Chapter 1
Introduction

1.1 WHAT ARE 'APPLIED' AND 'ENVIRONMENTAL' GEOPHYSICS?

In the broadest sense, the science of *Geophysics* is the application of physics to investigations ofthe Earth, Moon and planets. The subject is thus related to astronomy. Normally, however, the definition of 'Geophysics' is used in a more restricted way, being applied solely to the Earth. Even then, the term includes such subjects as meteorology and ionospheric physics, and other aspects of atmospheric sciences.

To avoid confusion, the use of physics to study the interior of the Earth, from land surface to the inner core, is known as *Solid Earth Geophysics*. This can be subdivided further into *Global Geophysics*, or alternatively *Pure Geophysics*, which is the study of the whole or substantial parts of the planet, and *Applied Geophysics* which is concerned with investigating the Earth's crust and near-surface to achieve a practical and, more often than not, an economic aim.

'Applied geophysics' covers everything from experiments to determine the thickness of the crust (which is important in hydrocarbon exploration) to studies of shallow structures for engineering site investigations, exploring for groundwater and for minerals and other economic resources, to trying to locate narrow mine shafts or other forms of buried cavities, or the mapping of archaeological remains, or locating buried pipes and cables - but where in general the total depth of investigation is usually less than 100 m. The same scientific principles and technical challenges apply as much to shallow geophysical investigations as to pure geophysics. Sheriff(1991; p. 139) has defined *'applied geophysics'* thus:

> "Making and interpreting measurements of physical properties of the earth to determine sub-surface conditions, usually with an economic objective, e.g., discovery of fuel or mineral depositions."

'Engineering geophysics' can be described as being:

> 'The application of geophysical methods to the investigation of sub-surface materials and structures which are likely to have (significant) engineering implications."

As the range of applications of geophysical methods has increased, particularly with respect to derelict and contaminated land investigations, the sub-discipline of *'environmental geophysics'* has developed (Greenhouse 1991; Steeples 1991). This can be defined as being:

> 'The application of geophysical methods to thc investigation of near-surface physico-chemical phenomena which are likely to have (significant) implications for the management of the local environment."

The principal distinction between engineering and environmental geophysics is more commonly that the former is concerned with structures and types of materials, whereas the latter can also include, for example, mapping variations in pore-fluid conductivities to indicate pollution plumes within groundwater. Chemical effects are equally as important as physical phenomena. Since the mid-1980s in the UK, geophysical methods have been used increasingly to investigate derelict and contaminated land, with a specific objective of locating polluted areas prior to direct observations using trial pits and boreholes (e.g. Reynolds and Taylor 1992). Geophysics is also being used much more extensively over landfills and other waste repositories (e.g. Reynolds and McCann 1992). One ofthe advantages of using geophysical methods is that they are largely environmentally benign – there is no disturbance of sub-surface materials. An obvious example is the location of a corroded steel drum containing toxic chemicals. To probe for it poses the real risk of puncturing it and creating a much more significant pollution incident. By using modern geomagnetic surveying methods, the drum's position can be isolated and a careful excavation instigated to remove the offending object without damage. Such an approach is cost-effective and environmentally safer.

A further major advantage of the use of environmental geophysics in investigating contaminated sites is that large areas can be surveyed quickly at relatively low cost. This provides information to aid the location of trial pits and boreholes. The alternative and more usual approach is to use a statistical sampling technique (e.g. Ferguson 1992). The disadvantage of this is that key areas of contamination can easily be missed, reducing the value substantially of such direct investigation. By targeting direct investigations by using a preliminary geophysical survey to locate anomalous areas, there is a much higher certainty that the trial pits and boreholes constructed will yield useful results. Instead of seeing the geophysical survey as a cost, it should be viewed as adding value by making the entire site investigation more cost-effective.

There are obviously situations where a specific site investigation contains aspects of engineering as well as environmental geophysics and there may well be considerable overlap. Indeed, if each subdiscipline of applied geophysics is considered, they may be represented as shown in Figure 1.1, as overlapping. Also included are three other sub-disciplines whose names are largely self-explanatory: namely, *Archaeo-geophysics* (geophysics in archaeology), *hydro-geophysics* (geophysics in groundwater investigations), and *Glacio-geophysics*

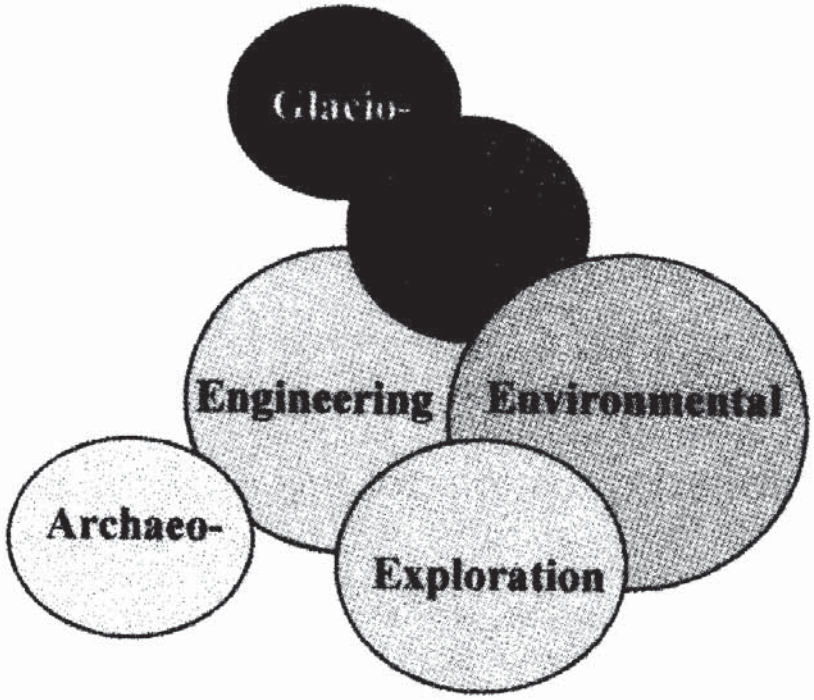


Figure 1.1 Inter-relationships between various sub-disciplines of applied geophysics

(geophysics in glaciology). The last one is the least well known, despite the fact that it has been in existence for far longer than either archaeo- or environmental geophysics, and is particularly well established within the polar scientific communities and has been since the 1950s.

The general orthodox education of geophysicists to give them a strong bias towards the hydrocarbon industry has largely ignored these other areas of our science. It may be said that this restricted view has delayed the application of geophysics more widely to other disciplines. Geophysics has been taught principally in Earth Science departments of universities. There is an obvious need for it to be introduced to engineers and archaeologists much more widely than at present. Similarly, the discipline of environmental geophysics needs to be brought to the attention of policy-makers and planners, to the insurance and finance industries (Doll 1994).

The term 'environmental geophysics' has been interpreted by some to mean geophysical surveys undertaken with environmental sensitivity - that is, ensuring that, for example, marine seismic surveys are undertaken sympathetically with respect to the marine environment (Bowles 1990). With growing public awareness of the environment and the pressures upon it, the geophysical community has had to be able to demonstrate clearly its intentions to minimise environmental impact (Marsh 1991). By virtue of scale, the greatest likely impact on the environment is from hydrocarbon and some mineral exploration, and the main institutions involved in these activities are well aware of their responsibilities. In small-scale surveys the risk of damage is much lower; but all the same, it is still important that those undertaking geophysical surveys should be mindful of their responsibilities to the environment and to others whose livelihoods depend upon it.

While the term 'applied geophysics' covers a wide range of applications, the importance of 'environmental' geophysics is particularly highlighted within this book. The growth of the discipline, which appears to be expanding exponentially, is such that this subject may outstrip the use of geophysics in hydrocarbon exploration during the early part of the next century and provide the principal area of employment for geophysicists. Whether this proves to be the case is for history to decide. What is clear, however, is that even in the last decade of this century, environmental geophysics is becoming increasingly important in the management of our environment. Ignore it at your peril!

1.2 GEOPHYSICAL METHODS

Geophysical methods respond to the physical properties of the sub-surface media (rocks, sediments, water, voids, etc.) and can be classified into two distinct types.

- Passive methods are those that detect variations within the natural fields associated with the Earth, such as the gravitational and magnetic fields.
- In contrast are the active methods, such as those used in exploration seismology, in which artificially generated signals are transmitted into the ground, which then modifies those signals in ways that are characteristic of the materials through which they travel. The altered signals are measured by appropriate detectors whose output can be displayed and ultimately interpreted.

Applied geophysics provides a wide range of very useful and powerful tools which, when used correctly and in the right situations, will produce useful information. All tools, if misused or abused, will not work effectively. One of the aims of this book it to try to explain how applied geophysical methods can be employed appropriately, and to highlight the advantages and disadvantages of the various techniques.

Geophysical methods may form part of a larger survey, and thus geophysicists should always try to interpret their data and communicate their results clearly to the benefit of the whole survey team and particularly to the client. An engineering site investigation, for instance, may require the use of seismic refraction to determine how easy it would be to excavate the ground (e.g. the 'rippability' of the ground). If the geophysicist produces results that are solely in terms of seismic velocity variations, the engineer is still none the wiser. The geophysicist needs to translate the velocity data into a rippability index with which the engineer would be familiar.

Few, if any, geophysical methods provide a *unique* solution to a particular geological situation. It is possible to obtain a very large number of geophysical solutions to some problems, some of which may be geologically nonsensical. It is necessary, therefore, always to ask the question: "Is the geophysical model geologically plausible?" If it is not, then the geophysical model has to be rejected and a new one developed which does provide a reasonable geological solution. Conversely, if the geological model proves to be inconsistent with the geophysical interpretation, then it may require the geological information to be re-evaluated.

> It is of paramount importance that geophysical data are interpreted within a physically constrained or geological framework.

1.3 MATCHING GEOPHYSICAL METHODS TO APPLICATIONS

The various geophysical methods rely on different physical properties and it is important that the appropriate technique be used for a given type of application.

