EENS 3050	Natural Disasters
Tulane University	Prof. Stephen A. Nelson
Earthquakes: Causes and Measurements	

This page last updated on 28-Aug-2013

Earthquakes

The objectives of this part of the course will to be gain an understanding of the science of earthquakes so that we can answer the following questions:

1. What causes earthquakes?
2. How are earthquakes studied?
3. What happens during an earthquake?
4. Where do earthquakes occur?
5. Can earthquakes be predicted?
6. Can humans be protected from earthquakes?

Most earthquakes occur along zones where the Earth's crust is undergoing deformation. Deformation results from plate tectonic forces and gravitational forces. The type of deformation that takes place during an earthquake generally occurs along zones where rocks fracture to produce faults. Before we can understand earthquakes, we first must explore deformation of rocks and faulting.

Within the Earth rocks are constantly subjected to forces that tend to bend, twist, or fracture them. When rocks bend, twist or fracture they are said to deform or strain (change shape or size). The forces that cause deformation are referred to as stresses. To understand rock deformation we must first explore stress and strain.

Stress and Strain

Stress is a force applied over an area. One type of stress that we are all used to is a uniform stress, called pressure. A uniform stress is where the forces act equally from all directions. In the Earth the pressure due to the weight of overlying rocks is a uniform stress and is referred to as *confining stress*. If stress is not equal from all directions then the stress is a differential stress. Three kinds of differential stress occur.

1. *Tensional stress (or extensional stress)*, which stretches rock;

2. *Compressional stress*, which squeezes rock; and

3. *Shear stress*, which result in slippage and translation.

Confining Stress
(Stress equal from all directions)

Tensional Stress

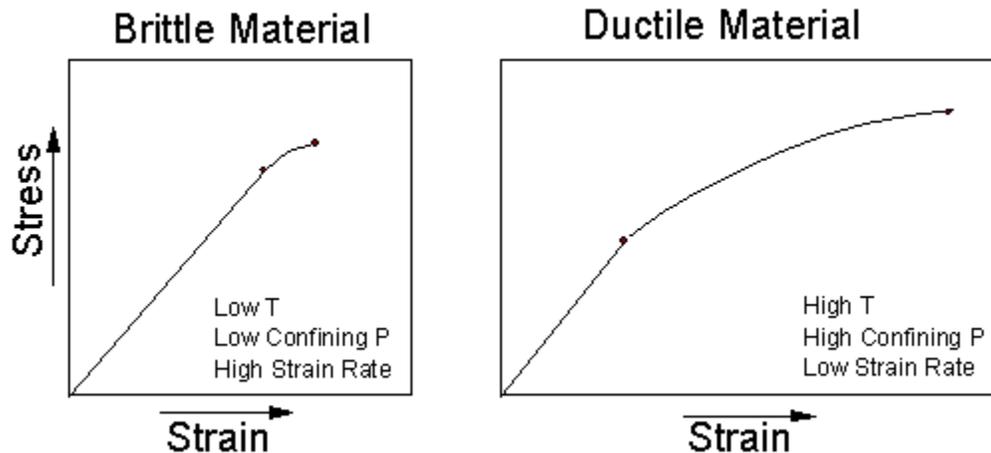Compressional Stress

Shear Stress
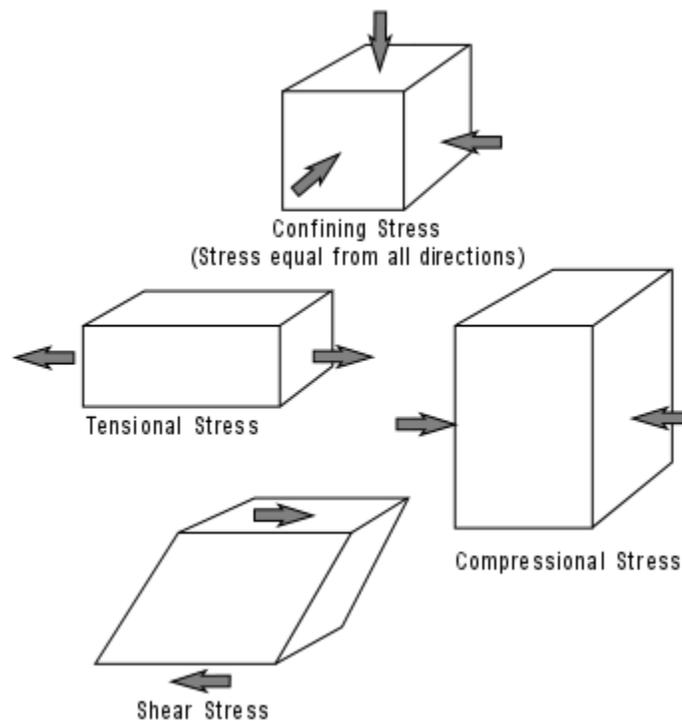
Stages of Deformation

When a rock is subjected to increasing stress it changes its shape, size or volume. Such a change in shape, size or volume is referred to as *strain*. When stress is applied to rock, the rock passes through 3 successive stages of deformation.

- *Elastic Deformation* -- wherein the strain is reversible.

- *Ductile Deformation* -- wherein the strain is irreversible.

- *Fracture* -- irreversible strain wherein the material breaks.
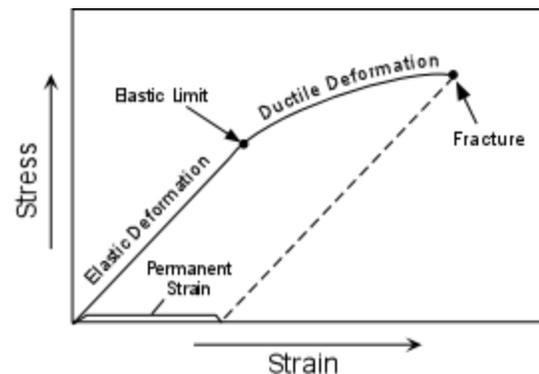
We can divide materials into two classes that depend on their relative behavior under stress.

