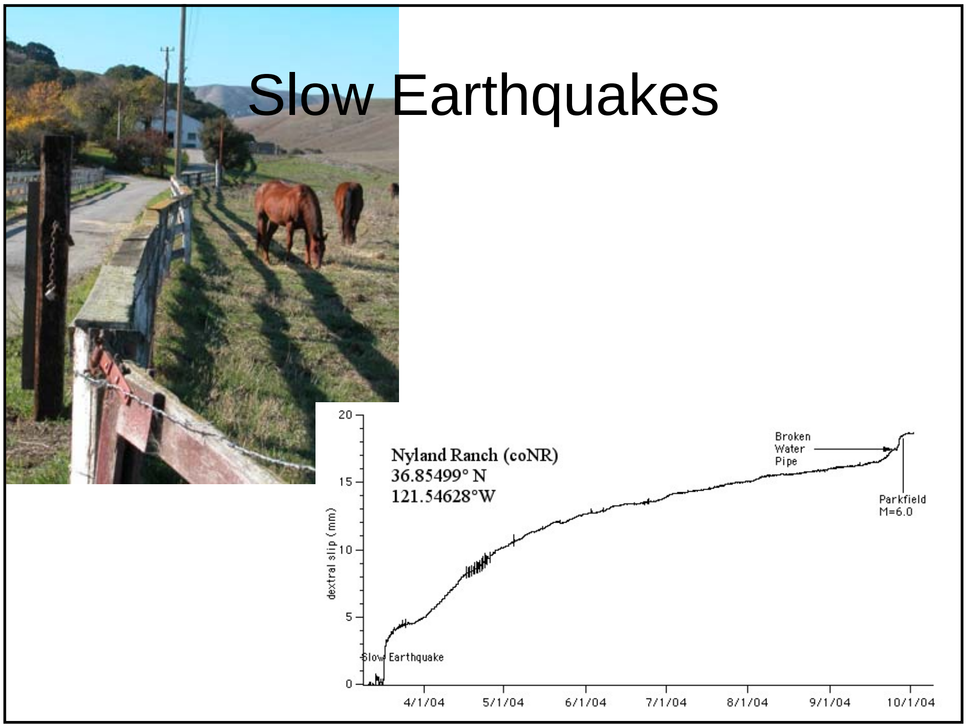
Overview of Seismotectonics

The relationship between earthquake occurrence and tectonic processes

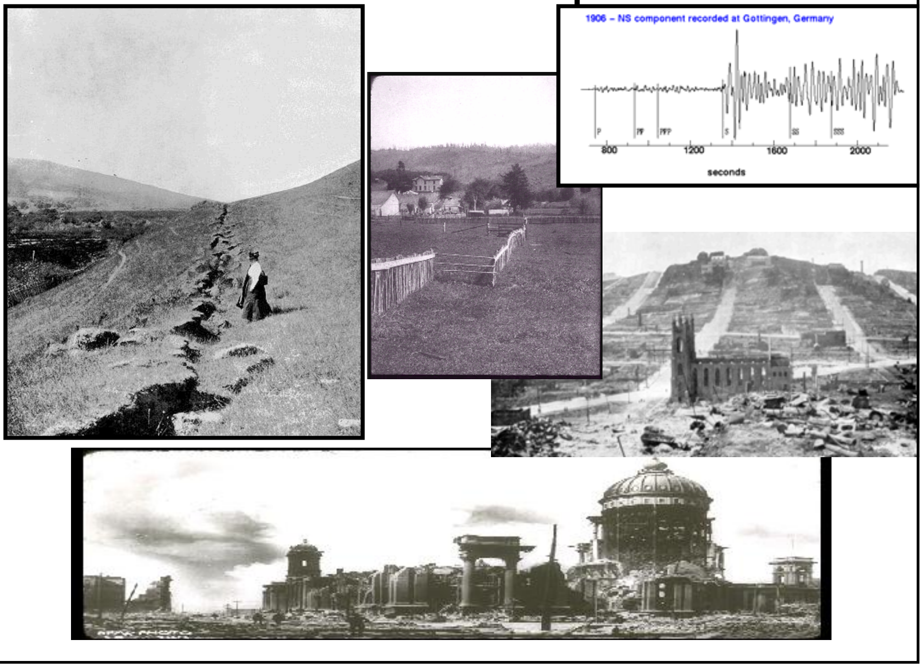
- What is an earthquake?
  - Earth faulting event?
  - Propagating elastic waves that are felt and can cause damage?
- Where do earthquakes occur?
- Earthquake model & useful definitions
  - Elastic rebound theory – earthquake cycle
  - Scalar seismic moment
  - Moment magnitude
  - Faulting types and how to read focal mechanism diagrams
- Overview of plate tectonics
  - Evidence
  - Absolute and relative plate motions
  - Types of plate boundaries
  - Triple junctions
- Tectonic environments of some notable earthquakes

Slow Earthquakes



Fast Earthquakes

1906 Earthquake



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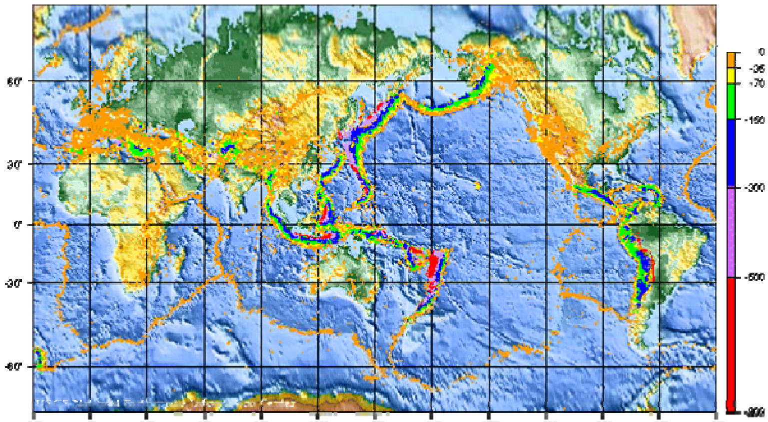
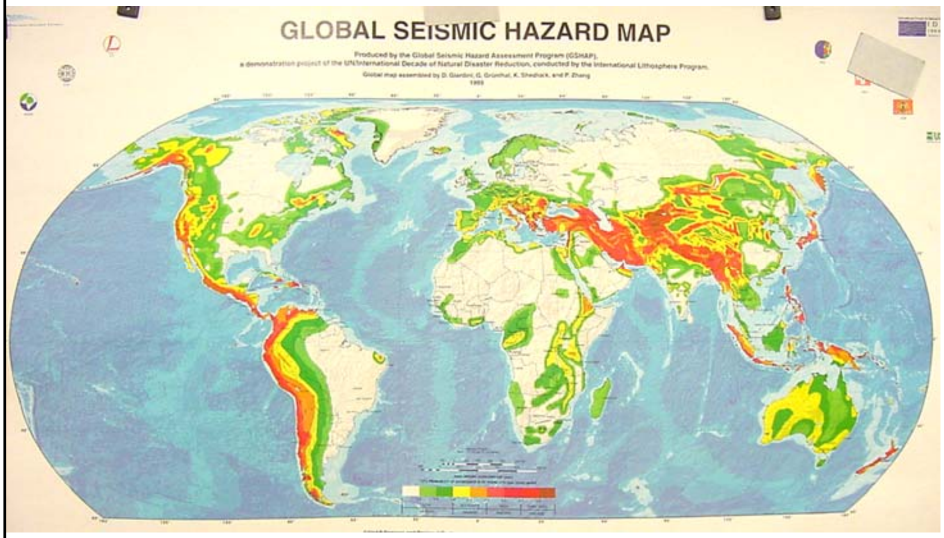
Where do earthquakes occur?

World Seismicity: 1990 - 2000





Absolute Plate Motion and Plate Boundary Type

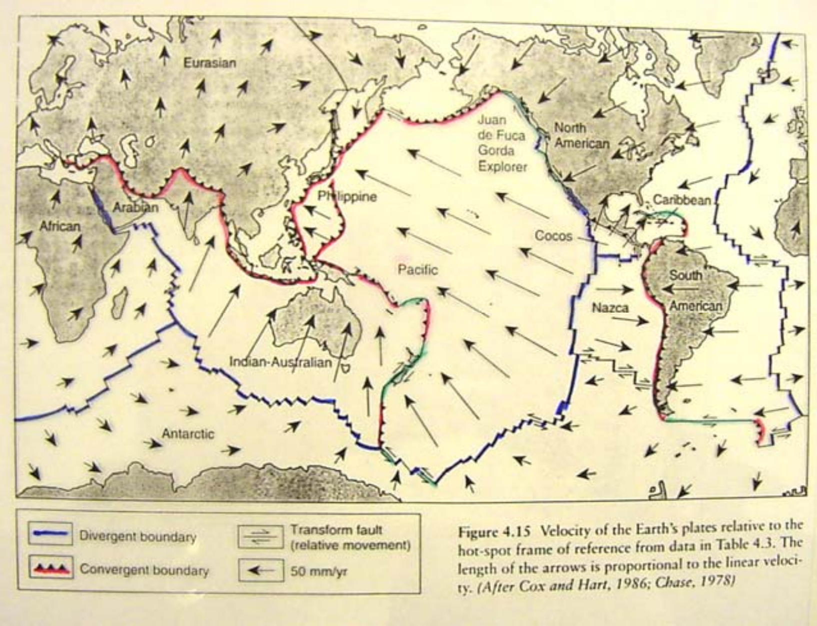
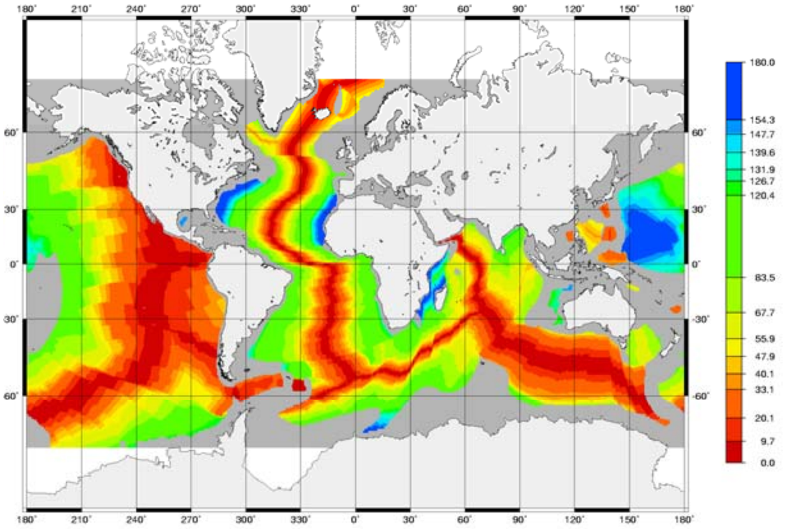
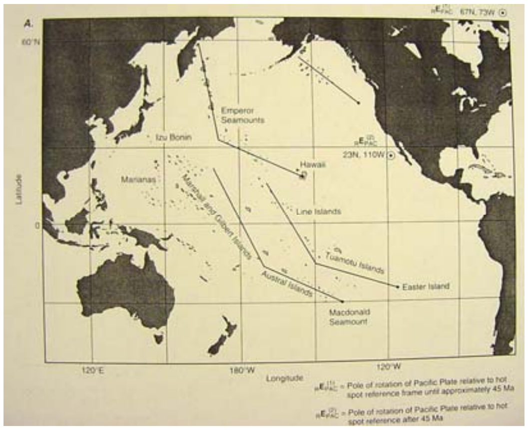


