A Concise History of Mainstream Seismology: 
Origins, Legacy, and Perspectives

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Abstract   The history of seismology has been traced since man first reacted literarily to the phenomena of earthquakes and volcanoes, some 4000 yr ago. Twenty-six centuries ago man began the quest for natural causes of earthquakes.

The dawn of modern seismology broke immediately after the Lisbon earthquake of 1755 with the pioneering studies of John Bevis (1757) and John Michell (1761). It reached its pinnacle with the sobering discourses of Robert Mallet (1862).

The science of seismology was born about 100 yr ago (1889) when the first teleseismic record was identified by Ernst von Rebeur-Paschwitz at Potsdam, and the prototype of the modern seismograph was developed by John Milne and his associates in Japan.

Rapid progress was achieved during the following years by the early pioneers: Lamb, Love, Oldham, Wiechert, Omori, Golitzin, Volterra, Mohorovičić, Reid, Zöppritz, Herglotz, and Shida. A further leap forward was gained by the next generation of seismologists, both experimentalists and theoreticians: Gutenberg, Richter, Jeffreys, Bullen, Lehmann, Nakano, Wadati, Sezawa, Stoneley, Pekeris, and Benioff.

The advent of long-period seismographs and computers (1934 to 1962) finally put seismology in a position where it could exploit the rich information inherent in seismic signals, on both global and local scales. Indeed, during the last 30 yr, our knowledge of the infrastructure of the Earth's interior and the nature of seismic sources has significantly grown. Yet, an ultimate goal of seismology, namely, the prediction of earthquakes, is not forthcoming. In spite of vast deployment of instruments and manpower, especially in the United States and Japan, no substantial progress has been made in this direction. The nonlinear dynamic processes at the sources of earthquakes are not yet understood, and with the lack of proper mathematical tools and physical theory, breakthrough is not apt to come through computers and seismographs.

The conclusion of the present historical study can be succinctly phrased as follows: seismology has reached a stage where its lofty goals cannot be pursued by seismologists alone. Unless we launch a concentrated interdisciplinary research effort, we shall always be surprised by the next major earthquake.

Introduction

"Everything is a matter of chronology"
Marcel Proust, Remembrance of Things Past

Seismology is an interdisciplinary science: most of the theory needed to interpret seismograms, prior to 1922, had been made available through the efforts of physicists and mathematicians of the seventeenth, eighteenth, nineteenth, and early twentieth centuries. Even after 1922, contributions made by applied mathematicians (Wiener, 1930; Lighthill, 1960), physicists (Jeans, 1923; Born, 1925; Fock, 1946), and engineers (La Coste, 1934), continued to play central roles in seismology.

Thus, the history of seismology is inseparable from the history of the great achievements in continuum mechanics, applied mathematics, and general wave theory. Moreover, it is not possible to isolate theoretical seismology from the rest.
of the science, since phenomenology, experiment, and theory are strongly linked throughout.

The history of seismology did not really begin in 1889; if we may compare this science to a plant, then 1889 was the year that the seed broke the surface. Its true origin may be placed on 1 November 1755, during the Lisbon earthquake—an event that changed dramatically man’s outlook on the phenomenon of earthquakes. Since then, major earthquakes continued to serve as milestones on the road of progress. [E.g., Mino-Owari, central Japan, 28 October 1891: first documentation of surface faulting. India, 12 June 1897: Oldham’s first observation of P, S, and R waves. California, 18 April 1906: Reid’s elastic rebound theory. Long-Beach, 10 March 1933: advent of earthquake engineering. Chile, 22 May 1960: experimental verification of the propagating rupture of faults and the Earth’s free oscillations.]

The year 1889 is nevertheless a remarkable year in the history of our science—the birth year of the teleseismic seismogram; seismology became at once a global science! Earthquakes ceased to be the local affairs of cities. A grand communication line has been opened, which goes across countries, continents, oceans—all geographical barriers were suddenly broken.

This was indeed the first revolution in seismology. The second revolution occurred during 1950 to 1955 when digital computers were first introduced in seismology. The ability to perform fast calculations increased the dimensionality of seismology both in space and time: huge amounts of data could suddenly be processed in a relatively short time; integrals and sums could be evaluated quickly, and equations of all sorts could be solved most efficiently.

As one delves into the history of seismology, one becomes gradually more and more fascinated with the internal logic of its heritage, with the people behind the discoveries, and with the intricate subtle interrelations between seismology, geology, astronomy, meteorology, and physics. However, unfolding this story before an audience is a totally different matter, for then the science historian must answer to himself and to others certain important questions: in what way does this history manifest itself? Does it abide by a chronological sequential order of events? Is it a linear process, does it swing back and forth, are there gaps, is it random or is it deterministic?

There are many ways of displaying the answers to these fundamental questions. Given the limits of our knowledge and the limited scope of the present article, I have decided to open with a short historical overview, followed by a more detailed list of “events.” The “events” cover nine disciplines:

1. phenomenology (P),
2. seismometry and experimental seismology (S),
3. theory of seismic fields in the earth (rays, waves, modes, beams) (T),
4. surface waves (SW),
5. free oscillations of the Earth (F),
6. seismic sources (SS),
7. Earth’s internal structure (E),
8. anelasticity (AE), and
9. anisotropy (AI).

Each “event” describes some step, or landmark, in the evolution of seismology; it is associated with a date (mostly a year), a short specification of the nature of the discovery or invention, associated persons, and finally a category (one of the above nine initials).

The choice of the items and of the individual scientists in these lists is unavoidably based on my own judgement, taste, and knowledge. There will always be arguments about omissions and commissions in such lists, and no two reviewers will emerge with identical choices. I must therefore define here the scope and intent of the writing, together with my criteria for exclusion of researchers.

Let us first address the problem of the role of the individual scientist in the history of science. As long as one is interested in scientific results only, one may ignore the man behind the discovery, and then time becomes amorphous, white science is anonymous. But as soon as one studies the evolution of ideas, the mask is unveiled and one is confronted with people, flesh and blood, and people have names, territories, and destinies. Like any other group of humans, they have their heroes, villains, and saints. Thus, their lives become an integral part of science, as well as their scientific achievements.

The scope of the present essay is limited to a succinct description of the landmarks (alias signposts; alias milestones) in the evolution of earthquake lore. The choice of these events was based on the following three rules:

1. Every item of the list could not have evolved without the "pre-knowledge" of some or all of its predecessors, i.e., no item is redundant; every link in the chain is essential, although not of equal importance.
2. Each item is referenced in a leading encyclopedia (e.g., Britannica) and/or an authoritative history book. I did not include information that had not been cross-referenced in at least two such sources (see References).
3. All results in theoretical seismology and seismometry are essential to the understanding and quantification of present-day phenomena and data analyses.

Credit by name was given to 150 men, the majority of whom are not alive today. The References, which cover the period up to 1964, includes the works of some additional 200 men of science.

Historical Overview

Early historical records contain references to earthquakes as far back as 2000 B.C.E. These accounts are, for the most part, of little value to the seismologist. There is a natural tendency to exaggeration in describing such phenomena, sometimes indeed to the extent of importing a supernatural element into the description. Nevertheless, attempts
were made by some ancient writers on natural philosophy to offer rational explanations of earthquake phenomena. These views (although based upon hypotheses which, as a rule, are too fanciful to be worth dwelling upon in great detail), as summarized in the writings of such historians and philosophers as Thucydides, Aristotle, Strabo, Seneca, Livy and Pliny, indicate very clearly that the early Greek philosophers had already abandoned the mythological explanations in favor of natural causes of earthquakes inside the earth.

Aristotle (ca. 340 B.C.E.) 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. The earliest instrument known to us that was made to respond to earthquake ground motion is the seismoscope, invented in 132 A.D. by the Chinese scholar Chang Heng. It revealed the direction of ground motion. Later seismoscopes were designed to also give the time of occurrence of a shock. This instrument is reputed to have detected some earthquakes not felt locally.

Not much was gleaned from the pages of medieval and later writers on earthquakes. In England, the earliest work worthy of mention is Robert Hooke's Discourse on Earthquakes (1667 to 1697). This publication, though containing many passages of considerable merit, tended but little to a correct interpretation of the phenomena in question. Equally unsatisfactory were the attempts of Joseph Priestley and some other scientific writers of the eighteenth century to connect the cause of earthquakes with electrical phenomena. Moreover, some scientists were not sure anymore of the natural origin of earthquakes, as we learn from a writer in the Philosophic Transactions of the Royal Society of London, as late as 1750 A.D., who deemed it expedient to apologize to "those who are apt to be offended at any attempts to give a natural account of earthquakes." Notwithstanding, stubborn facts of earthquake effects continued to accumulate, especially in the wake of the disastrous Lisbon earthquake of 1755. Finally, it was firmly established by the Rev. John Michell (1761), professor of geology at Cambridge, that earthquakes originate within the Earth. He declared that "earthquakes were waves set up by the shifting masses of rock miles below the surface . . . the motion of the earth in earthquakes is partly tremulous and partly propagated by waves which succeed each another," and he estimated that the earthquake waves after the Lisbon earthquake had traveled outward at 530 m/sec.

Another person to suggest that the influence of earthquakes propagate in the earth in the form of waves with finite velocity was Thomas Young (1807).

