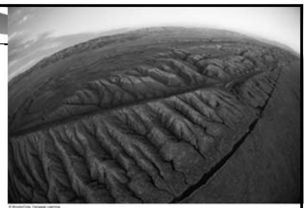


Chapter 9

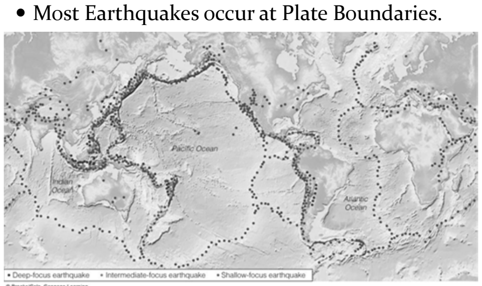
Earthquakes and the Earth's Interior

Introduction

- Earthquake – the sudden release of energy, usually along a fault, that produces shaking or trembling of the ground

Introduction

- Most Earthquakes occur at Plate Boundaries.



Introduction

- Earthquakes are very destructive and cause many deaths and injuries every year.
- Knowing what to do before, during, and after an earthquake could save your life or prevent serious injury.

Introduction

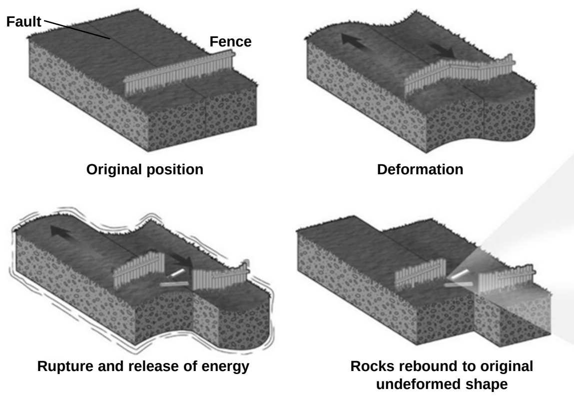
TABLE 9.1 Some Significant Earthquakes

Year	Location	Magnitude (estimated before 1935)	Deaths (estimated
1556	China (Shanxi Province)	8	1,000,000
1755	Portugal (Lisbon)	8.6	70,000
1906	U.S.A. (San Francisco, California)	8.3	3,000
1923	Japan (Tokyo)	8.3	143,000
1960	Chile	9.5	5,700
1964	U.S.A (Anchorage, Alaska)	8.6	131
1976	China (Tangshan)	8	242,000
1985	Mexico (Mexico City)	8.1	9,500
1988	Armenia	6.9	25,000
1990	Iran	7.3	50,000
1993	India	6.4	30,000
1995	Japan (Kobe)	7.2	6,000+
1999	Turkey	7.4	17,000
2001	India	7.9	14,000+
2003	Iran	6.6	43,000
2004	Indonesia	9	>220,000
2005	Pakistan	7.6	>86,000
2006	Indonesia	6.3	>6,200
2008	China (Sichuan Province)	7.9	>69,000
2010	Haiti	7.0	>220,000
2011	New Zealand	6.3	181
2011	Japan	9.0	>13,000

Elastic Rebound Theory

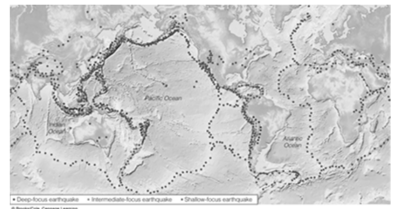
Elastic rebound theory - explains how energy is released during an earthquake. The idea was developed by H. F. Reid of the U.S. Geoloical Survey soon after the 1906 San Francisco earthquake.

- Rocks deform or bend
- Rocks rupture when pressure accumulates in rocks on either side of a fault and build to a level which exceeds the rocks' strength.
- Finally, rocks rebound and return to their original shape when the accumulated pressure is released.

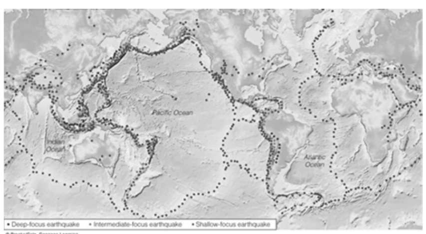


Where Do Earthquakes Occur, and How Often?

- About 80% of all earthquakes occur in the circum-Pacific belt.
- 15% within the Mediterranean-Asiatic belt.
- 5% occur largely along oceanic spreading ridges or within plate interiors.



