# ONE

# *The Search*

A little more than a century ago, the search for oil began. At first, no one knew much about where to look for it, and so landowners and speculators eagerly sought advice. In these early days, a colorful assortment of individuals who claimed to have special oil-finding powers offered a helping hand. The first to come forward used the forked branches that for centuries had been the tools for locating water wells, but within a few years their clients demanded more impressive equipment. Wondrous devices were invented that supposedly pointed to the hidden treasure of oil with crackling discharges of electricity, mysterious liquids that changed color, or various peculiar sounds. Most of these devices proved to be useless. Skeptics started calling them doodlebugs, and their inventors became known as "doodlebuggers."

From these beginnings emerged a new breed of doodlebugger whose prospecting methods were based on scientific principle rather than witchcraft. These individuals began piecing together information about geologic environments favoring the occurrence of oil. In some places, the rock exposures and landscape features guided the search for anticlines and other structures in which oil might have become trapped. But what about places like the Gulf coast of Texas and Louisiana where the landscape of low plains and swamps gave scant information of the underlying geology? Could instruments be designed to detect the structures of interest?

Early in the twentieth century, seismologists recognized the value of earthquake wave vibrations for probing the deep interior of the earth. Could these kinds of vibrations be used in the search for oil-bearing structures? At the same time, geodesists studying the shape of the earth realized that small variations in the strength of the earth's gravity were related to differences in the densities of underlying masses of rock. *Density* is a physical property found by dividing the mass of a rock specimen by its volume. Perhaps instruments sensitive to these variations in gravity could be designed for oil prospecting.

Other kinds of instruments had been used to prospect for ores long before the birth of the oil industry. For more than two centuries magnetic devices, basically compasses, were used in the search for iron ore. Natural electrical fields produced by buried sulfide ores were first detected early in the nineteenth century.

Seismic waves, gravity, magnetism, and electrical fields in the earth are the foundation of modern *exploration geophysics.* The aim of exploration geophysics is the discovery of hidden geologic features by indirect methods. These methods involve measurements made some distance away from the feature of interest, which may be an oil trap, an ore body, or a structure fundamental to an understanding of the geology of some region. Modern electronics and computer technology have greatly enhanced the quality of instruments now used in exploration geophysics. Let us look more closely at the different kinds of modern doodlebugging.

## EXPLORATION SEISMOLOGY

Our knowledge of the earth's deep interior has been largely conveyed by earthquakes, most of which are caused by the sudden movement of rock masses along a fault. As these rocks grind together, energy is released and produces vibrations which we call *seismic waves.* These waves spread throughout the earth like the ripples made by a pebble tossed into a quiet pond. Eventually, these seismic waves reach the earth's surface where they can be detected by instruments sensitive to ground vibrations. These instruments are called *seismometers.*

Earthquakes release the large amounts of energy needed to probe the deep mantle and core of the earth. But there are other ways to produce seismic waves that can be focused on geologic features closer to the earth's surface. These waves can be generated by explosions and then recorded on small seismometers, about the size of the human fist, which are placed nearby. This work is done by exploration seismologists who know how to control the paths of the seismic waves by the locations of explosives and seismometers. Their aim is to measure the *speed* of a seismic wave along different parts of its path in the earth. The speed changes as the wave moves from one kind of rock into another, depending on the physical properties of these materials.

Seismic wave speeds cover a large range of values in different kinds of rock and loose sediment. These values are most commonly given in the Système International (SI) units of meters per second (m/s), or in the non-SI units of kilometers per second (km/s) or feet per second (ft/s). For example, a wave moving 5000 m/s (16,400 ft/s) in sandstone may increase its speed to 6000 m/s (19,680 ft/s) in limestone. But these values are not the same for all layers of sandstone and limestone. The ranges of wave speed in different kinds of rock and the dependence of wave speed on the physical properties of rocks are discussed more fully in Chapter 2. It is important to point out that seismologists often interchange the terms *speed* and *velocity*. By strict definition, we should state the speed and direction of movement to describe velocity completely, but in common usage the direction is frequently omitted.

A seismic survey is usually conducted by placing seismometers along a straight line and then detonating an explosive close to one end. If the rock layers are horizontal or gently dipping, seismic waves follow uncomplicated paths. The two kinds of paths illustrated in Figure 1–1 are followed by *reflected seismic waves* and *refracted seismic waves*. The reflected waves have traveled downward to borders between rock layers where they bounce or echo back to the surface. In contrast, the refracted waves follow paths that bend at each border.

