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The scope of seismology

1.1 Early history

The observations of geologists make it probable that the Earth has suffered earthquakes for at least some hundreds of millions of years.

Early historical records in China contain references to earthquakes as far back as 1800 BC. The ancients attributed earthquakes to super-natural causes; indeed, a writer in the *Philosophic Transactions of the Royal Society of London* as late as AD 1750 apologised to 'those who are apt to be offended at any attempts to give a natural account of earthquakes'.

In Greek science, however, natural causes, such as underground explosions, were considered and Aristotle gave a classification of earthquakes into six types, according to the nature of the earth movement observed; for example, those which caused an upward earth movement, those which shook the ground from side to side, etc. Also, in the year AD 132, the Chinese philosopher Chang Heng devised an artistic earthquake weathercock for indicating the direction of the main impulse due to an earthquake; this instrument is reputed to have detected earthquakes not felt locally, but the internal mechanisms of the device are unknown.

About the middle of the eighteenth century AD, useful observations of earthquake effects began to accumulate. In 1760, John Michell in England published a notable memoir on earthquakes, in which he associated earthquakes with wave motion in the Earth. Most work on earthquakes during the late eighteenth and the early nineteenth century was concerned with geological effects of earthquakes, and with effects on buildings. It was noted, for instance, that, in the main, buildings on soft ground were more damaged by earthquakes than those on hard rock. Early in the nineteenth century, earthquake lists were being regularly published, and in 1840 von Hoff published an earthquake catalogue for the whole world.

About the middle of the nineteenth century, the foundations of instrumental seismology were laid when Robert Mallet suggested the

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setting up of a chain of observatories over the Earth's surface, and Palmieri in Italy devised a 'sismografo elettro-magnetico' capable of detecting earthquakes and of recording some features of the consequent local earth movements such as duration and direction. The history of seismology of this period includes the names of Nöggerath and Schmidt (Germany), who introduced the use of isoseismal lines to estimate the epicentre of an earthquake and the apparent speed of travel of the ensuing disturbance; of Perrey and Montessus de Ballore (France), who compiled notable earthquake records; and of de Rossi (Italy) and Forel (Switzerland), who together produced the Rossi–Forel intensity scale, the first well-known scale for estimating surface effects of earthquakes and determining isoseismal lines.

In 1892, a major step forward was taken in Japan when John Milne (aided by his association with James Ewing and Thomas Gray and later F. Omori) developed seismographs which were sufficiently compact and simple in operation to enable them to be installed and used in many parts of the world. The first identified recording of a distant earthquake was made in 1889 at Potsdam with horizontal pendulums designed by E. von Rebeur Paschwitz, based on earlier work by James Ewing. A large earthquake on 17 April 1889, had been felt in Japan before it was recorded at Potsdam (Fig. 1.1). From this time onwards, instrumental data on earthquakes began to accumulate and seismology developed from a qualitative to a quantitative science. A detailed history of seismometry to 1900 is given by J. Dewey and P. Byerly (1969).

Meanwhile, progress had been taking place on the mathematical 'front'. Studies of wave motion were fashionable among applied mathematicians throughout the nineteenth century, and mathematical theory relevant to seismology was produced. As early as 1828, Cauchy and Poisson determined the equations of motion of a disturbance in a perfectly elastic material, and Poisson showed that there could be two distinct types of waves (the seismological P and S waves) transmitted with different speeds through the interior of such a material. Stokes showed that the P and S waves were of dilatational and rotational types, respectively, and Green studied the reflection and refraction of elastic waves. Later came the work of Kirchhoff, Kelvin and Rayleigh, including Rayleigh's theory of waves on the boundary of a homogeneous elastic substance.

The close of the nineteenth century saw the identification (1900) by R.D. Oldham of the three main types of seismic waves – P, S and surface – on actual records from mechanical seismographs – nearly 70 years after the mathematical theory of P and S waves had been formulated.

