1 Introduction

1.1 Overview

Geophysics, the science of the physics of the Earth from its magnetosphere to the deep interior, is useful in characterizing the subsurface Earth. Solid-Earth geophysics employs techniques involving the measurement of force fields to study subsurface features and the processes that act upon them. Thus, geophysical studies serve a broad variety of geologic, natural resource, engineering, and environmental purposes. Gravity and magnetic methods, which measure very small spatial and temporal changes in the terrestrial gravity and magnetic force fields, have a wide range of uses from submeter to global scales. Although these methods in most cases fail to match the resolution and precision of direct observations, they are rapid, cost-effective, and non-invasive procedures of studying the inaccessible Earth and optimizing the location of drill holes for direct studies and other remote sensing studies which have higher resolution capabilities.

The application of gravity and magnetic methods generally involves a common approach consisting of planning, data acquisition, data processing, interpretation, and reporting phases. During the planning phase the appropriate method(s) are selected for meeting the objective of the study, and procedures for data acquisition, processing, and interpretation are established. These decisions are reached on the basis of experience, model studies, or test surveys. Special care is taken to determine an error or noise budget for the survey and to consider the propagation of errors, both random and systematic, through the data acquisition and processing chain. Selection of the distribution of observations in the survey region includes consideration of the objective of the study, the geologic, topographic, vegetative cover, and cultural features of the area, access over the region, and financial considerations. The geophysical observations are subject to numerous analytical processing steps to minimize effects from non-germane sources. Interpretation of these processed data involves not only determining the distribution of anomalous masses in the subsurface, but the nature of these masses. The latter commonly requires the translation of properties directly measured by the geophysical method into secondary properties, such as lithology, porosity, and strength, which are more directly related to the survey objective. Interpretation is achieved by transforming the survey data to quantitative models of the subsurface that satisfy the data. However, all interpretations are subject to ambiguities that to a degree depend on the implemented method and procedures and the integration of the results with collateral geological and geophysical information.

1.2 The Earth and its planetary force fields

Geophysics is an interdisciplinary science that integrates the observations, hypotheses, and laws of geology with the techniques and principles of physics to understand the composition, nature, structure, and processes of the Earth. Geophysics involves measuring and interpreting phenomena related to the physical nature of the Earth, from its center some 6,371 km beneath the surface to the outer limits of its magnetosphere at altitudes many times the

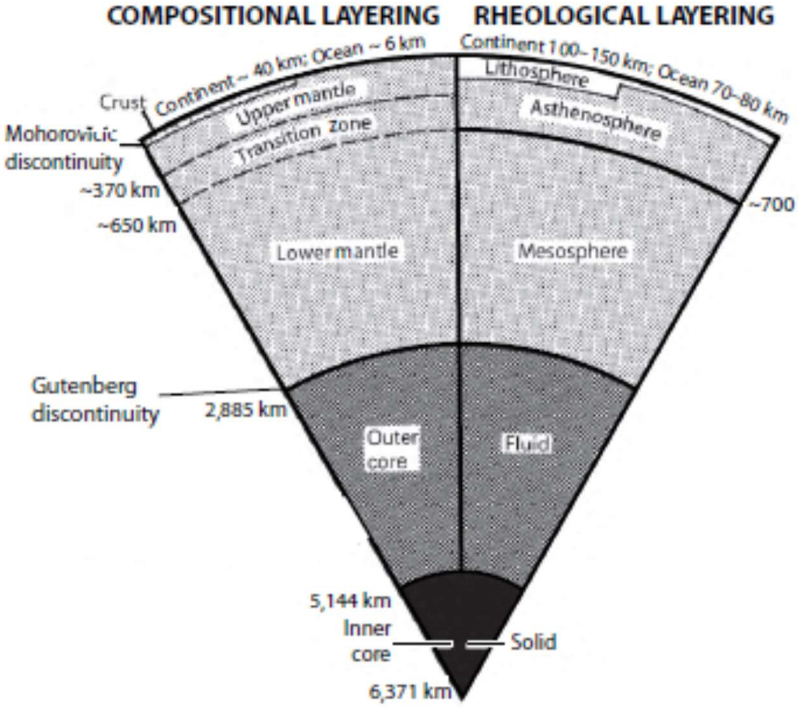

FIGURE 1.1 Cross-section of a segment of the Earth showing major first-order internal subdivisions in composition and mechanical or rheological properties. Table 1.1 lists the mean densities and magnetizations of the Earth's major structural components. Adapted from Keary and Vine (1990).

radius of the Earth. Thus, it incorporates investigations of the subsurface, hydrosphere, atmosphere, ionosphere, and magnetosphere. In this book, the focus is on solid-Earth geophysics, considering the properties and processes of the Earth primarily within the crust and uppermost mantle (lithosphere) as reflected in the spatial and temporal variations in gravity and magnetic force fields. We are all very aware of these planetary fields. The gravity field is the source of the force which causes all objects to be attracted toward the Earth, and the geomagnetic field controls the compass which is useful in determining geographic directions. These force fields have been and continue to be an important part of the science of geophysics.

Applications of gravity and magnetic methods include micro-scale surveys to map the physical property variations of the upper meter or two of the subsurface, or conducted within drill holes to establish the physical properties of the adjacent rocks. Larger-scale applications include regional to global surveys designed to image the deeper variations of the Earth's crust, mantle, and core (Figure 1.1). The crust is the outermost surface rind that consists of surface-like rocks extending to depths as great as 70 km. The crust overlies the mantle, made up of higher density and velocity but generally non-magnetic rocks and

TABLE 1.1 The average densities $<\sigma>$ and magnetizations $<J>$ in kg/m^3 and A/m, respectively, of the Earth's major structural elements shown in Figure 1.1.

Structure	$<\sigma>$	$<J>$
Upper crust	2,200–2,900	0–5
Lower crust	2,800–3,100	2–10
Upper mantle	3,300	0
Asthenosphere	3,300–4,000	0
Lower mantle	4.400–5,500	0
Outer core	9,900–12,200	0[a]
Inner core	12,800–13,100	0

[a]If the terrestrial field were caused by magnetization in the Earth's outer core, its effective magnetization would be $\sim 1.7 \times 10^3$ A/m.

extending to a depth of roughly 2,900 km, which in turn lies directly on the roughly spherical, dense, largely metallic core of the Earth in which the main terrestrial magnetic field originates. The lithosphere is the outermost semi-rigid shell consisting of the crust and uppermost mantle. It normally has a thickness of roughly 150 km beneath the continents and less in oceanic regions, and is the source of most of the variations in the gravity and magnetic fields of the Earth.

