EARTHQUAKES

Earthquakes may be more common than you think! The United States Geological Survey estimates that there are close to a half a million detectable earthquakes per year. While people feel approximately 100,000 of those, only approximately 100 cause damage. Historical records predict about 16 significant, those greater than a magnitude 6, earthquakes worldwide in any given year. It can be terrifying when the earth shakes, and earthquakes have caused massive damage and many injuries and deaths. Anyone who has lived through a strong earthquake cannot forget the experience. But geoscientists and engineers are getting better at understanding earthquakes, minimizing the amount of damage they cause, and reducing the number of people affected. In the time lapse video (Figure 5.0.1), you can see historical earthquakes that have occurred in Arizona.

Learning Objectives

After carefully reading this chapter, you should be able to:

Explain how the principle of elastic deformation applies to earthquakes.
Describe how the main shock and the immediate aftershocks define the rupture surface of an earthquake, and explain how stress transfer is related to aftershocks.
Describe the relationship between earthquakes and plate tectonics, including where we should expect earthquakes to happen at different types of plate boundaries and at what depths.
Distinguish between earthquake magnitude and intensity, and explain some ways of estimating magnitude.
Describe how earthquakes lead to the destruction of buildings and other infrastructure, fires, slope failures, liquefaction, and tsunami.
Discuss the value of earthquake forecasting, and describe some steps that governments and individuals can take to minimize the impacts of large earthquakes.
Describe earthquakes in Arizona.

5.1 Causes of Earthquakes

An earthquake is defined as the shaking of the ground, due to movements in the Earth’s crust. The movements, usually caused by plate tectonics, apply stress to rocks, which initially cause the rocks to deform elastically, storing the stress. Once enough stress is applied, the rocks will rupture (break) and release the stored energy, causing an earthquake. Most earthquakes are confined to plate boundaries, but earthquakes can also occur from volcanic activity or within a tectonic plate. The shifting and displacement occurs along the rupture surface, also referred to as a fault plane. The line where the fault plane intersects the Earth’s surface is called a fault or fault scarp. All earthquakes cause a rupture surface, but not all of them can be seen as a fault on the surface.

Figure 5.1.1. Depiction of the concept of elastic deformation and rupture. The plate boundary is shown as a dashed red line. In b the two plates are moving as shown by the arrows, but they are locked against each along the plate boundary so they are both deforming and the rocks are stressed. In c there has been a rupture along the boundary and the stress is released. Steven Earle, CC-BY.

Rupture Surface

The concept of a rupture surface is illustrated below (Fig. 5.1.2). An earthquake does not happen at a single point, it happens over an extended area. It also doesn't happen all at one time! The extent of a rupture surface and the amount of displacement will depend on several factors, including the type and strength of the rock, and the degree to which it was stressed or altered beforehand.

Figure 5.1.2. Propagation of failure on a rupture surface. In this case, the failure starts at the dark blue heavy arrow in the center and propagates outward, reaching the left side first (green arrows) and the right side last (yellow arrows). The size of the arrow are indicative of the amount of displacement. Steven Earle, CC-BY

Foreshocks and Aftershocks

Foreshocks are small earthquakes that precede a larger event. As previously mentioned, hundreds of thousands of earthquakes occur yearly as plates release stress and rupture, not all of these are foreshocks. In order to be considered a foreshock, a larger event must occur in the same area. Special attention is paid to swarms (groupings) of foreshocks in an area, as they may signify a larger event will occur. Aftershocks are also earthquakes, but they have been triggered by stress transfer from a preceding earthquake and they occur within the original rupture surface.

Video 5.1.3. The animation shows foreshocks, mainshocks and aftershocks locations in relation to the rupture surface during and earthquake (00:16)

Video Player
Media error: Format(s) not supported or source(s) not foundDownload File: https://prd-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/atoms/video/aftershocks.mp4?_=1

00:00
00:00

Aftershocks can be of any magnitude, but most are smaller than the earthquake that triggered them. Many aftershocks occur within seconds or minutes of the mainshock, but they can occur over days, weeks, months, or years. Figure 5.1.4 shows the distribution of aftershocks within the first 4 days of the devastating 9.0 earthquake of 2011 in Japan. The large yellow circle is the main earthquake event, and the rest of the circles represent aftershocks in the area of the fault. Though the main earthquake released a tremendous amount of energy and relieved stress on that part of the fault, a resulting increase in stress on nearby parts of the fault system contributed to the multiple aftershocks. Hundreds of aftershocks were recorded within a few days, and thousands have occurred since the original quake event.

Map of aftershocks of Japan Earthquake 2011
Figure 5.1.4. Map of the Sendai Earthquake, March 11, 2011 and aftershocks until March 14, 2011 at 11:20. The size of the circles is a function of magnitude, and the color indicates the date: light green: March 11; yellow: March 12; orange: March 13; red: March 14. Wikimedia Commons, Public Domain.

Stress Transfer

As already noted, aftershocks are related to stress transfer. For example, the main shock of the 9.0 earthquake in Japan in 2011 triggered aftershocks in the immediate area, which triggered more in the surrounding area, eventually extending along the fault plane in all directions. The earthquake, inclusive of aftershocks, also changed the stress on adjacent parts of the fault zone. Though the aftershocks all occur on the original rupture surface, stress transfer isn't restricted to the fault along which an earthquake happened. It can affect the rocks around the site of the earthquake and may lead to increased stress on other faults in the region. The effects of stress transfer don't necessarily show up right away. Segments of faults are typically in some state of stress, and the transfer of stress from another area is only rarely enough to push a fault segment beyond its limits to the point of rupture. The stress that is added by stress transfer accumulates along with the ongoing buildup of stress from plate motion and eventually leads to another earthquake (5).

Digging Deeper: Earthquakes only occur on Earth!

Lunar Fault Scarp
Figure 5.1.5. Lunar Fault Scarp (where the rupture surface meets the surface of the Moon). NASA, Public Domain.

Really, we’re talking about the concept of “quakes” – the release of stored energy due to the movement of rocks. They are only “Earthquakes” because they occur on Earth.

Moonquakes occur, and were first detected by the Apollo astronauts. Scientists believe that they are generated by the shrinking of the Moon. As the interior cools, the Moon shrinks, causing small ruptures to occur and quakes to be generated. Faults can bee seen on the surface of the moon!
Marsquakes have also been detected by NASA scientists! With more advancing missions to Mars, future marsquakes will become more intensively studied. Mars has had active volcanism in its past, and is thought to have a molten core, which may account for the quakes.

5.2 Earthquakes and Plate Tectonics

Plate boundaries were inferred from earthquake data, scientists drew the boundaries along areas of high seismicity. All tectonic boundaries have earthquakes associated with them, though they vary in size and frequency. The distribution and depth of earthquakes across the globe is shown in Figure 5.2.1. It is relatively easy to see the relationships between earthquakes and plate boundaries.