Most of the work on earthquakes during 1760 to 1840 was concerned with appraisals of geological effects, and effects on buildings. Early in the nineteenth century, earthquakes lists were being regularly published, and in 1840 there appeared the first earthquake catalog for the whole world.

In 1857, the first true seismologist (as we would now recognize the term in hindsight), appeared on the scene: Robert Mallet (1810 to 1881, Ireland), the engineer who laid the foundation of instrumental seismology. He was born in Dublin, and after taking his degree at Trinity College in that city, he went into his father's small engineering factory. After building a lighthouse and a number of bridges, he became interested in global seismicity and earthquake engineering problems. His detailed study of the damage caused by the Napolitan earthquake of 1857 led him to suggest the setting up of a network of observatories over the Earth's surface. He published the first world seismicity map and made the first systematic attempt to apply physical principles to earthquake effects (1862). Mallet made estimates of the epicentral depth and also carried out a number of experiments to determine the velocity of earth waves by setting off charges of explosives in different soils and by measuring the results on bowls of mercury set at varying distances up to 800 m away.

The first seismometer, deserving its name, was designed in 1841 by the physicist James David Forbes (1809 to 1868, Scotland). The name was coined by David Milne Home in 1841. A few years later, the name seismograph was given to an instrument built by Luigi Palmieri (1855) in the observatory on Vesuvius. It consisted of an inverted pendulum, hinged below by a cylindrical steel wire. A pencil attached to the top of the pendulum rod recorded the motion on paper. The first useful seismograph system, recording ground displacements, was constructed in Japan in 1880 by John Milne and his assistants James Alfred Ewing and Thomas Gray. However, this instrument had insufficient magnification and could record only local earthquakes.

In 1889, Ernst von Rebeur-Paschwitz (1861 to 1895, Germany) was experimenting in Potsdam with a modified form of Zöllner's horizontal pendulum ($V_0 = 50$, $T_0 = 18$ sec, no damping) when an earthquake from Japan was recorded. This event marks the birth of instrumental seismology in its worldwide sense. Stimulated by these observations, by 1894 Milne was able to design, construct, and test the now famous seismograph that bears his name. It was capable of detecting earthquake waves that had traveled many thousands of kilometers from their origin. Moreover, it was sufficiently compact and simple in operation to enable it to be installed and used in many parts of the world. It could record all three components of the ground displacements (up-down, east-west, north-south). From this time onward, precise instrumental data on earthquakes began to accumulate, and seismology has developed from the qualitative toward the quantitative side. The seismograph is to the earth scientist what the telescope is to the astronomer—a tool for peering into inaccessible regions. For that reason one may consider the year of the deployment of the Milne seismographs as an important milestone in the history of seismology. Indeed, since 1894, the number of instrumentally recorded earthquakes steady increased; the earliest known list of earthquakes with computed origin times and
epicenters is that for the period 1899 to 1903. Further improvement in the design of seismographs was due to Fusakichi Omori (1868 to 1923, Japan) and Emil Wiechert (1861 to 1928, Germany), who gave a detailed account of his mechanical seismograph (1900). Boris Borisovich Golitzin (1862 to 1916, Russia), designed the first electromagnetic seismograph with photographic recording (1906). Wiechert designed a seismograph in which the pendulum is vertical and inverted, being maintained by small springs pressing against supports rigidly attached to the ground. The mass of the pendulum is large (up to several tons), and the seismograph records both horizontal components at once. A cardinal development took place when Golitzin introduced the idea of recording ground motion by means of a ray of light reflected from the moving mirror of a galvanometer: the motion of the mirror is excited by an electric current generated by electromagnetic induction when the pendulum of the seismometer moves. The next development came in 1935, when Hugo Benioff (1899 to 1968, U.S.A.) designed and constructed an instrument to measure a component of ground strain.

The strain seismometer measures the variation in the distance between two points, some 30 m apart, caused by the passage of seismic waves. Benioff’s recording was electromagnetic, the original galvanometer period being 40 sec, subsequently increased to 480 sec. His strain seismograph was the first to record earth motions with periods up to the order of 1 hr, such as the gravest mode of the free oscillations of the Earth (1952).

The science of seismology aims simultaneously to obtain the infrastructure of the Earth’s interior with the aid of seismic wave phenomena, and to study the nature of earthquake sources with the ultimate goal of mitigating and eventually controlling the phenomenon. This double feature is apparent from the early days of this science.

The achievements toward the first goal began in 1799, when Cavendish employed Newton’s law of universal gravitation to estimate the Earth’s mean density \([\rho] = 3/(4\pi G) g(R)/R = 5.5\ g/cm^3\). As this density exceeded the density of surface rocks, the conclusion was that the density must increase with depth in the Earth. By means of observations of the tidal effect on the solid Earth, Lord Kelvin claimed in 1863 that the Earth as a whole is more rigid than glass. (This opinion has been confirmed later, when it was found that steel offers a better comparison, where the gravest mode of the Earth’s free oscillation is concerned.) In 1897, Wiechert conjectured from theoretical calculations that the Earth’s interior consists of a mantle of silicates, surrounding a core of iron. The existence of the Earth’s core was established by Richard Dixon Oldham (1858 to 1936, India and England) in 1906, from observations of earthquake waves.

In 1909, Andrija Mohorovičić (1857 to 1936, Zagreb) discovered a sharp material discontinuity at some level below the Earth’s surface (known today as the Moho), which could explain the travel times of seismic rays from a local earthquake. It was subsequently found to demarcate the base of the Earth’s crust. This discovery demonstrated that the structure of the Earth’s outer layers could be deduced from travel times of reflected and refracted seismic signals. This was known to John Milne already in or prior to 1906! (Milne, 1906, pp. 365–376.)

In 1914, Beno Gutenberg (1889 to 1960, Germany and U.S.A.) published his accurate determination of the depth of the boundary of the Earth’s core at 2900 km below the surface. (In 1926 he discovered a global low-velocity zone at a depth of 70 to 250 km in the Earth’s mantle, known as the asthenosphere.) In 1936, Inge Lehmann (1888 to 1993, Denmark) produced the first evidence of the existence of the Earth’s solid inner core with a radius of ca. 1400 km.

The advent of elastodynamics began with the discovery of longitudinal and transverse waves by Poisson in 1828, and their physical interpretation by Stokes in 1845. In 1885, Lord Rayleigh discovered, ahead of observations, another type of elastic waves (to be known later as the Rayleigh wave) that is associated with material discontinuities such as a free surface of a body. In 1897, Oldham identified on earthquake recordings (seismograms) the three main types of waves predicted by Poisson and Rayleigh, thus confirming that, at least for short-period wave motion (dominating periods: 0.1 to 1 sec), the Earth indeed behaves like an elastic body for which Hooke’s law may apply. In 1899, Cargill Gilston Knott (1856 to 1922, Scotland and Japan) derived the general equations for reflection and refraction of plane elastic waves at plane boundaries. This was needed to relate the amplitudes of the waves activating the seismometer to the corresponding seismogram traces, modified by the presence of the free surface of the Earth. In 1904, Horace Lamb (1849 to 1934, England) came forth with the first mathematical theory of a point-source earthquake in a half-space Earth model. He thus layed the theoretical foundation for the propagation of seismic waves in layered media. The first inverse problem in geophysics was formulated and solved in 1907 by Gustav (Ferdinand Joseph) Herglotz (1881 to 1953, Germany), enabling the intrinsic compressional and shear velocities to be determined from travel-time data. By 1909, E. Wiechert, K. Zoeppritz, and L. Geiger exploited this method and obtained for the first time a profile of compressional wave velocity in the Earth’s mantle. A significant contribution to theoretical seismology was made in 1911 by Augustus Edward Hough Love (1863 to 1940, England) with his discovery of a horizontally polarized surface wave (now known as the Love wave), from the analysis of which seismologists could derive estimates of the thickness of the Earth’s crust and its rigidity.

A further advance during 1915 to 1936 was made by Harold Jeffreys (1891 to 1989, England), who brought to bear 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 pre–World War II seismology has attained its level of precision.

Significant progress in seismology has been made
through the first four decades of the twentieth century: in 1901, the first Geophysical Institute was founded in Göttingen (Germany), and the number of seismic observatories capable of teleseismic recording reached 25 (compared to eight in 1894). By 1940, there were about 10 major seismic research centers and 250 seismic stations around the globe.

An international Association of Seismology was founded in 1905 at a meeting in Berlin of representatives from 23 countries, which met again in Rome in 1906 where it was decided to establish an international center at Strasbourg. The year 1919 saw the appearance of a bulletin of global recordings of earthquakes, published at Oxford, under the name International Seismological Summary (I.S.S.).

Following the catastrophic San Francisco earthquake of 18 April 1906, Harry Fielding Reid (1859 to 1944, U.S.A.) advanced his elastic rebound theory (1911): that earthquakes are associated with large fractures, or faults, in the Earth’s crust and upper mantle. As the rock is strained, elastic energy is stored in the same way that it is stored in a wound-up watch spring. The strain builds up until the frictional bond that locks the fault can no longer hold at some point on the fault, and it breaks. Consequently, the blocks suddenly slip at this point, which is the focus of the earthquake. (It was discovered in 1960 that once the rupture is initiated, it will travel at a speed of about 3.5 km/sec, continuing as much as 1000 km.) In great earthquakes, the slip, or offset, of the two blocks can be as large as 15 m. Once the frictional bond is broken, the elastic strain energy, which had been slowly stored over tens or hundreds of years, is suddenly released in the form of intense seismic vibrations—which constitute the earthquake. The process through which the frictional bond is "lubricated" to enable to commencement of the slip is yet not understood. About 10⁹ erg of strain energy is released from each cubic meter of the earthquake source volume. The greatest earthquakes each release energy from a strained volume of 1000 by 100 by 100 km = 10⁶ m³, which yields a total energy of 10²⁵ erg. This is about the equivalent of 1000 nuclear explosions, each with strength of 1 megaton (1 million tons) of TNT. It is of interest to note that the few large earthquakes each year release more energy than hundreds of thousands of small shocks combined. About 10⁶⁶ erg of seismic energy are released each year. This is about 1% of the yearly amount of heat energy reaching the Earth's surface from the interior.

