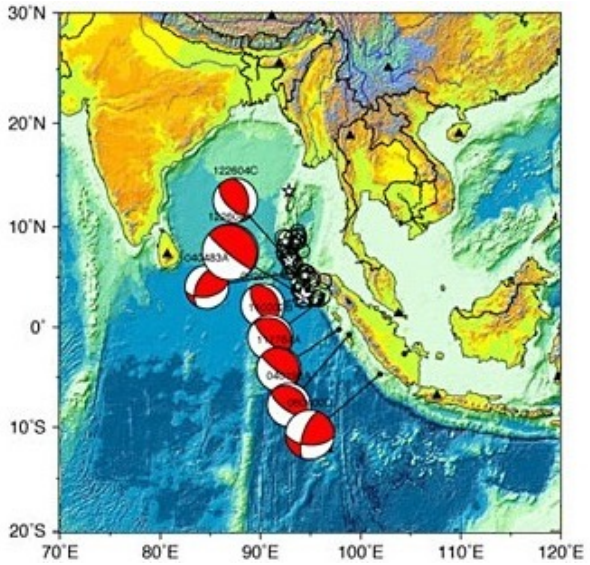
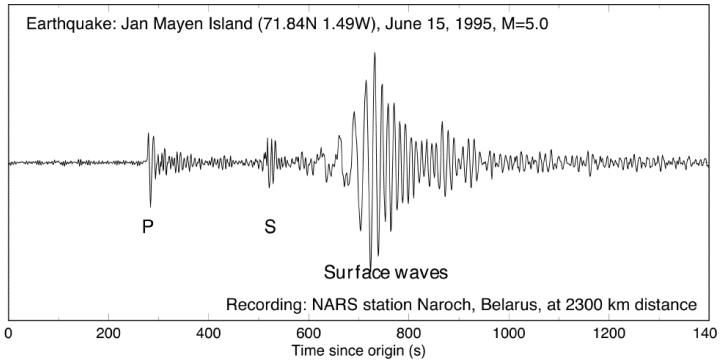
# Focal Mechanisms

- can analyze recorded seismic waveforms to determine the orientation of the fault that produced the earthquake
- observed the **polarity** of the first seismic wave
- called a **focal mechanism**

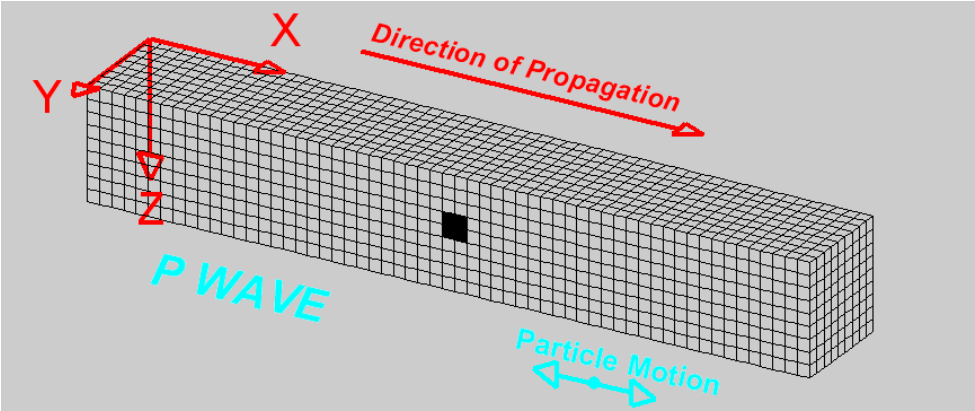
(fault plane solution, moment tensor solution, “beachball”)



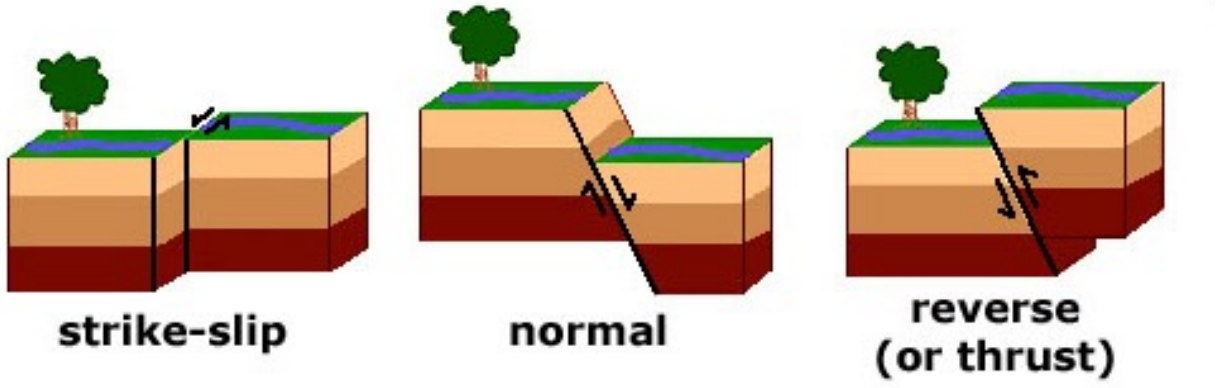
## Pseudo source: P-waves

**Most common approach**: Use P waves (polarity + amplitude) to analyze focal mechanisms. Other phases, such as S and Surface Waves could also be used, but the process is slightly more complex.




(http://web.ics.purdue.edu/~braile/edumod/waves/WaveDemo.htm)

**…to determine the type of fault that produced the earthquake**



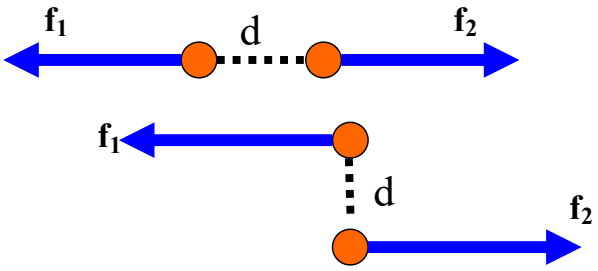
## A Better Representation of Source than Fault strike, dip and slip (geological description): *equivalent body forces*

***point source***: size of source << wavelength

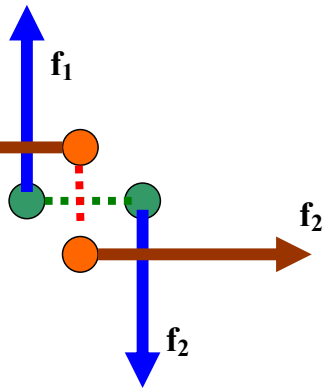
**External force** ---> generate a single force.

**Internal forces**: must act in a opposite direction to conserve momentum.

**Force couples**:




**Double couples**:




**Conserves angular momentum, *no net torque***

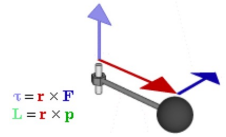
**Two competing theories regarding forces in the case of earthquakes:**

1. **Single couple**: two point forces acting opposite to each other across fault plane

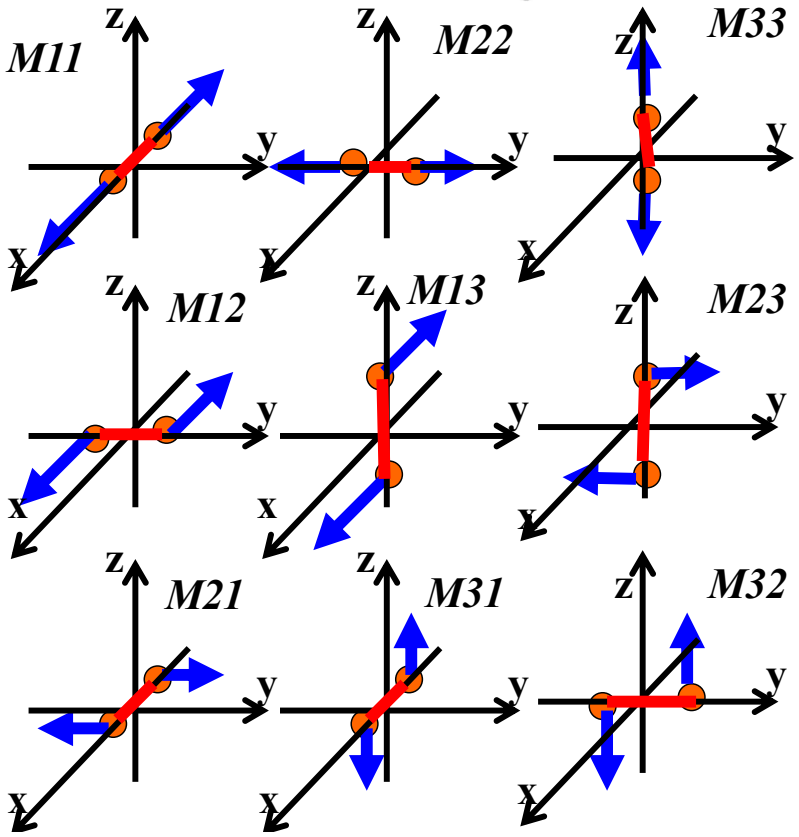
2. **Double couple**: four point forces (**double couple**) acting across two perpendicular planes that stop net rotation (preferred now)

