Environmental Geology
Chapter 8
Earthquakes and Related Phenomena

Fall 2015

Northridge - 1994

Kobe - 1995

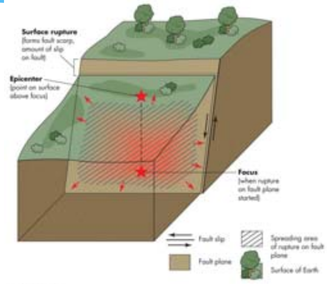
Mexico City - 1985

China - 2008

TABLE 8.1 Selected major earthquakes in the United States

Year	Locality	Damage (millions of dollars)	Number of Deaths
1811–1812	New Madrid, Missouri	Unknown	Unknown
1886	Charleston, South Carolina	23	60
1906	San Francisco, California	524	700
1925	Santa Barbara, California	8	13
1933	Long Beach, California	40	115
1940	Imperial Valley, California	6	9
1952	Kern County, California	60	14
1959	Hebgen Lake, Montana (damage to timber and roads)	11	28
1964	Alaska and U.S. West Coast (includes tsunami damage from earthquake near Anchorage)	500	131
1965	Puget Sound, Washington	13	7
1971	San Fernando, California	553	65
1983	Coalinga, California	31	0
1983	Central Idaho	15	2
1987	Whittier, California	358	8
1989	Loma Prieta (San Francisco), California	5000	62
1992	Landers, California	271	1
1994	Northridge, California	40,000	57
2001	Seattle, Washington	2000	1
2002	South-Central Alaska	(sparsely populated area)	0

Earthquakes



Earthquake Magnitudes

TABLE 8.2 Worldwide magnitude and frequency of earthquakes by descriptor classification

Descriptor	Magnitude	Average Annual No. of Events
Great	8 and Higher	1
Major	7–7.9	18
Strong	6–6.9	120
Moderate	5–5.9	800
Light	4–4.9	6200 (estimated)
Minor	3–3.9	49,000 (estimated)
Very minor	<3.0	Magnitude 2–3 about 1000 per day
		Magnitude 1–2 about 8000 per day

Source: U.S. Geological Survey, 2000, Earthquakes, facts and statistics, http://neic.usgs.gov, accessed 1/2/00.

TABLE 8.3 Relationships between magnitude, displacement, and energy of earthquakes

Magnitude Change	Ground Displacement Change[1]	Energy Change
1	10 times	About 32 times
0.5	3.2 times	About 5.5 times
0.3	2 times	About 3 times
0.1	1.3 times	About 1.4 times

[1]Displacement, vertical or horizontal, that is recorded on a standard seismograph.
Source: U.S. Geological Survey, 2000, Earthquakes, facts and statistics, http://neic.usgs.gov, accessed 1/2/00.

Earthquake Magnitudes

Richter Magnitude Scales (M_b, M_s, M_L)
- Used log-base 10 formula of form:

$$M = a + b \log D + \log (A/T)$$

- Incorporated distance, frequency and local corrections.

Moment Magnitude (Mw)
- Uses total energy released (seismic moment):

$$Mw = 2/3 \log M_o - 10.7$$

- Still Log(10)-based

Earthquake Intensity

TABLE 8.4 Modified Mercalli Intensity Scale (abridged)

Intensity	Effects
I	Felt by very few people
II	Felt by only a few persons at rest, especially on upper floors of buildings. Delicately suspended objects may swing.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake. Standing motor cars may rock slightly. Vibration feels like the passing of a truck.
IV	During the day felt indoors by many, outdoors by few. At night, some awakened. Dishes, windows, doors disturbed; walls make cracking sound; sensation like heavy truck striking building; standing motor cars rock noticeably.
V	Felt by nearly everyone; many awakened. Some dishes, windows, and so on, broken; a few instances of cracked plaster; unstable objects overturned; disturbances of trees, poles, and other tall objects sometimes noticed. Pendulum clocks may stop.
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; a few instances of fallen plaster or damaged chimneys. Damage is 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 persons driving cars.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings, with partial collapse; great in poorly built structures; panel walls thrown out of frame structures; fall of chimneys, factory stacks, columns, monuments, walls; heavy furniture overturned; sand and mud ejected in small amounts; changes in well water; disturbs persons driving cars.
IX	Damage considerable in specially designed structures; well-designed frame structures thrown out of plumb; great in substantial buildings, with partial collapse. Buildings are shifted off foundations. Ground cracked conspicuously. Underground pipes are broken.
X	Some well-built wooden structures are destroyed; most masonry and frame structures with foundations destroyed; ground badly cracked. Rails bent. Landslides considerable from riverbanks and steep slopes. Shifted sand and mud. Water is splashed over banks.
XI	Few, if any (masonry) structures remain standing. Bridges are destroyed. Broad fissures are formed in ground. Underground pipelines are taken out of service. Earth slumps and land slips on soft ground occurs. Train rails are bent.
XII	Damage is total. Waves are seen on ground surfaces. Lines of sight and level distorted. Objects are thrown upward into the air.