Where Do Earthquakes Occur, and How Often?



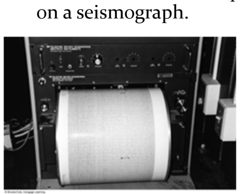
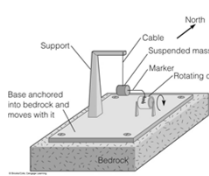
- More than 900,000 earthquakes occur per year, with more than 31,000 of those strong enough to be felt.

Where Do Earthquakes Occur, and How Often?



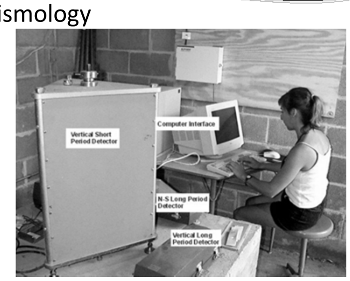
Seismology

- ***Seismology*** - study of earthquakes
  - The record of an earthquake, a seismogram, is made on a seismograph.

There are two types of seismographs – horizontal and vertical.

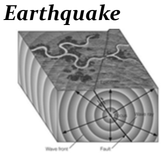
Seismology



The GSW Seismic Station currently has two horizontal instruments (EW and NS) and two vertical instruments (Long Period and Short Period).

Seismology

- ***The Focus and Epicenter of an Earthquake***
  - The point where an earthquake's energy is released is known as the focus.
  - The epicenter is that point on the surface vertically above the focus.

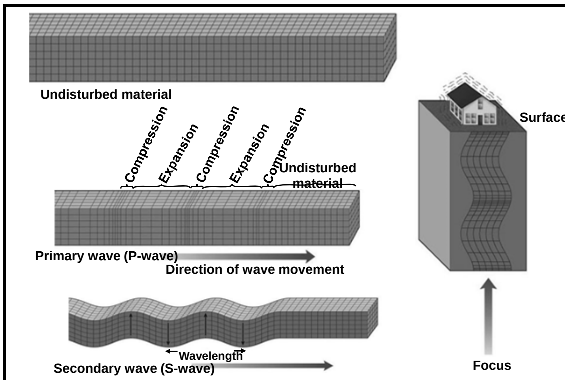


Seismic Waves

- Most of the damage and the shaking people feel during an earthquake is from the seismic waves.
  - Seismic waves are the result of vibrations that momentarily disturb the material – an elastic change.
  - Earthquake vibrations or seismic waves are of two kinds: body waves and surface waves.

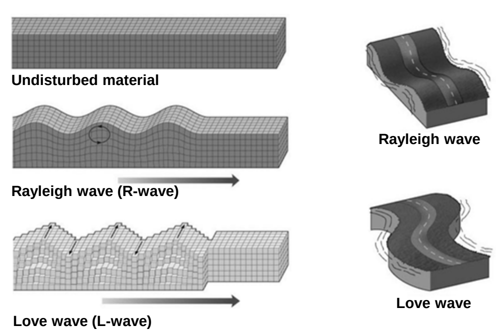
Seismic Waves

- ***Body waves*** are divisible into two types:
- P-waves or primary waves are compressional waves and travel faster than S-waves.
- S-waves or secondary waves are shear waves that cannot travel through liquids.

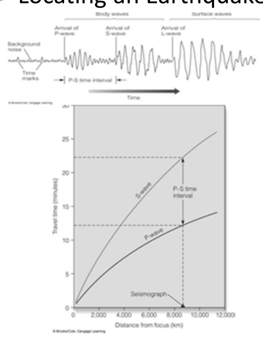


Seismic Waves

- ***Surface waves*** are divisible into two types, Rayleigh and Love waves, and exist only at or near the Earth's surface.
  - Rayleigh waves have an elliptical-retrograde motion (similar to water waves)
  - Love waves have a side-to-side motion in the horizontal plane only.



Locating an Earthquake



- First measure the S-P time difference on the seismogram.
- Then use a time-distance or Jeffreys-Bullen graph and the arrival time difference of the P- and S-waves to determine the distance to the earthquake.

Locating an Earthquake

- Finally plot the distance from each receiving station on a map.
  - A minimum of three (3) seismograph stations are required.
  - They will intersect at the epicenter of the earthquake.