Torque (or ***Moment***) of the system: $M_{ij} = f_i * d_j$

We can define moment tensor **M** as follows:




$$\mathbf{M} = \begin{bmatrix} M_{xx} & M_{xy} & M_{xz} \\ M_{yx} & M_{yy} & M_{yz} \\ M_{zx} & M_{zy} & M_{zz} \end{bmatrix}$$




**Diagonal terms**: compression or dilatation, where force direction is the same direction as lever, tends to lead to volume change

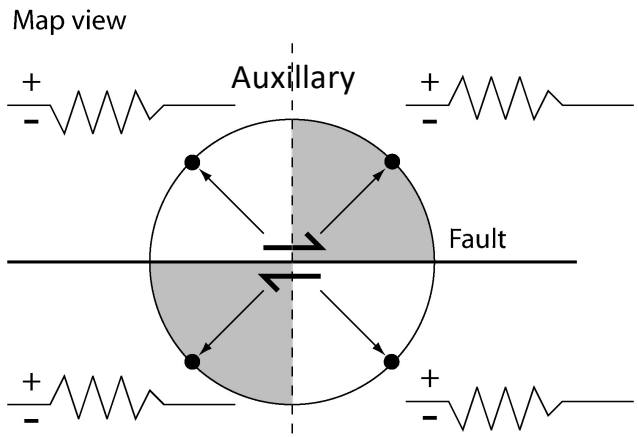
**Non-diagonal**: shear component

1st index: force direction, 1=x, 2=y, 3=z

2nd index: direction of unit normal to faut/auxiliary plane.
Mxx = $M_{11}$ = coupled forces oriented along x (or 1) direction

# Focal mechanism for a dextral strike-slip fault

• E-W strike, dip = 90° (vertical)




In this case, the **true fault** (East-West oriented) is **Dextral** = **right lateral**, clockwise rotation

**Auxiliary fault** = N-S oriented = **Left lateral** = Sinistral

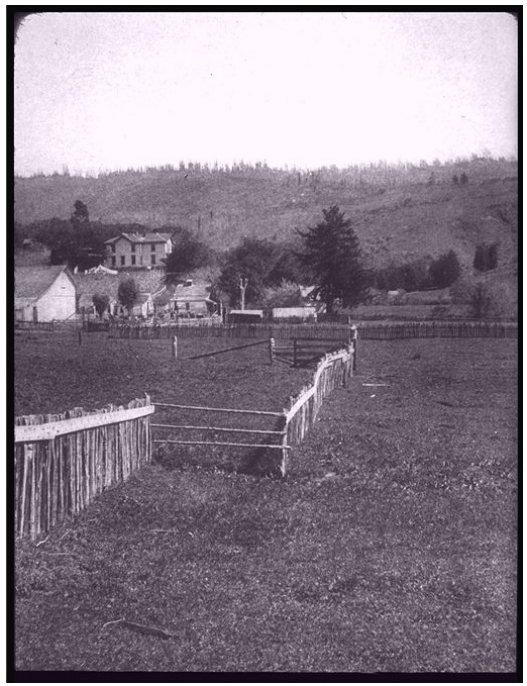
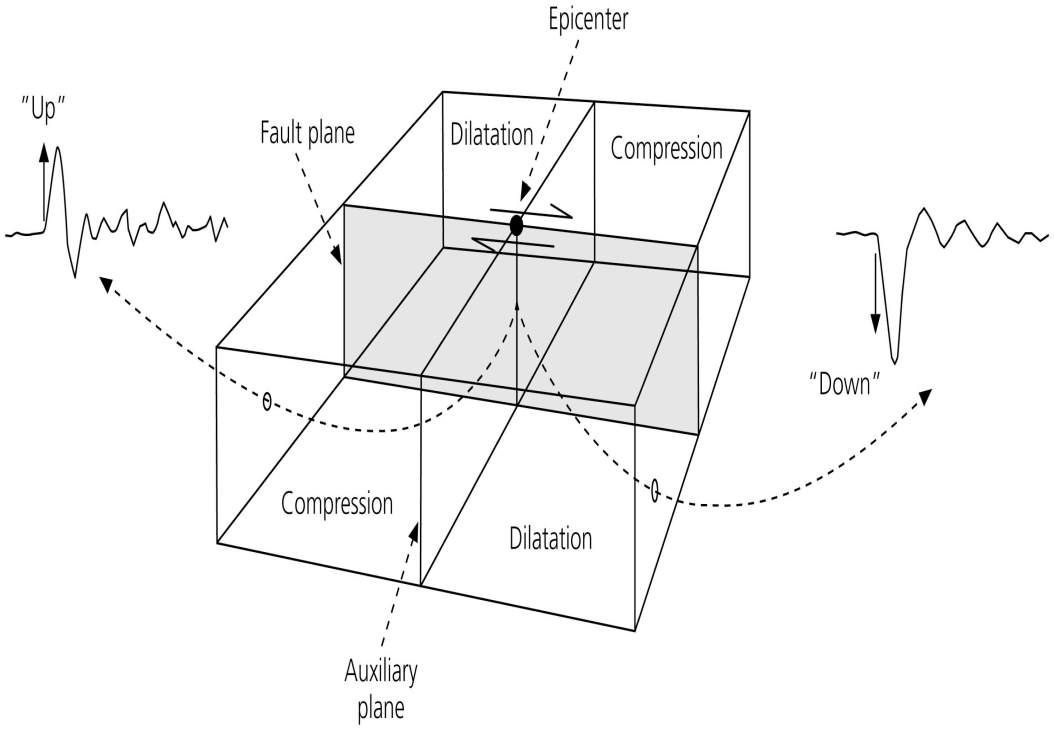


**Figure 4.2-4: First motions in relation to fault orientation.**




In this case, the **true fault** (roughly East-West oriented) is **Dextral** = **right lateral**, clockwise rotation = force vector across the fault from where you stand point to the right

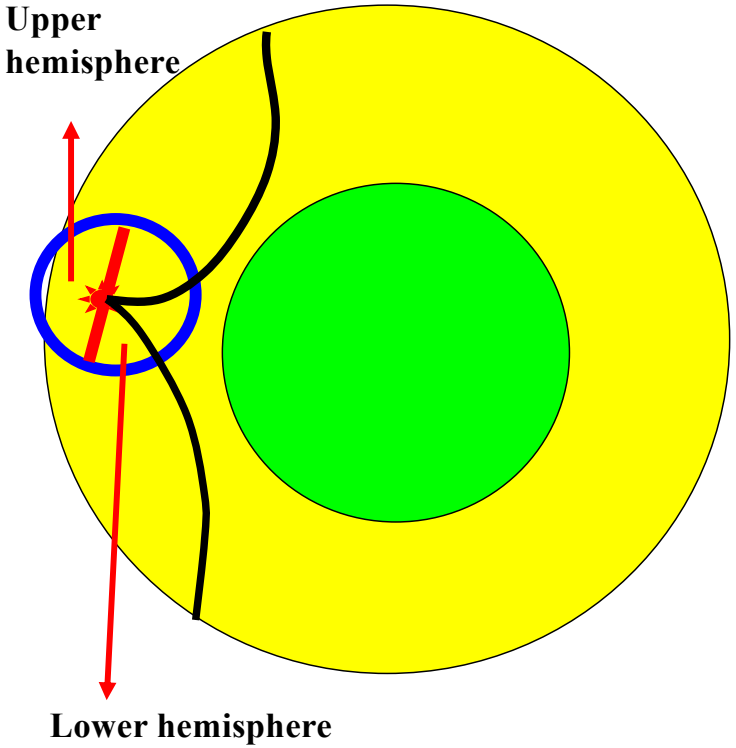
**Auxiliary fault** = N-S oriented = **Left lateral** = Sinistral

