

Chapter 6

Earthquakes

Introduction

Earthquakes are a shaking and vibration of the land surface. Such a phenomenon commonly is produced when rocks rupture during brittle failure along an old or new fault releasing stored up elastic strain energy as heat and seismic waves. However, it is important to note that not all earthquakes are generated by movement along brittlely failing faults. In fact, earthquakes can be generated during volcanic eruptions and nuclear explosions. Here, for the sake of simplicity, we only consider earthquakes generated during rupture along a new or old fault.

Seismic waves are waves of energy that elastically distort the material that they travel through. Hence, after a seismic wave has passed through an elastic body of rock, it returns to its original shape and volume (Figure 1).

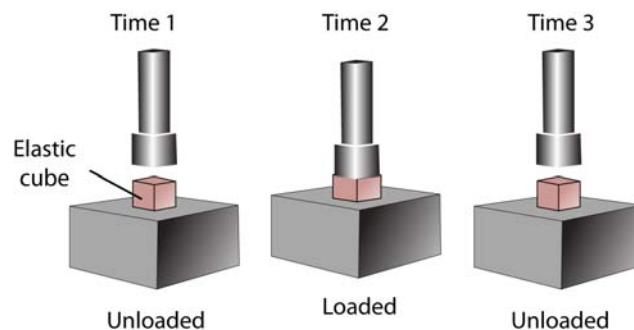


Figure 1. An elastic cube is loaded and then unloaded. During loading at time 2, the cube elastically distorts as it shortens in the direction of the applied load and extends at right angles to the free surface. At time 3 when the cube is unloaded, the elastic cube returns to its initial shape and volume. As seismic waves travel through the Earth, they act like the anvil, first loading and elastically distorting the rock that they encounter and then as they move onward unloading it.

Hypocenter and Epicenter

The region of initiation of seismic energy within the Earth during an earthquake is the focus or hypocenter (Figure 2). This is the initial region along which a new fault forms or an old fault ruptures. From the focus, slip along the fault spreads quickly. The position on the land surface immediately above the hypocenter is the epicenter (Figure 2). As rupture along a fault initiates, waves of energy travel outward from the hypocenter in a spherical fashion. These waves of energy are strongest nearest the hypocenter but gradually grow weaker further away from the site of initial rupture.

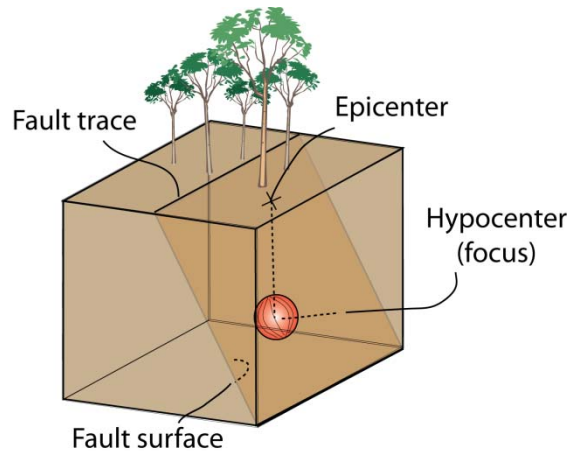


Figure 2. Schematic illustration of location of epicenter and hypocenter. Orange sphere is outward radiating seismic energy.

Body and Surface Waves

Seismic waves include body and surface waves. The former type of wave emanates spherically from the hypocenter traveling *entirely within* the interior of the Earth while the latter travels along *the surface* of the Earth emanating from the epicenter. Body waves are compressional or P-waves and shear or S-waves. Surface waves are Love and Rayleigh waves.

P- and S-waves

P-Waves. As the energy associated with P-waves moves outward in spherical fashion from the hypocenter it produces a series of contractions and expansions in the direction that it is traveling, i.e., in the wave propagation direction (Figure 3). During contractions, the distances between atoms in the material that the P-wave is passing through shorten, and as a result there is a small decrease in volume. During expansions, the distances between atoms in the material increase, and there is a small increase in volume. Following the complete passing of a P-wave, the elastically distorted Earth material returns to its original volume. P-waves can pass through liquids, solids, and gasses.

