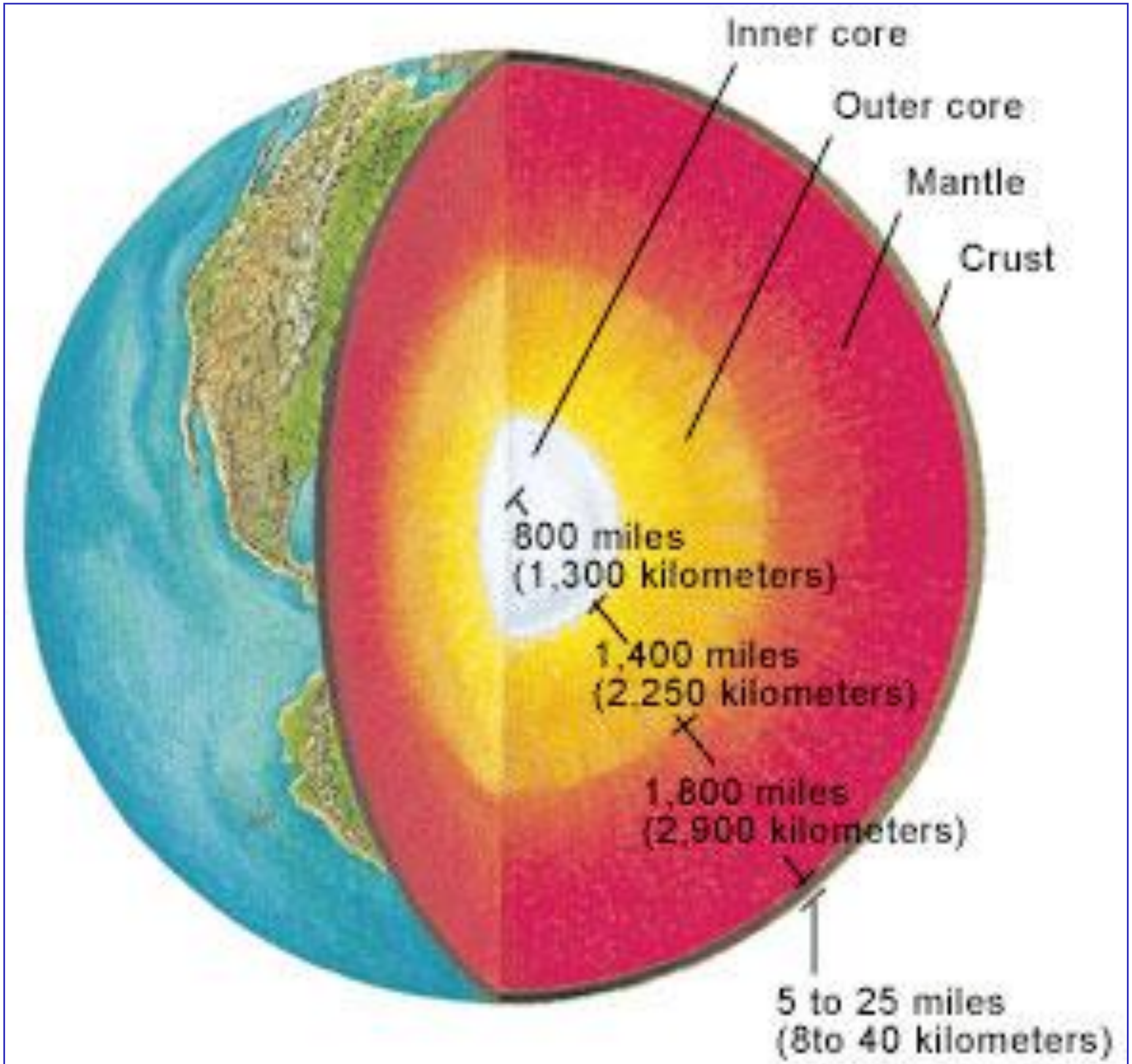
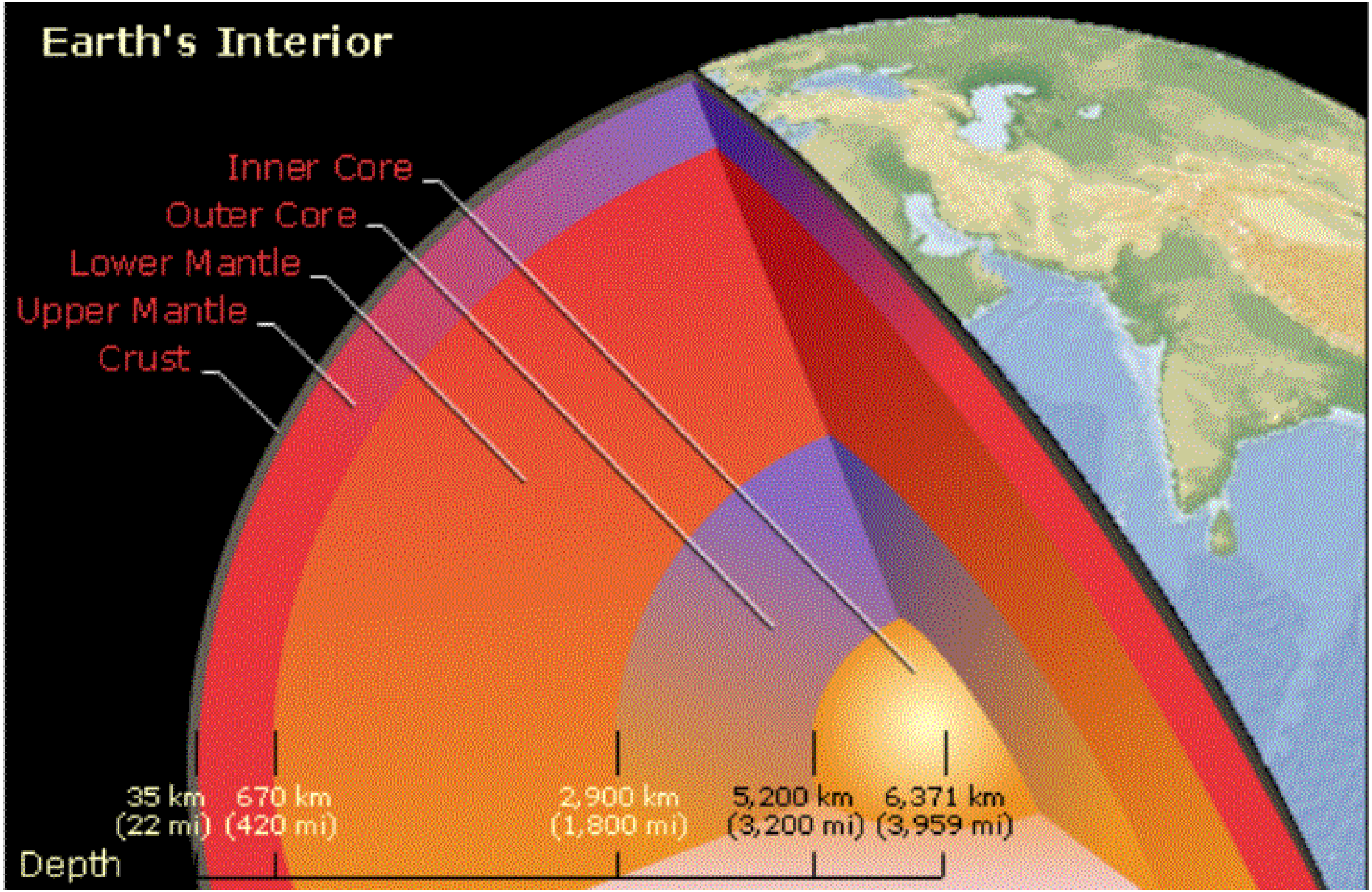
Earthquake Energy Release Mechanism

Ahmed Elgamal

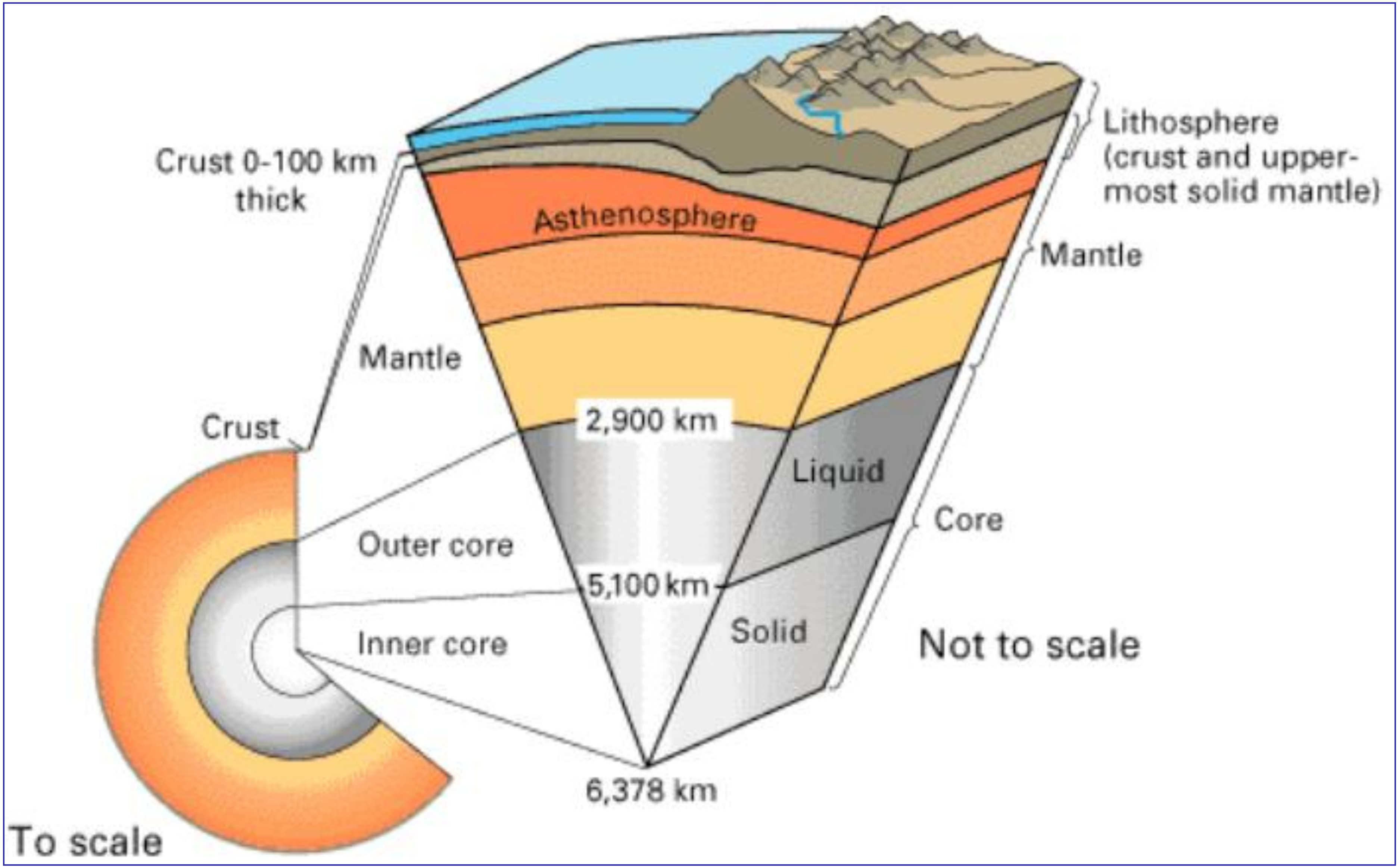
Earth's Interior





USGS' "This Dynamic Earth"

http://pubs.usgs.gov/gip/dynamic/dynamic.html



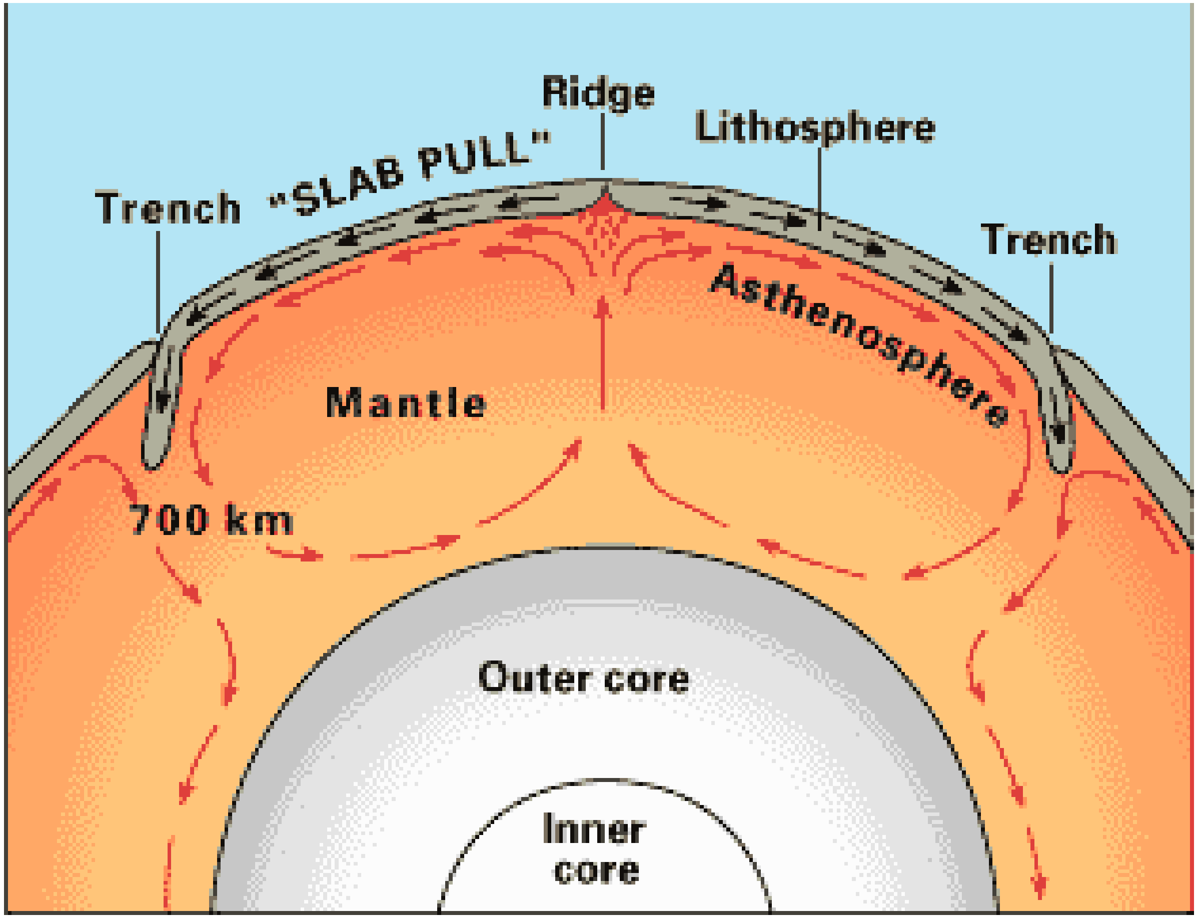
http://www.nasa.gov/worldbook/earth_worldbook_prt.htm

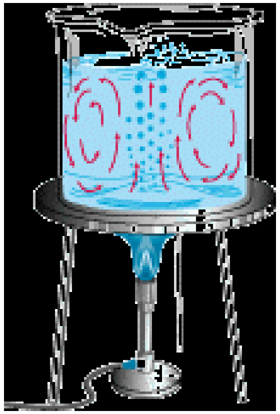
Pangaea, **Pangæa**, or **Pangea**, was the supercontinent that existed during the Paleozoic and Mesozoic eras about 250 million years ago, before the component continents were separated into their current configuration.

The single enormous ocean which surrounded Pangaea is known as Panthalassa.

http://en.wikipedia.org/wiki/Pangaea

The breaking up and formation of supercontinents appears to be cyclical through Earth's **4.6 billion** year history.





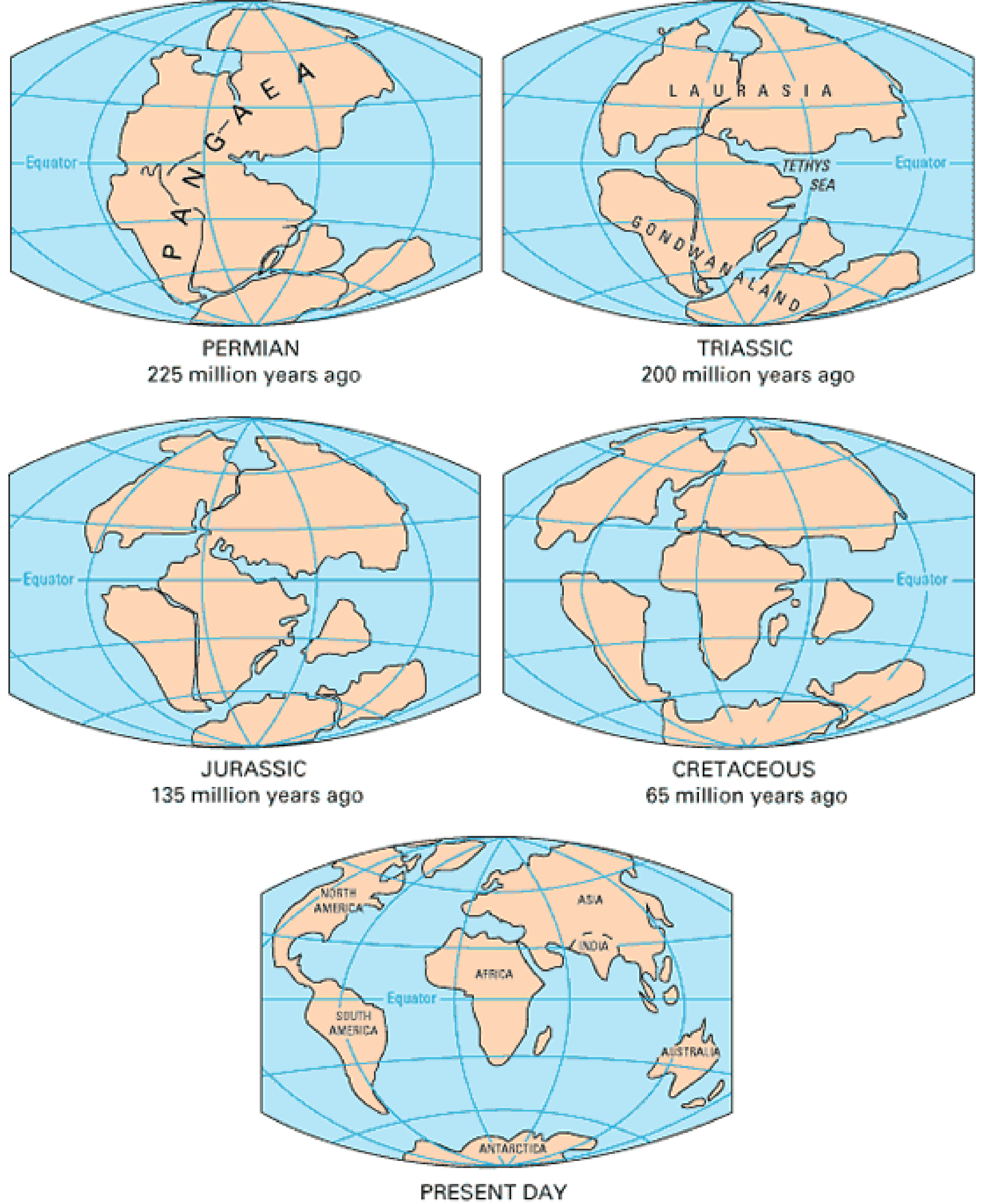
Why does the crust move?

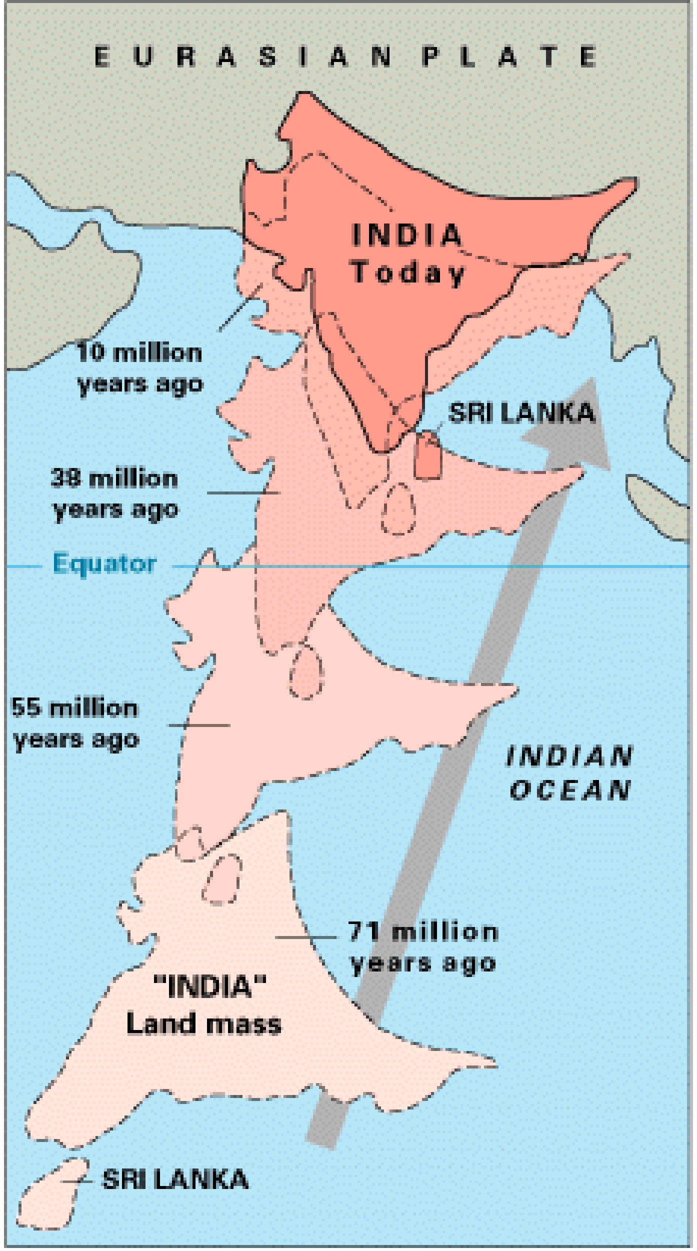
http://pubs.usgs.gov/gip/dynamic/dynamic.html

PLATE TECTONICS

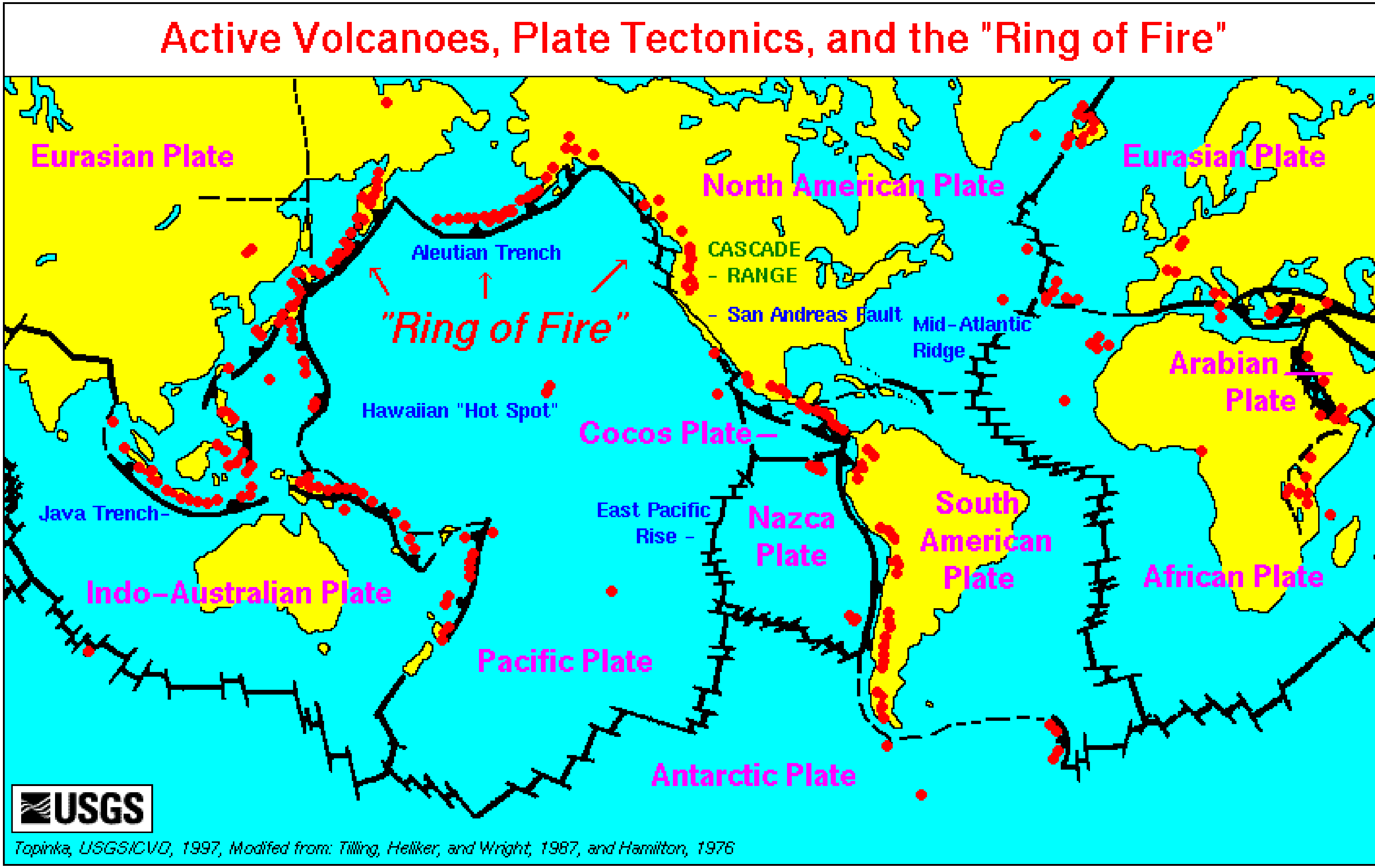
Continental Drift

Alfred Wegener (book published in 1915). While not entirely a new idea, Wegener provided some solid evidence.

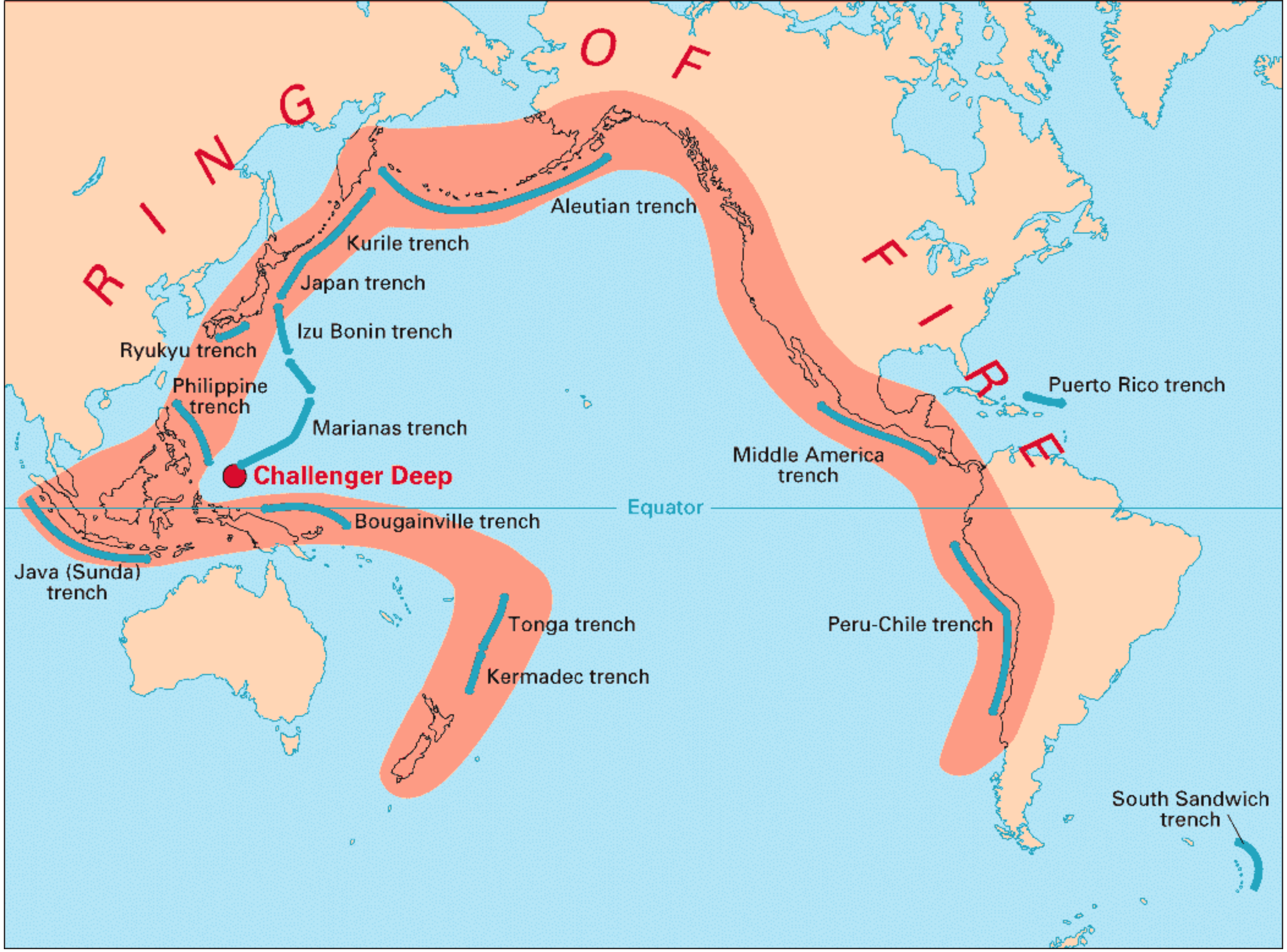




The 6,000-km-plus journey of the India landmass (Indian Plate) before its collision with Asia (Eurasian Plate) about 40 to 50 million years ago. India was once situated well south of the Equator, near the continent of Australia.

