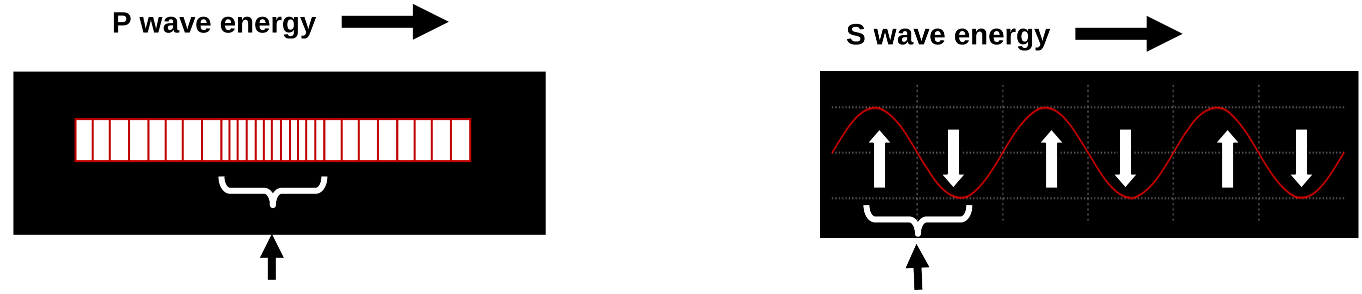
Chapter 7: Earthquakes

An earthquake occurs, quite literally, when the earth quakes. Most earthquakes are caused by subsurface fault rupture, as shown in Figure 7.4. As a fault moves, energy waves are generated that propagate outward in all directions, similar the movement of ripples in a pond outward in all directions from where a pebble tossed into the pond landed. In the case of a pebble landing in a pond, the impact of the pebble deforms the water surface, and energy waves are created as a result. In the case of an earthquake, the deformation of Earth's interior via fault movement creates seismic energy waves. Your text mentions other ways that earthquakes can be generated, including magma movement, mineral transformations, and even dehydration of water-rich minerals like serpentine. For the purposes of this chapter, however, we'll focus on fault-produced earthquakes.

One thing that might not be obvious about Figure 7.4 is that the seismic waves propagate outward from the earthquake source, or focus, in 3 dimensions. Imagine a series of energy spheres moving outward from the earthquake focus. If the earthquake location is to be shown in map view, it's often more convenient to plot the point on the ground surface directly above the earthquake focus—a point called the earthquake epicenter. Notice again in Figure 7.4 that the epicenter of an earthquake doesn't correspond with the surface trace of the fault on which the earthquake originates.

Most earthquakes happen suddenly, which makes them difficult to study in real time. Luckily for geologists, most aspects of earthquakes can be studied by the energy pulses they create, called seismic waves (Figure 7.5). Seismic waves come in two basic types: (1) body waves that travel in Earth's interior, and (2) surface waves that travel at or near Earth's surface. For the most part, we'll focus on body waves, which themselves come in two types, including primary (P) waves and secondary (S) waves. As discussed below, two types of surface waves include Love and Rayleigh waves.

Here's an online link that demonstrates the movement associated with P, S waves, and Surface (Love and Rayleigh) waves: **Seismic Waves—Figure 7.5.** Here's a diagram showing the way that P and S waves deform the solid Earth as they move through:



Temporary compression parallel to direction of wave travel ***(original shape is recovered after P wave moves through rock)***

Temporary shearing @ 90º to direction of wave travel ***(original shape is recovered after S wave moves through rock)***

Elastic properties of P and S waves.