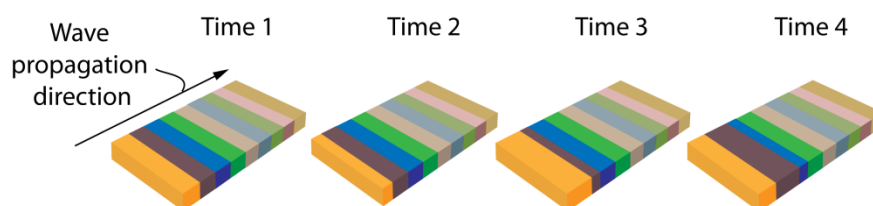


Figure 3. Time sequence showing effects of P-wave passing through a body of material. Note the orange cube at time 1 prior to the P-wave arriving. At time 2, the P-wave arrives and the orange cube contracts, and then at time 2 expands as the P-waves moves on to contracting the purple cube. At time 4 the orange cube returns back to its original volume while the purple cube expands as the P-wave moves on contracting the blue cube.

S-Waves. In contrast to P-waves, S-waves emanating outward in a spherical fashion from the focus produce shape rather than volumetric changes in Earth material (Figure 4). When an S-wave passes through the Earth it displaces particles in a direction perpendicular to the direction

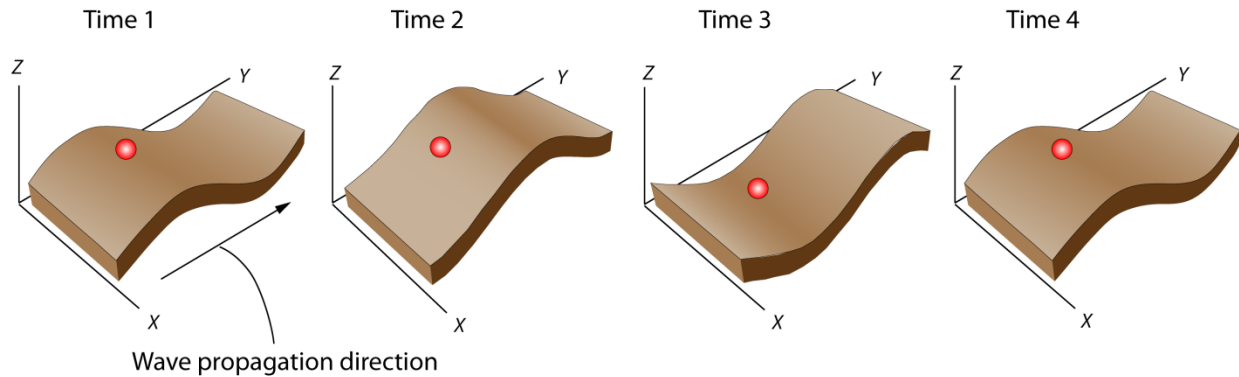


Figure 4. Time sequence showing effects of S-wave passing through a body of material. Note how the red particle riding on the S-wave moves up and down perpendicular to the wave propagation direction (i.e., parallel to Z axis).

that it is moving, i.e., its propagation direction. Because liquids cannot support a shape change, S-waves traveling through the interior of the Earth do not propagate through the liquid outer core and magma chambers.

Speeds of P- and S-Waves. Near the Earth's surface in continental regions P-waves can travel at speeds around 6 km/sec while S-waves travel at speeds around 3.5 km/sec. Because P-waves are faster than S-waves they arrive at seismic stations earlier than S-waves. For this reason they are often referred to as **primary waves** while the slower traveling S-waves, arriving a little later than the P-waves at the seismic station, are sometimes called **secondary waves**.

Surface Waves

Rayleigh Waves. Rayleigh waves as they move along the surface of the Earth distort it into a form much like an ocean wave (Figure 5). In other words, they displace the land surface at right angles to the direction that they are traveling. This displacement, though like that produced by an S-wave, dies out with depth.