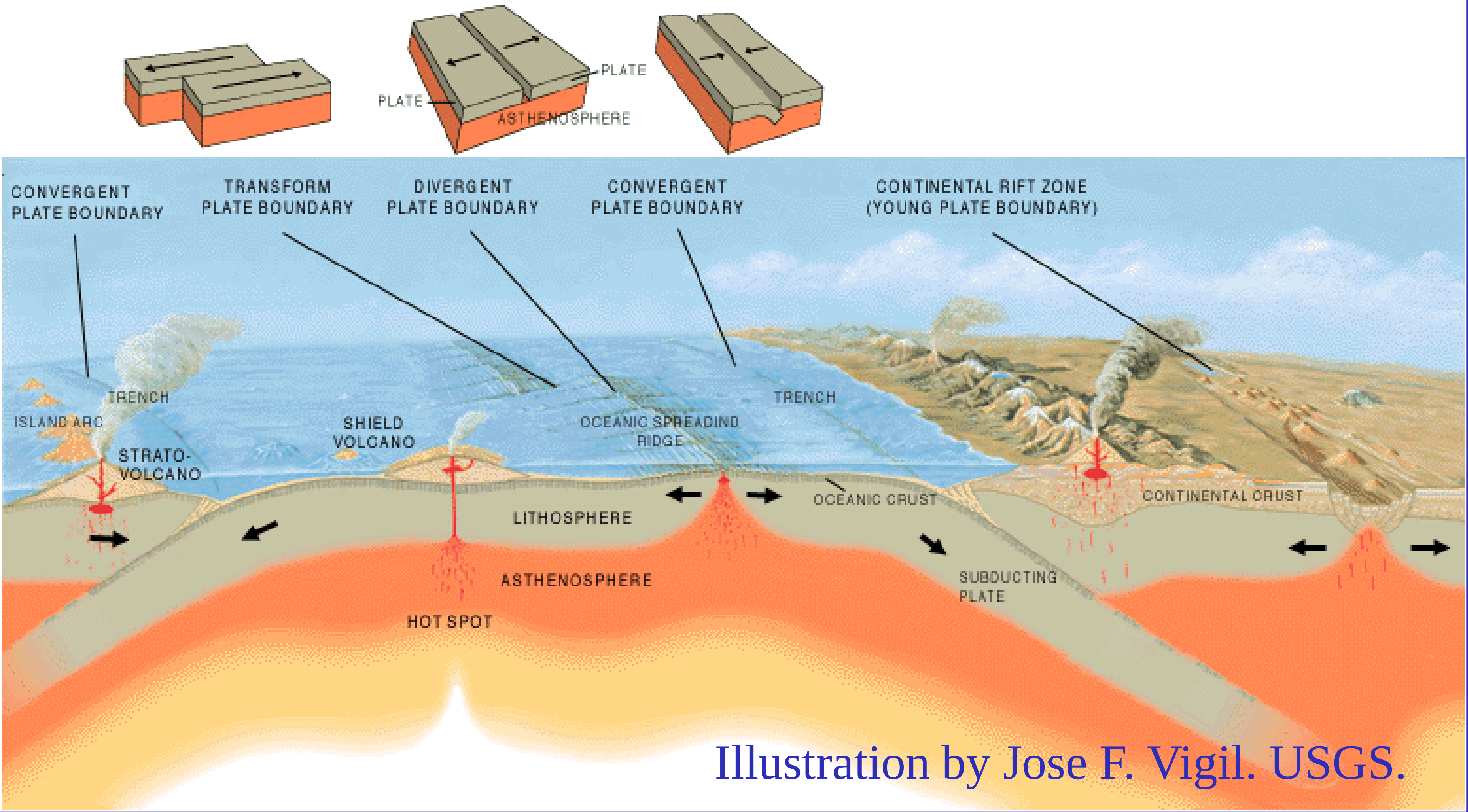


Most earthquake activity is along Plate Boundaries

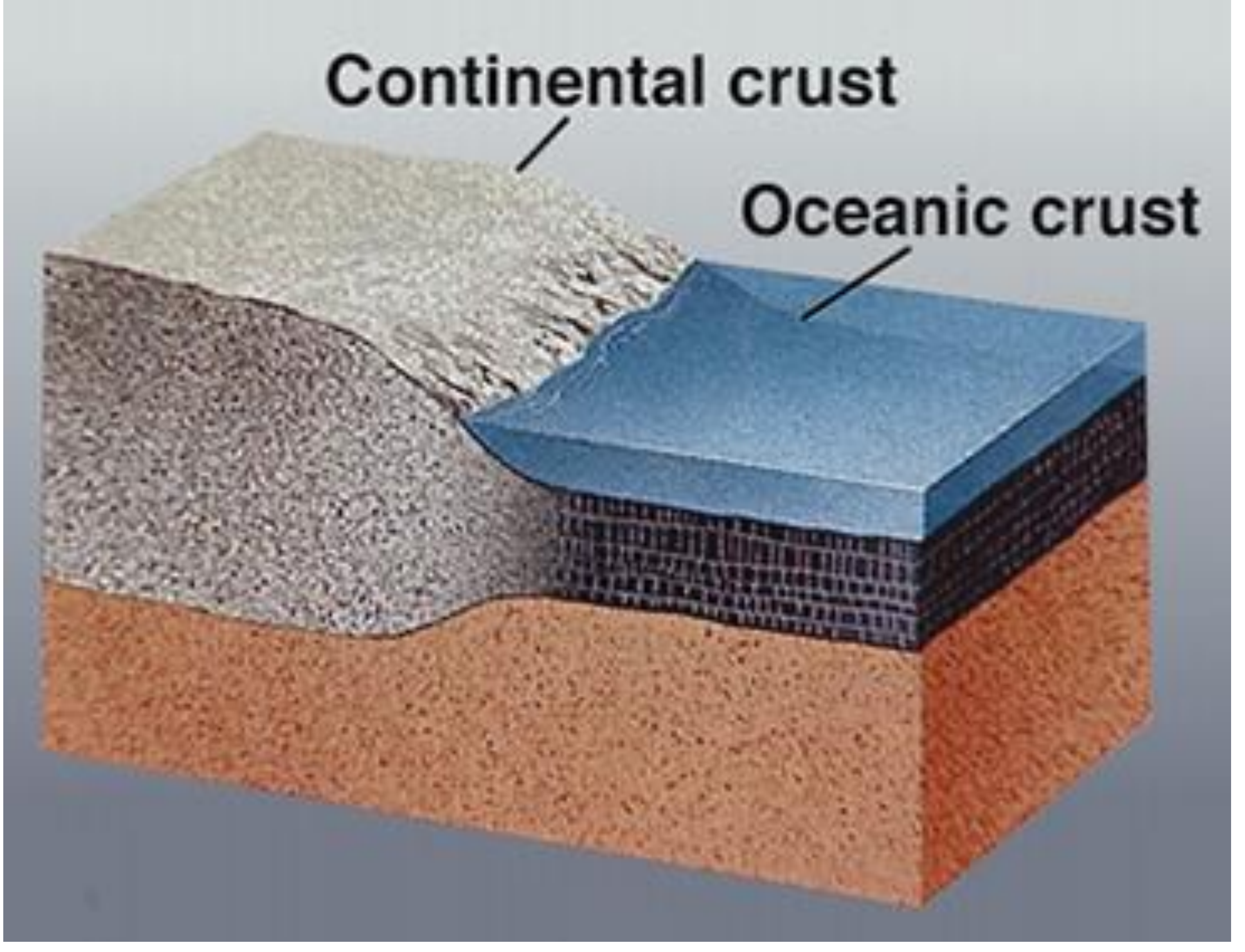


http://pubs.usgs.gov/gip/dynamic/understanding.html

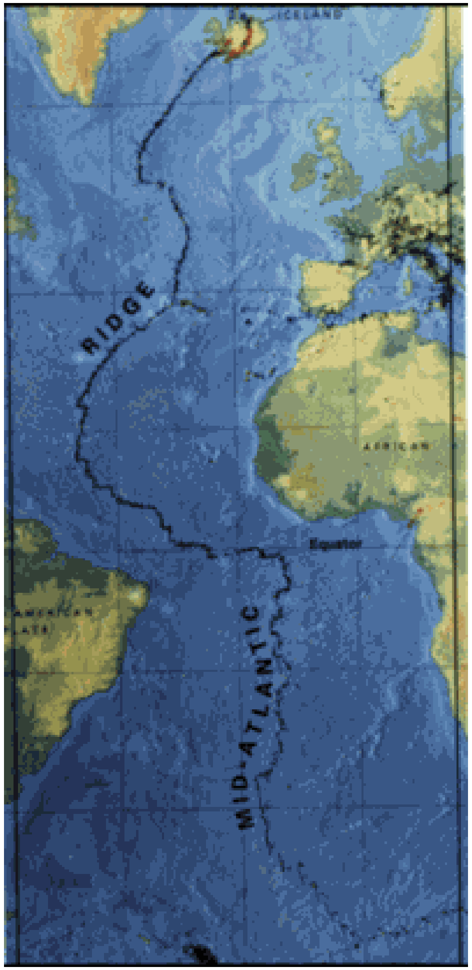
Volcanic arcs and oceanic trenches partly encircling the Pacific Basin form the so-called Ring of Fire, *a zone of frequent earthquakes and volcanic eruptions. The trenches are shown in blue-green. The volcanic island arcs, although not labeled, are parallel to, and always landward of, the trenches. For example, the island arc associated with the Aleutian Trench is represented by the long chain of volcanoes that make up the Aleutian Islands*.

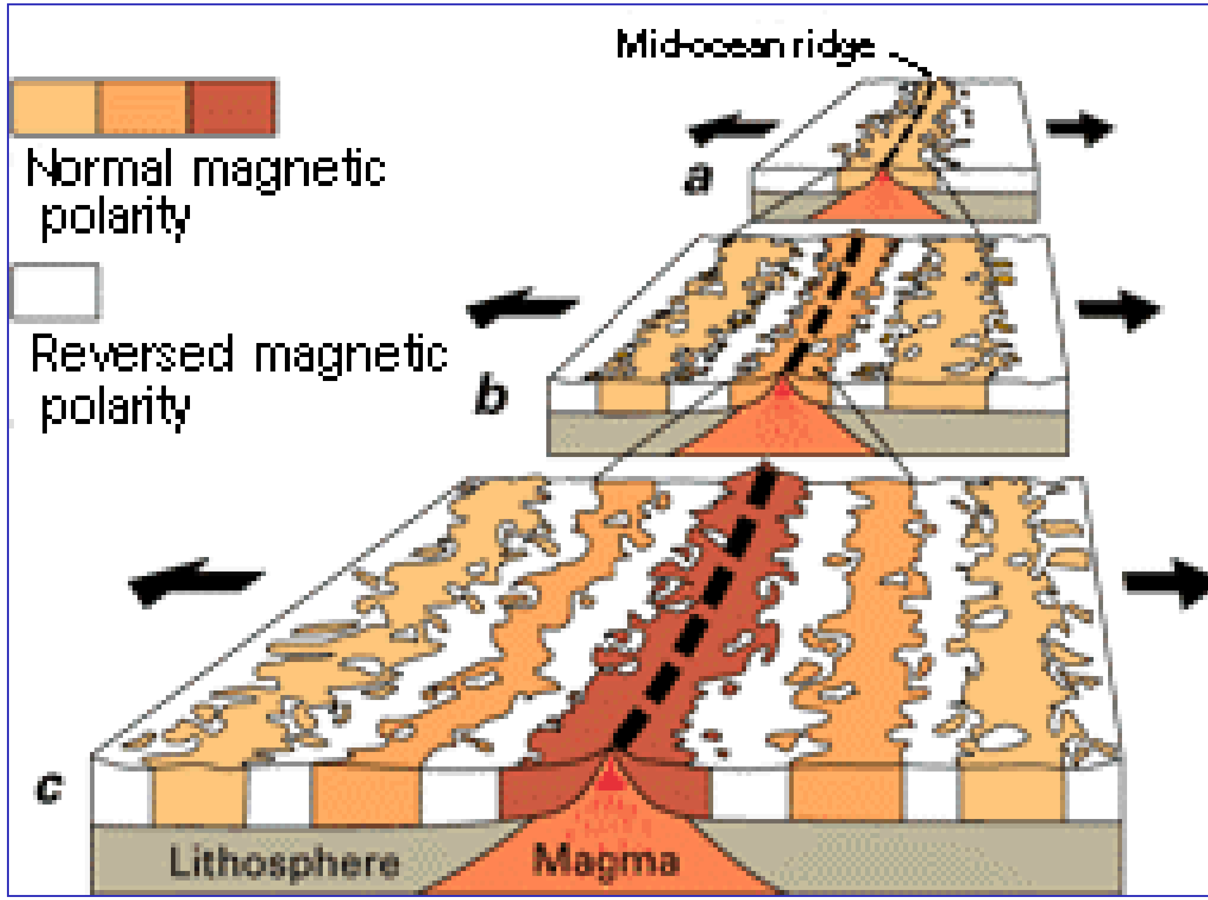


Generalized cross section through the ocean crust showing the uppermost layers of rocks under the ocean spreading out from the midoceanic ridge and sliding down under the volcanic island arc and active continental margin along the deep trench. Earthquake foci are concentrated at the tops of the descending layers and along the ridge. Magma rises upward above the subduction zones, and the erupting lava builds spectacular volcanic cones.

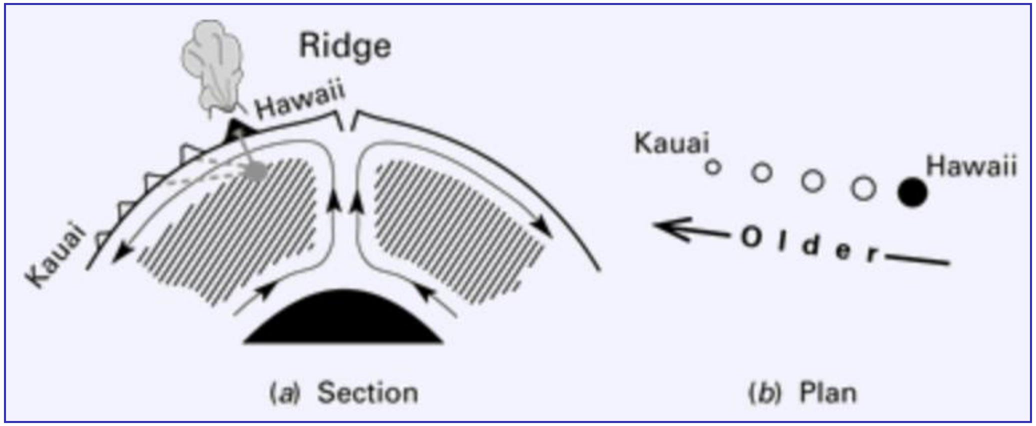


Oceanic crust 7-10 km and continental crust 30-40 km in thickness http://pubs.usgs.gov/gip/dynamic/understanding.html

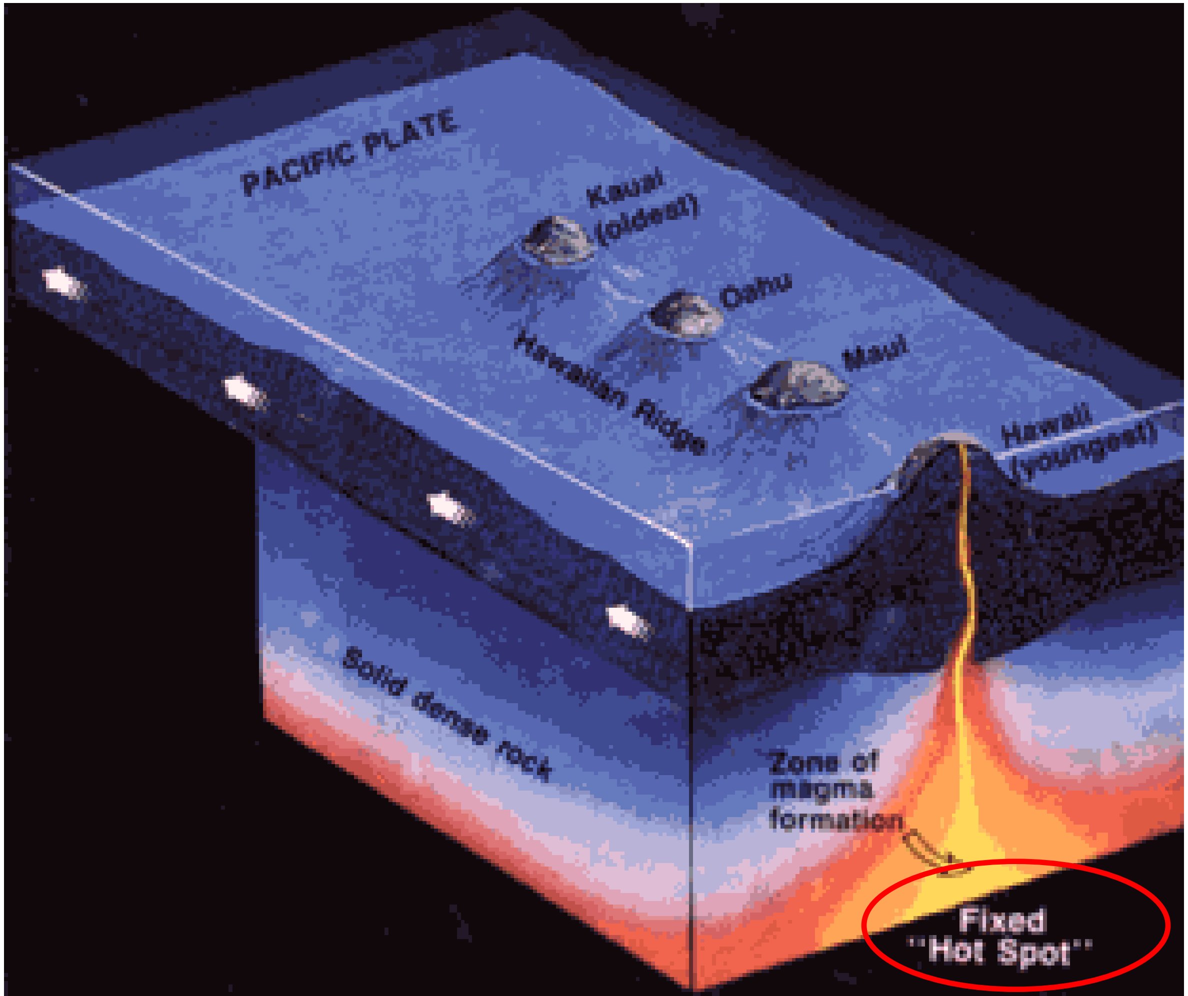




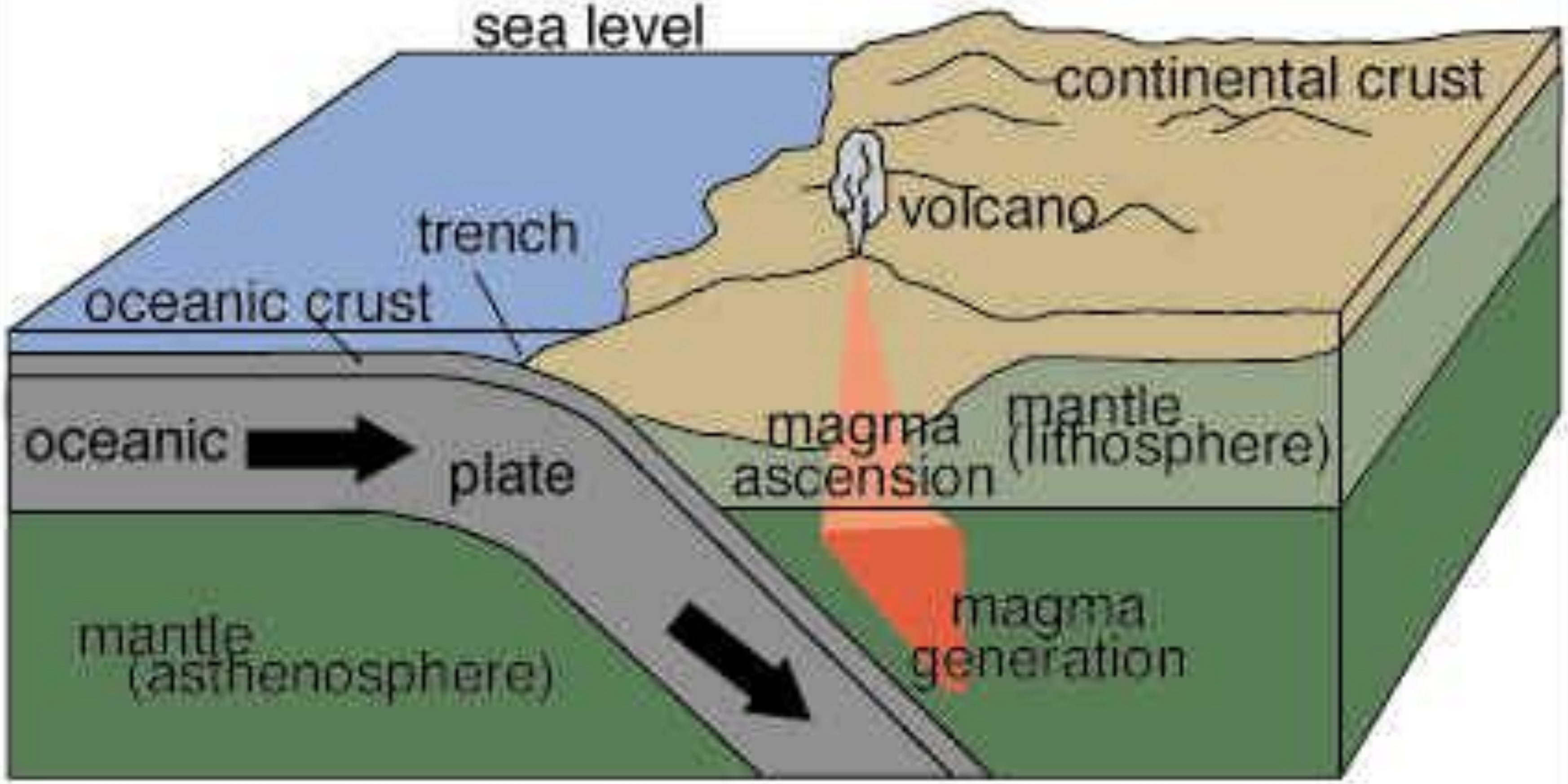
The Mid-Atlantic Ridge, which splits nearly the entire Atlantic Ocean north to south, is probably the best-known and most-studied example of a divergent-plate boundary. (Illustration adapted from the map This Dynamic Planet http://mineralsciences.si.edu/tdpmap/ *.)*



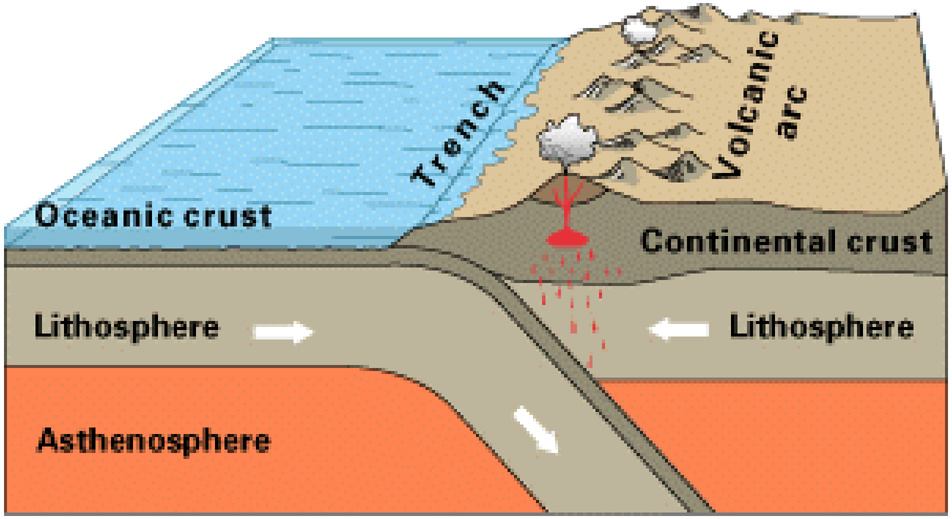
Ridge
Hawaii
Kauai
(a) Section
Kauai
Hawaii
Older
(b) Plan



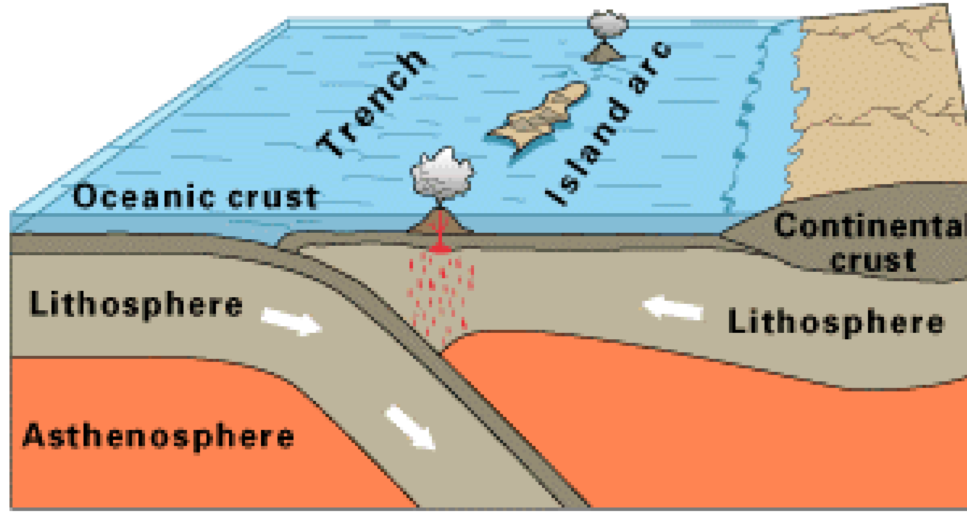
PACIFIC PLATE
Kauai (oldest)
Oahu
Maui
Hawaiian Ridge
Hawaii (youngest)
Solid dense rock
Zone of magma formation
Fixed "Hot Spot"



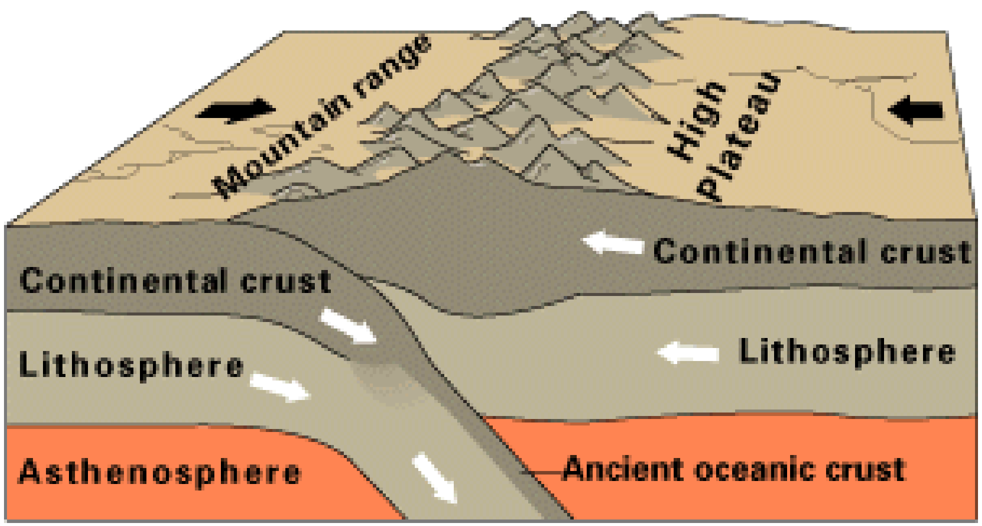
Magma is generated at subduction zones where dense oceanic plates are pushed under lighter continental plates.