The crust exhibits highly complex structural and compositional properties that reflect the effects of erosion, sedimentation, metamorphism, tectonics, and igneous activity, and the plastic movement of the mobile asthenosphere underlying the lithosphere that have occurred over the Earth's 4,600-Myr history. These processes have led to the differentiation of chemical elements, deposition of a variety of sediments, vertical and horizontal movements, zones of crustal weakness, and the focusing of geological processes, such as volcanism, in limited regions of the Earth. These variations in the nature of the lithosphere and specifically the crust that solid-Earth geophysicists map and investigate are of societal interest because they control the formation and distribution of the Earth's resources, and volcanic, earthquake, and other natural hazards. Geophysics is an efficient and effective method of conducting these investigations, avoiding the problems of direct sampling of the hidden Earth. Nonetheless, these studies come at a cost, because the results of their interpretation are to varying degrees ambiguous and lack the accuracy of direct measurements.

1.3 Basis of the gravity and magnetic methods

Gravity and magnetic methods are commonly referred to as potential field methods because the measurements involve a function of the potential of the observed field of force, either the terrestrial gravity or magnetic field, at the observation site. These methods are widely used at a variety of scales to investigate the Earth because in comparison to most other geophysical methods the acquisition of data is inexpensive and rapid, and for many applications the reduction and interpretation of the observations are relatively simple. Furthermore, gravity and magnetic methods always provide information about the subsurface. In addition, there is a large reservoir of these data covering the entire Earth in varying detail that are publicly available at minimal cost to the user.

1.3.1 Gravity

The gravity method involves measurement of very small variations in the Earth's gravitational field, of the order of a few parts per million or lower, caused by lateral variations in density. Most observations are made with highly specialized weighing devices, called gravimeters or gravity meters, which measure the acceleration of gravity. Less frequently, they are made with instrumentation which measures the gradient or vector components of the gravity field. Gravity variations useful for studying the solid Earth are observed on land, in surface and subsurface water vessels, in drill holes, in the air, and from satellites orbiting the Earth. The variations they measure are dependent on Newton's universal law of gravitation, which takes into account the differential mass and the distance between the source and observation point. Because density is a universal property of matter, gravity is ever-present, but only where the density of the Earth varies laterally will gravity variations be noted that can be related to changes in the nature and structure of the Earth.

Observed gravity variations called anomalies are the differences between the observed and the theoretical field based on planetary considerations and the assumption of radial symmetry of the Earth layers. The anomalies may be either positive or negative depending on the presence of mass excesses or deficiencies, as illustrated in Figure 1.2. Their interpretation is subject to uncertainties in the observation, reduction to anomaly form, and processing and limitations resulting from the inherent ambiguity in their interpretation. However, meaningful interpretations can be obtained with proper use of constraining, collateral geologic, and geophysical information.

A wide range of densities occurs within the crust, from the essentially zero density of air-filled voids in near-surface formations, to densities of unconsolidated sediments with their interstitial openings filled with either air or water, to the highest densities related to iron/magnesium-rich crystalline rocks and metallic ores. Even higher densities are associated with the radial shells that make up the mantle and the core of the Earth. The potentially broad range of contrasting densities in the near-surface, in the crust, and in subcrustal rock materials leads to the wide range of applications of the gravity method.

1.3.2 Magnetics

The magnetic method (commonly referred to as magnetics) is similar to the gravity method in that variations in a planetary field are measured, in this case the magnetic field of the Earth. Observations are readily made to a high precision with portable electronic magnetometers on land, drill holes, sea, and air including measurements from planet-orbiting satellites. Most land areas of the Earth have now been measured by airborne observations and much of the ocean area has been observed either by airborne or shipborne measurements, at least by widely spaced observations. Variations, or anomalies, in the magnetic field of the Earth obey Coulomb's law, which is comparable to Newton's law of gravitation, but takes into account the

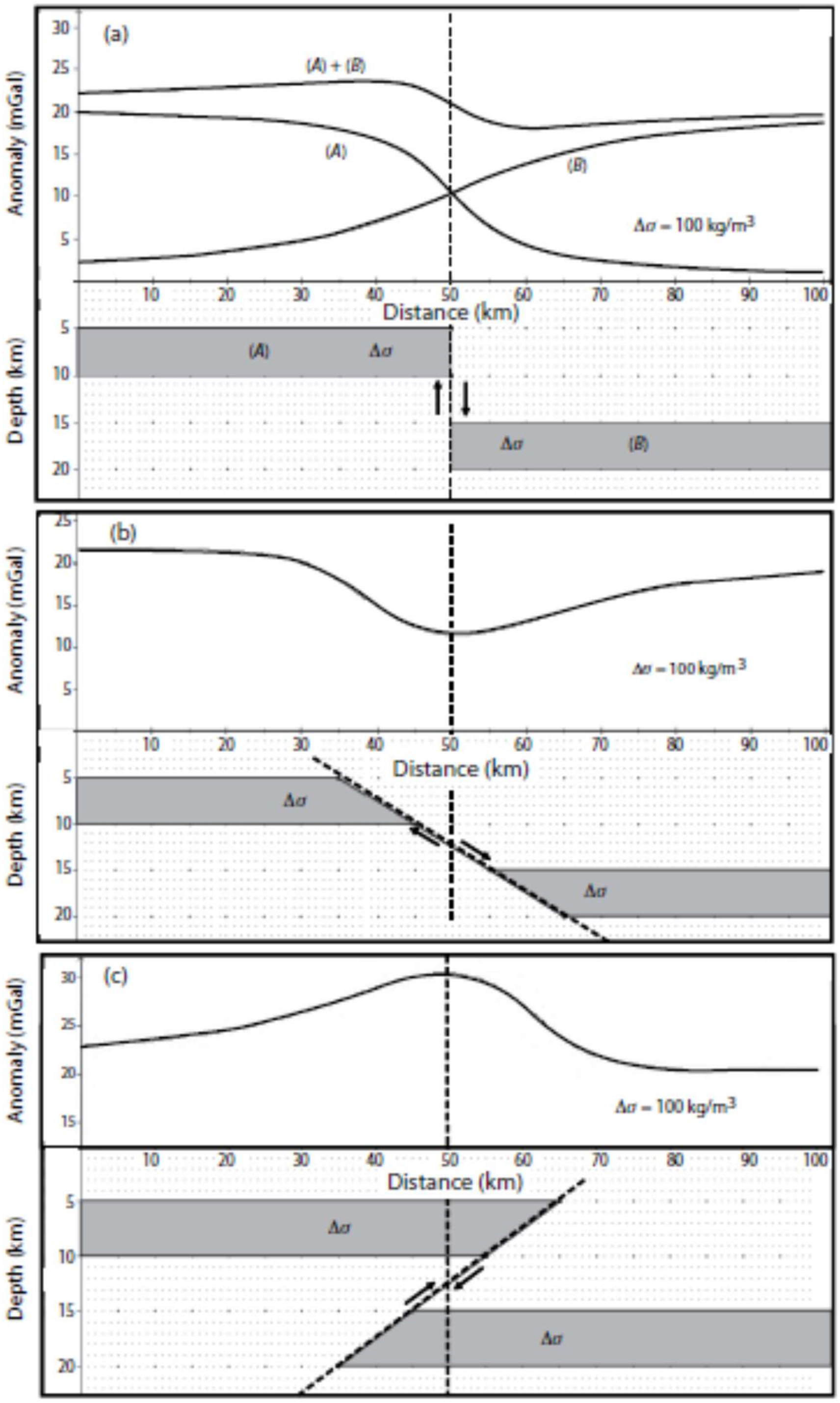

FIGURE 1.2 Examples of vertical gravity effects derived from faulting that offsets a layer of higher density within a formation of lower density. Panel (a) shows the layers vertically offset with the profiles of the gravity effects for the individual layer components (A) and (B), as well as for their total or superimposed effects (A + B). Panels (b) and (c) show the total gravity effect profiles for normal and reverse faulting of the horizontal layers. The illustrated gravity effect is the vertical acceleration of gravity given in units of milligals (mGal) where 1 mGal is equal to 10^{-3} cm/s^2 or 10^{-5} m/s^2.

