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 of the 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 (2002: p. 161) 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 that 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 subdiscipline of *'environmental geophysics'* has developed (Greenhouse, 1991; Steeples, 1991). This can be defined as being:

> *The application of geophysical methods to the investigation of near-surface bio-physico-chemical phenomena that 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 can be 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 of the advantages of using geophysical methods is that they are largely environmentally benign – there is no disturbance of subsurface 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.

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 six other subdisciplines whose names are largely self-explanatory: namely, *agrogeophysics* (the use of geophysics for agriculture and soil science),

An Introduction to Applied and Environment Geophysics, Second Edition. John Reynolds © 2011 John Wiley & Sons, Ltd. Published 2011 by John Wiley & Sons, Ltd.

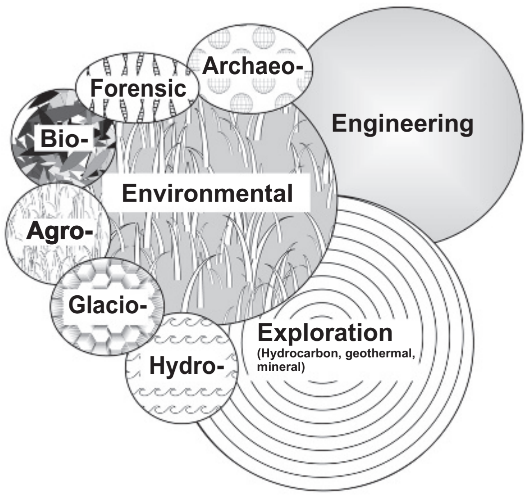

Figure 1.1 Inter-relationships between the various subdisciplines of applied geophysics. [C]

archaeo-geophysics (geophysics in archaeology), *bio-geophysics* (geophysical manifestation of microbial activity within geological materials), *forensic geophysics* (the application of geophysical methods to investigations that might come before a court of law), *glacio-geophysics* (geophysics in glaciology) and *hydro-geophysics* (geophysics in groundwater investigations; see Pellerin *et al.* (2009) and accompanying papers). Glacio-geophysics is particularly well established within the polar scientific communities and has been since the 1950s. The application of ground-based geophysical techniques for glaciological studies (and particularly on temperate glaciers) has come of age especially since the early 1990s (see for example the thematic set of papers on the geophysics of glacial and frozen materials, Kulessa and Woodward (2007)). Forensic geophysics is now recognised as a subdiscipline of forensic geoscience ('geoforensics'; cf. Ruffell and McKinley, 2008) and is used regularly in police investigations in searches for mortal remains, buried bullion, and so on: see Pye and Croft (2003) and Ruffell (2006) for a basic introduction and signposting to other literature. The subdiscipline of bio-geophysics has emerged over the last decade or so (e.g. Williams *et al.* 2005; Slater and Atekwana, 2009) and examines the geophysical signatures of microbial cells in the Earth, the interaction of microorganisms and subsurface geological materials, and alteration of the physical and chemical properties of geological materials as a result of microbial activity. The microbial activity may be natural, as in microbial bio-mineralisation, or artificial as in the insertion of bacteria into the ground to remediate diesel spills, for example. Perhaps the newest branch is agro-geophysics (Allred *et al.*, 2008; Lück and Müller, 2009), which has emerged over the last decade. Recent examples of these applications of geophysics include water retention capacity of agricultural soils (Lück *et al.*, 2009, effects of long-term fertilisation on soil properties (Werban *et al.*, 2009), and influences of tillage on soil moisture content (Müller *et al.*, 2009).

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. Although the growth of this discipline has increased dramatically since the 1990s, it has not been as universally accepted as some anticipated. The reasons for this include the reluctance of some engineers to adopt modern geophysical methods, site investigation companies make more money out of drilling and trial pitting, and the perceived high cost of using geophysics rather than appreciating the subsequent 'whole project life' cost-benefit. What is clear, however, is that engineering and environmental geophysics are becoming increasingly important in the management of our environment.

A further major advantage of the use of environmental geophysics in investigating sites is that large areas of the ground 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). Commonly, trial pits are located on a 50 m by 50 m grid, and sometimes 25 m by 25 m. The disadvantage of this is that key areas of contamination can easily be missed, substantially reducing the value 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. For instance, consider the example shown in Table 1.1. On this particular site in northwest London, three successive site investigations had been undertaken over a former industrial site, involving trial pits, boreholes, and stripping 0.3 m off the ground level. For a 2 ha area, only 32 trial pits would have been used to characterise the site, representing sampling of less than 1% by area. Typically, as long as a field crew can gain access to the site on foot and the majority of obstacles have been removed, a geophysical survey can access more than 90% by area of a site. A typical geophysical survey

Table 1.1 Statistics of the use of geophysical surveys or trial pitting on a 2 ha site.

	Trial pits	Geophysics
Total site area	20,000 m^2	20,000 m^2
Area sampled	192 m^2 [<1%]	19,000 m^2 [95%]
Number of samples	32 pits [3 m by 2 m]	9,500 to >38,000 stations
Depth of sampling	1–5 m (notional)[a]	5–6 m (notional)
Contracting costs	~£3,500	~£6,300
Cost/m^2	£18.23	£0.33
Typical success rate[b]	<10%	>90%
Sampling grid	25 m by 25 m	2 m x 1 m [EM31]; 2 m x <0.2 [mag]
Time on site	4 days	5 days

[a] Depends upon the reach of the mechanical excavator;
[b] Assuming the target has an area of 5 m by 5 m and has physical properties contrasting with those of the host material.

over a brownfield (former industrial) site would consist of a ground conductivity and magnetic gradiometry survey, using dGPS for position fixing. Consequently, the line interval would commonly be 2 m and with a station interval along the line as small as 0.1 m, using a sampling rate of ten measurements a second and a reasonable walking pace for hand-carried instruments. The relative depths of penetration are as deep as a mechanical excavator can reach, typically down to 5 m below ground level; for the geophysical survey, this is a function of the method and the effective contribution of the target to form an anomaly. For a ground conductivity meter (e.g. Geonics EM31), the nominal depth of penetration is 6 m.

Had intrusive methods alone been used, then the probability of finding a target with dimensions of 5 m by 5 m would be <10%, whereas with geophysical methods (in this case ground conductivity and magnetic gradiometry) the success rate would be greater than 90%. Unfortunately, some clients see only the relative costs of the two methods, and geophysics loses out each time on this basis. However, if the cost-benefit is taken on the basis of the degree of success in finding objects, then the geophysical survey wins by a large margin. This is the difference between *cost* and *cost-benefit*!

Instead of trying to have a competition between intrusive methods OR geophysics, the best practice is to use BOTH, where it is appropriate. By so doing, the geophysical survey can be used to target trial pits onto features that have been identified as anomalies by the geophysical survey. The benefit of this can be seen by reference to the two sets of ground models shown in Figure 1.2 (Reynolds, 2004b). The first model (Figure 1.2A) was produced purely as a consequence of four trial pits and one borehole. The second (Figure 1.2C) was derived following a geophysical survey (Figure 1.2B) and excavating on the locations of geophysical anomalies. It is clear that the combined approach has provided a much better knowledge of the subsurface materials.

Geophysical methods are being seen increasingly not just as a set of tools for site investigation but as a means of risk management. With the growing requirements for audit trails for liability, the risks associated with missing an important feature on a site may result in large financial penalties or legal action. For example, an environmental consultant may operate with a warranty to their client so that if the consultant misses a feature during a ground investigation that is material to the development of the site, they become liable for its remediation. A drilling contractor may want to have assurance that there are no obstructions or UneXploded Ordnance (UXO) at the location of the proposed borehole. Sites may be known to have natural voids or man-made cavities (cellars, basements) that, if not located, could represent a significant hazard to vehicles or pedestrians passing over them, with the risk that someone could be killed or seriously injured. Geophysical methods can locate live underground electricity cables effectively. Failure to identify the location of such a target could result in electrocution and death of a worker involved in excavation, and damage to such a cable.

