Preface

It seems like digging the past but I still remember the day when the second edition of Dobrin's book "Introduction to Geophysical Prospecting" appeared. Even in those days, presenting this subject in a single volume was no easy task. Since then, our knowledge and capabilities for discovering oil and other natural resources has undergone a sea change. The credit mostly goes to a large number of individuals who used their highly specialized knowledge to analyze and solve a vast diversity of problems. Their contributions are well documented and continue to appear in technical books and professional journals. However, most of them are primarily useful for those engaged in research and development. Other professionals often find them too specialized or highly mathematical in nature. "Exploration Geophysics" by Gadallah and Fisher is a timely product which will fill a much needed gap.

The authors endeavor to present a simplified version of the science of exploration geophysics. In line with their professional background, they have primarily dealt with the various aspects of seismic prospecting. However, they cover almost everything related to this subject. After a short description of nonseismic methods, the reader is first introduced to an important but relatively less familiar subject of seeking permit for the acquisition of field data. This follows a detailed discussion on the acquisition and processing of data by using as little mathematics as possible. Much of the remaining book deals with the migration and interpretation of seismic data as well as the various tools needed to accomplish these tasks such as velocity analysis and the use of borehole information. In order to present a complete picture, the authors do not hesitate to touch upon the most recent developments such as cross-hole tomography and 4-D seismic.

The book provides a broad outline of seismic exploration without burdening the reader with nitty-gritty details. On the other hand, the door is kept open for further study by providing a comprehensive list of technical articles at the end of various chapters. At the other end of the spectrum, those quite new to the subject will find several lists of exercises valuable for self-learning. The book may also prove useful to those who work closely with geophysicists such as geologists, petroleum engineers as well as exploration managers.

Houston, TX *Irshad Mufti*

Chapter 2
Overview of Geophysical Techniques

Introduction

Various geophysical surveying methods have been and are used on land and offshore. Each of these methods measures something that is related to subsurface rocks and their geologic configurations. Rocks and minerals in the earth vary in several ways. These include:

- *Density* – mass per unit volume. The *gravity method* detects lateral variations in density. Both lateral and vertical density variations are important in the *seismic method.*
- *Magnetic susceptibility* – the amount of magnetization in a substance exposed to a magnetic field. The *magnetic method* detects horizontal variations in susceptibility.
- *Propagation velocity* – the rate at which sound or seismic waves are transmitted in the earth. It is these variations, horizontal and vertical, that make the seismic method applicable to petroleum exploration.
- *Resistivity* and *induced polarization* – Resitivity is a measure of the ability to conduct electricity and induced polarization is frequency-dependent variation in resistivity. *Electrical methods* detect variations of these over a surface area
- *Self-potential* - ability to generate an electrical voltage. Electrical methods also measure this over a surface area.
- *Electromagnetic wave reflectivity and transmissivity* – reflection and transmission of electromagnetic radiation, such as radar, radio waves and infrared radiation, is the basis of *electromagnetic methods.*

The primary advantages of the gravity and magnetic methods are that they are faster and cheaper than the seismic method. However, they do not provide the detailed information about the subsurface that the seismic method, particularly seismic reflection, does. There may also be interpretational ambiguities present.

Electrical methods are well suited to tracking the subsurface water table and locating water-bearing sands Seismic methods can also be used for this purpose.

Electromagnetic methods are useful in detecting near surface features such as ancient rivers.

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There will be no further discussion of electrical or electromagnetic methods. The following paragraphs provide brief introductions to the gravity, magnetic, and seismic methods. The discussions of the gravity and magnetic methods included in this chapter serve to acquaint the reader with their general methods and applications. All subsequent chapters will deal with the seismic method.

The Gravity Method

A 70-kg man weighs less than 70 kg in Denver, Colorado and more than 70 kg pounds in Death Valley, California. This is because Denver is at a substantially higher elevation than sea level while Death Valley is below sea level. So, the farther from the center of the earth the less one weighs. What one weighs depends on the force of gravity at that spot and the force of gravity varies with elevation, rock densities, latitude, and topography. Mass, however, does not depend on gravity but is a fundamental quantity throughout the universe.

