Introduction to Geophysics

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PREFACE

This work was written as a beginning college textbook in geophysics. Its principal objectives are to familiarize the reader with the scope of geophysics in relation to the other sciences, to give him some insight into the methods used by geophysicists to study the earth, and to outline some of the most important discoveries of these researches.

When the author first began to teach geophysics in 1949, he found that several excellent books on geophysical prospecting were available. In general geophysics, on the other hand, all the available texts in English either were concerned with some individual subdivision of this science such as seismology, to the exclusion of all others, or appeared to be written on the assumption that the reader already knew a great deal about the subject. This lack of a comprehensive introductory text led to the present work. It has been written with a course composed half of juniors and seniors and half of graduate students in mind. The students in the author's course are drawn from many curricula: physics, geology, mineralogy, petroleum engineering, mining engineering, as well as geophysics and geochemistry. The book is intended to satisfy the needs of a broad range of specialists for a basic knowledge of the fundamental principles of geophysics. It is assumed that the student using the text will be familiar with the terminology of both geology and physics. One semester of geology and one year of college physics should be sufficient preparation for understanding the ideas presented here.

A nodding acquaintance with calculus is also assumed. It is the author's observation that the average geology student has the same opinion of calculus that a small boy has of castor oil. He has a high respect for it but avoids it with a terror which cannot be touched by reason. This is indeed unfortunate, but since it is the case, the use of mathematics has been kept at a minimum. Yet geophysics is an exact science, and geophysical ideas can in many cases be adequately presented only with the help of formulas. Elementary calculus has therefore been employed wherever its use leads to greater clarity or conciseness in presenting information. Where formulas are derived, all steps are included in the derivation so that the student who is not quick in mathematics will have no difficulty in understanding what is being stated. In the few cases, such as in Chap. 10, where moderately complex mathematical treatments are necessary for thorough presentation of fundamental concepts, the text is so written that the sections containing the mathematical proofs can be skipped over by students unable to appreciate them. This material has been included for the physicist using this text, since he will ordinarily desire a rigorous treatment.

It is planned that this book should serve not only as a textbook but as a reference work. Since geophysics has developed relatively rapidly as a science in recent years, there is a great deal of basic information which is still published only in one or two places, usually in technical journals. Because of this, an extensive bibliography has been included, especially for those subjects not thoroughly treated in more specialized works. All references are at the end of the book, and throughout the text, references are made simply by stating the author's name and the year of the publication. Since this is a textbook and not a technical paper, the references used are intended, in general, to direct the reader to a readily available, more detailed treatment of the subject, wherever possible a book or summary paper. References to original sources can usually be found in these secondary sources. It is hoped that advanced students and others using this book will find these references a stimulating introduction to geophysical literature.

The writing of this book would not have been possible without the help of many friends and fellow geophysicists who gave generously of their time and advice. The author particularly wishes to thank the following for reading chapters related to their specialties and suggesting improvements and additions to the material presented: O. Frank Tuttle, Leonard F. Herzog, and E. James Moore of The Pennsylvania State University; Beno Gutenberg of the California Institute of Technology; Sigmund Hammer of Gulf Research and Development Company; Harry H. Hess and the author's father, B. F. Howell, of Princeton University; and E. H. Vestine of Rand Corporation.

The kind cooperation of the many individuals and organizations who supplied a large part of the illustrations used is greatly appreciated. Specific acknowledgement will be found in each case in the text.

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CHAPTER 1

INTRODUCTION

Geophysics has an unusual position in the organization of science.[1] It has neither a unique methodology nor a particular area of interest which it can claim peculiarly for its own. By definition, geophysics is the application of the principles and practices of physics to the solution of problems related to the earth. It grew out of physics and geology and has no sharp boundaries which distinguish it from either. It constitutes a point of view toward earth science as a whole involving the experimental approach to an understanding of the planet we inhabit.

This approach is a logical step in the development of the methodology of science. Before the industrial revolution began to give men plentiful leisure to examine the world about them, so little of nature's pattern had been recognized that a man could aspire to learn all that was known of it at the time he lived. The early natural philosophers were interested in all manifestations of reality. However, as science developed, the body of accumulated data rapidly became so great that no one individual could study all of it, to say nothing of understanding the meaning of what he had examined. As a result, the idea of specialization developed. Today the physical sciences have become so subdivided that it would be difficult even to list all their branches. It has been said that as successive investigators seek to learn more and more about less and less, they may soon reach the point of knowing everything about nothing.