Source: From Wood and Neumann, 1931, by U.S. Geological Survey, 1974, Earthquake Information Bulletin 6(5): 28.

Earthquake Intensity

Northridge, 1994 (M6.7)

Seattle, 2001 (M6.8)

Earthquake Intensity

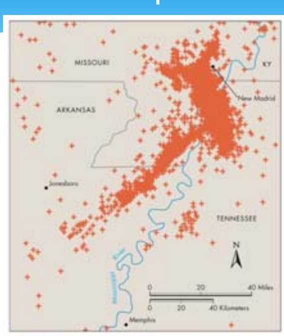
Intensity is affected by:

a) Local geology
b) Construction quality
c) Distance from the focus (depth and epicenter)
d) Duration of shaking

"Earthquakes don't kill people, buildings do"

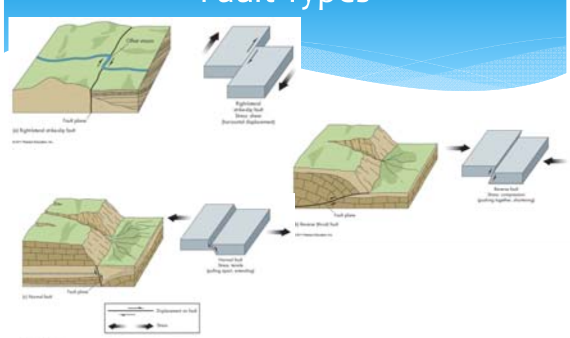
Earthquake Locations

Earthquake Locations

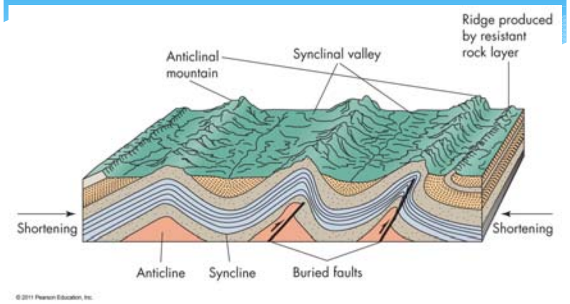


The New Madrid Seismic Zone
– earthquakes since 1974

Fault Types



Fault Types



Fault Zones and Segments

Fault zones are groups of related faults roughly parallel to each other. Fault zones can vary in width from < 1 m to several km.

Earthquake segments are those parts of a fault zone that have ruptured as a unit during historic and prehistoric earthquakes. These segments are most important when evaluating seismic hazard.

An active fault is one on which an earthquake has occurred during the last 10,000 years. Often, paleoseismic studies are needed to determine if a fault segment is active.

Some agencies (NRC) define faults as capable (50,000/500,000 years)

Fault Zones and Segments

Slip rate is defined as the ratio of slip (displacement) to the time interval over which it occurs.

The average recurrence interval on an active fault may be determined by:

- Paleoseismic data
- Slip rate
- Seismicity

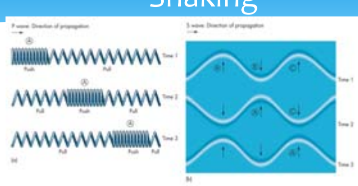
Problem: Fault slip rates and recurrence intervals change over time, so what does the average mean? Distribution may not be normal – earthquake clusters are not uncommon.

Fault Zones and Segments

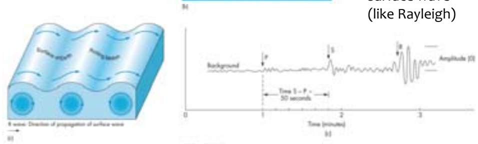
Tectonic Creep is slow movement along fault segments.

Slow Earthquakes are now recognized by scientists, where the motion is very small but distributed over a large fault area and can occur over days to even months.

