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اسم المادة بالعربي :الطرق الجذبية

اسم المادة بالإنكليزي: Potential Geophysics- Gravity Methods

عنوان المحاضرة : The principle and limintation of geophysical exploration methods

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1 The principles and limitations of geophysical exploration methods

1.1 Introduction

This chapter is provided for readers with no prior knowledge of geophysical exploration methods and is pitched at an elementary level. It may be passed over by readers already familiar with the basic principles and limitations of geophysical surveying.

The science of geophysics applies the principles of physics to the study of the Earth. Geophysical investigations of the interior of the Earth involve taking measurements at or near the Earth's surface that are influenced by the internal distribution of physical properties. Analysis of these measurements can reveal how the physical properties of the Earth's interior vary vertically and laterally.

By working at different scales, geophysical methods may be applied to a wide range of investigations from studies of the entire Earth (global geophysics; e.g. Kearey & Vine 1996) to exploration of a localized region of the upper crust for engineering or other purposes (e.g. Vogelsang 1995, McCann *et al.* 1997). In the geophysical exploration methods (also referred to as geophysical surveying) discussed in this book, measurements within geographically restricted areas are used to determine the distributions of physical properties at depths that reflect the local subsurface geology.

An alternative method of investigating subsurface geology is, of course, by drilling boreholes, but these are expensive and provide information only at discrete locations. Geophysical surveying, although sometimes prone to major ambiguities or uncertainties of interpretation, provides a relatively rapid and cost-effective means of deriving areally distributed information on subsurface geology. In the exploration for subsurface resources the methods are capable of detecting and delineating local features of potential interest that could not be discovered by any realistic drilling programme. Geophysical surveying does not dispense with the need for drilling but, properly applied, it can optimize exploration programmes by maximizing the rate of ground coverage and minimizing the drilling requirement. The importance of geophysical exploration as a means of deriving subsurface geological information is so great that the basic principles and scope of the methods and their main fields of application should be appreciated by any practising Earth scientist. This book provides a general introduction to the main geophysical methods in widespread use.

1.2 The survey methods

There is a broad division of geophysical surveying methods into those that make use of natural fields of the Earth and those that require the input into the ground of artificially generated energy. The natural field methods utilize the gravitational, magnetic, electrical and electromagnetic fields of the Earth, searching for local perturbations in these naturally occurring fields that may be caused by concealed geological features of economic or other interest. Artificial source methods involve the generation of local electrical or electromagnetic fields that may be used analogously to natural fields, or, in the most important single group of geophysical surveying methods, the generation of seismic waves whose propagation velocities and transmission paths through the subsurface are mapped to provide information on the distribution of geological boundaries at depth. Generally, natural field methods can provide information on Earth properties to significantly greater depths and are logistically more simple to carry out than artificial source methods. The latter, however, are capable of producing a more detailed and better resolved picture of the subsurface geology.

Several geophysical surveying methods can be used at sea or in the air. The higher capital and operating costs associated with marine or airborne work are offset by the increased speed of operation and the benefit of

Method	Measured parameter	Operative physical property
Seismic	Travel times of reflected/refracted seismic waves	Density and elastic moduli, which determine the propagation velocity of seismic waves
Gravity	Spatial variations in the strength of the gravitational field of the Earth	Density
Magnetic	Spatial variations in the strength of the geomagnetic field	Magnetic susceptibility and remanence
Electrical		
Resistivity	Earth resistance	Electrical conductivity
Induced polarization	Polarization voltages or frequency-dependent ground resistance	Electrical capacitance
Self-potential	Electrical potentials	Electrical conductivity
Electromagnetic	Response to electromagnetic radiation	Electrical conductivity and inductance
Radar	Travel times of reflected radar pulses	Dielectric constant

being able to survey areas where ground access is difficult or impossible.

A wide range of geophysical surveying methods exists, for each of which there is an 'operative' physical property to which the method is sensitive. The methods are listed in Table 1.1.

