

Giant Earthquakes: Why, Where, When, and What We Can Do

Seth Stein, Northwestern University



December 2004 Indian Ocean earthquake and tsunami



October 2005 Pakistan earthquake



SAN FRANCISCO EARTHQUAKE

April 18, 1906

3000 deaths
28,000 buildings
destroyed
(most by fire)
\$10B damage



“The whole street was undulating as if the waves of the ocean were coming toward me.”

“I saw the whole city enveloped in a pile of dust caused by falling buildings.”

“Inside of twelve hours half the heart of the city was gone”



EMERGENCY RESPONSE



Mayor formed citizen committee & took charge

Army immediately supported police & fire (how well?)

Prompt state, federal, & private aid

Displaced housed in tent cities with services

Free postal service provided

Tendency to blame fire rather than earthquake for damage

Eventually, earthquake damage accepted & safer buildings required



**“If, as they say,
God spanked the
town for being
over frisky**

**Why did he burn
the churches
down and spare
Hotaling's
whiskey?”**



What caused it?

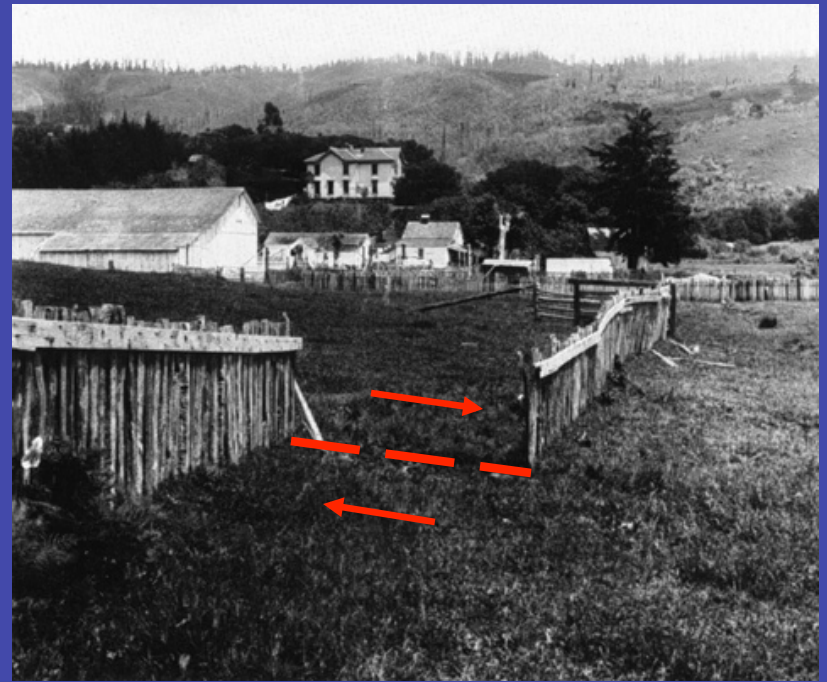
**What shook the
buildings?**

THE GROUND MOVED!

Average 12 feet (4 m)
of motion

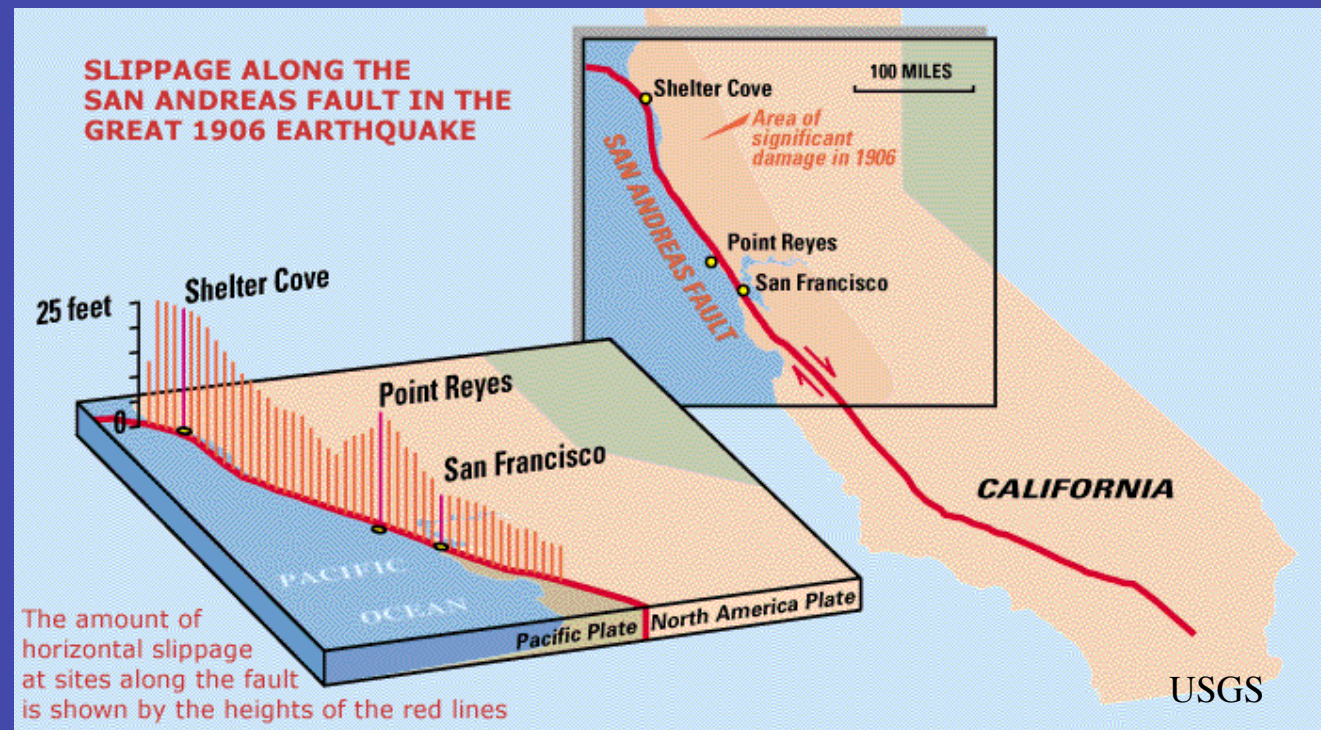
West side moved north

Motion along hundreds of
miles of San Andreas Fault



What is
the fault?

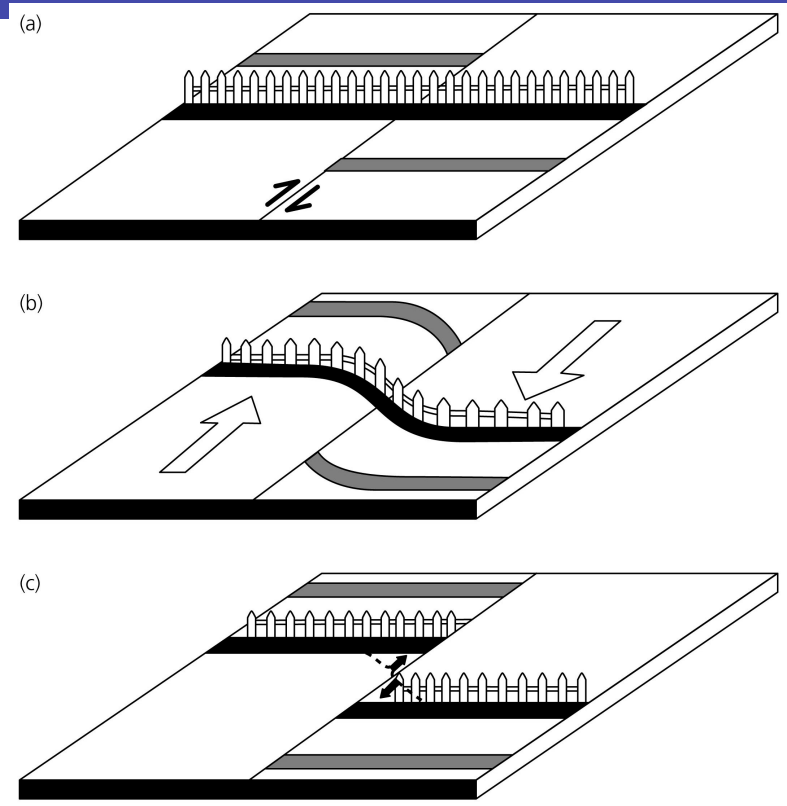
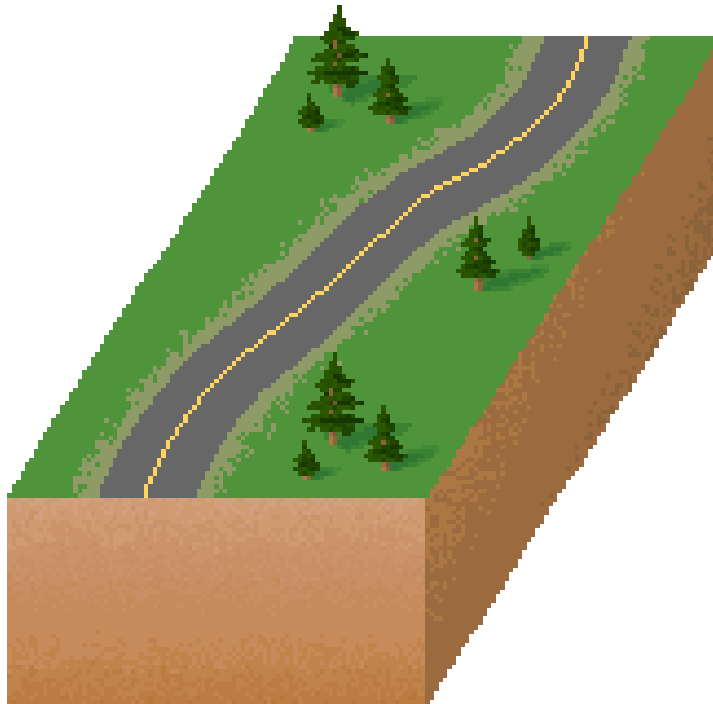
Why
does the
ground
move?



ELASTIC REBOUND

Over many years, rocks on opposite sides of the fault move, but friction on the fault "locks" it and prevents slip

Eventually strain stored is more than fault rocks can withstand, and the fault slips in earthquake



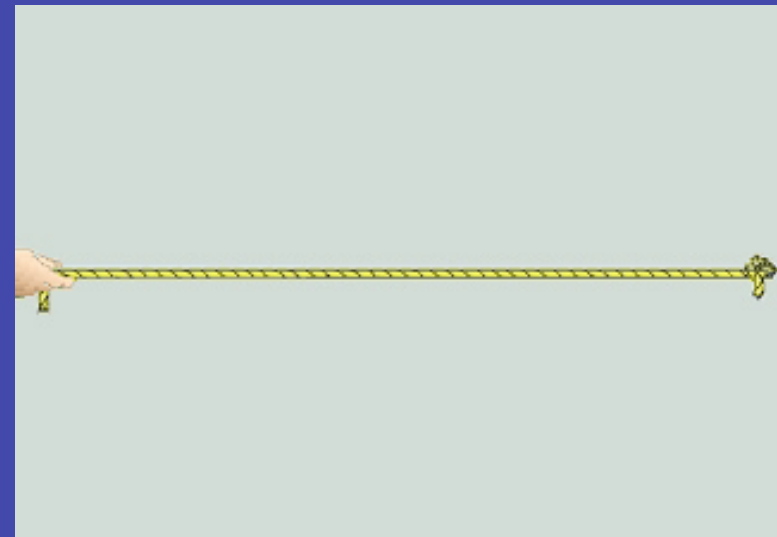
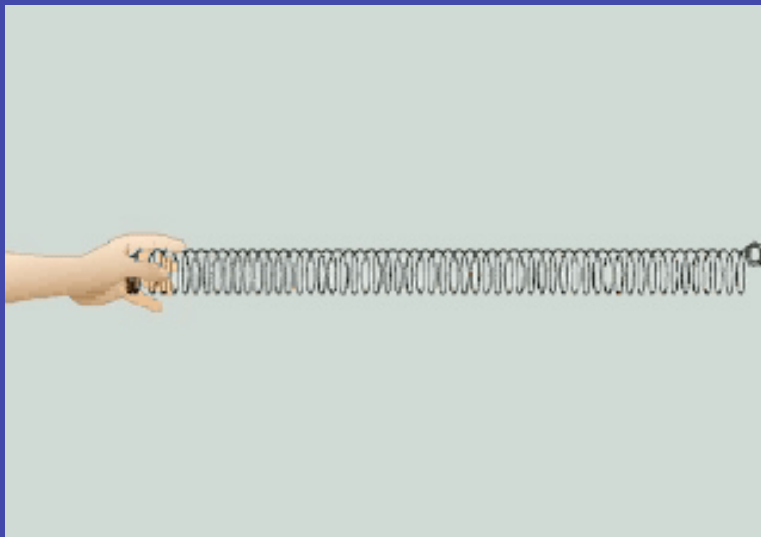
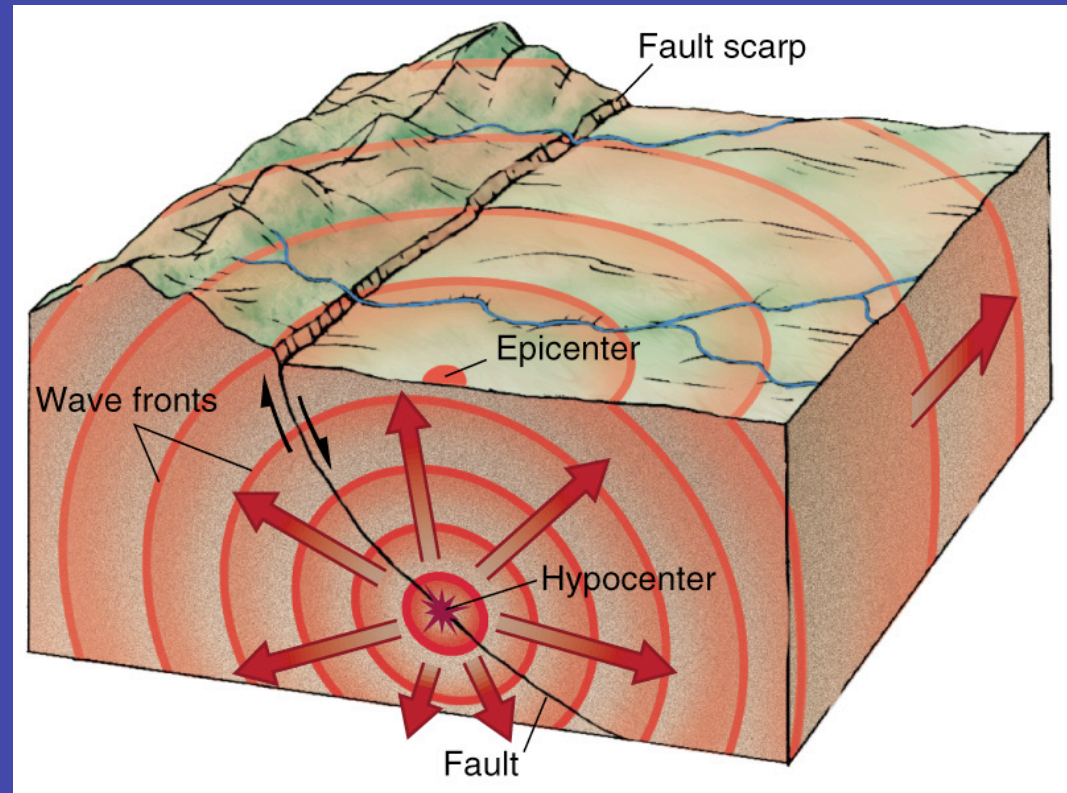
Took 60 years to figure out why this happens!

WHAT SHOOK THE BUILDINGS?

MOVEMENT OF THE FAULT GENERATED SEISMIC WAVES

Travel through solid earth

Like sound waves, light (electromagnetic) waves, or water waves



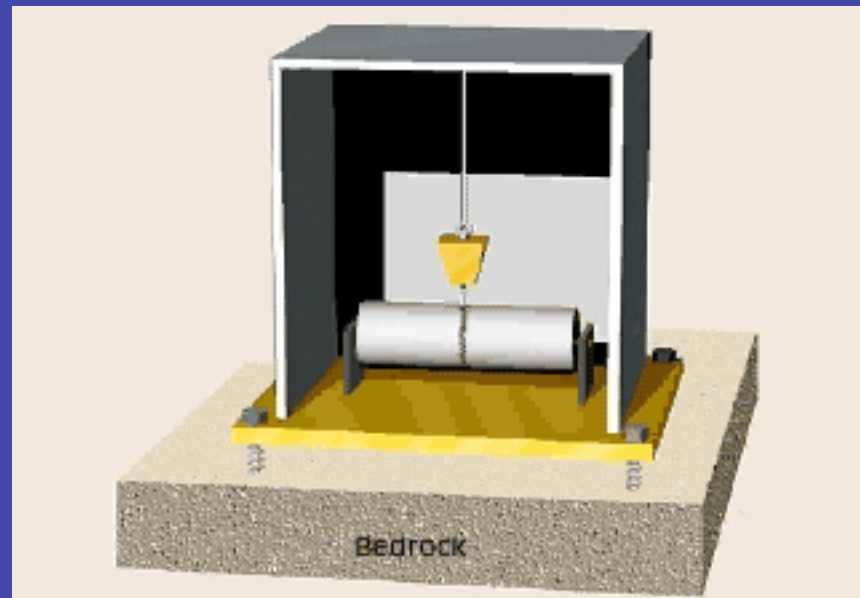
RECORD MOTION OF GROUND (SEISMIC WAVES) WITH INSTRUMENT ON GROUND

2nd century Chinese seismograph

Balls come from dragon's mouth when waves arrive



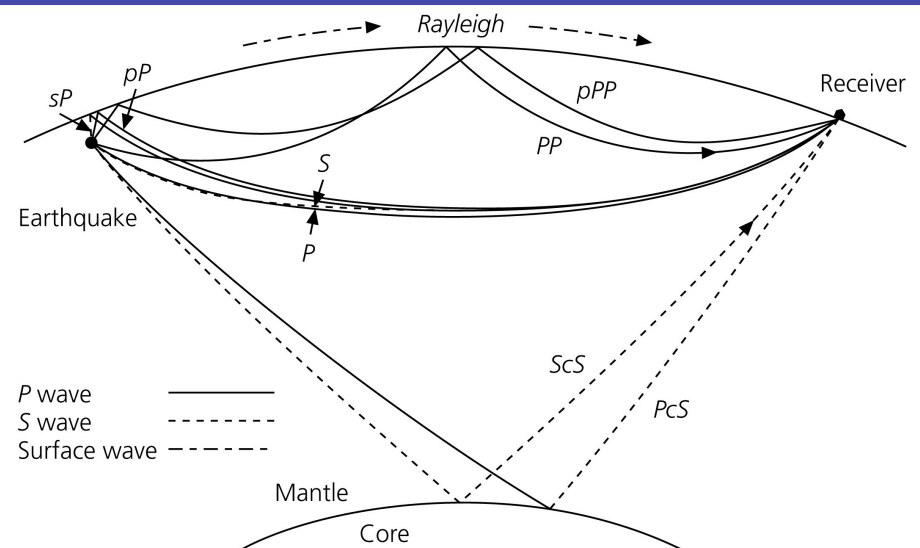
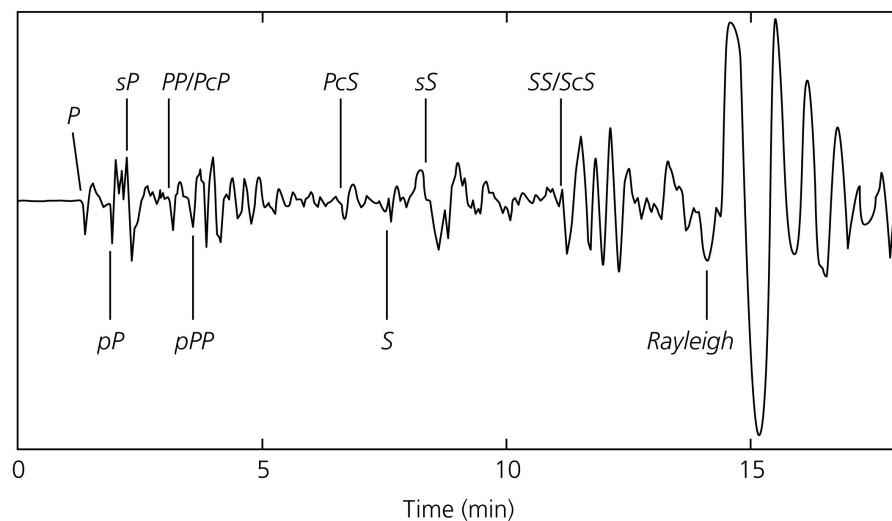
Seismometer - spring & mass system records ground motion with time



- 3 components (north-south; east-west, up-down)
- Precise timing (GPS satellites)
- Amplitude calibrated
- Digital recording and data available on WWW

SEISMIC WAVES TRAVEL THROUGH EARTH

Use to study
earthquakes &
structure of the
earth

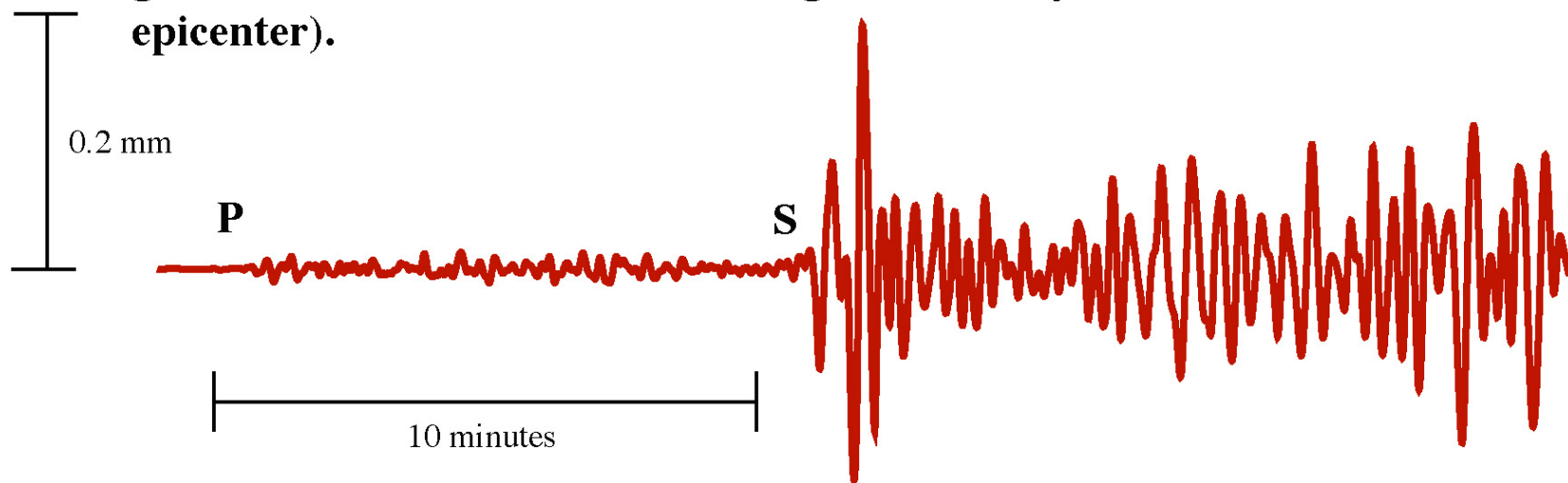


Where was the earthquake?