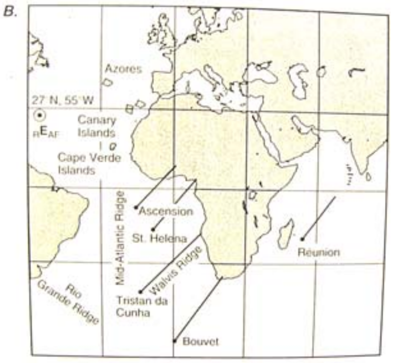
Figure 4.15 Velocity of the Earth's plates relative to the hot-spot frame of reference from data in Table 4.3. The length of the arrows is proportional to the linear velocity. *(After Cox and Hart, 1986; Chase, 1978)*

Age of the ocean floor & magnetic stripes

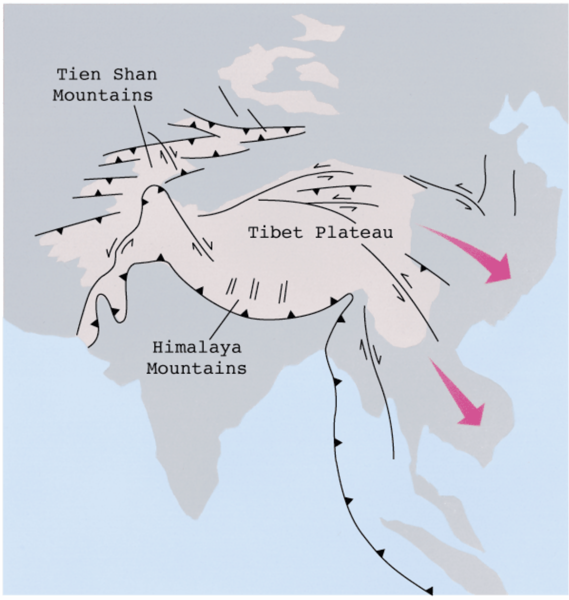


Hot Spot Tracks





GPS Deformation – Escape Tectonics of Tibet



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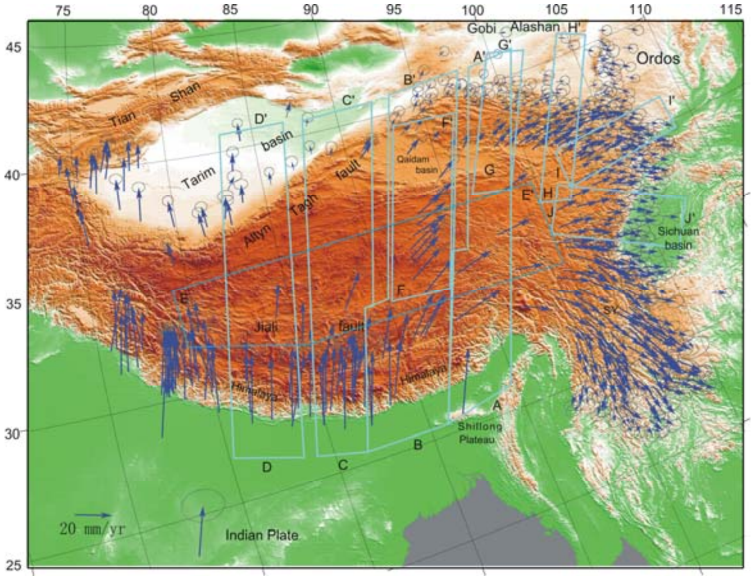
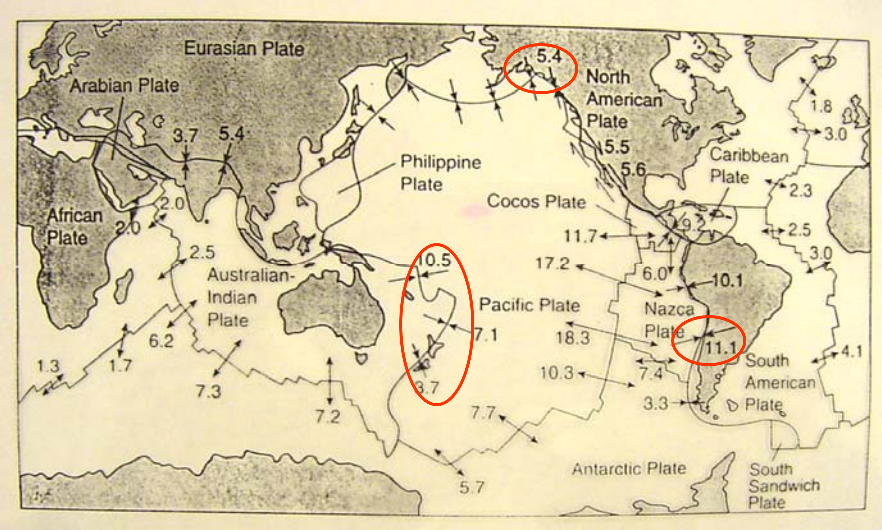


Relative Plate Motions (cm/yr)



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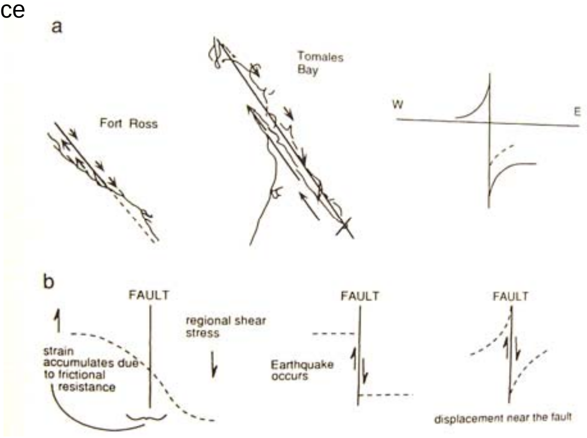
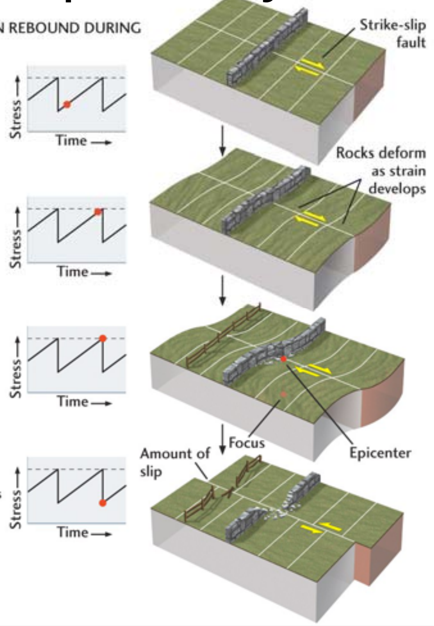
- Earthquake model
  - Elastic rebound theory (H. F. Reid, 1910)
  - Necessary conditions
    - Deformable elastic medium
    - Brittle rheology, or
    - Frictional resistance on pre-existing fault
    - Outside driving force



The Earthquake Cycle

ROCKS DEFORM ELASTICALLY, THEN REBOUND DURING AN EARTHQUAKE RUPTURE



Steady elastic strain accumulation

TIME 1
A farmer builds a stone wall across a right-lateral strike-slip fault a few years after its last rupture.

TIME 2
Over the next 150 years, the relative motion between blocks on either side of the locked fault causes the ground and the stone wall to deform.

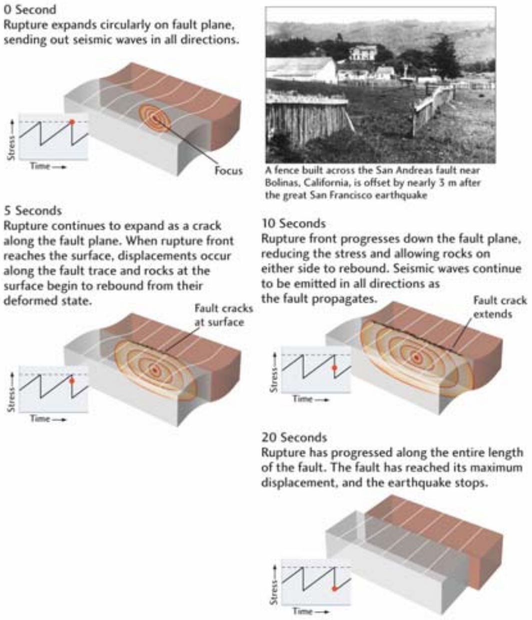
TIME 3
Just before the next rupture, a new fence is built across the already-deformed land.

When the stress exceeds the strength of the fault, a rupture begins at the first point of failure—the focus—beneath the epicenter on the surface. The rupture expands rapidly across the fault,

Elastic rebound

TIME 4
The rupture displaces the fault, lowering the stress, and the elastic rebound restores the blocks to their pre-stressed state. Both the rock wall and the fence are shifted equal amounts across the fault trace. The rebound straightens the rock wall, but the fence exhibits a reverse curve.

The Earthquake Cycle



0 Second
Rupture expands circularly on fault plane, sending out seismic waves in all directions.

A fence built across the San Andreas fault near Bolinas, California, is offset by nearly 3 m after the great San Francisco earthquake

5 Seconds
Rupture continues to expand as a crack along the fault plane. When rupture front reaches the surface, displacements occur along the fault trace and rocks at the surface begin to rebound from their deformed state.

10 Seconds
Rupture front progresses down the fault plane, reducing the stress and allowing rocks on either side to rebound. Seismic waves continue to be emitted in all directions as the fault propagates.

20 Seconds
Rupture has progressed along the entire length of the fault. The fault has reached its maximum displacement, and the earthquake stops.

When the stress exceeds the strength of the fault, a rupture begins at the first point of failure—the focus—beneath the epicenter on the surface. The rupture expands rapidly across the fault,

Elastic rebound

TIME 4
The rupture displaces the fault, lowering the stress, and the elastic rebound restores the blocks to their pre-stressed state. Both the rock wall and the fence are shifted equal amounts across the fault trace. The rebound straightens the rock wall, but the fence exhibits a reverse curve.

