EARTHQUAKES

An earthquake is the sudden movement of the ground caused by the rapid release of energy that has accumulated along fault zones in the earth's crust. The earth's fundamental structure and composition are revealed by earthquakes through the study of waves that are both reflected and refracted from the interior of the earth.

PRINCIPAL TERMS

- **crust:** the uppermost 5-40 kilometers of the earth
- **deformation:** a change in the shape of a rock
- **elastic rebound:** the process whereby rocks snap back to their original shape after they have been broken along a fault as a result of an applied stress
- **lithosphere:** the solid part of the upper mantle and the crust where earthquakes occur
- **mantle:** the thick layer under the crust that contains convection currents that move the crustal plates
- **strain:** the percentage of deformation resulting from a given stress
- **stress:** a force per unit area

Stress

Earthquakes are sudden vibrational movements of the earth's crust and are caused by a rapid release of energy within the earth. They are of critical importance to humans because they reveal much about the interior of the earth and because they are one of the most destructive naturally occurring forces found on earth.

The outermost skin of the earth, called the crust, is in constant motion as a result of large convection cells within the upper mantle that circulate heat from the interior of the earth toward the surface. The crust of the earth is about 5 kilometers thick in the oceanic basins and about 40 kilometers thick in the continental masses, while the upper mantle is about 700 kilometers thick. Because the crust is relatively thin compared to the upper mantle, the crust is broken up into several plates that float along the top of each convection cell in the upper mantle. Most earthquakes occur along the boundaries separating the individual plates and are represented by faults that may be thousands of kilometers long and tens of kilometers deep. Although the vast majority of earthquakes occur along these plate boundaries, some also occur within the plate interior. The rocks on either side of the fault fit tightly together and produce great resistance to movement. As the blocks of rock attempt to move against one another, the resistance of movement causes stress, which is a force per unit area, to build up along the fault. As the stress continues to build, the rocks in the immediate vicinity slowly deform, or bend, until the strength of the rock is exceeded at some point along the fault. Suddenly, the rocks break violently and return to their underformed state, much as a rubber band snaps to its original shape when it breaks. This rapid release of stress is called elastic rebound. The point at which the stress is released is called the focus of an earthquake, and that point at the earth's surface directly above the focus is called the epicenter.

Seismic Wave Motion

The release of energy associated with elastic rebound manifests itself as waves propagating away from the focus. When these waves of energy reach the surface of the earth, the land will oscillate, causing an earthquake. These waves move through the earth in two ways.

P (primary) waves move in a back-and-forth motion in which the motion of the rock is in the same direction as the direction of energy propagation. This type of wave motion is analogous to placing a spring in a tube and pushing on one end of the spring. The motion of the spring in the tube is in the same direction as is the motion of the energy. These waves are called primary because they move through the earth faster than do other waves—up to about 25 kilometers per second. Thus, P waves are the first waves to be received at a seismic recording station. Because the individual atoms in a rock move back and forth along the direction of energy movement, P waves can move through solids and liquids and, for this reason, do not tell geologists much about the state (solid or liquid) of a given rock at depth.

In contrast to P waves, for S waves, the rock motion is perpendicular to the direction of energy propagation. Guitar strings vibrate in a similar manner. Each part of the guitar string moves back and forth while the energy moves along the string to the ends. S waves are the second waves to be received at a seismic recording station and derive their name from this fact. Unlike P waves, S waves cannot move through liquids but can move through solids. Thus, when a P wave is received by a seismic station but is not followed by an S wave, seismologists know that a liquid layer is between the focus of the earthquake and the receiving seismic station.

Both S and P waves are bent, or refracted, as they move in the earth's interior. This refraction occurs as the result of the increase in density of rocks at greater depths. Furthermore, both types of waves are reflected off sharp boundaries, representing a change in rock type located within the earth. Thus, by using these properties of S and P waves, geologists have mapped the interior of the earth and know whether a given region is solid or liquid.