For example, gravity methods are sensitive to density contrasts within the sub-surface geology and so are ideal for exploring for major sedimentary basins where there is a large density contrast between the lighter sediments and the denser underlying rocks. It would be quite inappropriate to try to use gravity methods to search for localized near-surface sources of groundwater where there is a negligible density contrast between the saturated and unsaturated rocks. It is even better to use methods that are sensitive to different physical properties and are able to complement each other and thereby provide an integrated approach to a geological problem. Gravity and magnetic methods are frequently used in this way.

Case histories for each geophysical method are given in each chapter along with some examples of integrated applications where appropriate. The basic geophysical methods are listed in Table 1.1 with the physical properties to which they relate and their main uses. Table 1.1 should only be used.as a guide. More specific information about the applications of the various techniques is given in the appropriate chapters.

Some methods are obviously unsuitable for some applications but novel uses may yet be found for them. One example is that of ground

Table 1.1 Geophysical methods and their main applications

Geophysical method	Chapter number	Dependent physical property	Applications (see key below) 1	2	3	4	5	6	7	8	9	10
Gravity	2	Density	**P**	**P**	s	s	s	s	!	!	s	!
Magnetic	3	Susceptibility	**P**	**P**	**P**	s	!	m	!	**P**	**P**	!
Seismic refraction	4,5	Elastic moduli; density	**P**	**P**	m	**P**	s	s	!	!	!	!
Seismic reflection	4,6	Elastic moduli; density	**P**	**P**	m	s	s	m	!	!	!	!
Resistivity	7	Resistivity	m	m	**P**	**P**	**P**	**P**	**P**	s	**P**	m
Spontaneous potential	8	Potential differences	!	!	**P**	m	**P**	m	m	m	!	!
Induced polarization	9	Resistivity; capacitance	m	m	**P**	m	s	m	m	m	m	m
Electromagnetic (EM)	10	Conductance; inductance	s	**P**	**P**	**P**	**P**	**P**	**P**	**P**	**P**	m
EM–VLF	11	Conductance; inductance	m	m	**P**	m	s	s	s	m	m	!
EM – ground penetrating radar	12	Permitivity; conductivity	!	!	m	**P**	**P**	**P**	s	**P**	**P**	**P**
Magneto-telluric	11	Resistivity	s	**P**	**P**	m	m	!	!	!	!	!

P = primary method; s = secondary method; m = may be used but not necessarily the best approach, or has not been developed for this application; (!) = unsuitable

Applications

1 Hydrocarbon exploration (coal, gas, oil)
2 Regional geological studies (over areas of 100s of km^2)
3 Exploration/development of mineral deposits
4 Engineering site investigations
5 Hydrogeological investigations
6 Detection of sub-surface cavities
7 Mapping of leachate and contaminant plumes
8 Location and definition of buried metallic objects
9 Archaeogeophysics
10 Forensic geophysics

radar being employed by police in forensic work (see Chapter 12 for more details). If the physical principles upon which a method is based are understood, then it is less likely that that technique will be misapplied or the resultant data misinterpreted. This makes for much better science.

Furthermore, it must also be appreciated that the application of geophysical methods will not necessarily produce a unique geological solution. For a given geophysical anomaly there may be many possible solutions each of which is equally valid geophysically, but which may make geological nonsense. This has been demonstrated

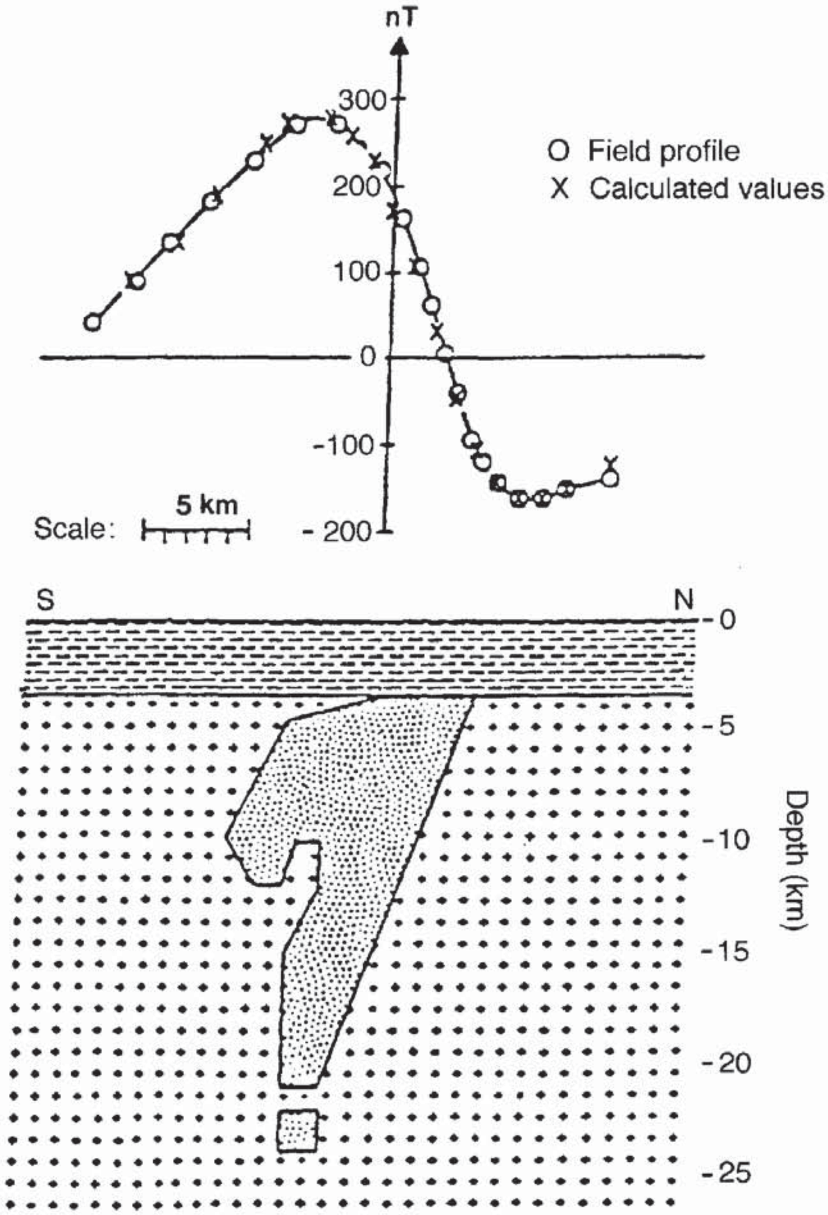


Figure 1.2 A magnetic anomaly over Lausanne, Switzerland, with a hypothetical and unreal model for which the computed anomaly still fits the observed data. After Meyer de Stadelhofen and Juillard (1987)

very clearly in respect to a geomagnetic anomaly over Lausanne in Switzerland (Figure 1.2). While the model with the form of a question mark satisfies a statistical fit to the observed data, the model is clearly and quite deliberately geological nonsense in order to demonstrate the point. However, geophysical observations can also place stringent restrictions on the interpretation of geological models. While the importance of understanding the basic principles cannot be over-emphasised, it is also necessary to consider other factors that affect the quality and usefulness of any geophysical survey, or for that matter of *any* type of survey whether it is geophysical, geochemical or geotechnical. This is done in the following few sections.

1.4 PLANNING A GEOPHYSICAL SURVEY

1.4.1 General philosophy

Any geophysical survey tries to determine the nature of the subsurface, but it is of paramount importance that the prime objective of the survey be clear right at the beginning. The constraints on a commercial survey will have emphases different from those on an academic research investigation and, in many cases, there may be no *ideal* method. The techniques employed and the subsequent interpretation of the resultant data tend to be compromises, practically and scientifically.

There is no short-cut to developing a good survey style; only by careful survey planning backed by a sound knowledge of the geophysical methods and their operating principles, can cost-effective and efficient surveys be undertaken within the prevalent constraints. However, there have been only a few published guidelines - e.g. British Standards Institute BS 5930 (1981), Hawkins (1986), Geological Society Engineering Group Working Party Report on Engineering Geophysics (1988). Scant attention has been paid to survey design, yet a badly thought-out survey rarely produces worthwhile results. Indeed, Darracott and McCann (1986, p. 85) said that:

> "dissatisfied clients have frequently voiced their disappointment with geophysics as a site investigation method. However, close scrutiny of almost all such cases will show that the geophysical survey produced poor results for one or a combination of the following reasons: inadequate and/or bad planning of the survey; incorrect choice or specification of technique, and insufficiently experienced personnel conducting the investigation."

It is hoped that this chapter will provide at least a few pointers to help construct cost-effective and technically sound geophysical field programmes.

1.4.2 Planning strategy

Every survey must be planned according to some strategy, or else it will become an uncoordinated muddle. *The mere acquisition of data does not guarantee the success of the survey.* Knowledge (by way of masses of data) does not automatically increase our *understanding* of a site; it is the latter we are seeking, and knowledge is the means to this.

One less-than-ideal approach is the 'blunderbus' approach - take along a sufficient number of different methods and try them all out (usually inadequately owing to insufficient testing time per technique) to see which ones produce something interesting. Whichever method yields an anomaly, then use that technique. This is a crude statistical approach, such that if enough techniques are tried then at least one must work! This is hardly scientific or cost-effective.

The success of geophysical methods can be very site-specific and *scientifically-designed* trials of adequate duration may be very worthwhile to provide confidence that the techniques chosen will work or that the survey design needs modifying in order to optimise the main survey. It is in the interests of the client that suitably experienced geophysical consultants are employed for the vital survey design, site supervision and final reporting.

So what are the constraints that need to be considered by both clients and geophysical survey designers? An outline plan of the various stages in designing a survey is given in Figure 1.3. The remainder of this chapter discusses the relationships between the various components.

1.4.3 Survey constraints

The first and most important factor is that of *finance.* How much is the survey going to cost and how much money is available? The cost will depend on where the survey is to take place, how accessible the proposed field site is, and on what scale the survey is to operate. An airborne regional survey is a very different proposition to, say, a local, small-scale ground-based investigation. The more complex the survey in terms of equipment and logistics, the greater the cost is likely to be.