Early in the process of subdivision, four branches of science were recognized. These are chemistry, the study of the properties of matter; physics, the study of the forces acting on matter; geology,[2] the study of matter as it occurs in the earth; and biology, the study of matter as it occurs in living organisms. To these are often added astronomy, which

[1] Throughout the discussion which follows, the word science will be used as a synonym for physical science unless otherwise noted.

[2] The term geology is commonly used with two different meanings. In its broader sense, used here, it is synonymous with all of earth science including the study of the air and the oceans. In its more restricted use, geology means the study of the accessible rocks of the earth's crust.

deals with the rest of the universe aside from the earth, and mathematics, the science of forms and numbers. Because it does not deal with matter directly, mathematics is often not included among the physical sciences. Astronomy is often treated as a branch of physics. From this point of view, science can be portrayed as a tetrahedron, as shown in Fig. 1.1. Each field of study has its place somewhere in the tetrahedron.

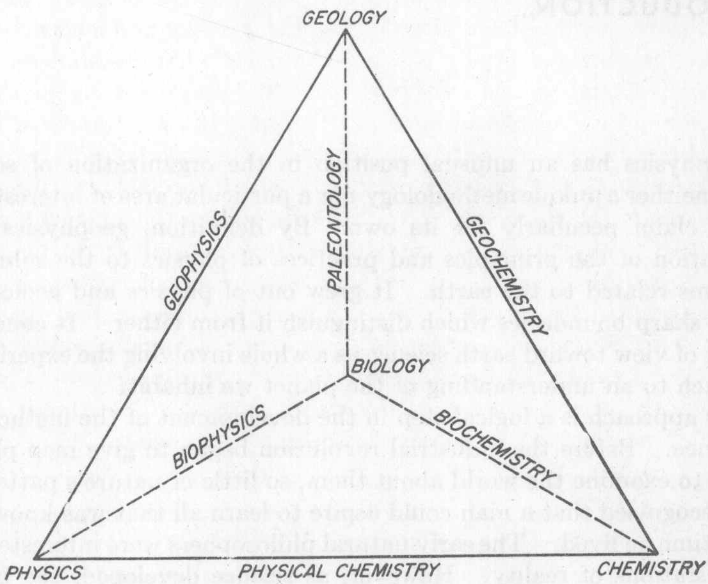

Fig. 1.1 The tetrahedron of physical science.

Until science began to diversify, the investigator was not tempted to emphasize one subject over any other. Thus, Sir Isaac Newton, who is often thought of as a physicist, also contributed to what we now call geology when he proposed the contraction theory of mountain building. As knowledge increased, certain fields were investigated more thoroughly than others and came to be considered as separate and distinct. Classification of knowledge into individual subjects tended to separate scientists and left the intermediate areas relatively undeveloped. When this overemphasis was recognized, new specialities developed which dealt with these in-between fields. Geophysics is one of these.

Science begins with observation. The recognition that experiment and not reference to authority is the best way to solve a problem marks the beginning of modern times and the end of the Renaissance. Our modern science and technology grew in their entirety from this single basic principle. In the beginning all science was largely descriptive. Kepler is remembered for his description of the motions of the planets; Harvey, for

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his demonstration of the circulation of the blood. The science of geology, probably because of the complexity of the medium with which it deals, has remained largely descriptive until recently. On the other hand, physics, which deals with forces and the relationships of bodies to one another regardless of their occurrence in nature, developed early into a laboratory science. Because conditions in the laboratory could be carefully controlled, the physicist soon progressed to the point of measuring quantities he could not see directly, such as gravity and electric current.

When the geologist finally reached the point where he understood the earth well enough to be ready to test his hypotheses by experiment, physicists and chemists had already developed the techniques of making the necessary measurements. As a result, the most rapidly expanding frontiers in earth science today are those where specialists in other fields are working with geologists. Geophysics is an example of such a domain.

