ELEMENTARY SEISMOLOGY

By CHARLES F. RICHTER

CALIFORNIA INSTITUTE OF TECHNOLOGY

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PREFACE

THIS BOOK developed from a lecture course organized particularly for students in geology who do not plan to specialize in seismology or geophysics. Because of the dual nature of the subject, it is necessary to strike a proper balance between instrumental seismology and field work.

When the course was given originally, mathematics was held to a low level. At present, geophysical theories and methods are permeating every branch of geology and effecting a gradual revolution of our thinking; for this reason it becomes desirable, if not mandatory, to give mathematics a more comprehensive treatment. To meet this requirement without too great a demand on the student, mathematics in the body of the book is kept at the minimum consistent with intelligent comprehension. Details and long proofs are given in appendixes. The fundamental concepts of stress, strain, and elasticity are developed in Chapter 16; the unprepared student will find it possible to use the book without working through this chapter. However, the material in Chapter 15, covering the principle of the seismograph, cannot be passed over if the student is to make intelligent use of the results of instrumental seismology. He might as well attempt to use modern petrological data without understanding the microscope.

Due emphasis on mathematics does not imply the other extreme of underrating field observation and field training. Great harm is done by poorly trained men who hasten about in the field, observe a small part of the evidence, and publish premature conclusions which are actual obstacles to serious investigation. Throughout the book, and especially in Chapters 11, 13, and 14, there are suggestions for proper seismological field work.

One reason for setting forth the methods and assumptions of seismology in detail is that geologists and engineers often accept results too literally and apply them beyond the limits of accuracy. The opposite error, of rejecting definite instrumental results because they conflict with conclusions from hasty field work, is less common now than formerly. Throughout the text, possible sources of misdirection of both kinds are pointed out for the benefit of the working geologist.

Many textbook generalizations on tectonic earthquakes are based on only a small part of the available literature. For this book the collections by Montessus de Ballore and by Davison have been extended and their interpretations revised.

Although the book is intended primarily for elementary students, it includes descriptive and reference material for instructors and research workers. Except where it is necessary to refer to original contributions, publications in the more generally accessible journals have been given preference, especially the *Bulletin of the Seismological Society of America* which is available in most large libraries.

Material omitted or given abbreviated treatment as being too advanced or too special, or needing too much space, includes:

1. General geophysics apart from seismology.
2. Discussion of the cause and nature of mountain-building.
3. Derivation of earthquake mechanism from seismograms (especially when there is dip slip).
4. Microseisms (treated briefly in Chapter 23).
5. Damage and other effects of well-investigated earthquakes where there is no direct evidence of faulting.
6. Theory of elastic waves in media not homogeneous or not isotropic, including layered media.
7. Theory of plastic deformation and of fracture.
8. Calculation of earthquake energy from seismograms.
9. Seismograph construction and testing.

Geography and statistics of earthquakes are discussed in outline only; further details are given in *Seismicity of the Earth.*

The discussion of prospecting for oil and minerals by seismic methods is limited to a short statement of general principles. The interested student should refer to special handbooks. However, techniques change with extreme rapidity; books must be supplemented by study of current periodicals, and if possible by personal contact with the work.

Of special interest to engineers are Chapters 3, 8, 11, and 24, and Appendixes II and III. Appendix II, on safe construction, is presented with apology; its subject matter is too important to pass over completely, but adequate treatment including constructional details would call for another volume, by another hand.

Chapters 4 and 5 discuss a few selected earthquakes as illustrative examples. For the sake of completeness, these descriptions include material which otherwise would have been deferred to later chapters.

I am under many obligations, notably to my colleagues Beno Gutenberg, Hugo Benioff, R. H. Jahns, C. R. Allen, and Frank Press, and to Dr. Markus Båth of Uppsala, who read the manuscript and offered valuable suggestions and references. The book as it stands would have been impos-

sible without the extraordinary resources of Professor Gutenberg's personal library.

I am profoundly grateful for having had the opportunity of field work on earthquakes with the late and affectionately remembered John P. Buwalda. Over many years, I learned much from association and discussion with Harry O. Wood.†

The Seventh Pacific Science Congress in New Zealand (1949) afforded a splendid opportunity, not only to become acquainted with the local circumstances of that interesting region, but also to broaden my whole outlook in the geological sciences. In this book, California seismology has been discussed at length because it provides first-hand material for illustration. Comparison with New Zealand has been emphasized to avoid giving the book too parochial a character. For the necessary data and discussion I am indebted to Professors C. A. Cotton and W. N. Benson, Dr. C. A. Fleming, and Dr. A. R. Lillie. Professor Cotton has placed me under further heavy obligations by reviewing those chapters dealing with New Zealand; he has helped me to remove inaccuracies and add many paragraphs of new material.