1.2 Geophysical methods

Geophysical methods respond to the physical properties of the subsurface 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,

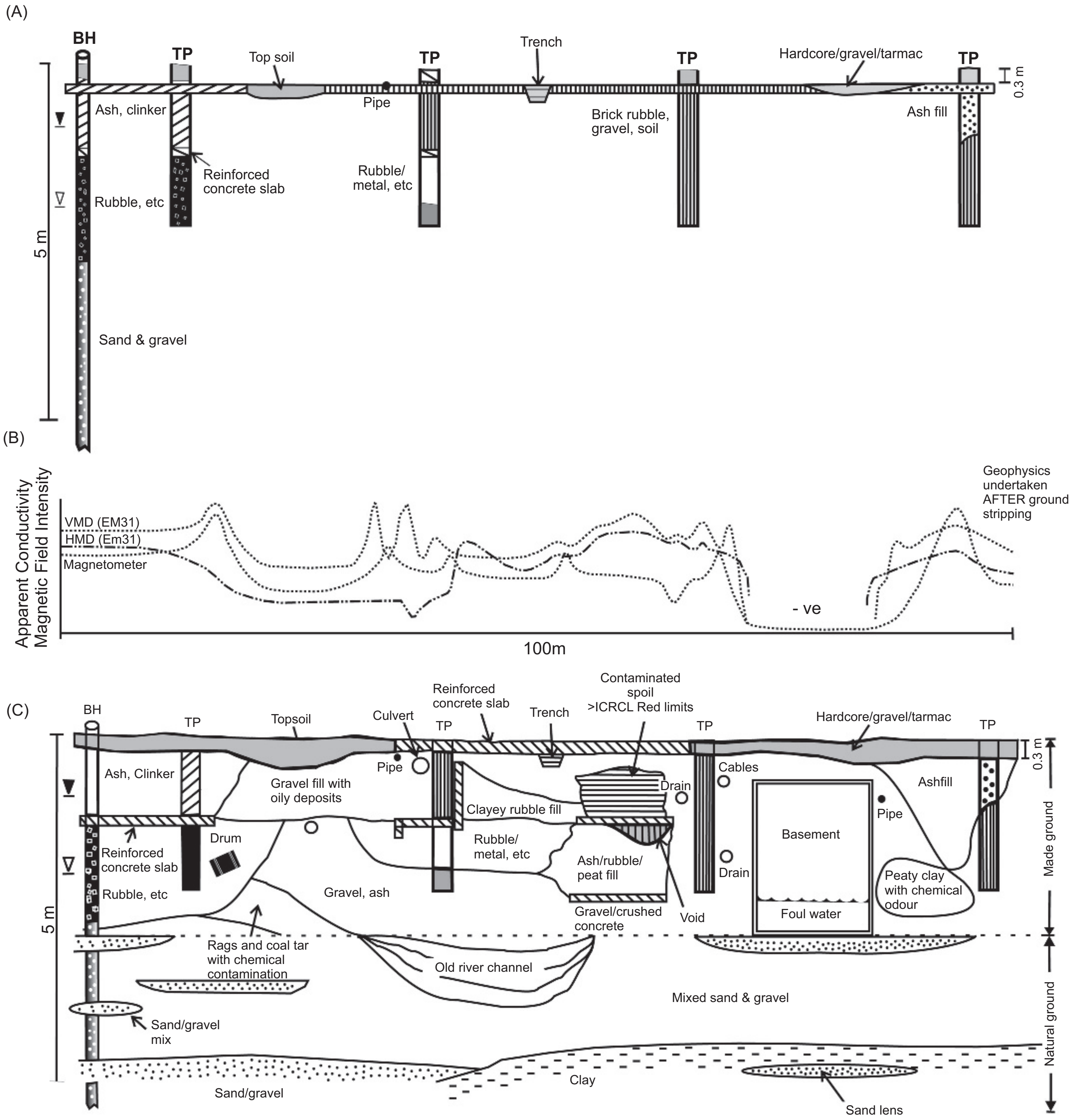

Figure 1.2 Ground models derived from (A) an intrusive investigation only, (B) a combined profile from a comprehensive geophysical survey, and (C) final interpretation of a subsequent intrusive investigation targeted on the geophysical anomalies. [C]

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 (i.e. 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 subsurface geology and so are ideal for exploring 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 localised 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 1.2 with the physical properties to which they relate and their main uses. Table 1.2 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 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 the 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 very clearly in respect of a geomagnetic anomaly over Lausanne in Switzerland (Figure 1.3). 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: British Standards Institute BS 5930 (1981), Hawkins (1986), Geological Society Engineering Group Working Party Report on Engineering Geophysics (1988), and most recently, their revised report published in 2002 (McDowell *et al.*, 2002), although see a review of this publication by Reynolds (2004b). 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 important that geophysicists maintain a sense of realism when marketing geophysical methods, if expectations are to be matched by actual outcomes. Geophysical contractors tend to spend the vast majority of their time on data acquisition and a minimal amount of time on interpretation and reporting. 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

Table 1.2 Geophysical methods and their main applications

			Applications (see key below)											
Geophysical method	Chapter number	Dependent physical property	1	2	3	4	5	6	7	8	9	10	11	12
Gravity	2	Density	P	P	s	s	s	s	x	x	s	x	x	x
Magnetic	3	Susceptibility	P	P	P	P	x	m	x	P	P	x	x	P
Seismic refraction	4, 5	Elastic moduli; density	P	P	m	s	s	s	x	x	x	x	x	x
Seismic reflection	4, 6	Elastic moduli; density	P	P	m	s	s	m	x	x	x	x	x	x
Resistivity	7	Resistivity	m	m	P	P	P	P	P	s	P	P	m	x
Spontaneous potential	8	Potential differences	x	x	P	m	P	m	m	m	x	P	x	x
Induced polarisation	9	Resistivity; capacitance	m	m	P	m	s	m	m	m	m	P	m	x
Electro-Magnetic (EM)	10, 11	Conductance; inductance	s	P	P	P	P	P	P	P	P	m	m	P
EM – VLF	12	Conductance; inductance	m	m	P	m	s	s	s	m	m	x	x	x
EM – GPR	13, 14	Permittivity; conductivity	x	x	m	P	P	P	s	P	P	m	P	s
Magneto-telluric	12	Resistivity	s	P	P	m	m	x	x	x	x	x	x	x
Magnetic Resonance Sounding (MRS)	12	Magnetic moment; porosity	x	x	x	x	P	x	m	x	x	x	x	x
Radiometrics	15	γ-radioactivity	s	s	P	s	x	x	x	x	x	x	x	x

P = primary method; s = secondary method; m = may be used but not necessarily the best approach, or has not been developed for this application; x = 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/environmental site investigation
5 Hydrogeological investigations
6 Detection of subsurface cavities
7 Mapping of leachate and contaminant plumes
8 Location and definition of buried metallic objects
9 Archaeogeophysics
10 Biogeophysics
11 Forensic geophysics
12 UneXploded Ordnance (UXO) detection

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 ‘blunderbuss’ 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 at a given location, 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 geophysicists are employed for the vital survey design, site supervision and final reporting. Indeed, the latest guidelines (McDowell *et al.*, 2002) extol the virtues of employing what is being called in the UK an *Engineering Geophysics Advisor* (EGA). Some of the benefits of employing an Engineering Geophysics Advisor are:

- The survey design is undertaken objectively;
- The appropriate geophysical contractor(s) is/are selected on the basis of their capability and expertise, not on just what kit they have available at the time;
- The contractor is supervised in the field (to monitor data quality, survey layout, deal with issues on site, gather additional information to aid the interpretation);

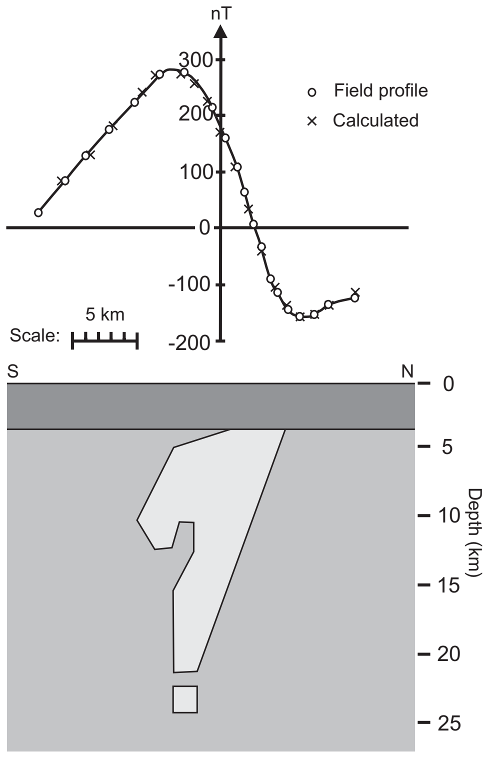

Figure 1.3 A magnetic anomaly over Lausanne, Switzerland, with a hypothetical and unreal model for which the computed anomaly still fits the observed data. After Meyer de Stadelhofen and Juillard (1987).