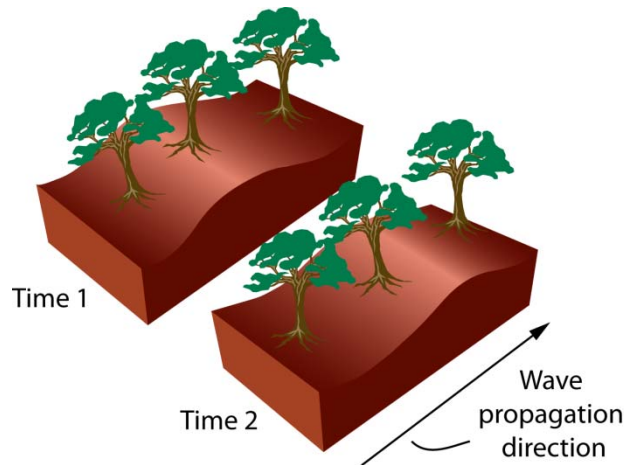


Figure 5. Rayleigh waves distort the land surface into a series of ocean-like waves that die out with depth.

Love Waves. Love waves displace Earth material at the surface in a horizontal snake-like motion (Figure 6). They do not travel through water.

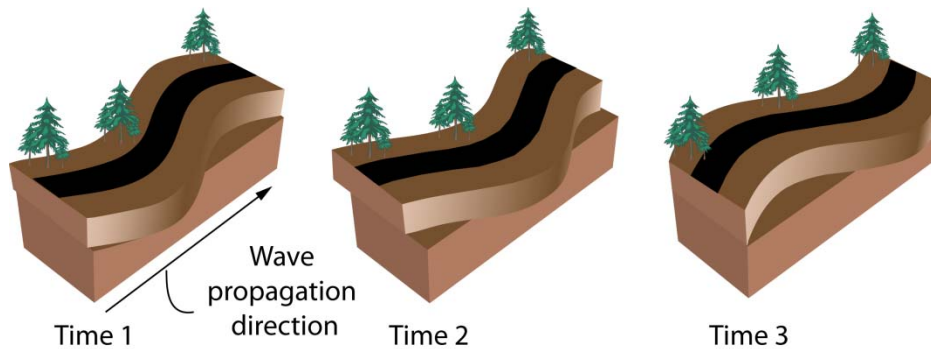


Figure 6. Love waves move in a snake-like motion parallel to the Earth's surface.

Destructiveness of Seismic Waves

Both Rayleigh and Love waves are more destructive to buildings than are P- and S-waves. Because of the vertical motion produced by Rayleigh waves they tend to be the most destructive while the back and forth motion of Love waves can knock buildings off their foundations.

Seismograph

A seismograph is the device used to record the vibrations produced during an earthquake. The idea behind many seismographs involves the concept of inertia. Our physics colleagues tell us that inertia is the resistance a mass has to sudden movement. In general, the greater the weight of an object, the greater it will resist movement during an earthquake.

Seismologists are geologists that study earthquakes. They have used the idea of inertia in their construction of so called “inertial seismographs”. In practice they suspend a dense heavy object from a spring or wire (Figure 7). Because of its great weight, the suspended object has so much resistance to movement that when the spring or wire it is attached to is suddenly extended during an earthquake it does not move. As shown in Figure 7, a pen attached to the dense object is in contact with paper fixed to an adjacent rotating drum. As the land surface vibrates during an Earthquake, the pen inscribes on the paper a record of the vibrations.

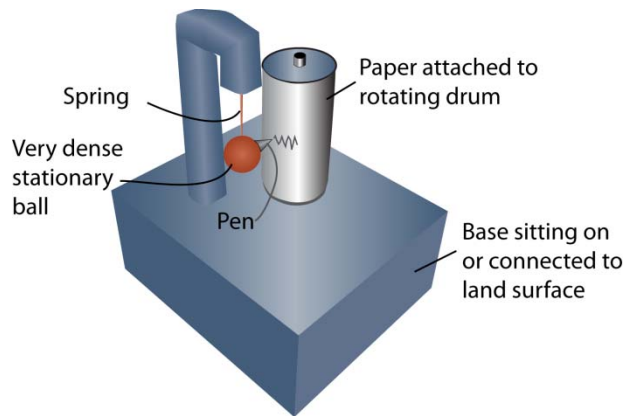


Figure 7. The key elements of an inertial seismograph are a very dense stationary ball holding a pen, and a piece of paper attached to a rotating drum. During an earthquake, the base and drum vibrate with the land surface. In contrast, the dense ball and attached pen do not. See text for additional discussion.

A typical record collected from a seismograph is shown in Figure 8. Note that the x-axis of the record is time while the y-axis is amplitude, a measure of the size of the seismic waves.