The science of geophysics came into being as a result of the need of the geologist for new tools. As various techniques of experiment were applied to earth problems, whole new areas of investigation developed. Because of their relation to the older sciences of physics and geology, it was natural to group all these specialties under the one general name geophysics, even though they were diverse in nature. The American Geophysical Union breaks geophysics into eight subdivisions:

Meteorology—the science of the air
Hydrology—the science of ground water, both surface and underground
Oceanography—the science of the oceans
Seismology—the science of earthquakes and other ground vibrations
Volcanology—the science of volcanoes and related phenomena
Geomagnetism—the science of the earth's magnetic and electric phenomena
Geodesy—the science of the earth's shape and gravitational field
Tectonophysics (tectonics of geodynamics)—the science of the deformations of rocks, as in mountain building and other diastrophism

Four other fields are commonly named in classifications of geophysics:

Glaciology—dealing with water where it occurs as ice, usually considered to be a branch of hydrology
Geothermometry—dealing with the heat of the earth. Geothermometry is related to volcanology but is broader in conception. It is concerned with the temperature of the earth and with the effect of temperature on physical and chemical processes and the flow of heat. It includes the sources of the earth's heat, such as natural radioactivity. Volcanology is best classed as a subdivision of geothermometry.
Geocosmogony—dealing with the origin of the earth
Geochronology—the dating of events in the earth's history

The American Geophysical Union includes two other fields which it links with volcanology in its classification. The first of these is geochemistry, which relates geology to chemistry as geophysics relates it to physics. In any logical classification geochemistry deserves a position as an independent field of equal rank with geophysics, though it is often hard to say where the one science ends and the other begins. The second field is petrology, the science of the origin, evolution, and description of rocks. Petrology overlaps both volcanology and geochemistry in its area of interest.

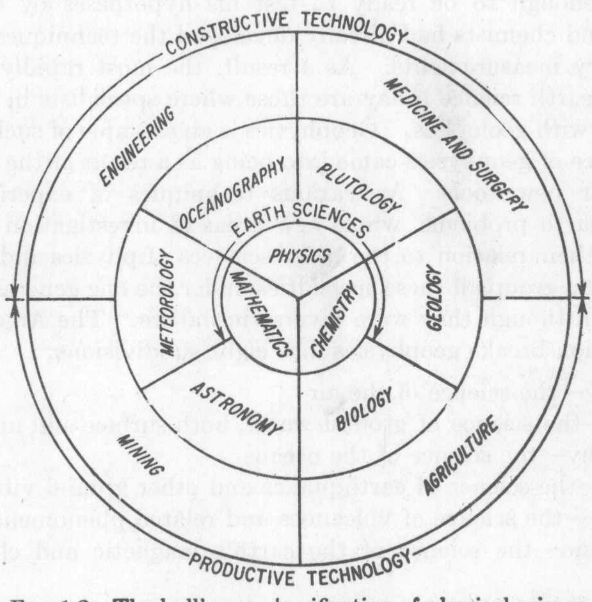

FIG. 1.2 The bull's-eye classification of physical science.

It is difficult to fit such a diverse collection of subdivisions into the simple picture of the organization of science presented above. Figure 1.2 is a rational classification which is better suited to showing the organization of science as it is today. In the center are the basic sciences of physics, chemistry, and mathematics, on which the other sciences depend. The basic sciences are concerned with the properties of matter independent of its natural occurrence. Thus the chemist may discuss properties of oxygen which it possesses whether it occurs as a gas in the air, combined with water in the ocean, or in a silicate molecule deep within the earth.

The second circle contains the applied sciences, divided into the realms with which they deal. Oceanography, meteorology, and astronomy are concerned with the oceans, the air, and the universe outside our terrestrial globe. Biology is concerned with the organisms which live upon it.

The realm of geology (used here in its more restricted meaning) is the exposed rocks of the earth's crust, from its surface to the bottom of the deepest wells. Beneath the thin shell which we can observe directly is the bulk of our earth, seen only by means of the tools of the geophysicist and geochemist. This realm of science is here named plutology.

This book might well have been called "Introduction to Plutology," as this subterrain is the area with which it is concerned. The scope of geophysics is too great to be treated adequately in one text, no matter how elementary. Meteorology, oceanography, and hydrology each would require as much discussion as all the chapters of this book which follow this one. Although the physical methods used in studying the air and water of the earth are in many cases similar to those involved in plutology, the differences between the gaseous and liquid environments and the solid part of the earth make great modifications in the details of these methods.

The principal objective of plutology is the determination of the composition and structure af the earth's interior and the history of its changes, past, present, and future. This objective is shared with geology. The geophysicist seeks to reach it by indirect measurements. Geologists depend largely on direct observations of rocks for knowledge of the earth. Geophysics is distinguished from geology by its emphasis on field and laboratory experiments.

