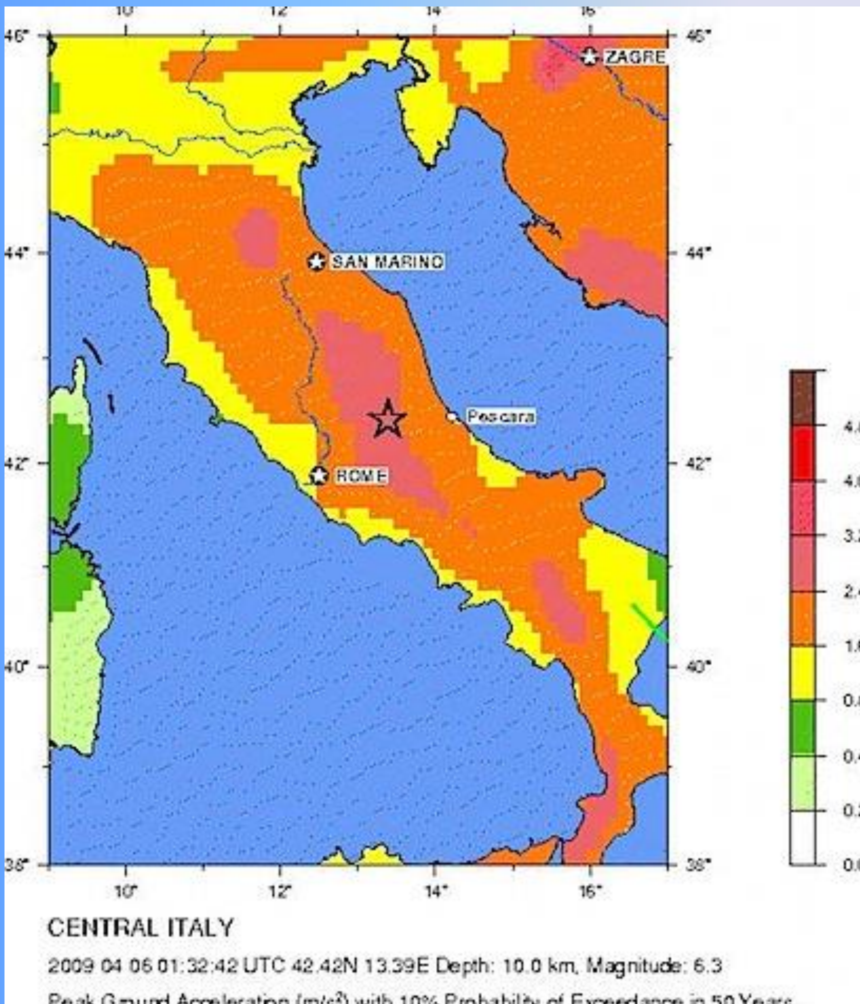

Earthquakes
1995 Kobe, Japan

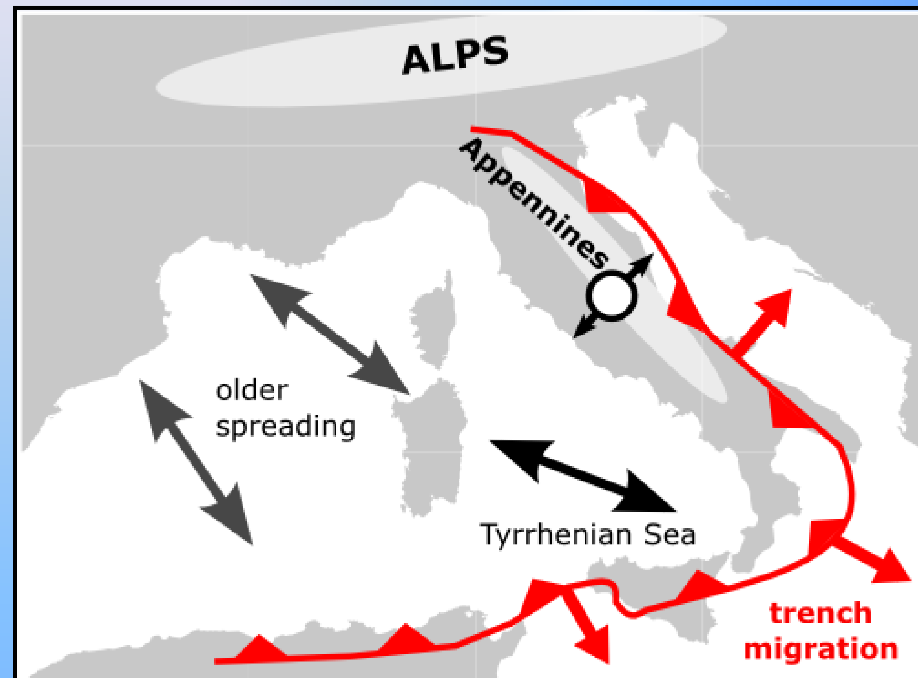
L'Aquila, Italy – April 6, 2009



- 6.3 Mw intensity
- At least 227 fatalities
- 1,000 injured
- Felt throughout central Italy




Apennine Mountain Belt



- Apennines – Formed by subduction
- The April 6th earthquake is related to normal faulting and east-west extensional tectonics
  - Caused by the Tyrrhenian basin opening faster than compression between the Eurasian and African plates

Causes of Earthquakes

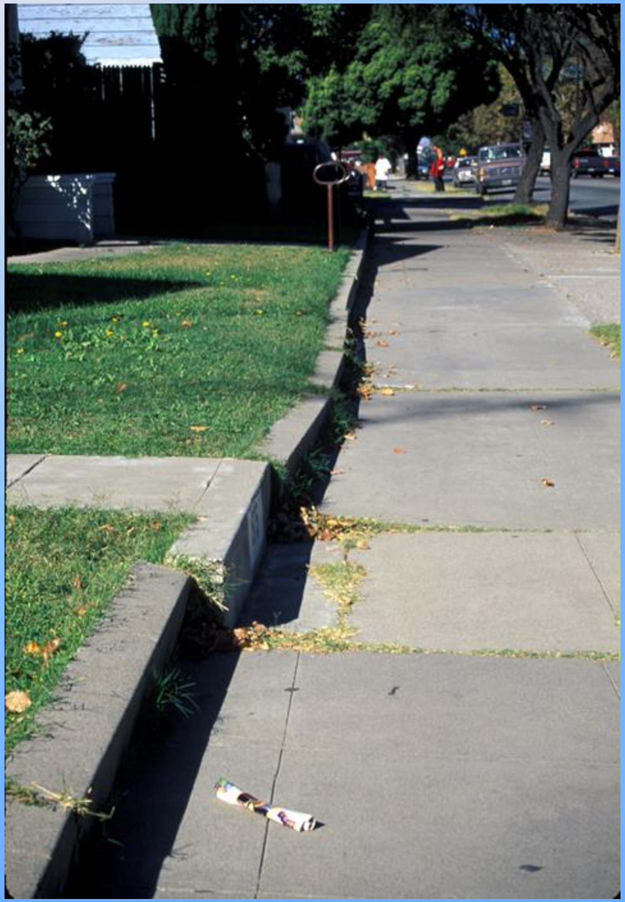
- **What is an earthquake?**
  - An earthquake is the trembling or shaking of the ground caused by the sudden release of energy from the rocks in Earth’s subsurface.

Large Releases of Energy Accompany . . .

1. Volcanic Eruptions

2. Explosions

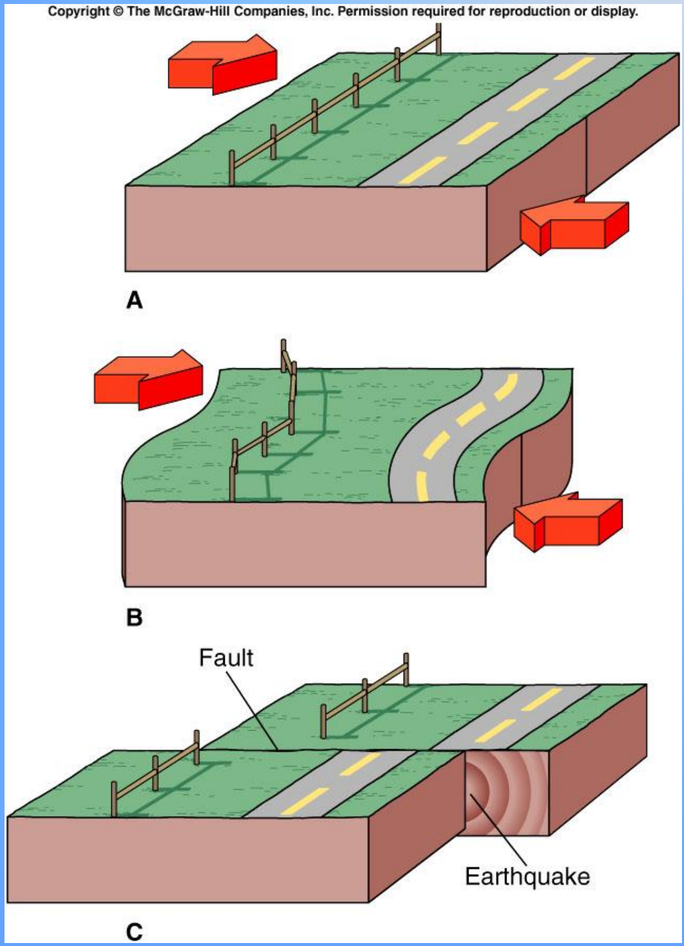
3. Crustal movement along faults

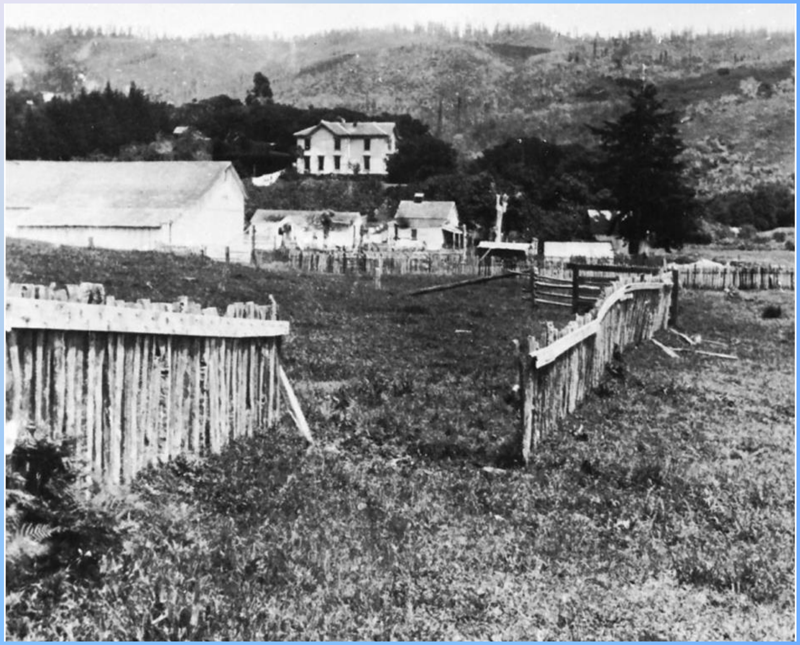


Causes of Earthquakes

A. Elastic Rebound Theory

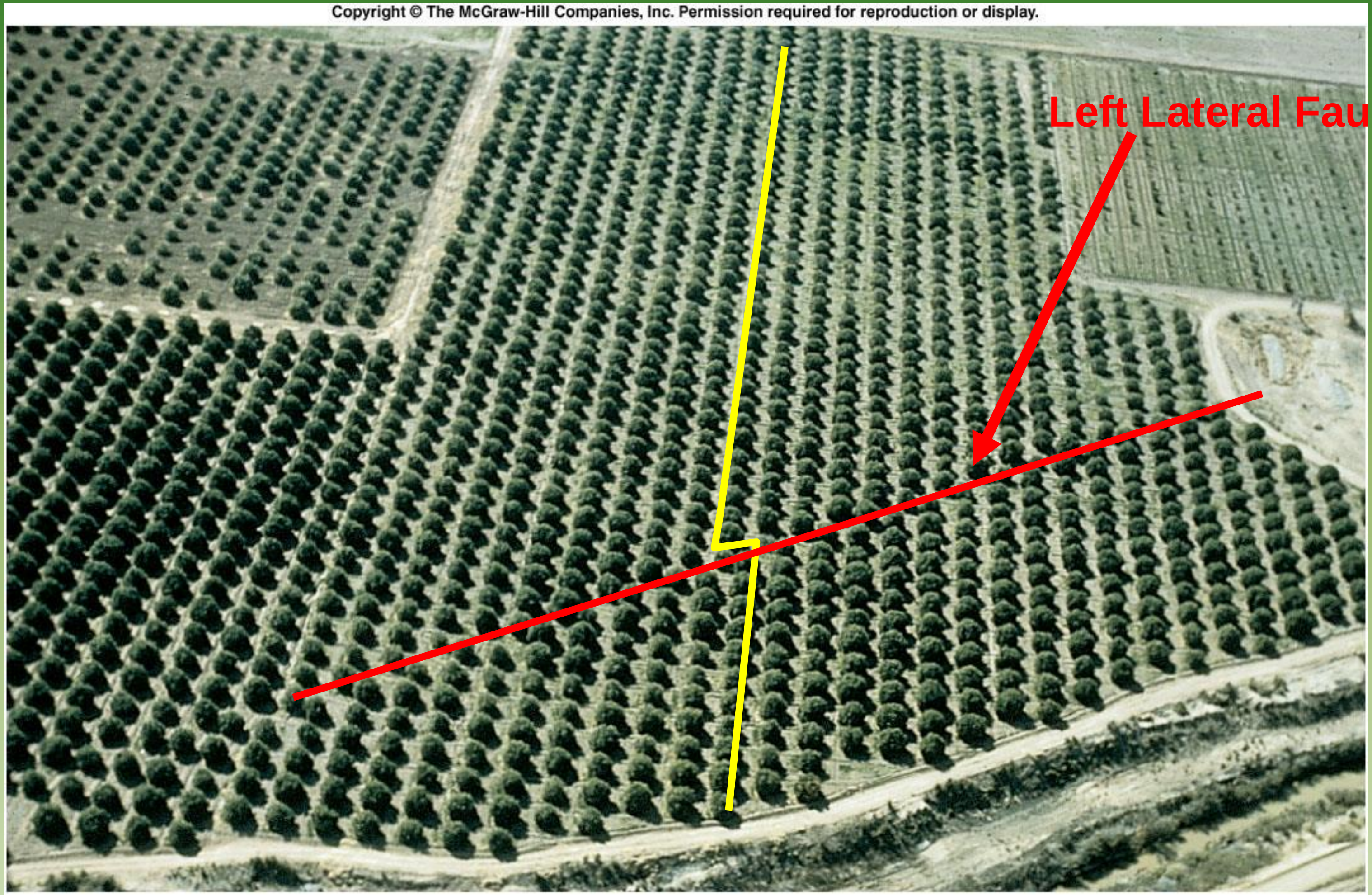
- Sudden release of progressively stored strain





- **Tectonic forces act on a rock over a long period of time**
- **Stored energy exceed the rock's strength**
- **Rock suddenly breaks, causing an earthquake**

Horizontal Displacement



Trees in an orchard, 1979, El Centro, CA

B. Faults

- **The most common source of earthquakes felt by people**

- Fault motions don't necessarily break the surface.
  - **Recent California earthquakes are related to buried thrust faults.**
  - **Eastern U.S. earthquakes have no surface displacement**
- Faults cause *hazards.*

Scarp caused by the Denali fault earthquake in Alaska, November 3, 2002

C. Weak Fault Model Theory

- New theory that faults are weak and only need small stress to cause and earthquake.
- Conflicts with traditional theory that faults are strong and very large stress is necessary to break rocks.

D. Mineral Transformation Theory

- Cause of deep quakes associated with *subduction*
- Explains how cold, subducting rock breaks
  - Under high temperature and pressure it should behave in a ductile manner.
- Pressure causes minerals to collapse into denser forms along fractures

Seismic Waves

Vibrations caused by energy released by an earthquake

A. Origin

1. ___Focus___________

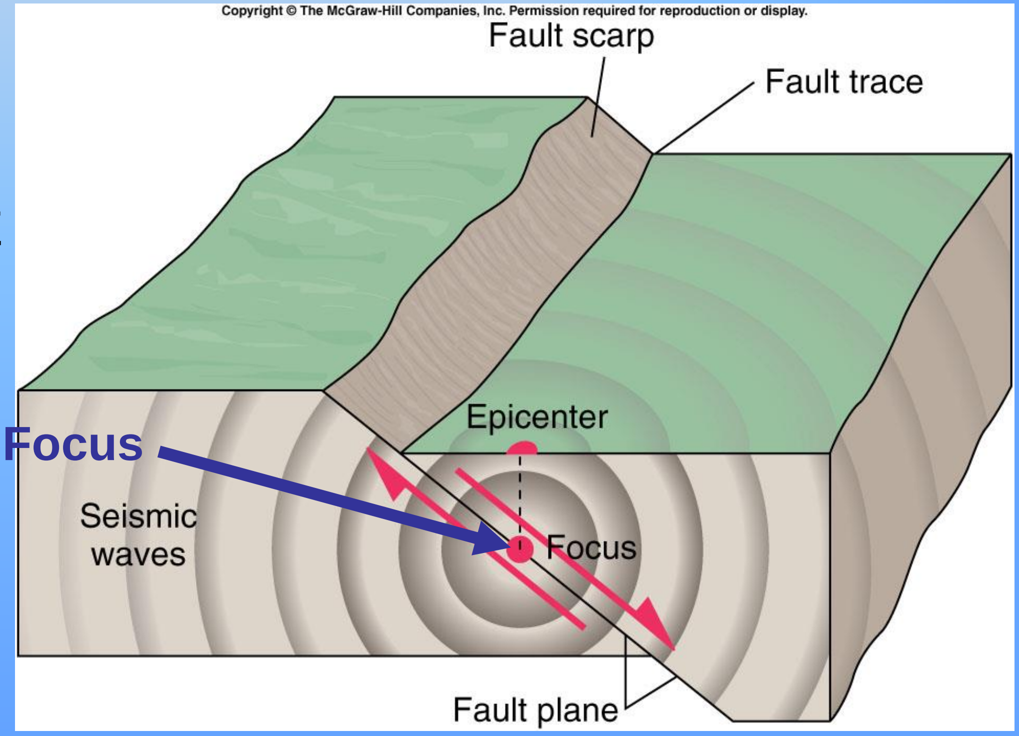
   a. Also called the ___hypocenter___________

   b. The point of ___origin___ of an earthquake

   c. The center of an earthquake

   d. Seismic waves radiate outward

   e. Intensity is greatest near the focus

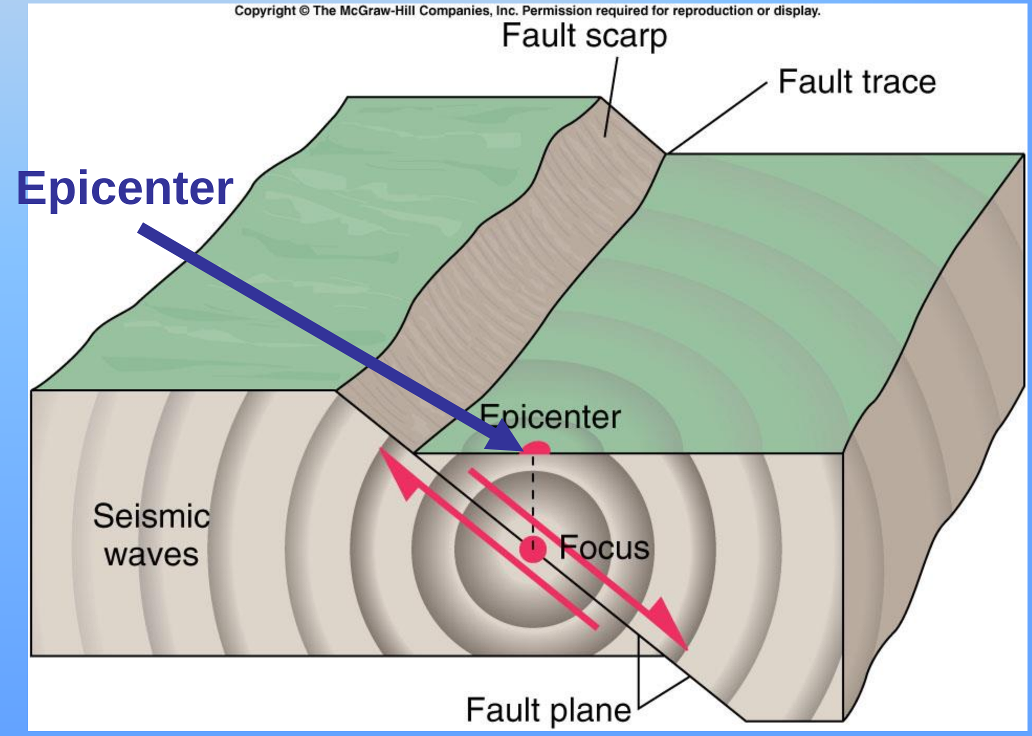


2. **Epicenter**

a. The on **Earth's surface directly above the focus**.

b. Often the location of **greatest damage** .

c. The center of an earthquake



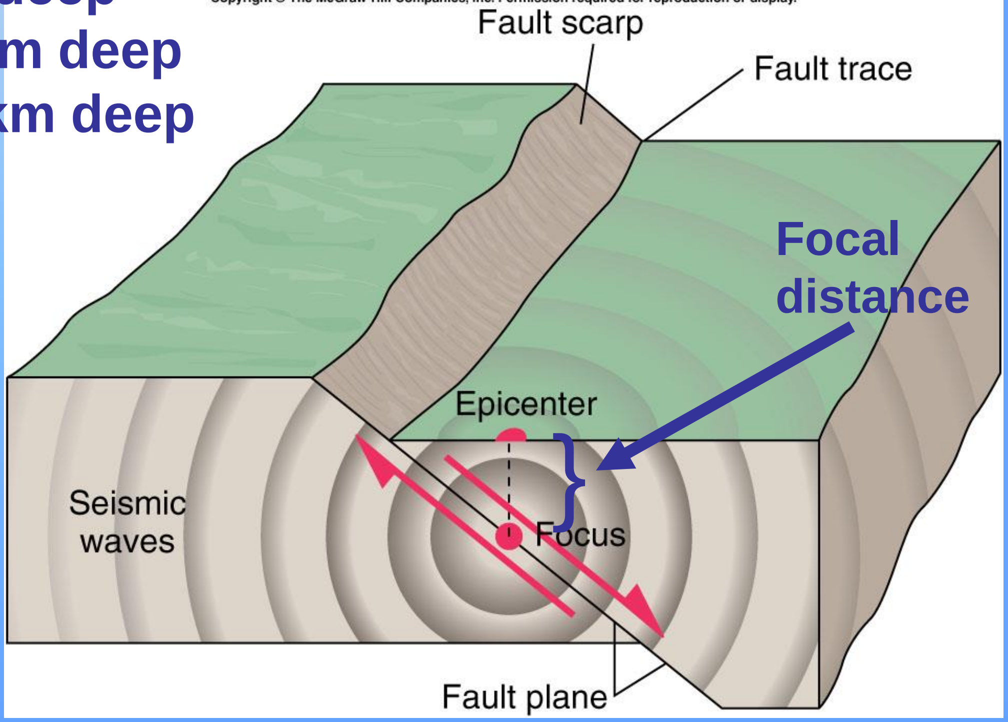
3. Depth of Focus

- Also called the focal distance or hypocenter distance.

a. The distance between the focus and **epicenter**

b. Maximum depth is about 670 km

- **Shallow Focus: 1 – 70 km deep**
- **Intermediate Focus: 70 – 350 km deep**
- **Deep Focus: 230 – 670 km deep**



Types of Seismic Waves

1. __Body__ Waves

a. Seismic waves that travel within Earth's subsurface

b. Two types of Body Waves

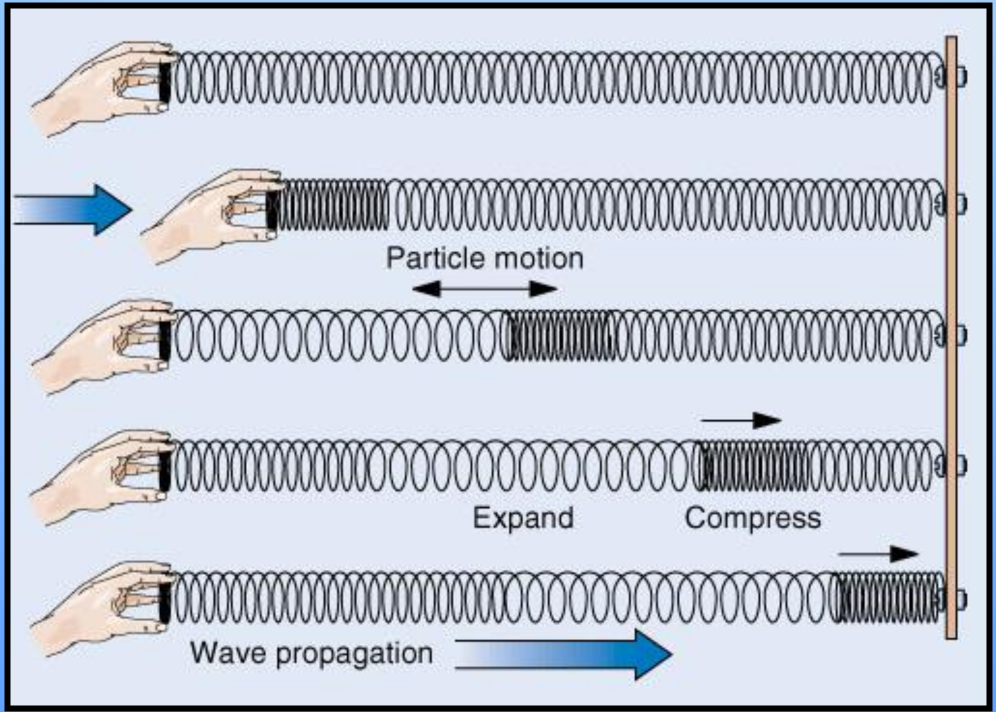
i. P - Wave (Primary Wave)

(a) Compressional Wave

(b) Rock particles vibrate back and forth parallel to the direction of wave propagation.

