Fundamentals of Earth Sciences (ESO 213A)

Dibakar Ghosal
Department of Earth Sciences

Earthquakes continued

Previous Class:* *Earthquakes

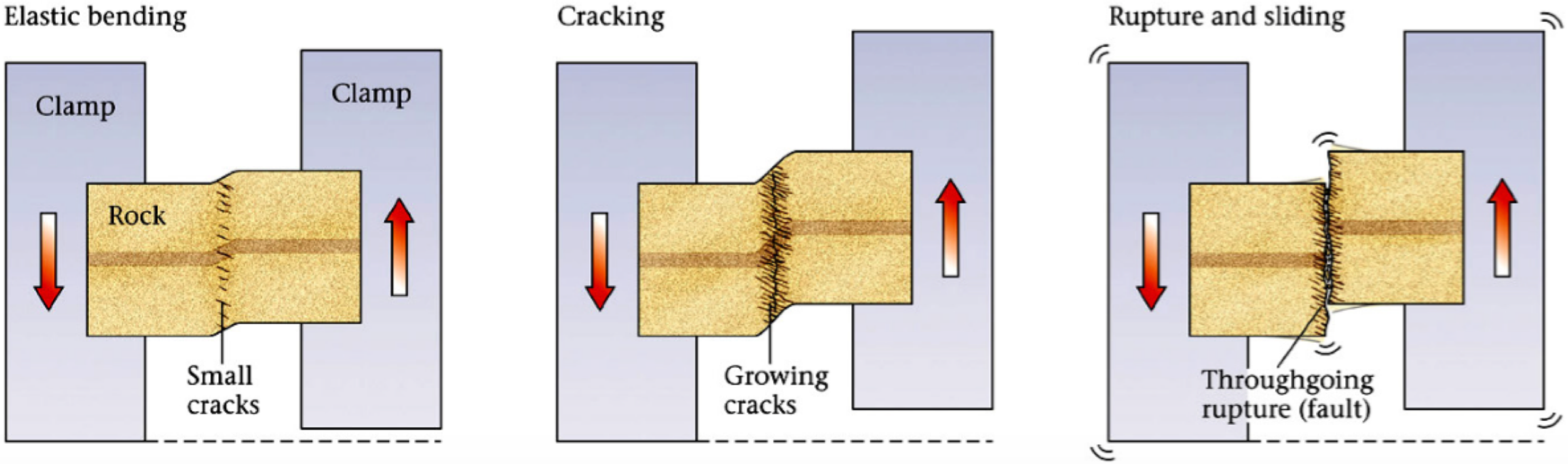
Formation of Faults

- Faults and thus earthquakes form because of stress & strain
  - Plate motion causes rocks to deform or bend
  - Stress and strain become localized
  - Eventually the strength of the rock is overcome
  - BAM!! The rock ruptures and snaps forward releasing the accumulated stress/strain.
    - The process is known as ***elastic rebound theory***

Elastic strain:
strain that is recoverable

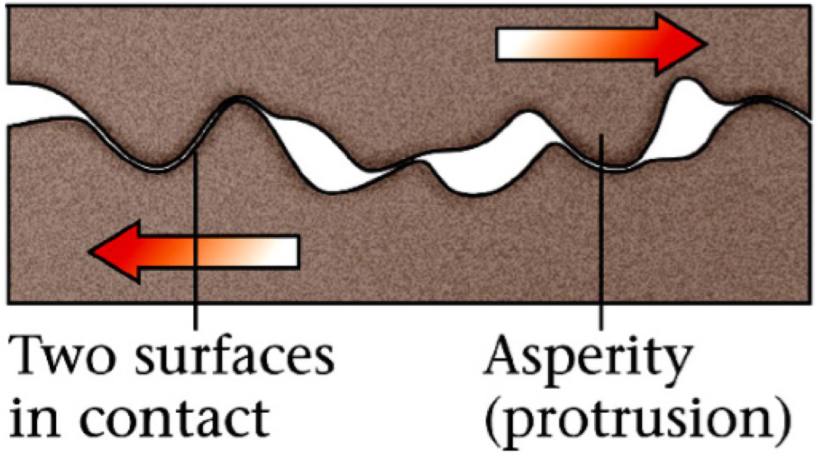
New cracks form and
link together

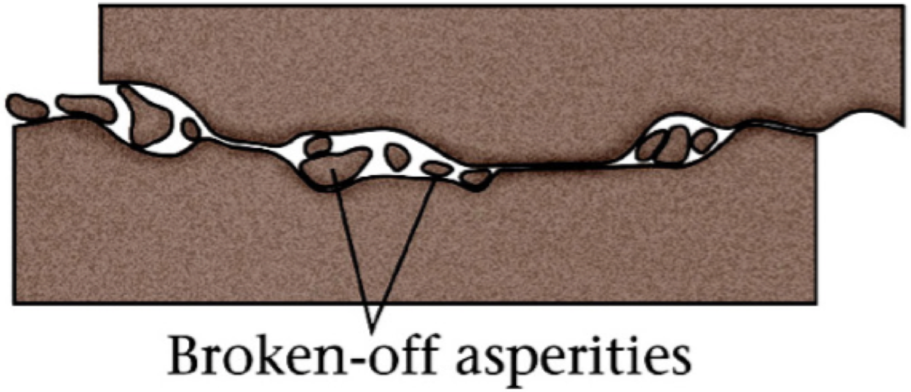
A through-going fault
forms and sliding occurs
causing a ***stress drop***



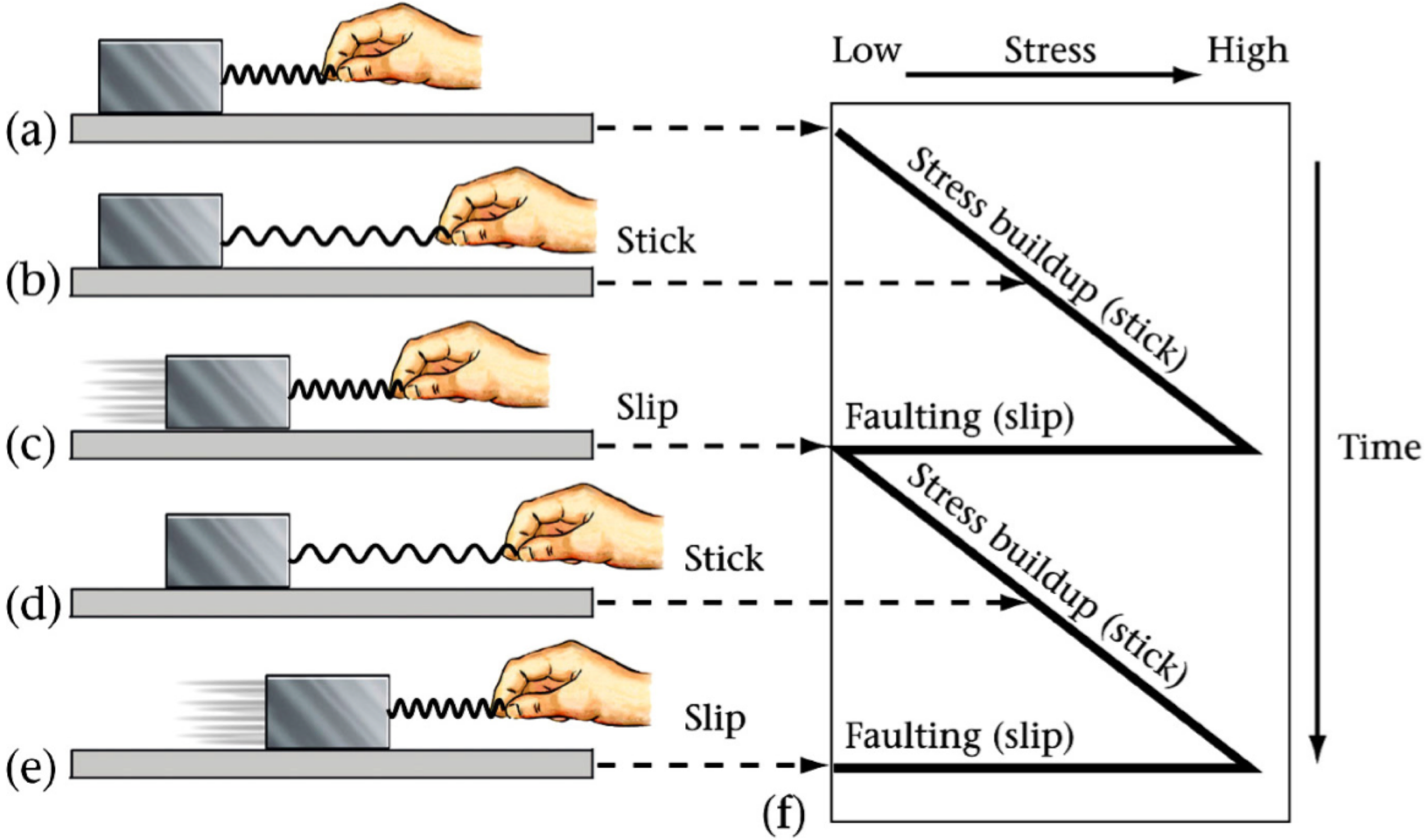
Faults & Friction

- Like a brick sliding across a table, faults, too, are subject to friction
- Friction, on the micro-scale, is caused by **asperities**, bumps and irregularities along a surface that resist sliding
- All other factors equal, faults with more cumulative slip may be smoother and therefore have lower friction (e.g. the San Andreas Fault has very low friction)
    - Once a fault is formed it is a permanent scar that is weaker than the surrounding rock





Stick Slip Behavior



- Without stick slip behavior, large earthquakes would not happen!
  - Faults would constantly move (i.e. ***creep***) and not build up significant stress

Measuring the Size of Earthquakes

Two measurements that describe the <u>size</u> of an earthquake are:

1. Intensity—a measure of the degree of earthquake shaking at a given locale based on the amount of damage
2. Magnitude estimates the amount of energy released at the source of the earthquake.

Measuring the Size of Earthquakes

- Intensity scales
  - The Modified Mercalli Intensity Scale was developed using California buildings as its standard.
  - The drawback of intensity scales is that destruction may not be a true measure of the earthquake's actual severity.

TABLE 11.1 Modified Mercalli Intensity Scale

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.
III	Felt quite noticeably indoors, especially on upper floors of buildings, but many people do not recognize it as an earthquake.
IV	During the day felt indoors by many, outdoors by few. Sensation like heavy truck striking building.
V	Felt by nearly everyone, many awakened. Disturbances of trees, poles, and other tall objects sometimes noticed.
VI	Felt by all; many frightened and run outdoors. Some heavy furniture moved; 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.
VIII	Damage slight in specially designed structures; considerable in ordinary substantial buildings with partial collapse; great in poorly built structures. (Fall of chimneys, factory stacks, columns, monuments, walls.)
IX	Damage considerable in specially designed structures. Buildings shifted off foundations. Ground cracked conspicuously.
X	Some well-built wooden structures destroyed. Most masonry and frame structures destroyed. Ground badly cracked.
XI	Few, if any, (masonry) structures remain standing. Bridges destroyed. Broad fissures in ground.
XII	Damage total. Waves seen on ground surfaces. Objects thrown upward into air.

Measuring the Size of Earthquakes

Earthquake *magnitude* is based on the measured amplitude recorded on a seismogram as wave amplitude reflects the earthquake size after correction for geometrical spreading and attenuation applied.

General form of Magnitude scales:

$$M = \log(A/T) + F(h, \Delta) + C$$

A is the amplitude of the signal

T is its dominant period

F is a correction for the variation of amplitude with the earthquake's depth h and distance Δ from the seismometer

C is a regional scale factor

Richter scale

Based on the amplitude of the largest seismic wave recorded
Accounts for the decrease in wave amplitude with increased distance
The largest magnitude recorded on a Wood–Anderson seismograph was 8.9.
Magnitudes less than 2.0 are not felt by humans.
Each unit of Richter magnitude increase corresponds to a tenfold increase in wave amplitude and a 32-fold energy increase.

