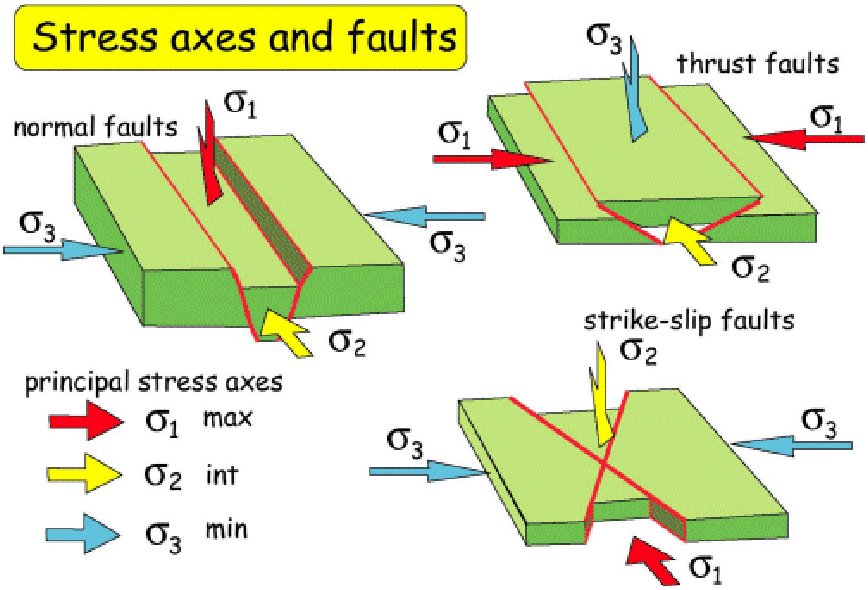
C2.2 The physics of Earthquakes

C2.2.1 Stress axes and faults

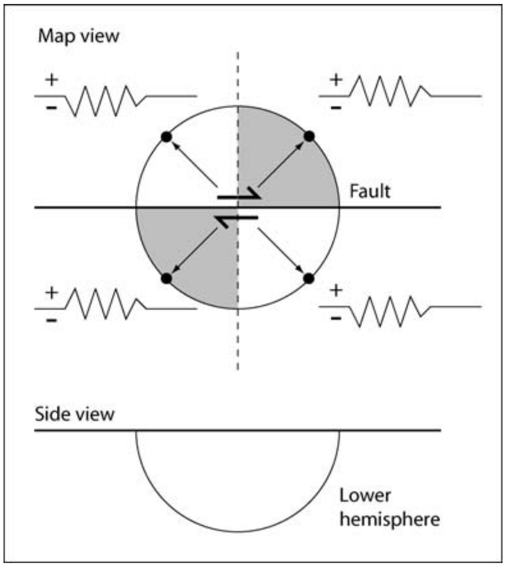
- Most earthquakes occur because of the mechanical failure on brittle faults.
- The type of faulting is a consequence of the stress pattern causing the failure.



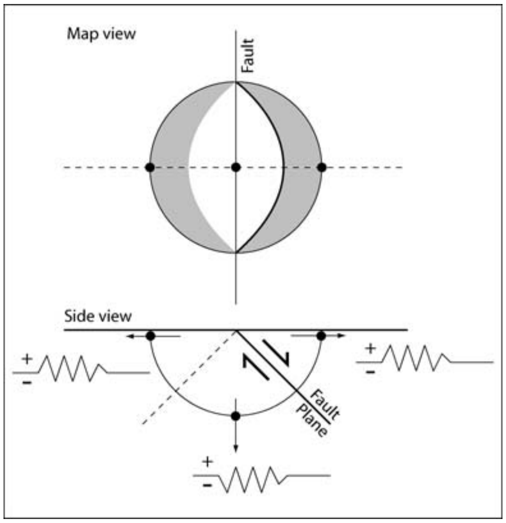
Greatest shear occurs on a plane at an angle of 45° to both the maximum and minimum stress axes.

σ_1 horizontal	σ_3 vertical	**Thrust fault**
σ_1 vertical	σ_3 horizontal	**Normal fault**
σ_1 horizontal	σ_3 horizontal	**Strike-slip fault**

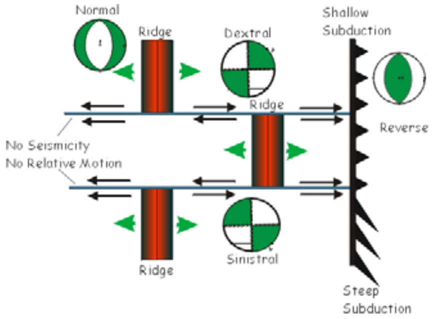
C2.2.2 Focal mechanisms and fault plane solutions



- Consider a strike-slip fault, with east-west strike direction that ruptures in an earthquake
- The direction of fault motion will determine if the first motion of a P-wave will be a compression or a dilation.
- The **focal mechanism** can be determined by considering a **hemisphere** below the earthquake hypocentre (focal sphere).
- Directions corresponding to a **compressive** first motion are shaded **black or grey.**
- Directions corresponding to a **dilation** as first motion are shaded **white**.
- *Fowler Figure 4.22 and 4.23*



- Can do same analysis for a normal fault, dipping at 45° with strike oriented North-South
- Pattern for a thrust fault is similar but with compressional-dilational areas reversed.
- Thrust and normal faults shown in *Fowler Figure 4.25*
- Three types of faults give a different focal mechanisms. These can be used to determine the direction of motion on plate boundaries.



- Generally this process is applied in reverse. **Observations** of first arrivals at many seismic stations from around the world are analysed and used to determine the **fault plane solution**. The fault-plane solution is the distribution of P and T axes that best fit the observed data.