The type of physical property to which a method responds clearly determines its range of applications. Thus, for example, the magnetic method is very suitable for locating buried magnetite ore bodies because of their high magnetic susceptibility. Similarly, seismic or electrical methods are suitable for the location of a buried water table because saturated rock may be distinguished from dry rock by its higher seismic velocity and higher electrical conductivity.

Other considerations also determine the type of methods employed in a geophysical exploration programme. For example, reconnaissance surveys are often carried out from the air because of the high speed of operation. In such cases the electrical or seismic methods are not applicable, since these require physical contact with the ground for the direct input of energy.

Geophysical methods are often used in combination. Thus, the initial search for metalliferous mineral deposits often utilizes airborne magnetic and electromagnetic surveying. Similarly, routine reconnaissance of continental shelf areas often includes simultaneous gravity, magnetic and seismic surveying. At the interpretation stage, ambiguity arising from the results of one survey method may often be removed by consideration of results from a second survey method.

Geophysical exploration commonly takes place in a number of stages. For example, in the offshore search for oil and gas, an initial gravity reconnaissance survey may reveal the presence of a large sedimentary basin that is subsequently explored using seismic methods. A first round of seismic exploration may highlight areas of particular interest where further detailed seismic work needs to be carried out.

The main fields of application of geophysical surveying, together with an indication of the most appropriate surveying methods for each application, are listed in Table 1.2.

Exploration for hydrocarbons, for metalliferous minerals and environmental applications represents the main uses of geophysical surveying. In terms of the amount of money expended annually, seismic methods are the most important techniques because of their routine and widespread use in the exploration for hydrocarbons. Seismic methods are particularly well suited to the investigation of the layered sequences in sedimentary basins that are the primary targets for oil or gas. On the other hand, seismic methods are quite unsuited to the exploration of igneous and metamorphic terrains for the near-surface, irregular ore bodies that represent the main source of metalliferous minerals. Exploration for ore bodies is mainly carried out using electromagnetic and magnetic surveying methods.

In several geophysical survey methods it is the local variation in a measured parameter, relative to some normal background value, that is of primary interest. Such variation is attributable to a localized subsurface zone of

Table 1.2 Geophysical surveying applications.

Application	Appropriate survey methods*
Exploration for fossil fuels (oil, gas, coal)	S, G, M, (EM)
Exploration for metalliferous mineral deposits	M, EM, E, SP, IP, R
Exploration for bulk mineral deposits (sand and gravel)	S, (E), (G)
Exploration for underground water supplies	E, S, (G), (Rd)
Engineering/construction site investigation	E, S, Rd, (G), (M)
Archaeological investigations	Rd, E, EM, M, (S)

* G, gravity; M, magnetic; S, seismic; E, electrical resistivity; SP, self-potential; IP, induced polarization; EM, electromagnetic; R, radiometric; Rd, ground-penetrating radar. Subsidiary methods in brackets.

distinctive physical property and possible geological importance. A local variation of this type is known as a *geophysical anomaly*. For example, the Earth's gravitational field, after the application of certain corrections, would everywhere be constant if the subsurface were of uniform density. Any lateral density variation associated with a change of subsurface geology results in a local deviation in the gravitational field. This local deviation from the otherwise constant gravitational field is referred to as a gravity anomaly.

Although many of the geophysical methods require complex methodology and relatively advanced mathematical treatment in interpretation, much information may be derived from a simple assessment of the survey data. This is illustrated in the following paragraphs where a number of geophysical surveying methods are applied to the problem of detecting and delineating a specific geological feature, namely a salt dome. No terms or units are defined here, but the examples serve to illustrate the way in which geophysical surveys can be applied to the solution of a particular geological problem.

Salt domes are emplaced when a buried salt layer, because of its low density and ability to flow, rises through overlying denser strata in a series of approximately cylindrical bodies. The rising columns of salt pierce the overlying strata or arch them into a domed form. A salt dome has physical properties that are different from the surrounding sediments and which enable its detection by geophysical methods. These properties are: (1) a relatively low density; (2) a negative magnetic susceptibility; (3) a relatively high propagation velocity for seismic waves; and (4) a high electrical resistivity (specific resistance).