(c) Travel very fast (4 to 7 km/sec (9,000 to 15, 000 mph) and is the first to reach a recording station following an earthquake

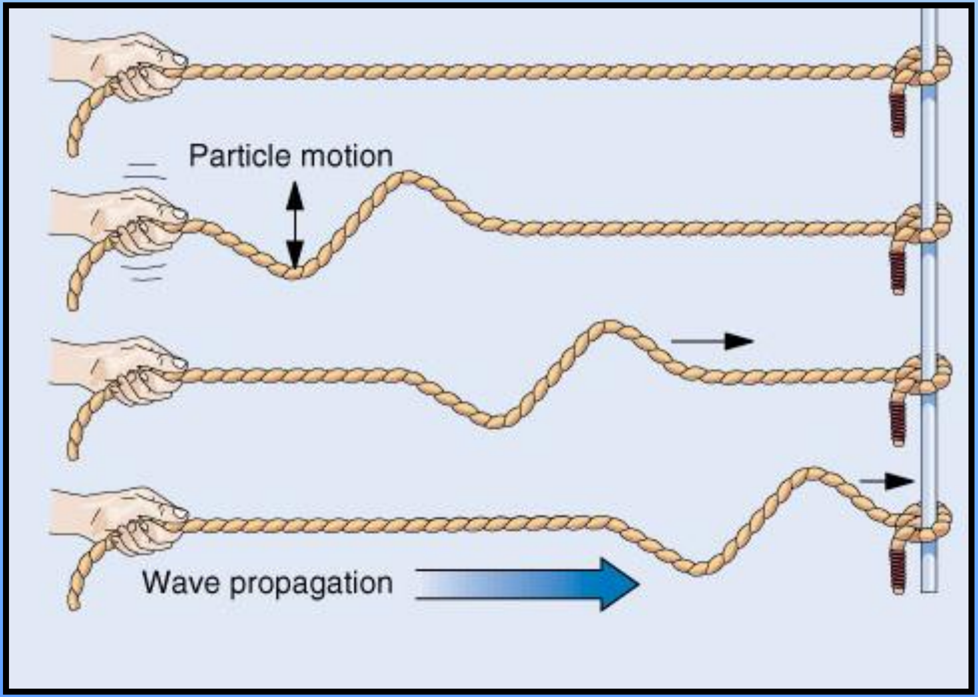
(d) Can travel through all three phases of matter.



ii. S - Wave (Secondary Wave)

(a) Transverse *Wave* generated by shearing motion.

- Rock particles vibrate at right angles to the direction of wave propagation.
- Travels slower than a P Wave (2 to 5 km/sec.)
- Easily travels through solid rock but *will not* be transmitted through fluids (liquids and gases).



2. ___Surface___ Waves

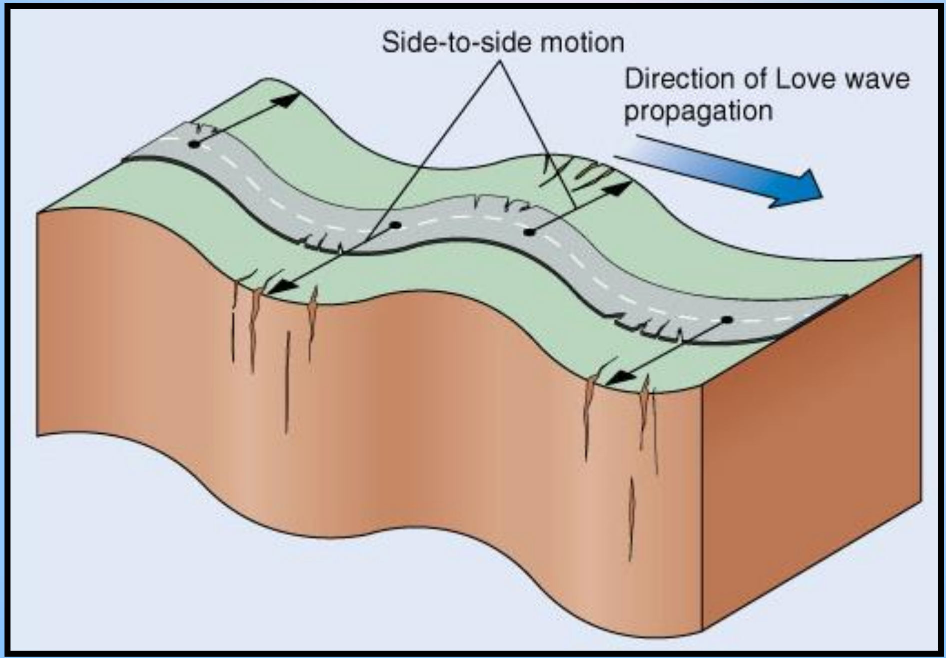
a. The___slowest___waves generated by earthquakes

b. Responsible for more ___damage___ because they:

   i. produce more ground movement

   ii. travel more slowly than body waves

i Love Waves



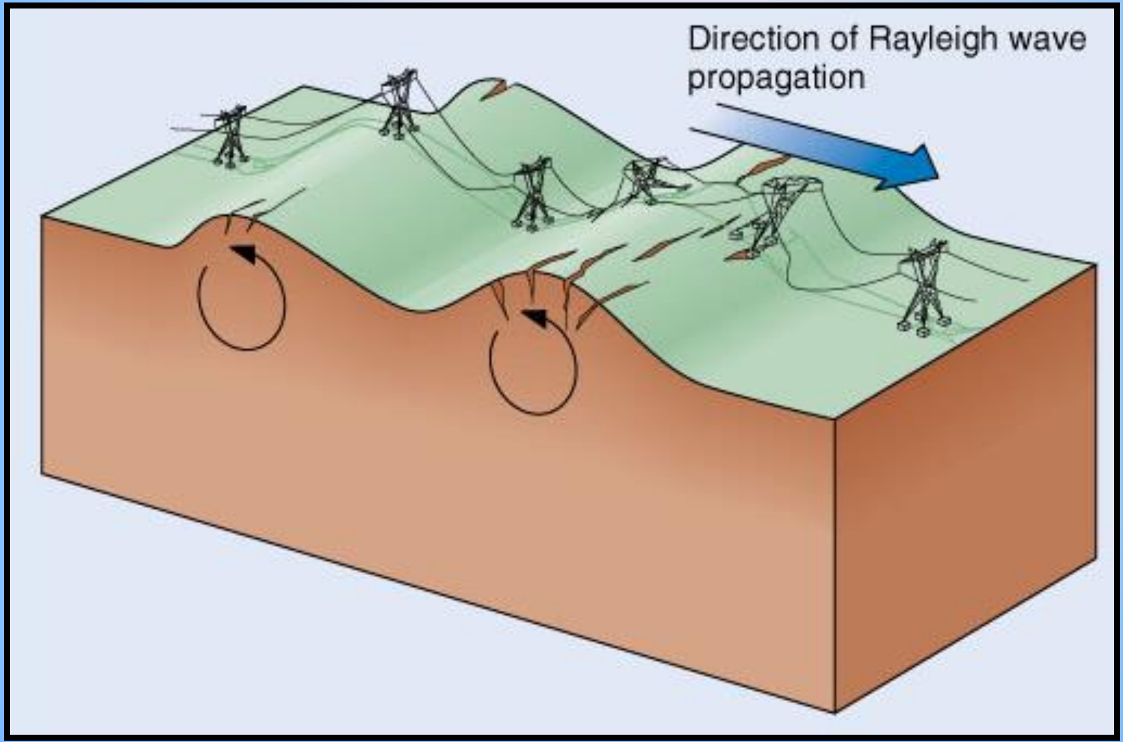
(a) No ___vertical___ displacement

(b) Ground moves ___side to side___ in a horizontal plane at right angles to the direction of wave travel.

(c) The horizontal movement is responsible for knocking buildings off their foundations and for the destruction of highway bridge supports.

(d) Do not travel through water.

ii. Rayleigh Waves



(a) Behave like rolling ______ocean______ waves

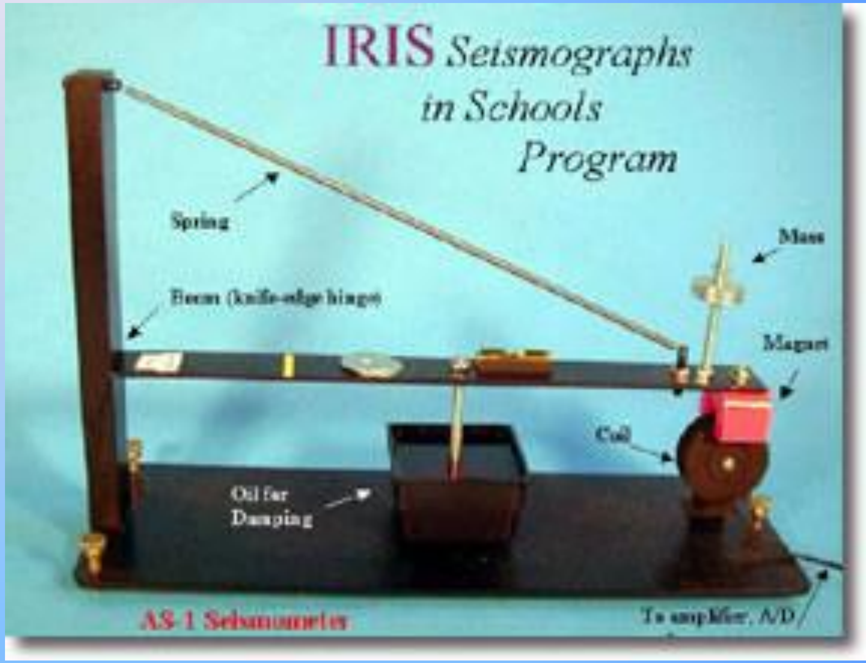
(b) Ground moves in an ____elliptical____path opposite the direction the wave passes (unlike ocean waves where the elliptical movement is the other way)

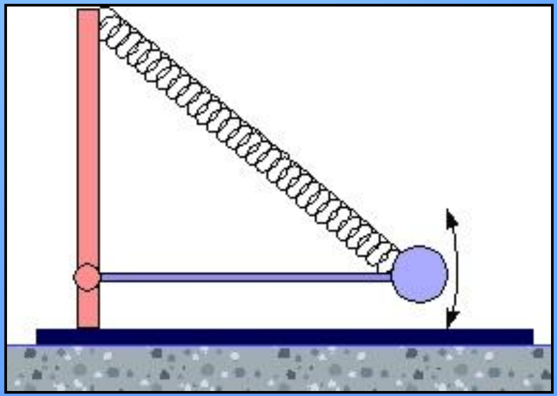
(c))The cause great ground movement and are slower than Love waves. As a result, they are very destructive to buildings.

A. Instruments Used to Measure Seismic Waves

1. **Seismometer**

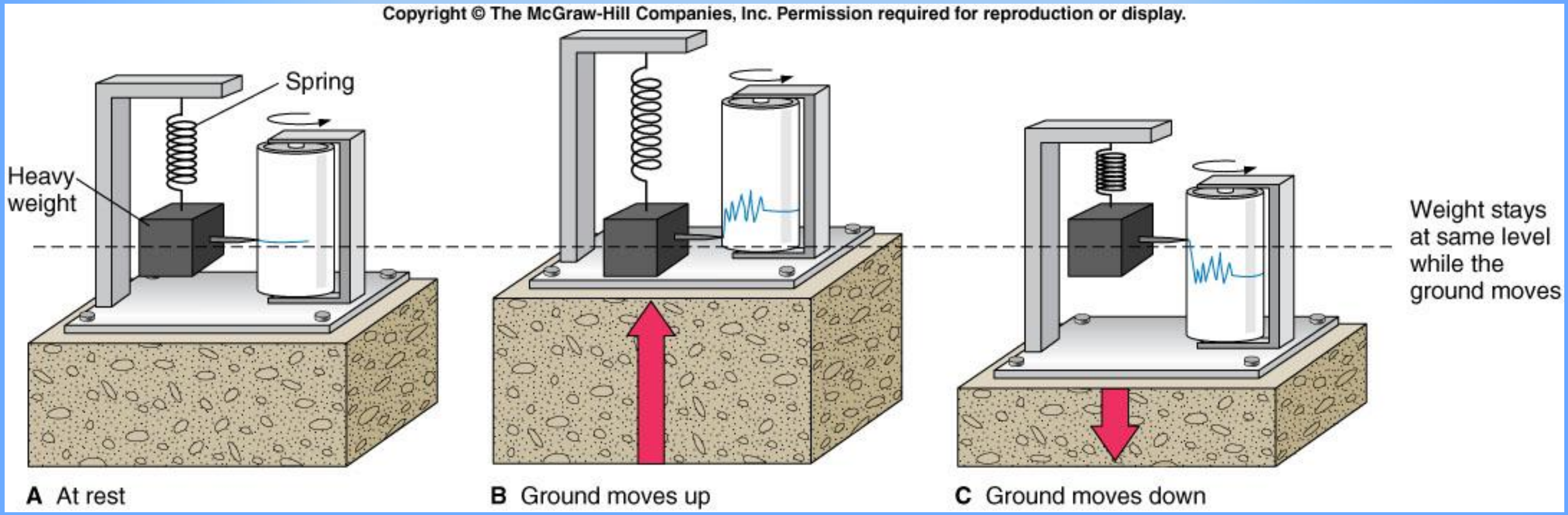
- Heavy weight suspended from a frame by springs
  - Remains motionless due to inertia
  - Point of reference for ground motion
- Can measure vertical or horizontal motion



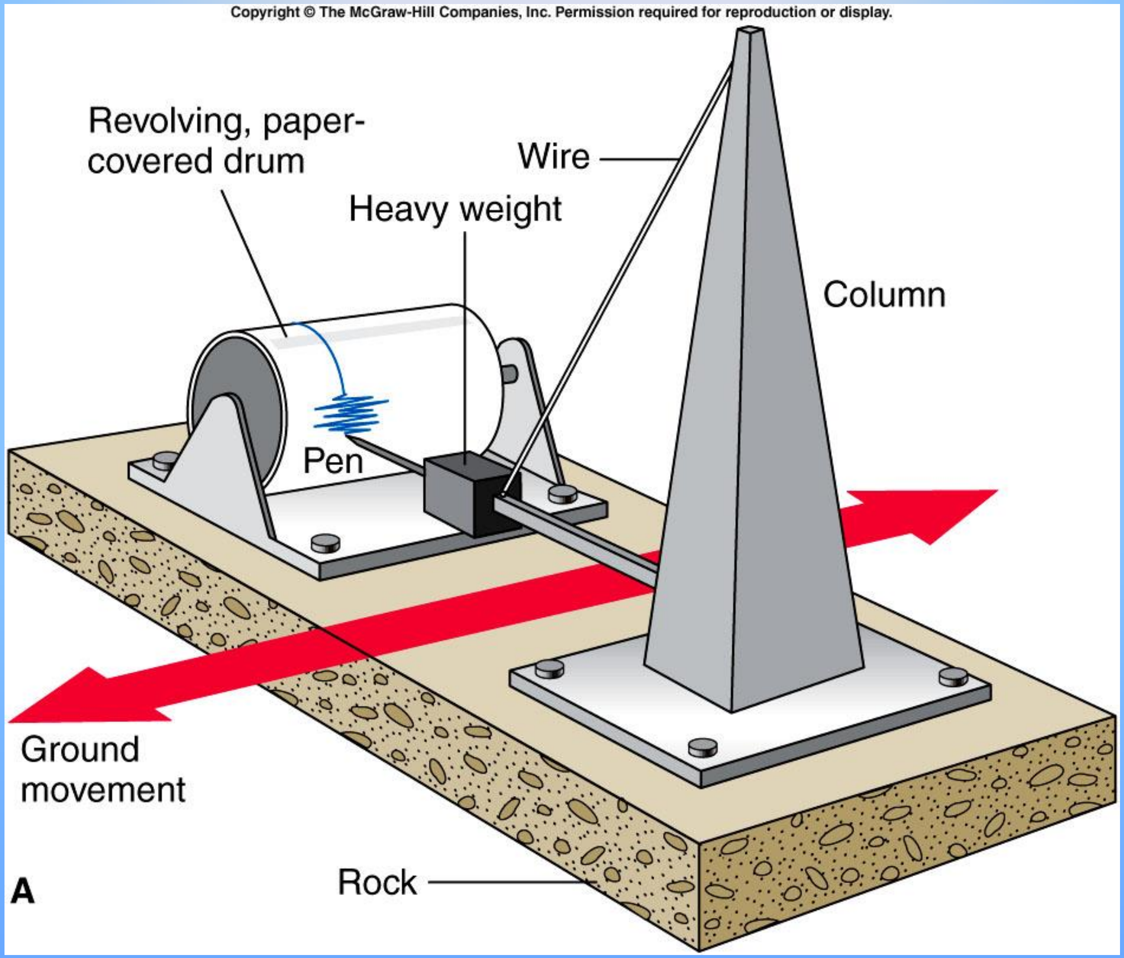


2. Seismograph

- A seismometer that can record ground vibrations.
- The record is usually a squiggly line drawn on a moving strip of paper.

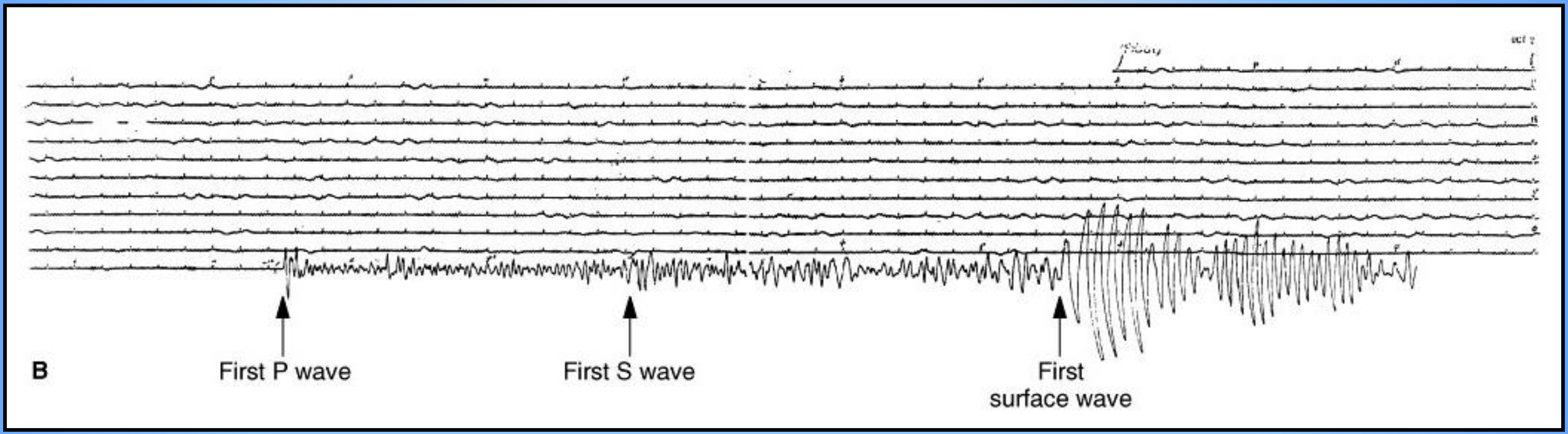


Seismograph for Horizontal Ground Motion



Seismogram

- The paper record of the vibrations

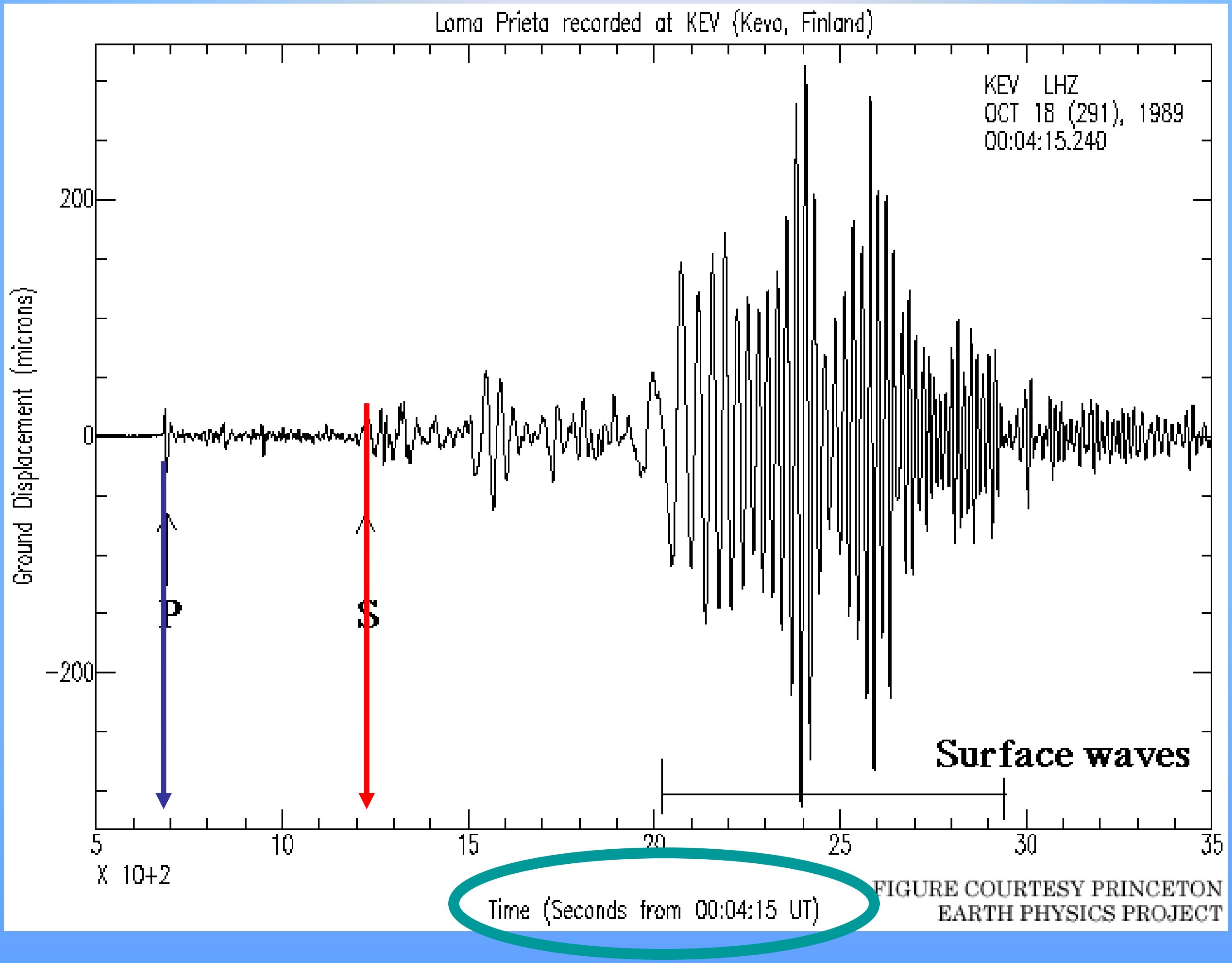


Determining Earthquake Locations

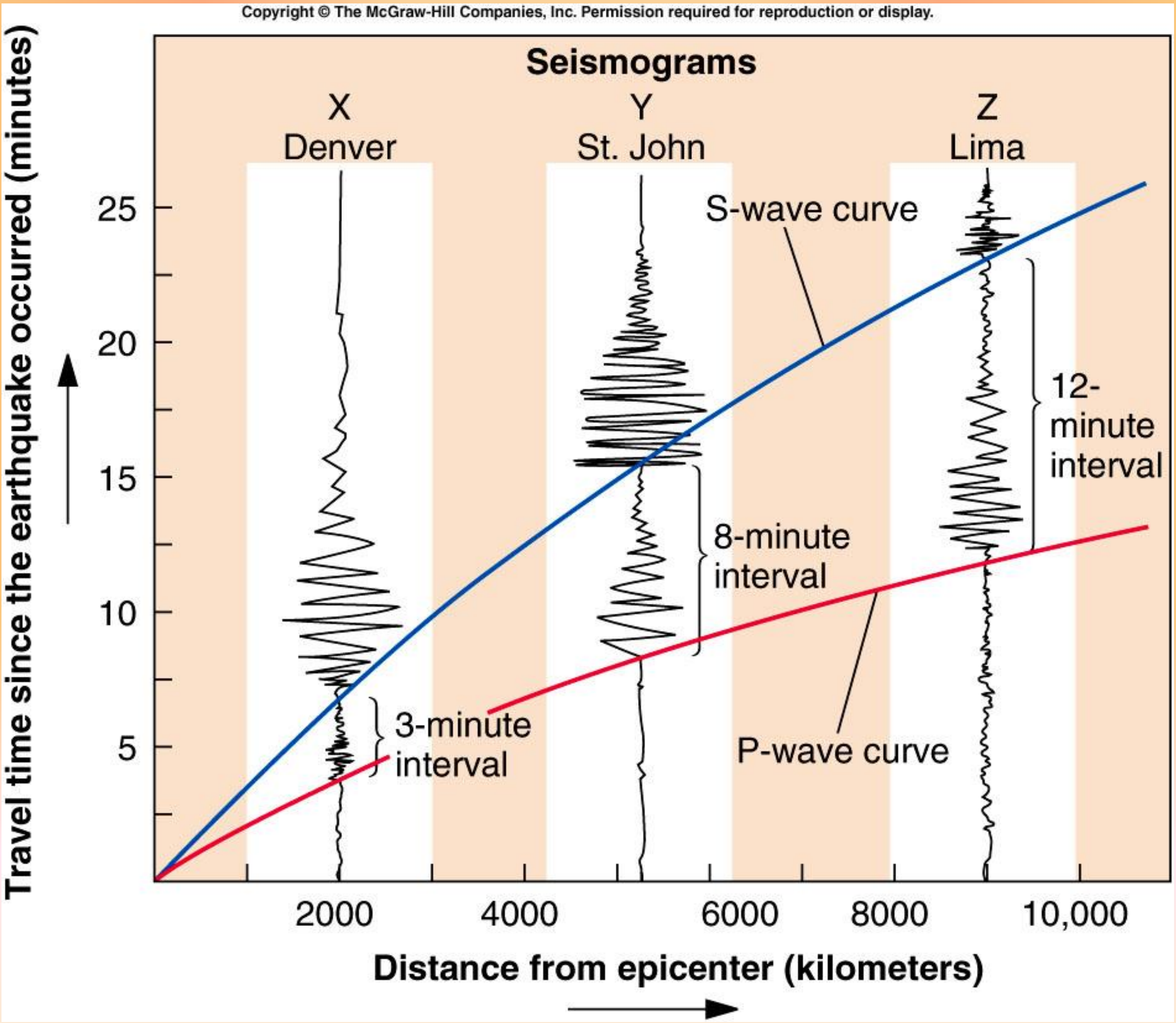
1. A minimum of **three** separate locations is required.