**Problem: Ambiguity between fault and auxiliary fault determination based on P polarity!!**

# Lower Hemisphere Projection

Visualization of 'Beachballs':

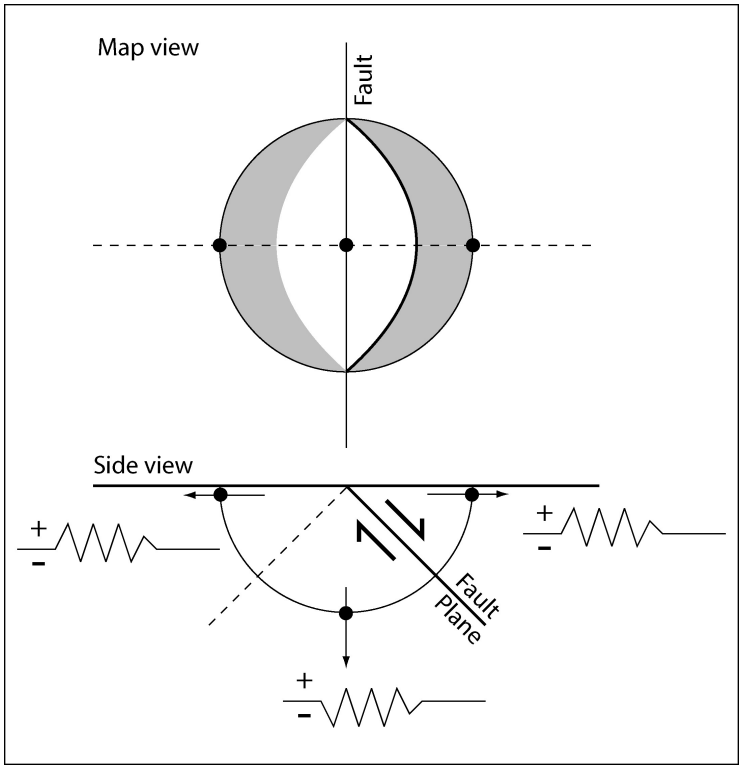
Map view (conventional): Looking down on the focal sphere (a sphere that contain the fault system). There should be 4 quadrants (2 light 2 dark). Imagine using a circular, semi-transparent sheet of a paper to cover the top of the beachball. The beachball is the projection of the lower hemisphere (imagine the top half is removed) when a flashlight shines at the bottom where dilatation quadrant is light and compressive quadrant is dark.

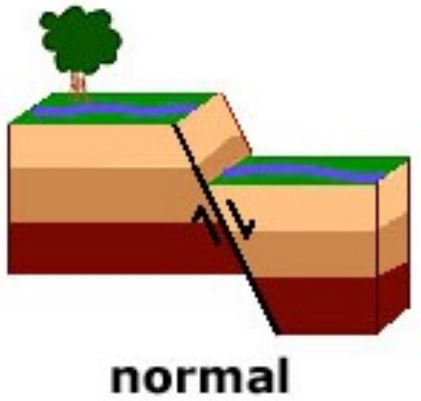



The "beachballs" are lower focal hemisphere projections of the radiation patterns.

# Focal mechanism for a normal fault

- N-S strike
- dipping at 45˚ East



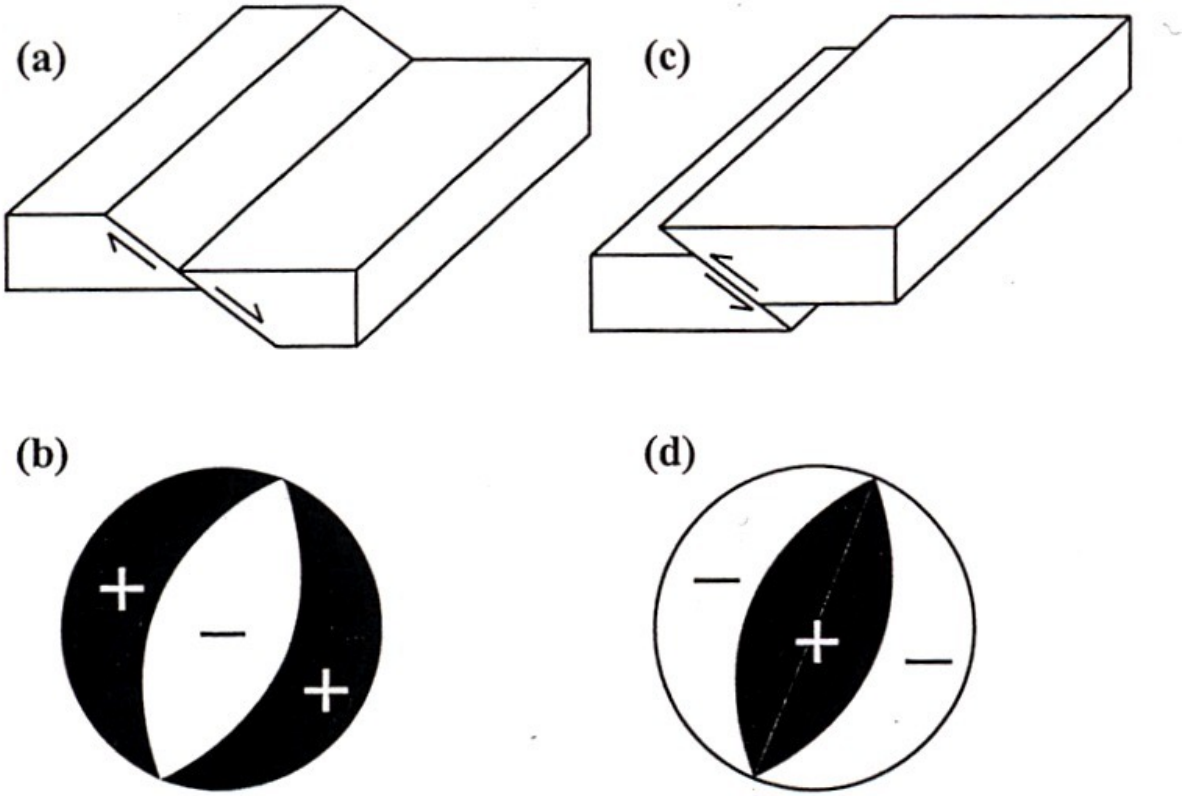




Presentation of beachballs:

**Map view (conventional)**

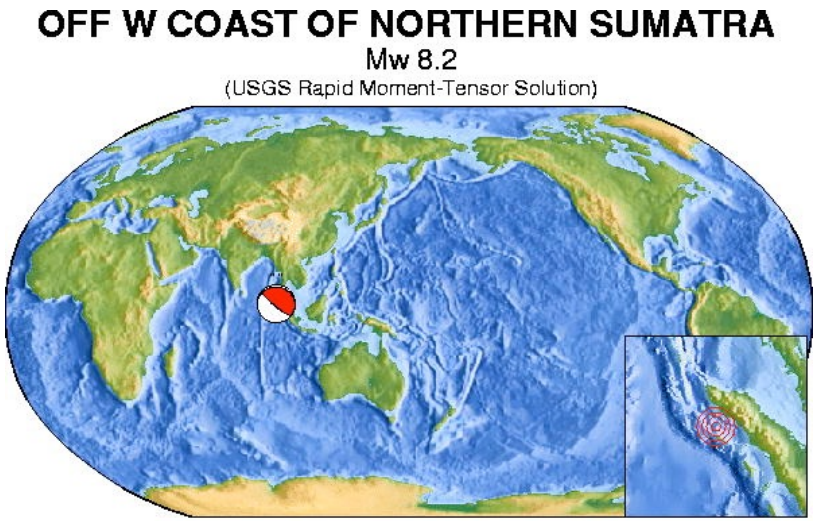
Side-view: helpful to visualize but not usually shown

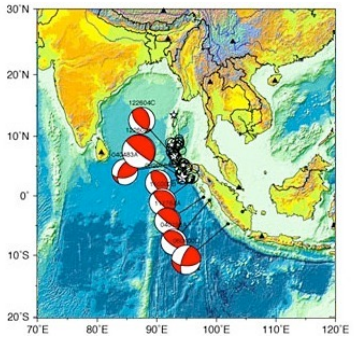
## Focal mechanisms




(Fowler Figure 4.25)