Friction: Stick-Slip vs. Creep

- Earthquakes in the Lab:

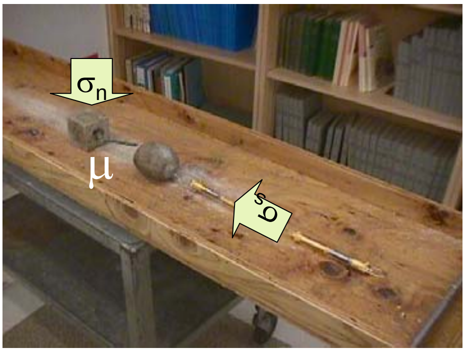
Earthquake like behavior

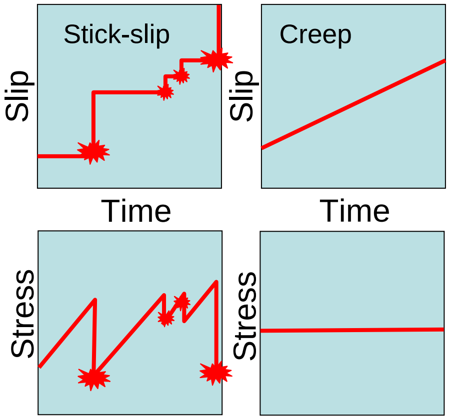
Strength of faults

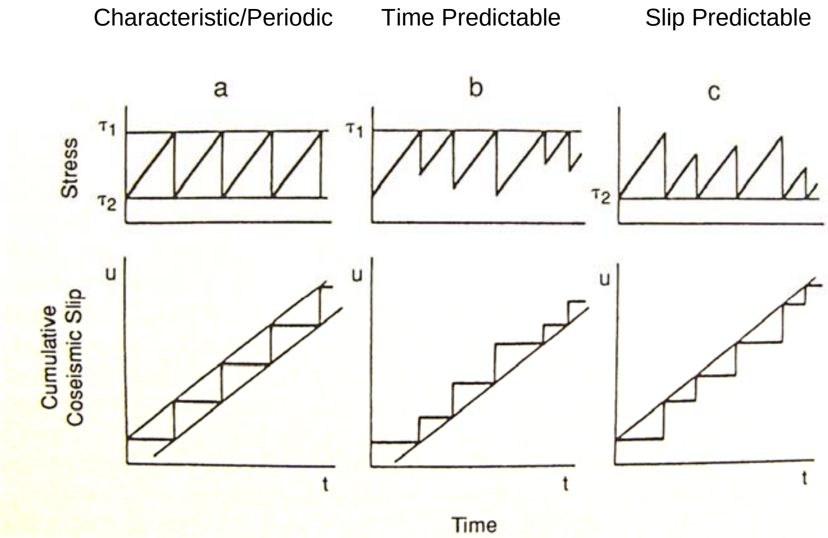
  - Increasing normal stress increases frictional strength

↖Amonton's law $\sigma_s = \mu\sigma_n$

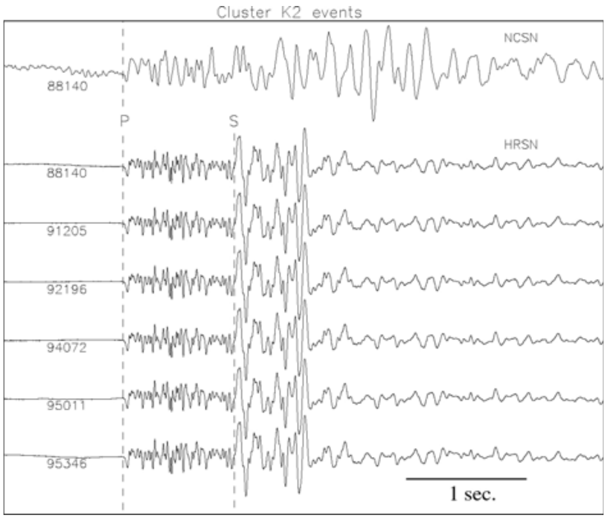
- Earthquakes indicate stick slip
- Some faults (including the Hayward fault) also have steady creep







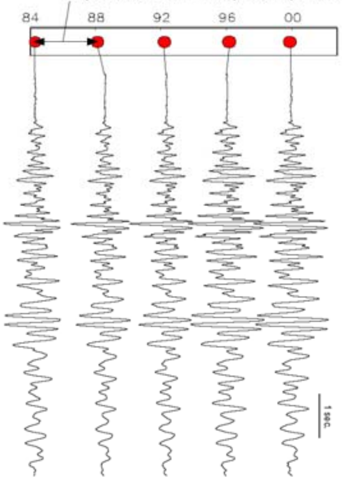
Repeating Micro Earthquakes Display Characteristic Earthquake Behavior



Characteristically Repeating Micro-quakes:

(Example from the Hayward Fault.)

Tr (recurrence interval) = 3.98(+/- 0.15) years



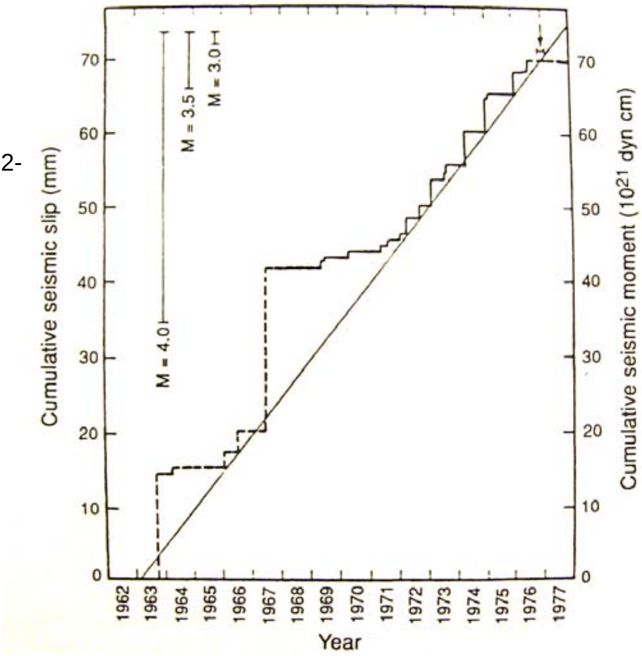
Mag. = 1.38 (+/- 0.05)

Same:
- Seismograms (mechanisms)
- Magnitudes
- Locations
- Recurrence Intervals (approximately)

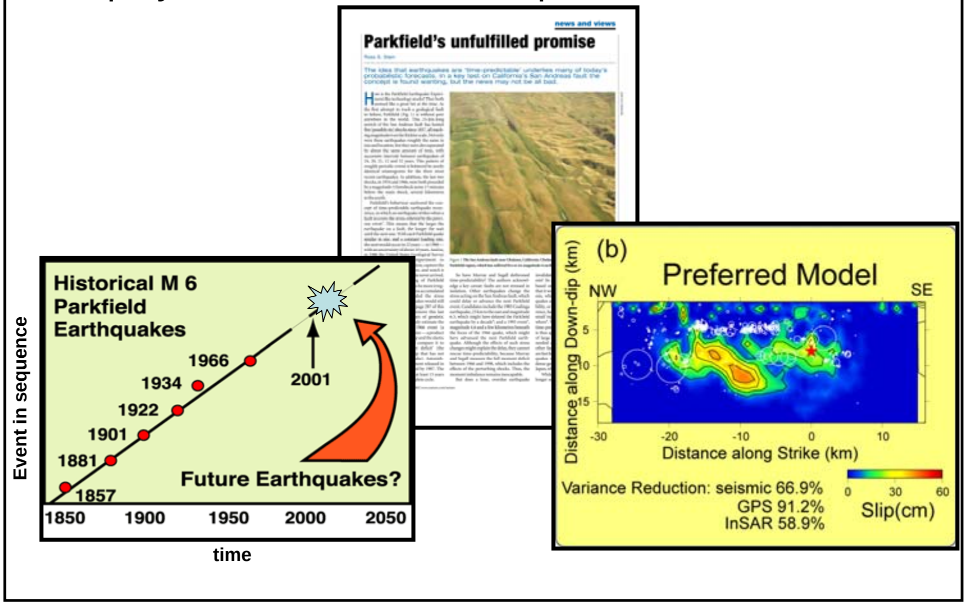
⇓

- Repeated Rupture of the Same Fault Patch
- Ongoing Fault Loading

Cumulative slip on the Calaveras fault from 1962-1978 displays time predictable behavior



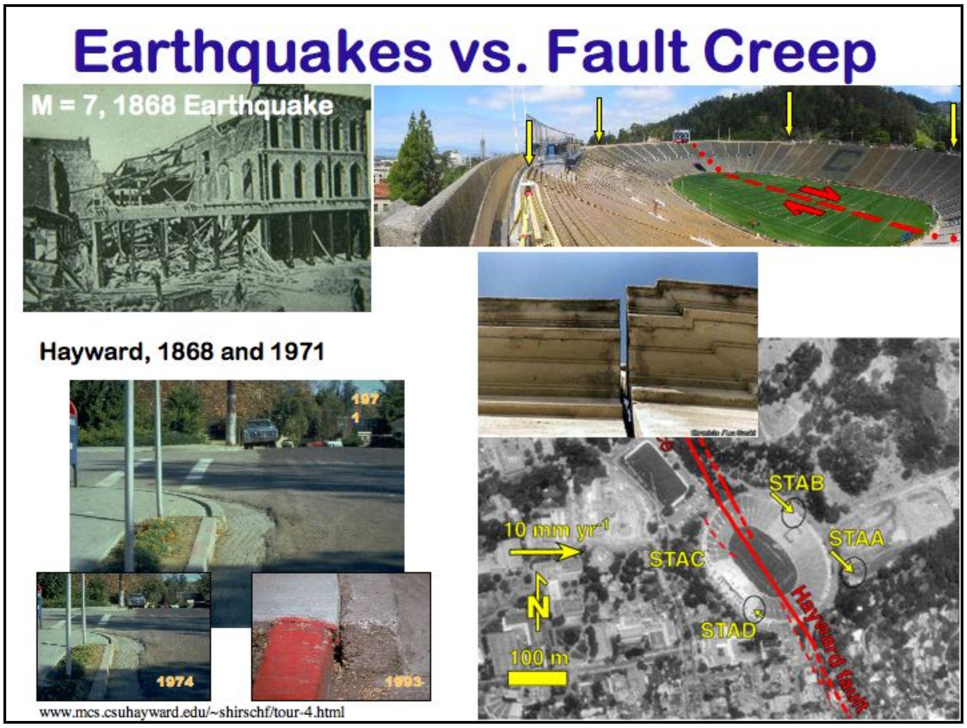
Unfortunately the 2004 Parkfield Earthquake Displayed Neither Time or Slip Predictable Behavior


news and views

Parkfield's unfulfilled promise

Ross S. Stein

The idea that earthquakes are 'time-predictable' underlies many of today's probabilistic forecasts. In a key test on California's San Andreas fault the concept is found wanting, but the news may not be all bad.