Professor V. P. Gianella kindly reviewed the pages of Chapter 28 which deal with Owens Valley and Nevada earthquakes. He furnished many additional details and references.

During several visits to Pasadena, Professor Chuji Tsuboi contributed greatly to our understanding of Japan and its geophysical research, in a manner which it is a deep pleasure to acknowledge. He has read Chapter 30 and provided many valuable suggestions.

I am indebted to Lt.-Col. Ernest Tillotson for a large portfolio of original data on the African earthquake of 1928, and to Dr. J. B. Auden for notes on the tectonics of India and references on the earthquake of 1762.

For advice on engineering and insurance points I wish to thank Dr. G. W. Housner and Mr. H. M. Engle.

Illustration has been in charge of Mr. J. M. Nordquist. Figures have been drafted by him and by Mrs. Dorothy Hammond, Miss Phyllis Cangelosi, and Mrs. Barbara Dixon.

Maps from *Seismicity of the Earth* are reproduced with permission of the Princeton University Press. Much material on the seismology of Japan is summarized or quoted, by permission, from A. Imamura, *Theoretical and Applied Seismology*, published by Maruzen Co., Tokyo, 1937.

Except for quoted matter, I take full responsibility for statements in the text.

C. F. R.

Pasadena, California

March 1, 1957

† Deceased, February 1958.

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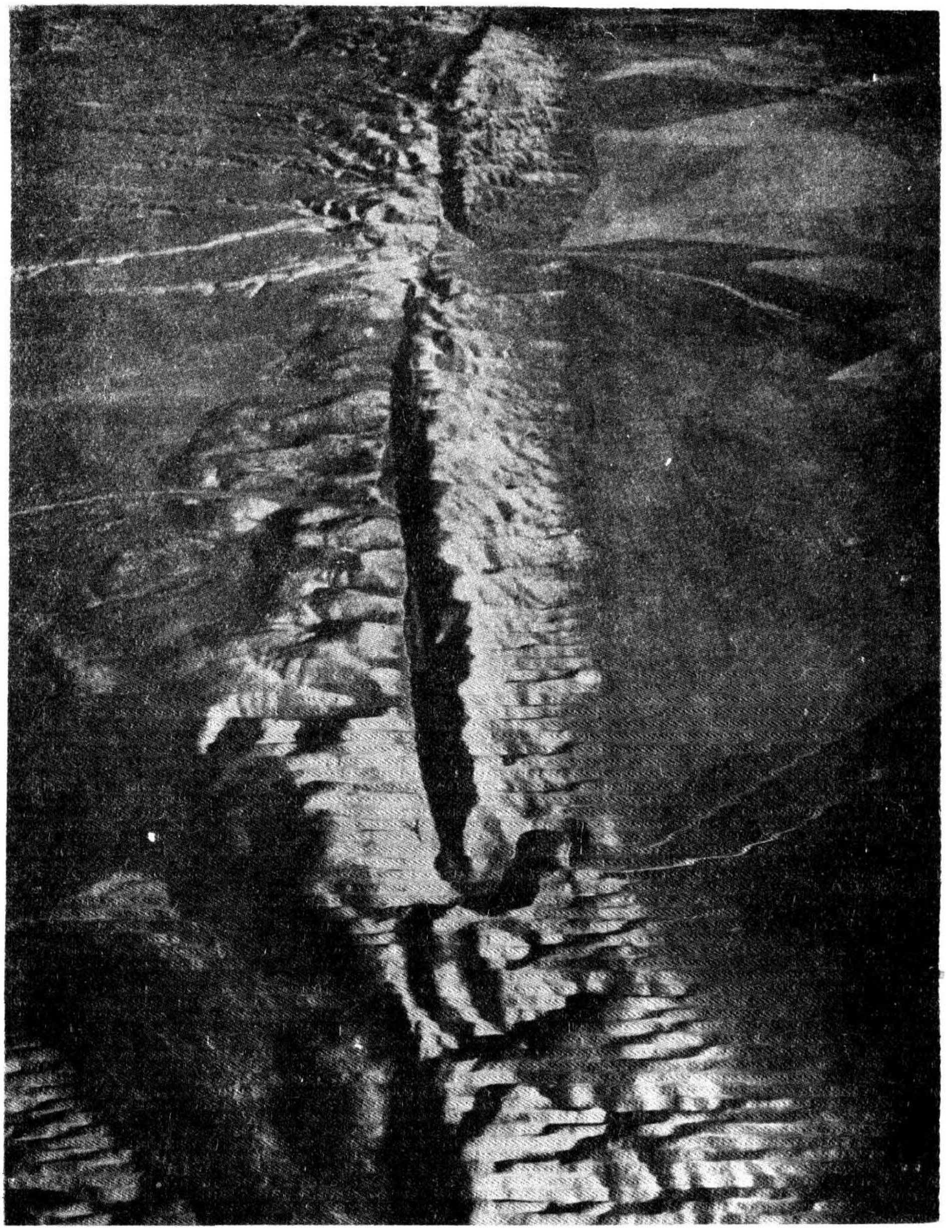
Nature and Observation of Earthquakes