- *Brittle materials* have a small to large region of elastic behavior, but only a small region of ductile behavior before they fracture.

- *Ductile materials* have a small region of elastic behavior and a large region of ductile behavior before they fracture.

Brittle Material — Low T, Low Confining P, High Strain Rate (Stress vs. Strain)

Ductile Material — High T, High Confining P, Low Strain Rate (Stress vs. Strain)

How a material behaves will depend on several factors. Among them are:

- Temperature - At high temperature molecules and their bonds can stretch and move, thus materials will behave in more ductile manner. At low Temperature, materials are brittle.

- Confining Pressure - At high confining pressure materials are less likely to fracture because the pressure of the surroundings tends to hinder the formation of fractures. At low confining stress, material will be brittle and tend to fracture sooner.

- Strain rate -- Strain rate refers to the rate at which the deformation occurs (strain divided by time). At high strain rates material tends to fracture. At low strain rates more time is available for individual atoms to move and therefore ductile behavior is favored.

- Composition -- Some minerals, like quartz, olivine, and feldspars are very brittle. Others, like clay minerals, micas, and calcite are more ductile This is due to the chemical bond types that hold them together. Thus, the mineralogical composition of the rock will be a factor in determining the deformational behavior of the rock. Another aspect is presence or absence of water. Water appears to weaken the chemical bonds and forms films around mineral grains along which slippage can take place. Thus wet rock tends to behave in ductile manner, while dry rocks tend to behave in brittle manner.

Evidence of Former Deformation

Evidence of deformation that has occurred in the past is very evident in crustal rocks. For example, sedimentary layers and lava flows generally are deposited on a surface parallel to the Earth's surface (nearly horizontal). Thus, when we see such layers inclined instead of horizontal, evidence of an episode of deformation is present.

In order to uniquely define the orientation of a planar feature we first need to define two terms - strike and dip. For an inclined plane the *strike* is the compass direction of any horizontal line on the plane. The *dip* is the angle between a horizontal plane and the inclined plane, measured perpendicular to the direction of strike.
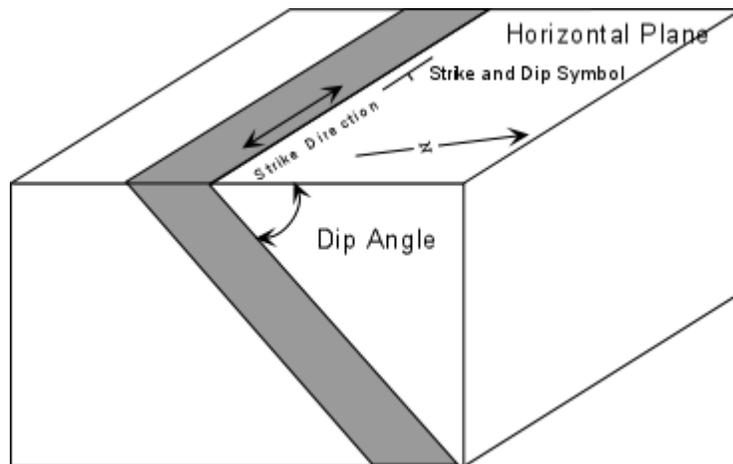
In recording strike and dip measurements on a geologic map, a symbol is used that has a long line oriented parallel to the compass direction of the strike. A short tick mark is placed in the center of the line on the side to which the inclined plane dips, and the angle of dip is recorded next to the strike and dip symbol. For beds with a 90° dip (vertical) the short line crosses the strike line, and for beds with no dip (horizontal) a circle with a cross inside is used.
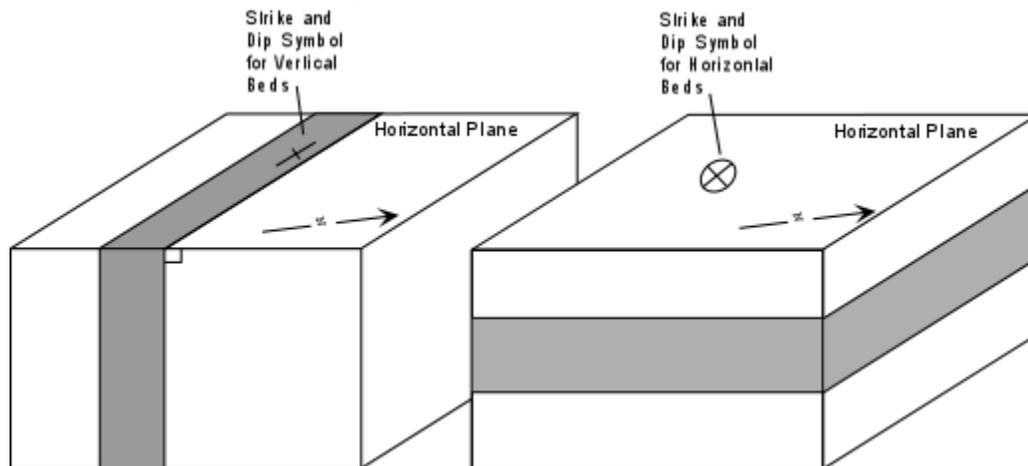
Fracture of Brittle Rocks

Joints
Joints are fractures in rock that show no slippage or offset along the fracture. Joints are usually planar features, so their orientation can be described as a strike and dip.   They form from as a result of extensional stress acting on brittle rock. Such stresses can be induced by cooling of rock (volume decreases as temperature decreases) or by relief of pressure as rock is eroded above thus removing weight.

Joints are zones of weakness,so their presence is critical when building anything from dams to highways. For dams, the water could leak out through the joints leading to dam failure. For highways the joints may separate and cause rock falls and landslides.

Faults - Faults occur when brittle rocks fracture and there is an offset along the fracture. When the offset is small, the displacement can be easily measured, but sometimes the displacement is so large that it is difficult to measure.

Types of Faults

Faults can be divided into several different types depending on the direction of relative displacement. Since faults are planar features, the concept of strike and dip also applies, and thus the strike and dip of a fault plane can be measured. One division of faults is between dip-slip faults, where the displacement is measured along the dip direction of the fault, and strike-slip faults where the displacement is horizontal, parallel to the strike of the fault.