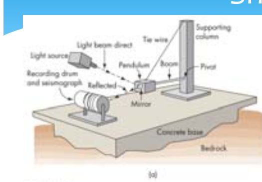
Earthquake Waves and Ground Shaking



Love Wave? Side-to-side motion in horizontal plane; surface wave (like Rayleigh)

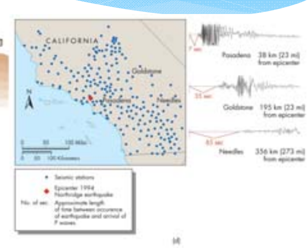


Earthquake Waves and Ground Shaking

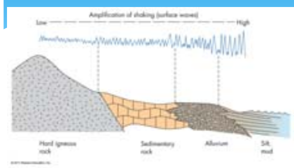


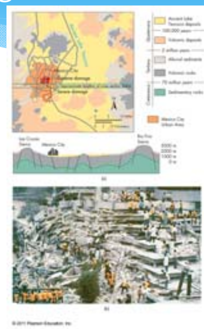
Seismographs record earthquakes.

Earthquake waves separate with distance, and get smaller. In addition, higher frequency waves go away (attenuation).



Earthquake Waves and Ground Shaking





Amplification occurs as waves travel through unconsolidated sediments.

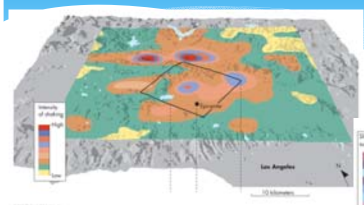
Even though the epicenter for the M8.1 Mexico City Earthquake of 1985 was 100's of km away, severe damage occurred due to amplification.

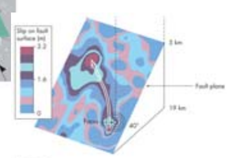
Earthquake Waves and Ground Shaking

Amplification occurs as waves travel through unconsolidated sediments.

The 1989 Loma Prieta Earthquake is another good example of damage distributions controlled by geology.

Earthquake Waves and Ground Shaking

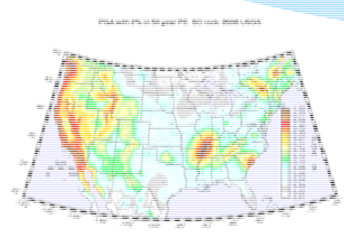




Directivity happens as greater intensity of shaking occurs in the direction of fault slip along an earthquake fault.

The 1994 Northridge Earthquake shows directivity well.

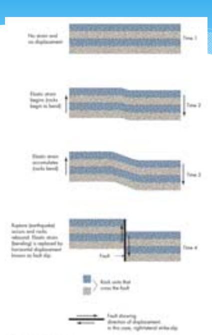
Earthquake Waves and Ground Shaking



Ground Acceleration during earthquakes is often expressed in terms of %g, where g is the acceleration of gravity (g = 9.8 m/s²).

Accelerations >0.3g can cause damage. >0.7g can cause widespread damage. Poor construction can fail at 0.1g

Earthquake Cycle



Earthquake cycle or elastic rebound hypothesis developed after 1906 San Francisco earthquake.

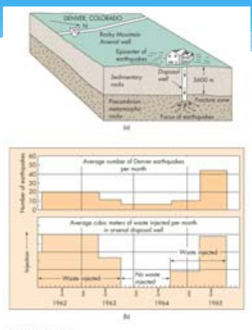
Cycle:
Seismic inactivity -> major earthquake -> aftershocks -> increased seismicity and deformation -> foreshocks -> major earthquake.

Dilatancy-Diffusion Model

The Dilatancy-Diffusion Model proposes that water at seismogenic depths plays a major role in the generation of earthquakes. As rocks undergo elastic strain, they dilate (increase in volume) allowing fractures to develop. As dilation continues, an influx of water into the fractures causes an increase in seismic velocity and weakens the rocks. This can lead to slip and earthquakes. Increases in fluid pressure can facilitate earthquakes or failures along fracture surfaces. The fault-valve mechanism hypothesizes that fluid pressures rise until failure occurs, and earthquake happens and fluids migrate upwards along the faults. Faults in effect act as conduit for fluids.

Another term for a similar idea is hydroseismicity, where earthquakes can be generated in non-tectonic regions by deep circulations of fluids in fractured rocks.

