states that a conductor carrying electrical current, indicated by the thumb on the right hand, will generate a magnetic field in the direction indicated by the coiled fingers of the right hand (Figure 3.27A). The injection of current at specific points along a pipe has one marked effect (Figures 3.27B and C). The polarity of the magnetic anomaly will be reversed either side of the injection point as the current is flowing in opposite directions away from it and into the ground. The point at which the polarity reverses (Figure 3.27B) indicates the position of current injection. The figure shows the magnitudes and senses of the western and eastern anomaly peaks for each survey line. Lines 9–13 have a positive western peak and corresponding negative eastern peak while lines 14–17 south of the injection point have a negative western peak and positive eastern peak (Figure 3.27C). The magnitude of the anomaly will also decrease away from the injection point. The magnitudes determined for survey lines south of the injection point are slightly larger than those for northern lines as the flying height was 40 m lower to the south. Mean flying height was 257 m. These characteristics are diagnostic of cathodically protected pipes and can be used to tell them apart from linear fault structures whose polarity does not switch along its length, although its magnitude may vary along the strike of the fault. Having identified a linear anomaly as being due to a cathodically protected pipe, the anomaly can be filtered out of the dataset.



3.6.3 Data reduction

In order to produce a magnetic anomaly map of a region, the data have to be corrected to take into account the effect of latitude and, to a lesser extent, longitude. As the Earth's magnetic field strength varies from 25 000 nT at the magnetic equator to 69 000 nT at the poles, the increase in magnitude with latitude needs to be taken into account. Survey data at any given location can be corrected by subtracting the theoretical field value F_{th}, obtained from the International Geomagnetic Reference Field, from the measured value, F_{obs}. This works well in areas where the IGRF is tied-in at or near to Geomagnetic Observatories, but in many places the IGRF is too crude. Instead, it is better to use a local correction which can be considered to vary linearly over the magnetic survey area. Regional latitudinal (ϕ) and longitudinal (θ) gradients can be determined for areas concerned and tied to a base value (F_0), for example, at the south-east corner of the survey area. Gradients northwards ($\delta F/\delta\phi$) and westwards ($\delta F/\delta\theta$) are expressed in nT/km and can easily be calculated for any location within the survey area. For example, in Great Britain, gradients of 2.13 nT/km north and 0.26 nT/km west are used. Consequently, the anomalous value of the total field (δF) can be calculated arithmetically, as demonstrated by the example in Box 3.7.

Another method of calculating the anomalous field δF is to determine statistically the trend of a regional field to isolate the higher-frequency anomalies, which are then residualised in the same way that gravity residuals are calculated. The regional field is subtracted from the observed field to produce a residual field (δF) (Figure 3.28A). If the survey is so laterally restricted, as in the case of small-scale archaeological, engineering or detailed mineral prospecting surveys (e.g. $< 500\,\text{m} \times 500\,\text{m}$ in area), the use of regional gradients is not practicable. Instead, profile data can be referred to a local base station (F_b) which is remote from any suspected magnetic sources. In this case, the anomalous field δF is obtained by subtracting the base value (F_b) from every diurnally corrected observed value F_{obs} along the profile ($\delta F = F_{\text{obs}} - F_b$), as illustrated in Figure 3.28B.

Box 3.7 Anomalous total field strength δF

$$\delta F = F_{\text{obs}} - (F_0 + \delta F/\delta\phi + \delta F/\delta\theta) \quad (\text{nT})$$

where F_{obs} is the measured value of F at a point within the survey area with coordinates (x, y); F_0 is the value at a reference point ($x = 0$; $y = 0$); $\delta F/\delta\phi$ and $\delta F/\delta\theta$ are the latitudinal and longitudinal gradients respectively (in units of nT/km).

Example: For a station 15 km north and 18 km west of a reference station at which $F_0 = 49\,500$ nT with gradients $\delta F/\delta\phi = 2.13$ nT/km north, and $\delta F/\delta\theta = 0.26$ nT/km west, and the actual observed field $F_{\text{obs}} = 50\,248$ nT, the magnetic anomaly δF is:

$$\begin{aligned}\delta F &= 50\,248 - (49\,500 + 2.13 \times 15 + 0.26 \times 18)\,\text{nT} \\ &= 711\,\text{nT}\end{aligned}$$

Figure 3.27 *(opposite)* Variation in magnetic anomalies associated with a cathodically protected pipe in north-east Oklahoma, USA. (A) Right-hand rule applied to a pipe through which a current is passed to show direction of magnetic flux lines. (B) Peak amplitudes for western and eastern parts of profile anomalies, of which two for lines 13 and 14 are shown in (C). Note the relative amplitudes of the anomalies on lines 13 and 14 either side of the current injection point (arrowed). Data from Gay (1986), by permission