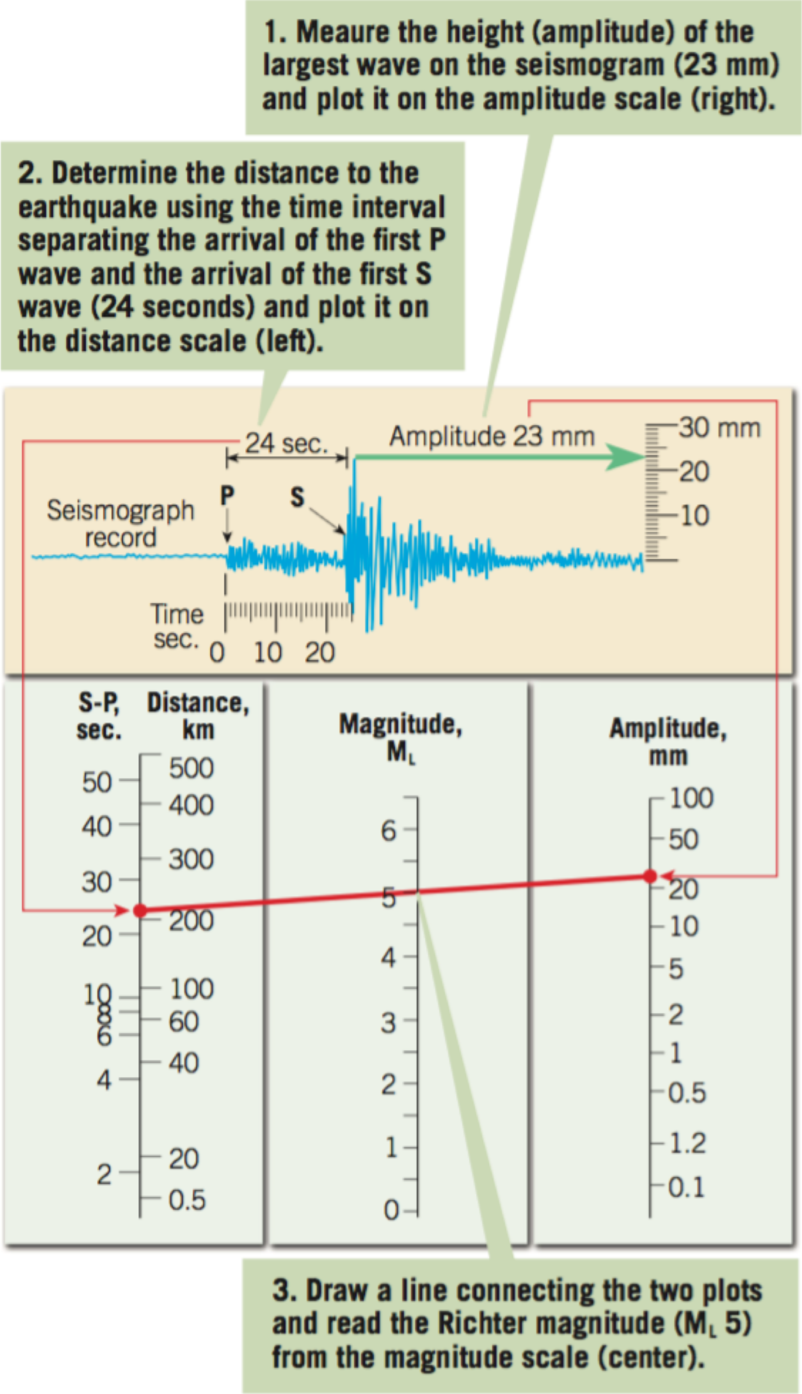
Magnitude scales are logarithmic, so an increase in one unit, as from magnitude "5" to a "6", indicates a ten-fold increase in seismic wave amplitude.

Measured magnitudes range more than 10 units because the displacements measured by seismometers span more than a factor of 10^{10}.

"Richter scale" (local magnitude) was introduced by Charles Richter in 1935 for Southern California earth-quakes measured on a *Wood-Anderson* seismograph.

$$M_L = \log A + 2.76 \log \Delta - 2.48$$

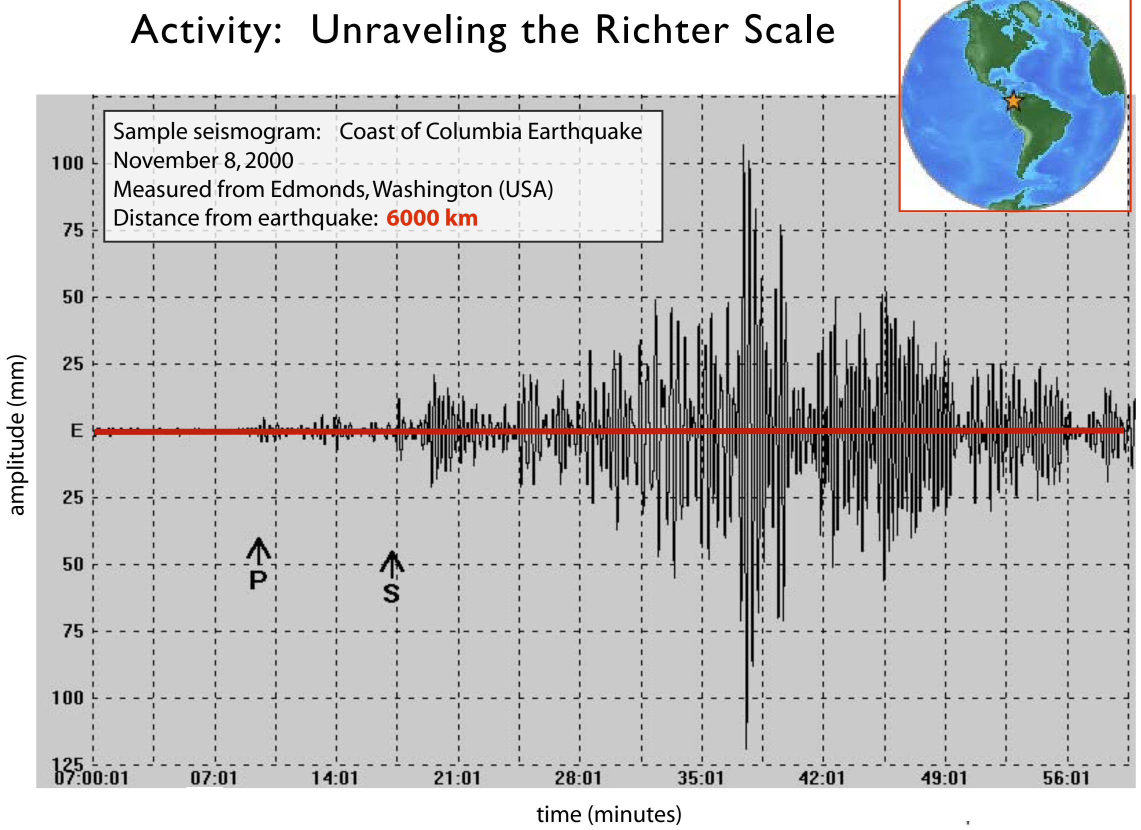
The instrument period (0.8 s) and nearly constant (shallow) depth are incorporated in the constants, and the distance is in km.

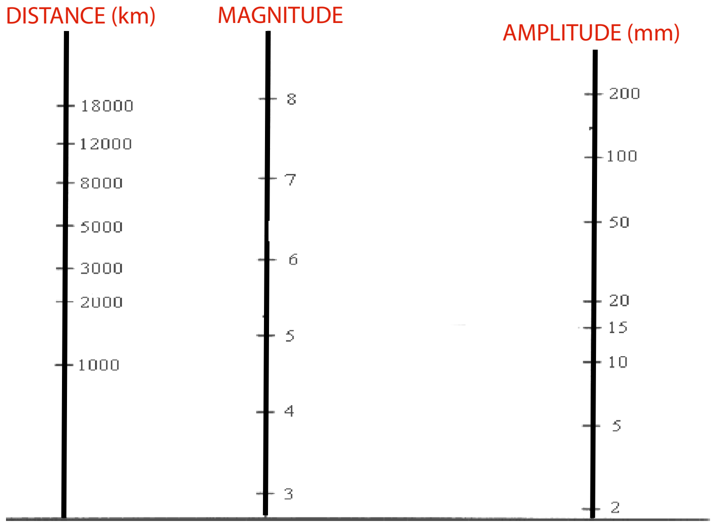


Magnitude vs. Ground Motion and Energy

Magnitude Change	Ground Motion Change (amplitude)	Energy Change (approximate)
4.0	10,000 times	1,000,000 times
3.0	1000 times	32,000 times
2.0	100 times	1000 times
1.0	10.0 times	32 times
0.5	3.2 times	5.5 times
0.1	1.3 times	1.4 times

Activity: Unraveling the Richter Scale





What is the magnitude? ___________________________

Body wave magnitude:

$$m_b = \log(A/T) + Q(h, \Delta)$$

A is the ground motion amplitude in microns after the effects of the seismometer are removed

T is the wave period in seconds

Q is an empirical term depending on the distance and focal depth.

Surface wave magnitude (measured using the largest amplitude, zero to peak, of the surface waves):

$$M_s = \log(A/T) + 1.66 \log \Delta + 3.3 \qquad \text{(general form)}$$

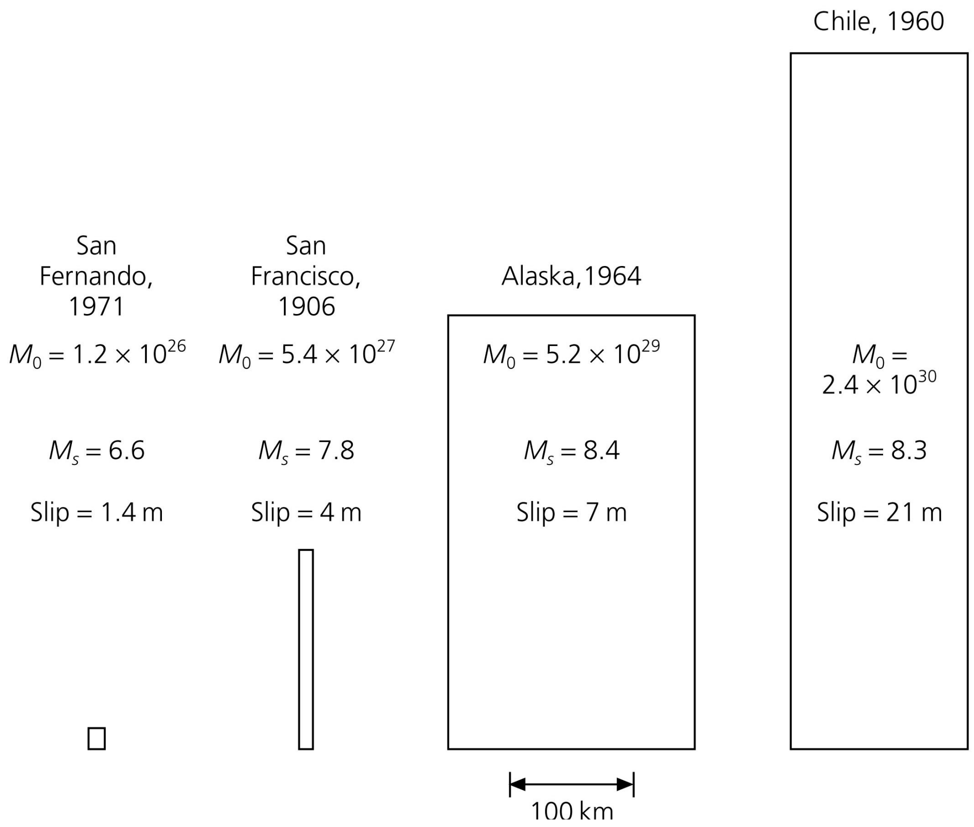
$$M_s = \log A_{20} + 1.66 \log \Delta + 2.0 \qquad \text{(for 20 second period Rayleigh waves)}$$

(Δ is in degrees)

Other Magnitude scales

- Several "Richter-like" magnitude scales have been developed.
- **Moment magnitude** was developed because none of the "Richter-like" magnitude scales adequately estimate very large earthquakes.
- Derived from the amount of displacement that occurs along a fault

Figure 4.6-3: Comparison of the magnitudes of four earthquakes.



Moment magnitude:

$$M_w = \frac{\log M_0}{1.5} - 10.73$$

(with M_0 in dyn-cm)

Earthquake	Body wave magnitude m_b	Surface wave magnitude M_s	Fault area (km^2) length × width	Average dislocation (m)	Moment (dyn-cm) M_0	Moment magnitude M_w
Truckee, 1966	5.4	5.9	10 × 10	0.3	8.3×10^{24}	5.8
San Fernando, 1971	6.2	6.6	20 × 14	1.4	1.2×10^{26}	6.7
Loma Prieta, 1989	6.2	7.1	40 × 15	1.7	3.0×10^{26}	6.9
San Francisco, 1906		8.2	320 × 15	4	6.0×10^{27}	7.8
Alaska, 1964	6.2	8.4	500 × 300	7	5.2×10^{29}	9.1
Chile, 1960		8.3	800 × 200	21	2.4×10^{30}	9.5