When a mass is suspended from a spring, the amount the spring stretches is proportional to the force of gravity. This force, F, is given by F = mg, where g is the *acceleration of gravity*. Since mass is a constant, variations in stretch of the spring can be used to determine variations in the acceleration of gravity, g.

Figure 2.1 illustrates the principle of gravity exploration. On the left the surface elevation is moderate but there is a thick sedimentary section overlaying the basement complex. At the center the surface elevation is near sea level and the subsurface has a sedimentary section of normal thickness and density overlaying an "average" basement complex. On the right the surface elevation is also moderate but there is a thin sedimentary section resulting in the basement complex being close to the surface.

The center part of Fig. 2.1 represents the "normal" earth situation and the suspended mass stretches the spring a "normal" amount here. On the left, the thick

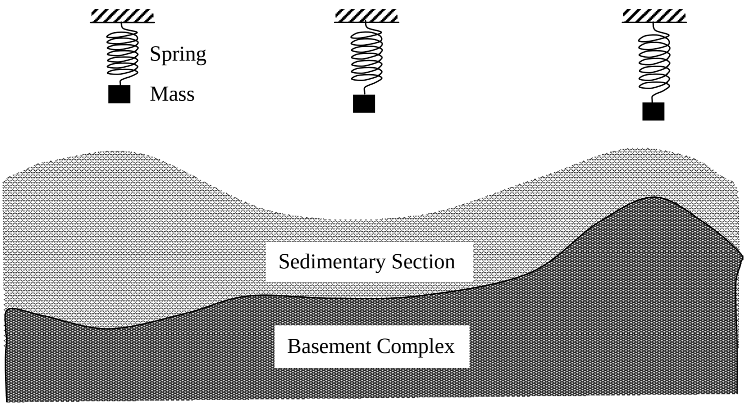

Fig. 2.1 The gravity method

sedimentary section has lower density than the basement rocks so the “pull” of the earth is reduced, resulting in the suspended mass stretching the spring less than the “normal” amount. The situation on the right is the opposite. The higher density basement rocks closer to the surface causes the “pull” of the earth to be greater, stretching the spring more than the “normal” amount.

An instrument called a *gravimeter* is used to measure g at “stations” spaced more or less evenly over the area being surveyed. Raw readings are corrected for elevation, latitude, and topography. The normal value of g is subtracted from the corrected readings, yielding *residual gravity*. The values of residual gravity are plotted at the respective station locations and contours of equal residual gravity are drawn. Closed contours represent *gravity anomalies* that can be used to infer subsurface geologic structures.

The value of g at sea level is about $980\text{cm}/\text{s}^2$. Since the variations of g are relatively small, cm/s^2 is a bit large for measuring them. The unit used for measuring residual gravity is the *milligal* (*mgal*), or one-thousandth of a *gal*, where a gal is $1\text{cm}/\text{s}^2$. The gal is named for Galileo. Figure 2.2 is an example of a final gravity map. Contour interval is 1 mgal.