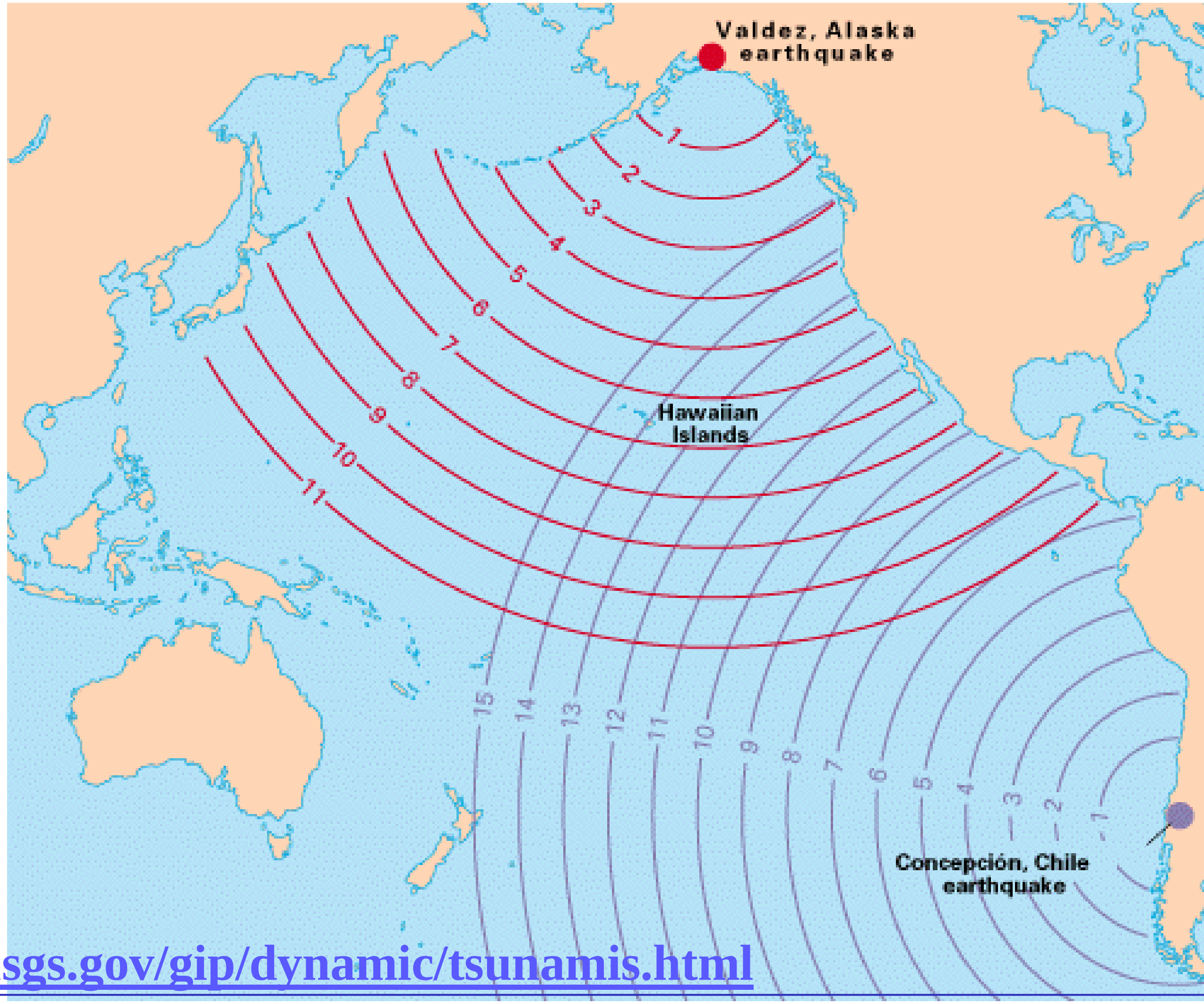
Oceanic-continental convergence



Oceanic-oceanic convergence

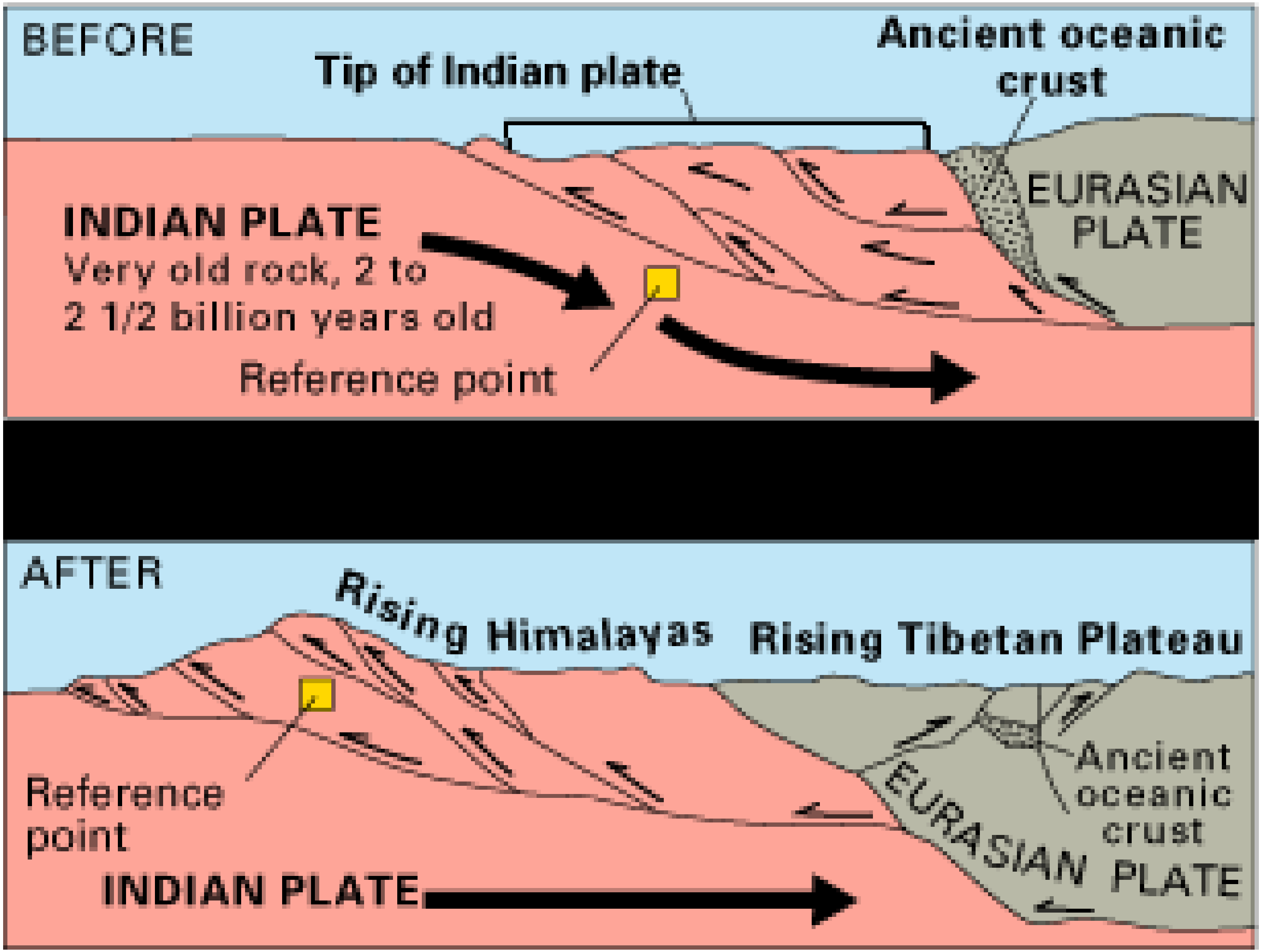


Continental-continental convergence



http://pubs.usgs.gov/gip/dynamic/tsunamis.html

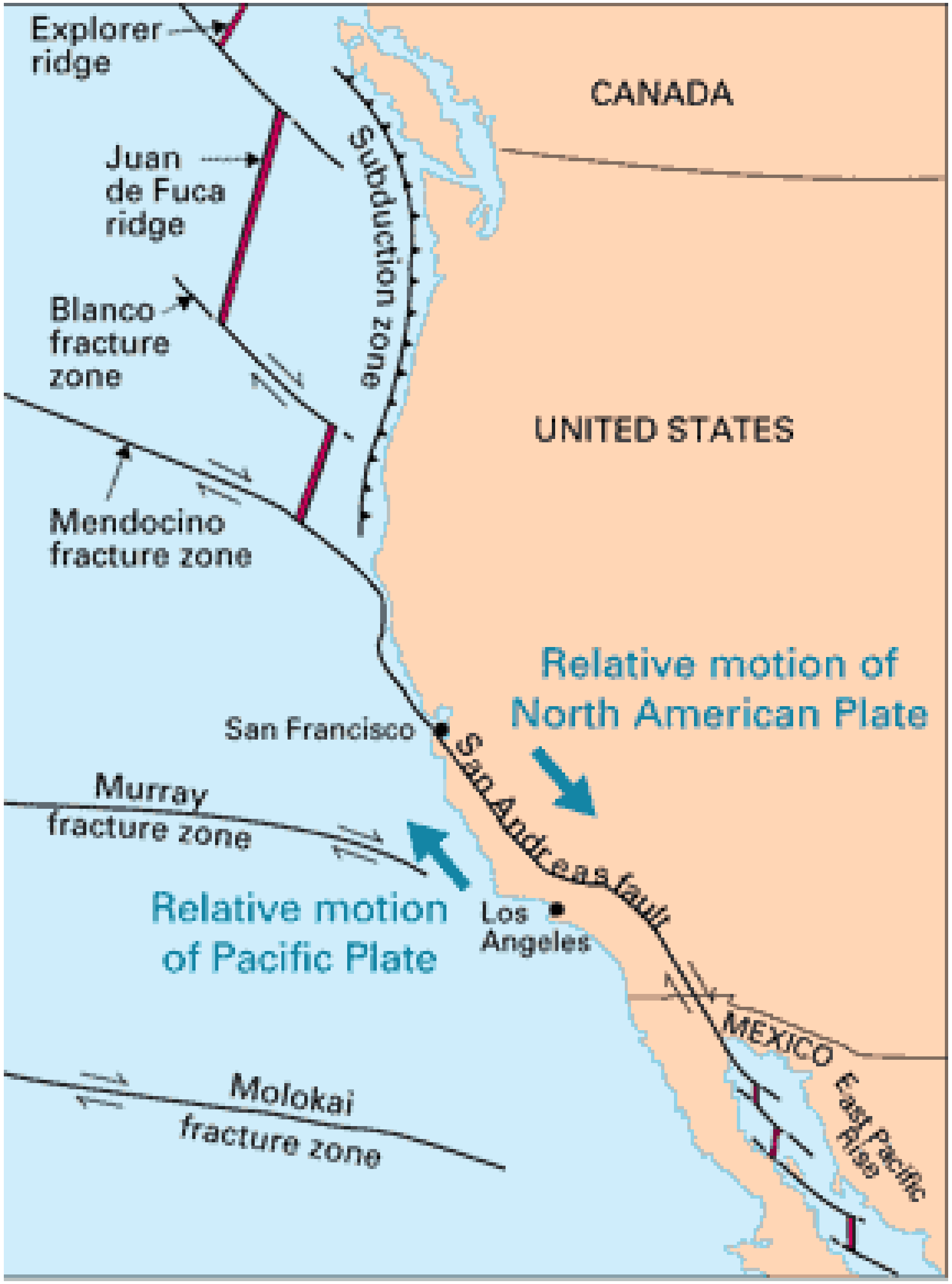
The Hawaiian Islands are especially vulnerable to destructive tsunamis generated by major earthquakes in the circum-Pacific Ring of Fire. Travel times (in hours) are shown for the tsunamis produced by the 1960 Concepción, Chile, earthquake (purple curves) and by the 1964 Good Friday, Valdez (Anchorage), Alaska earthquake (red curves). The 1960 tsunamis killed 61 people and caused about $24 million in damage.



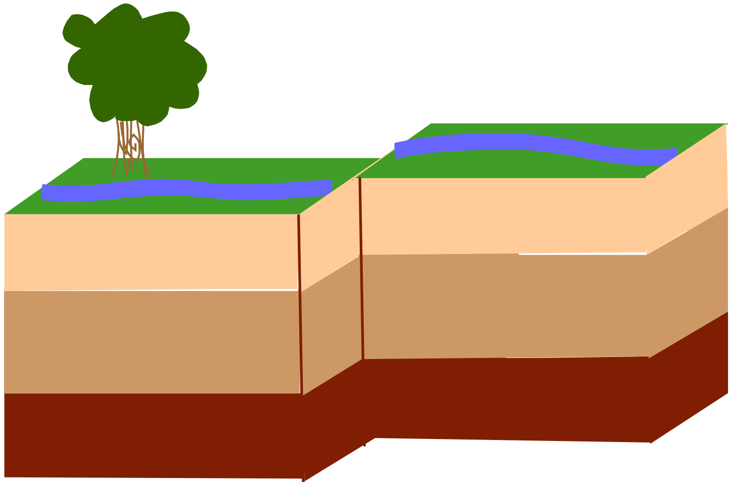
BEFORE
Ancient oceanic crust
Tip of Indian plate
EURASIAN PLATE
INDIAN PLATE
Very old rock, 2 to 2 1/2 billion years old
Reference point
AFTER
Rising Himalayas
Rising Tibetan Plateau
Ancient oceanic crust
Reference point
EURASIAN PLATE
INDIAN PLATE

The Blanco, Mendocino, Murray, and Molokai fracture zones are some of the many fracture zones (transform faults) that scar the ocean floor and offset ridges (see text). The San Andreas is one of the few transform faults exposed on land.

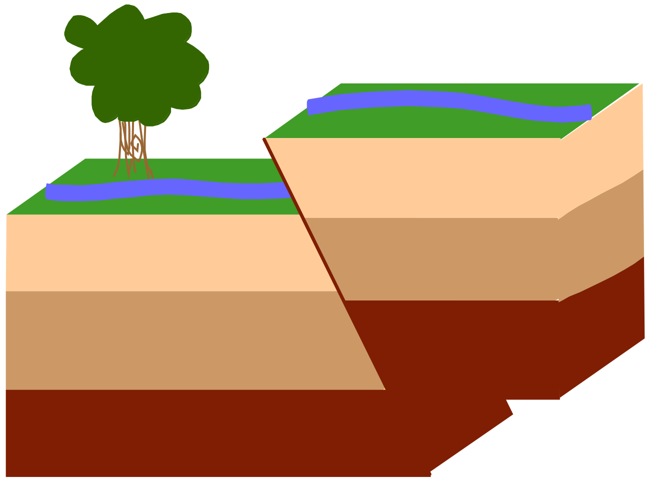
The San Andreas fault zone, which is about 1,300 km long and in places tens of kilometers wide, slices through two thirds of the length of California. Along it, the Pacific Plate has been grinding horizontally past the North American Plate for 10 million years, at an average rate of about 5 cm/yr. Land on the west side of the fault zone (on the Pacific Plate) is moving in a northwesterly direction relative to the land on the east side of the fault zone (on the North American Plate).



Three Types of Faults



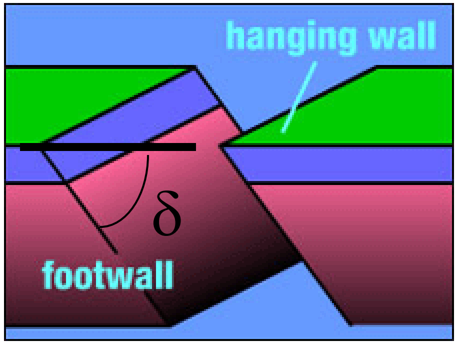
Strike-Slip Fault



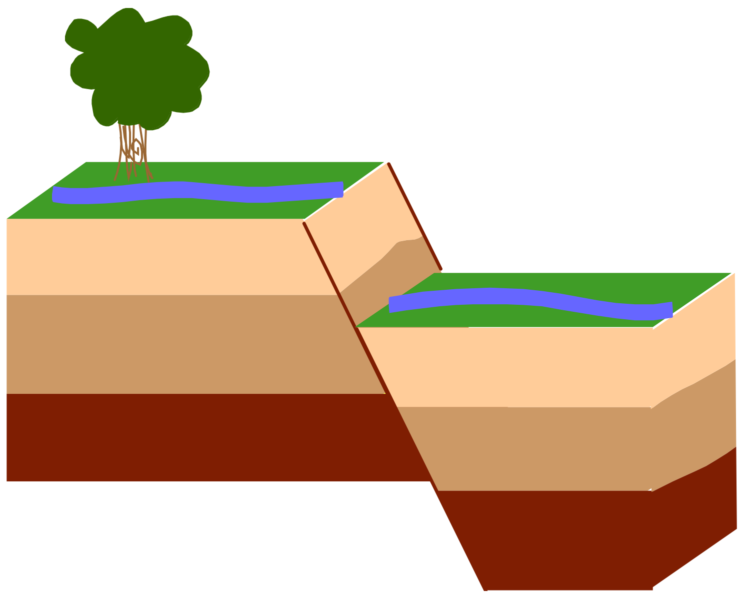
Thrust or Reverse Fault

USGS (after Lisa Wald)

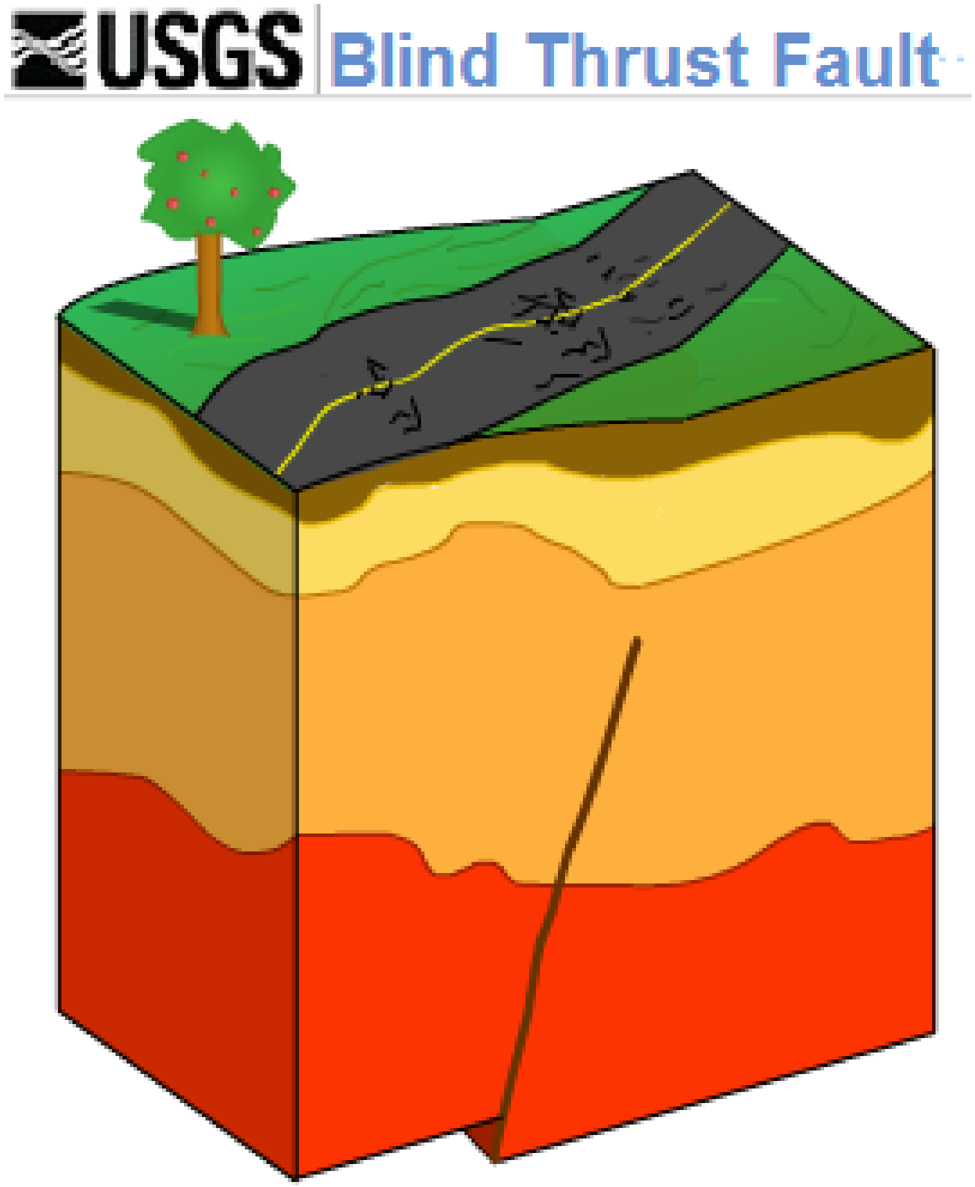
Hanging wall and footwall configuration (based on dip angle δ)



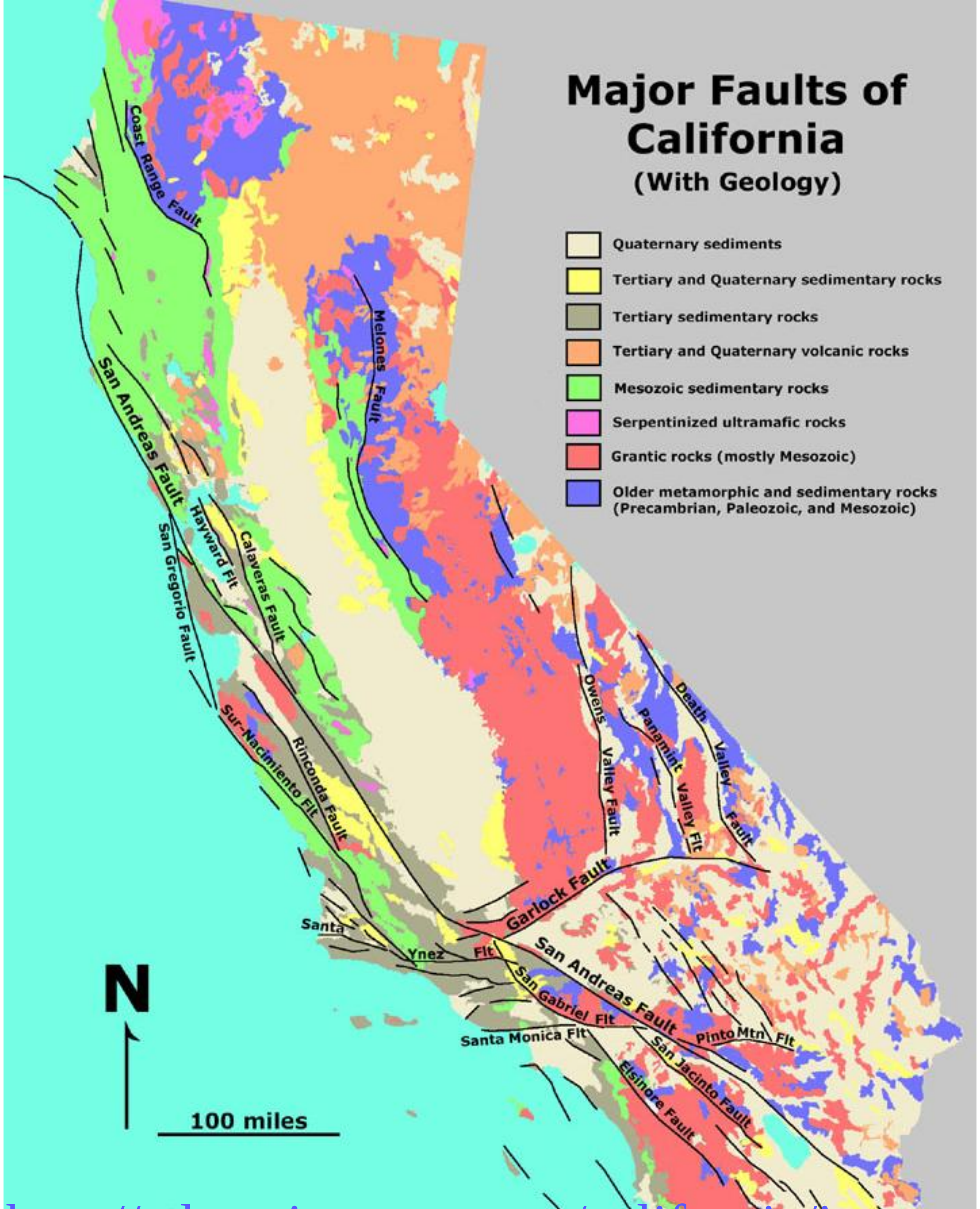
http://www.nasa.gov/audience/forstudents/5-8/features/F_Earth_Has_Faults.html

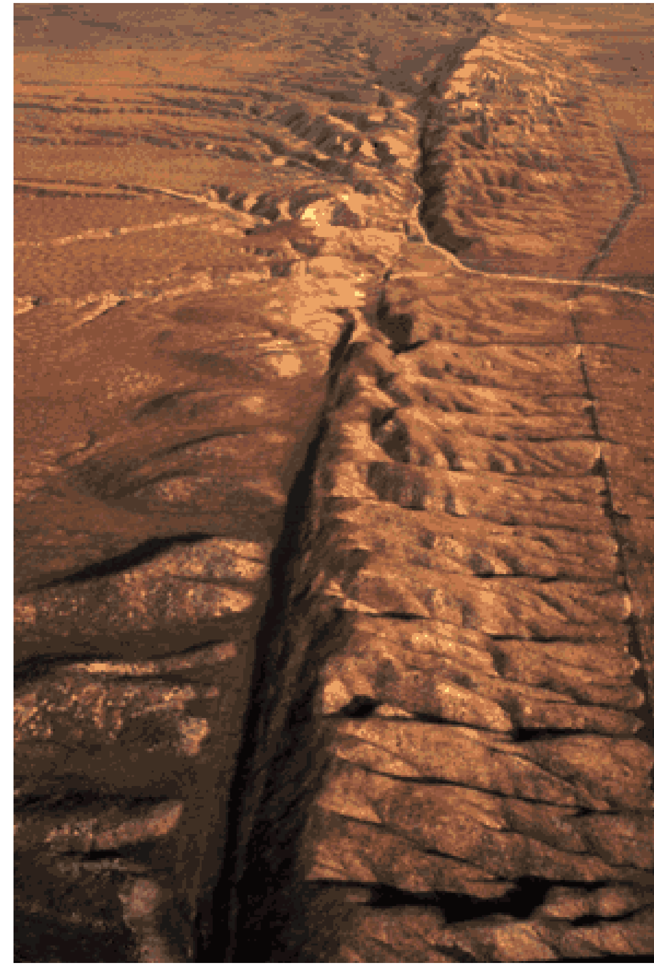


Normal Fault



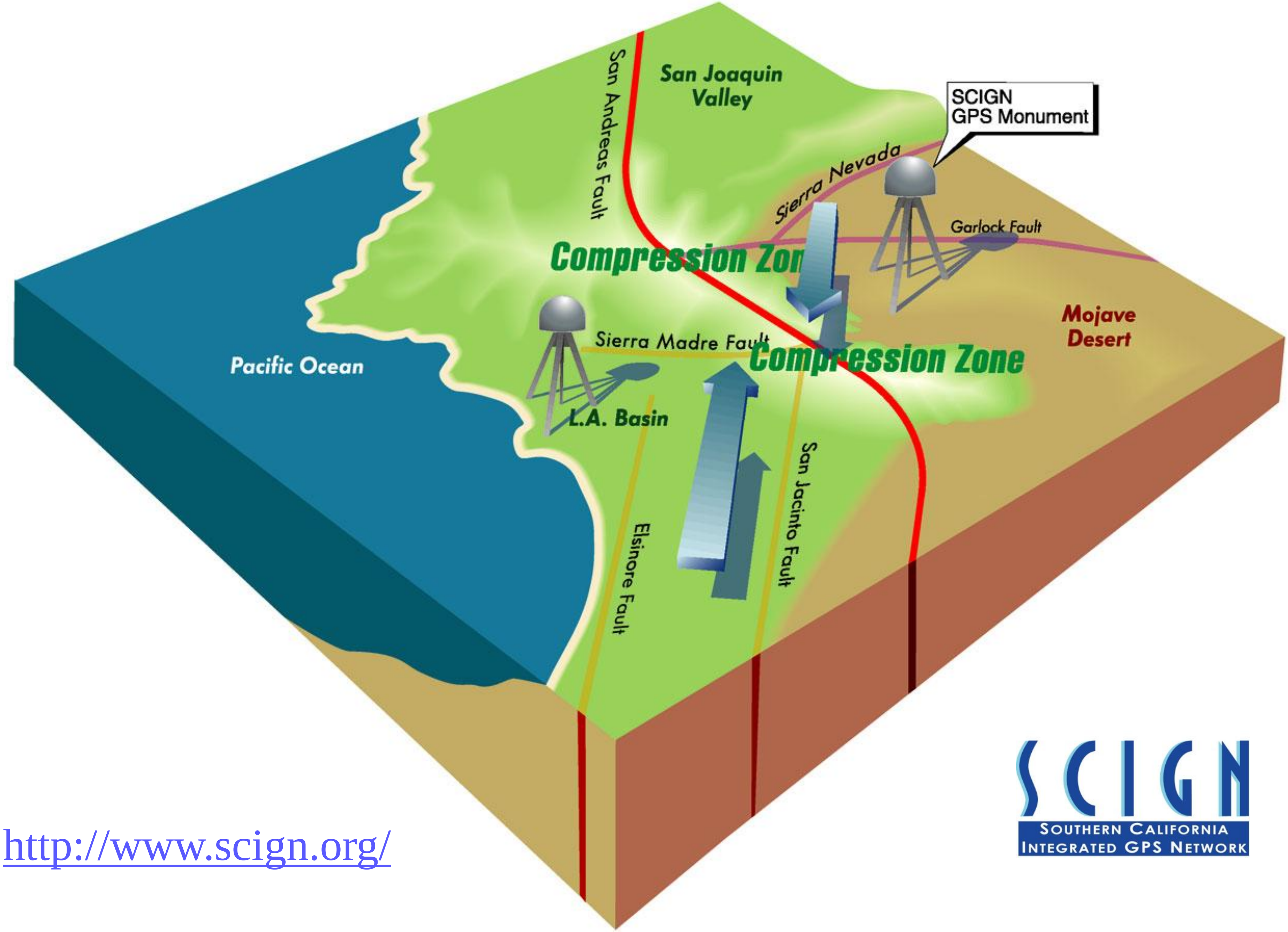
http://earthquake.usgs.gov/learn/glossary/?term=blind%20thrust%20fault





Aerial view of the San Andreas fault slicing through the Carrizo Plain in the Temblor Range east of the city of San Luis Obispo. (Photograph by Robert E. Wallace, USGS.)

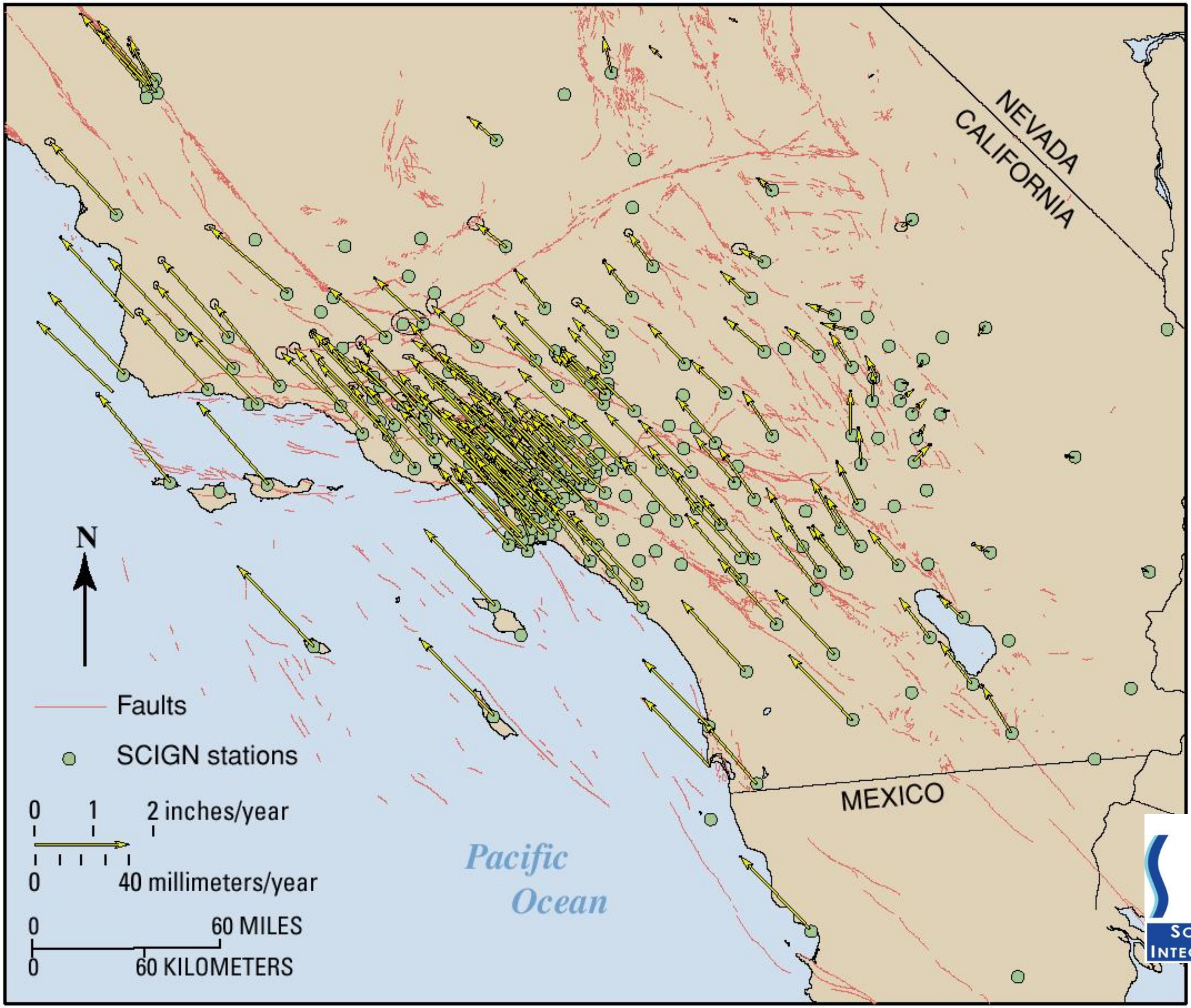
http://education.usgs.gov/california/images/faults2.jpg