Earthquake Magnitude and Energy Equivalent

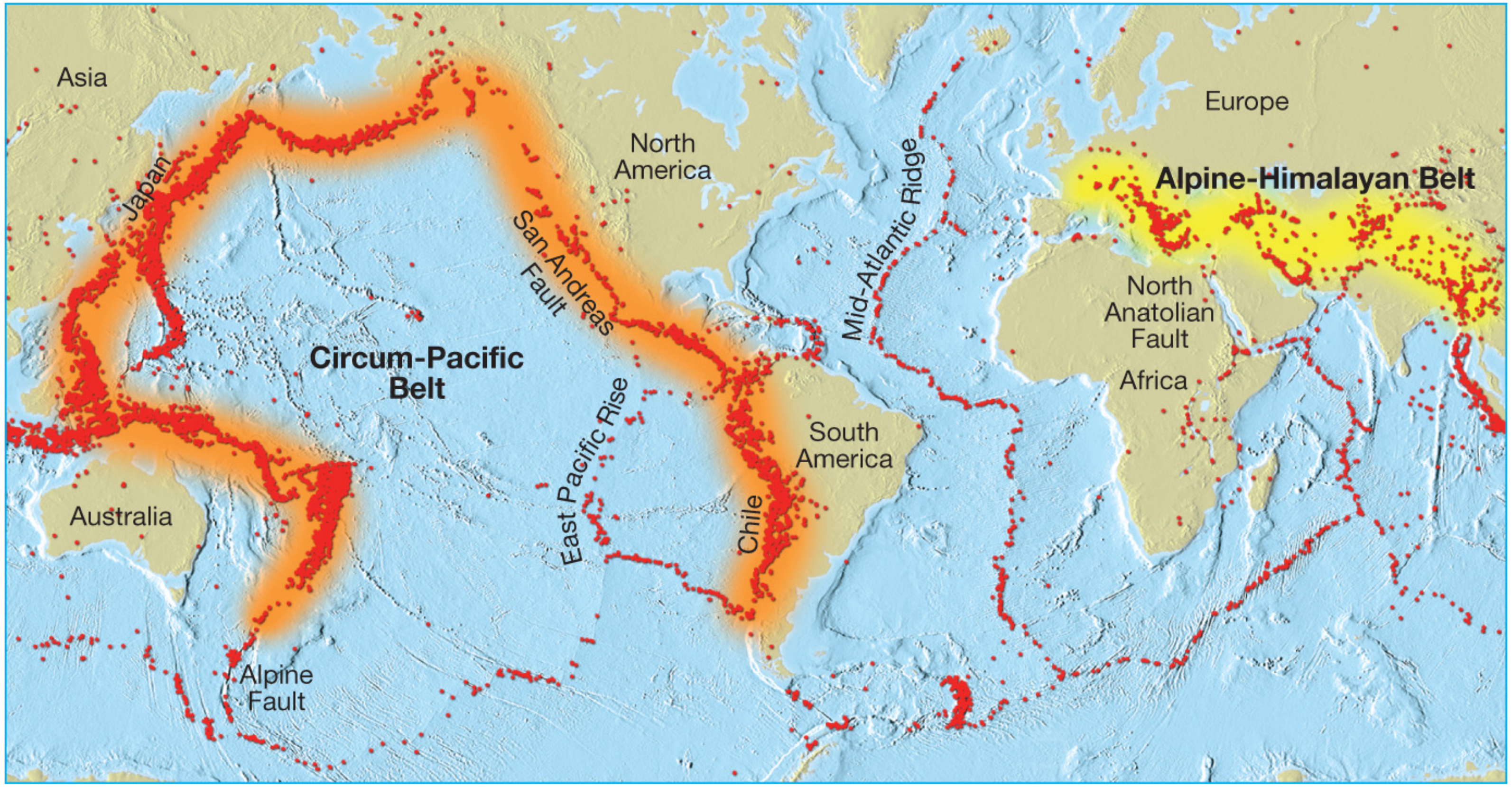
Frequency and Energy Released by Earthquakes of Different Magnitudes

Magnitude (Mw)	**Average Per Year**	**Description**	**Examples**	**Energy Release** (equivalent kilograms of explosive)
9	<1	**Largest recorded earthquakes–** destruction over vast area massive loss of life possible	Chile, 1960 (M 9.5); Alaska, 1964 (M 9.0); Japan, 2011 (M 9.0)	56,000,000,000,000
8	1	**Great earthquakes–** severe economic impact large loss of life	Sumatra, 2006 (M 8.6); Mexico City, 1980 (M 8.1)	1,800,000,000,000
7	15	**Major earthquakes–** damage ($ billions) loss of life	New Madrid, Missouri 1812 (M 7.7); Turkey, 1999 (M 7.6); Charleston, South Carolina, 1886 (M 7.3)	56,000,000,000
6	134	**Strong earthquakes–** can be destructive in populated areas	Kobe, Japan, 1995 (M 6.9); Loma Prieta, California, 1989 (M 6.9); Northridge, California, 1994 (M 6.7)	1,800,000,000
5	1319	**Moderate earthquakes–** property damage to poorly constructive buildings	Mineral, Virginia, 2011 (M 5.8); Northern New York, 1994 (M 5.8); East of Oklahoma City, Oklahoma, 2011 (M5.6)	56,000,000
4	13,000	**Light earthquakes–** noticable shaking of items indoors, some property damage	Western Minnesota, 1975 (M 4.6); Arkansas, 2011 (M 4.7)	1,800,000
3	130,000	**Minor earthquakes–** felt by humans, very light property damage, if any	New Jersey, 2009 (M3.0) Maine, 2006 (M3.8)	56,000
2	1,300,000	**Very minor earthquakes–** felt by humans, no property damage		1,800
	Unknown	Generally not felt by humans, but may be recorded		56

Data from USGS

Locating the Source of Earthquakes

- Earthquake belts
  - About 95% of the energy released by earthquakes originates in a few relatively narrow zones that wind around the globe.
  - Major earthquake zones include the Circum-Pacific belt, Mediterranean Sea region to the Himalayan complex, and the oceanic ridge system.

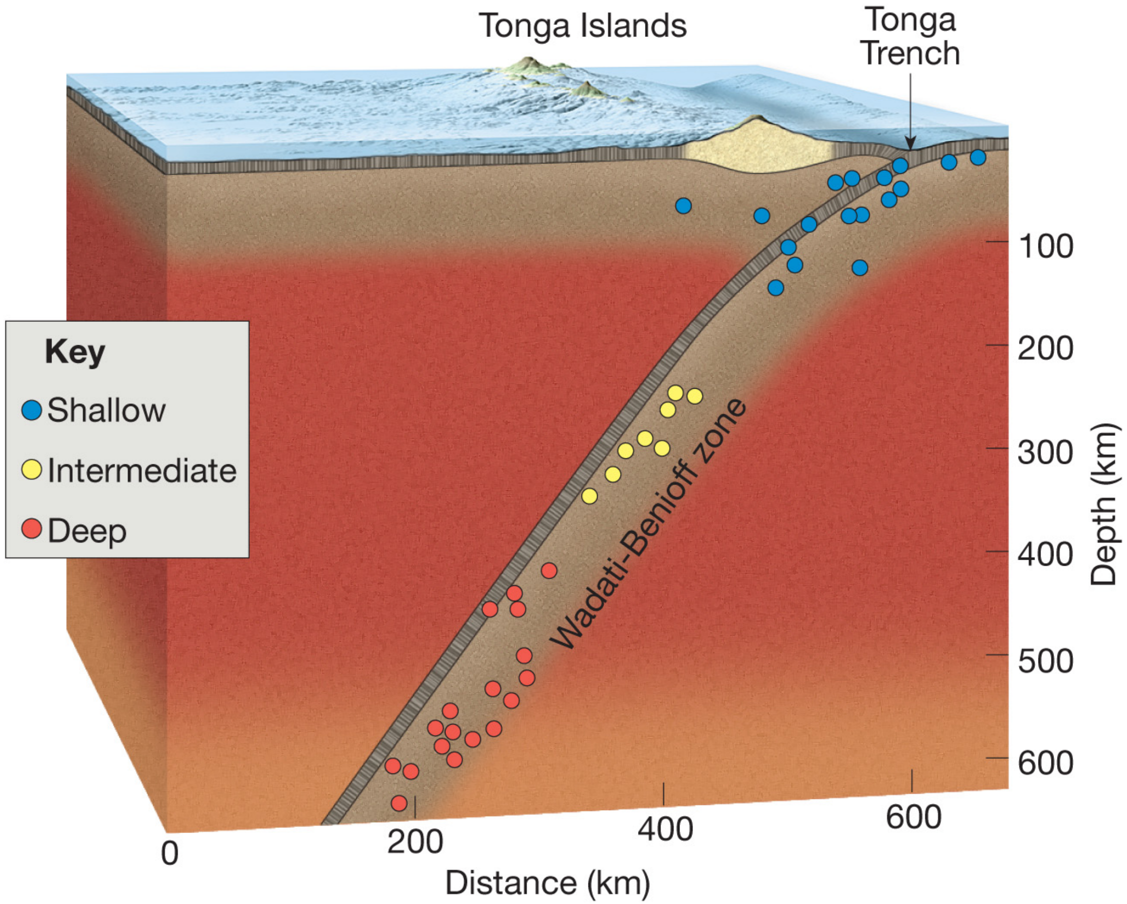


Can Earthquakes Be Predicted?

- Short-range predictions
  - The goal is to provide a warning of the location and magnitude of a large earthquake within a narrow time frame.
  - Research has concentrated on monitoring possible precursors—phenomena that precede a forthcoming earthquake, such as measuring uplift, subsidence, and strain in the rocks.
  - **Currently, no reliable method exists for making short-range earthquake predictions.**
- Long-range forecasts
  - Give the probability of a certain magnitude earthquake occurring on a time scale of 30 to 100 years, or more.
  - Based on the premise that earthquakes are repetitive or cyclical
    - Using historical records or paleoseismology
  - Are important because they provide information used to:
    - Develop the Uniform Building Code
    - Assist in land-use planning

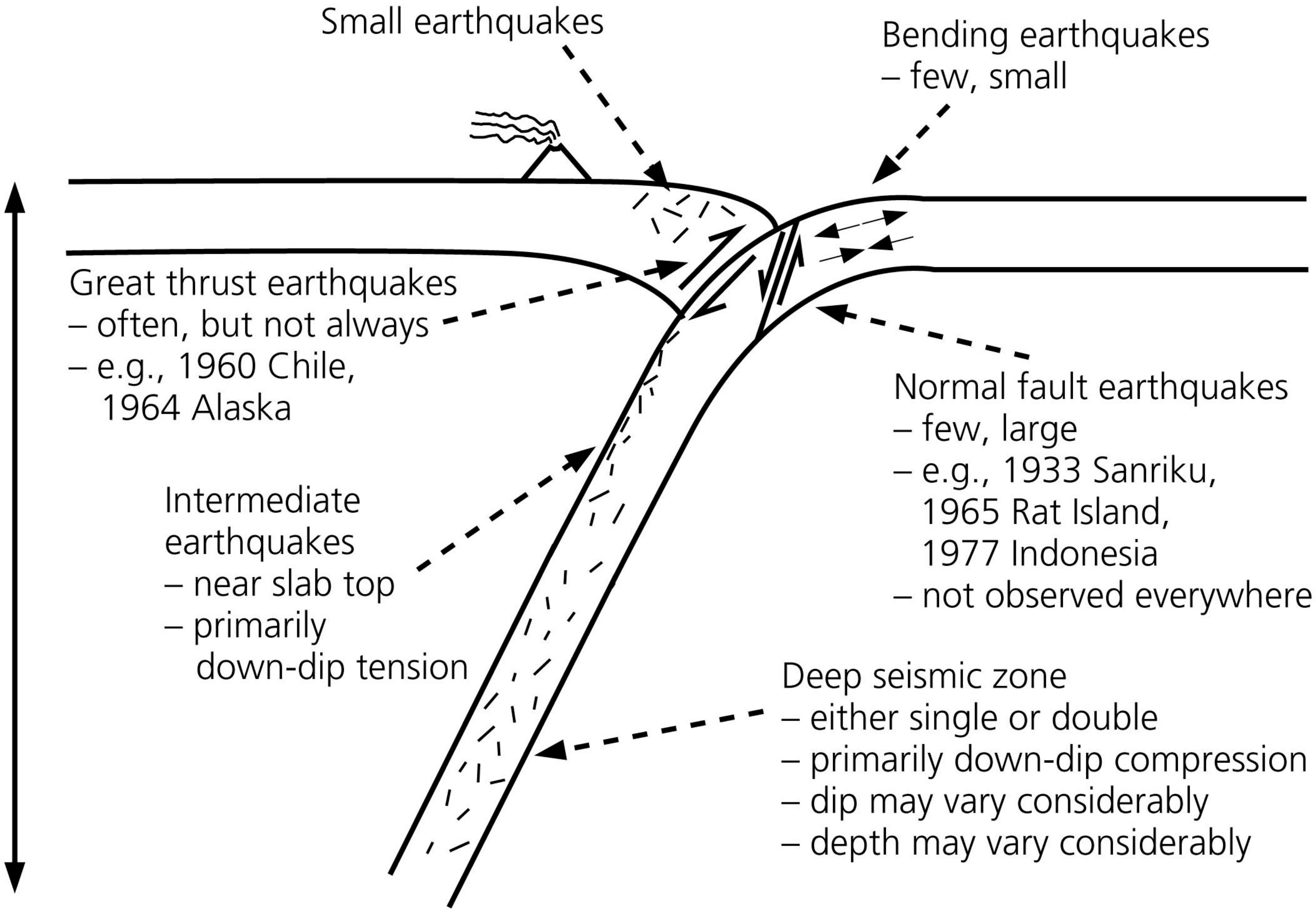
Earthquakes—Evidence for Plate Tectonics

- A good fit exists between the plate tectonics model and the global distribution of earthquakes.
  - The connection of deep-focus earthquakes and oceanic trenches is further evidence.
  - Only shallow-focus earthquakes occur along divergent and transform fault boundaries.
- Earthquake depths
  - Earthquakes originate at depths ranging from 5 to nearly 700 kilometers.
  - Earthquake foci are arbitrarily classified as:
    - Shallow (surface to 70 kilometers)
    - Intermediate (between 70 and 300 kilometers)
    - Deep (over 300 kilometers)
- Definite patterns exist.
  - Shallow-focus earthquakes occur along the oceanic ridge system.
  - Almost all deep-focus earthquakes occur in the circum-Pacific belt, particularly in regions situated landward of deep-ocean trenches.



Earthquake Distribution Near the Tonga Trench

Figure 5.4-2: Various earthquake types observed at subduction zones.



