CHAPTER

1 Introduction

Geophysical methods respond to differences in the physical properties of rocks. Figure 1.1 is a schematic illustration of a geophysical survey. Over the area of interest, instruments are deployed in the field to measure variations in a physical parameter associated with variations in a physical property of the subsurface. The measurements are used to infer the geology of the survey area. Of particular significance is the ability of geophysical methods to make these inferences from a distance, and, for some methods, without contact with the ground, meaning that geophysics is a form of remote sensing (*sensu lato*). Surveys may be conducted on the ground, in the air or in-ground (downhole). Information about the geology can be obtained at scales ranging from the size of a geological province down to that of an individual drillhole.

Geophysics is an integral part of most mineral exploration programmes, both greenfields and brownfields, and is increasingly used during the mining of orebodies. It is widely used because it can map large areas quickly and cost effectively, delineate subtle physical variations in the geology that might otherwise not be observed by field geological investigations and detect occurrences of a wide variety of mineral deposits.

It is generally accepted that there are few large orebodies remaining to be found at the surface, so mineral exploration is increasingly being directed toward searching for covered and deep targets. Unlike geochemistry and other remote sensing techniques, geophysics can see into the subsurface to provide information about the concealed geology. Despite this advantage, the interpretation of geophysical data is critically dependent on their calibration against geological and geochemical data.

◂ Folded massive nickel sulphide mineralisation in the Maggie Hays mine, Western Australia. The field of view is 1.2 m wide. Photograph: John Miller.

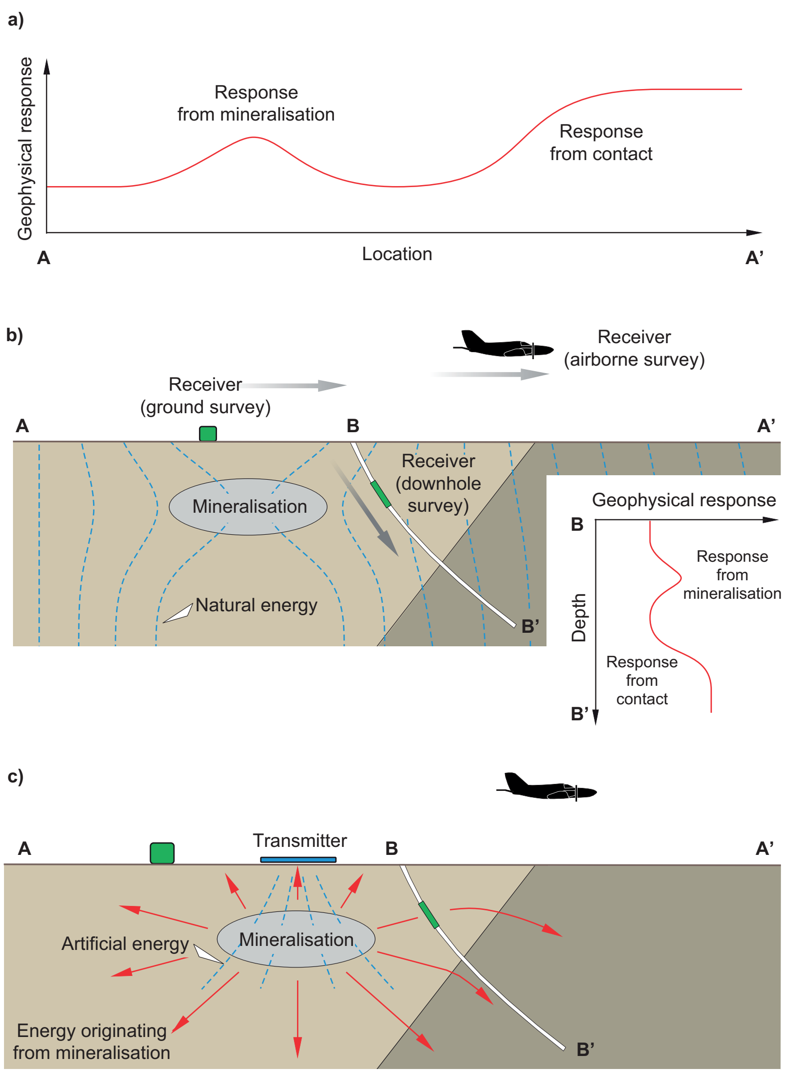

Figure 1.1 Geophysical surveying schematically illustrated detecting mineralisation and mapping a contact between different rock types. Instruments (receivers) make measurements of a physical parameter at a series of locations on or above the surface (A–A′) or downhole (B–B′). The data are plotted as a function of location or depth down the drillhole (a). (b) Passive geophysical surveying where a natural source of energy is used and only a receiver is required. (c) Active geophysical surveying where an artificial source of energy (transmitter) and a receiver are both required.