2. For *each* location . . .

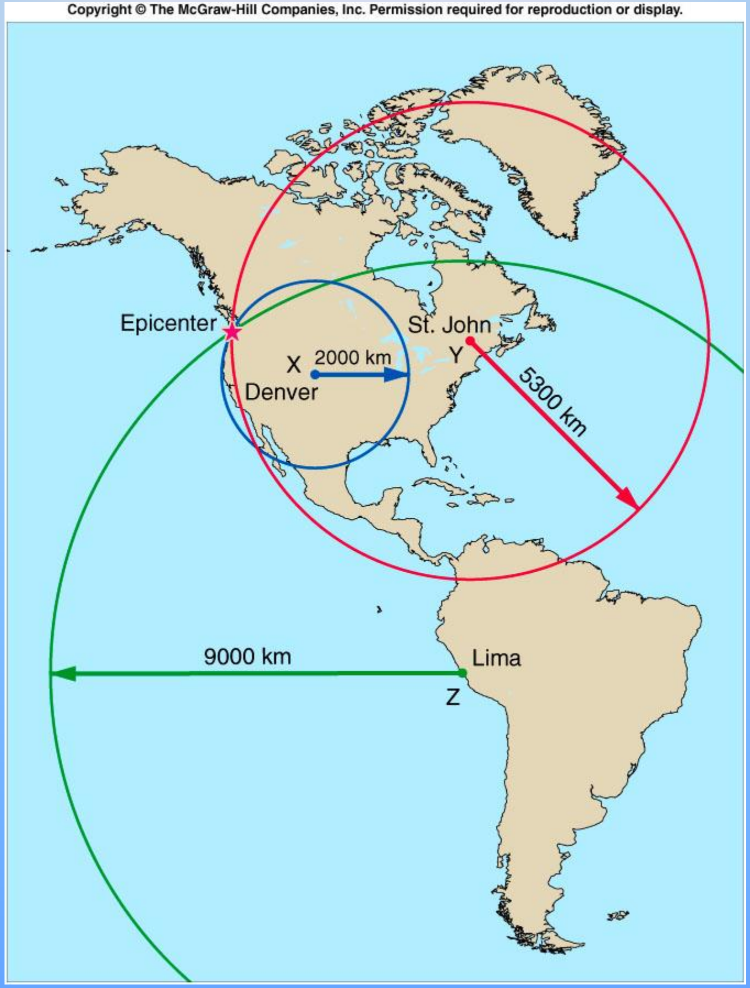
Determine the Arrival Times of the P-Wave and the S-Wave



Find the Distance to the Epicenter for Each Location



Construction of Circles Around Each Location

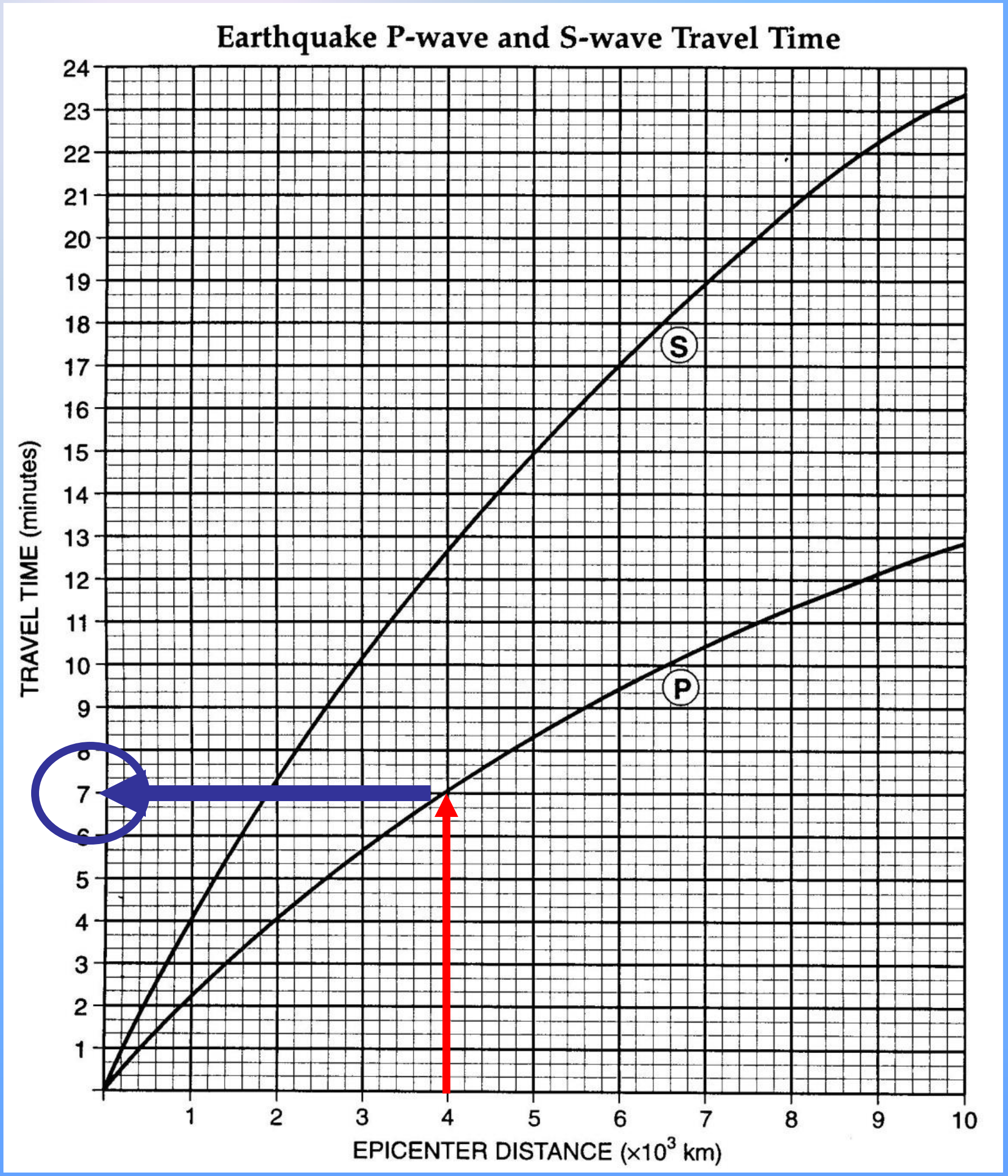


Finding Epicenters Animation

- http://highered.mcgraw-hill.com/sites/dl/free/0073135151/90798/16_08.swf

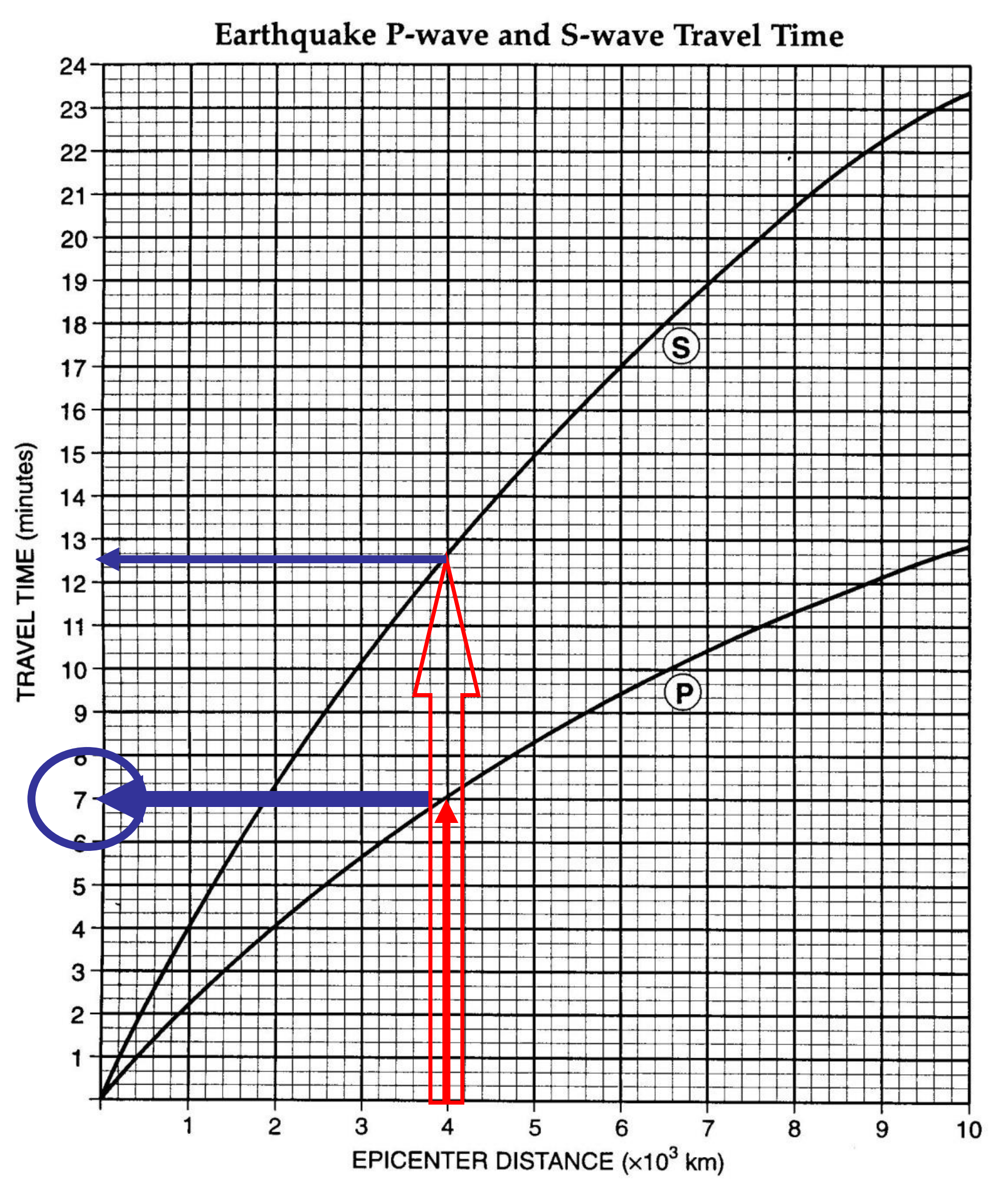
Finding Distance to the Epicenter

- The distance to the epicenter is 4,000 km.
- Find the travel time of the P-Wave.
- **7 minutes**



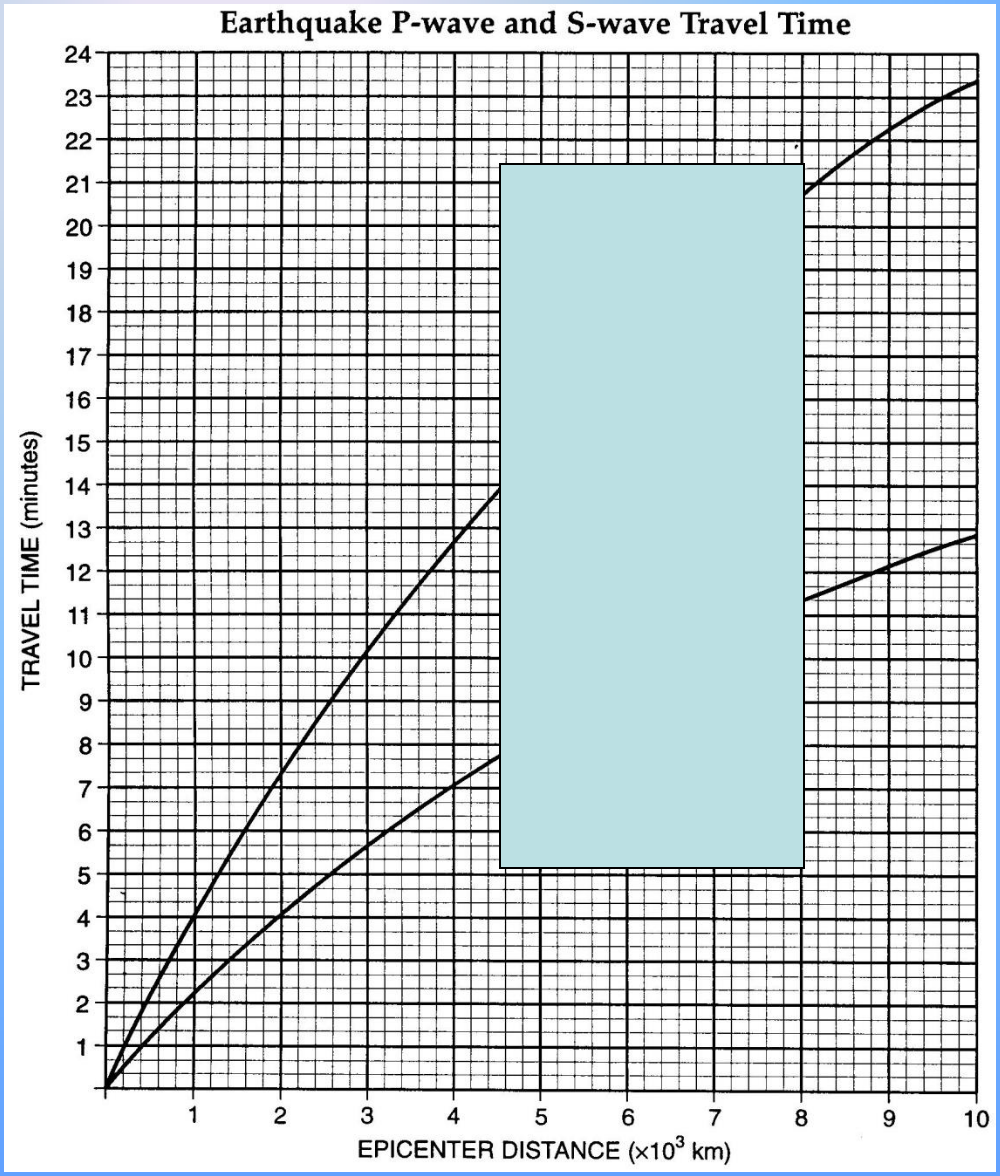
Finding Distance to the Epicenter

- The distance to the epicenter is 4,000 km.
- Find the travel time of the S-Wave.
- **7 minutes**
- The S-Wave's travel time is
- **12 min, 40 sec.**



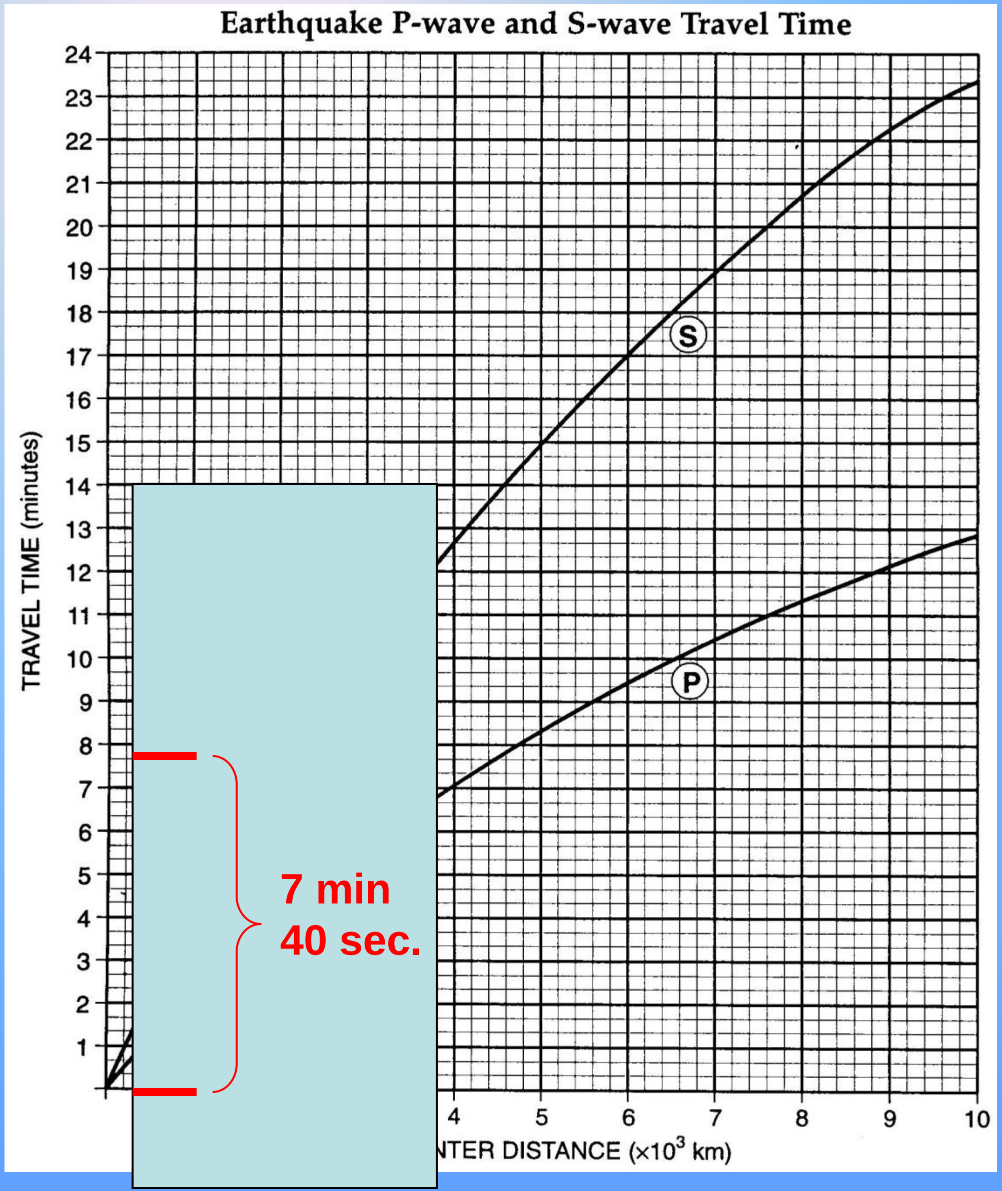
Finding Distance to the Epicenter

- Find the epicenter distance if the difference in arrival times is:
  - **7 min., 40 sec.**



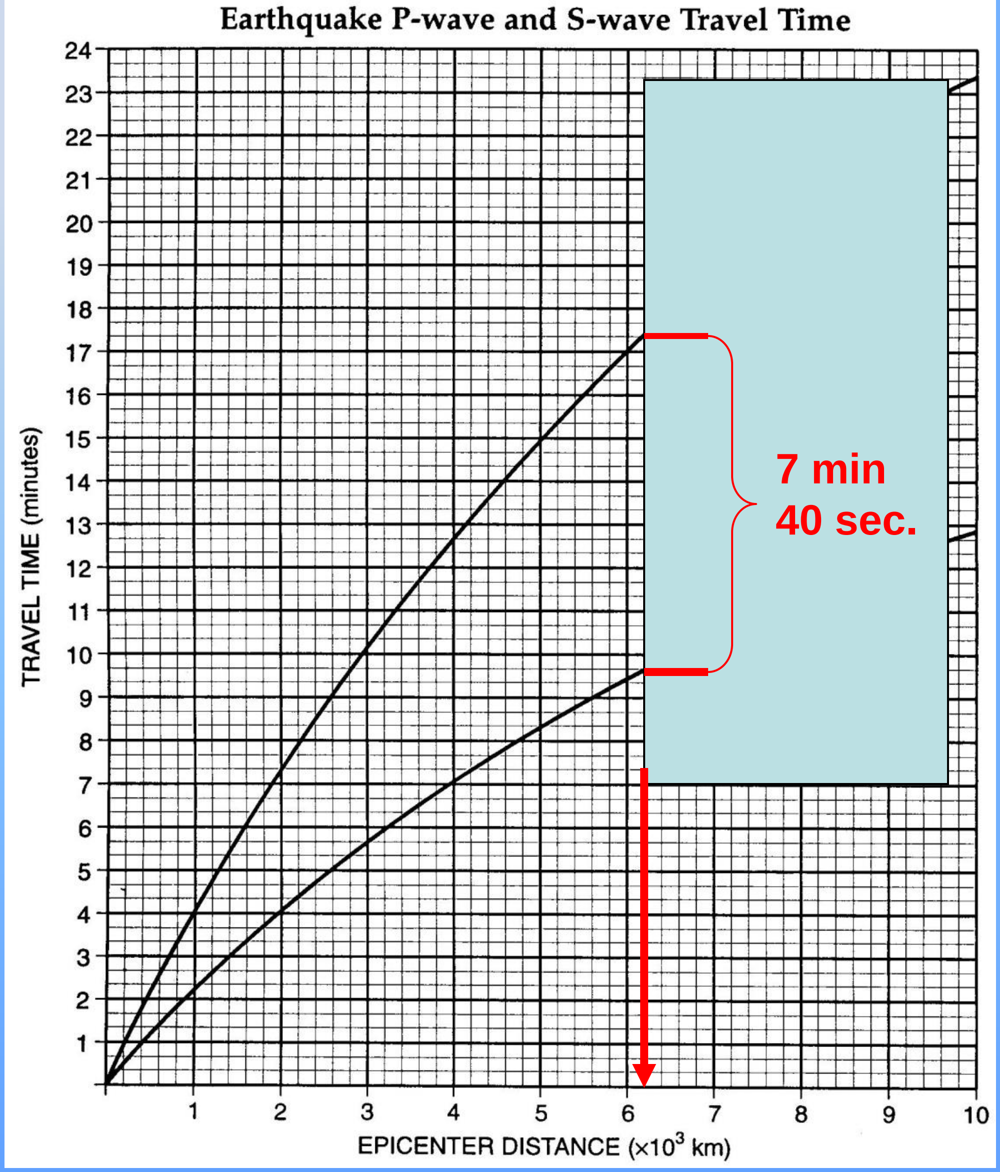
Finding Distance to the Epicenter

- Find the epicenter distance if the difference in arrival times is:
  - **7 min., 40 sec.**



Finding Distance to the Epicenter

- Find the epicenter distance if the difference in arrival times is:
  - **7 min., 40 sec.**
- **6,200 km**



Find the Distance to the Epicenter

- The 1st P-wave arrived at 08:06:10
- The 1st S-wave arrived at 08:12:00
  - Find the difference in arrival times

Hrs. min. sec.