How big was it (magnitude)?

Which way did the ground move?

1906 San Francisco Earthquake ($M_w = 7.9$) seismogram (N-S ground motion) recorded in Göttingen, Germany (9080 km from epicenter).



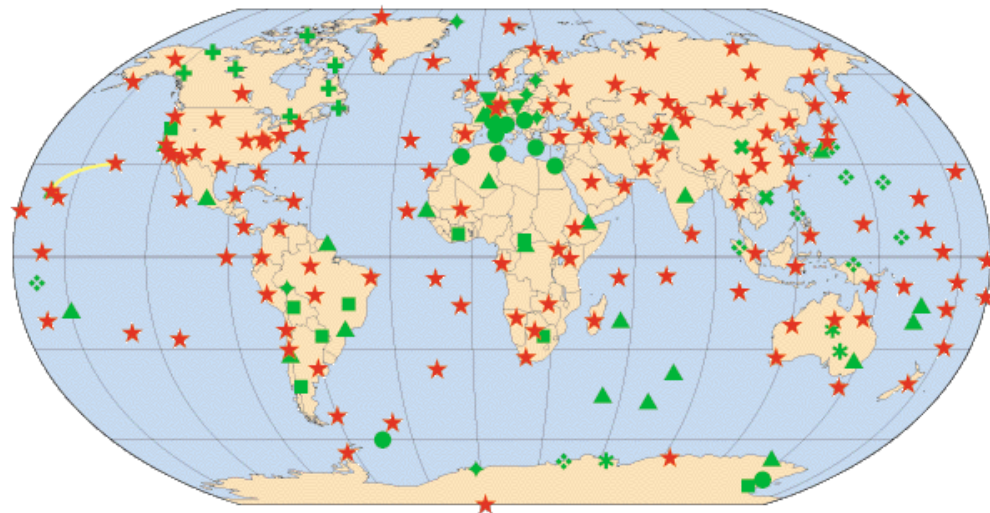
EARTHQUAKE LOCATION

Use times when seismic waves arrive at many seismometers to find

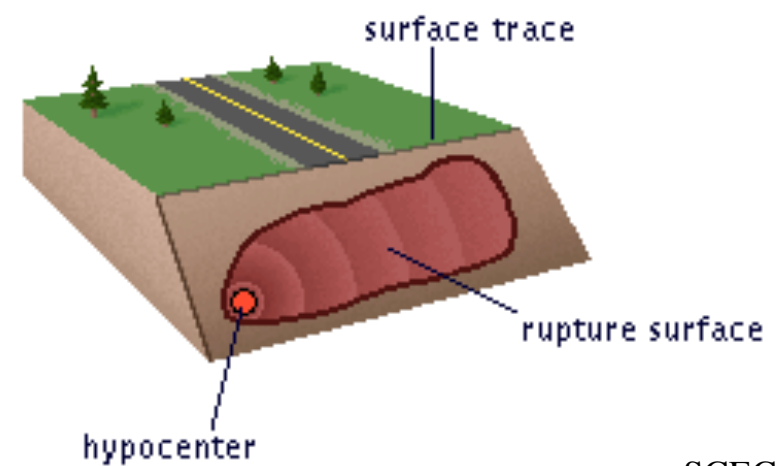
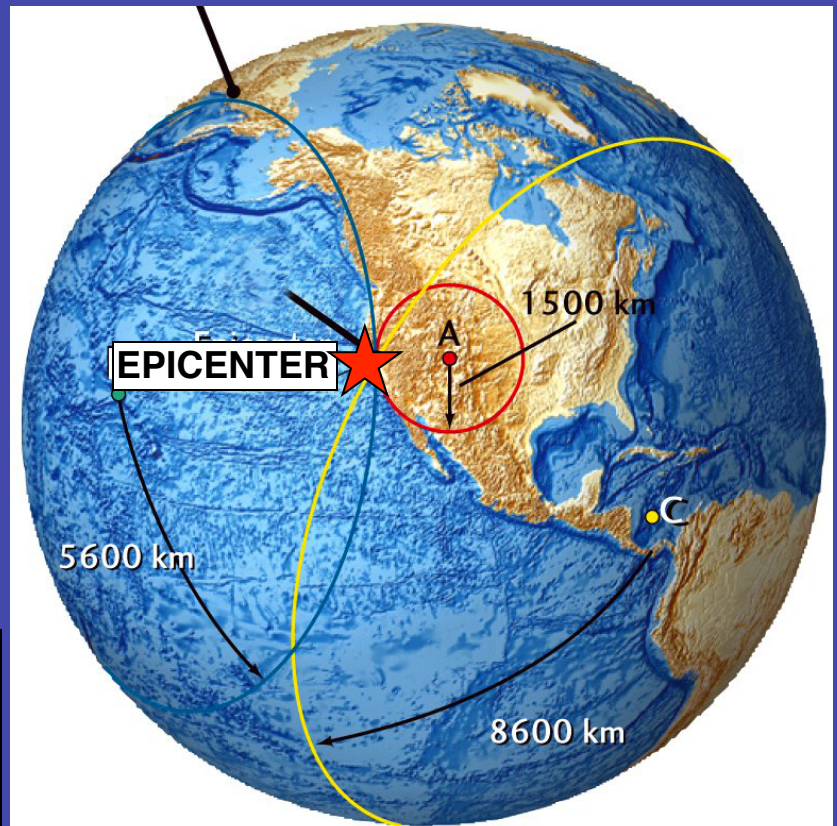
Epicenter - position on surface

Hypocenter - location & depth

GSN & FEDERATION OF DIGITAL BROADBAND SEISMIC NETWORKS (FDSN)

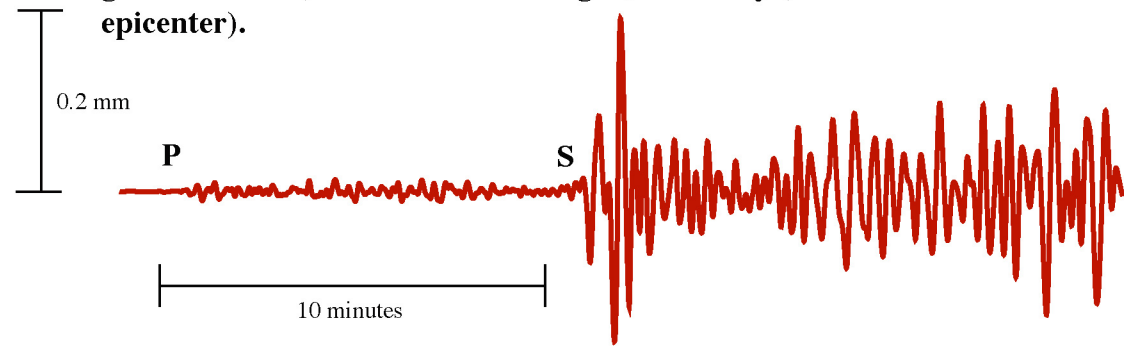


IRIS GSN France Japan Italy Germany China Australia U.S. Canada Other
★ ▲ ◆ ● ✦ ✧ ✨ □ ✚ ▼



HOW BIG ? USE MAGNITUDE

1906 San Francisco Earthquake ($M_w = 7.9$) seismogram (N-S ground motion) recorded in Göttingen, Germany (9080 km from epicenter).



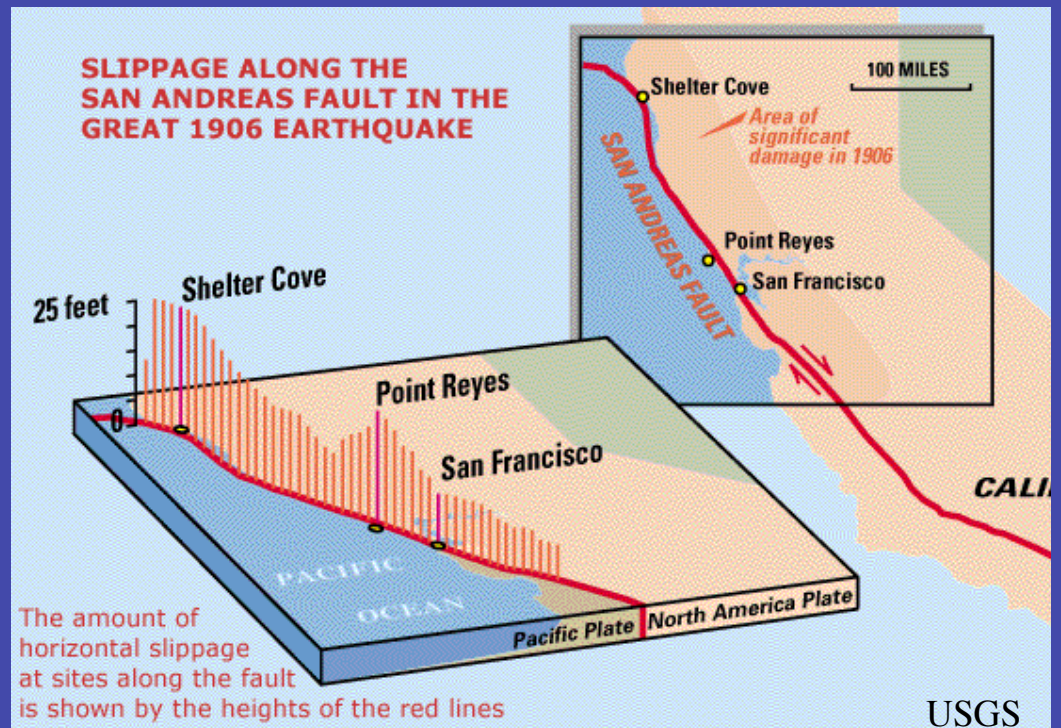
1906 magnitude 7.9

Bigger earthquakes:

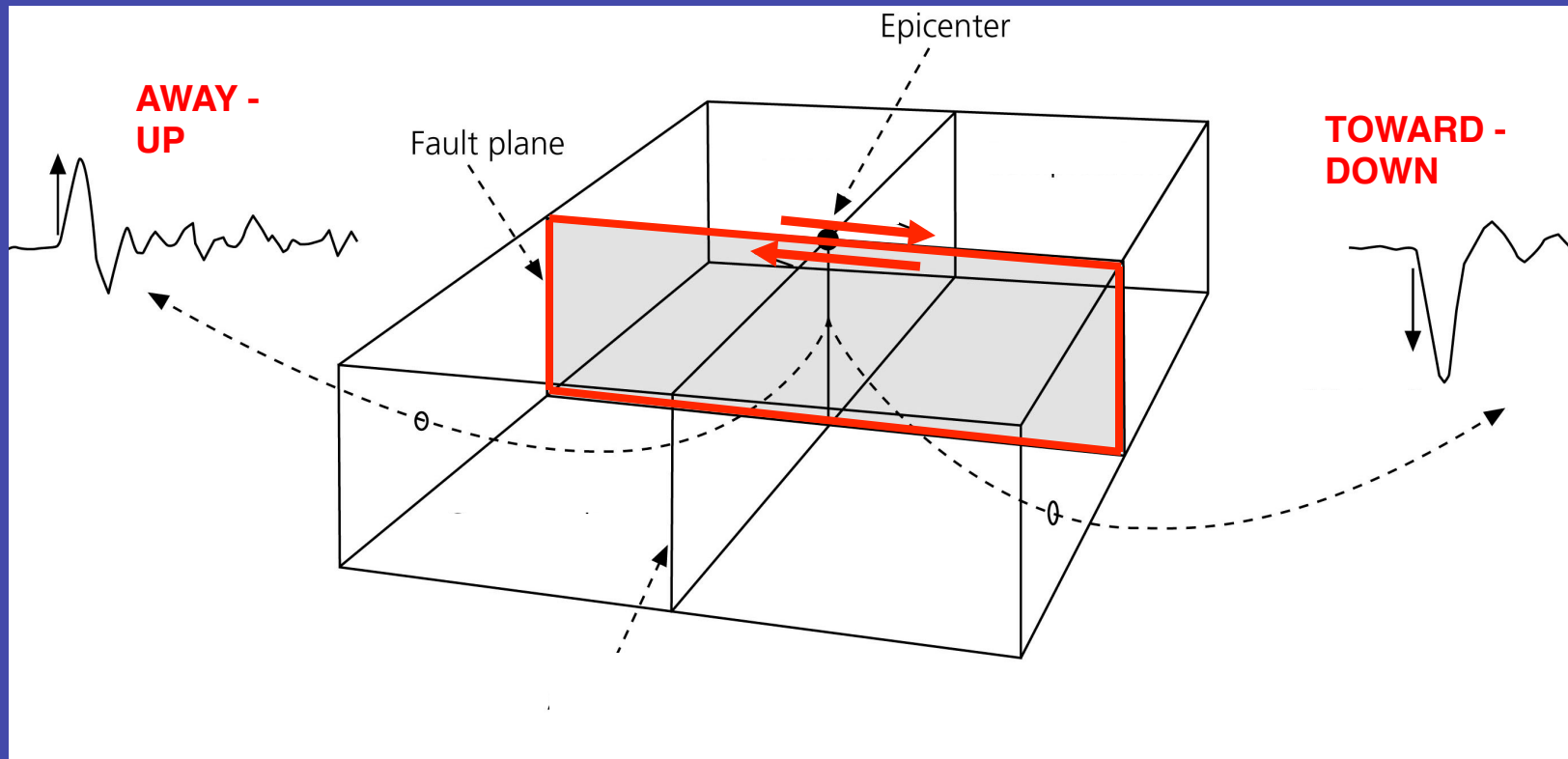
Longer faults

Faulting to greater depth

Ground moves further



HOW DID THE FAULT MOVE?



Shapes of seismic wave pulses depend on where seismometer is relative to the fault

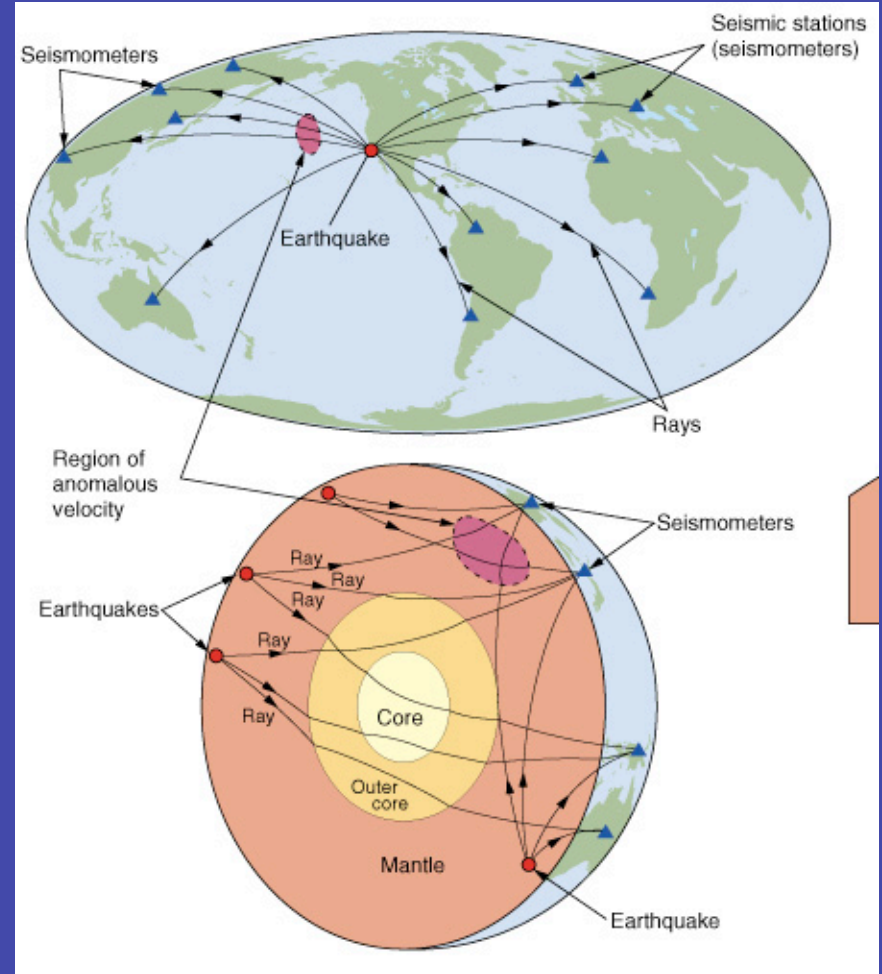
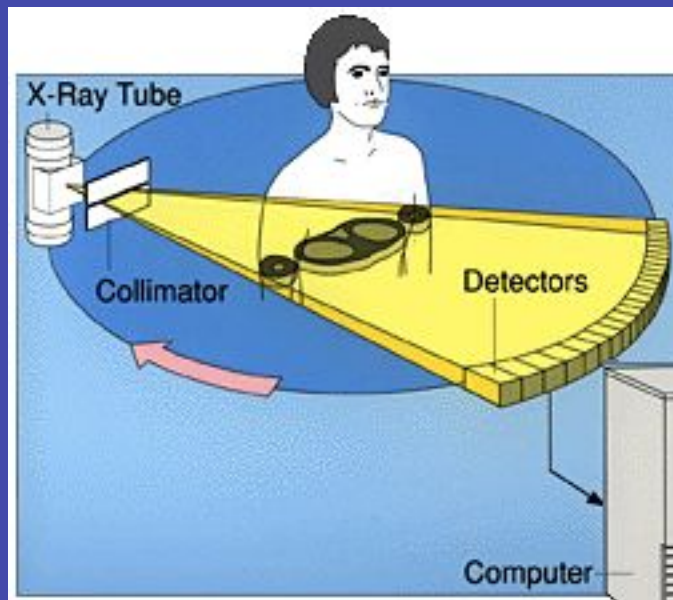
SEISMIC WAVES LET US "SEE" INSIDE THE EARTH

Like we do with:

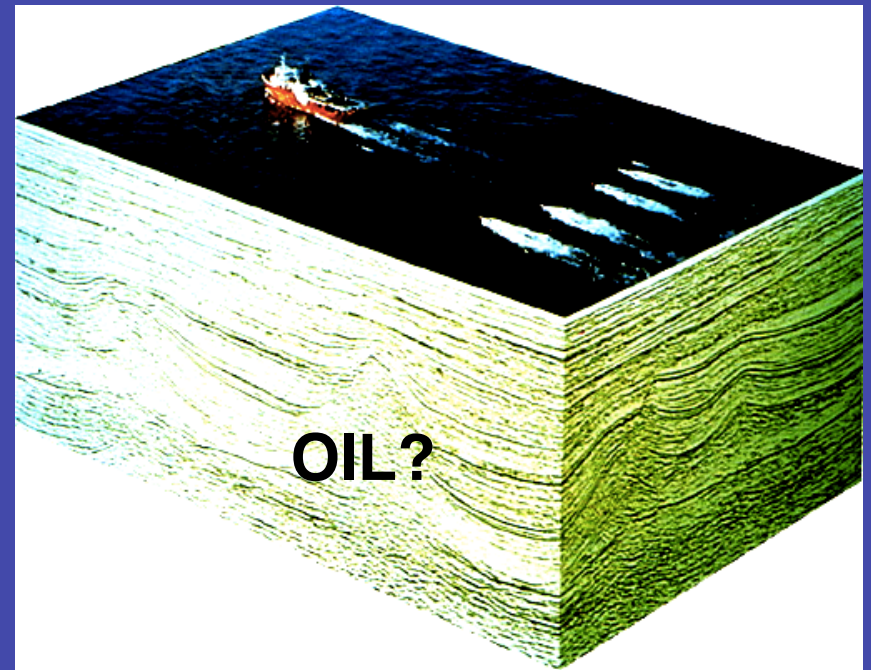
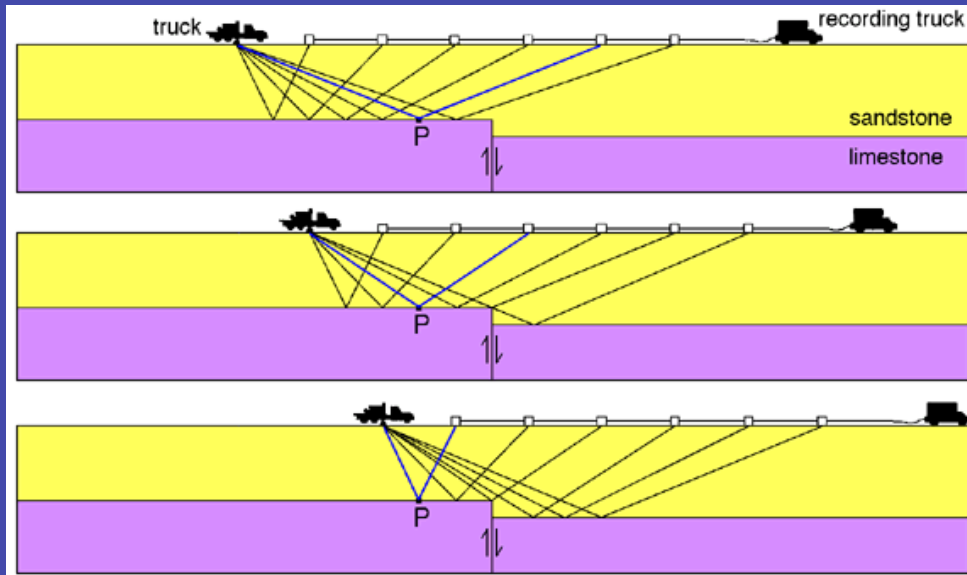
Light waves

Sound waves

X-rays



LOOK FOR OIL & GAS



OR MUCH DEEPER...