- Dip Slip Faults - Dip slip faults are faults that have an inclined fault plane and along which the relative displacement or offset has occurred along the dip direction. Note that in looking at the displacement on any fault we don't know which side actually moved or if both sides moved, all we can determine is the relative sense of motion.

  For any inclined fault plane we define the block above the fault as the ***hanging wall block*** and the block below the fault as the ***footwall block.***

  - ***Normal Faults -*** are faults that result from horizontal tensional stresses in brittle rocks and where the hanging-wall block has moved down relative to the footwall block.
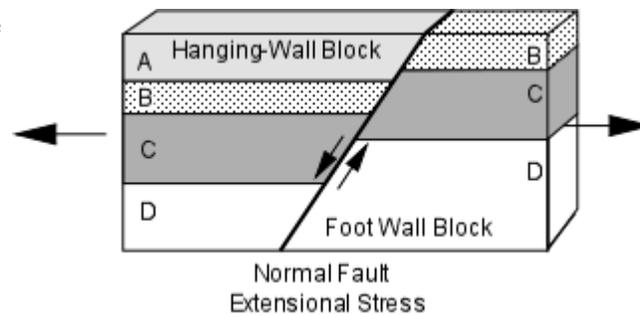

    Horsts & Grabens - Due to the tensional stress responsible for normal faults, they often occur in a series, with adjacent faults dipping in opposite directions. In such a case the down-dropped blocks form ***grabens*** and the uplifted blocks form ***horsts***. In areas where tensional stress has recently affected the crust, the grabens may form ***rift valleys*** and the uplifted horst blocks may form linear mountain ranges. The East African Rift Valley is an example of an area where continental extension has created such a rift. The basin and range province of the western U.S. (Nevada, Utah, and Idaho) is also an area that has recently undergone crustal extension. In the basin and range, the basins are elongated grabens that now form valleys, and the ranges are uplifted horst blocks.
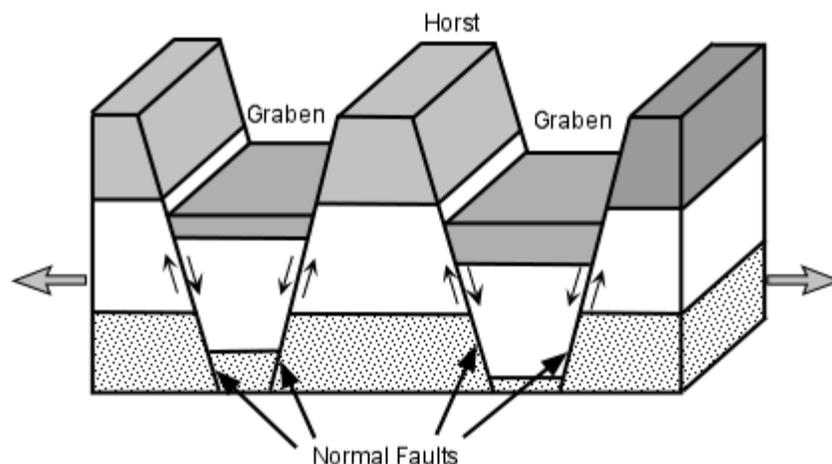
o ***Reverse Faults*** - are faults that result from horizontal compressional stresses in brittle rocks, where the hanging-wall block has moved <u>up</u> relative the footwall block.


Reverse Fault
Compressional Stress
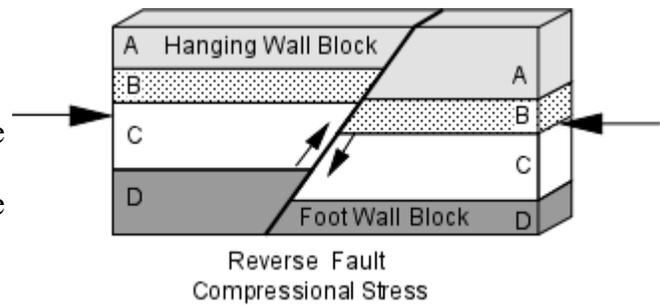
A ***Thrust Fault*** is a special case of a reverse fault where the dip of the fault is less than 45°. Thrust faults can have considerable displacement, measuring hundreds of kilometers, and can result in older strata overlying younger strata.


Thrust Fault
Compressional Stress
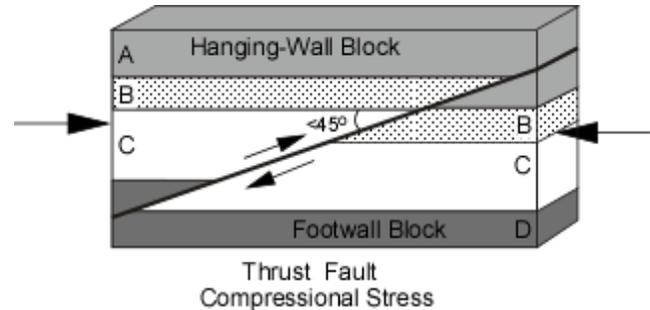
o ***Strike Slip Faults*** - are faults where the relative motion on the fault has taken place along a horizontal direction. Such faults result from shear stresses acting in the crust. Strike slip faults can be of two varieties, depending on the sense of displacement. To an observer standing on one side of the fault and looking across the fault, if the block on the other side has moved to the left, we say that the fault is a ***left-lateral strike-slip fault***. If the block on the other side has moved to the right, we say that the fault is a ***right-lateral strike-slip fault***. The famous San Andreas Fault in California is an example of a right-lateral strike-slip fault. Displacements on the San Andreas fault are estimated at over 600 km.

