ESS 202

House after tsunami, Brumbaugh 8-18

Today: The Size of an Earthquake

- Intensity
- Magnitude
- Moment

Earthquake effects

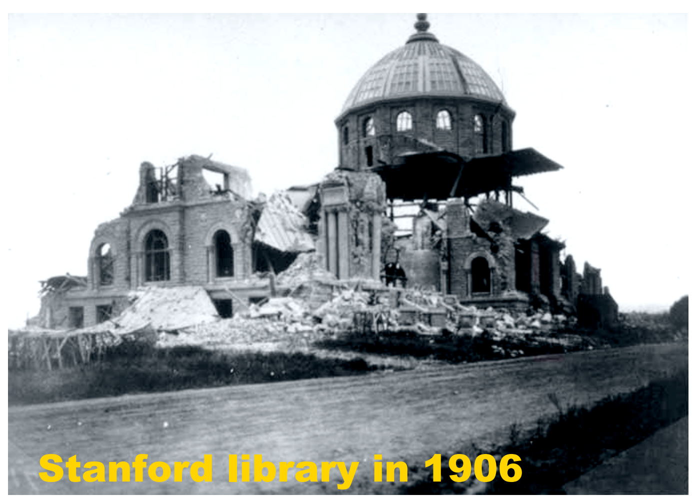
- Natural Hazards
  - Ground shaking
    - Structural collapse
    - Falling objects
  - Ground settling
  - Landslides and avalanches
  - Fault offset
  - Tsunamis and seiches

Landslide

Bolt, 12-11

More quake effects

- Man-aided hazards
  - Floods from dam failure
  - Fires
  - Toxic spills



Stanford library in 1906

San Francisco in 1906

Measuring earthquakes

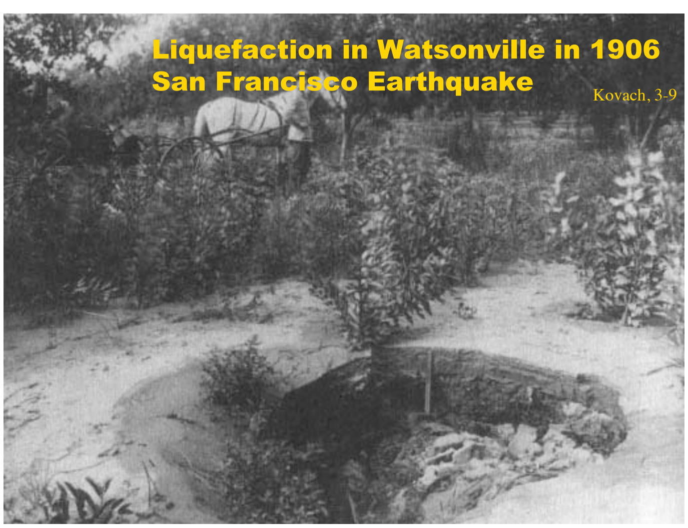
- 1. Felt reports - Intensity
  - Not precise, but best data for old earthquakes
- 2. Seismic measurements
- 3. Mapping of rupture zone
- 4. Geodetic measurements of ground shift

Measuring earthquake size

- 1. Intensity - IX
- 2. Magnitude - 7
- 3. Seismic moment - 10^{20} N-m

Intensity

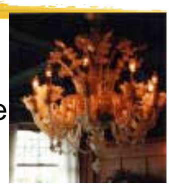
- Measures shaking and damage
- Obtained from
  - the damage done to buildings
  - changes in Earth's surface
  - felt reports
- Uses Modified Mercalli Intensity Scale
  - shaking levels from I to XII
- Useful for historical earthquakes, described in old newspapers, personal accounts, etc.



Limitations of Intensity

- Not a true measure of size because
  - depends on distance from epicenter, and
  - varies with building practices, and
  - varies with rock or soil type.
- So the same earthquake will shake different places with different intensities.
- But maximum intensity experienced in a given earthquake correlates with that earthquake's magnitude.

Barely felt



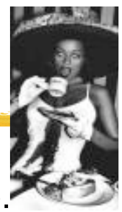
- I. Not felt by people except under especially favorable circumstances.
- II. Felt only by persons at rest on the upper floors of buildings. Some suspended objects may swing.
- III. Felt by some people who are indoors, but it may not be recognized as an earthquake. The vibration is similar to that caused by the passing of light trucks. Hanging objects swing.