The time between great earthquakes is about 50 to 100 yr in California and somewhat less in more active seismic regions, such as Japan or the Aleutians. Thus, the time required to build up the elastic strain energy in the rocks adjacent to a fault is enormous compared with the time that elapses during the release of stored energy.

The present state of knowledge of earthquake phenomena precludes the reliable prediction of the time of occurrence of the next major earthquake in any given location. Perhaps the most apt remark in this regard was given long ago by Mark Twain: “I was gratified to be able to answer promptly, and I did. I said I did not know.”

Since 1556, about 6 to 7 million persons have been killed by earthquakes.

Calendar of Progress

ca. 2100 to 600 B.C.E. Biblical allusions to major earthquakes on the Dead Sea fault system occurring since ca. 2100 B.C.E. (P)

c. 1560 B.C.E. and 759 B.C.E. Although the primary causes of these events were attributed by prophets and the scribes of the Bible to a single supreme power, the descriptions of the phenomena itself are rather accurate, and must have originated with keen observers of nature. These were among the first documented literary reactions of men to natural phenomena. (P)

c. 585 B.C.E. Thales of Miletos (624 to 546 B.C.E.) was the first to expound the theory of a natural cause for earthquakes; he proposed that they were caused by water. (P)

c. 550 B.C.E. Anaximenes of Miletos (585 to 525 B.C.E.), pupil of Anaximander, went further than his teacher in completely ignoring the mythical elements in the natural laws. He taught that, with age, the Earth broke down under its own weight, thus causing the motion of earthquakes. (P)

c. 340 B.C.E. Aristotle (384 to 322 B.C.E.) speculated that earthquakes are caused by air in motion: air trapped inside the Earth shakes the Earth as it is trying to escape. This theory influenced European thought till the seventeenth century. (P)

c. 45 A.D. Lucius Annaeus Seneca gave the best summary of the views on earthquakes in the Greco-Roman tradition: earthquakes are caused by natural causes such as water, air, or fire, located inside the Earth. (P)

c. 1260 Albertus Magnus (1206 to 1280) recognized the vibratory character of the motion of earthquakes. (P)

1638 Galileo Galilei considered for the first time the resistance of solids to rupture. His enquiries gave the direction that was subsequently followed by many investigators.

1660 Robert Hooke stated the one-dimensional linear stress-strain relationship, thus laying the foundation for the theory of elasticity (published in 1678). (T)

1664 Athanasius Kircher (1601 to 1680) proposed a system of channels of fire inside the Earth that end in the surface at the volcanoes; earthquakes are related to the motion of the fire inside these tunnels working against the rocks that block this motion. (P)

1696 Johann Zhan added to the Aristotelian theory that the air trapped inside the Earth is mixed with flammable material. (P)

1703 Martin Lister (1638 to 1712) and Nicolas Lemery (1645 to 1715) broke away from the Aristotelian theory of earthquakes and conjectured that the internal fire that produces earthquakes and volcanoes was produced by chemical means through a mixture of iron, sulphure, and salt with water. The important aspect of this theory, which became very pop-
ular in the eighteenth century, was that the source of an earthquake was an explosion produced by the mixing inside the Earth of the same chemicals used for explosives. Isaac Newton, in his *Opticks* (1704), refers to this theory in Book III, Part I, Query 31. He stated that when these minerals are accumulated in a subterranean cave they explode with a great shaking of the Earth. (P)

1749 *Comte de Buffon* (1707 to 1788) proposed that an explosion of inflammable materials, such as the fermentation of pyrites, produces a quantity of heated air in subterranean chambers that could escape horizontally for a great distance through underground tunnels and caves. This would explain why earthquakes are felt through a long distance. (P)

1755 1 November. Lisbon earthquake. Some effects are scientifically described. (P)

1757 *John Bevis* (or Bevans; 1693 to 1771) published in London a remarkable volume on *The History and Philosophy of Earthquakes* in which he collected accounts of the Lisbon earthquake from diverse authentic sources. His survey, the first of its kind, was subsequently used by John Michell (1761).

1761 Following the Lisbon earthquake, *John Michell* demonstrated that earthquakes originate within the Earth and that waves spread out from the source throughout the Earth’s interior (his velocity = 530 m/sec) (incidentally, he originated the concept of a black hole). Nevertheless, Michell still held to the explosive theory of earthquakes. (P)

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

1798 *Henry Cavendish* determined the mean density of the Earth, invoking Newton’s law of universal gravitation \[ (\rho) = 3g(R)/(4\pi GR) \approx 5.448 \text{ g/cm}^3 \]. (E)

1807 *Thomas Young* defined the modulus of elasticity \( (Y = \tau, \varepsilon_0, \varepsilon_1) \) and was the first to recognize shear as an elastic strain.

1819 16 June. Earthquake in Cutch, India. Earliest well-documented observations of faulting accompanying the earthquake. (P)

1821 to 1831 *C. L. M. H. Navier, A. L. Cauchy, and S. D. Poisson* discovered the fundamental equations of linear elastodynamics. *Navier* (1821), a disciple of Fourier and professor of analytical mechanics at the École Polytechnique in Paris, was first to derive the elastodynamic displacement equation, and the equation of motion of a viscous fluid. He laid the foundation to the mathematical theory of elasticity (definition of stress and strain tensors, 3D stress-strain relation for a general anisotropic solid), and correctly established the number of elastic constants for isotropic and non-isotropic media. His equation of motion (in modern notation) reads: \( \dot{T} + \dot{\rho} = \rho[\dot{\varepsilon} + \dot{\varepsilon}] \). (T)

1826 to 1839 *A. J. Fresnel* (1826), *S. D. Poisson* (1828), *A. L. Cauchy* (1830), and *G. Green* (1839) discussed the propagation of plane waves through crystalline media, and obtained equations for the velocity of propagation in terms of the direction of the normal to the wave front.

They found that, in general, wave surfaces have three sheets. *Cauchy* established the stress-strain relations for general anisotropic crystals in terms of 21 coefficients. (AI)

1828 *S. D. Poisson* established the existence of compressional and shear waves in elastic solids (observed by Oldham, 1897). His finding created at the time a new difficulty in the wave theory of light: if the ether behaved like an elastic solid, two types of light waves should be visible. Maxwell circumvented the difficulty by ascribing the ether a Poisson ratio \( \sigma = 1/2 \) (infinite longitudinal velocity). (T)


1840 *Von Hoff* published an earthquake catalog of the world. (P)

1841 Reports on earthquake investigations began to appear intermittently in the General Reports of the British Association for the Advancement of Science (prepared regularly by John Milne from 1881). (P)

First mechanical seismometer designed by *James David Forbes*. (S)

1845 *G. G. Stokes* defined the moduli of elastic compressibility and rigidity. (E)

1848 *Lord Kelvin* integrated the equation of elastostatics. (T)

1849 *G. G. Stokes* formulated the fundamental equation for viscous fluids. (T)

1852 to 1859 *G. Lamé* defined the elastic parameters of homogeneous media and the concept of stress ellipsoid. (T)

1855 *Luigi Palmieri* built a seismometer for use in the Vesuvius observatory. (S)

1857 16 December. Earthquake east of Naples, Italy. Field investigations by *Robert Mallet*; first systematic attempt to apply physical principles to earthquake effects in detail. According to him, earthquakes are caused "either by the sudden flexure and constraint of the elastic materials forming a portion of the earth's crust, or by their giving way and becoming fractures." Mallet published the first world seismicity map (1860) and made first attempts to measure velocities of seismic waves. He was indeed the first true seismologist. (P)

1863 *Lord Kelvin* used tidal observations to show that the mean rigidity of the Earth exceeds that of ordinary steel \( (\mu) \sim 1.45 \times 10^2 \text{ cgs} \). (E)

1869 F. Zöllner constructed a horizontal seismograph. (S)

1872 *E. Betti* discovered the reciprocity relation and the "Betti relation" leading later to the representation theorem of elastodynamics.

1874 *De Rossi* sets the first earthquake intensity scale.