1.1 Physical versus chemical characterisation of the geological environment

The geophysical view of the geological environment focuses on variations in the physical properties within some volume of rock. This is in direct contrast with the geological view, which is primarily of variations in the bulk chemistry of the geology. The bulk chemistry is inferred from visual and chemical assessment of the proportions of different silicate and carbonate minerals at locations where the geology happens to be exposed, or has been drilled. These two fundamentally different approaches to assessing the geological environment mean that a particular area of geology may appear homogeneous to a geologist but may be geophysically heterogeneous, and vice versa. The two perspectives are complementary, but they may also appear to be contradictory. Any contradiction is resolved by the 'chemical' versus 'physical' basis of investigating the geology. For example, porosity and pore contents are commonly important influences on physical properties, but are not a factor in the various schemes used by geologists to assign a lithological name, these schemes being based on mineralogical content and to a lesser extent the distribution of the minerals.

Some geophysical methods can measure the actual physical property of the subsurface, but all methods are sensitive to physical property contrasts or relative changes in properties, i.e. the juxtaposition of rocks with different physical properties. It is the changes in physical properties that are detected and mapped. This relativist geophysics approach is another fundamental aspect that differs from the absolutist geological approach. For example, one way of geologically classifying igneous rocks is according to their silica content, with absolute values used to define categories such as felsic, intermediate, mafic etc. The geophysical approach is equivalent to being able to tell that one rock contains, say, 20% more silica than another, without knowing whether one or both are mafic, felsic etc.

The link between the geological and geophysical perspectives of the Earth is *petrophysics* – the study of the physical properties of rocks and minerals, which is the foundation of the interpretation of geophysical data. Petrophysics is a subject that we emphasise strongly throughout this book, although it is a subject in which some important aspects are not fully understood and more research is urgently required.

1.2 Geophysical methods in exploration and mining

Geophysical methods are used in mineral exploration for geological mapping and to identify geological environments favourable for mineralisation, i.e. to directly detect, or target, the mineralised environment. During exploitation of mineral resources, geophysics is used both in delineating and evaluating the ore itself, and in the engineering-led process of accessing and extracting the ore.

There are five main classes of geophysical methods, distinguished according to the physical properties of the geology to which they respond. The *gravity* and *magnetic* methods detect differences in density and magnetism, respectively, by measuring variations in the Earth's gravity and magnetic fields. The *radiometric* method detects variations in natural radioactivity, from which the radioelement content of the rocks can be estimated. The *seismic* method detects variations in the elastic properties of the rocks, manifest as variations in the behaviour of seismic waves passing through them. Seismic surveys are highly effective for investigating layered stratigraphy, so they are the mainstay of the petroleum industry but are comparatively rarely used by the minerals industry.

The electrical methods, based on the electrical properties of rocks and minerals, are the most diverse of the five classes. Electrical conductivity, or its reciprocal resistivity, can be obtained by measuring differences in electrical potentials in the rocks. When the potentials arise from natural processes the technique is known as the *spontaneous potential* or *self-potential* (SP) method. When they are associated with artificially generated electric currents passing through the rocks, the technique is known as the *resistivity* method. An extension to this is the *induced polarisation* (IP) method which measures the ability of rocks to store electric charge. Electrical properties can also be investigated by using electric currents created and measured through the phenomenon of electromagnetic induction. These are the *electromagnetic* (EM) methods, and whilst electrical conductivity remains an important factor, different implementations of the technique can cause other electrical properties of the rocks to influence the measurements.

The physical-property-based categorisation described above is complemented by a two-fold classification of the geophysical methods into either *passive* or *active* methods (Fig. 1.1b and c).

Passive methods use natural sources of energy, of which the Earth's gravity and magnetic fields are two examples, to investigate the ground. The geophysical measurement is made with some form of instrument, known as a *detector*, *sensor* or *receiver*. The receiver measures the *response* of the local geology to the natural energy. The passive geophysical methods are the gravity, magnetic, radiometric and SP methods, plus a form of electromagnetic surveying known as *magnetotellurics* (described in online Appendix 4).