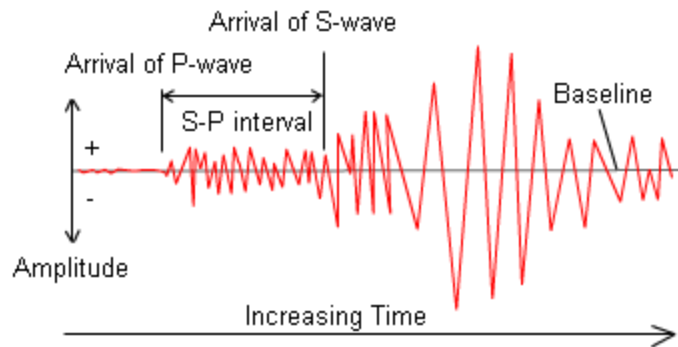


Figure 8. An example of a seismographic record or seismogram derived from an earthquake.

The S-P time interval is the delay in arrival time between the P- and S-waves. It is proportional to the distance traveled by the waves. In other words, the S-P time interval will be large at seismic stations located great distances from the epicenter and relatively small at stations located closer to the epicenter. As you will learn in the following sections, if the S-P

time interval is known from at least three different seismic stations, then it can be used to locate the epicenter of an earthquake.

Locating the Epicenter

Seismologists have placed seismographs throughout the world. They can locate the epicenters of most earthquakes from this array of seismographs, and the idea that P- and S-waves travel at different speeds.

In order to understand the basic principles behind determining the epicenter of an earthquake, consider the locations of the three seismic stations shown in Figure 9. If an earthquake occurs on the fault located between the three stations, then P- and S-waves will radiate outward in spherical fashion from the hypocenter. As shown in Figure 9, the P-wave will travel faster than the S-wave, and will reach each of the seismic stations before the S-wave. Moreover, the S-P interval increases from Station A to B to C.