- Note the **inherent ambiguity** in the fault plane solution. The fault motion could have been along the true fault plane, or an auxiliary plane at 90°

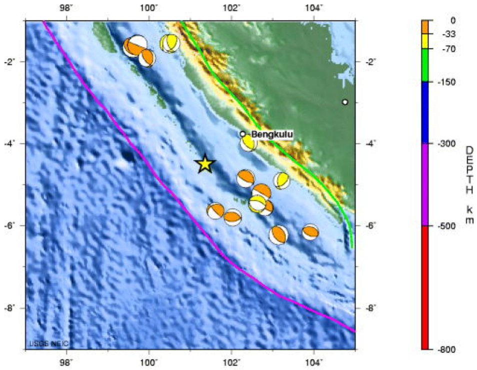
- Example *Fowler 4.26*

- Online results often available immediately after an earthquake.
- Example of a **centroid moment tensor** (CMT) solution from the M=8.4 earthquake close to Sumatra on September 12 2007.

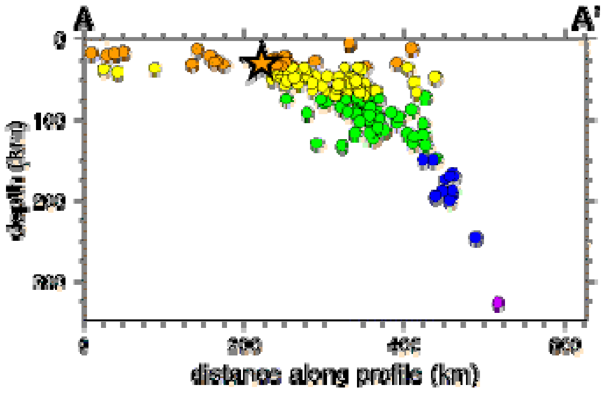
- Note that this is a thrust fault with a shallow dip.

```
           -----------
       ###############----
     ####################---
   ########################---
  -###############   ########--
 ----############# T #########--
 ------###########   #########--
---------######################--
-----------####################--
--------------#################--
-----------------##############--
 -------------------###########-
 -------   ------------########-
  ------ P -----------------##-
   -----   ------------------#
     ----------------------#
       -------------------
           -----------
```

- http://earthquake.usgs.gov/eqcenter/eqinthenews/2007/us2007hear/
- Historical fault plane solutions can also elucidate the mechanisms. Spatial distribution of seismicity is also important (see below)

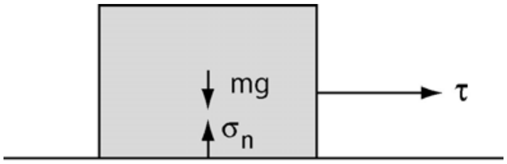


SOUTHERN SUMATRA, INDONESIA
2007 09 12 11:10:26 UTC 4.50S 101.36E Depth: 34 km, Magnitude: 8.4
Historic Moment Tensor Solutions



Generate your own fault plane solutions
http://www1.gly.bris.ac.uk/~george/focmec.html

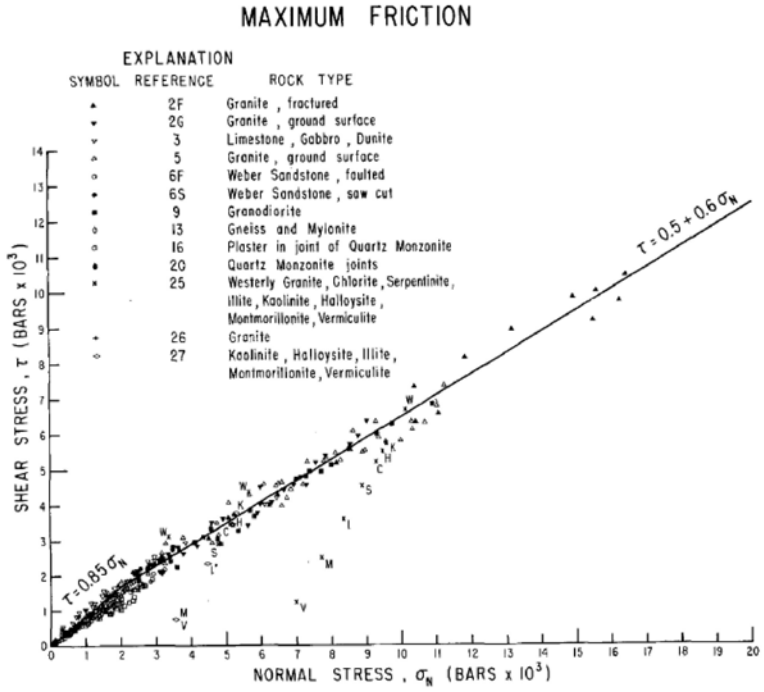
C2.2.3 Rock friction



- The plane between the block and the surface has a normal stress σ_n which is caused by the weight of the block (*F=mg*)
- A shear stress τ is applied and increased until the block begins to slide.
- For sliding to occur $\tau > \mu_S \sigma_n$
- μ_S is called the **coefficient of static friction**

Byerlee's Law

- Measurements on crustal rocks at realistic pressures show a **linear relationship** known as Byerlee's Law:



High normal stress	$\sigma_n > 200$ MPa	$\tau = 50 + 0.6\sigma_n$
Low normal stress	$\sigma_n < 200$ MPa	$\tau = 0.85\sigma_n$