A global map of earthquake activity. The earthquakes occur at the boundaries between Earth's tectonic plates. The colors indicate the depth of the earthquakes, with red being the shallowest and green the deepest. Lisa Christiansen, Caltech Tectonics Observatory. CC-BY-NC
Figure 5.2.1. A global map of earthquake activity. The earthquakes occur at the boundaries between Earth’s tectonic plates. The colors indicate the depth of the earthquakes, with red being the shallowest and green the deepest. Lisa Christiansen, Caltech Tectonics Observatory. CC-BY-NC
Earthquakes are also relatively common at a few intraplate (within a tectonic plate) locations. Some are related to human activities, such as mining or oil fracking. Others occur naturally and are related to the buildup of stress due to continental rifting or the transfer of stress from other regions. Yellowstone National Park, in the northwest United States, is an example of a place that experiences earthquakes within a tectonic plate. Located hundreds of miles from a plate boundary, over 48,000 earthquakes have been recorded in the park since 1973, though most are very small and not noticeable to people (6).

Most earthquakes occur at plate boundaries, though their sizes, locations, and frequency vary. The figure above not only shows the location of earthquakes, but it shows their depths. Along divergent boundaries, like the mid-Atlantic ridge and the East Pacific Rise, earthquakes are common, but in a narrow zone at shallow depth. Shallow earthquakes are also common along transform boundaries, such as the San Andreas Fault. Of course earthquakes also occur at convergent boundaries, whether they involve continental or oceanic crust. Along subduction zones, as oceanic crust descends, earthquakes are very abundant. The subducting slab causes a much broader zone of earthquakes and at greater depth in the crust than other plate boundaries.

Earthquakes at Divergent Boundaries

Divergent boundaries are usually found in oceanic crust, like the Mid-Atlantic Ridge. Some earthquakes occur on spreading ridges, but they tend to be small and infrequent because of the relatively high rock temperatures in the areas where spreading is taking place. Though the mechanism of plate tectonics at this boundary causes large-scale spreading, transform faults often link the diverging segments, and it is there that the majority of earthquakes occur. Figure 5.2.2 provides a closer look at magnitude (M) 4 and larger earthquakes in an area of divergent boundaries in the mid-Atlantic region near the equator. The spreading segments of the mid-Atlantic ridge are offset by some long transform faults. Most of the earthquakes are located along the transform faults, rather than along the spreading segments, although there are clusters of earthquakes at some of the ridge-transform boundaries.

Locations of earthquakes of magnitude 4 and greater from 1990 to 2010 along two mid-ocean ridges. Plate boundaries are marked in red. Arrows show the direction of plate motion. Left: Rapidly spreading Pacific-Antarctic ridge with earthquakes concentrated along transform faults. Right: Slowly spreading Southwest Indian Ridge, with earthquakes along both spreading segments and transform faults. Source: Karla Panchuk (2017) CC BY 4.0.

Figure 5.2.2. Locations of earthquakes of magnitude 4 and greater from 1990 to 2010 along two mid-ocean ridges. Plate boundaries are marked in red. Arrows show the direction of plate motion. Left: Rapidly spreading Pacific-Antarctic ridge with earthquakes concentrated along transform faults. Right: Slowly spreading Southwest Indian Ridge, with earthquakes along both spreading segments and transform faults. Karla Panchuk (2017) CC BY 4.0.

Earthquakes at Transform Boundaries

image

Figure 5.2.3 San Andreas Fault with plate motions. USGS, Public Domain

As previously discussed, transform boundaries generate many earthquakes as the tectonic plates slide by each other. Transform boundaries tend to have steeper rupture surfaces, which cause the earthquakes to occur in a narrow zone and limits their size. The largest earthquakes on transform boundaries are in the order of a magnitude (M) 8. The most well known transform fault in North America is the mighty San Andreas Fault, located between the North American and Pacific plates. Figure 5.2.3 shows this boundary. At this scale, the fault appears to be a single line, but it is actually an intricate network of smaller faults. Thousands of earthquakes occur along this fault every year, but major events happen every 100-150 years. Using this calculation, the southern portion of the San Andreas is more likely to produce a large earthquake, because the last major event was in 1857, whereas the northern portion had a major earthquake in 1906.

Earthquakes at Convergent Boundaries

Many earthquakes, both large and small, occur at convergent boundaries. The pattern and distribution of the earthquakes is related to the type of crust involved. Whether continental or oceanic crust is converging, the largest earthquakes occur at these boundaries.

Subduction Zones

Subduction zones occur where ocean-ocean and ocean-continent plates collide, and oceanic crust is subducted beneath an overriding plate. In the figure below, convergence occurs between the continental crust on the North America Plate and the oceanic crust of the Cocos Plate. At boundaries like these, the earthquakes occur on the continental crust and get deeper with distance from the trench. There are also various divergent and transform boundaries in the area shown in the Figure 5.2.4, and as we've seen in the mid-Atlantic area, more earthquakes occur along the transform versus divergent boundaries.

Figure 5.2.4. Distribution of earthquakes of M4 and greater in the Central America region from 1990 to 1996 (red: 0 to 33 kilometers depth, orange: 33 to 70 kilometers depth, green: 70 to 300 kilometers depth, blue: 300 to 700 kilometers depth) Spreading ridges are heavy lines, subduction zones are toothed lines, and transform faults are light lines. (Earthquakes Around the Mid-Atlantic Ridge © Steven Earle after Dale Sawyer, Rice University, CC-BY)

Figure 5.2.5. Cross-sectional (side) view of a subduction zone. Distribution of earthquakes of M4 and greater in the Central America region from 1990 to 1996 (red: 0 to 33 kilometers depth, orange: 33 to 70 kilometers depth, green: 70 to 300 kilometers depth, blue: 300 to 700 kilometers depth) Spreading ridges are heavy lines, subduction zones are toothed lines, and transform faults are light lines. (Earthquakes Around the Mid-Atlantic Ridge © Steven Earle after Dale Sawyer, Rice University, CC-BY)

Continent-Continent Convergence

The most famous example of continent-continent convergence is at the India-Eurasia plate boundary, shown in Figure 5.2.6 below. Initially, subduction took place at this boundary, but today the India Plate continues to push into the Eurasia Plate with no actual subduction taking place. There are transform faults on either side of the India Plate in this area as well.