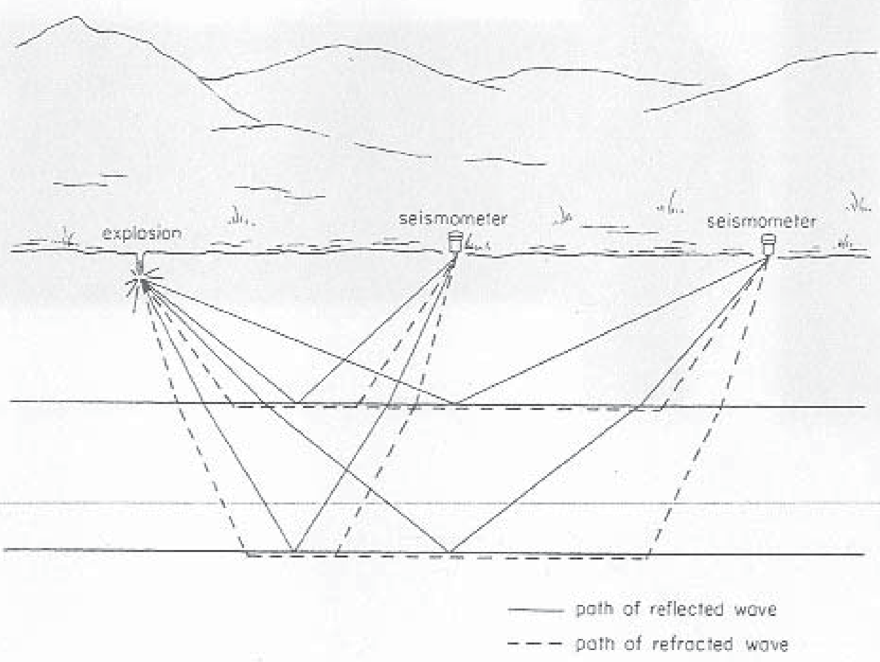


**Figure 1–1**
Seismic waves produced by a small explosion are reflected and refracted through different rock layers before reaching the seismometers. Paths show how these waves echo from a boundary or bend into a different direction when crossing a boundary from one layer into another.

Have you ever poked a stick into a pond? Recall how it appeared to bend at the water surface because of the bending, or refraction, of the light rays. This also happens to seismic waves.

Be sure to observe in Figure 1–1 that more than one seismic wave reaches each seismometer. Every wave reaching the seismometer produces a momentary impulse on a record of ground vibration. Such a record is called a *seismogram.* It indicates the times when different refracted and reflected waves reach the seismometer. These values of time are analyzed by an exploration seismologist to find out the wave speed in the different rock layers and thicknesses of these layers. The methods of analysis are described in Chapters 3 and 4.

Some seismic surveys are easily done by two or three people. Suppose that a highway department or construction company asks about the thickness of loose soil and gravel covering bedrock along a proposed roadway or building site. Such questions can perhaps be answered by placing a dozen seismometers in a line 5 meters apart (Figure 1–2). By detonating a one-half kilogram explosive charge, we