Left-Lateral Strike-Slip Fault   Right-Lateral Strike-Slip Fault

Shear Stress
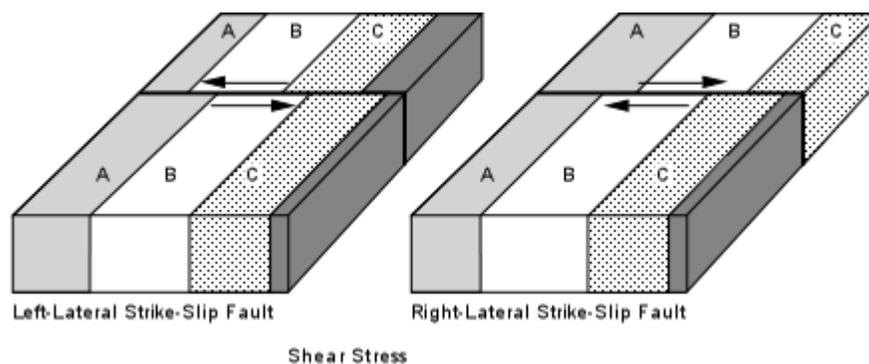
Transform-Faults are a special class of strike-slip faults. These are plate boundaries along which two plates slide past one another in a horizontal manner. The most common type of transform faults occur where oceanic ridges are offset. Note that the transform fault only occurs between the two segments of the ridge. Outside of this area there is no relative movement because blocks are moving in the same direction. These areas are called fracture zones. The San Andreas fault in California is also a transform fault.
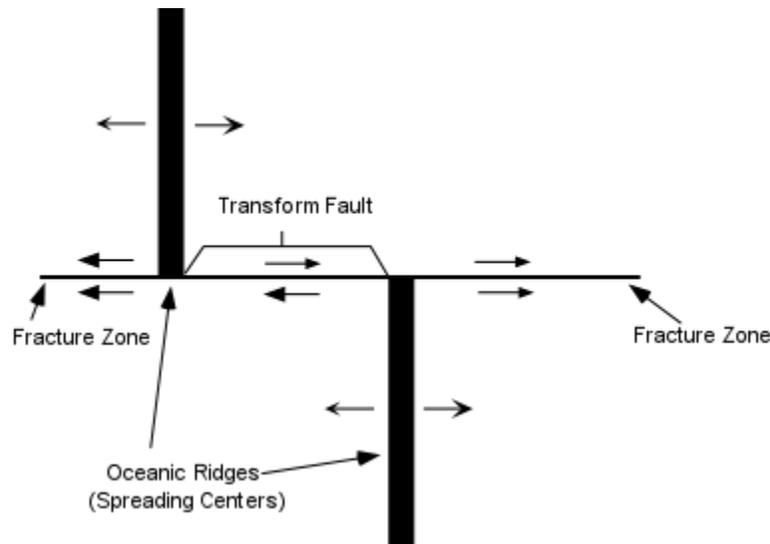
Blind Faults - are faults that does not break the surface - rocks above the fault have behaved in ductile fashion and folded over the tip of the fault.
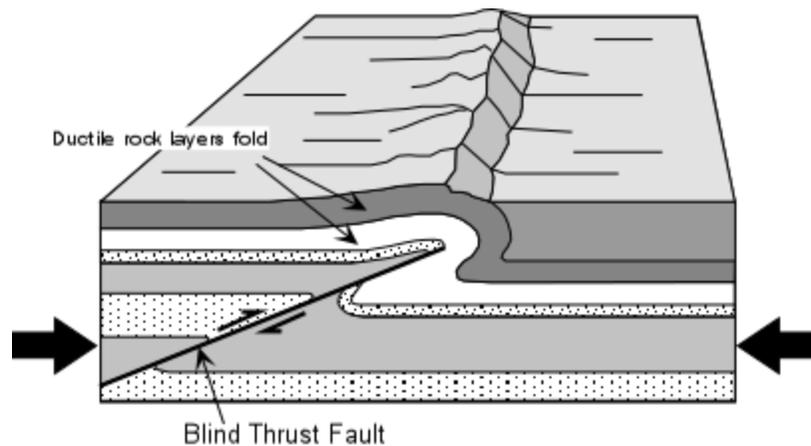
Active Faults- An active fault is one that has shown recent displacement and likely has the potential to produce earthquakes. Since faulting is part of the deformation process, ancient faults can be found anywhere that deformation has taken place in the past. Thus, not every fault one sees is necessarily an active fault.

Surface Expression of Faults - Where faults have broken the surface they are shown on maps as fault lines or fault zones. Recent ruptures of dip slip faults at the surface show a cliff that is called a fault scarp.

Strike slip faults result in features like linear valleys, offset surface features (roads, stream channels, fences, etc.) or elongated ridges

How Faults Develop - When tectonic forces generate stress, rocks start to deform elastically. Eventually small cracks to form along the fault zone. When rupture occurs, the stored elastic energy is released as seismic waves.
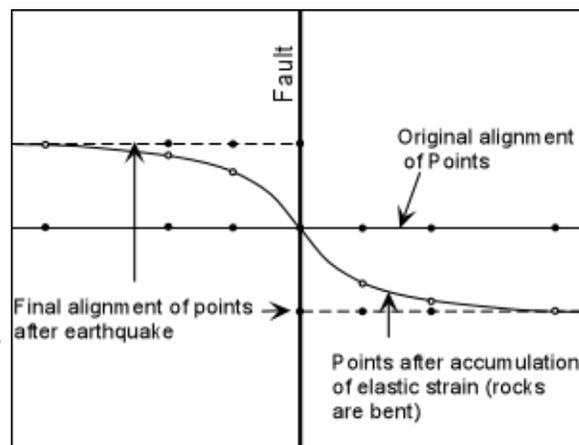
Earthquakes

Earthquakes occur when energy stored in elastically strained rocks is suddenly released. This release of energy causes intense ground shaking in the area near the source of the earthquake and sends waves of elastic energy, called seismic waves, throughout the Earth. Earthquakes can be generated by bomb blasts, volcanic eruptions, and sudden slippage along faults. Earthquakes are definitely a geologic hazard for those living in earthquake prone areas, but the seismic waves generated by earthquakes are invaluable for studying the interior of the Earth.