The Modified Mercalli scale is also on the web

Felt (more)

- IV. Felt by many people who are indoors, by a few outdoors. At night some people are awakened. Dishes, windows and doors are disturbed; walls make creaking sounds; stationary cars rock noticeably. The sensation is like a heavy object striking a building; the vibration is similar to that caused by the passing of heavy trucks.

Felt (still more)



- V. Felt indoors by practically everyone, outdoors by most people. At night, sleepers are awakened and some run out of buildings. Liquids are disturbed and sometimes spilled. Small unstable objects and some furnishings are shifted or upset. Doors close or open.

Hazardous

- VI. Felt by everyone, and many people are frightened and run outdoors. Walking is difficult. Small church and school bells ring. Windows, dishes, and glassware are broken; liquids spill; books and other standing objects fall; pictures are knocked from the walls; furniture is moved or overturned. Poorly built buildings may be damaged, and weak plaster will crack.

Worse hazard

- VII. Causes general alarm. Standing upright is very difficult. Persons driving cars also notice the shaking. Damage is negligible in buildings of very good design, slight to moderate in well-built ordinary structures, considerable in poorly-built structures. Some chimneys are broken; interiors experience considerable damage; architectural ornaments fall. Small slides occur along sand or gravel banks of water channels; concrete irrigation ditches are damaged. Waves form in the water and it becomes muddied.

Big problem

- VIII. General fright and near panic. The steering of cars is difficult. Damage is slight in specially designed structures, considerable in ordinary buildings. Poorly built or designed buildings experience partial collapses. Numerous chimneys fall; the walls of frame buildings are damaged; interiors experience heavy damage. Frame houses that are not properly bolted down may move on their foundations. Decayed pilings are broken off. Trees are damaged. Cracks appear in wet ground and on steep slopes. Changes in the flow or temperature of springs and wells are noted.

Bigger problem

- IX. Panic is general. Interior damage is considerable in specially designed structures. Ordinary buildings suffer severe damage with partial collapses; frame structures thrown out of plumb or shifted off their foundations. Unreinforced masonry buildings collapse. The ground cracks conspicuously and some underground pipes are broken. Reservoirs are damaged.

Quite a problem

- X. Most masonry and many frame structures are destroyed. Even specially designed structures may suffer serious damage. Some well-built bridges are destroyed, and dams, dikes, and embankments are seriously damaged. Large landslides are triggered by the shock. Water is thrown onto the banks of canals, rivers, and lakes. Sand and mud are shifted horizontally on beaches and flat land. Rails are bent slightly. Many buried pipes and conduits are broken.

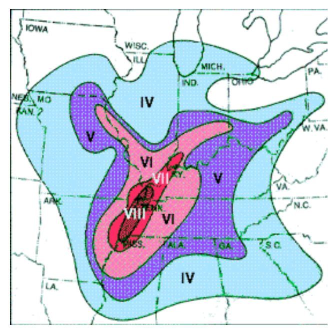
Rarely, if ever, seen

- XI. Few, if any, masonry structures remain standing. Other structures are severely damaged. Broad fissures, slumps and slides develop in soft or wet soils. Underground pipe lines and conduits are put completely out of service. Rails are severely bent.
- XII. Damage is total, with practically all works of construction severely damaged or destroyed. Waves are observed on ground surfaces, and all soft or wet soils are greatly disturbed. Heavy objects are thrown into the air, and large rock masses are displaced.

Intensity Map

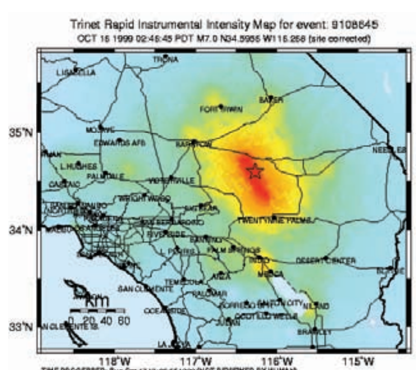
- Shows contours of areas with a similar level of damage on the Modified Mercalli scale.