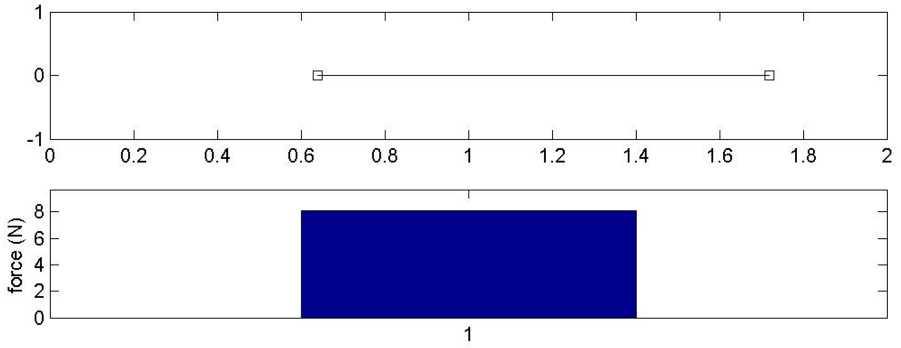
Reference : Byerlee, J., Friction of Rocks, *Pageoph*, 116, 615-626, 1987.

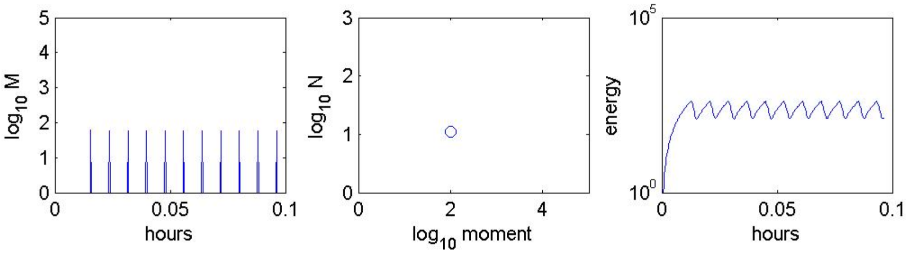
A lower co-efficient of friction can be caused by the presence of fluids or clay minerals in the fault. See discussion later on about the apparent weakness of the San Andreas Fault.

Stick-slip motion

Example 1

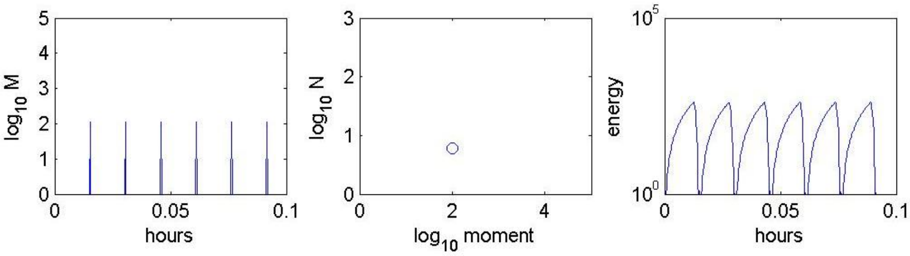
- Commonly observed that the coefficient of friction varies with sliding rate.
- When no motion occurs $\mu = \mu_S$ = static friction coefficient
- When motion occurs $\mu = \mu_D$ = dynamic friction coefficient
- Commonly observed that $\mu_S > \mu_D$
- This **dynamic weakening** leads to the possibility of **stick-slip motion**
- This is illustrated in the following MATLAB animation : **eq1mass_line.m**
- Two masses are connected by a **spring**
- Right hand mass (m_1) moves at a constant velocity to the right (v_{drive} = 2 m/s)
- Bar chart shows tensional force in the spring (Newtons)
- Static coefficient of friction $\mu_S = 0.9$
- Frictional force keeping m_2 in place = $\mu_S g m_2$





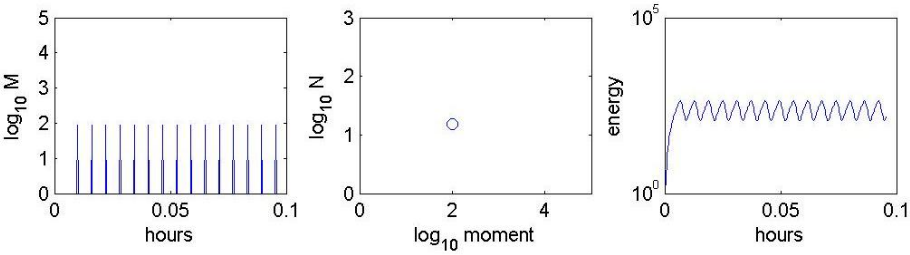
- When tensional force is stronger than frictional force, the mass m_2 slides right.
- Dynamic coefficient of friction $\mu_D = 0.7$
- $\mu_D < \mu_S$ means that once m_2 slides, it keeps moving for a while.
- This corresponds to an “earthquake” and the masses turn red on display.
- MATLAB script computes the position, velocity and acceleration. These quantities are updated for many short time steps.
- During an earthquake, the stress in the spring is released. However, not all the energy stored in the spring is released.
- Once m_2 stops moving return to $\mu = \mu_S$
- This produces a sequence of **regular** earthquakes, all with the same size (M=1.8).
- M = moment of earthquake, which is a measure of the energy release. (see the definition later on). N is the number of earthquakes with that moment.

Example 2 - change μ_D to 0.4 (more dynamic weakening)



- This allows almost all the stored energy to be released during the earthquake, which results in a **longer repeat time** between earthquakes.
- The size (moment) of the earthquake is increased compared to previous case

Example 3 - increase v_{drive} to 4 m/s (faster fault motion)



- Same size of earthquake as Example 1
- Repeat time between earthquakes is shorter.