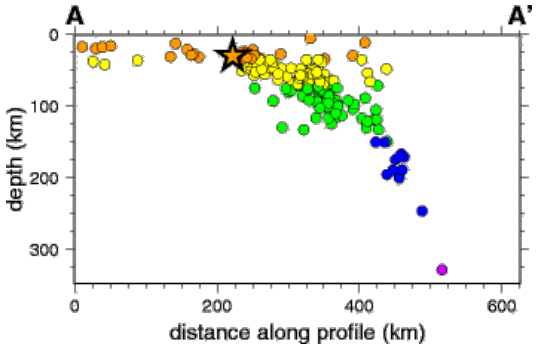
# Focal mechanism for 2004 Sumatra earthquake



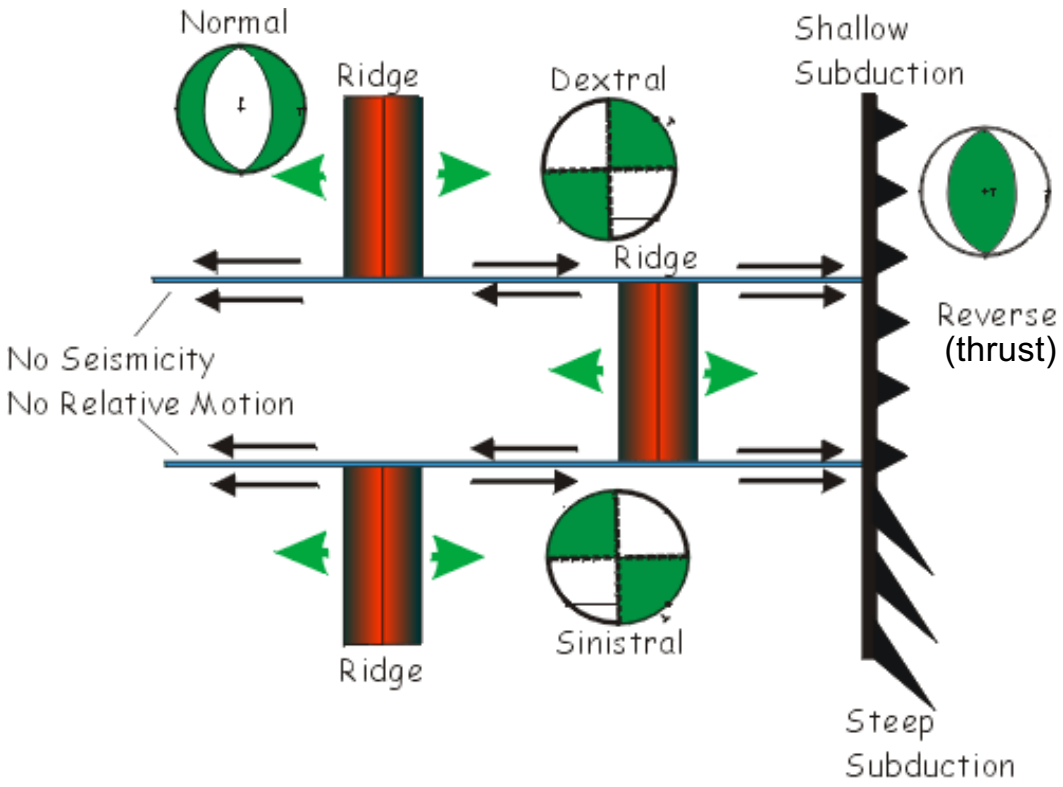



**What type of fault produced this earthquake?**




(USGS website)

# Focal mechanisms for plate boundary earthquakes

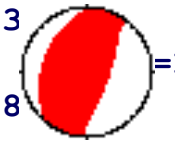


# Typical Global Centroid Moment Tensor (CMT) Solution

This is a typical 'Global Centroid Moment Tensor (CMT)' solution, disseminated by Lamont-Doherty Lab (Columbia University) after a relatively large (Mag > 5.0) earthquake. The earthquake mechanism is obtained by analyzing P, S, and Surface wave phases from all available seismic stations. The program returns a single solution of the earthquake initiation time (the 'centroid time', which corresponds to the time that half of the moment has been released from the seismic source), location (depth, lat, lon), magnitude, and moment tensor elements.

**010176A** KERMADEC ISLANDS REGION

```
  Date: 1976/ 1/ 1   Centroid
Time:  1:29:53.4 GMT
  Lat= -29.25  Lon=-176.96
  Depth= 47.8   Half duration=
9.4
  Centroid time minus hypocenter
time: 13.8
  Moment Tensor: Expo=26  7.680
0.090 -7.770 1.390 4.520 -3.260
  Mw = 7.3    mb = 6.2    Ms =
0.0   Scalar Moment = 9.56e+26
  Fault plane:  strike=202
dip=30   slip=93
  Fault plane:          =18
dip=60   slip=88
```



**Earthquake Magnitude Controversy**:

Seismologists use a **Magnitude** scale to express the seismic energy released by each earthquake.

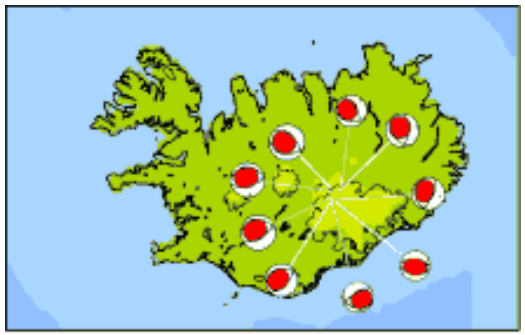
People keep saying Richter magnitude, but it is really not a very helpful in terms of understanding sources.

# Earthquake Focal Mechanisms

**Figure 4.4-6: Selected moment tensors and their associated focal mechanisms.**

| Moment tensor | Beachball | Moment tensor | Beachball |
|---|---|---|---|
| $\frac{1}{\sqrt{3}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}$ |  | $-\frac{1}{\sqrt{3}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&1\end{pmatrix}$ |  |
| $-\frac{1}{\sqrt{2}}\begin{pmatrix}0&1&0\\1&0&0\\0&0&0\end{pmatrix}$ |  | $\frac{1}{\sqrt{2}}\begin{pmatrix}1&0&0\\0&-1&0\\0&0&0\end{pmatrix}$ |  |
| $\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&-1\\0&0&0\\-1&0&0\end{pmatrix}$ |  | $\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&0\\0&0&-1\\0&-1&0\end{pmatrix}$ |  |
| $\frac{1}{\sqrt{2}}\begin{pmatrix}-1&0&0\\0&0&0\\0&0&1\end{pmatrix}$ |  | $\frac{1}{\sqrt{2}}\begin{pmatrix}0&0&0\\0&-1&0\\0&0&1\end{pmatrix}$ |  |
| $\frac{1}{\sqrt{6}}\begin{pmatrix}1&0&0\\0&-2&0\\0&0&1\end{pmatrix}$ |  | $\frac{1}{\sqrt{6}}\begin{pmatrix}-2&0&0\\0&1&0\\0&0&1\end{pmatrix}$ |  |
| $\frac{1}{\sqrt{6}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&-2\end{pmatrix}$ |  | $-\frac{1}{\sqrt{6}}\begin{pmatrix}1&0&0\\0&1&0\\0&0&-2\end{pmatrix}$ |  |

Example of 'Fried Egg' Earthquakes



The last two rows are usual mechanisms that are related to CLVD components, that is, the sum of two smaller elements are exactly the same as the third. This corresponds to tensile crack, etc.

# Examples of irregular earthquakes

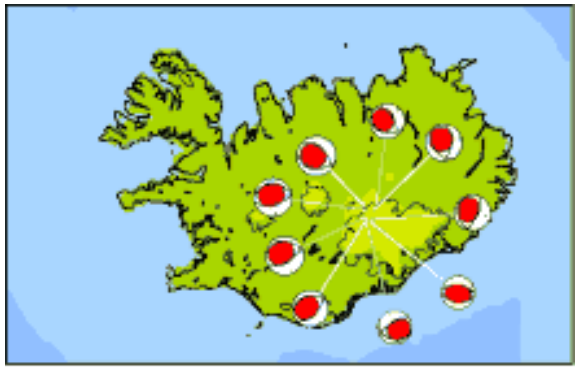
CLVD (compensated Linear Vector Dipole)

**Possible explanations:**

(1) deflating magma chamber in cone-shaped setting

(2) A combination of two pure double-couple earthquakes.