Global Distribution of Earthquakes

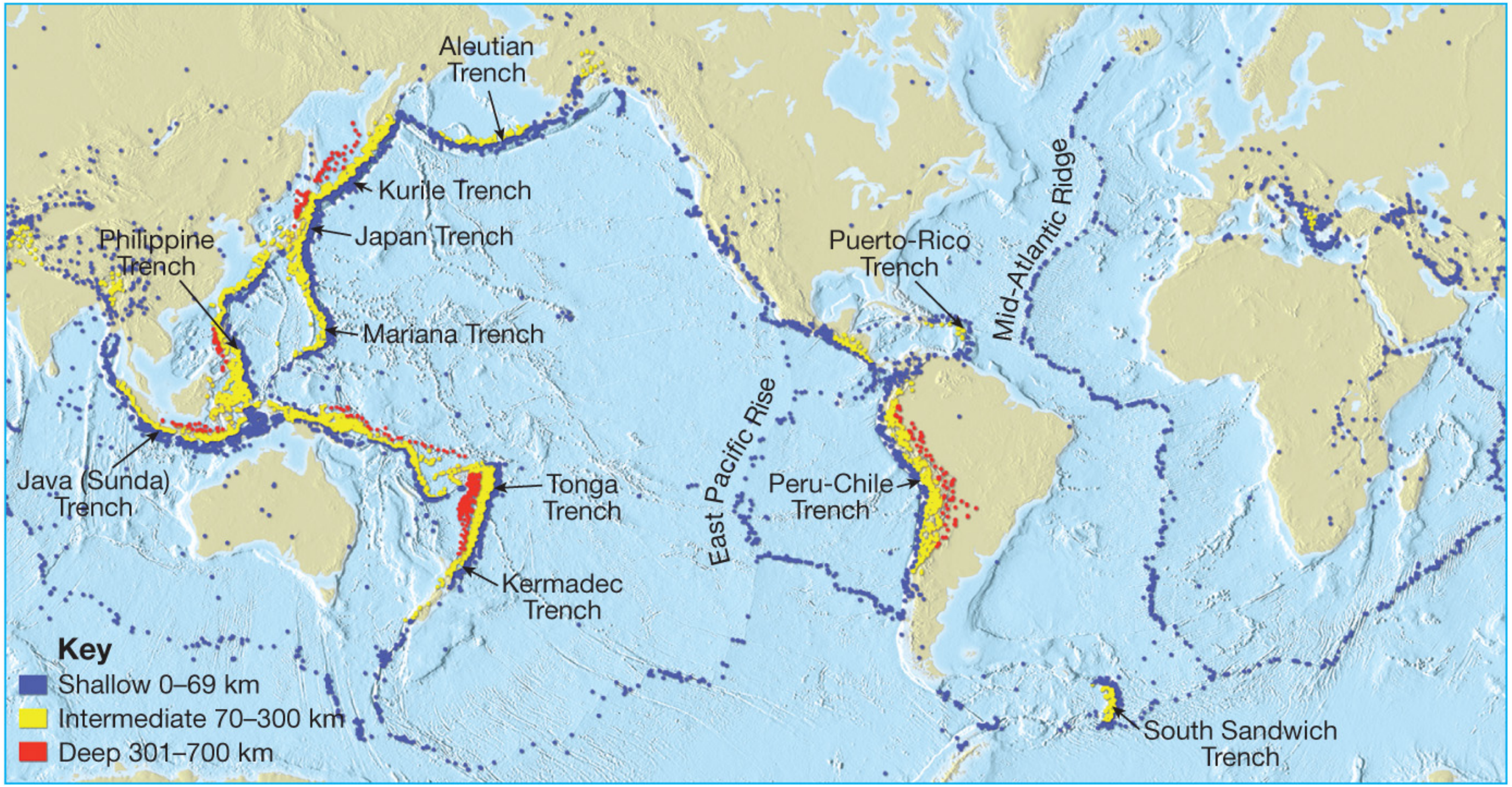


Figure 5.1-1: Cartoon of plate tectonics.

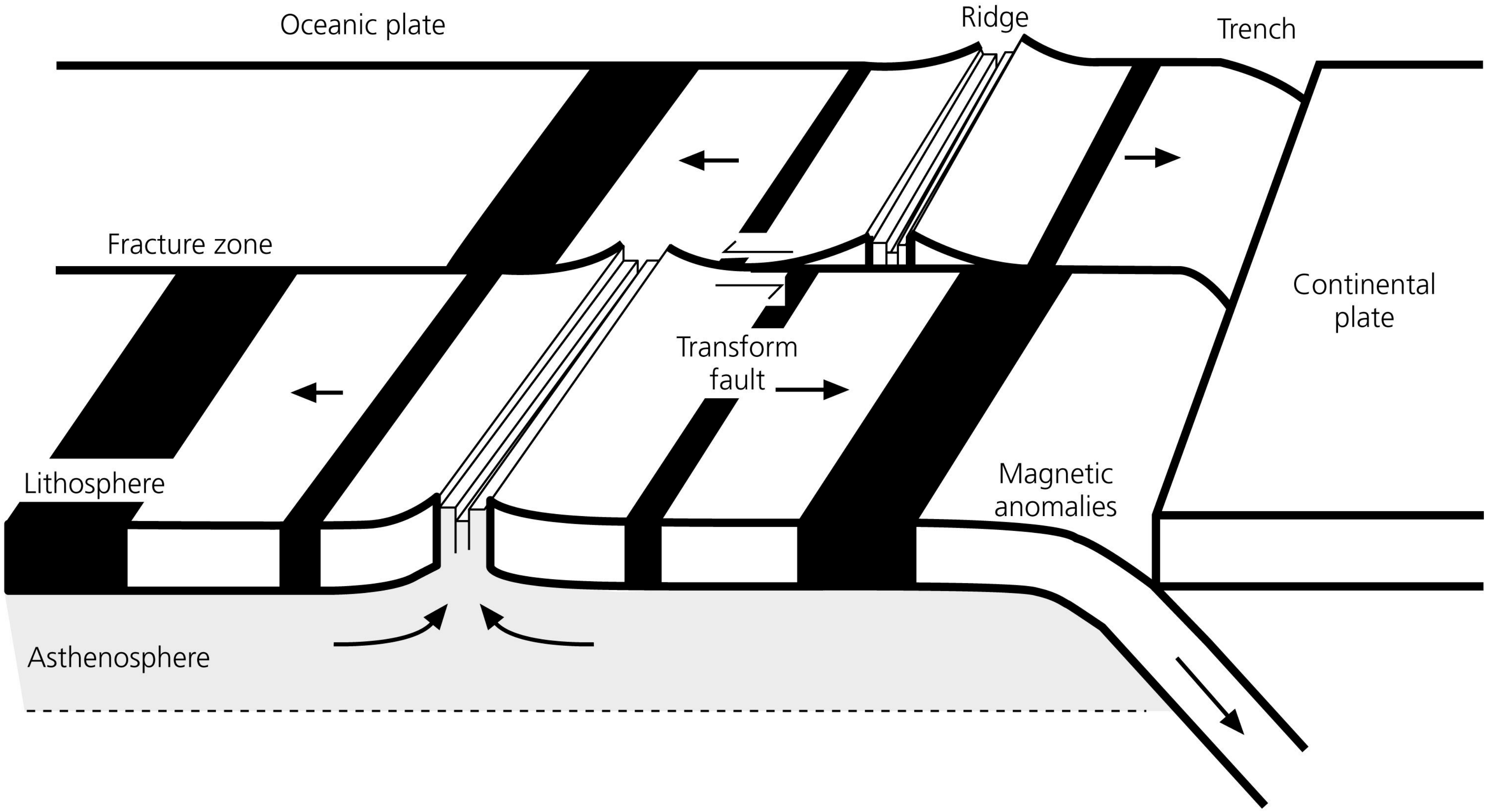


Figure 4.2-14: Focal mechanisms for various fault mechanisms.

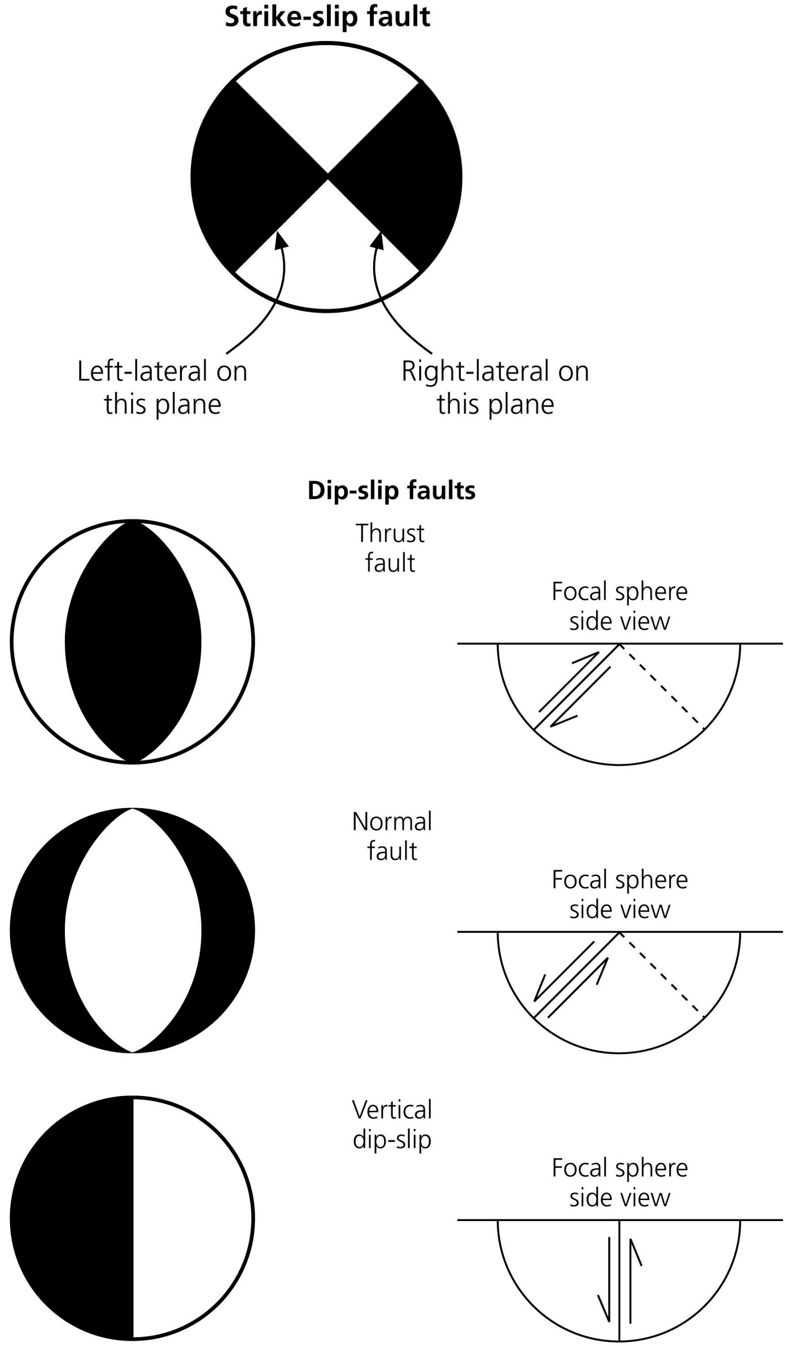


Figure 4.2-15: Fault mechanisms for earthquakes with one identical fault plane.