- The contractor's factual report is reviewed objectively;
- The field data and any processed data from the contractor are scrutinised prior to further analysis and modelling;
- The analysis, modelling, and interpretation can be undertaken by specialists who have the time and budget to do so, to extract the necessary information to meet the survey objectives for the Client;
- The analysis can incorporate additional information (geological, historical, environmental, engineering, etc.) and integrate it to produce a more holistic interpretation and more robust recommendations for the Client.

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 1.4. The remainder of this chapter discusses the relationships between the various components.

1.4.3 Survey constraints

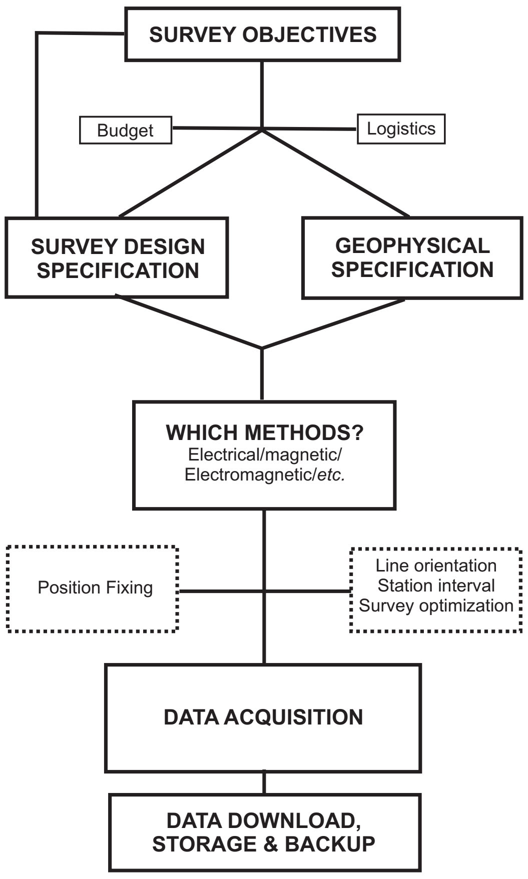

Figure 1.4 Schematic flow diagram to illustrate the decision-making leading to the selection of geophysical and utility software. After Reynolds (1991a).

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 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 1.3. This list is not exhaustive but serves to highlight the most 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).

Table 1.3 Basic elements of a survey budget.

Staffing	Management, technical, support, administration, etc.
Operating costs	*Including logistics*
Cashflow	*Assets versus useable cash*
Equipment	*For data acquisition and/or data reduction/analysis – computers and software; whether or not to hire, lease or buy*
Insurances	*To include public, employer's and professional indemnity insurances, 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*

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, additional field assistants, 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 or yak.

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 landowners 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 the UK 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 of local 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, and so on. Religious traditions must be respected to avoid difficulties.

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 1.5) which indicates variations in physical properties relative to some background value (Figure 1.6). 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.

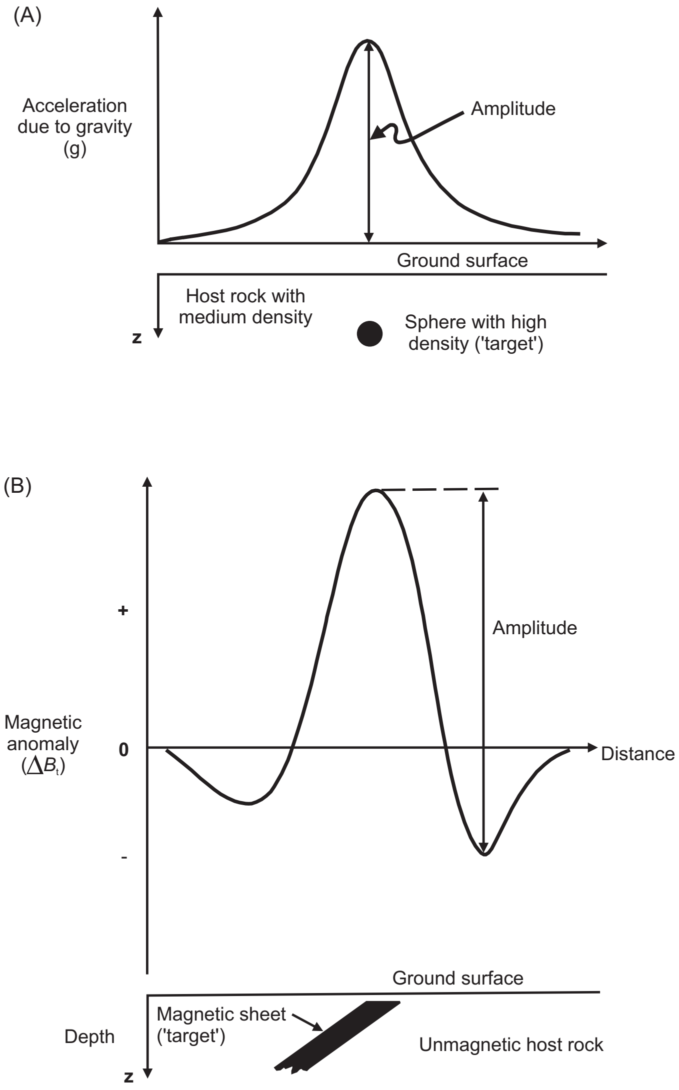

Figure 1.5 Examples of (A) a gravity anomaly over a buried sphere, and (B) a magnetic anomaly over an inclined magnetic sheet. For further details of gravity and magnetic methods, see Chapters 2 and 3 respectively.

Consider the situation where saline water intrudes into a near-surface aquifer; saline water has a high conductivity (low resistivity) in comparison with fresh water 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 fresh water. Similarly, seismic methods would not work as there is no significant difference in seismic wave velocities between the two saturated zones. Table 1.1 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.