1874 to 1892 Earliest linear theories of internal friction
and attenuation losses in elastic solids by O. E. Meyer (1874), L. Boltzmann (1876), J. C. Maxwell (1876), Lord Kelvin (1878), and W. Voigt (1892). (AE)

1877 to 1904 B. Christoffel (1877) derived the cubic equation for the three plane-wave phase velocities in general anisotropic elastic media, for any given direction of the normal to the plane (Christoffel's equation). His work was followed up by Lord Kelvin (1904), who described the nature of the displacement vectors (polarization) and defined a twelfth degree wave surface in velocity space. (AI)

1878 R. Horencz's classification of earthquakes (volcanic, tectonic, etc.). (P)

1880 John Milne, James Alfred Ewing, and Thomas Gray constructed in Japan the first useful seismograph system for the recording of local earthquakes. (On 22 February 1880 they were able to obtain satisfactory records of a local tremor.) (S)

1881 Lord Rayleigh's principle of eigenvalue perturbation. (Rayleigh's variational principle.)

1882 R. Canaval coined the names: foreshock, aftershock.

1883 to 1884 Rossi–Forel scale for earthquake effects published (based on observations in Italy and Switzerland). (P)

1885 In a theoretical study, Lord Rayleigh discovered that, in addition to the known dilatational and shear body waves (Poisson, 1828), a homogeneous elastic substance can accommodate a third wave at its boundary. This is subsequently known as the Rayleigh wave. (Rayleigh considered free waves in a sourceless medium.) (SW)

1888 A. Schmidt argued that since in general wave velocity must increase with depth in the Earth, wave paths will be curved and concave upward toward the Earth's surface. (T)

1889 Milne began the production of the "Shide Circulows," which dealt with earthquakes. (P)

17 April, 17 hr 21 min. The birthday of instrumental seismology in its worldwide sense: the first teleseismic event (a Japanese earthquake), recorded by Ernst von Rebeur-Paschwitz in Potsdam, Germany, with a modified form of Zöllner's horizontal pendulum ($V_o = 50, T_o = 18$ sec, no damping $\Delta = 8221$ km; origin time ca. 17 hr 10.3 min GMT). (S)

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

1892 to 1894 Milne and his associates develop in Japan a compact seismograph system for worldwide use. Useful instrumental data began to accumulate in a number of stations in Japan, Europe, and the United States, and seismology emerged as a quantitative science. (S)

1895 F. Omori established a law for aftershock time series. (P)

1897 12 June. Great Indian earthquake. Investigated by R. D. Oldham. (P)

R. D. Oldham identified on seismograms the three types of waves predicted by Poisson (1828) and Rayleigh (1885). (T)

Emil Wiechert worked out numerical details of an Earth model consisting of a core of uniform density $\rho_1 = 8.21$ g/cm$^3$ and radius $a_1 = 5000$ km surrounded by a rock shell of uniform density $\rho_2 = 3.2$ g/cm$^3$. A model of this type was contemplated earlier by Kelvin and P. G. Tait (1879), and R. R. Radia (1885). Wiechert conjectured that the central core is metallic. (E)

1898 T. J. I'A Bromwich studied the influence of gravity on elastic waves, and in particular on the vibrations of an elastic globe. (F)

1899 C. G. Knott derived the reflection and refraction coefficients of plane seismic waves at planar discontinuities. (T)

1900 World seismicity maps prepared by John Milne and Ferdinand Montessus de Ballore. (P)

Emil Wiechert constructed a three-component mechanical seismograph system. (S)

1901 Geophysical Institute founded at Göttingen, Germany, by Emil Wiechert. (P)

1902 Improved intensity scale published by G. Mercalli in Italy. (P)

1904 A. E. H. Love gave an exact singular analytic solution to the inhomogeneous Navier equation in an infinite solid: $(\lambda + \mu) \text{grad div } \vec{u} + \mu \nabla^2 \vec{u} + \rho \ddot{\vec{F}} = \rho (\partial^2 \vec{u})/\partial t^2$. He then proceeded to construct Green's functions for a variety of derived point sources such as dipoles, couples, center of compression, and center of rotation. Love based his work on previous results of G. G. Stokes (who in 1849 modelled a light origin as a point source of $SH$ waves in the luminiferous elastic ether), and L. M. Lorenz (1861) who showed how to solve the above equations in terms of potentials.

In the same article, Love derived for the first time the three-dimensional elastodynamic integral representation theorem, which is essentially an extension of Kirchhoff's theorem for elastic isotropic media. Love's integral, however, was not written in compact tensor notation. Moreover, the fundamental singular solution of elastodynamics (Green's tensor) does not appear explicitly in his analysis.

A closely related representation theorem was given independently by C. Somigliana (1905 to 1906). (SS)

H. Lamb presented the first mathematical model of an earthquake in a half-space configuration. The generation of elastic waves by the application of time-dependent surface tractions on the boundary of a half-space or in it, is known as Lamb's problem. Lamb represented a point force in a semi-infinite homogeneous isotropic elastic medium as a divergent Fourier–Bessel integral. In lack of computational means, he could only sketch the displacement transients at the far field for a vertical surface traction and certain im-
pulsive source time functions. His results confirmed the existence of Rayleigh waves. (SW)

He thus generated the first far-field synthetic seismogram. Moreover, he anticipated the later Cagniard method (1939), but did not recognize its generality. (SS)

1904 to 1905  F. T. Trouton, A. O. Rankine (1904), and P. Phillips (1905) discovered a logarithmic creep law \[ \frac{d\gamma}{dt} = q \log(1 + t/t_0) \], which gives a fair description of the strain in specimens under long continued stress. [Applied to rocks in 1956 by C. Lomnitz and generalized by H. Jeffreys (1958) to the Earth as a whole.] (AE)

1905 R. Becker developed the theory of the standard linear solid with continuous relaxation, as a physical model of anelasticity. The model yields a bandlimited constant \( Q \) by a continuous superposition of single relaxation mechanisms. Applied to seismic wave propagation in the Earth in 1976. (AE)

1905 to 1912 Establishment of elementary ray theory for seismic signal propagation in a spherically symmetric Earth model by H. Benndorf \((p = \frac{dT}{dA}, 1905)\), K. Zöppritz, and E. Wiechert. (T)

1906 18 April. California earthquake. Observed faulting and slip. (P)

Boris Borisovich Golitzin designed and built the first electromagnetic seismograph with photographic recording. (S)

22 March. John Milne delivered the Bakerian Lecture in which he announced the discovery of the “Moho discontinuity”! In his own words: “Preceding the large waves of a teleseismic disturbance we find preliminary tremors . . . for (ray paths) which lie within a depth of 30 miles, the recorded speeds do not exceed those which we would expect for waves of compression in rocky material. This therefore, is the maximum depth at which we should look for materials having similar physical properties to those we see on the earth’s surface. Beneath this limit, the materials of the outer part of this planet appear rapidly to merge into a fairly homogeneous nucleus with high rigidity.” In the same lecture Milne was also the first to observe (1906) that breaks in the trajectory of the secular motion of the Earth’s North Pole (relative to its mean position) could be correlated with the occurrence of major earthquakes during 1892 to 1904. A quantitative theory of this effect was given only in 1970. (E)

R. D. Oldham supplied positive seismological evidence for the presence of a central core of an approximate radius of 1600 km. (He found a substantial delay in the arrival of P waves at angular distances beyond 120° from an earthquake focus, and inferred that the Earth contains a central region characterized by an average P velocity appreciably less than that in the surrounding shell, later to be called the mantle.) It was found that the mantle everywhere transmits P and S waves and is thus solid for stresses with periods not greatly exceeding tidal periods. No S waves were observed below the mantle, and it was surmised that most of the core is molten. (E)

G. Angenheister obtained first values for absorption coefficients of surface waves in the period range 20 to 25 sec \((g \approx 2.8 \times 10^{-4} \text{ km}^{-1}; Q \approx 180)\). This was the first use of observed wave amplitudes for the estimate of attenuation. Similar results followed by Meissner (1913), Wegener (1912), Golitzin (1913), and Gutenberg (1924). (AE)

M. R. Frechet: functional calculus (the “Frechet derivative”).

1906 to 1911 Following the San Francisco earthquake, seismologists realized that crustal earthquakes are associated with finite faulting, fracture, and slip. H. F. Reid studied the geodetic measurements along the San Andreas Fault before and after its rupture (18 April 1906) and consequently expounded (1911) his elastic rebound theory, which drew attention to the significance of elastic strain energy in connection with earthquakes: a tectonic earthquake occurred when the stresses in some region inside the Earth have accumulated to the point of exceeding the strength of the material, leading rapidly to fracture. This information was not conveyed to the level of seismic source models, and consequently the natural development of seismic source theory was arrested for the next 50 yr. (SS)

1907 Vito Volterra presented his theory of dislocations, incorporating previous results of E. Betti (Betti’s relation, Betti reciprocity theorem, 1872), and C. Somigliana (Somigliana’s relation, 1885 to 1889). Previously (1894) Volterra derived a two-dimensional integral representation theory. (SS)

1907 to 1910 K. Zöppritz evolved the first travel-time tables for a few seismic phases (1907). G. Herglotz (1907) and, independently, H. Bateman (1910), gave an exact analytical solution to an Abel-type integral equation, the solutions of which determine the intrinsic velocity as a function of the radial distance from the Earth’s center. This enabled seismologists to invert the ray travel-time data \((T, \Delta)\) in terms of the intrinsic velocity at the turning point of the ray. Through 1909 to 1910 E. Wiechert, Zöppritz, and L. Geiger used this method to calculate velocities of longitudinal waves in the mantle. (E)

1909 Andrija Mohorović found evidence in Croatia of a sharp increase in the P-wave velocity at depth, which he placed at 54 km below the Earth’s surface. Later work by others showed such an increase to be worldwide, and the boundary where it occurred came to be called the Mohorović discontinuity (the depth of this discontinuity is in general about 35 km below the surface in continental shield areas, reaches 70 km under some mountain ranges, and can be as little as 5 km or so below the floors of deep oceans. The region of the Earth above the Moho is now called the crust. (E)