Earthquakes vs. Fault Creep

M = 7, 1868 Earthquake

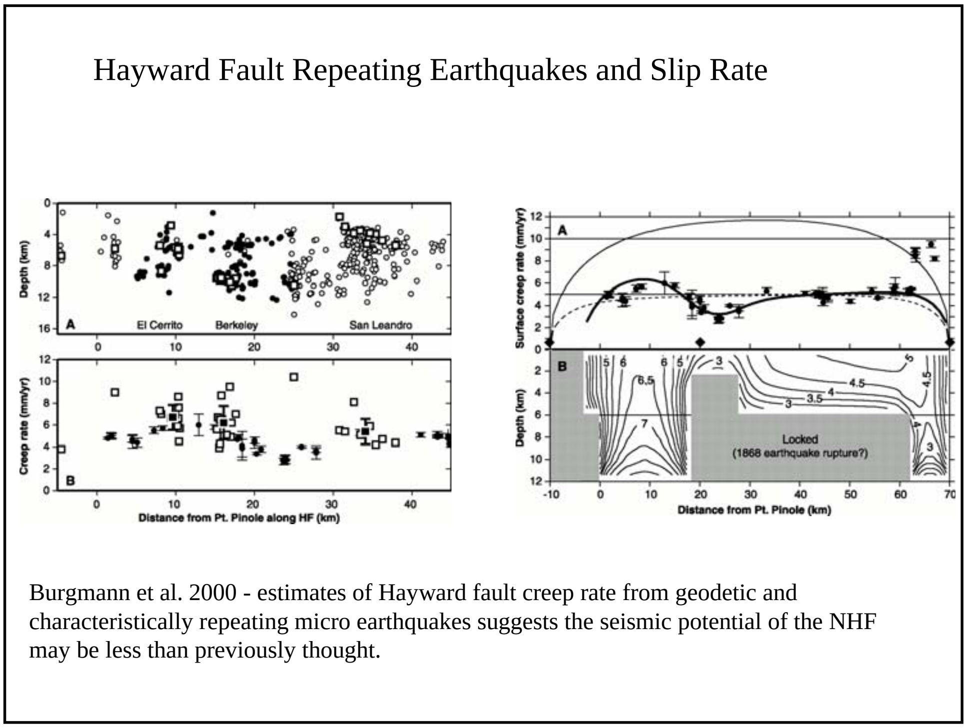
Hayward, 1868 and 1971

1971

1974

1993

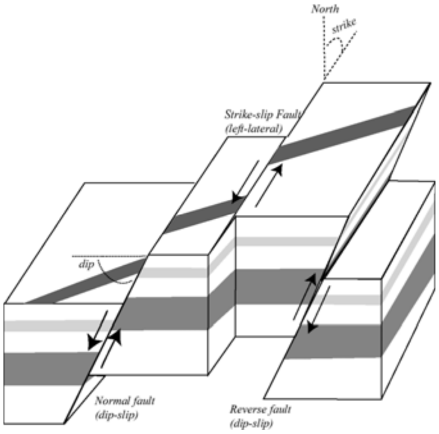
www.mcs.csuhayward.edu/~shirschf/tour-4.html

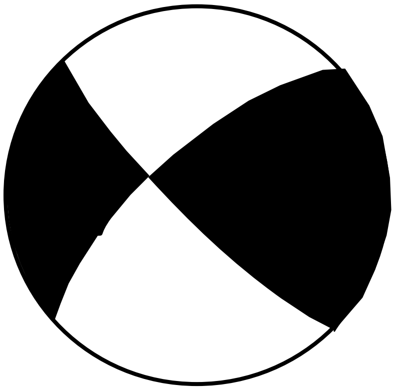


Hayward Fault Repeating Earthquakes and Slip Rate

Burgmann et al. 2000 - estimates of Hayward fault creep rate from geodetic and characteristically repeating micro earthquakes suggests the seismic potential of the NHF may be less than previously thought.

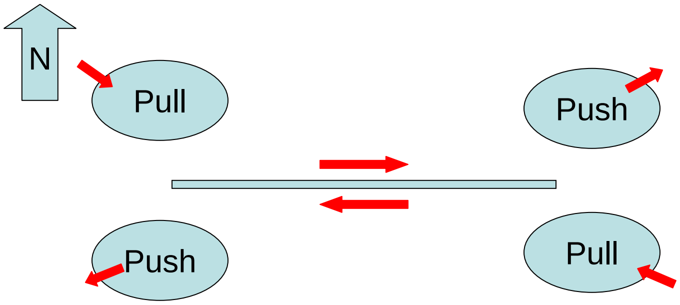
Types of Faulting





How does this relate to this?

Sign of First Motion
Earthquake Geometry



N

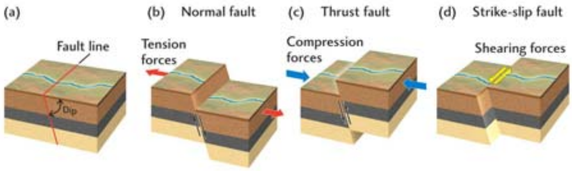
Pull

Push

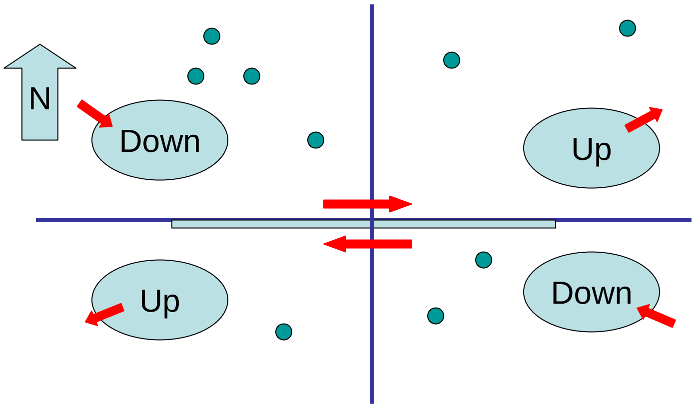
Push

Pull

Fault motion of different kinds of faults (normal, reverse, strike-slip) will produce distinctive seismic wave characteristics

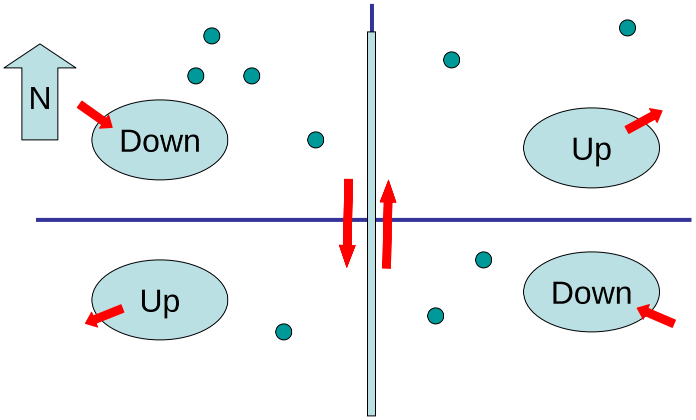


Earthquake Geometry



- First motion on vertical seismograph

Earthquake Geometry



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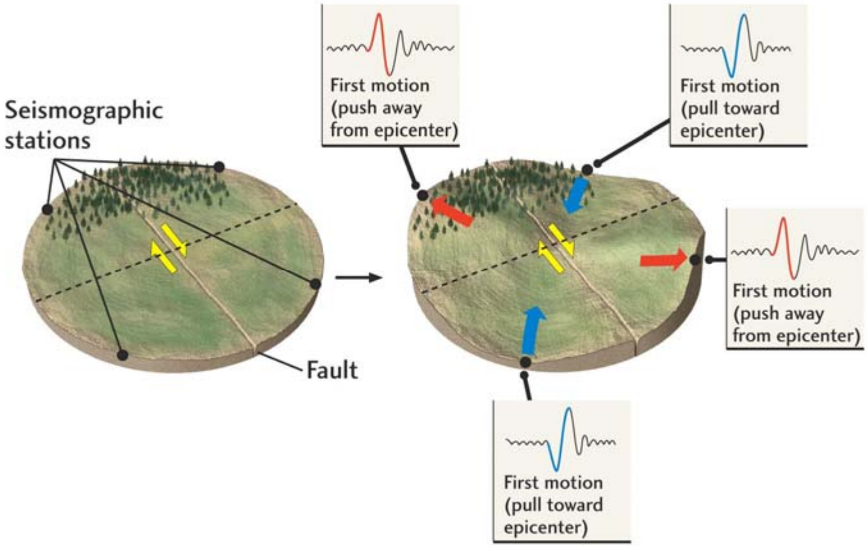
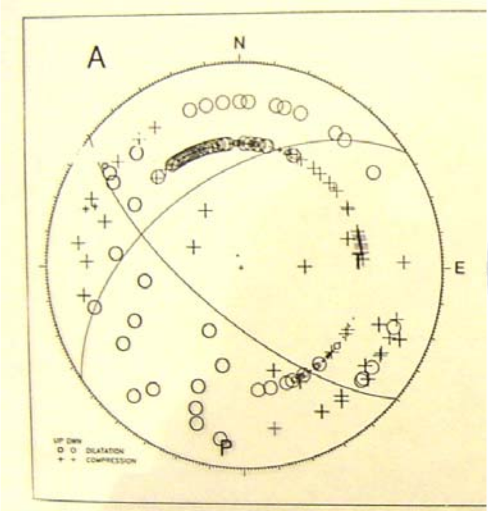
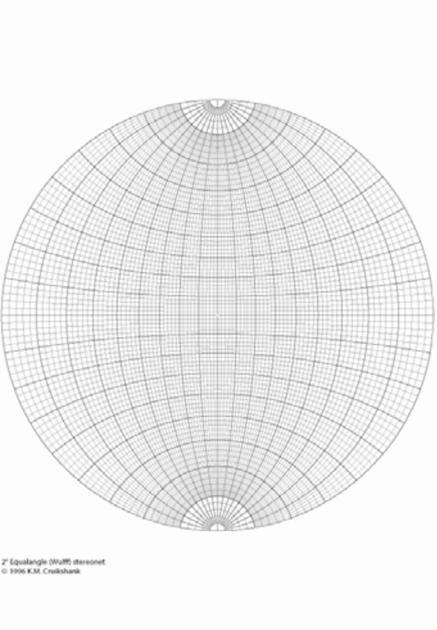
Earthquake Geometry



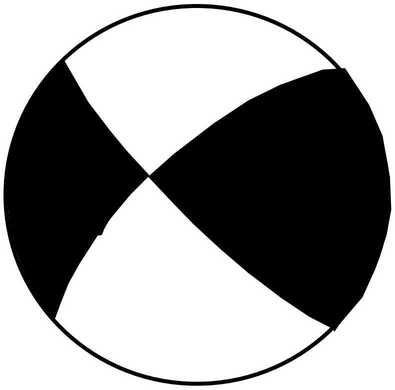
Loma Prieta First Motions





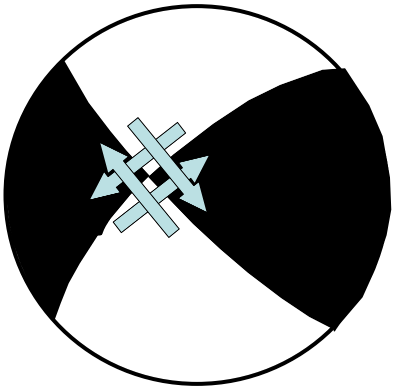
Earthquake Geometry – The Focal Mechanism