FRONTISPIECE *View southeastward along the San Andreas Rift, San Luis Obispo County, California. Drainage descending from the highland at the left to the Carrizo Plain on the right is interrupted by the Rift and deflected in consequence of right-hand strike-slip. [Photo by William A. Garnett.]*

CHAPTER 1

Introduction to Seismology

A YOUNG SCIENCE

Investigating earthquakes is a live field of study, continually breaking down old fences and taking in new territory. It is useless to attempt exact definition; we usually say that *seismology is the science of earthquakes and related phenomena.*

Seismology developed later than most of the physical sciences. It is now as difficult to think of the seismologist without his characteristic instrument, the seismograph, as to imagine a modern astronomer without a telescope. The telescope dates from about 1600, but the first effective seismographs were built between 1879 and 1890.

In studying any earthquake one should carefully note its date in relation to the state of the science at the time. Not merely instruments, but also the whole background of information and investigation, change so rapidly that it makes an enormous difference, in terms of what we may expect to learn about it, whether an earthquake took place in 1850, 1880, 1910, 1930, or 1955.

PROGRESS OF SEISMOLOGY

As astronomy existed long before the telescope, so is seismology older than the seismograph; but our information about early earthquakes comes mainly from unscientific sources. Ancient accounts of earthquakes do not help us much; they are incomplete, and accuracy is usually sacrificed to make the most of a good story. Useful reports begin in the eighteenth century.

The following dates represent milestones in the progress of our knowledge of earthquakes and the earth to 1923.

1755, November 1. Lisbon earthquake. Some effects scientifically described.

1783, February 5 and following. Earthquakes in Calabria, Italy. Investigated by scientific commissions.

1819, June 16. Earthquake in Cutch, India. Earliest well-documented observations of faulting accompanying an earthquake.

1857, December 16. Earthquake east of Naples, Italy. Field investigation by Robert Mallet; first systematic attempt to apply physical principles to earthquake effects in detail.

1880. First effective seismographs developed by Gray, Milne, and Ewing in Japan.

1883–1884. Rossi-Forel scale for earthquake effects published (based on work in Italy and Switzerland).

1889, April 18. First identified seismogram of a distant earthquake. An instrument at Potsdam, Germany, recorded an earthquake in Japan.

1891, October 28. Mino-Owari earthquake, Japan. Large fault displacements; great damage. Imperial Earthquake Investigation Committee set up in consequence.

1896. Committee on Seismology formed by the British Association for the Advancement of Science. Enabled John Milne to establish seismograph stations with world-wide distribution.

1897, June 12. Great Indian earthquake. Investigated by R. D. Oldham.

1901. Geophysical Institute founded at Göttingen, Germany, by E. Wiechert.

1902. Improved intensity scale published by G. Mercalli in Italy.

1903. International Seismological Association founded. General improvement in recording and reporting earthquakes.

1906, April 18. California earthquake. Observed faulting; elastic-rebound theory of earthquakes formulated by H. F. Reid (Johns Hopkins University).

1906. Electromagnetic seismographs developed by B. Galitzin in Russia.

1909, October 8. Earthquake in Croatia. A. Mohorovičić (at Zagreb) discovered a sharp change in the speed of seismic waves at the base of the continental crust.

1913. First accurate determination of the depth of the earth's core, by B. Gutenberg (at Göttingen).

1918. First year covered by the *International Seismological Summary*, collating readings from most of the seismological stations of the world.