In the Earth this cycle can be observed by slow elastic deformation between earthquakes, often with a timescale of centuries. During an earthquake the energy is released in a few seconds. This is termed **elastic rebound**. See Fowler(2005) Figure 4.19

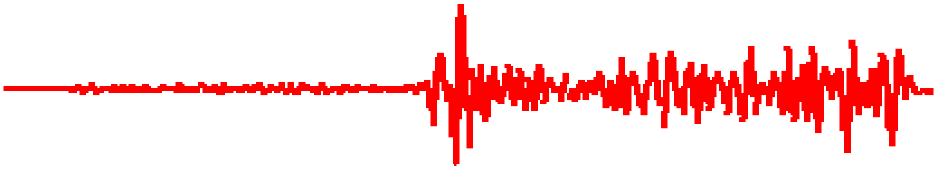
See …… http://www.uwgb.edu/DutchS/EarthSC202Notes/quakes.htm

(a) (b) (c)

(a) Offset sidewalk in Hollister, California in 1999. This motions has been caused by creep on the Calaveras Fault.
(b) Offset river channel caused by 1999 Izmit Earthquake in Turkey.
(c) Offset gas station that resulted from the 1999 Izmit Earthquake in Turkey.

C2.2.4 Measuring the size of earthquakes

(a) Gutenberg-Richter Scale (1935)



$$M_S = \log_{10}\left(\frac{A_S}{T}\right) + 1.66\log_{10}\Delta + 3.3$$

A_S = amplitude of **surface wave** motion in microns

T = period of surface wave (around 20 seconds)

Δ = distance to earthquake epicentre (degrees)

- Empirical measure developed in Southern California to convert magnitude of ground motion at a seismic station into a measure of the size of a distant earthquake.
- The 'S' denotes surface wave.
- By choosing the surface waves, this measure records the maximum amount of shaking.

(b) Body wave magnitude

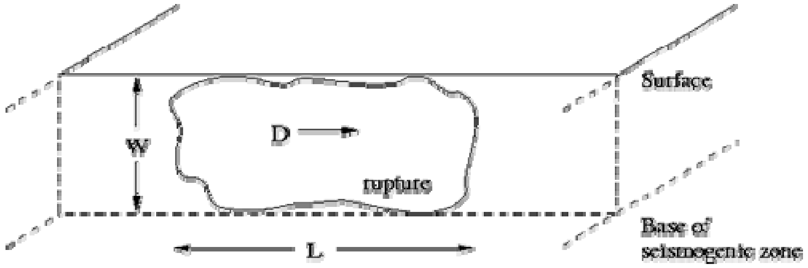
Alternative definition from amplitudes of P-waves with period 1-5 seconds. These are the first arrivals and have a smaller amplitude than the surface waves, which can make measurement more difficult.

$$M_B = \log_{10}\left(\frac{A_P}{T}\right) + 0.01\Delta + 5.9$$

Related to Gutenberg-Richter magnitude as: $M_B = 0.56M_S + 2.9$

(c) Seismic moment

The previous measures compute the size of an earthquake from ground motion during the earthquake. The size of an earthquake can also be expressed in terms of how much the Earth moved during an earthquake



Seismic moment is defined as:

$$M_0 = \mu D A$$

where the an area of fault-plane A slips a distance of D during the earthquake (A=LW) and shear modulus = μ

Can express a moment magnitude as

$$M_W = \frac{2}{3}\log_{10} M_0 - 6$$

This is generally a more reliable estimate of the size than either M_b or M_S

L : Determine from observations of surface rupture. Also from INSAR data.
D : Determine from surface observations of rupture

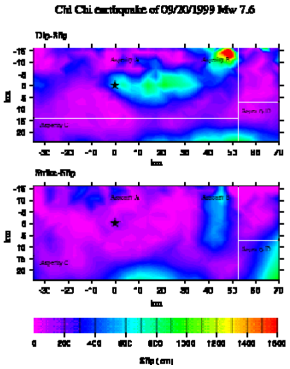

Spitak, Armenia, (1988)


Duzce, Turkey, (1999)

W : More difficult to estimate, but cannot exceed depth of brittle-ductile transition. Constraints from aftershock distribution, surface deformation (INSAR etc)

Inversion of waveform data

Example from Chi-Chi earthquake in Taiwan in 1999
http://seismo.berkeley.edu/annual_report/ar99_00/node19.html



(d) Mercalli scale

This is another way of measuring the size of an earthquake through the damage it causes.
Details : http://en.wikipedia.org/wiki/Mercalli_intensity_scale
http://earthquake.usgs.gov/learning/topics/mercalli.php