Measuring the Strength of an Earthquake

- *Extensive damage, fatalities and injuries result from earthquakes.*
  - Intensity and magnitude are the two common measures of an earthquake's strength.
    - *Intensity is a qualitative measurement*
    - *Magnitude is a quantitative measurement.*

Measuring the Strength of an Earthquake

- ***Intensity*** - An earthquake's intensity is expressed on a scale of I to XII known as the Modified Mercalli Intensity Scale. Intensity is a measure of the kind of damage which occurs.

TABLE 9.2 Modified Mercalli Intensity Scale

I	Not felt except by a very few under especially favorable circumstances.
II	Felt by only a few people at rest, especially on upper floors of buildings.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing automobiles may rock slightly.
IV	During the day felt indoors by many, outdoors by few. At night some awakened. Sensation like heavy truck striking building, standing automobiles rocked noticeably.
V	Felt by nearly everyone, many awakened. Some dishes, windows, etc. broken, a few instances of cracked plaster. Disturbance of trees, poles, and other tall objects sometimes noticed.
VI	Felt by all, many frightened and run outdoors. Some heavy furniture moved. A few instances of fallen plaster or damaged chimneys. Damage slight.
VII	Everybody runs outdoors. Damage negligible in buildings of good design and construction; slight to moderate in well-built ordinary structures; considerable in poorly built or badly designed structures; some chimneys broken. Noticed by people driving automobiles.
VIII	Damage slight in specially designed structures; considerable in normally constructed buildings with possible partial collapse; great in poorly built structures. Fall of chimneys, monuments, walls. Heavy furniture overturned. Sand and mud ejected in small amounts.
IX	Damage considerable in specially designed structures. Buildings shifted off foundations. Ground noticeably cracked. Underground pipes broken.
X	Some well-built wooden structures destroyed; most masonry and frame structures with foundations destroyed; ground badly cracked. Rails bent. Landslides considerable from river banks and steep slopes. Water splashed over river banks.
XI	Few, if any (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service.
XII	Damage total. Waves seen on ground surface. Objects thrown upward into the air.

Measuring the Strength of an Earthquake

- Factors that determine an earthquake's intensity include
- distance from the epicenter
- focal depth of the earthquake
- population density
- geology of the area
- type of building construction
- the duration of ground shaking

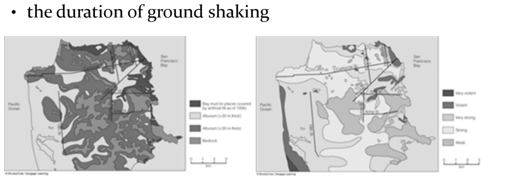
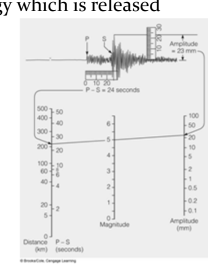


Fig. 9.11, p. 210

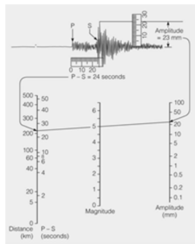
Measuring the Strength of an Earthquake

- ***Magnitude*** - The magnitude of an earthquake is a measure of the amount of energy which is released
  - Magnitude scales are based upon a formula originally determined by Charles Richter.
  - Magnitude is determined by measuring the sizes of particular seismic waves on seismograms.



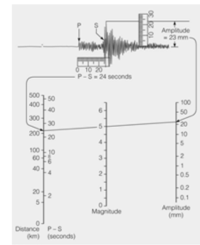
Measuring the Strength of an Earthquake

- Magnitude determination also includes corrections for
  - distance to the earthquake
  - depth of the earthquake
  - local geology



Measuring the Strength of an Earthquake

- All magnitude scales are logarithmic with respect to amplitude.
- Each whole-number increase in magnitude is a 10-fold increase in wave amplitude.
- Each whole number increase in magnitude corresponds to ~30-fold increase in energy released.



Measuring the Strength of an Earthquake

- ***There are four magnitude scales in common use:***
  - Local Magnitude (M_L) – calculated from S-wave on a horizontal seismograph (this is the original "Richter scale").
  - Body Wave Magnitude (M_b) – calculated from distant P-wave arrivals on a vertical seismograph.
  - Surface Wave Magnitude (M_S) – calculated from the Rayleigh wave on a vertical seismograph.
  - Moment Magnitude (M_W) – calculated using the total energy release as estimated from the entire seismogram.