Although S and P waves represent the way seismic energy moves through the earth, once this energy reaches the earth's surface, much of it is converted to another type of wave. L (Love) waves move in the same manner as do S waves, but they are restricted to surface propagation of energy. L waves have a longer wavelength and are usually restricted to within a few kilometers of the epicenter of an earthquake. These waves cause more damage to structures than do P and S waves because the longer wavelength causes larger vibrations of the earth's surface.

Earthquake Intensity

The amount of energy released by an earthquake is of vital importance to humans. Many active fault zones, such as the famous San Andreas Fault in California, produce earthquakes on an almost daily basis, although most of these earthquakes are not felt and cause no damage to human-made structures. These minor earthquakes indicate that the stress that is accumulating along some portion of a fault is continuously being released. It is only when the stresses accumulate without continual release that large, devastating earthquakes occur. The intensity of an earthquake is dependent not only on the energy released by the earthquake but also on the nature of rocks or sediments at the earth's surface. Softer sediments such as the thick muds that underlie Mexico City will vibrate with a greater magnitude than will the very rigid rocks, such as granites, found in other parts of the world. Thus, the great earthquake that devastated Mexico City in 1985 was in part the result of the nature of the sediments upon which the city is built.

For a given locality, earthquakes occur in cycles. Stress accumulates over a period of time until the forces exceed the strength of the rocks, causing an increase in minor earthquake activity. Shortly thereafter, several foreshocks, or small earthquakes, occur immediately before a large earthquake. When a large earthquake occurs, it is usually followed by many aftershocks, which may also be rather intense. These aftershocks occur as the surrounding rocks along the fault plane readjust to the release of stress by the major earthquake. The cycle then repeats itself with a renewed increase in stress along the fault. Although seismologists can usually tell which part of the seismic cycle a region is experiencing, it is difficult to predict the duration of each of these cycles; thus, it is impossible to predict precisely when an earthquake will occur.

Seismographs

Seismographs are the primary instruments used to study earthquakes. All seismographs consist of five fundamental elements: a support structure, a pivot, an inertial mass, a recording device, and a clock. The support structure for a seismograph is always solidly attached to the ground in such a fashion that it will oscillate with the earth during an earthquake. A pivot, consisting of a bar attached to the support structure via a low-friction hinge, separates a large mass from the rest of the seismograph. This pivot allows the inertial mass to remain stationary during an earthquake while the rest of the instrument moves with the ground. The recording device consists of a pen attached to the inertial mass and a roll of paper that is attached to the support structure. Finally, the clock records the exact time on the paper so that the time of arrival of each wave type is noted. When an earthquake wave arrives at a seismic station, the support structure moves with the ground. The inertial mass and the pen, however, remain stationary. As the paper is unrolled, usually by a very accurate motor, the wave is recorded on the paper by the stationary pen. Modern seismographs, however complex in design, always contain these basic elements. The clock, which each minute places a small tick mark on the recording, is calibrated on a daily basis by a technician using international time signals from atomic clocks. The recording pen often consists of an electromagnet that converts movement of the inertial mass relative to the support structure to an electrical current that drives a light pen. The light pen emits a narrow beam of light onto long strips of photographic film that are developed at a later date. Digital seismographs record measurements electronically using computers. A global network of these machines is overseen by the FDSN, the International Federation of Digital Seismograph Networks.

Richter and Mercalli Scales

Seismologists have adopted two widely used scales, which are called the Richter and Mercalli scales, to measure the energy released by an earthquake. The Richter magnitude scale is based on the amplitude of seismic waves that are recorded at seismic stations. Because seismic stations are rarely located at the epicenter of earthquakes, the amplitude of the seismic wave must be corrected for the amount of energy lost over the distance that the wave traveled. Thus, the Richter magnitude reported by any seismic station for a given earthquake will be approximately the same. Richter magnitudes are open-ended, meaning that any amount of seismic energy can be calculated. The weakest earthquakes have Richter magnitudes less than 3.0 and release energy less than 10^{14} ergs. These earthquakes are not usually felt but are recorded by seismic stations. Earthquakes between magnitudes 4.0 and 5.5 are felt but usually cause no damage to structures; they release energy between 10^{15} and 10^{16} ergs. Earthquakes that have magnitudes between 5.5 and 7.0 cause slight to considerable damage to buildings and release energy between 10^{18} and 10^{24} ergs. Earthquakes that are greater than 7.5 on the Richter scale generate energy up to 10^{25} ergs—as much as a small nuclear bomb.