Figure 5.2.6. Distribution of earthquakes in the area where the India Plate is converging with the Asia Plate (data from 1990 to 1996, red: 0 to 33 kilometers, orange: 33 to 70 kilometers, green: 70 to 300 kilometers). The double line along the northern edge of the India Plate indicates convergence, but not subduction, and transform boundaries are seen on both sides. Plate motions are shown in millimeters per year. S. Earle, CC-BY

The entire northern India and southern Asia region is very seismically active. Earthquakes are common in northern India, Nepal, Bhutan, Bangladesh and adjacent parts of China, and throughout Pakistan and Afghanistan. While many of the earthquakes are related to the transform faults on either side of the India Plate, most of the others are related to the significant tectonic squeezing caused by the continued convergence of the India and Asia Plates. That squeezing has caused the Asia Plate to be thrust over top of the India Plate, building the Himalayas and the Tibet Plateau to enormous heights. These types of faults, where continental crust ramps up over adjacent continental crust are called thrust faults. Hundreds more earthquakes occur at this boundary than are drawn on the figure, but they cannot be seen at this scale. (5)

Figure 5.2.7. Schematic diagram of the India-Asia convergent boundary, showing examples of the types of faults along which earthquakes are focused. The devastating Nepal earthquake of May 2015 took place along one of these faults. Earle, CC-BY

The schematic above (Fig. 5.2.7) shows the thrust faults and rock types that are found at the Himalayas. Notice that the boundary is also not volcanic, because subduction is no longer occurring. The top of the Himalayan mountains, the highest elevation on the Earth's surface, is comprised of sedimentary rocks!

Human-Induced Earthquakes

Can humans create earthquakes? Not intentionally, but the answer is yes, and here is why. If a water reservoir is built on top of an active fault line, the water may lubricate the fault and weaken the stress built up within it. This may either create a series of small earthquakes or potentially create a massive earthquake. Also, the sheer weight of the reservoir r's water can weaken the bedrock causing it to fracture. Then the obvious concern is if the dam fails. Earthquakes can also be generated if humans inject other fluids into a fault, such as sewage or chemical waste. Finally, nuclear explosions can trigger earthquakes. One way to determine if a nation has tested a nuclear bomb is by monitoring the earthquakes and energy released by the explosion (4).

Backyard Geology: Earthquakes in Arizona

image

Figure 5.2.8. Arizona Seismic Belt. AZGS, CC-BY

Arizona has a very active history of earthquakes along fault lines. Because most of them are smaller and occur deep within the crust, very few of them actually rupture the surface. There has only been one earthquake greater than a magnitude seven (M7) in recorded history. While there is no plate boundary currently associated with Arizona, subduction boundaries existed in Arizona's geologic past. There are remnants of a subducted plate that went beneath the North American plate up to approximately 35 million years ago. The plate has not completely melted in the mantle. The ancient boundary is now sutured, but something analog to a scar remains in the landscape. Most earthquakes, therefore, occur in a linear zone across AZ, referred to as a seismic belt (Figure 5.2.8). This seismicity belts marks the ancient plate boundary, it is a weakened zone that keeps the record of continent formation.

5.3 Measuring and Locating Earthquakes

Focus and Epicenter

The point of initial breaking or rupturing, where the displacement of rocks occurs along the rupture surface, is called the focus. The focus is always at some depth below the ground surface in the crust, and not at the surface, as shows in Figure 5.3.1. From the focus, the displacement propagates up, down, and laterally along the fault plane. The displacement produces shock waves, creating seismic waves. Notice that the location of the fault scarp may be a distance from the epicenter. The larger the displacement and the further it propagates, the more significant the seismic waves and ground shaking. More shaking is usually the result of more seismic energy released. The epicenter is the location on the Earth's surface vertically above the point of rupture (focus). The epicenter is also the location that most news reports give because it is the center of the area where people are affected. The focus is the point along the fault plane from which the seismic waves spread outward. (1)

Figure 5.3.1 Focus and Epicenter by the Utah Geologic Survey, Public Domain.

Seismic Waves

Seismic waves are an expression of the elastic energy released after an earthquake that travel either along the Earth's surface (surface waves) or throughout the Earth's interior (body waves). When seismic energy is released, the first waves to propagate out are body waves that pass through the planet's interior. Body waves include primary waves (P waves) and secondary waves (S waves).

Body Waves

Primary waves are the fastest seismic waves. They move through the rock via compression, very much like sound waves move through the air. Particles of rock move forward and back during the passage of the P waves. Primary waves can travel through both fluids and solids. Secondary waves travel slower and follow primary waves, propagating as shear waves. Particles of rock move from side to side during the passage of S waves. Due to this motion, secondary waves cannot travel through liquids, plasma, or gas.

image

Figure 5.3.2 Seismic waves are simulated using a spring and rope attached to a fixed surface. Top: P-waves travel as pulses of compression. Bottom: S-waves move particles at right angles to the direction of motion. Panchuk, K (2018) CC BY 4.0

Because the interior of the Earth is not made of a single, homogenous substance, body waves do not travel uniformly through it. Seismic waves reflect (bounce), refract (bend), and speed up with depth as they encounter various boundaries and densities within the Earth. This behavior typically happens at the boundaries between the crust, mantle, and core. Because S waves cannot move through a liquid, they are blocked by the liquid outer core, creating a shadow zone on the opposite side of the planet to the earthquake source. P waves also have a shadow zone, created from areas that occur due to the pattern of refraction (Figure 5.3.3).

image

Figure 5.3.3 Patterns of seismic wave propagation through Earth's mantle and core. S-waves do not travel through the liquid outer core, so they leave a shadow on Earth's far side. P-waves do travel through the core, but because the waves that enter the core are refracted, there are also P-wave shadow zones. S Earle (2016) CC BY 4.0

Surface Waves

Surface waves are slower moving seismic wave, and are produced when body waves reach the Earth's surface. Two distinctly different waves are created spread out along the surface of the earth until they dissipate. Love waves produce horizontal ground shaking and, ironically from their name, are the most destructive. Rayleigh waves produce an elliptical motion of points on the surface, with longitudinal dilation and compression, like ocean waves. However, with Raleigh waves, rock particles move in a direction opposite to that of water particles in ocean waves. (1)

image

Figure 5.3.4 Surface waves travel along Earth's surface and have a diminished impact with depth. Rayleigh waves (left) cause a rolling motion, and Love waves (right) cause the ground to shift from side to side. S. Earle (2015) CC BY 4.0

Seismographs

Seismographs are instruments used to measure seismic waves. They measure the vibration of the ground using pendulums or springs. The seismograph principle involves mounting a recording device solidly to the earth and suspending a pen or writing instrument above it on a spring or pendulum. As the ground shakes, the suspended pen records the shaking on the recording device. The graph resulting from measurements of a seismograph is a seismogram. Seismographs of the early 20th century were mostly springs or pendulums with pens on them that wrote on a rotating drum of paper (Figure 5.3.5). Digital ones now use magnets and wire coils to measure ground motion. Typical seismograph arrays measure vibrations in three directions: north-south (x), east-west (y), and up-down (z). (1)

image

Figure 5.3.5 Seismograph Recording. Wikimedia Commons, CC-BY

Body waves and surface waves are recorded on seismograms, with P waves arriving first, S waves second, and surface waves following.