New Madrid, 1812



Intensity Map

- Shows contours of areas with a similar level of damage on the Modified Mercalli scale.
- Guessed from measurements at 10 to 100's of locations.
- Mainly comes from places with buildings.
- Not a direct measurement of ground motion.
- Intensity maps still being made.
  - But scientists don't use them much now
  - Mainly useful for
    - comparing historical earthquakes with current ones
    - and showing public what shook how much



Perceived Shaking	Not felt	Weak	Light	Moderate	Strong	Very strong	Severe	Violent	Extreme
Potential Damage	none	none	none	Very light	Light	Moderate	Moderate to Heavy	Heavy	Very heavy
Peak Acc. (%g)	<0.17	0.17-1.4	1.4-3.9	3.9-9.2	9.2-18	18-34	34-65	65-124	>124
Peak Vel. (cm/s)	<0.1	0.1-1.1	1.1-3.4	3.4-8.1	8.1-16	16-31	31-60	60-116	>116
INSTRUMENTAL INTENSITY	I	II-III	IV	V	VI	VII	VIII	IX	X+

Hector Mines Earthquake, Oct. 16, 1999

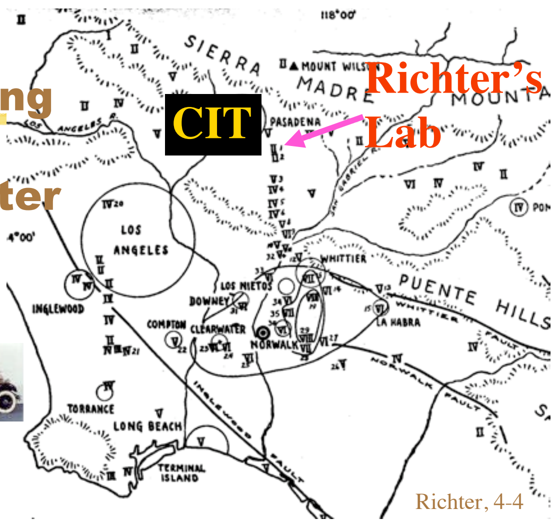
ESS 202

1929 Whittier, CA quake

New Zealand 1929

- 8:46 am, July 8th, M = 4.7
- Dawn of earthquake science
  - Some new instruments, gung-ho group
  - Callers reported strong shaking in Whittier
  - Not noticed by scientists in Pasadena
  - Scientists jump in car and drive south
- Interesting as an example of technique
  - The measurement of intensity

Driving with Richter



Richter, 4-4

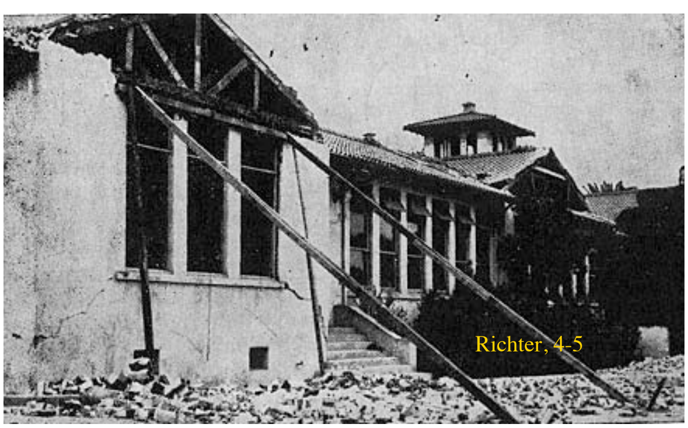
Notes from the drive

1. Shock of short duration felt by one person, seated; not by others (II).
2, 3. Not noticed; felt by other persons nearby (II).
4. Doors rattled (IV).
5. Heavy rattling of doors, windows, showcases, etc. (IV+).
6. Near hilltop. Rattling of toilet articles, small vases, dishes (IV).
8. Low ground. Small frame house creaked and groaned. All chairs moved. Slight alarm; ran out of house (V).
9. Low ground. Statuette fell. One block away, chimney fell (VI+).
10. Cigarette packs slid off shelves. Telephone wires whipped violently up and down as result of motion of poles (V–VI). Higher ground than No. 9.
11. Store goods off shelves. Shook building and gasoline pumps heavily (V+). Here information began to be obtained as to extensive minor damage in and near Whittier; but the first locality visited in Whittier showed comparatively low intensity.
12. Entering northwestern part of Whittier. Rolling hill ground higher than the business center. General rattling; few articles disturbed, none upset. Duration of felt shaking estimated at about 1 minute (V).