- The second nodal plane is at 90° from the first
- Draw the Up quadrant sectors solid

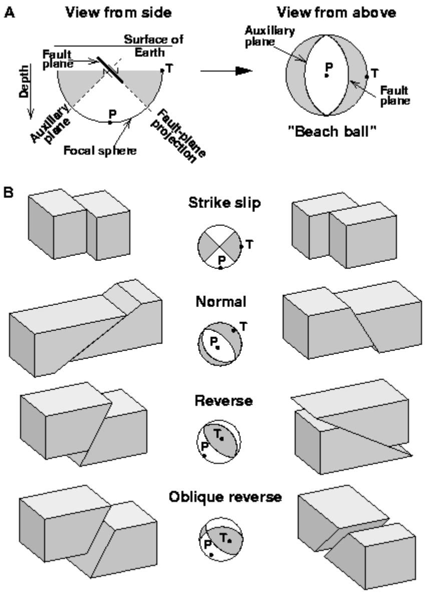


Earthquake Geometry – The Focal Mechanism

- The second nodal plane is at 90° from the first
- Draw the Up quadrant sectors solid
- A focal mechanism always indicates 2 possible fault planes
- How do we figure out which is the actual rupture?



Recent Earthquakes of Each Type



1999 Izmit, Turkey

2004 Parkfield, CA

1983 Borah Peak

1993 Klamath Falls, OR

2003 San Simeon, CA

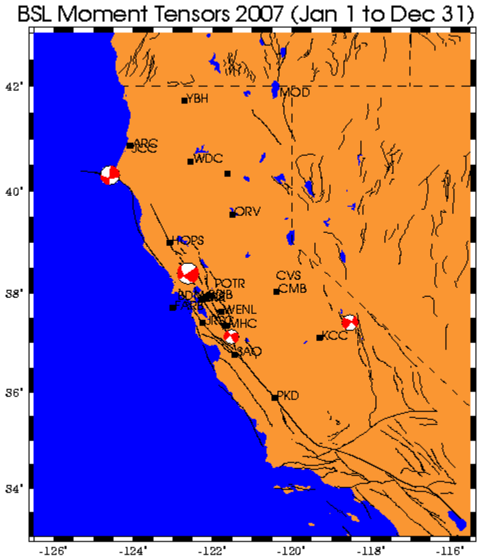
2005 Sumatra

1989 Loma Prieta, CA

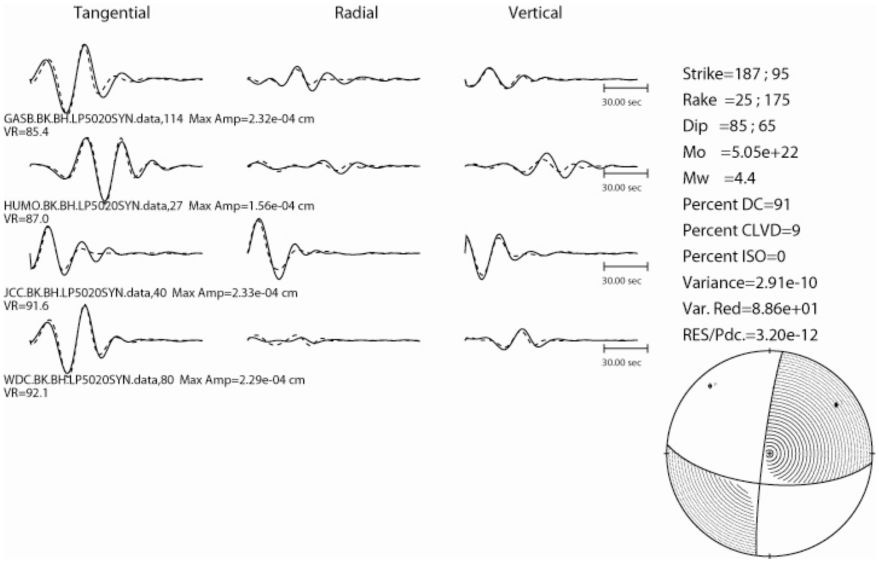
- •Dark quadrant is compressional.
- •Slip goes towards compressional quadrants

USGS Figure

Berkeley Seismological Laboratory Moment Tensors This Year



January 23, 2007 Mw4.4 Mendocino



GASB.BK.BH.LP5020SYN.data,114 Max Amp=2.32e-04 cm
VR=85.4

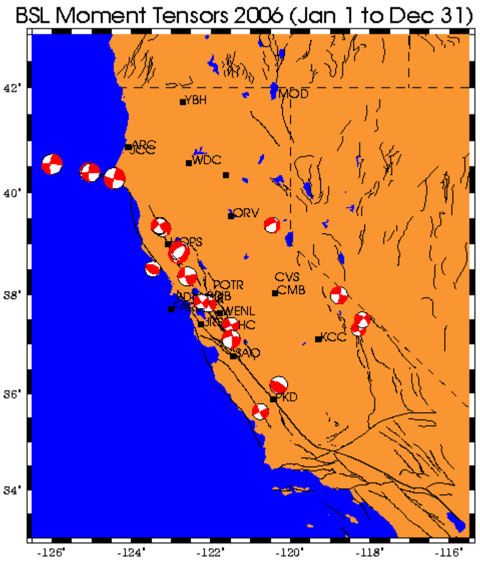
HUMO.BK.BH.LP5020SYN.data,27 Max Amp=1.56e-04 cm
VR=87.0

JCC.BK.BH.LP5020SYN.data,40 Max Amp=2.33e-04 cm
VR=91.6

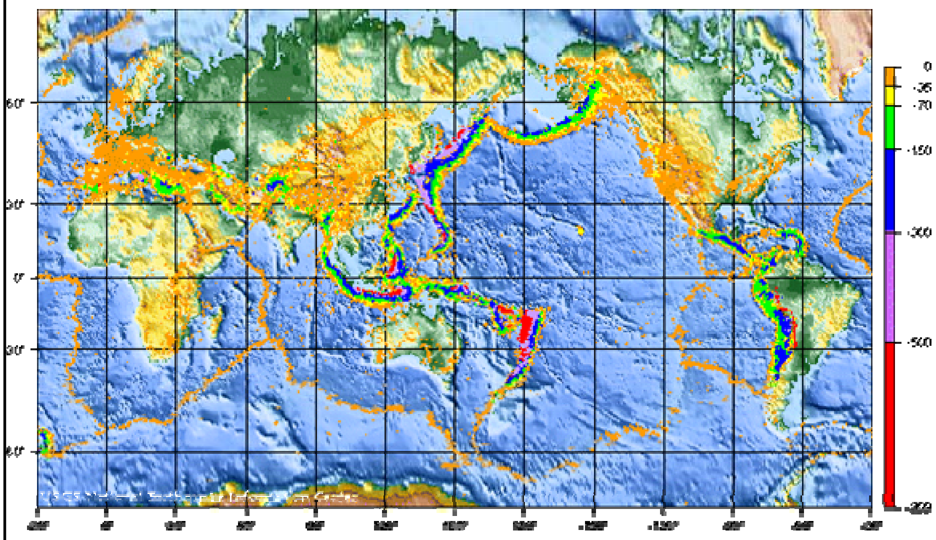
WDC.BK.BH.LP5020SYN.data,80 Max Amp=2.29e-04 cm
VR=92.1

Strike=187 ; 95
Rake =25 ; 175
Dip =85 ; 65
Mo =5.05e+22
Mw =4.4
Percent DC=91
Percent CLVD=9
Percent ISO=0
Variance=2.91e-10
Var. Red=8.86e+01
RES/Pdc.=3.20e-12

And last year


BSL Moment Tensors 2006 (Jan 1 to Dec 31)

World Seismicity: 1990 - 2000



Absolute Plate Motion and Plate Boundary Type

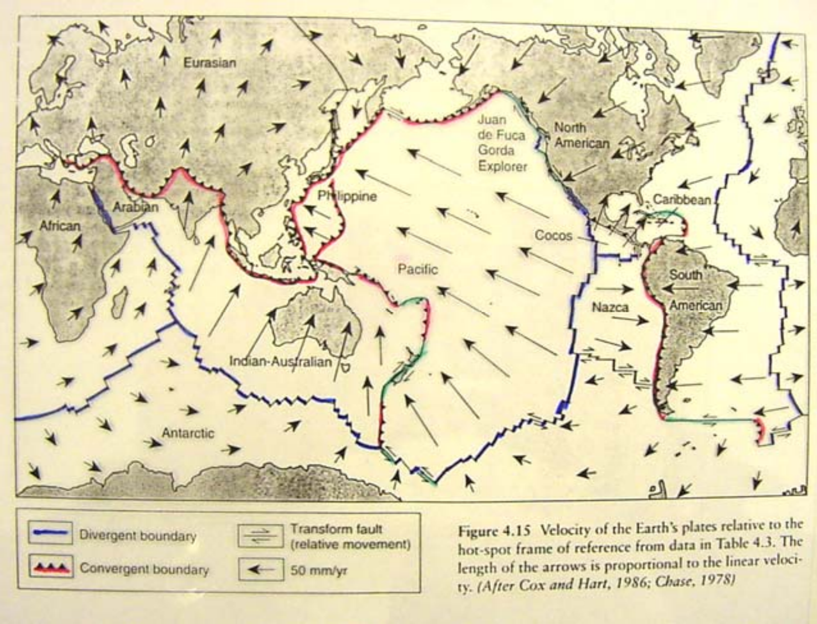
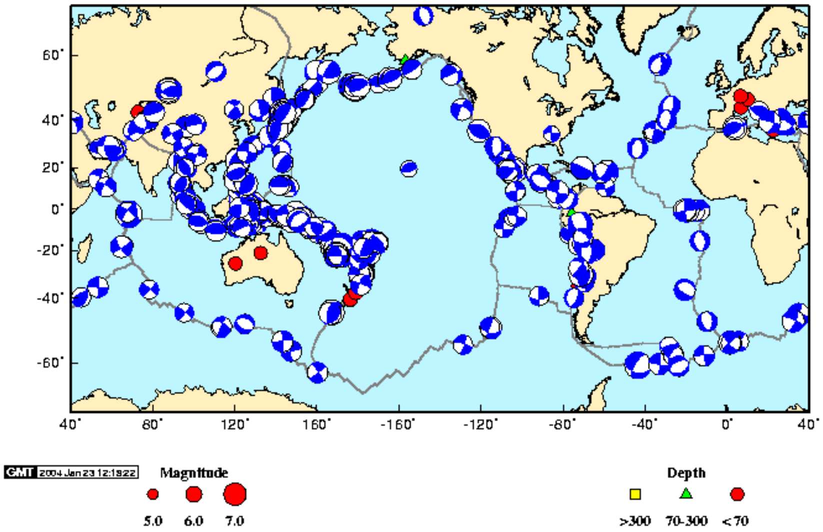