http://www.scign.org/

SCIGN
SOUTHERN CALIFORNIA INTEGRATED GPS NETWORK

Minor Bend in San Andreas Fault north of LA and related local Seismic activity



Very dense sensor network to monitor Ground displacement before and after an EQ

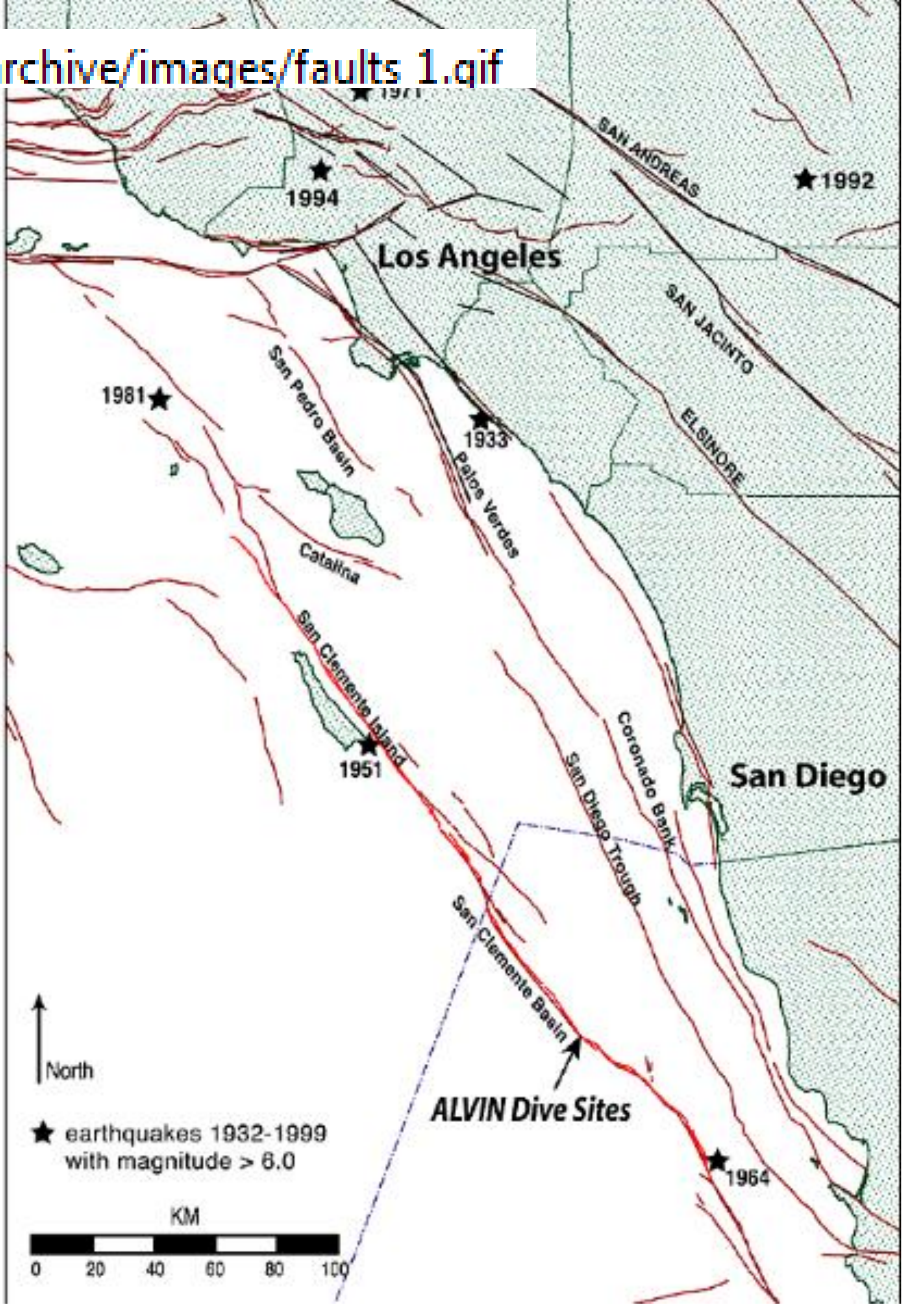
SCIGN
SOUTHERN CALIFORNIA INTEGRATED GPS NETWORK

http://www.scign.org/

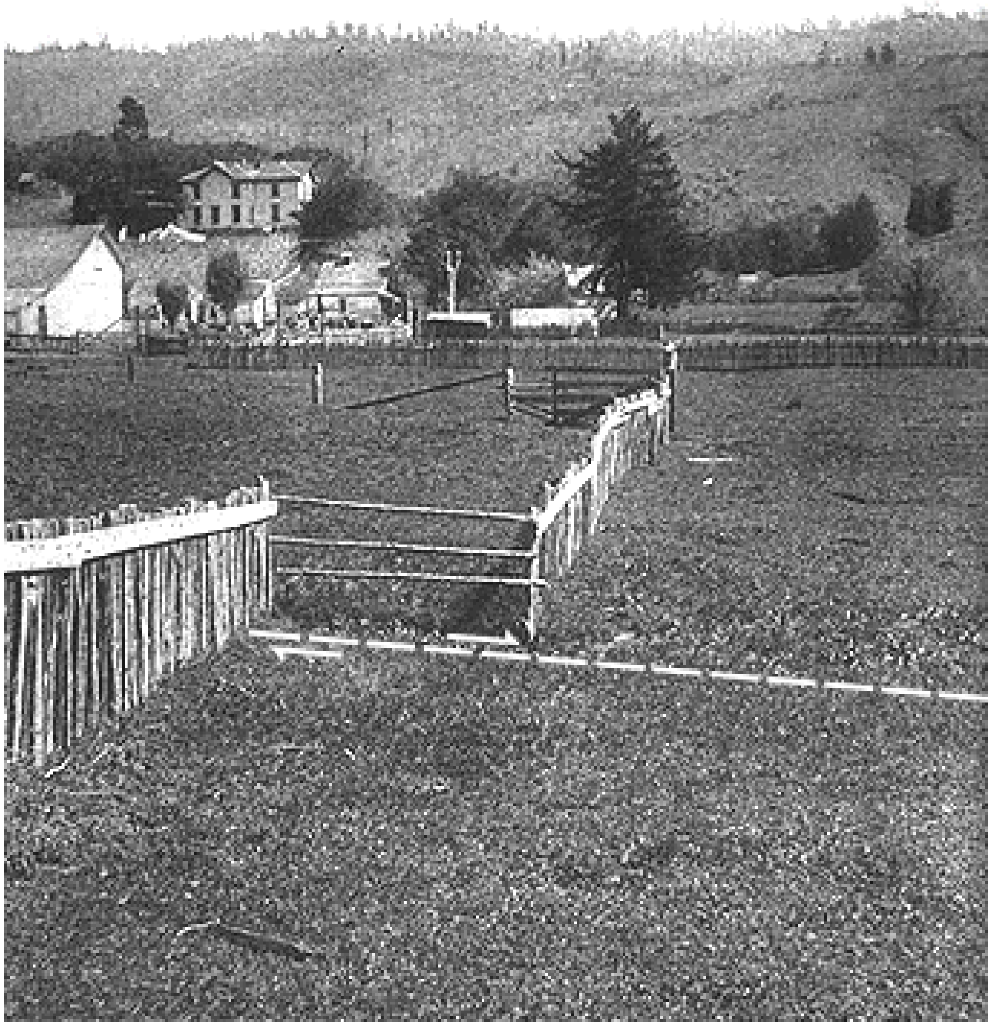
http://www.oar.noaa.gov/spotlite/archive/images/faults 1.gif

Faults: San Diego Area

1993 Long Beach Eq.
1971 San Fernando Eq.
1992 Landers Eq.
1994 Northridge Eq.



http://geomaps.wr.usgs.gov/sfgeo/quaternary/stories/marin_rupture.html



This photo shows a fence near Bolinas offset about ten feet during the 1906 earthquake.

http://geology.utah.gov/surveynotes/gladasked/gladfault_address.htm

Newly formed fault scarp from the 1954, magnitude 6.8 Dixie Valley, Nevada, earthquake. Note the tilting and deformation of the ground surface on the down-dropped side of the fault.

Normal Fault

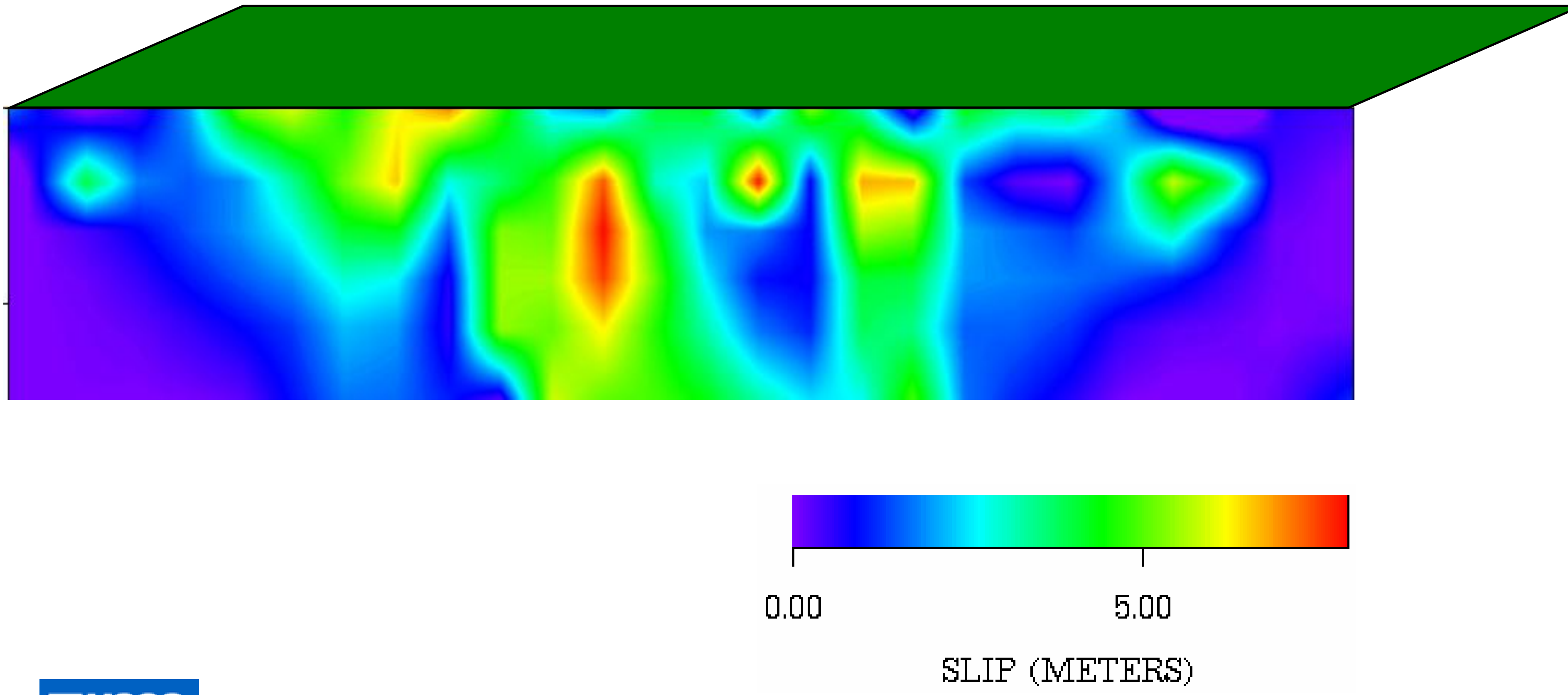
Earthquake Effects - Surface Faulting

Landers, CA 1992

USGS (after Lisa Wald)

Rupture on a Fault

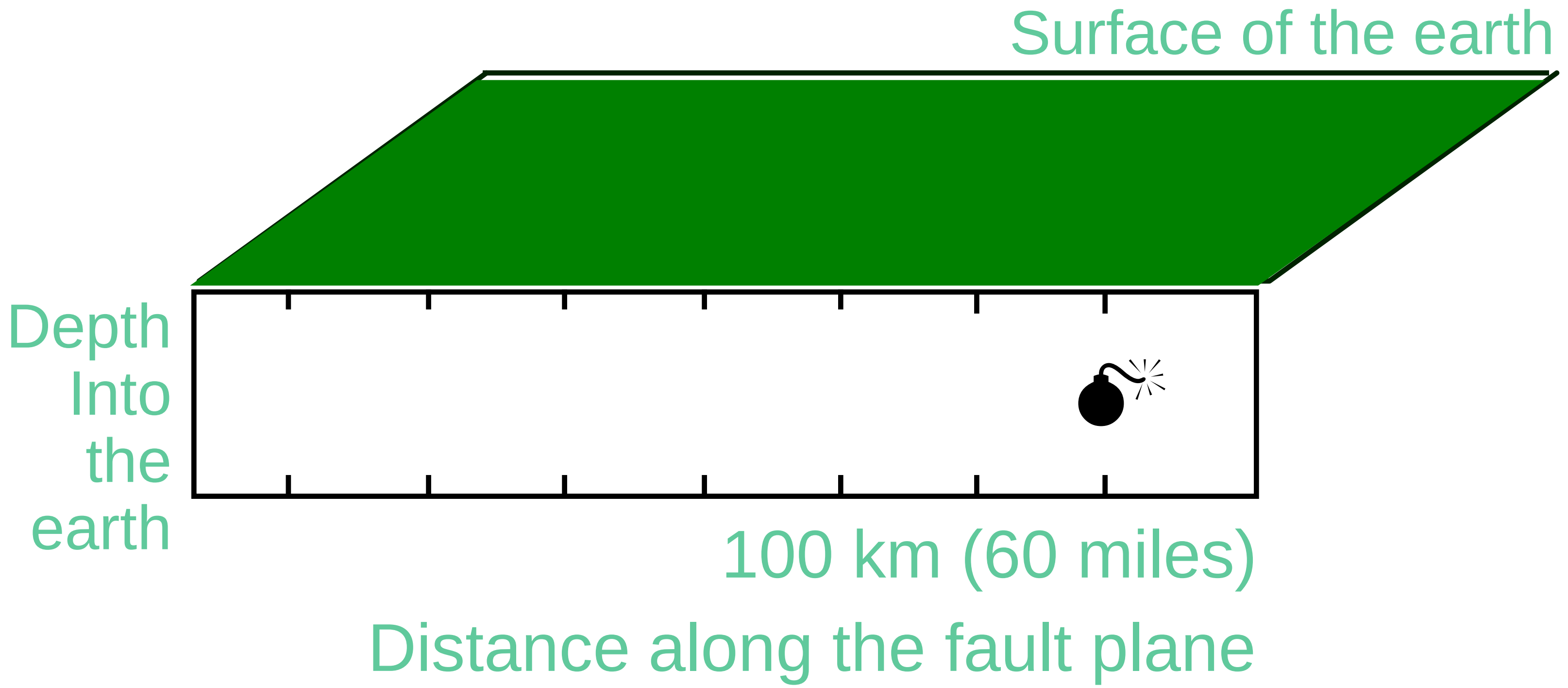
Total Slip in the M7.3 Landers Earthquake



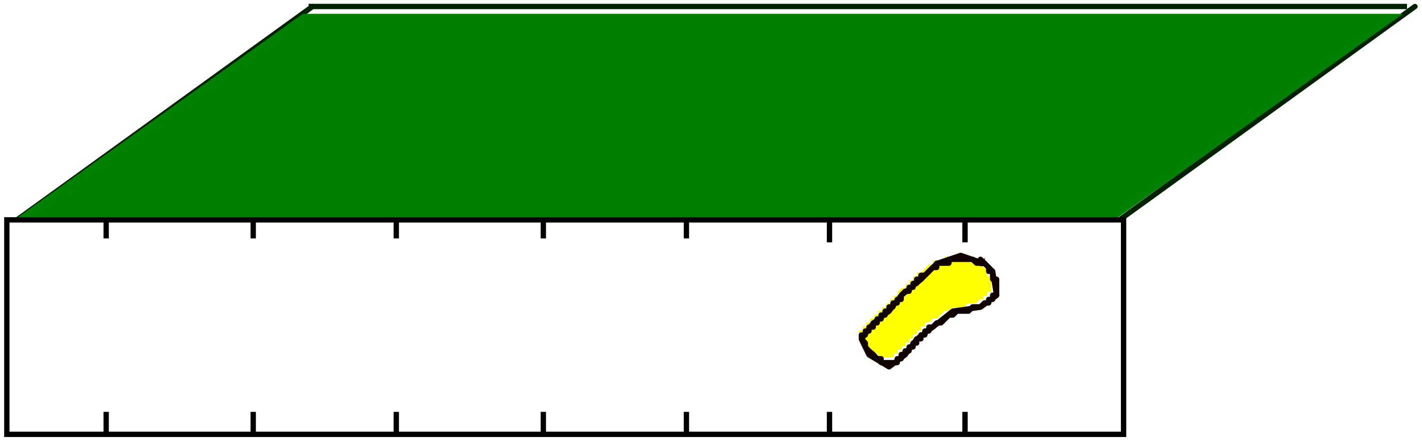
(Lisa Wald, USGS)