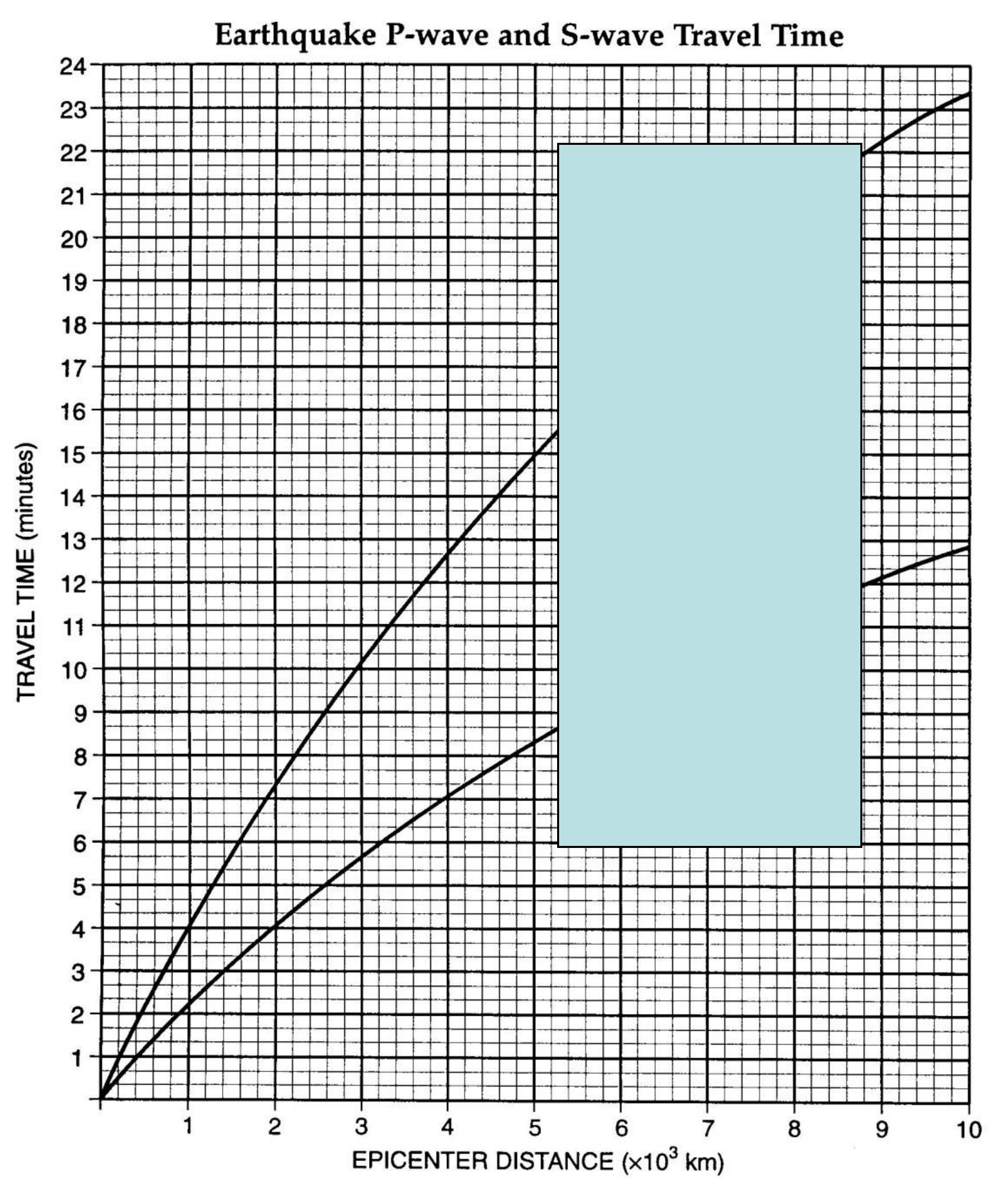
$$\begin{array}{r} \textcolor{red}{11}\ \ \textcolor{red}{60} \\ 08:\cancel{12}:\cancel{00} \\ -\ 08:06:10 \\ \hline \textcolor{red}{\mathbf{00:05:50}} \end{array}$$

1. **Borrow one minute for the seconds column.**
2. **Remember that this is equal to 60 seconds.**

Finding Distance to the Epicenter

- Find the epicenter distance if the difference in arrival times is:

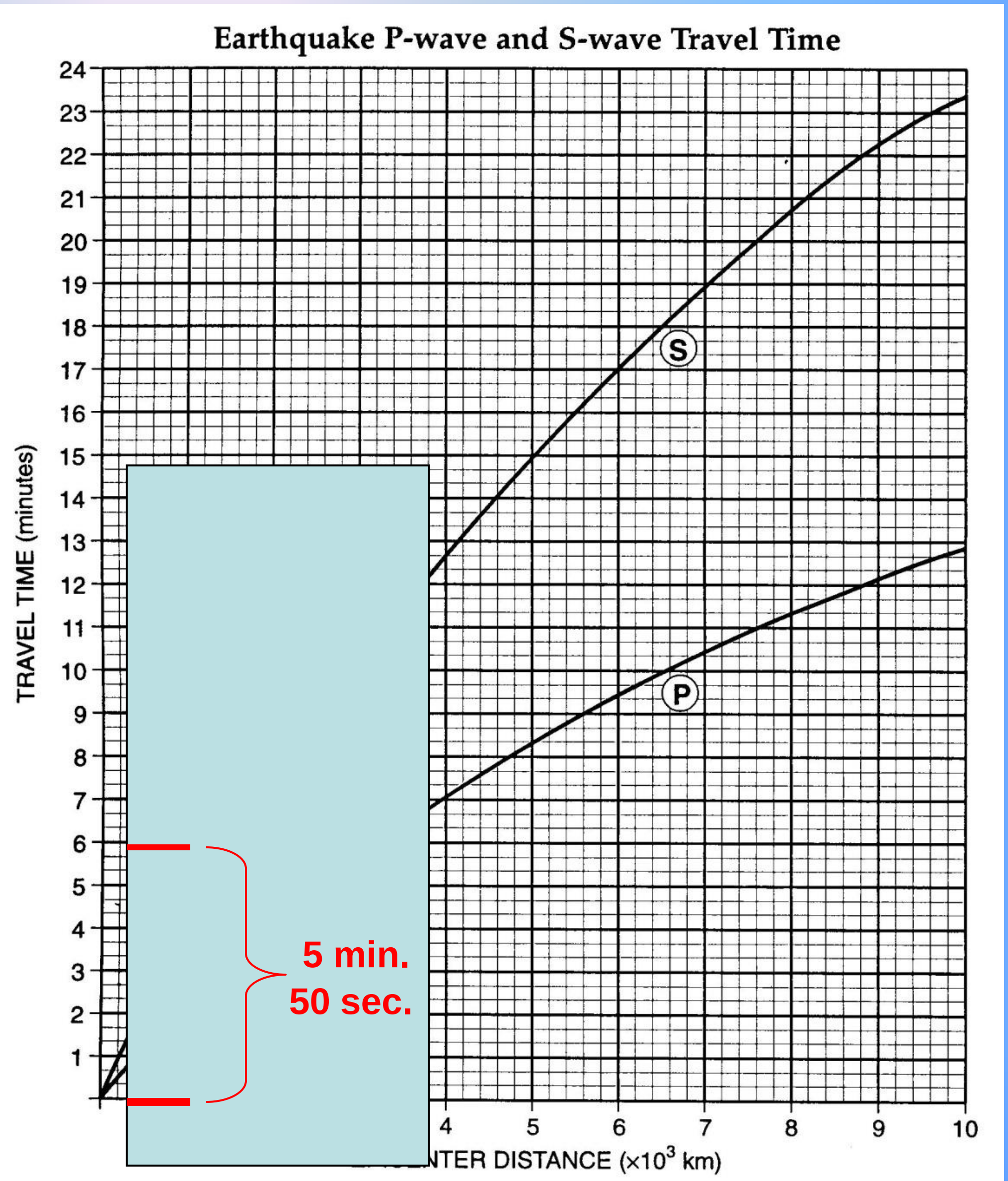
5 min., 50 sec.



Finding Distance to the Epicenter

- Find the epicenter distance if the difference in arrival times is:

5 min., 30 sec.

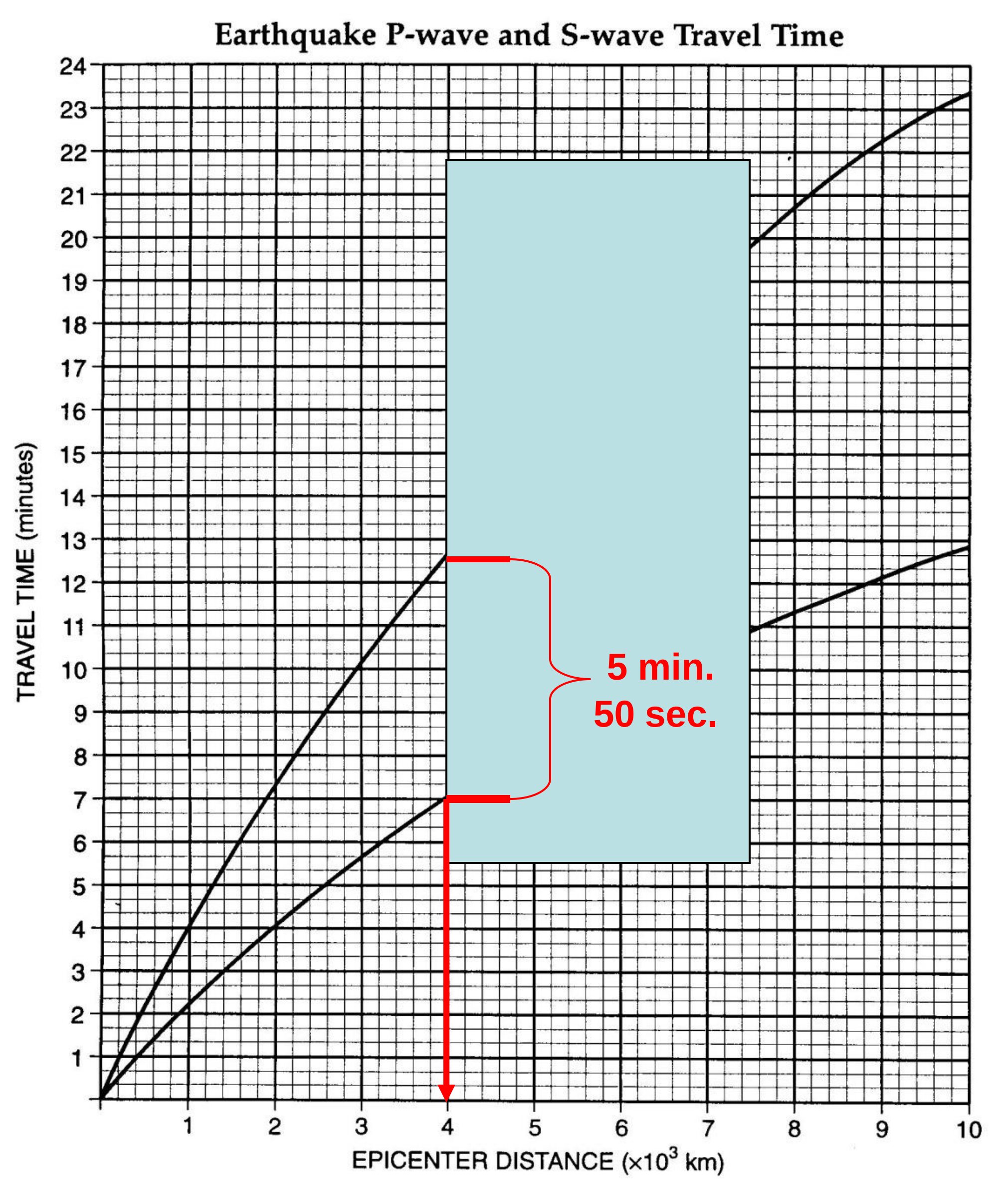


Finding Distance to the Epicenter

- Find the epicenter distance if the difference in arrival times is:

  5 min., 50 sec.

- The distance to the epicenter is 4,000 km



Measuring Earthquake Magnitude

(Intensity)

1. Modified Mercalli Scale

- Measures the earthquake's effect on people and buildings

Modified Mercalli Intensity Scale of 1931 (Abridged)

I. Not felt except by a very few under especially favorable circumstances.

II. Felt only by 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 like passing of truck. Duration estimated.

IV. During the day felt indoors by many, outdoors by few. At night some awakened. Dishes, windows, doors disturbed; walls made cracking sound. Sensation like heavy truck striking building. Standing motor cars rocked noticeably.

V. Felt by nearly everyone; many awakened. Some dishes, windows, etc., broken; a few instances of cracked plaster; unstable objects overturned. Disturbance 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 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 motor 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. Persons driving motor cars disturbed.

IX. Damage *considerable* in specially designed structures; well-designed frame structures thrown out of plumb; *great* in substantial buildings, with partial collapse. Buildings shifted off foundations. Ground cracked conspicuously. Underground pipes broken.

X. Some well-built wooden structures destroyed; most masonry and frame structures destroyed with foundations; ground badly cracked. Rails bent. Considerable landslides from river banks and steep slopes. Shifted sand and mud. Water splashed (slopped) over banks.

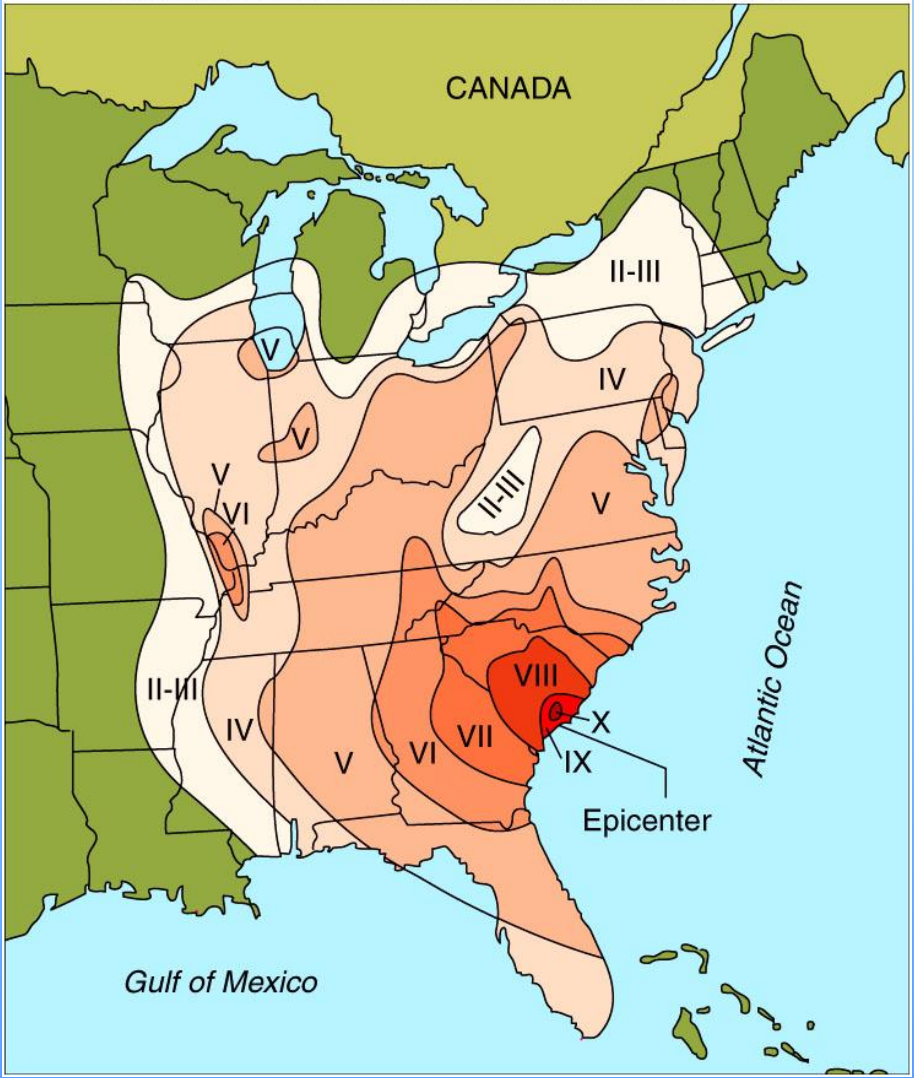
XI. Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground. Underground pipelines completely out of service. Earth slumps and land slips in soft ground. Rails bent greatly.

XII. Damage total. Waves seen on ground surface. Lines of sight and level distorted. Objects thrown upward into the air.

From Wood and Neumann, 1931, *Bulletin of the Seismological Society of America*

Mercalli Intensity Map

1886 Charleston, South Carolina Earthquake



2. __Richter__ Scale

- 1935 – Charles Richter
- Numerical open-ended scale
- Difference of two consecutive numbers
  - 10X increase of vibration amplitude
  - 32X increase in energy

Understanding the Richter Scale

Richter Magnitude	Feels like KG of TNT	Extra Information
0-1	0.6 -20 kilograms of dynamite	We can not feel these.
2	600 kilograms of dynamite	Smallest quake people can normally feel.
3	20,000 kilograms of dynamite	People near the epicenter feel this quake.
4	60,000 kilograms of dynamite	This will cause damage around the epicenter. It is the same as a small fission bomb.
5	20,000,000 kilograms of dynamite	Damage done to weak buildings in the area of the epicenter.
6	60,000,000 kilograms of dynamite	Can cause great damage around the epicenter.
7	20 billion kilograms of dynamite	Creates enough energy to heat New York City for one year. Can be detected all over the world. Causes serious damage.
8	20 billion kilograms of dynamite	Causes death and major destruction. Destroyed San Francisco in 1906.
9	20 trillion kilograms of dynamite	Rare, but would causes unbelievable damage!

- **Based on the Wood-Anderson seismograph at 100 km from the epicenter**
- **Based on shallow focus earthquakes in CA**
- **Maximum reported magnitude is 8.6**

3. **Seismic Moment** Scale (Moment Magnitude)

- Currently used to determine an earthquake’s magnitude.
- Based on:
  - length of the fault rupture
  - surface area of the rupture
  - amount of rock displacement
  - tensile strength of the rock
- The media often still uses ***Richter Scale*** for this method

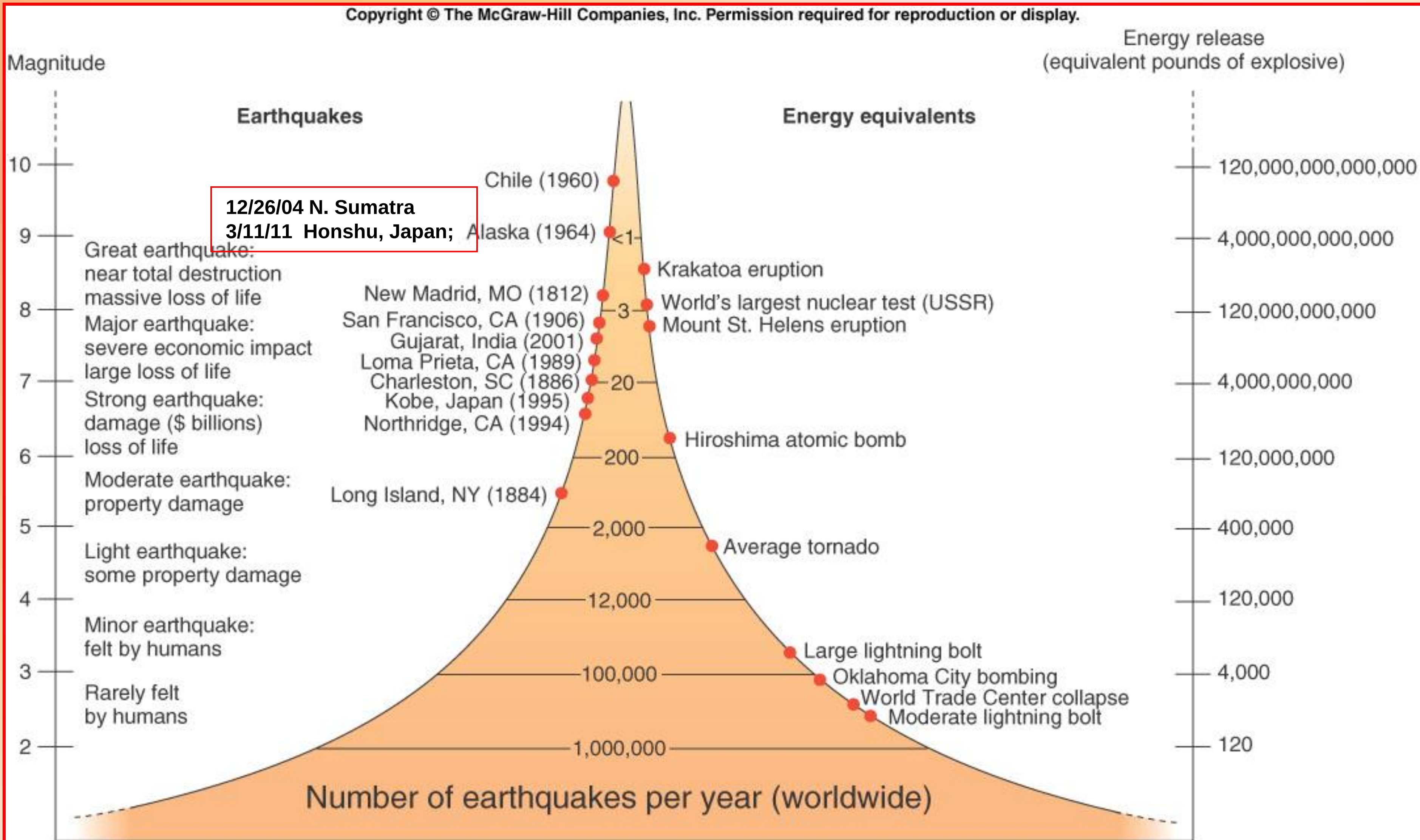
Table 16.2

Comparison of Earthquake Magnitude, Description, Intensity, and Expected Annual World Occurrence

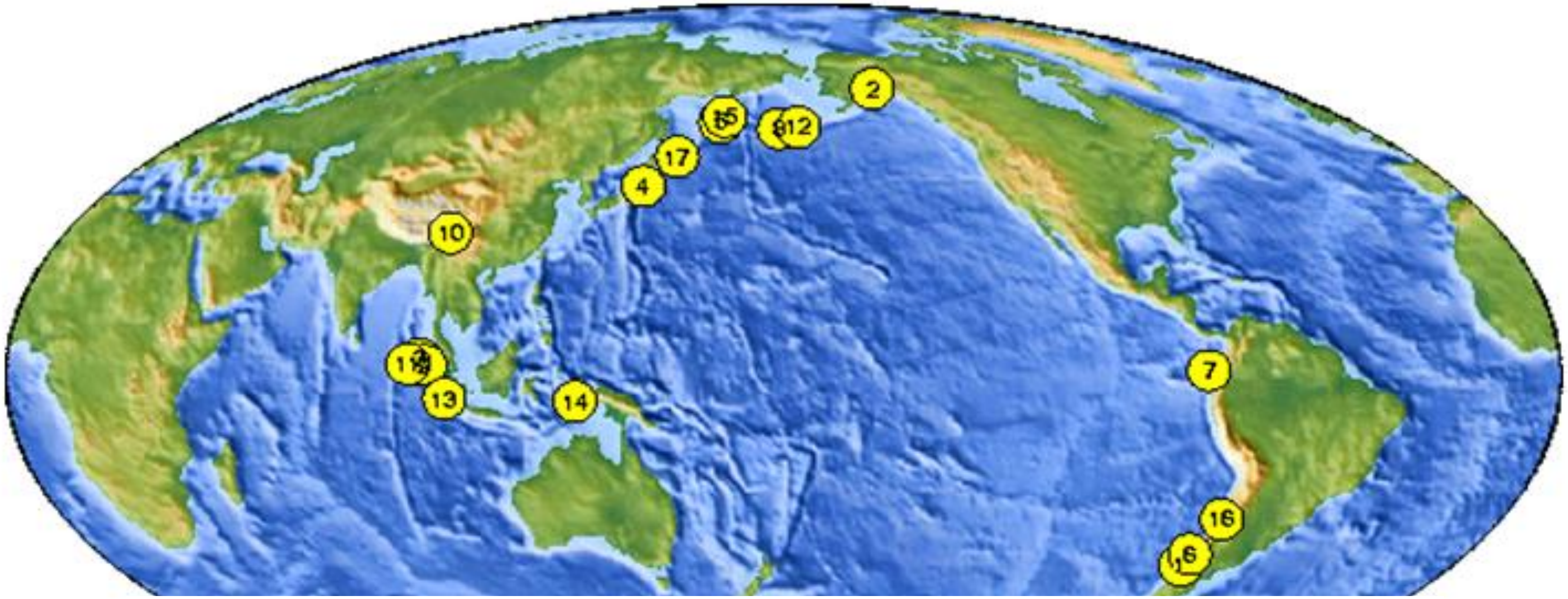
Richter Magnitude	Description	Maximum Expected Mercalli Intensity at Epicenter	Annual Expected Number
2.0	Very minor	I Usually detected only by instruments	600,000
2.0–2.9	Very minor	I–II Felt by some indoors, especially on upper floors	300,000
3.0–3.9	Minor	III Felt indoors	49,000
4.0–4.9	Light	IV–V Felt by most; slight damage	6,200
5.0–5.9	Moderate	VI–VII Felt by all; damage minor to moderate	800
6.0–6.9	Strong	VII–VIII Everyone runs outdoors; moderate to major damage	266
7.0–7.9	Major	IX–X Major damage	18
8.0 or higher	Great	X–XII Major and total damage	1 or 2

Source: U.S. Geological Survey

Moment Magnitude



Largest Earthquakes in the World Since 1900

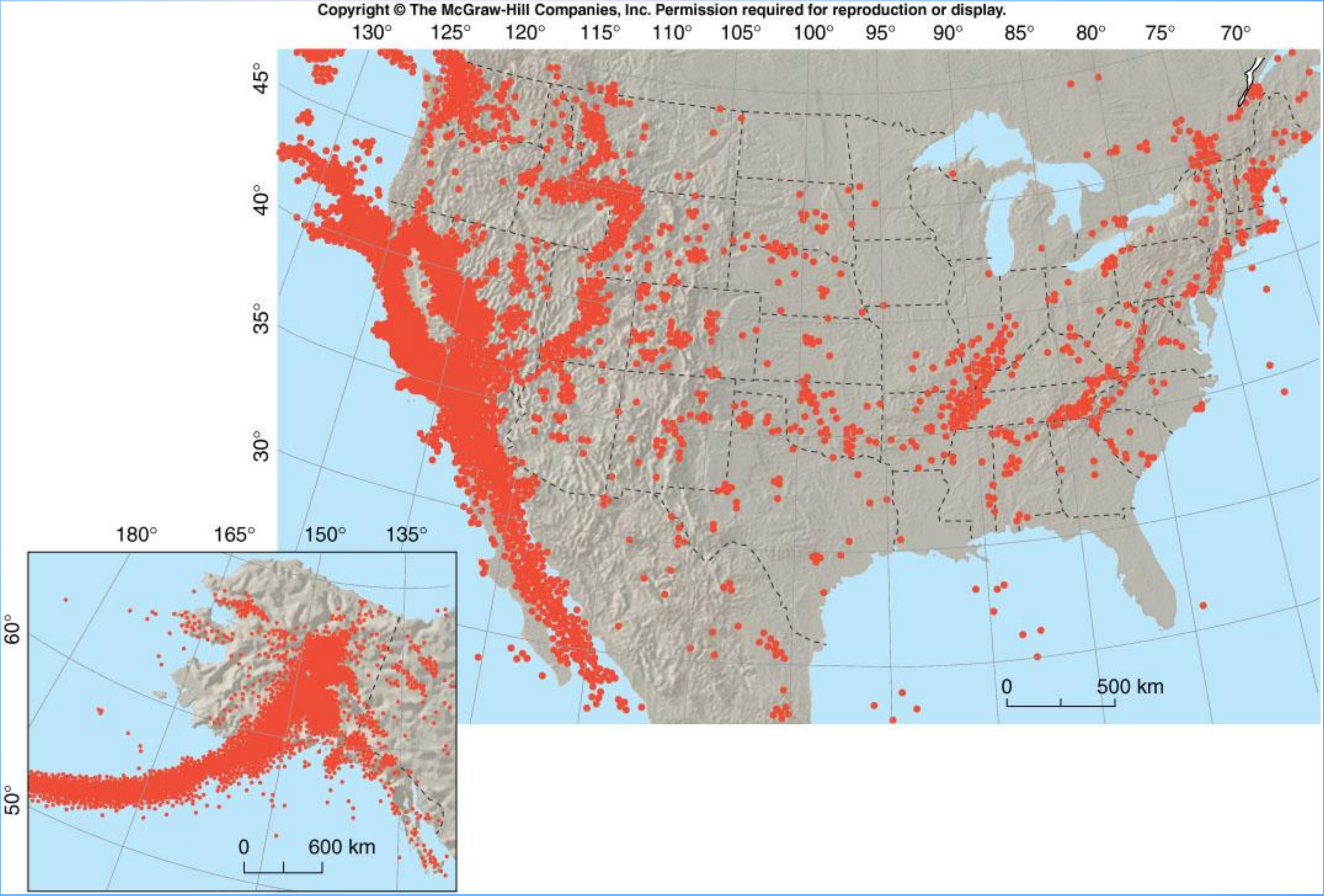


	Location	Date UTC	Magnitude	Lat.	Long.
1.	Chile	1960 05 22	9.5	-38.29	-73.05
2.	Prince William Sound, Alaska	1964 03 28	9.2	61.02	-147.65
3.	Off the West Coast of Northern Sumatra	2004 12 26	9.1	3.30	95.78
4.	Near the East Coast of Honshu, Japan	2011 03 11	9.0	38.322	142.369
5.	Kamchatka	1952 11 04	9.0	52.76	160.06
6.	Offshore Maule, Chile	2010 02 27	8.8	-35.846	-72.719
7.	Off the Coast of Ecuador	1906 01 31	8.8	1.0	-81.5
8.	Rat Islands, Alaska	1965 02 04	8.7	51.21	178.50
9.	Northern Sumatra, Indonesia	2005 03 28	8.6	2.08	97.01
10.	Assam - Tibet	1950 08 15	8.6	28.5	96.5
11.	Off the west coast of northern Sumatra	2012 04 11	8.6	2.311	93.063