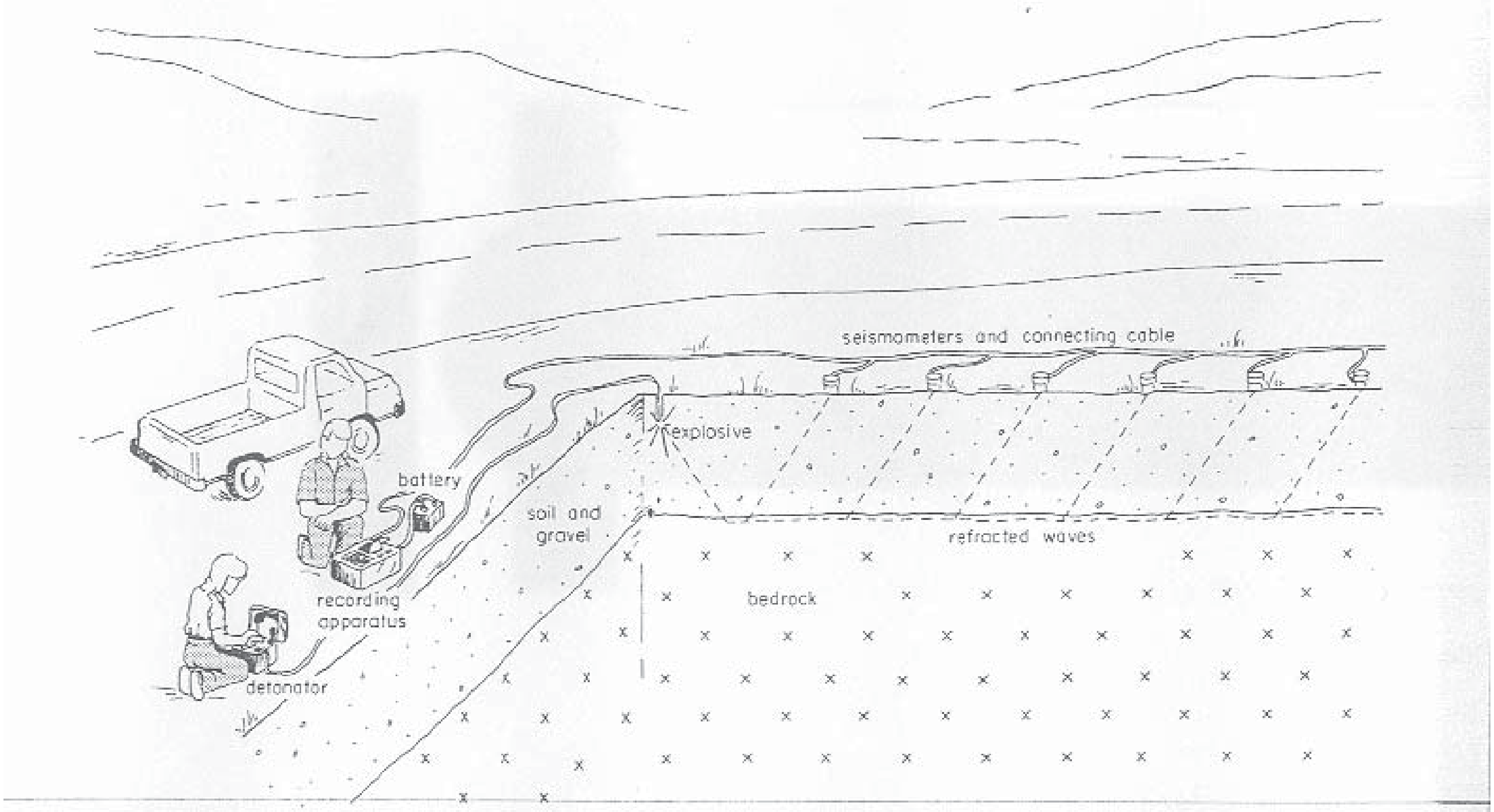


**Figure 1–2**
Seismic refraction experiment to measure the thickness of soil and gravel that covers solid bedrock. The times required for refracted waves to reach seismometers at different distances are measured. These times are analyzed to find the speed of the waves and the thickness of the top layer.

can produce refracted waves that will reach depths of about 15 meters. Instead of an explosive charge, we might produce the seismic waves by dropping a weight or pounding the ground with a sledge hammer. Ordinarily, two or three people would take about one-half hour to complete the measurements and calculate the depth to bedrock. In such a survey, the line of seismometers should extend a distance about four times greater than the maximum depth of interest. They would analyze only refracted waves, because the reflected waves would be too weak to detect.

In the search for oil, seismic surveys commonly probe as deep as 10 km (32,800 ft). Attention is focused on reflected waves that are recorded on hundreds or even thousands of seismometers in lines sometimes more than 5 km long. A crew of between 10 and 20 people is needed to move seismometers, cables, and other equipment. Rather than explosives, many doodlebugging crews are equipped with heavy vibrator trucks that press large vibrating pads on the ground to generate seismic waves. The most common survey procedure is to arrange the seismometers in a line along a road (Figure 1–3). An explosive or vibrator produces seismic waves that are recorded after reflecting, or echoing, from the buried rock layers. The equipment is then moved a short