Slip on an earthquake fault

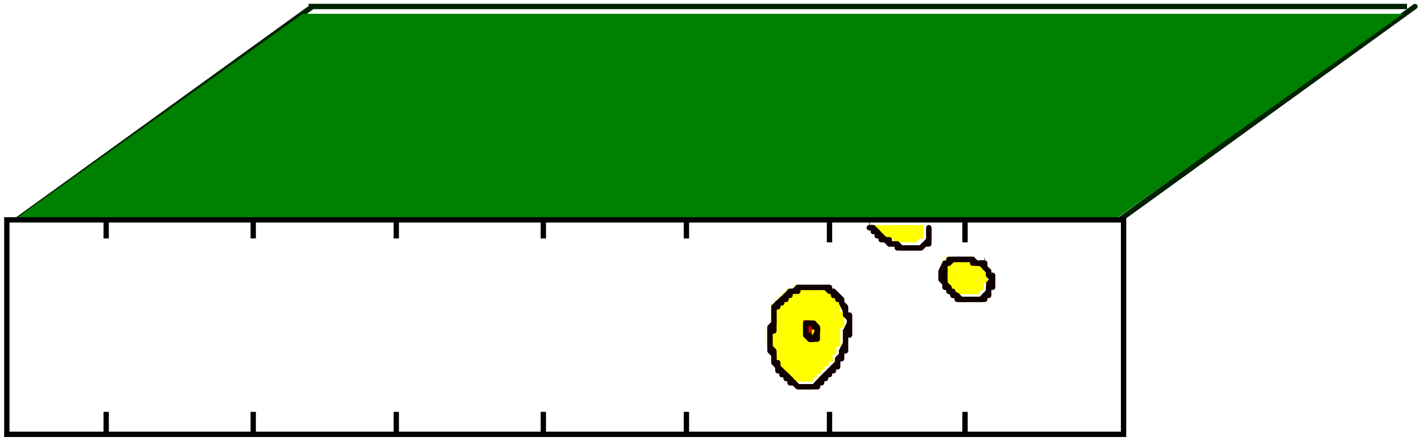
START



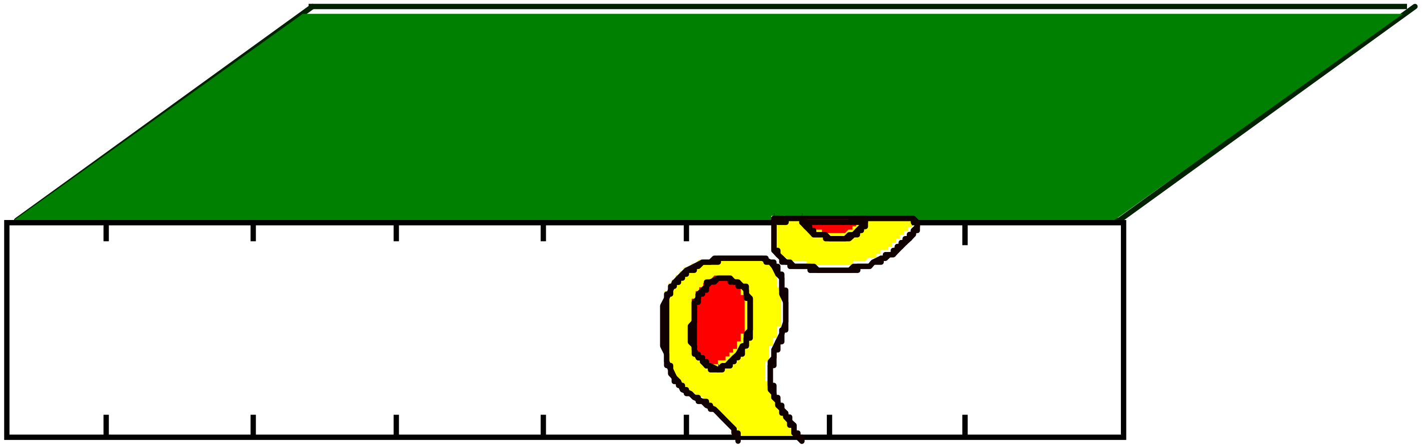
Slip on an earthquake fault
Second 2.0



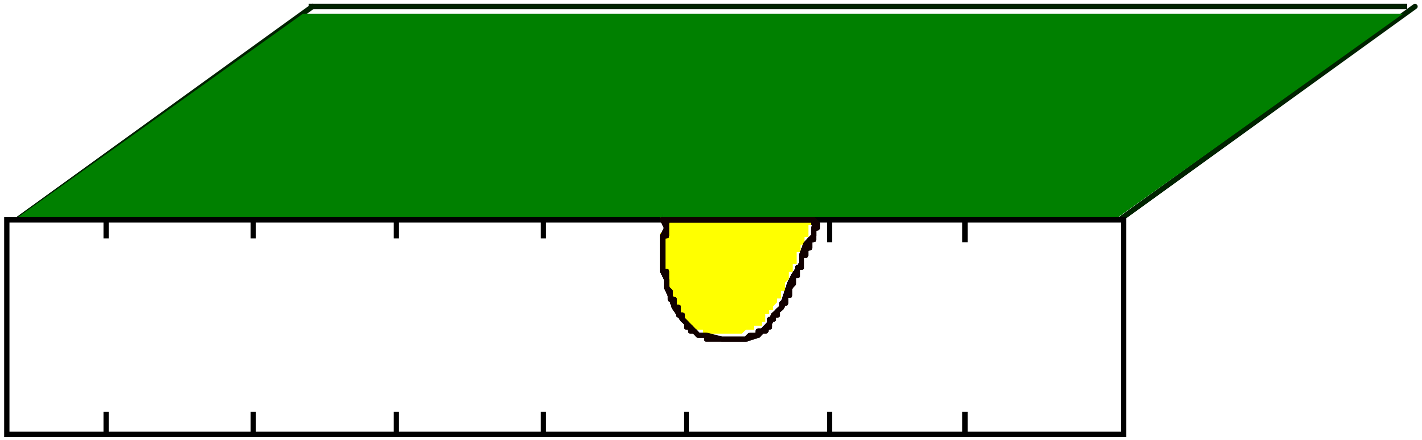
Slip on an earthquake fault
Second 4.0



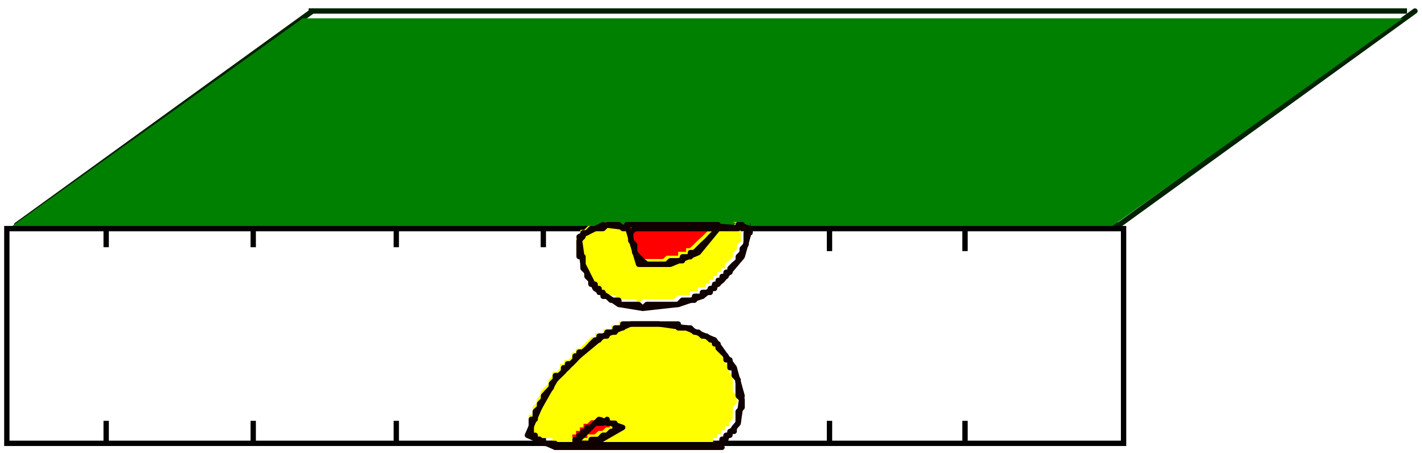
Slip on an earthquake fault
Second 6.0



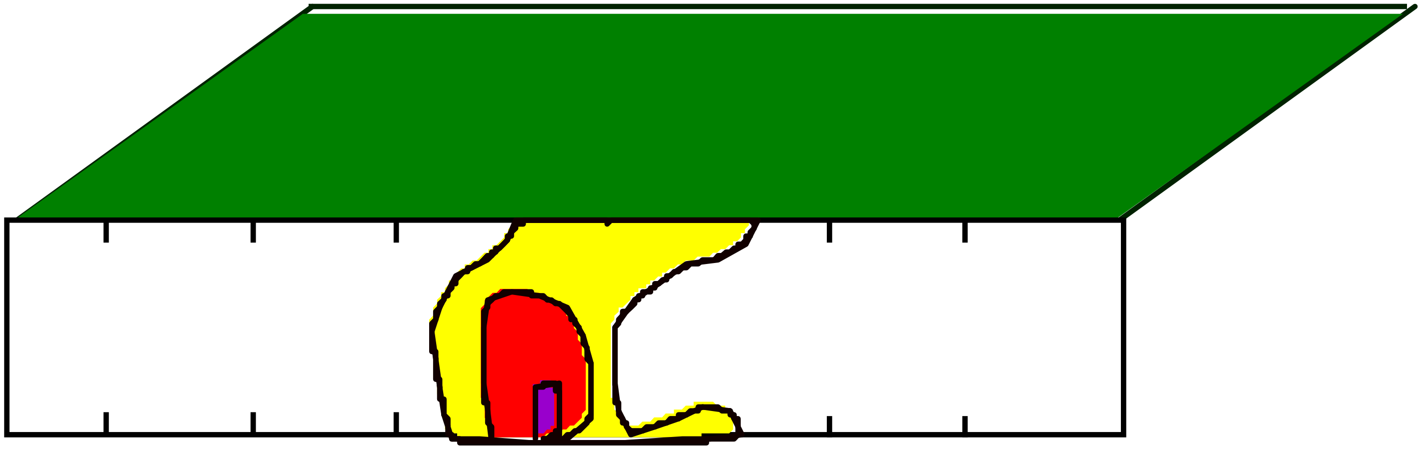
Slip on an earthquake fault
Second 8.0



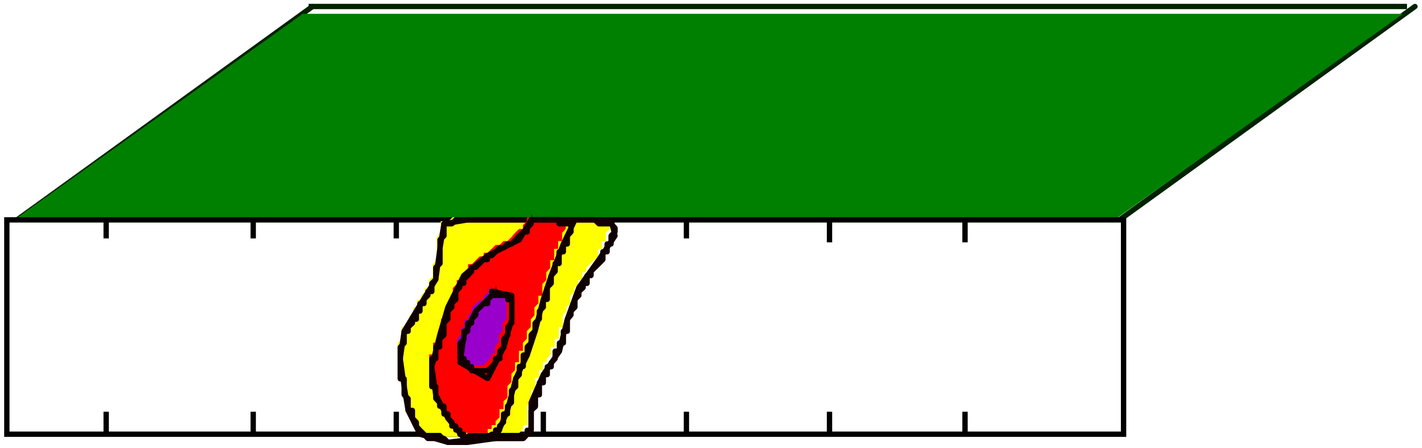
Slip on an earthquake fault
Second 10.0



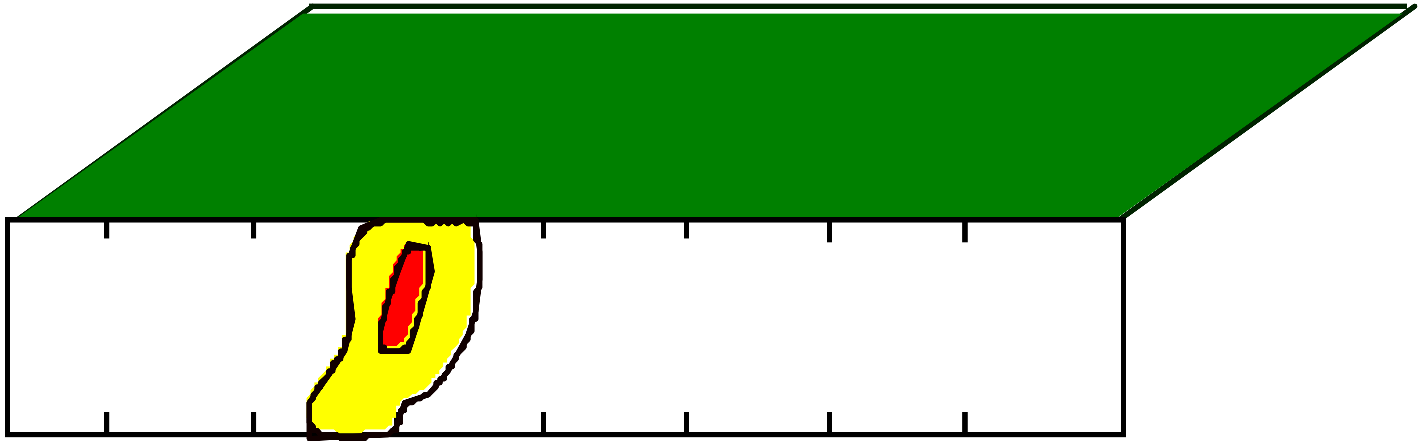
Slip on an earthquake fault
Second 12.0



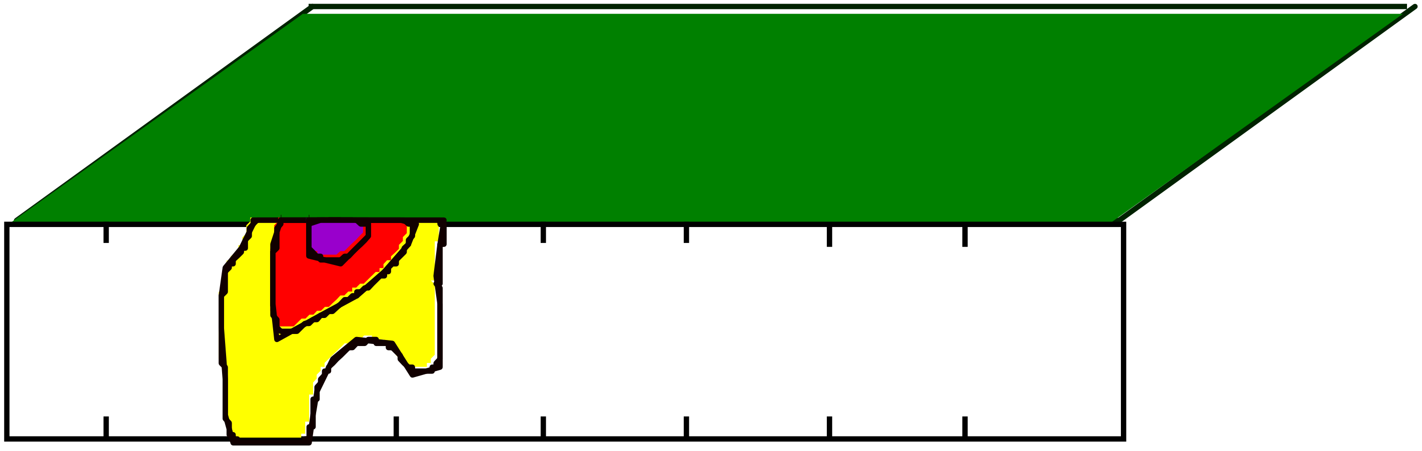
Slip on an earthquake fault
Second 14.0



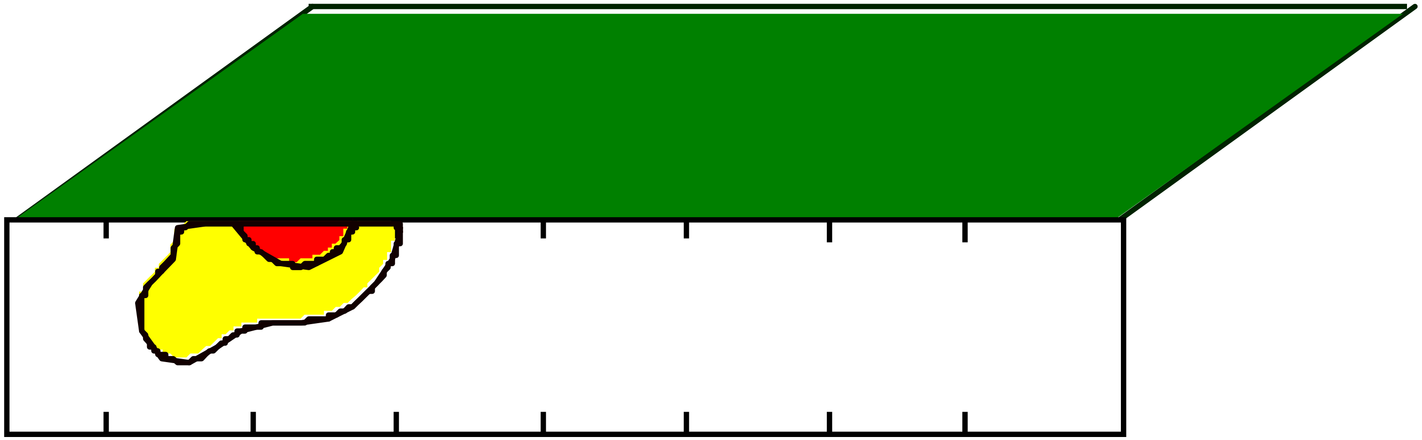
Slip on an earthquake fault
Second 16.0



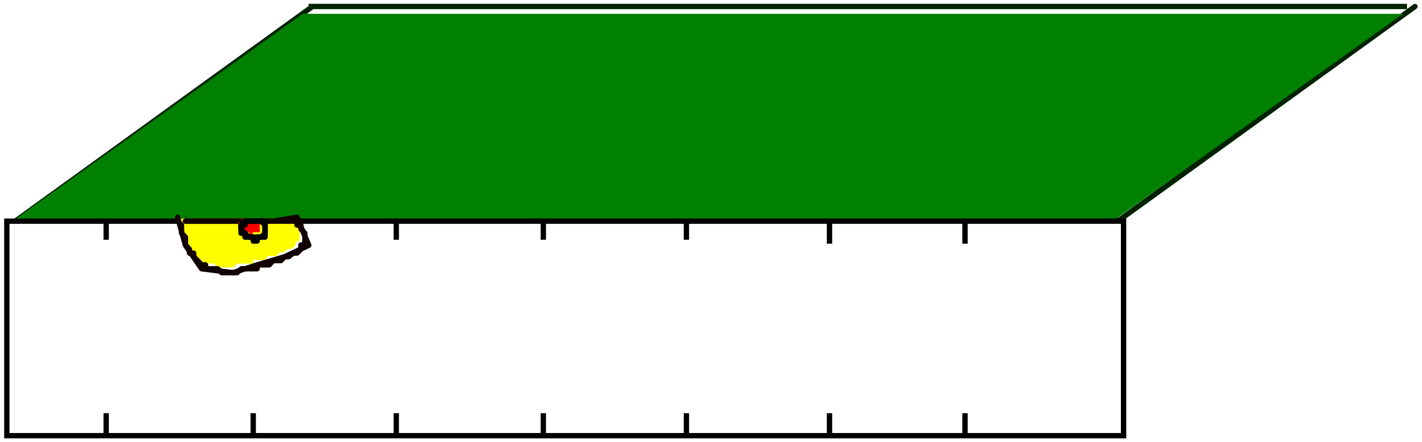
Slip on an earthquake fault
Second 18.0



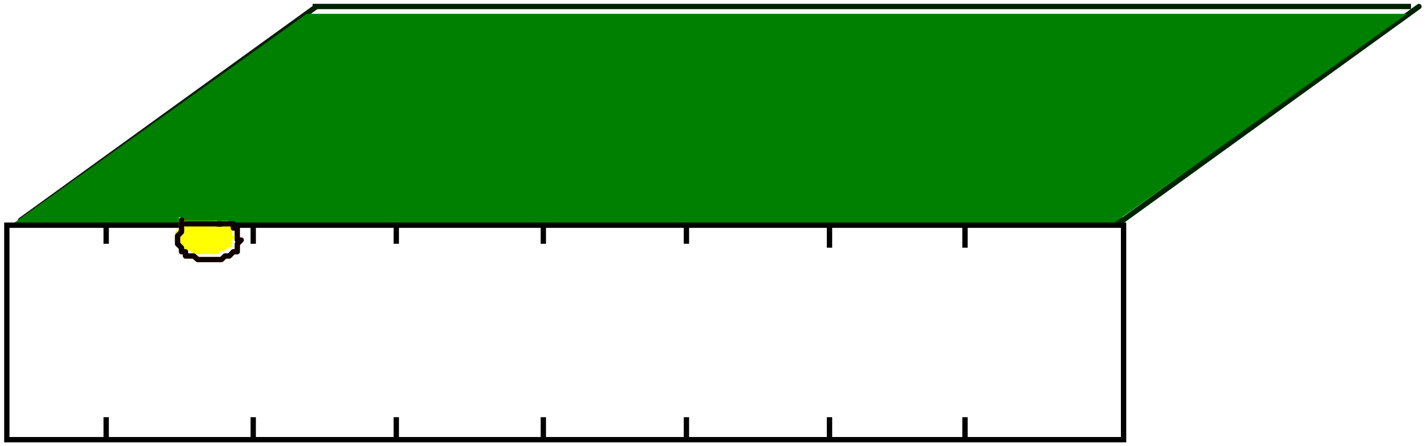
Slip on an earthquake fault
Second 20.0

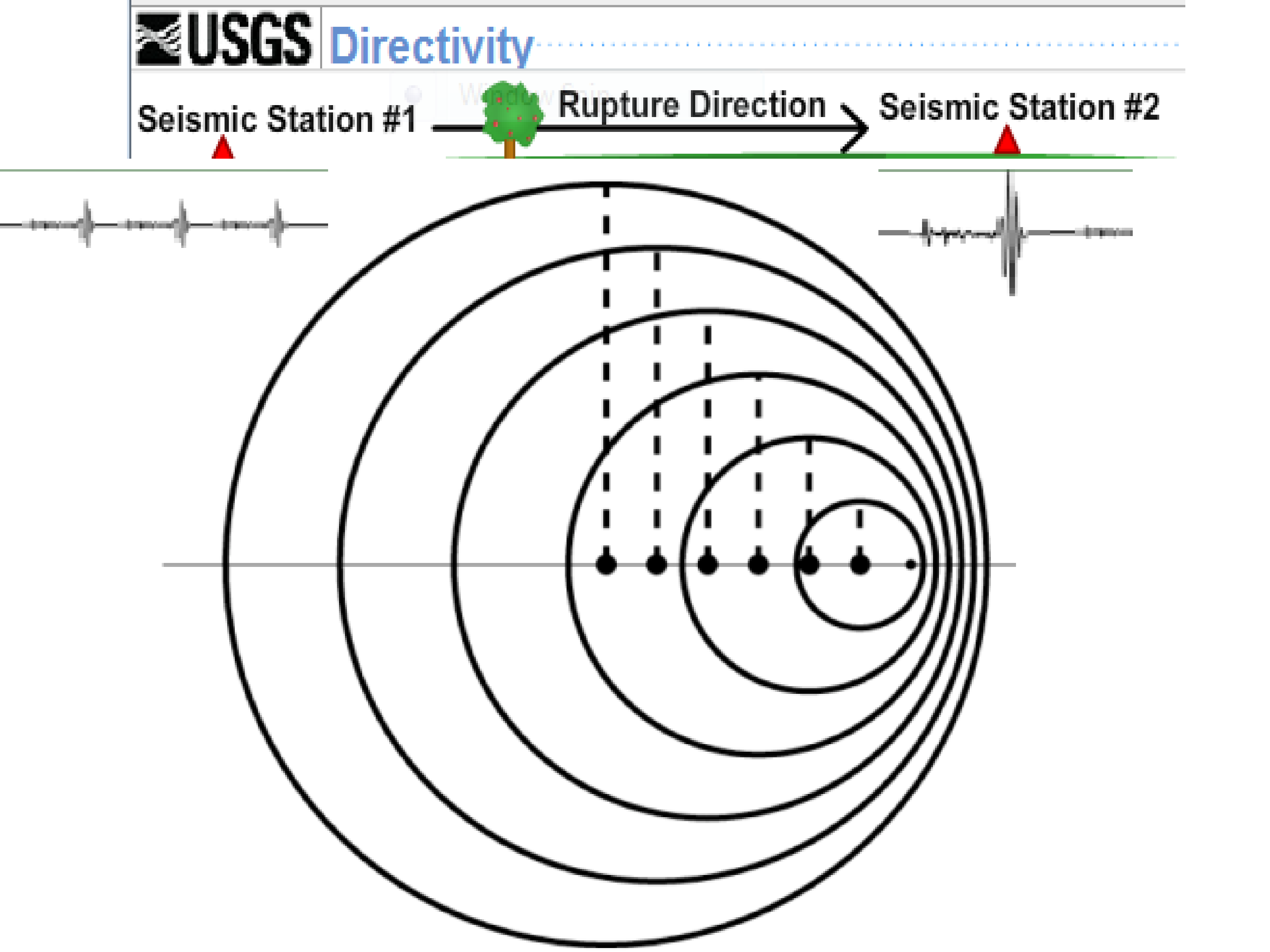


Slip on an earthquake fault
Second 22.0

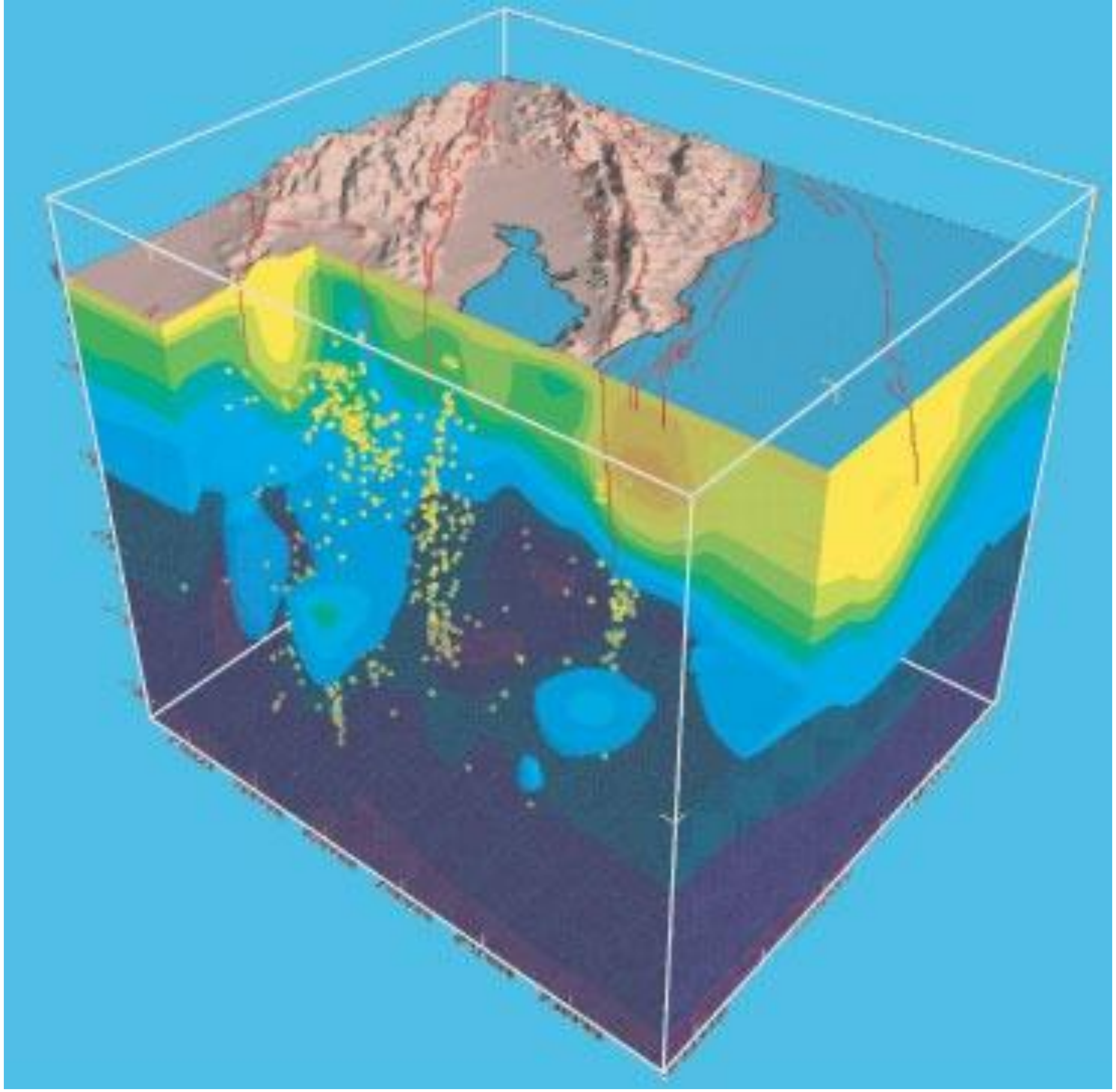


Slip on an earthquake fault
Second 24.0




USGS
Directivity
Seismic Station #1
Rupture Direction
Seismic Station #2

U.S. Geological Survey
Professional Paper 1658
Crustal Structure of the Coastal and MarineSan Francisco Bay Region, California
Tom Parsons, Editor



http://geopubs.wr.usgs.gov/prof-paper/pp1658/

Upper-crustal seismic velocity structure of the San Francisco Bay region, as determined from local-earthquake and controlled-source traveltimes. Red lines denote surface fault traces. Lateral changes in seismic velocity correlate with faults at depth that result from different rock units offset by faults. Yellow spheres show locations of some of the earthquake hypocenters uses in analysis. View southeastward.

Development of a Fault Rupture Model

Magnitude 9.1 OFF THE WEST COAST OF NORTHERN SUMATRA
Sunday, December 26, 2004 at 00:58:53 UTC

Preliminary Rupture Model
Contributed by Chen Ji, Caltech

DATA Process and Inversion

We used the GSN broadband data downloaded from the IRIS DMC. We analyzed 15 teleseismic P waveforms and 13 SH waveforms selected based upon data quality and azimuthal distribution. Waveforms are first converted to displacemen by removing the instrument response and then are used to constrain the slip history based on a finite fault inverse algorithm (Ji et al, 2002). We use the hypocenter from the USGS (Lon.=95.78 deg.; Lat.=3.30 deg.). The fault planes are defined by slightly modifying the quick moment tensor solution from HARVARD (strike=320 deg. and dip =11 deg.)

Result

The seismic moment release on this plane is 3.57x10**29 dyne.cm using a 1D crustal model interpolated from CRUST2.0 (Bassin et al., 2000). The total rupture duration is 200 sec and the peak slip is about 20 m. The rupture propagates northwestward for nearly 400 km with a speed of 2.0 km/sec.

http://neic.usgs.gov/neis/eq_depot/2004/eq_041226/neic_slav_ff.html

Comparison of data and synthetic seismograms

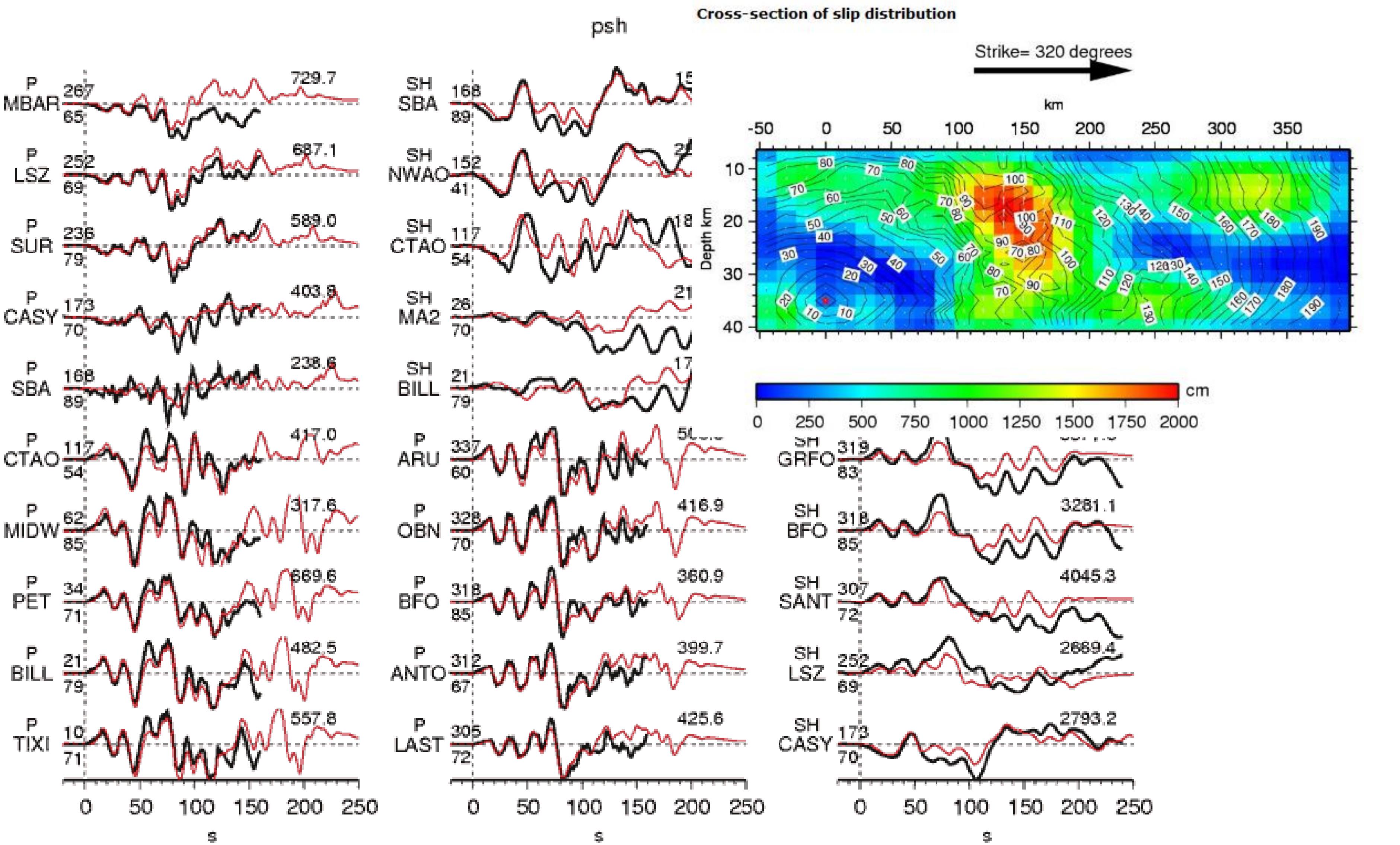


Figure: The data are shown in black and the synthetic seismograms are plotted in red. Both data and synthetic seismograms are aligned on the P or SH arrivals. The number at the end of each trace is the peak amplitude of the observation in micrometers. The number above the beginning of each trace is the source azimuth and below it is the epicentral distance.

http://neic.usgs.gov/neis/eq_depot/2004/eq_041226/neic_slav_ff.html

Cross-section of slip distribution

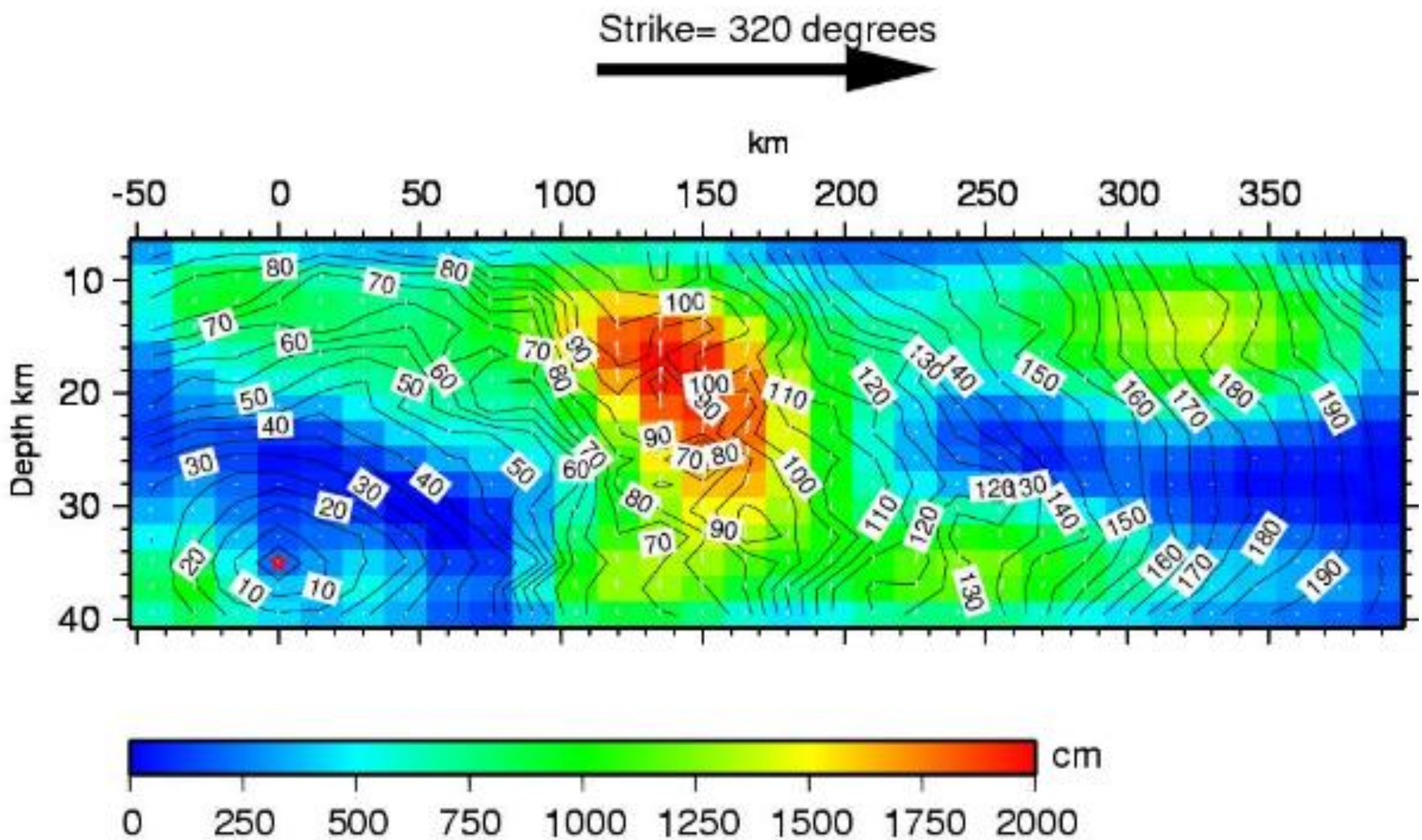


Figure: The big black arrow shows the fault's strike. The colors show the slip amplitude and white arrows indicate the direction of motion of the hanging wall relative to the footwall. Contours show the rupture initiation time and the red star indicates the hypocenter location.

http://neic.usgs.gov/neis/eq_depot/2004/eq_041226/neic_slav_ff.html

http://neic.usgs.gov/neis/eq_depot/2004/eq_041226/neic_slav_ff.html

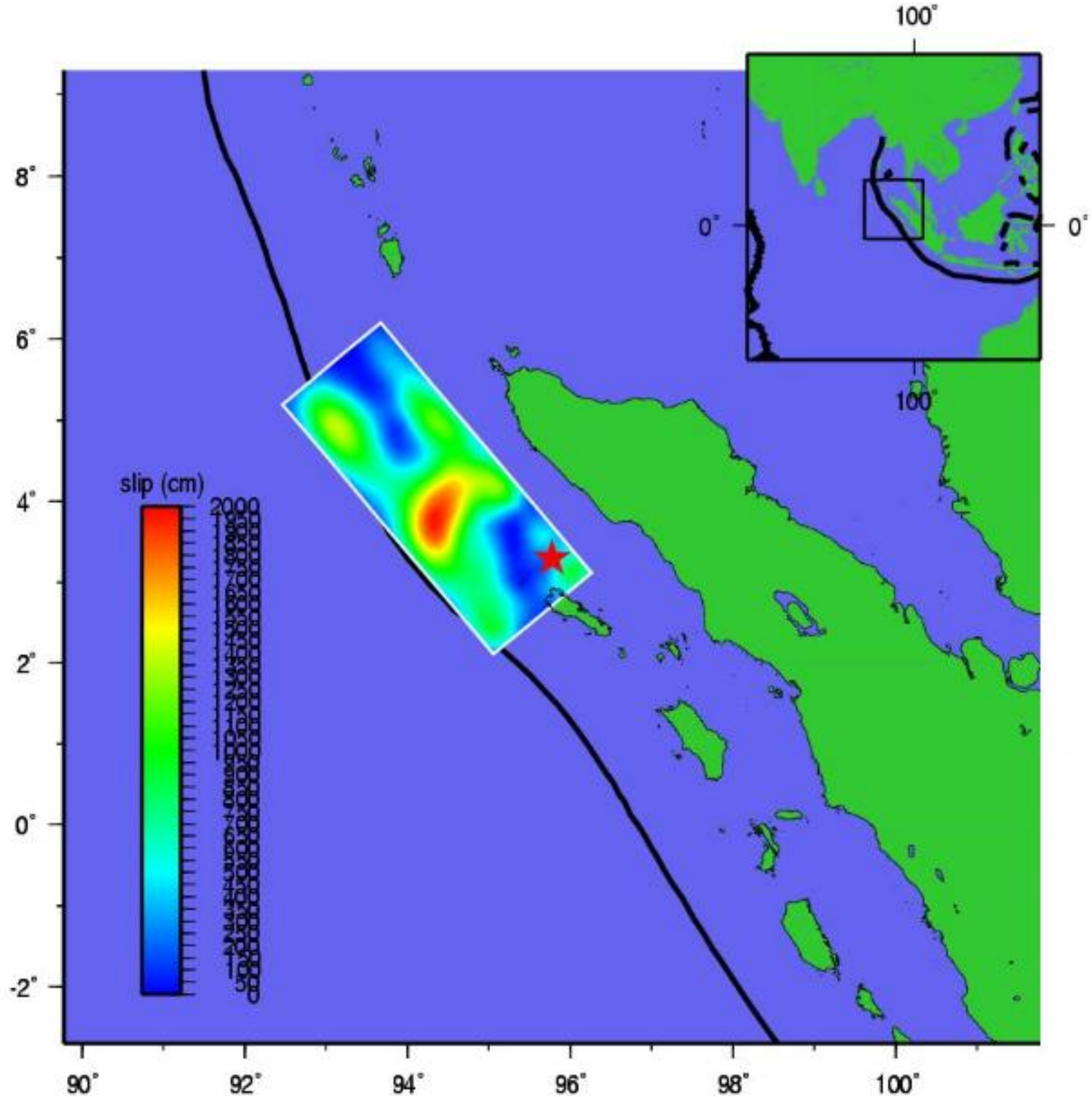


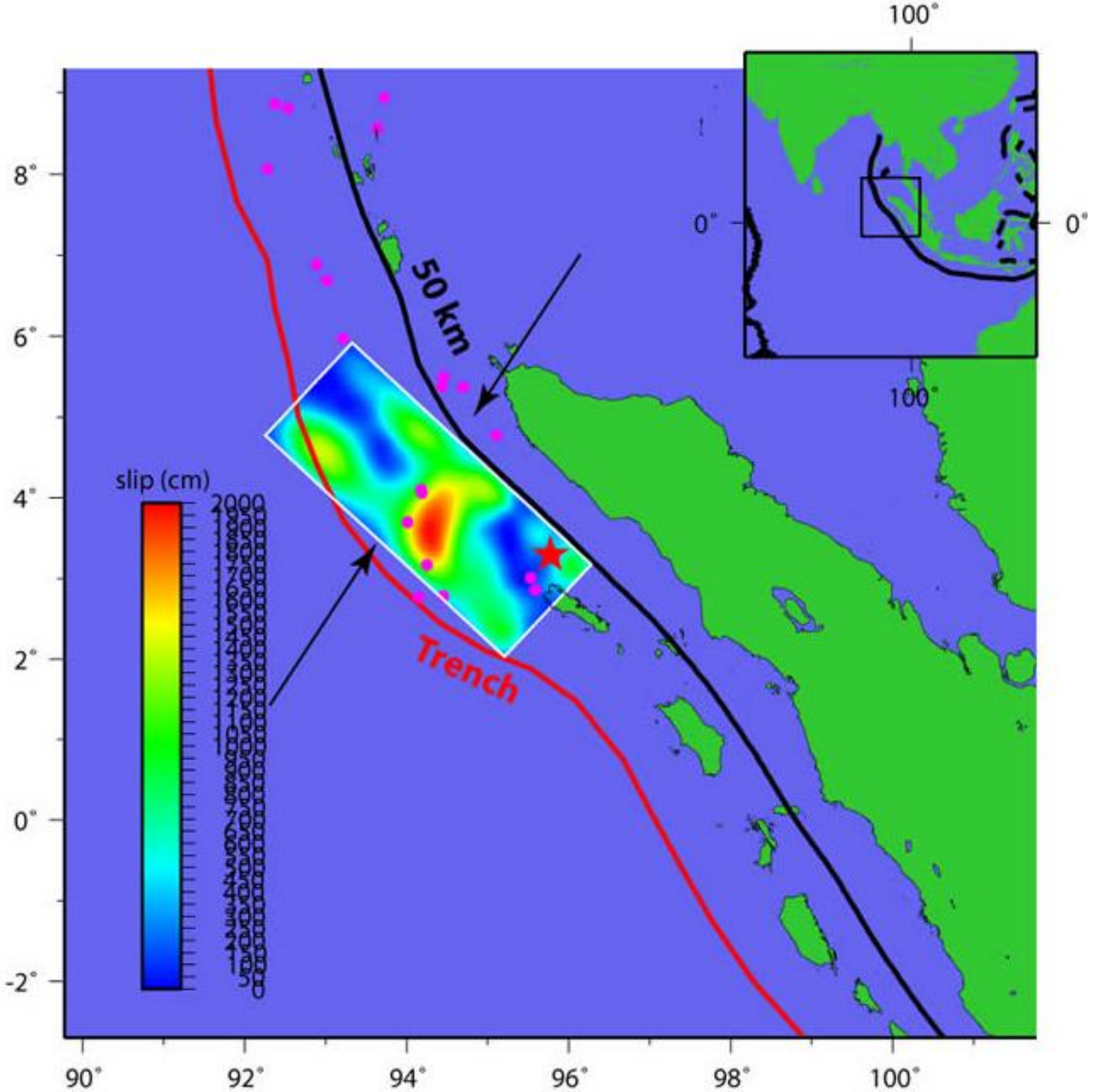
Figure: Surface projection of the slip distribution. The ocean is plotted in blue and land is plotted in green. The black line indicates the plate boundary (data from Dr. Lisa Gahagan, Paleo-Oceanographic Mapping Project at University of Texas at Austin).