SEISMOLOGY SHOWS EARTH IS A LAYERED PLANET

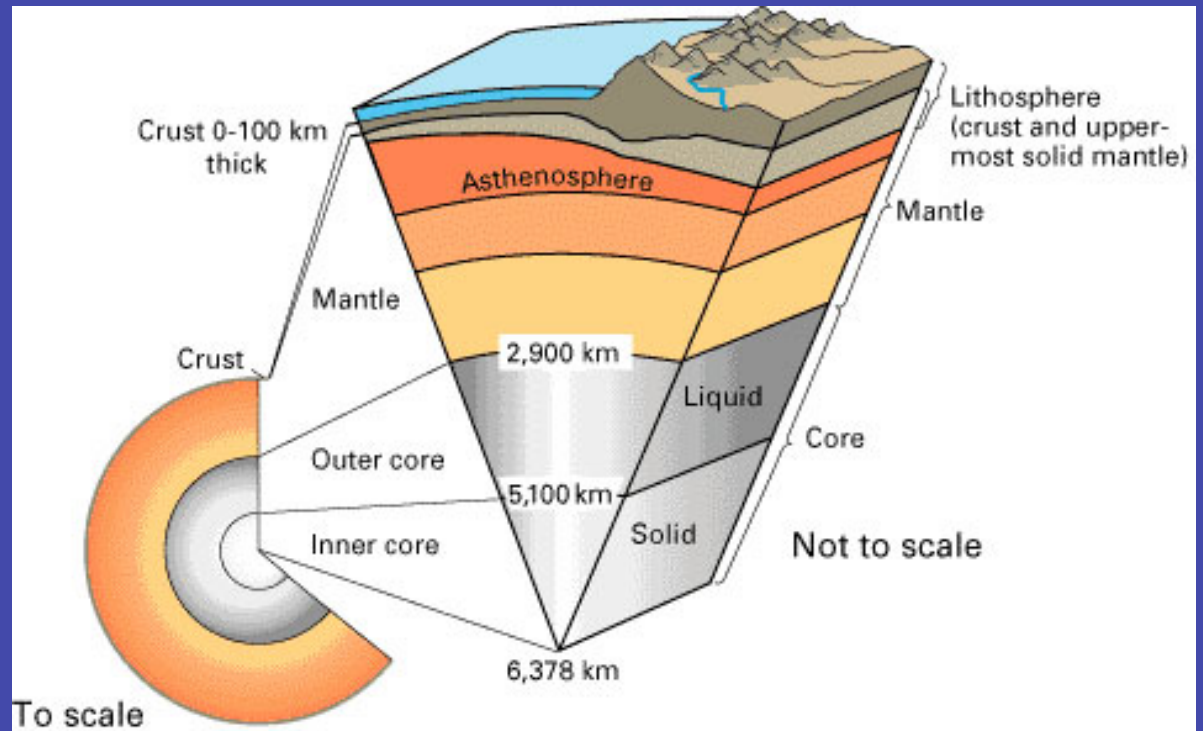
LAYERS EVOLVED OVER BILLIONS OF YEARS

COLD, STRONG
100 km OUTER
LAYER:

THE PLATES
("thin scum")

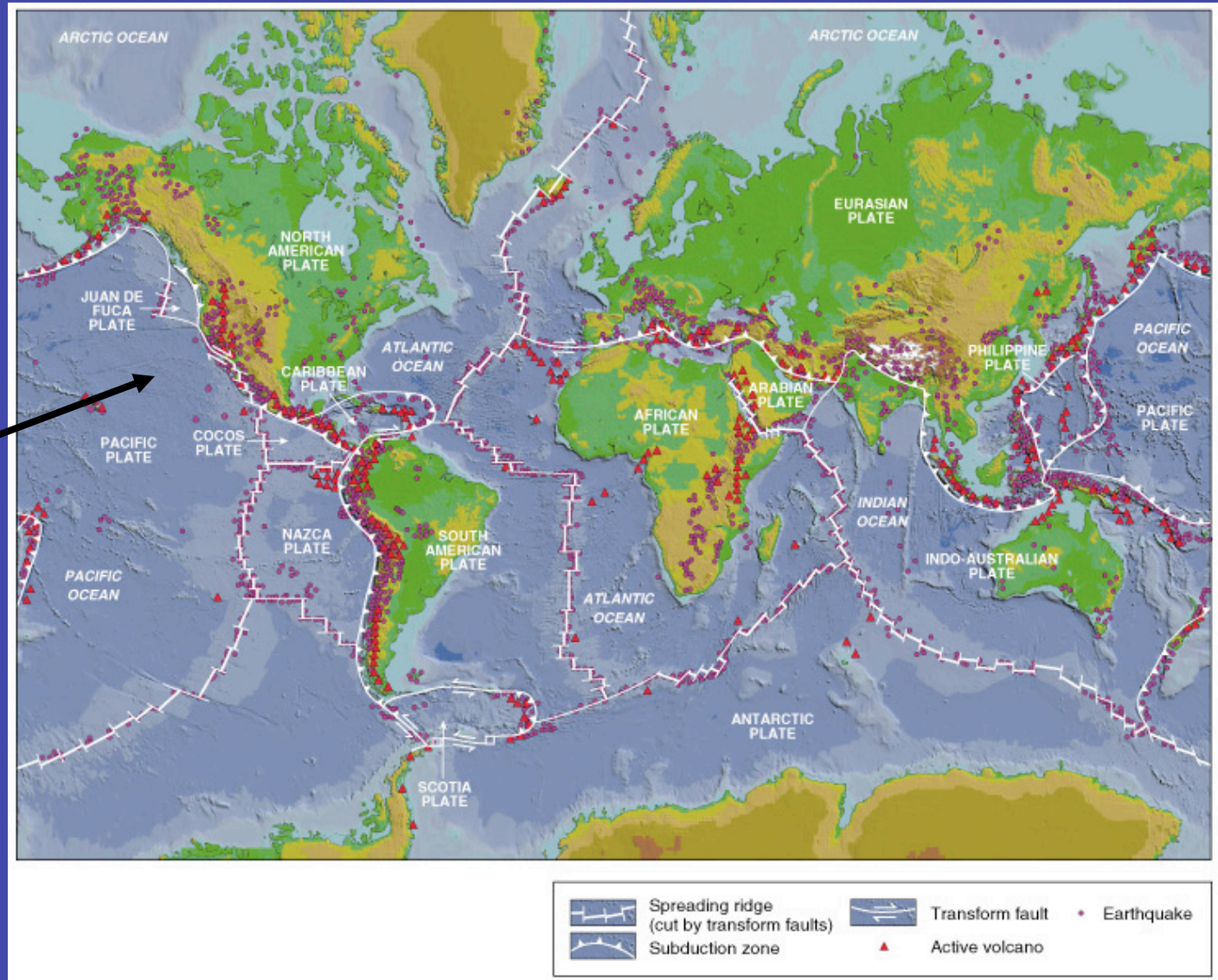
MOVE OVER
WEAKER

ASTHENOSPHERE



EARTH'S SURFACE DIVIDED INTO PLATES

San
Andreas
fault:
boundary
between
Pacific &
North
American
plates



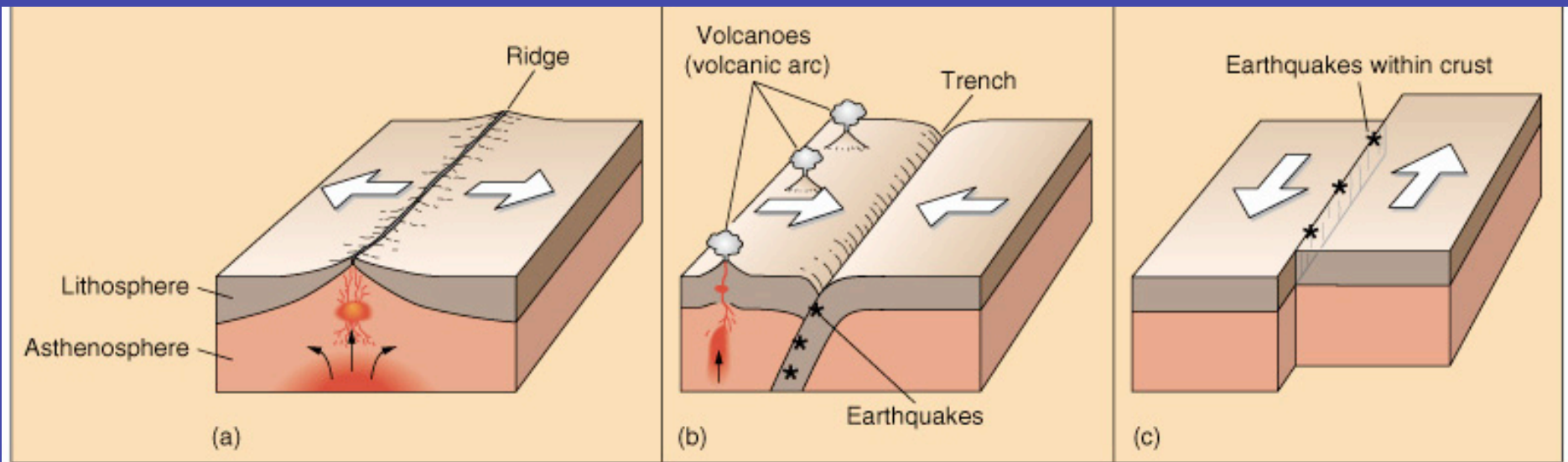
**EXCITING THINGS - EARTHQUAKES & VOLCANOES
HAPPEN AT THEIR BOUNDARIES**

PLATES MOVE AT A FEW INCHES PER YEAR (AS FAST AS FINGERNAILS GROW)

**RIDGE - NEW
PLATE FORMS**

**SUBDUCTION
- PLATE
DESTROYED**

**TRANSFORM -
PLATES SLIDE
BY**



**DIFFERENT MOTIONS MAKE DIFFERENT
BOUNDARIES**

WESTERN NORTH AMERICA

Three Plates:

Juan de Fuca

North America

Pacific



Three Boundaries:

Cascadia subduction zone

San Andreas transform

Gulf of California spreading center

SAN ANDREAS FAULT



San
Francisco
Bay Area



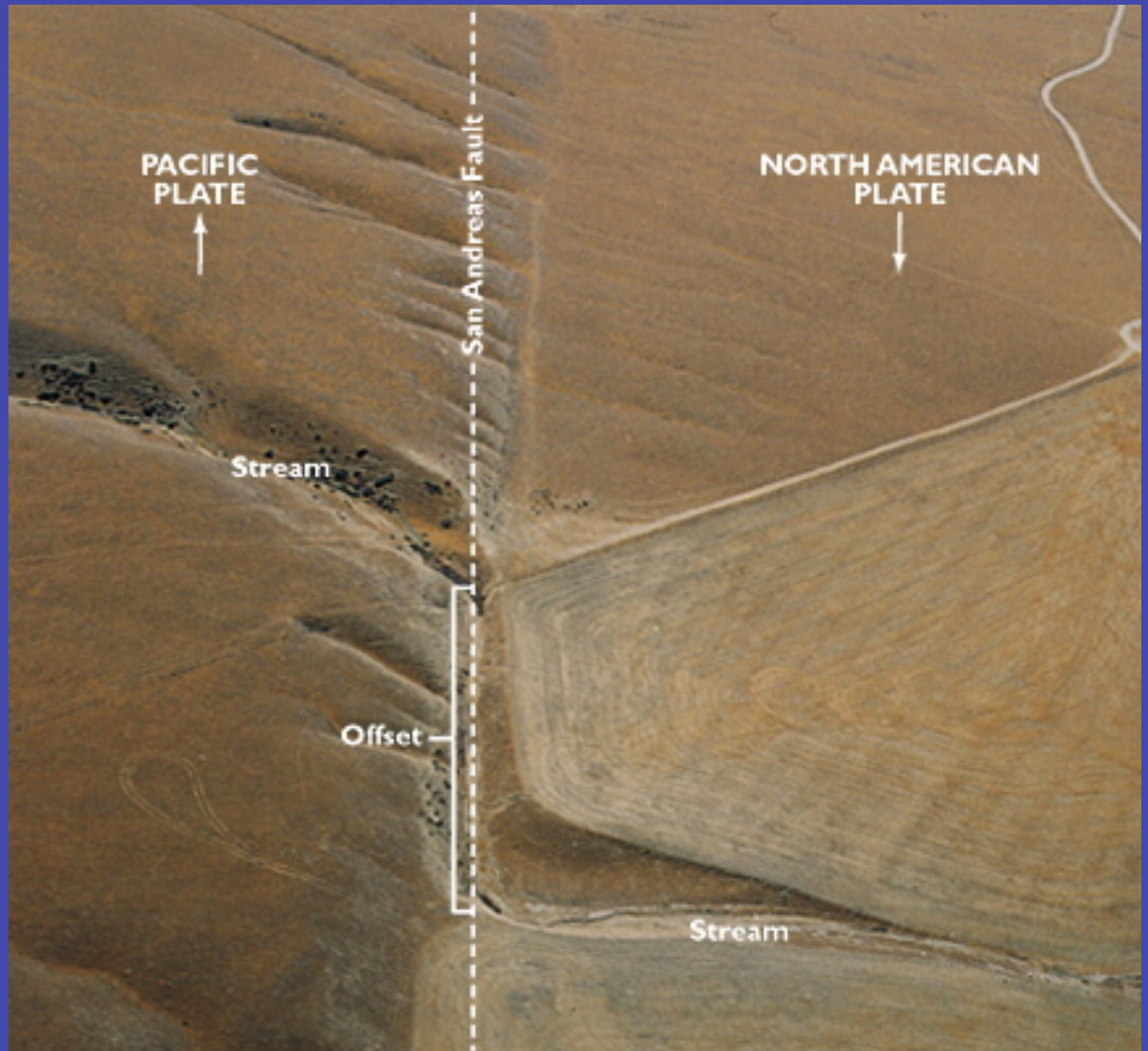
San Andreas Fault - Carrizo Plain, California

Over time, slip in earthquakes adds up to plate motion

About 35 mm/yr motion between Pacific and North America shown by offset stream

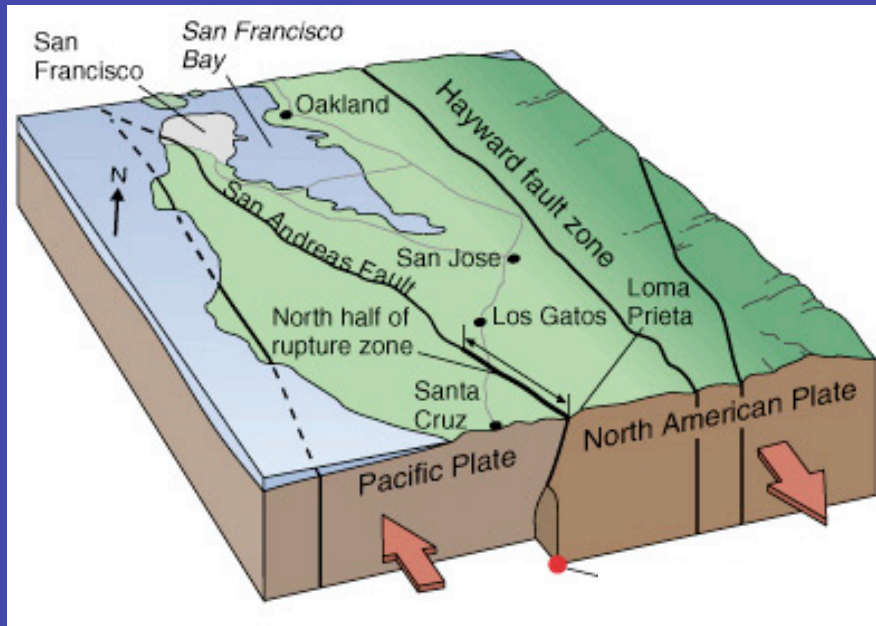
Expect earthquakes about every (3.5 m) / (35 mm/yr) or 100 years