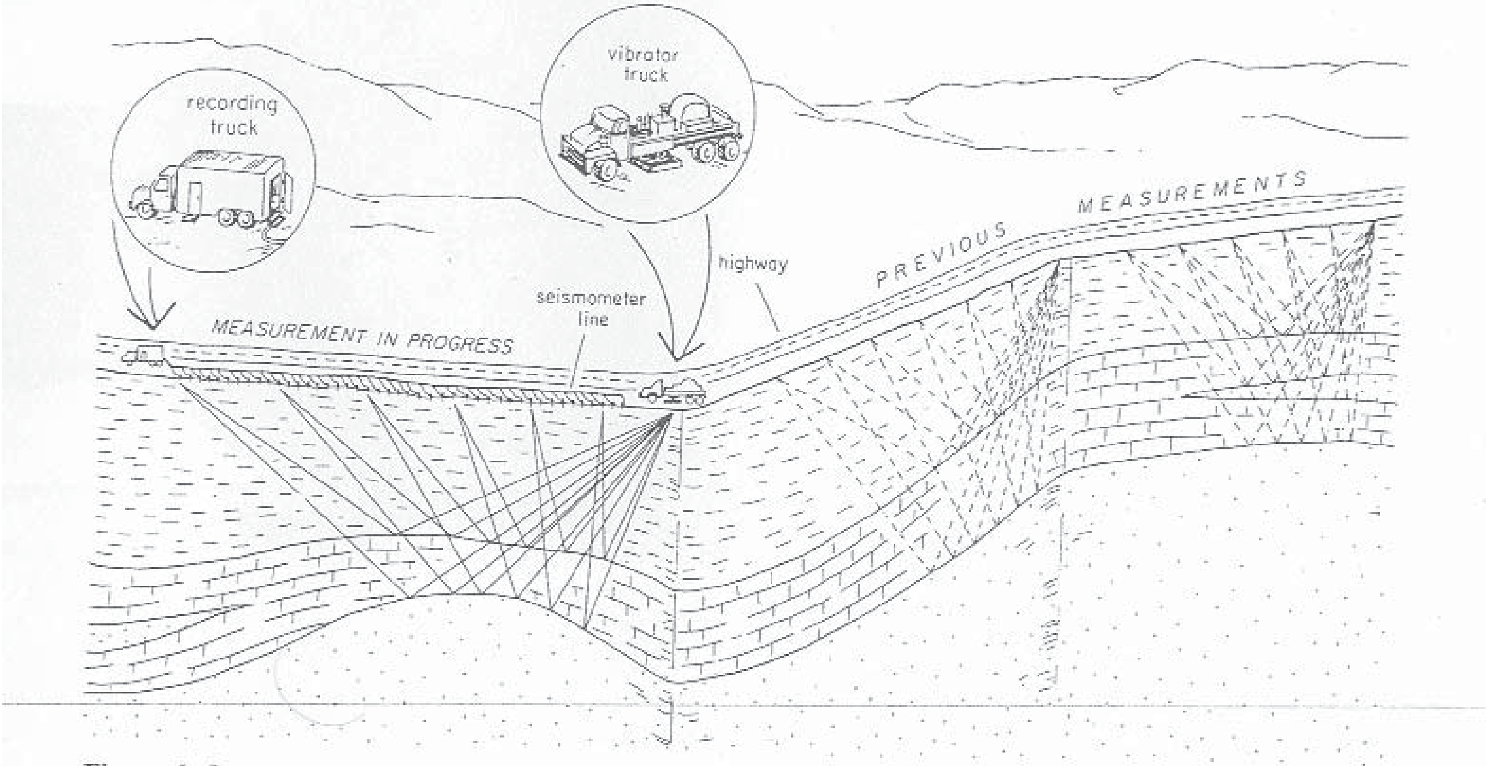


**Figure 1–3**
Seismic reflection experiment for detecting geologic structures in which oil and natural gas may be trapped, the times of echoes from different layer boundaries are measured, and this information is used to calculate layer thicknesses.

distance along the road, and the experiment is repeated. By examining seismograms recorded in this way, we can observe changes in the times that different reflected waves appear. Depths to different rock layers change as the survey passes over buried structures such as the anticline illustrated in Figure 1–3.

Professional seismic crews are an important part of the oil industry. The number of active crews fluctuates with the market for oil and natural gas. During times of high demand, more than 500 crews can be found operating in different parts of the world. Field procedures of these crews are described in Chapter 5.

A serious difficulty in exploration seismology is the often confusing pattern of unwanted vibrations received by the seismometer. Wind blowing on trees, traffic along a road, and waves reflected or refracted from geologic features other than those of interest all produce these unwanted vibrations. Sometimes they are so strong that they obscure the waves that the exploration seismologist hopes to record. The methods described in Chapter 6 for reducing or eliminating the undesirable vibrations rely on special arrangements of seismometers and computer processing of seismograms.

## GRAVITY AND GEOLOGY

The attraction of gravity is not exactly the same everywhere on the earth's surface. There are small variations from place to place because of irregularities in rock density. Recall that the density of a rock specimen is obtained by dividing its mass by its volume. This physical property is described either in the SI units of kilograms per cubic meter (kg/m$^3$) or in units of grams per cubic centimeter (g/cm$^3$).

The exploration geophysicist hopes to distinguish different kinds of rock by detecting density irregularities from measurements of the attraction of gravity. For example, a buried salt dome that penetrates layers of shale (Figure 1–4) would produce a small but measurable decrease in the attraction of gravity, because the salt density of 2.0 g/cm$^3$ is smaller than the shale density of about 2.6 g/cm$^3$. Exploration geophysicists are particularly interested in locating salt domes because accumulations of petroleum and natural gas have been discovered above and on the flanks of many of these structures.

We can measure the earth's gravitational attraction with a small portable instrument called a *gravimeter*. Basically, it consists of a small object supported by a very sensitive spring which is stretched by the weight of the object. Because of variations in the attraction of gravity, however, this weight changes as the gravimeter is moved from place to place. Therefore, the stretch of the spring changes. It is possible to detect minute changes in the attraction of gravity by carefully measuring the stretch of the spring in different locations. The design and operation of gravimeters is discussed in Chapters 7 and 8.

A gravity survey is done by reading a gravimeter at many different locations in an area (Figure 1–4). These locations can be less than 1 km apart, or perhaps several kilometers apart depending on the size and depth of the geologic features of interest. It usually takes less than five minutes to operate the gravimeter at each location. This work can be done by one person, but additional people may be needed to make elevation and position measurements and to transport equipment in remote areas. Gravity survey crews of one or more persons have worked in most parts of the world. In addition to land-based surveys,