Active geophysical methods involve the deliberate introduction of some form of energy into the ground, for example seismic waves, electric currents, electromagnetic waves etc. Again, the ground's response to the introduced energy is measured with some form of detector. The need to supplement the detector with a *source* of this energy, often called the *transmitter*, means that the active methods are more complicated and expensive to work with. However, they do have the advantage that the transmission of the energy into the ground can be controlled to produce responses that provide particular information about the subsurface, and to focus on the response from some region (usually depth) of particular interest. Note that, confusingly, the cause of a geophysical response in the subsurface is also commonly called a *source* – a term and context we use extensively throughout the text.

1.2.1 Airborne, ground and in-ground surveys

Geophysical surveying involves making a series of measurements over an area of interest with survey parameters appropriate to the scale of the geological features being investigated. Usually, a single survey instrument is used to traverse the area, either on the ground, in the air or within a drillhole (Fig. 1.1). Surveys from space or on water are also possible but are uncommon in the mining industry. In general, airborne measurements made from a low-flying aircraft are more cost-effective than ground measurements for surveys covering a large area or comprising a large number of readings. The chief advantages of airborne surveying relative to ground surveying are the greater speed of data acquisition and the completeness of the survey coverage.

As exploration progresses and focuses on smaller areas, there is a general reduction in both the extent of geophysical surveys and the distances between the individual readings in a survey. Airborne surveys are usually part of the reconnaissance phase, which is often the initial phase of exploration, although some modern airborne systems offer higher resolution by surveying very close to the ground and may find application in the later stages of exploration. Ground and drillhole surveys, on the other hand, offer the highest resolution of the subsurface. They are mostly used for further investigation of areas targeted from the reconnaissance work for their higher prospectivity, i.e. they are used at the smaller prospect scale.

Methods that can be implemented from the air include magnetics, known as *aeromagnetics*; gravity, sometimes referred to as *aerogravity* or as currently implemented for mineral exploration as *airborne gravity gradiometry*; radiometrics; and electromagnetics, usually referred to as *airborne electromagnetics* (AEM). All the geophysical methods can be implemented downhole, i.e. in a drillhole. Downhole surveys are a compact implementation of conventional surface surveying techniques. There are two quite distinct modes of making downhole measurements: *downhole logging* and *downhole surveying*.

Downhole logging is where the *in situ* physical properties of the rocks penetrated by a drillhole are measured to produce a continuous record of the measured parameter. Downhole logs are commonly used for making stratigraphic correlations between drillholes in the sedimentary sequences that host coal seams and iron formations. Measurements of several physical parameters, producing a suite of logs, allow the physical characterisation of the local geology, which is useful for the analysis of other geophysical data and also to help plan future surveys, e.g. Mwenifumbo *et al.* (2004). Despite the valuable information obtainable, *multiparameter logging* is not ubiquitous in mineral exploration. However, its use is increasing along with integrated interpretation of multiple geophysical datasets.

Downhole surveying is designed to investigate the larger region surrounding the drillhole, with physical property variations obtained indirectly, and to indicate the direction and even the shape of targets. That is, downhole electrical conductivity logging measures the conductivity of the rocks that form the drillhole walls, whereas a downhole electromagnetic survey detects conductivity variations, perhaps owing to mineralisation, in the volume surrounding the drillhole. Downhole geophysical surveys increase the radius of investigation of the drillhole, increase the depth of investigation and provide greater resolution of buried targets.

Geophysical surveys are sometimes conducted in open-pit and underground mines; measurements are made in vertical shafts and/or along (inclined) drives, usually to detect and delineate ore horizons. There exists a rather small literature describing underground applications of geophysics, e.g. Fallon *et al.* (1997), Fullagar and Fallon (1997) and McDowell *et al.* (2007), despite many successful surveys having been completed. Application and implementation of geophysics underground tend to be unique to a particular situation, and survey design requires a fair degree of ingenuity to adapt the arrangement of transmitter and receiver to the confines of the underground environment. They are usually highly focused towards determining a specific characteristic of a small volume of ground in the immediate surrounds. Electrical and mechanical interference from mine infrastructure limits the sensitivity of surveys, which require a high level of planning and coordination with mining activities. Also, data from in-mine surveys require particular skills to interpret the more complex three-dimensional (3D) nature of the responses obtained: for example, the response may emanate from overhead, or the survey could pass through the target. The generally unique nature of underground geophysical surveys and our desire to emphasise the principles and common practices of geophysics in mineral exploration restrict us from describing this most interesting application of geophysics, other than to mention, where appropriate, the possibilities of using a particular geophysical method underground.