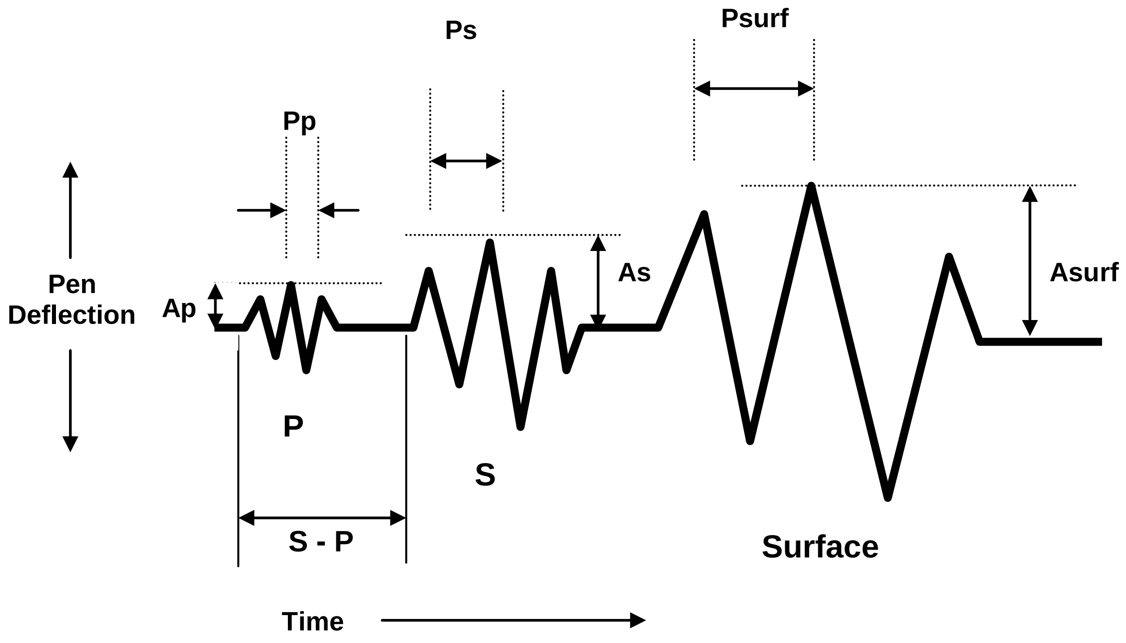
Notice that P waves cause compressional, elastic vibration parallel to the direction of wave movement. S waves, by contrast, propagate by elastic shearing, which causes Earth's interior to vibrate perpendicular to the direction of wave movement. Love waves are like sideways S waves--they propagate sideways in a horizontal plane. Rayleigh waves are a bit like rolling ocean waves.

In terms of the relative velocities of various seismic waves, P waves travel the fastest (4-7 km/sec), followed by slightly slower S waves (2-5 km/sec), followed by surface waves (slowest). P waves can travel through solids, liquids, and gases, whereas S waves can only travel through solids. Since liquids and gases don't possess shear strength, S waves (which propagate via shearing) can't pass through liquids or gases.

Earthquake waves are recorded on instruments called seismographs. The permanent record of an earthquake recorded on a seismograph is called a seismogram. As we'll see below, many aspects of earthquakes can be studied from seismogram records. Here's a link that illustrates **How a Seismograph Works (scroll down to 8.3).**

Notice that the drawing pen is essentially stationary with respect to the rest of the instrument. Truth be told, the animation you just looked at illustrates how older seismographs work. In many modern seismographs, an electronic sensor in Earth's shallow interior converts ground shaking into an electrical signal, which in turn gets converted into pen vibration or even just a squiggle on a computer screen. In any case, the squiggly lines (i.e., wave arrivals) on the seismogram tell us a lot about earthquakes.

Your text doesn't have a detailed figure of a labeled seismogram record, so here's a typical (albeit simplified) seismogram with various seismic wave features labeled:



Typical seismogram record.

The following important points apply:

- The seismogram record shown above is essentially an x-y plot of pen deflection verses time.

- The three wave arrivals are easy to spot, with P waves arriving first, S waves arriving next, and Surface waves arriving after the S waves.

- Each wave set consists of several individual waves of each type.

