SEISMOLOGY AND VOLCANOLOGY

Ludmil Christoskov
Geophysical Institute of the Bulgarian Academy of Sciences, Sofia, Bulgaria

Keywords: Attenuation, body wave, core, crater, crust, earthquake, elastic constants (modules), epicenter, fault, hypocenter, lava, longitudinal wave (P), Love wave (Q), macroseismic intensity, magma, magnitude, mantle, precursors, prediction, Rayleigh wave (R), recurrence law, seismic hazard, seismic ray, seismic source, strain, stress, transverse wave (S), volcano, volcanic eruption

Contents

Summary

Seismology and volcanology are sciences investigating two excessively interesting and disastrous natural phenomena—earthquakes and volcanoes. Among the disasters on Earth, earthquakes should be classified as the most unfavorable ones. Approximately a quarter of Earth's dry land is in active earthquake zones along the main seismic belts. Seismology is the study of earthquake sources, the seismic waves propagating through Earth, and the resulting unfavorable impacts on the surface. Seismological studies and results are the basis for the present ideas about the deep structure and physical properties of our planet. The practice of earthquake prediction is related not only to its pure scientific importance but also to humankind's need for effective protection from earthquake disasters. Regarding the prediction problem, humankind owes much to seismology. Volcanic eruptions are spectacular phenomena that have piqued human curiosity since ancient times. They can cause great harm, but on the other hand they can also be of benefit to man. Periods of extreme volcanic activity can influence the climatic

conditions and the evolution of flora and fauna. Volcanic eruptions and deposits are a remarkable source of fertile lands, of mineral resources, and of the formation of continents themselves.

1. Seismology

Seismology is the study of earthquakes. The name comes from the Greek *seismos* (earthquake) and *logos* (science). Seismology can be considered an ancient and at the same time a modern science. Ancient, because from antiquity, the impacts of earthquakes have drawn attention, and modern because only since the middle of the nineteenth century has it been possible to study earthquake phenomena more comprehensively from a scientific and methodological point of view. Seismology has its own object of study, methods, tools, and instrumentation. The object is borrowed from geology, the methods are physical, the basic tools are mathematical, and the instrumentation is mainly mechanical and electronic.

1.1. History and Development

Earthquakes have played an important role in the geological history of our planet. The first descriptions of earthquakes come from China and refer to 3000-2000 BC. In world histories, the strongest events since 2000 BC are dated. Considerations on the nature of the phenomena also appeared early. Thales of Milet (ca. 700-600 BC) thought Earth was a sphere floating in water and high seas caused earthquakes. Heraklit (ca. 600-500 BC) thought fire was at the root of everything and assumed volcanoes caused earthquakes. Aristotle (ca. 400 BC) considered earthquakes were the result of “dense air and vapors” within Earth. The Chinese mathematician and astronomer Chan Hen constructed the first seismoscope in AD 132.

Many centuries of accumulation of knowledge in all fields of natural sciences passed. In the second half of the seventeenth century, the English scientist Robert Hook published the fundamental law of the elasticity theory (1678). The development in mechanics and mathematics during the first half of the nineteenth century stimulated progress in seismology. In 1828, the Frenchman S.D. Poisson predicted theoretically the existence of longitudinal and transverse elastic waves. In the period 1828-1831, Poisson and the Russian scientist M. Ostrogradski wrote the first works on general methods for integrating the equations of the elasticity theory. In England in 1837, J. Green introduced the elastic potential and determined that 21 elastic modules characterized the anisotropic bodies. The Englishman G.G. Stocks presented the first mathematical model of earthquake sources. The German scientist G. Kirchoff gave the solution of the wave equation in 1855. The Irish researcher Robert Mallet used the accumulated knowledge in studying the strong earthquake of 1857 in Naples, Italy and realized the first attempt of applying the physical principles for explanation of the earthquake impacts. In this sense, he is probably the founder of the physics of earthquakes. It is impossible herein to mention all the results obtained, so a short chronological list is given below:

1879–1880	A group of English scientists constructed seismographs in Japan.
1883	The 10-grade macroseismic scale of Rossi-Forel was developed.
1885	Lord Rayleigh (England) theoretically predicted the existence of surface waves.