Figure 4.15 Velocity of the Earth's plates relative to the hot-spot frame of reference from data in Table 4.3. The length of the arrows is proportional to the linear velocity. *(After Cox and Hart, 1986; Chase, 1978)*

ANSS Catalog - 01/01/2003-12/31/2003 - M >= 5.5



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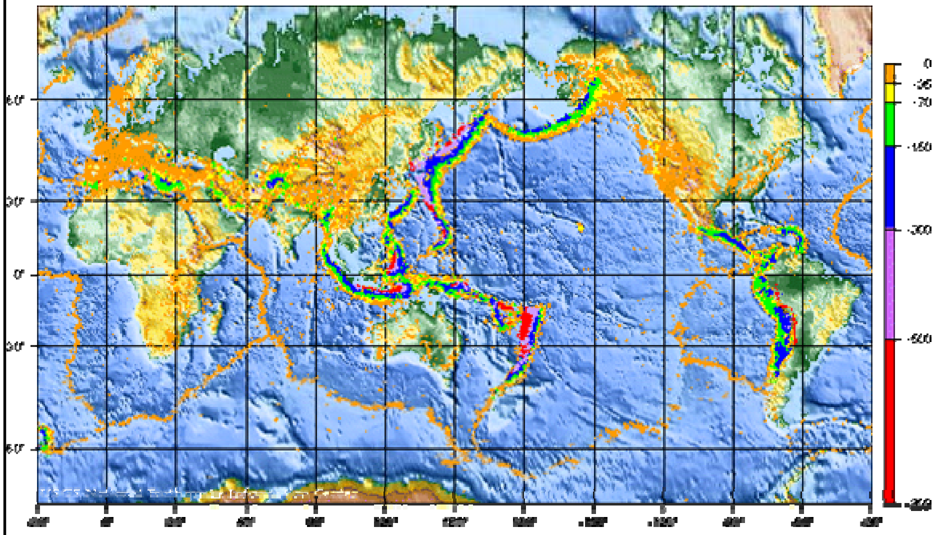


Basic Quantification

- Seismic Potency
  - Potency=area*slip
- Scalar Seismic Moment
  - Mo=rigidity*area*slip=μAD
  - Has units of energy and is proportional to energy through the stress drop (change)h
- Moment Rate
  - $\dot{M}_0 = \mu A \dot{D}$
- Magnitude
  - Mw=2/3*log(Mo)-10.7 or
  - Log(Mo)=1.5Mw+16.05 (a unit of magnitude increase corresponds to a 31-fold increase in energy)
- Statistics
  - Gutenberg-Richter
  - Omori Law

Size - Frequency Relationship

Frequency of Occurrence of Earthquakes Based on Observations since 1900

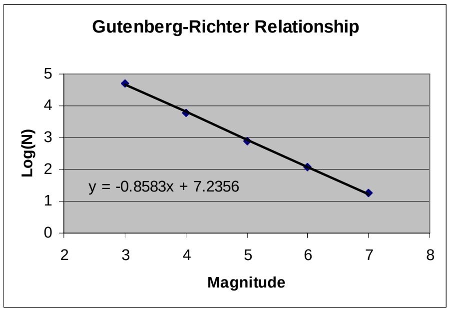
Great	**> 8**		**higher**	**1/year**
Major	**7**	**-**	**7.9**	**18**
Strong	**6**	**-**	**6.9**	**120**
Moderate	**5**	**-**	**5.9**	**800**
Light	**4**	**-**	**4.9**	**~6,200**
Minor	**3**	**-**	**3.9**	**~49,000**
Micro	**1**	**-**	**3**	**~9000/day**

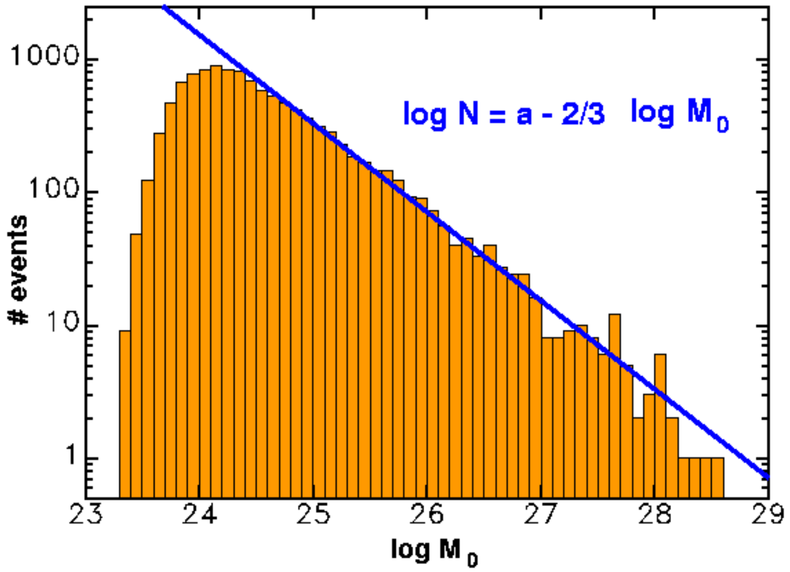
From neic.usgs.gov/neis/bulletin/mag7.html#1999

Gutenburg-Richter Relationship:

Log (number) = a + b*(magnitude)

Log (N) = a + b*M





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Micro	**1**	**-**	**3**	**~9000/day**

From neic.usgs.gov/neis/bulletin/mag7.html#1999

M7 ~ 1.99e+22 ergs

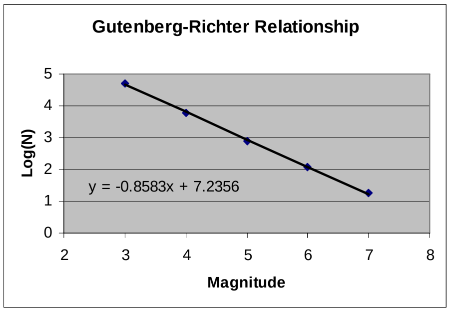
M6 ~ 6.30e+22 ergs ~ 1/30M7

It takes 32 M6 events to equal the moment of 1 M7, but M6 are only 10x more frequent

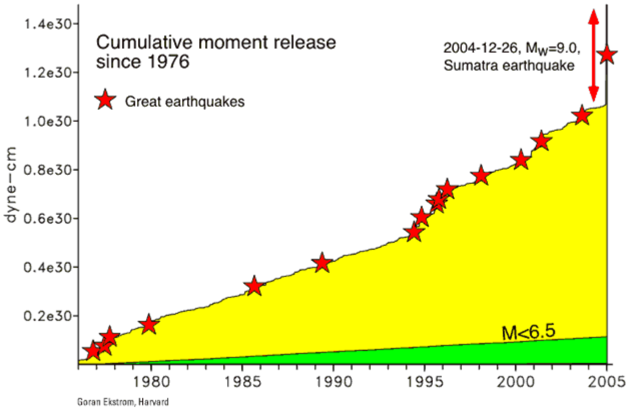
Gutenburg-Richter Relationship:

Log (number) = a + b*(magnitude)

Log (N) = a + b*M



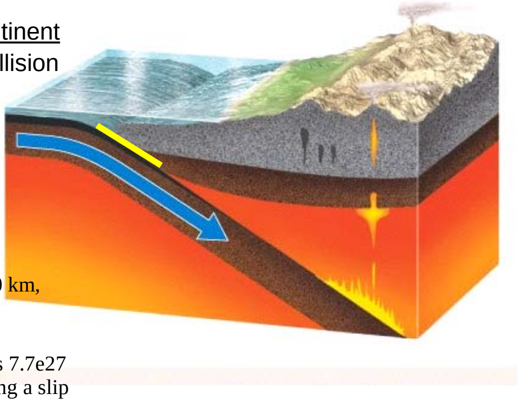
Cumulative Seismic Moment in Great Earthquakes



Goran Ekstrom, Harvard

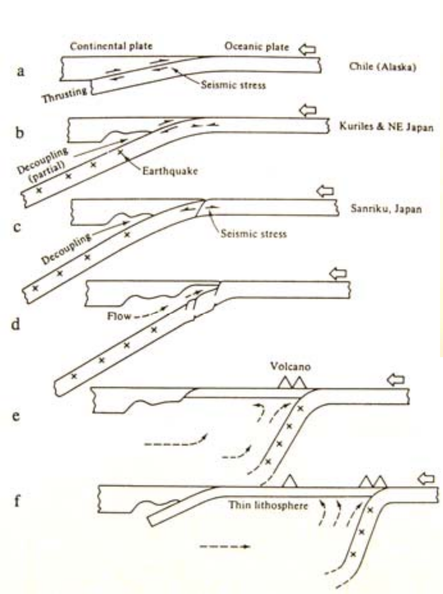
Convergent Boundaries

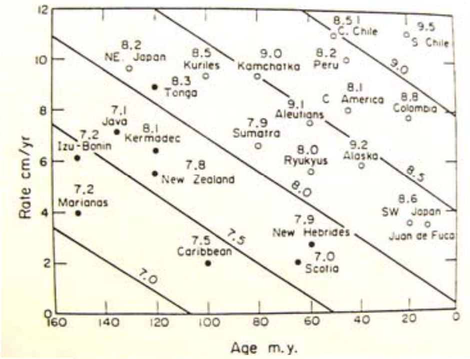
- Mostly ocean-ocean, and ocean-continent
- ~10% involve continent-continent collision
- Classic geometry

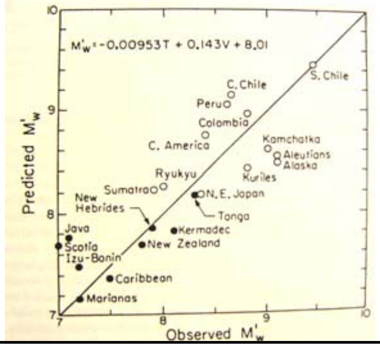


- Consider the Chilean EQ of 1960
  - μ=3.5e11 dyne cm, L=1000 km, W=200 km, D=22m
  - Mo=1.5e30 dyne cm and Mw=9.4
  - The moment rate of the same segment is 7.7e27 dyne cm/year or a Mw=7.9/year assuming a slip rate of 11 cm/yr
  - The recurrence time of Mw9.4 events is about 200 years