- The height of each wave is called wave amplitude (shown by vertical arrows—**Ap, As,** and **Asurf** for P, S, and Surface wave amplitudes). Notice that wave amplitude for a particular wave set is measured from the background level of the seismogram up to the top of the tallest wave for a particular wave set (not from trough to crest).

- The time for each wave to complete one wave cycle is called wave period (shown by horizontal arrows, measured from the crest of one wave to the crest of the next wave—**Pp, Ps,** and **Psurf** for P, S, and Surface wave periods).

- The time gap between the first S waves and the first P waves (**S - P** on seismogram) is called the "S minus P time difference", or "delta t (Δt)". Notice that the S–P time difference is just the gap in time between the arrival of the first P waves the first S waves.

- In general, P waves will be the first to reach a distant location (because they travel at the fastest velocity), but P waves will shake the ground less violently than S and Surface waves (because P wave amplitudes are typically smaller). In addition, P waves will cause the ground to shake in more of a rapid, vibratory manner than S and Surface waves because P wave periods are typically lower than S and Surface wave periods.

- Since P waves travel faster than S waves, Δt increases with increasing distance from the earthquake origin. This can actually be felt in some cases. Have you ever felt a quake as a single jolt, like someone backed a truck into a building? If so, you probably felt an earthquake that originated nearby, before the P waves could get too far ahead of the S waves. On the other hand, have you ever felt a quake that starts slowly at first, then, after a few seconds, really becomes violent? In this case, the initial shaking you felt probably marked the arrival of the first P waves, with their smaller wave amplitudes, followed a few seconds later by the more violent (larger-amplitude) S waves. In this case, the quake was far enough away that the P waves got a few seconds ahead of the S waves.

A True Story…

Back in 1989, there was a moderately large, Magnitude 7.1 earthquake in the Santa Cruz Mountains that shook the entire San Francisco Bay region, resulting in severe damage and a number of deaths—the Loma Prieta earthquake.

At the moment the earthquake struck, my mom, who lives in the San Francisco area, was talking on the phone with her sister in New Orleans. For the first few seconds of the quake, my mom was not worried, casually commenting to her sister that, "We're having an earthquake."

At this point, my mom was only feeling the P waves from the distant quake, which had relatively small wave amplitudes. A few seconds later, the shaking became more violent, and dishes began to rattle…

At this point, mom told her sister, "Oh, this is a pretty decent size quake!" By then, she was undoubtedly feeling the first S wave arrivals with their larger wave amplitudes…

Several seconds later, the last thing my aunt heard before the phone line went dead was my mom screaming into the phone, "OH MY GOD, THIS IS TERRIBLE!!" At this point, the large-amplitude surface waves had arrived. The phone line was severed, and my aunt wasn't able to reach my mom for several days!

Luckily, my mom wasn't hurt, our house survived with only some minor cracking, and I got a good story out of it!

Your book has a well-written section on measuring and locating earthquakes. In general, the S-P time difference (Δt) can be used to figure out the distance to an earthquake, because as distance to an earthquake increases, so does the S-P time difference.

Near where an earthquake occurs, the P waves will arrive only slightly ahead of the S waves, and the S-P time difference will be small. But for distant locations, the P waves will arrive well ahead of the first S waves, as shown in Figure 7.9.

Such information can tell us the distance to an earthquake source but not the direction. A minimum of three seismogram records is needed to pinpoint, or triangulate, the location of the earthquake on a map (i.e., the epicenter). Here's a link to an animation showing how an earthquake epicenter can be located: **Earthquake Location—Figs. 7.8, 7.9, & 7.10.**

Another aspect of an earthquake is its size, which can be measured in two ways: (1) the damage caused, or (2) the amount of energy released. I won't say much about the first method; you can read about this on your own (see Table 7.1—Modified Mercalli Intensity Scale).

For many scientific applications, the size of the earthquake is represented by a single number, called magnitude, which is related to the energy released. Earthquake magnitude can be calculated from seismic wave amplitudes. In general, the larger the wave amplitude, the more energy released, and thus the larger the earthquake magnitude.