Measuring the Strength of an Earthquake

- Seismologists now commonly use the seismic-moment magnitude scale, especially for all earthquakes over magnitude 6.0
- The seismic-moment magnitude scale more effectively measures the amount of energy released by very large earthquakes

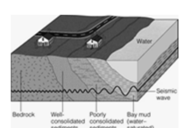
Measuring the Strength of an Earthquake

- ***Moment vs. Surface Wave Magnitude***

Earthquake	M_S	M_W
1906 San Francisco	8.3	7.9
1960 Chile	8.3	9.5
1964 Alaska	8.4	9.2
2004 Indonesia	8.2	9.1

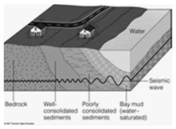
The Destructive Effects of Earthquakes

- ***Ground Shaking***
  - The most destructive of all earthquake hazards is ground shaking.
  - An area's geology, earthquake magnitude, the type of building construction, and duration of shaking determine the amount of damage caused.



The Destructive Effects of Earthquakes

- ***Ground Shaking***
  - Poor building construction leads to the most fatalities during earthquakes.



The Destructive Effects of Earthquakes

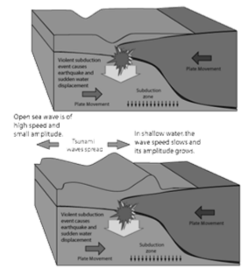
- Liquefaction occurs when clay loses its cohesive strength during ground shaking

The Destructive Effects of Earthquakes

- ***Fire*** occurs when gas and water lines break

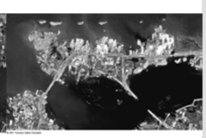
The Destructive Effects of Earthquakes

- ***Tsunami: Killer Waves*** and Subduction Zones



http://hydrogen.physik.uni-wuppertal.de/hyperphysics/hyperphysics/hbase/waves/tsunami.html

The Destructive Effects of Earthquakes

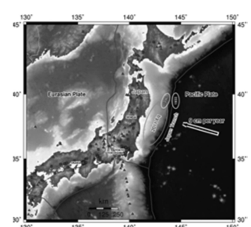


BEFORE AFTER

- ***Tsunami: Killer Waves*** – in 2004, a magnitude 9.0 earthquake offshore from Sumatra generated the deadliest tsunami in history.

The Destructive Effects of Earthquakes

- ***Tsunami: Killer Waves*** – in 2011, a magnitude 9.0 earthquake offshore from Japan generated another devastating tsunami.



The Destructive Effects of Earthquakes

- ***Ground Failure*** – landslides and rock slides are responsible for huge amounts of damage and many deaths.


- ***Ground failure*** can result in building / road collapse


Earthquake Prediction

- ***Earthquake Prediction Programs***
  - Earthquake prediction research programs are being conducted in the United States, Russia, China, and Japan.
  - Research involves laboratory and field studies of rock behavior before, during, and after large earthquakes, as well as monitoring major active faults.
  - Related studies, unfortunately, indicate that most people would probably not heed a short-term earthquake warning.

Earthquake Prediction

- Two approaches to earthquake prediction:
- Precursor studies -- study phenomena that occur just before an earthquake
- Historical studies -- examine the history of earthquake activity along a fault

Earthquake Prediction

- ***Earthquake Precursors*** – short-term and long-term changes within the Earth prior to an earthquake that assist in prediction.
  - Foreshocks (smaller earthquakes before the "big one")
  - Surface elevation changes and tilting
  - Ground water table fluctuations
  - Changes in electromagnetic fields
  - Anomalous animal behavior

Earthquake Prediction

Precursor Studies – Strain Accumulation

- A way to estimate the likelihood of future earthquakes is to study how fast strain accumulates.
- When plate movements build the strain in rocks to a critical level the rocks will suddenly break and slip to a new position (Elastic Rebound Theory).

Earthquake Prediction

Precursor Studies – Strain Accumulation

- Scientists measure how much strain accumulates along a fault segment each year, how much time has passed since the last earthquake there, and how much strain was released in the last earthquake.
- This information is then used to calculate the time required for the accumulating strain to build to the level that results in an earthquake.
- Complication: such detailed information about faults is rare.

Earthquake Prediction – The Parkfield Experiment

❖ For the past 150 years, large earthquakes have occurred an average of every 22 years on the San Andreas fault near Parkfield, California.

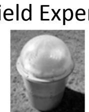
❖ Because of the consistency and similarity of these earthquakes, scientists started an experiment to "capture" the next Parkfield event.