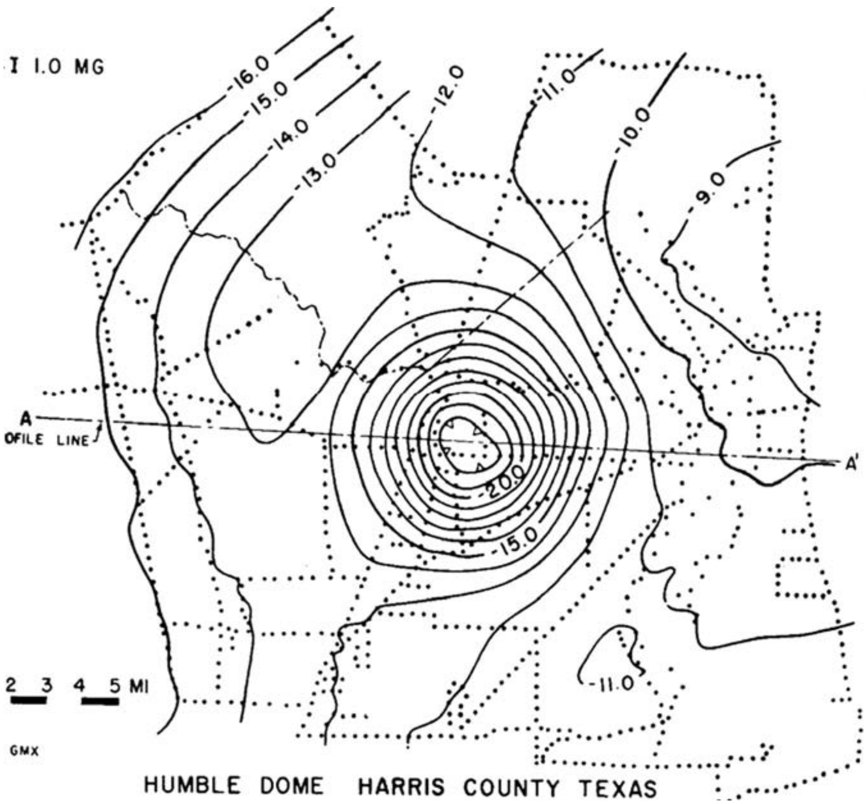

Fig. 2.2 Gravity map example

Interpretation of gravity data is done by comparing the shape and size of these anomalies to those caused by bodies of various geometrical shapes at different depths and differing densities.

The Magnetic Method

The earth's outer core is made of molten iron and nickel. Convection currents in the core result in motion of charged particles in a conductor, producing a magnetic field. The field behaves as though there is a north magnetic pole in the southern hemisphere and a south magnetic pole in the northern hemisphere. However, the magnetic poles of the earth are not coincident with the geographic poles of its axis. Currently, the north magnetic pole is located in the Canadian Northwest Territories northwest of Hudson Bay and the south magnetic pole is near the edge of the Antarctic continent. Note that the positions of the magnetic poles are not fixed but constantly change. The magnetic poles drift to the west at the rate of 19–24 km per year.

As a result of the shifting poles there is a change in the direction of the field, referred to as a secular variation. This is a periodic variation with a period of 960 years. In addition there are annual and diurnal, or daily, variations.

A magnetic field can be described by magnetic lines of force that are invisible. These lines can be thought of as flowing out of the south magnetic pole and into the north magnetic pole. A compass needle aligns itself along the magnetic line of force that passes through it. If the compass needle were free to move vertically as well as horizontally, it would point vertically downward at the north magnetic pole, vertically upward at the south magnetic pole and at intermediate angles away from the magnetic poles. Figure 2.3 illustrates the earth's magnetic field. A compass needle aligns itself along the line of force passing through it.

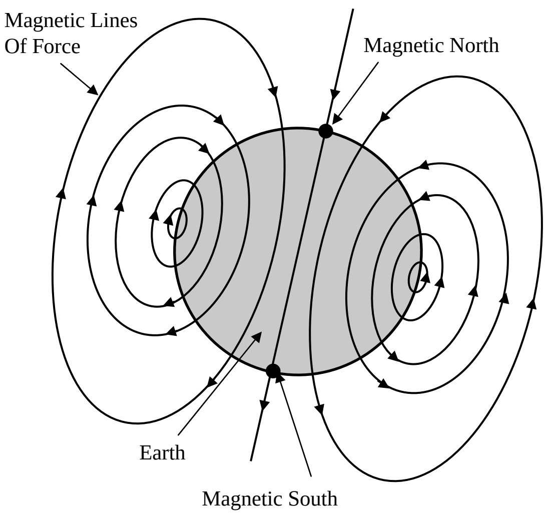

Fig. 2.3 Earth's magnetic field

In addition to these known variations in the magnetic field, local variations occur where the basement complex is close to the surface and where concentrations of ferromagnetic minerals exist. Thus, the primary applications of the magnetic method are in mapping the basement and locating ferromagnetic ore deposits.