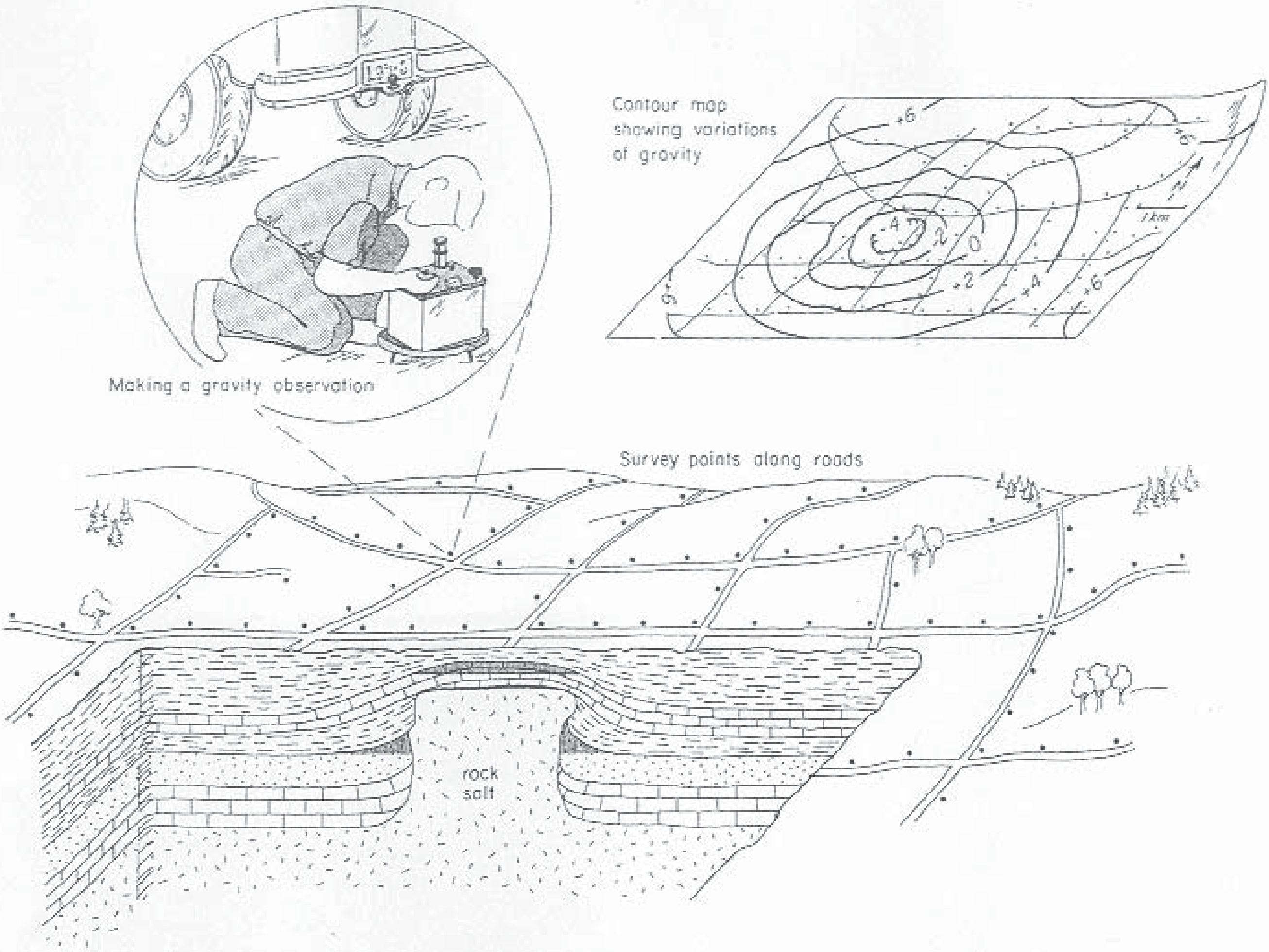


**Figure 1–4**
A gravity survey for detecting salt structures. Survey results are contoured on a map so that patterns of gravity variation indicative of these features can be recognized. In this example, a pattern showing a small decrease in gravitational attraction suggests the presence of a low-density salt dome.

gravimeters can be operated on ships, and recently they have been installed in helicopters for airborne surveys.

We cannot immediately make geologic interpretations from gravimeter measurements. First, adjustments are made to show how latitude and elevation also influence the attraction of gravity. After making the appropriate adjustments, discussed in Chapter 8, we obtain values that indicate irregularities in rock density. We can use these values to prepare profiles and contour maps that indicate gravity variations related to geologic features. Referring again to Figure 1–4, we can see how the particularly low values over a small area of such a map might indicate a hidden salt dome that had intruded heavier beds of shale.

The results of a gravity survey can be difficult to interpret because the gravimeter feels the combined gravitational pull of many different geologic features. Exploration geophysicists have developed data processing techniques, discussed in Chapter 9, to bring a gravity variation of particular interest into clearer focus. We use these results to make judgments about the shape and depth of the feature that produces that particular variation in gravity.

## MAGNETISM AND GEOLOGY

The magnetic compass is one of our greatest inventions, but in some places it is not a reliable guide. Compass direction can be strongly deflected near concentrations of a few kinds of magnetizable minerals. Over three centuries ago, prospectors began using this feature of the compass to advantage in their search for ores associated with magnetic minerals such as magnetite.

Early instruments were designed to measure the direction of a delicately balanced magnet. Emphasis then shifted to measuring the strength of the earth's magnetic force on ingeniously designed test magnets. These measurements are made with instruments called *magnetometers*.