1.5.2 Optimum line configuration and survey dimensions

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 1.7A). Consideration needs to be given to the correct orientation and length of the profile (see below). Data values from a series of parallel lines or from a grid can be contoured to produce a *map* (Figure 1.7B) 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 1.7C), especially if computer graphics are used (e.g. shaded relief maps as in Figure 1.7D), 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 and mining records. However, in many cases, strike direction may not be known at all and test lines may be necessary to determine strike direction prior to 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

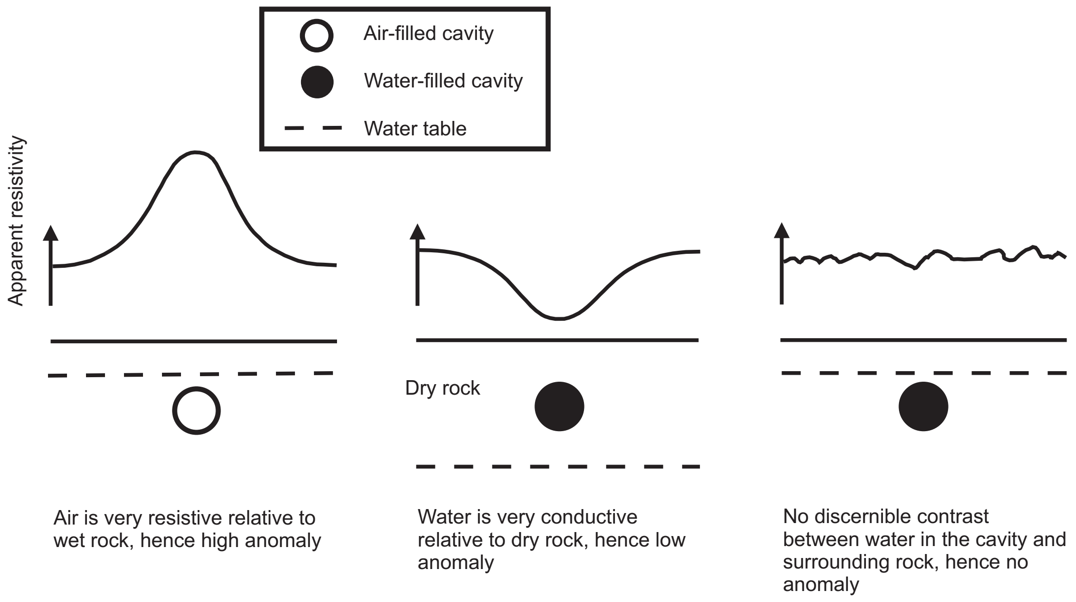

Figure 1.6 Contrasts in physical properties from different geological targets give rise to a target. When there is no contrast, the target is undetectable geophysically. [C]

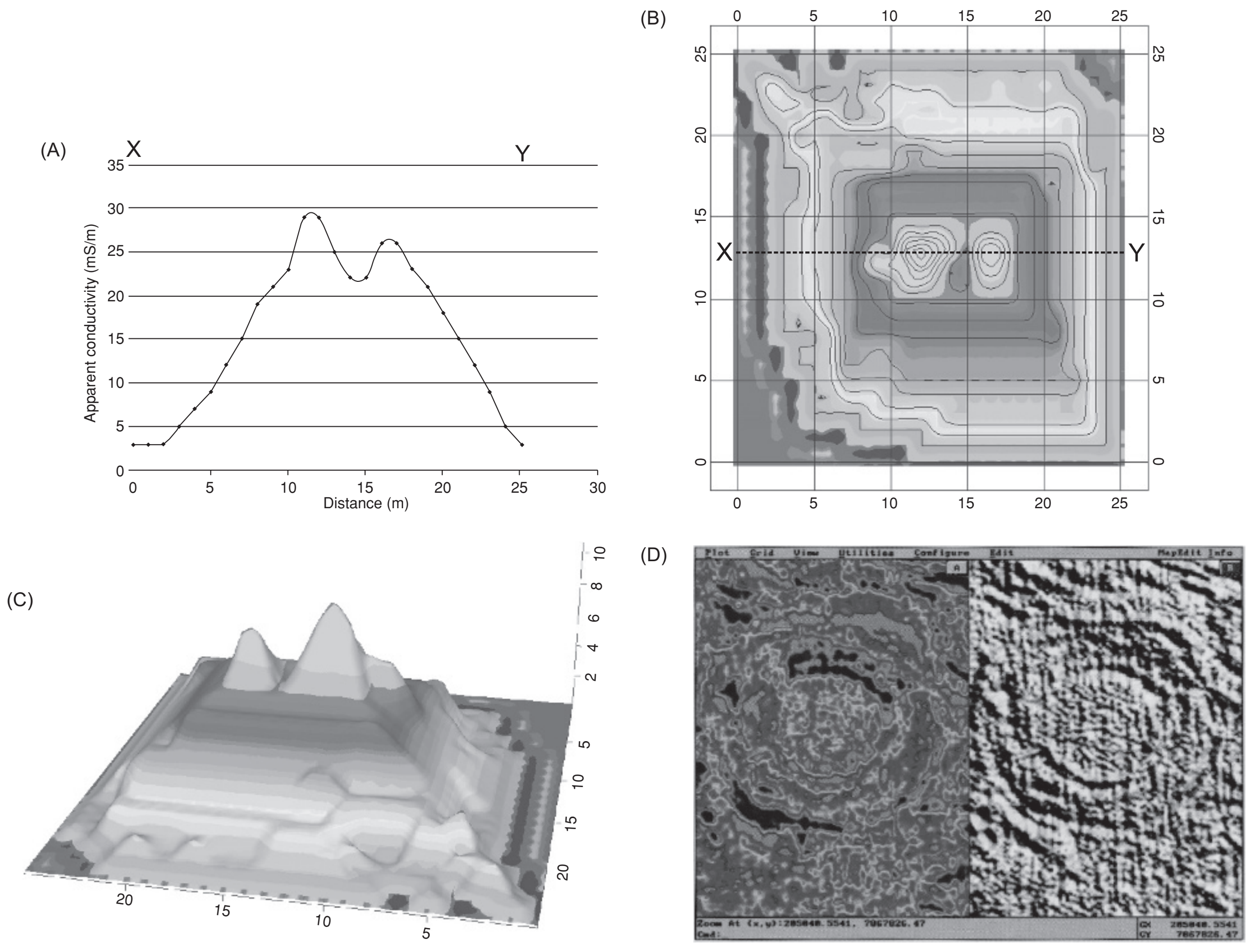

Figure 1.7 Geophysical anomaly plots: (A) profile, (B) map, and (C) isometric projection. All three plots are from the same set of electromagnetic ground-conductivity data (see Chapter 11). (D) A shaded relief/grey-scale shadow display can enhance features that otherwise would be hard to visualise – in this case the display is of magnetic data over an area in which faulting appears as a series of features that possibly may be part of a meteorite impact crater. Photo courtesy of Geosoft Europe Ltd. [C]

checked in case there has been a simple misprint in data entry, or there might have been an error in fixing position 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.

Geophysical investigations can take the form of four types of dimensional survey to investigate the spatial (x,y,z) and temporal (t) variations in the geophysical properties of the subsurface. A one-dimensional (1D) *sounding* at a specific location yields information as a function of depth (z), such as with the Vertical Electrical Sounding method (see Chapter 7, section 7.4.1). Profiling (2D) along a given (x or y) transect as illustrated in Figure 1.7A indicates variations in geophysical properties with depth (z). When a series of parallel 2D (x,z) profiles is surveyed, the results may be gridded and interpolated in the y-direction to present the data in map and/or isometric projection form (as shown in Figures 1.7B and 1.7C) or as a data volume. While the results may look three-dimensional, they should be referred to as *2.5 dimensional*, or *pseudo-3D*. True 3D spatial surveys take the form of a geophysical source that transmits a signal that is detected after passing through the subsurface to a *grid* rather than a *line* of sensors laid out on the ground surface, for example. When time-lapse surveys are undertaken, this can be referred to as providing an additional (time, T) dimension to the survey, so that a 4D survey would comprise a true 3D (x,y,z) spatial survey repeated over the same sensor layout after a period of time (t). Similarly, 2D surveys repeated as time lapse investigations, such as in monitoring remediation of ground contamination, could also be referred to as being 3D (x,z,t), but this would cause confusion with a 3D (x,y,z) spatial survey. To differentiate between them a 2D time lapse survey can be referred to as a 2D-T survey, rather than 3D. A repeated time-lapse sounding (z,t) can be referred to as a 1D-T survey to differentiate it from a 2D (x,z) spatial survey.

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.

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.