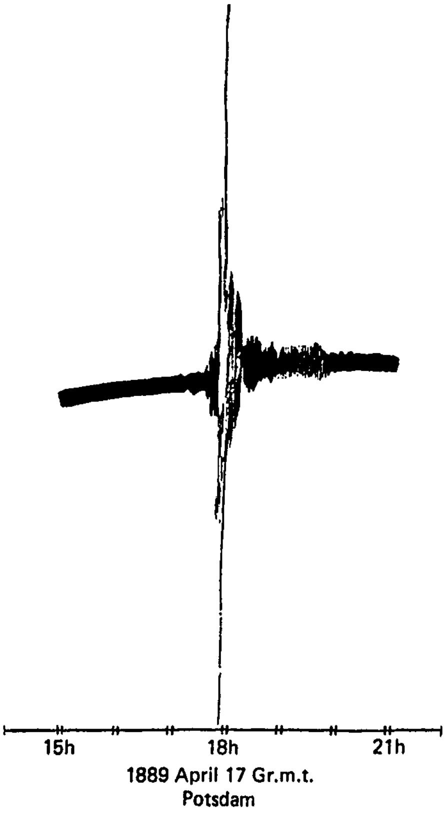

Fig. 1.1. Seismogram made by a horizontal pendulum in Potsdam, Germany of a Japanese earthquake, 17 April, 1889.

In the first decade of this century, effective seismographs capable of recording three components of short- and long-period waves were constructed by E. Wiechert and B.B. Galitzin. Seismic waves recorded by these instruments immediately aroused the curiosity of mathematicians and geophysicists. In 1904, Lamb attacked the problem of the generation of surface seismic waves. In his Adams Prize Essay of 1911, Love explained the occurrence of a type of surface wave not included in the theory of Rayleigh and made a comprehensive study of vibrations of a compressible gravitating planet.

In 1906, Oldham used recorded seismic waves to show that the Earth has an extensive central core. In the same year, the great San Francisco earthquake occurred, leading to modern ideas about the source of earthquake waves. An International Association of Seismology was founded in 1905 which became, in 1951, the International Association of Seismology and Physics of the Earth's Interior (IASPEI).

1.2 Developments from 1915 to 1960

In this period, seismological data were used to resolve the Earth's internal structure to a remarkable degree. The period started with vague notions about a molten central core and finished with well-determined values of the density, pressure, compressibility, rigidity and gravity throughout practically the whole Earth.

On the instrumental side, there was a notable expansion of a world-wide system of earthquake observatories. By 1920, about 80 stations operated Wiechert type instruments, about 45 had Milne or Milne–Shaw seismographs, and a number had the electromagnetic Galitzin or Galitzin–Wilip instruments which used photographic recording. In the 1930s, H. Benioff designed an extremely successful vertical component seismograph. This short-period instrument provided much higher amplifications of the ground motion than were previously available and made a key contribution to increased detection and measurement precision of seismic waves.

The period saw the rise of the *International Seismological Summary* and the development of an international co-operation that has not been excelled in any other branch of study.

Travel-time tables evolved from crudest beginnings, through the Zöppritz–Turner tables, to the 1940 Jeffreys–Bullen and Gutenberg–Richter tables, in which errors of the order of minutes had been reduced to errors of the order of seconds.

The work of Herglotz and others enabled P and S velocities to be deduced from the travel-time data. These in turn furnished information on compressibility–density and rigidity–density ratios throughout much of the Earth.

In 1914, Gutenberg published his accurate determination of the depth of the boundary of the central core, one of the early results of a long and distinguished career.

Jeffreys became interested in seismology around this time and brought to bear elegant mathematical and statistical methods and a great knowledge of wider geodynamical problems. His attention to scientific method and statistical detail has been one of the main forces through which seismology has attained its present level of precision, and the sample of his

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results quoted in this book gives some indication of the extent of his contributions (still continuing in 1984).

In 1936, Inge Lehmann produced the first evidence from seismograms of the existence of the Earth's inner core. By 1940, Bullen was able to classify the Earth's interior broadly into a number of shells or regions occupying ranges of depth from the surface to the centre (see § 13.1.5). His construction of Earth Model A was completed around this time, giving close estimates of the interior density and elastic parameters.

Further resolution was made of the Earth's outer layers by near-earthquake studies, by surface-wave studies and, later, by explosion seismology. Starting from the work of A. Mohorovičić in 1909, investigators determined the overall thickness of layers down to the discontinuity that bears his name and, as well, determined the P and S velocities inside the layers. It was also established that crustal thickness is much less under oceans than under continents.