1.2.2 Geophysical methods and mineral deposits

The physical properties of the geological environment most commonly measured in mining geophysics are density, magnetism, radioactivity and electrical properties. Elastic (seismic) properties are not commonly exploited. In general, density, magnetism and radioactivity are used to map the geology, the latter when the nature of the surface materials is important. The limited use of electrical properties is due to their non-availability from an airborne

Table 1.1 **Geophysical methods commonly used in the exploration and exploitation of some important types of mineral deposits. Brackets denote lesser use. Also shown, for comparison, are methods used for petroleum exploration and groundwater studies. L – downhole logging, M – geological mapping of prospective terrains, D – detection/delineation of the mineralised environment. The entries in the density column reflect both the use of ground gravity surveys and anticipated future use of aerogravity. Developed from a table in Harman (2004).**

Deposit type	Density	Magnetism	Electrical properties	Radioactivity	Elastic properties
Iron formation associated Fe ores	M D L	M D	D	M (L)	
Coal	(M) L	M D	L	L	M D L
Evaporite-hosted K				L	M D L
Fe-oxide Cu–Au (IOCG)	M D	M D	D	D	
Broken Hill type Ag–Pb–Zn	M (D)	M	D		
Volcanogenic massive sulphide (VMS) Cu–Pb–Zn	M (D)	M	D	D	
Magmatic Cu, Ni, Cr and Pt-group	M D	M D	D		
Primary diamonds	M	M	(M)		
Uranium	M	M	M	D L	
Porphyry Cu, Mo	M	M D	D	D	
Sedimentary exhalative (SEDEX) Pb–Zn	M	M (D)	D		
Greenstone belt Au	M	M			
Epithermal Au	M	M		M	
Placer deposits	M	(M)	M		M
Sediment-hosted Cu–Pb–Zn	M	M	D		
Skarns	M	M D	(D)		
Heavy mineral sands		M D		M D	
Mineralisation in regolith and cover materials, e.g. Al, U, Ni			D	M D	
Groundwater studies			M D L	L	M
Petroleum exploration and production	(M) L	(M)	(M) L	L	M (D) L

platform, although AEM-derived conductivity measurements are becoming more common. Direct detection of a mineralised environment may depend upon any one or more of density, magnetism, radioactivity, electrical properties and possibly elasticity. Table 1.1 summarises how contrasts in physical properties are exploited in exploration and mining of various types of mineral deposits, and in groundwater and petroleum studies.

1.2.3 The cost of geophysics

The effectiveness and cost of applying any 'tool' to the exploration and mining process, be it geological, geochemical, geophysical, or drilling, are key considerations when formulating exploration strategies. After all, the ultimate aim of the exploration process is to discover ore within the constraints of time and cost, which are usually determined outside the realms of the exploration programme. In both exploration and production the cost of drilling accounts for a large portion of expenditure. An important purpose of geophysical surveying is to help minimise the amount of drilling required.

The cost of a geophysical survey includes a fixed mobilisation cost and a variable cost dependent upon the volume of data collected, with large surveys attracting

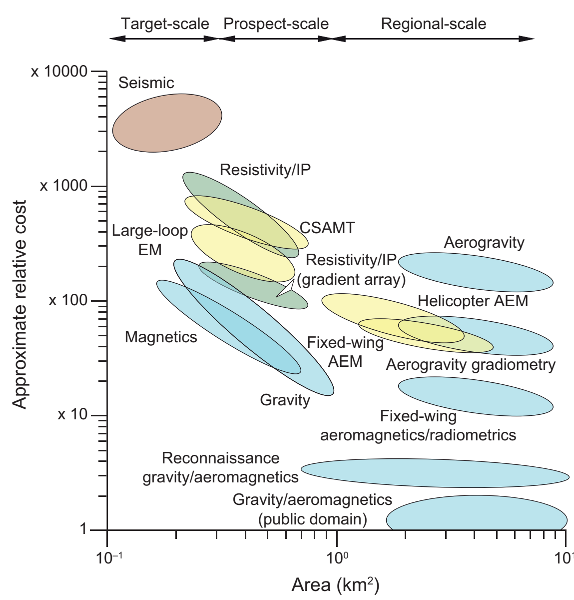

Figure 1.2 Approximate relative costs per square kilometre of different kinds of geophysical surveys and the approximate variation with size of the survey area. AEM – airborne electromagnetics, CSAMT – controlled source audio-frequency magnetotellurics, EM – electromagnetics, IP – induced polarisation. Redrawn with additions, with permission, from Fritz (2000).