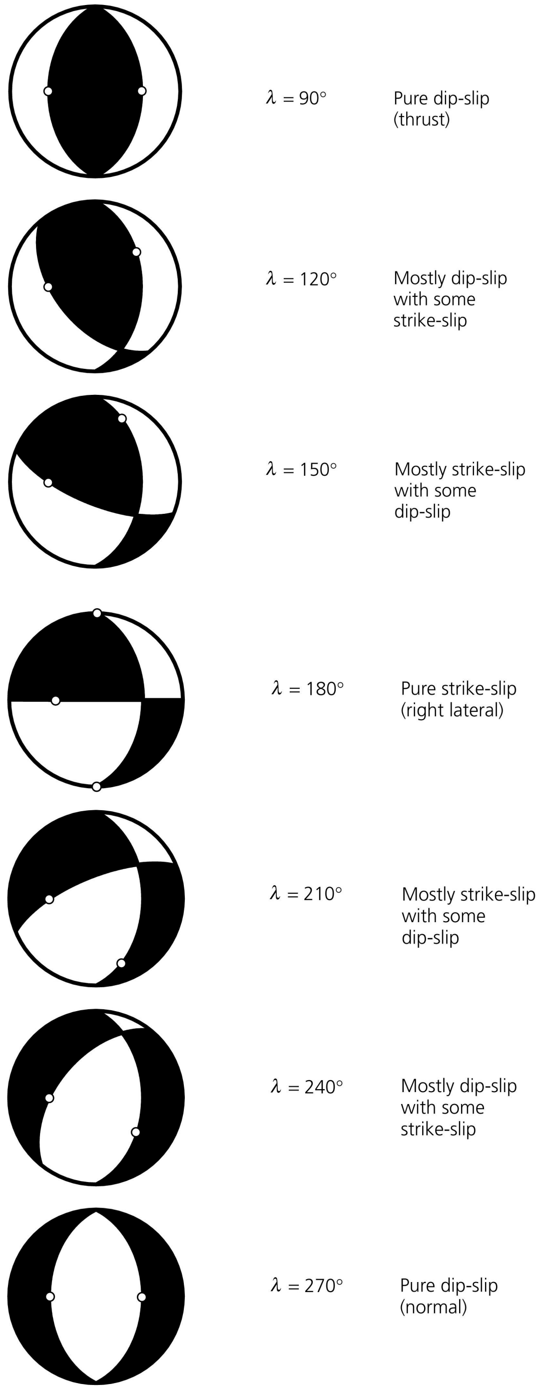
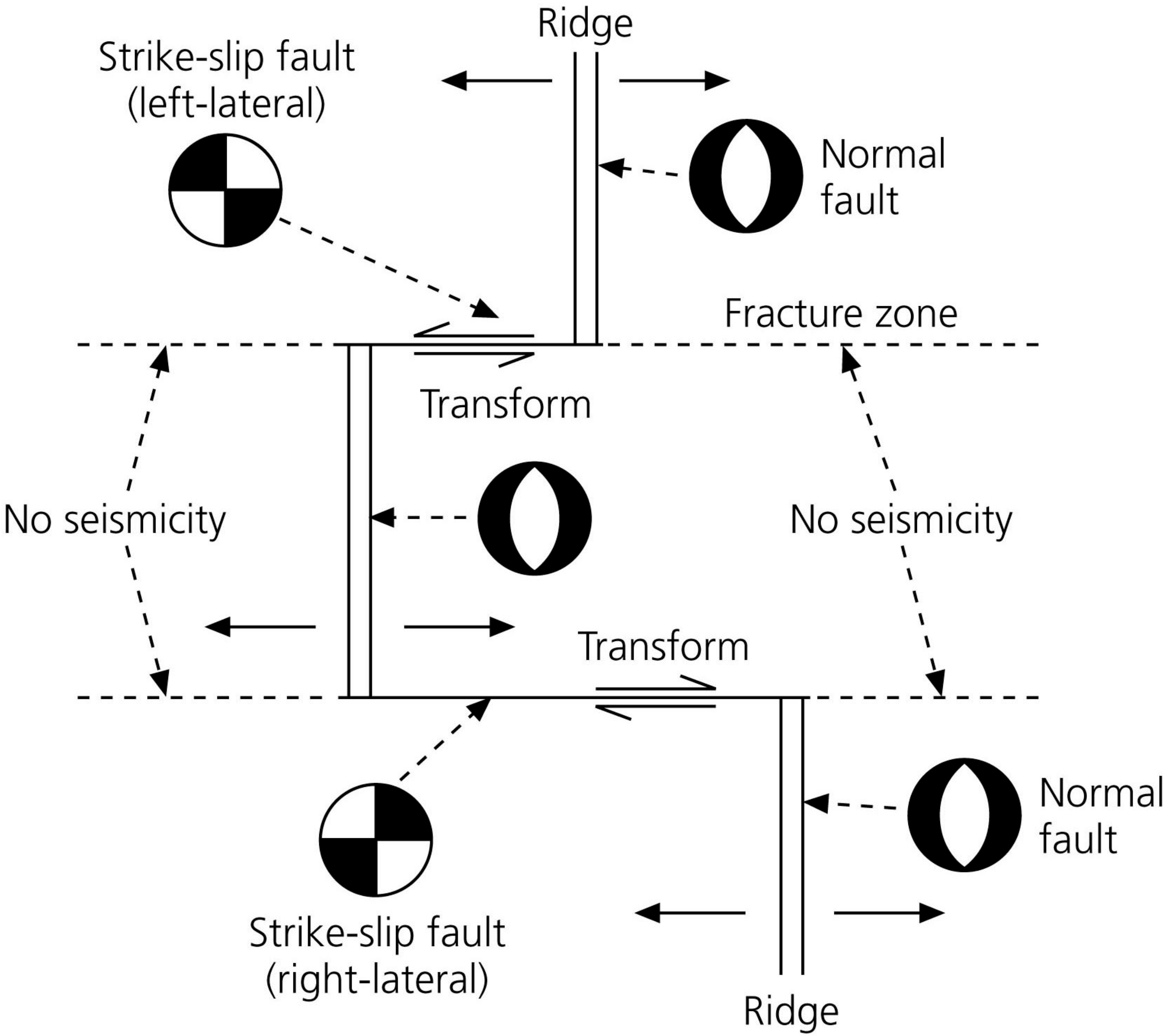
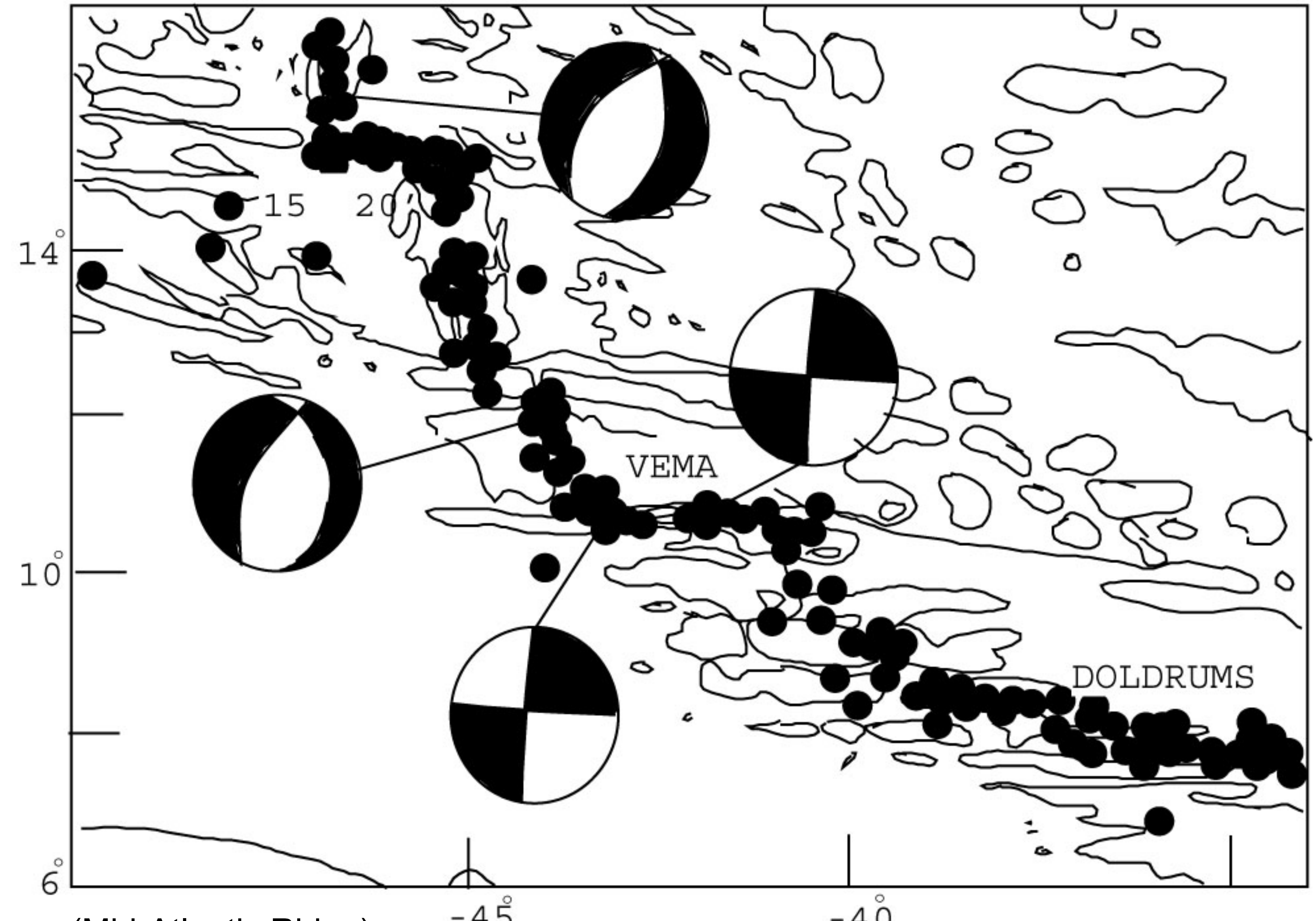


Figure 5.3-1: Tectonic settings of earthquakes along an oceanic spreading center.

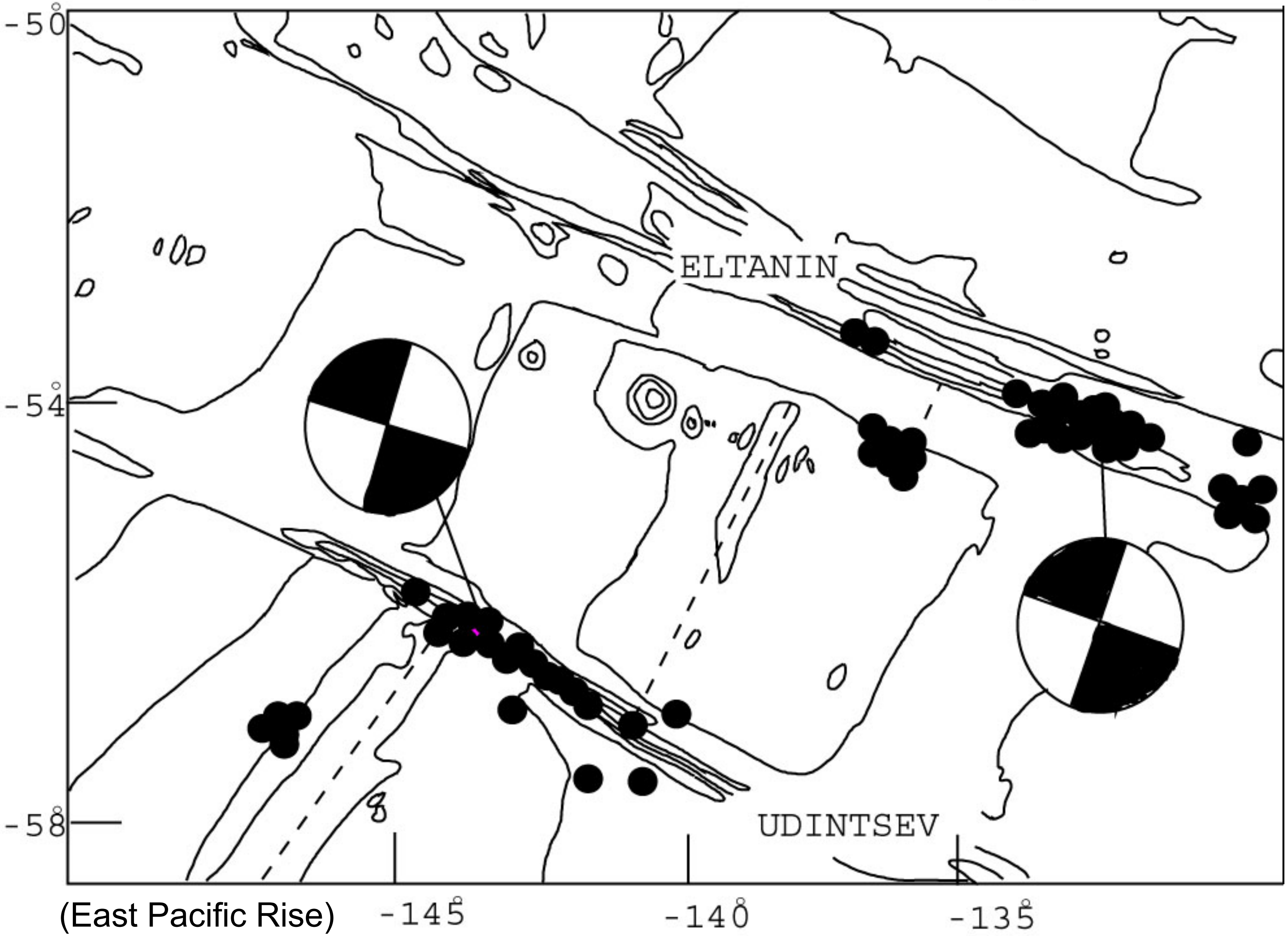


SLOW RIDGE 3.3 cm/yr



(Mid-Atlantic Ridge)

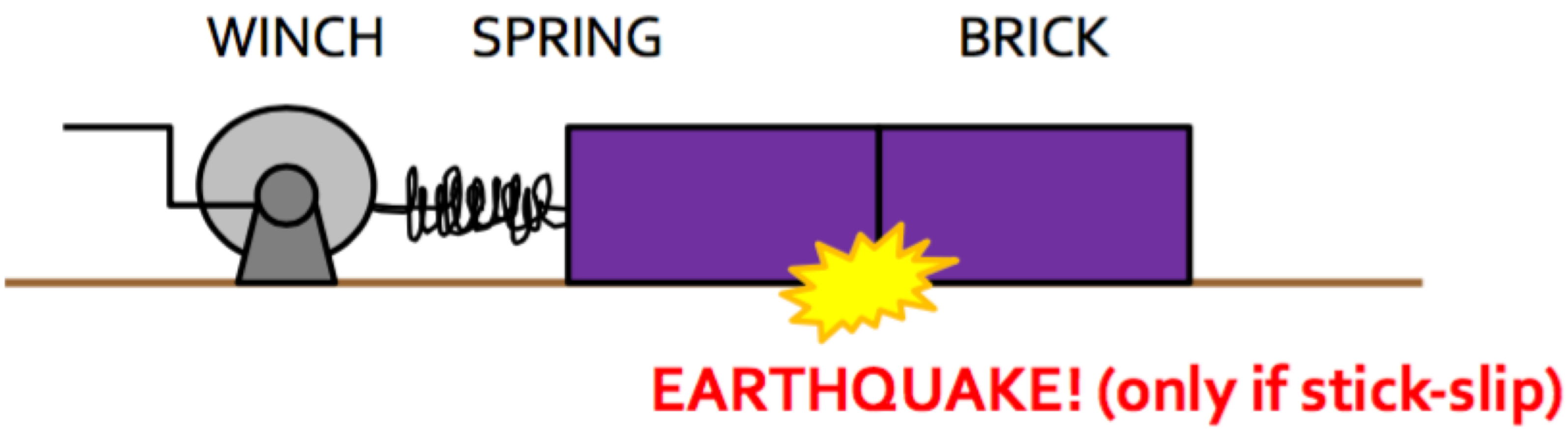
FAST RIDGE 9.0 cm/yr



(East Pacific Rise)