Earthquakes in the United States

Western States

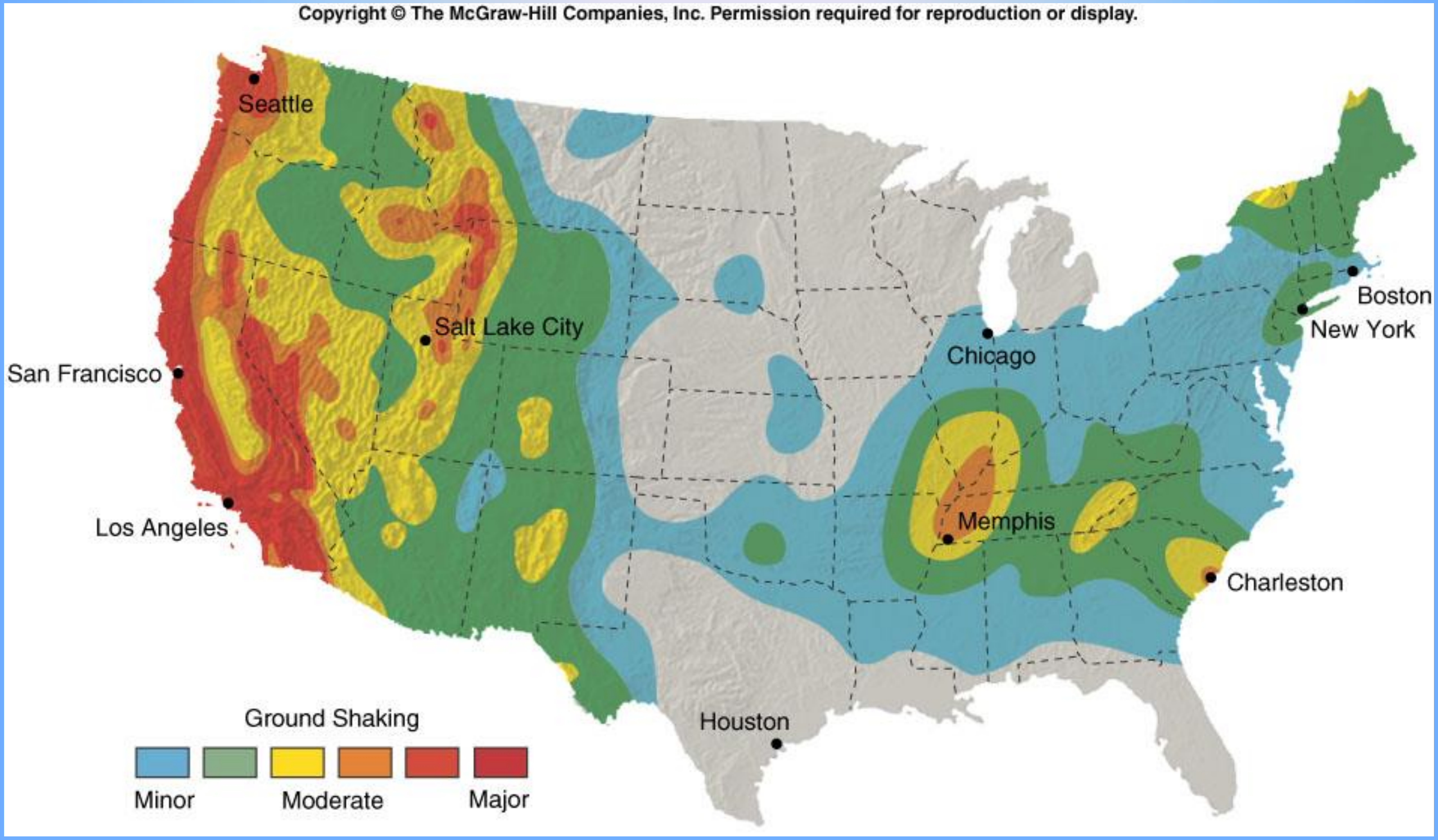
- **Most U.S. Earthquakes**
- **Alaskan earthquakes are mostly south of Aleutian Islands**



Earthquakes east of the Rockies:

- **Not as common**
- **Smaller and deeper**
- **Associated with deeply buried inactive faults of old *divergent plate* boundaries and *failed rifts* (aulacogens)**

U.S. Seismic Hazard Map



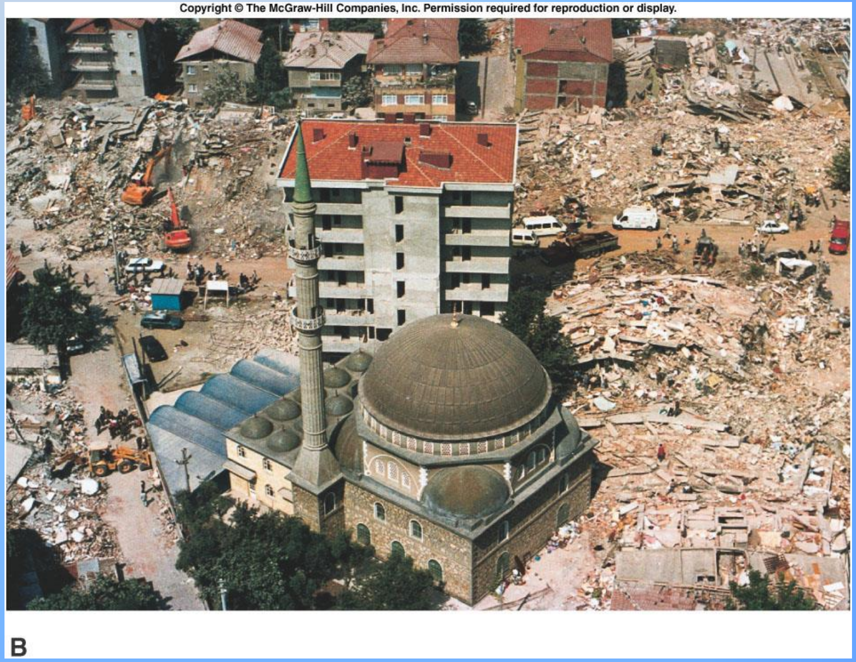
Based on expected amount of ground shaking and damage (USGS –National Seismic Mapping Project)

Effects of Earthquakes

A. Ground Motion

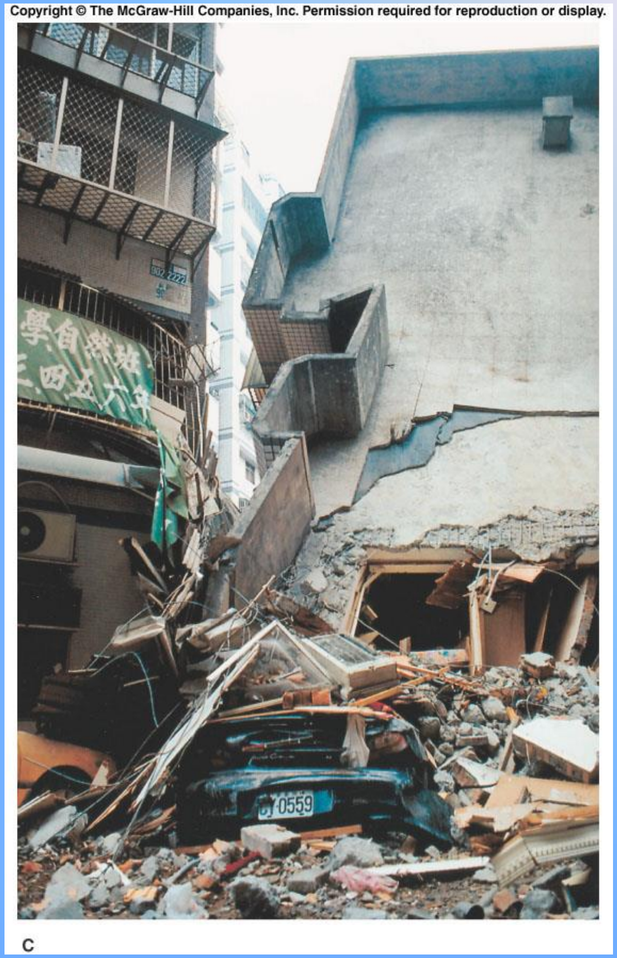
- The trembling and shaking of Earth's land surface
- The cause of building failure

Kobe, Japan (1995)



Izmit, Turkey (1999)

Building Failure



Gurarat, India (2001)

Taiwan, 1999

Loma Prietra, CA (1989)

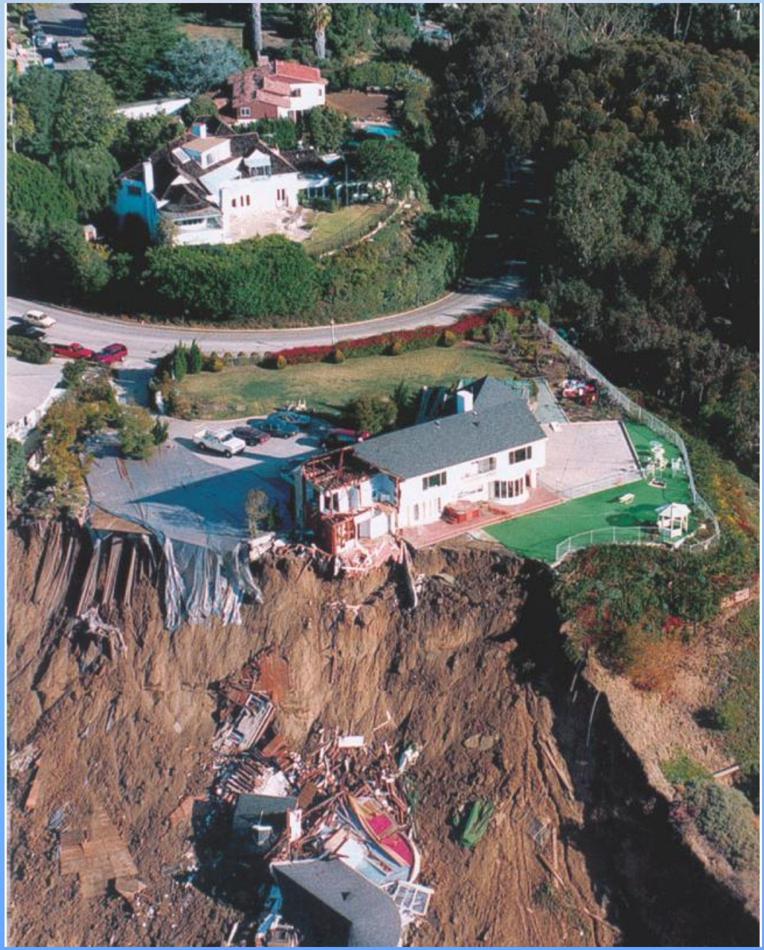
B. ___Fire___

San Francisco, 1906

Northridge, CA
1994

C. Landslides

1. **Can be triggered by ground motion**



Northridge, CA (1994)

Madison Canyon, Montana Earthquake 1959

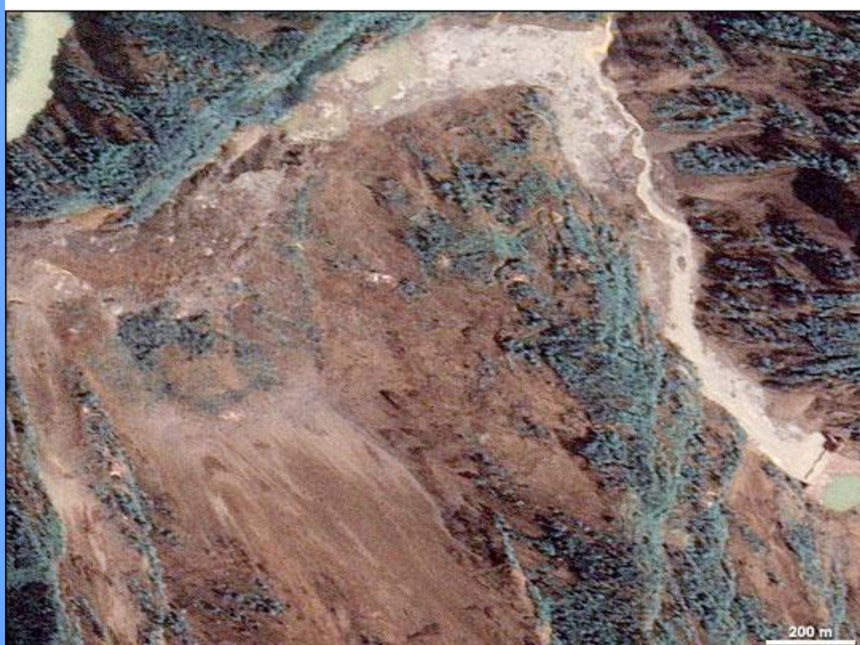
China Earthquake: May 12, 2008
8.0 mw

2006

2008

This pair of high-resolution, photo-like images from Taiwan's Formosat-2 satellite on May 14, 2006 (left), and May 14, 2008 (right) shows several landslides, a collapsed bridge, and a bridge submerged by a newly formed lake.

May 14, 2006



May 14, 2008

May 14, 2006

May 15, 2008

May 19, 2008

2. Liquefaction

- Water saturated soil turns from solid to “liquid” due to ground motions.
- May occur minutes after an earthquake
- Flows like water

Nigata, Japan, 1964

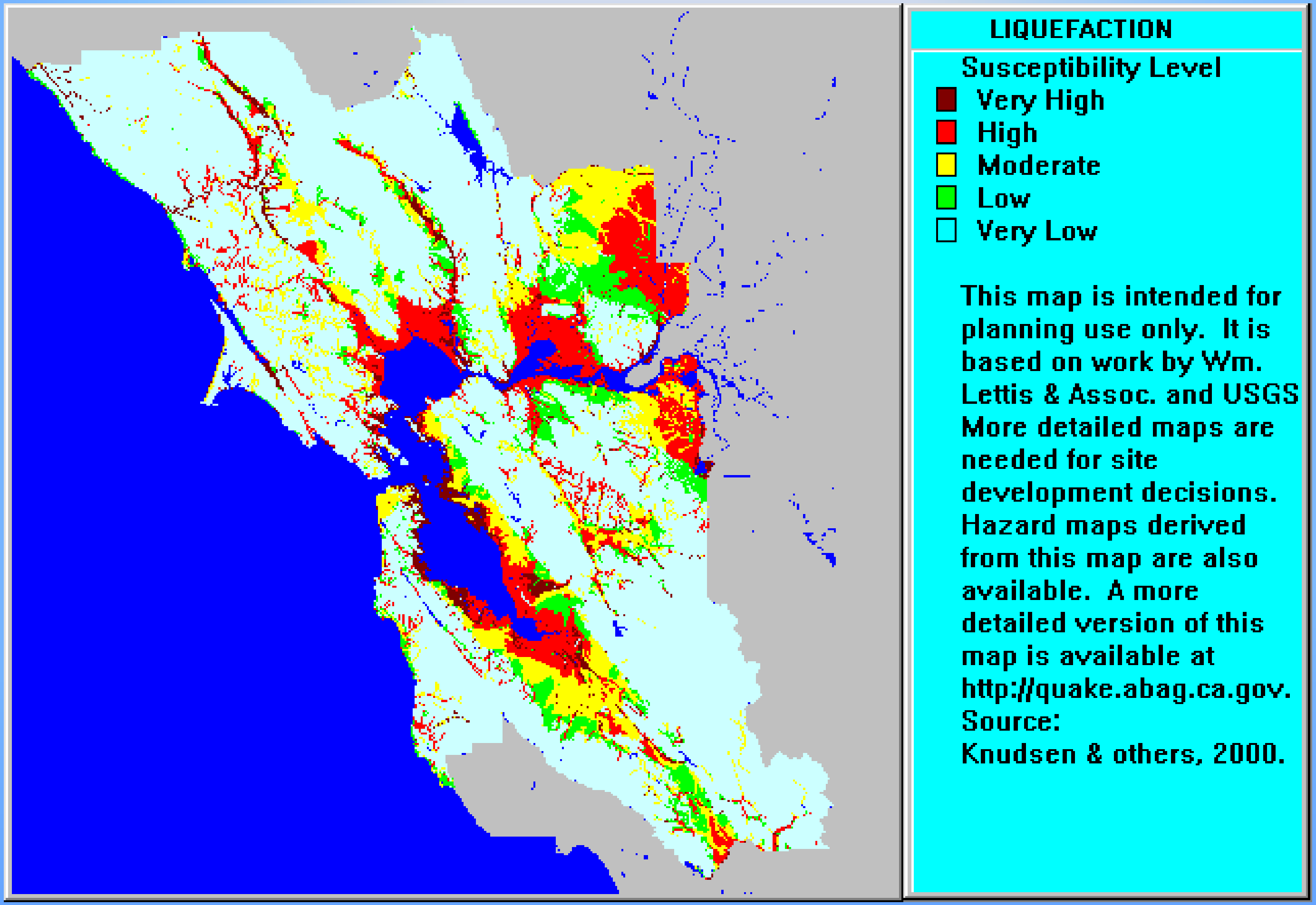
Liquifaction (Japan earthquake 3/11/11) :

http://www.youtube.com/watch?v=I3hJK1BoRak

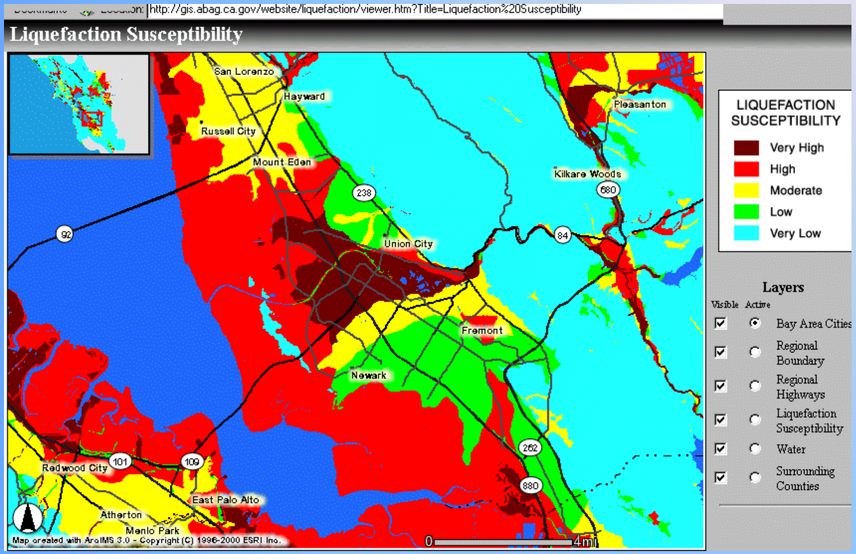
Ground Motion (Japan earthquake 3/11/11):

http://www.youtube.com/watch?v=K_BD3NnR07c

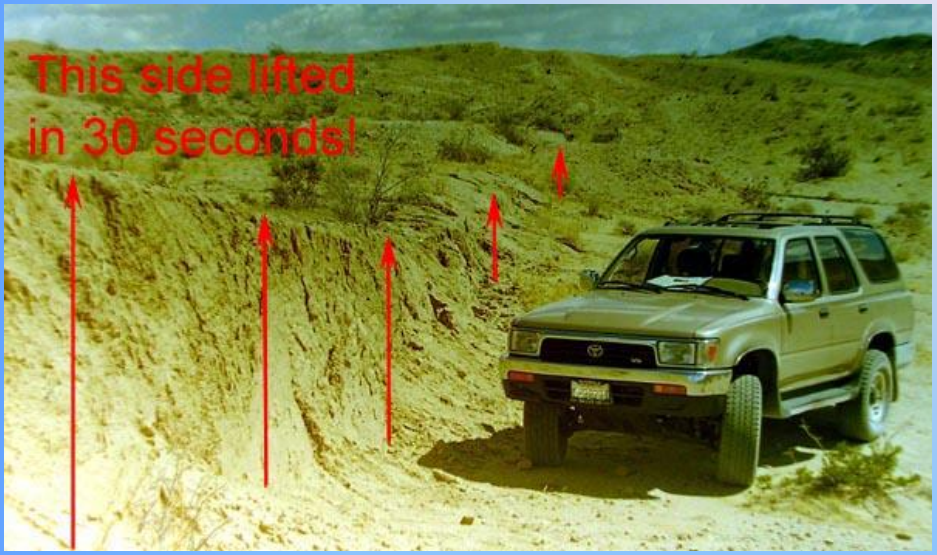
Liquefaction Hazards in the San Francisco Bay Area



Liquefaction



D. Permanent Displacement of the Land Surface

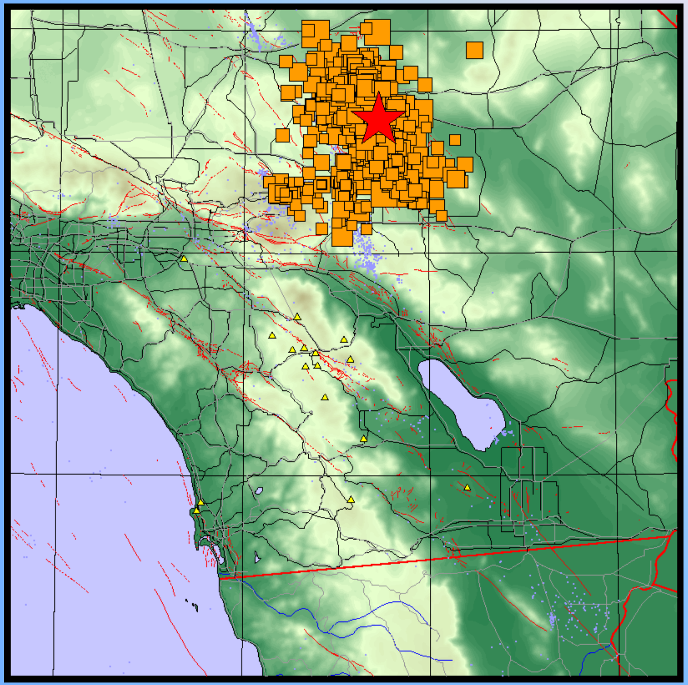


Death Valley

16 ft. scarp in Alaska

1. Rocks may move vertically or horizontally or even diagonally.
2. May affect very large areas.
3. **Scarp**: A fault trace that may appear as a low cliff or as a closed tear in the ground.

E. Aftershocks


Joshua Tree National Park

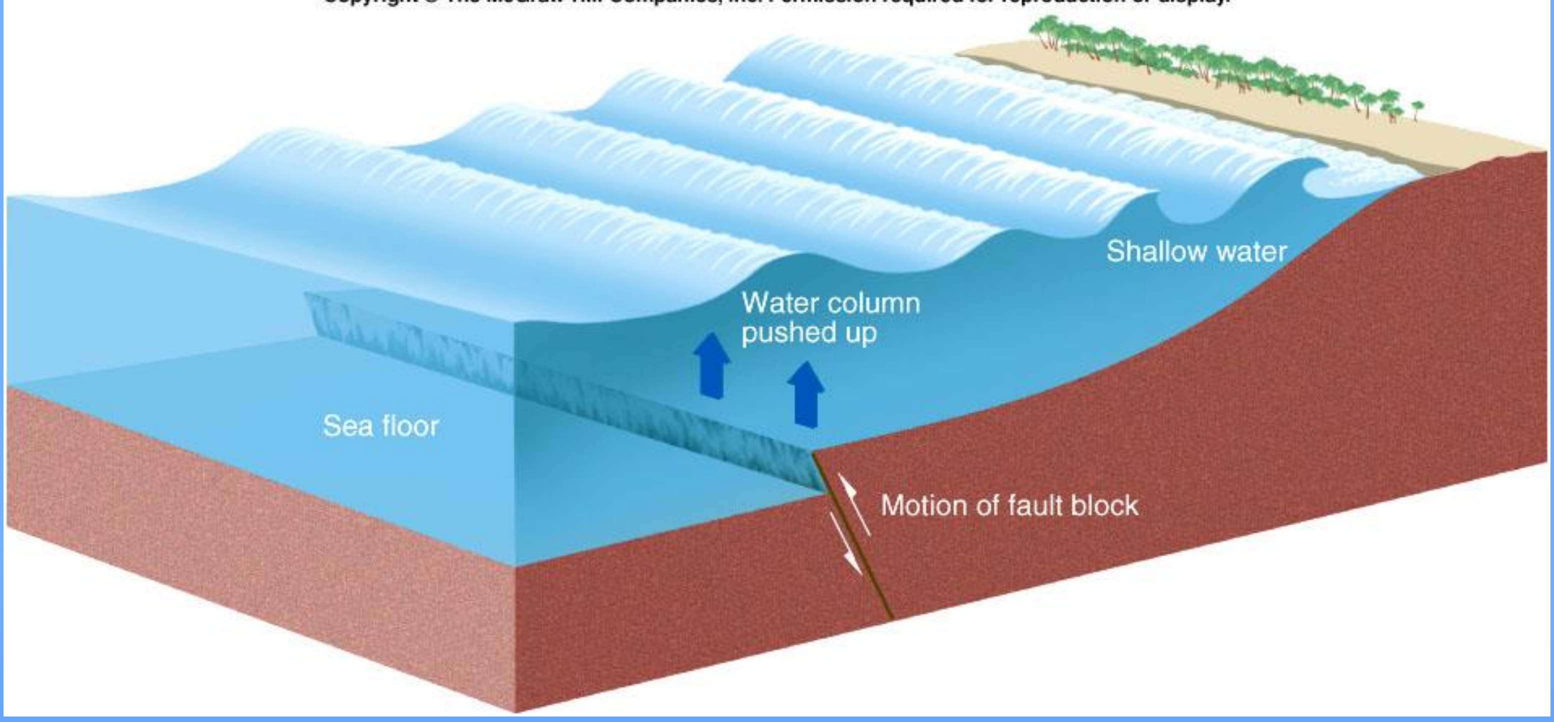

Landslide in El Salvador

- Small earthquakes following the main trembler
- May cause considerable damage to already weakened structures or land and rocks.