favourable economies-of-scale. Additional costs can be incurred through 'lost time' related to factors such as adverse weather and access restrictions to the survey area, all preventing progress of the survey. Local conditions are widely variable, so it is impossible to state here the costs of different kinds of geophysical surveys. Nevertheless, it is useful to have an appreciation for the approximate relative costs of various geophysical methods compared with the cost of drilling. Drilling is not only a major, and often the largest, cost in most exploration and mining programmes, it is often the only alternative to geophysics for investigating the subsurface.

Following the approach of Fritz (2000), Fig. 1.2 shows the approximate relative cost of different geophysical methods. Of course the costs on which these diagrams are based can be highly variable owing to such factors as the prevailing economic conditions and whether the surveys are in remote and rugged areas. They should be treated as indicative only. The seismic method is by far the most expensive, which is one reason why it is little used by the mining industry, the least expensive methods being airborne magnetics and radiometrics. The areas over which information is gathered for each method are compared in Fig. 1.3, noting that cost estimates are equated to the estimated total cost of a single 300 m drillhole, including logging, assaying, remediation etc. The drillhole provides reliable geological information to a certain depth, but only from a very small area. Drilling on a grid pattern at 25 m intervals over an area of 1 km^2 would cost a few tens of millions of dollars, but would only sample 3 ppm of the volume. Geophysical methods provide information from vastly greater areas and volumes, albeit in a form that is not necessarily geologically explicit and will not necessarily directly identify mineralisation. Despite this, appropriately designed geophysical surveys and appropriately chosen data analysis are highly effective for optimally targeting expensive drillholes.

1.3 About this book

Our focus is an explanation of the principles and modern practice of geophysics in the search for mineral deposits. The explanations are presented from a perspective relevant to a mining industry geologist.

Throughout the text we emphasise the key aspects of mineral exploration geophysics, in particular those aspects that affect the interpretation of geophysical data. These include petrophysics, the foundational science of geophysics; numerical processing of the data; the creation and interpretation of raster imagery; problems presented by deeply weathered environments; geophysical characteristics of geologically complex basement terrains; and the inability to remove noise completely from the measurements. We introduce the term '*geophysical paradox*', where to fully understand the geophysical signal (the information of interest) and the noise (the interference producing uncertainty in the signal) requires information about the subsurface, but the purpose of the geophysical survey is to acquire this very information. We emphasise the need to understand this fundamental aspect of geophysics when working with geophysical data.

There have been many developments in geophysics in recent years. We have deliberately avoided presenting older techniques and practices not used widely today, leaving descriptions of these to earlier texts.

The text is structured around the main geophysical methods with each described in its own separate chapter. General aspects of the nature of geophysical data, their