1911 A. E. H. Love explained the occurrence of a transversely polarized surface waves not included in the theories of Rayleigh and Lamb. It was subsequently known as the Love wave in layered elastic media, and its existence on seismograms was diagnostic of the Earth’s crust. Love’s work gave rise to a large number of mathematical investigations and yielded much information on the structure of continents and oceans. (SW)
He presented the theory of oscillations of a uniform gravitating compressible sphere and obtained a period of 60 min for the gravest mode of his steel-like earth model. (F)

1912 H. Lamb suggested that group velocity may be applicable to the theory of seismic surface waves and the interpretation of seismograms. (SW)

1914 Beno Gutenberg studied records of earthquakes that had epicentral distances of over 80° from Göttingen. He had found that at a depth of 2900 km, the velocity of longitudinal waves decreased from 13.25 to 8.5 km/sec and that the radius of the core is about 3500 km, a value little different from modern determinations. (E)

1914 to 1919 A. A. Michelson and H. G. Gale used an interferometer to measure body tides in the solid Earth by the disturbance of the water level in two vertical tubes with a long horizontal connection underground. With this gear they were able to measure the Earth’s mean rigidity. (S)

1915 to 1936 Harold Jeffreys introduced advanced mathematical and statistical methods into seismic data analysis. (T)

1917 J. Radon: “Radon transform.’’

1917 to 1925 J. Shida (1917) first noticed certain irregularities in the distribution of polarities of the initial P-wave motion as observed on seismograms in an area within a radius of a few hundred kilometers around the source. Shida found that the epicentral region is divided into four parts by two perpendicular lines intersecting at the epicenter. Observations by Nakamura (1922), Gherzi (1923), and Somville (1925) followed. (SS)

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

1919 H. Weyl presented the spherical wave function as a Fourier integral over all complex values of spherical angles in wavenumber space.

1920 L. M. Hoskins studied the free oscillations of a gravitating radially inhomogeneous sphere. (F)

1921 E. Meissner used observations of group-velocity dispersion of Rayleigh waves to model the Earth’s crust. About the same time, E. Tams and G. Angenheister noticed already that seismic surface waves over paths in the Pacific region travel faster than and are differently dispersed from those in continental regions, and suggested that there are significant differences in the crustal structures. (SW)

1922 Existence of deep earthquakes established by H. H. Turner. (P)

1923 1 September. Earthquake, destructive at Tokyo and Yokohama. Detailed investigation; many published reports. Earthquake Research Institute established at Tokyo. (P)

Appearance of the first ISS (International Seismological Summary) for earthquakes of 1918. From 1923 to 1963, the ISS was the most comprehensive publication on earthquake occurrence. Origin times and epicenters for all sufficiently well-read earthquakes were reported. For earthquakes 1918 to 1929, the Zöppritz–Turner travel-time tables were used in preparing the ISS; for 1930 to 1936, the preliminary JB tables of 1935, and from 1937 onward, the JB tables of 1940. (P)

J. H. Jeans developed the basic asymptotic theory of the Earth’s normal modes (Jean’s formula), relating the phase velocity at a given eigenfrequency to the colatitudinal mode number associated with that frequency. (F)

Hiroshi Nakano showed that the observed patterns of initial motions are explainable in terms of certain combinations of point forces of the classical Stokes–Love solution. One of the models, known as a double couple, is a combination of two orthogonal couples with zero moment. It was shown to be equivalent to a pressure and tension acting simultaneously at right angles. (SS)

E. D. Williamson and L. H. Adams coupled values of \( \phi = k/p = a^2 - 4/3\beta^2 \) from seismological data with the equation \( dp/dr = -GMp/r^2 \phi \) to obtain estimates of density gradients in the Earth. Using the available seismological data and taking \( p \) as continuous, they constructed an Earth model consistent with the values of the Earth’s mass and moment of inertia. Their value for the density just below the crust is 3.3 g/cm³ (ultrabasic rock), proposing an olivine-like composition for the mantle. Their work also supplied the first direct evidence that there is substantial change of chemical composition in the Earth’s deep interior. (E)

Wenzel, Kramers, Brillouin, and Jeffreys (WKBJ) developed independently an approximate explicit solution to some differential equations that govern the transition region from wave to geometrical optics.

1923 to 1937 Using travel times of near-field headwaves \((P_0, P_0, S_0, S_0, S_0, S_0)\) from European earthquakes, V. Conrad (1923 to 1927) and H. Jeffreys (1926 to 1937) obtained a three-layer crustal model (sediments, granite, basalt). (E)

1924 to 1928 R. Stoneley proved the existence of an interface wave propagating at solid–solid or solid–fluid discontinuities, subsequently known as the Stoneley wave (waves generated by the diffraction of curved fronts of body waves at a plane boundary). This was important to exploration geophysicists since it modeled sediment–rock interface in shallow seas. Stoneley also emphasized (1925) the importance of surface-wave group-velocity dispersion for modeling the Earth’s crust. In 1926, Stoneley was able to show (from observations of group-velocity dispersion of Rayleigh and Love waves) that the Euroasiatic crust is twice as thick as that of the Pacific region \((H = 10 \text{ km})\), and therefore that the crustal structures of the two regions differ significantly. (SW)

1925 J. A. Anderson and H. O. Wood developed the torsion seismometer. (S) Jun Shida discussed the possibility of observing the free oscillations of the Earth. (He designed an electromagnetic seismograph with pendulum period of 180 sec and galvanometer period of 1200 sec!) (F)

1926 First use of observed absolute wave amplitudes from seismograms in the estimation of earthquake energy release by H. Jeffreys. These were used by him to demonstrate the existence of a liquid core in the Earth. (P)
K. Uller formulated the general Navier equations in inhomogeneous media. (T)

E. Meissner invoked the Rayleigh principle to determine group velocities for Love waves without resorting to numerical differentiation (Meissner's formula). H. Jeffreys (1961) extended this work to Rayleigh waves. (SW)

Beno Gutenberg proposed a low-velocity layer in the outermost 100 to 200 km of the mantle, arguing from evidence on bodily wave amplitude. Later work substantiated this claim. The main seismological evidence appeared to be sufficiently met by assuming a negative rigidity gradient inside part of the outermost 200 km, a condition that is feasible in the light of evidence on temperature gradients. Gutenberg produced new evidence for his conjecture in 1939. (E)

M. Born: "Born approximation."

1926 to 1960 Perry Byerly developed a graphical method of displaying the initial motion distributions on a plane, and determining therefrom the fault-plane solutions. Thousands of earthquakes were solved in this way by his students, disciples, and colleagues. The method had two drawbacks: first, the initial motion is characteristic only of the first fraction of a second of the complex rupture process, which may last hundreds of seconds in major seismic events. Second, the initial P-wave motion is not sufficient to determine which of the two fault-plane solutions is the real fault. It is indeed disheartening that as far as realistic source models were concerned, seismologists were sidetracked for 56 yr (since Reid!) on studies of initial motion alone. Yet, fault-plane solutions were a key to later work on tectonic plate motions. (SS)

1927 T. Terada and C. Tsuboi conducted experimental model studies of seismic waves. (S)

V. Viisilä measured ground displacements by means of interference of light waves. (S)

1927 to 1928 K. Sezawa formulated scattering of elastic waves by spheres, cylinders, and apertures. (T)

1927 to 1940 K. Sezawa (1927), H. Jeffreys (1931), and N. Ricker (1940) studied the damping of pulses in viscoelastic media and applied the theory to propagation of seismic waves in the Earth. This was needed for magnitude and energy determinations, as well as for the physical state of the crust and upper mantle. (AE)

1927 to 1950 K. Sezawa, H. Jeffreys, and R. Stoneley worked out the dispersion theory of surface-wave propagation in crustal models with two layers. (SW)

1928 K. Wadati demonstrated the existence of deep-focus earthquakes in Japan. (P)

1930 A. Sieberg published a comprehensive treatise on the geography of earthquakes. (P)

N. Wiener developed generalized harmonic analysis, forging the tools for computerized signal analysis. (P)

1932 L. B. Slichter extended the Herglotz–Bateman travel-time inversion method to multi-layered horizontal structures. (T)

1933 Quantitative instrumental study on the effects of earthquakes on man made structures by N. H. Heck and F. Neumann following the Long Beach earthquake of 10 March 1933. (P)

1934 L. J. B. La Coste invented the zero-length-spring long-period vertical seismograph. (S)

1934 to 1944 Measurements of seismic velocities in exploration geophysics from travel times of P, SV, and SH waves disclosed that many rocks in sedimentary basins exhibit significant degree of anisotropy. (AI)

1935 Charles F. Richter introduced an instrumental earthquake magnitude scale. This was based on an earlier attempt by Wadati in Japan (1931). (P)

Hugo V. Benioff designed and built the linear strain seismograph. (S)

F. B. Blanchard uses a well-gauge as a seismometer. (S)

Norman A. Haskell determined the mean viscosity of the asthenosphere from the rate of uplift of the Earth's crust after the melting of the last Pleistocene ice sheets. He found a kinematic viscosity of the order of $3 \times 10^{21}$ cgs units. (E), (AE)

1936 Inge Lehmann postulated the existence of an inner core to account for the amplitudes of P waves between angular distances of $105°$ and $142°$ previously thought to be diffracted waves. The radius of the inner core was found by B. Gutenberg (1938) and by H. Jeffreys (1939) to be about 1200 to 1250 km. (E)

1939 H. Jeffreys applied the Airy theory of diffraction near a caustic to the seismological case of wave diffraction by the Earth's core ($\Lambda = 142°$). (T)

1939 to 1958 The Jeffreys–Bullen Seismological Tables.