1887	Seismological stations were installed in California.
1889	The first distant earthquake (in Japan) was recorded in Potsdam, Germany, on April 17.
1892	In Japan, the English scientist J. Milne constructed a seismograph suitable for the creation of a world network of stations.
1897	R.D. Oldham (England) showed that records of distant earthquakes consisted of three waves: first and second “preliminary” (now P and S) and “large” (now surface) waves.
1898	In Japan, F. Omori constructed seismographs which became widely used in the world.
1900	Omori created the first version of the Japanese sever-grade macroseismic scale.
1901	Wiechert constructed the “Wiechert” astatical seismograph.
1903	The International Seismological Association (now IASPEI) was founded; E.H. Love, England, developed the theory of point sources.
1904	H. Lamb (England) set forth the theoretical fundamentals of wave propagation in a layered medium.
1906	B.B. Galitzin (Russia) constructed the first electromagnetic seismograph which revolutionized seismological recording; H.F. Reid (USA) created the elastic rebound theory of earthquake source studying the April 18 disastrous earthquake in California (published 1910).
1909	The Croatian scientist A. Mohorovičić discovered the boundary between the crust and mantle, now known as Moho discontinuity.
1910	L. Geiger (Germany) created a method for determining the earthquake hypocenter parameters.
1911	Love worked out the theory of the horizontally polarized surface waves.
1912	The Mercalli-Cankani-Sieberg (MCS) 12-grade macroseismic scale was created.
1913	B. Gutenberg (Germany) determined the radius of Earth’s core.
1918	The first volume of the International Seismological Summary (ISS) was published.
1922	H.H. Turner (England) suspected the existence of deep-focus earthquakes. (Their existence was confirmed by K. Wadati [Japan] in 1928.)
1923	The Great Kanto earthquake occurred in Japan, demolishing Tokyo and Yokohama; the Earthquake Research Institute (ERI) was established.
1925	The Wood-Anderson short-period torsion seismograph was constructed in the USA.
1931	Wood and F. Neuman created the Modified Mercalli Scale (MM) for USA.
1935	Ch. Richter (USA) published the magnitude scale for nearby earthquakes.
1936	Inge Lehmann (Denmark) proved the existence of a solid inner core.
1940	H. Jeffreys (England) and K.E. Bullen (Australia) published the contemporary seismological travel times tables.
1945	Gutenberg published the teleseismic magnitude scales; Gutenberg and Richter introduced the earthquake recurrence law.
1948	G.A. Gamburtsev (Russia) suggested the establishment of earthquake prognostic sites
1951	The European Seismological Commission (ESC) was established.
1952	H. Honda (Japan) published the methodology for determining the earthquake mechanism.
1960	Earth’s free oscillations were recorded after the strong Chile earthquake

1964 The International Seismological Center started publishing the ISC bulletin; the 12-grade macroseismic scale of Medvedev-Sponheuer-Karnik (MSK) was published.

1965 The large aperture seismic array (LASA) in Montana (USA) was put into operation.

1966 K. Aki, Japan, introduced the seismic moment.

1967 Global seismicity and earthquake generation was connected with plate tectonics.

1970 NASA sent a seismograph to the Moon and obtained the first moonquake records.

1975 The strong earthquake of 4 February in China was successfully predicted.

1979 The IASPEI Manual of Seismological Observatory Practice was issued.

1985 The Norwegian regional mini seismic array (NORESS) was put into operation.

1990 The International Decade for Natural Disaster Reduction (IDNDR) was launched.

1.2. Main Problems and Trends

So far, there is not any generally adopted scheme concerning the main problems, branches, and trends of seismology. Taking into consideration the known views a synthesized generalization has been attempted.

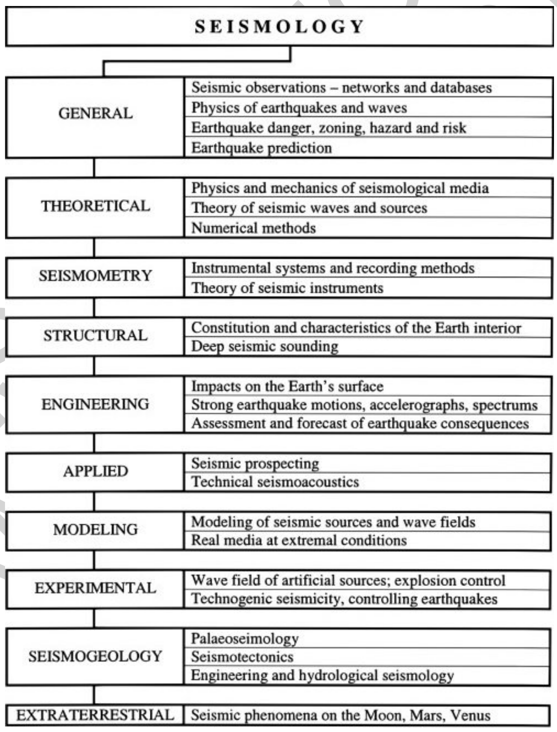

Figure1. Main branches of seismology

The following main problems can be considered: (1) the study of earthquakes as a manifestation of contemporary geological activity; (2) clarification of the nature and properties of earthquake sources; (3) investigation of Earth's wave field, and the kinematic and dynamic parameters of seismic waves; (4) a solution to the direct and inverse problems concerning Earth's structure and internal properties; (5) elaboration on the theoretical basis of seismic sources and waves; (6) data recording, processing, storage, and distribution of realized seismic events; (7) improved methods and instrumentation for recording seismic waves; (8) evaluation of seismic hazard and risk; (9) better prediction of earthquakes.