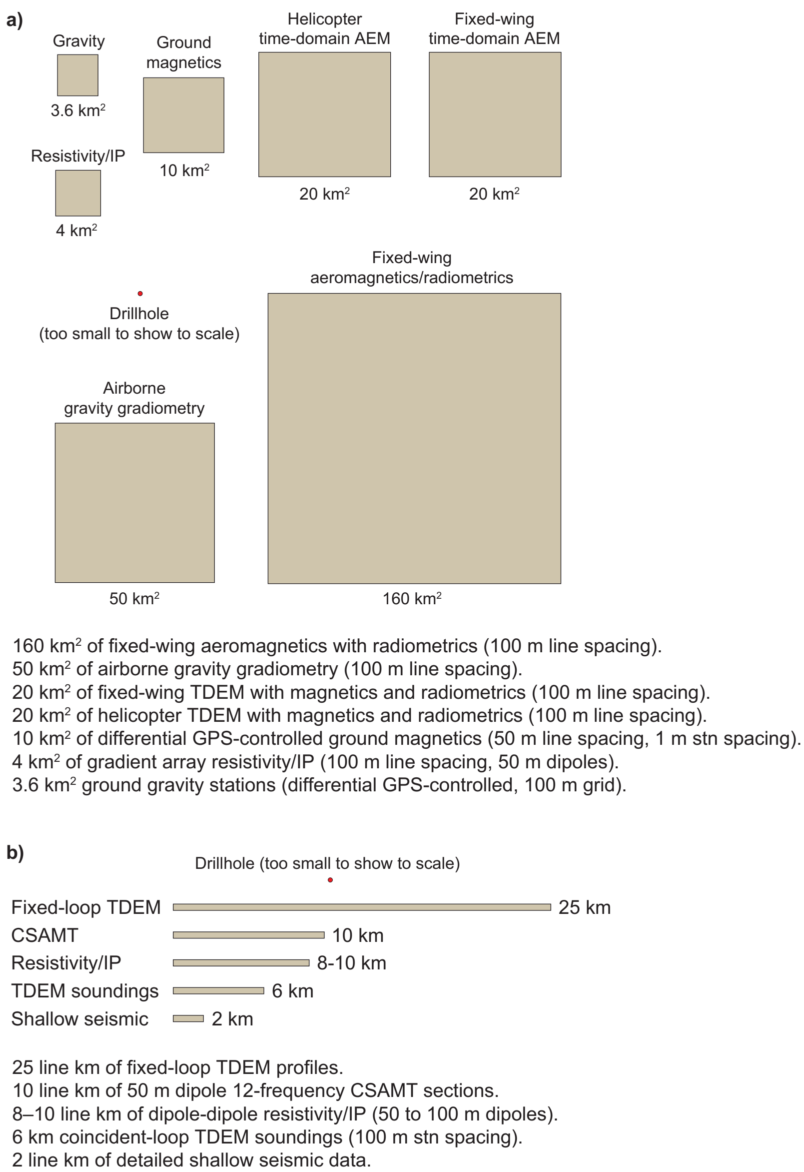

Figure 1.3 Approximate relative (a) areas and (b) line lengths sampled by geophysical surveys costing the equivalent of a single 300 m deep diamond drillhole. The area of the drillhole is shown for comparison. AEM – airborne electromagnetics, CSAMT – controlled source audio-frequency magnetotellurics, GPS – global positioning system, IP – induced polarisation, TDEM – time domain electromagnetics. Redrawn with additions, with permission, from Fritz (2000).

acquisition, processing, display and interpretation, common to all methods, are described first in a general chapter, Chapter 2. Essential, and generally applicable, details of vectors and waves are described in the online Appendices 1 and 2, respectively. The other chapters are designed to be largely self-contained, but with extensive cross-referencing to other chapters, in particular to Chapter 2. We have responded to the widespread complementary use of gravity and magnetics by describing them in a single combined chapter, Chapter 3. Geophysical methods less commonly used by the mining industry are described in online Appendices 3 to 6. Appendix 7 lists sources of information about mineral exploration geophysics, especially case histories. The principles described are demonstrated by examples of geophysical data and case studies from a wide variety of mineral deposit types from around the world. All deposits referred to are listed in Table 1.2 and their locations shown on Fig. 1.4.

At the conclusion of each chapter we provide a short list of appropriate resource material for further reading on the topic. The references cited throughout the text emphasise those we believe suit the requirements of the exploration geoscientist.

Table 1.2 Locations of deposits and mineralised areas from which geophysical data are presented. IOCG – iron oxide copper gold, MVT – Mississippi Valley-type, SEDEX – sedimentary exhalative, VMS – volcanogenic massive sulphide.