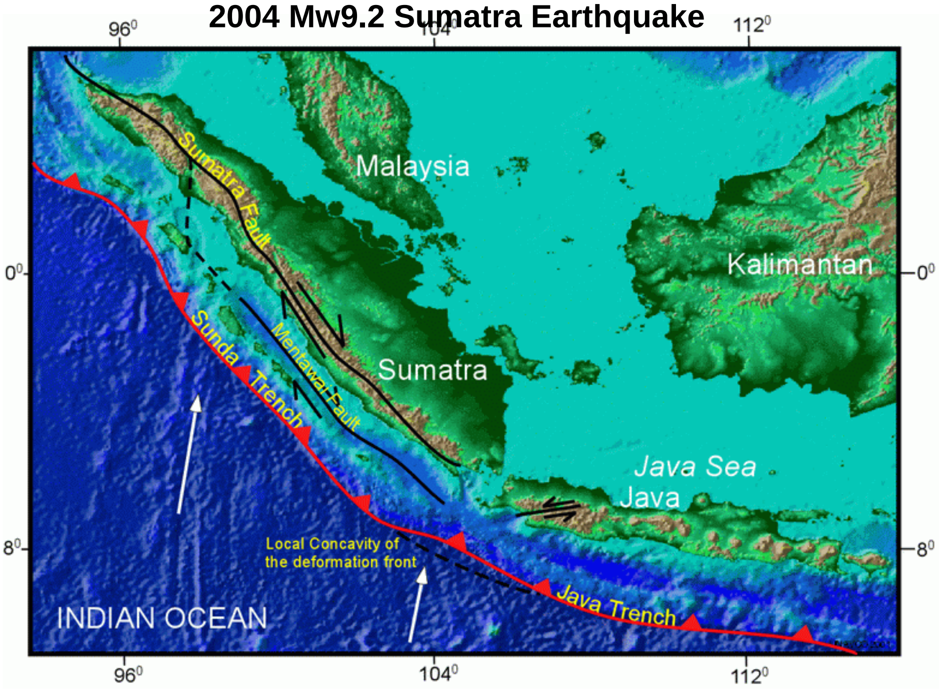
In subduction zones the shallow dipping fault (10-20 degrees can lead to a large contact patch and therefore great earthquakes

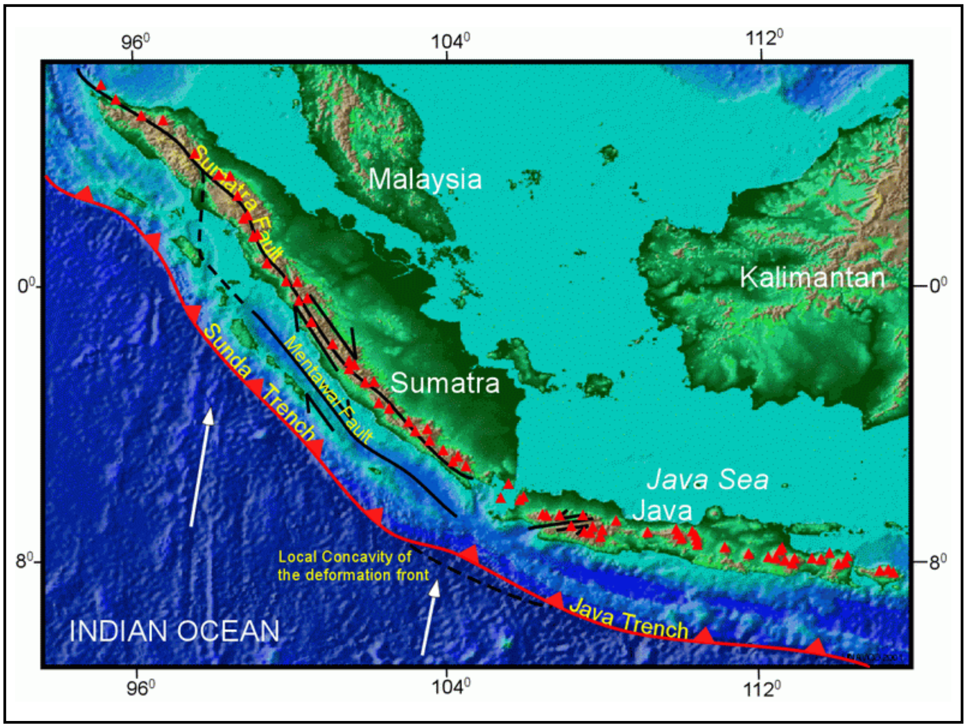


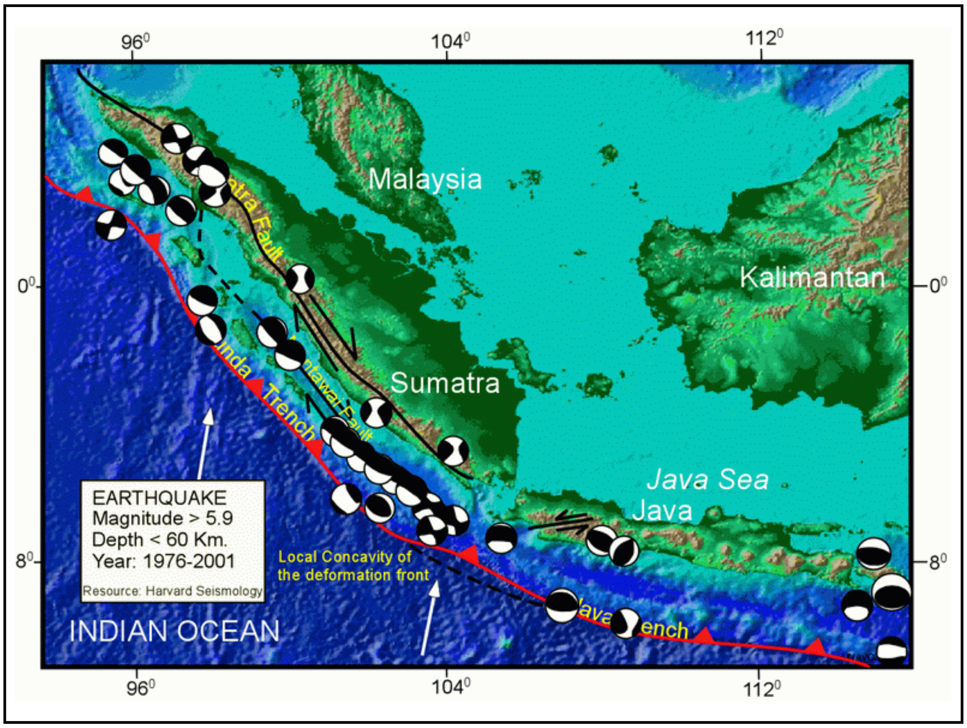


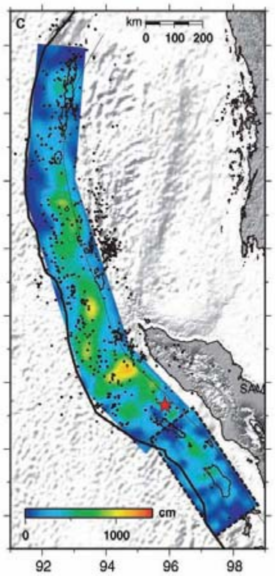


2004 Mw9.2 Sumatra Earthquake

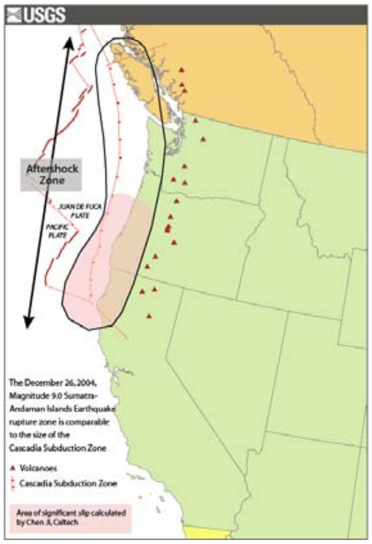



96⁰
104⁰
112⁰
0⁰
8⁰
Malaysia
Kalimantan
Sumatra
Sumatra Fault
Mentawai Fault
Sunda Trench
Java Sea
Java
Local Concavity of
the deformation front
Java Trench
INDIAN OCEAN

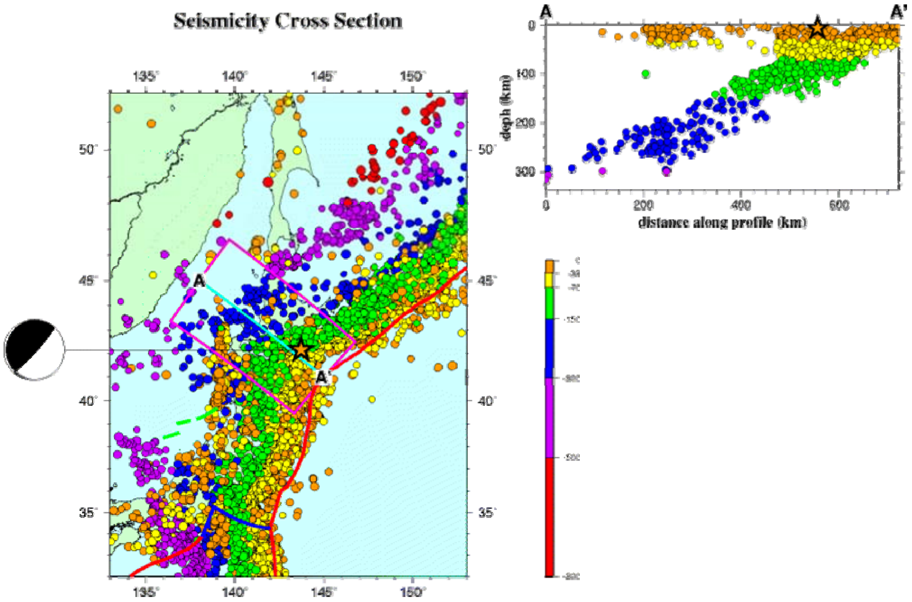

96⁰
104⁰
112⁰
0⁰
8⁰
Malaysia
Kalimantan
Sumatra
Sumatra Fault
Mentawai Fault
Sunda Trench
Java Sea
Java
EARTHQUAKE
Magnitude > 5.9
Depth < 60 Km.
Year: 1976-2001
Resource: Harvard Seismology
Local Concavity of
the deformation front
Java Trench
INDIAN OCEAN