Another important development was the experimental and theoretical investigation, especially by Bridgman, Adams, Williamson and Birch, of the behaviour of matter at pressures and temperatures prevailing in the outer mantle of the Earth.

Following the dislocations of World War II, there was a growth of seismological studies and the total output of results on Earth structure jumped sharply. The stimulus of the International Geophysical Year of 1957–58 led to an increase in the number of first-class seismological observatories, but the mix of seismograph types made comparison of waves between different stations relatively imprecise and non-productive.

Most notable among the achievements at the end of the fifties was a great extension in the spectrum of recorded seismic waves. At one extreme, the instrumentation of seismic prospecting enabled frequencies of order 100 Hz to be measured in ground movements. At the other, new seismographs enabled measurements to be made of surface waves with periods extending up to 10 min and of free oscillations of the whole Earth with periods of about an hour. The spectral gaps between seismic wave vibrations of the order of seconds and daily tidal oscillations of the Earth were at last bridged. In addition, rugged accelerographs were designed that could record the strong ground motions in large earthquakes.

The methods of explosion seismology were greatly developed in the post-war period, particularly in the oil industry. Another development with artificial sources occurred with the advent of nuclear explosions, that changed the face of seismology radically on both the theoretical and observational sides.

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1.3 The period since 1960

1.3.1 Seismology and nuclear explosions

With the advent of nuclear explosions, it became possible to extend the seismic explosion method, and all the experimental controls that go with it, to problems of the Earth's deep interior.

Although, so far, seismic applications of nuclear explosions have been mainly secondary to other purposes, a quantity of valuable information has been derived.

The first atom bomb was exploded in New Mexico on 1945 July 16 d 12 h 29 m 21 s (UT) at latitude 33° 40′ 31″ N and longitude 106° 28′ 29″ W from a tower 100 ft above the ground. The origin-time at source was uncertain by 15 s, the time here given being that estimated by Gutenberg from seismic data; this time is considered to be reliable within 2 s. It has become customary to express the energy yielded in a nuclear explosion in terms of equivalent kilotons or megatons of TNT explosive ($1 \text{ kt} = 10^3$ tons; $1 \text{ Mt} = 10^6$ tons). The yield for this explosion was about 19.3 kt.

On 1946 July 24, the first underwater atomic explosion took place 30 m below the ocean surface near Bikini Atoll. This was the first nuclear explosion for which source data were made generally available. It was recorded at eight seismic stations at distances between 69°.0 and 78°.6. Gutenberg and Richter gave P readings for those stations, from which Bullen determined a mean residual of -1.8 ± 0.8 s against the J.B. tables for a surface focus. The negative residuals were attributed to crustal differences between the Bikini and the average continental region. The explosion, meagrely recorded as it was, gave a glimpse of what might be achieved for seismology through nuclear explosions.

In March 1954, it was announced that a hydrogen bomb had been exploded near Bikini. Burke-Gaffney identified a corresponding P wave onset at Riverview Observatory and the identification was confirmed when routine readings arrived from Brisbane. From this start he found readings of seismic waves from four such explosions in routine station bulletins from twelve countries. The readings enabled him and Bullen to compute origin-times which, later, proved to be accurate within 0.0, 0.4, 0.6 and 0.1 s, respectively, for the four explosions.

From the seismic readings of these explosions, Burke-Gaffney and Bullen found negative P residuals, and also found that the P travel times from Bikini to the United States and Australia agreed within less than a second. An unexpected result of some significance was the identification of

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waves preceding the usual waves recorded after passage through the Earth's core (see §13.6.5).

In 1956, a series of atomic explosions took place at Maralinga in central Australia and led to the first reliable crustal knowledge in a region where it had not been possible to make inferences from natural earthquakes.

Following an address on seismological aspects of nuclear explosions at the 1957 meeting in Toronto of the IASPEI, the first public release was made of source details of a coming nuclear explosion in Nevada. This was the Rainier explosion of 1957 September 19, which took place 250 m below the surface and was the first underground nuclear explosion. Intense efforts were made by seismologists to record seismic waves from it, but geophysical rewards were not great; the yield was only 1.7 kt with only a small proportion of the energy going into seismic waves.