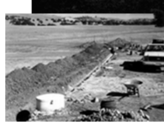
Earthquake Prediction – The Parkfield Experiment

Types of Instrumentation

A dense web of instruments was employed

<u>Continuous Monitoring</u>:
- GPS
- Borehole Strainmeters
- Electronic Distance Measurement
- Creepmeter
- Water Well Level Monitoring





Earthquake Prediction – The Parkfield Experiment

Types of Instrumentation

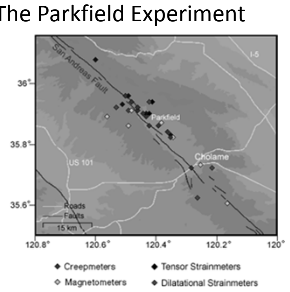
<u>Discontinuous Monitoring</u>:
- Tiltmeters
- Ultralow Frequency (ULF) EM Fields
- Liquifaction Array
- Reflection Seismology
- Ground Radon and Soil Hydrogen



Earthquake Prediction – The Parkfield Experiment

Types of Instrumentation

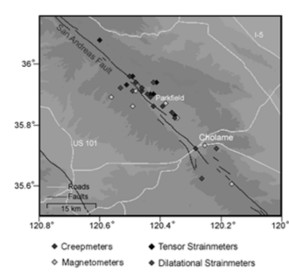
<u>Seismic Monitoring</u>:
- High Resolution Borehole
- Small Aperture Array
- Accelerometers (3-C)
- Strong Motion Seismometers



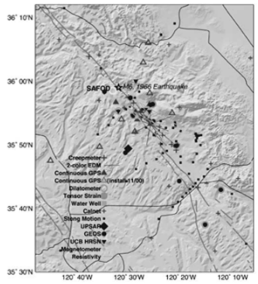
Earthquake Prediction – The Parkfield Experiment

Types of Instrumentation

<u>Other Monitoring</u>:
- Magnetic Fields
- Magnetotellurics
- Electrical Resistivity
- Fault Rupture Camera

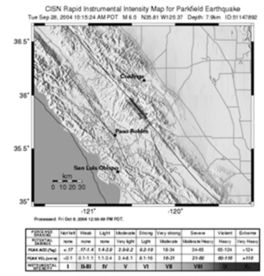


Earthquake Prediction – The Parkfield Experiment

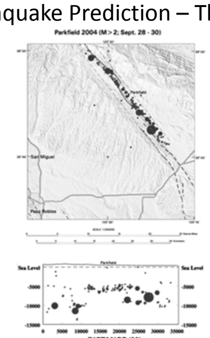


Earthquake Prediction – The Parkfield Experiment

Magnitude 6.0 Earthquake, September 28, 2004



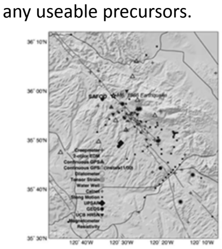
Earthquake Prediction – The Parkfield Experiment



Aftershocks, Magnitude 6.0 Earthquake September 28, 2004

Earthquake Prediction – The Parkfield Experiment

The Bottom Line:
In spite of many years of study, the Parkfield experiment did not reveal any useable precursors.



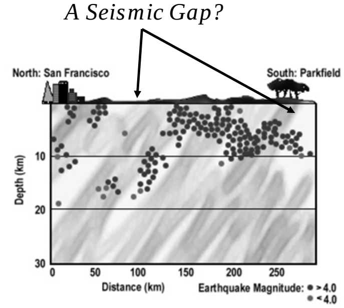
Historical Studies

❖ Seismic gap theory -- areas that have not experienced a big quake have been storing strain longer and are more likely to rupture.

❖ Probabilistic Hazard Analysis -- Try to determine the frequency of earthquakes along fault, and use this information to determine when the next earthquake is likely to occur.

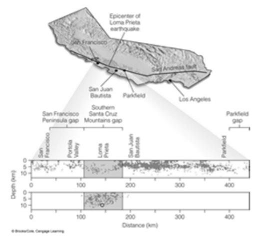
Historical Studies

A Seismic Gap?



Historical Studies

The 1989 Loma Prieta Earthquake



Historical Studies

Problems with the Seismic Gap Hypothesis?

