# 1 Seismology, the science of earthquakes

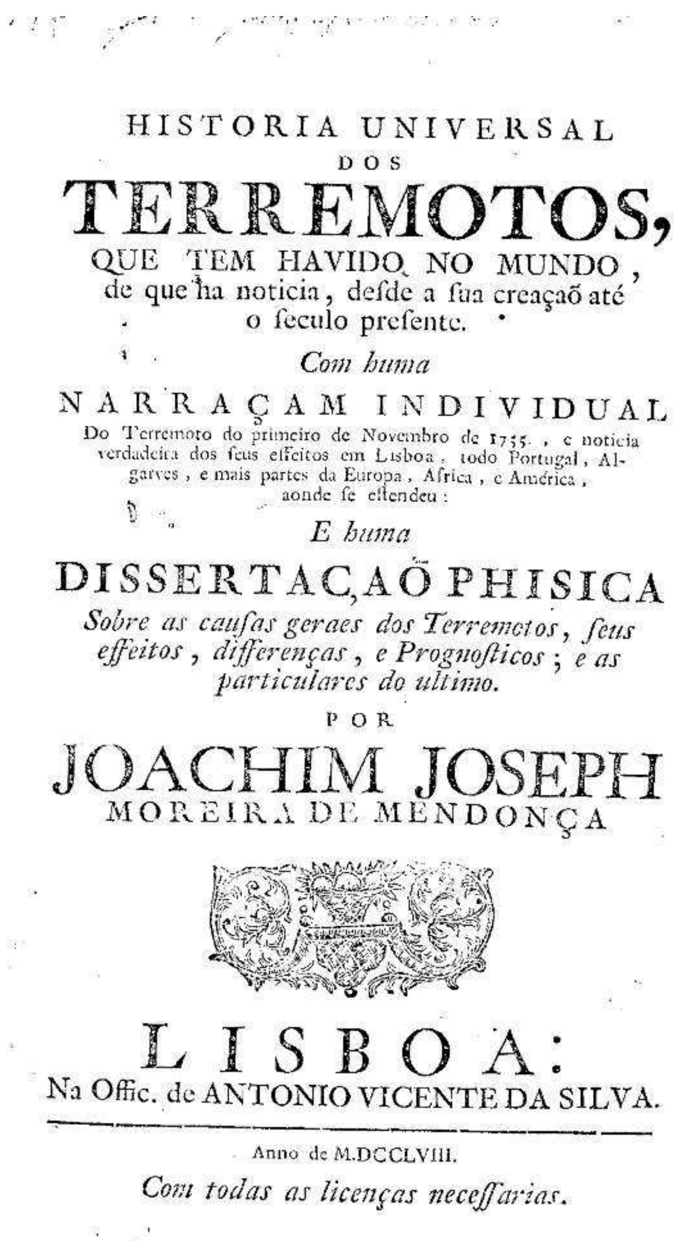
The term *seismology* is derived from two Greek words, *seismos*, shaking, and *logos*, science or treatise. Earthquakes were called *seismos gês* in Greek, literally, shaking of the Earth; the Latin term is *terrae motus*, and from the equivalents of these two terms come the words used in most occidental languages. Seismology means, then, the science of the shaking of the Earth or the *science of earthquakes*. The term seismology and similar ones in other occidental languages (séismologie, sismología, Seismologie, etc.) began to be used at around the middle of the nineteenth century. In this chapter we present a very short overview of the history of seismology (brief information about pertinent historical developments can also be found in each chapter), a discussion of seismology considered as a multidisciplinary science, its theoretical and observational aspects, international cooperation, and a summary of books, journals, and websites.