And so on, for two more days

Richter, p. 38

East Whittier School - 1929

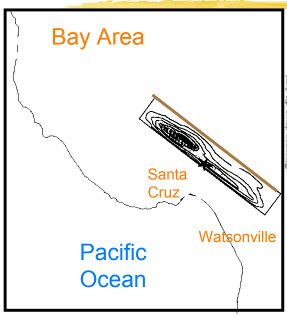


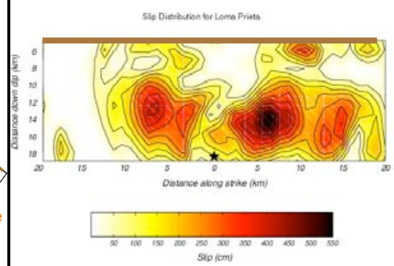
Richter, 4-5

Loma Prieta as example 18 October 1989

- Faulting details
  - 40 km by 20 km rupture area
  - Up to 4 meters of slip
  - M = 7 (not defined until later in lecture)
  - $10,000,000,000 in damage and 62 deaths
  - Mostly right-lateral motion on San Andreas
- 12 special volumes, ~300 papers
  - Was first big California quake for a while

Fault slip in Loma Prieta quake





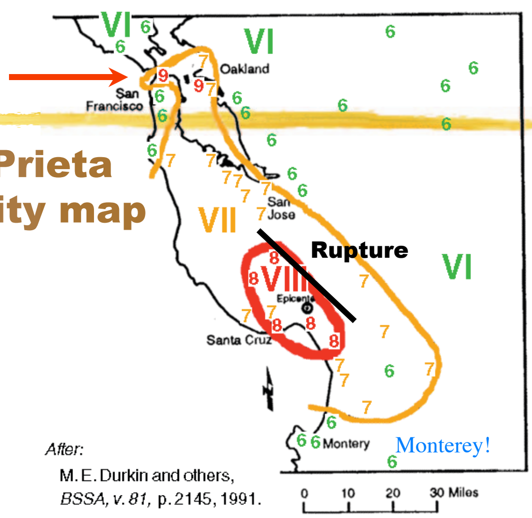
(two different models for rupture are shown

P. Martin Mai, Stanford

Loma Prieta isoseismals

- I'm not sure why this map was made.
  - Technique is obsolete.
  - Maybe done to compare with older quakes that only had isoseismal damage data.
  - Maybe bad habits are hard to break.
- Also, note that although there are many faults, only part of one broke in this earthquake.

Loma Prieta Intensity map



J. Louie

After:
M. E. Durkin and others, *BSSA*, *v. 81*, p. 2145, 1991.

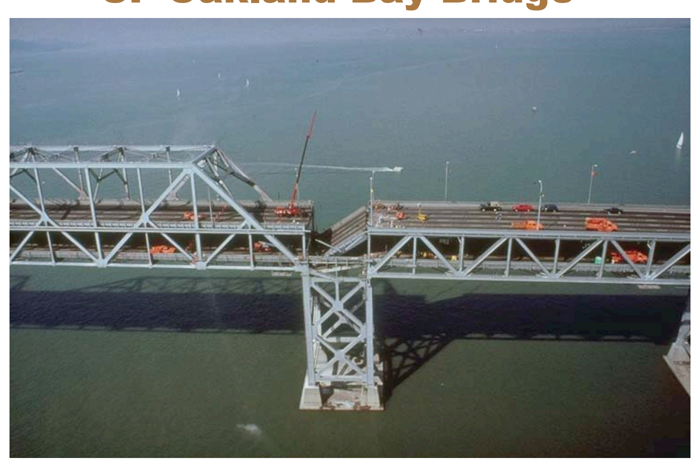
Loma Prieta liquefaction

Bolt, 9-3

Figure 9.3 Sand boils from liquefaction effects on Marina Green, San Francisco after the 1989 Loma Prieta earthquake. [Courtesy of Timothy Barker.]