CJ's Comments:

It is noteworthy that the seismic data we used only could constrain the slip in first 220 sec. Hence, we can not totally rule out later, smaller slip if it occurred further north.

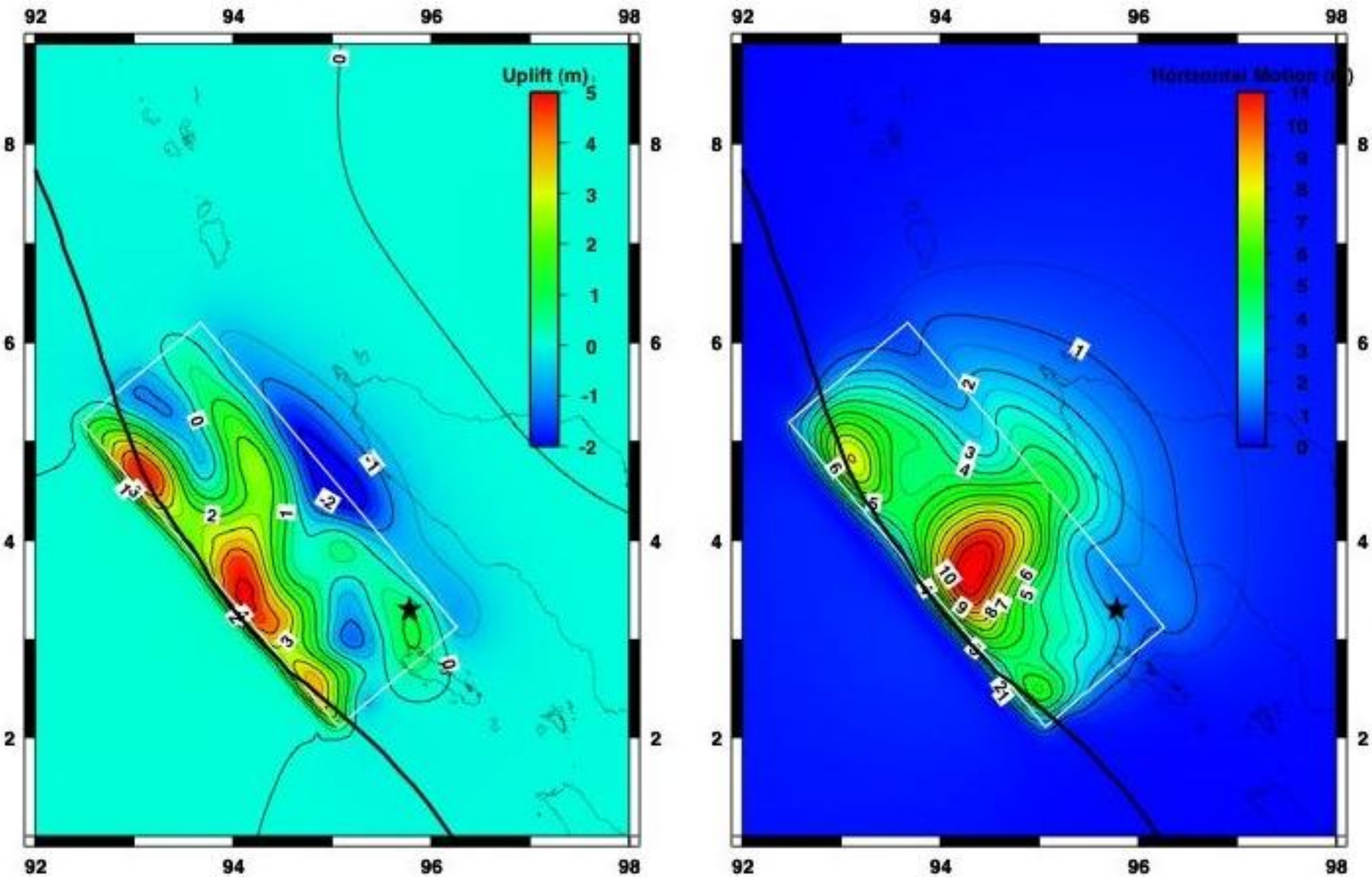
We notice that the location of the biggest asperity correlates well with a nearly 30 degree bend of the subducted India plate. In the figure shown below, we let the fault plane rotate 7 deg. counterclockwise to match the 0 and 50 km isodepth contours of Gundmundsson and Sambridge (1998). It is clear that the northern boundary of the biggest asperity is along the hinge line of the slab (indicated by arrows). The pink circles are big aftershocks (>5) downloaded from the NEIC. Five of them locate at the north boundary as well. The large slip associating with the bend of the fault plane is a common feature, e.g., 1999 Chi-Chi earthquake (Ji et al., 2003, JGR).

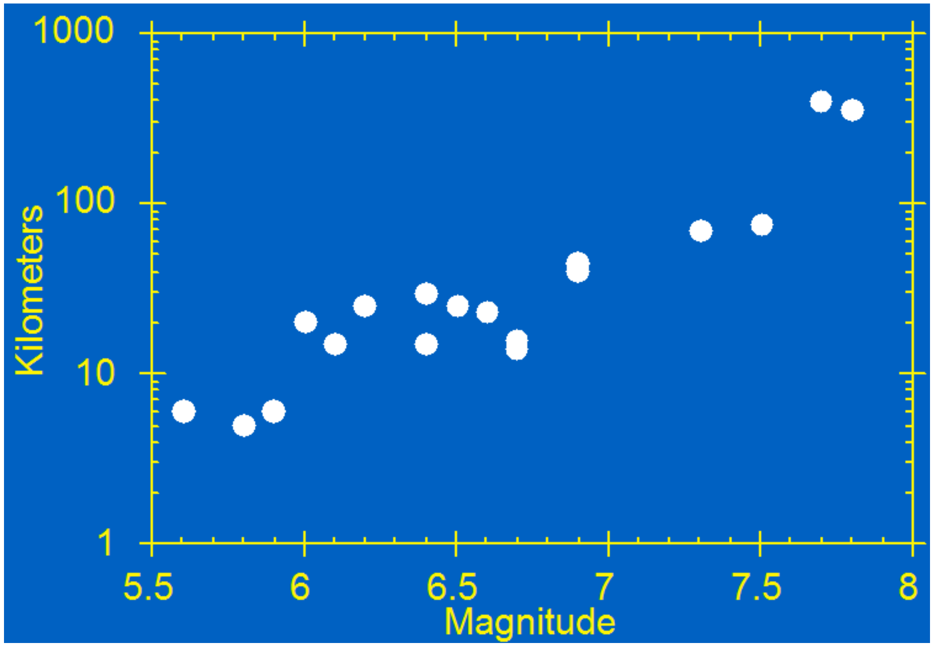
This result also suggests that we need use at least two fault segments with different strikes to model the rupture of this event. We are currently working on such a model and we will provide an update as it becomes available.

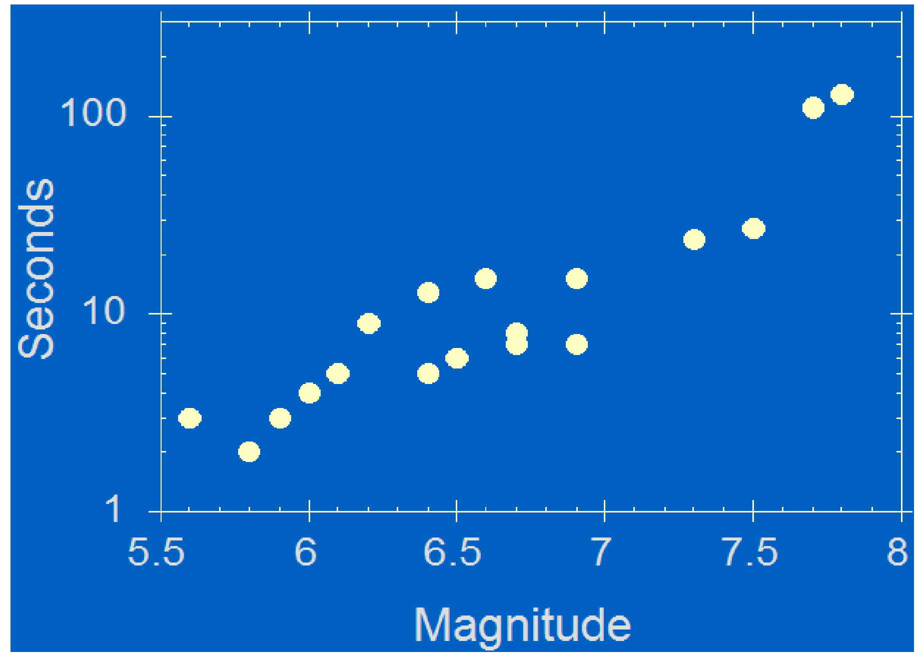


100°
8°
6°
4°
2°
0°
-2°
50 km
Trench
slip (cm)
2000
0
90°
92°
94°
96°
98°
100°

(below) Predicted static surface displacements (in meters) for vertical (left) and horizontal (right) components of motion. Based on the single-place finite fault source model shown.







Bigger Faults make Bigger Earthquakes

Bigger Earthquakes last a longer time

Lisa Wald, (USGS)

Representative Fault Rupture Scenario

U.S. Geological Survey
Fact Sheet 014-03

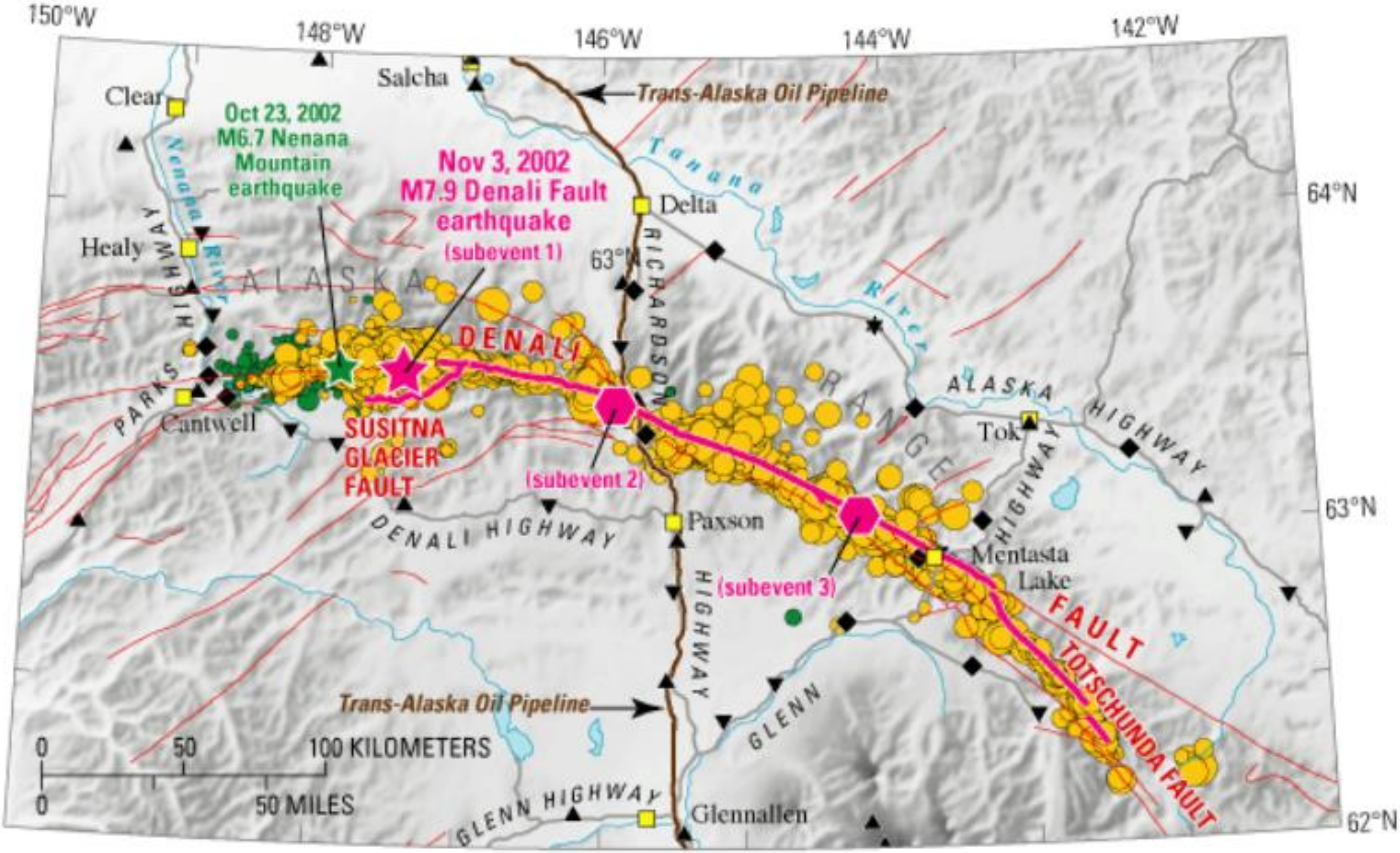
Rupture in South-Central Alaska—The Denali Fault Earthquake of 2002

A powerful magnitude 7.9 earthquake struck Alaska on November 3, 2002, rupturing the Earth's surface for 209 miles along the Susitna Glacier, Denali, and Totschunda Faults. Striking a sparsely populated region, it caused thousands of landslides but little structural damage and no deaths. Although the Denali Fault shifted about 14 feet beneath the Trans-Alaska Oil Pipeline, the pipeline did not break, averting a major economic and environmental disaster. This was largely the result of stringent design specifications based on geologic studies done by the U.S. Geological Survey (USGS) and others 30 years earlier. Studies of the Denali Fault and the 2002 earthquake will provide information vital to reducing losses in future earthquakes in Alaska, California, and elsewhere.

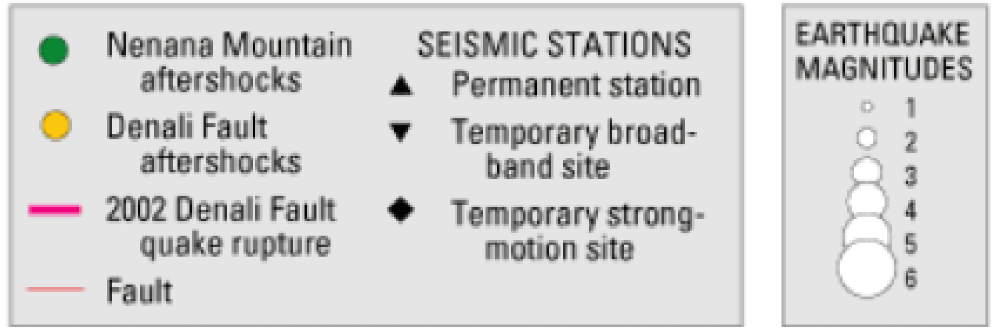
Shortly after midday on November 3, 2002, a magnitude 7.9 earthquake ruptured the Denali Fault in the rugged Alaska Range, about 90 miles south of Fairbanks. Called the Denali Fault earthquake, this shock was the strongest ever recorded in the interior of Alaska. Although comparable in size and type to the quake that devastated San Francisco in 1906, the Denali

http://pubs.usgs.gov/fs/2003/fs014-03/

Fault earthquake caused no deaths and little damage to structures because it struck a sparsely populated region of south-central Alaska.



http://pubs.usgs.gov/fs/2003/fs014-03/



The November 3, 2002, magnitude (M) 7.9 Denali Fault earthquake was the strongest ever recorded in the interior of Alaska. Like most earthquakes of its size, it was complex, consisting of several subevents. It started with thrust (upward) motion on a previously unknown fault, now called the Susitna Glacier Fault. This rupture continued on the Denali Fault, where largely horizontal "right-lateral" movement (in which the opposite side moves to the right, when you look across the fault) propagated eastward at more than 7,000 miles per hour. As the rupture propagated, it offset streams, glacial ice, frozen soil, and rock, opening some cracks so wide that they could engulf a bus. The rupture crossed beneath the Trans-Alaska Oil Pipeline and terminated on the Totschunda Fault, 184 miles east of the epicenter, about 90 seconds after the quake began. The maximum horizontal movement (fault offset) of about 29 feet occurred in the eastern part of the rupture, near subevent 3.

http://pubs.usgs.gov/fs/2003/fs014-03/

This powerful shock may have been triggered by a magnitude 6.7 temblor, the Nenana Mountain earthquake, that occurred nearby on the same fault 10 days earlier. Like the Denali Fault quake, the Nenana Mountain shock caused only limited damage because of its remote location. In contrast, the 1994 Northridge, California, earthquake, which had the same magnitude, caused 67 deaths and $40 billion in damage when it struck the densely populated Los Angeles region.

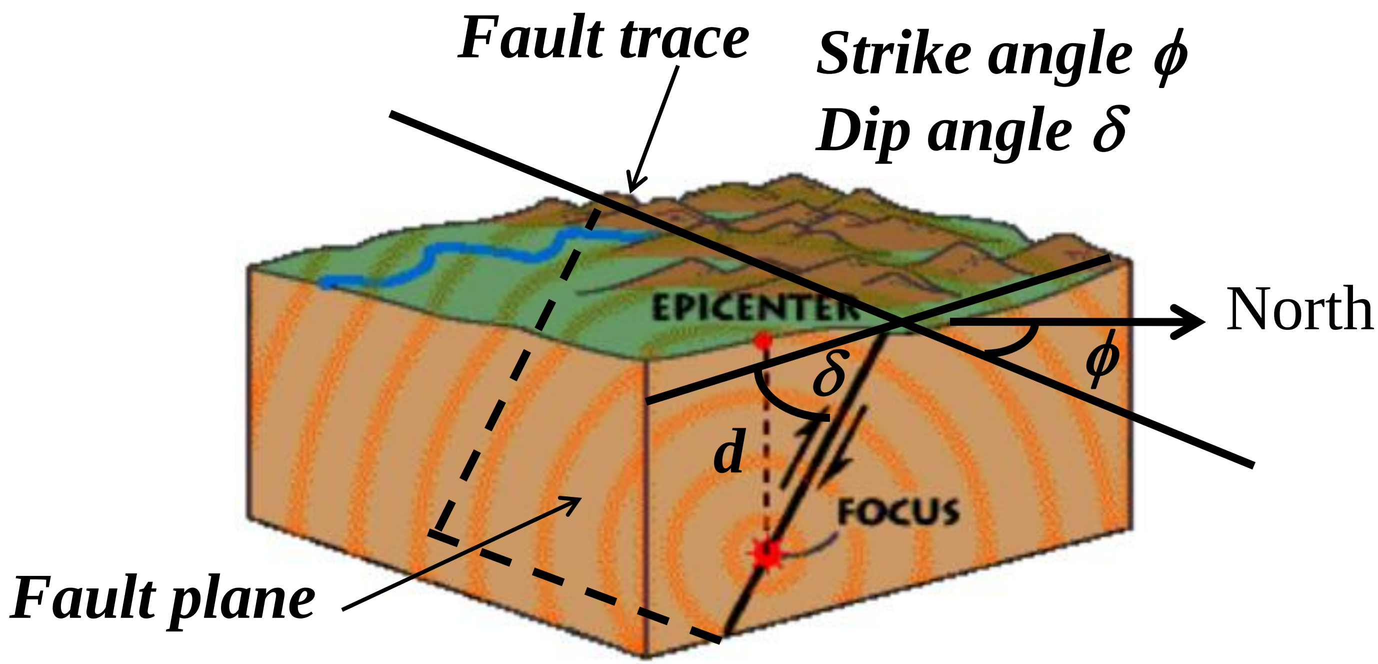
Effects of the Denali Fault Quake

The Denali Fault earthquake ruptured the Earth's surface for 209 miles, crossing beneath the vital Trans-Alaska Oil Pipeline, which carries 17% of the U.S. domestic oil supply. Although slightly damaged by movement on the fault and by intense shaking, the pipeline did not break in the quake, averting a major economic and environmental disaster. This success is a major achievement in U.S. efforts to reduce earthquake losses.

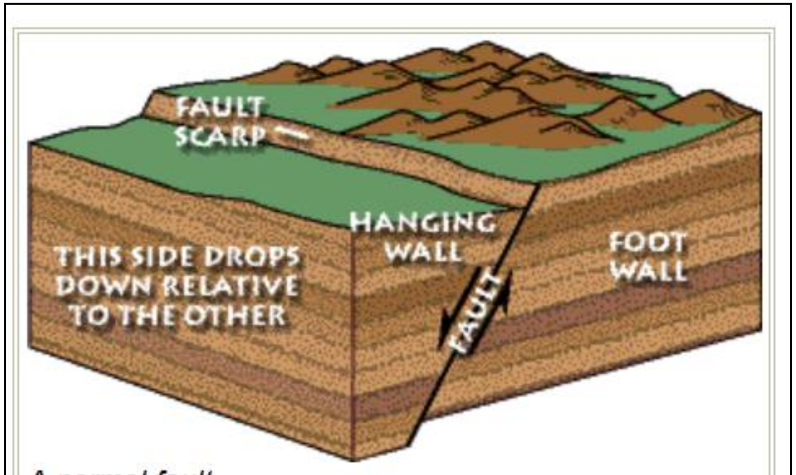
Violent, prolonged shaking from the quake triggered thousands of landslides, especially on the steep slopes of the Alaska Range. Mountainsides gave way, burying the valleys and glaciers below in deposits of rock and ice as much as 15 feet thick. The majority of landslides clustered in a narrow band extending about 8 to 12 miles on either side of the rupture.
One facility that was badly damaged by the earthquake was the runway at Northway Airport, 40 miles from the eastern part of the November 3, 2002, fault rupture. The runway was

http://pubs.usgs.gov/fs/2003/fs014-03/

Fault Rupture Terminology



Focus is also known as Hypocenter



A normal fault.

Modified after:
http://geomaps.wr.usgs.gov/parks/deform/geqepifoc1.html

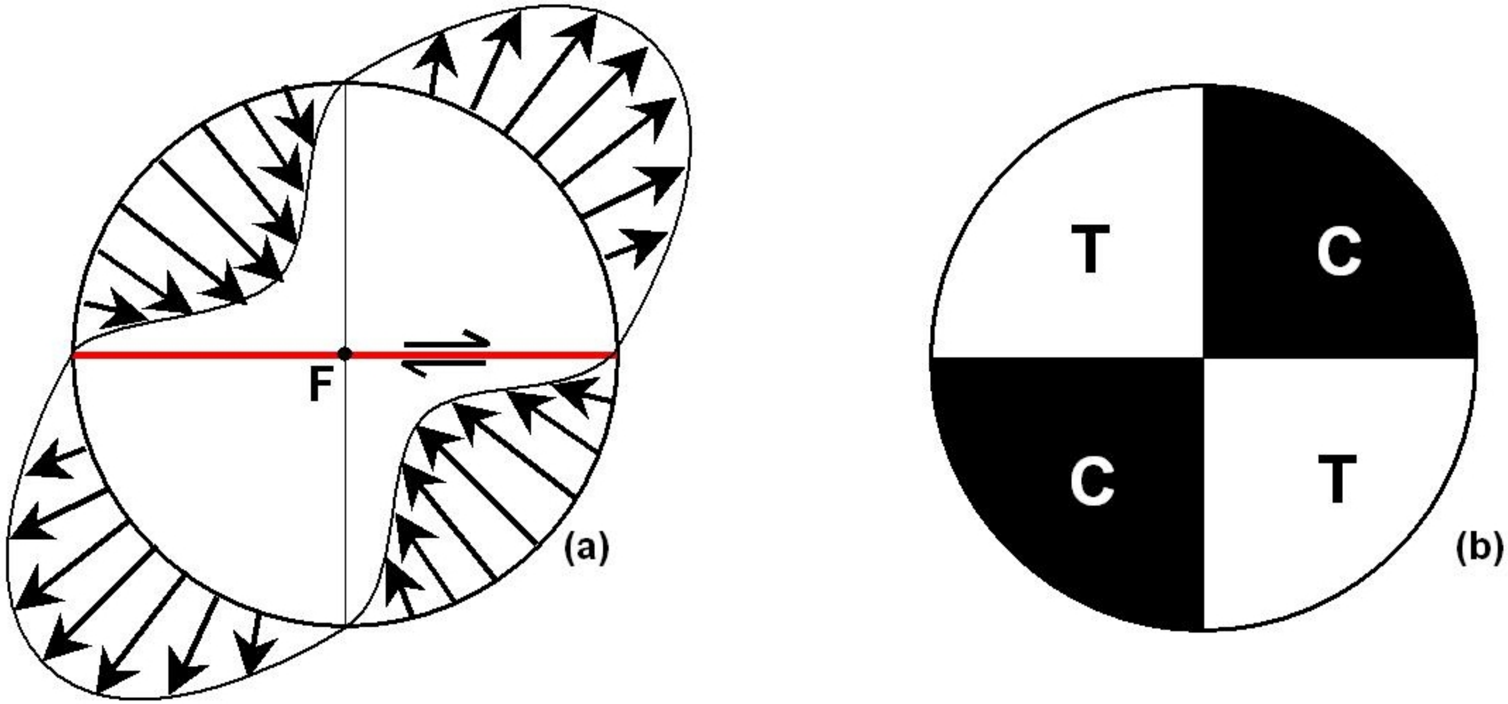
http://geomaps.wr.usgs.gov/parks/deform/gnormal.html

In many earthquakes, d is in the range of a few kilometers but it can be hundreds of kilometers in some regions (e.g. Japan sea) associated with a deep ocean trench. Few earthquakes occur below 200 km.

Arbitrarily, d classifies earthquakes as:
300 km < d deep focus earthquakes
70 km < d < 300 km intermediate focus earthquakes
d < 70 km shallow focus earthquakes

Shallow focus earthquakes cause most devastation in California, usually within the upper 10 km with few as deep as 15 km or so (e.g. the 1989 Loma Prieta earthquake occurred at depth 15 – 18 km, which is unusually deep for California earthquakes).

Focal Mechanism Introduction)



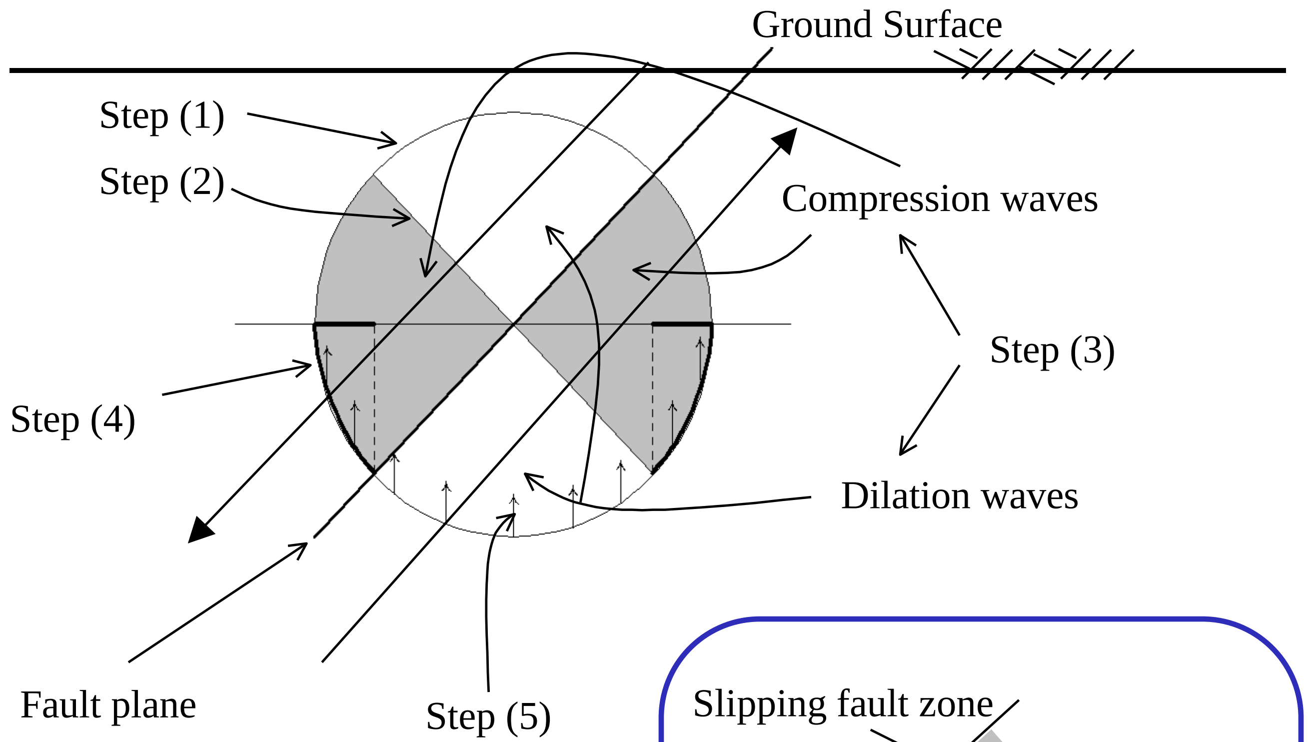
Schematic diagram showing the direction of initial movement of particles around the focus (F) of an earthquake on a W-E dextral strike-slip fault, viewed from above (a) and the equivalent zones of compressional (C) and tensional (T) sense first motion in the seismic waves radiating outward (b).