Origin of Earthquakes

Most natural earthquakes are caused by sudden slippage along a fault zone. The ***elastic rebound theory*** suggests that if slippage along a fault is hindered such that elastic strain energy builds up in the deforming rocks on either side of the fault, when the slippage does occur, the energy released causes an earthquake.

This theory was discovered by making measurements at a number of points across a fault. Prior to an earthquake it was noted that the rocks adjacent to the fault were bending. These bends disappeared after an earthquake suggesting that the energy stored in bending the rocks was suddenly released during the earthquake.

Friction between the blocks then keeps the fault from moving again until enough strain has accumulated to overcome the friction and generate another earthquake. Once a fault forms, it becomes a zone of weakness - so long as the tectonic stresses continue to be present more earthquakes are likely to occur on the fault. Thus faults move in spurts and this behavior is referred to as ***Stick Slip***.

If there is large displacement during an earthquake, a large earthquake will be generated. Smaller displacements generate smaller earthquakes. Note that even for small displacements of only a millimeter per year, after 1 million years, the fault will accumulate 1 km of displacement.

Fault Creep - Some faults or parts of faults move continuously without generating earthquakes. This could occur if there is little friction on the fault & tectonic stresses are large enough to move the blocks in opposite directions. This is called fault creep. If creep is occurring on one part of a fault, it is likely causing strain to build on other parts of the fault.

### Seismology, The Study of Earthquakes

When an earthquake occurs, the elastic energy is released sending out vibrations that travel throughout the Earth. These vibrations are called seismic waves. The study of how seismic waves behave in the Earth is called ***seismology***.

- The source of an earthquake is called the *focus*, which is an exact location within the Earth were seismic waves are generated by sudden release of stored elastic energy. The *epicenter* is the point on the surface of the Earth directly above the focus. Sometimes the media get these two terms confused.
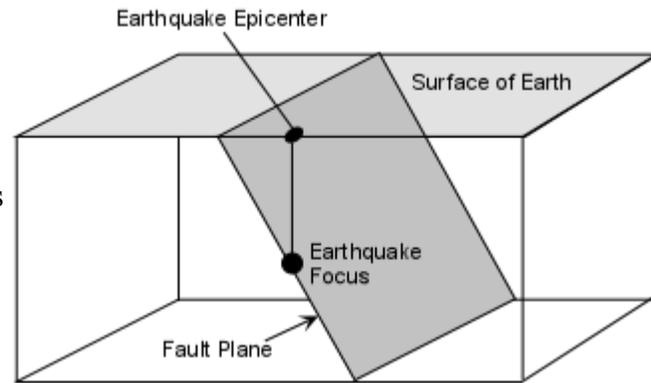
Seismic waves emanating from the focus can travel in several ways, and thus there are several different kinds of seismic waves.

- ○ *Body Waves* - emanate from the focus and travel in all directions through the body of the Earth. There are two types of body waves: P -waves and S-waves:
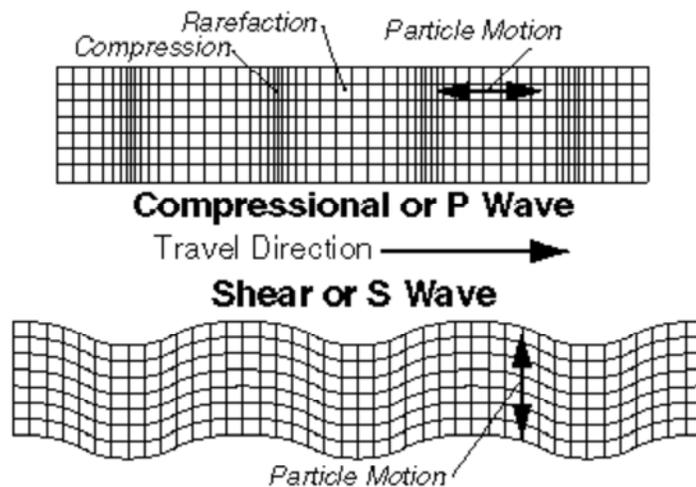
  - ■ *P - waves* - are Primary waves. They travel with a velocity that depends on the elastic properties of the rock through which they travel.

$$V_p = \sqrt{[(K+4/3\mu)/\rho]}$$

  - ■ Where, V_p is the velocity of the P-wave, K is the incompressibility of the material, μ is the rigidity of the material, and ρ is the density of the material.

    P-waves are the same thing as sound waves. They move through the material by compressing it, but after it has been compressed it expands, so that the wave moves by compressing and expanding the material as it travels. Thus the velocity of the P-wave depends on how easily the material can be compressed (the incompressibility), how rigid the material is (the rigidity), and the density of the material. P-waves have the highest velocity of all seismic waves and thus will reach all seismographs first.

  - ■ *S-Waves* - Secondary waves, also called shear waves. They travel with a velocity that depends only on the rigidity and density of the material through which they travel:

$$V_S = \sqrt{\mu / \rho}$$

S-waves travel through material by shearing it or changing its shape in the direction perpendicular to the direction of travel. The resistance to shearing of a material is the property called the rigidity. It is notable that liquids have no rigidity, so that the velocity of an S-wave is zero in a liquid. (This point will become important later). Note that S-waves travel slower than P-waves, so they will reach a seismograph after the P-wave.