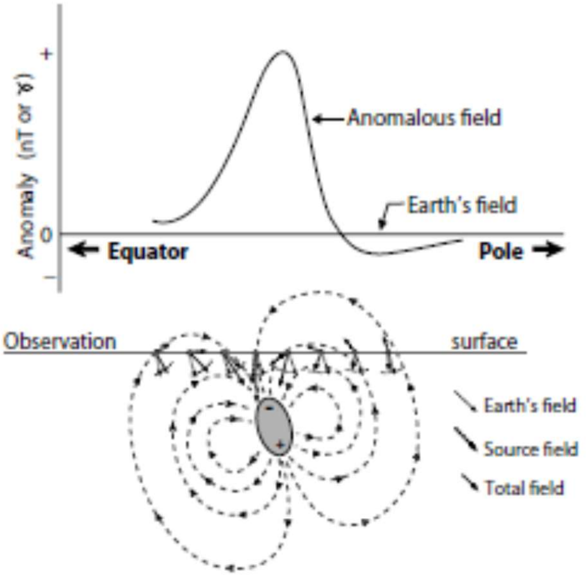

FIGURE 1.3 Example of the total magnetic field variation (anomaly) caused by the magnetic effect of a buried magnetic object (shaded area) magnetized by the Earth's field. The sum of the magnetic field of the anomalous source and the Earth's field produce the observed total magnetic intensity anomaly profile at the top of the figure. Note the asymmetry of the anomaly owing to the inclined magnetization and the negative component of the anomalous field caused by the positive pole of the magnetic source.

magnetic polarization variations of the Earth rather than its mass. Magnetic polarization is dependent on the magnetic susceptibility and the remanent or permanent magnetization of Earth materials. Magnetic susceptibility is a measure of the ease with which a material can be magnetized in the current magnetic field of the Earth; remanent magnetization is the permanent magnetization previously acquired and retained by the material.

All magnetic materials, including the Earth, have two poles, north and south or positive and negative, and thus are called dipolar. Objects of high magnetic susceptibility become polarized or magnetized when they are present in the Earth's dipolar geomagnetic field. Magnetic field observations taken over a buried magnetized object will measure both the positive and negative fields associated with the dipolar magnetization of the object. The resulting anomaly from a high magnetic susceptibility object will combine the fields of both poles as, for example, illustrated in Figure 1.3, but will be dominated by the pole nearest to the observation. The magnetic field of the Earth will induce in the northern geomagnetic hemisphere a negative pole near the top of the anomalous source and a positive pole near the base of the source. The negative pole, being in closer proximity to the observations, will produce a greater attraction on a north-seeking pole (+) than the repulsion from the negative pole. Accordingly, the magnetic field over the anomalous source will be dominated by an increase in the magnetic field over the Earth's field as shown in Figure 1.3. An inverse anomaly dominated by a decrease in the field would be observed over an object with lower magnetization than the surrounding Earth materials. The magnetization of an object magnetized in the Earth's magnetic field will align with the Earth's field. As a result the anomalous field will vary with location on the Earth's surface owing to the dipolar nature of the main field which roughly aligns with the axis of rotation and the resulting changes in the main field over the Earth's surface.

Unlike crustal rock densities, which generally vary by less than a half-order of magnitude and are directionally independent, magnetic polarization commonly varies over several orders of magnitude, giving rise to large property contrasts, and is directionally variable. The directional attribute of magnetization complicates the interpretation of measurements of the magnetic field, as do the presence of both positive (attractive) and negative (repulsive) poles within all magnetic materials as illustrated in Figure 1.3.

An advantage of the magnetic method over the gravity method is that the field varies inversely one power faster with distance to the source than does the gravity field from the same source. As a result, the magnetic method is more sensitive to the source depth, which is commonly an important objective in interpretation of the observations. Furthermore, the resolving power of the method to distinguish independent sources is greater than that of the gravity method. Magnetic field variations are derived from only a few minerals, and these occur only as accessory minerals in most rocks. However, the measured variations are several parts in a hundred thousand or greater; thus magnetic variations are easier and less costly to map than are gravity anomalies from similar sources. Also, magnetic measurements can readily be made from simple, mobile platforms increasing the surveying rate, making them cost-efficient. As a result the magnetic method is widely applied as a reconnaissance tool in geophysical studies and has several specialized applications in shallow subsurface and crustal studies.

1.4 Foundations of geophysical methods

The foundations of geophysics were developed in the last few centuries through scientific studies of surface geological features by pioneering geologists and the study by early physicists of natural force fields of the Earth. From the seventeenth century onwards, geologists such as Steno, Smith, Werner, Hutton, Playfair, and Lyell established the basic laws of geology, and explained the formation of rocks. These and other principles are explained in introductory geological texts. The reader unfamiliar with the basics of geology is encouraged to learn the key concepts presented in these books because they are fundamental to the understanding and application of geophysical methods in general, and the gravity and magnetic methods in particular.

Contemporaneous to the early geologic studies, physicists investigated a variety of terrestrial force fields and developed theories and laws to explain their observations. Beginning in the sixteenth century, such prominent scientists in the history of physics as Newton, Galilei, Gilbert, Gauss, Coulomb, Volta, Oersted, Ampere, Bouguer, Faraday, Fresnel, and Maxwell contributed greatly to the science of geophysics. By the mid-nineteenth century, they and their peers had essentially established the foundations of gravitational, magnetic, and electrical fields of the Earth and the basic theory upon which are based current studies of these fields in geophysics. At about that time, instrumentation was becoming available for field geophysical measurements and the potential for subsurface studies with these measurements was being identified.

Building upon improved instrumentation and interpretational techniques developed in the succeeding decades of the twentieth century, particularly after World War I, great progress was made in the use of gravity and magnetic methods in the search for Earth resources. Technological developments, primarily in electronics, during World War II made instrumentation improvements that led to the broad use of computers, electronic magnetometers, accelerometers, ground-penetrating radar, digital recording, and other advanced instrumentation of geophysics. Post-World War II geophysical investigations in geomagnetism, seismology, paleomagnetism, and isotopic age dating of rocks led to the development of the paradigms of seafloor spreading and plate tectonics by Vine, Matthews, Morley, Morgan, Sykes, Runcorn, Oliver, Wilson, Heirtzler, Dalrymple, and others. These paradigms explain the slow movement of crustal units over the Earth's surface as well as the destruction of existing crust and the construction of new crust by interaction with the Earth's mantle. These concepts are essential to understanding the evolution and the geological and physical processes of the Earth, and thus to the application of gravity and magnetic methods.