Actually more like 200 yrs because not all motion on San Andreas



Distributed motion between North American & Pacific Plates

Most on San Andreas: some on other faults



San Francisco area - SAF
broke in 1906: M 7.9

Hayward fault broke in
1868: M 7

Distributed motion between North American & Pacific Plates

Most on San Andreas: some on other faults

Los Angeles area - SAF broke in 1857: M 7.9

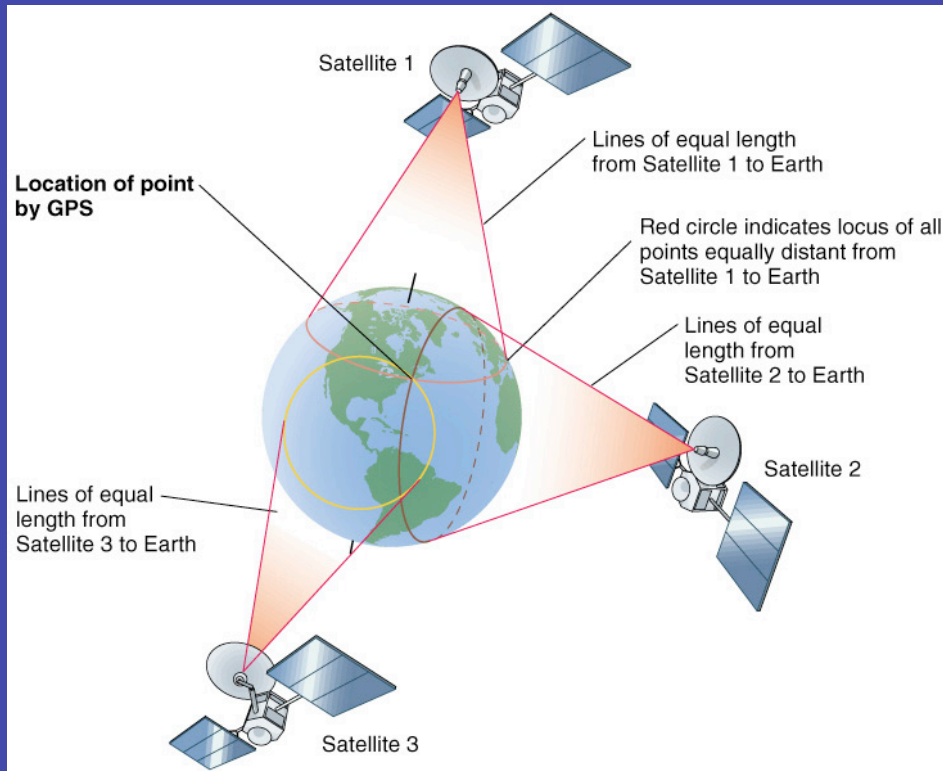


Smaller but damaging earthquakes on other faults

1994 Northridge M 6.7
58 deaths, \$20B damage

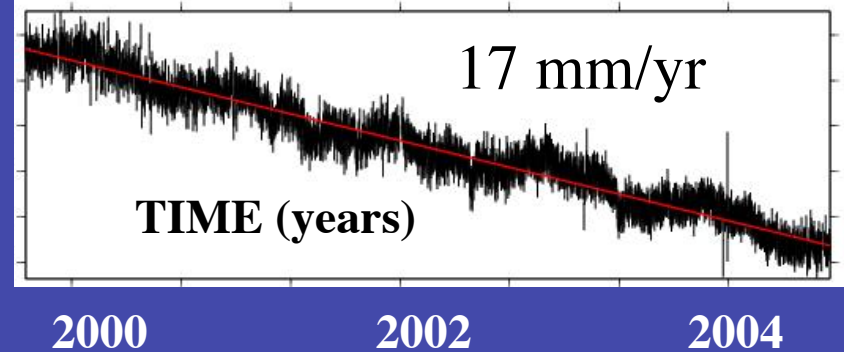
FIND FAULT & PLATE MOTIONS USING GPS GLOBAL POSITIONING SYSTEM

Find site position to few mm



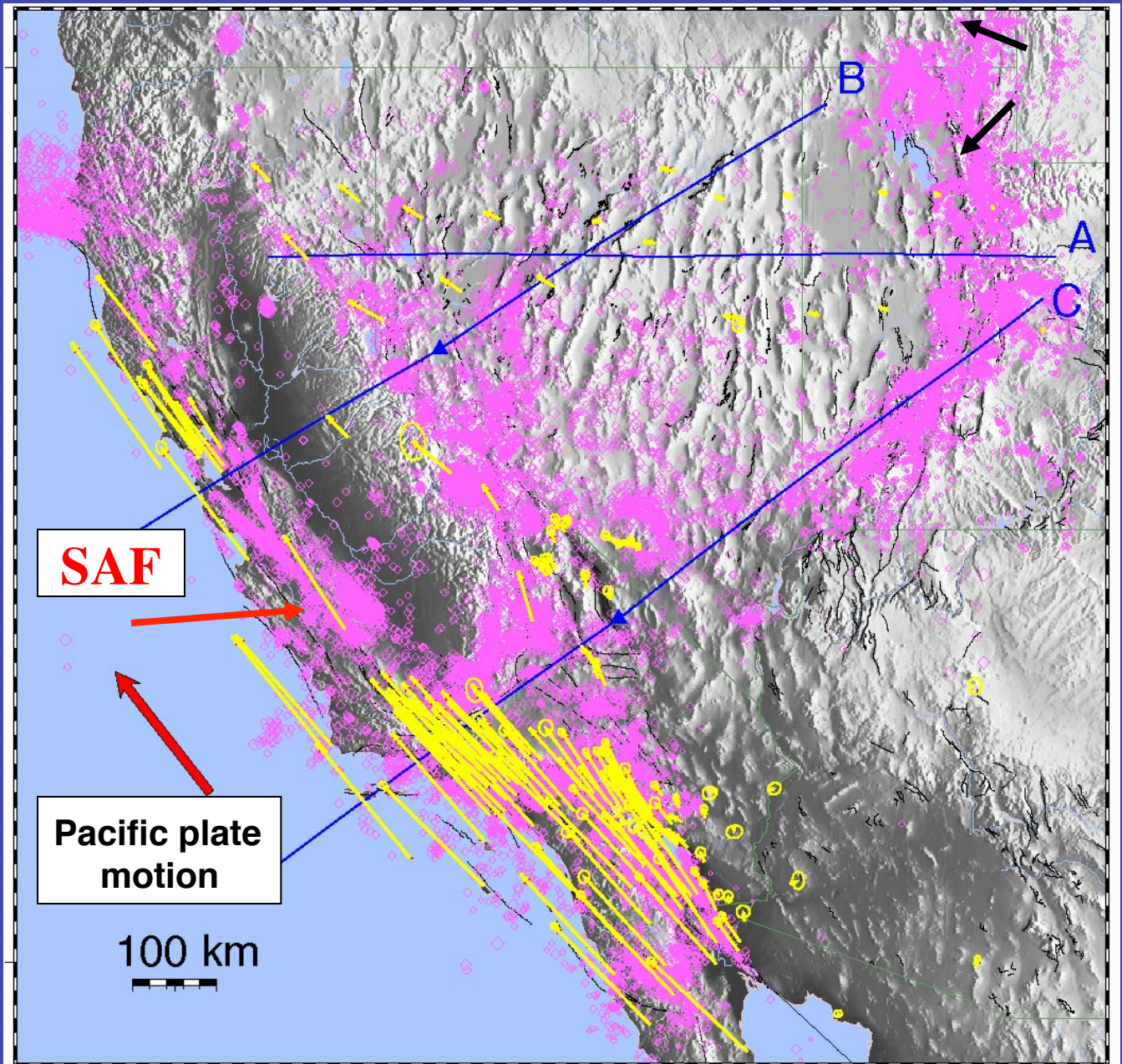
Change in position over time gives motion to precision of mm/yr

POSITION



**SOME
PACIFIC -
NORTH
AMERICA
MOTION
SPREAD AS
FAR EAST
AS UTAH &
MONTANA**

GPS site
motions
relative to
North America
- and
earthquakes -
show broad
boundary zone



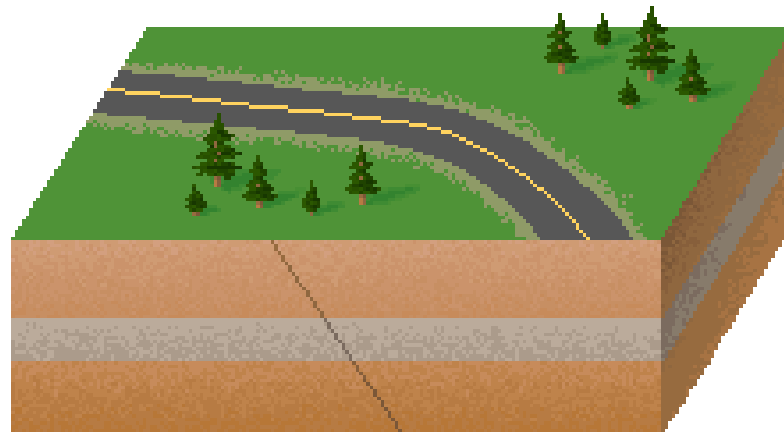
124°W

↑ 10mm/yr

Bennett et al, 1999

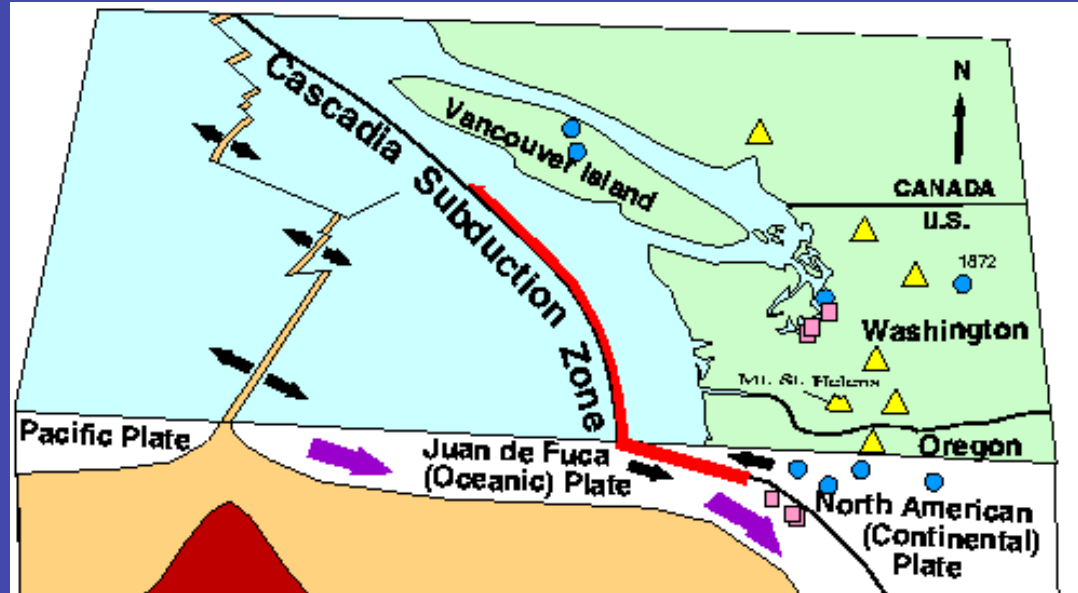
110°W

Wasatch fault, Salt Lake City, Utah



Hebgen Lake, Montana
1959 M 7.5

JUAN DE FUCA PLATE SUBDUCTING BENEATH NORTH AMERICA



The Olympian
SERVING WASHINGTON'S SOUTH PUGET SOUND
THURSDAY, MARCH 1, 2001
www.theolympian.com

GOOD WEATHER
HIGH 51 LOW 38
FORECAST: D8

Epicenter 11 miles northeast of Olympia
More than two dozen buildings damaged
Dozens of injuries; no South Sound deaths

6.8 QUAKE

WHAT YOU NEED TO KNOW NOW

BRIDGE DAMAGE
The North Sound bridge has been closed indefinitely because of visible damage.

BUILDING DAMAGE
The Capitol Complex and other city buildings have been closed and it may be a week.

ROAD CLOSURES
The Olympic Expressway will be closed for a week.

SCHOOL CLOSURES
The Olympia, North Thurston, and Vancouver schools will be closed today and Friday.

WORKERS
School districts in Snohomish and Pierce counties will be closed today and Friday.

By [Name]

OLYMPIA — South Sound today with-
out a major earthquake that caused widespread damage and left thousands of people injured.

The magnitude 6.8 quake struck at 10:55 a.m. and lasted about 10 seconds. It was centered 10 miles northeast of Olympia.

The quake the city's largest since 1949. It resulted in dozens of injuries and property damage.

The city of Olympia closed all schools and canceled all events.

The Pacific Avenue bridge in Olympia was closed because of damage.

The state seismologist said the quake was the largest in the South Sound since 1949.

The quake was felt in a 100-mile radius.

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The quake was felt in a 100-mile radius.



State buildings shut till Monday

BY PATRICK CONNOR, STAFF WRITER AND JACQUE WILSON

OLYMPIA — The earth quake that struck South Sound on Thursday was centered in the area, shaking the area, shut off the state Capitol dome and damaged the state's largest building.

The quake struck on the day the state's largest building was closed for a week.

The quake was felt in a 100-mile radius.

The quake was felt in a 100-mile radius.

The quake was felt in a 100-mile radius.

2001 Nisqually earthquake (\$2B damage)

Mt Saint Helens 1980 eruption (57 deaths; \$2B damage)



MOST EARTHQUAKES AT PLATE BOUNDARIES, WHERE MOTION IS FAST

SOME FROM SLOW MOTION INSIDE PLATES

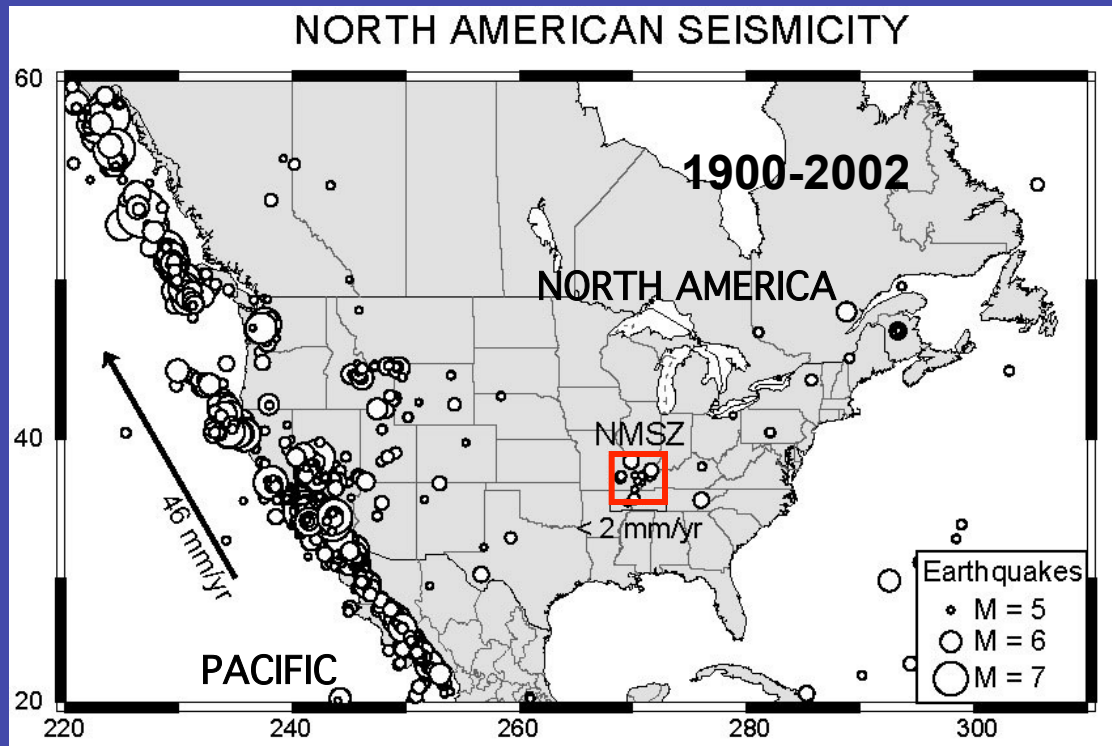
New Madrid seismic zone in central U.S.

M 7 earthquakes in
1811-12

Small earthquakes
continue

Big ones might
happen again

Don't know why,
when, how
dangerous



INDIA MOVES NORTH COLLIDING WITH EURASIA

COMPLEX PLATE BOUNDARY ZONE

Deforms large region

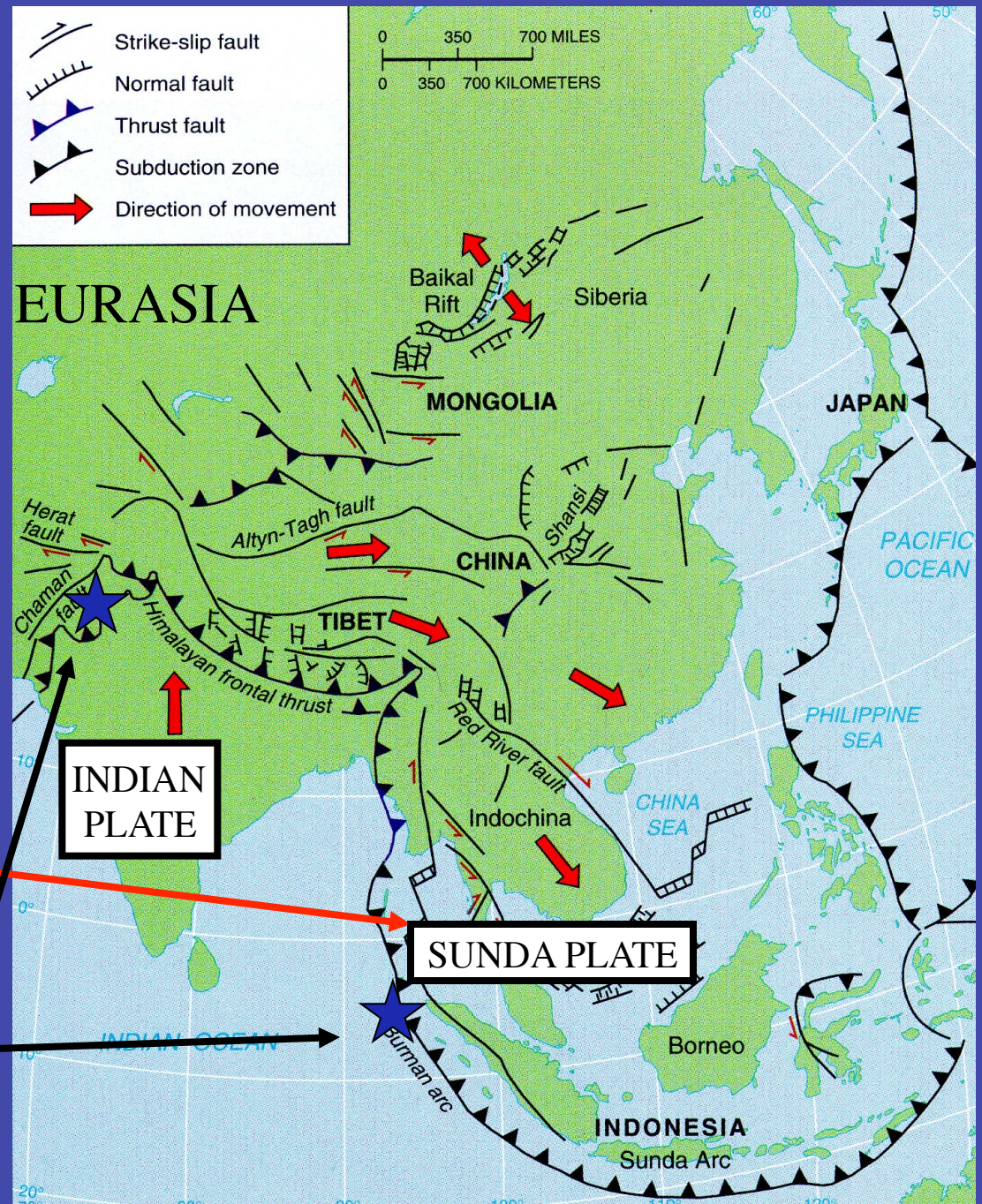
Many small plates (microplates)

Burma microplate

Earthquakes result:

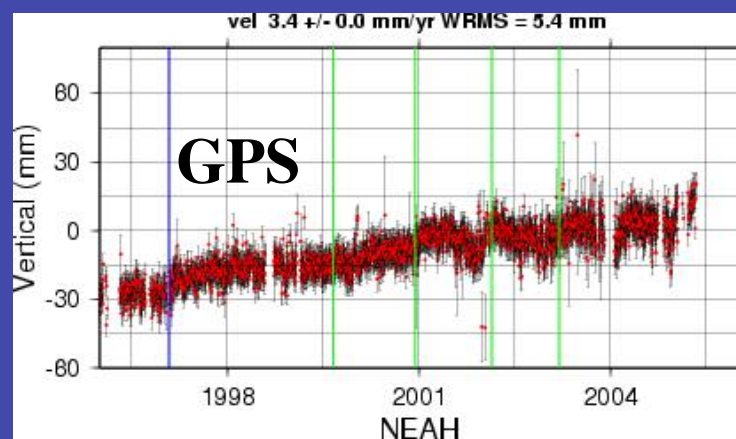
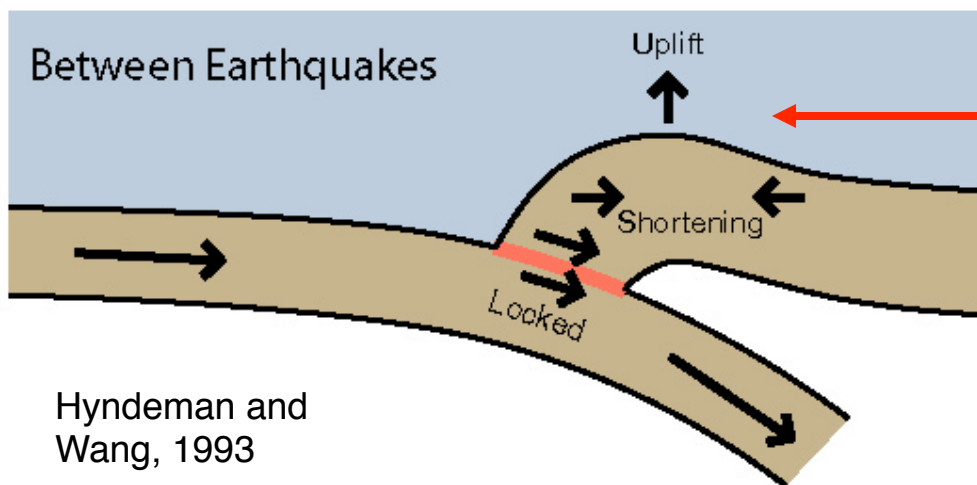
12/2004 Sumatra