1922. Deep-focus earthquakes discovered by H. H. Turner in the course of editing the *International Summary* (at Oxford, England).

1923, September 1. The Kwantō earthquake, destructive at Tokyo and Yokohama. Detailed investigation; many published reports. Earthquake Research Institute established at Tokyo in consequence.

Many of these items are major themes for later chapters in this book. It should be noticed how truly international seismology is. Important contributions are made at present by hundreds of recording stations and dozens of research centers in all parts of the world.

"BELIEVE IT OR NOT?"

Reports on earthquake effects must be considered critically. Earthquakes are exciting and sometimes spectacular events, offering opportunity for mistakes and exaggeration. Accounts in the popular press, or observations by untrained persons, can be used for scientific purposes only with caution. Even scientific men without adequate training in seismology are sometimes responsible for misinformation. The serious student needs knowledge both of earthquakes and of the psychology of error. In dealing with earthquakes of old date, he also needs a knowledge of history; proper interpretation of documents may call for the help of professional historians.

Data in seismology accumulate slowly; much depends on investigating large earthquakes, which are not frequent. Actual harm has been done to the science by premature conclusions from fragmentary data, repeated from publication to publication. Few seismologists have had the admirable tact of the Russian who wrote (his own translation), "For lack of material we restrain ourselves from any kind of conclusions."

EARTHQUAKE EFFECTS

Many occurrences of different kinds have been called earthquakes (see Chapter 12). At this point we are not concerned with definition, but with the nature of earthquake observations.

A large earthquake usually attracts general attention only because it destroys houses and other works of man or breaks up and changes the ground surface. Such strong effects are limited to a relatively small area. The field geologist investigating this area finds evidence bearing on the mechanical cause of the earthquake. Faulting has been observed to occur together with twenty or thirty large earthquakes, and most important earthquakes are believed to originate in this way. Crustal blocks are raised, tilted, or displaced laterally by faulting, with corresponding effects on terrain.

The commoner consequences of earthquakes are related only indirectly to this primary geological, *tectonic,* process. When faulting breaks the rocks, waves of elastic compression or distortion spread out through the solid earth as waves spread over a pond, or as quivering spreads through jelly. These waves arriving at the surface of the earth shake it—violently near the source of a great earthquake, mildly at distant points. This shaking is responsible for most of the ordinary earthquake damage, and for nearly all minor earthquake phenomena.

With seismographs we can trace the wave disturbance far beyond the limits of destruction, and well beyond the limits of shaking felt by persons.

Sensitive instruments register major earthquakes at all distances, even near the antipodes of the heavily shaken area, thus demonstrating that such events disturb the whole earth.

SEISMOLOGY A DUAL SCIENCE

Seismology is a borderline field between geology and physics. It calls for sound physical thinking, as do all the geological sciences. Its data result from widely different techniques including especially those of field geology and (because of the seismograph) those of laboratory physics. This duality arises from the real division in nature between the visible earthquake phenomenon and the invisible waves of elastic disturbance. Few persons are well trained and practiced in both techniques; progress in seismology depends on cooperation between physicists and geologists.

THE GEOLOGIST AND SEISMOLOGY

Interpretation of seismograms depends partly on geological findings in the field. Where faulting or other geological processes occur, the geologist's knowledge is indispensable. His judgment is often called for to separate significant primary effects from such secondary occurrences as large landslides.

Observing and reporting earthquake effects in the field involve special problems, such as the behavior of objects and materials when violently shaken and the characteristics of wave motion in solid bodies. The competent geologist is no more deterred by these minor obstacles than by the special problems of volcanology, glaciology, or paleontology.

Because opportunity to investigate a strong earthquake is not common, most of the field work is done by persons without previous experience. Repetition of old and familiar errors, waste of limited time on unimportant or well-understood matters, overlooking of significant details, and incomplete reporting of unusual observations may result. Common errors are:

(1) Description of secondary effects, such as slides and fissures due to shaking, as if they were direct evidence of faulting.

(2) Overhasty identification of a conspicuous fault as the source of an earthquake, or of an erosional feature as an active fault.

(3) Failure to specify the direction of fault displacement (particularly of horizontal slip).

(4) Attribution of non-volcanic shocks to volcanic causes.

(5) Uncritical adoption of the observations and conclusions of untrained witnesses.

(6) Underestimation of the effect of unconsolidated ground increasing

the shaking, or of weak construction increasing its effects; this may lead to mismapping of intensities and mislocation of the source of the earthquake.