It is important to remember that the geophysics component of a survey is usually only a small part of an exploration programme and thus the costs of the geophysics should be viewed in relation to those of the whole project. Indeed, the judicious use of geophysics can save large amounts of money by enabling the effective use of resources (Reynolds 1987a). For example, a reconnaissance survey can identify smaller areas where much more detailed investigations ought to be undertaken – thus removing the need to do saturation surveying. The factors that influence the various components of a budget also vary

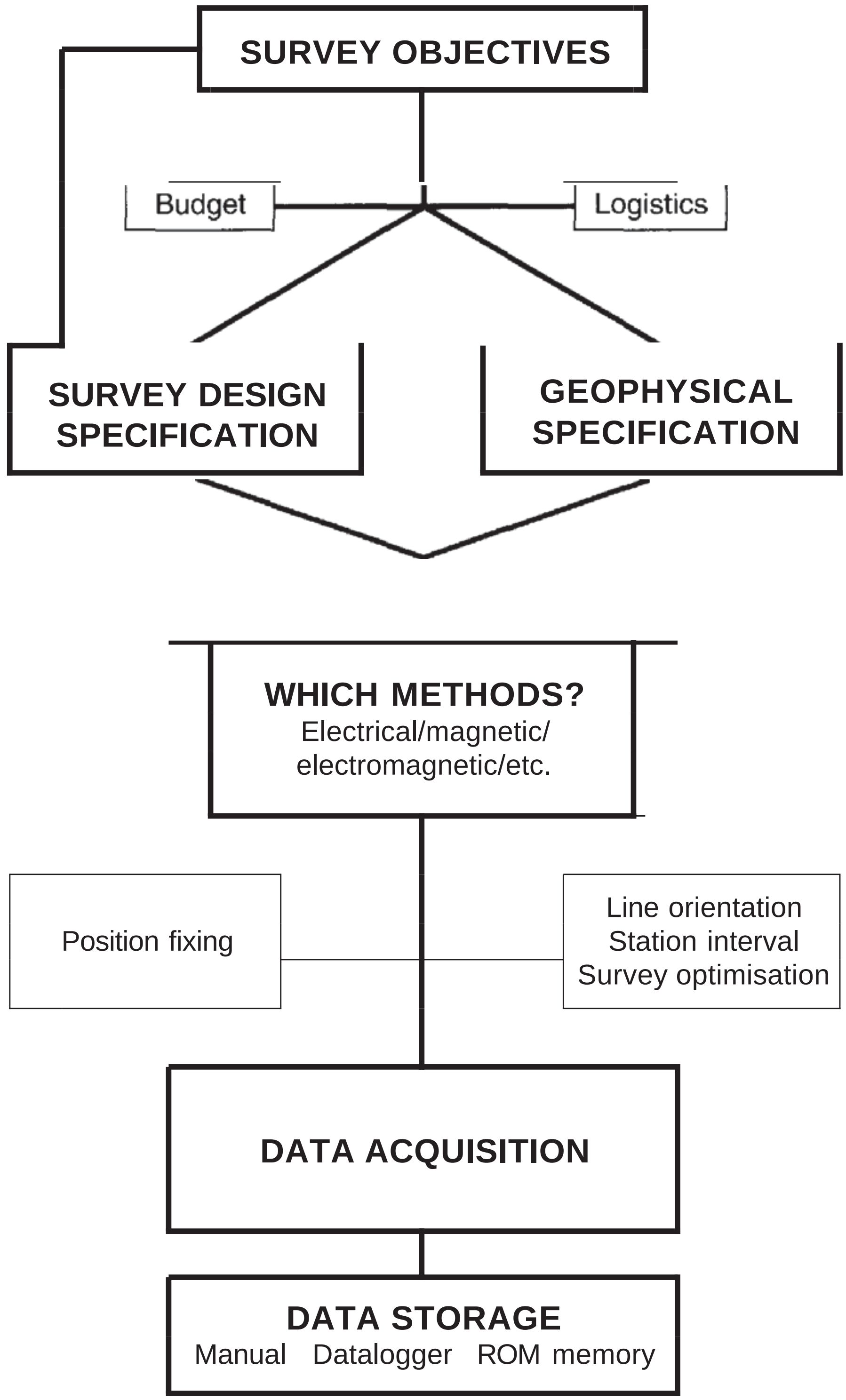


Figure 1.3 Schematic flow diagram to illustrate the decision-making process leading to the selection of geophysical and utility software. From Reynolds (1991a), by permission

from country to country, and from job to job, and there is no magic formula to guarantee success.

Some of the basic elements of a survey budget are given in Table 1.2. This list is not exhaustive but serves to highlight the most

Table 1.2 Basic elements of a survey budget

Staffing	Management, technical, support, administration, etc.
Operating costs	Including logistics
Cashflow	Assets versus usable cash
Equipment	For data acquisition and/or for data reduction/analysis - computers and software; whether or not to hire or buy
Insurance	To include liability insurance, as appropriate
Overheads	Administration; consumables; etc.
Development costs	Skills, software, etc.
Contingencies	Something is bound to go wrong at some time, usually when it is most inconvenient!

common elements of a typical budget. Liability insurance is especially important if survey work is being carried out as a service to others. If there is any cause for complaint, then this may manifest itself in legal action (Sherrell 1987).

It may seem obvious to identify *logistics* as a constraint but there have been far too many surveys ruined by a lack of even the most basic needs of a survey. It is easy to think of the main people to be involved in a survey - i.e. geologists, geophysicists, surveyors - but there are many more tasks to be done to allow the technical staff the opportunity to concentrate on the tasks in hand. Vehicles and equipment will need maintaining, so skilled technicians and mechanics may be required. Everybody has to eat and it is surprising how much better people work when they are provided with well-prepared food: a good cook at base camp can be a real asset. Due consideration should be paid to health and safety and any survey team should have staff trained in First Aid. Admittedly it is possible for one person to be responsible for more than one task, but on large surveys this can prove to be a false economy. Apart from the skilled and technical staff, local labour may be needed as porters, labourers, guides, translators, etc., or even as armed guards!

It is all too easy to forget what field conditions can be like in remote and inaccessible places. It is thus important to remember that in the case of many countries, access in the dry season may be possible whereas during the rains of the wet season, the so-called roads (which often are dry river beds) may be totally impassable. Similarly, access to land for survey work can be severely hampered during the growing season with some crops reaching 2-3 metres high and consequently making position fixing and physical access extremely difficult. There is then the added complication that some surveys, such as seismic refraction and reflection, may cause a limited amount of damage for which financial compensation may be sought. In some cases, claims may be made even when no damage has been caused! If year-round access is necessary the provision of all-terrain vehicles and/or helicopters may prove to be the only option, and these are never cheap to operate.

Where equipment has to be transported, consideration has to be given not only to its overall weight but to the size of each container. It can prove an expensive mistake to find that the main piece of equipment will not pass through the doorway of a helicopter so that alternative overland transport has to be provided at very short notice; or to find that many extra hours of flying time are necessary to airlift all the equipment. It may even be necessary to make provision for a bulldozer to excavate a rough road to provide access for vehicles. If this is accounted for inadequately in the initial budgeting, the whole success of the survey can be jeopardised. Indeed, the biggest constraint in some developing countries, for example, is whether the equipment can be carried by a porter or will fit on the back of a pack-horse.

Other constraints that are rarely considered are those associated with *politics, society* and *religion.* Let us take these in turn.

Political constraints This can mean gaining permission from land-owners and tenants for access to land, and liaison with clients (which often requires great diplomacy). The compatibility of staff to work well together also needs to be considered, especially when working in areas where there may be conflicts between different factions of the local population – such as tribal disputes or party political disagreements. It is important to remember to seek permission from the *appropriate* authority to undertake geophysical fieldwork. For example, in Great Britain it is necessary to liaise with the police and local government departments if survey work along a major road is being considered, so as to avoid problems with traffic jams. In other cases it may be necessary to have permission from a local council, or in the case of marine surveys, from the local harbour master so that appropriate marine notices can be issued to safeguard other shipping. All these must be found out well before the start of any fieldwork. Delays cost money!

Social constraints For a survey to be successful it is always best to keep on good terms with the local people. Treating other people with respect will always bring dividends (eventually). Each survey should be socially and environmentally acceptable and not cause a nuisance. An example is in not choosing to use explosives as a seismic source for reflection profiling through urban areas or at night. Instead, the seismic vibrator technique should be used (see Chapter 4). Similarly, an explosive source for marine reflection profiling would be inappropriate in an area associated with a lucrative fishing industry because of possibly unacceptably high fish-kill. In designing the geophysical survey, the question must be asked: "Is the survey technique socially and environmentally acceptable?"

Religious constraints The survey should take into account local social customs which are often linked with religion. In some Muslim countries, for example, it is common in rural areas for women to be the principal water-collectors. It is considered inappropriate for the women to have to walk too far away from the seclusion of their homes. Thus there is no point in surveying for groundwater for a tubewell several kilometres from the village (Reynolds 1987a). In addition, when budgeting for the provision oflocal workers, it is best to allow for their 'sabbath'. Muslims like to go to their mosques on Friday afternoons and are thus unavailable for work then. Similarly, Christian workers tend not to like being asked to work on Sundays, or Jews on Saturdays. Religious traditions must be respected to avoid difficulties.

However, problems may come iflocal workers claim to be Muslims on Fridays and Christians on Sundays - and then that it is hardly worth anyone's while to have to work only on the Saturday in between so they end up not working Friday, Saturday or Sunday! Such situations, while sounding amusing, can cause unacceptable delays and result in considerably increased survey costs.

1.5 GEOPHYSICAL SURVEY DESIGN

1.5.1 Target identification

Geophysical methods locate boundaries across which there is a marked contrast in physical properties. Such a contrast can be detected remotely because it gives rise to a *geophysical anomaly* (Figure 1.4) which indicates variations in physical properties relative to some background value (Figure 1.5). The physical source of each anomaly is termed the *geophysical target.* Some examples of targets are trap structures for oil and gas, mineshafts, pipelines, ore lodes, cavities, groundwater, buried rock valleys, and so on.

In designing a geophysical survey, the type of target is of great importance. Each type of target will dictate to a large extent the appropriate geophysical method(s) to be used, and this is where an understanding of the basic geophysical principles is important. The physical properties associated with the geophysical target are best detected by the method(s) most sensitive to those same properties.