The main branches and trends of seismology are schematically given in Figure 1. The classical branches as well as the newly formed ones, such as the experimental or the extraterrestrial seismology, are included. The main branches are presented on the right of the diagram.

1.3. Earth's Earthquake Activity

Earthquakes are not evenly and randomly distributed on Earth. They are concentrated along the so-called seismic belts, which coincide with the contact zones between the largest geostructures: the tectonic plates (see *Tectonic Processes*). The main ones are the Pacific, Eurasian, American, African, Indian, Arctic, Nasca, and Philippine plates. The contact zones are formed by three types of boundaries: constructive (divergent, spreading), destructive (convergent, colliding) and transform faults. The oceanic ridges along which the plates move apart from one another (spreading zones) and form the new oceanic crust are constructive zones. The spreading velocity along the mid-Atlantic ridge varies between 1 and 10 cm per year, and in the Pacific the velocity is, on average, 5 cm per year. The destructive boundaries are the result of collisions between opposing plates, which the subduction (Wadati-Benioff) zones in the oceans. The transform faults are regulators of the relative horizontal movements and displacements between lithospheric plates. The reasons for the relative movements of the plates are connected with the convective fluxes in the mantle under conditions of an active lithosphere, i.e., with the behavior of heavy solid bodies or plates "floating" on a plastic or partially melted astenosphere.

The strongest earthquakes are associated with collision zones and transform faults. According to the source depth, the earthquakes are divided into three groups: shallow (surface to 70 km), intermediate (70–300 km), and deep events (300–700 km). Deep earthquakes are typical for subduction zones, their depth increasing from the contact line between the plates in the direction of sinking of one plate.

There are two main earthquake belts—the Pacific Ocean belt (PO) and the Alpo-Himalayan belt (AH). The PO belt almost completely encircles the Pacific in the transition sections towards the land. The AH belt passes from the Atlantic through the Mediterranean Sea, Minor and Middle Asia, the Himalayas, China, and Indo-China (divided into northern and southern branches) and ends on the Pacific coast. The secondary belts are the Atlantic, Indian, and South African belts. The dominant annual portion of the earthquake energy is realized along the PO belt (75–80%) and the AH belt (15–20%), while only about 5% is attributed to all other belts.

An assessment of earthquake frequency can be obtained from the recurrence law of Gutenberg-Richter, expressed by the relation

$$\log N = a - bM$$

where N is the annual number of earthquakes of magnitude M with a mean recurrence period $T = 1/N$ (measured in years) and a and b are empirical coefficients. An approximate evaluation of these coefficients for Earth is $a = 7.8$ and $b = 0.9$ ($a = 6.7$, $b = 0.9$ for shallow events with $M \geq 6$).

The mean annual sum of realized earthquake energy is almost a constant and is of the order of 1–2 10^{18} J. In Table 1 the mean parameters for the different earthquake categories are given. Earthquakes with $M \geq 5$ can cause unfavorable consequences. It is seen that the first two categories—the great and major events—form the annual sum of the realized earthquake energy. The seismological stations in the world record annually more than 100,000 earthquakes, most of which are very small.

Category	**Magnitude** (M)	**Energy** (E) $\log(E) = 4.8 + 1.5M$ (J)	**Mean annual events** (N)
Great	>8	$>10^{17}$–10^{18}	1–2
Major	7–8	10^{15}–10^{17}	15–20
Strong	6–7	10^{14}–10^{15}	100–150
Moderate	5–6	10^{12}–10^{14}	750–1000
Light	4–5	10^{11}–10^{12}	5000–7000
Minor	<4	$<10^{11}$	>100 000

Table 1. Categories of Earth's earthquakes and the parameters that define them

Some historical earthquakes that left enduring traces in the memories of eyewitnesses and deserved the specialist's attention should be noted. One example is the Lisbon earthquake of November 1, 1755, with an epicenter in the Atlantic Ocean. Lisbon and vicinity were almost completely ruined, and because of the high tsunami waves, the casualties were about 50000. The earthquake of October 28, 1891, in Mino-Ovari, Japan, left strong traces on Earth's surface. After the earthquake, a fault of 100 km was formed with relative horizontal and vertical displacements up to 4 m and 7 m, respectively. About 197 000 buildings were demolished and casualties were over 7000. The most stupendous and well documented historical earthquake is that in Assam (India) of June 12, 1897. Destruction was observed over an area of 350 000 km^2, and in the epicentral zone, over 75 000 km^2, everything manmade was demolished. People observed Earth waves with amplitudes of about 30 cm. In the epicentral zone, strong changes in the landscape were observed and the faults had amplitudes up to 12 m.