Surface waves do lose energy quickly, so they are not measured at great distances from the focus. Seismograph technology across the globe record the arrival of seismic waves from each earthquake at many station sites. The distance to the epicenter can be determined by comparing arrival times of the P and S waves. Electronic communication among seismic stations and connected computers used to make calculations mean that locations of earthquakes and news reports about them are generated quickly in the modern world. (1)

image

Figure 5.3.6 Multiple seismographs combined to show the dramatic movements from the magnitude 9.0 earthquake, Japan, 2011. Wikimedia Commons, CC-BY.

Locating Earthquakes

Each seismograph gives the distance from that station to the earthquake epicenter. Three or more seismograph stations are needed to locate the epicenter of an earthquake through triangulation . Using the arrival-time difference from the first P wave to the first S wave, one can determine the distance from the epicenter, but not the direction. The distance from the epicenter to each station can be plotted as a circle, the distance being equal to the circle's radius. The place where the circles intersect demarks the epicenter (Figure 5.3.7). This method also works in three dimensions with spheres and multi-axis seismographs to locate not only the epicenter but also the depth of the earthquake's focus.

Triangulation can be used to locate an earthquake. The seismometers are shown as green dots. The calculated distance from each seismometer to the earthquake is shown as a circle. The location where all the circles intersect is the location of the earthquake epicenter.
Figure 5.3.7 Triangulation can be used to locate an earthquake. The seismometers are shown as green dots. The calculated distance from each seismometer to the earthquake is shown as a circle. The location where all the circles intersect is the location of the earthquake epicenter.
USGS, Public Domain

Seismograph Network

The International Registry of Seismograph Stations lists more than 26,000 seismographs on the planet. Seismologists can use and compare data from sets of multiple seismometers dispersed over a wide area, a seismograph network. By collaborating, scientists can map the inside of the earth's properties, detect large explosive devices, and predict tsunamis. The Global Seismograph Network, a set of worldwide linked seismographs that distribute real-time data electronically, consists of more than 150 stations that meet specific design and precision standards. The Global Seismograph Network helps the Comprehensive Nuclear-Test-Ban Treaty Organization monitor for nuclear tests. The USArray is a network of hundreds of permanent and transportable seismographs within the United States. The USArray is being used to map the subsurface through a passive collection of seismic waves created by earthquakes. (1)

Video 5.3.1. How does a seismometer work? How do scientists use it to monitor and measure earthquakes? Would you like how to use your smart phone as a seismometer? Watch until the end! (3:33)

Determining Earthquake Size

There are typically two questions that are asked immediately after an earthquake: Where did it occur? How big was it? Previously we discussed the science behind determining where an earthquake occurred. Earthquake size is usually described by either their intensity or their magnitude. Intensity describes the severity of an earthquake in terms of the effects of the Earth's surface on society. Initially, all earthquakes were described using intensity scales, but these scales are inconsistent and biased depending on where the event occurred. Magnitude describes the amount of energy released at the focus of an earthquake, regardless of how it is felt or damage that occurs. Over time, several magnitude scales have been created, and earthquakes today are given magnitude (M) numbers to describe them.

Modified Mercalli-Intensity Scale

There are many scales for intensity, but the United States commonly uses the Modified Mercalli scale. The Modified Mercalli Intensity Scale is a qualitative scale (I-XII) of the intensity of ground shaking based on damage to structures and people's perceptions (Figure 5.3.8). This scale can vary depending on the location and population density (urban vs. rural). It was also used for historical earthquakes, which occurred before quantitative measurements of magnitude could be made. The Modified Mercalli Intensity maps show where the damage is most severe based on questionnaires sent to residents, newspaper articles, and reports from assessment teams. Recently, USGS has used the internet to help gather data more quickly.

image

Figure 5.3.8. Modified Mercalli Intensity Scale. USGS, Public Domain.

Richter Scale

Magnitude is the most common measure of earthquake size, as it determines the size of the earthquake at the focus and is the same number no matter where you are or what the shaking may feel like. Though outdated and no longer used, the Richter scale is the most well-known magnitude scale devised for an earthquake and was the first one developed by Charles Richter at CalTech. This was the magnitude scale used historically by early seismologists. The Richter scale magnitude is determined from measurements on a seismogram. Magnitudes on the Richter scale are based on measurements of the maximum amplitude of the needle trace measured on the seismogram and the arrival time difference of S and P waves, which gives the distance to the earthquake. (1)

The Richter scale is a logarithmic scale, based on powers of 10. The amplitude of the seismic wave recorded on the seismogram is ten times greater for each increase of 1 unit on the Richter scale. That means a magnitude six earthquake shakes the ground ten times more than a magnitude 5. However, the actual energy released for each 1-unit magnitude increase is 32 times greater. That means energy released for a magnitude six earthquake is 32 times greater than a magnitude 5 earthquake. The Richter scale was developed for distances appropriate for earthquakes in Southern California and on seismograph machines in use there. Its applications to more considerable distances and massive earthquakes are limited. Therefore, most agencies no longer use Richter's methods to determine the magnitude but generate a quantity called the Moment Magnitude, which is more accurate for large earthquakes measured at the seismic array across the earth. As numbers, the moment magnitudes are comparable to the magnitudes of the Richter Scale. The media still often give magnitudes as Richter Magnitude even though the actual calculation was of moment magnitude. (1)

image

Figure 5.3.9 This plot shows on the X-axis the time it takes to recover from an earthquake. On the y-axis, the cost of the earthquake. In the black scale on top, the Richter scale increases from left to right. Notice that values associated with catastrophic earthquakes and compare them to disasters and disruptions. Earthquake Severity. Wikimedia Commons (2007), Public Domain.

Moment Magnitude Scale

The Moment Magnitude Scale depicts the absolute size of earthquakes, comparing information from multiple locations and using a measurement of actual energy released calculated from the cross-sectional area of rupture, amount of slippage, and the rigidity of the rocks. Because of the unique geologic setting of each earthquake and because the rupture area is often hard to measure, estimates of moment magnitude can take days to months to calculate. (1)

Like the Richter magnitude, the moment magnitude scale is logarithmic. Both scales are used in tandem because the estimates of magnitude may change after a quake. The Richter scale is used as a quick determination immediately following the quake (and is usually reported in news accounts), and the moment magnitude is calculated days to months later. The magnitude values of the two magnitudes are approximately equal except for massive earthquakes.

Video 5.3.2. Compare the Richter scale and the moment magnitude scale (5:39). Produced by IRIS.