o *Surface Waves* - Surface waves differ from body waves in that they do not travel through the Earth, but instead travel along paths nearly parallel to the surface of the Earth. Surface waves behave like S-waves in that they cause up and down and side to side movement as they pass, but they travel slower than S-waves and do not travel through the body of the Earth. Surface waves are often the cause of the most intense ground motion during an earthquake.
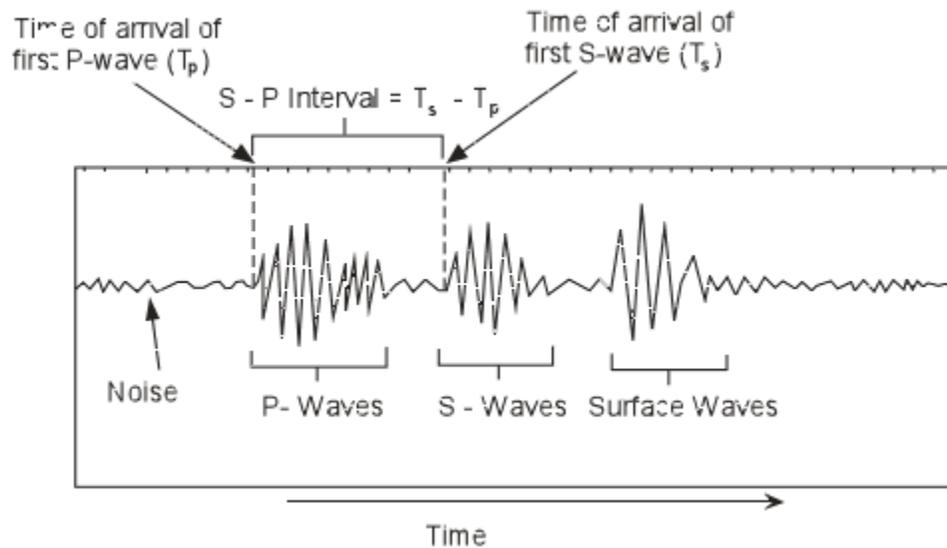
- **Seismometers -**
  Seismic waves travel through the Earth as vibrations. A *seismometer* is an instrument used to record these vibrations, and the resulting graph that shows the vibrations is called a *seismogram*. The seismometer must be able to move with the vibrations, yet part of it must remain nearly stationary.
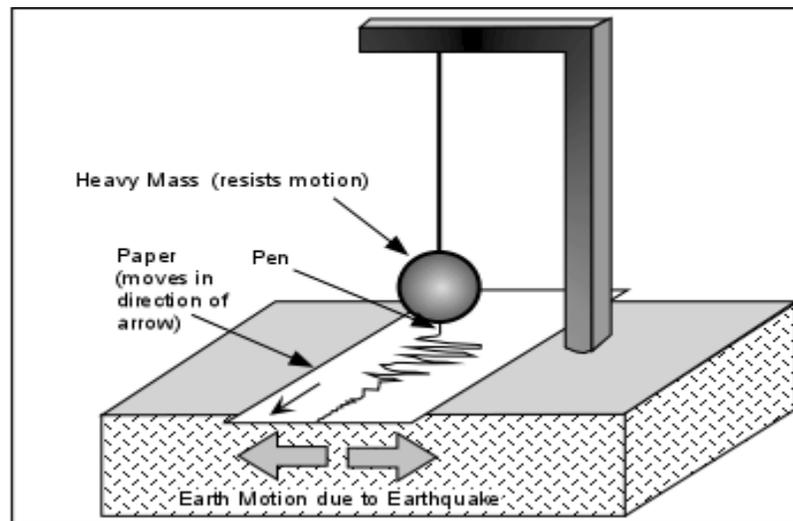
This is accomplished by isolating the recording device (like a pen) from the rest of the Earth using the principal of inertia. For example, if the pen is attached to a large mass suspended by a wire, the large mass moves less than the paper which is attached to the Earth, and on which the record of the vibrations is made. Modern instruments are digital and don't require the paper.

The record of an earthquake, a seismogram, as recorded by a seismometer, will be a plot of vibrations versus time. On the seismograph, time is marked at regular intervals, so that we can determine the time of arrival of the first P-wave and the time of arrival of the first S-wave. (Note again, that because P-waves have a higher velocity than S-waves, the P-waves arrive at the seismographic station before the S-waves)

Time of arrival of first P-wave (T_p)

Time of arrival of first S-wave (T_s)

S - P Interval = $T_s - T_p$

Noise

P- Waves   S - Waves   Surface Waves

Time

- Locating the Epicenters of Earthquakes - To determine the location of an earthquake epicenter, we need to have recorded a seismograph of the earthquake from at least three seismographic stations at different distances from the epicenter. In addition, we need one further piece of information - that is the time it takes for P-waves and S-waves to travel through the Earth and arrive at a seismographic station. Such information has been collected over the last 80 or so years, and is available as travel time curves.

  From the seismographs at each station one determines the S-P interval (the difference in the time of arrival of the first S-wave and the time of arrival of the first P-wave. Note that on the travel time curves, the S-P interval increases with increasing distance from the epicenter.