## 1.1 The historical development

In antiquity, the first rational explanations of earthquakes, beyond mythical stories, are from Greek natural philosophers beginning with Thales of Miletos in the sixth century BC. Aristotle (in the fourth century BC) discussed the nature and origin of earthquakes in the second book of his treatise on meteors (*Meteorologica*). The term meteors was used by the ancient Greeks for a variety of phenomena believed to take place somewhere above the Earth's surface and below the orbit of the Moon, such as rain, wind, thunder, lightning, comets, but also earthquakes and volcanic eruptions inside the Earth. The term meteorology derives from this word, but in modern use it refers only to atmospheric phenomena. Aristotle, following other Greek authors, such as Anaxagoras, Empedocles, and Democritus, proposed that the cause of earthquakes consists in the shaking of the Earth due to underground dry heated vapors or winds trapped in its interior and trying to leave toward the exterior. This explanation was part of his general theory for all meteors caused by various types of exhalations of gas or vapor (*anathymiaseis)* that extend from inside the Earth to the Lunar orbit. This theory was spread more widely by the encyclopedic Roman authors Lucius Anneus Seneca and Gaius Plinius (Pliny the Elder). It was commented upon by medieval philosophers such as Albert the Great and Thomas of Aquinus, and, with small changes, was accepted in the West until the seventeenth century. For example, in 1678 Athanasius Kircher, a Jesuit professor at the Roman College, in his book *Mundus Subterraneus*, related earthquakes and volcanoes to a system of fire conduits (*pyrophylacia*) and another of air (*aerophylacia*) inside the Earth. With the birth of modern science in the seventeenth and eighteenth centuries, Martin Lister and Nicolas Lemery proposed that earthquakes are caused by explosions of flammable material concentrated in some interior regions. This explanation was accepted and propagated by Isaac Newton and Georges-Louis Buffon.

The great Lisbon earthquake of 1 November 1755, which caused widespread destruction in that city and produced a large tsunami, may be considered the starting point of modern seismology. In 1758, Joachim Moreira de Mendonça published *Historia Universal dos Terremotos*, a study on the causes of earthquakes with one of the first global catalogs (Fig. 1.1). In 1760, John Michell was one of the first to relate the shaking due to earthquakes to the propagation of elastic waves inside the Earth. This idea was further developed by, among others, Thomas Young, Robert Mallet, and John Milne. Descriptions of damage due to earthquakes and the compilation of lists of their occurrence can be traced back to very early dates. Sometimes these lists include other natural disasters such as floods, famines, and plagues. The first catalogs of earthquakes published in Europe were at the end of the seventeenth century, by Marcello Bonito and Joannes Zahn (Chapters 2 and 16).

Robert Mallet was aware of starting a new science when in 1848 he wrote: “The present paper constitutes, so far as I am aware, the first attempt to bring the phenomenon of the earthquake within the range of exact science, by reducing to system the enormous mass of disconnected and often discordant and ill observed facts which the multiplied narratives of earthquakes present, and educing from these, by appeal to the established laws of the higher mechanics, a theory of earthquake motion” (Mallet 1848). His study of the Naples earthquake of 1857 constitutes one of the first basic works of modern seismology (Mallet, 1862). Mallet developed the theory of the seismic focus from which elastic waves are propagated in all directions and connected the occurrence of earthquakes with changes in the Earth’s crust that are often attended by dislocations and fractures, abandoning the explosive theory. Geologists such as Charles Lyell and Eduard Suess had related earthquakes to volcanic and tectonic motions, and, at the beginning of the twentieth century, Ferdinand Montessus de Ballore and August Sieberg assigned the cause of earthquakes to orogenic processes and contributed to many aspects of observational seismology (Chapter 16 and 17). Two fundamental steps in the process of quantification and formalization of seismology are the development of seismic instrumentation to record the ground motion produced by earthquakes, opening the possibility of having quantified observations and application of the principles of the theory of continuous mechanics. Thus, seismology ceased to be a purely naturalist science. The first instruments used to observe the shaking of the ground were based on oscillations of a pendulum and started to be used in around 1830. By the end of the century, the first seismographic continuous recordings had been produced. In 1889, Ernst von Rebeur Paschwitz recorded, in Potsdam, an earthquake that took place in Tokyo; this was the first seismogram recorded at a large distance. Among the first names related to the development of seismologic instrumentation are those of John Milne and Fusakishi Omori, with the inclined pendulum, Emil Wiechert with the inverted pendulum, Boris B. Galitzin with the electromagnetic seismograph, and Hugo Benioff with variable magnetic reluctance (Chapter 3). Towards the end of the nineteenth century and beginning of the twentieth, Wiechert, Karl Zöppritz, and Richard D. Oldham, among others, published the first studies of the