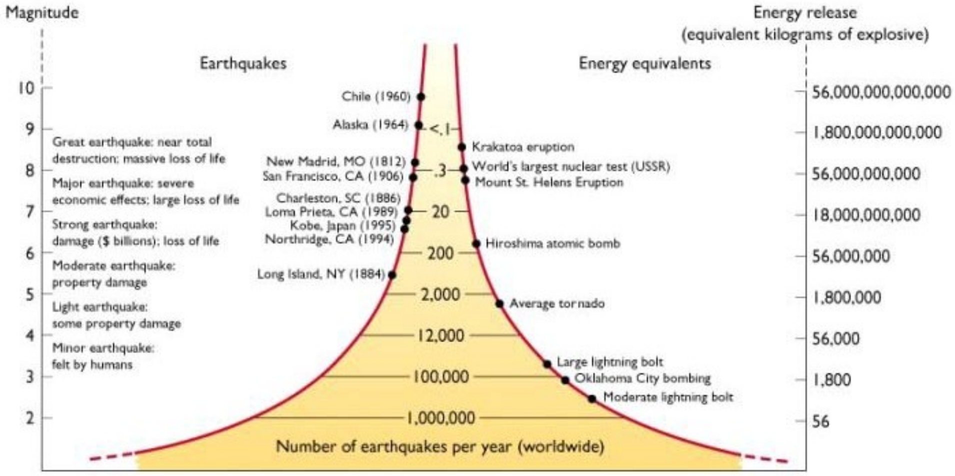
Number	Name	Description
I	Instrumental	Detected by seismographs, usually not felt.
II	Feeble	A few people might notice movement if they are at rest and/or on the upper floors of tall buildings.
III	Slight	Felt by many, often mistaken for a passing vehicle. Shaking felt indoors; hanging objects swing back and forth. People outdoors might not realize that an earthquake is occurring.
IV	Moderate	Most people indoors feel movement. Hanging objects swing, parked cars might rock. Dishes, windows, and doors rattle. The earthquake feels like a heavy truck hitting the walls. A few people outdoors may feel movement.
V	Rather strong	Almost everyone feels movement. Sleeping people are awakened. Doors swing open or closed, dishes are broken, pictures on the wall move. Cracked walls, trees disturbed.
VI	Strong	Felt by all. Many run outdoors. Slight damage occurs. Stronger shaking can cause people to fall over and walls and ceilings to crack. People walk unsteadily; windows break; pictures fall off walls. Furniture moves. Trees and bushes shake
VII	Very strong	Everyone runs outdoors. Poorly built buildings suffer severe damage. Slight damage everywhere else. Difficult to stand; plaster, bricks, and tiles fall; large bells ring. Drivers feel their cars shaking. Some furniture breaks. Loose bricks fall from buildings. People fall over.
VIII	Destructive	Tall buildings sway, furniture breaks, cars swerve. Everyone runs outdoors. Moderate to major damage. Minor damage to specially designed buildings. Chimneys and walls collapse. Drivers have trouble steering. Houses that are not bolted down might shift on their foundations. Tree branches break. Hillsides might crack if the ground is wet. Water levels in wells might change.
IX	Ruinous	Ground cracks, well-constructed buildings damaged, pipes break. All buildings suffer major damage. General panic; damage to foundations; sand and mud bubble from ground. Reservoirs suffer serious damage.
X	Disastrous	Landslides, ground cracks widely. Major damage. Most buildings and their foundations are destroyed. Some bridges are destroyed. Water is thrown on the banks of canals, rivers, and lakes. Railroad tracks are bent slightly.
XI	Very disastrous	Bridges and buildings destroyed, large fissures open. Almost all structures fall. Very wide cracks in ground. Railway tracks bend; roads break up; rocks fall. Underground pipelines are destroyed.
XII	Catastrophic	Rocks moved, objects thrown about. Total destruction. Ground surface waves seen. River courses altered. Large amounts of rock may move.

http://www.seed.slb.com/en/scictr/watch/seismology/intensity.htm

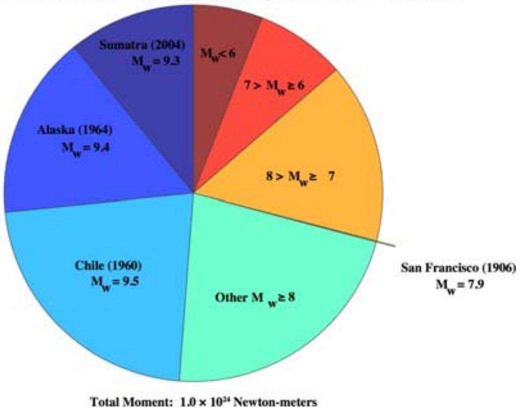
(e) Energy and earthquakes

Earthquakes can release huge amounts of energy. The figure below gives an idea of how a given magnitude relates to other phenomena.

Additional energy-magnitude information can be found at:
http://www.uwgb.edu/DutchS/EarthSC202Notes/quakes.htm

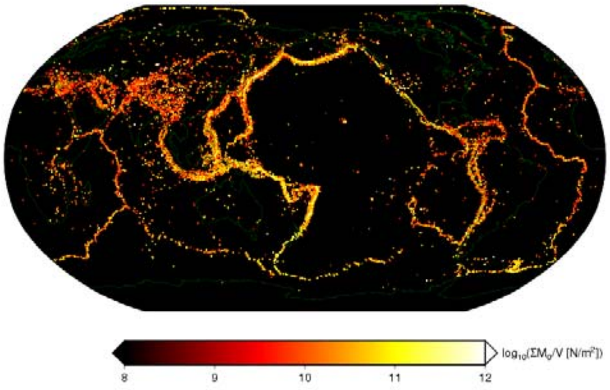


Global Seismic Moment Release January 1906 - December 2005



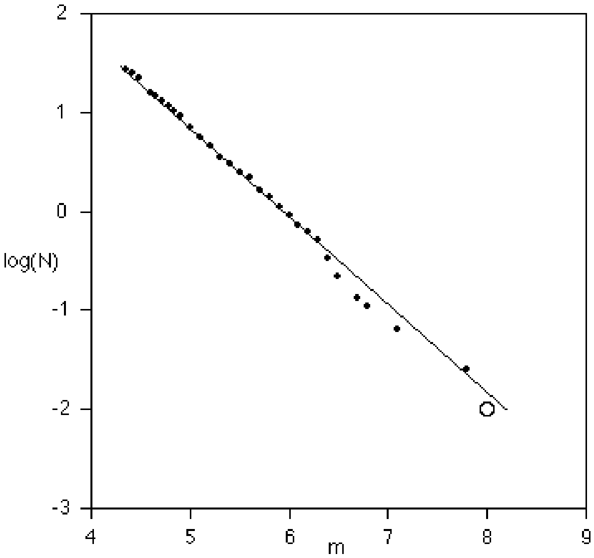
During the century from 1906-2005 almost half of the energy released was in just three earthquakes.