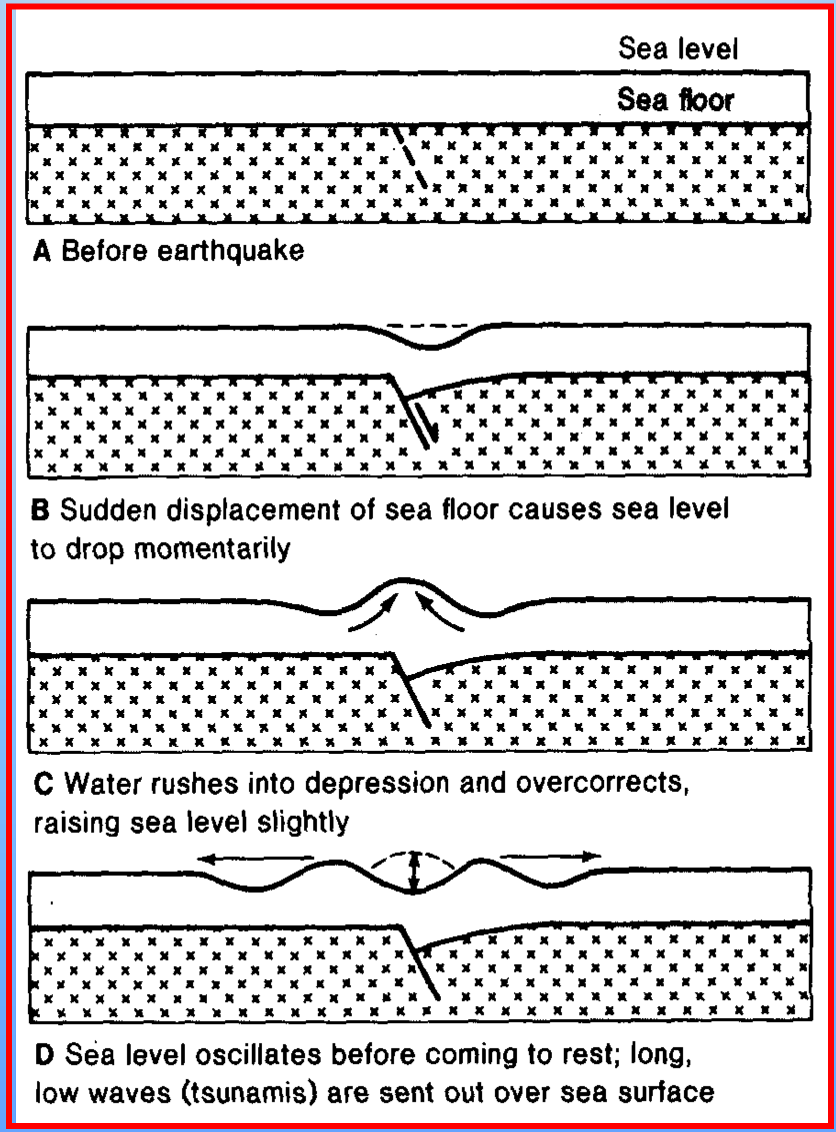
F. __Tsunami__ (Seismic Sea Waves

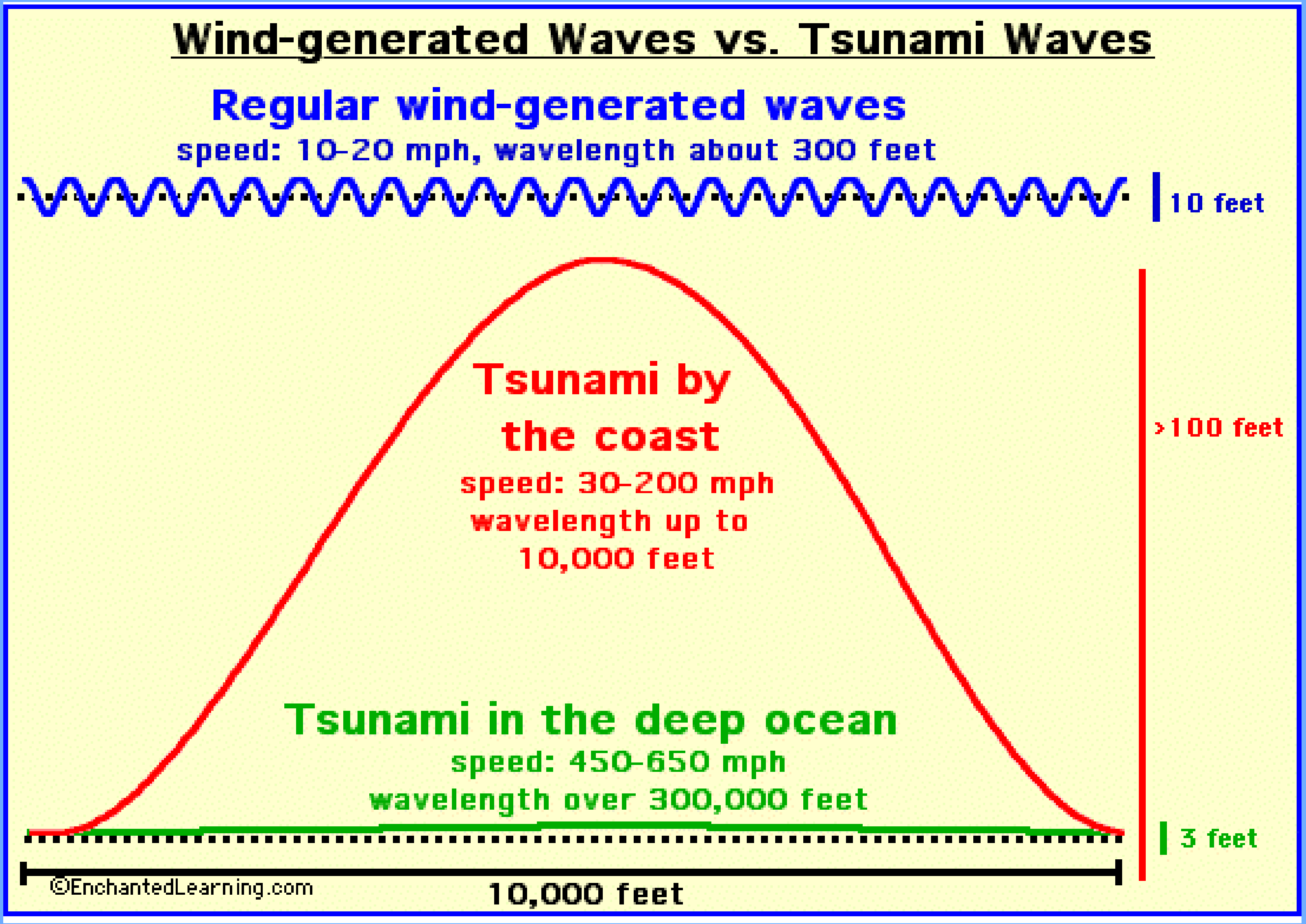
Causes of Tsunamis

- Vertical displacement of the ocean floor
- Can also be caused by submarine landslides



Tsunami Formation

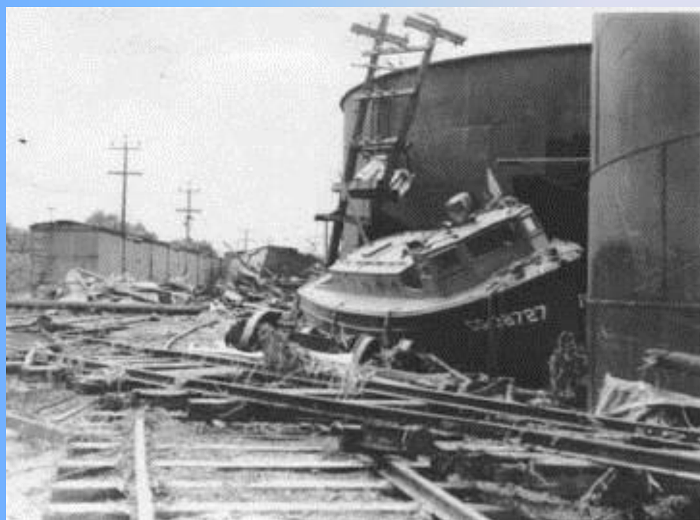



Wind-generated Waves vs. Tsunami Waves
Regular wind-generated waves
speed: 10-20 mph, wavelength about 300 feet
10 feet
Tsunami by the coast
speed: 30-200 mph
wavelength up to 10,000 feet
>100 feet
Tsunami in the deep ocean
speed: 450-650 mph
wavelength over 300,000 feet
3 feet
©EnchantedLearning.com
10,000 feet

Tsunamis

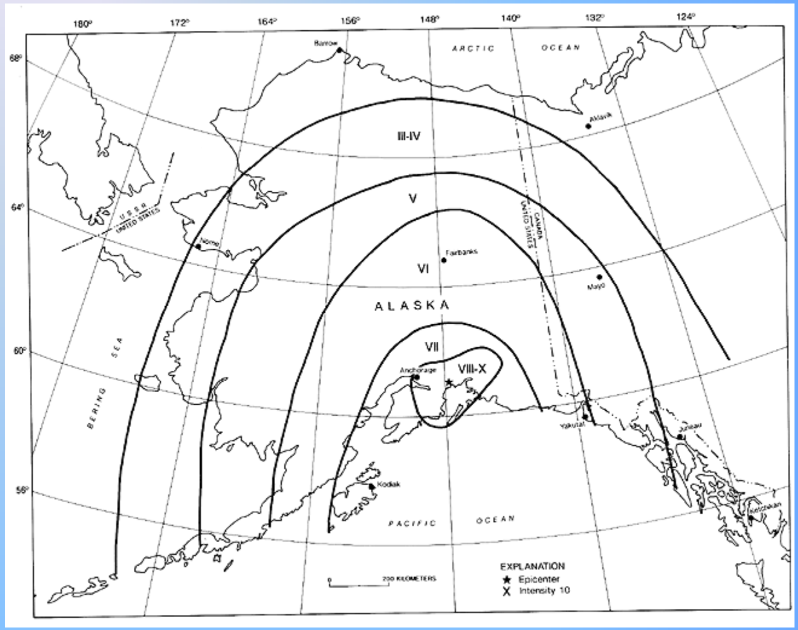
- Low waves radiate from the point of origin.
- In deep water
  - the speed is 450 mi/hr (725 km/hr)
  - Wave height is 0.6 to 2 m
- Wave slows near shore and builds in height

Hilo, Hawaii (1946)



Alaska, 1964

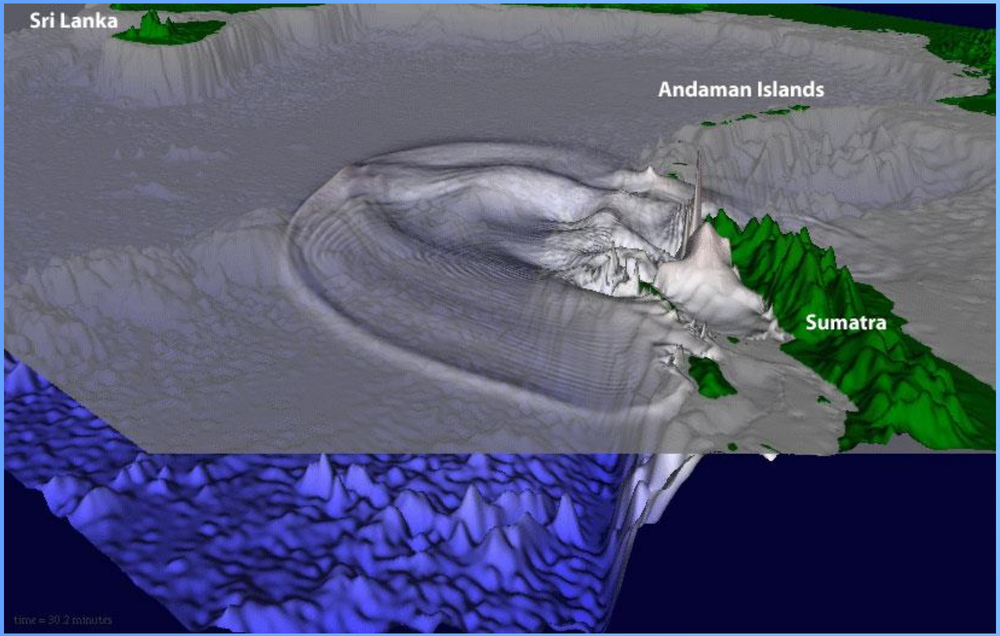

TEXACO

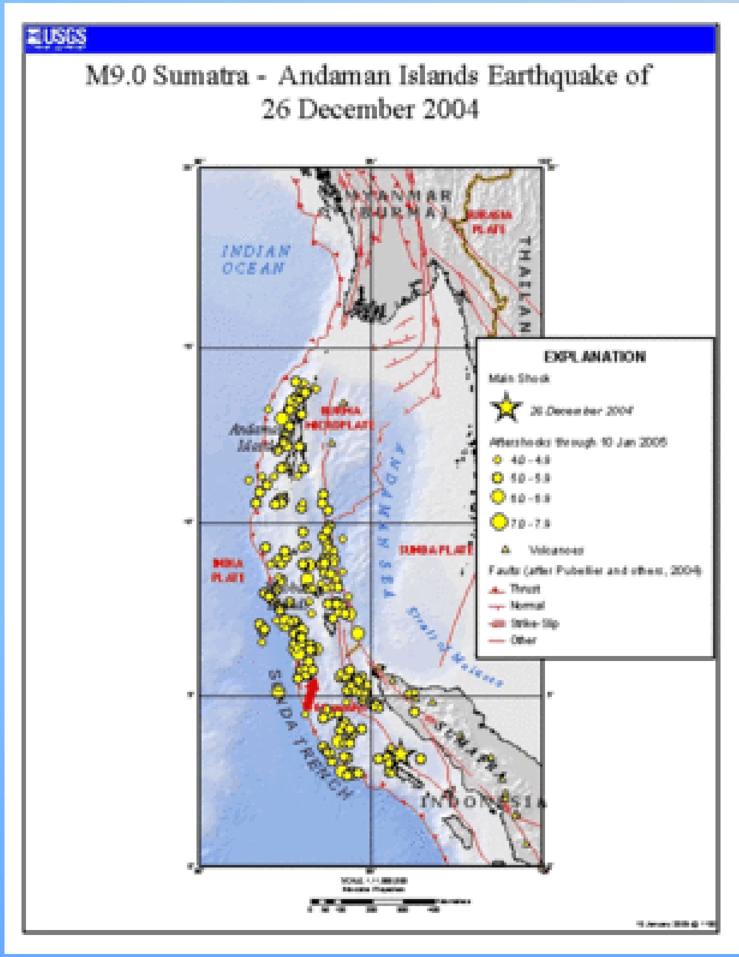

180°
172°
164°
156°
148°
140°
132°
124°
68°
64°
60°
56°
Barrow
ARCTIC
OCEAN
Aklavik
III-IV
V
VI
VII
VIII-X
U.S.S.R.
UNITED STATES
CANADA
UNITED STATES
Nome
Fairbanks
Mayo
ALASKA
Anchorage
Yakutat
Juneau
Ketchikan
Kodiak
BERING
SEA
PACIFIC
OCEAN
0
200 KILOMETERS
EXPLANATION
★ Epicenter
X Intensity 10

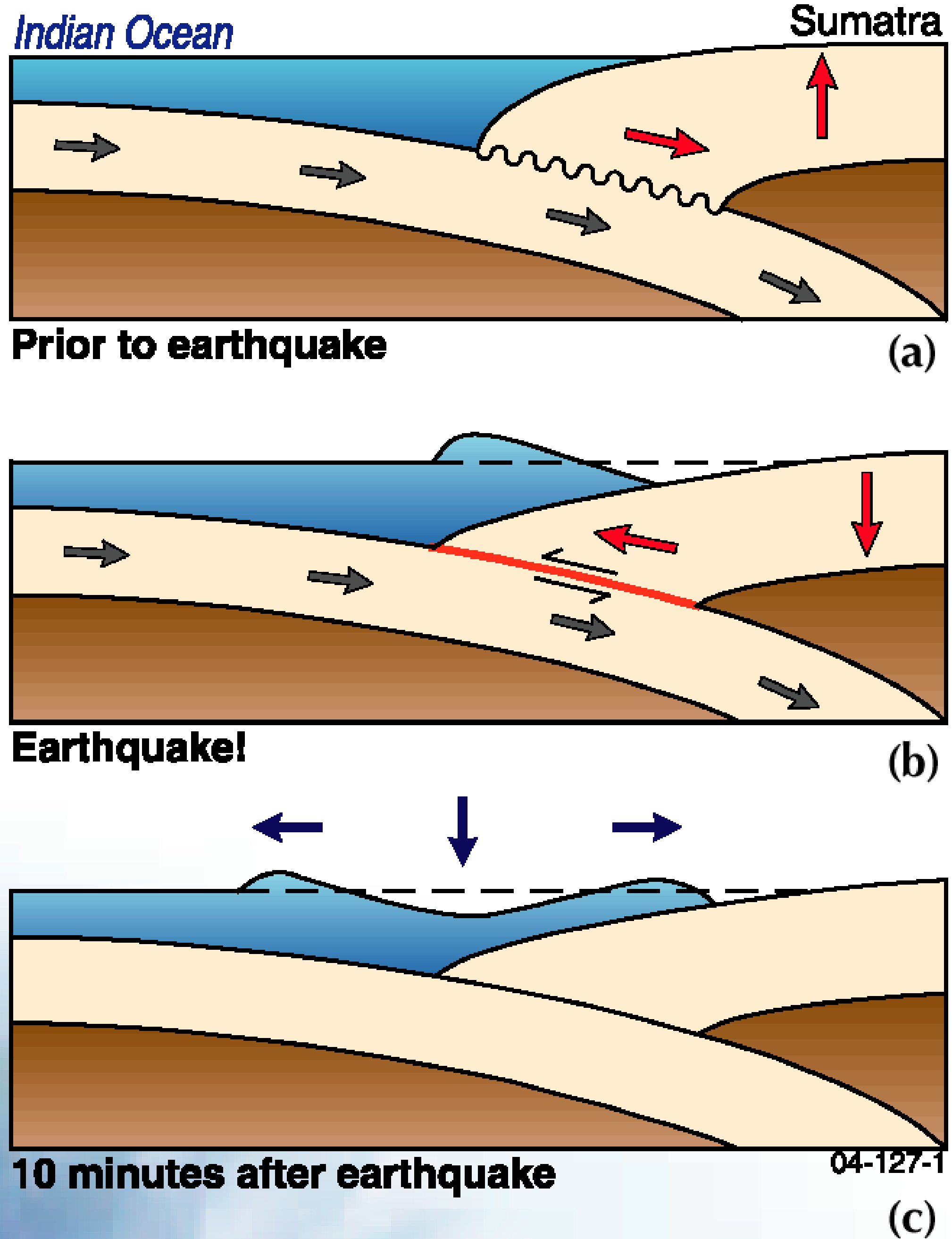
Sumatra-Andaman Earthquake December 26, 2004

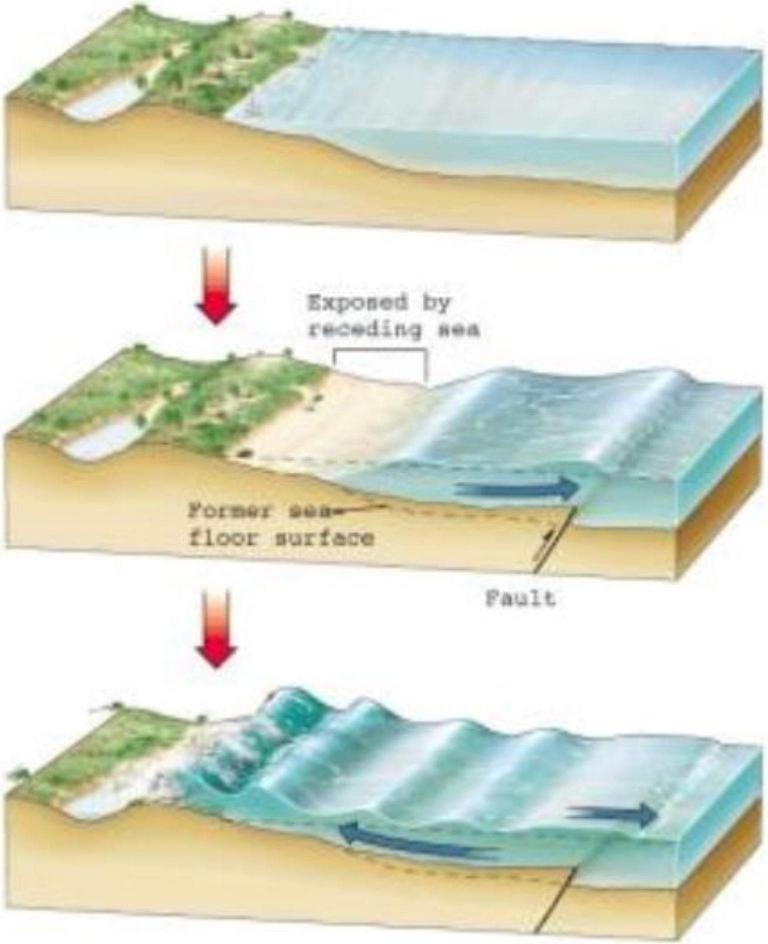
- Fault line 750 mi (1200 km) where India Plate subducts under Burma Plate
- Displacement
  - 10 m (33 feet) lateral
  - 4 -5 m (13 -16 ft.) vertical
- Generated massive tsunamis
  - 186,000 people dead
  - 42,883 people missing