HISTORIA UNIVERSAL
DOS
TERREMOTOS,
QUE TEM HAVIDO NO MUNDO,
de que ha noticia, desde a sua creaçaõ até
o seculo presente.
*Com huma*
NARRAÇAM INDIVIDUAL
Do Terremoto do primeiro de Novembro de 1755. , e noticia verdadeira dos seus effeitos em Lisboa, todo Portugal, Algarves, e mais partes da Europa, Africa, e América, aonde se estendeu:
*E huma*
DISSERTAÇAÕ PHISICA
*Sobre as causas geraes dos Terremotos, seus effeitos, differenças, e Prognosticos; e as particulares do ultimo.*
POR
JOACHIM JOSEPH
MOREIRA DE MENDONÇA
LISBOA:
Na Offic. de ANTONIO VICENTE DA SILVA.
Anno de M.DCCLVIII.
*Com todas as licenças necessarias.*

Fig. 1.1 Title page of Joachim Moreira de Mendonça (1758) *Historia Universal dos Terremotos*, written after the 1755 Lisbon earthquake (New York Public Library).

propagation of seismic waves, based on early work on the theory of elasticity (Chapter 4). The first models of the interior of the Earth based on seismologic observations were proposed between 1900 and 1940 by, among others, Oldham, Beno Gutenberg, Harold Jeffreys, Keith E. Bullen, and James B. Macelwane (Chapter 9).

Since 1945, seismology has experienced a very rapid development. Details of this development and names associated with it can be found in the introductions to each chapter and elsewhere in this book. In this rapid evolution, two important subjects are the propagation of elastic waves in the Earth and the mechanism of the generation of earthquakes. Both include theoretical and observational aspects. Observations of seismic waves have improved and multiplied with the development of seismologic instrumentation, from early mechanical seismographs with analog recording, to the present systems with a broadband response, electronic amplification, and digital recording (Chapter 3). In the study of the propagation of seismic waves, the Earth is approximated by models that have progressed from the early very simple models of homogeneous elastic media or media divided into layers to those with three-dimensional heterogeneity, including anelasticity and anisotropy (Chapters 4 to 15). Models of the source of earthquakes have developed from simple models of point foci to those including the complex process of fracture and friction of crustal material along faults (Chapters 16 to 20). These developments have contributed to an increase in knowledge about the complex processes that cause earthquakes and the properties and composition of the materials of the Earth's interior. Other aspects of seismology concern the occurrence of earthquakes in time and space (seismicity), its relation to tectonic processes (seismotectonics), the evaluation of seismic hazard and risk, and the problem of earthquake prediction and earthquake early-warning systems. These aspects of seismology have also significantly expanded in the latest years (Chapter 21).

## 1.2 Seismology, a multidisciplinary science

Recent trends in seismology tend to overemphasize those aspects related to the generation and propagation of seismic waves. With this emphasis, Keiti Aki and Paul G. Richards (1980) define seismology as a science based on data called seismograms, which are the records of mechanical vibrations. Thorne Lay and Terry C. Wallace (1995), following this point of view, define seismology as the study of the generation, propagation, and recording of elastic waves in the Earth (and other celestial bodies), and of the sources that produce them, and conclude that recordings of ground motion as a function of time, or seismograms, provide the basic data for seismologists. A similar approach is followed by Seth Stein and Michael Wysession (2003). However, Cinna Lomnitz (1994) considers this approach to be rather narrow, because seismograms provide us with much less information about earthquakes than is needed. Moreover, this definition downplays many other aspects present in the complex phenomena of earthquakes.