10/2005 Pakistan

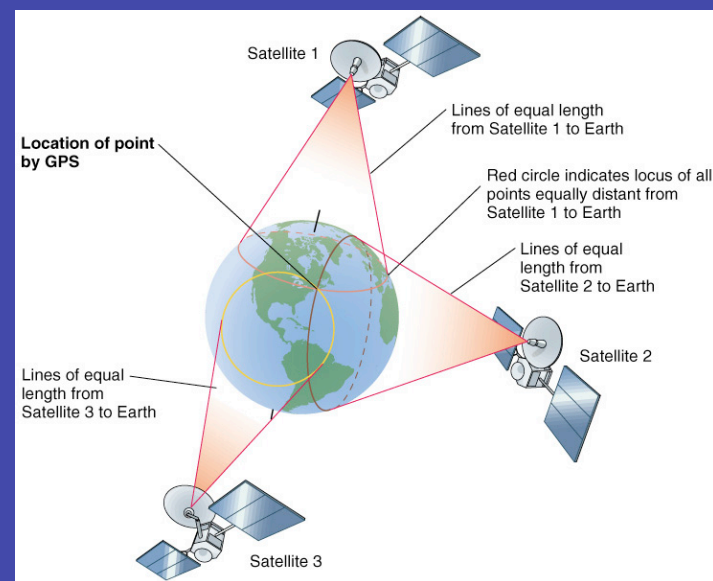


Molnar & Tapponnier, 1977

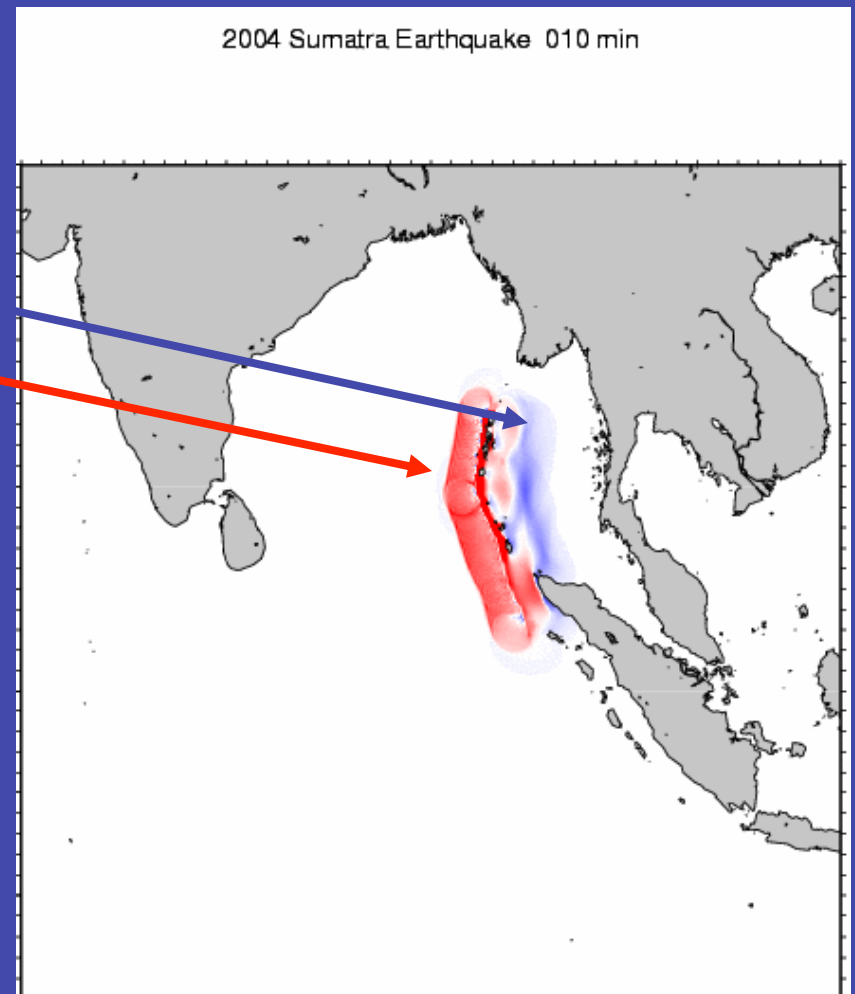
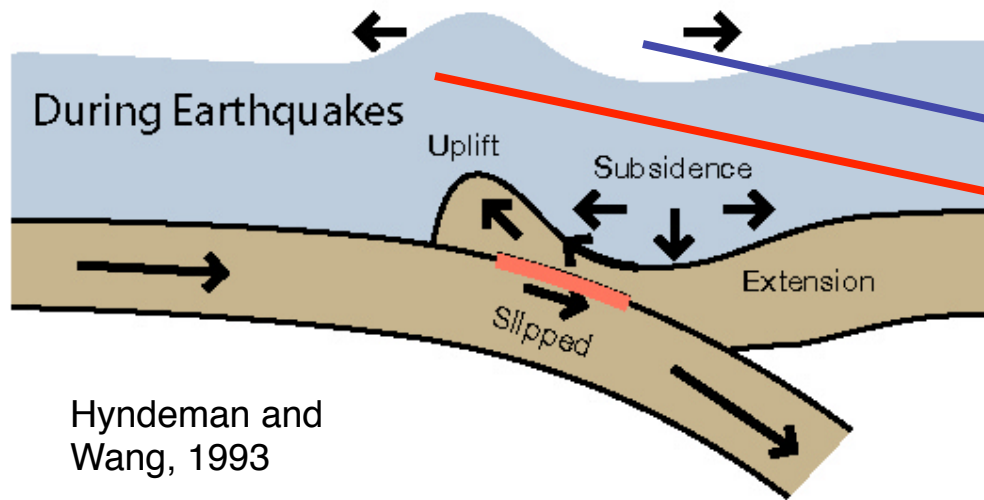
TSUNAMI GENERATION I: OVERRIDING PLATE FLEXED BETWEEN MAJOR EARTHQUAKES



Indian plate
subducts beneath
Burma microplate



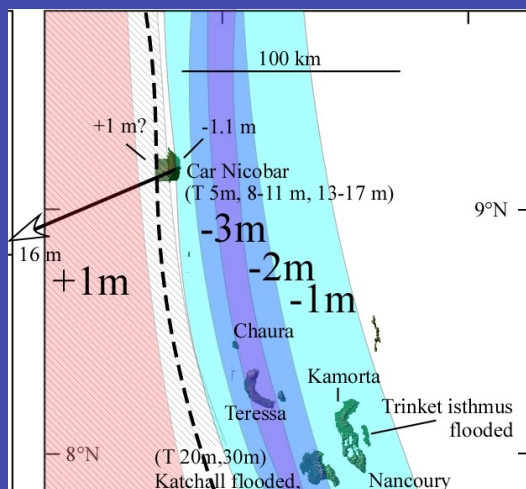
TSUNAMI GENERATION II: SEAFLOOR REBOUNDS DURING EARTHQUAKE



Water motion:
Red - up, blue down

Islands
 went up &
 down

R. Bilham

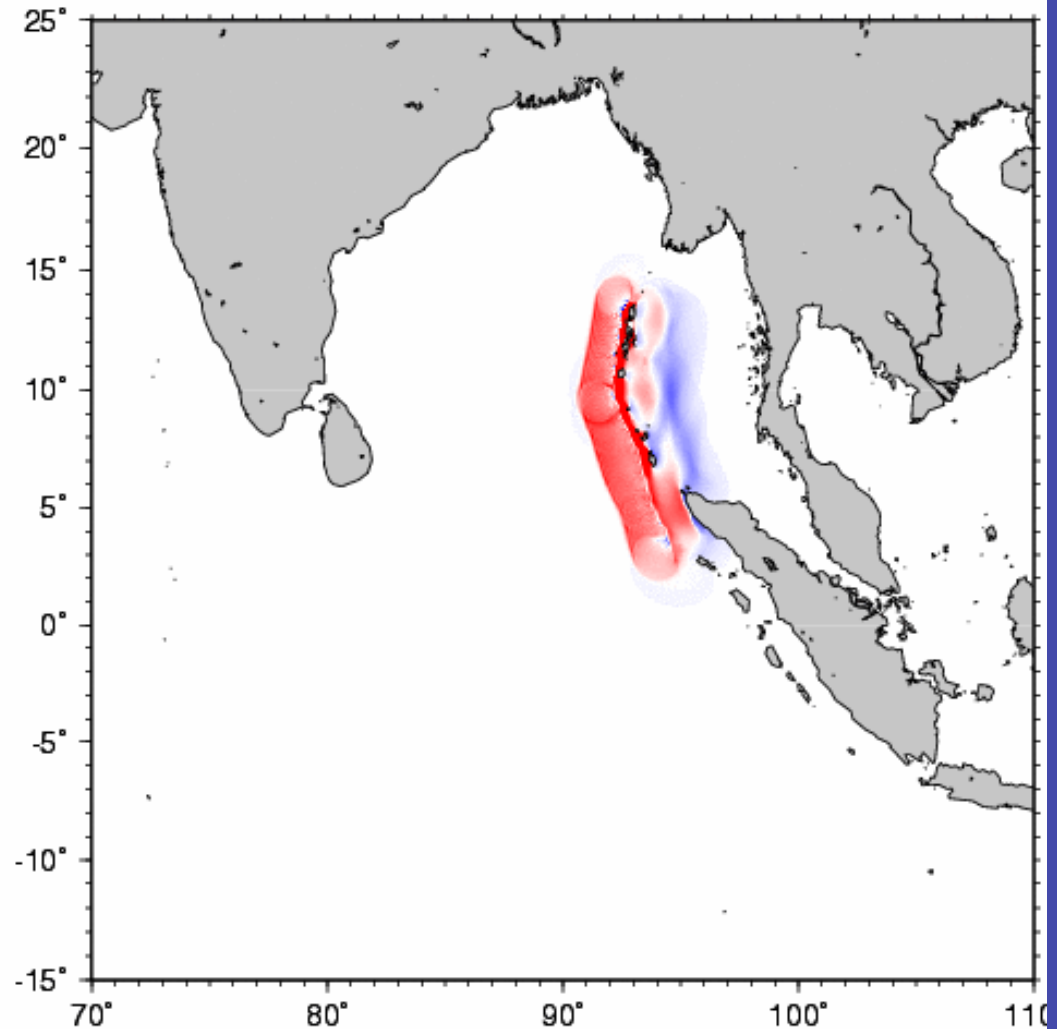


**Tsunami
generated along
fault, where sea
floor displaced,
and spreads
outward**

**Travels at speed
of jet plane**

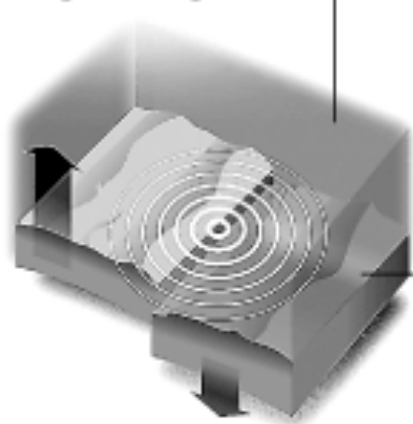
**Reached Sri
Lanka in 2 hrs,
India in 2-3**

2004 Sumatra Earthquake 010 min

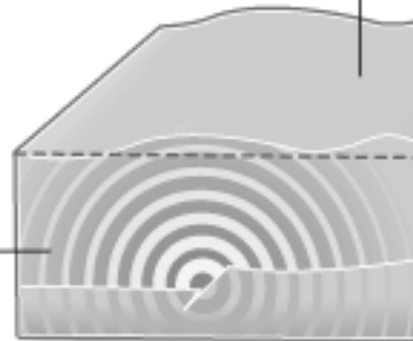


KHAO LAK, THAILAND DECEMBER 26, 2004

1 Earthquakes cause the ocean floor to collapse in places and rise elsewhere, displacing water and generating waves.

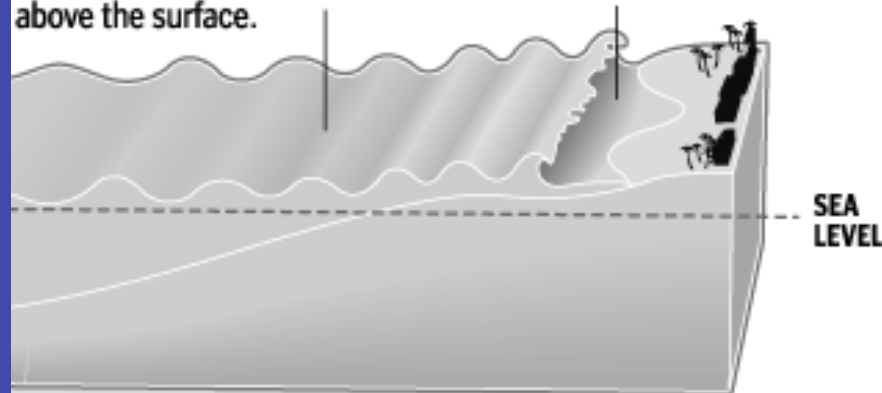


2 Initial waves, largely underwater, travel very fast toward the shore.



SOURCES: Staff reports, Associated Press

3 In the shallow waters near the shore, the waves decrease in speed while rising in height above the surface.



4 The tsunami reaches the shore, causing severe flooding and extreme currents.



ILLUSTRATION BY THE ASSOCIATED PRESS; GRAPHIC BY THE WASHINGTON POST

Seattle Times 2/24/05



Tsunami damage



Dec. 27: An aerial view shows the tsunami-stricken areas near the coastal outskirts of Banda Aceh, capital city of Indonesia's Aceh province.



BANDA ACEH

BANDA ACEH: 8 minute tsunami travel time

First Line of Surviving Structures – Concrete and on Columns

Some shaking damage

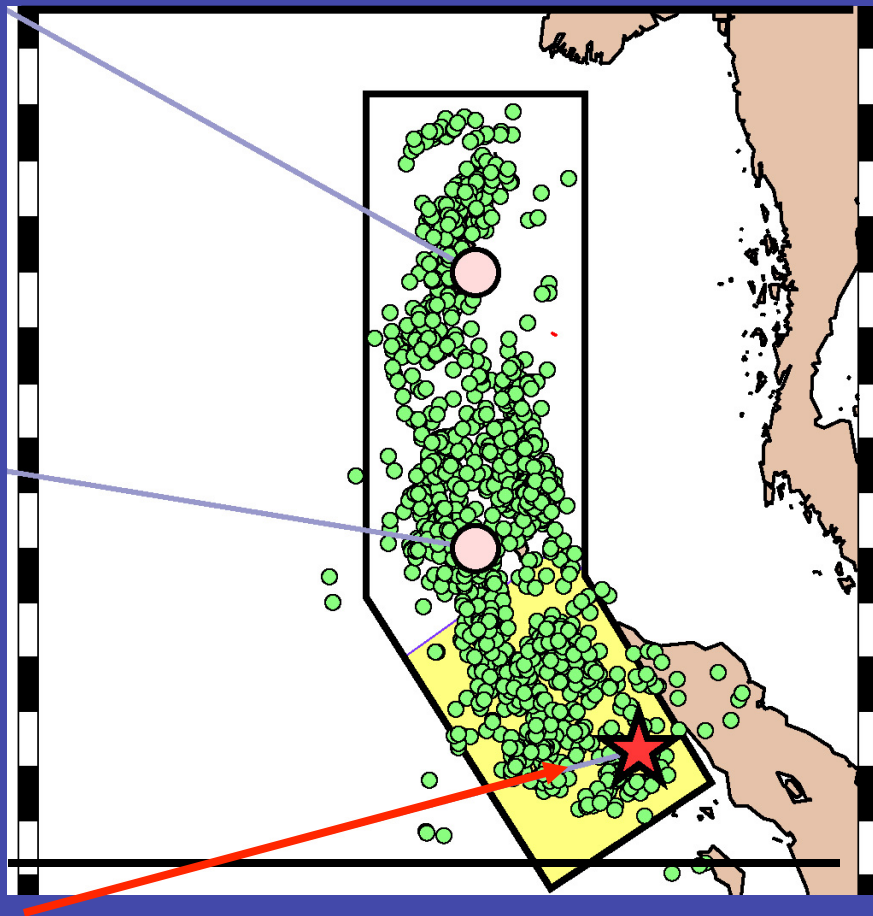
Complete Destruction





THAILAND

**SEISMOGRAMS SHOW RUPTURE
PROPAGATED ALONG 750 MILE LONG
AFTERSHOCK ZONE IN 500 SECONDS:
5,400 miles per hour**



EPICENTER



Ishii et al., 2005

MAGNITUDE 9.3

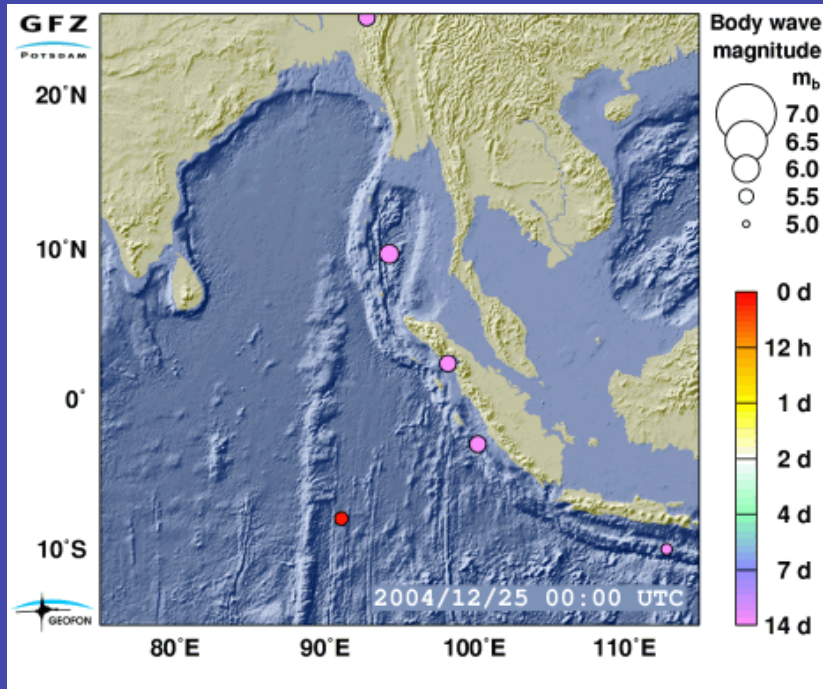
FAULT AREA:

750 miles long

125 miles down dip

AVERAGE SLIP:

33 feet



Aftershocks show fault area

SUMATRA 2004

**MAGNITUDE
DEPENDS ON
FAULT AREA x
AVERAGE SLIP**

**NORTHRIDGE
1994**

Mw 6.7
slip 1 m



**LOMA
PRIETA
1989**

Mw 6.9
slip 2 m



**SAN
FRANCISCO
1906**

Mw 7.8
slip 4 m



“the big one”