Number	Deposit name	Commodities	Deposit style/type	Country	Section
1	Adams	Fe	Iron formation	Canada	3.11.3
2	Almora	Graphite		India	5.5.4.1
3	Balcooma	Cu–Ag–Au	VMS	Australia	5.8.3.1
4	Bell Allard	Zn–Cu–Ag–Au	VMS	Canada	6.7.4.2
5	Blinman	Cu	Sediment hosted	Australia	4.7.4
6	Bonnet Plume Basin	Coal		Canada	3.10.6.2
7	Broken Hill area	Pb–Zn–Ag	Broken Hill type	Australia	3.7
8	Buchans	Zn–Pb–Cu	VMS	Canada	4.7.5
9	Butcherbird	Mn	Supergene	Australia	5.9.5.1
10	Cluff Lake area	U	Unconformity style	Canada	4.7.5
11	Cripple Creek district	Ag–Au–Te	Epithermal	USA	3.4.7
12	Cuyuna Iron Range	Fe	Iron formation	USA	5.5.3.2
13	Dugald river	Zn–Pb–Ag	SEDEX	Australia	4.7.5
14	Eloise	Cu–Au	SEDEX	Australia	5.7.7.1
15	Elura	Zn–Pb–Ag	VMS	Australia	2.6.1.2
16	Enonkoski (Laukunkangas)	Ni	Magmatic	Finland	5.8.4
17	Ernest Henry	Cu–Au	IOCG	Australia	5.7.7.1
18	Estrades	Cu–Zn–Au	VMS	Canada	5.6.6.3
19	Franklin	U	Sandstone type	USA	5.6.8.2
20	Gölalana	Cr	Magmatic	Turkey	3.11.5
21	Golden Cross/Waihi-Waitekauri epithermal area	Au–Ag	Epithermal	New Zealand	3.9.7 4.6.6 4.7.3.2 A4.7.2
22	Goongewa/Twelve Mile Bore	Pb–Zn	MVT	Australia	5.6.7
23	Goonumbla/North Parkes area	Cu–Au	Porphyry	Australia	3.11.4 4.6.6
24	Iron King	Pb–Zn–Cu–Au–Ag	VMS	USA	4.6.6
25	Jharia Coalfield	Coal		India	3.11.5 5.5.3.2
26	Jimblebar	Fe	Iron formation	Australia	4.7.5
27	Joma	Fe–S	Massive pyrite	Norway	2.9.2 5.5.3.1
28	Kabanga	Ni	Magmatic	Tanzania	3.9.8.2
29	Kerr Addison	Au	Orogenic	Canada	3.11.3
30	Kimheden	Cu	VMS	Sweden	5.5.3.2

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Table 1.2 (*cont.*)

Number	Deposit name	Commodities	Deposit style/type	Country	Section
31	Kirkland Lake	Au	Orogenic	Canada	2.8.1.1 3.11.3
32	Las Cruces	Cu–Au	VMS	Spain	3.7
33	Lisheen	Zn–Pb–Ag	Carbonate-hosted	Eire	5.7.4.2 5.7.4.3
34	London Victoria	Au	Lode	Australia	3.11.4.1 A6.3.5
35	Maple Creek	Au	Placer	Guyana	A5.3.4.1
36	Marmora	Fe	Skarn	Canada	2.6.4 3.11.5
37	Mirdita Zone	Cu	VMS	Albania	5.5.3.1
38	Mount Isa	Pb–Zn–Cu	SEDEX	Australia	5.8.2 A5.4.1
39	Mount Keith area	Ni	Magmatic	Australia	A3.3.1.1
40	Mount Polley	Cu-Au	Porphyry	Canada	2.8.2
41	Murray Brook	Cu–Pb–Zn	VMS	Canada	2.9.2
42	New Insco	Cu	VMS	Canada	5.5.3.1
43	Olympic Dam	Cu–U–Au–Ag–REE	IOCG	Australia	2.7.2.3 5.6.6.3
44	Pajingo epithermal system (Scott Lode, Cindy, Nancy and Vera)	Au	Epithermal	Australia	5.6.6.4
45	Palmietfontein	Diamond	Kimberlite-hosted	South Africa	5.6.6.1 5.6.6.2
46	Pine Point	Pb–Zn	MVT	Canada	2.9.2 5.6.6.4
47	Port Wine area	Au	Placer	USA	3.11.1
48	Poseidon	Ni	Magmatic	Australia	A3.4.1
49	Prairie Evaporite	K	Evaporite	Canada	4.7.5 6.5.2.5
50	Pyhäsalmi	Ni	Magmatic	Finland	2.10.2.3
51	Qian'an District	Fe	Iron Formation	China	3.10.1.1
52	Red Dog	Zn–Pb	SEDEX	USA	5.6.6.3
53	Regis Kimberlite	Diamond	Kimberlite-hosted	Brazil	A4.7.1
54	Rocky's Reward	Ni	Magmatic	Australia	A5.3.4.2
55	Safford	Cu	Porphyry	USA	5.5.4.2
56	Sargipalli	Graphite		India	5.5.3.1
57	Silvermines	Zn–Pb–Ag	Carbonate-hosted	Eire	5.6.6.2

Table 1.2 (*cont.*)