Video Player

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05:39

Backyard Geology: Seismic Network in Arizona

The Arizona Geologic Survey (AZGS), working with geoscientists at Northern Arizona University (NAU), built and maintains a statewide seismic monitoring network to record earthquakes and to look for patterns of seismic activity. In 2017, the Arizona Broadband Seismic Network (ABSN) was expanded from 8 to 13 stations, strategically located to provide statewide coverage and to capture more of the seismicity throughout Arizona. More than 3,000 historic (1852-2017) earthquake events have been recorded and compiled.

image
Figure 5.3.10. An AZGS research geologist is doing maintenance on seismic equipment contained in a plastic vault that must be exhumed before work can begin. AZGS, CC-BY.

5.4 Earthquake Hazards and Risk

Hazards

Earthquakes generate a multitude of associated hazards. Some are related to the underlying geology of the area and intensity and duration of shaking, while human built structures make others worse. Some are a combination of effects.

Shaking Intensity, Duration, and Underlying Geology

It seems intuitive, but more significant shaking and duration of shaking will cause more destruction than less shaking and shorter shaking. In addition, intensity can be affected by resonance. Resonance is when the frequency of seismic energy matches a building's natural frequency of shaking, determined by properties of the building, and intensifies the shaking's amplitude. This famously happened in the 1985 Mexico City Earthquake, where buildings of heights between 6 and 15 stories were especially vulnerable to earthquake damage. Skyscrapers designed with earthquake resilience have dampers, and base isolation features to reduce resonance. Changes in the structural integrity of a structure could alter its resonance. Conversely, changes in measured resonance can indicate potential changes in structural integrity. (1)

Amplification can also occur depending on the material in the subsurface (Figure 5.4.1). Amplification refers to the levels of shaking that may be increased by softness of the surface rocks, topography, and thickness of surface sediments. The image below shows the potential amplification predicted in the Los Angeles region.

image

Figure 5.4.1 Map of Amplification in Los Angeles. USGS, Public Domain.

Another good example of this is in the Oakland area near San Francisco, where parts of a two-layer highway built on soft sediments collapsed during the 1989 Loma Prieta earthquake (Fig. 5.4.2). At least two properties of the Earth's crust conspired to cause this collapse: it was built on loose soils that shook much more strongly than surrounding regions on stronger ground, and variations in the thickness of the Earth's crust between the epicenter of the Loma Prieta earthquake in the Santa Cruz Mountains and Oakland actually focused energy toward Oakland and downtown San Francisco. (5)

Figure 5.4.2. The Cypress Structure, the freeway approach to the Bay Bridge from Oakland, collapsed during the Loma Prieta earthquake, killing 42 people. USGS, Public Domain.

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Building Design

Building damage is also greatest in areas of soft sediments, and multi-story buildings tend to be more seriously damaged than smaller ones. Buildings can be designed to withstand most earthquakes, and this practice is increasingly applied in earthquake-prone regions. Turkey is one such region, and even though Turkey had a relatively strong building code in the 1990s, adherence to the code was poor, as builders did whatever they could to save costs, including using inappropriate materials in concrete and reducing the amount of steel reinforcing (Figure 5.4.4). The result was that there were over 17,000 deaths in the 1999 M7.6 Izmit earthquake. After two devastating earthquakes that year, Turkish authorities strengthened the building code further, but the new code has been applied only in a few regions, and enforcement of the code is still weak, as revealed by the amount of damage from a M7.1 earthquake in eastern Turkey in 2011. (5)

Figure 5.4.4. Buildings Damaged by the 1999 Earthquake, Izmit, Turkey. USGS, Public Domain.

Fires

Fires are commonly associated with earthquakes because fuel pipelines rupture and electrical lines are damaged when the ground shakes. Most of the damage in the great 1906 San Francisco earthquake was caused by massive fires in the downtown area of the city. Some 25,000 buildings were destroyed by those fires, which were fuelled by broken gas pipes. Fighting the fires was difficult because water mains had also ruptured. The risk of fires can be reduced through P-wave early warning systems if utility operators can reduce pipeline pressure and close electrical circuits. (5)

Figure 5.4.4. Some of the effects of the 2011 Tohoku earthquake in the Sendai area of Japan. An oil refinery is on fire, and a vast area has been flooded by a tsunami. United States Navy, Public Domain

Figure 5.4.5. San Francisco Fire, 1906. Library of Congress, Public Domain

Landslides

Landslides by themselves are a major geologic hazard, since they are widespread. Earthquakes are important triggers for failures on slopes that are already weak. An example is the Las Colinas slide in the city of Santa Tecla, El Salvador, which was triggered by a M7.6 offshore earthquake in January 2001 (Fig. 5.4.6). This is just one of many hundreds of slope failures that resulted from that earthquake. Over 500 people died in the area affected by this slide. (5)

A debris slide that wiped out a large section of a residential area.

Figure 5.4.6. The Las Colinas debris flow at Santa Tecla (a suburb of the capital San Salvador) triggered by the January 2001 El Salvador earthquake. USGS, Public Domain

Liquefaction

Figure 5.4.7. Collapsed apartment buildings in the Niigata area of Japan. The material beneath the buildings was liquefied to varying degrees by the 1964 earthquake. Wikimedia Commons, Public Domain

Ground shaking during an earthquake can be enough to weaken rock and unconsolidated materials to the point of failure, but in many cases the shaking also contributes to a process known as liquefaction in which an otherwise solid body of sediment is transformed into a liquid mass that can flow. When water-saturated sediments are shaken, the grains become rearranged to the point where they are no longer supporting one another. Instead, the water between the grains is holding them apart and the material can flow. Liquefaction can lead to the collapse of buildings and other structures that might be otherwise undamaged. A good example is the collapse of apartment buildings during the 1964 Niigata earthquake (M7.6) in Japan (Fig. 5.4.7). Liquefaction can also contribute to slope failures and to fountains of sandy mud (sand volcanoes) in areas where there is loose saturated sand beneath a layer of more cohesive clay. (5)

Tsunami

Tsunami (the Japanese word for harbor wave) is a series of massive ocean waves generated from earthquakes, underwater volcanic eruptions, underwater landslides, or potentially even asteroid impacts. Anything the has the potential to displace a huge amount of water can generate a tsunami, even a nuclear blast. Tsunami do not really consist of moving water, but rather the movement of energy through water.