Sumatra-Andaman Earthquake

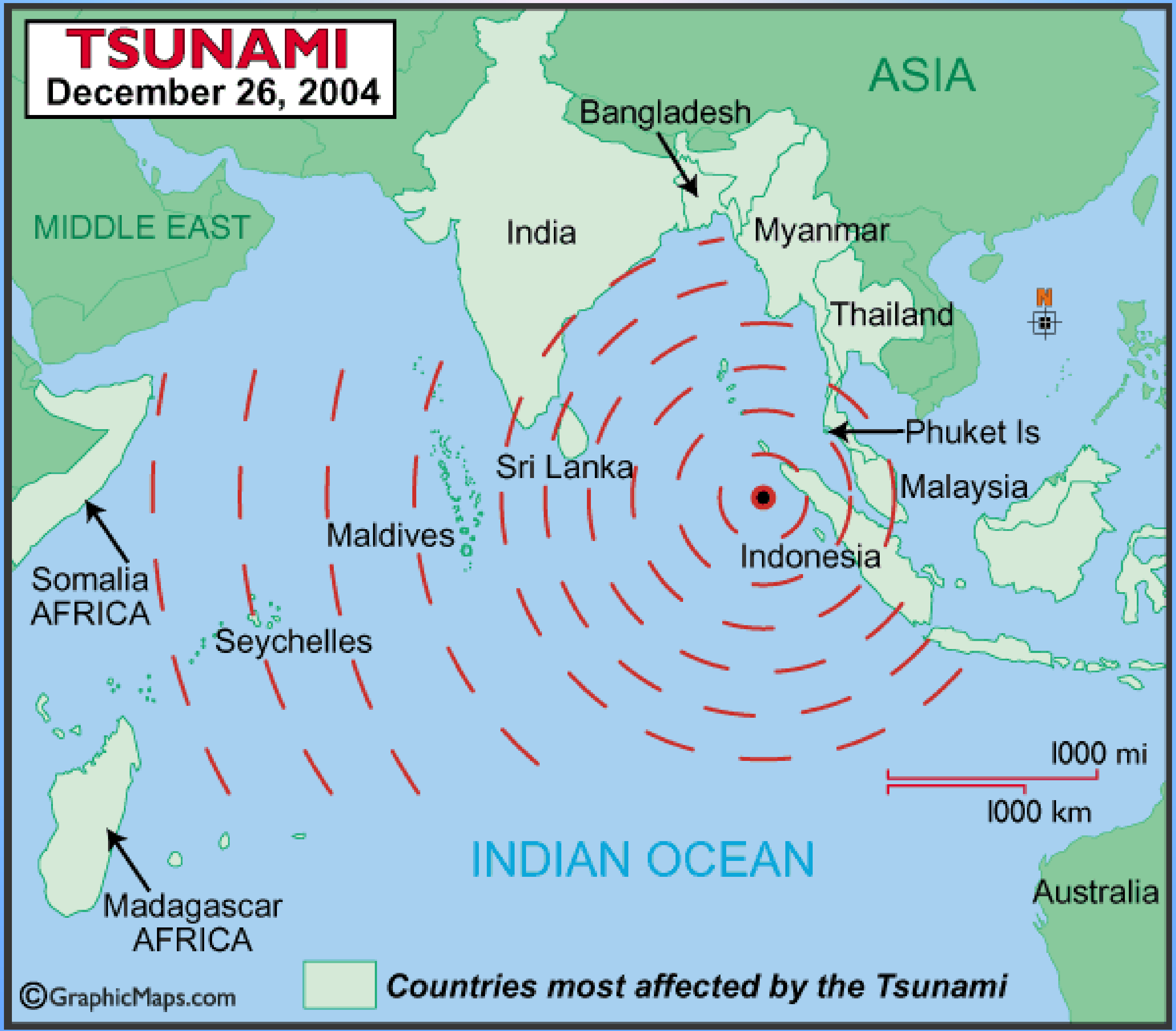




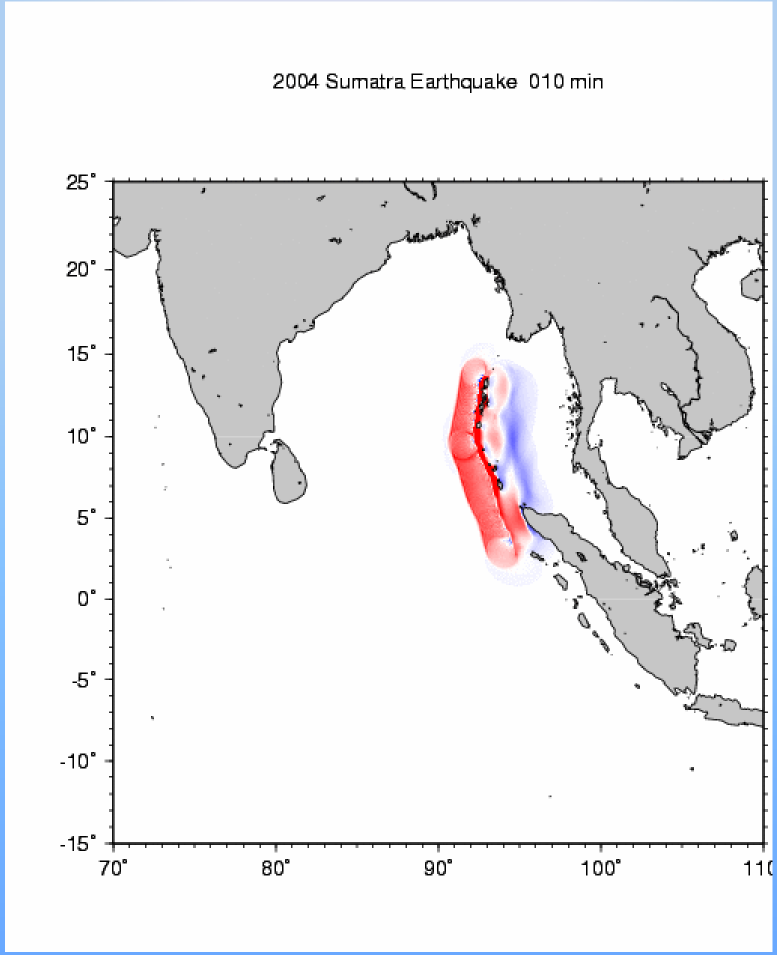




Tsunami = “harbor wave”

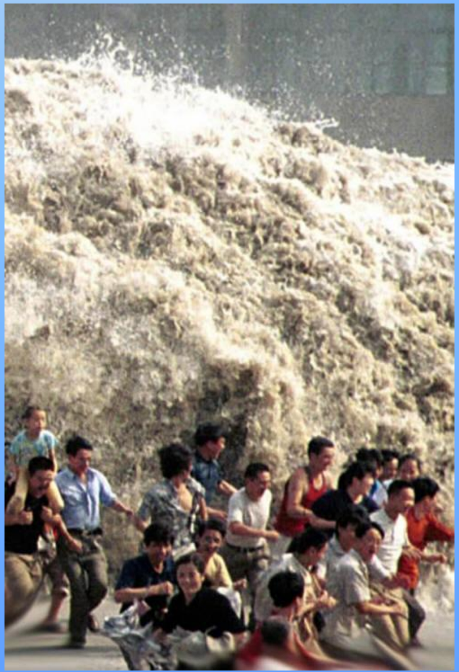

TSUNAMI
December 26, 2004
ASIA
Bangladesh
MIDDLE EAST
India
Myanmar
Thailand
N
Phuket Is
Sri Lanka
Malaysia
Maldives
Indonesia
Somalia
AFRICA
Seychelles
1000 mi
1000 km
INDIAN OCEAN
Australia
Madagascar
AFRICA
©GraphicMaps.com
Countries most affected by the Tsunami

Tsunami Animation



Sumatra Tsunami



Banda Aceh
On the Island of Sumatra

Japan Earthquake March 11, 2011

Magnitude: **9.0**
Location: **38.297°N, 142.372°E**
Depth: **30 km (18.6 miles)**
Region: **NEAR THE EAST COAST OF HONSHU, JAPAN**

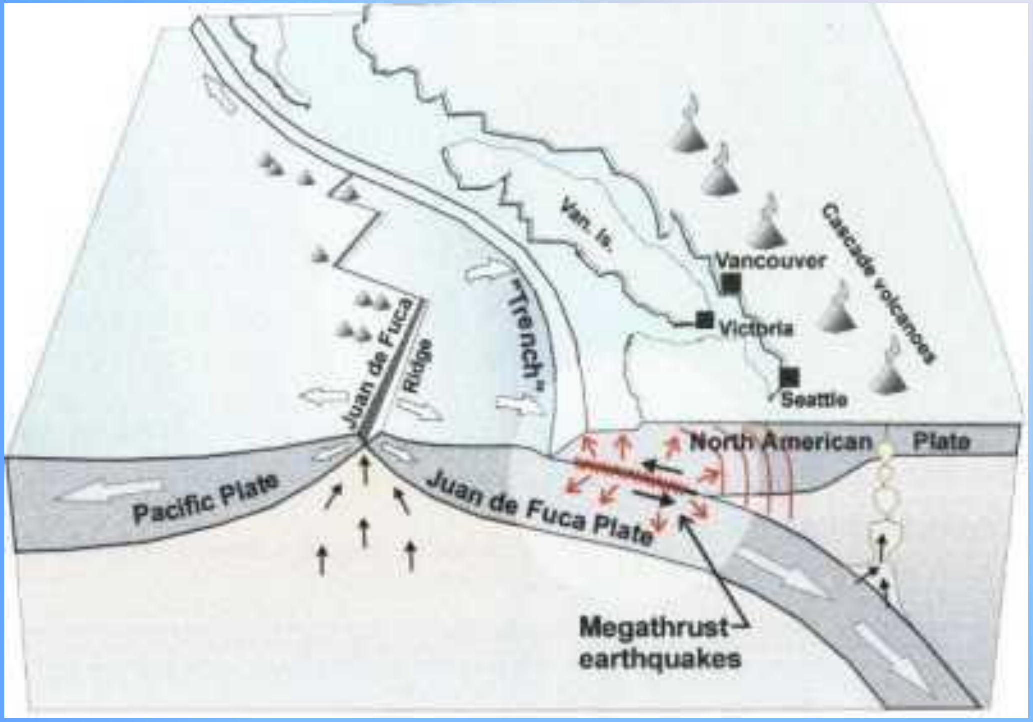
Summary:
At least 15,703 people killed, 4,647 missing, 5,314 injured, 130,927 displaced and at least 332,395 buildings, 2,126 roads, 56 bridges and 26 railways destroyed or damaged by the earthquake and tsunami

Tectonics: resulted from thrust faulting near the subduction zone plate boundary between the Pacific and North America plates. The Pacific plate moves approximately westwards with respect to the North America plate at a rate of 83 mm/yr, and begins its westward descent beneath Japan at the Japan Trench.

Modeling of the rupture of this earthquake indicate that the fault moved upwards of 30-40 m, and slipped over an area approximately 300 km long (along-strike) by 150 km wide (in the down-dip direction).

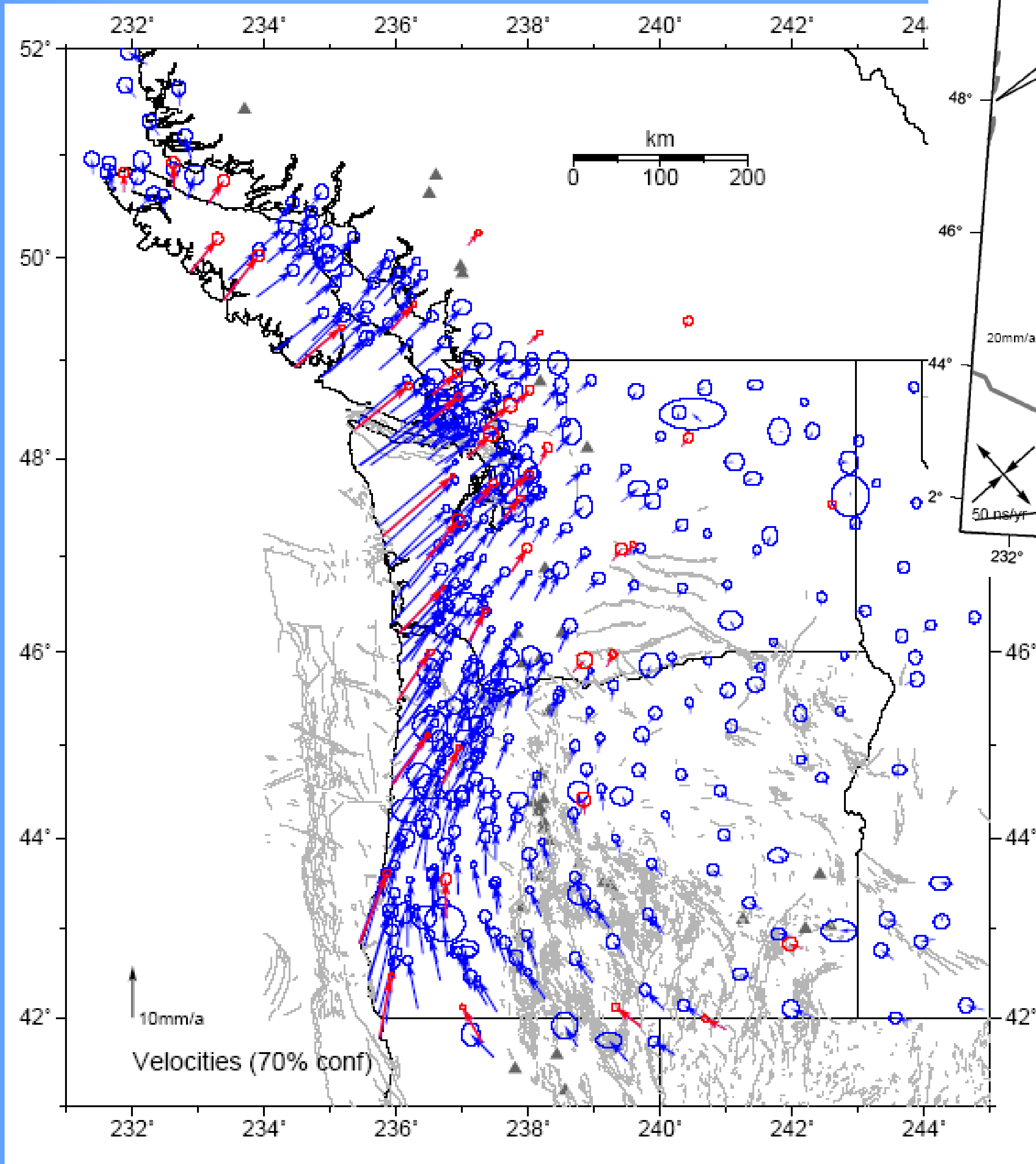
- http://www.youtube.com/watch?v=w3AdFjklR50

US Pacific Northwest

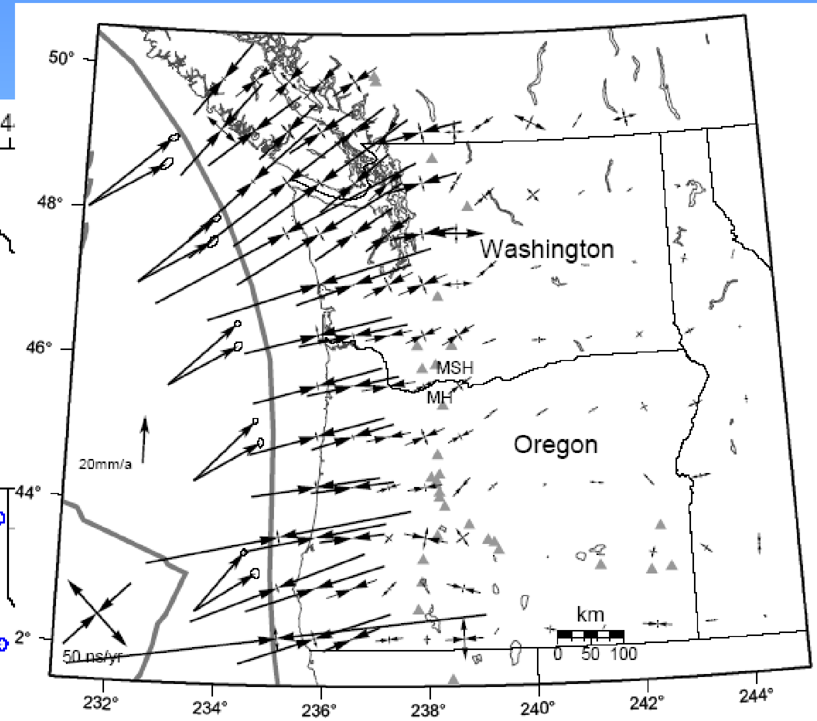


Coastal marshes buried by tsunami sands are clear evidence that tsunamis have struck the Oregon coast many times over the past few thousand years.

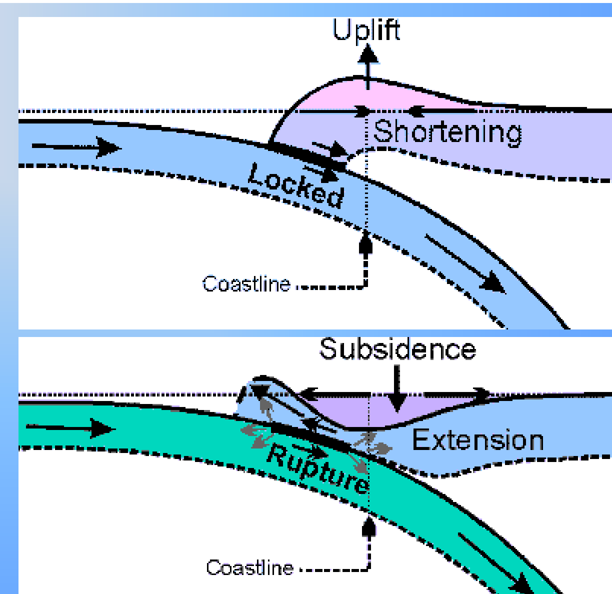
Offshore Oregon and Washington there sits a loaded subduction zone similar to the Sumatra subduction zone.



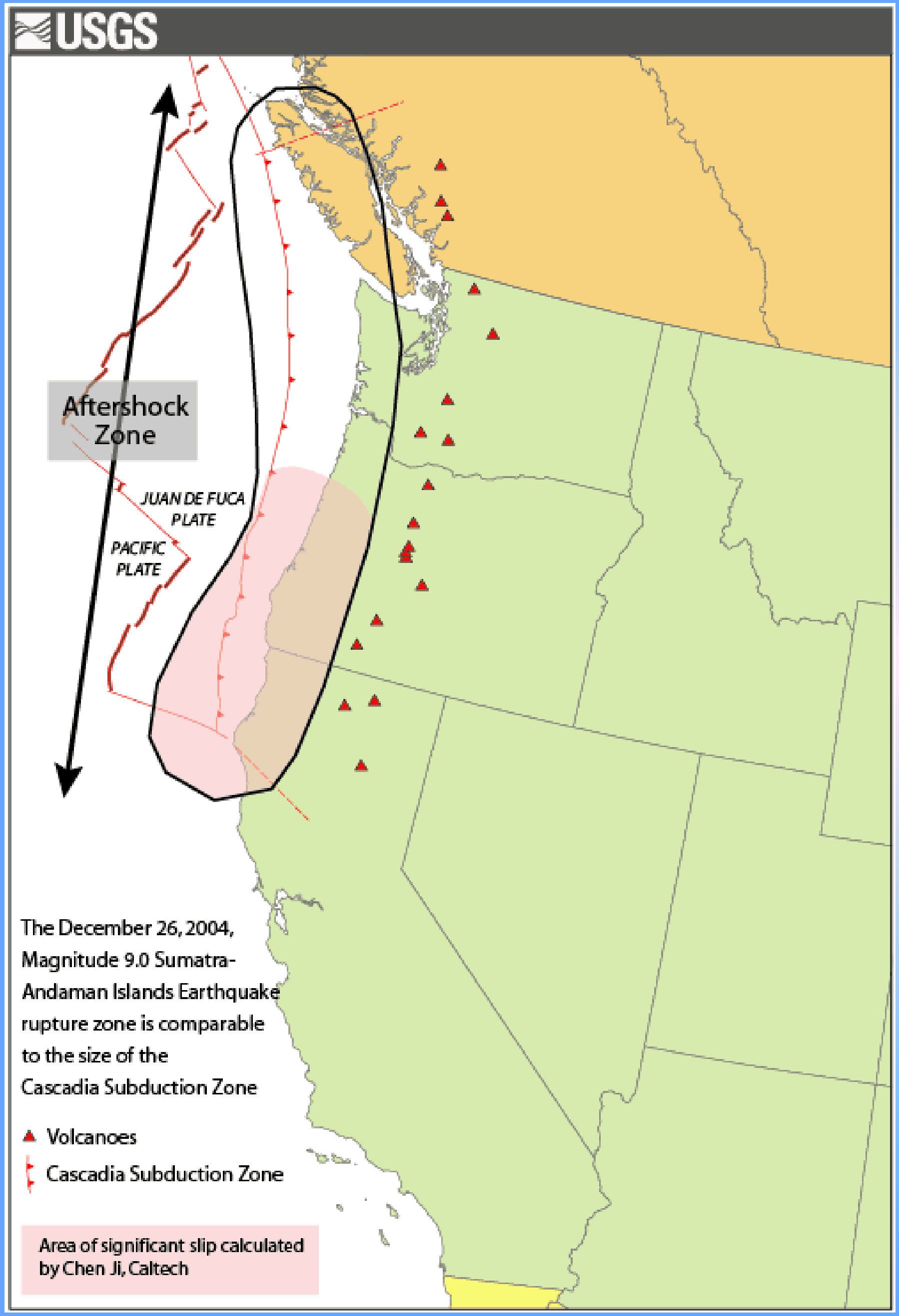
232° 234° 236° 238° 240° 242° 244°
52° 50° 48° 46° 44° 42°
km
0 100 200
10mm/a
Velocities (70% conf)



50° 48° 46° 44° 42°
232° 234° 236° 238° 240° 242° 244°
Washington
Oregon
MSH
MH
20mm/a
50 ns/yr
km
0 50 100

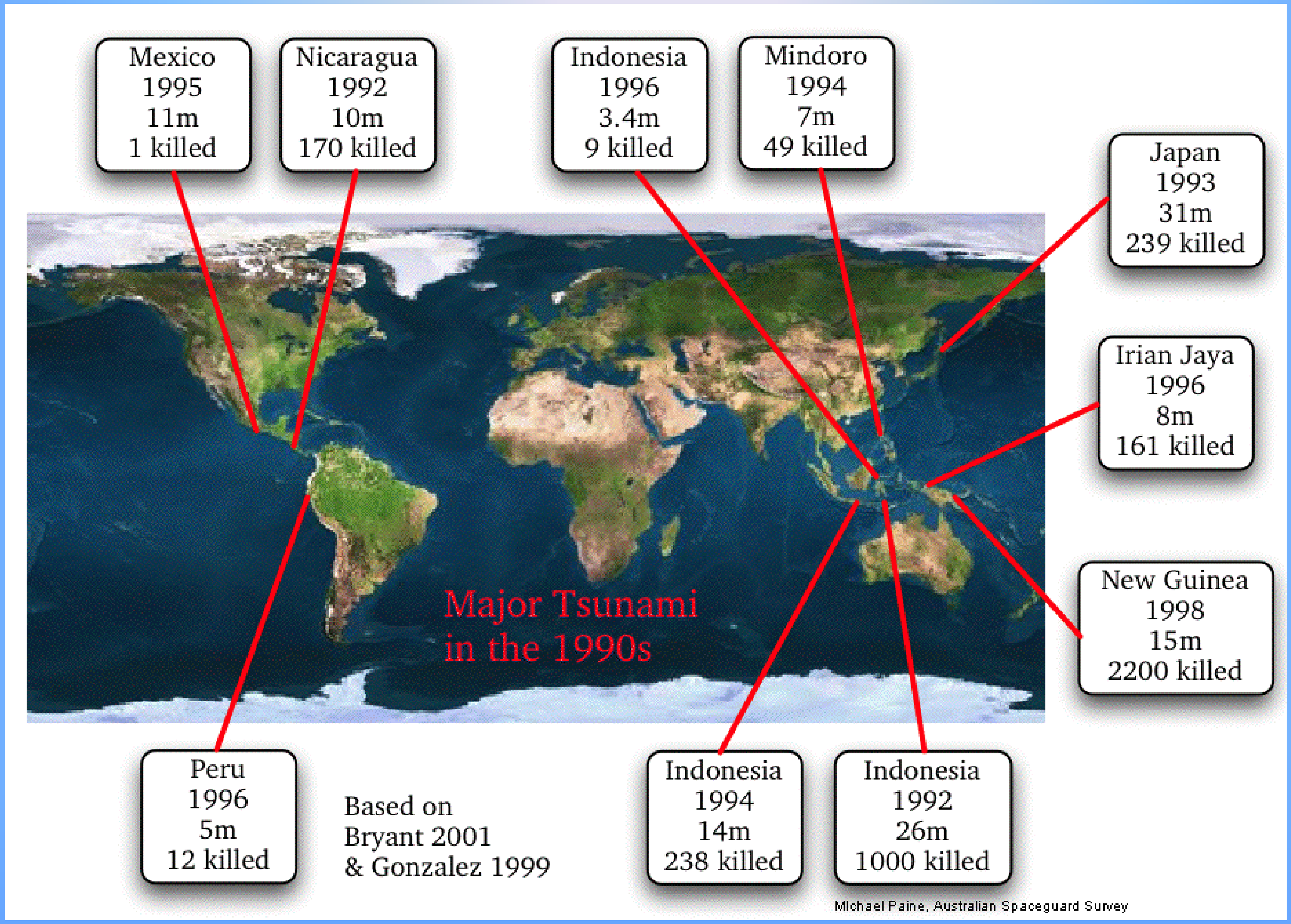


Uplift
Shortening
Locked
Coastline
Subsidence
Extension
Rupture
Coastline



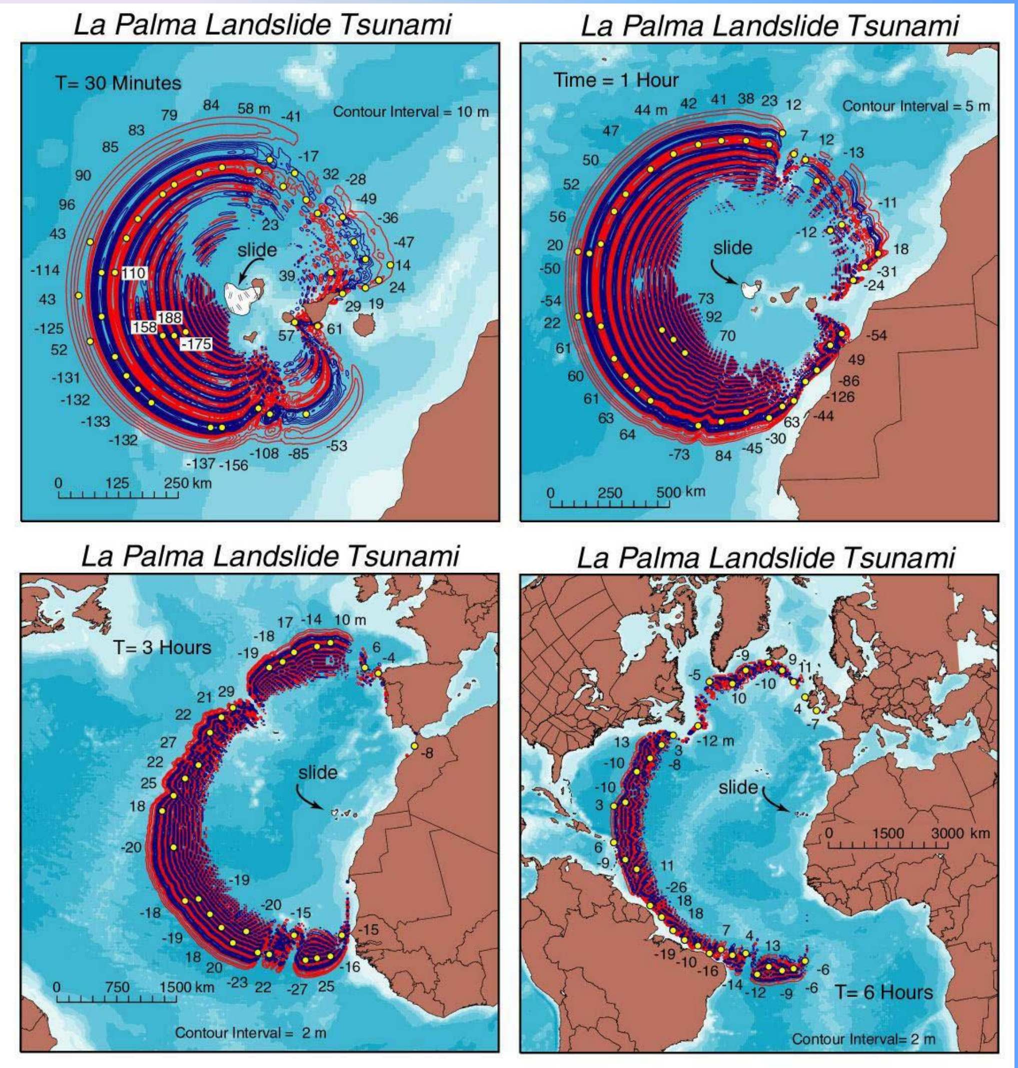
Sumatra fault area superimposed on US Pacific Northwest