The instruments used to measure the earth's magnetic field are called magnetometers. What is actually being measured is the *intensity* or *field strength* of the earth's field. This is measured in *Tesla (T)*. Since the objective of the magnetic method is to detect relatively small differences from the theoretical value of magnetic intensity, these are measured in *NanoTesla (nT)* or *gammas* (γ).$(1\ nT = 10^{-9}\ T = 1\ \gamma.)$

Today, most magnetic surveys are made from airplanes. While flying over a predetermined path (usually, a set of parallel flight lines), the magnetic field is continuously recorded. The raw magnetometer readings must be corrected for diurnal variations and other known causes of magnetic intensity variations. The residual field is determined by subtracting the theoretical values for the area of survey from the corrected magnetometer readings. The residuals are plotted on a map and contours of equal gammas are drawn. See Fig. 2.4.

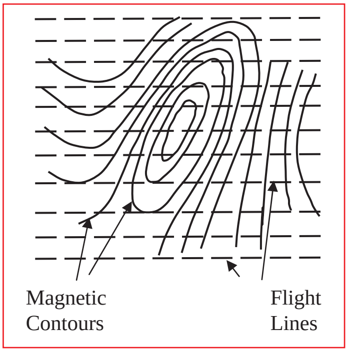

Fig. 2.4 Magnetic map

Closed contours indicate magnetic *anomalies* caused by local ferromagnetic bodies or anomalous depths to the basement. Interpretation is similar to that for gravity except the bodies of various geometrical shapes at different depths differ in magnetic susceptibilities rather than densities.

The Seismic Method

The seismic method is rather simple in concept. An energy source (dynamite in the early days) is used to produce seismic waves (similar to sound) that travel through the earth to detectors of motion, on land, or pressure, at sea. The detectors convert the motion or pressure variations to electricity that is recorded by electronic instruments.

L. Palmiere developed the first ’seismograph’ in 1855. A seismograph is an instrument used to detect and record earthquakes. This device was able to pick up and record the vibrations of the earth that occur during an earthquake. However, it wasn’t until 1921 that this technology was used to help locate underground oil formations.

There are two paths between source and receiver of particular interest – reflection and refraction. In Fig. 2.5 layers 1 and 2 differ in rock type, in the rate at which seismic waves travel (*acoustic or seismic velocity*), and *density* (mass per unit volume). When the seismic waves encounter the boundary between layers 1 and 2 some of the energy is reflected back to the surface in layer 1 and some is transmitted into layer 2. If the seismic velocity of layer 2 is faster than in layer 1, there will be an angle at which the transmitted seismic wave is bent or refracted to travel along the boundary between layers, as shown in Fig. 2.5. These two path types are the bases of seismic *reflection* and *refraction* surveys.

Figure 2.6 illustrates seismic reflection operations. Instead of a single detector as in Fig. 2.5, 24 detectors are laid out on the surface. Seismic energy travels downward with some being reflected at the boundary between layers 1 and 2 back to the detectors. (Note: actual operations involve recording many reflections from many subsurface reflectors from many more detectors than are shown here.)

Reflection seismic data are displayed as *seismic records* consisting of several *seismic traces*. A seismic trace, often presented as a “wiggly line”, represents the response of a single seismic detector (or connected group of detectors) to the earth’s movement caused by the arrival of seismic energy. Figure 2.7 illustrates a simulated seismic reflection record that was developed from Fig. 2.6. (This is called a *shot record* because all traces represent energy from a single source or shot.) Traces are ordered by *offset* or distance from the source.

Similar “wiggles” can be followed from trace-to-trace starting at about 0.165 s on trace 1 and ending at about 0.78 s on trace 24. This *event* is the first break refraction. It is refraction from the base of the shallow near surface layer that is too thin to adequately show in Fig. 2.6. Note that a straight line can be drawn through this event.

A second event is shown in Fig. 2.7. This event, the reflection from the boundary between layers 1 and 2, starts at about 1.90 s on trace 1 and ends at about 1.99 s on trace 24. Note that it is not straight but curved.

A seismic reflection survey generates a large number of shot records that cover the area under study. Modern methods call for recording reflections such that there is a common midpoint between sources and detectors on many different shot records.