Human-Induced Earthquakes



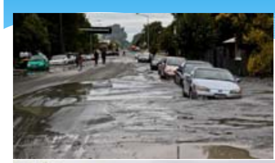
Human-induced earthquakes can occur due to:

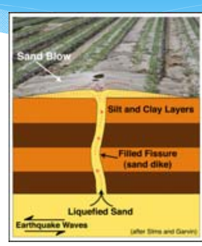
a) Loading (reservoir-induced seismicity)
b) Deep waste disposal (Rocky Mountain Arsenal)
c) Underground nuclear testing

Effects of Earthquakes

Shaking and Ground Rupture

Effects of Earthquakes





Liquifaction from New Madrid region (above) and Christchurch, NZ (left)

http://keithwoodford.wordpress.com/2011/02/27/understanding-the-christchurch-earthquake-building-damage/
And http://mptuttle.com/newmadrid3.html

Effects of Earthquakes

Landslides (2002 Alaska M7.9)

Effects of Earthquakes

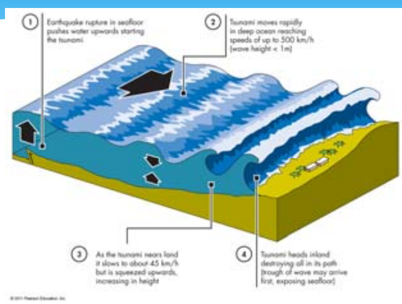
Fire (1995 Kobe, Japan M6.9)

Effects of Earthquakes

Other effects:

a) Disease
b) Regional elevation changes

Tsunami



Tsunami are generated by movement of the sea floor, or by mass movements displacing millions of tons of water.

Tsunami

Tsunami (2004 Indonesia, M9.0)
Japan 2011

Tsunami

Pacific Ocean tsunami travel times.

Earthquake Risk

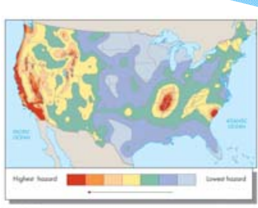
Earthquake risk assessment is primarily done using a probabilistic approach resulting in a forecast of this type:

"An earthquake of magnitude 6+ has a probability of *P* over the next *X* years."

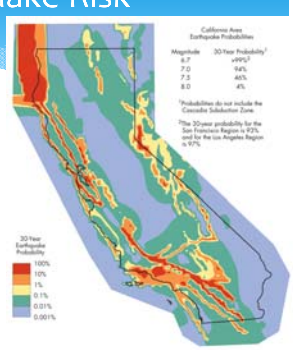
Risk is estimated using

- Geology, particularly the location of capable or active faults
- Paleoseismology, to understand the pre-historic earthquake history
- Geodesy, plate movements, speeds, etc. determined by GPS and satellites
- Seismology, location and magnitude of earthquakes along particular faults

Earthquake Risk



Earthquake hazard map, USA



Earthquake hazard map, CA

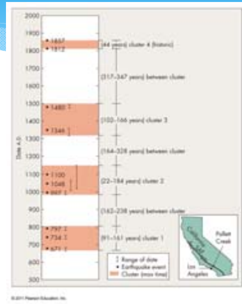
Short Term Prediction

Short-term prediction of earthquakes is not possible. Even after the decades-long Parkfield Experiment in California, looking for definite precursors appears to be elusive at best. Things that have been used as earthquake predictors/precursors are:

- Patterns and frequencies of small earthquakes before a major earthquake
- Preseismic deformation of the ground surface (shape change)
- Emission of radon gas
- Seismic Gaps
- Anomalous animal behavior

Short-Term Prediction

North Anatolian Fault, Turkey



Seismic History of California

Earthquake Hazard Reduction Programs

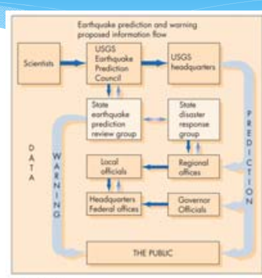
The National Earthquake Hazard Reduction Program has the following major goals:

1) Develop and understanding of the source (measurements and models)
2) Determine earthquake potential (fully characterizing active regions)
3) Predicting the effects of earthquakes
4) Apply research results

Earthquake Hazard Reduction Programs

Adjustments to earthquake activity include:

a) Structural protection (engineering solutions)
b) Land-use planning (don't build close to active faults!)
c) Increased insurance and relief efforts



Earthquake Hazard Reduction

To avoid destruction like this, if you live in or near and earthquake prone area, you will need to prepare for the eventuality of a large event.

- Before the event, educate yourself. Have a plan and practice it
- Duck, Cover and Hold during the event
- Afterwards, don't panic! Check on your family and neighbors and check for water and gas leaks. If your home is damaged, be prepared to go elsewhere. Be prepared for aftershocks.