Engdahl et al. (1998), $z \leq 50$ km



C2.2.5 Frequency magnitude relations

There are more small earthquakes than large earthquakes.



- Example from Southern California for period 1932-1972.
- Note that departures from a straight line are observed for M>6
- These large events are infrequent and the observation period (40 years) is not enough to record a statistically significantly number.

- This is described **empirically** by the Gutenberg-Richter Law:

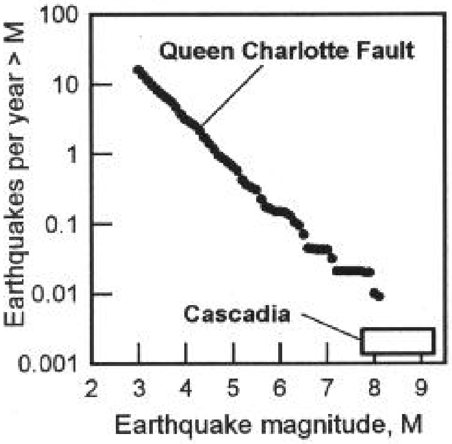
$$\log N = a - bM_S$$

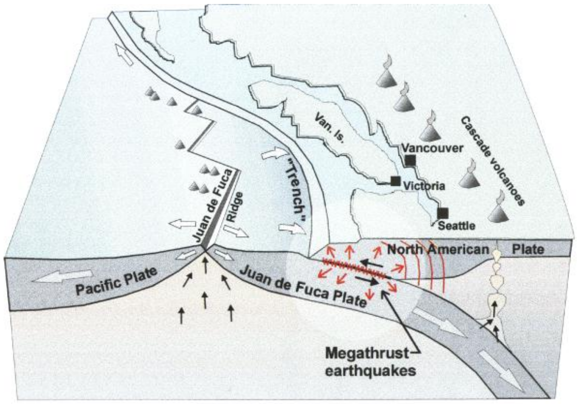
- *N* is number of events of magnitude M_S
- a and *b* are empirical constants
- Worldwide observed that b =1
- Following numbers from Fowler.

M	Description	Number per year
>8	Great	1-3
7-8	Major	<20
6-7	Strong	180
5-6	Moderate	1,800
4-5	Light	10,000
3-4	Minor	90,000
2-3	Very minor	1,000,000

Queen Charlotte Fault

- This example shows the earthquake statistics on the Queen Charlotte Fault.
- This is a transform fault to the north of the Cascadia subduction zone.
- The largest earthquakes occur very infrequently.
- If an M=9 event occurs on this fault, then it's frequency of occurrence can (in principle) be estimated.

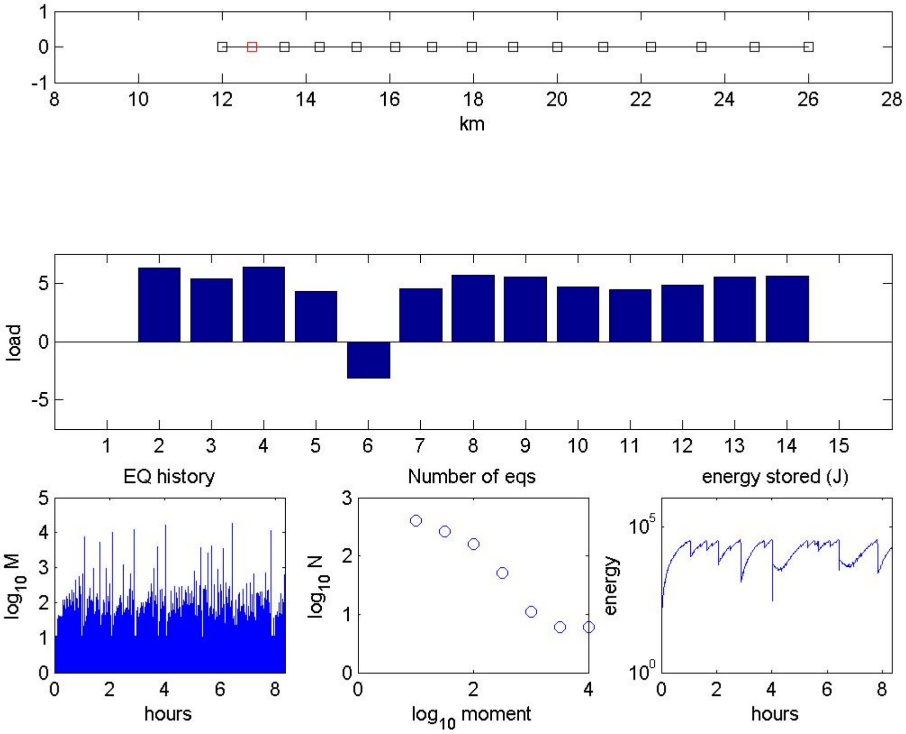




http://seismescanada.rncan.gc.ca/zones/cascadia/megafig_e.php

MATLAB animation : **eq15mass_ring_2007.m**

- Similar to demonstration above, but with 15 masses moving on a line
- Masses at each end are moved at constant rate
- $\mu_S = 0.7$ and $\mu_D = 0.6$
- Can think of this as representing a set of fault segments. If one segment ruptures then a small earthquake results. If the rupture can break into adjacent segments then a larger earthquake will occur.