Iceland Bargabunga Volcano

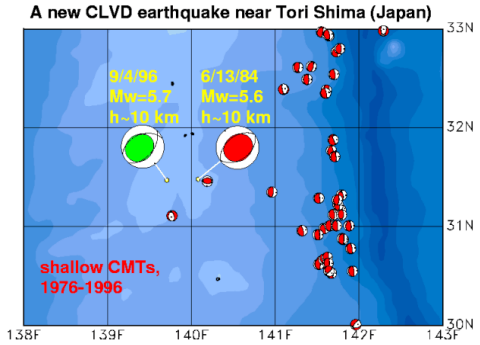


**Nettles and Ekstrom, 03**

$$\begin{pmatrix} M_0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & -M_0 \end{pmatrix} + \begin{pmatrix} 0 & 0 & 0 \\ 0 & -2M_0 & 0 \\ 0 & 0 & 2M_0 \end{pmatrix} = \begin{pmatrix} M_0 & 0 & 0 \\ 0 & -2M_0 & 0 \\ 0 & 0 & M_0 \end{pmatrix}$$

In this case, the first is a pure double-couple, with two non-zero diagonal elements

Essence: Curved fault plane that is represented by two straight segments



# Earthquake magnitudes

***What is the size of an earthquake?***

**Two approaches:**

**(1) Intensity** – mostly qualitative

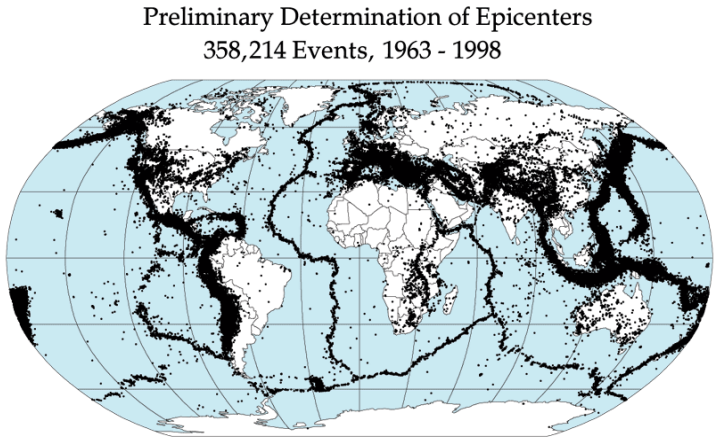
• describes the actual shaking that occurs at a site

• depends on:

- earthquake rupture processes
- distance from earthquake
- local conditions (geology, building structure)

**(2) Magnitude** – quantitative

• based on the amplitude of the seismic waves that are produced by fault slip




(http://en.wikipedia.org/wiki/Earthquake)

# Earthquake intensity: Mercalli intensity scale

| 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/subcontent.aspx?id=740)

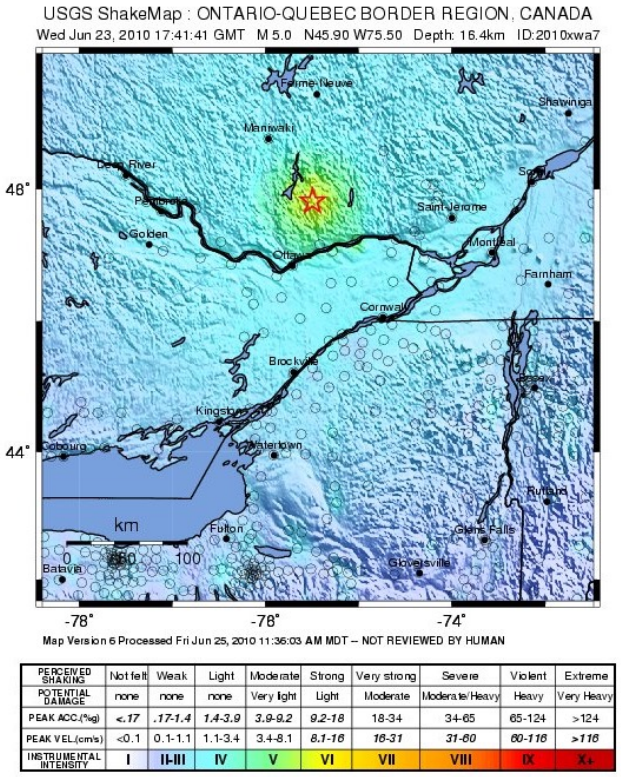
# Shakemap

(http://earthquake.usgs.gov/eqcenter/shakemap/)

• ground motion and shaking intensity based on instrument readings – near real-time

**2010-06-23: Near Ottawa**

Shake map is used to determine building code, which is the government mandated code during construction, i.e., each building has to be constructed to withstand a certain or magnitude earthquakes.