1. The relatively low density of salt with respect to its surroundings renders the salt dome a zone of anomalously low mass. The Earth's gravitational field is perturbed by subsurface mass distributions and the salt dome therefore gives rise to a gravity anomaly that is negative with respect to surrounding areas. Figure 1.1 presents a contour map of gravity anomalies measured over the Grand Saline Salt Dome in east Texas, USA. The gravitational readings have been corrected for effects which result from the Earth's rotation, irregular surface relief and regional geology so that the contours reflect only variations in the shallow density structure of the area resulting from the local geology. The location of the salt dome is known from both drilling and mining operations and its subcrop is indicated. It is readily apparent that there is a well-defined negative gravity anomaly centred over the salt dome and the circular gravity contours reflect the circular outline of the dome. Clearly, gravity surveys provide a powerful method for the location of features of this type.

2. A less familiar characteristic of salt is its negative magnetic susceptibility, full details of which must be deferred to Chapter 7. This property of salt causes a local decrease in the strength of the Earth's magnetic field in the vicinity of a salt dome. Figure 1.2 presents a contour map of the strength of the magnetic field over the Grand Saline Salt Dome covering the same area as Fig. 1.1. Readings have been corrected for the large-scale variations of the magnetic field with latitude, longitude and time so that, again, the contours reflect only those variations resulting from variations in the magnetic properties of the subsurface. As expected, the salt dome is associated with a negative magnetic anomaly, although the magnetic low is displaced slightly from the centre of the dome. This example illustrates that salt domes may be located by magnetic surveying but the technique is not widely used as the associated anomalies are usually very small and therefore difficult to detect.

3. Seismic rays normally propagate through salt at a higher velocity than through the surrounding sediments. A consequence of this velocity difference is that

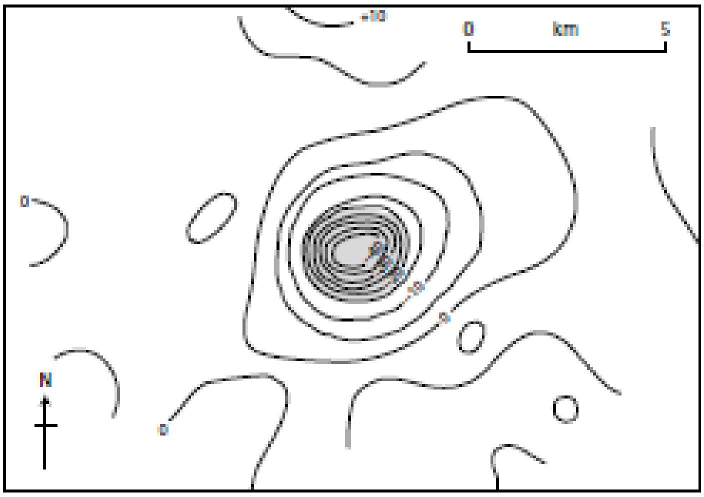


Fig. 1.1 The gravity anomaly over the Grand Saline Salt Dome, Texas, USA (contours in gravity units — see Chapter 6). The stippled area represents the subcrop of the dome. (Redrawn from Peters & Dugan 1945.)