Figure 5.4.8. Elastic deformation and rebound of overriding plate at a subduction setting (B). The release of the locked zone during an earthquake (C) results in both uplift and subsidence on the sea floor, and this is transmitted to the water overhead, resulting in a tsunami. S. Earle, CC-BY

Earthquakes that take place beneath the ocean have the potential to generate tsunami. The most likely situation for a significant tsunami is a large (M7 or greater) subduction-related earthquake, because the seafloor is dramatically moved. As shown in Figure 5.4.8, during the time between earthquakes the overriding plate becomes distorted by elastic deformation; it is squeezed laterally and pushed up. When an earthquake happens, the plate rebounds and there is both uplift and subsidence on the sea floor, in some cases by as much as several meters vertically over an area of thousands of square kilometers. This vertical motion is transmitted through the water column where it generates a series of waves that then spread across the ocean. Subduction earthquakes with magnitude less than 7 do not typically generate significant tsunami because the amount of vertical displacement of the sea floor is minimal. Sea-floor transform earthquakes, even large ones (M7 to M8), don’t typically generate tsunami either, because the motion is mostly side to side, not vertical. (5) While tsunami can affect any coastal region, they are much more likely in areas with subduction zones, like the Pacific Ring of Fire.

Tsunami waves travel at velocities of several hundred kilometers per hour and easily make it to the far side of an ocean in about the same time as a passenger jet. The simulated one shown in Figure 5.4.9 is similar to that created by the 1700 Cascadia earthquake off the coast of British Columbia, Washington, and Oregon, which was recorded in Japan nine hours later. (5)

Figure 5.4.9. Maximum Tsunami Amplitude. A model of the tsunami wave heights (colors) and travel time contours from the 1700 Cascadia earthquake (M9). Tsunami wave amplitudes typically increase in shallow water. NOAA/PMEL/Center for Tsunami Research, Public domain.

Risk

Earthquakes cause a lot of damage. This damage can include structural damage to buildings, fires, damage to bridges, highways, pipelines and electrical transmission lines, initiation of slope failures, liquefaction, and tsunami. The types of impacts depend to a large degree on where the earthquake is located: whether it is predominantly urban or rural, densely or sparsely populated, highly developed or underdeveloped, and, of course, on the ability of the infrastructure to withstand shaking.

As we have discussed, a geologic hazard is the potential for loss or damage. However, the risk can vary related to population and infrastructure, as well as other factors, of the place where the hazard occurs. We will focus on the geologic hazards in general, but it is important to remember the context in which the hazard occurs.

5.5 Forecasting and Mitigating Earthquakes

Prediction

It has long been a dream of seismologists, geologists, and public safety officials, to be able to accurately predict the location, magnitude, and timing of earthquakes on time scales that would be useful for minimizing danger to the public and damage to infrastructure (e.g., weeks, days, hours). Many different avenues of prediction have been explored, such as using observations of warning foreshocks, changes in magnetic fields, seismic tremor, changing groundwater levels, strange animal behavior, observed periodicity, stress transfer considerations, and others. So far, none of the research into earthquake prediction has provided a reliable method. Although there are some reports of successful earthquake predictions, they are rare, and many are surrounded by doubtful circumstances. (5)

The problem with earthquake predictions, as with any other type of prediction, is that they have to be accurate most of the time, not just some of the time. We have come to rely on weather predictions because they are generally (and increasingly) accurate. But if we try to predict earthquakes and are only accurate 10% of the time (and even that isn’t possible with the current state of knowledge), the public will lose faith in the process very quickly, and then will ignore all of the predictions. Efforts are currently focused on forecasting earthquake probabilities, rather than predicting their occurrence. (5)

There was great hope for earthquake predictions late in the 1980s when attention was focused on part of the San Andreas Fault at Parkfield, about 200 kilometers south of San Francisco. Between 1881 and 1965 there were five earthquakes at Parkfield, most spaced at approximately 20-year intervals, all confined to the same 20 kilometer-long segment of the fault, and all very close to M6. Both the 1934 and 1966 earthquakes were preceded by small foreshocks exactly 17 minutes before the main quake.

Figure 5.5.1. Earthquakes on the Parkfield segment of the San Andreas Fault between 1881 and 2004. S. Earle, CC-BY

The U.S. Geological Survey recognized this as an excellent opportunity to understand earthquakes and earthquake prediction, so they armed the Parkfield area with a huge array of geophysical instruments and waited for the next quake, which was expected to happen around 1987. Nothing happened! The “1987 Parkfield earthquake” finally struck in September 2004 (Fig. 5.5.1). Fortunately all of the equipment was still there, but it was no help from the perspective of earthquake prediction. There were no significant precursors to the 2004 Parkfield earthquake in any of the parameters measured, including seismicity, harmonic tremor, strain (rock deformation), magnetic field, the conductivity of the rock, or creep, and there was no foreshock. In other words, even though every available technique was used to monitor it, the 2004 earthquake came as a complete surprise, with no warning whatsoever. (5)

Figure 5.5.2. Probabilities of a M6.7 or larger earthquake over the period 2014 to 2043 on various faults in the San Francisco Bay region of California. USGS, Public Domain

The hope for earthquake prediction is not dead, but it was hit hard by the Parkfield experiment. The current focus in earthquake-prone regions is to provide forecasts of the probability of an earthquake of a certain magnitude within a certain time period—typically a number of decades—while officials focus on ensuring that the population is educated about earthquake risks and that buildings and other infrastructure are as safe as can be. An example of this approach for the San Francisco Bay region of California is shown in the adjacent figure. Based on a wide range of information, including past earthquake history, accumulated stress from plate movement, and known stress transfer, seismologists and geologists have predicted the likelihood of a M6.7 or greater earthquake on each of eight major faults that cut through the region (Fig. 5.5.2). The greatest probabilities are on the Hayward, Rogers Creek, Calaveras, and San Andreas Faults. As shown, there is a 72% chance that a major and damaging earthquake will take place somewhere in the region prior to 2043. (5)

As we've discussed already, it's not sufficient to have strong building codes, they have to be enforced. Building code compliance is quite robust in most developed countries, but is sadly inadequate in many developing countries.

Mitigation

The best we can do with earthquake hazard mitigation is work on engineering manmade structures to withstand shaking, research and understand earthquake occurrence, create early warning systems, and educating the population.

Engineering Design

Earthquakes do not kill people; falling buildings and highways kill people. History has taught us the importance of building codes to create safer buildings. Many of the massive death tolls reported by earthquakes are caused by poorly built buildings rather than the earthquake itself. In general, buildings or structures built out of brick, stone, mud, or reinforced concrete fair poorly in large earthquakes because there is very little flexibility in the structures as the ground shakes. The best types of buildings to be in are those built of wood because of there flexibility; the house may not be habitable after the earthquake, but they won't crumble or collapse on people. Buildings with weak floors or basement garages are also susceptible to collapsing. (4)

There are several techniques engineers have developed to help buildings withstand the destructive power of earthquakes. Many buildings are being built or retrofitted with diagonal braces that can withstand the ground motions caused by an earthquake. Tall buildings also tend to sway at different frequencies them to slam into each other during an earthquake. If engineers know how much a building will sway, they can determine how far apart buildings must be built.