In a more traditional approach, seismology is defined in a broader sense as the science of the study of earthquakes. The analysis of seismic waves forms a very important part of seismology, but not its totality. Bruce A. Bolt (1978) considers the task of seismologists to be the study of all aspects of earthquakes, including their causes, occurrence, and properties. For Bullen (1947), it is evident that the study of earthquakes belongs to many fields of knowledge, such as physics, chemistry, geology, engineering, and even philosophy. For this reason many authors consider seismology as a multidisciplinary science (Macelwane and Sohon, 1936; Madariaga and Perrier, 1991).

There is no doubt that the study of seismic waves recorded by seismographs and their physico-mathematical formulation is fundamental to seismology, for example, to the study of the mechanism causing earthquakes and the constitution of the Earth's interior. However, this does not imply that wave analysis is the only source of information about earthquakes. The seismicity of a region, for example, cannot be understood correctly if solely instrumentally recorded earthquakes are considered. Owing to the long return periods for large earthquakes, the study of historical earthquakes is essential. The need to go even farther back into the past has promoted the study of other types of information from archeoseismicity and paleoseismicity. The characteristics of large earthquakes cannot be fully understood without geologic field observations after their occurrence. Comparison of geodesic measurements before and after earthquakes is another important source of knowledge. Modern satellite observations such as from global positioning system (GPS) and interferometric synthetic aperture radar (INSAR) provide very useful seismological information. All these types of data are important in helping one to interpret the nature of earthquakes and their consequences, and must be integrated with information obtained from the analysis of seismic waves.

Two parts of seismology with a marked multidisciplinary character are the evaluation of seismic risk and work toward the prevention and the prediction of earthquakes. In the first case, the interaction of seismologists with geologists and engineers is necessary in order to correctly assess earthquake hazards, expected ground motion, soil conditions, seismic zonation, and the responses of structures and buildings. In the second, many of the suggested precursory phenomena (for example, electromagnetic signals, changes in resistivity, emissions of radon gas, and changes in geodesic measurements) are not directly related to seismic waves. Progress in the difficult problem of earthquake prediction cannot be achieved without a great multidisciplinary effort involving scientists working in many fields, such as seismologists, engineers, geologists, and physicists. In recent years emphasis has been placed on earthquake prevention with the development of detailed seismic risk analyses, robust seismic building codes, and earthquake early warning systems. Depending on correct assessment of the seismic risk and the adequacy of the design and construction of buildings, the damage from earthquakes, especially loss of human lives, may vary greatly. Finally, we must not forget that earthquakes are natural disasters that affect human lives (Zeilinga de Boer and Sanders, 2005; Coen, 2013). The response of the population to the occurrence of an earthquake must also be taken into account, with all its serious psychological, social, and economic consequences. Seismologists cannot be indifferent to all these problems.

## 1.3 Divisions of seismology

Seismology can be divided into three disciplines: seismology in the strict sense, seismic engineering, and seismic exploration. Seismology treats the occurrence of earthquakes and their related phenomena and is primarily based on application of the principles of the mechanics of a continuous medium, and in particular of the theory of elasticity to them.

As has already been mentioned, its two main subjects are the generation of earthquakes and the vibrations and propagation of seismic waves inside the Earth. From observations of these vibrations, together with other types of data, we derive our knowledge about the nature of earthquakes, the structure of the Earth's interior, and its dynamic characteristics. The part of seismology that deals with seismologic instrumentation, called seismometry, studies the physical theory of the various types of instruments used to measure seismic motion.

Seismic or earthquake engineering is an applied science that deals with how the motion produced by earthquakes affects buildings and other man-made structures. Starting from the characterization of ground displacement, velocity, and acceleration, seismic engineering proceeds to consider their effects on structures and seeks to design them to resist such motions. If earthquake-resistant structures are not to be unnecessarily expensive, a reliable evaluation of the expected ground motion at a particular site is necessary. For this task, an assessment of the seismic risk for a particular zone is needed. This assessment includes consideration of many factors, such as the occurrence of earthquakes near a site, their source mechanism, seismic wave attenuation and soil conditions, and the vulnerability of structures. The complete evaluation of seismic risk implies the statistical analysis of all these factors and requires the collaboration of seismologists, engineers, and geologists.