Earth magnetism has two principal sources, described in Chapter 10. By far the strongest part is produced in the molten core by flow of ionized fluids. The other part, which is much weaker, arises from contrasts in the concentration of magnetite and a very few other minerals in the rocks of the earth's crust. This second part is of greater interest to exploration geophysicists. Here the numerous local variations indicate different geologic features. The size of such a variation is described by a unit of magnetic intensity called the *gamma* ($\gamma$). More recently, some geophysicists have used an SI unit called the *nannotesla* (nT). It is interchangeable with the gamma and has the same numeric value.

Most magnetic variations of interest to exploration geophysicists are a few hundred, or perhaps a few tens of gammas, in size, although some are larger than 2000 gammas. They indicate differences in the magnetic susceptibility of rocks in the crust. *Magnetic susceptibility* is a number without units that describes the capacity of the rock to acquire magnetism. Suppose that a dike of gabbro with a susceptibility of 0.005 intrudes granite where the susceptibility is less than 0.001. Depending on the size of the dike, we might detect a variation of 100 or 200 gammas as we pass over it with a magnetometer. If the dike consisted mostly of magnetite and associated ore minerals, the susceptibility could be larger than 0.1. A variation of more than 1000 gammas might be measured, depending on its size and distance from the magnetometer.

Most magnetometers are compact devices small enough to carry in a suitcase. Some are operated on tripods or are hand held. Most magnetometers, however, are mounted in airplanes and record variations in magnetism more or less continuously along closely spaced flight paths. The variations obtained in this way indicate how an ore-bearing structure might be discovered (Figure 1–5). Airborne magnetic surveying has been done over large areas of the world. Surveys have also been done at sea using magnetometers trailed from ships.

Geophysicists compile profiles and contour maps to display the variations measured over an area. The data processing techniques described in Chapter 11 are similar to those ap-