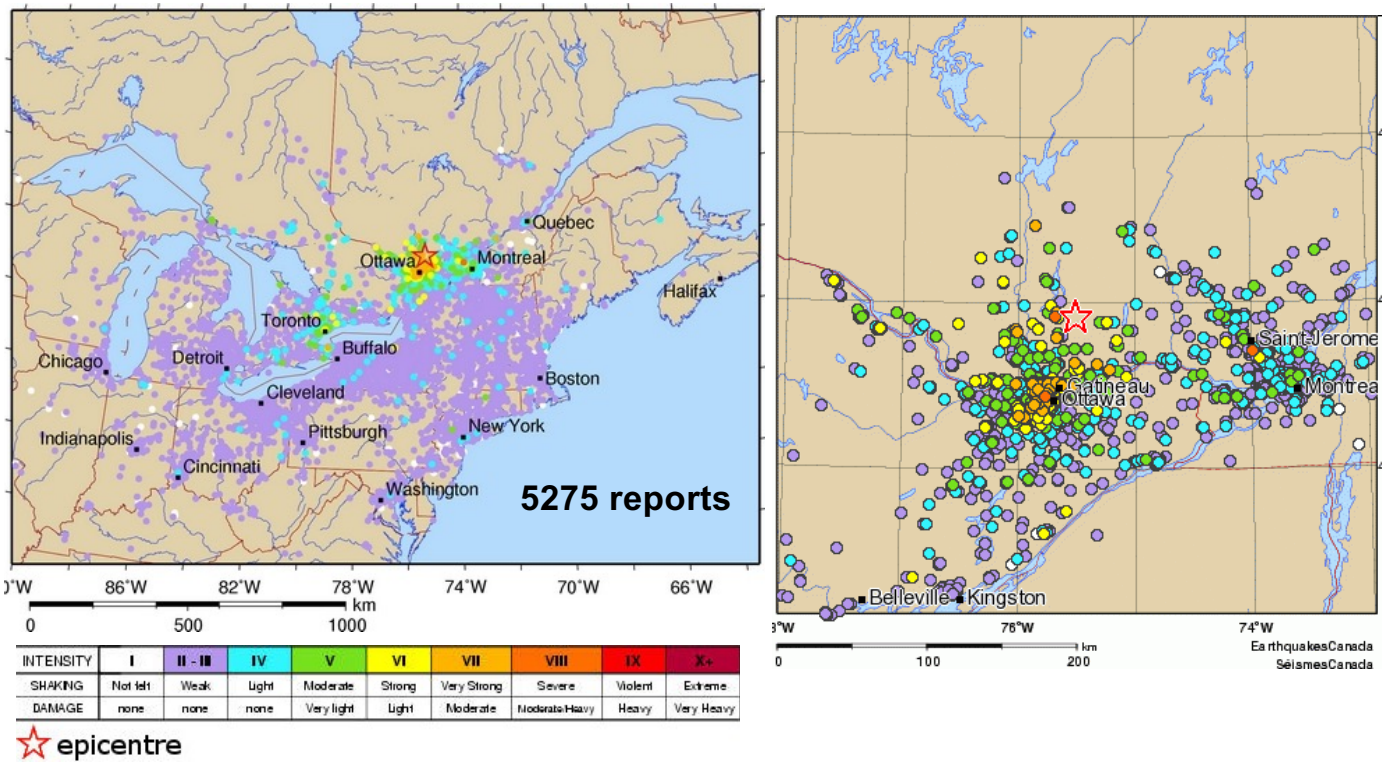


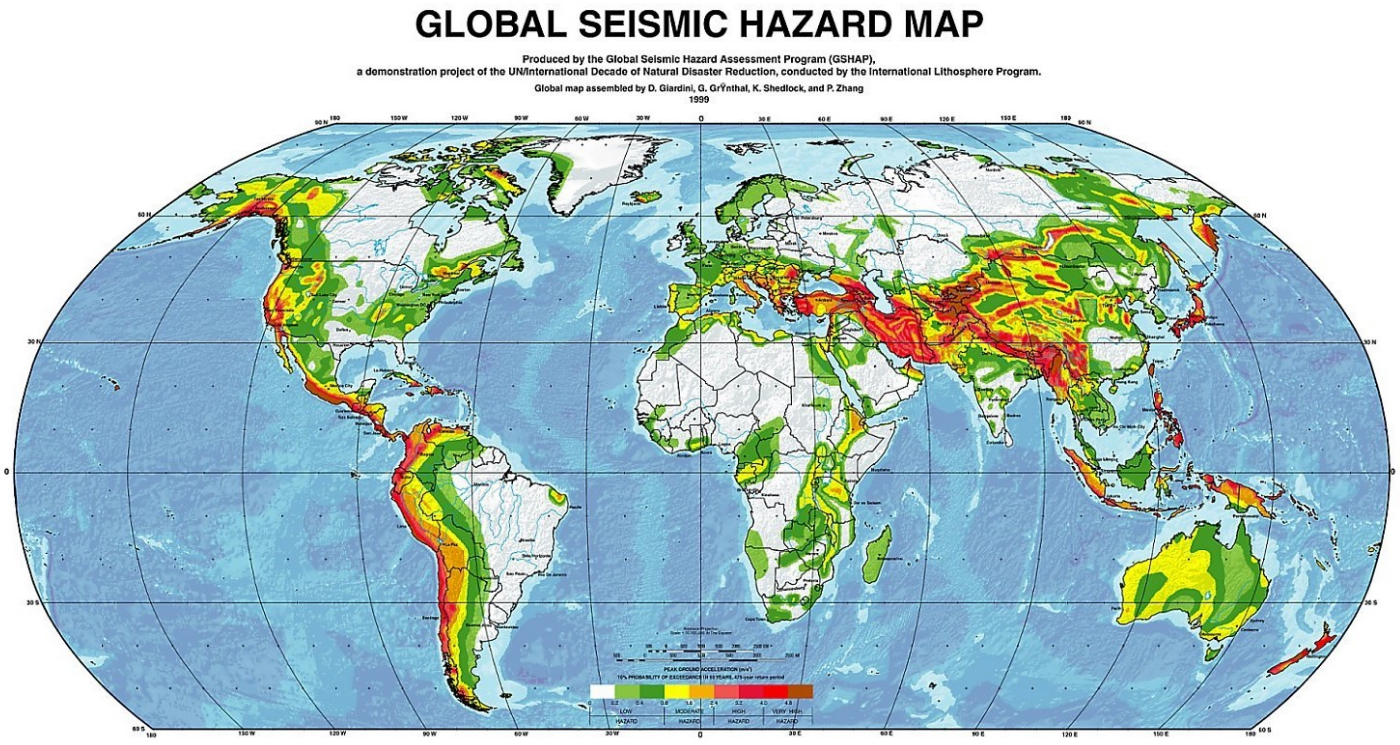

| PERCEIVED SHAKING | Not felt | Weak | Light | Moderate | Strong | Very strong | Severe | Violent | Extreme |
|---|---|---|---|---|---|---|---|---|---|
| POTENTIAL DAMAGE | none | none | none | Very light | Light | Moderate | Moderate/Heavy | Heavy | Very Heavy |
| PEAK ACC.(%g) | *<.17* | *.17-1.4* | *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+ |

# Internet questionnaires

CANADA: http://earthquakescanada.nrcan.gc.ca/dyfi-lavr/list-liste-eng.php

**2010-06-23: Near Ottawa**






- gives the probability of a given level of ground shaking
  - reflects proximity to earthquakes and local geology
- on this map (from 1999): 10% probability of peak ground acceleration (horizontal, $m/s^2$) over the next 50 years
- used for building codes

(http://www.seismo.ethz.ch/GSHAP/)

# Earthquake magnitude (quantitative)

- reflects energy released by fault slip
- magnitude is a characteristic of the earthquake itself
- an earthquake has only **one magnitude** (of a given type)
    - it is **not correct** to say that an earthquake was a “magnitude 6” in one location and a “magnitude 4” at another location
- the **intensity** can vary with location (distance from earthquake), but the magnitude does not
- all magnitudes are based on logarithmic scales
- most use the measured amplitude of seismic waves

Gutenberg-Richter Scale (1935) - a local scale for Southern California - based on the amplitude of ground vibrations he observed -he needed something to tell the Press! Worth noting that these magnitude curves are completely empirical measures.



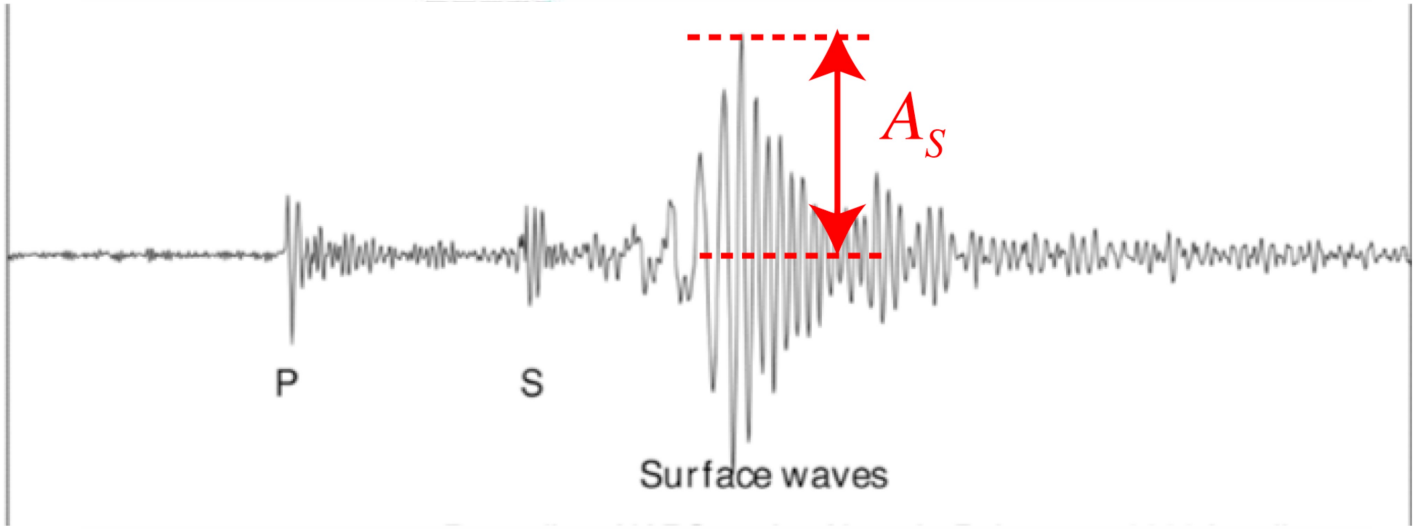
## (1) Surface wave magnitude ($M_S$)

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

- maximum horizontal amplitude of Rayleigh waves (17-23 s period)
- $A_S$ = observed amplitude in microns ($10^{-6}$ m)
- $\Delta$ = angular distance from the earthquake (in degrees, not km)
- provides a good assessment of ground shaking
- best suited for shallow earthquakes (<50 km depth)



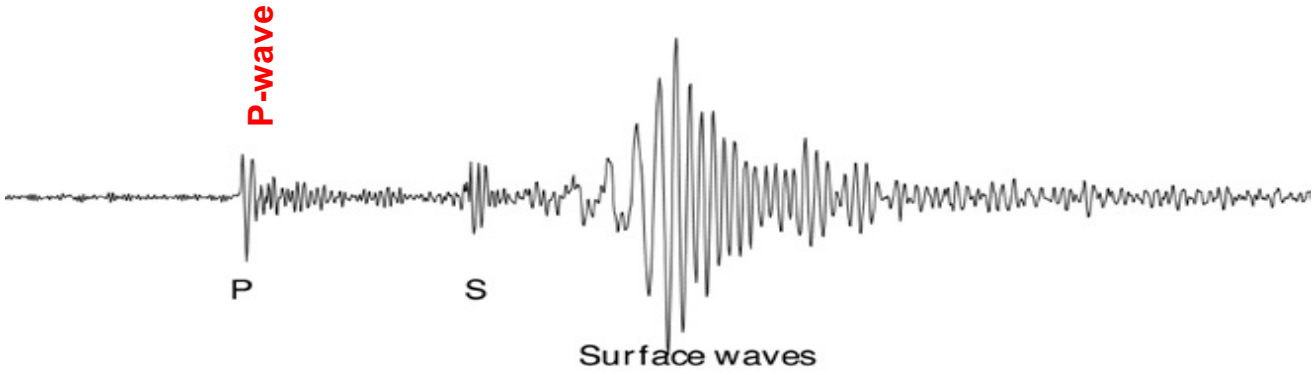
# Maximum Amplitude of Ground Shaking Determines Richter Magnitude