The latter half of the twentieth century saw technological improvements that resulted in more precise, portable, and inexpensive instrumentation and faster computations. The continuing improvement in computers has been fundamental to all of geophysics. Not only have computers made it possible to collect and store huge amounts of data, but they are the keystones to current data processing and presentation technology responsible for today's broad success and acceptance of geophysics.

Progress in geophysics has been driven by societal needs and economic factors as well as by technological advances. In the 1920s and 1930s, the worldwide surge in the number and use of automobiles, with their gasoline-powered internal combustion engines, increased the need for petroleum products. This need could not be met solely with production from petroleum traps located by surface geologic information and wildcat drilling. Geophysics stepped into this void by greatly increasing the chances of discovery. The growth in petroleum exploration geophysics was accelerated by the ever-increasing demands of the post-war surge in the world's economy. The societal and economic pressure caused a revolution in petroleum exploration geophysics that continues today. In a similar way, post-World War II industrial developments and the depletion of mineral resources during the global war forced the broadening of mineral exploration to the geophysical search for new mineral districts and ore deposits which have little or no surface indication.

Petroleum geophysical exploration began with instrumental developments in the early part of the twentieth century that permitted gravity to be measured with a precision necessary to study subsurface geologic structures. These developments led to the first geophysical discovery of petroleum in the United States, which was by the gravity method, in the early 1920s. The use of gravity in petroleum exploration reached a peak shortly after World War II, but its relative role decreased as the reflection seismic method was improved, largely as a result of the computational power of computers and related theoretical developments. Nonetheless, the gravity method has a significant niche and is especially valuable used in concert with the reflection seismic method to constrain possible interpretations. The improvements in the gravity method for hydrocarbon exploration have given impetus to its use not only for this application, but also for shallow zone and regional exploration of the Earth. The successful development of techniques for measuring gravity to a precision useful for exploration using airborne and satellite platforms has given the method a new range of applications.

The magnetic method has been used since the seventeenth century in mineral exploration, especially for iron ore prospecting, but with the advent of airborne magnetic observations after World War II, it has been used on a broad basis for regional geological studies in petroleum

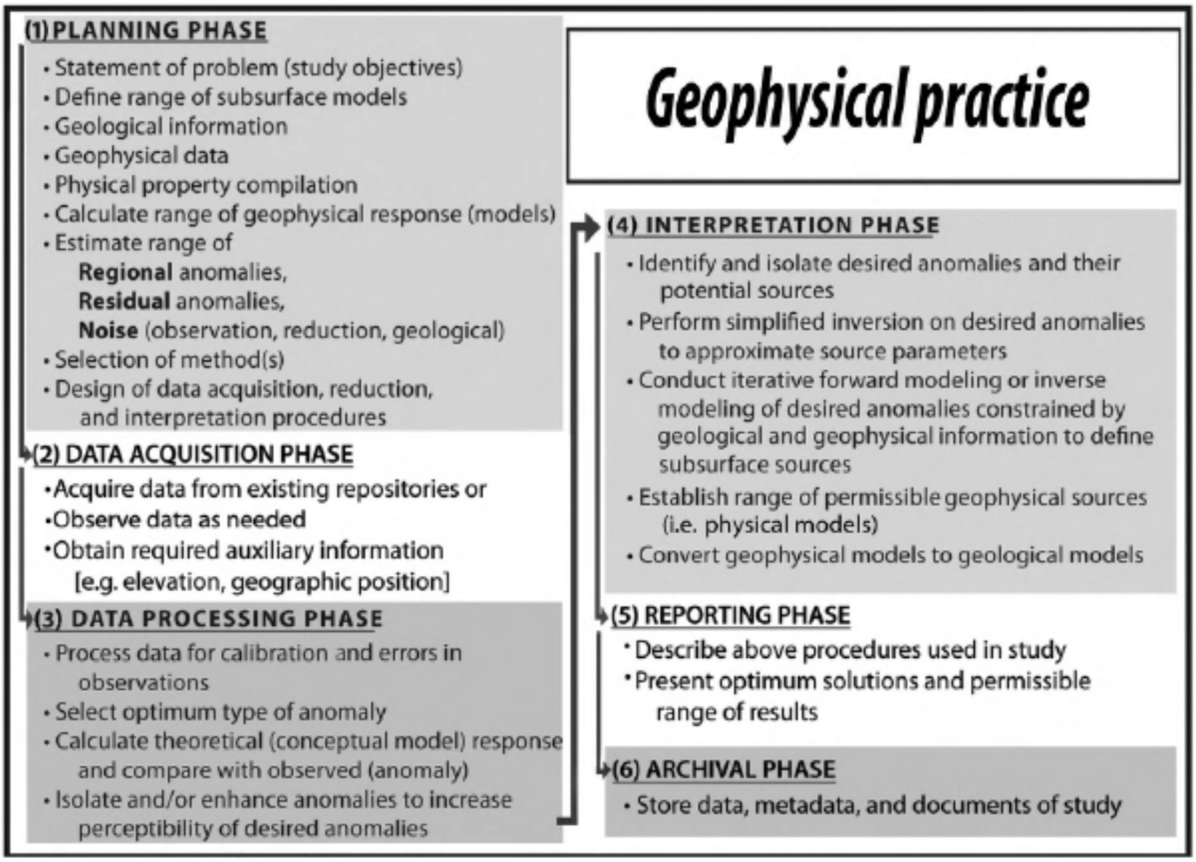

FIGURE 1.4 The geophysical practice for implementing the gravity and magnetic methods involves a sequence of six phases.

exploration, both detailed and regional studies in mineral exploration, and in geologic mapping of crystalline rock terrains where the rock units have varying magnetic polarization. It has also proved useful in identifying ferrometallic objects in the near surface, such as buried well casings, storage containers, and unexploded ordnance and the study of archaeological sites.

The development of satellites and other space age technologies since the 1960s has greatly advanced regional exploration of the surfaces and deep interiors of the Earth and other planetary bodies. Political considerations do not limit satellite operations so that essentially any region is available to satellite remote sensing and geophysical mapping efforts. Unprecedented timing and positioning data from the constellation of Global Positioning Satellites (GPS) greatly expedite modern geophysical survey efforts, while the communication capabilities of satellites allow access to geophysical experiments literally worlds away from our offices and laboratories. Satellite gravity and magnetic observations, in particular, are yielding important new insights on the nature, architecture, and dynamics of the Earth and other terrestrial planets.