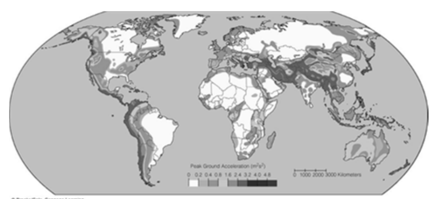
An article by Rong, Jackson and Kagan of UCLA indicates that predictions based upon different versions of the seismic gap theory are essentially no better than random guessing.

So, where do we go from here???

Historical Studies

Earthquake Frequency

Scientists study the past frequency of large earthquakes in order to determine the future likelihood of similar large shocks.



Historical Studies

Earthquake Frequency

Example:
If a region has experienced four magnitude 7 or larger earthquakes during 200 years of recorded history, and if these shocks occurred randomly in time, then scientists would assign a 50 *percent probability* to the occurrence of another magnitude 7 or larger quake in the region during the next 50 years.

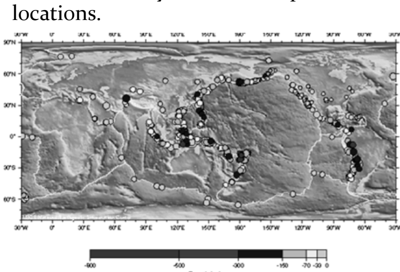
Historical Studies

Earthquake Frequency

But in many places, ***the assumption of random occurrence with time may not be true***, because when strain is released along one part of the fault system, it may actually increase the strain on another part.

Historical Studies

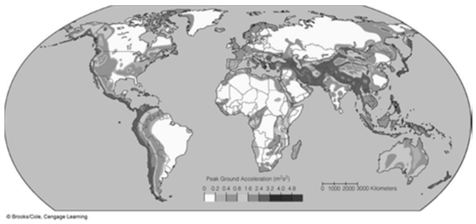
- Because earthquakes occur most often near plate boundaries, they will be more probable in these locations.



http://neic.usgs.gov/neis/qed/

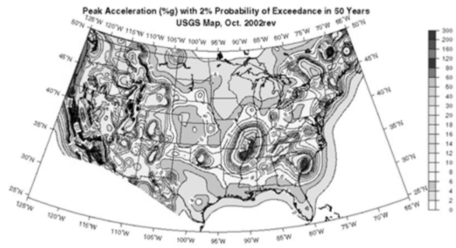
Historical Studies

- Seismic risk maps help geologists in determining the likelihood and potential severity of future earthquakes based on the intensity of past earthquakes.



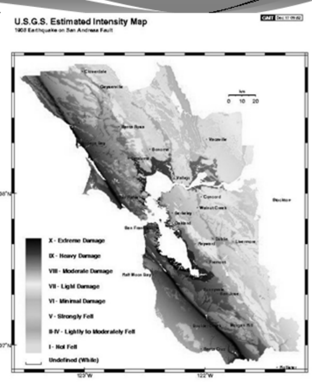
Historical Studies

Seismic Hazard Maps: the size is usually measured as a percentage of the acceleration of gravity (g), or 980 cm/s².



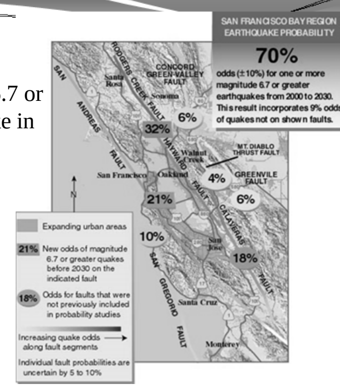
Earthquakes

Intensity diagram if a 1906-size (M_S=8.3) earthquake hits the San Francisco Bay Area.



Earthquakes

Probability of a 6.7 or greater earthquake in the Bay Area.



Earthquakes

Seismic Hazard Reduction

In the absence of reliable short-term earthquake prediction, must discourage development in earthquake-prone areas or require that buildings be reinforced to withstand shaking better.

Earthquake Prediction

- **Earthquake Preparation**

TABLE 9.3 What You Can Do to Prepare for an Earthquake

Anyone who lives in an area that is subject to earthquakes or who will be visiting or moving to such an area can take certain precautions to reduce the risks and losses resulting from an earthquake.