## (2) Body wave magnitude ($m_b$)

$$m_b = \log_{10}\left(\frac{A}{T}\right)_{max} + 0.01\Delta + 5.9$$

- maximum amplitude of body waves – usually P-waves (1-5 s period)
- have a correction for distance, $\Delta$ = distance in degrees
- better suited for deep earthquakes
- but body waves have a low amplitude – can be hard to measure amplitude



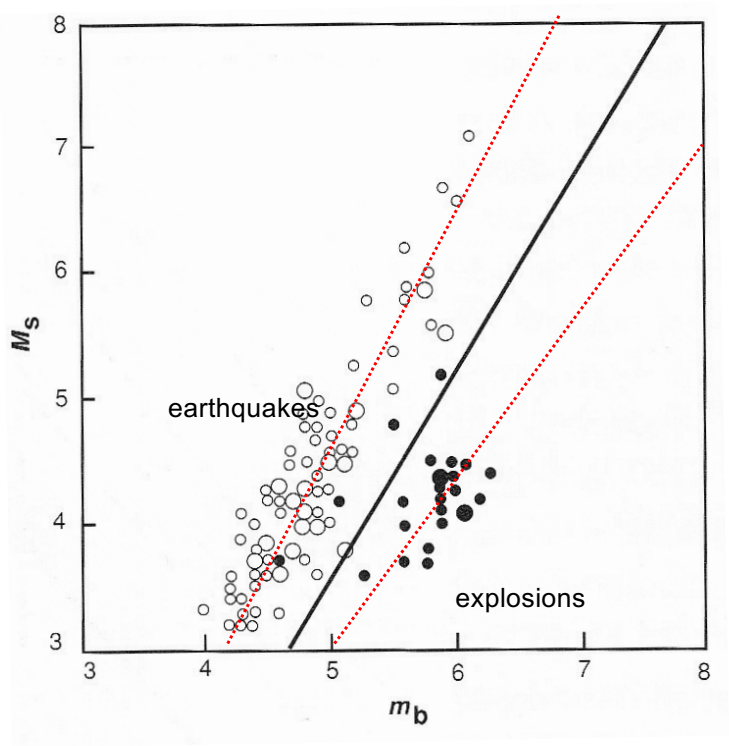
## Comparison of $M_S$ and $m_b$

- $M_S$ – uses surface wave amplitudes
- $m_b$ – uses body wave amplitudes

→ $M_S$ and $m_b$ can be different for the same earthquake

- but larger earthquakes will have a large $M_S$ and a large $m_b$
- an empirical relationship is:

$$m_b = 0.55M_S + 2.94$$



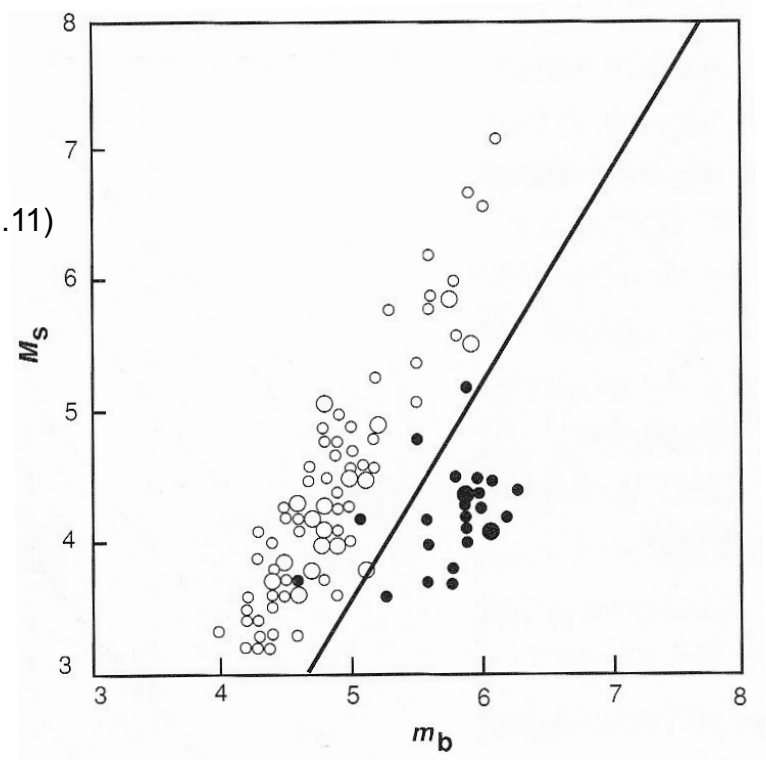

(Fowler – Fig 4.11)

# (3) Richter magnitude ($M_L$)

- L = local magnitude scale
- Richter magnitude was developed for use in California
- based on the largest displacement recorded on a specific type of seismometer (a Wood-Anderson torsion seismometer)
- it is **not applicable** to other regions
- it is still used but not commonly (contrary to media reports)
- many regions have defined a local magnitude scale ($M_L$) for quantifying the size of local earthquakes

# (4) Seismic moment and moment magnitude

(Fowler – Fig 4.11)




• limitations of scales based on amplitude of specific seismic waves:

1. only one aspect of the earthquake rupture is used
2. these scales saturate for large earthquakes

– as earthquake size increases, more energy is released at long periods

→ amplitude of short period energy will underestimate the earthquake size

$m_b$ saturates at magnitudes of 5.5-6.0

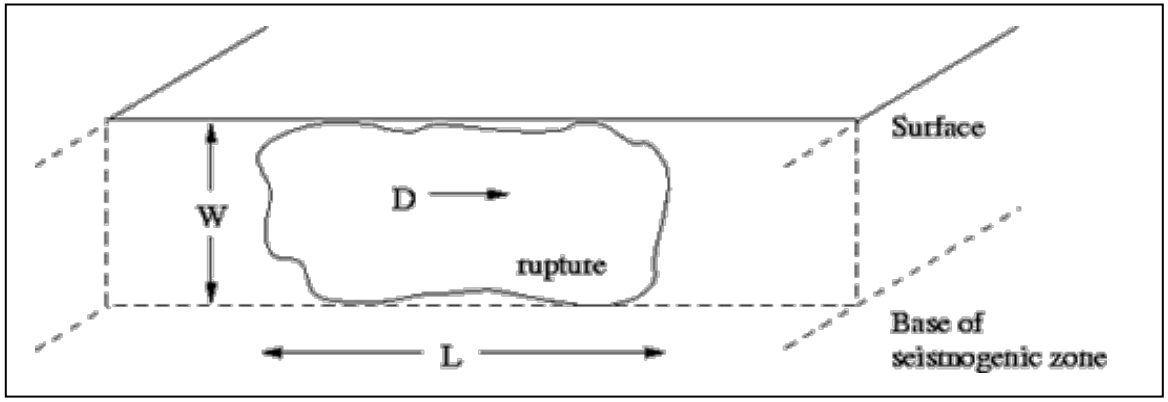
$M_S$ saturates at magnitudes of about 8.0.

Rupture length (L) and amount of slip (D) can be measured using observations of surface rupture. **The moment magnitude** is solved based on seismic moment at the source, which is NOT based on P/S/surface wave amplitude at a station.