Consider the situation where saline water intrudes into a near-surface aquifer; saline water has a high conductivity (low resistivity) in comparison with freshwater and so is best detected using electrical resistivity or electromagnetic conductivity methods; gravity methods would be inappropriate because there would be virtually no density contrast between the saline and freshwater. Similarly, seismic methods would not work as there is no significant difference in seismic wave velocities between the two saturated zones. Table 1.1

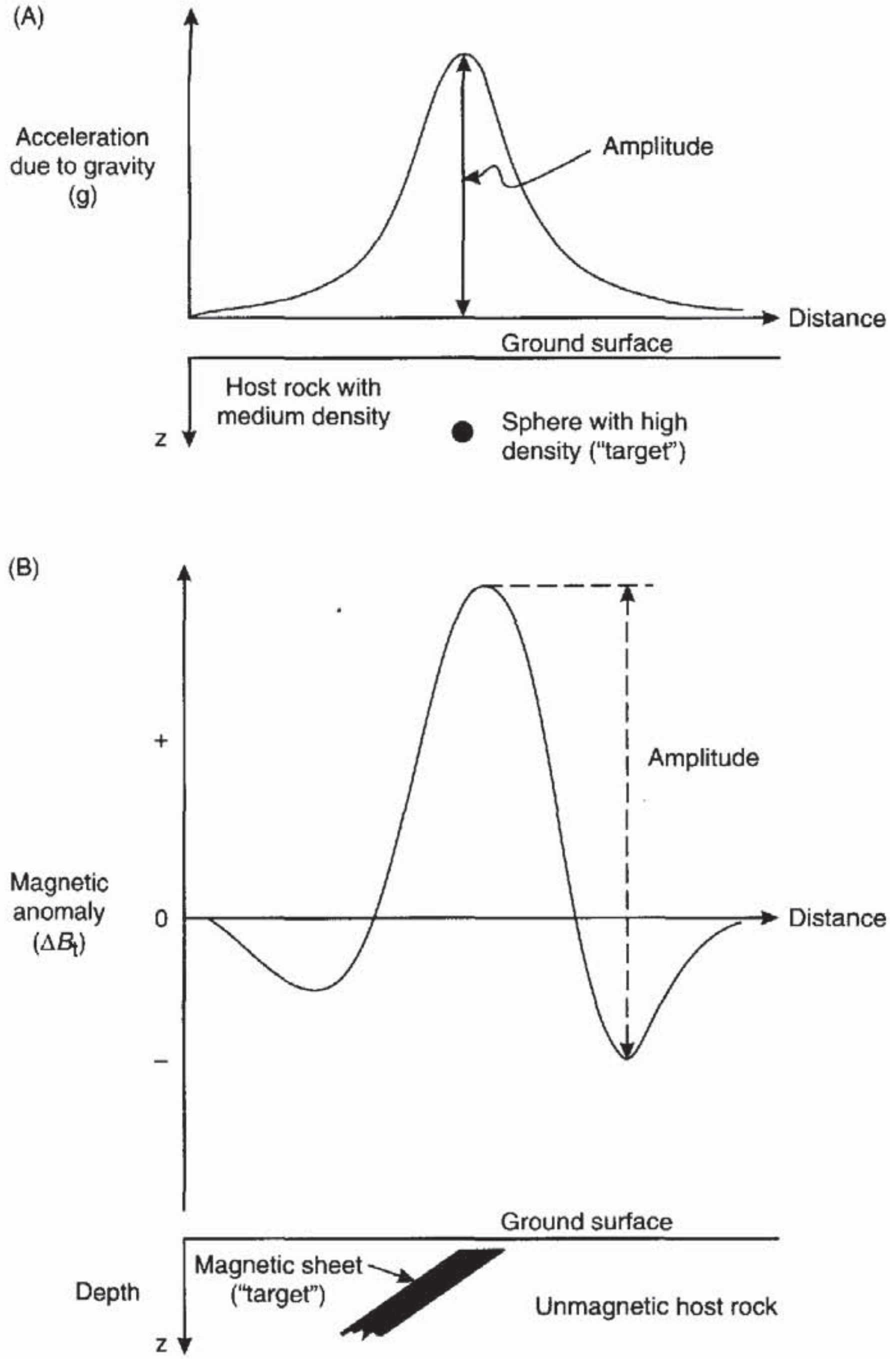


Figure 1.4 Examples of (A) a gravity anomaly over a buried sphere, and (B) a magnetic anomaly over an inclined magnetic sheet. For further details of gravity and magnetic methods, see Chapters 2 and 3 respectively

provides a ready means of selecting an appropriate technique for the major applications.

Although the physical characteristics of the target are important, so are its shape and size. In the case of a metallic ore lode, a mining company might need to know its lateral and vertical extent. An examination of the amplitude of the anomaly (i.e. its maximum peak-to-peak value) and its shape may provide further information about where the target is below ground and how big it is.

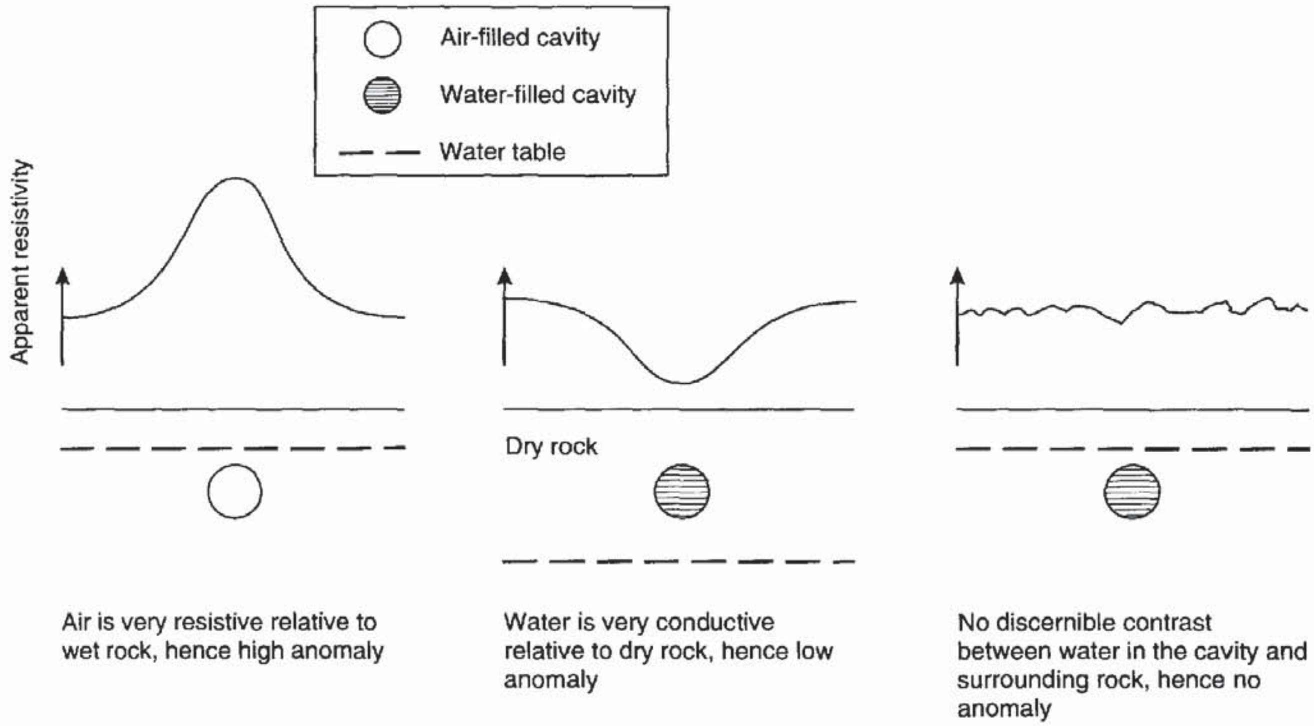


Figure 1.5 Contrasts in physical properties from different geological targets give rise to a geophysical target. When there is no contrast, the target is undetectable geophysically

1.5.2 Optimum line configuration

So far only the types of geological target and the selection of the most appropriate geophysical methods have been discussed. In order to complete a technically competent survey several other factors need to be given very careful thought. How are the data to be collected in order to define the geophysical anomaly? Two concepts need to be introduced, namely *profiling* and *mapping*.

Profiling is a means of measuring the variation in a physical parameter along the surface of a two-dimensional cross-section (Figure 1.6A). Consideration needs to be given to the correct orientation and length of profile (see below). Data values from a series of parallel lines or from a grid can be contoured to produce a *map* (Figure 1.6B) on which all points of equal value are joined by *isolines* (equivalent to contours on a topographic map). However, great care has to be taken over the methods of contouring or else the resultant map can be misleading (see Section 1.5.3). There are many other ways of displaying geophysical data (Figure 1.5C), especially if computer graphics are used (e.g. shaded relief maps as in Figure 1.6D), and examples are given throughout the book.