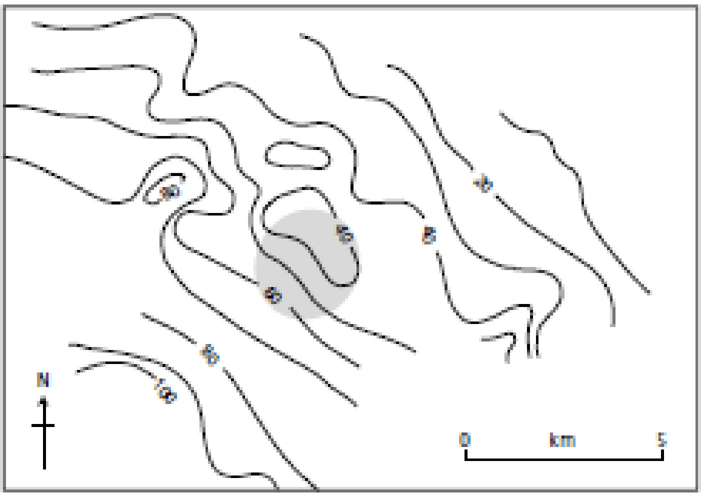
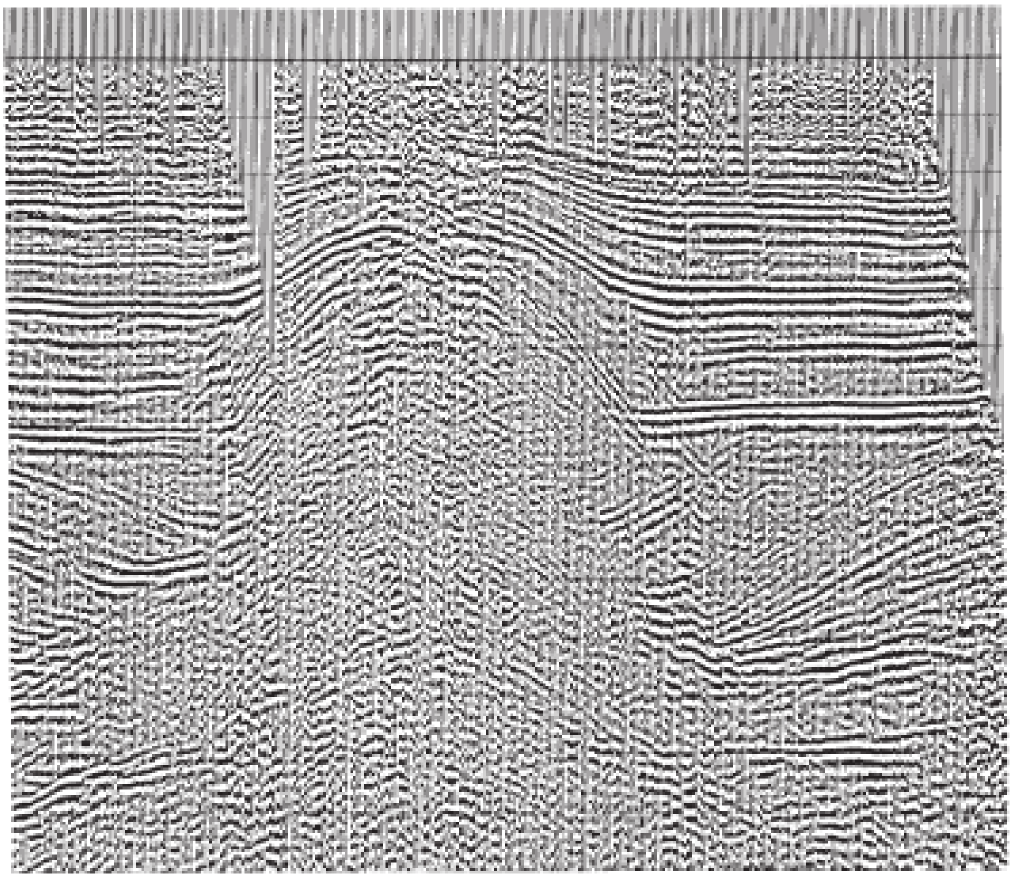


Fig. 1.2 Magnetic anomalies over the Grand Saline Salt Dome, Texas, USA (contours in nT — see Chapter 7). The stippled area represents the subcrop of the dome. (Redrawn from Peters & Dugan 1945.)

any seismic energy incident on the boundary of a salt body is partitioned into a refracted phase that is transmitted through the salt and a reflected phase that travels back through the surrounding sediments (Chapter 3). These two seismic phases provide alternative means of locating a concealed salt body.