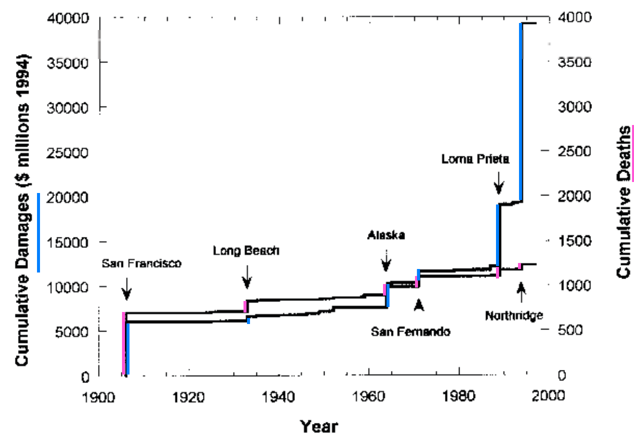
1 fatality, sitting at base of cliff

SF-Oakland Bay Bridge

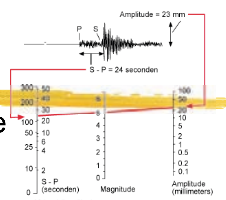


Cypress section of 880 near Oakland

Earthquake damage and deaths



Magnitude



- Measure of the earthquake size
- Determined from seismograms
- Determined by
  - taking the logarithm of the largest ground motion recorded during a particular seismic wave type
  - applying a correction for distance from seismometer to the epicenter
- Several types of magnitude
  - depends mainly on seismic wave type (e.g., P, S, or surface)

Size: Magnitude

- Logarithms are used because earthquakes and resulting ground motion range over many orders of magnitude in size (energy)
- Correction for distance used because amplitude decreases with distance from the earthquake
  - as energy spreads out over larger area
  - Seismometers aren't always at the same distance from earthquake

Logarithms

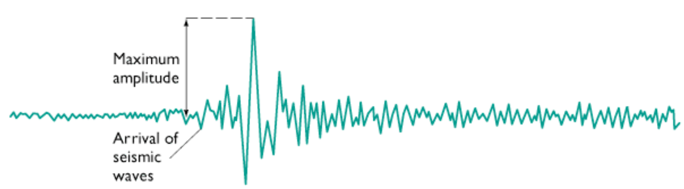
- **$\log_{10} 10^x = x$**
- $\log_{10} 1{,}000{,}000 = \log_{10} 10^6 = 6$
- $\log_{10} 1{,}000{,}000{,}000 = \log_{10} 10^9 = 9$
- $\log_{10} 10^{23} = 23$
- $\log_{10} 1 = \log_{10} 10^0 = 0$
- $\log_{10} 0.0001 = \log_{10} 10^{-4} = -4$
- $\log_{10} 2 = \log_{10} 10^{0.3} = 0.3$

Diff is 3

Manageable numbers

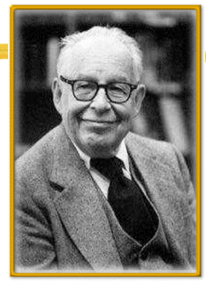
Also handles small numbers

Wave amplitude



Each kind of wave (phase), such as the P wave, S wave, or surface wave, has its own amplitude at each station for each earthquake.

Charles Francis Richter

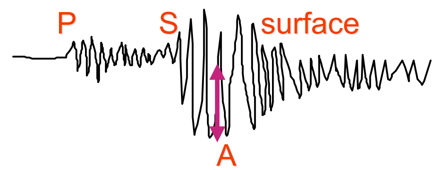


- 1900-1985
  - Made Richter scale in 1935

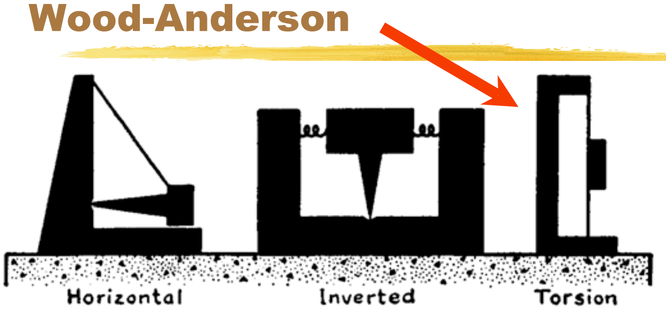
Never had a grad student.
Held the phone in his lap so no one else could answer first.
Dedicated nudist.
Had a seismometer on his coffee table.