The best orientation of a profile is normally at right-angles to the strike of the target. A provisional indication of geological strike may be obtained from existing geological maps, mining records, etc. However, in many cases, strike direction may not be known at all and test lines may be necessary to determine strike direction prior to

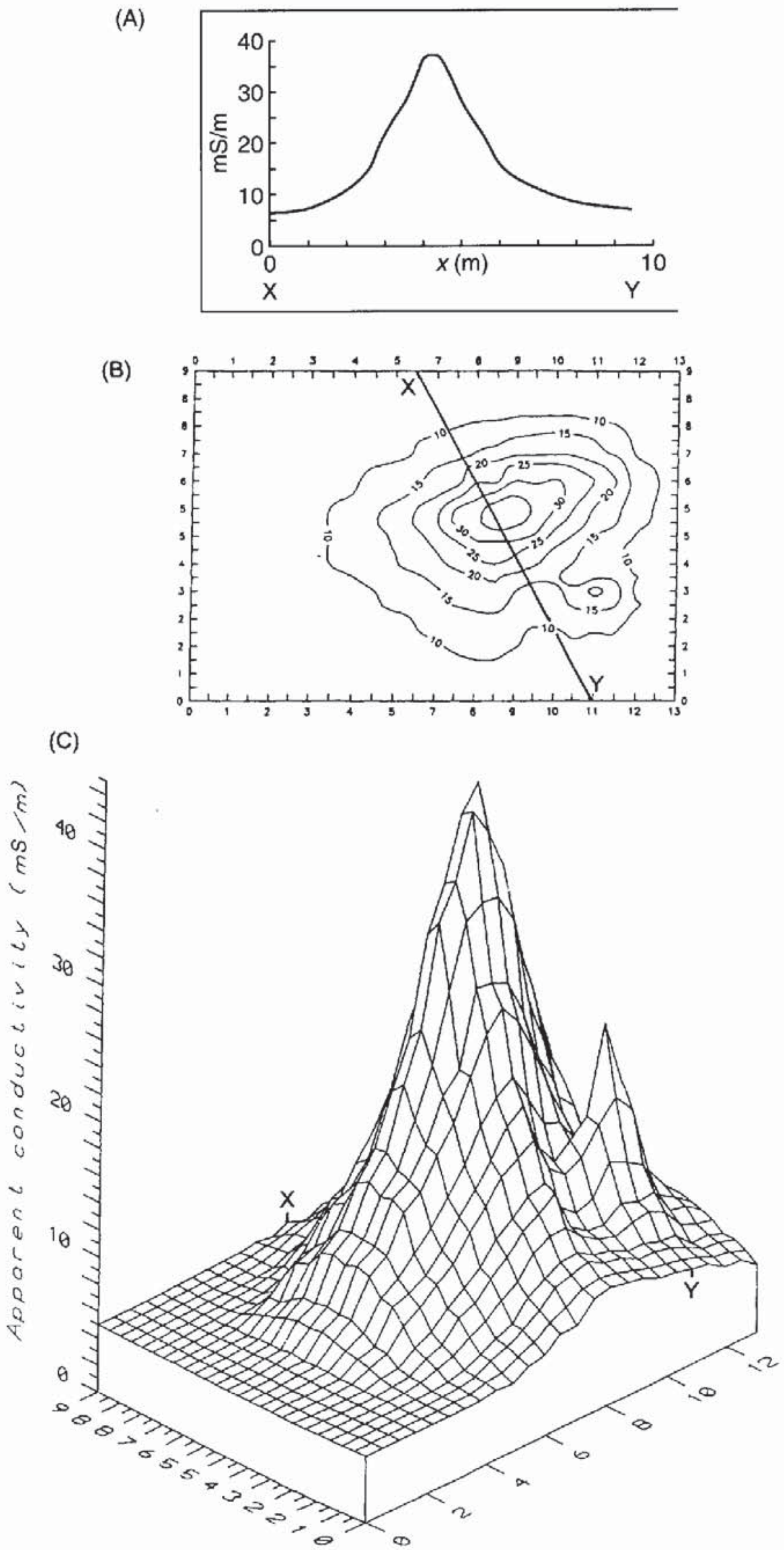
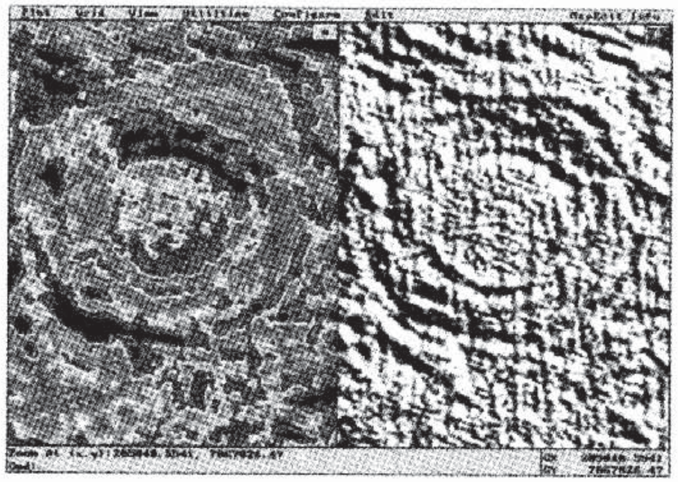


Figure 1.6 Geophysical anomaly plots: (A) profile, (B) map, and (C) isometric projection. All three plots are from the same set of electromagnetic ground-conductivity data (see Chapter 11). (D) A shaded relief/greyscale shadow display can enhance features that otherwise would be hard to visualise – in this case the display is of magnetic data over an area in which complex faulting appears as a series of concentric features that possibly may be part of a meteorite impact crater. Photos courtesy of Geosoft Europe Ltd

(D)



the main survey. The length of the profile should be greater than the width of the expected geophysical anomaly. If it is not, then it may be impossible to define a background value to determine the true anomaly amplitude and the value of the survey would be reduced greatly. The choice of line orientation also has to take into account sources of noise (see Section 1.5.4). If a map is required then it is advisable to carry out 'tie-lines' (cross-cutting profiles), the intersections (*nodes*) of which should have identical values. If the data are not the same at the nodes then the values need to be checked in case there has been a simple misprint in data entry, or there might have been an error in position-fixing or in instrumental calibration. When such data are compared, make sure all necessary data corrections have been made (see the individual chapters for details and examples) so that like is compared with like. Nodal values are vital for data quality control.

1.5.3 Selection of station intervals

The point at which a discrete geophysical measurement is made is called a *station* and the distances between successive measurements are *station intervals*.

It is fundamental to the success of a survey that the correct choice of station intervals be made. It is a waste of time and money to record too many data and equally wasteful if too few are collected. So how is a reasonable choice to be made? This requires some idea of the nature and size of the geological target. Any geophysical anomaly found will always be larger than the feature causing it. Thus, to find a mineshaft, for example, with a diameter of, say, 2 m, an anomaly with a width of at least twice this might be expected. Therefore, it is necessary to choose a station interval that is sufficiently small to be able to resolve the anomaly, yet not too small as to take far too long to be practicable.

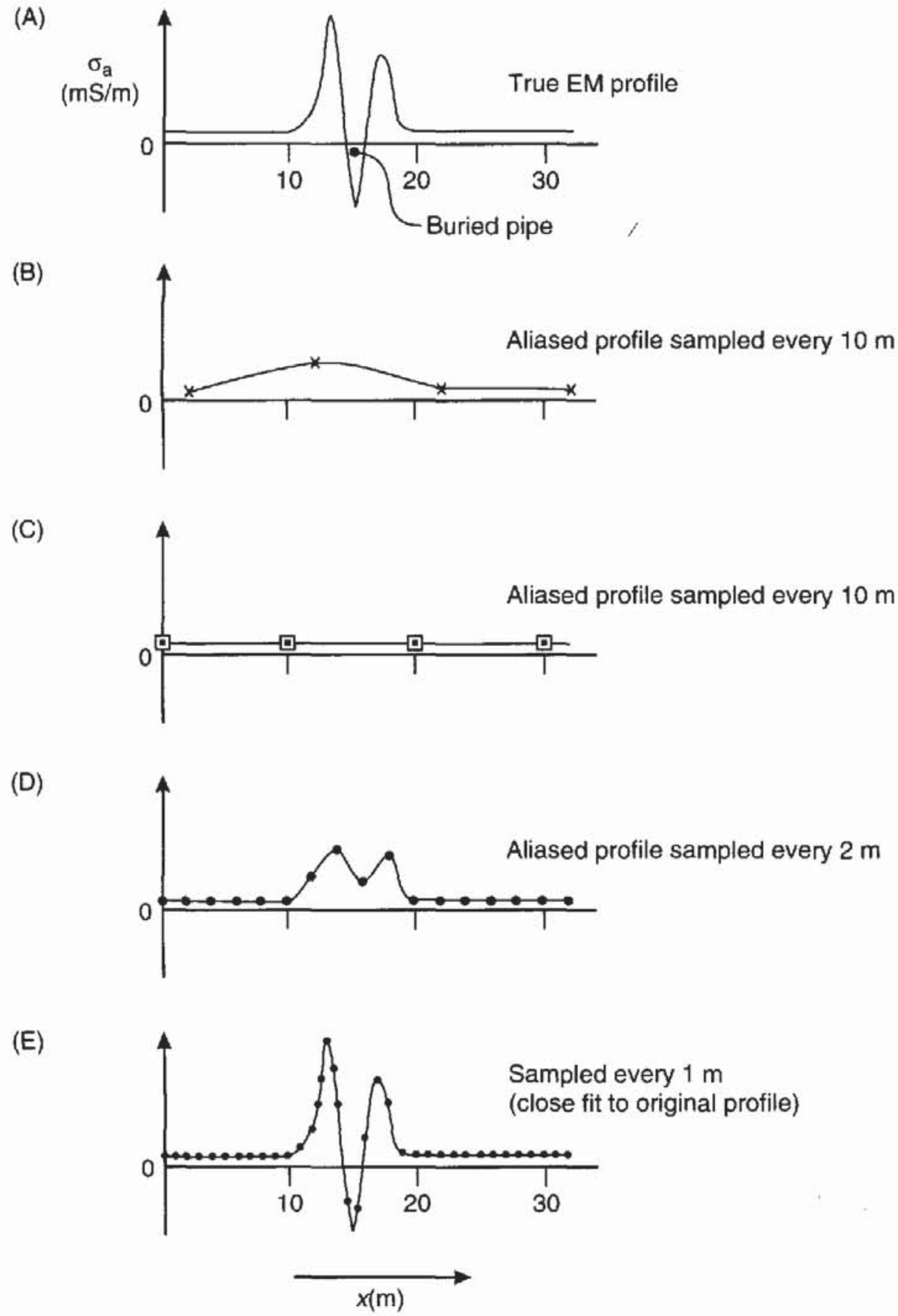


Figure 1.7 Examples of various degrees of spatial aliasing using different sampling intervals. (A) shows a continuously sampled profile. (B) and (C) show sampling every 10 m, but at different points along the profile. (D) shows sampling every 2 m: the profile is still aliased. (E) shows sampling every 1 m: this profile is the closest to that in (A)

Reconnaissance surveys tend to have coarser station intervals in order to cover a large area quickly and to indicate zones over which a more detailed survey should be conducted with a reduced station interval and a more closely spaced set of profiles.