1.5 Geophysical practices

The gravity and magnetic methods are described in individual chapters that follow. However, in addition to the fundamentals specific to the individual methods, there are general principles and practices that are used in geophysical exploration programs. They are sufficiently general that a description of them serves as an introduction to the use of both gravity and magnetic methods. Whether they deal with the selection of the geophysical method, the design of a data acquisition and processing program, the reporting of an investigation or any one of the numerous components that mark a successful geophysical campaign, they are for the most part nothing more than the application of appropriate scientific methodology (Figure 1.4). The following description assumes that the program involves all phases from planning to report preparation and archiving the data and results. Programs may also focus on previously surveyed data that already have been reduced to anomaly form, where only the latter phases are applicable. Nonetheless, considering the factors for the phases described below will help to determine the usefulness of existing data. In the individual sections dealing with the gravity and magnetic methods, descriptions are provided of the data acquisition, processing, and interpretation phases, but the planning phase is focused on the principles of the methods and the survey objectives.

1.5.1 Planning phase

The planning phase is perhaps the most important step in the geophysical approach because it is in this stage that fundamental decisions are made regarding the nature and procedures of the program. Appropriate planning requires collecting and using all available geological and geophysical data and interpretations, and establishing strong communication links among the interested parties regardless of their particular expertise. Plans should only be finalized after all parties have had the opportunity to interact.

Planning is subdivided into two segments: first, the selection of the appropriate method(s) and, second, the design of the survey and the subsequent data processing and interpretation. To be successful, both require a clear exposition of the objective of the survey. Important collateral information is the specification of the volume of interest to the survey – that is, the areal as well as the depth extent of interest. This subsurface volume is limited as much as possible within the framework of the problem because the areal extent of the survey is a major factor in determining the cost of the survey. In addition, the survey procedures are tuned to the depth of interest as dictated by the survey objectives.

The most important consideration in the selection of the method for a study is to determine if the target sources will produce an observable anomaly even in the presence of extraneous signals. This requires estimation of the anticipated source volume, depth, and physical property contrast as well as evaluation of potential geologic, observational, and processing noise and errors. Information on the physical properties of the Earth materials in the subsurface volume being investigated is important to all phases of the application of geophysical methods, but particularly in planning studies when target anomalies are being estimated. Rock property data are obtained from *in situ* measurements on the site, sample measurements, and general tabulations. The character of target anomalies may come from experience in related situations, forward modeling of both anticipated anomalies and potential anomaly noise, or test surveys. The latter are particularly useful where information needed for modeling of sources and estimating noise and errors is lacking. The parameters of the source targets commonly cover a range of values necessitating the study of a distribution of anomaly characteristics. Evaluation of anticipated anomalies in reference to the objectives of the investigation may suggest the use of multiple methods. The combined use of gravity and magnetic methods is particularly powerful in studying crystalline rock terrains that consist of large volume sources with both density and magnetic polarization contrasts.

Once the optimum geophysical method or methods have been selected for a study, the survey must be designed to accomplish the objectives in a minimum time at the lowest possible cost without jeopardizing the quality of the survey. The anticipated signal from the anomalous geologic features of interest will dictate many of the attributes of the survey design. Survey design is a matter of maximizing the information obtained and required within the financial limits of the survey. This is often accomplished with a heuristic method based on experience and knowledge of field characteristics, or on a statistically based experiment design methodology as described by Curtis (2004a and 2004b). The areal coverage of the survey, of course, will be a function of the size of the study area and the anticipated size, depth, and depth extent of the anomalous features. The greater are these parameters, the larger the required size of the survey area. The anomalies often must be isolated from regional and noise effects, thus the survey area must extend well beyond the study area or the areal configuration of the anomalous feature. This is well illustrated for both the gravity and magnetic methods in Figures 1.2 and 1.3, respectively, where the anomaly needed for identification and analysis of the subsurface feature (that is, the fault in the gravity anomaly illustration and the ferrous source in the magnetic anomaly illustration) extends well beyond the immediate region of the anomalous feature.

Critical concerns in planning surveys are selection of the data density and precision. These are determined by the objectives of the survey and characteristics of the anticipated signals. For most objectives the anomalous signal including the maximum gradients must be fully measured, not simply the maximum amplitude of the anomalous signal. In gravity and magnetic surveys it is necessary to map the gradients of the anomalies to effect a useful interpretation. This requirement necessitates closely spaced and high-precision observations. Forward modeling of the range of anticipated anomalies, including their size, properties, and position, provides a basis for selecting the required data density and precision.

In general, sampling theory specifies that the station interval should be no greater than half the length of the smallest dimension that needs to be mapped in the survey. This interval or spacing is referred to as the Nyquist wavelength and its inverse as the Nyquist frequency. It is the maximum spacing that should be used between measurement points, although in practice the sampling interval should be considerably less than the Nyquist sample interval if the gradients of the measurements are of interest or the higher-frequency noise components must be mapped and isolated from the desired signal.

In gravity and magnetic methods, the separation between observations is directly proportional to the depth of investigation – that is, the greater the target depth, the greater is the permissible station spacing. Often a separation approximately equal to half of the depth to anticipated sources is used in surveys. However, generalizations regarding separation of measurement points are of limited value because of the need to consider the specific attributes of the survey. As a result, it may be desirable to determine quantitatively the probability that a specific anomaly will be detected utilizing the sampling theorem, with stations located either randomly through a region or on a regular grid (e.g. SAMBUELLI and STROBBA, 2002). Wherever possible, it is desirable to conduct test surveys over a limited, representative portion of the survey area or noise tests to select the optimum survey layouts.

1.5.2 Data acquisition phase

In the data acquisition phase, the actual field and necessary related data are measured and recorded. Auxiliary observations that are made in addition to the primary geophysical measurements include essential data for the reduction of the measurements to an interpretable form (e.g. station elevation or flight altitude, surrounding topographic relief, and water depth). Instrumentation must be selected to meet the precision requirements of the survey as established in the planning phase as efficiently as possible. Actual field procedures are dictated by the survey objectives, sources of noise, surface and weather conditions, instrumentation, and access within the survey area. For example, access may limit the survey to discrete observations along roads rather than a grid pattern more useful in interpretation. Observations are commonly made along traverses which are oriented perpendicular to the prevailing strike direction of the anomalies, separated at greater distances than the observations along the traverse. The distance between traverses is determined by estimating the length of the continuity of the character of the anomalies along their strike direction.

Gravity and magnetic methods are particularly effective in a reconnaissance or regional study mode because they are fast and efficient; while other methods may provide better detail and resolution, they are likely to be more costly and time-consuming. Use of gravity and magnetic methods early in an exploration program sequence can delimit an area for detailed investigations with other methods and improve the survey design to obtain maximum information from measurements. For example, magnetic measurements which often can be taken quickly and inexpensively from an airborne platform may be used to delineate likely faulted areas. In this way limited sectors of a large region can be isolated for study and evaluation in much greater detail by slower and more costly methods, like the seismic reflection method. Similarly, regional gravity surveys may be used to determine the strike direction of prevailing geological features within an area which can guide the selection of the direction of detailed traverses along which gravity or other geophysical fields or forces are measured.