H. Jeffreys (1939) and B. Gutenberg (1951 to 1958) produced each statistically well-based spherically symmetric and laterally averaged distribution of compressional and shear-velocity profiles in the Earth, based on large quantities of data. The differences between their respective curves are small except in the outer part of the mantle and in the transition zone between the outer and inner core. Both models ignore the Earth’s anelasticity, anisotropy, lateral inhomogeneity, and asphericity. K. E. Bullen was able to classify the Earth’s interior (1940 to 1942) into a number of shells occupying ranges of depth from the surface to the center. He also contributed to the inverse problem of density distribution. (E)

1939 to 1960 Transition period; end of the classical age of the Oxford–Cambridge analytical school. Final attack on the Lamb problem with the aid of the transform calculus. It resulted in a better understanding of the nature of the various seismic and acoustic signals transmitted through half-space models of the Earth. For half a century after Lamb’s seminal paper of 1904, the main thrust of theoretical seismology was aimed at an exact analytical solution of the “problem” and the numerical evaluation of the ensuing displacement transients. Of the many publications on the subject, three studies stand out: L. Cagniard (1939) addressed the problem of an explosion (cylindrical symmetry, unit-step time dependence) buried in a half-space or in a configuration of two welded
half-spaces. He used the Laplace transform method with his own ingenious way of inversion, in which the integrand of the Bromwich inversion integral is forced into a form of a Laplace transform of a calculable integral.

C. L. Pekeris presented in 1955 the first computer-generated synthetic seismogram for a point force in a Poisson solid (\(\lambda = \mu\)). In the precomputer era, many methods of approximation were used to extract useful information out of the Lamb integral representation. Most efficient was the saddle-point method, through which initial motions at the far field could be obtained at relative ease. (T,SS)

Lapwood (1949) was able to develop further the results of Lamb; using the saddle-point method of approximation, his line-source field integrals yielded several subsidiary phases (besides the classical P, S, and Rayleigh waves), which arise due to diffraction of the source’s cylindrical wavefronts at the planar free surface.

1942 to 1956 First empirical relations between earthquake magnitude, intensity, energy, acceleration, and frequency of occurrence established by B. Gutenberg and C. F. Richter. (P)

1946 Nuclear testing began. The use of underground nuclear explosions as point sources, each with accurately known location and time of origin, greatly enhanced the capabilities of seismic studies of the Earth’s interior. The first event of this type for which data became available to seismologists was the underwater explosion near Bikini Atoll on 24 July 1946. Since then, data from over 1000 nuclear explosions have been analyzed and studied in research centers around the world. (P)

1949 R. Stoneley examined the effect of anisotropy on elastic surface waves and established their existence for certain symmetry regimes. Under anisotropy conditions prevailing in the Earth’s crust and upper mantle, dispersion curves are little affected by anisotropy. (AI)


1952 Perry Byerly developed the general theory of the hinged seismometer with support, in general motion. (S)

B. Gutenberg and C. Richter defined the surface-wave magnitude, \(M_s\), for shallow-focus earthquakes in terms of the maximum amplitude of the ground motion for crustal surface waves having a 20-sec period. (SW)

1953 Integral formulation of Huygens’ principle for steady-state vector elastic waves: W. D. Kupradse, P. M. Morse, and H. Feshbach independently extracted from the Stokes–Love solution the fundamental singular solution of elastodynamics, otherwise known as the elastic Green’s tensor \(G_0\). The elastodynamic integral representation theorem was then compactly expressed in terms of this tensor \([G_{ij}]\) both in the time and frequency domains. (SS)

1953 to 1965 Observation and interpretation of seismic interface phases and guided waves came with the increasing frequency and dynamic ranges of seismograph systems on one hand, and computational capabilities on the other; crustal guided waves (since 1953), pseudo Rayleigh waves (1959), leaking interface modes, and PL phase (1960 to 1961). (T)

1954 With the advent of their new long-period seismograph system, M. Ewing and F. Press extended the recording and analyses of Rayleigh and Love waves up to periods of the order of 100 sec. (SW)

1955 Quantitative studies on the effects of strong ground-motion earthquakes on man-made structures. (S)

1955 to 1960 Y. Sato introduced Fourier-transform methods into the analysis of surface-wave dispersion and attenuation. (SW)

1956 F. Press developed the method of determination of crustal structure from phase-velocity dispersion of crustal and mantle surface waves. (SW)

Nelly Jobert calculated the free-oscillations periods of a heterogeneous Earth model, using the Rayleigh principle. (F)

V. A. Vvedenskaya was first to obtain the double-couple equivalence for an effective point source of slip.

1958 F. Press, M. Ewing, and F. Lehner completed the development of a stable long-period seismograph system for worldwide use. (S)

Hugo Benioff drew attention to ultralong waves with a period of ca. 57 min, which he noticed on his strain seismograms of the Kamchatka earthquake of 4 November 1952 (recording was made in an old mine tunnel at Isabella, California). (F)

A rigorous derivation of the 3D time-domain integral representation theorem in terms of the Green’s tensor, valid for unbounded regions was provided (1958). (SS)

J. A. Stekete proved the equivalence theorem, stating that the displacement field produced by a dislocation on a plane element in an elastic body equals that produced by a double couple on that plane. This lead to the definition of a source moment equal to \(\mu S\), where \(\mu\) is the rigidity over the fault of area \(S\) and dislocation \(U\). Stekete derived the equivalence by comparing the Stokes–Love (1903) solution for a double couple with Volterra’s (1907) solution for a corresponding dislocation. (SS)

1958 to 1965 Seismic data on attenuation of seismic rays, waves, and modes in the Earth pointed to a quasi constancy of \(Q\) over the period band \(10^{-3}\) to \(10^3\) sec. Various physically realizable mechanisms of attenuation were suggested. Perturbative inversion schemes were set up to derive the intrinsic anelastic parameters of the mantle from the observed surface attenuation data (1965). (AE)
The effect of azimuthal isotropy on the wave fronts and rays from a localized point force was derived through an integral representation of the field in terms of Fourier integrals. These were estimated asymptotically through stationary phase approximation. (AI)

F. C. Karal and J. B. Keller formulated the theory of ray propagation in inhomogeneous elastic media based on Ullé's equation (1926).

1960 22 May. Chile. The first major earthquake in history to be studied comprehensively both macroseismically and instrumentally. (P)

Existence of the free oscillations of the Earth firmly established by various groups of observers in Europe, Japan, and the United States from analyses of records of the great Chilean earthquake of 22 May 1960. Observations yielded also the expected splitting of the degenerated eigenfrequencies due to the Earth's diurnal rotation (1961). The matching of the observed spectral lines with theoretical calculations equipped seismologists with a new tool to sample the gross structure of the Earth's interior (C. L. Pekeris, G. Backus, F. Gilbert). (F)

Analyses of seismograms revealed that energy release in tectonic earthquakes takes place through a propagating rupture over the causative fault. The theory provides for a simple way to recover the fault length and the average rupture velocity from the spectral directivity of body waves and surface waves. It was thus found that the source of the Chilean earthquake of 22 May 1960 released its energy along a fault 1000-km long, with an average rupture velocity of 3.5 km/sec. (SS)

Linear system theory was applied to show that surface-wave signals can be sent back to the source by a spectral-phase “bookkeeping” of far-field data. The “initial-phases” of the far field could then serve as a diagnostic signature for the temporal and spatial character of the source. (SS)

1960 to 1964 Far-field phase and amplitude spectra of long-period surface waves were used for the study of source mechanisms of earthquakes and upper-mantle structure. (SW)

1961 to 1966 The moving-source discovery led to the formation of the kinematic dislocation model with the following source parameters: fault length, rupture velocity, rise time, fault width, and slip. The model is characterized by three basic features:

- The far displacement field is determined by the slip velocity on the fault. The radiation pattern is diagnostic of the source and depends on the source parameters.
- The short-period components of the radiation are coherent only over distances considerably smaller than the total fault length.
- The energy budget of major earthquakes requires the assumption of a superimposed irregular component of motion on the fault during rupture. (SS)

1962 to 1969 Advances in numerical techniques of data analysis and processing digital filtering, multi-dimensional Fourier analysis, F-K transforms, time-varying spectra, and fast Fourier transforms. Increase of dynamic ranges of seismograph systems and computer capabilities. (T)

1963 Francis Birch noticed that the relation between $a = kj\rho$ and density in a wide range of elements and compounds depends systematically on their mean atomic weight. On this basis, the seismological Earth models suggest that the inner core is almost pure iron. (E)

1963 to 1967 Deployment of 120 WNNSS in 60 countries. Advent of broadband three-component analog recordings on magnetic tape. (S)

1964 The ISS was replaced by the ISC (International Seismological Center, Newbury, England). It received about 80,000 readings each month from about 1200 stations, worldwide. (P)

1964 to 1965 Unraveling the latent interrelations and dualities between rays, waves, and modes of the Earth’s global seismic field. Asymptotic theory of the normal mode solution are applied. (Jean's formula, Watson's transformation, etc.) (T)

1964 to 1969 Large-aperture seismometer arrays come into vogue. Construction of feedback-controlled seismometers. (S)

1965 Seismologists in the United States proposed a 10-yr program of research for earthquake prediction. (P)

Benioff's strainmeter equipped with continuous interferometric calibration. (S)

1966 Advent of the optical maser strainmeter. (S)

1966 to 1980 Additional evidence on the distributions of the density, incompressibility, and rigidity in the interior of the Earth arose from recordings of the free oscillations of the Earth excited by the Chilean earthquake of 1960. Inversion schemes show the capability of observations of long-period oscillations of the Earth to discriminate between different Earth models. (E)

1967 to 1969 The conjecture of continental drift, propounded in 1912 by Alfred L. Wegener (1880 to 1930), verified in the framework of earthquake seismology; global seismicity patterns linked to plate motions. (P)

Development of the dynamical model of plate tectonics, which rendered global theoretical explanation to seismicity patterns. In this context, the kinematic source model was instrumental in estimating long-term accumulation of slip along major fault systems.