Local or Richter magnitude

- $M_L = \log_{10}(A)$ where
  - A is the maximum seismic wave amplitude in microns (10^{-6} m) recorded on a standard seismograph (Wood-Anderson) at a distance of 100 km from the epicenter



Wood-Anderson

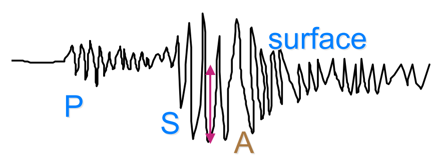


Mirror on a copper wire

Richter, p. 221

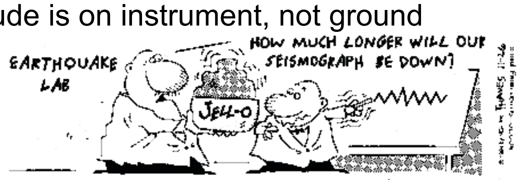
Local or Richter magnitude

- If seismograph not 100 km from epicenter:
  - M_L = log10 (A) + C(distance) where
    - A is the maximum seismic wave amplitude in microns (10^{-6} m) recorded on a standard seismograph
    - C is a correction factor that is a function of distance from the seismograph to the epicenter



Examples

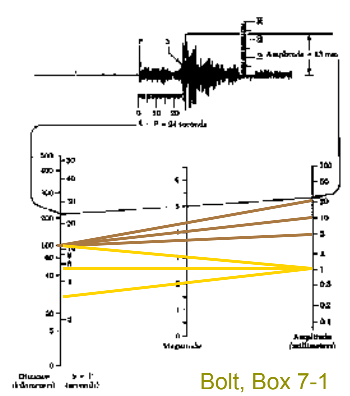
- If amplitude is 1 micron =1/1000 mm then M_L=0
- If amplitude is 1 mm then M_L=3
- If amplitude is 1000 mm then M_L=6
- Amplitude is on instrument, not ground motion



Richter magnitude

Bigger amplitude => bigger magnitude

Greater distance => bigger magnitude



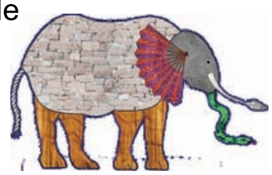
Bolt, Box 7-1

Procedure for calculating the local magnitude, M_L

1. Measure the distance to the focus using the time interval between the S and the P waves (S − P = 24 seconds)
2. Measure the height of the maximum wave motion on the seismogram (23 millimeters)
3. Place a straight edge between appropriate points on the distance (left) and amplitude (right) scales to obtain magnitude M_L = 5.0

Types of Magnitude

- M_L - Local or Richter magnitude
  - Original magnitude, developed by Charles Richter in 1930's
  - uses S wave recorded within 300 km of epicenter
- m_b - Body-wave magnitude
  - uses P wave recorded at 30° to 90° distance
- M_S - Surface wave magnitude
  - uses surface wave
- M_W - Moment magnitude
  - uses seismic moment - Next



How small can earthquakes get?

- The magnitude scale has no intrinsic upper or lower limit.
- Earthquakes with magnitude as small as -2 have been recorded by very sensitive seismometers.
  - log 0.01 = -2
  - Released energy equivalent to that produced when a brick is dropped from a table to the ground.

How large can earthquakes get?