For a series of seismic rays travelling from a single shot point into a fan of seismic detectors (see Fig. 5.21), rays transmitted through any intervening salt dome will travel at a higher average velocity than in the surrounding medium and, hence, will arrive relatively early at the recording site. By means of this 'fan-shooting' it is possible to delineate sections of ground which are associated with anomalously short travel times and which may therefore be underlain by a salt body.

An alternative, and more effective, approach to the seismic location of salt domes utilizes energy reflected off the salt, as shown schematically in Fig. 1.3. A survey



(a)

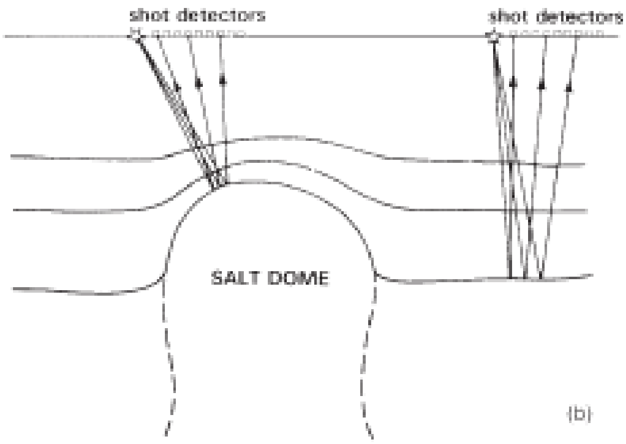


Fig. 1.3 (a) Seismic reflection section across a buried salt dome (courtesy Prakla-Seismos GmbH). (b) Simple structural interpretation of the seismic section, illustrating some possible ray paths for reflected rays.

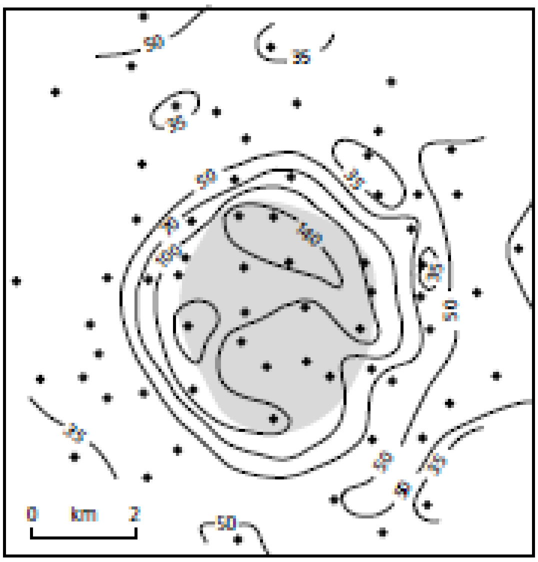


Fig. 1.4 Perturbation of telluric currents over the Haynesville Salt Dome, Texas, USA (for explanation of units see Chapter 9). The stippled area represents the subcrop of the dome. (Redrawn from Boissonas & Leonardon 1948.)

configuration of closely-spaced shots and detectors is moved systematically along a profile line and the travel times of rays reflected back from any subsurface geological interfaces are measured. If a salt dome is encountered, rays reflected off its top surface will delineate the shape of the concealed body.