Plate-tectonic theory holds that the Earth's upper shell (lithosphere) consists of several (about eight) large and quasi-stable slabs called plates. The thickness of each plate extends to a depth of about 80 km; the plates move horizontally relative to neighboring plates, on a layer of softer rock. The rate of movement ranges from 1 to 10 cm a year over a lower strength shell, called the asthenosphere. At the plate edges where there is contact with adjoining plates, boundary tectonic forces operate on the rocks, causing physical and chemical changes in them. New lithosphere is created at mid-oceanic ridges by the upwelling and cooling of magma.
from the Earth’s mantle. In order to conserve mass, the horizontally moving plates are absorbed at the ocean trenches where a subduction process carries the lithosphere downward into the Earth’s interior. The plate theory is consistent with high seismicity along the edges of the interacting plates. Interplate earthquakes must be explained by other mechanisms. (SS)

1968 to 1985 Asymptotic wave theories in vertically inhomogeneous media: generalized rays for a layered Earth model with application to core phases diffraction, and tunneling. First-order decoupled equations of motion. The acoustic approximation in exploration seismology. WKBJ approximations, and extended WKBJ methods. (T)

Parabolic wave equation, Gaussian beams, and the paraxial approximate solution of the wave equation (Leontovich and Fock, 1946). (T)

Seismologists obtained (1972) numerical solutions of the vector Navier equation in isotropic inhomogeneous media with boundaries, showing coupling, mode conversion, scattering, and diffraction. Parabolic theory used to solve forward-scattering problems in inhomogeneous media. (T)

1969 The Apollo passive seismic experiment. (S)

Development of high-gain broadband long-period electromagnetic seismograph system, with digital recording. (S)

1969 to 1977 Analyses of travel times and polarization of seismic waves furnished evidence for anisotropy in the Earth’s crust and mantle (e.g., polarization of higher mode surface waves). Development of methods for calculating ray amplitudes in anisotropic media. (AI)

1970 NASA (U.S.A.) put a seismograph on the moon. (S)

Earth strain measurements with laser interferometer. (S)

1970 to 1985 Asymptotic ray theory: 3D two-point raytracing of both travel times and amplitudes in general media (inhomogeneous and anisotropic), ray-series expansion, and dynamic raytracing in ray-centered coordinates. Modifications of expansions around turning points, caustic, shadow zones, etc. (Complemented by modal expansions, finite-difference methods, or finite-element methods for short-time or near-field behavior.) (T)

1970 to 1988 New trends in 3D seismic modeling: solving forward and inverse problems of scattering and diffraction in inhomogeneous elastic media (both deterministic and stochastic), and across irregular boundaries:

• Kirchhoff–Helmholtz integral formula (Huygens’ principle) is used in various problems:

(a) Scattering by smooth obstacles: an algorithm is established for numerical calculation of the scattering of vector elastic waves by smooth obstacles of arbitrary shape (T-matrix method for forward scattering).
(b) Calculations of body-wave amplitudes in the Earth (1981 to 1983). In this scheme, ray theory (eikonal) is used in conjunction with Green’s theorem for slowly varying elastic media (ray-Kirchhoff forward method).
(c) Migration of stacked reflection data (Kirchhoff migration) through which discontinuity surfaces are imaged in exploration seismology (1973 to 1988). The above Kirchhoff method is also used for data migration in inhomogeneous media (inverse scattering problem). Geometrical migration was developed by J. G. Hagedroon (1954) and A. W. Musgrave (1961). During 1971 to 1978, the following migration schemes were developed: wave-equation migration, Fourier-transform migration, Kirchhoff migration, frequency-wavenumber (FK) migration, and Born–WKBJ inversion migration.

• Seismic wave tomographic inversion (1984 to 1992). The application of the Radon transform began in 1967 in astrophysics (Bracewell). It reached seismology in 1981, and emerged in 1984 as an imaging method for determining subsurface structure. Its uses are as follows:

(a) Mapping the upper mantle from inversion of seismic data (normal modes, body-wave travel times, and surface-wave dispersion and attenuation): teleseismic body-wave travel times on arrays yield lateral velocity variations, both regionally and globally. Travel-time delays are backprojected along ray paths, against a reference velocity model.
(b) Diffraction tomography in seismic exploration from cross-borehole measurements. (T)

1971 A global network of observing seismic stations (WWNSS) established by the U.S. Coast and Geodetic Survey. (S)

A mercury tiltmeter developed at the Massachusetts Institute of Technology. (S)

1972 to 1987 Theoretical and numerical calculations of the free oscillations of the Earth take into account perturbations due to asphericity, anisotropy, anelasticity, and lateral inhomogeneity. (F)

1972 to 1992 After the consolidation of the theory of the kinematic source model and its verification through the analyses of hundreds of earthquake seismograms, the theory developed further in the direction of more complex media to account for the effects of anisotropy and lateral heterogeneity. The availability of fast electronic computers enabled theoreticians to calculate the fields of earthquake sources in more realistic media subjected to the Navier equation: div $\mathbf{T}(\mathbf{u}) - \rho((\nabla \mathbf{u})/(\partial t^2)) = - \mathbf{F}(\mathbf{r}, t) - \text{div} \mathbf{M}(\mathbf{r}, t)$, where $\mathbf{F}$ is the source’s force density and $\mathbf{M} = n \mu \mathbf{F}_{\omega n} = \mathbf{n} \mu \mathbf{C}$ is the source’s moment tensor density [for isotropic media $\mathbf{M} = \lambda (\nabla \cdot \mathbf{n}) + \mu (\nabla \cdot \mathbf{n})$]. Calculations of the moment density of earthquakes became routine during the past decade. The above formulation is also suitable for problems of scattering of elastic waves by inhomogeneities where the sources are generated virtually by the scatterers. (SS)

1974 to 1992 Development of computational perturba-
tive schemes for the quantification of surface-wave fields in Earth models that account for lateral heterogeneity, anisotropy, anelasticity, and scattering. Ray and Gaussian-beam theory of surface-wave propagation on a sphere. (SW)

1976 Causal dispersion due to attenuation of waves and normal modes is observed. (AE)

1977 to 1992 Improved $\gamma$ and $Q$ measurements from global networks enable seismologists to invert attenuation of free-oscillation data and study the effects of mantle anelasticity on nutations, Earth tides, and tidal variations in rotation rate. They study the effect of a shallow low-viscosity zone on the mantle flow, and the geoid anomalies.

Seismologists try to separate attenuation of surface waves due to scattering from the overall observed attenuation. Seismology enters a stage where seismic imaging of the interior uses all available data. (AE) Establishment of the theory of seismic fields generated by point sources in multi-layered anisotropic media. Topics of research include the following: shear-wave splitting, scattering by anisotropic inclusions, dynamic ray tracing in anisotropic media, free oscillations in a slightly anisotropic Earth, and ray-centered coordinates in anisotropic media. (AI)

1978 Ocean-bottom seismographs (OBS) placed on the seafloor off the Pacific coast of central Honshu, Japan. (S)

1980 to 1992 With the ever-increasing quantity and quality of seismic data, deviations from isotropy, spherical symmetry, and pure elasticity could be observed with greater precision.

On the other hand, the mounting capabilities of digital electronic computers enabled seismologists to use more sophisticated forward and inverse computational schemes.