Before an earthquake:

1. Become familiar with the geologic hazards of the area where you live and work.
2. Make sure your house is securely attached to the foundation by anchor bolts and that the walls, floors, and roof are all firmly connected together.
3. Heavy furniture such as bookcases should be bolted to the walls; semiflexible natural gas lines should be used so that they can give without breaking; water heaters and furnaces should be strapped and the straps bolted to wall studs to prevent gas-line rupture and fire. Brick chimneys should have a bracket or brace that can be anchored to the roof.
4. Maintain a several-day supply of fresh water and canned foods, and keep a fresh supply of flashlight and radio batteries, as well as a fire extinguisher.
5. Maintain a basic first-aid kit and have a working knowledge of first-aid procedures.
6. Learn how to turn off the various utilities at your house.
7. Above all, have a planned course of action for when an earthquake strikes.

During an earthquake:

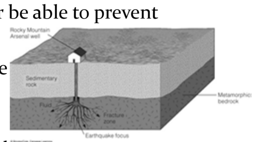
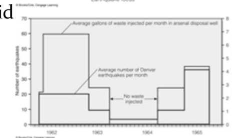
1. Remain calm and avoid panic.
2. If you are indoors, get under a desk or table if possible, or stand in an interior doorway or room corner as these are the structurally strongest parts of a room; avoid windows and falling debris.
3. In a tall building, do not rush for the stairwells or elevators.
4. In an unreinforced or other hazardous building, it may be better to get out of the building rather than to stay in it. Be on the alert for fallen power lines and the possibility of falling debris.
5. If you are outside, get to an open area away from buildings if possible.
6. If you are in an automobile, stay in the car, and avoid tall buildings, overpasses, and bridges if possible.

After an earthquake:

1. If you are uninjured, remain calm and assess the situation.
2. Help anyone who is injured.
3. Make sure there are no fires or fire hazards.
4. Check for damage to utilities and turn off gas valves if you smell gas.
5. Use your telephone only for emergencies.
6. Do not go sightseeing or move around the streets unnecessarily.
7. Avoid landslide and beach areas.
8. Be prepared for aftershocks.

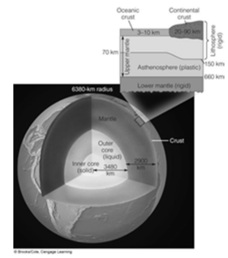
Earthquake Control

- Because of the tremendous energy involved, it seems unlikely that humans will ever be able to prevent earthquakes.
  - However, it might be possible to release small amounts of the energy stored in rocks
  - One promising means of earthquake control is by fluid injection along locked segments of an active fault

What is Earth’s Interior Like?

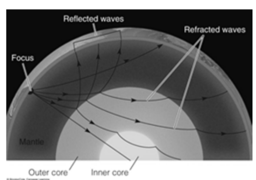
- The concentric layers of Earth, from its surface to interior, are :
- Oceanic / Continental crust
- Rocky mantle
- Iron-rich core
  - liquid outer core
  - solid inner core



What is Earth’s Interior Like?

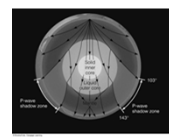
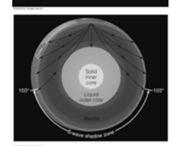
Geologist study the bending or refraction and reflection of P- and S-waves to help understand Earth's interior.

- This indicates boundaries between layers of different densities called discontinuities.



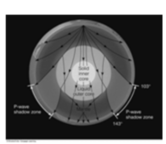
The Core

- The P- and S-waves both refract and reflect as they cross discontinuities.
- This results in shadow zones. These shadow zones reveal the presence of concentric layers within the Earth, recognized by changes in seismic wave velocities at discontinuities.

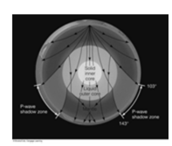
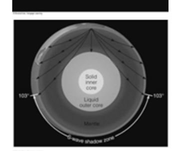
The Core

- P-wave discontinuities indicate a decrease in P-wave velocity at the core-mantle boundary at about 2900 km.
- Core discovered in 1906 by R. D. Oldham.



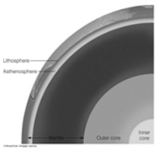

The Core

- S-wave discontinuities result in a much larger shadow zone. S-waves are completely blocked from passing thru liquids, therefore the outer core is liquid
- Harold Jeffreys – S-wave shadow zone = liquid outer core (1926)

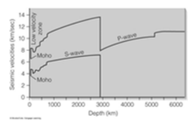



The Core

- ***Density and Composition of the Core***

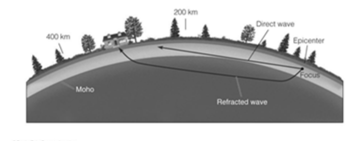


- The density and composition of the concentric layers have been determined by the behavior of P-waves and S-waves.
- Inner core is thought to be iron and nickel (evidence from meteorites). Solid Inner Core discovered in 1936 by Inge Lehmann
- Outer core iron with 10 to 20% lighter substances
- Mantle probably ultramafic silicate minerals.