- The end springs undergo frequent earthquakes and transfer stress to adjacent springs. Once 2 or more springs fail together , a larger "earthquake" occurs.

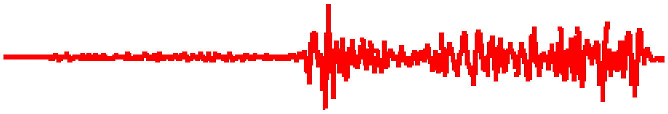
- More complicated pattern than previous example with one mass.
- Many small earthquakes and fewer larger earthquakes.
- Larger events (M=4) followed by period of no earthquakes.
- Larger events (M=4) associated with a major energy loss.
- Shows some characteristics of a chaotic system. This includes the period-doubling, non-repeating behaviour and high sensitivity to initial conditions.

This computer model is obviously too simple to represent a real fault, but it does reproduce some important aspects of the sequence of earthquakes observed on a real fault zone.

- approximate straight line on number-moment plot (Gutenberg-Richter relationship)
- upper limit to maximum size of earthquake
- random, non-repeating sequence of earthquakes
- period of low activity after the largest events have released significant energy

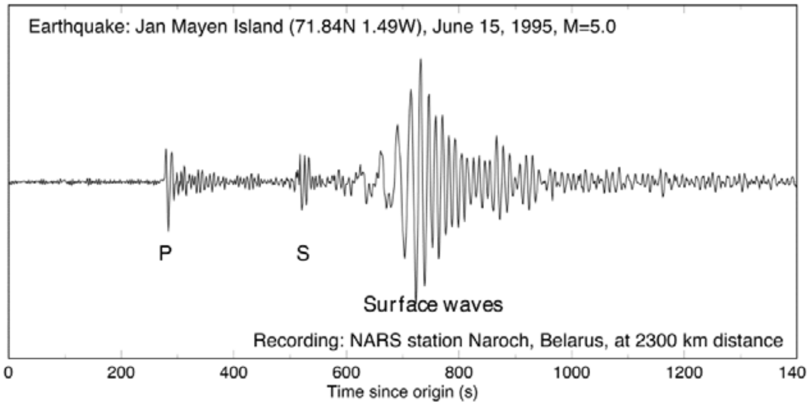
C2.2.6 Typical seismograms

(1) Historical recording



Seismogram recorded in Gottingen (Germany) of the 1906 San Francisco earthquake.
http://earthquake.usgs.gov/regional/nca/1906/18april/seismogram.php

(2) Modern high quality seismic record



http://www.uweb.ucsb.edu/~shao/links.html

(3) Almost real time seismic data from the POLARIS network

- NRCan operates a national seismic network. This was supplemented by the POLARIS project beginning around 2001.
- List of recent events recorded on a Canadian network that uses satellite telemetry to return signals from remote areas.
- Note that signal-to-noise ration varies with earthquake magnitude and distance.

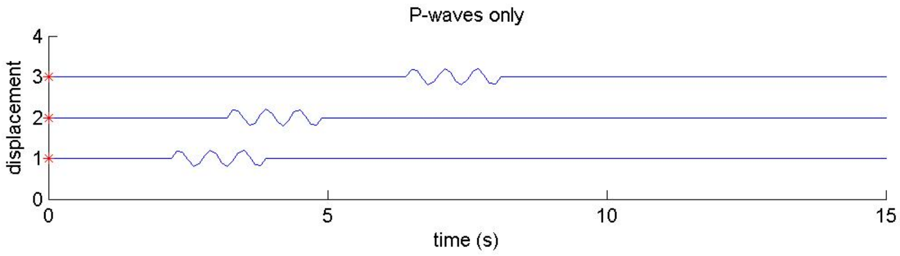
http://www.polarisnet.ca/events/data/waveform.html

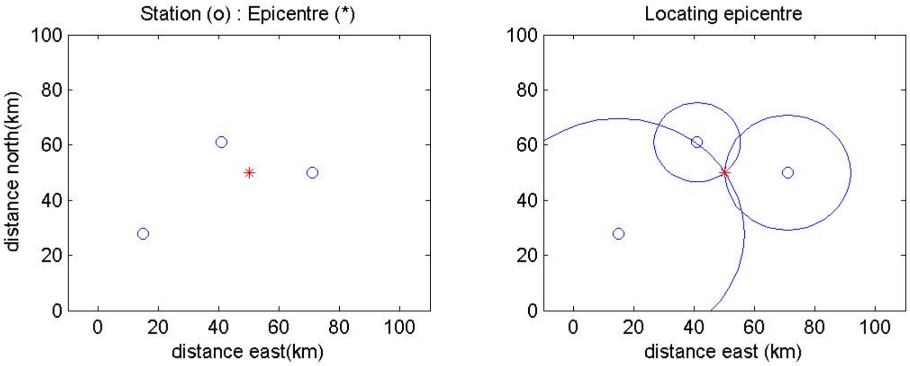
C2.2.7 Earthquake locations

Hypocenter : location at which rupture begins. Note that the rupture will have a finite size, but the location determined is usually where it begins.