Information on more recent earthquake activity after 1900 can be obtained from Table 2, where some data on the most destructive events are listed. In the number of casualties, two events stand out, the first one in Japan in 1923 and the second one in China in 1976.

Date	**Magnitude**	**Deaths**	**Damage (10^6 US$)**	**Region**

1902-04-19	8.3	2 000	>	Guatemala
1904-04-04	7.8	>105	>	Struma, Bulgaria
1905-04-04	8.6	20 000	>>	N India
1906-04-18	8.3	700	400	California, USA
1906-08-17	8.6	3 760	>	Chile
1908-12-28	7.5	75 000	>>	Messina, Italy
1909-01-23	7.3	5 500	?	Iran
1918-02-13	7.3	100 000	>>	Kwantung, China
1920-12-16	8.5	100 000	>>	Kansu, China
1923-09-01	8.3	142 807	2800	Tokyo, Japan
1927-05-22	8.0	40 912	>>	Nan Shan, China
1934-01-15	8.4	10 700	>>	Nepal, India
1939-01-25	8.3	28 000	100	Chile
1939-12-26	7.9	32 700	>>	E Turkey
1944-01-15	7.8	8 000	100	S Argentina
1948-10-05	7.3	19 800	>>	Ashkhabat
1950-08-15	8.6	1 526	2000	Assam, India
1957-12-13	7.3	2 000	>	Iran
1960-02-29	5.9	12 000	>>	Agadir, Morocco
1960-05-22	8.5	5 700	675	Chile
1962-09-01	7.3	12 225	>>	NW Iran
1963-07-26	6.1	1 070	500	Skopje, Macedonia
1964-03-28	8.5	115	538	Alaska, USA
1968-08-31	7.3	15 000	10	Iran
1970-05-31	7.8	66 000	530	N Peru
1974-05-10	6.8	20 000	?	Yunnan, China
1976-02-04	7.5	23 000	1100	Guatemala
1976-07-27	8.0	655 237	>>	Tangshan, China
1977-03-04	7.2	1 500	800	Vranchea, Romania
1980-10-10	7.3	3 500	>>	El Assnam, Algeria

Table 2. Some significant earthquakes after 1900

Earthquakes are some of Earth's worst disasters. Statistically, after 1970 earthquakes dominate with about 35% of the world's damage and casualties, while floods and tropical cyclones each account for 20%. The annual risk for casualties is evaluated to be 2–3 × 10^{-6}, while the risk of flu or car accidents is significantly larger, about 2 × 10^{-4}. The high consequences of earthquakes are explained by two main factors. The first one is connected with the environmental conditions and socio-economic development. Approximately a quarter of dry land falls in active seismic zones. Such zones cover the most climatically and geographically favorable regions with a significant concentration of human and material resources, and therefore, a higher risk when seismic events occur. The second factor is determined by the still limited efficiency of earthquake resistance measures, and in some cases, by underestimation or neglect of the real danger from earthquakes. From this viewpoint, humankind owes much to seismology, earthquake engineering, and some socio-economic sciences.

-
-
-

Bibliography

Aki K. and Richards P.G. (1980). *Quantitative Seismology*. Vols. I and II. 932 pp. San Francisco: W.H. Freeman. [This presents general aspects of theoretical seismology in a very advanced and comprehensive way.]

Bath M. (1968). *Mathematical Aspects of Seismology*. 415 pp. Amsterdam: Elsevier. [This presents the mathematical background of seismology.]

Bath M. (1981). Earthquake magnitude—recent research and current trends. *Earth Science Reviews* **17**, 315–398. [This presents a comprehensive reference on earthquake energy classification.]

Ben-Menahem A. and Singh S.J. (1981). *Seismic Waves and Sources*. 1108 pp. New York: Springer-Verlag. [This presents the basic problems of seismic wave generation and propagation using the vector calculus approach.]

Bullen K.E.and Bolt B.A. (1987). *An Introduction to the Theory of Seismology*. 499 pp. London: Cambridge University Press. [This book covers all aspects of general seismology at the university level.]