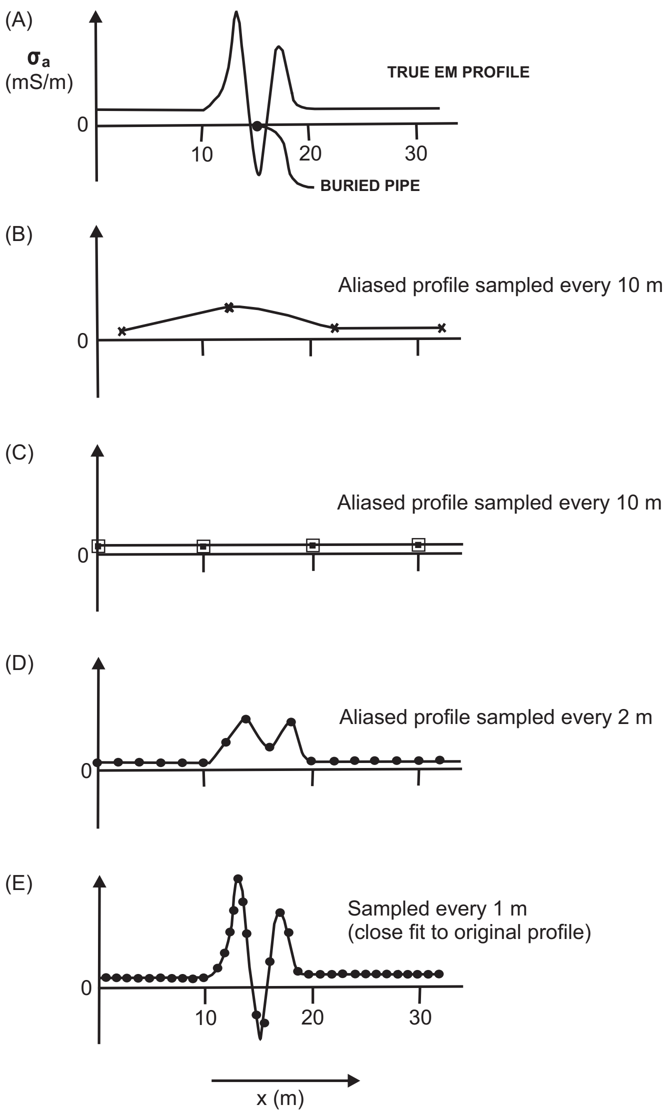

Figure 1.8 Examples of various degrees of spatial aliasing using different sampling intervals. (A) shows a continuously sampled profile. (B) and (C) show sampling every 10 m, but at different points along the profile. (D) shows sampling every 2 m: the profile is still aliased. (E) shows sampling every 1 m: this profile is the closest to that in (A).

Consider Figure 1.8A 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 1.8B, or to miss it entirely (Figure 1.8C). The resultant profiles with 2 m and 1 m sampling intervals are shown in Figures 1.8D and 1.8E respectively. The smaller the sampling interval, the better the approximation is to the actual anomaly (compare with Figure 1.8B or C). The loss of high-frequency information, as in Figures 1.8B 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

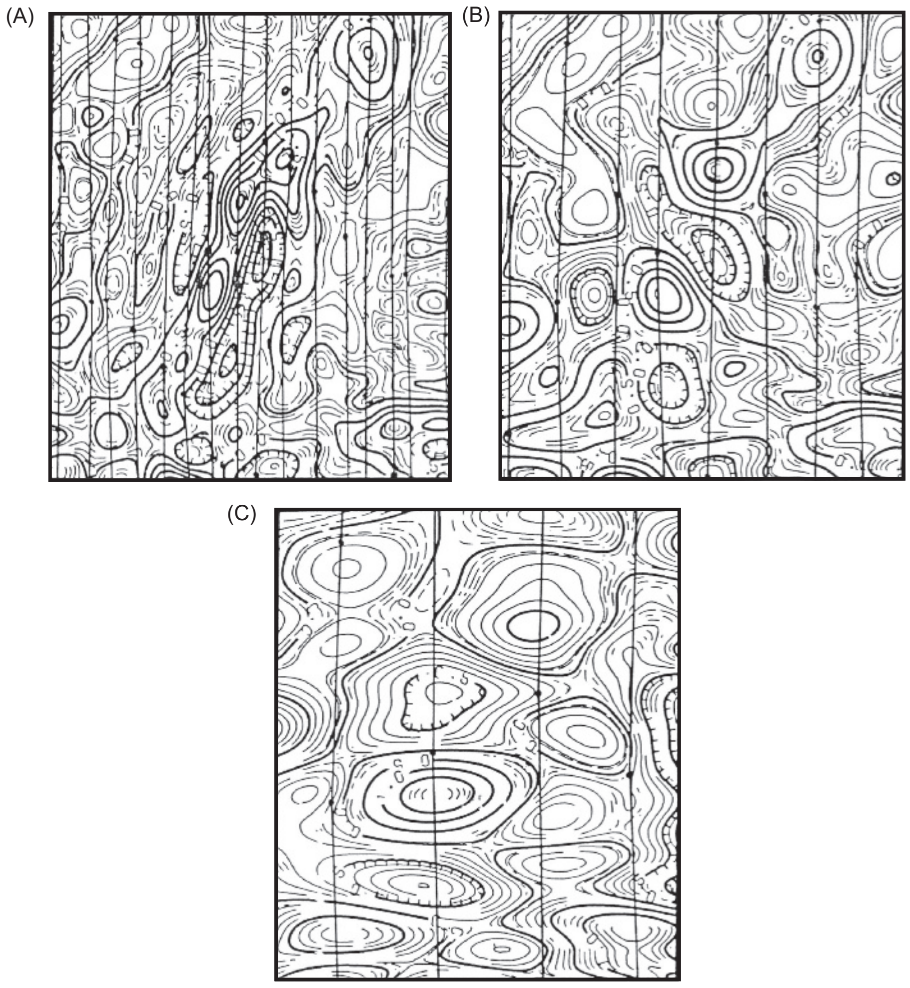

Figure 1.9 Example of spatial aliasing on aeromagnetic data, showing the loss of higher-frequency anomalies, increasing separation between flight lines and the increased 'bullseye' effect caused by stretching the data too far. From Hood *et al.* (1979), by permission.

artificially and appear as lower-frequency anomalies. A common characteristic of spatially aliased gridded data is the 'bullseye' effect (see Figure 1.9) 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 inappropriately designed field programme.

Figure 1.9 shows a hypothetical aeromagnetic survey. The map in Figure 1.9A was compiled from contouring the original data at a line spacing of 150 m. Figures 1.9B 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 1.9A 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 1.9C.

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. Further advice about the effects of different gridding routines is available from the relevant software providers either through their manuals, software 'help' keys or online via the Internet. Do not just use the default settings and hope for the best!

Similar aliasing problems associated with contouring can arise from radial survey lines and/or too few data points, as exemplified by Figure 1.10. Figure 1.10A and B both have 64 data points over the same area, and two effects can be seen very clearly: in Figure 1.10A 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 1.10B. The even grid in Figure 1.10B highlights the second effect (even more pronounced in Figure 1.10C), which is the formation of bullseyes around individual data points. The inadequacy of the number of data points is further demonstrated in Figure 1.10C, which is based

