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R. D. Russell
J. Tuzo Wilson

Physics and Geology

SECOND EDITION

INTERNATIONAL STUDENT EDITION

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GEOLOGY**

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PREFACE

The first edition of this book was an outgrowth of courses on the physics of the earth given by the authors between 1946 and 1959 to senior undergraduate and graduate students in the Department of Physics and in the Department of Geology at the University of Toronto. As a consequence the book has two aims:

1. To give students of geology an introduction to the physics of the earth
2. To give scientists in other fields some knowledge of geology and its relation to geophysics

In the authors' view the earth should be regarded as an active body, the physiology as well as the anatomy of which can be studied. In the past, geology has been chiefly concerned with describing that part of the earth's surface exposed above the sea and with tracing the earth's later history as indexed by fossils. Methods developed and applied during the past few years, however, have made it possible to describe the whole earth, from its deep interior to its outer atmosphere. The earth's development has been put into better perspective on an absolute time scale, and it has been possible to suggest the physical nature and causes of some of its processes. It is this broader picture of terrestrial behavior which the authors have tried to sketch, blending the older outlines of geology with the newer colors of physics.

The objectives of the book have remained the same, but the development of the subject has been so rapid that almost every part of the book has had to be rewritten. The opportunity has been taken to add an extensive list of references.

When the first edition was being written, the three authors were working together in the physics laboratories of the University of Toronto, but their backgrounds were such that they could easily divide the preparation of the draft manuscript, for in addition to training in physics, Dr. Jacobs is a mathematician, Dr. Russell a chemist, and Dr. Wilson a geologist. Nevertheless they collaborated closely in writing and rewriting that edition.

Since then two of the authors have moved to other universities so that, although the preparation of a second edition has necessarily become a more difficult undertaking, the authors hope that this edition still reflects the blend of varied backgrounds that contributed to its development. All three authors continue to accept joint responsibility, although it seems fair to mention that Dr. Jacobs wrote the greater part of Chaps. 1, 2, 4, 7, 8, 9, and 10 and Secs. 11–4 to 11–6. Dr. Russell wrote Chaps. 5, 6, and part of 3, and Dr. Wilson the rest. Dr. Jacobs also undertook the task of assembling the whole.

The authors wish to thank their colleagues in their three universities and elsewhere for much sound advice and help. Mr. A. Aiken and Mr. K. Khan helped prepare many of the illustrations. Mrs. G. Dinwoodie played an important part in assembling the material and especially in collating the references.

In addition to the Universities of Alberta, British Columbia, and Toronto and the respective provincial agencies, the authors have received assistance in carrying out research, which formed the basis for parts of this book, from the National Research Council of Canada, the Defence Research Board of Canada, the Geological Survey of Canada, the Dominion Observatory (now the Earth Physics Branch), and other bodies and companies some of which were mentioned in the preface to the first edition. To all these and to their many patient secretaries who over the years have typed and retyped drafts we express our thanks.

J. A. JACOBS

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J. TUZO WILSON

CONTENTS

1
THE UNIVERSE AND THE SOLAR SYSTEM

1-1 INTRODUCTION

Before discussing in detail any particular aspect of the surface features or interior constitution of the earth, it is well to consider it first in its proper setting as a member of the solar system. Sooner or later in any discussion of the physical processes which occur within the earth, questions about its origin and early history are bound to arise. These in turn lead to the problem of the origin of the solar system and to other far-reaching astrophysical questions. Such questions are, in their very nature, bound to be extremely controversial, but it is wrong to ignore them, for the answers are important in many matters connected with the later development of the earth. Detailed studies of the thermal history of the earth, for example, depend quite critically on what initial temperatures are chosen. The origin of the earth will therefore be discussed at some length in this chapter; this will help in assessing the validity of particular earth models which will be constructed in later chapters. Before doing so, it will be convenient to introduce some of the terms which will be used by giving a brief account of some of the main features of the earth's surface and interior.

The earth is almost spherical in form, with a diameter of slightly less than 8000 miles. To be more precise and to give figures in the cgs units which will be used throughout this book, the earth has the shape of a spheroid with a mean equatorial radius of 6378.388 km and a polar radius of 6356.912 km. These are the figures adopted internationally. The radius of a sphere having the same volume is 6371.2 km, and a value of 6371 km will be used in any calculation. The earth's mass is 5.975×10^{27} g, and its average density is just over 5.5 g/cm^3. The average density of surface rocks, on the other hand, is approximately 2.8 g/cm^3 so that there must be a density increase toward the earth's center, where the pressure exceeds 3.5×10^{12} dynes/cm^2 ($\approx$ 3½ million atm). The temperature also increases toward the center. The average value of the surface gradient is about 30°C/km, but this gradient is not maintained at depth. The temperature at the center of the earth is almost certainly less than 10,000°C, and probably is no more than 5000°C.