1.5.3 Data processing phase

The nature and role of the data processing phase may vary considerably between gravity and magnetic methods and with the survey objectives. In general, the data processing requirements of the magnetic method are considerably simpler than for the gravity method largely because of the intense magnetic polarization contrasts in the crust of the Earth. For example, in some magnetic studies to locate near-surface ferrometallic bodies, the amplitudes of anomalies are sufficiently large that no data processing is needed. However, this is the uncommon situation, particularly with the increasing demands for precision in the results of geophysical studies. Accordingly, most survey objectives and methods lead to data in which the signal to be used in interpretation is significantly distorted by extraneous effects. Data processing is used to remove these extraneous effects and enhance the desired signal for interpretational purposes. Generally, data processing is performed subsequent to acquisition of the raw or observed data, but field processing may be used to minimize unwanted signals. For example, the stabilization of a gravimeter in field procedures may minimize wind-driven accelerations acting on the meter, and field processing by digital filtering can be used to supplement the effect of the field procedure.

Data processing may include several steps. The first is to prepare the data for interpretation by removing the effects of instrumentation as calibration adjustments and correction for instrument instability. These data are then reduced for known or predictable effects upon the observed data by calculating the theoretical value of the observation at a specific site using all known variables, such as elevation and planetary effects, and subtracting this predicted value from the observed measurement to obtain the anomalous value or anomaly. Data available in publicly available data banks commonly are at this level of processing. The next step is some form of digital filtering to remove wavelengths smaller (noise) and larger (regional) than the anomalies of interest. The purpose of this stage is to enhance particular attributes of the anomaly or signal that will increase its perceptibility and to isolate anomalies of interest for interpretational purposes. Although these procedures are highly automated in most data processing schemes, human interaction is required to establish optimum procedures and parameters.

1.5.4 Interpretation phase

The procedures involved in interpretation of the force field measurements into the nature and distribution of subsurface materials or associated processes relevant to the objectives of the investigation are highly varied depending on the goals and scope of the survey and the experience and skills of the interpreter. Successful interpretation commonly involves intangible qualities of the interpreter such as experience, observational powers, ability to visualize in three dimensions, and the intellectual capacity to organize and integrate a variety of often disparate types of information. As such, it is viewed in some quarters as an art, but most interpretation follows an orderly logical process, often called scientific methodology, using the methods of deduction or induction to proceed from processed data to a successful conclusion.

For simple survey problems, the interpretation phase is largely qualitative and is essentially terminated with the successful identification and isolation of anomalies. For example, if the location of bedrock highs is the objective of a gravity survey, the interpretation is completed with the isolation of gravity anomaly highs associated with the greater density bedrock contrasting with the overburden of unconsolidated sediments. In this and similar cases, the distinction between the data processing and interpretation phases becomes blurred. If the goal of the gravity survey is not simply to isolate bedrock highs, but is to determine the bedrock configuration, a more quantitative interpretation procedure must be applied.

Quantitative interpretation uses inversion to quantify possible geometric and physical property parameters of the subsurface that can satisfy the observed data. The essential element of inversion is the forward model that produces a synthetic set of estimates or effects for comparison with the actual observations. Acceptable models of the subsurface are typically judged by how well the modeled effects match the observed data in amplitude and shape. However, an acceptable model cannot guarantee a unique solution for the data because the forward model is always a mathematical simplification of the subsurface conditions, and it and the observed data always contain errors. In addition, the non-uniqueness of gravity and magnetic inversions is further exacerbated by the inherent source ambiguity of any anomaly solution. Thus, ancillary geological and geophysical constraints are commonly invoked to limit the range of acceptable models from an inversion.

Multiple approaches are available for solving inversion problems. A common methodology involves trial-and-error comparisons of observed geophysical signals with the effects from a presumed subsurface model. Through an iterative process the parameters of the presumed subsurface model are modified until a close match is obtained between the observed and estimated values. This so-called forward or direct modeling approach is especially appropriate when dealing with a relatively small data set and a simple subsurface model where only a few unknown parameters must be evaluated.

For more complex inverse problems involving greater numbers of observations and model unknowns, so-called inverse modeling approaches are desirable. These approaches commonly assume the forward model of the relevant volume of the Earth from the measurements, their distribution, and boundary conditions imposed by the geological setting. Modern inversions typically invoke the linear forward model as a series of simultaneous equations where the unknown geometric or physical property parameters can be estimated by fast matrix inversion methods.

The nonlinear forward model has more limited use because the computational labor of implementing the related inversion is much greater than for linear inversion. The nonlinear inversion requires the investigator to explore solution space generated typically by a large number of simulations where values of the unknown parameters have been randomly selected. These simulations, for example Monte Carlo simulations, are graphically or numerically processed for solution maxima or minima that may mark acceptable solutions.

A final step in the interpretation phase is to transform the quantitative model obtained by inversion into appropriate geological parameters. That is, the geometric and physical property estimates that satisfy the anomalous field must be converted into an effective geological context. For example, the geological significance of the physical properties or property contrasts interpreted from the observed data is best appreciated when related to the lithology and secondary physical characteristics of the formations. This is illustrated in Figure 1.5 where an observed gravity anomaly is shown that is closely matched by the effect of a cylindrical source of a positive density contrast.

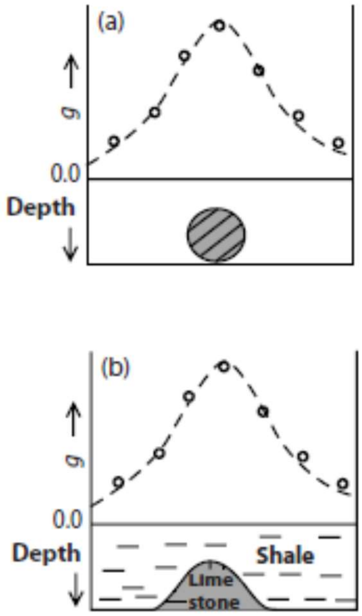

FIGURE 1.5 (a) Schematic illustration of the match of observed gravity anomalies (open circles) with the theoretical gravity effects (dashes) from a cylindrical source. (b) Translation of the horizontal cylindrical source in (a) into the geologic context of a limestone bed folded into an overlying lower-density shale. The gravitational effects of the idealized cylindrical source and the folded limestone are essentially equivalent.