In 1958, the field of forensic seismology was emphasised when a Geneva Committee of representatives from several countries produced a report on the detection of nuclear explosions, making considerable reference to seismology. Up to the present, underground nuclear explosions have been detonated by the United States, the Soviet Union, the United Kingdom, France (in North Africa and the Pacific Ocean), the People's Republic of China and India.

From 1958 onward, increasing quantities of source data on nuclear explosions were released publicly by the United States and increasing efforts were put into studies of seismological aspects. (Fig. 13.5 shows seismic waves recorded from an underground nuclear explosion at Novaya Zemlya, USSR, recorded in California.) A detailed history of these matters has been written by Bolt (1976).

A summary of recent seismological research on test-ban treaty verification is given in the *Bulletin of the Seismological Society of America*, **72B**, 1982. The main questions discussed involve new high resolution seismographs, estimating explosion yield, application of seismic arrays, wave attenuation in the Earth, and wave amplitude (magnitude) and spectral discriminants.

1.3.2 Standard global recording

By 1958, when the conference of experts met in Geneva to discuss the technical basis for a nuclear test ban treaty, there were in operation only about 700 seismographic stations equipped with seismographs of various types and frequency responses. Few instruments were calibrated so that actual ground motions could not be measured and timing errors of several seconds were common. A special panel set up in the United States in 1959,

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chaired by L.V. Berkner, recommended the installation of a worldwide standardised seismographic network (WWSSN). Foreign observatories cooperated with the US Coast and Geodetic Survey in installing and operating the new equipment. Each station consisted of six seismographs – three short-period seismographs and three long-period seismographs. Timing and accuracy were maintained by crystal clocks and a calibration pulse was placed daily on each record. Local observatories lent originals of the seismograms to the United States Coast and Geodetic Survey to be copied, and seismologists in any country could request copies for a nominal charge. By 1967, the WWSSN consisted of about 120 stations distributed in 60 countries. Other countries, such as Canada, which did not participate directly in the WWSSN, upgraded their own stations to be compatible with the standardised network. The resulting data provided the basis for significant advances in research in earthquake mechanisms, global tectonics, and the structure of the Earth's interior.

By the 1980s a further upgrading of permanent seismographic stations began, using digital equipment. Among the networks of global digital seismographic stations now operating (see Fig. 1.2) are the seismic research

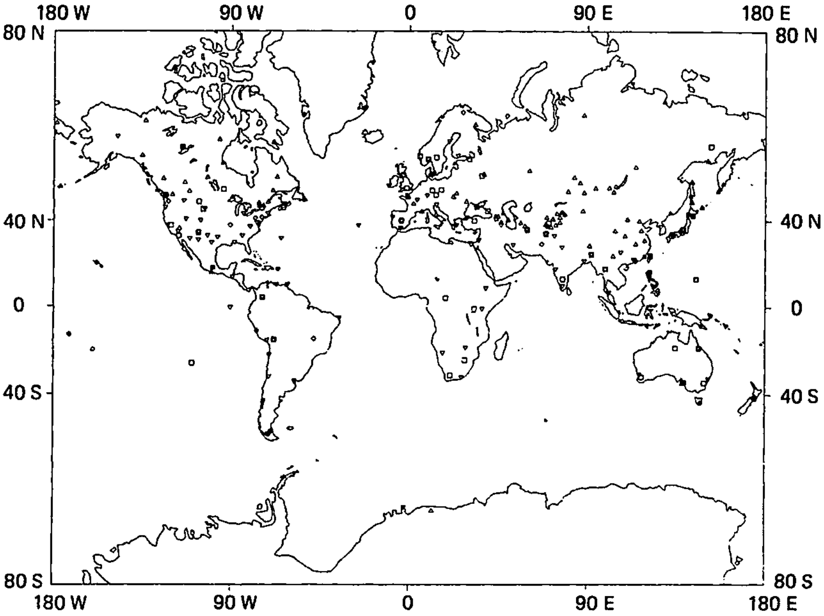

Fig. 1.2. Locations of WWSSN (or equivalent) and digital stations reporting earthquake records in 1983. (Courtesy W. Rinehart, NOAA.)