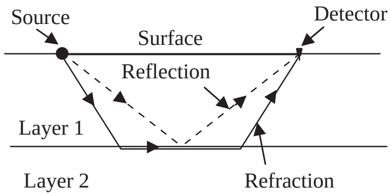

Fig. 2.5 Reflection and refraction

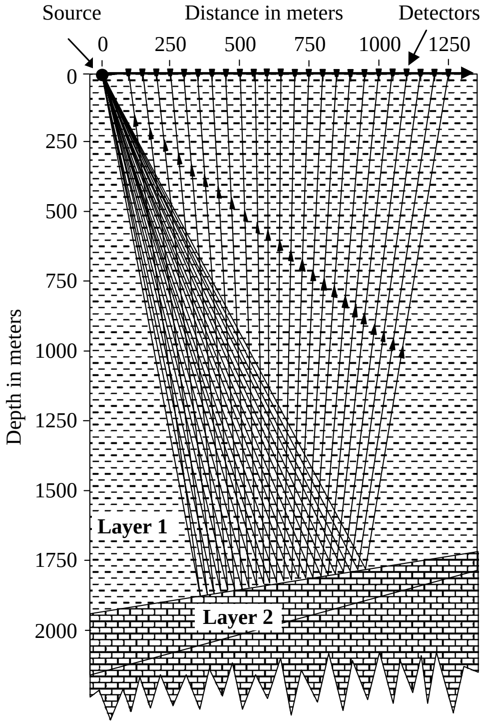

Fig. 2.6 Seismic reflection method

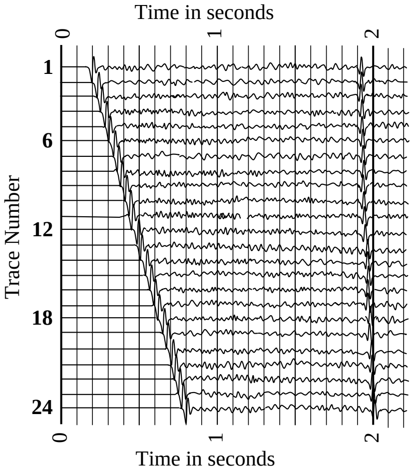

Fig. 2.7 A simulated seismic reflection record, based on Fig. 2.6

In seismic data processing the traces that share these common midpoints are collected together as *common midpoint* or *CMP records.* The assumption is that these traces record from the same subsurface reflection points and are combined, or *stacked*, into a single trace, called a *CMP trace.* Other processes are applied to the data to enhance the signal, minimize noise, and improve interpretability.

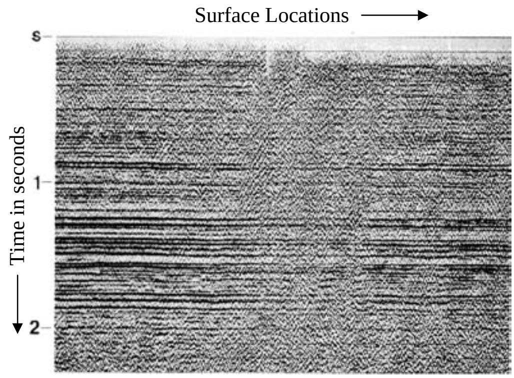

Fig. 2.8 A seismic section

When processing is complete, all the CMP traces are displayed side by side comprising a *seismic section*. The section is an image of the subsurface, that can be used to plan drilling and development programs. The section in Fig. 2.8 shows many rock beds and a potentially hydrocarbon-bearing structure.

The reflection method has been the most successful seismic method for identifying subsurface geologic conditions favorable to the accumulation of oil and gas. The greater part of this book discusses and explains this method.

Figure 2.9 illustrates the seismic refraction method. Here, seismic waves travel faster in layer 2 than in layer 1, i.e. – *seismic velocity* is higher in layer 2 than in layer 1. The seismic waves that arrive at the layer boundary at the *critical angle* are bent or refracted along the boundary. At the receiver end, seismic waves are refracted upward at the same angle. Additional refractions may occur at deeper boundaries, if the seismic velocities below the boundaries are faster than those above the boundaries.

Figure 2.10 is a simulated seismic refraction record based on Fig. 2.9. Again two events are apparent. The first is the refraction from the boundary between layer 1 and 2. The second is the direct arrival from the source.