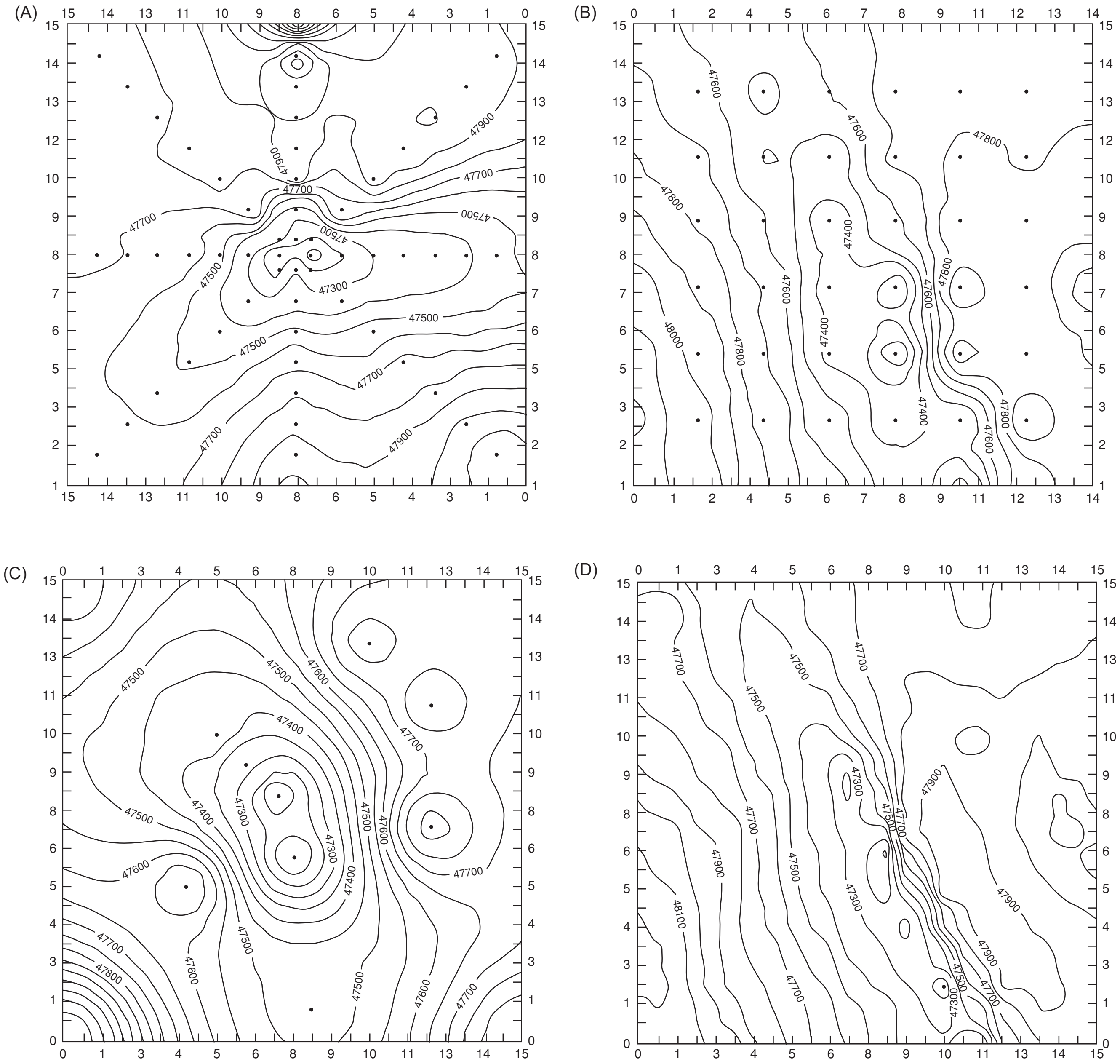

Figure 1.10 Examples of contouring different patterns of data. (A) shows set of radial lines, and (B) an even grid of data, both with 114 points per square kilometre. (C) has too few data points unevenly spread over the same area (23 data points per square kilometre). (D) shows an even grid of 453 points per square kilometre. The contours are isolines of total magnetic field strength (units: nanoteslas); the data are from a ground magnetometer investigation of northwest Dartmoor, England.

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 1.10D has been compiled on the basis of 255 data points, and exposes the observed anomalies much more realistically.

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 such as wind and rain, waves, and electrical and magnetic storms (Figure 1.11).

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, since power lines will induce unwanted voltages in the survey wires. Before a survey starts, it is always advisable to consult with public utility

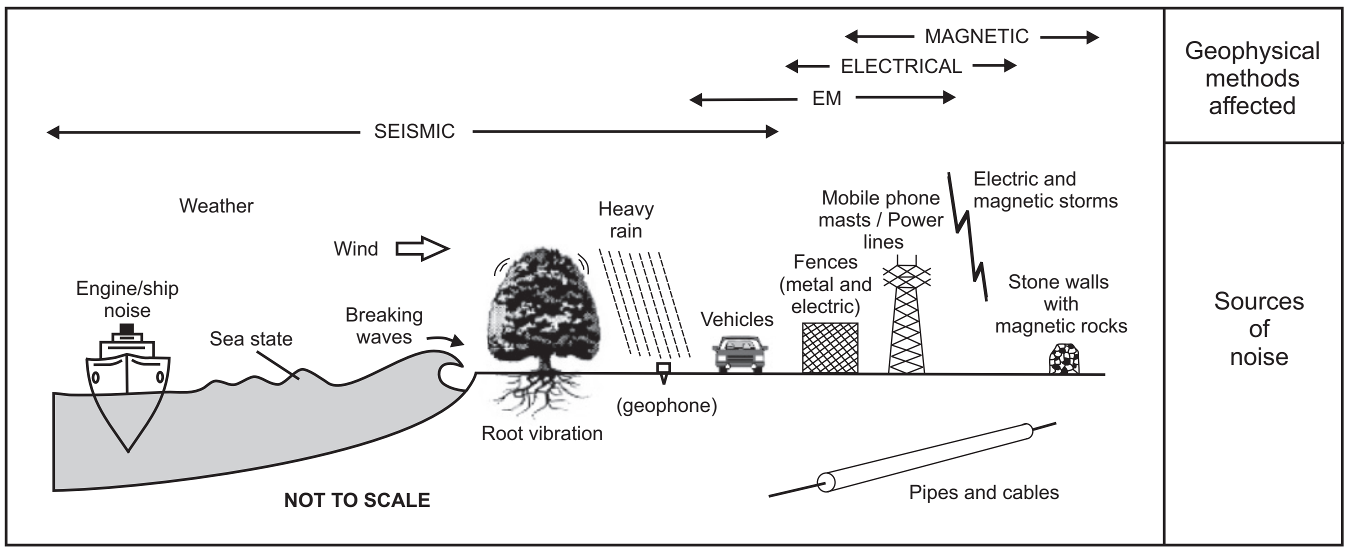

Figure 1.11 Schematic illustrating some common sources of geophysical noise.

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.

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 1.12). *Coherent noise*, such as that produced by power lines, occurs systematically (Figure 1.12A) 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 1.12B).

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 river water 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 raindrops, 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 1.13). 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 (2003).

Where a survey with a single instrument lasts longer than a day, it is recommended that a base line is established that can be re-surveyed quickly each day to check on the repeatability of the method. If the sets of data taken on two consecutive days are not similar it suggests there is a problem with the instrument set-up. Also any day-on-day drift of the equipment will become apparent, and this drift will need to be corrected in any subsequent data processing of the combined dataset. Furthermore, the repeatability check also indicates the variations that occur in the data due to the way the instrument is being deployed (different operator, slightly different carrying position, etc.). These differences will help in determining the minimum contour interval that should be selected when displaying the data. For example, if the repeatability check indicates that there is a ±1 milliSiemens/m difference on readings, then there is no justification for displaying the data with a 0.5 mS/m contour interval, as this is significantly smaller than the uncertainty in the readings and is not physically significant. It is possible to apply a more statistically rigorous approach and calculate the standard deviation of the data. The minimum contour interval should not be smaller than the standard deviation.