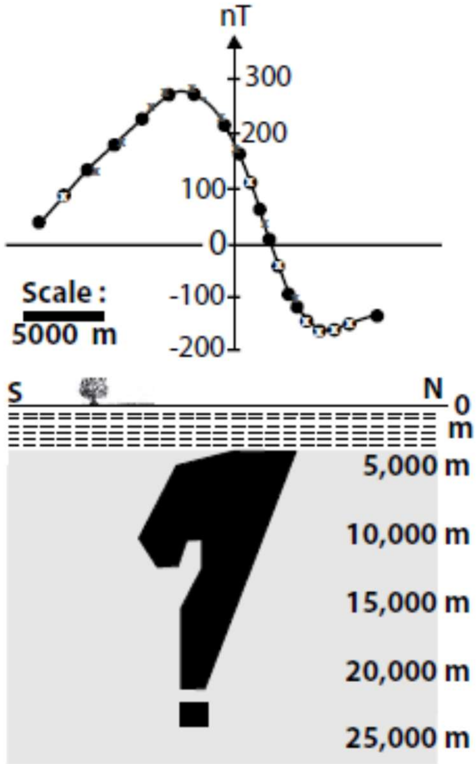

FIGURE 1.6 Comparison of the observed and calculated magnetic values across a subsurface source near Lausanne, Switzerland, with the configuration of the magnetic source used in the calculation shown in the underlying geological cross-section. The absurdity of the shape of the source denies the credibility of the interpretation. The observed data (dots) were modeled (crosses) with the black 2D body of volume magnetic susceptibility 0.00345 CGSu subjected to a polarizing field intensity of 46,450 nT with an inclination of 62°. Adapted from Meyer de Stadelhofen and Juillard (1987).

In geological terms, the cylindrical source effect can be taken as the effect of an anticline which brings limestone into juxtaposition with overlying lower-density shale.

Consideration of the stages in the interpretational process clearly shows that the process is subject to ambiguity, where multiple solutions are equally compatible with the available geophysical information. This is an inherent property of potential field methods regardless of the accuracy of the measurements and processing and the sophistication of the interpretational procedures.

A striking example of the ambiguity of geophysical data is presented in the tongue-in-cheek illustration of Figure 1.6. This figure shows the close correspondence between the observed field and calculated magnetic values along a profile across a magnetic anomaly near Lausanne, Switzerland, of unknown origin. The close correspondence of the field and calculated values gives a false sense of credibility to the forward model interpretation. Clearly the question-mark shape indicates the absurdity of the source configuration.

Fortunately, the interpreter can decrease the potential ambiguity in interpretation, although it can never be completely eliminated. For example, ambiguity can be minimized by the integrated interpretation of two or more geophysical signals derived from common sources. This takes advantage of the different physical responses of fields and their varying sources and degrees of ambiguity. In a similar manner, geological and physical property information can be extremely valuable in establishing boundary conditions for possible interpretations. Because interpretations are fundamentally non-unique, however, it is appropriate to conduct several analyses based on different assumptions to find the range of possible interpretations. This is referred to as a sensitivity analysis.

1.6 Nature of geophysical data

Data in this book are presented in SI units (SIu), except in specific situations where alternative units are more meaningful to the user of the data or the interpretation. SI is the abbreviation for Le System International d'Unites, which is a system of units that is broadly accepted internationally by governmental agencies and professional societies. This system has similarities to the metric system of units, but

TABLE 1.2 SI units (SIu) used in this book.

Quantity	SIu	Symbol
Base units		
Length	meter	m
Mass	kilogram	kg
Time	second	s
Supplementary units		
Plane angle	radian	rad
Solid angle	steradian	sr
Derived units		
Acceleration	meter/s^2	m/s^2 = 10^5 mGal
Area	square meter	m^2
Density	kilogram/m^3	kg/m^3 = 10^3 g/cm^3
Energy	joule	J = N/m
Force	newton	N = kg × m/s^2
Magnetizing force	ampere/meter	A/m
Magnetic flux	weber	Wb = volts × s
Magnetic flux density	tesla	T = Wb/m^2 = 10^9 γ (or nT)
Pressure	pascal	Pa = N/m^2
Viscosity (dynamic)	pascal second	Pa × s
Work	joule meter	J × m

is not identical to it. The base and supplementary units of the SI system together with their combinations, called derived units, that are common to geophysical studies in this book are listed in Table 1.2. Note that SIu is used as the abbreviation for SI units throughout this book.

It is important that only significant figures be retained in the data: that is, no figures should be kept in the data stream beyond the first doubtful one. In rounding off numbers to the nearest significant figure, the number should be increased to the next highest digit if the following number is 5 or more. Zeros are significant only if they are preceded by digits or are necessary to establish the position of the decimal point.

1.6.1 Data documentation

Data measured in geophysical surveys, whether consisting of a single observation at a single site or repetitive observations at multiple sites, require annotations to describe the survey, the specific site of the measurement, instrument characteristics, processing applied, and in many cases the environmental conditions of the measurement. These annotations are commonly referred to as metadata. The specific annotation and the manner in which the annotations are recorded vary with the type of measurement.

The adequate annotation of measured data is only one example of "best" practices that are important in quality assurance. Quality assurance has long been important to geophysical investigators, but as a formal process it has been recognized only in recent decades. It has become particularly important in geophysical studies related to engineering problems such as the siting of critical structures. The potential impact of failure of these structures as a result of incorrect conclusions drawn from faulty investigations, with the resulting effect on humans and the environment, has encouraged regulatory and licensing agencies of the government as well as private industry to insure that the studies are conducted at the highest possible level of quality. As a result, quality assurance has become a required element in the acquisition and processing of geophysical data in many types of both commercial and governmental geophysical surveys. This is intended to insure the integrity of the studies and the quality of the data and resulting data processing and interpretation.

1.6.2 Data errors

Measurements of forces and fields are subject to uncertainty as a result of a variety of errors. Errors or noise are the difference between the truth and the actual measurement, and thus are analogous to anomalies which are at the heart of most geophysical studies. Errors may originate from the instrumentation system and the observer, the reduction and processing of data, and geophysical interpretation. Errors or noise also may be caused by mistakes by the geophysical analyst, but not all errors are mistakes. In fact most errors in geophysical studies are not caused by humans, and in many cases the sources of noise are unknown and unavoidable.

Errors are of two basic types, systematic and random. Systematic errors are consistent deviations within a measurement system. They may be constant or vary in either a linear or nonlinear manner with some attribute of the system or its environment, such as the amplitude of the measurement or the temperature of the system. They are caused, for example, by incorrect instrumentation calibration, poor design of apparatus, incorrect identification of baseline values, and some personal errors. The latter may originate from the tendency of an observer to consistently misread a galvanometer that is used in the measurement system or by a consistent bias in interpretation by an analyst. The conclusions from studies which have only systematic errors may be consistent in themselves and therefore be precise, but inaccurate on an absolute basis. Systematic errors or noise can be difficult to detect because they will not show up in repetitive measurements by the same system. They can only be identified by making the same measurement with a different measurement system involving changes in the observer/analyst, measurement instrumentation, data processing scheme, and interpretation procedures.

Random errors are deviations from the truth that occur by chance, and thus are unpredictable and subject to the laws of probability. They are the deviations or errors we observe in repetitive observations. They exhibit no correlation with attributes of the measurement system or source of the field measured and are unrelated to other measurements made by the system. They arise from inconsistencies in the sources, instrumentation instabilities, and observer/analyst non-systematic errors. Random errors take on a normal distribution, that is a large number of repetitive observations or results will assume a normal (i.e. bell-shaped or Gaussian) distribution around a central value that is the arithmetic mean of a set of numbers. Statistical tests can be used to determine if a data set reasonably approximates a normal distribution. Individual numbers of the set of normally distributed values are equally likely to be positive or negative relative to the average, but extreme variations are less likely to occur. The frequency of occurrence is much greater for those values that are nearer to the average value.