Christoskov L., Kondorskaya N.V., and Vanek J. (1979, 1983). *Homogeneous Magnitude System of the Eurasian Continent.* Part I*: P waves*. 57 pp. Part II: *S and L waves*. 44 pp. Boulder, Colorado: World Data Center A for Solid Earth Geophysics. [This presents a complete reference on the magnitude classification of seismic events.]

Dziewonski A.M. and Anderson D.L. (1981). Preliminary reference Earth model. *Physics of the Earth and Planetary Interiors* **25**, 297–356. [This presents the data on the recent "PREM" model of Earth.]

Fisher R.V. and Shmincke H.-U. (1984). *Pyroclastic Rocks*. 472 pp. Berlin: Springer-Verlag. [This provides extensive information about volcanoes and volcanic rocks.]

Gadomska B. (1983). *The Mechanism of Earthquakes—A Review of the Graphical Representation of Fault-Plane Solutions*. 87 pp. Finland: Institute of Seismology–University Helsinki. [This explains practical approaches to earthquake mechanism solutions.]

Ganse R.A. and Nelson J.B. (1981). *Catalog of Significant Earthquakes 2000 B.C.-1979*, 154 pp. Boulder, Colorado: W.D.C. A for Solid Earth Geophysics. [This is a complete reference of the main parameters of the strong earthquakes, damage assessments inclusive].

Gutenberg B. and Richter C.F. (1954). *Seismicity of the Earth and Associated Phenomena*. Second edition. 310 pp. Princeton: University Press [This is aclassic book on Earth's seismic activity.]

Karnik V. (1968, 1971). *Seismicity of the European Area*. Part I. 364 pp. Praha: Academia. Part II. 219 pp. Dordrecht, Holland: D. Reidel. [This is a comprehensive reference on European seismicity.]

Macdonald G.A. (1972). *Volcanoes*. 510 pp. Englewood Cliffs, New Jersey: Prentice-Hall. [This classic book provides comprehensive information about volcanology and volcanoes.]

Miachkin V.I. (1978). *Processes of Earthquake Preparedness*. [in Russian.] 232 pp. Moscow: Nauka. [This presents the physical nature of earthquake sources and the relevant prediction methods.]

Oliver C. (1988). *Volcanoes*. 228 pp. Oxford: Basil Blackwell. [This presents an account of volcanoes, their activity, and their geographical and social importance.]

Proceedings of the Seminar on Earthquake Prediction Case Histories. (1983). 207 pp. Geneva: United Nations Disaster Relief Organization. [This is a summary of internationally used approaches in earthquake prediction, including successful predictions.]

Rikitake T. (1976). *Earthquake Prediction*. 357 pp. Amsterdam: Elsevier. [This is a review book on earthquake prediction.]

Willmore P.L., ed. (1979). *Manual of Seismological Observatory Practice*. Boulder, Colorado: World Data Center A for Solid Earth Geophysics. [This present methods and approaches used in the practice of seismology.]

Wood R.M. (1987). *Earthquakes and Volcanoes*. 160 pp. New York: Weidenfield and Nicolson. [This provides easy-to-read information on earthquake and volcano activity.]

Biographical Sketch

Ludmil Christoskov ,was born in 1936 in Sofia, Bulgaria. He is a graduate of the Mining and Geology University, receiving his master's degree in Geophysics in 1959. He has worked more than 40 years in the section of Seismology at the Geophysical Institute of the Bulgarian Academy of Sciences. His major interests cover the problems of regional seismology, geodynamics and natural hazard evaluations, investigation and modeling of the geophysical media, etc. He gained his PhD degree in 1972, became Associate Professor of Seismology in 1973, received a DSc in Physical Sciences in 1984, and became Professor in Seismology in 1986. Since 1977, Professor Christoskov has been a titular lecturer in Seismology in the Meteorology and Geophysics Department of Sofia University. He is a member of the International Association of Seismology and Physics of the Earth's Interior, the European Seismological Commission, the Bulgarian Geophysical Society, the International Students Institute–Tokyo and was the Chairman of the Expert Council for seismic risk at the National Coordinating Council of the Permanent Government Commission of Natural Disasters in 1991. Since 1995 he has been Corresponding Member of the Bulgarian Academy of Sciences. Professor Christoskov is author or co-author of over 250 publications and 10 monographs published in Bulgaria and abroad. The main topics of the publications are quantification of the earthquakes, seismological networks and data processing, seismicity and seismic zoning, seismic sources modeling and identification, prognostic approaches in seismology, etc. A textbook on seismology authored by Professor Christoskov is in press.