Coulomb theory

Hypothesis: Faults interact by the transfer of stress

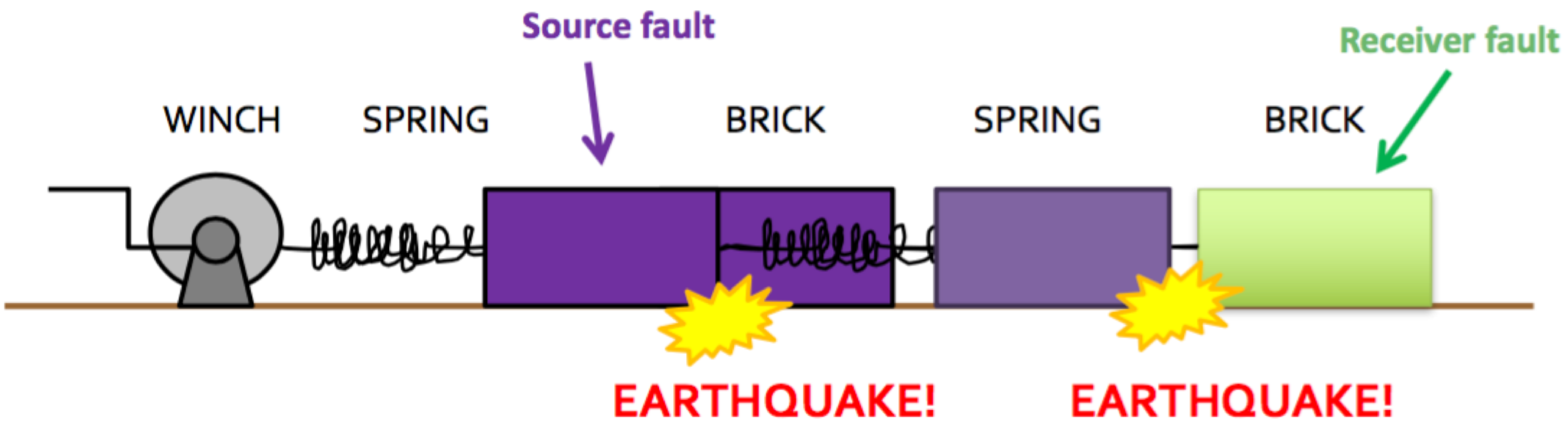


<u>Force Balance – Brick will not move until</u>:

Force on spring > **Force resisting motion**

(its length change x its stiffness) (the weight of the brick x friction on surface)

Coulomb theory



- Add another spring & brick
- If you start cranking winch, **PURPLE** will move first. Then tension on spring will move **GREEN**.

+ ΔCFS = closer to failure

- ΔCFS = farther from failure

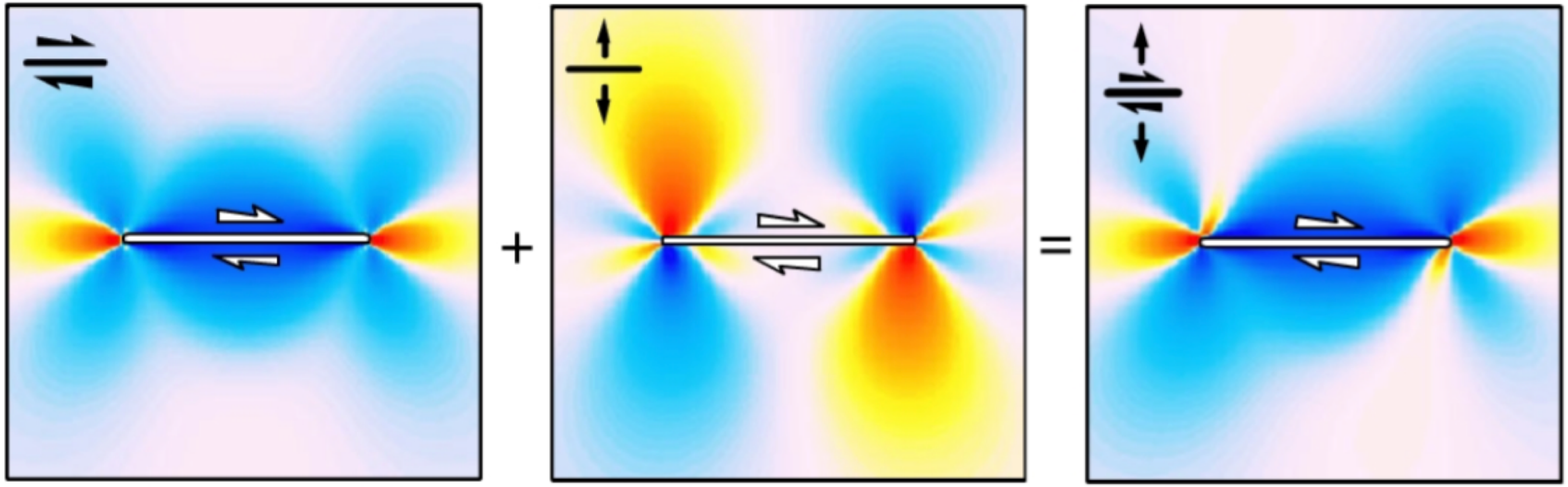
Coulomb stress calculation

Coulomb stress change = shear stress change + (coefficient of friction x normal stress change)

$$\Delta CFS = \Delta\tau_s + \mu' \Delta\sigma_n$$

How the Coulomb Stress Change is Calculated

Stress Rise Drop
promotes or inhibits failure

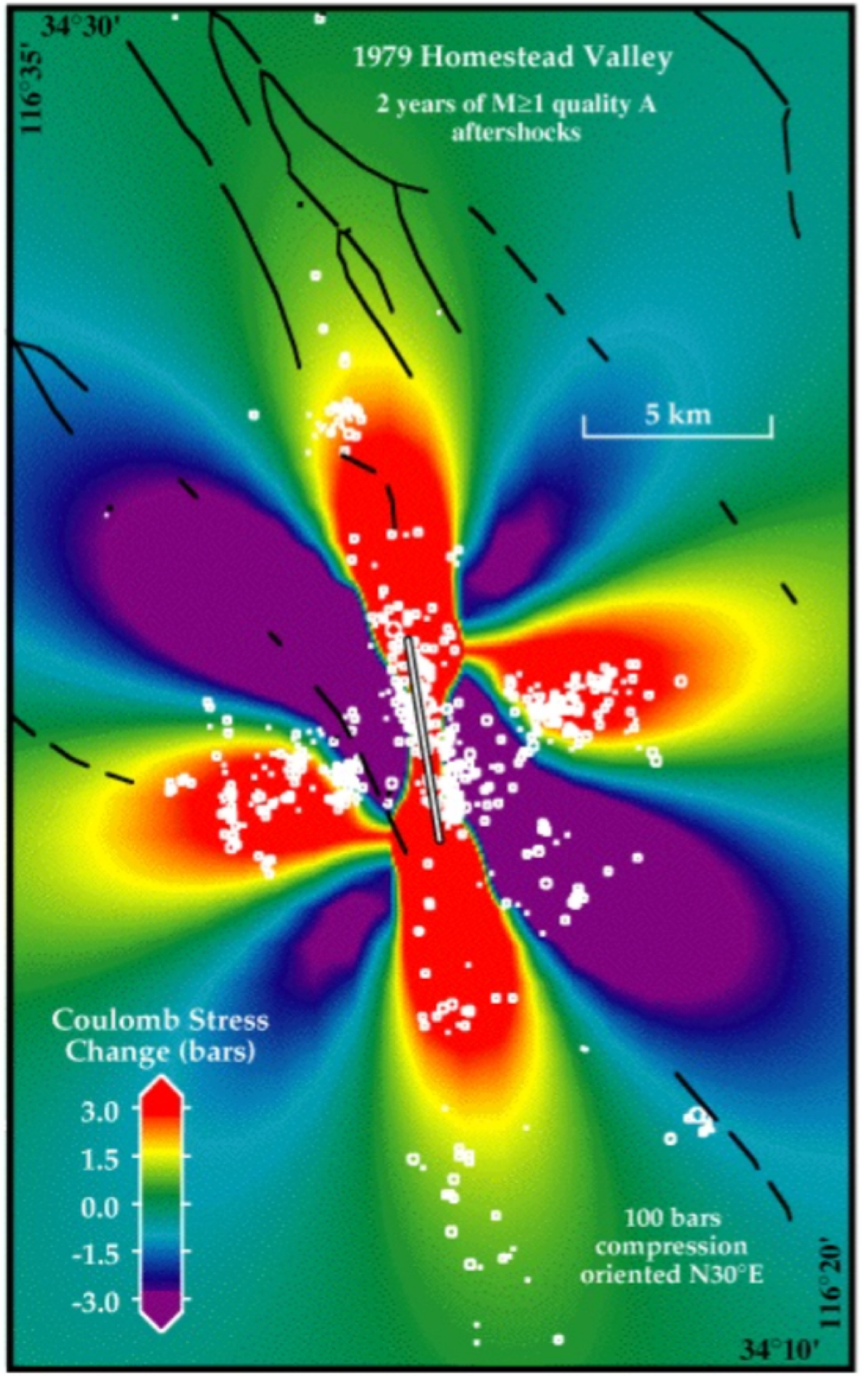


Shear stress change	+	Friction coefficient x normal stress change	=	Coulomb failure stress change
$\Delta\tau_s$	+	$\mu' (\Delta\sigma_n)$	=	$\Delta\sigma_f$

- Example calculation for faults parallel to master fault

From King et al (BSSA, 1994)

Coulomb stress changes after 1979 Homestead Valley Earthquake, California. Aftershocks are plotted in white.
(King, 1994)