Distance from Epicenter

Travel Time

S-wave travel time

P-wave travel time

S - P interval for seismographic station 3

S - P interval for seismographic station 2

S - P interval for seismographic station 1

d_1 d_2 d_3

Distance to epicenter for seismographic stations 1, 2, and 3
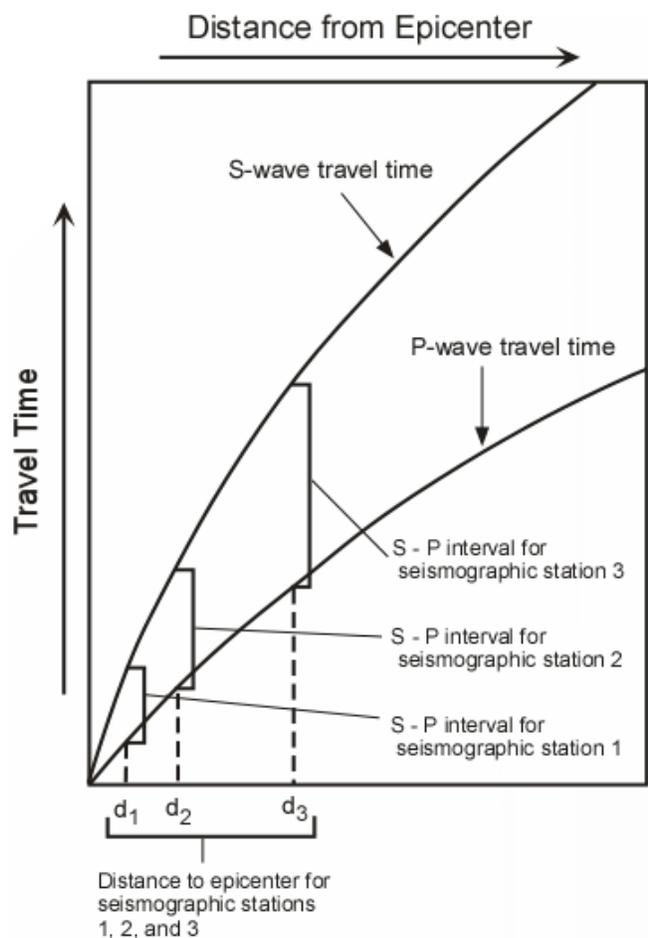
Thus the S-P interval tells us the distance to the epicenter from the seismographic station where the earthquake was recorded. Thus at each station we can draw a circle on a map that has a radius equal to the distance from the epicenter. Three such circles will intersect in a point that locates the epicenter of the earthquake.
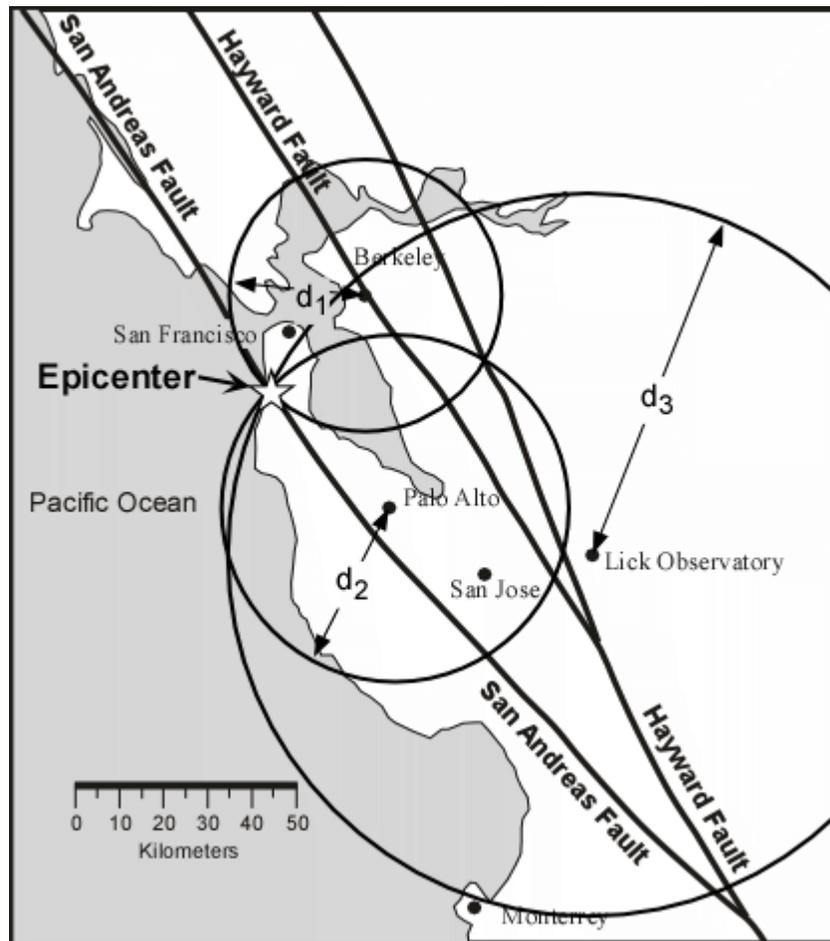
- Magnitude of Earthquakes - Whenever a large destructive earthquake occurs in the world the press immediately wants to know where the earthquake occurred and how big the earthquake was (in California the question is usually - Was this the Big One?). The size of an earthquake is usually given in terms of a scale called the Richter Magnitude. Richter Magnitude is a scale of earthquake size developed by a seismologist named Charles Richter. The Richter Magnitude involves measuring the amplitude (height) of the largest recorded wave at a specific distance from the earthquake. While it is correct to say that for each increase in 1 in the Richter Magnitude, there is a tenfold increase in amplitude of the wave, it is **incorrect** to say that each increase of 1 in Richter Magnitude represents a tenfold increase in the size of the Earthquake (as is commonly incorrectly stated by the press).
    - A better measure of the size of an earthquake is the amount of energy released by the earthquake. While this is much more difficult to determine, Richter gave a means by which the amount of energy released can be estimated:

$$\text{Log } E = 11.8 + 1.5 \text{ M}$$

Where Log refers to the logarithm to the base 10, E is the energy released in ergs, and M is the Richter Magnitude.

Anyone with a hand calculator can solve this equation by plugging in various values of M (magnitude) and solving for E, the energy released. I've done the

calculation for you in the following table:

Magnitude	Energy (ergs)	Factor
1	2.0×10^{13}	31 x
2	6.3×10^{14}	
3	2.0×10^{16}	31 x
4	6.3×10^{17}	
5	2.0×10^{19}	31 x
6	6.3×10^{20}	
7	2.0×10^{22}	31 x
8	6.3×10^{23}	

From these calculations you can see that each increase in 1 in Magnitude represents a 31 fold increase in the amount of energy released. Thus, a magnitude 7 earthquake releases 31 times more energy than a magnitude 6 earthquake. A magnitude 8 earthquake releases 31 x 31 or 961 times as much energy as a magnitude 6 earthquake.

- Although the Richter Magnitude is the scale most commonly reported when referring to the size of an earthquake, it has been found that for larger earthquakes a more accurate measurement of size is the ***moment magnitude, Mw.*** The moment magnitude is a measure of the amount of strain energy released by the earthquake as determined by measurements of the shear strength of the rock and the area of the rupture surface that slipped during the earthquake.

- Note that it usually takes more than one seismographic station to calculate the magnitude of an earthquake. Thus you will hear initial estimates of earthquake magnitude immediately after an earthquake and a final assigned magnitude for the same earthquake that may differ from initial estimates, but is assigned after seismologists have had time to evaluate the data from numerous seismographic stations.