In the past decade or so, we witnessed the first 3D images of seismic velocities and anisotropy in the mantle and inner core, along with refinement of the detailed velocity structure near major internal boundaries such as the inner core--outer core, core--mantle, and upper mantle--lower mantle transition zones. Through seismic tomography, seismologists have exploited the accumulated $P$- and $S$-wave data base of millions of travel times and thousands of waveforms as well as new, digitally recorded data sets of surface waves and their standing-wave counterparts, free oscillations. The sources for seismic waves are primarily earthquakes, distributed globally in mid-ocean ridges, subduction zones, and along strike-slip faults. This computational process of 3D global tomographic imaging of the deep interior is divisible into three distinct stages:

- **Amassing** a wide-frequency-range data base (fraction of a second to 1 hr) of compressional and shear body waves, long-period surface waves, and free-oscillations time series. Given the quasi-elastic behavior of the Earth for short-time-scale transient loads, these elastic waves spread through the interior from their respective sources, reflecting, refracting, and converting between wave types whenever they encounter changes in material properties.
- **Inversion** of the above data to determine density and elastic properties at all depths in the planet. This is the tomographic mapping stage: high-precision measurement and images are required since lateral fluctuation in velocity are at most a few percent of the average velocity at a given depth.
  - **Interpreting** the 3D seismic velocities and density variations as manifestations of the dynamic thermally driven convective process of the mantle--core flow regime. Since shear stresses involved in flow can induce recrystallization and preferred orientation of the anisotropic minerals, the mantle may acquire a bulk anisotropy. If this anisotropy affects seismic wave propagation in the Earth to an observable level, it can eventually be inverted to yield further information on the flow regime. (E)

1981 Two-dimensional surface digital strong-motion array of aperture 2 km used in Taiwan to record near-field acceleration vectors. (S)

1982 Over 100 digital seismic stations operate worldwide. About 30 of these constitute the GDSN network (Global Digital Seismograph Network). (S)

1986 to 1992 Research is mostly computer oriented. The main topics are as follows:

- Inversion of seismic data for lateral heterogeneity and anisotropy. Global images of the Earth’s interior.
- Wave propagation from realistic earthquake sources in multi-layered anisotropic media.
- Nonlinear inversion problems.
- Scattering from rough interfaces and randomly distributed scatterers.
- Wave propagation in finely layered media.
- Ray perturbation theory and the Born approximation.
- Wave theory in complex media.
- Core dynamics.
- Application of GPS (Global Positioning System) to crustal deformation measurements.
- Higher order Gaussian beams. (T)

1988 to 1992 Morphological fault studies: a study of offset or deformations of large crustal earthquakes that occur within continental interiors. Systematic quantitative study of the surface morphology around faults, in lieu of analyses of historical seismicity. (Long recurrence times indicate that historical seismicity is not sufficient to give adequate estimation of the seismic hazard in regions of moderate seismicity. The morphological approach is less time consuming and cheaper than the technique of trenching, upon which most of the paleoseismological studies of the last decade have been based.) The three-dimensional geometry of active fault systems, including segmentation and bifurcation, are determined by careful combined use of satellite images, air photos, and topographic and geological maps. Once that geometry is defined, quantities like slip rates, slip vectors, and recurrence times of large events may be retrieved by measurements of the morphological record using a digital the-
It can thus be said that we belong to a generation that bridged between the precomputer era and the age of the electronic revolution.

A number of important observations and conclusions can be readily drawn from our historical enquiry: our first concern is with the factors that have accelerated or impeded the growth of ideas in seismology, especially throughout the twentieth century. The obvious stimuli of rapid growth were as follows:

- Occurrence of major devastating earthquakes in cultural centers, and global singular geophysical events (e.g., Lisbon, 1755; Mino-Owari, 1891; Chile, 1960).
- Economic stimulators (e.g., exploration for oil).
- Advances in mathematics and in theoretical physics (e.g., quantum mechanics).
- Technological breakthroughs (solid-state physics, lasers, holography, communication, computers, satellites, etc.).
- Exploration of the moon and the solar system.
- Nuclear explosion tests and Test Ban Treaties verification (1963 to 1976).

Impediments are harder to pinpoint, but they are probably mainly due to wars, economic recessions, and lack of vision and perspective of scientific leaders. A striking example is furnished by the inadequacy of the seismological community during 1912 to 1950 to exploit the theoretical know-how that had been accumulated until the eve of World War I. The following list summarizes what seismologists knew in the year 1912:

- Dislocation theory (Volterra, 1907).
- Representation theorem (Love, 1904).
- Logarithmic creep law (Trouton and Rankine, 1904).
- Cagniard's method (Lamb, 1904).
- Continental drift theory ( Wegener, 1912).
- Slip and fracture on long faults (Reid, 1906).
- \( \sigma_1 S_2 \sim 57 \) (Love, 1911).
- \( \gamma_0 (20 \alpha) = 2.8 \times 10^{-4} \text{ km}^{-1} \) ( Angenheister, 1906).
- Group-velocity dispersion for crustal structure (Lamb, 1912).
- Standard linear solid with continuous relaxation (Becker, 1905).
- Breaks in secular pole motion (Milne, 1906).

The next question that concerns us is the rate of growth of knowledge in seismology. There is certainly no unique way to quantify the concept of "knowledge." One may, however, estimate certain parameters that are related to growth. For example, by

- Counting the yearly number of printed pages in four leading journals during this century (BSSA, JGR, Geophysics, GRS) (now GJI). Assuming exponential growth \( n = N_0 e^{rt} \), it is found that \( t \approx 15 \text{ yr} \), i.e., printed pages doubled every 15 yr.
- Assembling bibliography lists of some 50 textbooks pub-
lished during the twentieth century. This renders a chronological list of some 1000 papers, which was taken as the kernel of knowledge. Assuming, again, the above growth law, there resulted a doubling-up period of 25 yr. It means that the yearly number of papers with significant novelty increased by a factor of 16 since 1892.

- The number of seismic stations increased exponentially since 1900, with $\lambda \approx 15$ yr [$N(1900) \approx 25$; $N(1992) \approx 2000$].
- The population of seismologists increased exponentially since 1892 with $\lambda \approx 15$ yr [$N(1892) \sim 50$; $N(1992) \sim 5000$].

Thus, four independent processes indicate a doubling-up period of 15 to 25 yr.

It is tempting to make assumptions about the future, based on the past record. Do we see today visible trends in the evolution of seismology? First, there is clear transition to computer-oriented research. During my recent visits to leading research centers in Europe and the United States, I noticed that most of the Ph.D. students in seismology were engaged in one form or another of "computer simulation games" or seismic-data reduction schemes, with insufficient efforts to construct new theoretical physical models. There was too much reliance on finite-difference and finite-element algorithms, and only modest endeavors to come up with new ideas. Who then will forge the new mathematical weapons, so badly needed today in nonlinear source dynamics?

Nevertheless, there is no escape from the fact that the role of the computer will increase, as its speed and capacity will rise as a result of new technological innovations.

As the number of seismic sensors will continue to mount, so will the data recorded by these systems. We shall certainly witness data acquisition by networks via international telemetry.

The role of satellites in geodetic strain measurements will become more central. All told, seismology will move toward, what I call, the holistic stage: imaging the Earth's interior and seismic sources with all available data.

Will all this lead eventually to earthquake forecasting? Clearly, the ultimate test of every scientific theory worthy of its name, is its ability to predict the behavior of a system governed by the laws stated by the said discipline. Apart from the obvious goal of imaging the Earth's interior, which is now proceeding with great vigor, the prediction of earthquakes is the most important target of contemporary seismology. How do we stand now on this issue?

During 1935 to 1960, the study of an earthquake meant two things: assignment of magnitude and plotting the pattern of initial motions. Thousands of earthquakes were analyzed in this way.

Another 30 yr passed by, and instead of magnitude, we talk about moment, and instead of initial motions, we plot radiation patterns, and computers spit out fault lengths, stress drops, etc. The terminology changed, the semantics changed, but the source dynamics are essentially the same as those known to Henry Fielding Reid in 1906. Seismologists are handicaped; meteorologists can put their sensors in the eye of a hurricane, we cannot put a sensor in the focal region. So far, most of our knowledge of the source came from measurements at the far field. We do not have yet a physical theory regarding the processes that take place at and near the earthquake source, neither prior to the event nor even at the time of its occurrence.

It was stated in the introduction that seismology has always been an interdisciplinary science. In this respect it is similar to medicine: The knowledge of anatomy alone is not sufficient to cure a patient; you need the chemistry of drugs, the physics of lasers, and the mathematics of tomography for diagnosis treatment and surgery.

Therefore, prediction must be first and foremost recognized as a problem at the junction of the sciences of engineering, geology, physics of condensed matter, and nonlinear mathematics.

Prediction is not a matter of wave propagation at all, and the conventional seismometer is not the adequate tool to accomplish this goal.

So, just sprinkling the face of the Earth with seismographs, and hooking up these instruments to computers and satellites is not the answer either.

What then, must be done to advance the cause of prediction? A major interdisciplinary effort is needed to develop a prediction scheme based on multi-premonitory phenomena: it means that the near field of a future focal zone must first be identified, and then monitored for electrical, magnetic, acoustic, seismic, and thermal precursors simultaneously and continuously.

The young science of seismology has now reached a critical point in its evolutionary trail. In a relatively short time it has gained valuable knowledge on the structure of the Earth's interior and on the nature of seismic sources.

Like a traveler who reaches a crossroad, we must halt our forward rush, look back, and take stock. Let us meditate for a moment on our achievements and weigh them against the shortcomings: did we exploit all our opportunities, were the signals properly read and understood, or were some missed or misinterpreted...? The history of seismology teaches us that the standards set by our predecessors are high; the spirits of the founders, Navier, Poisson, Stokes, Rayleigh, Milne, Love, Lamb, Volterra, Wiechert, Golitzin, Mohorovičić, Omori, Shida, Lehmann, Gutenberg, Richter, Jeffreys, Bullen, Pekeris, and Benioff breathe constantly on our necks. We must not fail.

It is perhaps adequate to end our essay with the words of T. S. Eliot in his "Four Quartets" (1942):

"We shall not cease from exploration
And the end of all our exploring
Will be to arrive where we started
And know the place for the first time."
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