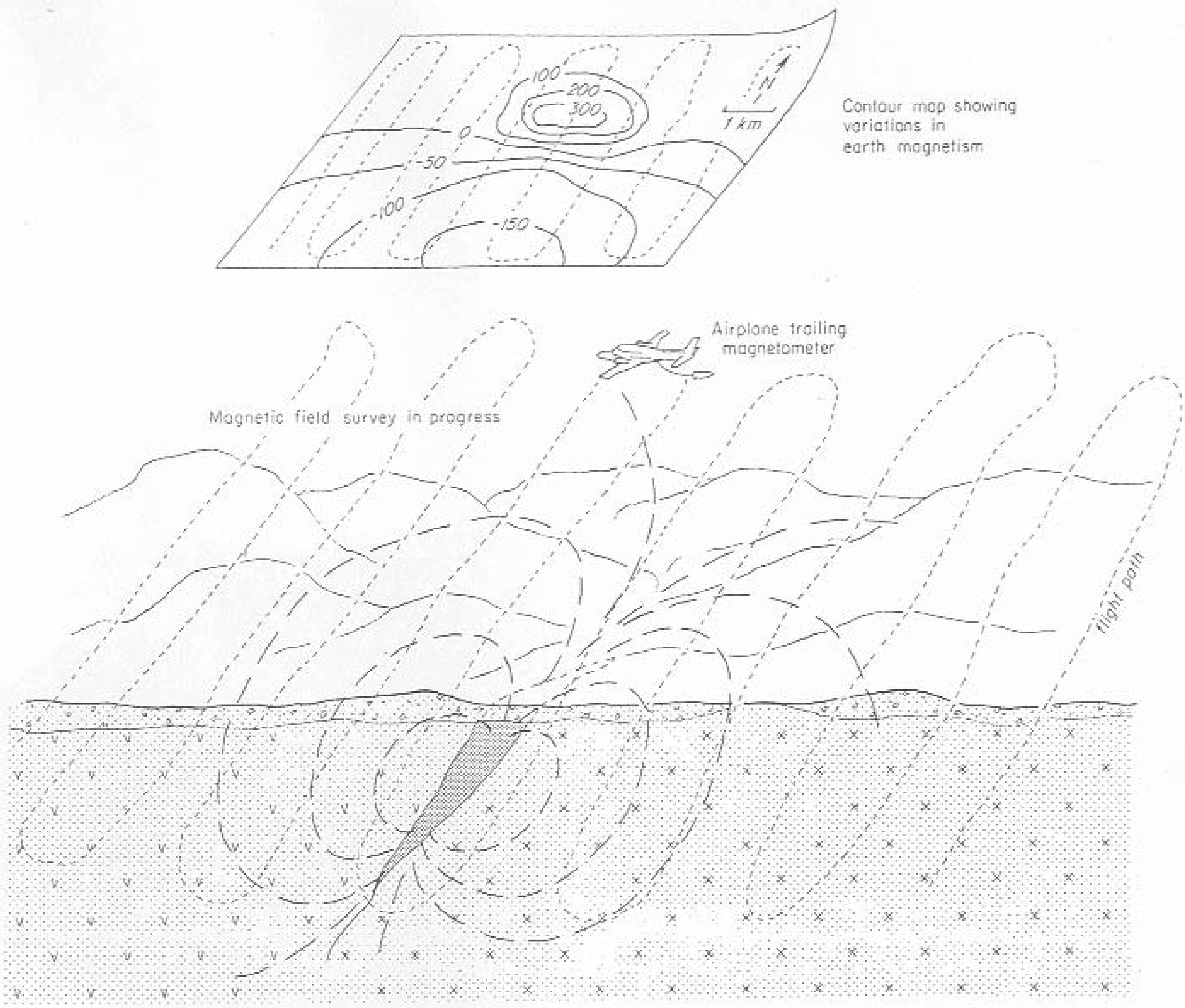


**Figure 1–5**
Airborne magnetometer survey for locating magnetized ores. A contour map prepared from the survey data indicates patterns of variation in the strength of earth magnetism. Irregular patterns on such a map are caused by concentrations of magnetized rock.

plied to gravity data and are used to bring certain variations into clearer perspective. Theoretical magnetic variations are then calculated for different geologic features to find the one that would produce a pattern that compares most closely to the measured pattern. These procedures are introduced in Chapter 12.

## ELECTRICAL PROSPECTING

Geophysicists have devised several techniques for measuring electrical properties of rocks in the earth. One of these properties describes the resistance of rock to the flow of electric current. This property of *resistivity* can be used to distinguish different kinds of rock. Another property of interest is the capacity of a rock mass to become polarized in an electric field. Polarization results from a concentration of positive electric charge on one side of the mass and negative charge on the opposite side. We might think of this polarized rock as a natural battery buried in the earth.

The first electrical prospecting instruments were designed to detect naturally polarized ore bodies. For example, some massive sulfide bodies appear to be permanently polarized because of the way different ions became concentrated by weathering processes and the flow of ground water. By connecting a voltmeter between two electrodes placed in the ground, we can measure a voltage difference produced by such a polarized mass. Its location is indicated by a pattern of voltage variation obtained from measurements repeated at regular intervals over an area.

It is not necessary to rely exclusively on natural electric fields. By connecting a battery between two electrodes, we can compel current to flow through the earth. Then we can connect a voltmeter between two other electrodes to measure voltage differences produced by this current (Figure 1–6). The information is used to calculate rock resistivity. Measurements are made with the electrodes arranged in the different spacings described in Chapter 13 to determine how resistivity changes with depth. Surveys designed to reach depths of several hundred meters can be done with compact equipment that fits in a suitcase-sized container. Metal rods driven into the ground are satisfactory electrodes.

When we compel an electric current to flow in the ground, rocks containing metallic ions tend to become temporarily polarized. This process is called *induced polarization* (IP). It persists for a brief time after the current is shut off, depending on the kinds of metallic elements present and their concentrations. Measurements of the time required to dissipate this polarization have proved very useful in the search for sulfide ores. An IP survey is done by making these measurements with the same electrode spacing at uniformly spaced locations in the area of interest.

Other kinds of electromagnetic devices using test coils have been designed to study the flow of electric current in the earth. Basically, the equipment consists of a large primary input coil and a secondary receiver coil. An alternating current in the primary coil produces magnetic effects that induce the electric currents to flow in the ground in patterns that depend on rock resistivity. These ground currents, in turn, produce magnetism that compels current to flow in the receiver coil. The strength and frequency of this secondary current provides information about rock resistivity. Various coil configurations sensitive to different features of interest can be operated on the ground or in low-flying airplanes.

## GEOPHYSICAL WELL LOGGING

The traditional way to find out what lies underground has been to drill a hole and see. But what kind of information does the drill provide? The rock cuttings that are flushed from the hole may have been mixed so that