There are a number of peculiarities about the surface features of the earth. Less than 30 percent of the earth's surface is land, which is markedly concentrated in the Northern Hemisphere, the oceans being concentrated in the Southern Hemisphere. This contrast is reversed in polar regions. Moreover, 81 percent of all the land is concentrated in one hemisphere, with its pole in Brittany, the corresponding "water hemisphere" having its pole near New Zealand. There is also a curious antipodal relation between land and sea. Although about 45 percent of the surface has sea opposite sea, only 1.4 percent has land opposite land. T. Hatherton has shown that the probability of most of the land being opposite to sea (as at present) could be due to chance, although whether this arrangement of surface features has existed throughout geological time is an intriguing question, and one on which complete agreement has not yet been reached. (See Chaps. 13 and 14, where polar wandering and continental drift are discussed in some detail.) The oceans hold as many geophysical problems as, or more than, the continents do. The greatest ocean depth exceeds the greatest mountain height, and there are mighty mountain ranges on the ocean floor which rival any of the ranges visible on land today.

The topmost layers of the earth are called the *crust*. Its thickness and composition are not constant, but vary between the continental crust, which consists of 30 to 60 km of light rocks (such as gneiss, granodiorite, and granite), and the oceanic crust, made up of dark rocks (such as basalt) usually not more than 5 to 6 km thick. The upper part of the crust is a thin and discontinuous layer of sedimentary rocks and oceanic deposits. That part of the earth between the crust and a depth of approximately 2900 km is called the *mantle*, and for the remaining part–inside the mantle–the word *core* is used. The boundaries between these three main divisions of the earth, the crust, mantle, and core, are sharp and distinct and mark large changes in seismic velocities, the evidence for which will be discussed more fully in the next chapter. The boundary between the crust and mantle is called the Mohorovičić discontinuity, or Moho.

Another useful division is based on the ability of different layers to flow. The crust and uppermost mantle to a depth of about 70 km are cold enough to be rigid and brittle so that they fracture rather than flow and are called the *lithosphere*, or *tectosphere*. Below that, a layer called the *asthenosphere*, or *rheosphere*, is hot enough and is under sufficiently low pressure so that it is capable of slow deformation and flow. At a depth of a few hundred kilometers, pressure leads to increased rigidity again. Changes in phase and in composition, and particularly changes in water content, may lead to changes in viscosity. The terms *sial* and *sima* were introduced before the advent of seismic information to distinguish on chemical grounds between rocks rich in *si*lica and *al*umina and those rich in *si*lica and *ma*gnesia, but with increasingly precise knowledge, these and many other older concepts and terms have become obsolete.

1-2 THE SOLAR SYSTEM

Until the time of Copernicus (1473-1543) it was generally held that the earth was the center of the universe and that around it revolved the sun, the moon, the planets then known, and the stars. This geocentric theory, or Ptolemaic theory, of the universe became ever more complicated and artificial as it tried to take account of the increasing accuracy of the observations and the newly discovered astronomical phenomena. Copernicus reintroduced the idea which had occurred to Aristarchus in 200 B.C. that the sun was the central body around which the earth and the other planets revolved in circular paths. The earth was thus displaced from its position as the center of the universe, being relegated to the status of a mere planet of an undistinguished star in a galaxy which itself is but an ordinary member of an uncountable number of galaxies. The astronomical observations of Galileo (1564-1642), following the invention of the telescope, confirmed the Copernican theory. The researches of Kepler (1571-1630), based on more accurate observations than were available to Copernicus, showed that the planetary orbits were not exactly circular, but elliptical with the sun at a focus. The discovery of the law of universal gravitation by Newton (1643-1727) gave impetus to the theoretical study of planetary motions, and Kepler's laws, which before had seemed distinct and unconnected, were shown to follow as simple deductions from Newton's law. A most sensational achievement was the discovery of a new planet, Neptune, in 1846. Using the discrepancies between the calculated and observed positions of Uranus, Adams (1819-1892) and Le Verrier (1811-1877), independently and unknown to each other, showed that they could be accounted for on the assumption that they were caused by the attraction on Uranus of an unknown planet; moreover, they were able to locate the position of the unknown planet, which was in due course observed through the telescope.