Finally, engineers are placing rubber pads at the base of newly built and retrofitted buildings that act as shock absorbers. (4)

Early Warning Systems

A few seconds could mean all the difference between life and death during an earthquake. ShakeAlert is an earthquake early warning (EEW) system that detects significant earthquakes so quickly that alerts can reach many people before shaking arrives. ShakeAlert is not earthquake prediction, rather a ShakeAlert Message indicates that an earthquake has begun and shaking is imminent. is a product of the USGS Earthquake Hazards Program in conjunction with the regional seismic networks. Not only can this information give citizens a few extra seconds during an earthquake, it can also provide valuable near-real-time maps of ground motion and shaking intensity following significant earthquakes. These maps are used by federal, state, and local organizations, both public and private, for post-earthquake response and recovery, public and scientific information, as well as for preparedness exercises and disaster planning. (6)

Earthquake Preparedness

Everywhere in the world has disasters, so nowhere is safe. But everyone should be prepared for the type of disasters their region experiences. Everyone should have a 72 hour kit prepared in your car and house. Recently the Federal Emergency Management Agency (FEMA) stated that citizens should prepare a 5-day kit in case federal, state, and local agencies can not reach you. Learn more how you can prepare at Ready.gov. Here are a few more items you should think about with disaster preparedness (4).

Each member in your family should also know where to meet in case of a disaster.
The number one reason people end up in the hospital after an earthquake is glass on their feet. Having a pair of old shoes under your bed can reduce that probability.
Know how to shut off your gas line if you smell gas in your house. If it requires a wrench to shut off, always have one next to the line for a quick shutoff. You will know if you have a gas leak because the gas companies place a chemical in the gas that will smell like rotten eggs.
Make sure your water heater is attached to your house. If your water heater falls over and the gas line breaks, your house can catch fire.
If you and your family are safe, take care of others in need.
Finally, for those interested, look into getting CERT certified as a first responder.

Backyard Geology: Lake Mary Fault, Arizona

It’s important to understand all the research that goes into understanding earthquakes and helps scientists predict their potential future effects. Arizona has seen plenty of Earthquake Activity in its past! Watch the video below to see how the Lake Mary Fault shows how multiple events can create a fault zone and then determine what you can do to prepare for this type of event.

Video 5.5.1. Arizona State Geological Survey (2013). Lake Mary Fault, Arizona. CC-BY.

5.6 Attribution and References

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(5) Physical Geology – 2nd Edition by Steven Earle is licensed under CC BY 4.0.

(6) United States Geological Survey (USGS) is licensed under Public Domain.

Media Assets

5.0

Video 5.1. Arizona Geological Survey (2011) Time lapse: Historic earthquake epicenters of Arizona. [Online video]. Retrieved April 19, 2021 from https://youtu.be/TjgLe0hCWXw

Time lapse video of historical earthquakes that have occurred in Arizona 1852-2011

5.1

Fig. 5.1.1. Earle, S. (n.d.) Physical Geology – 2nd Edition. Depiction of elastic deformation and rupture. Retrieved April 19, 2021 from https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/06/elastic-deformation.png

Depiction of the concept of elastic deformation and rupture.

Fig. 5.1.2. Earle, S. (n.d.) Physical Geology – 2nd Edition. Propagation of failure on rupture surface. Retrieved April 19, 2021 from https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/Propagation-of-failure.png

Image showing the direction and magnitude of ruptures along the rupture surface during an earthquake

Video 5.1.3. United States Geological Survey, (n.d.) Foreshocks, Mainshocks, & Aftershocks. https://prd-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/atoms/video/aftershocks.mp4. Public Domain

Video showing foreshocks, mainshocks, and aftershocks locations along the rupture surface.

Fig. 5.1.4. Wikimedia Commons (March, 2011)). Map of Sendai Earthquake. Retrieved April 19, 2021 from

https://en.wikipedia.org/wiki/2011_T%C5%8Dhoku_earthquake_and_tsunami#/media/File:Map_of_Sendai_Earthquake_2011.jpg

Map of main earthquake event and subsequent aftershocks in the following 3 days.
Fig. 5.1.5. NASA (n.d.) Lunar Fault Scarp. Retrieved April 19, 2021 from https://www.nasa.gov/sites/default/files/styles/full_width/public/thumbnails/image/press_image_1_v2.jpg?itok=tvHkaaC0

Image of a fault scarp in the moon.
5.2
Fig. 5.2.1. Christiansen, L (n.d.) A global map of seismic activity. Retrieved April 19, 2021 from https://www.nsf.gov/news/mmg/media/images/global_seismicity_h.jpg

An image showing the pattern and depth of global earthquake activity.
Fig. 5.2.2. Panchuk, K. (2017) Locations of earthquakes of magnitude 4 and greater from 1990 to 2010 along two mid-oceanic ridges. Retrieved April 19, 2021 from https://openpress.usask.ca/app/uploads/sites/29/2017/11/Div_Trans_Eq.png

Image showing the relationships of earthquakes along divergent and transform boundaries. Arrows show the direction of plate movement.
Fig. 5.2.3. USGS (n.d) San Andreas Fault. Retrieved April 19, 2021 from https://upload.wikimedia.org/wikipedia/commons/7/76/Sanandreas.jpg

Map of the San Andreas fault showing plate motions.
Fig. 5.2.4. Earle, S (n.d.) Physical Geology – 2nd Edition. Retrieved April 19, 2021 from https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/subduction-quakes.png

Distribution of earthquakes of M4 and greater in the Central America region from 1990 to 1996
Fig. 5.2.5. Earle, S (n.d) Physical Geology – 2nd Edition. Retrieved April 19, 2021 from https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/Kuril-Islands.png

Graphic of cross-sectional view of distribution of earthquakes of M4 and greater in the Central America region from 1990 to 1996.
Fig. 5.2.6. Earle, S (n.d) Physical Geology – 2nd Edition. Retrieved April 19, 2021 from https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/India-Plate.png

Figure showing distribution of earthquakes in the area where the India Plate is converging with the Asia Plate.
Fig. 5.2.7. Earle, S (n.d) Physical Geology – 2nd Edition. Retrieved April 19, 2021 from https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/India-Asia-convergent-boundary.png

Schematic diagram of the India-Asia convergent boundary, showing examples of the types of faults along which earthquakes are focused. The devastating Nepal earthquake of May 2015 took place along one of these faults.
Fig. 5.2.8. Arizona Geological Survey (n.d.) AZ Seismic Belt. Retrieved April 19, 2021 from https://azgs.arizona.edu/sites/default/files/styles/azgs_optimized_large/public/NAZ%20seismic%20zone%20labeled.jpg?itok=BYD6Rifv