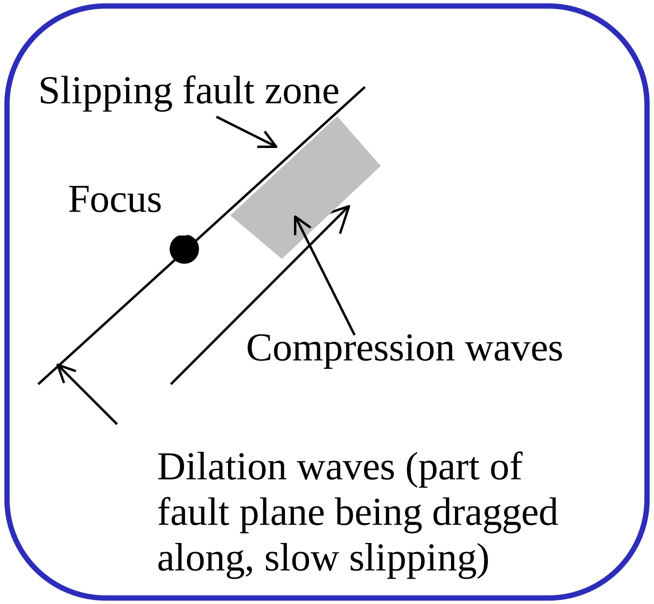
Note that due to the symmetry, an identical pattern would result from movement on an N-S sinistral strike-slip fault passing through the focus

http://en.wikipedia.org/wiki/File:Focal_mechanism_01.jpg#file

Note: Please see useful reference at: http://www.learninggeoscience.net/free/00071/index.html

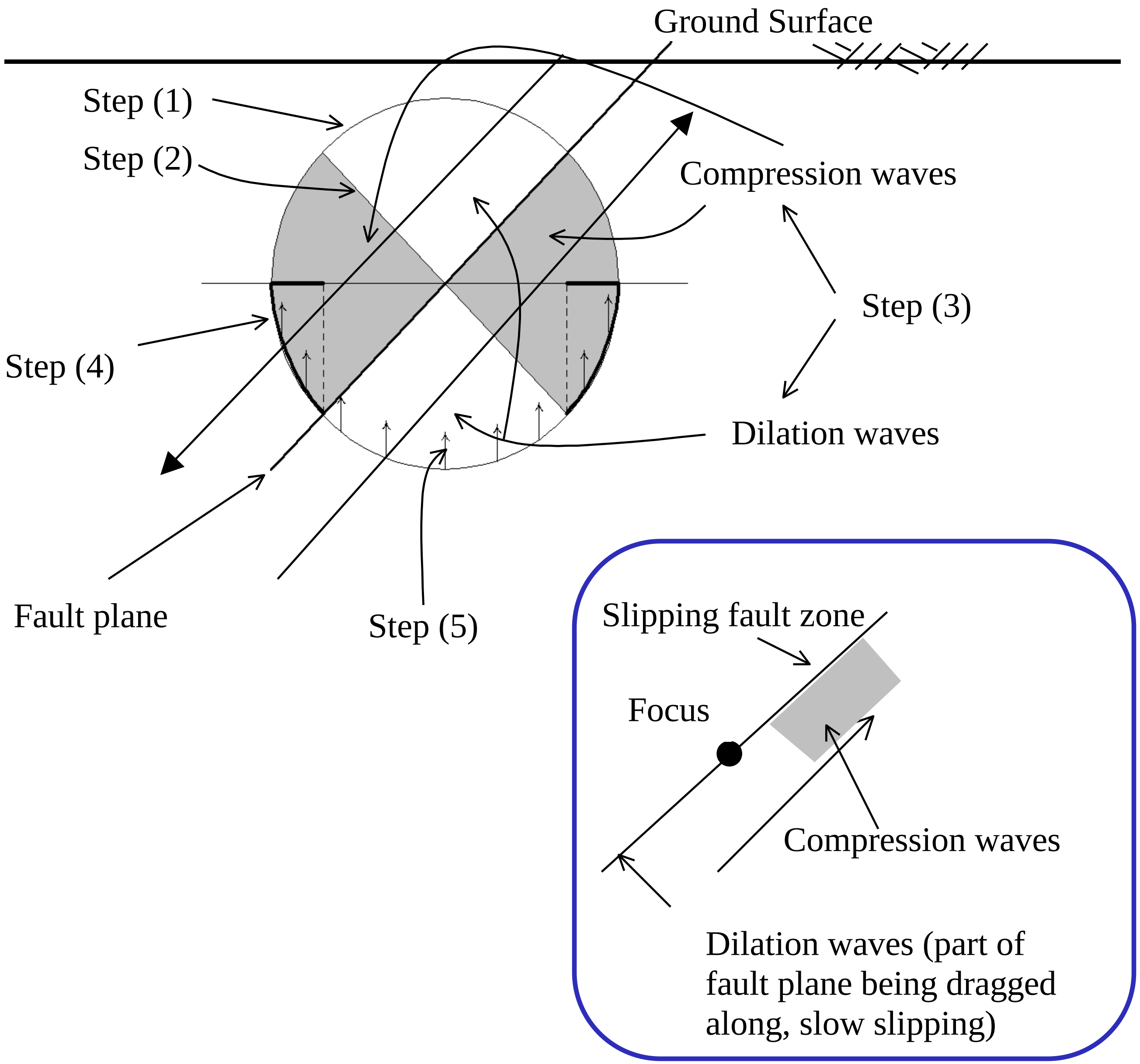
Focal Mechanism (5-steps)





Focal solution

Ahmed Elgamal



Step (1): Draw sphere with fault plane as a central circle.

Step (2): draw plane perpendicular to fault plane and direction of slip going through center of sphere.

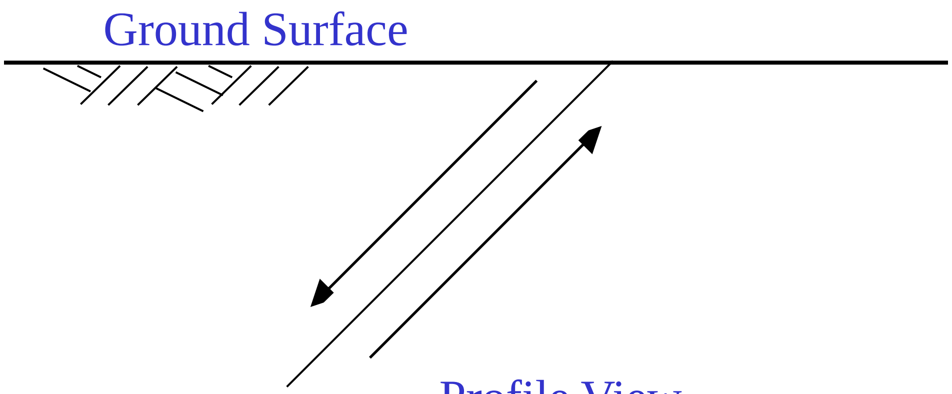
Step (3): Define the zones in compression and in dilation (slip arrow heads define compression and tails define dilation).

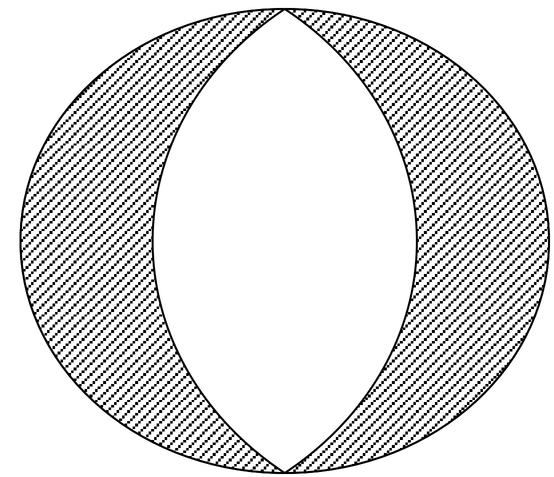
Step (4): Darken the zone in compression within the lower hemi-sphere surface.

Step (5): Project the lower semi-sphere surface on to the central horizontal circle (what you get is the focal solution.

In the case discussed above, the projection (Focal solution) is (see below):

Normal Fault



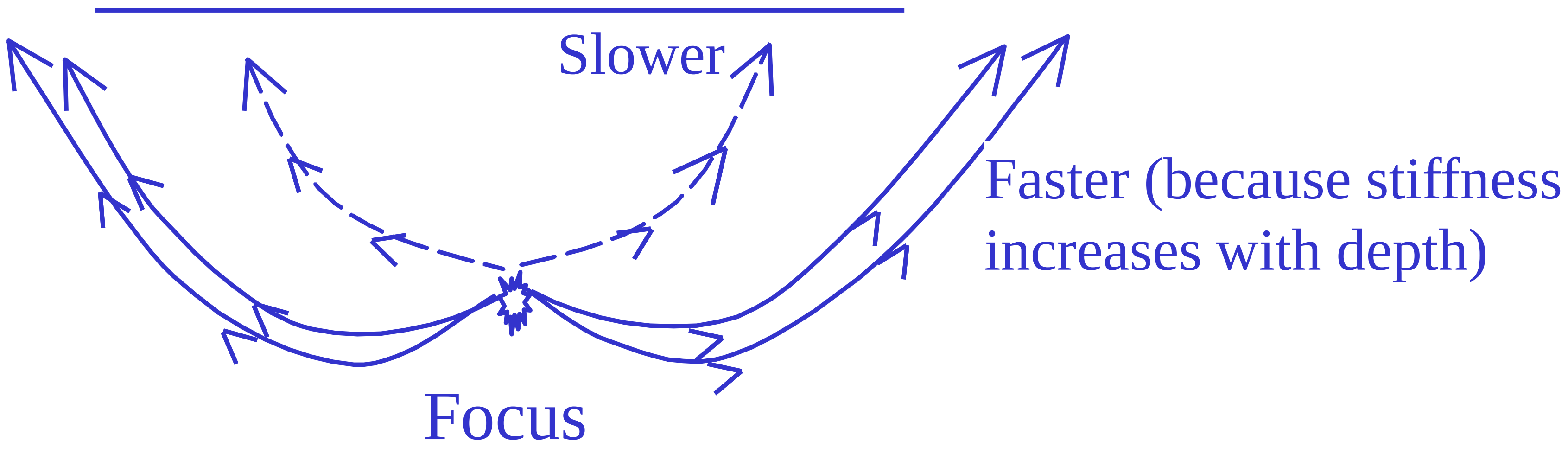


Additional information (e.g., fault plane surface trace or other) will be needed to distinguish which of the two arcs corresponds to the fault plane (see homework problem).

Notes:

1) The compression-dilation zones are actually inferred from the waves going through the lower hemisphere and recorded at ground surface in terms of up and down P-wave first arrival pulses (from which we define our focal solution). That means that the Focal solution is determined from observed first P-wave arrival (up pulse/down pulse or tension/compression).

2) Away from the epicenter, these pulses arrive from waves that propagated downwards into the ground and reached the surface first.



3) Often, we look at the lower hemisphere of a small sphere around the source, and mark the compression and tensile zones (where compressive of dilation waves have propagated). In some cases, we look at upper hemisphere (maybe near epicenter).

Focal solution (cont.)

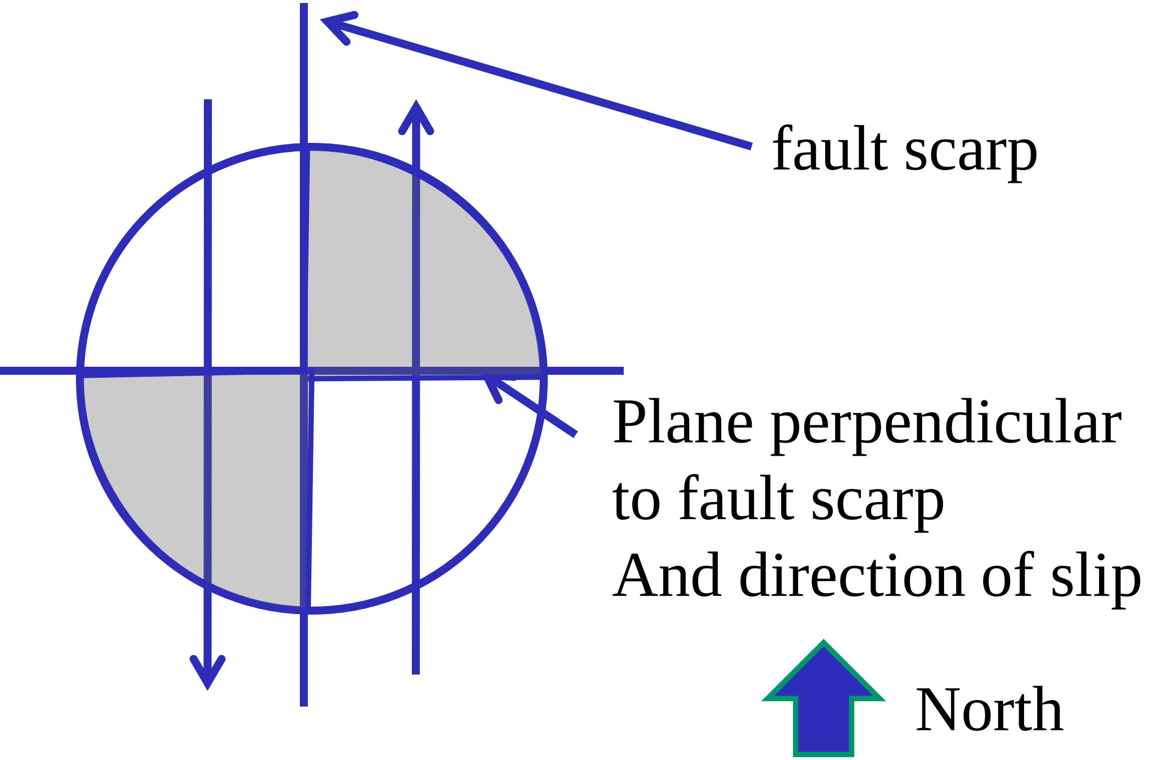
Some Simple cases:

Assume fault dip angle is 90 degrees (vertical fault plane)

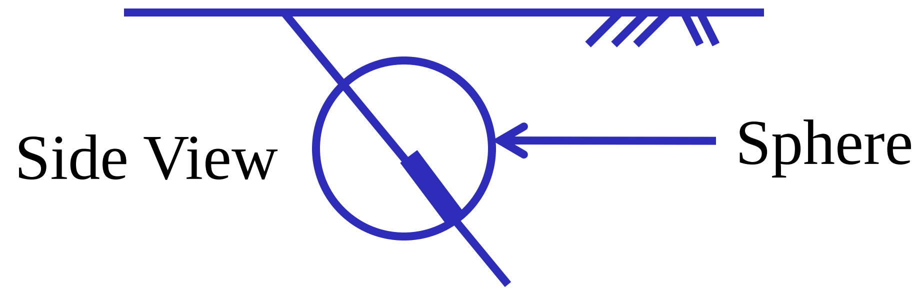
Assume pure strike slip (lateral motion)

Look in Bird's eye view (Plan view) at the fault scarp

Focal solution shows direction of fault displacement

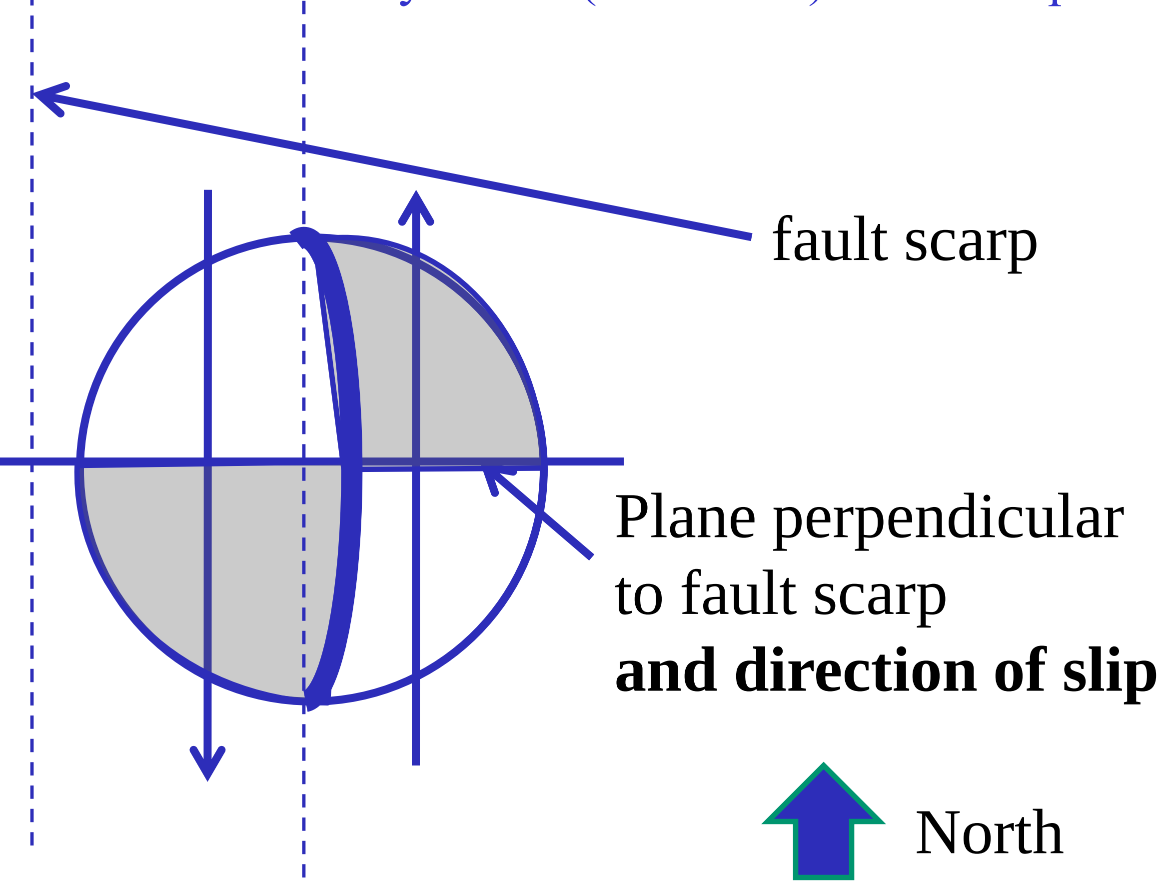


Some Simple cases (cont.):



Assume fault dip angle is 75 degrees (vertical fault plane) and pure strike slip

Look in Bird's eye view (Plan view) at central plane of sphere



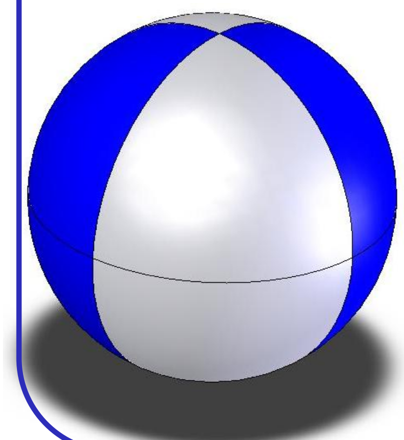
Focal solution (cont.)

Some Simple cases:

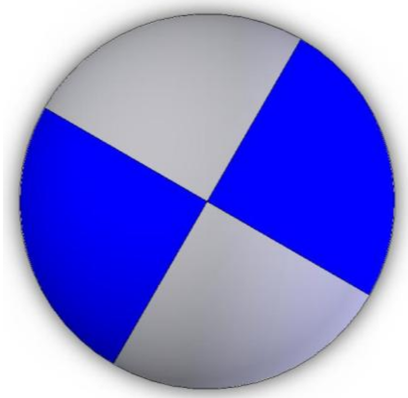
Assume fault dip angle is 90 degrees (vertical fault plane) and pure strike slip

Look in Bird's eye view (Plan view) at the fault scarp

Focal solution shows direction of fault displacement



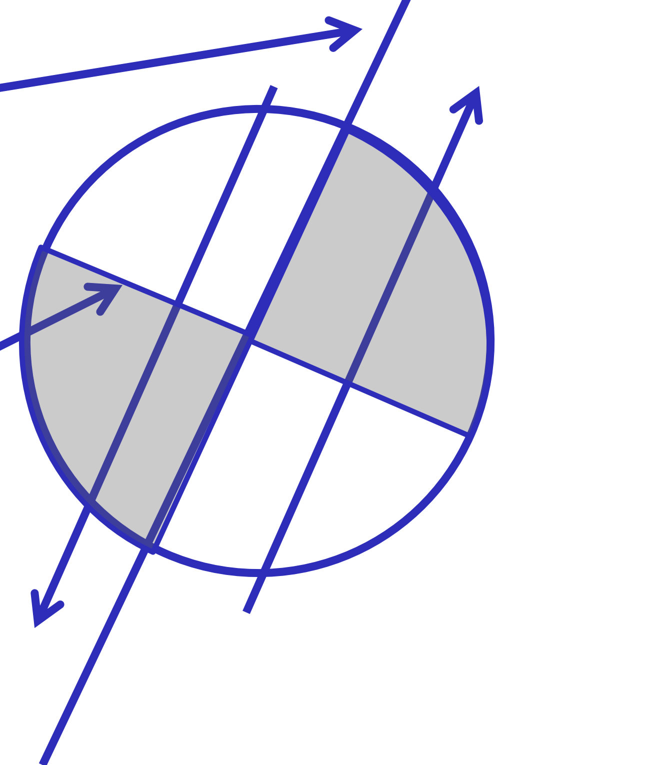
3D view
for
visualization

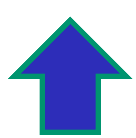


Graphics by Tracey Becker

fault scarp

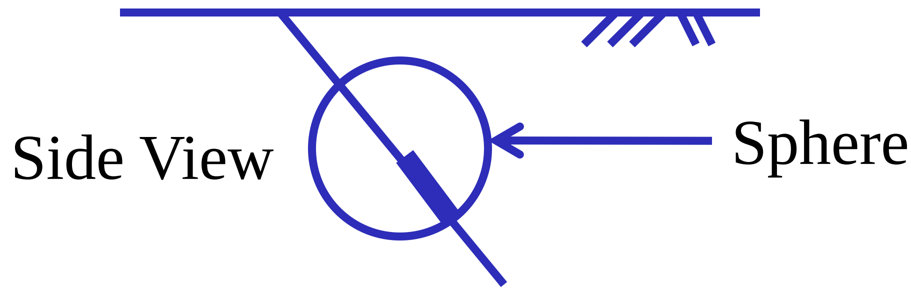
Plane perpendicular
to fault scarp
And direction of slip





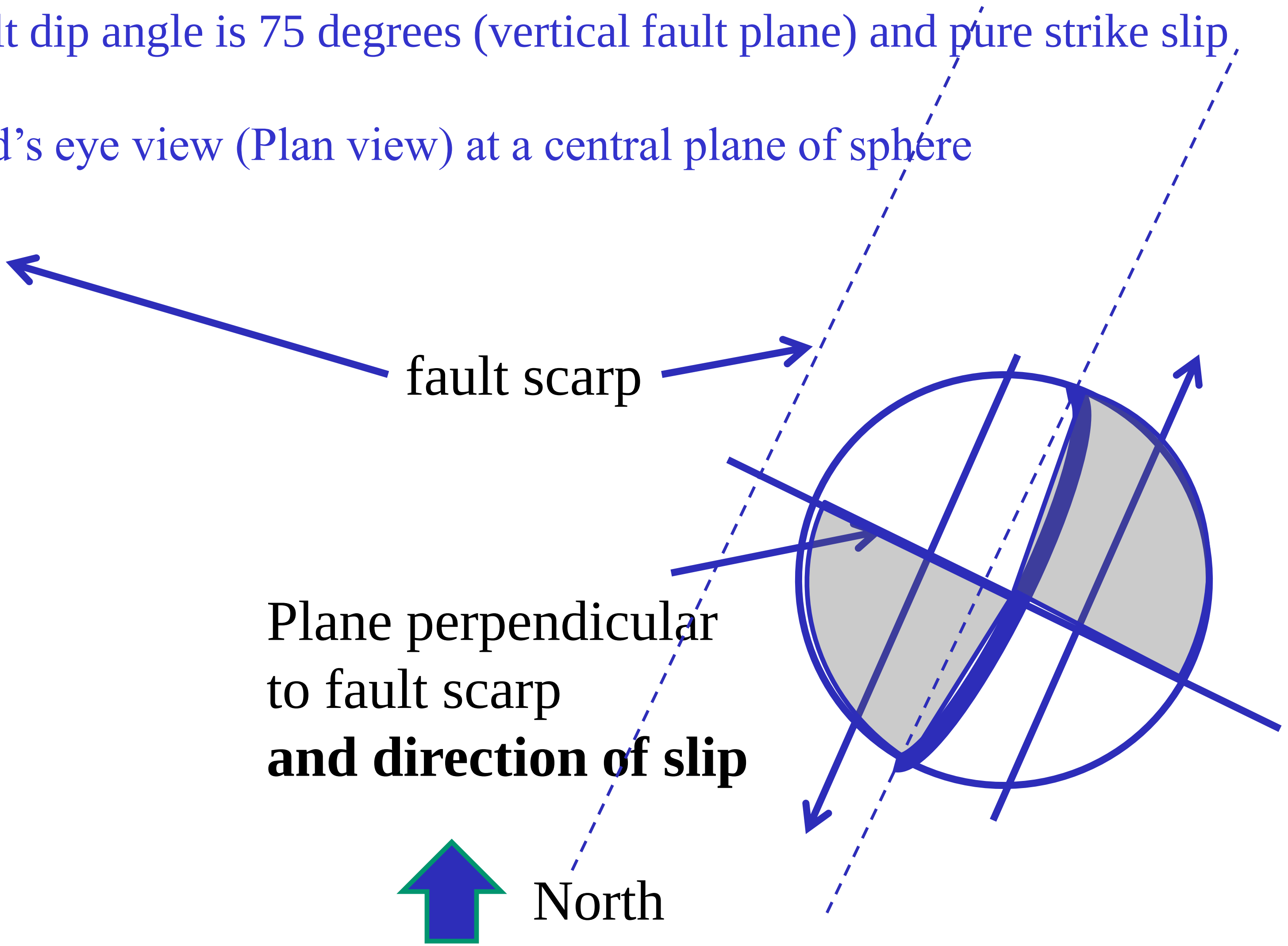
North

Some Simple cases (cont.):



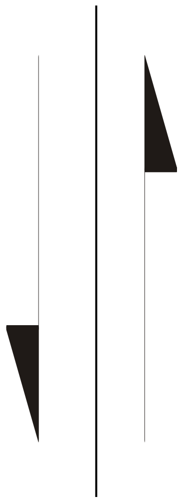
Assume fault dip angle is 75 degrees (vertical fault plane) and pure strike slip

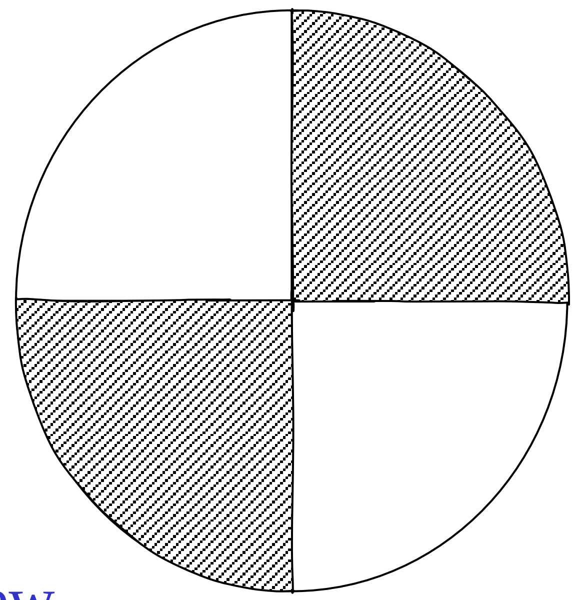
Look in Bird's eye view (Plan view) at a central plane of sphere



Examples of Focal Solution (mechanism)

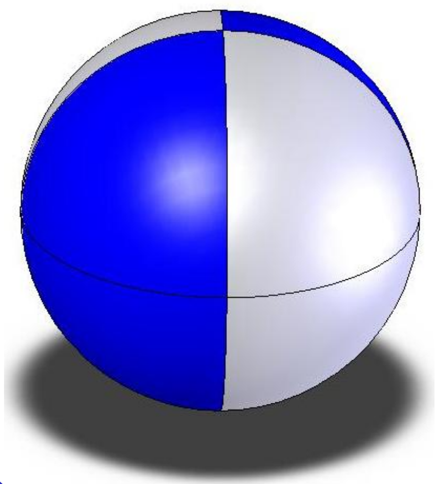
A. Strike-Slip Fault
(Plan View)