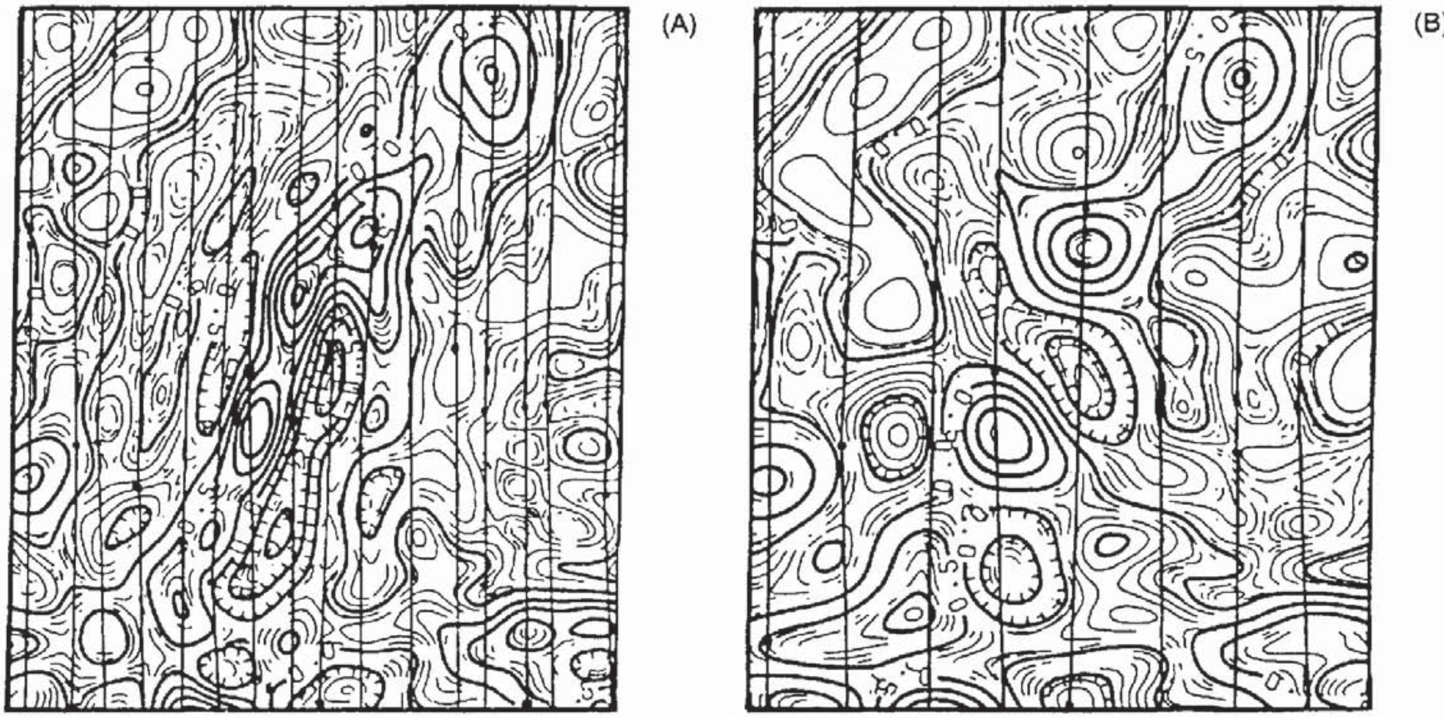
Consider Figure 1.7A in which a typical electromagnetic anomaly for a buried gas pipe is shown. The whole anomaly is 8 m wide. If a 10 m sampling interval is chosen, then it is possible either to clip the anomaly, as in Figure 1.7B, or to miss it entirely (Figure 1.7C). The resultant profiles with 2 m and 1 m sampling intervals are shown in Figures 1.7D and 1.7E respectively. The smaller the sampling interval, the better the approximation is to the actual anomaly (compare with Figure 1.7B or C). The loss of high-frequency information, as in Figures 1.7B and C, is a phenomenon known as *spatial aliasing* and should be avoided.

Another form of spatial aliasing may occur when gridded data are contoured, particularly by computer software. If the grid network is too coarse, higher-frequency information may be smeared artificially and appear as lower-frequency anomalies. A common characteristic of spatially aliased gridded data is the 'bullseye' effect (see Figure 1.8) where the contouring program has had too little information to work on and so has contoured around individual data points or has linked data together unjustifiably (Cameron *et al.* 1976; Hood *et al.* 1979; Reid 1980; Wu 1990). This kind of problem can be created by an inadequately detailed or an inappropriately designed field programme.

Figure 1.8 shows a hypothetical aeromagnetic survey. The map in Figure 1.8A was compiled from contouring the original data at a line spacing of 150 m. Figures 1.8B and C were recontoured with line spacings of 300 m and 600 m respectively. The difference between the three maps is very marked, with a significant loss of information between Figures 1.8A and C. Noticeably the higher-frequency anomalies have been aliased out, leaving only the longer-wavelength (lower-frequency) features. In addition, the orientation of the major anomalies has been distorted by the crude contouring in Figure 1.8C.

Spatial stretching occurs on datasets acquired along survey lines separated too widely with respect to along-line sampling. This spatial aliasing can be removed or reduced using mathematical functions, such as the Radon Transform (Yuanxuan 1993). This method provides a means of developing a better gridding scheme for profile line-based surveys. The specific details of the method are beyond the scope of this chapter and readers are referred to Yuanxuan's paper for more information.

Similar aliasing problems associated with contouring can arise from radial survey lines and/or too few data points, as exemplified by Figure 1.9. Figure 1.9A and B both have 64 data points over the same area, and two effects can be seen very clearly: in Figure 1.9A the orientation of the contours (one marked 47 500 nT) artificially follows that of the line of data points to the top left-hand corner, whereas the orientation is more north–south in Figure 1.9B. The even grid in Figure 1.9B highlights the second effect (even more pronounced in Figure 1.9C), which is the formation of bullseyes around individual data points. The inadequacy of the number of data points is further demonstrated in Figure 1.9C, which is based on only 13 data values, by the formation of concentric contours that are artificially rounded in the top left and both bottom corners. For comparison, Figure 1.9D has been compiled on the basis of 255 data points, and exposes the observed anomalies much more realistically.



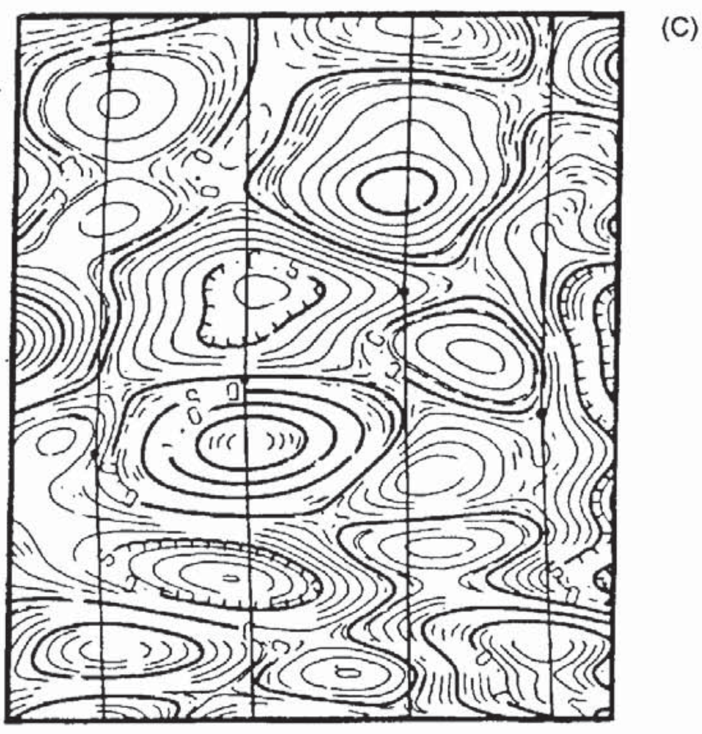


Figure 1.8 Example of spatial aliasing on aeromagnetic data, showing the loss of higher-frequency anomalies with increasing separation between flight lines and the increased 'bullseye' effect caused by stretching the data too far. From Hood *et al.* (1979), by permission

1.5.4 Noise

When a field survey is being designed it is important to consider what extraneous data (*noise*) may be recorded. There are various sources of noise, ranging from man-made sources ('cultural noise') as diverse as electric cables, vehicles, pipes and drains, to natural sources of noise