Number	Deposit name	Commodities	Deposit style/type	Country	Section
58	Singhblum	Cu	Disputed	India	5.5.3.2
59	South Illinois Coalfield	Coal		USA	6.7.4.1
60	Sulawesi Island	Ni	Lateritic	Indonesia	A5.3.4.1
61	Telkkälä Taipalsaari	Ni	Magmatic	Finland	2.10.2.3
62	Thalanga	Zn–Pb–Cu–Ag	SEDEX	Australia	2.8.1
63	Thompson	Ni	Magmatic	Canada	3.11.5
64	Trilogy	Cu–Au–Ag–Pb–Zn	VMS	Australia	5.7.7.1
65	Tripod	Ni	Magmatic	Canada	5.7.7.1
66	Uley	Graphite		Australia	5.6.8.1
67	Uranium City area	U	Unconformity style	Canada	4.7.3.1
68	Victoria	Graphite		Canada	5.6.9.5
69	Voisey Bay	Ni	Magmatic	Canada	6.8.2
70	Wallaby	Au	Orogenic	Australia	3.11.2
71	Witwatersrand Goldfield	Au	Palaeoplacer	South Africa	6.7
72	Woodlawn	Cu–Pb–Zn	VMS	Australia	5.6.9.4
73	Yankee Fork Mining District	Ag–Au	Epithermal	USA	3.8.6 3.9.7
74	Yeelirrie	U	Calcrete-hosted	Australia	4.7.3.1

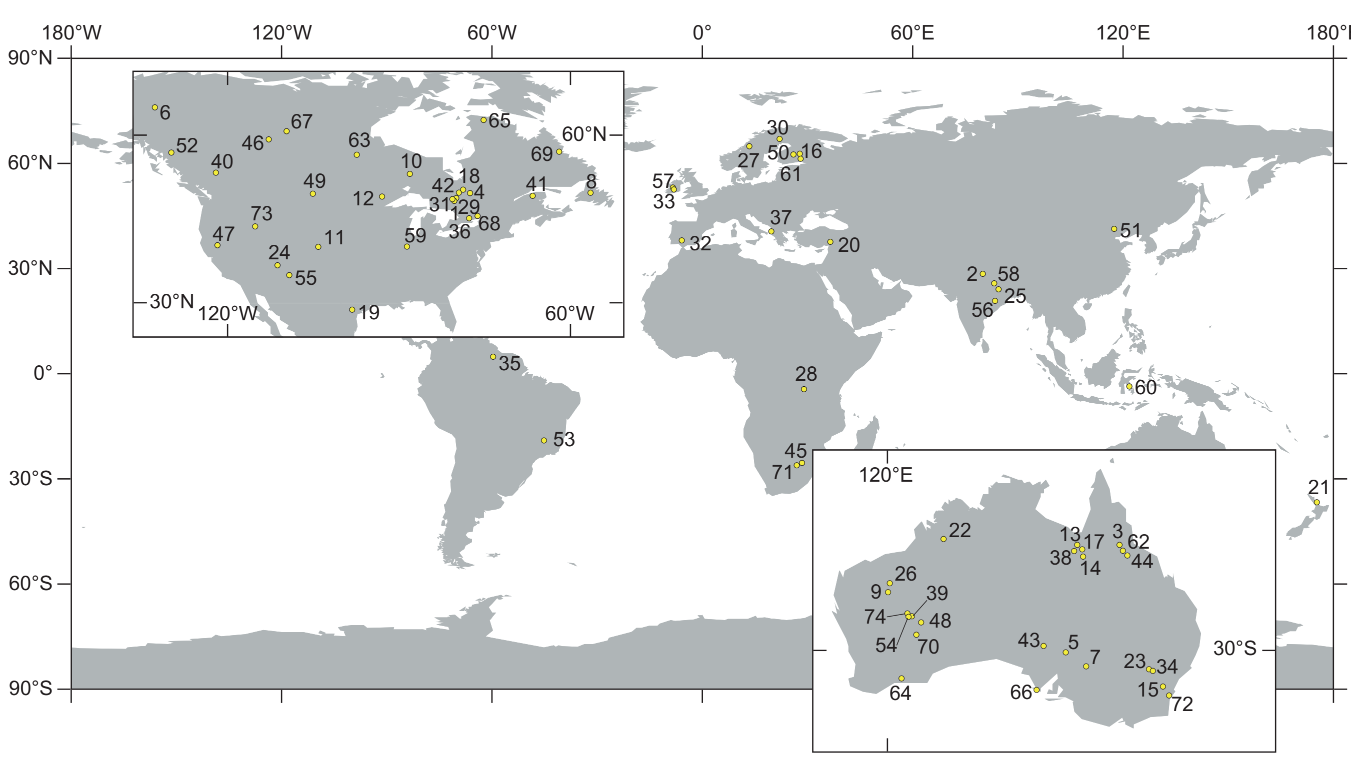

Figure 1.4 Locations of deposits and mineralised areas from which geophysical data are presented.