- The largest earthquake well-recorded occurred in Chile in 1960 & had M_W = 9.5
  - (Not 9.9, as asserted in Bolt's book!? (4th ed.)
- We've only been recording for about 50 years so even larger earthquakes have probably occurred in the past
- Upper limit controlled by area of plate boundary likely to break at once

Largest ego in geoscience

Quentin Williams
UCSC

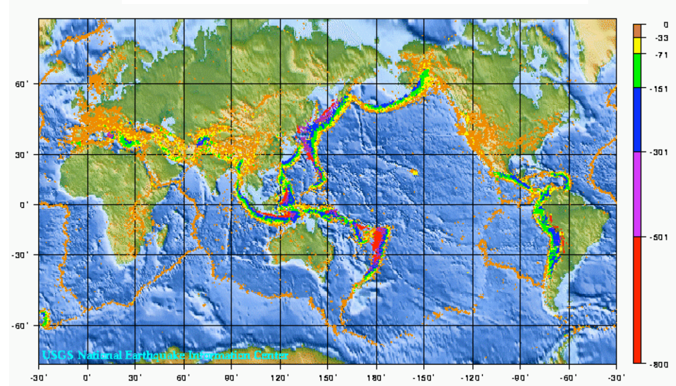
Maximum size of quakes

- Subduction zones
  - Some bigger than M=9
    - 1960 Chile quake was 9.5
    - 1964 Alaska quake was 9.2
  - Larger volume with cold rock
    - Bigger cracks, thus larger magnitudes
- Transform and ridge quakes
  - Biggest quakes we've seen are M=8
    - San Francisco 1906 was 7.9
  - Most are smaller than M=7

How deep are quakes?

- All types of boundaries have shallow quakes
  - 0 to 30 km depth
- Subduction zones also have deeper events
  - As deep as 650 km
    - Subduction is dragging cold material down
    - Cold material is more brittle
  - Deeper events: breakage of subducting slab
    - Mostly from the pull of the weight of the sinking slabs
    - Some are also caused by bending of sinking slab
    - Not from rubbing together of plates

World seismicity: 1975-1995

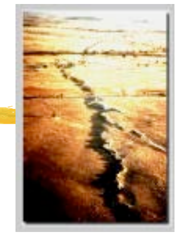


NEIC web page

Why don’t quakes extend deeper?

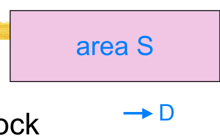
- Temperature increases with depth.
- There is also more pressure, variations in composition, and changes in crystal structure, but these limit < 700 km depth.
- If material is within a few hundred degrees of its melting temperature, it quietly flows rather than suddenly cracks in an earthquake.

Seismic Moment



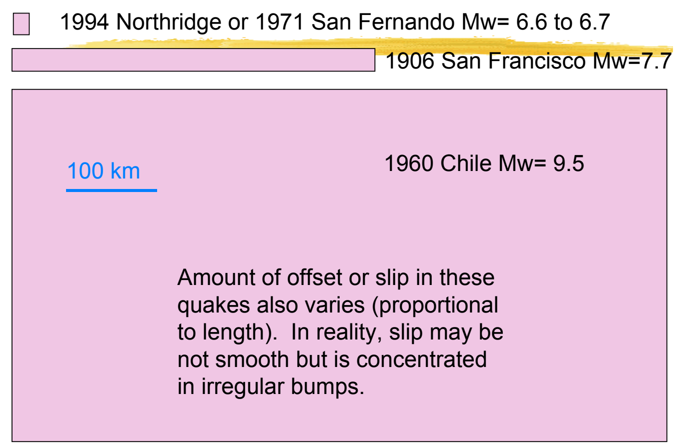
- Modern method for measuring magnitude
- Based on physical size of ruptured area, amount of slip, and rigidity of the rock
- Determined from
  - observations of surface offset (slip) and fault length (surface rupture length or area covered by aftershocks) **or**
  - from seismograms by special processing.

Definition of Seismic Moment



- $M_0 = \mu D S$ where
- μ is the rigidity of the rock
- D is the amount of slip (offset, dislocation) between the two sides of the fault
- S is the surface area that ruptured
- Units are force times length
  - Newton-meters, dyne-cm
- Varies over many orders of magnitude

Relative sizes of fault planes vary greatly



Moment Magnitude

- $M_W = 2/3(\log M_0) - 6.0$ where
- M_0 is seismic moment in Newton-meters.
- Is now replacing other magnitude scales, such as Richter magnitude or surface wave magnitude.
  - Provides a consistent measure of size of earthquakes from the smallest microearthquakes to the greatest earthquakes ever recorded.