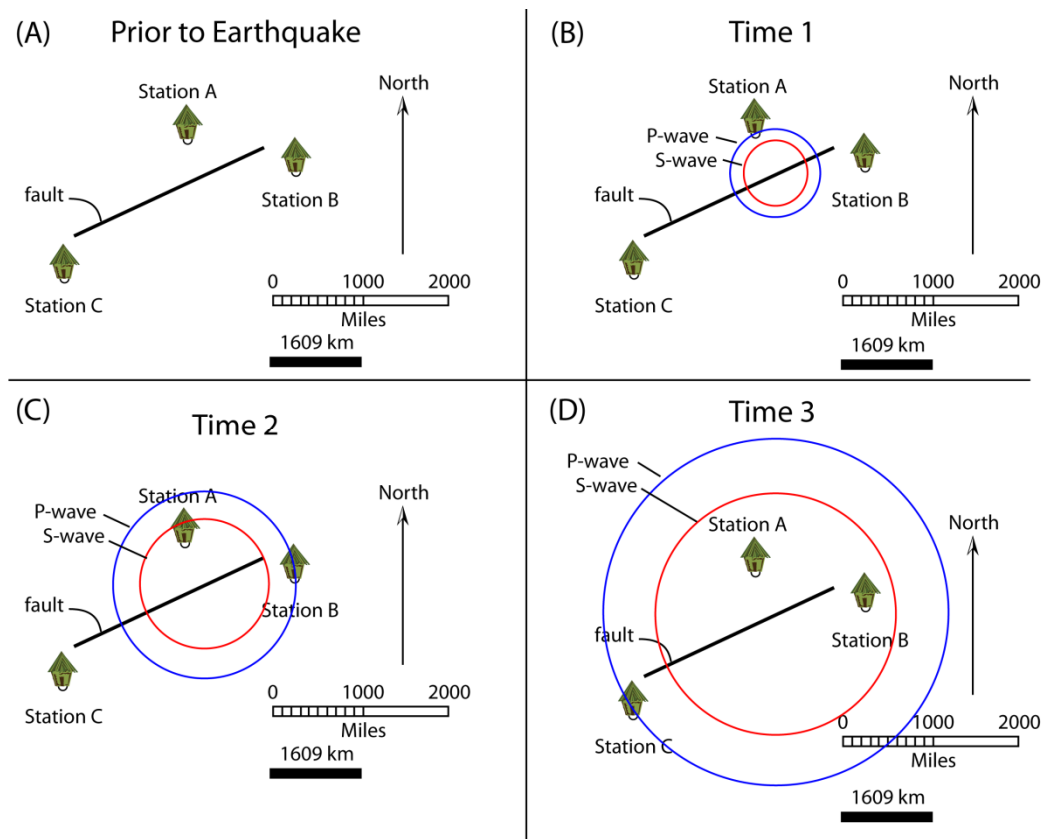


Figure 9. (A) Locations of seismic stations A, B, and C. (B) At time 1, following an earthquake on the NE one third of the fault, Station A, being closest to the epicenter, records the earthquake first as P waves and then S waves arrive. (C) As the seismic energy continues to radiate outward from the epicenter, station B, being at an intermediate distance from the epicenter, next receives first P waves and then S waves. (D) At time 3, station C, lying at the greatest distance from the epicenter, receives first P and then S waves. Note how the separation distance between P and S arrivals, i.e., the S-P interval increases from station A to B to C.

From analyzing many earthquakes in a given region seismologists know the relationship between the S-P interval and the distance to an earthquake's epicenter. The basic tool that they use is the travel-time graph (Figure 10). On such a graph, time is plotted along the y-axis and distance traveled from epicenters is shown on the x-axis. Characteristic travel-time curves for P- and S-waves are also provided. As shown in Figure 10, the vertical distance separating the two curves is the S-P interval.

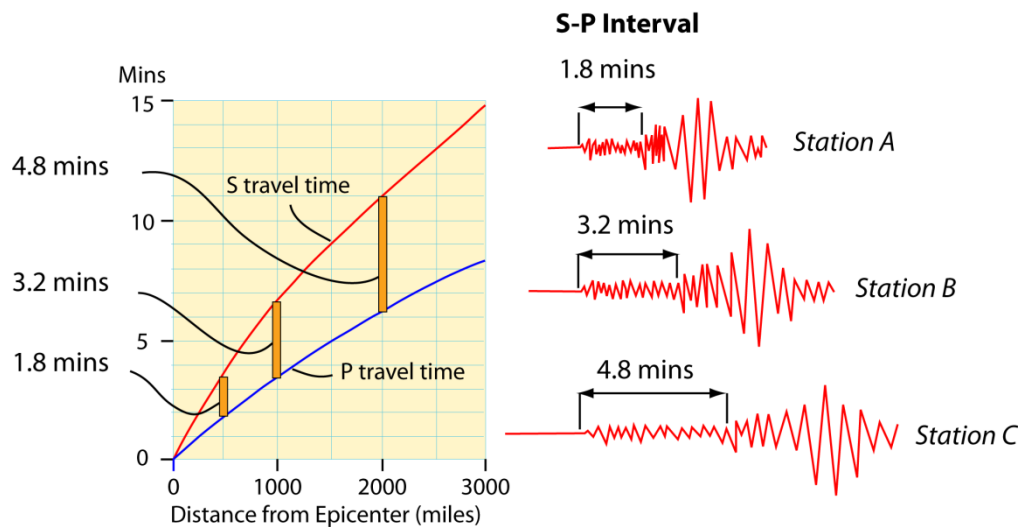


Figure 10. Travel-time graph for earthquake shown in Figure 9.

Also shown in Figure 10 are three seismic records collected at stations A, B, and C (see Figure 9 for their locations) during an earthquake. Station A is closer to the epicenter than is B, while station C is the farthest away. Hence, the S-P interval is smaller at station A, intermediate in size at station B, and the greatest at station C.

Using the travel-time graph characteristic of our hypothetical region, we can estimate readily the distance to the epicenter. In Figure 10, the orange bar labeled 1.8 minutes is the S-P interval for station A. Note that it fits snugly between the red and blue curves drawn on the travel-time graph, and lies on a vertical blue grid line that intersects the x-axis (labeled Distance from Epicenter) at 500 miles. We conclude that station A is located 500 miles from the epicenter. At station B, the S-P interval is 3.2 minutes and at station C the S-P interval is 4.8 minutes. Using Figure 10 verify that these times translate into distances of 1000 and 2000 miles respectively.