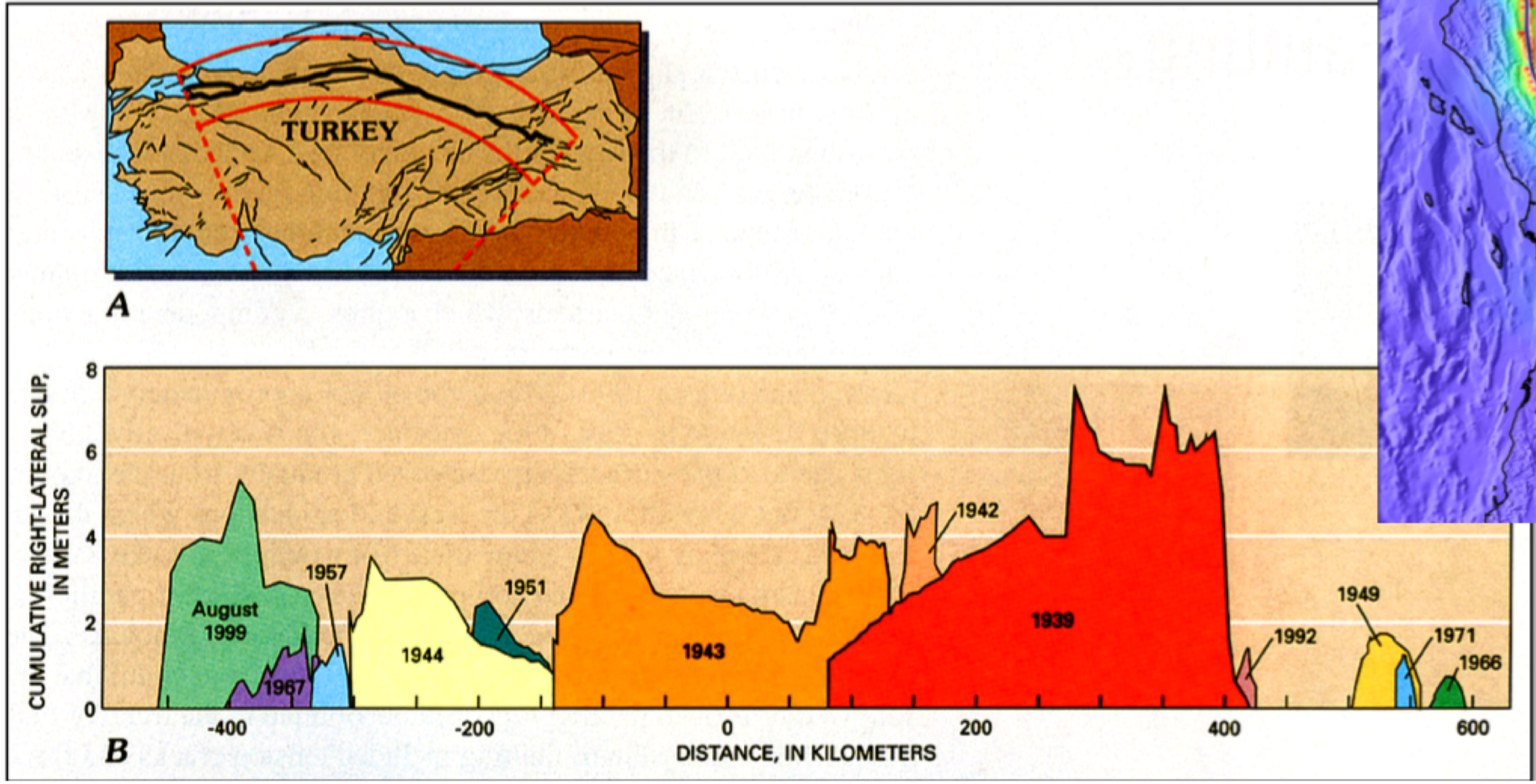


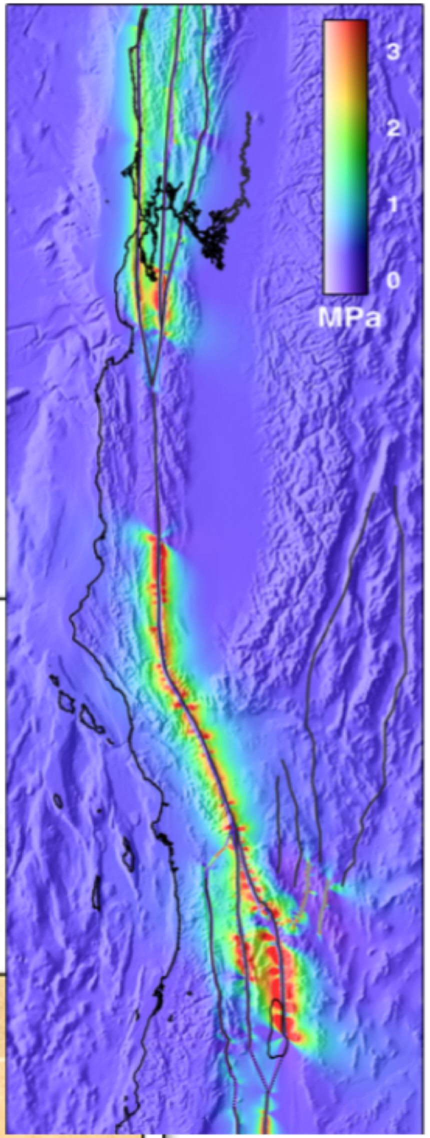
The location of aftershocks tend to cluster in areas of increased coulomb stresses.

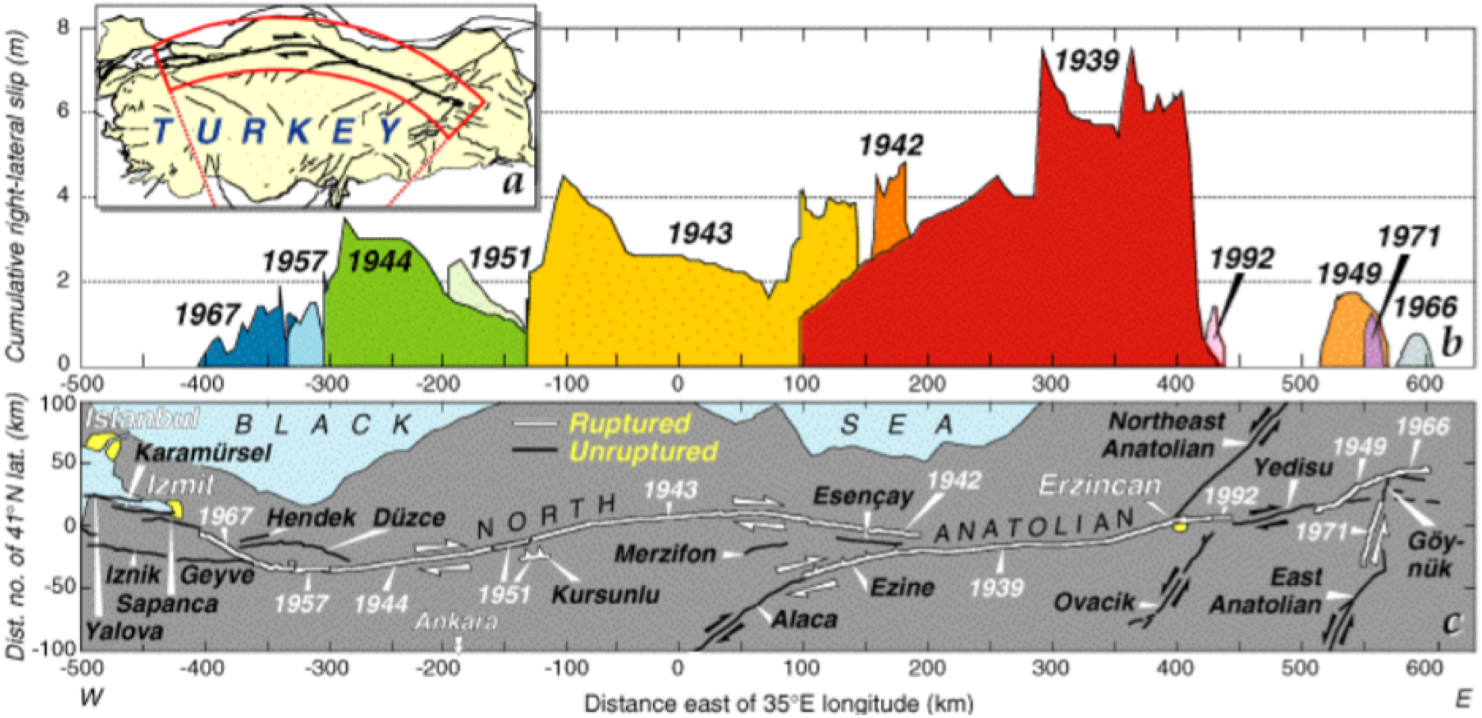
Aftershocks take place with decreased regularity in areas of decreased stress. These areas are known as "stress shadows".

Seismic Gaps & Stress Triggering

- ***Seismic Gaps***: Areas where the fault has not moved in a long time
  - These regions may be the next to go (i.e. San Andreas)→
- ***Stress Triggering***: When an earthquake happens, the motion changes the stress on nearby faults, possibly making them more or less likely to fail.
  - The North Anatolian Fault (below) is an excellent example of both of these phenomenon

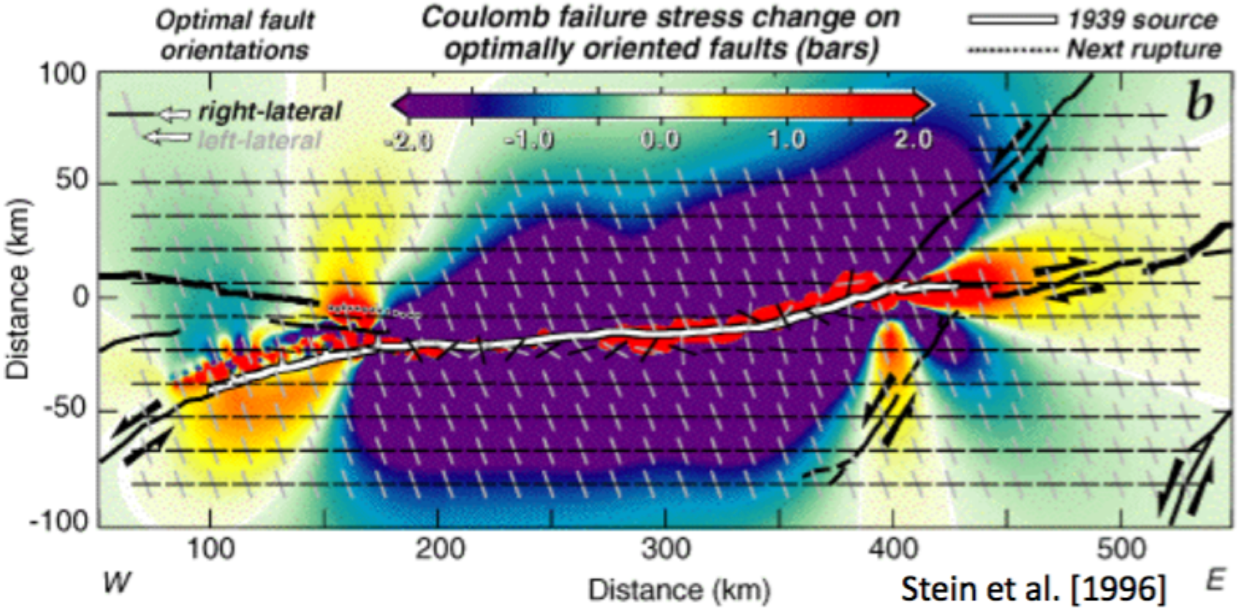






(b) Cumulative right-lateral slip associated with M>=6.7 earthquakes; the sequence ruptured from warm to cool colors.

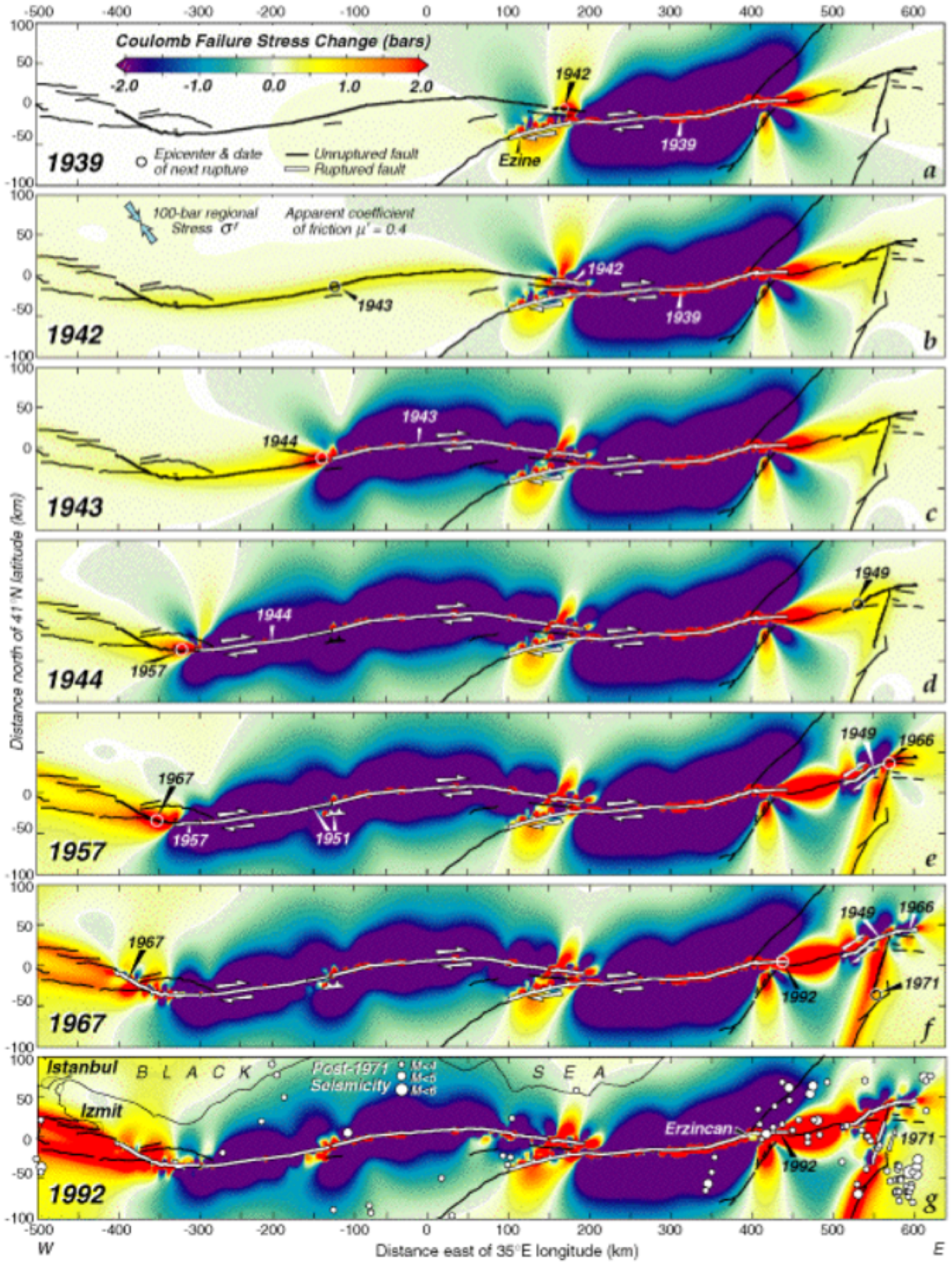
(c) The region inscribed by the solid red line in a is projected relative to the Anatolia-Eurasia rotation pole, so that a transform fault would strike due east-west; the North Anatolian fault is seen to deviate less than 40 km from being a simple right-lateral transform.