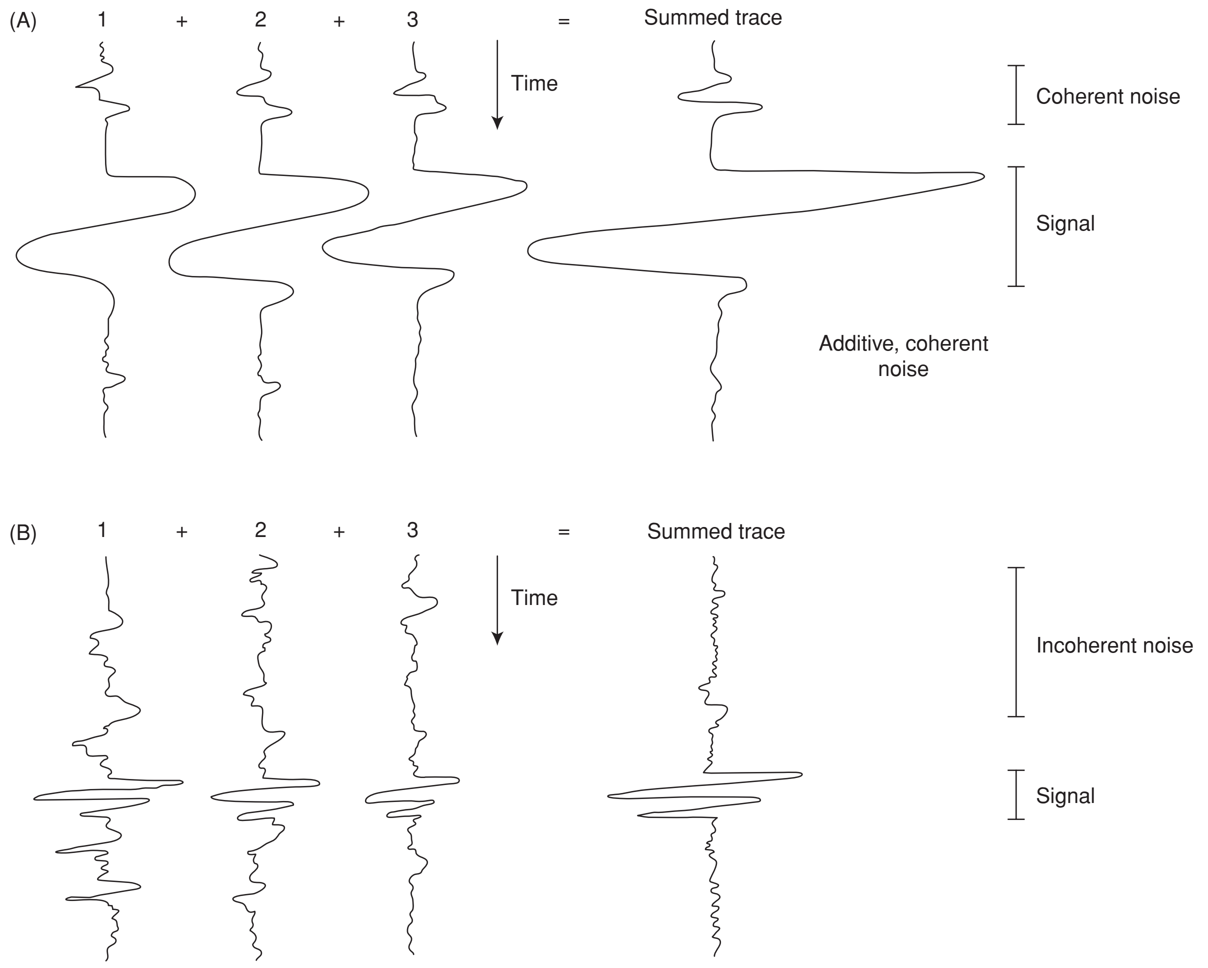

Figure 1.12 The effect of summing three traces with (A) coherent and (B) incoherent noise.

1.5.5 Position fixing

Knowing the position of any data point accurately within a survey and relative to prominent ground features is essential. This can vary from being able to deploy a tape measure through to making integrated measurements using differential Global Positioning Systems (dGPS). The key is that whichever method is used, it is possible to re-occupy a given location to within the specified accuracy of the survey. There have been too many examples of where an intrusive test (such as a trial pit) is excavated over what is supposed to be the position of a geophysical anomaly, but the errors in surveying mean that the two are not coincident. The trial pit effectively samples the wrong ground and no association is made between what was causing the geophysical anomaly and the ground truth result.

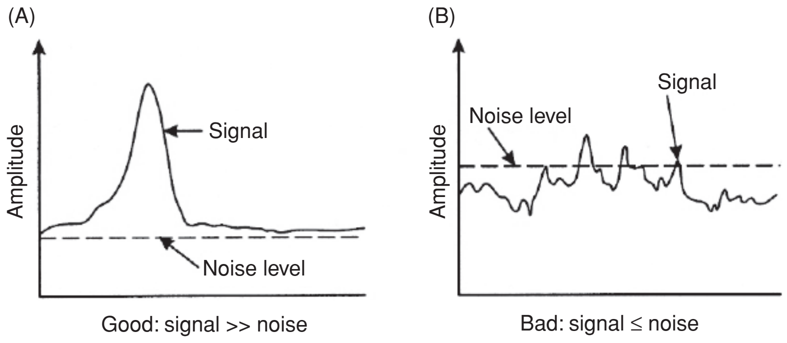

Figure 1.13 Signal-to-noise ratio. In (A) the signal has a much larger amplitude than that of the background noise, so the signal can be resolved. In (B) the signal amplitude is less than, or about the same as, that of the noise and thus the signal is lost in the noise.

A key benefit of using geophysical methods is to be able to target intrusive tests on the basis of the geophysical data. Obtaining accurate ground truth information is very important to correlate with the geophysical results so that the physical interpretations can be extrapolated spatially on the basis of the geophysical data. It is essential, therefore, that being able to set out a survey, whether for a geophysical investigation or locating the correct position for a borehole or trial pit, is carried out accurately (e.g. Crawford, 1995).

When using dGPS, there is often an issue about being able to plot dGPS positions of features onto their corresponding position on a local map, for example. In some cases, there may be several metres difference between the dGPS position and the position on a site plan using local coordinates. It then becomes important to be able to reconcile different map systems.

The World Geodetic System 1984 (WGS84) is a global coordinate system designed for use anywhere in the world, with coordinates usually expressed as latitude, longitude and ellipsoid height. A high-accuracy version of WGS84, known as the International Terrestrial Reference System (ITRS), has been created in a number of versions since 1989, and is suitable for international high-accuracy applications, such as in geophysical surveys. As the continents are moving in relation to each other, up to 0.12 m per year, there is a problem in maintaining the accuracy of a coordinate system. The European Terrestrial Reference System 1989 (ETRS89) was established as the standard precise GPS coordinate system throughout Europe which accounts for continental motion. The relationship between ITRS and ETRS89 is precisely defined at any point in time by a simple transformation published by the International Earth Rotation Service (ITRS). Most national mapping agencies in Europe have adopted the ETRS89 as a standard coordinate system for precise GPS surveying.

Survey data can be exported from data-logging instruments in World Geodetic System 1984 (WGS84) format and imported into Geosoft's Oasis Montaj software, for example, where they can be transformed to OSGB 1936, the British National Grid coordinates, using an automatic transform. Furthermore, to cope with slight distortions in the OSGB36 *Terrestrial Reference Frame* (TRF) it is necessary to use a 'rubber-sheet' stretch-style transformation that works with a grid expressed in terms of easting and northing coordinates. The grids of easting and northing shifts between ETRS89 and OSGB36 cover Britain at a resolution of one kilometre. From these grids a northing and easting shift for each point to be transformed is obtained by a bilinear interpolation, which is called the National Grid Transformation OSRTN02 (Ordnance Survey, 2008). To account for the slight difference in the WGS84 to British National Grid transform a Geosoft '.wrp' file can be created to rectify the data to a DXF version of a site plan supplied by the client. This way, the dGPS positions for the acquired data plot in the correct position on a digital site plan provided in OSGB coordinates. In the UK the Ordnance Survey provides automatic transforms via its website (www.ordnancesurvey.co.uk/gps). Geographical Information System software also provides coordinate transformation algorithms. For surveys undertaken outside of the UK, reference should be made to the relevant national survey institution or agency to obtain the relevant coordinate transformation algorithms, where necessary.

Care should also be taken when alternative coordinate systems are used, such as by metro companies and mining companies where their underground coordinate systems may be slightly skewed relative to those at the surface. When integrating data, the coordinate systems need to be transformed so that they are consistent with each other. In addition, long sinuous survey tracks, such as those for railways, pipelines and roads, may take advantage of the '*Snake*' projection (Iliffe *et al.*, 2007; Iliffe, 2008a,b). The original route of the infrastructure (pipe, railway or road) is passed to the 'Snakemaker' design software in the form of seed points at discrete intervals along the route. The program then fits a three-dimensional trend line through these, along which the scale factor is unity. The program generates a curvilinear rectangle along the trend line, indicating the region in which scale factor distortion is less than the permitted maximum, usually 20 ppm for rail projects (see also Iliffe and Lott, 2008).