4. Earth materials with anomalous electrical resistivity may be located using either electrical or electromagnetic geophysical techniques. Shallow features are normally investigated using artificial field methods in which an electrical current is introduced into the ground and potential differences between points on the surface are measured to reveal anomalous material in the subsurface (Chapter 8). However, this method is restricted in its depth of penetration by the limited power that can be introduced into the ground. Much greater penetration can be achieved by making use of the natural Earth currents (telluric currents) generated by the motions of charged particles in the ionosphere. These currents extend to great depths within the Earth and, in the absence of any electrically anomalous material, flow parallel to the surface. A salt dome, however, possesses an anomalously high electrical resistivity and electric currents preferentially flow around and over the top of such a structure rather than through it. This pattern of flow causes distortion of the constant potential gradient at the surface that would be associated with a homogeneous subsurface and indicates the presence of the high-resistivity salt. Figure 1.4 presents the results of a telluric current survey of the Haynesville Salt Dome, Texas, USA. The contour values represent quantities describing the extent to which the telluric currents are distorted by subsurface phenomena and their configuration reflects the shape of the subsurface salt dome with some accuracy.

1.3 The problem of ambiguity in geophysical interpretation

If the internal structure and physical properties of the Earth were precisely known, the magnitude of any particular geophysical measurement taken at the Earth's surface could be predicted uniquely. Thus, for example, it would be possible to predict the travel time of a seismic wave reflected off any buried layer or to determine the value of the gravity or magnetic field at any surface location. In geophysical surveying the problem is the opposite of the above, namely, to deduce some aspect of the Earth's internal structure on the basis of geophysical measurements taken at (or near to) the Earth's surface. The former type of problem is known as a *direct* problem, the latter as an *inverse* problem. Whereas direct problems are theoretically capable of unambiguous solution, inverse problems suffer from an inherent ambiguity, or non-uniqueness, in the conclusions that can be drawn.

To exemplify this point a simple analogy to geophysical surveying may be considered. In *echo-sounding*, high-frequency acoustic pulses are transmitted by a transducer mounted on the hull of a ship and echoes returned from the sea bed are detected by the same transducer. The travel time of the echo is measured and converted into a water depth, multiplying the travel time by the velocity with which sound waves travel through water; that is, $1500\,m\,s^{-1}$. Thus an echo time of 0.10 s indicates a path length of $0.10 \times 1500 = 150$ m, or a water depth of $150/2 = 75$ m, since the pulse travels down to the sea bed and back up to the ship.

Using the same principle, a simple seismic survey may be used to determine the depth of a buried geological interface (e.g. the top of a limestone layer). This would involve generating a seismic pulse at the Earth's surface and measuring the travel time of a pulse reflected back to the surface from the top of the limestone. However, the conversion of this travel time into a depth requires knowledge of the velocity with which the pulse travelled along the reflection path and, unlike the velocity of sound in water, this information is generally not known. If a velocity is assumed, a depth estimate can be derived but it represents only one of many possible solutions. And since rocks differ significantly in the velocity with which they propagate seismic waves, it is by no means a straightforward matter to translate the travel time of a seismic pulse into an accurate depth to the geological interface from which it was reflected.

The solution to this particular problem, as discussed in Chapter 4, is to measure the travel times of reflected pulses at several offset distances from a seismic source because the variation of travel time as a function of range provides information on the velocity distribution with depth. However, although the degree of uncertainty in geophysical interpretation can often be reduced to an acceptable level by the general expedient of taking additional (and in some cases different kinds of) field measurements, the problem of inherent ambiguity cannot be circumvented.

The general problem is that significant differences from an actual subsurface geological situation may give rise to insignificant, or immeasurably small, differences in the quantities actually measured during a geophysical survey. Thus, ambiguity arises because many different geological configurations could reproduce the observed measurements. This basic limitation results from the unavoidable fact that geophysical surveying attempts to solve a difficult inverse problem. It should also be noted that experimentally-derived quantities are never exactly determined and experimental error adds a further degree of indeterminacy to that caused by the incompleteness of the field data and the ambiguity associated with the inverse problem. Since a unique solution cannot, in general, be recovered from a set of field measurements, geophysical interpretation is concerned either to determine properties of the subsurface that all possible solutions share, or to introduce assumptions to restrict the number of admissible solutions (Parker 1977). In spite of these inherent problems, however, geophysical surveying is an invaluable tool for the investigation of subsurface geology and occupies a key role in exploration programmes for geological resources.

References

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