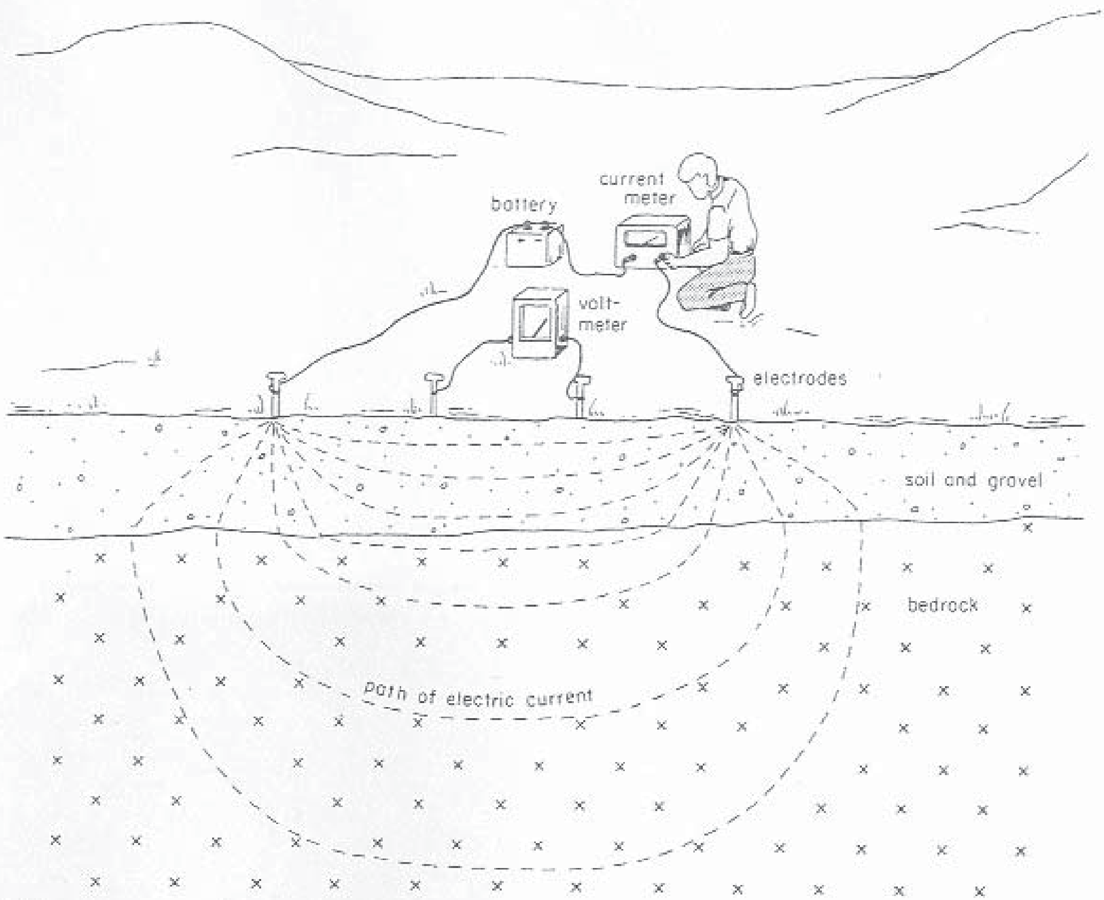


**Figure 1–6**
A survey of electrical resistivity can be used to find the thickness of soil and gravel that covers solid bedrock. Changes in the resistivity measured with different electrode spacings are related to the thickness of this layer.

we cannot tell exactly where they came from. A tool is needed that can be lowered into the hole to detect properties of the rock through which it passes. This is called a well logging tool.

The most widely used well-logging tools measure rock resistivity and natural voltages, seismic wave speeds, and radioactive properties. Less frequently used are special tools for measuring gravity variations, magnetism, and temperature. The well logging tools described in Chapter 14 produce continuous charts that indicate how these physical properties change while the various detectors move in the borehole.

Well logging is done in most oil wells, mining exploration wells, and in many water wells. Several companies offer a large selection of services. They maintain facilities in many parts of the world from which trucks or ships can be dispatched to make measurements in any well in a particular district.

## PHYSICAL UNITS

The units that must be used for describing measurements and physical properties of the earth are introduced throughout this book. The literature of geophysics includes different combinations of the meter.kilogram.second (m.k.s) metric system, the centimeter.gram. second (c.g.s) metric system, and the British system. In recent years, efforts have been made to encourage worldwide adoption of a system based on m.k.s units. As noted earlier, this system is called the Système International and is abbreviated SI. Although SI units are becoming widely used, several non-SI units remain in common use.

## BLENDING GEOLOGY AND PHYSICS

Geologists began learning about salt domes almost a century ago. The first information came from chance discoveries. Physics played no role at this point because no one knew enough about salt structures to figure out which principles of physics might be applicable. Using bits of information from drill cuttings, geologists eventually pieced together ideas about the shape and dimensions of these salt structures. With this knowledge they could turn to physics for ideas about how to search for them. Here was the source of knowledge about how to calculate the gravitational effects of objects of different shapes and how to measure these effects.

The search for salt domes is only one of many examples of how geophysicists look to geology for knowledge about what kinds of rocks and structure exist in nature and then turn to physics for ideas about how to find them. This book is concerned with the techniques used to calculate and measure the physical effects of different geologic features.

The interpretation procedure used by geophysicists is to compare a measured effect with values calculated for some standard model of earth structure. For example, the times of seismic waves measured from a seismogram could be compared with times calculated for travel through a sequence of flat layers. If the calculated times closely match the measured times, we conclude that the thicknesses and wave speeds of the flat layers in our model are a good representation of earth structure at that location. A poor comparison would indicate that the flat layer model is inappropriate. We might then use other formulas to calculate the times of seismic waves along paths through a more complicated model of sloping layers that dip at different angles. A better comparison with measured times would tell us that this interpretation is more realistic.

We can compare measured variations in gravity with those calculated for structures of different shape and density. A favorable comparison with values calculated for a vertical cylindrical form might tell us that the measured gravity variation could be explained by a salt dome. However, we might reject this interpretation if our measurements compared more closely with results calculated for a prism of different shapes. From these examples we can understand how knowledge of geology determines the standard models of earth structure that should be considered. Principles of physics can then be used to derive equations for predicting the seismic, gravimetric, magnetic, and electrical effects of these models. An understanding of geology again becomes important in our judgments about the actual rocks that are represented by the physical properties of a model.