With some equipment used with a dGPS antenna, the location of any data point and that of the antenna will be coincident. However, in other cases, there may be a physical separation between the location of the measurement point and that of the antenna, creating a *layback* or *offset*, which has to be corrected for in any subsequent data display. Furthermore, if direction of travel and layback are not taken into account when correcting positions of data, artefacts can be introduced into the contoured data such as the herringbone effect. Methods such as EM31 ground conductivity profiling (Chapter 11) are particularly prone to this, depending upon the orientation of the dipole boom. If alternate lines are surveyed in opposite directions, the data are acquired with the transmitter and receiver in opposite directions and this can also generate a 'herring bone' effect; the transmitter–receiver orientation must be kept constant throughout the survey. In other methods, such as in high-resolution over-water sub-bottom seismic reflection profiling or marine magnetometry, the offset between instrument platforms and the dGPS antenna can be significant (tens of metres). Fix positions marked on the recorded seismic sections must have layback applied so that the position of the seismic trace is correct with respect to its location on the ground. An example of a layback diagram from a marine survey is shown in Figure 1.14. See Chapter 4, Section 4.6.2, for further details of marine survey positional issues.

In marine surveys in tidal regions, it is also essential that records are kept of tidal levels with respect to specified chart datums. In the UK, the chart datum is defined as that at Newlyn in Cornwall. Bathymetric data must be corrected to that specific datum so that seabed levels can be expressed in terms of elevations relative to chart datum. This makes correlation with borehole data far easier, as geological interfaces on borehole logs are defined in terms of both depth below a specific level (typically the moon pool of a drilling rig – the platform through which the drill string passes) and elevation relative to datum. Vertical profiles through the water column to measure the speed of sound in water should be acquired regularly in order to correct echo sounding results accurately to water depths.

1.5.6 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

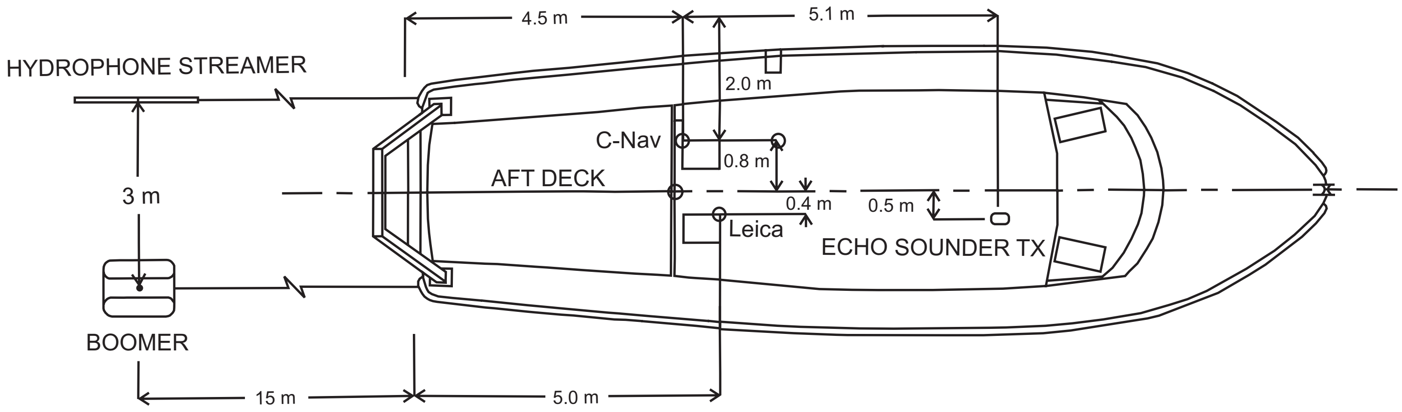

Figure 1.14 Example of field geometry diagram for an over-water Sub-Bottom Profiling and water bathymetry survey.

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.

As automatic data-logging with simultaneous position fixing with dGPS and computer analysis have become commonplace, it is increasingly important to standardise the format in which the data are recorded 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. It is also important to be able to manage large volumes of data. For example, a major survey using ground penetrating radar can easily generate many gigabytes of data per day. Making standard back-ups becomes no trivial matter. 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. 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 has been a proliferation of software. One major software house generating commercially available geophysical computer packages is Geosoft Ltd in Canada, who also produce 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. A search on the Internet produces a plethora of lists of software, freeware and commercially-available packages. Intending users should take considerable care about the selection of software to find those packages that are well-established (i.e. the majority of bugs have been resolved) and have demonstrated their reliability. In the UK over the last few years the Association of Geotechnical Specialists (AGS) have established a file format for the production of intrusive investigation results, including borehole geophysics. Many clients now require contractually that datafiles are produced in AGS format or are compatible with this format. Increasingly, such datafile formats provide communication with major engineering Computer Aided Design (CAD) and Geographical Information System (GIS) software. In addition, geophysical software (Geosoft Oasis Montaj) can be linked to a GIS (such as ArcGIS) using their bridging software (Target), which greatly enhances the scope of geo-rectified and integrated outputs. Other software systems may also provide comparable capabilities. However, some proprietary interpretation software packages may be distinctly limited in their capability. Anyone intending to use the results should ensure that they are aware of how the data are analysed and what implications this might have for the use of any interpretations arising. It is strongly advised that clients engage an independent geophysical consultant to advise them so that they commission surveys that meet their needs, not just satisfy the desires of bidding contractors.

There is also a growing recent trend amongst contractors to try to develop ways in which data can be downloaded, gridded and interpreted on the same day that the data are acquired, and the faster the better. This is not necessarily a beneficial step. While it might provide a selling point for the contractor, experience suggests that this is not necessarily in the client's interests. Firstly, the acquisition of far greater quantities of data in shorter time periods often results in the data not being viewed as regularly during acquisition as was done previously. Bad data, spikes, and the like, are now often only identified back in the office when it is too late to re-acquire data. Furthermore, the ubiquitous 'default' setting on software allows people not to think about what they are producing – as long as the output looks alright, it must be alright! This is not always the case. In shallow seismic reflection profiling, as undertaken for marine dredge surveys, for instance, semi-automatic horizon picking software may miss or mis-pick events. It is not uncommon for marine geophysics contractors to dump datasets on clients without undertaking appropriate data quality control checks. Unless there is a conscious effort to apply some reasonable quality control, the final deliverables for the Client may be incorrect, incomplete or both.

The increased use of gridding packages means that subtle details in the individual profiles may be missed; maxima are reduced and minima increased through the gridding routines. In some cases this 'filtering' can result in important anomalies being missed completely. While rapid data gridding and data visualisation are important parts of quality control, when it is applied correctly, they should not be substitutes for interpretation, an aspect that is worryingly on the increase.

Bibliography

General geophysics texts

Milsom, J. (2003) *Field Geophysics* (3^{rd} edn). Chichester: John Wiley & Sons Ltd.

Telford, W.M., Geldart, L.P., Sheriff, R.E. and Keys, D.A. (1990) *Applied Geophysics* (2^{nd} edn). Cambridge.

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 audio-visual materials (slides, videos, etc.). Since 1995, the EEGS has published the *Journal of Environmental and Engineering Geophysics*. In January 1996 the European Section of the EEGS launched the first issue of the *European Journal of Environmental and Engineering Geophysics*, which since 2003 has been published under the title *Near Surface Geophysics* by the EAGE. The EAGE also publishes *Geophysical Prospecting* and *First Break*. The journal entitled *Archaeological Prospection* has been available since 1995.

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 *et al.*, 2008), which are also available online at www.english-heritage.org.uk/upload/pdf/GeophysicsGuidelines.pdf.

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.