The geologist has a public responsibility in connection with earthquakes. He should be able properly to inform engineers, architects, property owners, and public officials without being too reassuring or needlessly alarming. He should form a clear idea of the long-term nature of earthquake risk, as well as its relation to the location of faults and the character of ground or foundation.

Because of the dispersion of seismological literature, geologists often overlook or ignore it. A recent paper on the geomorphology of a highly seismic region discusses rift valleys and faults but completely ignores well-described faulting on two historical occasions, omits study of earthquake locations made at seismological stations, and ends with an airy generality to the effect that the frequent earthquakes show that block movements are still going on. One objective of the present book is to make the results of seismology more accessible to the geologist and thus reduce the probability of such oversights.

RESULTS FROM THE SEISMOGRAPH

From the geologist's point of view, the most significant results of operating seismograph stations all over the world are:

(1) Location of all important earthquakes, in depth as well as in geographical position, even under the oceans or in remote parts of the continents.

(2) Determination of the structure of the earth, both of the upper crust and of the deep interior.

(3) Evidence as to the mechanical nature of earthquakes, including the details of the process of faulting deduced from the character of recorded elastic waves.

Fundamentally important, from the point of view of general physics, is the observation of elastic waves which have passed through the central part of the earth, where the pressure is of the order of millions of atmospheres. Since such pressures cannot be approached in the laboratory, this is valuable information about the properties of matter which partially justifies extrapolating ordinary physical principles to apply under those extreme conditions.

APPLICATIONS OF SEISMOLOGY

Prospecting by the seismic method, using explosives to generate small artificial earthquakes, is of great economic importance, particularly in the oil industry. Geologically valuable information is often obtained in this way.

The original purpose of the seismograph, the detailed recording of motion in a strong earthquake, is now carried on with special instruments of low magnification. Engineers and architects use this information in designing earthquake-resistant structures. One frequently employed type of experiment consists in applying motions, representative of those recorded in actual earthquakes, to models representative of buildings and other engineering structures, actual or proposed.

Continuous recording of earthquakes leads to compiling statistics valuable to insurance men and others interested in long-term risk. To be useful, such statistics must discriminate critically between small and large shocks.

Prediction of earthquakes in any precise sense is not now possible. Any hope of such prediction looks toward a rather distant future. Cranks and amateurs frequently claim to predict earthquakes. They deceive themselves, and to some extent the public, partly because it is not generally known how frequent earthquakes are. If small shocks are counted, 100,000 a year is a conservative estimate.

GEOPHYSICS

Geophysics is the application of general physical principles to the earth. Logically this would include all the geological sciences. Some of the recognized branches of geophysics, with their subject matter, are:

(1) Seismology: earthquakes and related phenomena
(2) Volcanology: volcanoes, hot springs, etc.
(3) Hydrology: ground and surface water
(4) Oceanography: the seas
(5) Meteorology: the atmosphere
(6) Geodesy: the size and form of the earth
(7) Terrestrial magnetism: the earth's magnetic field
(8) Tectonophysics: a newly named branch which deals with the physics of geologically significant processes in the earth

The study of the force of gravity is so closely connected with the problems of geodesy that it usually is referred to that branch. Atmospheric electricity, logically a part of meteorology, has long been associated with the study of terrestrial magnetism. The physics of the upper atmosphere, which includes the ionosphere or Heaviside layer, has expanded so much lately that when its enthusiasts write or speak of "geophysics" they mean only this one field. There has been a similar narrow use of "geophysics" to mean prospecting for oil and minerals by geophysical methods; other than the seismic method, these include measurements of gravity, the magnetic field, and electric conductivity, as well as chemical and radiological techniques—in fact, almost every procedure which might imaginably have bearing on the finding of oil has been used.

The study of the internal constitution of the earth is less a branch of geophysics than a research program, using data of many kinds. This work has a fundamental bearing on geology, since it profoundly affects theories about the origin and history of our planet. Many of the important data for this purpose are taken from seismology, but determinations of heat flow to the surface of the earth, measurements of gravity and terrestrial magnetism, and astronomical observations are all involved.

Many students in geology now wish to continue into geophysics, pure or applied; often they find their lack of mathematical preparation a serious obstacle. Some graduate students are appalled and a little offended at being confronted with differential equations, never having attended a formal course in that subject. Yet such a course is not an absolute necessity; the basic requirements are elementary algebra, trigonometry, and differential calculus. Many students do not completely grasp algebra and trigonometry during their secondary-school years, and attain only a hazy understanding of calculus.