Mw 9.3
slip 11 m

FAULT LENGTH

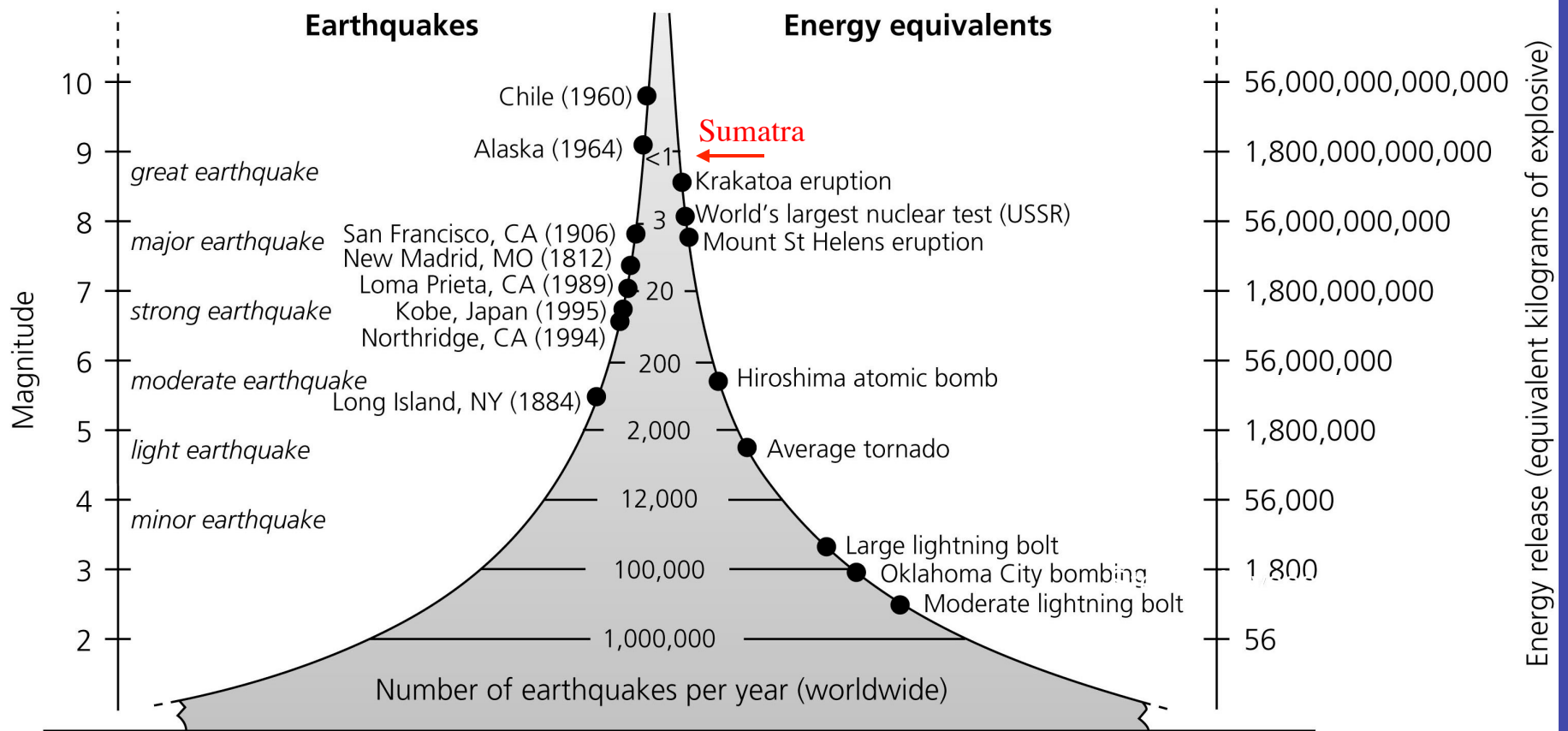
FAULT WIDTH

150 km

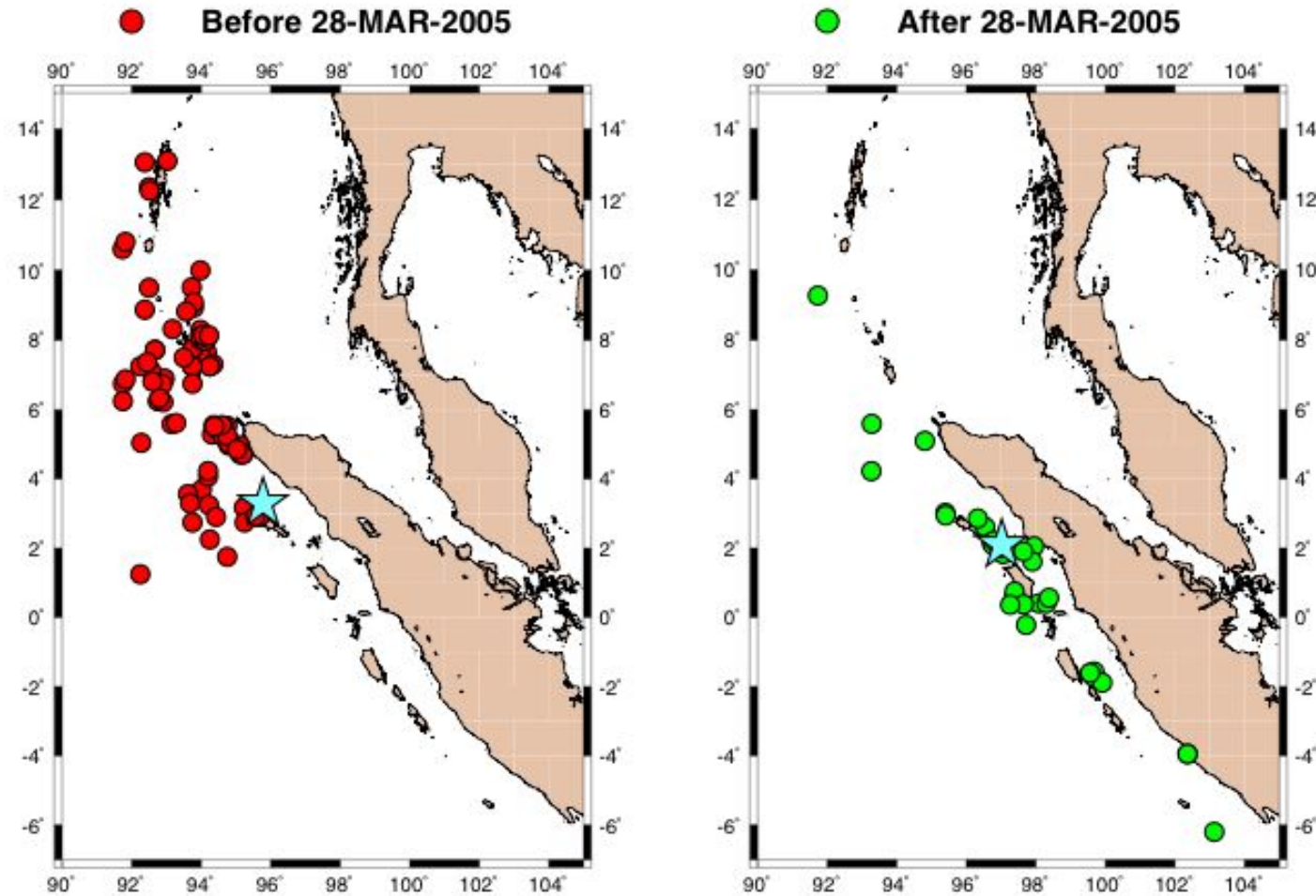
MAGNITUDE 9 EARTHQUAKES ARE INFREQUENT

Only 3 since 1960

Figure 1.2-2: Comparison of frequency, magnitude, and energy release.

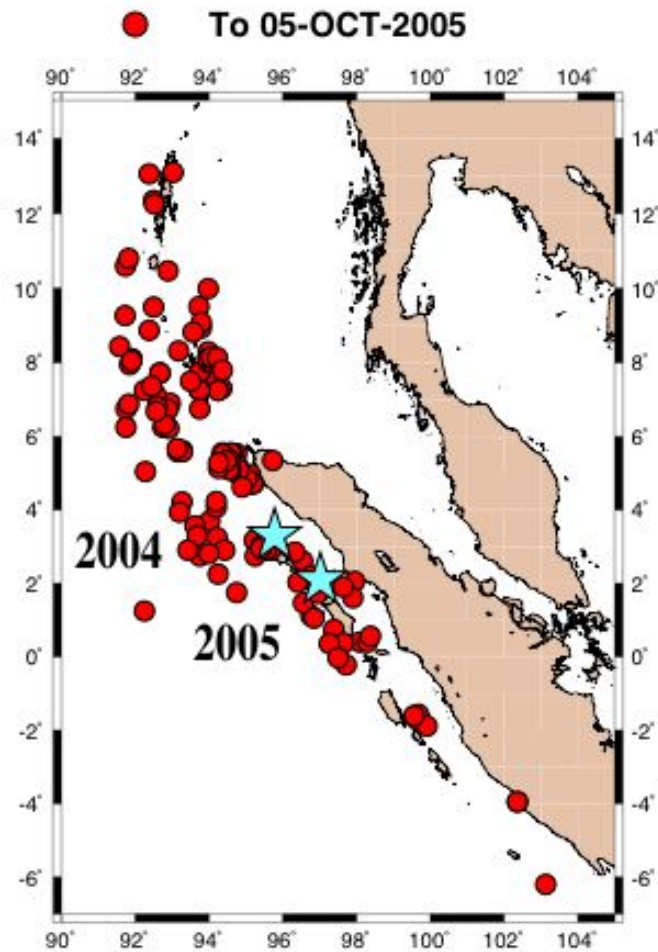


AFTERSHOCKS FOR MONTHS AFTER DECEMBER 26 EARTHQUAKE RAISED STRESS ON SEGMENT TO SOUTH

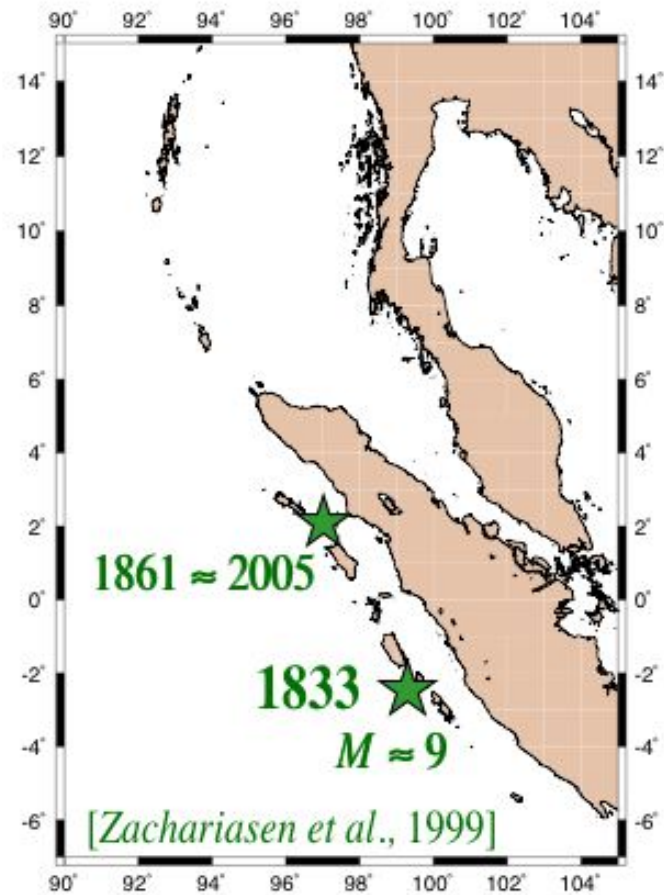


WHICH BROKE MARCH 28 IN M 8.7 EARTHQUAKE

WHAT'S NEXT?



HISTORICAL EVENTS

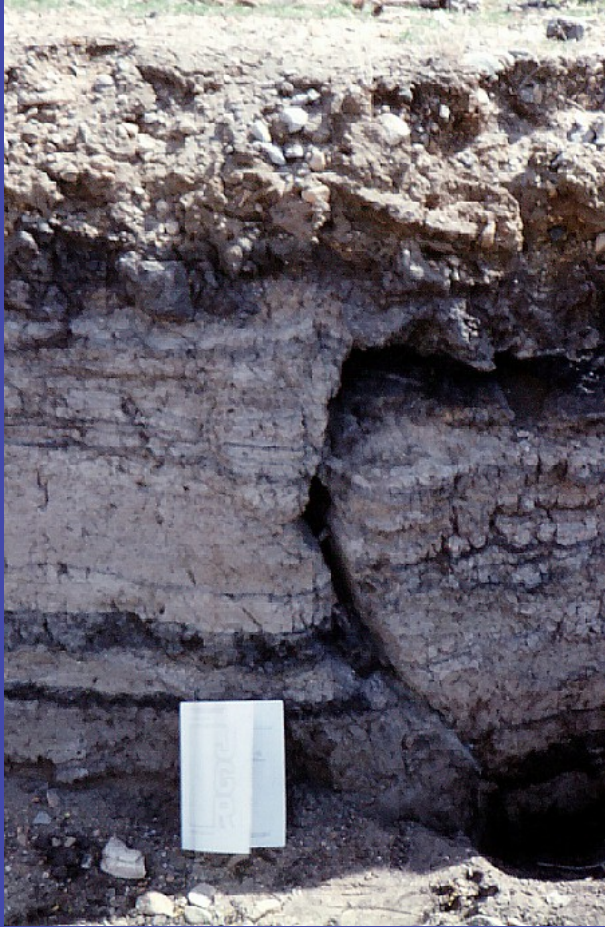


WHAT CAN WE DO?

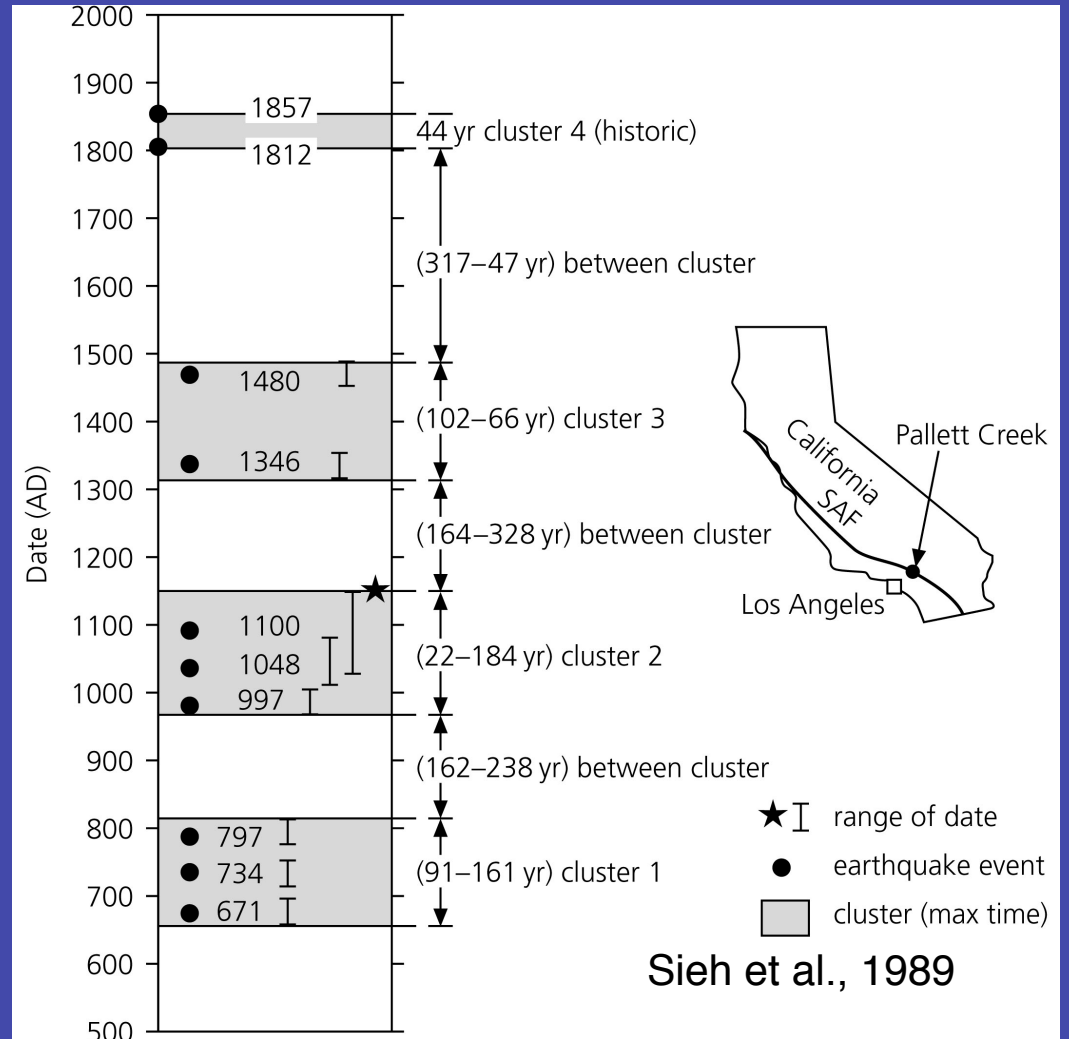
- Learn more about earthquakes, their causes, & effects
- Predict earthquakes (looks hard or impossible)
 - Prepare for earthquakes & mitigate their damage (natural processes become disasters because of human actions)
- Accept earthquakes as part of our living planet

HARD TO PREDICT EARTHQUAKES

time between them is very variable



Extend earthquake history with geologic record



$M > 7$ mean 132 yr σ 105 yr
Estimated probability in 30 yrs 7-51%

SEISMIC GAP MODEL

Long plate boundary like San Andreas or oceanic trench breaks in segments

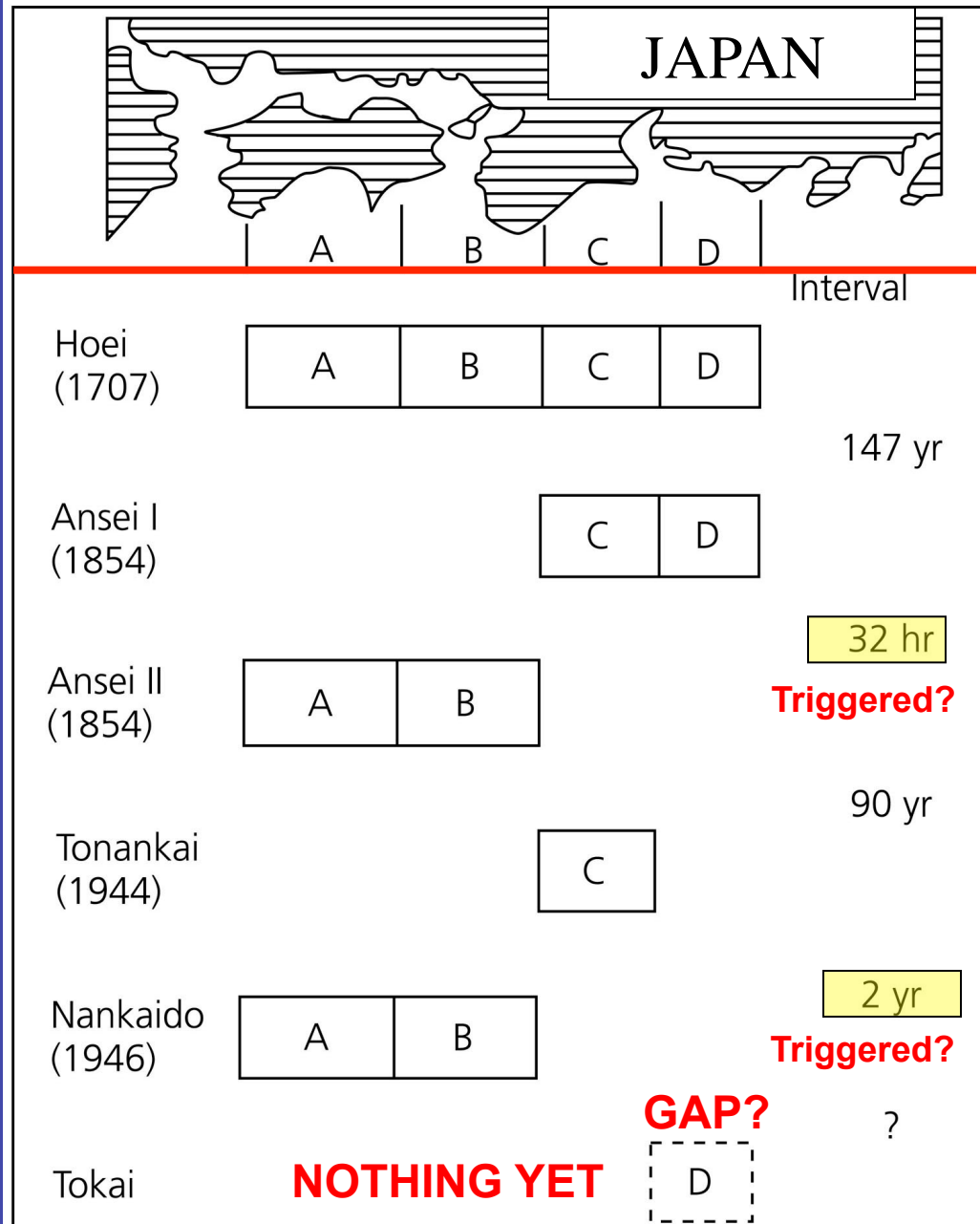
Expect plate motion to cause earthquakes in gaps that haven't broken for a long time

Japanese waiting for Tokai earthquake for 50+ years

Nothing yet...

Ando, 1975

Figure 5.4-27: Time sequence of large subduction zone earthquakes along the Nankai trough.



PARKFIELD, CALIFORNIA SEGMENT OF SAN ANDREAS

M 5-6 earthquakes about every 22 years:
1857, 1881, 1901, 1922, 1934, and 1966

In 1985, expected next in
1988; predicted at 95%
confidence by 1993

Didn't occur till 2004
(16 years late)



RESEARCH NEWS

Parkfield Quakes Skip a Beat

Seismologists' first official earthquake forecast has failed, ushering in an era of heightened uncertainty and more modest ambitions

WHY CAN'T WE PREDICT EARTHQUAKES?

So far, no clear evidence for observable behavior before earthquakes.