In seismic exploration, seismological methods are applied to the search for mineral resources, especially oil deposits. These methods are based on the reflection and refraction of artificially generated seismic waves in geologic structures associated with the presence of such deposits. The methods that have proved to be most effective are those based on vertical reflection of waves. Closely spaced distributions of wave generators and detectors together with complex processing of the digital data allow one to obtain detailed images of the upper part of the Earth's crust. The increasing demand for energy resources makes this work more and more important.

## 1.4 Theory and observations

Just as in all experimental sciences, theoretical and observational aspects of seismology must be considered. The first are based on the principles of the mechanics of continuous media, with the assumption that the Earth is an imperfectly elastic body in which vibrations are produced by earthquakes. The study of the generation of these vibrations constitutes the theory of the source mechanism. In this theory, different models of the processes occurring at the foci of earthquakes are proposed. They range from the more simple instantaneous point sources to the more complex fracture processes. The aim is to approximate the process of fracture and slip that takes place along geologic faults.

Vibrations in the Earth can be treated using two approaches: wave propagation and normal modes theory. The first approach considers waves propagating inside the Earth or on its surface. The second considers the eigenvibrations or oscillations of the Earth as a whole. This second approach is necessary when wave lengths are near the dimensions of the Earth. In the simplest models, the Earth behaves like a homogeneous isotropic perfectly elastic medium. For some problems the flat-Earth approximation may be sufficient, whereas others require treatment of its sphericity. Heterogeneity in the Earth can be treated using layered models with different elastic properties for each layer, or models in which these properties vary with the spatial coordinates. The assumption of a spherical radially heterogeneous medium is useful in providing a close approximation to the real Earth. Ray theory is employed as a useful high-frequency approximation to wave propagation in heterogeneous media. Surface waves in layered media describe wave dispersion with the separation of phase and group velocities. The lack of perfect elasticity is accounted for by introducing the attenuation of vibrations and waves and by considering viscoelastic models. Isotropic models are adopted as a first approximation but further analysis needs to consider anisotropic conditions. By proceeding through these successive modifications in models of the Earth, its imperfect elasticity, heterogeneity, and anisotropy can be adequately considered.

An important part of seismologic observations consists in the recording of the ground's motion by instruments installed on its surface. Nowadays, classical analog seismograms on photographic paper have largely been replaced by digital data kept on magnetic tapes or compact disks, which can be obtained directly from world data banks through the Internet practically in real time. Previously to their interpretation through the use of digital computers, seismologic observations usually needed careful complex numerical processing. As has already been mentioned, important seismologic data are also provided by other sources, for example, historical records of damage from pre-instrumental earthquakes, field observations of structural damage and ground deformation after earthquakes, geodesic measurements related to the occurrence of earthquakes, *in situ* stress measurements, and geologic and tectonic implications. A modern source of seismological observations is provided by continuous high-rate GPS data of coseismic displacements. GPS records function like a new type of seismogram. Crustal deformations produced by large earthquakes can be obtained by modern INSAR observations. Observations of field geology and damage to structures after earthquakes also provide an important source of information. Progress in methods of observation of all kinds of seismologic data has allowed one to apply models of increasing complexity to the problems of the generation of earthquakes and determination of the structure of the Earth's interior.