In Figure 11 a circle with radius 500 miles is plotted with station A at its center. This result tells us that the epicenter lies somewhere along this circle. However, we don't know where along the circle the epicenter lies. However, a circle with a radius of 1000 miles plotted around station B intersects the circle from station A at two points, one of which is the epicenter. Unfortunately, without plotting the results from station C, we don't know which of the two points to choose. However, unless the earthquake was produced by rupture on an unmapped fault, then the point lying on the fault might be the epicenter. Plotting a circle

around station C with a radius of 2000 miles confirms our suspicions as all three circles intersect in a single point. Moreover, note that this point simultaneously satisfies the three conditions that the epicenter must be located 500 miles, 1000 miles, and 2000 miles from seismic stations A, B, and C respectively. It must therefore be the epicenter of the earthquake. The fact that the epicenter is located on the fault suggests that brittle failure along the fault produced the earthquake.

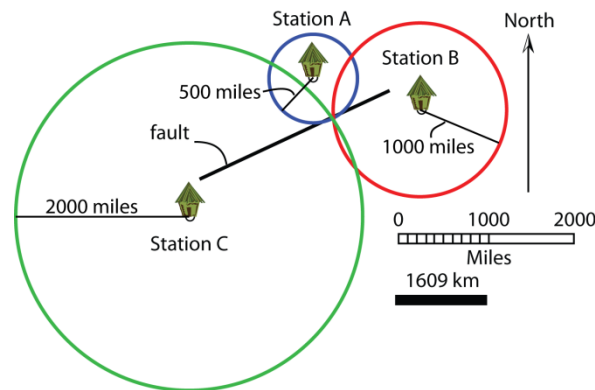


Figure 11. Using the S-P interval, the distance to the epicenter can be determined from a minimum of three seismic stations located at three different distances from the earthquake.

Earthquake Magnitudes

The amplitude of the squiggly curve of the seismogram provides information about the energy released during an earthquake. The Richter magnitude is determined by the peak amplitude on a seismogram derived from a Ward-Anderson seismometer, a special but ubiquitous type of seismometer. The measured peak amplitude is scaled to a distance of 100 kilometers (62.1 miles) from the epicenter of an earthquake. The Richter magnitude scale is logarithmic, with commonly reported magnitudes varying from 1 to a little over 9. Each unit increase in magnitude corresponds to a ten-fold increase in amplitude. For example, a magnitude 2 earthquake produces a signal with an amplitude that is ten times larger than a magnitude 1 signal. A magnitude 3 earthquake would produce a signal with an amplitude one hundred times larger than a magnitude 1 signal.

Though the above ideas seem straight forward enough, energy in a wave is in fact a function of both amplitude and frequency. This latter parameter is the number of waves that pass a given stationary point each second. Frequency differs from one earthquake to another. The most energetic earthquakes have a higher proportion of low frequency waves than do the least energetic. Taking these factors in to consideration, seismologists have estimated that there is a thirty-two-fold increase in energy in going from one Richter unit to the next. In other words, a magnitude 3 earthquake releases 1024 times (32×32) the energy of a magnitude 1 earthquake.

The seismic moment, M_0 , is another way of measuring the magnitude of an earthquake. In equation form it can be written

$$(1) \quad M_o = \mu Sd$$

where μ is the shear strength of the faulted rock, S is the area of the fault surface that ruptured, and d is the average displacement on the fault. Seismologists believe that the seismic moment is a more consistent measure of earthquake size than is Richter magnitude. This factor led Drs. T. Hanks and H. Kanamori to introduce in 1979 the moment magnitude scale. In equation form, the moment magnitude, M_w , can be written as

$$(2) \quad M_w = 2/3 \log_{10}(M_o) - 10.7.$$

The three largest reported moments are for the 1960 Chile earthquake (M_w 9.6), the 2004 Sumatra earthquake (M_w 9.3), and the 1964 Alaska earthquake (M_w 9.2).

Seismologists often divide earthquakes based on their magnitudes into the classes shown in Table 1. The largest magnitude earthquakes that occur along convergent margins generally fall into the major and great classes, while the largest magnitudes characteristic of transform boundaries like the San Andreas fault fall into the moderate to major classes. In contrast, most seismic events in divergent margin settings fall into the light and minor classes.