Maybe lots of tiny earthquakes happen frequently, but only a few grow by random process to large earthquakes

In chaos theory, small perturbations can have unpredictable large effects - flap of a butterfly's wings in Brazil might set off a tornado in Texas

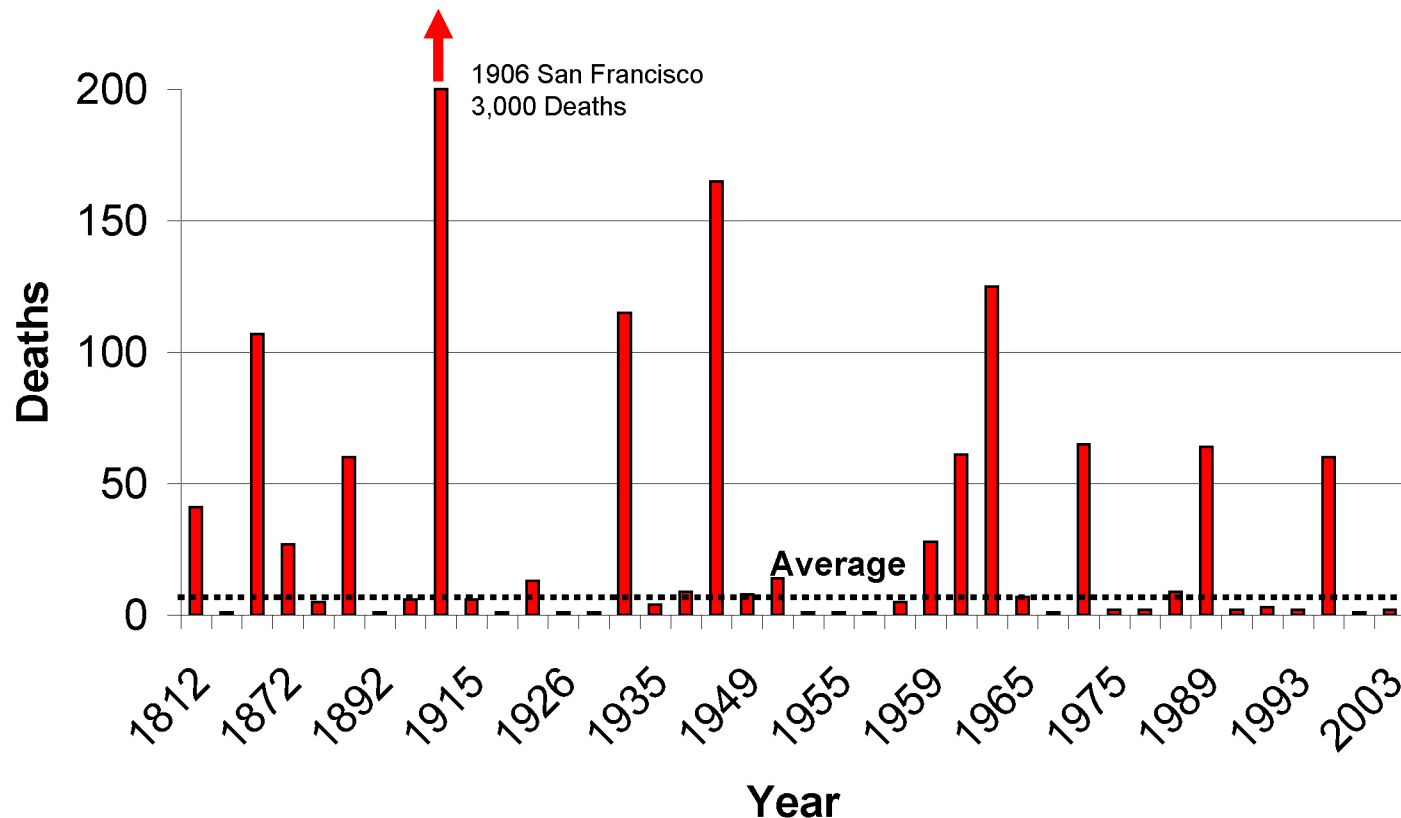


If there's nothing special about the tiny earthquakes that happen to grow into large ones, the time between large earthquakes is highly variable and nothing observable should occur before them.

If so, earthquake prediction is either impossible or nearly so.

“It's hard to predict earthquakes, especially before they happen”

Annual Deaths in the United States from Earthquakes 1812-2003



U.S. average 6 deaths per year, but can be many more for large earthquake

Some foreign countries much more (more people living along plate boundary, weaker construction)

U.S. EARTHQUAKES

Infrequent, but occasionally major, fatalities and damage

Moderate (M 6.7) 1994 Northridge earthquake: 58 deaths, \$20B damage

Challenge: find mitigation strategy that balances cost of safer construction with benefits, given other possible uses of resources

Tough problem!

Table 1.2-3. Some causes of death in the United States, 1996.

Heart Attack	733,834
Cancer	544,278
Stroke	160,431
Lung disease	106,143
Pneumonia/Influenza	82,579
Diabetes	61,559
Motor vehicle accidents	43,300
AIDS	32,655
Suicide	30,862
Liver disease/Cirrhosis	25,135
Kidney disease	24,391
Alzheimer's	21,166
Homicide	20,738
Falling	14,100
Poison	10,400
Drowning	3,900
Fires	3,200
Suffocation	3,000
Bicycle accidents	695
Severe Weather ¹	514
In-line skating ²	25
Football ²	18
Skateboards ²	10
Earthquakes (1811-1983) ³	9
Earthquakes (1984-1998)	9

¹From the National Weather Service (property loss due to severe weather is \$10-15 B/year, comparable to the Northridge earthquake, and individual hurricanes can go up to \$25 B.

²From the Consumer Product Safety Commission

³From Gere and Shah [1984].

All others from the National Safety Council and National Center for Health Statistics.

DAMAGE DEPENDS ON WHERE AND HOW WE BUILD

“Earthquakes don't kill people; buildings kill people.”

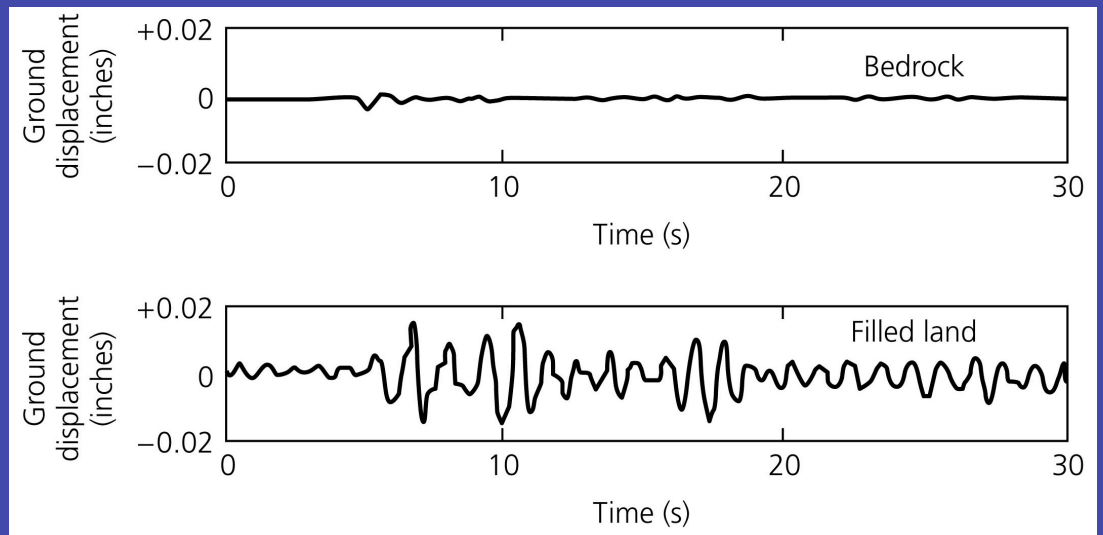


**1989 LOMA PRIETA, CALIFORNIA EARTHQUAKE:
M 7.1**

**Mile of two level freeway collapsed, crushing cars
& causing 42 deaths**

1989 LOMA PRIETA, CALIFORNIA EARTHQUAKE

Houses
collapsed in
Marina district
of San
Francisco, on
landfill that
amplified
shaking

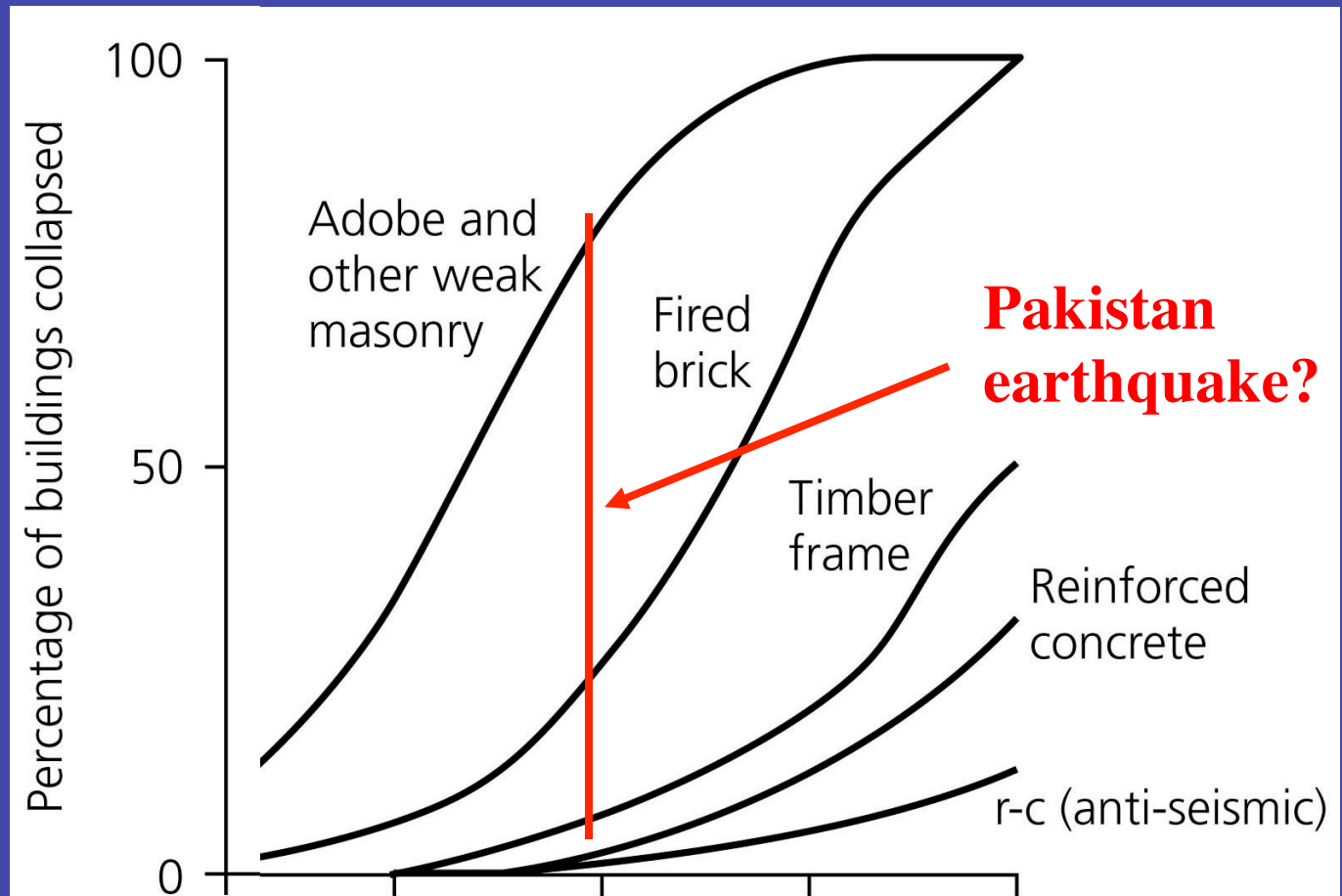


DAMAGE DEPENDS ON BUILDING TYPE

RESISTANT CONSTRUCTION REDUCES EARTHQUAKE RISKS



Pigs had it wrong



Pakistan earthquake?

STRONGER SHAKING →

ADOBE



12/03 Bam, Iran
M 6.6 27,000 deaths

BRICK



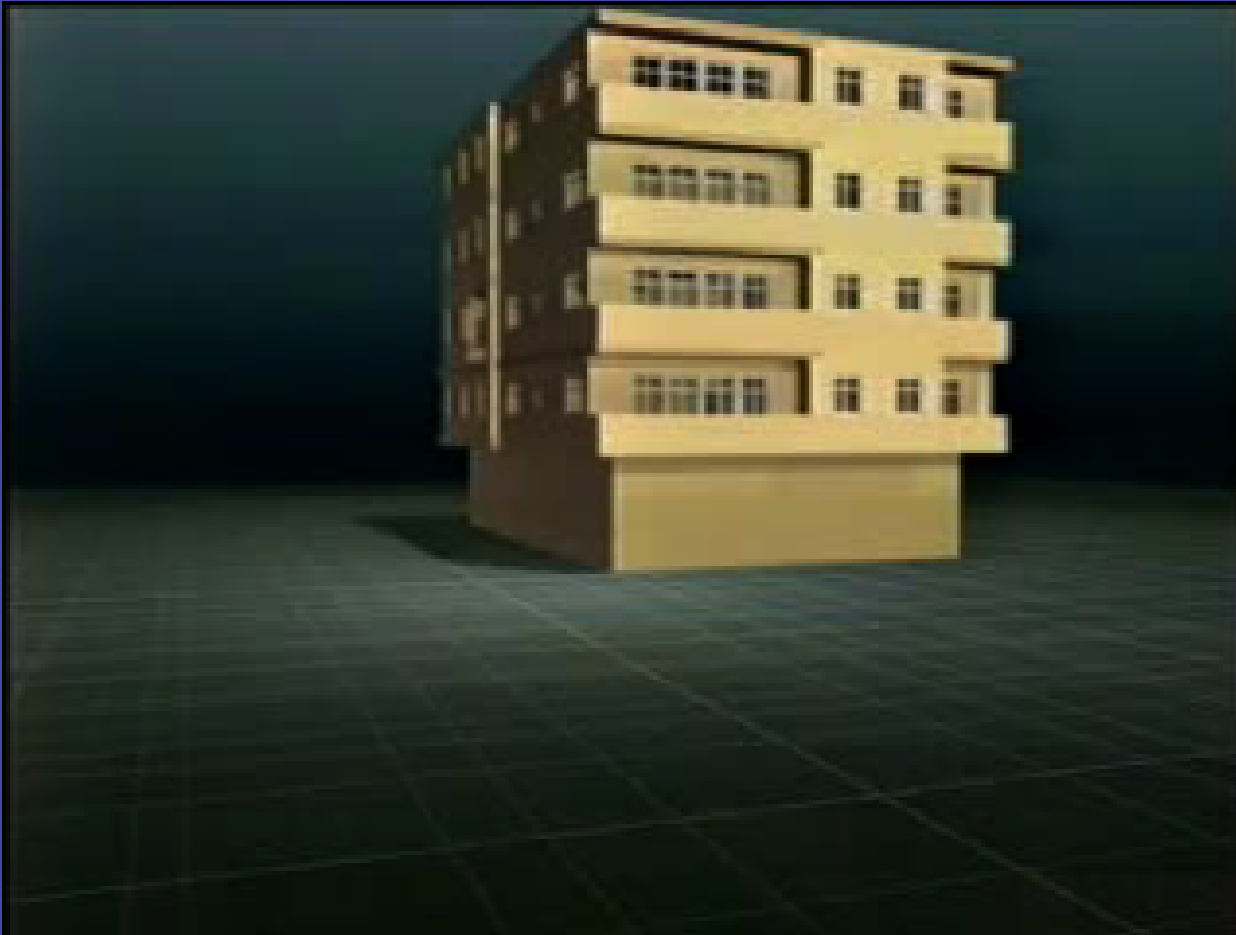
10/05 Pakistan M 7.6
80,000 deaths

CONCRETE



2/71 San Fernando,
California M 6.6 65 deaths

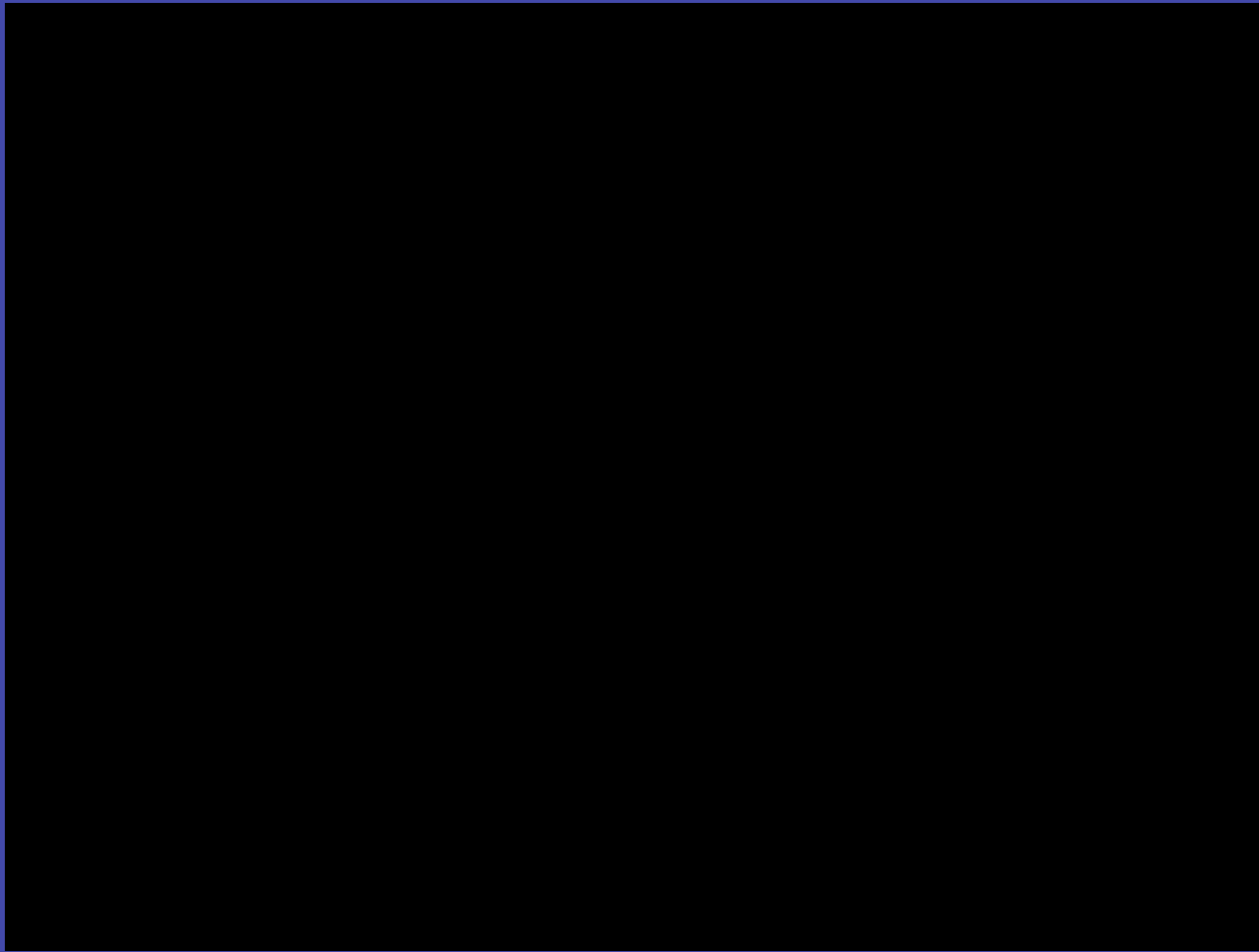
MODERN CONSTRUCTION WITHOUT SEISMIC STRENGTHENING: Concrete buildings



USGS

40,000 in California. 8,000 schools, including 239 in Los Angeles. Downtown Los Angeles has about 500.

RETROFIT FOR SEISMIC STRENGTHENING



USGS

Problem: retrofit cost close to that of razing building & starting over. \$24 B needed for California hospital retrofits!

PROBLEM: UNFUNDED MANDATE

Property owners don't benefit (can't charge higher rent) & so resist

Maybe society should fund:
Would public pay higher taxes for safety?

October 11, 2005

latimes.com : California

E-mail s

How Risky Are Older Concrete Buildings?

- State officials say many should be retrofitted for quakes. Others say cost would outweigh benefit.

By Sharon Bernstein, Times Staff Writer

Tens of thousands of older concrete buildings across California represent the state's largest remaining risk of serious damage in a major earthquake, seismic safety officials say.

Constructed as department stores, schools, parking structures and office buildings from the 1930s through the early 1970s, these buildings typically consist of large, open lower stories held up by unreinforced or poorly reinforced concrete pillars.

ADVERTISEMENT

Unhealthy air
can result in
lung disease,
asthma,
emphysema

Quick Quiz



After several collapsed in the 1971 San Fernando earthquake, seismic safety codes were upgraded to require that any new concrete buildings be better constructed. Many seismic experts say preexisting structures — known as non-ductile concrete buildings — need to be retrofitted to bring them up to current standards.

"It's well recognized within the earthquake professional community that many California non-ductile concrete buildings are at unacceptable risk of collapse in moderately strong shaking," said Thomas Heaton, professor of engineering seismology at Caltech.

Because many of the older concrete buildings tend to be filled during the day with office workers, schoolchildren or people parking their cars, the death and injury toll from an earthquake that caused several of the structures to collapse could be staggering, said Heaton.

But building owners and business organizations have long fought efforts to require retrofits, arguing that the risk is overstated. And they say that in some cases, the cost of retrofits comes close to that of razing a building and starting over. Neither the state nor local governments have required that the structures be reinforced.

"If you're going to use a 'sky is falling' scenario, then maybe you can justify" a retrofit requirement, said Carol Schatz, president of the Central City Assn. "But if you're going to put a bunch of commercial property owners out of business in the process, what have you accomplished?"

Property owners and business associations opposed a proposal last year by City Councilmen Greig Smith and Alex Padilla to count the number of unreinforced concrete buildings in Los Angeles. The measure didn't make it out of a council committee.