The relation between observations and theories or models can be approached through direct and inverse problems. The direct problem refers to the determination of ground displacements from theoretical models of the generation and propagation of seismic waves. In the direct problem, theoretical models are assumed *a priori* and from them synthetic displacements are determined, which are then compared with observations. If they agree, we consider the model well suited to observations. However, in many instances, there is no assurance of its uniqueness and many other models may equally well satisfy the same observations. The inverse problem consists in estimation of the parameters of a theoretical model from observations. This is often a more complicated problem than the direct one. Observations are always incomplete and contain errors, so that a solution of the inverse problem may only exist in a probabilistic sense. In general, inverse problems become more intractable as the number of parameters of the model increases. The mathematics of inverse problems requires, generally, the solution of non-linear integral equations. Linearization of the problem is a standard procedure that leads, very often, to large unstable systems of equations. Difficulties in the solution of inverse problems lead to their substitution by repeated solutions of direct problems until sufficient agreement between observations and synthetic data predicted by the assumed models is reached.

## 1.5 International cooperation

The main objectives of seismology require the cooperation of, and exchange of observations among, scientists from different parts of the world. This collaboration was accomplished from early times through private initiatives. The global character of large earthquakes soon required the establishment of institutional cooperation at national and international levels. The first organizations were national ones such as the Seismological Society of Japan, created after the earthquake of 1880 with Milne as first secretary. In 1890, the Committee for the Investigation of Earthquakes was founded, also in Japan, of which Omori was president from 1897 to 1923. In Italy, the Italian Seismological Society (*Società Sismologica Italiana*) was created in 1895; Luigi Palmieri, Timoteo Bertelli, and Giuseppe Mercalli were among its first members. Another national society with great influence in the history of seismology is the Seismological Society of America, which was founded in 1906 as a response to the great San Francisco earthquake, with Charles Davidson as its first president. The idea of an international association of seismology was first proposed by Georg Gerland, during the Sixth International Congress of Geography that was held in London in 1895. In 1904, the International Association of Seismology was finally created, but it was suppressed in 1916. Since 1922, seismology has formed a section of the International Union of Geodesy and Geophysics (IUGG), created in 1919. In 1930, the IUGG was reorganized and included as one of its associations the International Association of Seismology, which finally, in 1951, received its present name of the International Association of Seismology and Physics of the Earth's Interior (IASPEI). One of its commissions is the European Seismological Commission (ESC), which was founded in 1951. There are also active seismology sections of geophysical scientific societies such as the American Geophysical Union (AGU) and European Geosciences Union (EGU).

Exchange of seismologic data between observatories was carried out in the past through the publication of seismologic bulletins. These bulletins preserve a great wealth of information about earthquakes of the early instrumental period. One of the first publications of epicenter determinations was The Reports of the Seismological Committee of the British Association for the Advancement of Science, which started in 1911 with the determinations for the period 1899–1903. In 1922, this publication became the International Seismological Summary (ISS), its first volume being dedicated to the earthquakes of 1918. Later, in 1963, the publication was continued by the International Seismological Centre (ISC), Newbury, UK. The Bureau Central International de Séismologie (BCIS) was created in Strasbourg in 1906 and published a bulletin with epicenter determinations from 1904 until 1975. In 1976, the Centre Séismologique Européen Méditerranéen (CSEM) was created by the ESC with the task of determining hypocenters of earthquakes of the Mediterranean region. Other agencies also started to publish epicenter determinations, such as, in North America, the

Jesuit Seismological Association that was active between 1925 and 1960 and the United States Coast and Geodetic Survey (USCGS), which was later transferred to the National Earthquake Information Center (NEIC), which is dependent on the United States Geological Survey (USGS). Since 1968, its monthly publication Preliminary Determination of Epicenters has included also information on determinations of focal mechanisms for sufficiently large earthquakes. Similar information has also been published since 1977 by Harvard University and was continued from 2006 onwards by the Global Centroid Moment Tensor Project. At present there are several world centers of seismologic data, including digital seismograms from broad-band stations, such as IRIS (USA), GEOFON (Germany), and ORFEUS (Holland).

## 1.6 Books, journals, and websites

A list of books which cover the different topics relevant in seismology is given in the Bibliography. It is divided into three sections: general seismology, special topics in seismology, and elasticity and wave mechanics. Some of these books are mentioned in the following paragraphs.