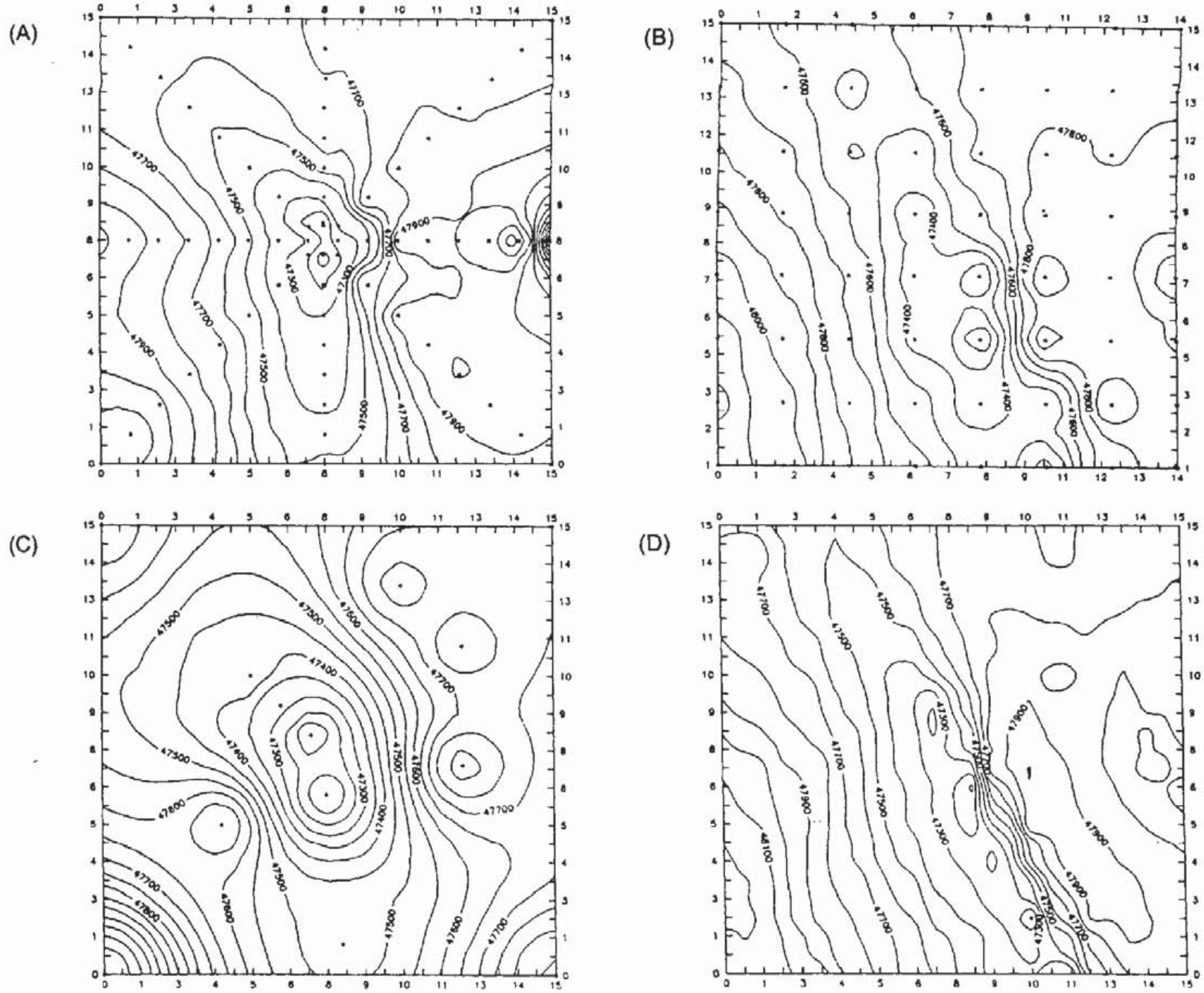


Figure 1.9 Examples of contouring different patterns of data. (A) shows a set of radial lines, and (B) an even grid of data, both with 114 points per square kilometre. (C) has too few data points unevenly spread over the same area (23 data points per square kilometre). (D) shows an even grid of 453 data points per square kilometre. The contours are isolines of total magnetic field strength (units: nanoteslas); the data are from a ground magnetometer investigation of north-west Dartmoor, England

such as wind and rain, waves, and electric and magnetic storms (Figure 1.10).

Some aeromagnetic and electrical methods can suffer badly from cathodic currents that are used to reduce corrosion in metal pipes (Gay 1986). Electrical resistivity surveys should not be conducted close to or parallel to such pipes, nor parallel to cables as power lines will induce unwanted voltages in the survey wires. Before a survey starts, it is always advisable to consult with public utility companies which should, given enough time, provide maps of their underground and overhead facilities. It is important to check on the location of water mains, sewers, gas pipes, electricity cables, telephone cables and cable-television wires. In many cases such utilities may mask any anomalies caused by deeper-seated natural bodies. Furthermore, should direct excavation be required, the utilities underground may be damaged if their locations are not known.

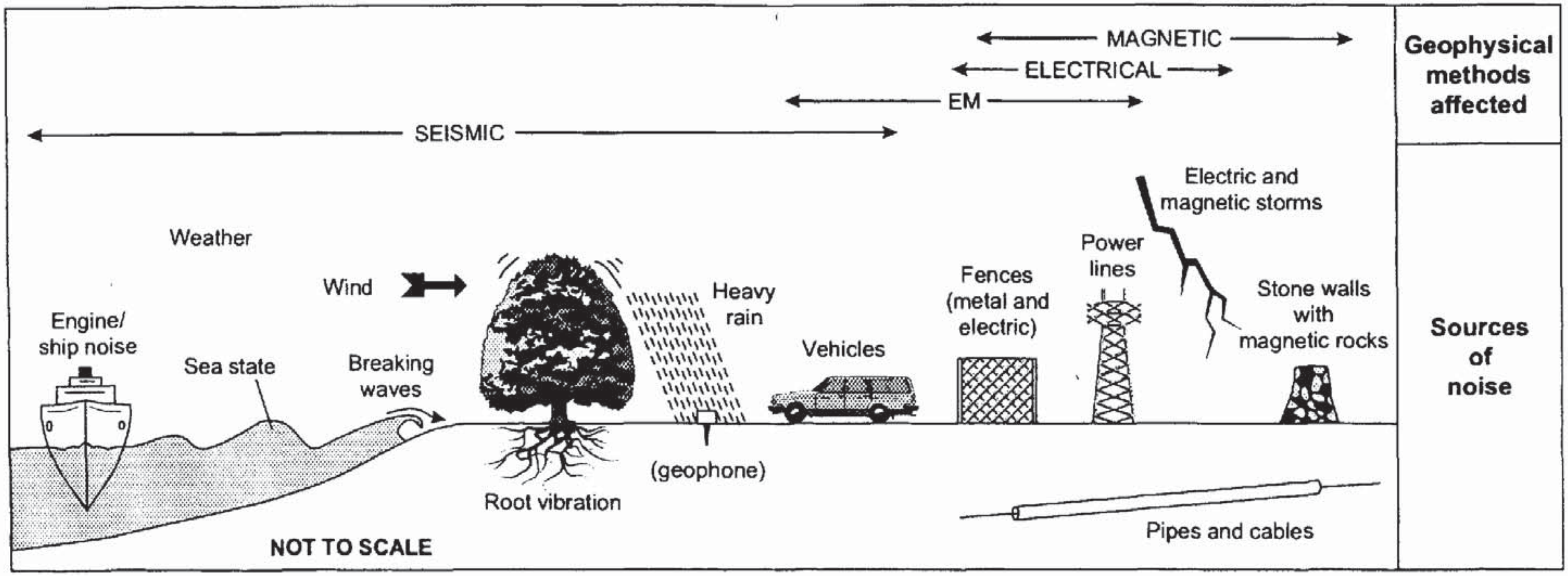


Figure 1.10 Schematic illustrating some common sources of geophysical noise

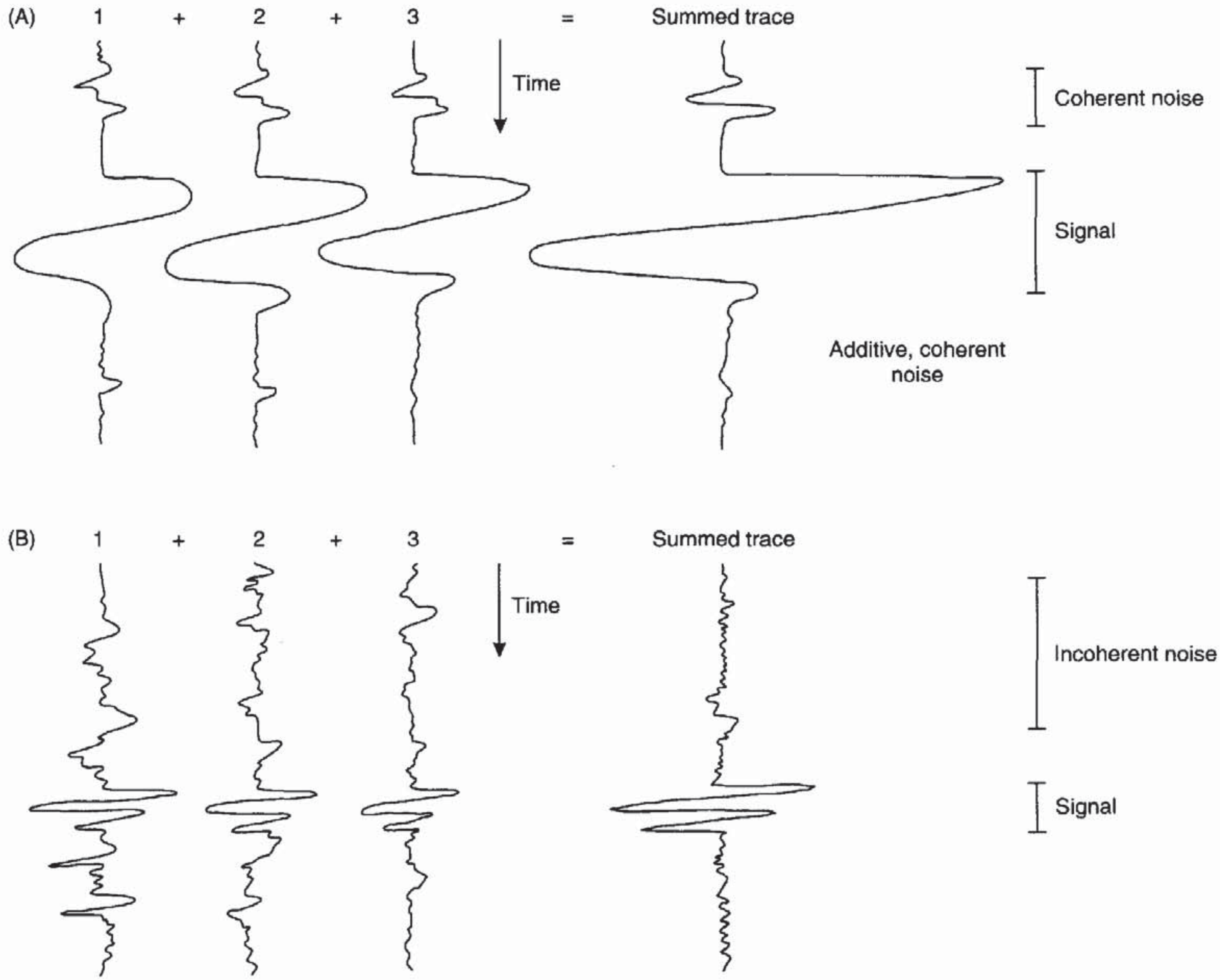


Figure 1.11 The effect of summing three traces with (A) coherent and (B) incoherent noise

It is also worth checking on the type of fencing around the survey area. Wire mesh and barbed wire fences, and metal sheds can play havoc with electromagnetic and magnetic surveys and will restrict the area over which sensible results can be obtained. It also pays to watch out for types of walling around fields as in many areas wire fences may be concealed by years of growth of the local vegetation. In addition, when undertaking a magnetic survey, be on the lookout for stone walls built of basic igneous rocks as these can give a noticeable magnetic anomaly.