The Mercalli intensity scale is based not on the energy released by an earthquake but rather on the amount of shaking that is felt on the ground; it rates earthquakes from Roman numerals I to XII. Unlike the Richter scale, the Mercalli scale provides descriptions of sensations felt by observers and of the amount of damage that results from an earthquake. Thus, an earthquake of Mercalli intensity I is felt by only a very few persons, while an earthquake of intensity XII causes total destruction of virtually all buildings.

Both the Mercalli and Richter scales have advantages and disadvantages. The Mercalli scale provides the public with a more descriptive understanding of the intensity of an earthquake than does the Richter scale. The damage caused by an earthquake is a function not only of the energy released by such an event but also of the nature of the sediments or rocks upon which the buildings in the vicinity are constructed. The Richter scale is best used to study specifically the amount of energy released by an earthquake. Finally, the Richter scale, which is purely quantitative, does not rely on subjective observations such as those required by the Mercalli scale.

Triangulation Techniques

The exact location of an earthquake epicenter can be deduced from three seismographic stations using triangulation techniques. Because the P and S waves travel at different velocities in the earth, seismologists can determine the distance from the station to the epicenter. They calculate the difference in time between the first arrival of the P and S waves, respectively, at the station. They then multiply this time difference by the product of the P and S velocities and divide by the difference in wave velocities to obtain the distance to the epicenter. The earthquake must have occurred along a circle whose radius is the distance so calculated and whose center is the seismographic station; any three stations that record the event can be used to draw three such circles, which will intersect at a single point. This point is the epicenter.

Earthquake Prediction

Earthquakes are one of the most important processes that occur within the earth because they have such a profound effect on how and where people should develop cities. Geologists understand how and where earthquakes occur, yet despite their best efforts, they still cannot accurately determine when an earthquake will happen. They are merely able to predict that a large earthquake will occur in a particular region "in the near future." Very great earthquakes of magnitude 8 or greater, such as the San Francisco earthquake of 1906, occur about every five to ten years throughout the world. Industrialized societies, such as Japan, the United States, and many European countries, have developed buildings that are capable of withstanding devastating seismic catastrophes, but other countries are not as fortunate. Furthermore, some great earthquakes occur in regions that are not considered seismically active. The great Charleston, South Carolina, earthquake of 1886 and the Tangshan, China, earthquake of 1976 are examples of seismic events that could not have been easily predicted using modern technology. In such regions, buildings are not designed to withstand devastating earthquakes. Finally, many regions of the world do not experience earthquakes on a daily basis and, therefore, their governments lack the motivation to plan adequately for such potentially catastrophic events.

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Further Reading

Abaimov, S. G., et al. "Earthquakes: Recurrence and Interoccurrence Times." *Pure and Applied Geophysics* 165 (2008): 777-795. Provides an analysis of the statistical probability of earthquake recurrence at the San Andreas Fault. Background in statistics needed to fully comprehend equations.

Bolt, Bruce A. *Earthquakes and Geological Discovery*. New York: Scientific American Library, 1993. As the title suggests, an excellent introductory text on earthquakes. Earthquake prediction is discussed extensively in one chapter. The illustrations and photographs of the effects of earthquakes add considerably to the text. Anyone interested in earthquakes will find this an invaluable source.

Doyle, Hugh A. *Seismology*. New York: John Wiley, 1995. A good introduction to the study of earthquakes and the earth's lithosphere. Written for the layperson, the book contains many useful illustrations.

Emergency Management BC. *A Simple Explanation of Earthquake Magnitude and Intensity*. Ministry of Public Safety and Solicitor General, Provincial Emergency Program. 2007. Provides fundamental content on earthquakes, written for the layperson.