One root of this difficulty is that many geological departments still rate field geological experience, and even paleontology, far above basic physics and mathematics. This extreme point of view is out of date; it results in drawing into geology students whose preparation or proficiency in mathematics is deficient. References below to papers by Hubbert, by Schriever, and by others, are given to illustrate the need for sounder mathematical physics in geology proper, as well as in geophysics.

General References and Reading

THE FOLLOWING books and papers are recommended for study; they or their equivalents should be available in any seismological library. Most of them are general works of reference; some are important original contributions; and a few are elementary and popularized treatments which may serve to introduce the subject. Special references follow each chapter; at this stage note particularly those for Chapter 25.

Geological classics

Lyell, C., *Principles of Geology.* (The 1st edition, 1830, is of interest chiefly as a historical monument. The material of greatest seismological importance was inserted in later editions; a good reference is the 12th edition—2 vols., 1875.)

Suess, E., *Das Antlitz der Erde,* Vols. 1–4; 1st ed. of Vol. 1, Prague, 1885; Vol. 4, 1903. (This great work has had an enormous influence on geophysics and seismology.)

———, *La Face de la terre*, Paris, Vols. 1–4, 1897–1913. (This edition, prepared and annotated under the direction of E. de Margerie, is far more than a mere translation; some students prefer it to the original.)

———, *The Face of the Earth*, Oxford University Press, Vols. 1–4, 1904–1909; Vol. 5 (index and maps), 1924.

General geophysics, and internal constitution of the earth (usually including seismology)

Gutenberg, B., ed., *Handbuch der Geophysik*, Borntraeger, Berlin, Vols. 1–4, 1929–1936. (Editing and publication of the remaining volumes was disorganized under the Nazi regime.) Vol. 1, *Die Erde als Planet*. Vol. 2, *Aufbau der Erde*. (Note especially Gutenberg, "Der physikalische Aufbau der Erde," pp. 450–564, and Born, A., "Der geologische Aufbau der Erde," pp. 565–867.) Vol. 3, *Veränderungen der Erdkruste*. Vol. 4, *Erdbeben*. (Very inclusive treatment of seismology.)

Angenheister, G., ed., *Wien-Harms Handbuch der Experimentalphysik*, Akademische Verlagsgesellschaft, Leipzig, Vol. 25, Part 1, "Geophysik 1," 1928 (concerned with the atmosphere and terrestrial magnetism); Part 2, "Geophysik 2, Physik des festen Erdkörpers und des Meeres," 1931 (contains some seismology).

Handbuch der Physik, Springer, Berlin, Vol. 47, *Geophysik* 1, 1956. (About half the contents is seismological.)

Gutenberg, B., "Geophysics as a science," *Geophysics*, vol. 2 (1937), pp. 185–187. (A brief summary and classification.)

Jeffreys, H., *The Earth*, Cambridge University Press, 3rd ed., 1952. (A research monograph, not a handbook. Often mathematically difficult, even for the advanced student. Treats most of the fundamental problems of seismology.)

Kuiper, G. P., ed., *The Earth as a Planet*, Chicago University Press, 1954.

"The planet Earth," *Scientific American*, vol. 193, No. 3 (Sept. 1955), pp. 1–211. (Good popular articles. Includes Bullen, K. E., "The interior of the earth," pp. 56–61.)

Gutenberg, B., ed., *Physics of the Earth*, Vol. VII, *Internal Constitution of the Earth*, McGraw-Hill, New York, 1939. 2nd ed., rev., Dover Publications, New York, 1951. (About half is seismological. Some chapters in the second edition were brought up to date, others almost not at all.)

Coulomb, J., *La Constitution physique de la terre*, Albin Michel, Paris, 1952.

Bullen, K. E., "Some trends in modern seismology," *Science Prog.*, vol. 43, No. 170 (April 1955), pp. 211–227. (Seismology with reference to the earth's interior.)

Gutenberg, B., "Neue Ergebnisse über den Aufbau der Erde," *Geol. Rundschau*, vol. 45 (1956), pp. 342–353.

Poldervaart, A., ed., "Crust of the Earth (A Symposium)," *Geol. Soc. Amer., Spec. Paper* No. 62 (1955). (Some important seismological data in Part I, "Nature of the Earth's Crust.")