observatories (SRO) in boreholes 100 m deep, modified high-gain, long-period (surface) observatories (HGLP and ASRO), and digital WWSSN stations (DWWSSN). In addition, a number of gravimeters with digital recording and response to very long wavelengths have been installed worldwide under the International Deployment of Accelerographs (IDA) network. The main thrust is to equip global observatories with seismographs able to record seismic waves over a broad band of frequencies. For example, at the University of California at Berkeley, broadband, three-component analogue recording on magnetic tape was commenced in 1964 and similar digital recording in 1980. Digital signals and magnetic tape storage at the advanced global stations provide more satisfactory measurements of earthquake waves than do photographic recordings and allow rapid input to high-speed computers for estimation of earthquake parameters. Details on the responses of some of these modern instruments are given in chapter 9. Some considerations of present and future trends can be found in the IASPEI Presidential Address 'Seismology in the digital age' given by B.A. Bolt in Hamburg in 1983.

1.3.3 Computers and complexity

A major aim in seismology is to infer the minimum set of properties of the earthquake source and of the Earth which will explain in detail the recorded wave trains. Until the 1960s, this goal was limited severely by the labour needed to evaluate theoretical models and to process the large amounts of recorded seismological data. Applications of high-speed computers cleared the way for major advances in both theoretical work and data handling in seismology.

On the theoretical side, more realistic models of Earth structure that included continental and oceanic boundaries, mountains, alluvial valleys and so on were explored rather than structures with simple geometries. Viscous, non-homogeneous and non-isotropic properties of rocks and soils were included in the analysis where significant. More sophisticated mathematical inverse problems were tackled whereby maximum likelihood estimates of the required parameters (e.g. wave velocity, structural dimensions, density, etc.) were determined from the observations along with resolution and confidence limits. More widespread statistical analyses became possible involving simultaneous analyses of worldwide recordings of seismic waves.

In particular, analysis of the waveforms in terms of the frequency spectra became widespread, and special computing algorithms based on Gauss's 'Fast Fourier Transform' developed by Cooley and Tukey became

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commonplace. The implication of array and filtering techniques developed in the oil industry were also recognised. Recorded waves from network stations were telemetered to one centre. Large arrays of seismometers were constructed, such as the large-aperture seismic array (LASA) in Montana. This array (closed in 1979) had a circular geometry with a diameter of 200 km and a basic configuration of 21 sub-arrays, each with 25 short-period vertical seismometers. Digital signals from each channel were prefiltered and the combined sub-array signals added after being given appropriate time delays to enhance a particular seismic wave pulse at a specified direction and speed. Such processing by on-line computers, already well-developed in radio astronomy, for example, provided resolution and precision previously unknown in seismology.

Modern mini-computers and microprocessors with peripheral display equipment, allowing the rapid display of wave forms and spectra, are now providing valuable application of graphics methods to seismology. As well, observational seismology is exploiting the storage and retrieval computer facilities that have been long recognised in allied sciences such as meteorology.

1.3.4 Extra-terrestrial seismology

Since 1957 October 4, when the first artificial satellite invaded outer space, the application of seismic methods to the study of extra-terrestrial bodies has been discussed. Space vehicles have carried equipment to the surface of the Moon and Mars to record seismic waves and seismologists on Earth have received telemetered signals. Just as the advent of efficient seismographs late last century led to our present knowledge of the Earth's interior, so will the placing of instruments on other planets lead to much new knowledge of their interiors, as recently reviewed by A.H. Cook (1980). Information may also be expected on many special topics, for example, meteorite impacts.

The experiments will not merely provide knowledge of the Moon and planets directly investigated; they can be expected to have important repercussions on the theories of the Earth's interior, and to influence the course of terrestrial geophysics in a number of ways.

Present knowledge of the interior of the Moon is comparable with, possibly slightly greater than, that of the Earth two decades after seismographs were available to record earthquakes. (See §13.2.4.)

The mass M', mean radius R', volume and mean density of the Moon are well determined as 7.35×10^{25} g, 1738 km, 2.20×10^{25} cm^3, and 3.34 g/cm^3