Tsunamis of the 1990's



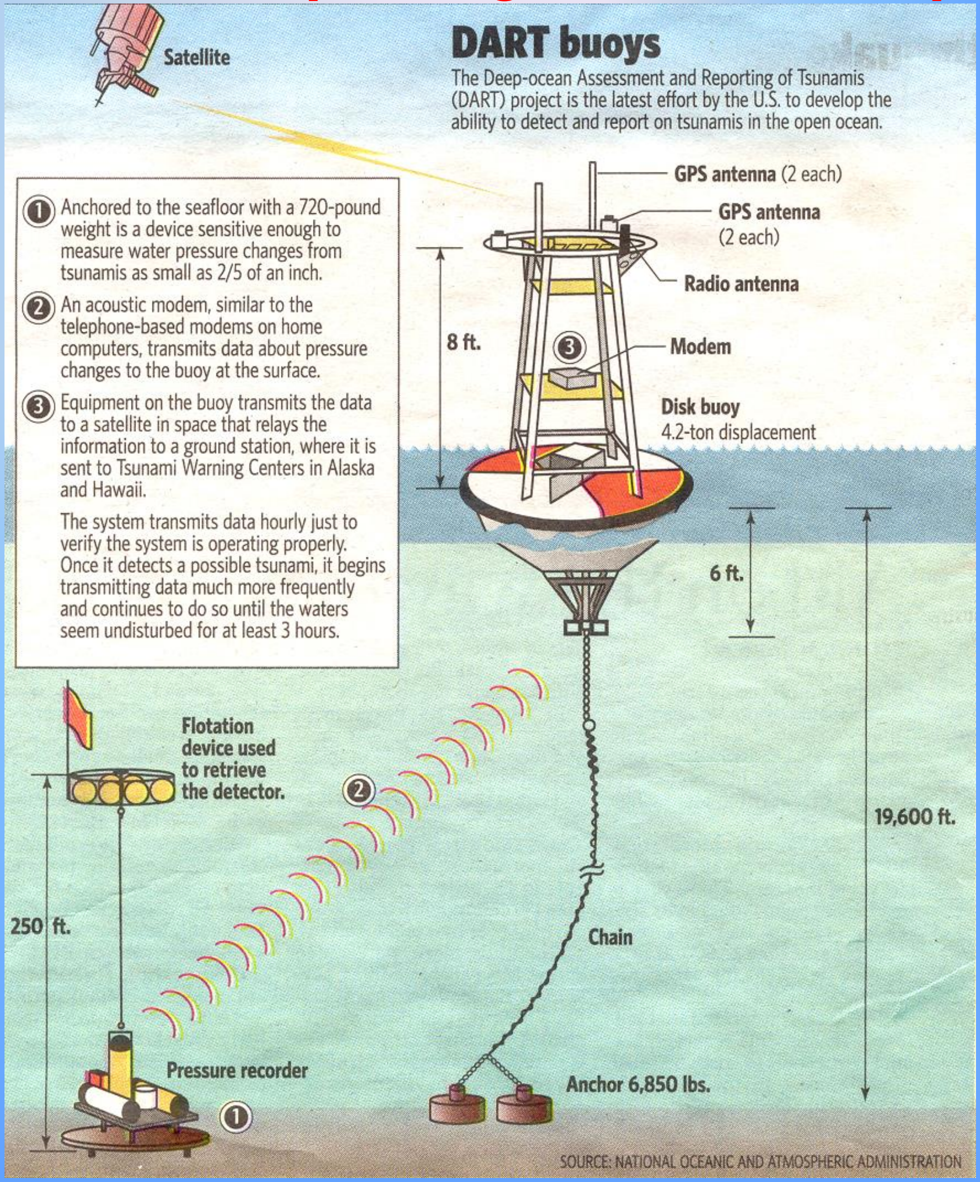
The Megatsunami

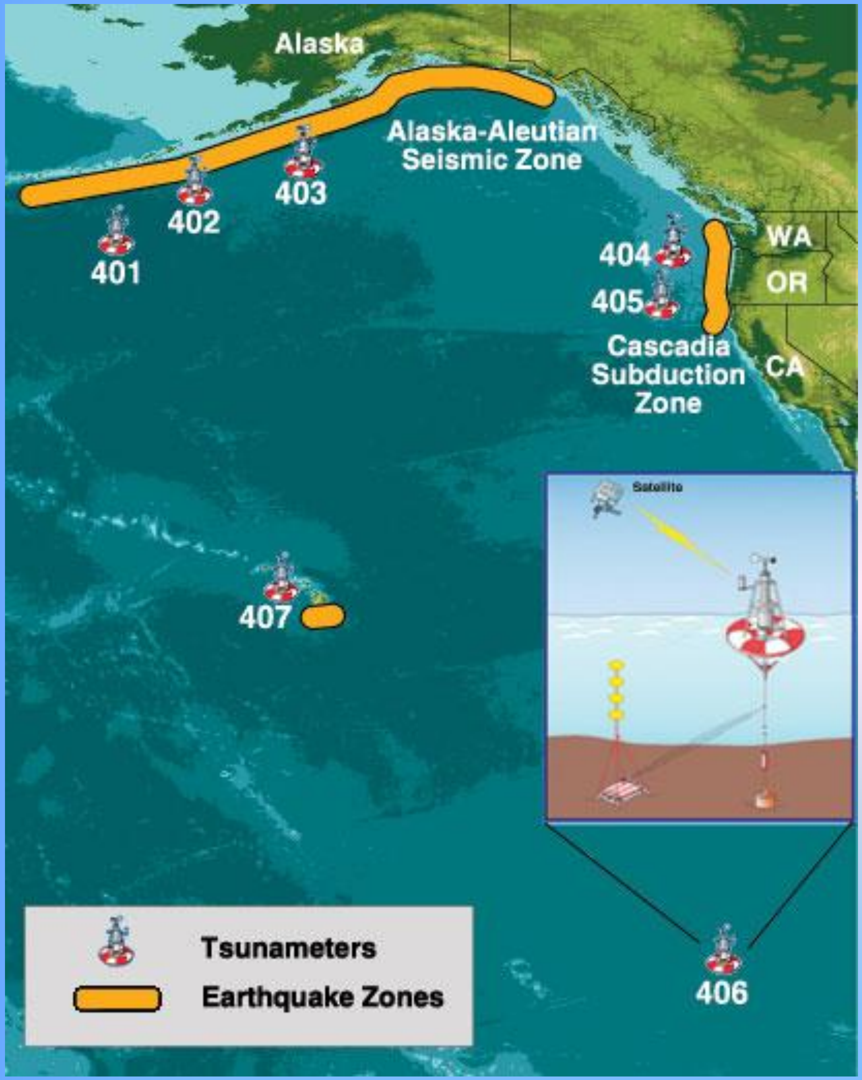
- La Palma
  - The most active volcano in the Canary Islands
  - The western part of the island could separate and 500 billion tons of rock and debris would hit the ocean
  - A tsunami 2x as high as the Empire State Building and traveling at 700 km/hr could be generated

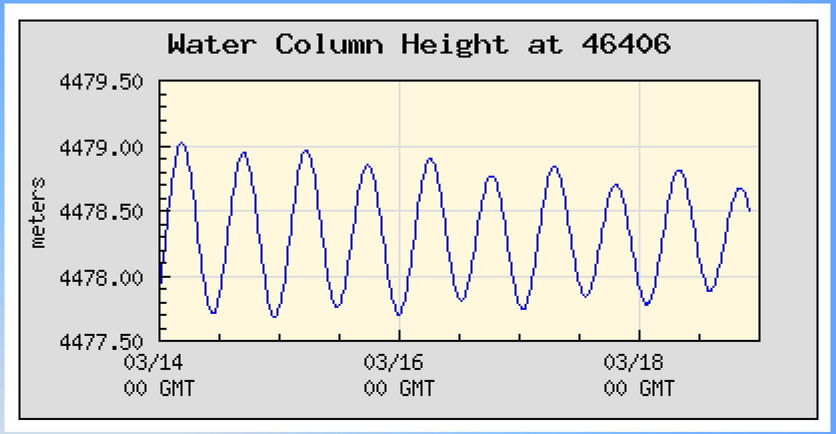


Pacific Warning System

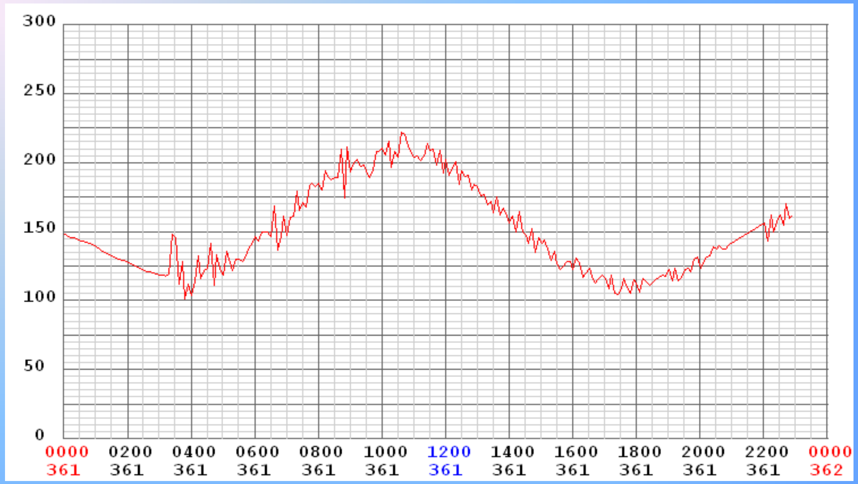
(Deep-ocean Assessment and Reporting of Tsunamis)





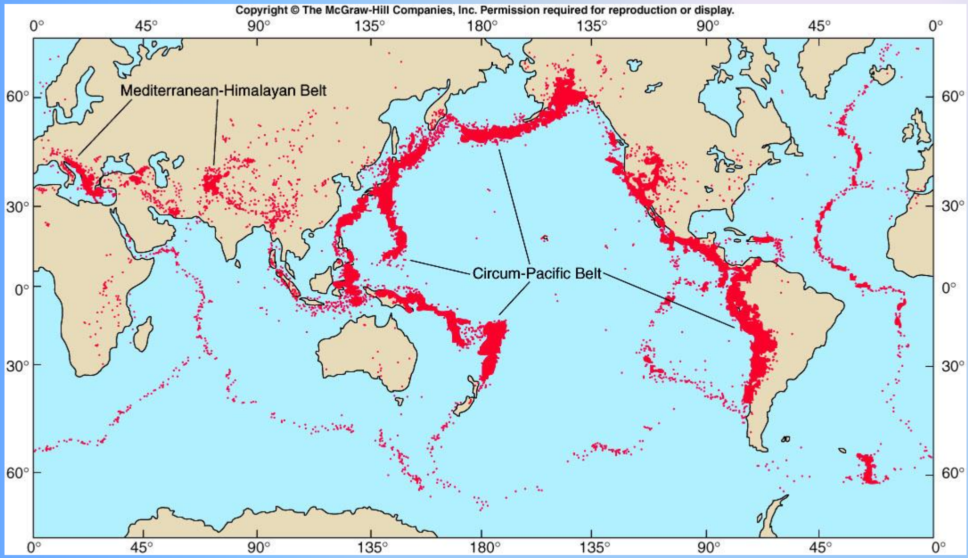


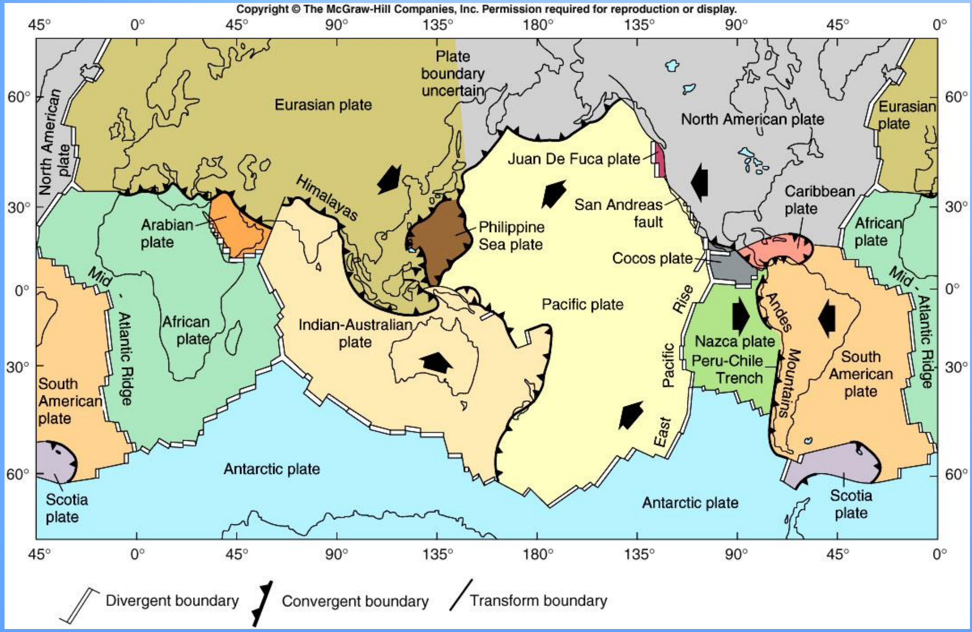
Normal tide gauge record



Record with passing tsunami

World Distribution of Earthquakes

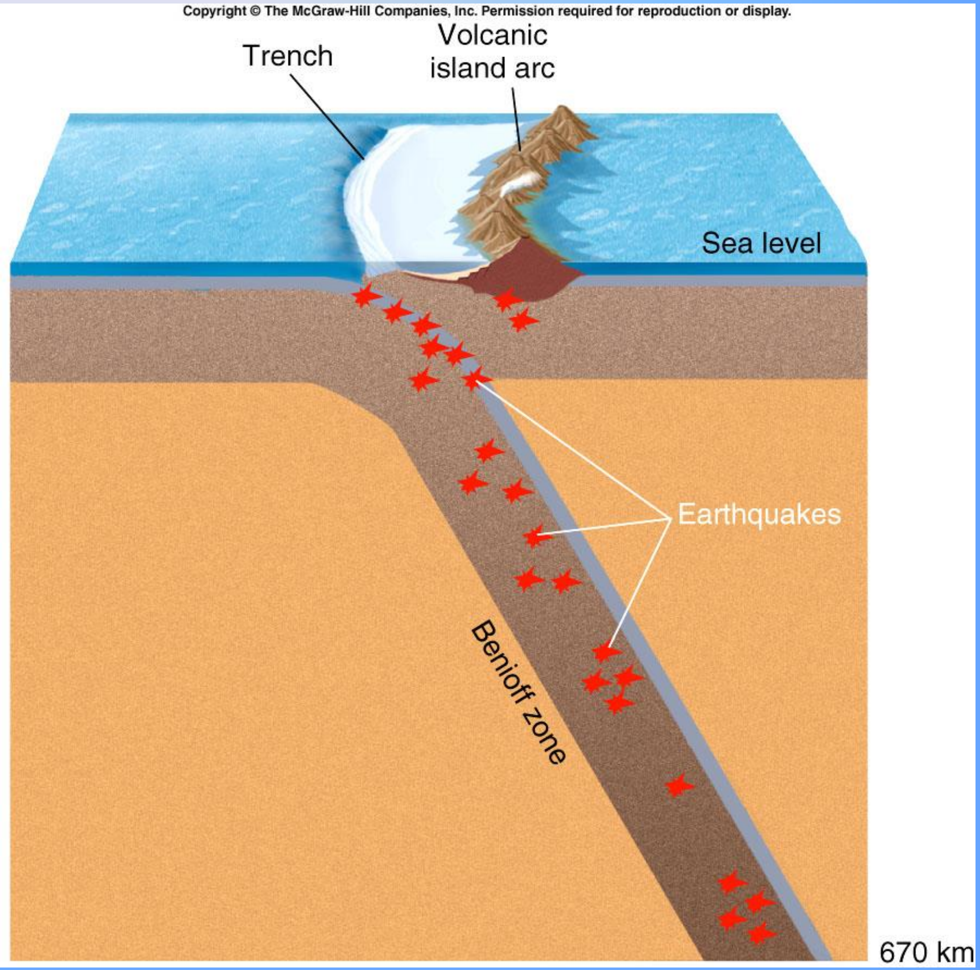




- Most earthquakes located in narrow geographic belts
- Belts correlated with plate boundaries
  - Circum-Pacific Belt
  - Mediterranean-Himalayan Belt
- Mid-Ocean Ridges
- Oceanic Trenches

Benioff Zones

- Earthquake zones beginning at ocean trenches
- Slope landward and downward at an angle of about 30º to 60º.
- Slopes under a continent or in a island arc.
- Make up most of the circum-Pacific belt
- Location of most intermediate an deep focus earthquakes



Earthquakes and Plate Boundaries

A. Using Seismographs for __First Motion__ Earthquake Studies

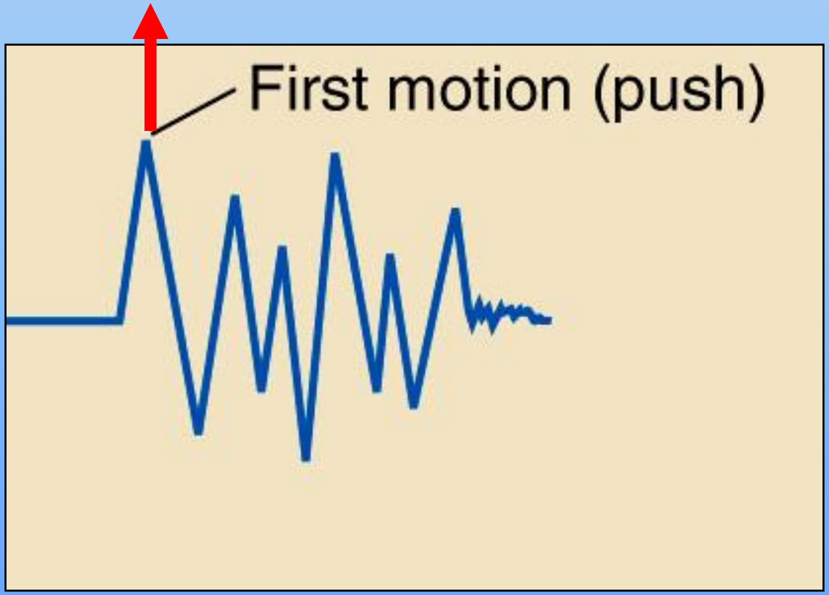
1. Used to determine overall movement along a plate boundary.
2. Pen motion represents the reaction of the P-Wave to rocks being pulled apart or compressed.
3. From the pen drawing on a seismogram first motion as a *push* or *pull* is determined.

a. ***Push***

i. First arrival waves cause the pen drawing to be deflected __**up**__.

ii. Rocks are moved __**towards**__ the seismograph location.

iii. Indicates the seismograph location experienced __**compression**__.

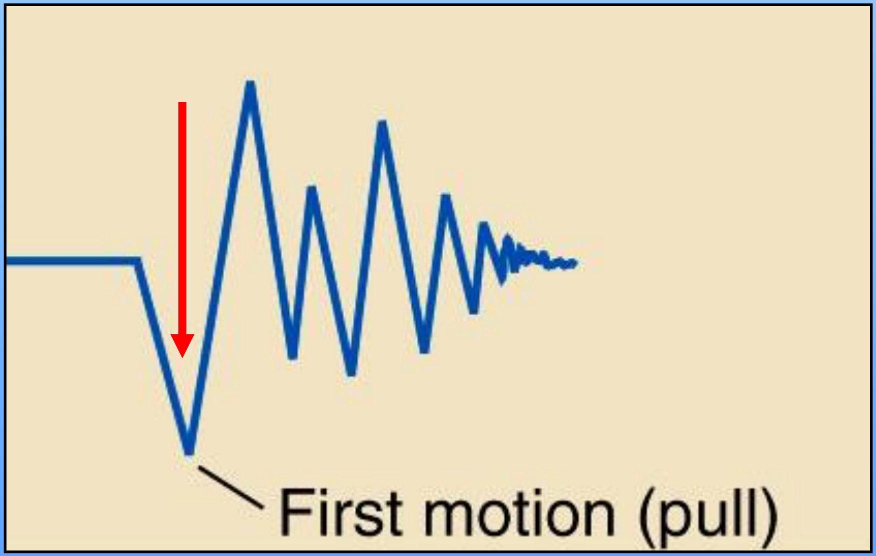


b. *Pull*

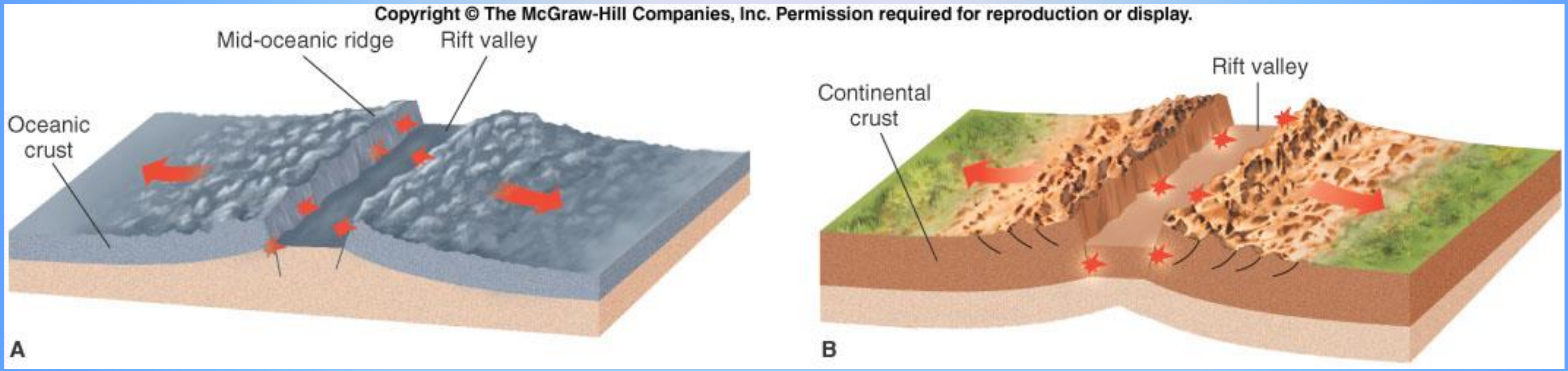
i. First arrival waves cause the pen drawing to be deflected __**down**__.

ii. Indicates rocks experienced __**dilation**__(were pulled apart).

iii. Rocks are moved __**away**__ from the seismograph station.



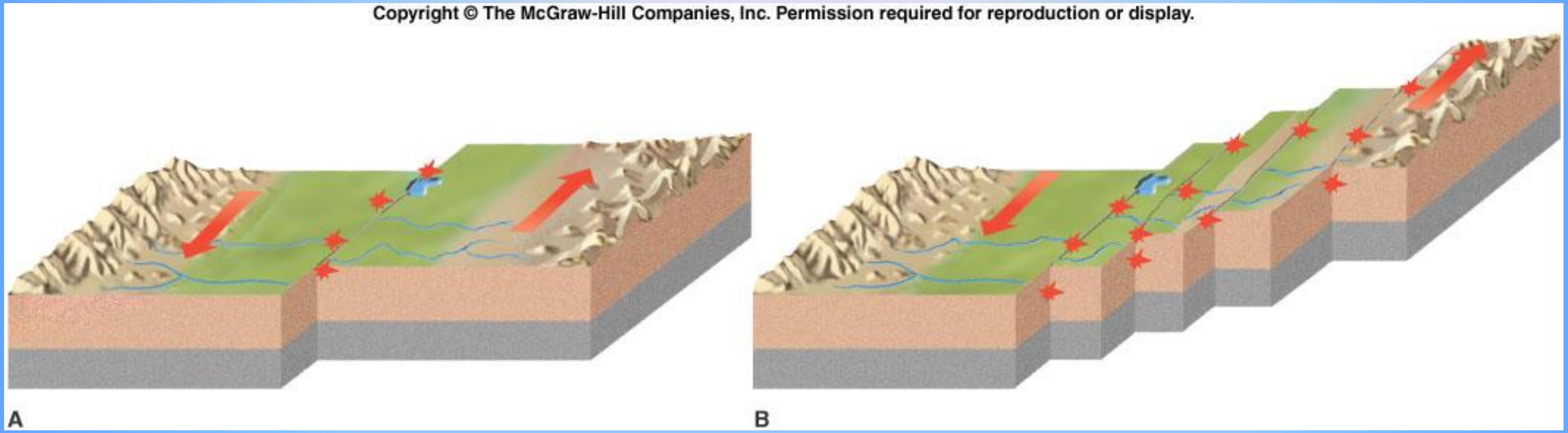
Divergent Boundaries



- **Shallow earthquakes**
- **Normal faulting**
- **First motion studies indicate extension along the ridge, indicating rifting**

- **Similar characteristics as mid-ocean ridges**
- **African rift is currently active**

Transform Boundaries



- *Shallow* earthquakes are located where plates move past each other.
- First motion studies indicate *strike-slip* motion.
- Earthquakes may be aligned in a narrow band along one faults forming a plate boundary (as with the San Andreas fault).
- .Earthquakes may form a broader zone along a system of parallel faults
  - Basin and Range faults in western U.S.
  - System of faults parallel and at an angle to the San Andreas forms a plate boundary at that location.

Convergent Boundaries

- Collision boundaries with shallow earthquakes
- Shallow earthquakes on outer part of trench result in normal faults
- Underthrusting – shallow earthquakes due to shallow subducting angle.
- Deep earthquakes probably due to mineral transformations