The planets fall into two groups, called the inner and outer planets. In order of distance from the sun, the inner planets are Mercury, Venus, Earth, and Mars, while the outer planets are Jupiter, Saturn, Uranus, Neptune, and Pluto. Some information of a general character on the planets is given in Table 1-1, which also includes data on the sun and moon. It can be seen that the four inner planets are

Table 1-1 CHARACTERISTICS OF THE SOLAR SYSTEM

Body	Mean density, g/cm^3	Total mass (earth masses)	Mean radius, km	Period of rotation,[a] days	Number of identified satellites[b]	Sidereal period,[c] years	Mean distance from sun, AU[d]	Eccentricity of orbit	Inclination of orbit to ecliptic,[e] rad
Sun	1.4	333,441	696,000	25.36	....	....	....	....	....
Mercury	6.03	0.0556	2434	59.7	0	0.241	0.3871	0.206	0.1221
Venus	5.11	0.8161	6056	−243.09	0	0.615	0.7233	0.007	0.0591
Earth	5.52	1.0123	6370	1.00	1	1.000	1.0000	0.017	
Mars	4.16	0.1076	3370	1.03	2	1.881	1.5237	0.093	0.0322
Jupiter	1.34	318.3637	69,900	0.40	12	11.865	5.2037	0.049	0.0228
Saturn	0.68	95.2254	58,500	0.43	10	29.650	9.5803	0.051	0.0434
Uranus	1.55	14.5805	23,300	0.89	5	83.744	19.1410	0.046	0.0135
Neptune	2.23	17.2642	22,100	0.53	2	165.451	30.1982	0.005	0.0309
Pluto	4.(?)	0.926(?)	3000	6.39	0	247.687	39.4387	0.250	0.2995
Moon	3.34	0.0123	1738	27.32	....	0.0748	....	0.055	0.0899

a The rotation periods for Mercury and Venus have been obtained by radar measurements. Until recently it was thought that the rotation period of Mercury was the same as its rate of revolution around the sun. Venus has a very dense atmosphere (almost entirely carbon dioxide) which conceals its surface and makes an optical estimate of its rotation period exceedingly difficult. The sun's period of rotation varies from 24.7 days at its equator to 26.6 days at latitude 35°

b A tenth satellite of Saturn was discovered by A. Dollfus in 1966.

c The sidereal period is the time of one revolution with respect to the stars.

d One astronomical unit (AU) is the mean distance from the Earth to the sun. It is 92,960,000 miles, or 149,598,000 km. (The distance from the Earth to the sun varies between 91,500,000 and 94,500,000 miles.) The distance from the Earth to the moon varies between 252,710 and 221,463 miles, the mean distance being 238,857 miles, or 384,403 km.

e The ecliptic is the plane of the Earth's orbit about the sun.

small planets, Earth being the largest of the group. With the exception of Pluto, the outer planets are very much larger than the inner ones. Pluto was discovered in 1930, and at present little is known about it. It has been suggested that it is possibly an escaped satellite of Neptune.

In 1801 a small planet called Ceres was discovered moving in a path between the orbits of Mars and Jupiter. That was the first of the minor planets (or asteroids, as they are often called) to be discovered. There are probably at least 30,000 of them; Ceres, the largest, has a diameter of about 730 km. The orbits of the minor planets lie essentially between those of Mars and Jupiter, and it has been suggested that the minor planets are the remnants of a major planet which was shattered into fragments at some stage in its history. However, a number of arguments have been advanced against this theory (see, for example, E. Anders, 1964, 1965); the origin of the asteroids will be discussed briefly in Sec. 1-5. The planetary distances r from the sun in astronomical units (AU) have been expressed by an empirical relationship known as Titius Bode's law.

$$r = 0.4 + 0.3 \times 2^n \qquad (1\text{-}1)$$

where $n = -\infty$ for Mercury, 0 for Venus, 1 for Earth, etc. There is no planet at a distance corresponding to $n = 3$, although the orbits of the minor planets fall in the area between those of Mars ($n = 2$) and Jupiter ($n = 4$).

Two things about the planetary orbits are of particular interest: (1) all the planets revolve around the sun in the same direction, and (2) the orbital planes of the planets, with the exception of Pluto, differ but little from the plane of the ecliptic. Moreover, the sun, moon, and planets, with the exception of Venus and Uranus, all rotate about their axes in the same sense as the planets revolve around the sun. These very special features must be taken into account when formulating any theory of the origin of the solar system.

By the first quarter of the present century, the development of giant optical telescopes and spectrographic methods of analyzing light had revealed that some of the diffuse and luminous stellar clouds called nebulas are distant concentrations of many thousands of millions of stars called galaxies. The Milky Way system is an example of a spiral galaxy, consisting of some 100,000 million stars in the shape of a lens. The sun is about 26,000 light years from the center of the spiral, which rotates with a period of about 200 m yr. Galaxies tend to be separated in space by distances averaging several times their diameters. They are scattered through all space visible to us with the largest telescopes. The most remote are so distant that light from them takes about 2000 m yr to reach the earth and registers only as faint marks on photographic plates exposed for many hours in the great 200-in. reflecting telescope at Palomar Mountain, California. In the last few years, the invention of another tool, radio astronomy, has made possible the detection of galaxies at even greater distances. Surveys show that galaxies tend to cluster in groups, containing up to a thousand or more. The distribution of clusters is a problem whose solution is vital to the present conflicting views on the origin of the universe.