HAZARD MAPPING

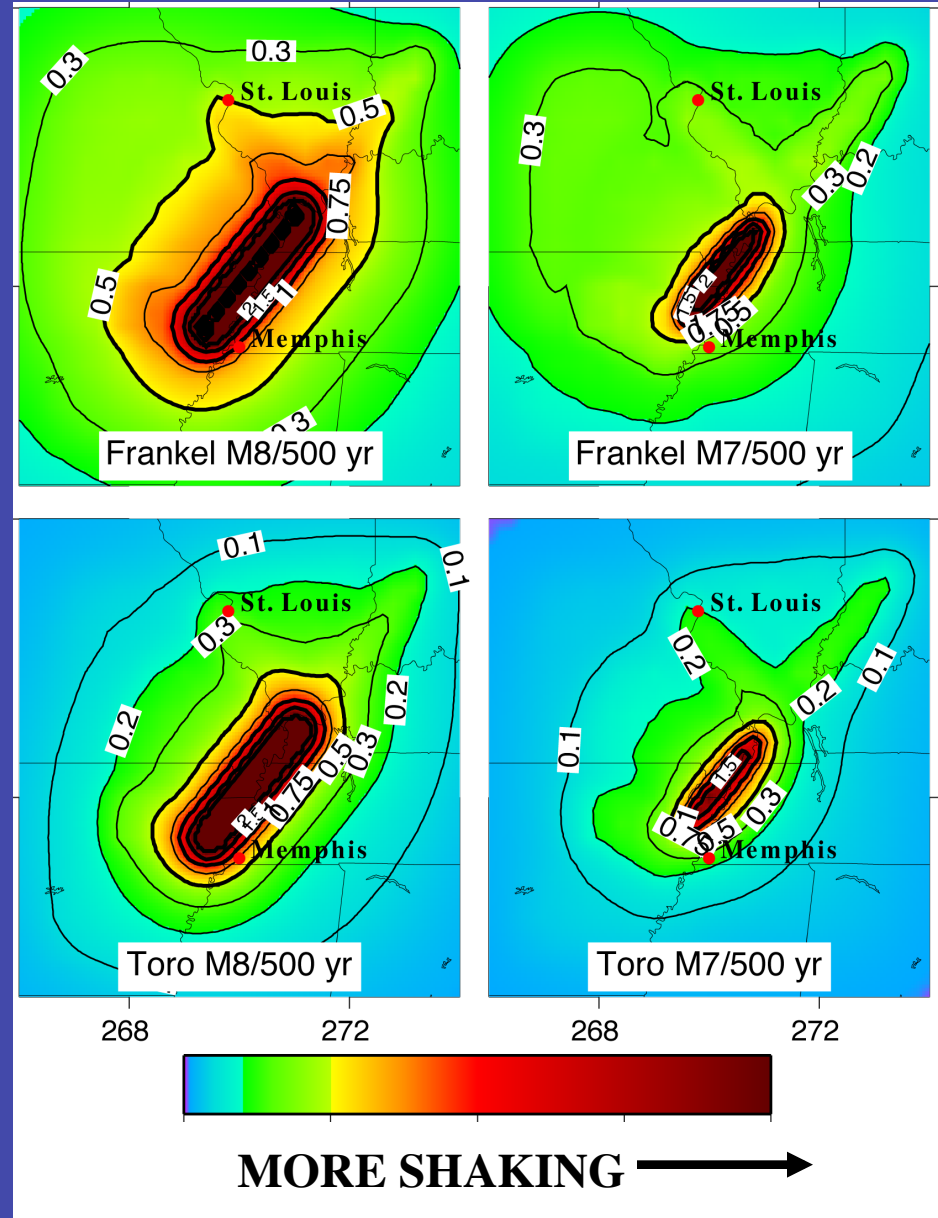
Try to predict future shaking

Tough: requires assuming how large & often future earthquakes will occur - and what shaking they'll do

Uncertain: "a game of chance, of which we still don't know all the rules"

Won't know how we did for 100s or 1000s of years

Even tougher to balance funds spent on earthquake



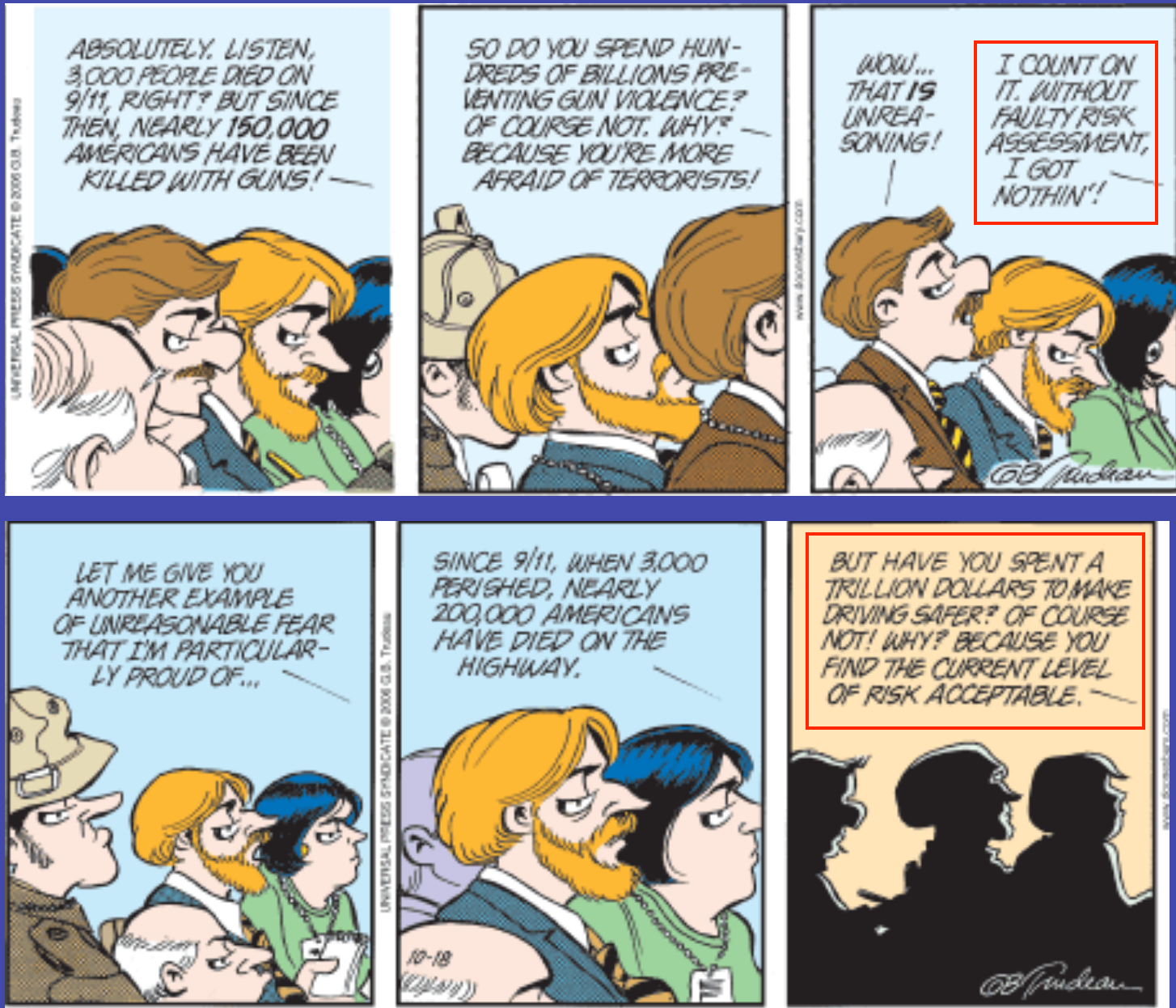
Maps for different assumed magnitudes & shaking



\$100M seismic retrofit of Memphis VA hospital, removing nine floors, bringing it to California standard

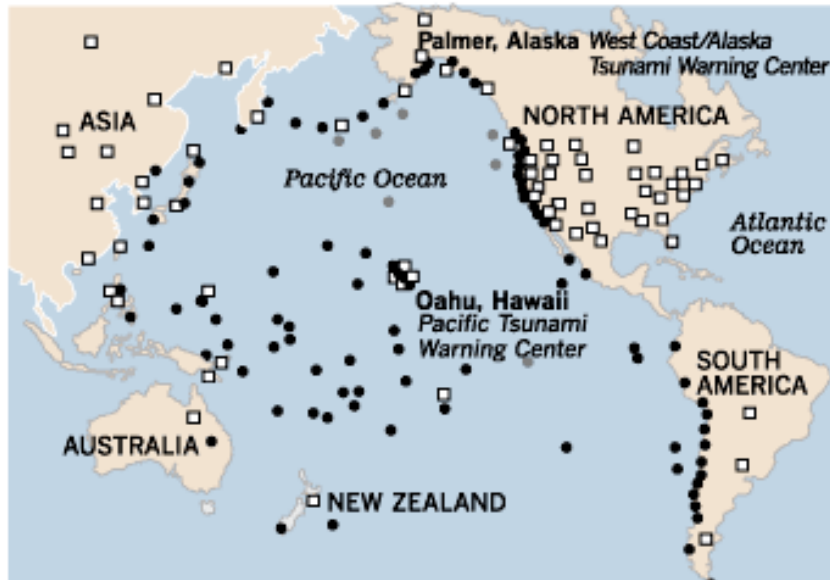
**Does this makes sense?
No right answer.**

RISK/BENEFIT BALANCE



Tsunami warning system in the Pacific Ocean

● Tide station ● Deep ocean sensor □ Seismograph station



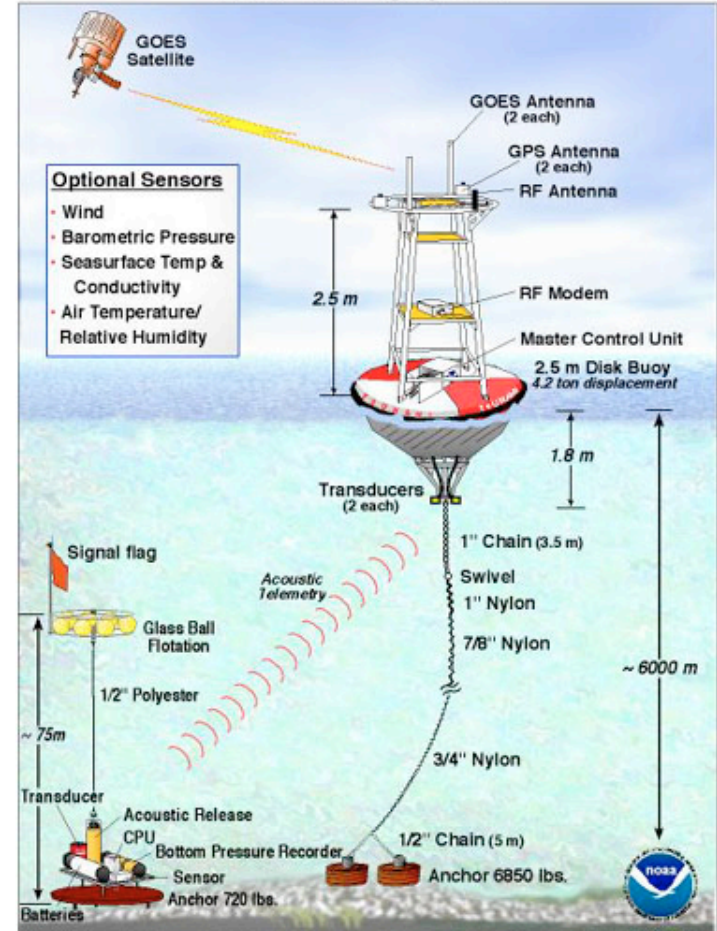
SEISMOMETERS DETECT MAJOR EARTHQUAKES

Challenges:

- Decide if there will be a tsunami in time to warn
- Get warning out
- Get people to act

TSUNAMI WARNING

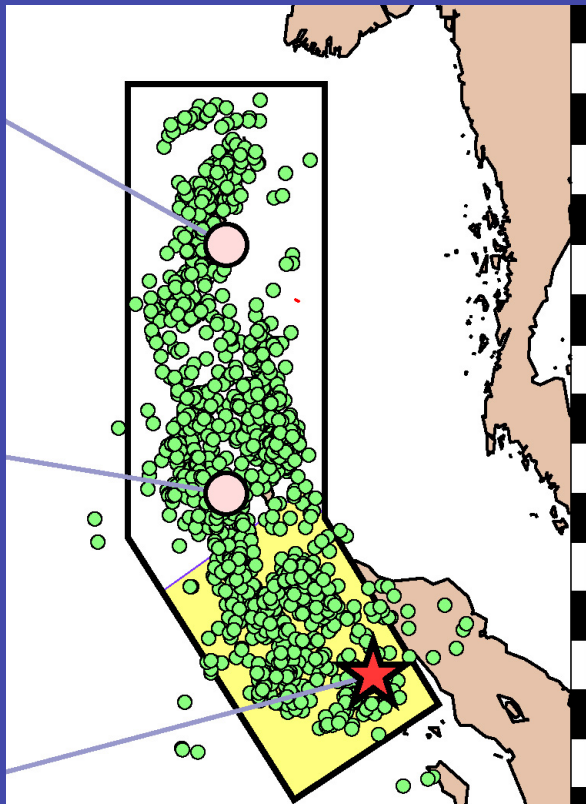
DART Mooring System



Ocean buoys can measure wave heights, verify tsunami and reduce false alarms

GPS COULD HELP

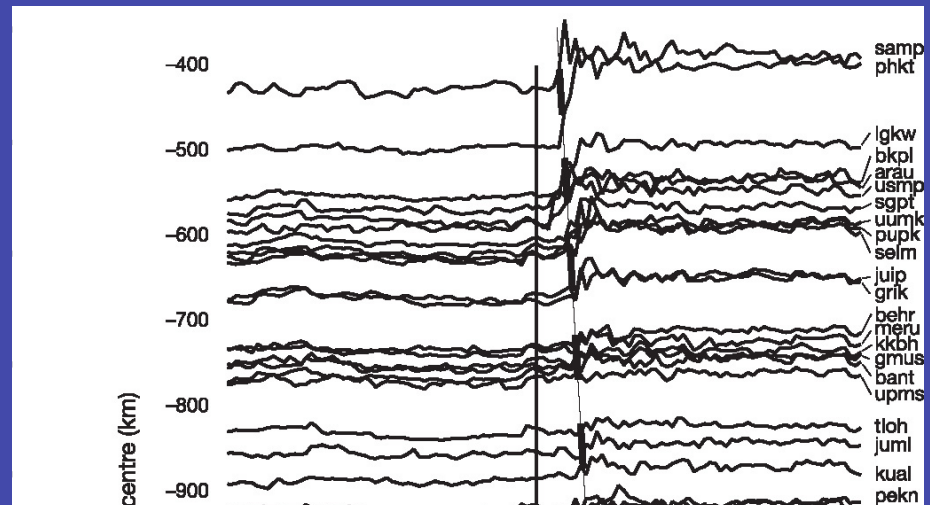
Giant earthquakes like Sumatra cause 5-10 inch ground motions hundreds of miles from epicenter



South Asia Tsunami

Failure to Gauge the Quake Crippled the Warning Effort

Earthquake's giant size & tsunami risk could have been identified in 15 minutes; not the hours it took



Vigny et al., 2005

Volcanoes produce atmospheric gases (carbon dioxide CO_2 ; water H_2O) that support life and keep planet warm enough for life ("greenhouse")

May explain how life (at midocean ridge hot springs)

Raises continents above sea level

Produces resources including fossil fuels

**WE NEED EARTHQUAKES:
PLATE TECTONICS IS
DESTRUCTIVE TO HUMAN
SOCIETY BUT CRUCIAL
FOR HUMAN LIFE**

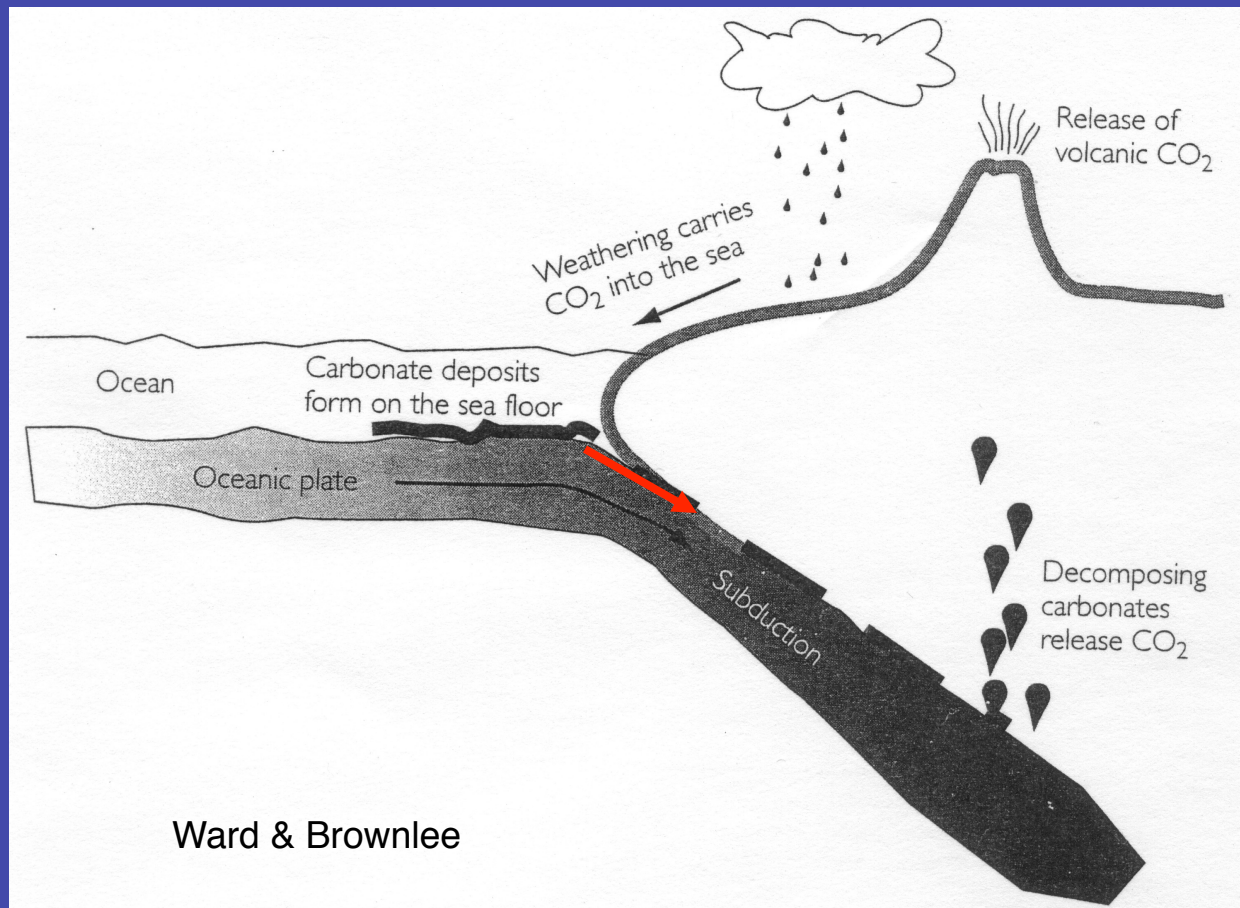


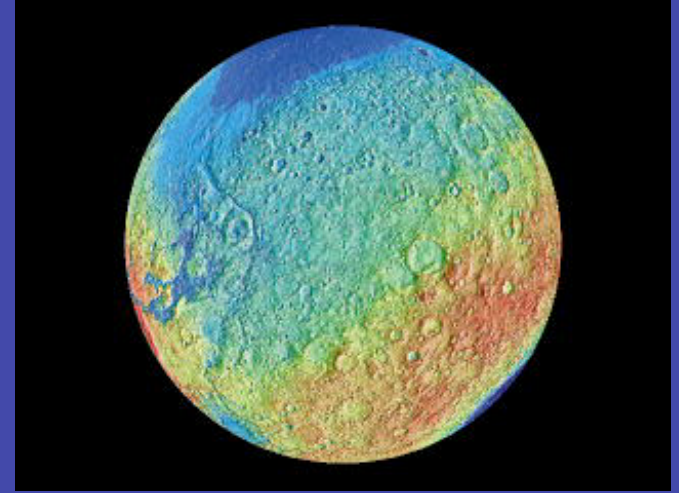
Plate tectonics maintaining the atmosphere may be part of why life survived on Earth, not Mars & Venus



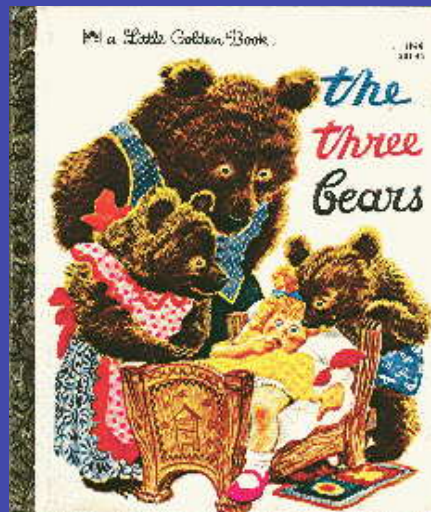
Venus is too hot



Earth is just right



Mars is too cold



“CIVILIZATION EXISTS BY GEOLOGICAL CONSENT - SUBJECT TO CHANGE WITHOUT NOTICE”

12/03 Bam, Iran M 6.6
27,000 deaths



Collapsed adobe buildings

12/03 San Simeon, CA M 6.5
2 deaths



Collapsed wine barrel stacks

NEED TO UNDERSTAND EARTHQUAKES, LIVE WITH THEM, & MINIMIZE THEIR EFFECTS ON SOCIETY