There are two forms of noise (Figure 1.11).

- *Coherent noise*, such as that produced by power lines, occurs systematically (Figure 1.11A) and may degrade or even swamp the wanted signals. As coherent noise usually occurs with a definable frequency (e.g. mains electricity at 50–60 Hz), appropriate filters can be used to remove or reduce it.

- In contrast, *incoherent noise*, such as that due to waves breaking on a seashore or to traffic, is random. When summed together it tends to cancel to some extent, so reducing its overall effect (Figure 1.11B).

High, but incoherent, noise levels are often associated with surveys along road verges. Metal-bodied vehicles passing by during an electromagnetic survey can cause massive but brief disturbances. Vehicles, particularly heavy lorries, and trains can set up short-lived but excessive acoustic noise which can ruin a seismic survey. So, too, can the effects of waves washing onto beaches or the noise of turbulent riverwater close to geophone spreads on a seismic survey. In exposed areas, geophones that have not been planted properly may pick up wind vibration acting on the geophones themselves and on the connecting cable, but also from trees blowing in the breeze, as the motion transmits vibrations into the ground via their root systems. Similar effects can be observed close to man-made structures. Unprotected geophones are very sensitive to the impact of rain drops which can lead to the curtailment of a seismic survey during heavy rain.

Cultural and unnecessary natural noise can often be avoided or reduced significantly by careful survey design. Increasingly, modern technology can help to increase the *signal-to-noise ratio* so that, even when there is a degree of noise present, the important geophysical signals can be enhanced above the background noise levels (Figure 1.12). Details of this are given in the relevant sections of later chapters. However, it is usually better to use a properly designed field technique to optimise data quality in the first instance rather than relying on post-recording filtering. Further details of field methods are given, for example, by Milsom (1989).

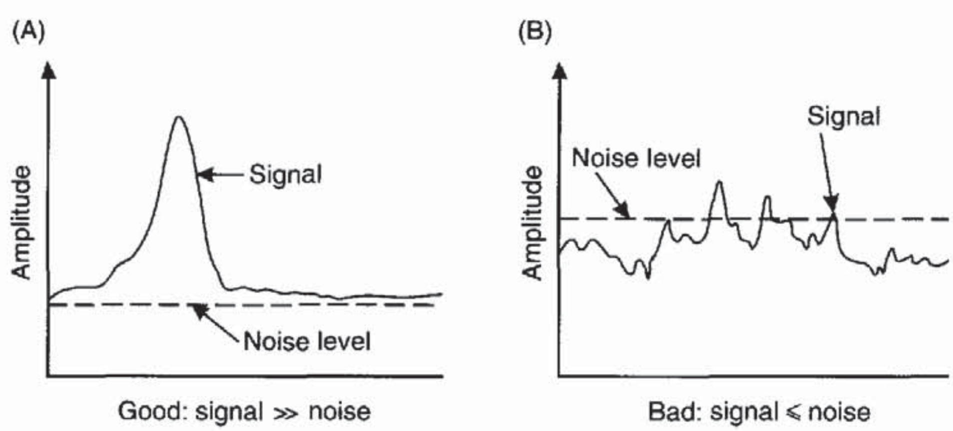


Figure 1.12 Signal-to-noise ratio. In (A) the signal has a much larger amplitude than that of the background noise, so the signal can be resolved. In (B) the signal amplitude is less than, or about the same as, that of the noise and thus the signal is lost in the noise

1.5.5 Data analysis

All too often data are acquired without regard for how they are to be processed and analysed. This oversight can lead to inadequate data collection or the recording of data in such a way that vast amounts of tedious transcribing or typing in of measurements has to be undertaken. Not only is this unproductive in terms of the person who has to do all the 'number crunching', but it often allows the introduction of errors into the datasets. The consequent back-checking to find the bad data takes up valuable time and money. It therefore pays dividends to think through how the data are to be collected in relation to the subsequent methods of data reduction and analysis. A scheme is presented in Figure 1.13.

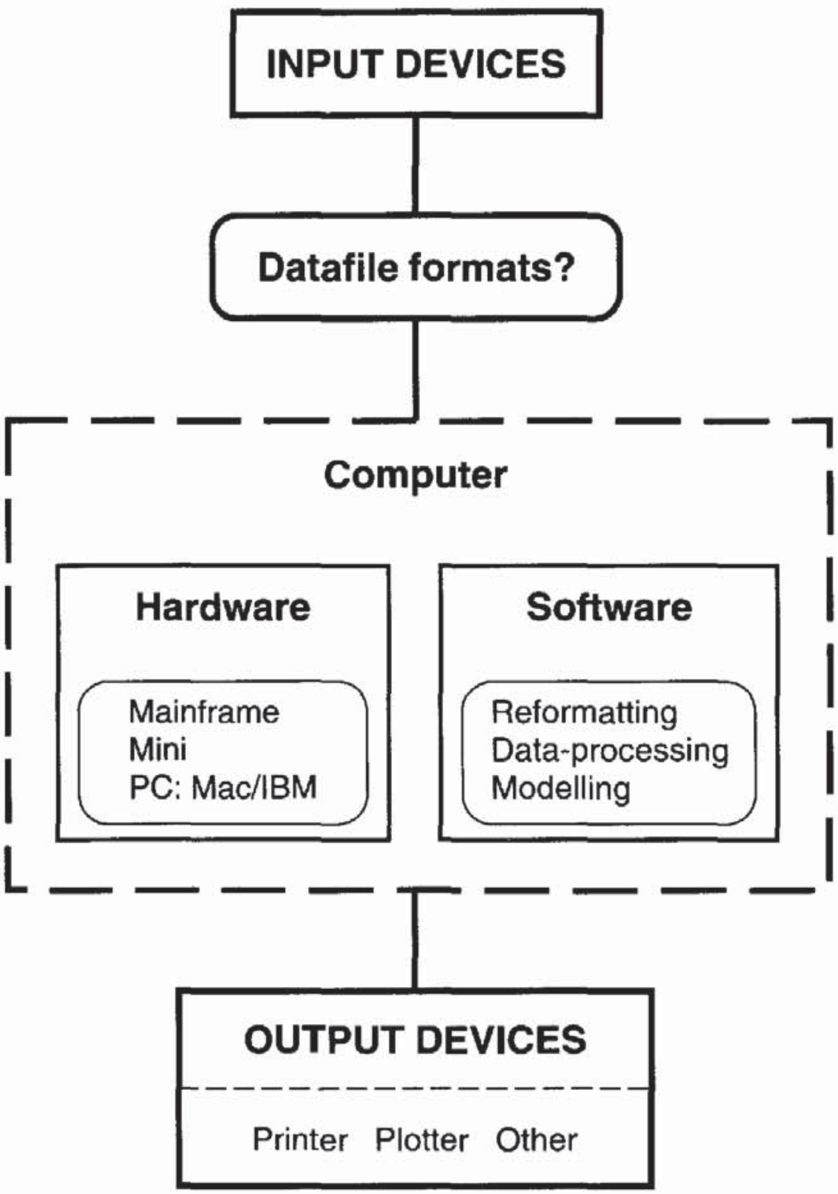


Figure 1.13 Schematic to show the relationship between various input devices, through data-file formats to the computer, and subsequently to some form of hardcopy device. From Reynolds (1991a), by permission

As automatic data-logging and computer analysis are becoming more commonplace (e.g. Sowerbutts and Mason 1984) it is increasingly important to standardise the format in which the data are recorded (Reeves and MacLeod 1986) to ease the portability of information transfer between computer systems. This also makes it easier to download the survey results into data-processing software packages. To make computer analysis much simpler it helps to plan the survey well before going into the field to ensure that the collection of data and the survey design are appropriate for the type of analyses anticipated. Even here, there are many pitfalls awaiting the unwary. How reliable is the software? Has it been calibrated against proven manual methods, if appropriate? What are the assumptions on which the software is based, and under what conditions are these no longer valid, and when will the software fail to cope and then start to produce erroneous results? (For an example of this, see Section 7.5.3.)

The danger with computers is that their output (especially if in colour) can have an apparent credibility that may not be justified by the quality of the data input or of the analysis. Unfortunately there are no guidelines or accepted standards for much geophysical software (Reynolds 1991a) apart from those for the major seismic data-processing systems. However, the judicious use of computers and of automatic data-logging methods can produce excellent and very worthwhile results (e.g. Sowerbutts and Mason 1984). Comments on some of the computer methods available with different geophysical techniques are made in the relevant chapters of this book, and some have been discussed more fully elsewhere (Reynolds 1991a).

For users of personal computers, there are two main software houses generating commercially available geophysical computer packages, namely Geosoft Ltd in Canada and Interpex Ltd in the USA. Geosoft also produces gridding and contouring packages, as does Golden Software (USA), producers of SURFER. Commercial products vary widely in their ranges of applications, flexibility and portability between different computers. Intending users of any software package should evaluate the software prior to purchase if possible.

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Further reading

See also monographs and special publications produced by the Society for Exploration Geophysicists (SEG), and by the Environmental and Engineering Geophysical Society (EEGS). The latter holds an annual Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP) and publishes the proceedings. Other organisations of note are the Australian Society of Exploration Geophysics (ASEG), the Canadian Exploration Geophysics Society, the South African Geophysical Association, and the European Association of Geoscientists and Engineers (EAGE), among others.

ASEG publishes the quarterly journal *Exploration Geophysics*; SEG publishes the journals *Geophysics* and *Geophysics: The Leading Edge*, and books, monographs and audiovisual materials (slides, videos, etc.). In July 1995, the EEGS published an inaugural volume of the *Journal of Environmental and Engineering Geophysics*, and in January 1996 the European Section of the EEGS launched the first issue of the *European Journal of Environmental and Engineering Geophysics*. The EAGE produces *Geophysical Prospecting*.

The list above gives a general idea of what is available. For those interested particularly in archaeological geophysics, very useful guidelines have been produced by the English Heritage Society (David 1995). During 1995, John Wiley & Sons Ltd produced the first two issues of another new journal entitled *Archaeological Prospection*.

The rapid growth in the number of journals and other publications in environmental and engineering geophysics demonstrates the growing interest in the subject and the better awareness of the applicability of modern geophysical methods.