The arithmetic mean is usually taken as the most probable value of the quantity. However, the arithmetic value is not the true value of the quantity because the mean depends on the number of measurements used in the calculation. The accuracy will increase as the number of values in a set of data increases. Because the mean is not the exact value of the quantity, it is common practice to estimate the accuracy of the calculated mean value. One method is to calculate the standard deviation which takes into account the number of observations. The standard deviation σ of a set of n observations $x_1, x_2, \ldots, x_n$ with mean $\bar{x}$ is

$$\sigma = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(x_i - \bar{x})^2}. \quad (1.1)$$

There is a 68.26% chance that the true value is within one standard deviation of the mean value and a 95.46% chance that it is within two standard deviations.

In a set of observations it is not uncommon to experience an outlier value that departs widely from the others. The question thus arises as to whether the outlier is due to a blunder and therefore should be rejected or should be considered in determining the statistics of the data set. If no obvious mistake is evident, a statistical test can be employed to test the validity of the measurement as a member of the set. One test, which is based on probability, states that if a single observation departs from the mean by more than three times the standard deviation, the observation should be discarded because the chances are 400 : 1 that the observation is due to a random error or blunder.

Most geophysical measurements require some mathematical manipulation or data processing before they are used for interpretational purposes. Commonly several mathematical steps are involved with multiple measurements and parameters, each with their own error expressed as a standard deviation. As a result, errors will propagate through the mathematical steps. Of course, it is possible for positive errors to be offset by negative errors, but because it is impossible to determine that this is the case, it is the norm to be conservative. Thus, the rules for calculating the net error for each mathematical manipulation assume the maximum error. The rule for both addition and subtraction is to add the standard deviations. Thus, the sum of two sets of numbers with means N_1 and N_2 and respective standard deviations σ_1 and σ_2 is

$$(N_1 \pm \sigma_1) + (N_2 \pm \sigma_2) = (N_1 + N_2) \pm (\sigma_1 + \sigma_2), \quad (1.2)$$

and their difference is

$$(N_1 \pm \sigma_1) - (N_2 \pm \sigma_2) = (N_1 - N_2) \pm (\sigma_1 + \sigma_2). \quad (1.3)$$

In multiplication, the rule is

$$(N_1 \pm \sigma_1)(N_2 \pm \sigma_2) = N_1 N_2 \left[1 \pm \left(\frac{\sigma_1}{N_1} + \frac{\sigma_2}{N_2}\right)\right], \quad (1.4)$$

whereas for division, it is

$$\frac{(N_1 \pm \sigma_1)}{(N_2 \pm \sigma_2)} = \frac{N_1}{N_2}\left[1 \pm \left(\frac{\sigma_1}{N_1} + \frac{\sigma_2}{N_2}\right)\right]. \quad (1.5)$$

The standard deviations also may be considered in determining the number of significant figures. As discussed above, in addition and subtraction, the standard deviation is considered directly, and in multiplication and division the percentages of the standard deviations are added to determine the number of significant figures.

Random errors or deviations in geophysical observations as described above may originate from a variety of sources including effects from geologic heterogeneities. These effects can be minimized by adding together a series of observations in which measurements include a coherent signal with random errors or signals superimposed. This procedure, commonly referred to as stacking, attenuates the random errors or noise by a factor of $\sqrt{n}$ with respect to the coherent signal, where n is the number of elements in the series. This procedure is used widely in geophysics to minimize random errors or noise.

1.7 Key concepts

- Geophysics involves the application of physical principles to the study of the Earth from its magnetosphere to its central core. Solid-Earth geophysics evolved from the study of surface geological units and observations of the terrestrial force fields, and the development of related laws and principles of geology and physics.
- Common characteristics of geophysical methods are their strong base in physical principles, the need for geologic information in all phases of conducting the methods, and the intensity of computational aspects necessary to make force-field observations geologically significant.
- Geophysical methods are advantageous because they can investigate portions of the Earth unavailable to direct exploration, but they are limited in their resolution, ability to provide unambiguous results, and direct information on the physical properties of the Earth.
- The gravity and magnetic methods have a rich tradition of investigating the Earth for over a century. They find useful applications in engineering and environmental studies, resource investigations, and general studies of the nature and processes of the Earth.
- Gravity and magnetic methods are employed in Earth studies at a variety of scales ranging from submeter to several hundreds of kilometers. Observations are made in drill holes within the Earth, on the Earth's surface, marine areas, and from altitudes of a few meters to hundreds of kilometers.
- Progress in geophysics has been driven by societal needs and economic factors and is made possible by technological advances leading to rapid, efficient data acquisition, processing, presentation, and interpretation.
- Geophysical methods are applied in a process that involves the key elements of planning, field measurement, data processing, and interpretation.
- The critical planning phase requires strong communications among the geophysicist, project engineer and scientist, and end-user. Essential steps during this phase are selection of the appropriate geophysical methods and procedures for data acquisition, processing, and interpretation. These decisions require an understanding of geophysical methods, the geological nature of the site, and the objective of the survey that is reached on the basis of experience, model studies, or test surveys.
- Data acquired during geophysical surveys are subject to a wide range of both random and systematic errors or noise. These need to be understood and minimized by field and data processing procedures to levels appropriate to the precision requirements of the objective. Error budgets are made and consideration is given to the propagation of the errors through the data stream from acquisition to interpretation.
- Field procedures must be adjusted to the objective of the survey, the local surface and cultural features, and the resources available. Planning of these procedures should be based on consideration of the cost/benefit ratio. The distribution of observations over the survey area is tuned to the objective of the survey and detail required by the range of anticipated anomalous signals.
- The physical properties of the Earth are important in all phases of applying geophysical methods. Knowledge of the properties at a specific site can be obtained from local *in situ* measurements, sample study, and generalized tabulations. However, care must be exercised in the use of physical property tables because of the commonly strong effect of local conditions and the environment on properties. In many near-surface studies, the objective is to determine properties of the Earth that are not directly measured, but are of a secondary nature, being related to primary properties measured by the method using empirical relationships which are subject to error.
- After the observed data are processed to isolate the desired signal from extraneous effects, interpretation proceeds by data inversion using inverse or iterative forward modeling of the subsurface until the processed data are matched. A wide variety of qualitative and quantitative procedures are used in the interpretation process, depending on the objectives of the survey and the character of the measured data. The result of the interpretation is a physical model that must be transformed into a geological model to achieve the objectives of the survey.
- Geophysical data are subject to a wide variety of errors, both systematic and random, despite protocols for quality assurance. Evaluation of these errors and their impact on the results is an important element of high-quality studies.