Less processing is applied to refraction data than reflection data. The main interest is in being able to pick the arrival time of refraction events. These times are

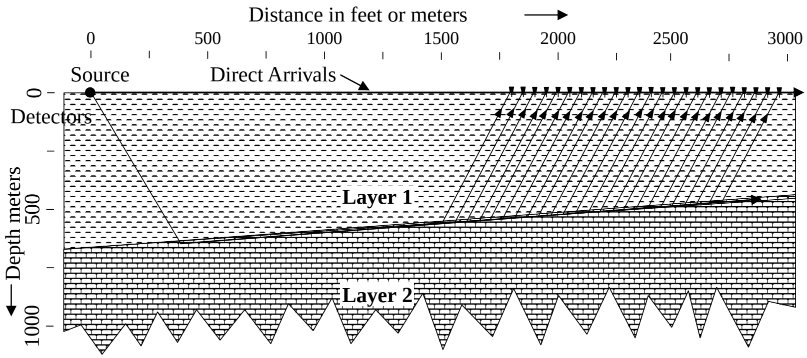

Fig. 2.9 Seismic refraction method

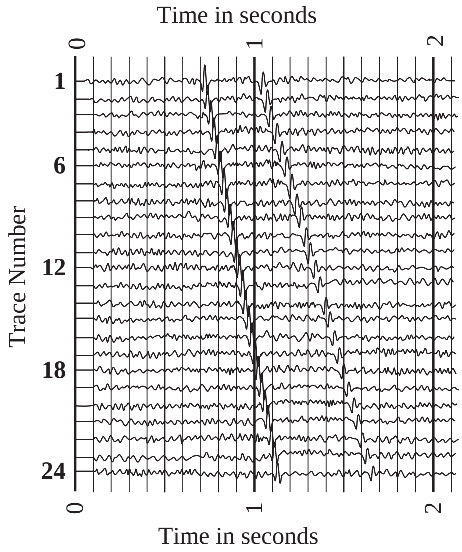

Fig. 2.10 A simulated seismic refraction record, based on Fig. 2.9

plotted against offsets (distances between source and receivers) in what are called T-X plots. Analysis and interpretation of these plots may allow determination of subsurface layer thicknesses and velocities.

The refraction method can supply data that allow interpreters to identify rock units, if the acoustic velocities are known. The refraction method can also be used to detail structure of certain deep, high-velocity sediments, where reflection data are not of sufficient quality.

Summary and Discussion

This chapter provides a brief review of the geophysical methods used in petroleum exploration and development. Chapter 3 gives the basic theory and principles upon which the seismic method is based. Chapter 4 covers seismic refraction surveys in somewhat greater depth. The rest of the book covers various aspects of seismic reflection methods.

Gravity and magnetic methods can be used for reconnaissance surveys to delineate areas of interest. They should be conducted before (or in conjunction with) the seismic method.

Today high-resolution 3-D seismic data are used to delineate petroleum reservoirs before drilling commences, determine optimum locations for initial drilling, select sites for development wells, and to monitor reservoirs throughout their various production cycles.

The seismic industry continues to develop ever more sophisticated methods. These are needed to allow discovery of petroleum deposits to replace depleted reserves. The more subtle nature of the reservoirs to be discovered, require more accurate information so that the fine details of a reservoir can be studied. These advanced methods are also needed to optimize petroleum production from known reservoirs.

There are many sources of data and information for the geologist and geophysicist in exploration for hydrocarbons. This includes a variety of measurements, commonly referred to as logs, obtained along the boreholes. However, this raw data alone would be useless without methodical processing and interpretation. Much like putting together a puzzle, the geophysicist uses sources of data available to create a model, or educated guess, as to the structure of rocks under the ground. Some techniques, including seismic exploration, allow the construction of a hand or computer generated visual interpretation of the subsurface. Other sources of data, such as that obtained from core samples or logging, are taken by the geologist when determining the subsurface geological structures. It must be remembered, however, that despite the amazing evolution of technology and exploration methods the only way of being sure that a petroleum or natural gas reservoir exists is to drill. The result of the improvement in technology and procedures is that exploration geologists and geophysicists can make better assessments of drilling locations.