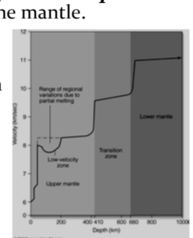
Earth's Mantle

- The boundary between the crust and mantle is known as the Mohorovičić Discontinuity.
- Discovered by Mohorovičić in 1909 when he noticed that seismic stations for nearby earthquakes received two sets of P- and S-waves. This meant that the set below the discontinuity traveled deeper but more quickly than the shallower waves.



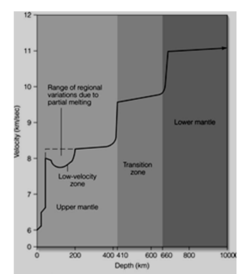
Earth's Mantle

- ***The Mantle's Structure, Density and Composition***: Several discontinuities exist within the mantle.
- The velocity of P- and S-waves decrease markedly from 100 to 250km depth, which corresponds to the asthenosphere.



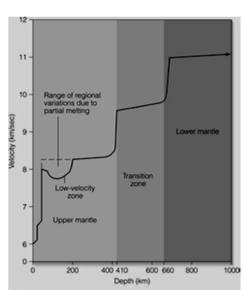
Earth's Mantle

- The asthenosphere is an important zone in the mantle because this is where magma is generated.



Earth's Mantle

- Decreased elasticity accounts for decreased seismic wave velocity in the asthenosphere
- This decreased elasticity allows the asthenosphere to flow plastically

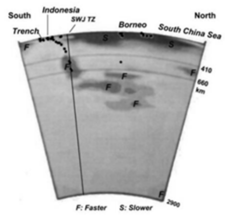


Earth's Mantle

- ***The Mantle's Structure, Density and Composition:***
  - Ultramafic (peridotite) is thought to represent the main composition in the mantle.
    - Experiments indicate that peridotite has the physical properties and density to account for seismic wave velocity in the mantle.
    - Peridotite makes up the lower parts of ophiolite sequences that represent oceanic crust and upper mantle.
    - Peridotite is also found as inclusions in kimberlite pipes that came from depths of 100 to 300 km.

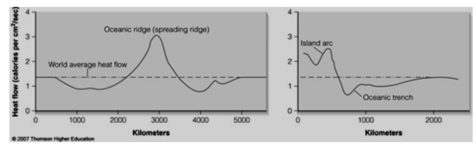
Seismic Tomography

- Tomography - a technique for developing better models of the Earth's interior.
- Similar to a CAT-scan for producing 3-D images, tomography uses seismic waves to map out changes in velocity within the mantle.



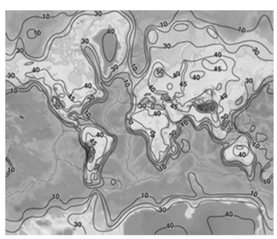
Earth's Internal Heat

- *Geothermal gradient* – measures the increase in temperature with depth in the earth. Most of Earth's internal heat is generated by radioactive isotope decay in the mantle.
- The upper-most crust has a high geothermal gradient of 25° C/km
- This must be much less in the mantle and core, probably about 1° C/km
- The center of the inner core has a temperature estimated at 6,500° C



Earth's Crust

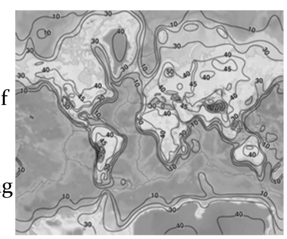
- Continental crust is mostly granitic and low in density, with an average density of 2.7 gm/cm³ and a velocity of about 6.75 km/sec.
- It averages about 35 kilometers thick, being much thicker beneath the shields and mountain ranges of the continents.



http://earthquake.usgs.gov/data/crust/

Earth's Crust

- Oceanic crust is mostly gabbro overlain by basalt, and has an average density of 3.0 gm/cm³ and a velocity of about 7 km/sec
- It ranges from 5-10 kilometers thick, being thinnest at the spreading ridges.



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