Farley, John E. *Earthquake Fears, Predictions, and Preparations in Mid-America*. Carbondale: Southern Illinois University Press, 1998. This book examines seismic activity, the practice of predicting earthquakes, and the hazards associated with them, focusing on the American Midwest. Bibliography, charts, and index.

Grotzinger, John, et al. *Understanding Earth*. 5th ed. New York: W. H. Freeman, 2006. This text includes one of the most complete descriptions of the causes of earthquakes, their measurement, where they occur, how they can be predicted, and how they affect humans. A map of the major plates is on the inside back cover. The glossary is huge and indispensable. Senior high school and college-level students should find this text suitable for general background information.

Hodgson, John H. *Earthquakes and Earth Structure*. Englewood Cliffs, N.J.: Prentice-Hall, 1964. This source provides the reader with an understanding of how earthquakes have been used to determine the structure and composition of the interior of the earth.

Hough, Susan. *Predicting the Unpredictable: The Tumultuous Science of Earthquake Prediction*. Princeton, NJ; Princeton University Press. 2010. The author provides a detailed, but non-technical description of the history of earthquake predictions. She identifies unresolved issues scientists have in making predictions. This text has a wide range of information.

McKenzie, D. P. "The Earth's Mantle." *Scientific American* 249 (September 1983): 66-78. This article, written at the college undergraduate level, is a very complete description of current scientific understanding of the interior of the earth.

Nichols, D. R., and J. M. Buchanan-Banks. *Seismic Hazards and Land-Use Planning*. U.S. Geological Survey Circular 690. Washington, D.C.: Government Printing Office, 1974. The effect of earthquakes on human-made structures is discussed in this short bulletin. Written explicitly for the layperson by the United States government, it provides additional sources of information for land-use planning.

Press, Frank. "Earthquake Prediction." *Scientific American* 232 (May 1975): 14-23. Press's article details geologists' current understanding of earthquake prediction. Also provides a discussion of the methods by which earthquakes can be predicted. Written at the college undergraduate level.

Prothero, Donald R. *Catastrophes!: Earthquakes, Tsunamis, Tornadoes, and Other Earth-Shattering Disasters*. Baltimore: Johns Hopkins University Press, 2011. This text provides a detailed and clear explanation of the many natural and anthropogenic disasters facing our planet. Each chapter is devoted to a different catastrophe, including earthquakes, volcanoes, hurricanes, ice ages, and current climate changes.

Tarbuck, Edward J., Frederick K. Lutgens, and Dennis Tasa. *Earth: An Introduction to Physical Geology*. 10th ed. Upper Saddle River, N.J.: Prentice

Hall, 2010. This college text provides a clear picture of the earth's systems and processes that is suitable for the high school or college reader. It has excellent illustrations and graphics. Bibliography and index.

United States Department of the Interior. *Earthquake Information Bulletin*. Washington, D.C.: Government Printing Office. This bimonthly bulletin provides the reader with a concise understanding of where earthquakes occur in the United States and which regions are likely to be affected in the future. Also lists other sources of information on earthquakes. For general and specialized readers.

See also: Continental Drift; Creep; Deep-Focus Earthquakes; Earthquake Distribution; Earthquake Engineering; Earthquake Hazards; Earthquake Locating; Earthquake Magnitudes and Intensities; Earthquake Prediction; Earth's Interior Structure; Earth's Lithosphere; Earth's Mantle; Elastic Waves; Experimental Rock Deformation; Faults: Normal; Faults: Strike-Slip; Faults: Thrust; Faults: Transform; Heat Sources and Heat Flow; Lithospheric Plates; Mantle Dynamics and Convection; Notable Earthquakes; Plate Motions; Plate Tectonics; San Andreas Fault; Seismic Observatories; Seismic Wave Studies; Seismometers; Slow Earthquakes; Soil Liquefaction; Stress and Strain; Subduction and Orogeny; Tectonic Plate Margins; Tsunamis and Earthquakes; Volcanism.