Table 1. Classes of Earthquakes

<i>Class</i>	<i>Magnitude</i>
Great	8 or larger
Major	7 – 7.9
Strong	6 – 6.9
Moderate	5 – 5.9
Light	4 – 4.9
Minor	3 – 3.9

Given the above information it is probably not surprising that of the top 10 earthquakes known to have occurred in North America, seven occurred along the converging boundary separating Alaska and the North American plate from the Pacific plate while one occurred along the Fort Tejon segment of the San Andreas transform (Table 2). The two large earthquakes that

Table 2. Top 10 Earthquakes in North America

Rank	Locale	Size
1	Prince William Sound, Alaska	9.2
2	Andreanof Islands, Alaska	9.1
3	Rat Islands, Alaska	8.7
4	Shumagin Islands, Alaska	8.2
5	New Madrid, Missouri	8.1
6	Yakutat Bay, Alaska	8.0
7	Andreanof Islands, Alaska	8.0
8	New Madrid, Missouri	8.0
9	Cape Yakataga, Alaska	7.9
10	Fort Tejon, California	7.9

LiveScience / SOURCE: USGS

occurred within the New Madrid seismic zone lie within a poorly understood seismic belt running through the mid-continental region of the conterminous United States.

It has been estimated that on a global basis, there are, on average, over 900,000 earthquakes per year with magnitudes less than 2.5. In contrast, there are, on average, ~30,000 minor through moderate (up to ~5.5), ~500 moderate (~5.5 - ~6.0), ~100 strong, and ~20 major earthquakes per year. Though typically memorable, great earthquakes only occur once every 5 to 10 years.

Earthquake Intensities

When an earthquake occurs the land surface vibrates and shakes, and as a result streets, houses, fences, bridges, and other structures are damaged. If we can determine how much damage has occurred, then we can determine the intensity of the earthquake. The modified Mercalli scale was developed to specifically measure the effect of an earthquake on people and buildings.

The modified Mercalli scale varies from *I* to *XII*, with higher Roman numerals indicating greater intensity (Table 3). In general, we would expect intensity to decrease outward away from the epicenter. However, over the last 50 years or so buildings and roads have been built under different types of engineering codes, and as a result such man-made structures have differing resistance to ground shaking during an earthquake. Hence, Mercalli intensities may vary from region to region and country to country as a function of building code and other

Table 3. The Modified Mercalli Intensity Scale

<i>I.</i> Not felt except by a very few under especially favorable conditions.	<i>II.</i> Felt only by a few persons at rest, especially on upper floors of buildings.
<i>III.</i> Felt quite noticeably by persons indoors, especially on upper floors of buildings. Many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibrations similar to the passing of a truck. Duration estimated.	<i>IV.</i> Felt indoors by many, outdoors by few during the day. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.
<i>V.</i> Felt by nearly everyone; many awakened. Some dishes, windows broken. Unstable objects overturned. Pendulum clocks may stop.	<i>VI.</i> Felt by all, many frightened. Some heavy furniture moved; a few instances of fallen plaster. Damage slight.
<i>VII.</i> Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable damage in poorly built or badly designed structures; some chimneys broken.	<i>VIII.</i> Damage slight in specially designed structures; considerable damage in ordinary substantial buildings with partial collapse. Damage great in poorly built structures. Fall of chimneys, factory stacks, columns, monuments, walls. Heavy furniture overturned.
<i>IX.</i> Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb. Damage great in substantial buildings, with partial collapse. Buildings shifted off foundations.	<i>X.</i> Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations. Rails bent.
<i>XI.</i> Few, if any (masonry) structures remain standing. Bridges destroyed. Rails bent greatly.	<i>XII.</i> Damage total. Lines of sight and level are distorted. Objects thrown into the air.

related factors. Nevertheless, as shown in Table 3, Mercalli scale indices of VI or lower measure the effects of the earthquake on people, while those of VII or higher measure the effects on buildings.

Closing Statement

Earthquakes have in the past devastated portions of major metropolitan centers in Los Angeles and San Francisco, California, and, in a single occurrence, have destroyed 100,000+ lives in distant lands such as China. They have at one time or another been felt in nearly all regions of the world, and serve as a nearly daily message that geology is an important aspect of the lives of the citizens of planet Earth.

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<http://earthquake.usgs.gov/learning/>