Richter Magnitude

The most famous earthquake magnitude scale is of course the Richter scale. To calculate Richter magnitude, the largest amplitude of a seismic wave is measured at a distance of 100 km from the earthquake epicenter.

You might see a problem already. What if we're not lucky enough to have a seismograph set up at exactly 100 km from the earthquake epicenter? Well, actually, this isn't a problem, because we know enough about how seismic wave amplitudes shrink (attenuate) with distance as they lose energy that if we can measure the wave amplitude at any distance, we can apply a correction factor to calculate what the amplitude would be at exactly 100 km from the earthquake.

For the mathematically inclined, here's Richter's original definition of magnitude, courtesy of the **Southern California Earthquake Center**:

"The (Richter) magnitude of any shock is taken as the logarithm of the maximum trace amplitude, expressed in microns, with which the standard short-period torsion seismometer would register that shock at an epicentral distance of 100 kilometers."

Nobody uses the true Richter scale anymore, because the "standard short-period torsion seismometer" Richter originally used to measure wave amplitudes has gone the way of the dinosaur.

Today, much better, more sensitive instruments are used. Even so, modern earthquake researchers use a variety of Richter-like scales to measure earthquake magnitude, many of which are also based on the maximum amplitude of various seismic waves.

Here's the equation for calculating Richter Magnitude (below)...don't worry! You don't need to memorize this equation, and I won't ask you to solve it. I'm just including it so you can see how the math relates to what we've been discussing:

$$\textbf{Richter Magnitude } (M_L) = \text{Log}_{10}\underset{\substack{\uparrow \\ \textit{A is max. wave} \\ \textit{height (amplitude).}}}{A} + 3*\text{Log}_{10}(8\underset{\substack{\uparrow \\ \textit{Δt is the S–P time} \\ \textit{difference.}}}{\Delta} t) - 2.92$$

Don't be concerned with the logarithmic nature of the above equation. The term, Log_{10} is just a mathematical operation Richter used to shrink down very large numbers to a more manageable size.

Bottom line, if we know both **A** (max. amplitude) and **Δt** (S – P), we can calculate **M_L** (Richter magnitude). How do we determine **A** and **Δt?** From a seismogram record!

In effect, the **$3*\text{Log}_{10}(8\Delta t) - 2.92$** term in Richter's equation is just a distance correction factor to shrink or stretch the wave amplitude to what it would be at exactly 100 km from the earthquake epicenter.

Moment Magnitude

The most objective measure of earthquake magnitude is called Moment Magnitude, and is based on a calculation called seismic moment:

$$\textbf{Seismic Moment } (M_o) = \text{Fault Slip} \times \underbrace{\text{Rock Strength}}_{\substack{\textit{shear modulus, actually…don't} \\ \textit{worry about the details ☺…}}} \times \text{Fault Plane Area}$$

Using the above calculation for seismic moment (**M_o**)**,** seismologists have devised the moment magnitude scale:

Moment Magnitude (M_w) = 2/3 x $\text{Log}_{10}(M_o)$ – 10.7

Once again, don't worry about the math. Just appreciate that the larger the seismic moment (**M_o**), the larger the moment magnitude (**M_w**)**.**

In general, larger moment magnitudes are associated with longer fault ruptures, stronger rocks, larger fault offsets, and greater energy release.

On the one hand, moment magnitude gives a much better estimate of the energy released during large earthquakes than Richter magnitude.

Unfortunately, it can take several weeks to calculate the moment magnitude of an earthquake after it occurs, because the area of the fault plane is typically estimated from the distribution of aftershocks. But once calculated, the moment magnitude of a quake is the best measure of the energy released during the quake.

Earthquake Magnitude and Energy

Because the Richter and moment magnitude scales are logarithmic (i.e., exponential), earthquake energy increases rather dramatically with increasing magnitude.