Ammon et al., 2005

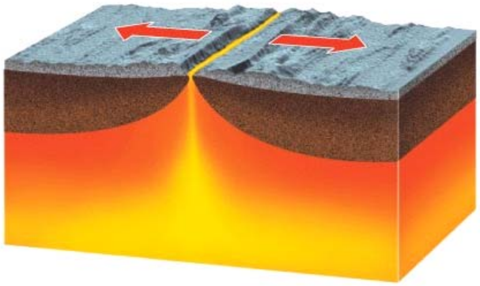


Kurile Subduction Zone – Hokkaido, Japan

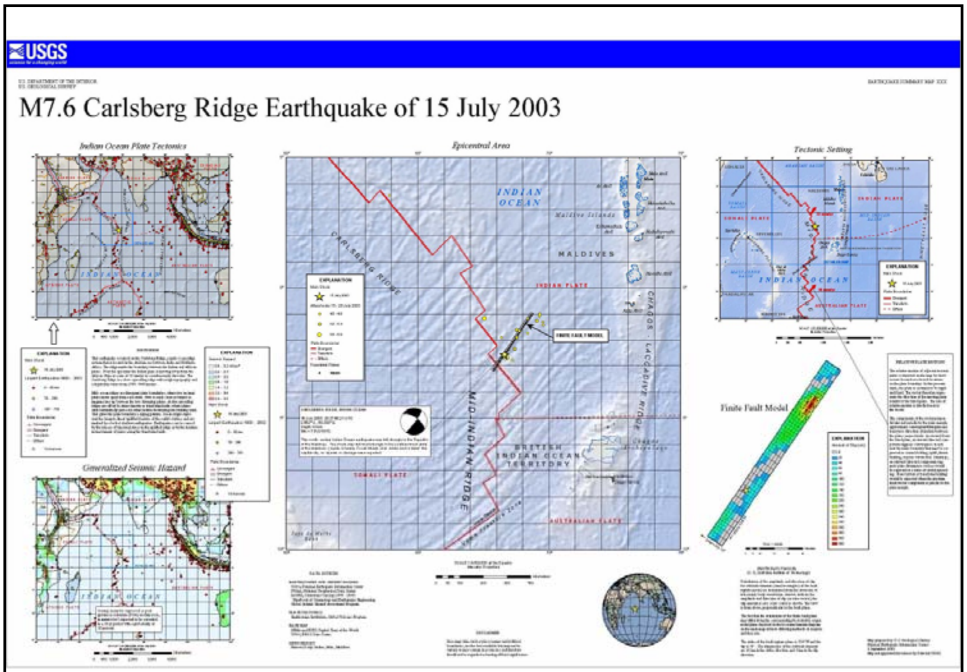


Divergent Boundaries

- Oceanic rifting
  - Normal-type events parallel to ridge axis
  - Strike-slip faulting on ridge-connenting transform faults
  - Normal events tend can be as large as 6-7 but tend to be small due to thin, warm crust
  - Transform events can be as large as magnitude 7-8
- Continental rifting
  - More complicated
  - Depth of faulting limited by relatively warm crust
  - Can get as large as magnitude 7 (e.g. 7.3 Borah Peak, Idaho)



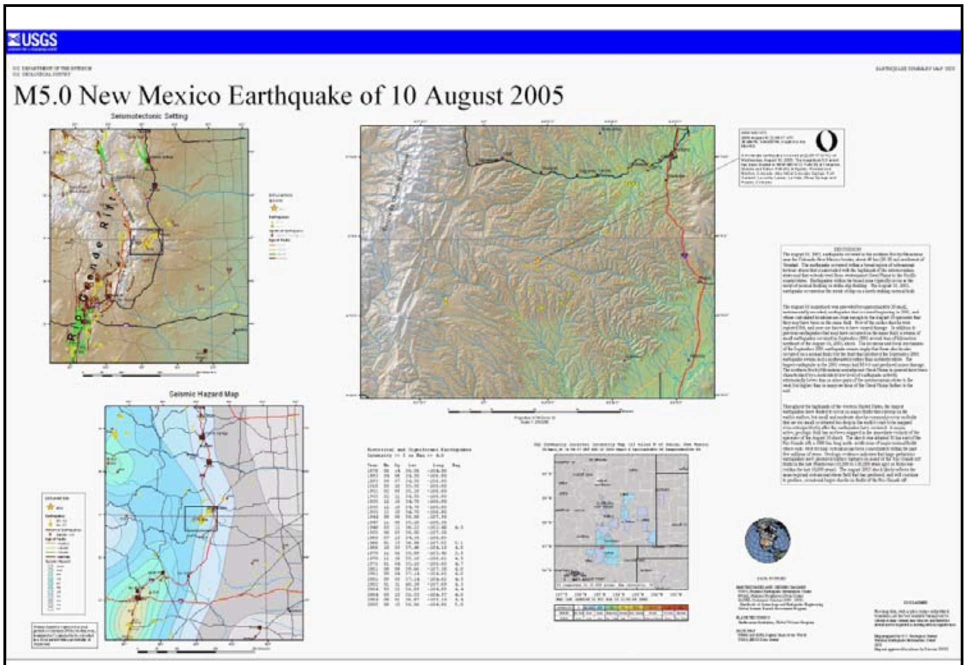
While fault length can grow normal events typical have dips close to 60-degrees and therefore the down-dip width is less than for reverse events



USGS

M7.6 Carlsberg Ridge Earthquake of 15 July 2003

http://neic.usgs.gov/neis/poster/2003/20030715_image.html



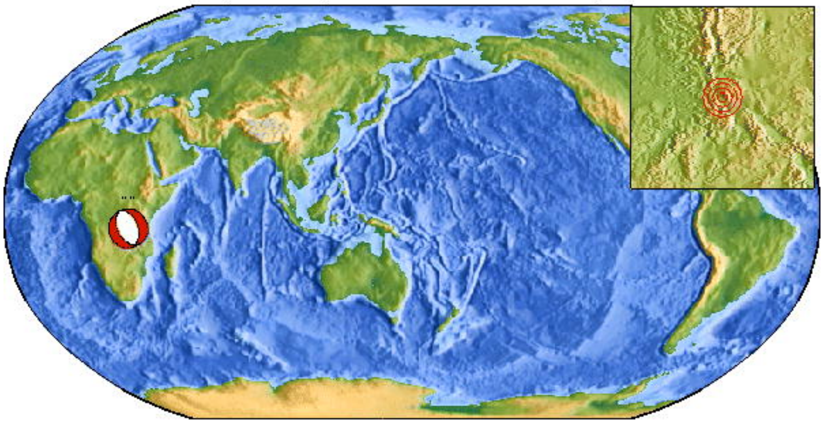
M5.0 New Mexico Earthquake of 10 August 2005

http://neic.usgs.gov/neis/poster/2005/20050810_image.html

LAKE TANGANYIKA REGION

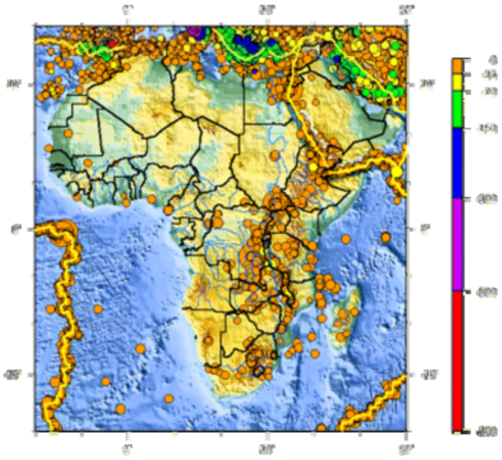
Mw 6.7

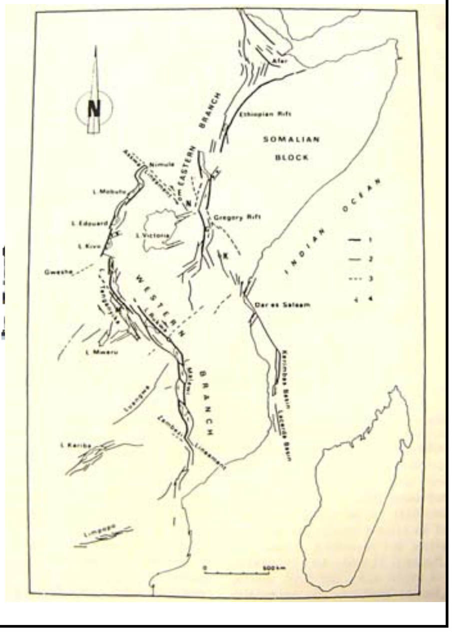
(USGS Rapid Moment-Tensor Solution)

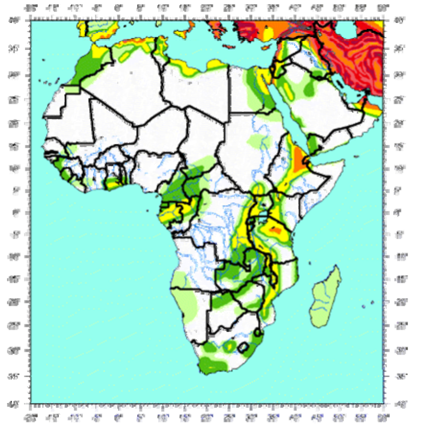


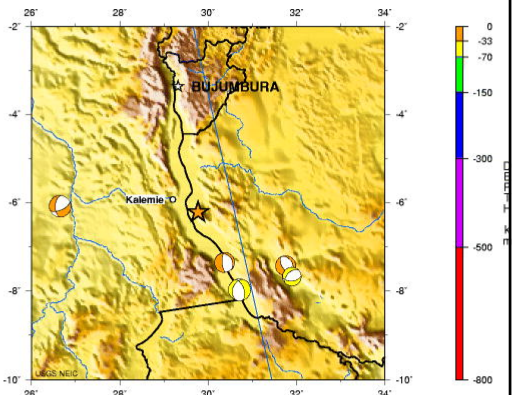
Date: 5 DEC 2005
Time: 12:19:55.47 UTC
Epicenter: -6.212 29.599
Depth: 36 km

Red Sea and East African Rifting


Seismicity of Africa, 1990 - 2000



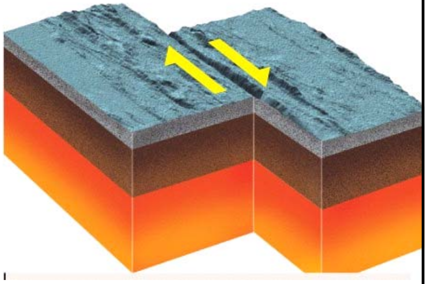

Peak Ground Acceleration (m/s²) with 10% Probability of Exceed



LAKE TANGANYIKA REGION, CONGO-TANZANIA
2005 12 05 12:19:56 UTC 6.22S 29.77E Depth: 22 km, Magnitude: 6.8
Historical Moment Tensor Solutions
Major Tectonic Boundaries: Subduction Zones -purple, Ridges -red and Transform Faults -green
USGS National Earthquake Information Center

Translational Boundaries

- Event size is limited by fault segmentation and depth of seismogenic zone
- SiO_2 begins to behave ductilely at 300C corresponding to roughly 10 to 15 km depth
- 1906, L=450km, W=15km, D=5m Mo=1.2e28 dyne cm and Mw=8.0
- Moment rate=4.3e25 dyne cm/yr or a Mw=6.4/yr assuming a slip rate of 1.8 cm/yr
- Recurrence interval of ~280 yrs



Next Time

- Continue discussion of seismotectonics focusing on California
- Investigate how this information can be used in characterizing seismic hazard, earthquake forecasting and prediction.
- Study material in Chapter 11