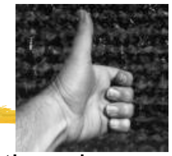
Utility of Intensity vs. magnitude

- Intensity based on damage
  - has one value for each neighborhood for each earthquake, so range of intensities for each quake
  - can be used for historical earthquakes
- Magnitude roughly based on energy
  - has one value for each earthquake
  - more modern and accurate measure

Magnitudes and fault rupture sizes

- Magnitude 8 = 250-500 km
- Magnitude 7 = 50 km
- Magnitude 6 = 10 km
- Magnitude 5 = 2 km
- Magnitude 4 = 400 m
- Magnitude 3 = 80m
- Magnitude 2 = 20m

Rule of Thumb



- On average a magnitude X+1 earthquake has
  - 10 times greater peak amplitude of shaking than a magnitude X earthquake
  - 3.3 longer length of fault and duration of slip
  - 33 times greater energy and moment release
- For example, this is how an M4 quake differs from an M3 quake

Rough comparison of magnitude and intensity

Magnitude	2	3	4	5	6	7	8
Peak Intensity	I-II	III	V	VI-VII	IX-X	IX-X	XI-XII
Perceptibility (kilometers)	0	15	80	150	220	440	800

Kovach, p. 44

Energy of Earthquakes

- Energy that goes into an earthquake is released from the elastic crust
  - Like a spring
- Energy that comes out of an earthquake distributed between
  - Radiated (wave) energy
    - Motion
  - Breaking rocks
  - Frictional heating

Hard to Measure

Earthquake energy comparison

Table 18.1 Earthquake Magnitudes and Energy

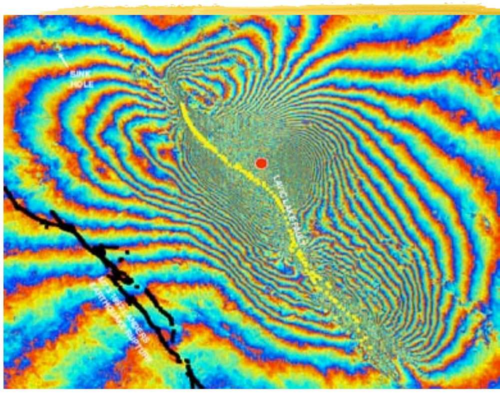
MAGNITUDE	ENERGY RELEASED (MILLIONS OF ERGS)	ENERGY EQUIVALENCE AND EFFECT
−2	600	100-watt light bulb left on for a week
−1	20,000	Smallest earthquakes detected (No)
0 Lightning bolt	600,000	Seismic waves from 1 pound of explosives
1 Tornado	20,000,000	A two-ton truck traveling 75 miles per hour
2	600,000,000	Not felt but recorded
3	20,000,000,000	Smallest earthquake commonly felt
4	600,000,000,000	Seismic waves from 100 tons of explosives
5	20,000,000,000,000	
6 Mt St. Helens	600,000,000,000,000	Damage varies from slight to great, depending on quality of construction
7	20,000,000,000,000,000	
8	600,000,000,000,000,000	1906 San Francisco (magnitude = 8.3)
9	20,000,000,000,000,000,000	Largest recorded earthquake (magnitude = 8.9); destruction nearly total
10	600,000,000,000,000,000,000	Approximately all the energy used in the United States in one year

SOURCE: Modified from U.S. Geological Survey.

What scales with magnitude?

M_w	Moment	Length	Slip	Energy	Duration
4	10^{15} N m	400 m	4 mm	6×10^{11} erg	0.1 s
5	3×10^{16} N m	2000 m	20 mm	2×10^{13} erg	0.5 s
9.5	2×10^{23} N m	1000 km	20 m	8×10^{19} erg	5 min

Geodetic moment



Hector Mine InSAR measures fault length and slip

→ Moment

$M_0 = \mu D S$

Geological Moment

Map slip and rupture length on the ground

$M_0 = \mu D S$

2002 Denali earthquake

Lee and Rubin, CWU

Review

- Seismometers
- Geodesy
- Intensity
- Magnitude
- Moment

Next

- West Coast