Stein et al. [1996]

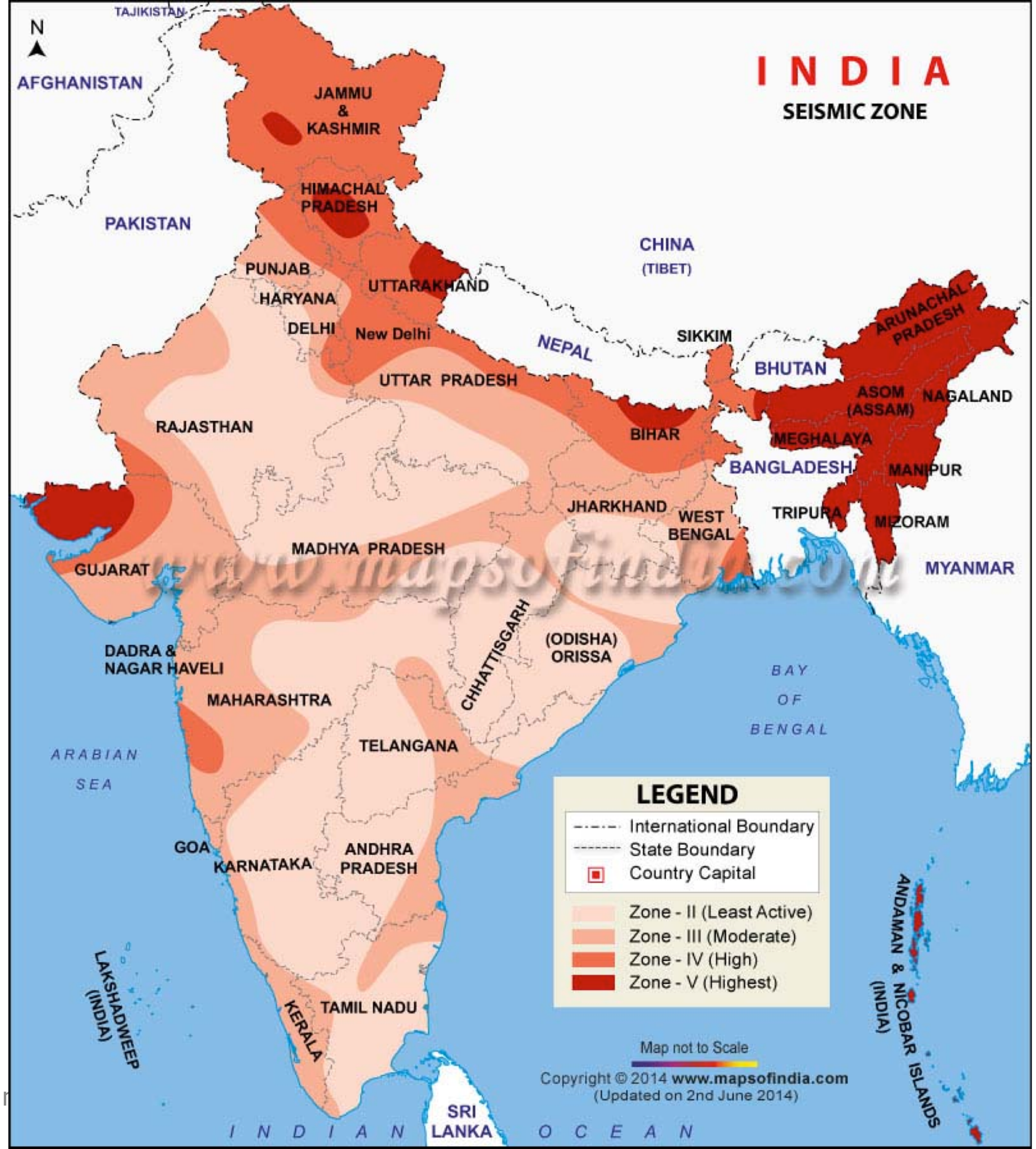
Stress changes associated with the 1939 earthquake. Color gradients show the Coulomb stress change on optimally oriented vertical strike-slip faults at a depth of 8 km.

Large rotations of the optimal planes are restricted close to the fault rupture, where the earthquake stress change is significant relative to the regional stress. Far from the 1939 rupture, rotation of the optimal planes is negligible.

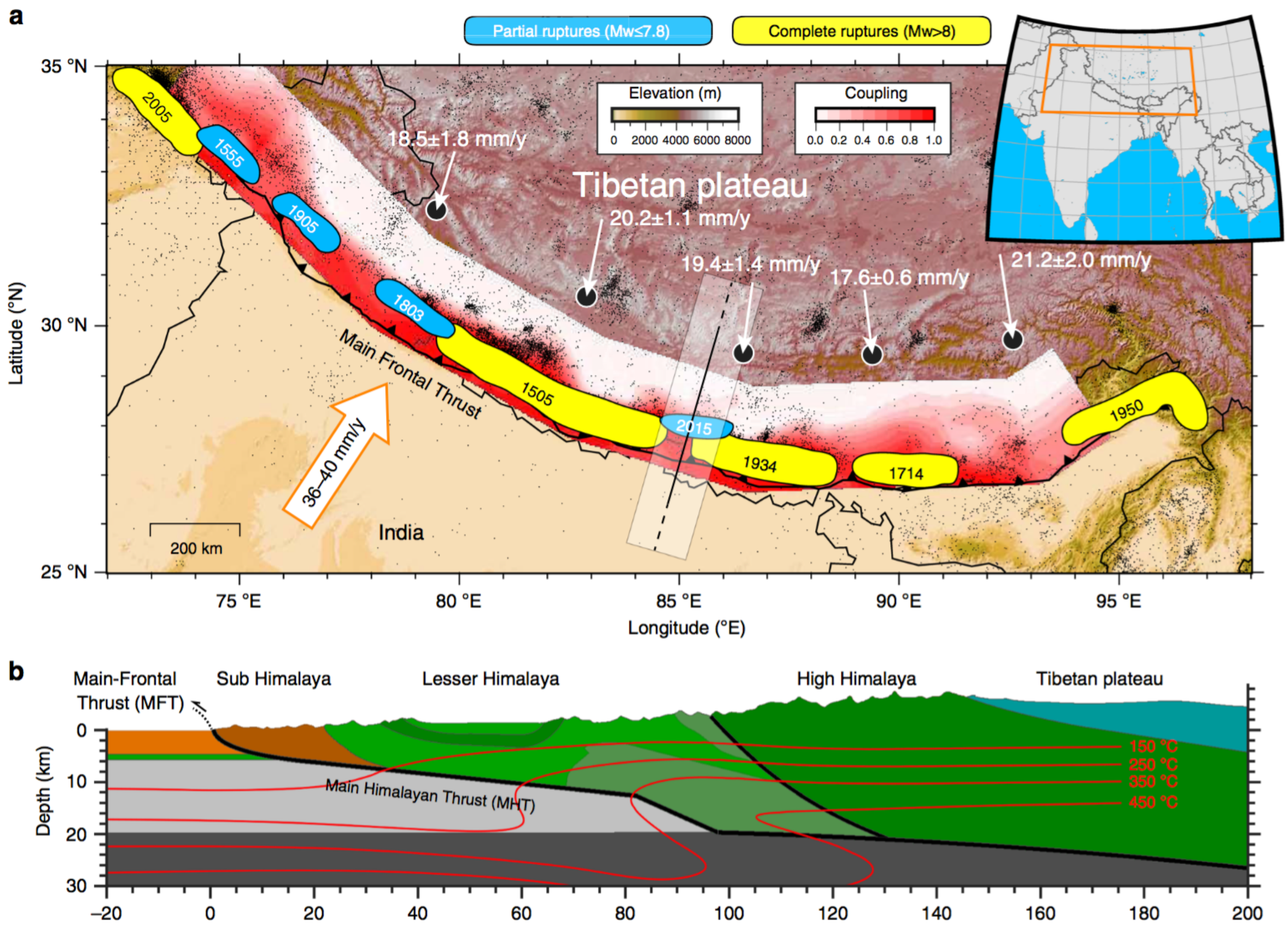


Cumulative stress changes caused by large earthquakes and steady deep slip on the North Anatolian fault since 1939.

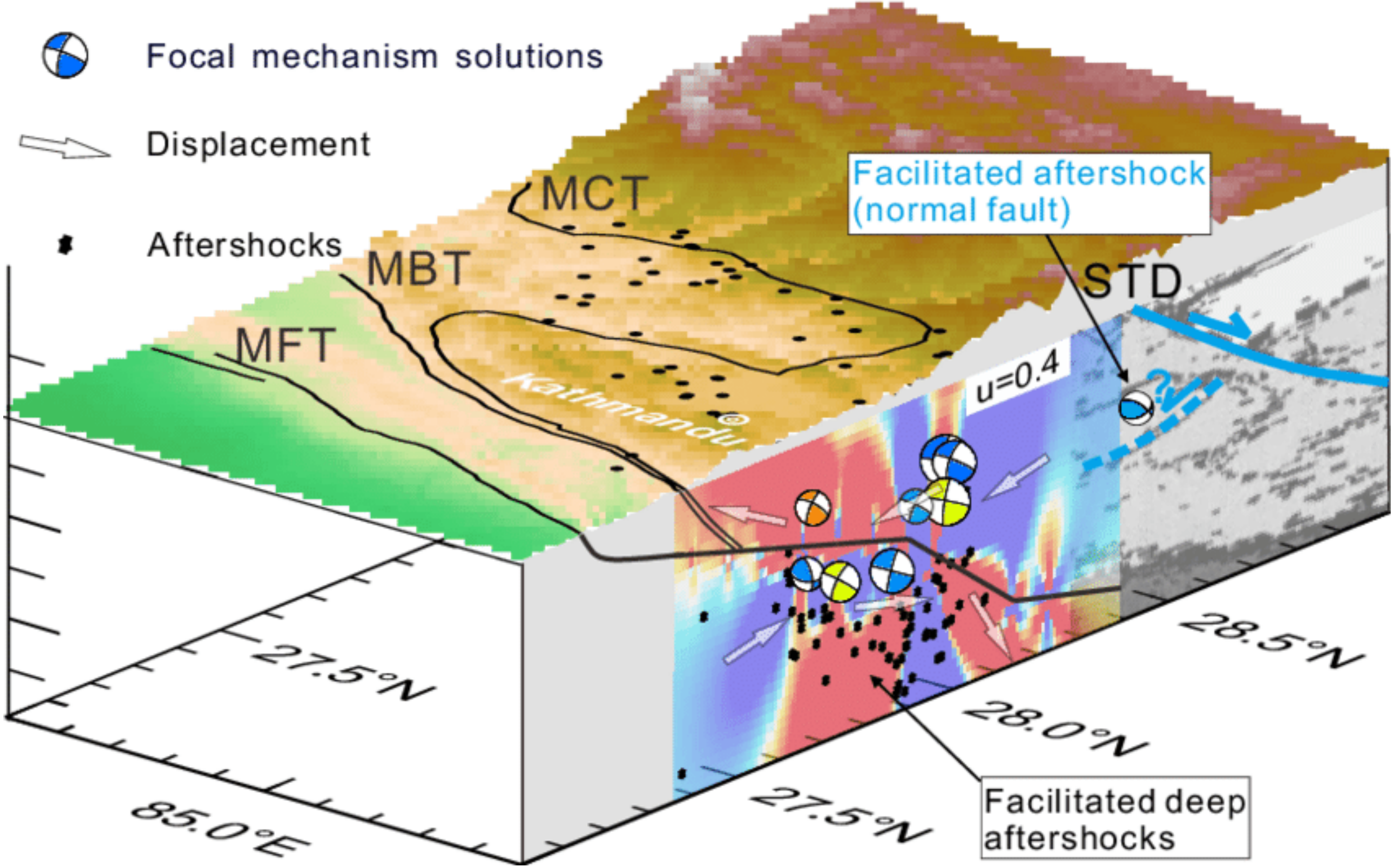
In each panel, the epicenter of the next earthquake to rupture is circled. All but the 1943 epicenter lie in regions where the stress rose significantly, typically by 2-5 bars, owing to the foregoing shocks and deep fault slip.


I N D I A
SEISMIC ZONE
N
TAJIKISTAN
AFGHANISTAN
PAKISTAN
JAMMU & KASHMIR
HIMACHAL PRADESH
PUNJAB
HARYANA
DELHI
New Delhi
UTTARAKHAND
CHINA (TIBET)
NEPAL
SIKKIM
BHUTAN
ARUNACHAL PRADESH
ASOM (ASSAM)
NAGALAND
MEGHALAYA
MANIPUR
TRIPURA
MIZORAM
BANGLADESH
MYANMAR
UTTAR PRADESH
BIHAR
RAJASTHAN
JHARKHAND
WEST BENGAL
MADHYA PRADESH
GUJARAT
CHHATTISGARH
(ODISHA) ORISSA
DADRA & NAGAR HAVELI
MAHARASHTRA
TELANGANA
ARABIAN SEA
BAY OF BENGAL
GOA
KARNATAKA
ANDHRA PRADESH
TAMIL NADU
KERALA
LAKSHADWEEP (INDIA)
ANDAMAN & NICOBAR ISLANDS (INDIA)
SRI LANKA
I N D I A N O C E A N
LEGEND
International Boundary
State Boundary
Country Capital
Zone - II (Least Active)
Zone - III (Moderate)
Zone - IV (High)
Zone - V (Highest)
Map not to Scale
Copyright © 2014 www.mapsofindia.com
(Updated on 2nd June 2014)
www.mapsofindia.com

Example from Himalaya



Dal Zilio et al., (2019)



Zhao et al., (2019)