Geology, biology, astronomy, and the geophysical sciences constitute a ring in Fig. 1.2 of applied sciences. They are "applied" because in them the "basic" sciences are used to explain the behavior of matter in its varied natural forms. They have sometimes been called descriptive sciences because in the past so much of the research in these fields has been devoted simply to studying the various forms in which matter can and does occur in nature. However, study of the universe and its inhabitants has not been limited to statements of what was found in it. The great progress man has made in mastering his own fate has resulted from his ability to capitalize on past experiences. For example, study of earthquakes has given a way of prospecting for oil, study of heredity in plants has shown how to grow better crops, and study of the atmosphere has taught us to predict weather.

The term "applied science" is often misused to refer to the outer ring of technologies. The latter are not sciences at all, though they depend on the sciences for the basic principles which guide their operations. The confusion arises from the intimate connection between basic information about the physical world and its practical applications. Science is systematic knowledge; it is the description and understanding of the universe in which we live, regardless of whether or not this knowledge has practical value. Technology is the use of this knowledge to benefit mankind.

The classification described above is two-dimensional only. Physical science cannot be properly comprehended unless we relate it to the less tangible activities of man. The social sciences connect to those shown in the chart through geography and psychology. Geography takes all of science and technology and relates them to man. Psychology describes man's reactions to the stimuli of his encounters with different aspects of the physical world and with his fellows.

In the chapters which follow, the different methods by which the geophysicist seeks information on the earth's interior will be outlined. In the last few decades, some of these methods have been highly developed in the search for petroleum and ore deposits. The special technological applications of geophysics to prospecting are the subject of numerous excellent texts (for example, Dobrin, 1952; Heiland, 1940). This work is a science text. It will concern itself with the broader problems of earth science and will leave the practical application of the methods described to the geophysical engineer.

Every earth scientist, especially the geologist, should be familiar with the various ways in which geophysics can help him understand the earth. This book is intended to show the potentialities and limitations of physical measurements made at or near the earth's surface as means of learning about the earth's hidden interior. The principal types of measurements which can be made will be outlined, and the significance of important data so far obtained will be discussed.

CHAPTER 2

ORIGIN OF THE EARTH

It is appropriate that a book dealing with the earth should start with how it came into being. One of the clearest lessons of geology is that everything we see is transient. Mountains are raised and worn away; great seas come and go. In the pages which follow, it will be shown that the features of the interior of the earth are no more permanent than its superficial appearance. What we observe today must be the result of what happened yesterday, and that, in turn, follows from earlier events, and so on as far back in time as one can go.

There is no true beginning to this history of change. Matter, either as mass or as energy, appears to be indestructible; so the rock, water, and air which make up the earth must always have existed in one form or another. When we refer to the origin of the earth, what we mean is not the creation of the matter of which it is composed, but the appearance of this matter as a single body which has had an individual existence from the time of its appearance to the present.

The omnipresence of change makes it certain that at some time the earth must have been very different from what it is now. There is a definite limit to the time that the earth can have existed in its present form. This is set by the changing proportions of the elements involved in radioactive disintegration (see Chap. 4). The fact that radioactive atoms exist at all on the earth today and have not completely disintegrated into more stable substances proves that the matter of which the earth is composed must once have been in a very different environment. The only place known where conditions may be right for the formation of the unstable elements is in the center of hot, dense stars. At some time, at least a part of the material from which the earth was formed must have been drawn from such a source. Since then great changes have taken place. The questions thus arise, what form could the material which today makes up the earth have had just before reaching its present general arrangement, and through what orderly transformation was the present condition reached?

2.1 Means of Studying the Universe. To approach the problem of what existed before there was an earth, a good method is to examine the forms in which matter exists elsewhere in the universe today. Since we can as yet rise only a little way above the solid surface of our planet, we must depend on information which comes to us from outer space. Such

FIG. 2.1 "Horsehead" nebula, a cloud of dark matter in Orion. *(Courtesy of Mount Wilson and Palomar Observatories.)*

information consists of two types: particles which enter our atmosphere and electromagnetic radiations such as light rays.

Most of the solid particles which strike the earth are evaporated by the heat generated by their passage through the air. Only in a few cases do some of the larger of these meteors reach the ground. They are found to consist of two principal types of material. The first of these is a stony substance composed largely of basic silicates such as are found in igneous

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