Map showing the distribution of major earthquakes across Arizona.
5.3
Fig. 5.3.1. Utah Geologic Survey (n.d.) Focus and Epicenter. Retrieved April 19, 2021 from https://geology.utah.gov/wp-content/uploads/svnt47-3_eq_early_warning_sys.gif

Schematic showing the relationship between the focus, earthquake, and fault scarp.
Fig. 5.3.2. Panchuck, K (2018). Retrieved April 19, 2021 from https://openpress.usask.ca/app/uploads/sites/29/2018/01/body_waves.png

Image showing seismic waves simulated using a spring and rope attached to a fixed surface. Top: P-waves travel as pulses of compression. Bottom: S-waves move particles at right angles to the direction of motion
Fig. 5.3.3. Earle, S (2016) Retrieved April 19, 2021 from https://openpress.usask.ca/app/uploads/sites/29/2018/03/shadow-2-SE.png

Image showing patterns of seismic wave propagation through Earth's mantle and core. S-waves do not travel through the liquid outer core, so they leave a shadow on Earth's far side. P-waves do travel through the core, but because the waves that enter the core are refracted, there are also P-wave shadow zones.
Fig. 5.3.4. Earle, S (2015). Retrieved April 19, 2021 from https://openpress.usask.ca/app/uploads/sites/29/2017/05/seismic-surface.png

Image showing surface waves, which travel along Earth's surface and have a diminished impact with depth. Rayleigh waves (left) cause a rolling motion, and Love waves (right) cause the ground to shift from side to side.
Fig. 5.3.5. Wikimedia Commons (November, 2018) Seismograph Recording. Retrieved April 19, 2021 from https://commons.wikimedia.org/wiki/File:Seismograph_recording.jpg

Image of Seismograph showing seismogram
Fig. 5.3.6. Wikimedia Commons (2011). Retrieved April 19, 2021 from https://live.staticflickr.com/5299/5520554611_1f2b88c5ef_b.jpg

Image showing multiple seismographs combined to show the dramatic movements from the magnitude 9.0 earthquake, Japan, 2011.
Fig. 5.3.7. USGS (n.d.) Retrieved April 19, 2021 from https://prd-wret.s3.us-west-2.amazonaws.com/assets/palladium/production/s3fs-public/styles/full_width/public/thumbnails/image/eq-ed-triangulation.gif

Image showing how Triangulation can be used to locate an earthquake.
Video 5.3.1. Geoscience Australia (May 18, 2020) Earthquake monitoring. Retrieved April 19, 2021 from https://youtu.be/GcNVpMZIlDo

Video showing how earthquakes are monitored and how seismic waves are measured.
Fig. 5.3.8. USGS (n.d.) Modified Mercali Intensity Scale. Retrieved April 19, 2021 from https://www.usgs.gov/media/images/modified-mercalli-intensity-scale

Image showing the Modified Mercalli Intensity Scale.
Fig. 5.3.9 Wikimedia Commons (2007) Earthquake severity. Retrieved April 19, 2021 from https://commons.wikimedia.org/wiki/File:Earthquake_severity.jpg

Image showing the relative size of the earthquake and severity.
Video 5.3.2. Incorporated Research Institutions for Seismology (n.d.) Retrieved April 19, 2021 from https://www.iris.edu/hq/inclass/uploads/videos/A_004A_momentmagnitude.mp4?_=1

Video showing the difference between the Richter Scale and Moment Magnitude
Fig. 5.3.10 Arizona State Geological Survey (n.d.) Retrieved April 19, 2021 from https://azgs.arizona.edu/sites/default/files/styles/azgs_optimized_large/public/azgs-photo-gallery/IMG_0004.JPG?itok=PGJux2hU

Image showing a research geologist uncovering a seismic station in Southern Arizona.
5.4
Fig. 5.4.1 USGS (n.d.) Retrieved April 19, 2021 from https://earthquake.usgs.gov/learn/glossary/images/amplification.jpg

Map of amplification potential in Los Angeles
Fig. 5.4.2 USGS (n.d) Retrieved April 19, 2021 from https://upload.wikimedia.org/wikipedia/commons/9/91/Cypress_collapsed.jpg

Image of the Cypress Structure, the freeway approach to the Bay Bridge, which collapsed during the Loma Prieta earthquake, killing 42 people.
Fig. 5.4.3 USGS (n.d.) Retrieved April 19, 2021 from https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/earthquake-in-the-Izmit.png

Images of Buildings Damaged by the 1999 Earthquake, Izmit, Turkey.
Fig. 5.4.4 United States Navy (n.d.) Retrieved April 19, 2021 from https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/Tohoku-earthquake.jpg

Photograph of effects of the 2011 Tohoku earthquake in the Sendai area of Japan.

Fig. 5.4.5 Library of Congress (n.d.) San Francisco Fire. Retrieved April 19, 2021 from https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/Fires-in-San-Francisco.jpg

Photograph of San Francisco Fire, 1906
Fig. 5.4.6 USGS (n.d.) Retrieved April 19, 2021 from https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/The-Las-Colinas-debris.jpg

The Las Colinas debris flow at Santa Tecla (a suburb of the capital San Salvador) triggered by the January 2001 El Salvador earthquake.
Fig. 5.4.7 Wikimedia Commons (n.d.) Retrieved April 19, 2021 from https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/Niigata.jpg

Aerial photograph of damage due to liquefaction from earthquake in Japan, 1964
Fig. 5.4.8 Earle, S. (n.d.) Retrieved April 19, 2021 from https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/Elastic-deformation.png

Figure of elastic deformation and rebound of overriding plate at a subduction setting
Fig. 5.4.9 NOAA (n.d.) Retrieved April 19, 2021 from https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/tsunami.png

Image of Maximum Tsunami Amplitude. A model of the tsunami wave heights (colors) and travel time contours from the 1700 Cascadia earthquake (M9).
5.5
Fig. 5.5.1 Earle, S (n.d.) Retrieved April 19, 2021 from https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/06/Parkfield-segment.png

Graph showing relative numbers of earthquakes on the Parkfield segment of the San Andreas.
Fig. 5.5.2 USGS (n.d.) Retrieved April 19, 2021 from https://opentextbc.ca/physicalgeology2ed/wp-content/uploads/sites/298/2019/08/bay-area-prob.png

Map showing probabilities of a M6.7 or larger earthquake over a period of 2014-2043 on various faults in the San Francisco Bay region of California.
Video 5.5.1. Arizona State Geological Survey (2013) Lake Mary Fault, Arizona. Retrieved April 19, 2021 from https://youtu.be/vi3TVP8l7rc

Video showing the development of the Lake Mary Fault system, Arizona.