Among the early treatises on seismology are those of:

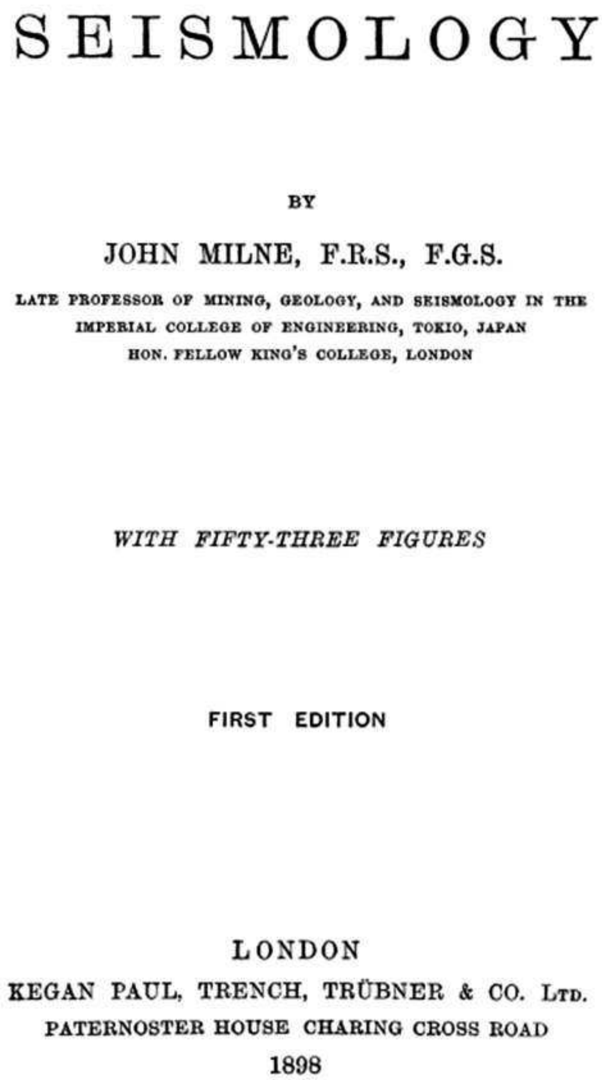
Mallet (1862), *Great Neapolitan Earthquake of 1857: The First Principles of Observational Seismology*.
Rudolf Hoernes (1893), *Erdbebenkunde*.
Milne (1898), *Seismology* (Fig. 1.2).

At the beginning of the last century, several books on seismology were published, among them were those by:

Sieberg (1904), *Handbuch der Erdbebenkunde*.
Hobbs (1907), *Earthquakes. An Introduction to Seismic Geology*.
Montessus de Ballore (1911), *La sismologie moderne*.
Galitzin (1914), *Vorlesungen der Seismometrie*.

From 1930, textbooks about seismology that may be considered modern started to be published. Only those of a general character will be mentioned (full references are given in the Bibliography):

Macelwane and Sohon (1936), *Introduction to Theoretical Seismology*. Part I, Geodynamics and Part II, Seismometry.
Byerly (1942), *Seismology*.
Bullen (1947), *An Introduction to the Theory of Seismology*.
Richter (1958), *Elementary Seismology*.
Sawarensky and Kirnos (1960), *Elemente der Seismologie und Seismometrie*.
Bath (1973), *Introduction to Seismology*.



SEISMOLOGY

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*WITH FIFTY-THREE FIGURES*

FIRST EDITION

LONDON
KEGAN PAUL, TRENCH, TRÜBNER & CO. LTD.
PATERNOSTER HOUSE CHARING CROSS ROAD
1898

Fig. 1.2 The title page of Milne's book on seismology (1898) (Cambridge University Press).

More recently, since 1979, several textbooks on general seismology at various levels have been published. Four excellent advanced books are:

Pilant (1979), *Elastic Waves in the Earth*.
Aki and Richards (1980), *Quantitative Seismology. Theory and Methods*.