- The moment magnitude for large earthquakes is usually greater than the Richter magnitude for the same earthquake. For example the Richter magnitude for the 1964 Alaska earthquake is usually reported as 8.6, whereas the moment magnitude for this earthquake is calculated at 9.2.

- The largest earthquake ever recorded was in Chile in 1960 with a moment magnitude of 9.5, The Summatra earthquake of 2004 had a moment magnitude of 9.0. Sometimes a magnitude is reported for an earthquake and no specification is given as to which magnitude (Richter or moment) is reported. This obviously can cause confusion. But, within the last few years, the tendency has been to report the moment magnitude rather

than the Richter magnitude.

- The Hiroshima atomic bomb released an amount of energy equivalent to a moment magnitude 6 earthquake.

- Note that magnitude scales are open ended with no maximum or minimum. The largest earthquakes are probably limited by rock strength. Meteorite impacts could cause larger earthquakes than have ever been observed.

Frequency of Earthquakes of Different Magnitude Worldwide		
Magnitude	Number of Earthquakes per Year	Description
> 8.5	0.3	Great
8.0 - 8.4	1	Great
7.5 - 7.9	3	Major
7.0 - 7.4	15	Major
6.6 - 6.9	56	Major
6.0 - 6.5	210	Destructive
5.0 - 5.9	800	Damaging
4.0 - 4.9	6,200	Minor
3.0 - 3.9	49,000	Minor
2.0 - 2.9	300,000	Minor
0 - 1.9	700,000	Minor

Modified Mercalli Intensity Scale

Note that the Richter magnitude scale results in one number for the size of the earthquake. Maximum ground shaking will occur only in the area of the epicenter of the earthquake, but the earthquake may be felt over a much larger area. The Modified Mercalli Scale was developed in the late 1800s to assess the intensity of ground shaking and building damage over large areas.

- The scale is applied after the earthquake by conducting surveys of people's response to the intensity of ground shaking and destruction.

- Thus, a given earthquake will have zones of different intensity all surrounding a zone of maximum intensity.

- The Modified Mercalli Scale is shown in the table below. Note that correspondence between maximum intensity and Richter Scale magnitude only applies in the area around the epicenter.

- Thus, a given earthquake will have zones of different intensity all surrounding a zone of maximum intensity.

- The Modified Mercalli Scale is shown in the table below. Note that correspondence

between maximum intensity and Richter Scale magnitude only applies in the area around the epicenter.

Intensity	Characteristic Effects	Richter Scale Equivalent
I	People do not feel any Earth movement	<3.4
II	A few people notice movement if at rest and/or on upper floors of tall buildings	
III	People indoors feel movement. Hanging objects swing back and forth. People outdoors might not realize that an earthquake is occurring	4.2
IV	People indoors feel movement. Hanging objects swing. Dishes, windows, and doors rattle. Feels like a heavy truck hitting walls. Some people outdoors may feel movement. Parked cars rock.	4.3 - 4.8
V	Almost everyone feels movement. Sleeping people are awakened. Doors swing open/close. Dishes break. Small objects move or are turned over. Trees shake. Liquids spill from open containers	4.9-5.4
VI	Everyone feels movement. People have trouble walking. Objects fall from shelves. Pictures fall off walls. Furniture moves. Plaster in walls may crack. Trees and bushes shake. Damage slight in poorly built buildings.	5.5 - 6.1
VII	People have difficulty standing. Drivers feel cars shaking. Furniture breaks. Loose bricks fall from buildings. Damage slight to moderate in well-built buildings; considerable in poorly built buildings.	5.5 - 6.1
VIII	Drivers have trouble steering. Houses not bolted down shift on foundations. Towers & chimneys twist and fall. Well-built buildings suffer slight damage. Poorly built structures severely damaged. Tree branches break. Hillsides crack if ground is wet. Water levels in wells change.	6.2 - 6.9
IX	Well-built buildings suffer considerable damage. Houses not bolted down move off foundations. Some underground pipes broken. Ground cracks. Serious damage to Reservoirs.	6.2 - 6.9
X	Most buildings & their foundations destroyed. Some bridges destroyed. Dams damaged. Large landslides occur. Water thrown on the banks of canals, rivers, lakes. Ground cracks in large areas. Railroad tracks bent slightly.	7.0 - 7.3
XI	Most buildings collapse. Some bridges destroyed. Large cracks appear in the ground. Underground pipelines destroyed. Railroad tracks badly bent.	7.4 - 7.9
XII	Almost everything is destroyed. Objects thrown into the air. Ground moves in waves or ripples. Large amounts of rock may move.	>8.0

- The Mercalli Scale is very useful in examining the effects of an earthquake over a large area, because it will is responsive not only to the size of the earthquake as measured by the Richter scale for areas near the epicenter, but will also show the effects of the efficiency that seismic waves are transmitted through different types of material near the Earth's surface.

- The Mercalli Scale is also useful for determining the size of earthquakes that occurred

before the modern seismographic network was available (before there were seismographic stations, it was not possible to assign a Richter Magnitude).

Examples of questions on this material that could be asked on an exam

1. Define the following terms (a), stress (b) confining stress, (c) differential stress, (d) tensional stress (e) compressional stress, (e) strain.

2. What are the three stages of deformation that all materials go through as stress is increased?

3. What is the difference between a brittle material and a ductile material?

4. Explain the following types of faults: (a) normal fault, (b) reverse fault, (c) thrust fault, (d) strike-slip fault, and (e) transform fault.

5. Explain the elastic rebound theory on the cause earthquakes.

6. What is the difference between the epicenter of an earthquake and the focus of an earthquake.

7. What are seismic waves and what is the difference between a P-wave, an S-wave and a Surface wave?

8. For each increase of magnitude by a factor of 1, how much more energy is released?

9. What is the difference between Richter magnitude and Moment magnitude and which of these scales is a more accurate measure of the energy released by large earthquakes?

10. What is the difference between the magnitude scale and the Modified Mercalli Intensity Scale?

References

Return to EENS 3050 Homepage