For every 1-point increase on the Richter scale, seismic wave amplitude increases by 10 times; however, energy release increases by approximately 32 times. You can see this effect clearly on Figure 7.12 for moment magnitudes as well. A magnitude 2 quake releases about as much energy as 120 pounds of explosives, whereas a magnitude 6 earthquake releases about as much energy as 120 *million* pounds of explosives, or almost as much energy as an atomic bomb blast! That is, a magnitude 6 quake releases about a million times more energy than a magnitude 2 quake! Wow!

Here's a quick, back-of-the-envelope calculation you can do to estimate the approximate difference in energy release between two earthquakes of different Richter magnitude:

Larger magnitude – smaller magnitude = result ➡ 30^{result} = difference in energy release.

Let's do a quick example.

Approximately how much more energy is released in a Mag 7 quake than a Mag 4 quake?

7 – 4 = 3 ➡ 30^3 = 30 x 30 x 30 = 27,000

So a Mag 7 quake releases approximately 27,000 times more energy than a Mag 4 quake!

If you have the interest and the time, here's a wonderful online exercise you can do that illustrates how seismologists actually determine earthquake location and magnitude: **Measure and Locate an Earthquake**…it'll take you about 20 minutes. In fact, I may make this a 5-pt exercise (I'll let you know!). After completing this exercise, you'll be given the opportunity to receive a personalized certificate as a "virtual seismologist." Pretty cool!

By this point in the course, you should be able to explain the general relationship between earthquakes and plate boundaries. Simply put, most earthquakes are concentrated along linear and arc-shaped belts that define active plate boundaries. In fact, as your text points out, plate boundaries are identified and defined by earthquakes. Combining our knowledge of plate tectonic theory with our understanding of earthquakes, we can make some broad generalizations about the earthquake activity (seismicity) associated with various plate boundary types:

- At divergent plate boundaries, earthquakes are typically shallow, restricted to a narrow band, and much lower in magnitude than those at convergent and transform boundaries. The reason that earthquakes at divergent boundaries are typically small is that rock is typically weak in tension. That is, when subjected to tensile stress along a divergent plate boundary, rock breaks quite easily, before large stresses can build up. This results in small earthquakes.

- At transform boundaries, earthquakes are typically shallow, range in size from small to large and are confined to a narrow bands along individual transform faults. Along the transform boundary between the Pacific and North American plates, the seismicity occurs in a very wide band because this boundary is defined by dozens of individual faults, not just the San Andreas Fault.

- At collision (i.e., continent-continent convergence) zones, earthquakes are shallow to intermediate in depth, range in size from small to large, and are characterized by broad zones of seismicity.

- At subduction zones (characterized by continent-ocean convergence and ocean-ocean convergence), earthquakes range in size from small to large and occur at shallow, intermediate, and deep depths.

In fact, very deep earthquakes *only* occur at subduction zones. This is because the cold, brittle oceanic plate that subducts can still behave in a brittle (breakable) fashion to depths of up to about 700 km. Everywhere else, Earth's mantle is too plastic at that depth for the rocks to break. If the rocks can't break, earthquakes can't occur.

It's actually possible to track the movement of subducting plates because they produce an inclined zone of seismicity that dips into the mantle, underneath the adjacent continent or island arc (Figure 7.23). These dipping seismic zones, called Benioff zones, were actually discovered before the development of plate tectonic theory, and remained a mystery until the subduction process was understood. Can you imagine the excitement of the first geologists who realized that these strange, dipping seismic zones—Benioff zones—were seismic proof of the subduction process?! Another connection between earthquakes and plate tectonics is that many devastating tsunamis like the 2004 tsunami off the coast of Sumatra are caused by vertical seafloor motion associated with large subduction zone quakes. Here's an animation of how a submarine earthquake can generate a tsunami: **Tsunami Animation—Fig. 7.19.**

Feel free to skim the very interesting section on the effects of earthquakes, which include ground motion, ground-surface displacement, landslides, and tsunamis.