Epicenter : point on surface directly above the hypocenter.

earthquake_locations_P_wave.m

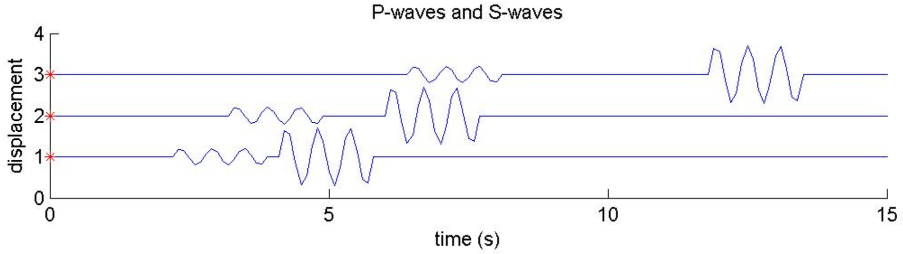


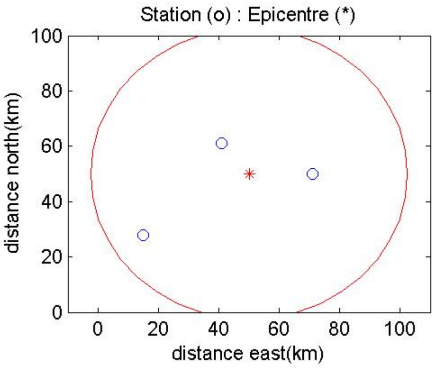


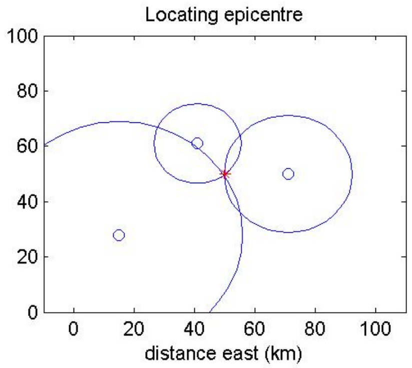
- Earthquake occurs at location marked by star at time t = 0
- Assume that P-waves travel horizontal in the Earth
- Note that P-waves are non-dispersive (body waves)
- Seismograms record P-waves at 3 stations. P-wave velocity is v_P
- From the travel time can compute ranges from each seismic station.
- Simple to show that $r_1 = t_1 v_P$; $r_2 = t_2 v_P$; $r_3 = t_3 v_P$
- One seismic station defines a circle on which the earthquake must have occurred.

- Cannot usually determine the azimuth from ground motion.
- Two seismic stations give two possible locations.
- Three seismic stations give a unique location (epicentre).
- Why will this not work in practice? **Do not know when earthquake occurred!**

earthquake_locations_PS_wave.m







- As before but both P-waves and S-waves recorded.

- S-waves travel slower than the P-waves

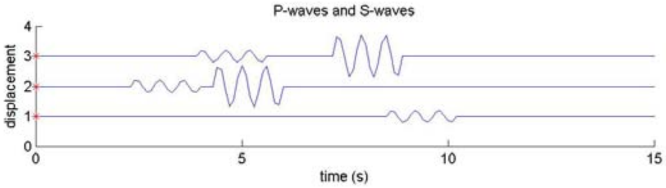
- If P-wave and S-wave arrivals overlap, it can be difficult to pick arrival time of the S-waves.

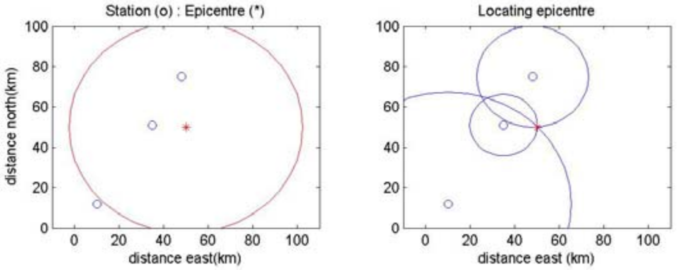
- The **time delay** between P-waves and S-waves increases with distance.

- Compute ranges as $r_1 = \dfrac{(t_1^S - t_1^P)v_P v_s}{(v_P - v_S)}$; $r_2 = \dfrac{(t_2^S - t_2^P)v_P v_s}{(v_P - v_S)}$; $r_3 = \dfrac{(t_3^S - t_3^P)v_P v_s}{(v_P - v_S)}$

- Can also compute the **time** at which the earthquake occurred

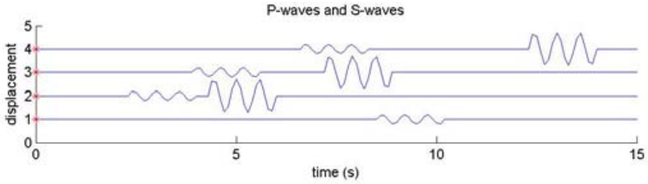
earthquake_locations_PS_wave_problem_1.m

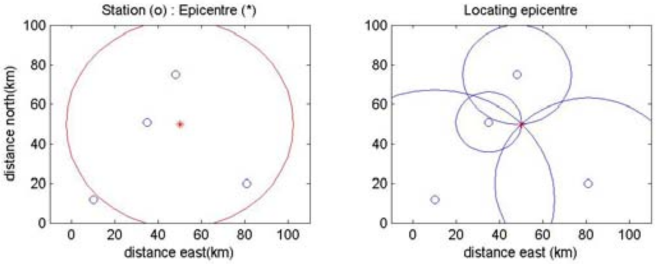




- When three seismic stations are **collinear**, a unique location is not obtained

earthquake_locations_PS_wave_problem_2.m





- Data from a fourth seismic station is needed to locate the epicentre

Extend this analysis to compute depth of hypocentre

- Consider earthquakes with hypocentres at 5 and 50 km recorded at a single seismic stations directly above. The deeper earthquake occurs a few seconds before the shallow earthquake, so both seismic waves would arrive at the same time.
- When working backwards from arrival time, cannot tell if it was a deep-early earthquake, or a later-shallower earthquake.