## (4) Seismic moment and moment magnitude

- more complete measure of earthquake magnitude:

→ relate energy released in an earthquake to amount of fault slip




**Seismic moment** is defined as: $M_0 = \mu DA$ (in N m or J)

where

A is the area of fault-plane that slips during the earthquake (A=LW)

D is the amount of slip

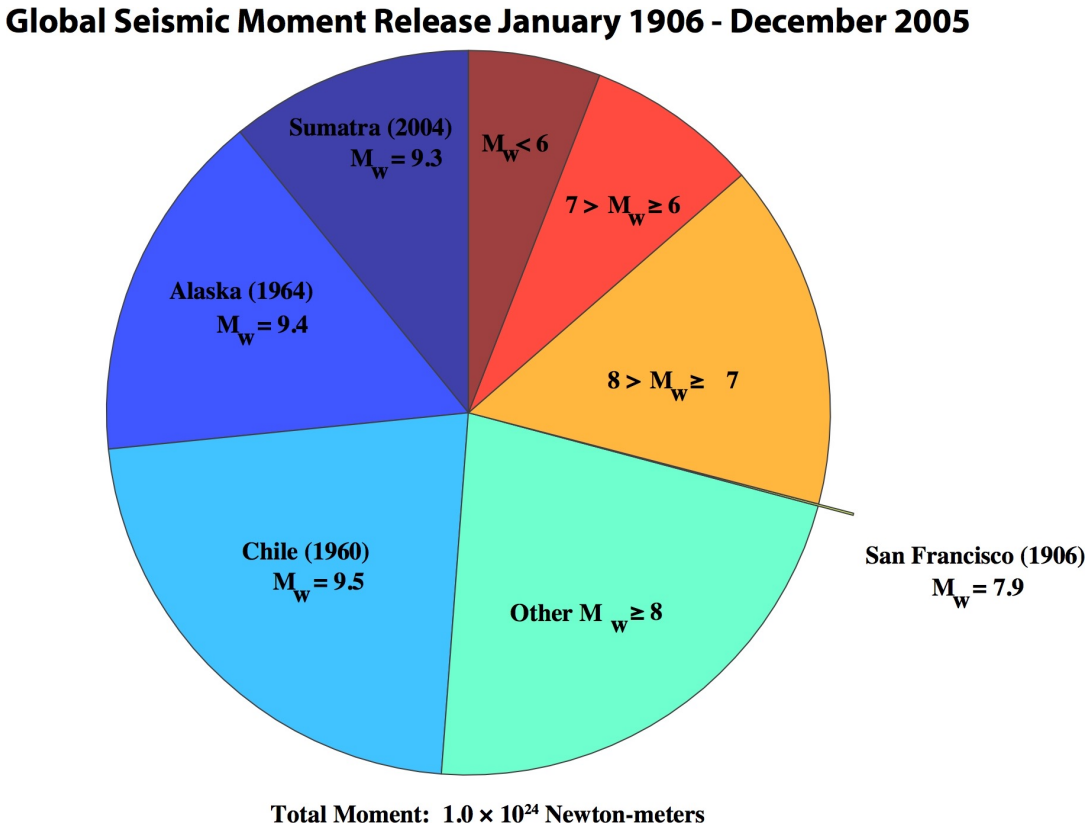
μ is the shear modulus of the fault material (material property), in Pascas (Pa, or kPa, or mPa)

The **moment magnitude** is: $M_W = \frac{2}{3}\log_{10} M_0 - 6.0$

# Energy released by earthquakes

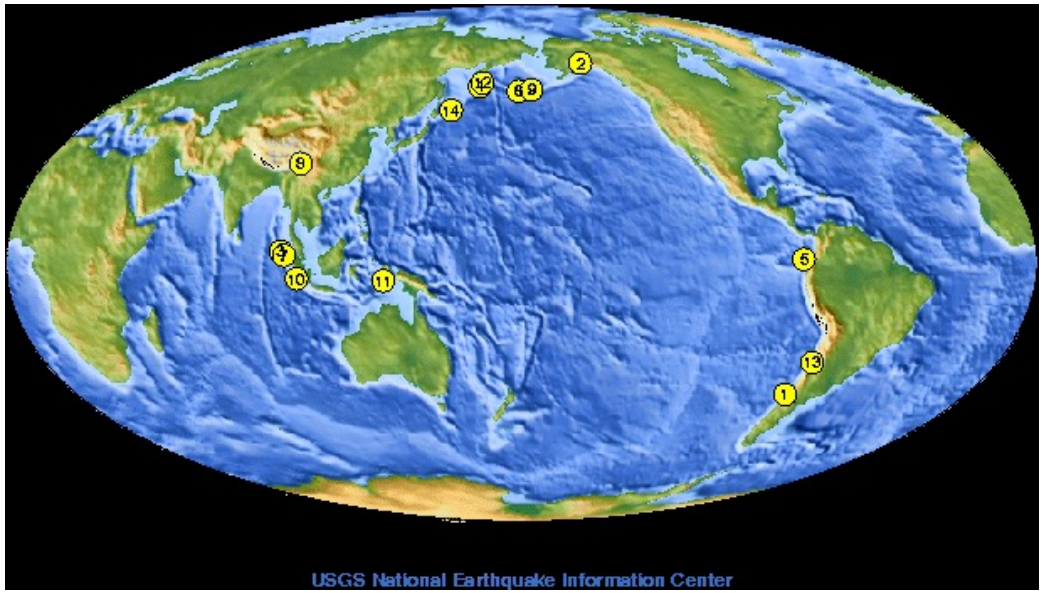
**Energy release is not uniform:**

- 75-80% in circum-Pacific region
- 15-20% in Alpine-Himalayan belt
- 3-7% at mid-ocean ridges
- 1% in intraplate earthquakes n (but **has increased since 2010 due to 'induced quakes**')



# Largest earthquakes since 1900 up to 2014

| | | | | | | | |
|---|---|---|---|---|---|---|---|
| 1. | Chile | $M_W$=9.5 | 1960 | 8. | Assam - Tibet | $M_W$=8.6 | 1950 |
| 2. | Alaska | $M_W$=9.2 | 1964 | 9. | Andreanof Island, AK | $M_W$=8.6 | 1957 |
| 3. | Sumatra | $M_W$=9.1 | 2004 | 10. | Banda Sea | $M_W$=8.5 | 1938 |
| 4. | Kamchatka | $M_W$=9.0 | 1952 | 11. | Southern Sumatra | $M_W$=8.5 | 2007 |
| 5. | Ecuador | $M_W$=8.8 | 1906 | 12. | Kamchatka | $M_W$=8.5 | 1923 |
| 6. | Rat Islands, Alaska | $M_W$=8.7 | 1965 | 13. | Chile-Argentina | $M_W$=8.5 | 1922 |
| 7. | Northern Sumatra | $M_W$=8.6 | 2005 | 14. | Kuril Islands | $M_W$=8.5 | 1963 |




(http://earthquake.usgs.gov/regional/world/10_largest_world.php)

# Frequency-magnitude relationship

There are more small earthquakes than large earthquakes.

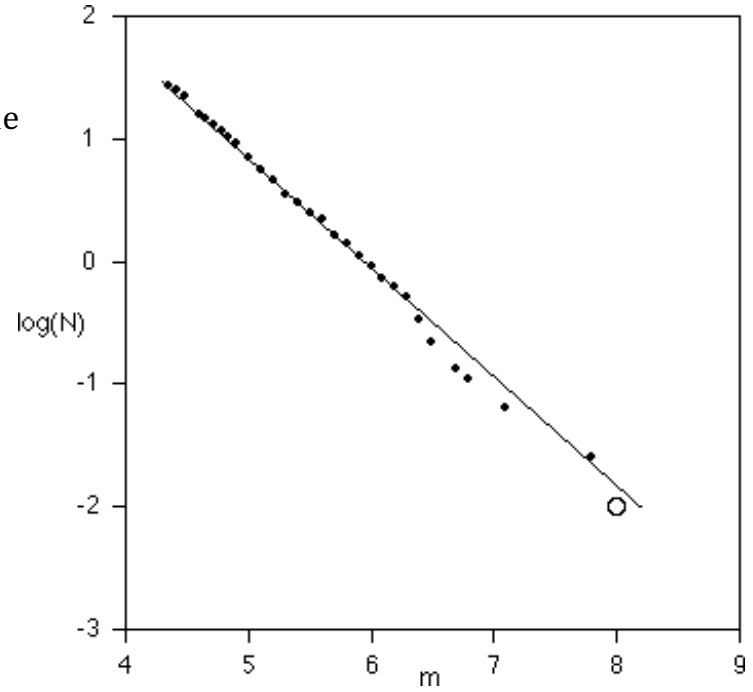
GLOBAL AVERAGES:

| 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 |

(Table from Fowler)

There is a similar distribution of earthquakes within smaller regions.

# Frequency-magnitude relationship for southern California (1932-1972)




- plot of the number of earthquakes per year that exceed a given magnitude
- observe a straight line
- departures from a straight line for **M > 6**
  - reflects relative short catalogue length (40 years) – not long enough to record a statistically significant number of large (infrequent) earthquakes
- this is observed in other regions
- can described empirically by the **Gutenberg-Richter Law**:

$$\log N = a - bM_S$$

- $N$ is number of events each year that exceed magnitude $M_S$
- $a$ and $b$ are empirical constants
- globally: $b$ =1