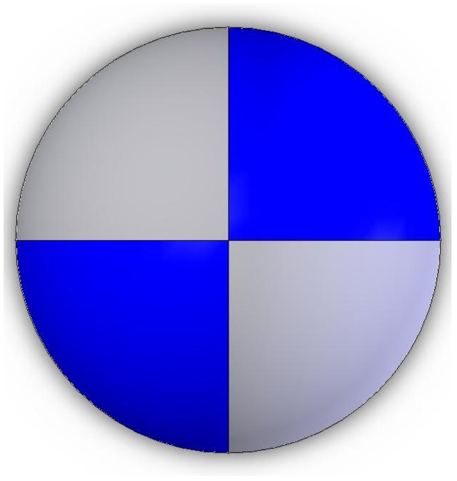




Map View

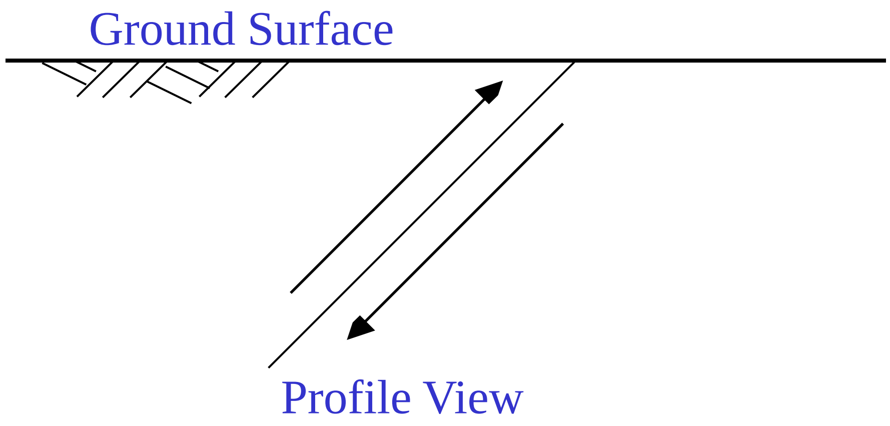
3D view for visualization

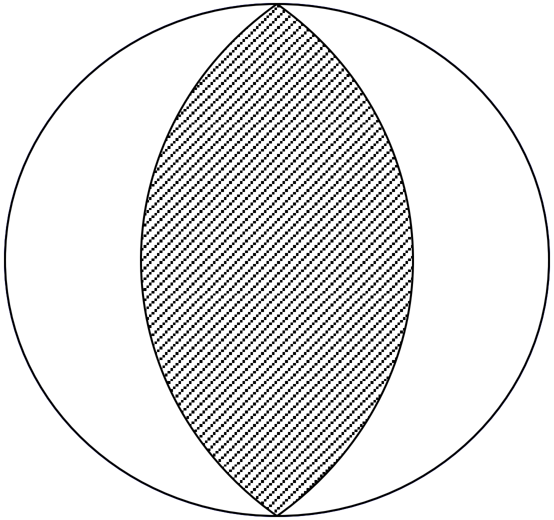




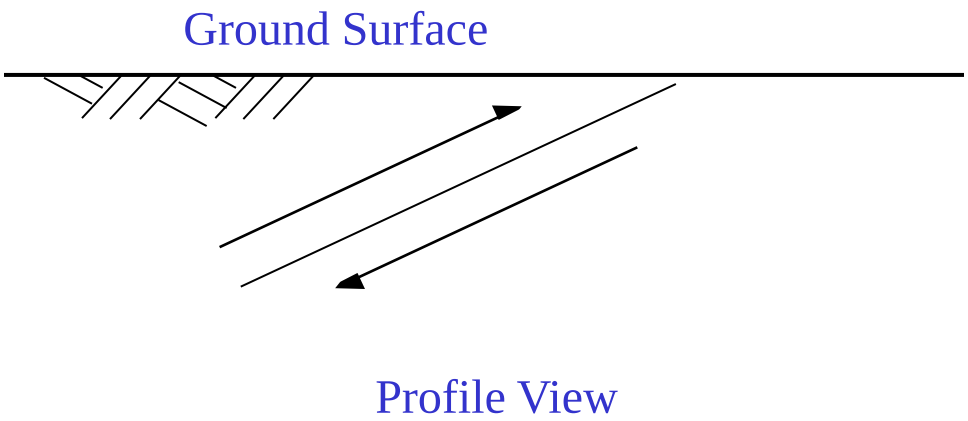
Graphics by Tracey Becker

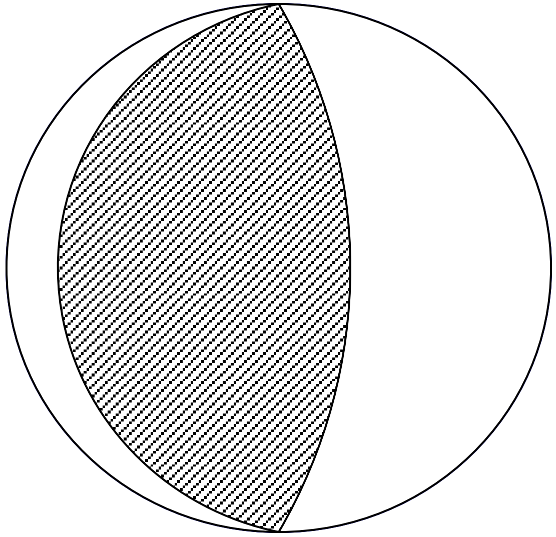
B. Reverse Fault



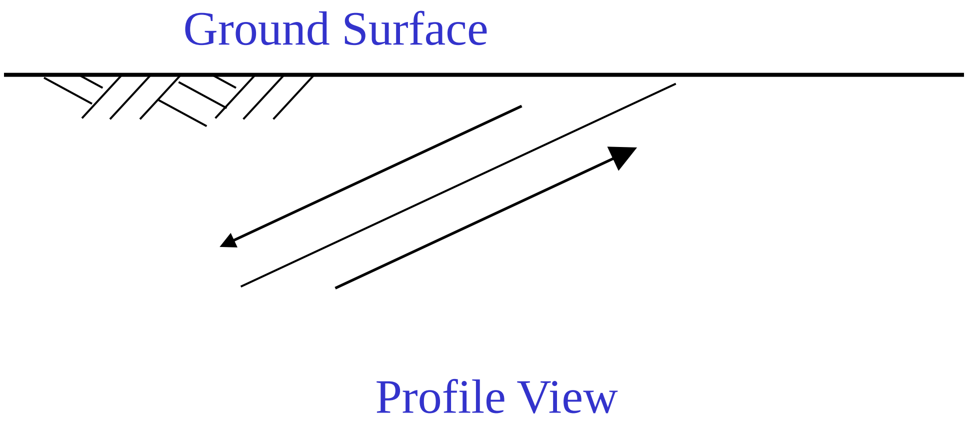


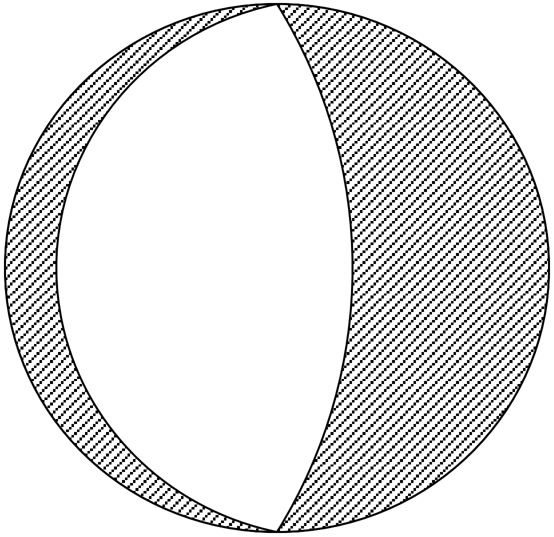
C. Low Angle Thrust Fault (reverse)



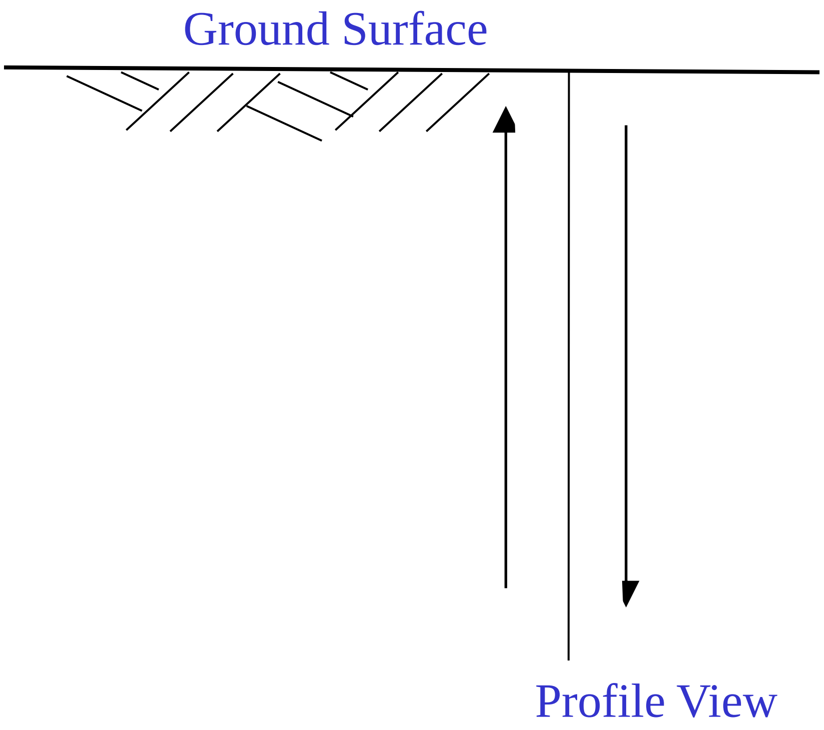


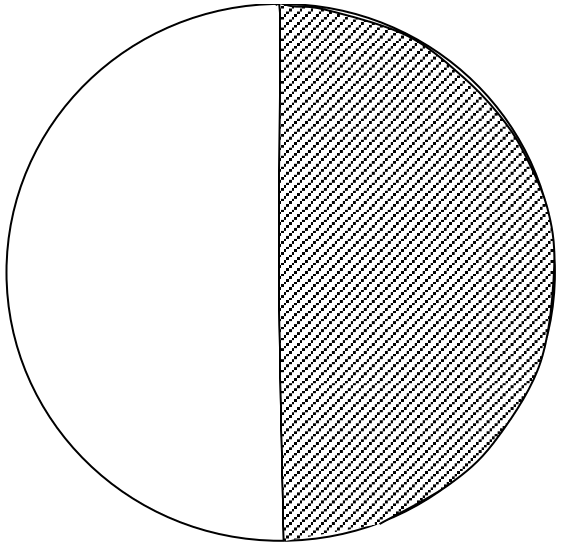
D. Low Angle Normal Fault



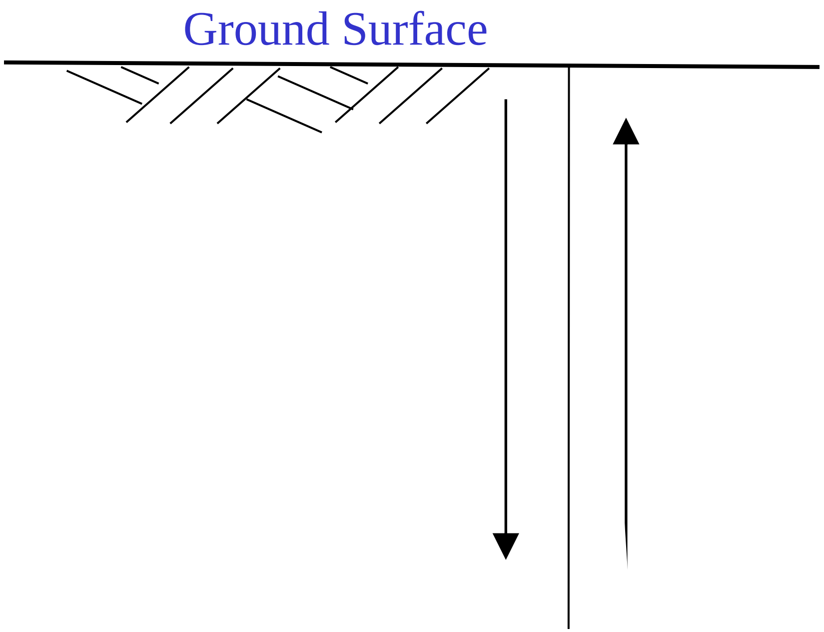


E. Vertical Dip-Slip

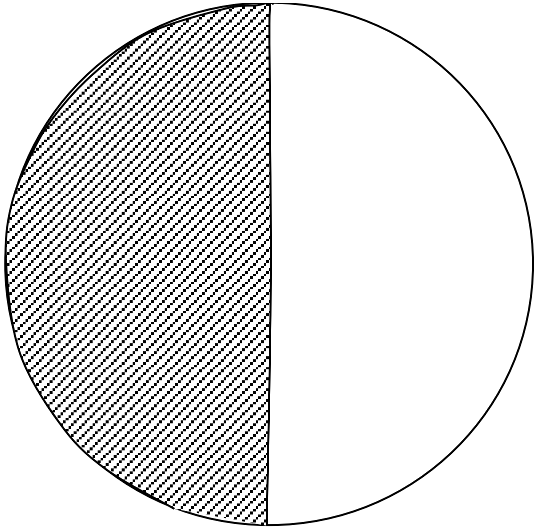


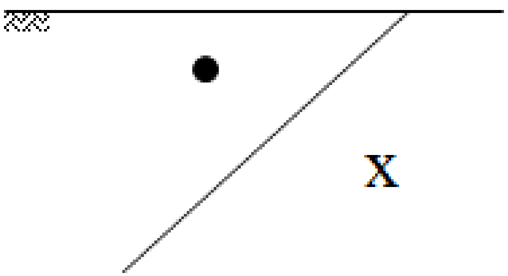


also

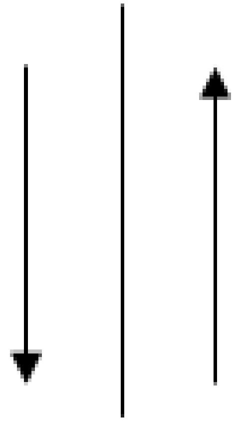


Profile View

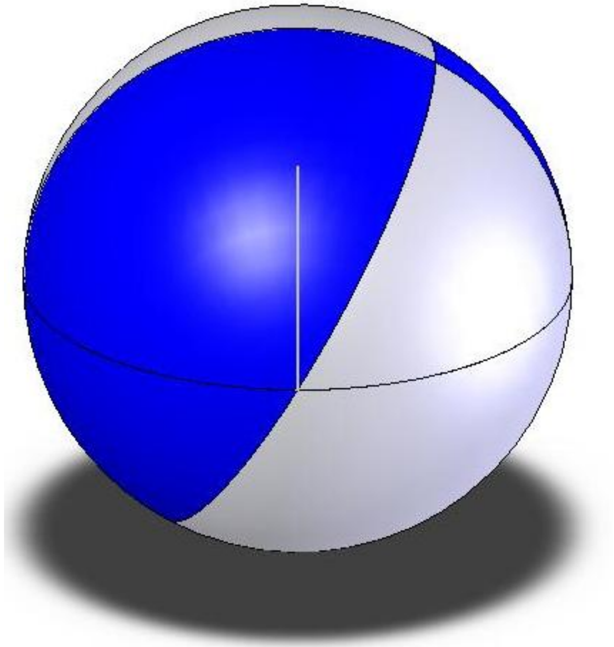




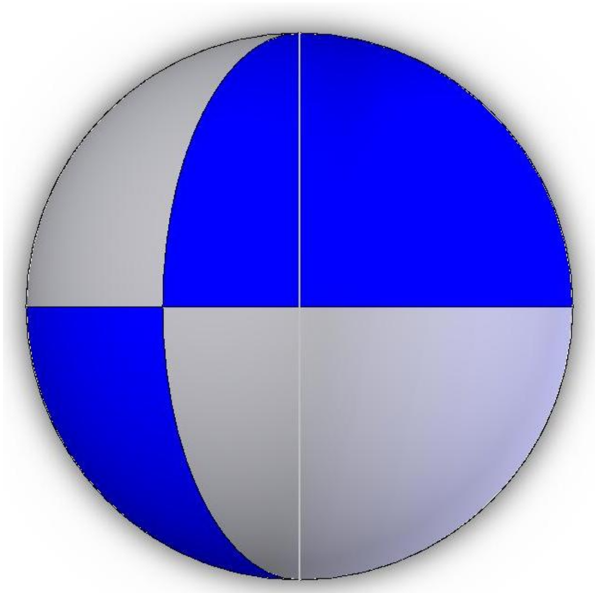
Side View



Plan View
(strike slip)



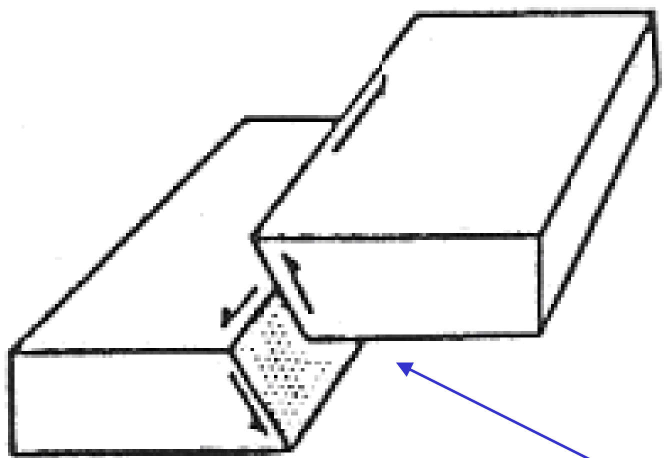
3-Dimensional view
For visualization



Focal mechanism

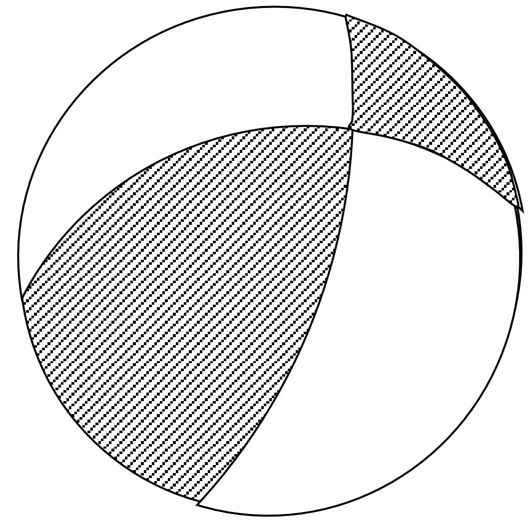
Graphics by Tracey Becker

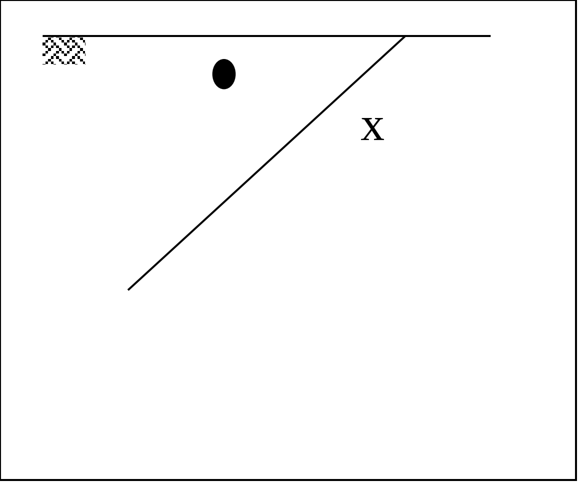
F. Oblique-slip (Left-lateral-reverse)



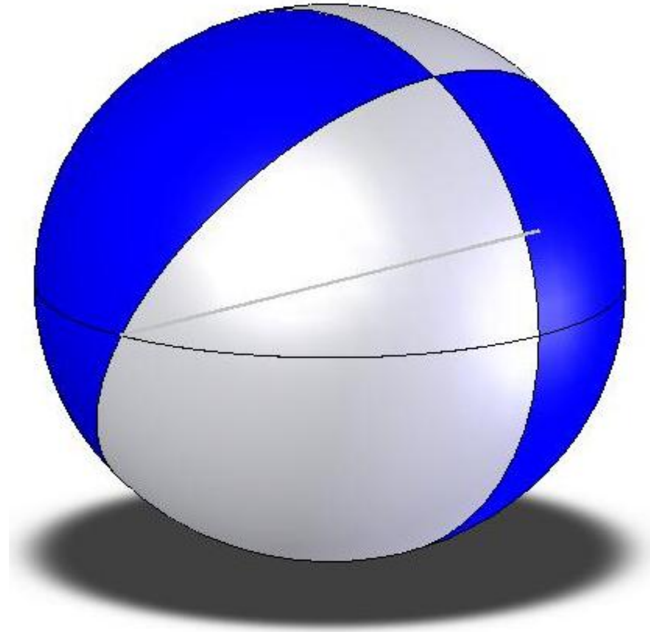
Oblique-slip
(left-lateral reverse)

Combination
of strike-slip
and dip-slip

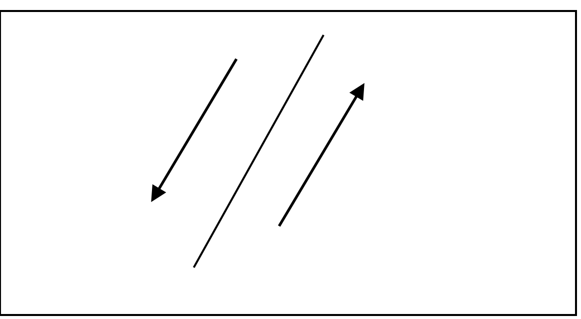




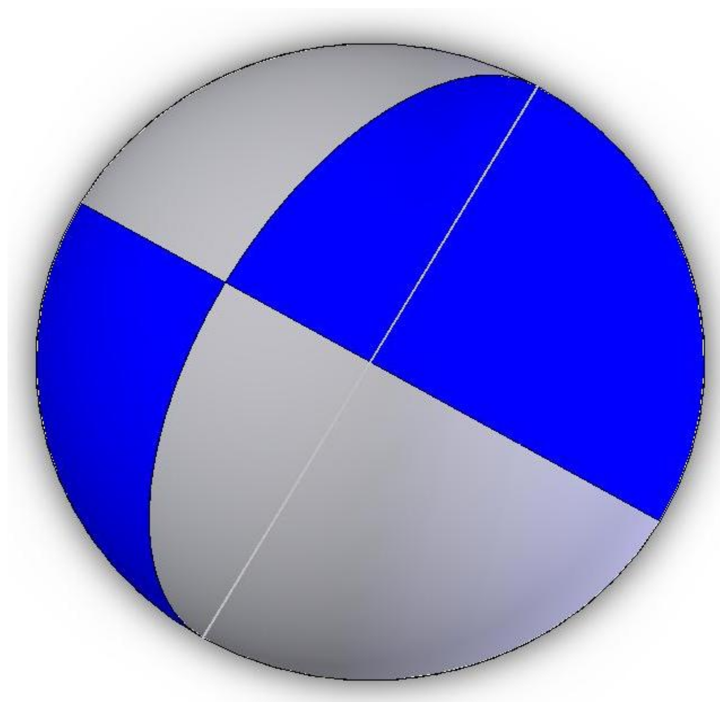
Side View



3-Dimensional view
For visualization

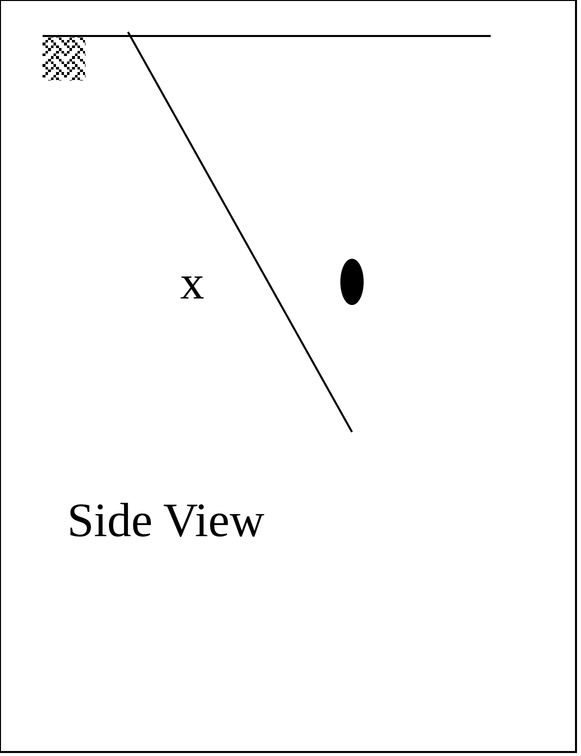


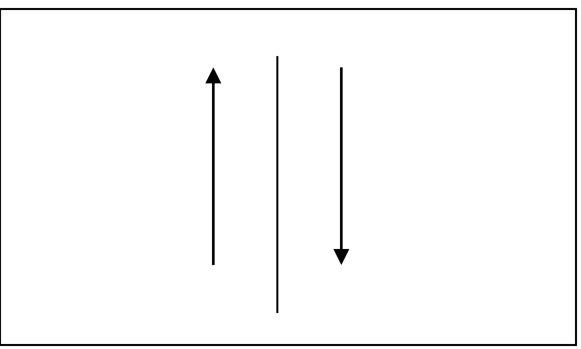
Plan View (strike slip)



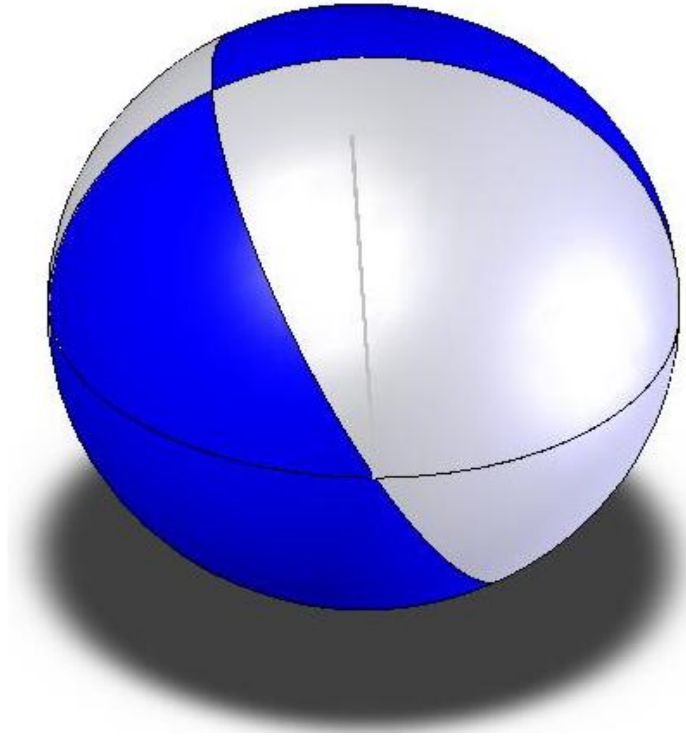
Focal mechanism

Graphics by Tracey Becker

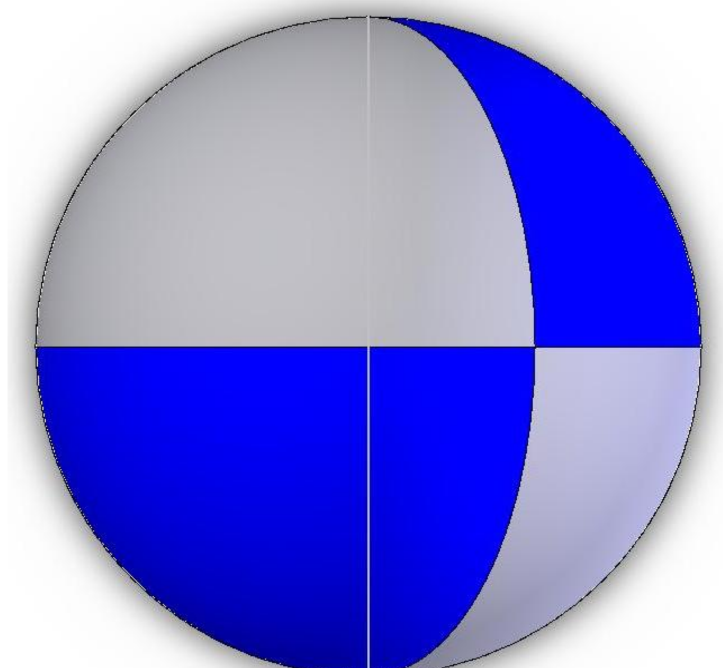




Plan View (strike slip)

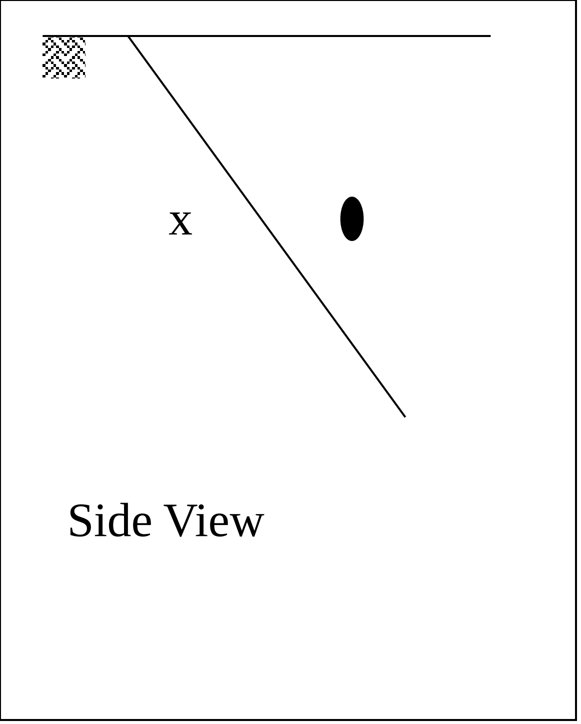


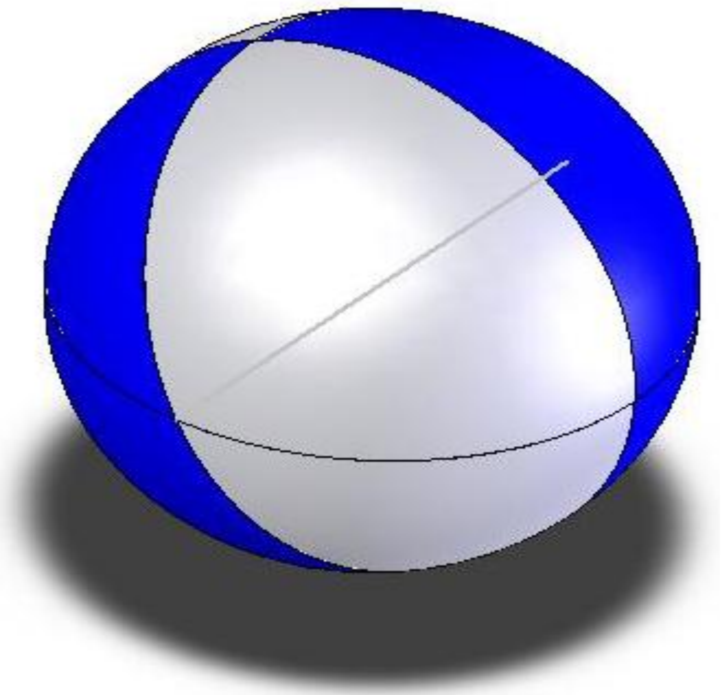
3-Dimensional view
For visualization

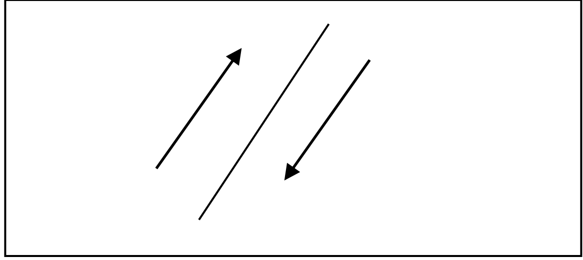


Focal mechanism

Graphics by Tracey Becker

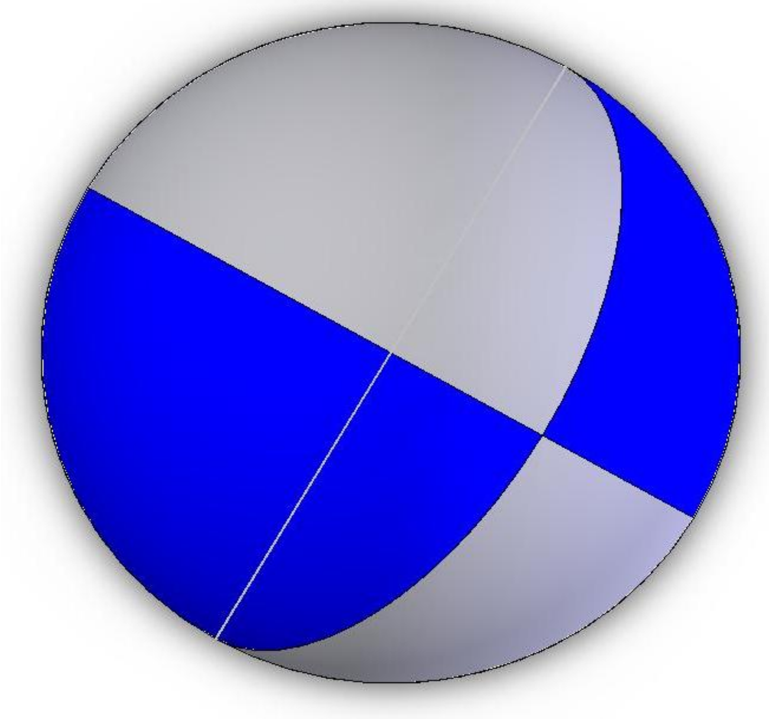






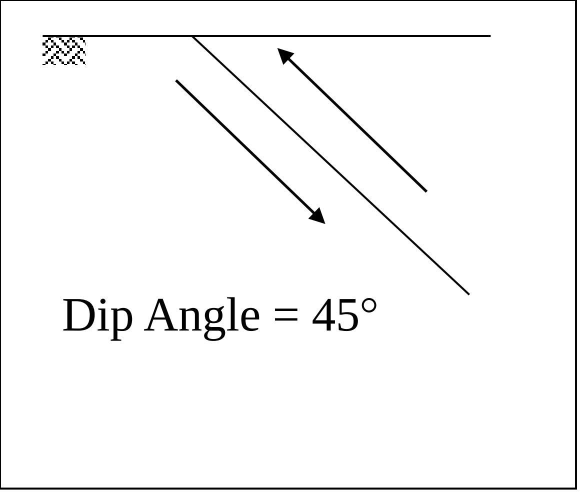
Plan View (strike slip)

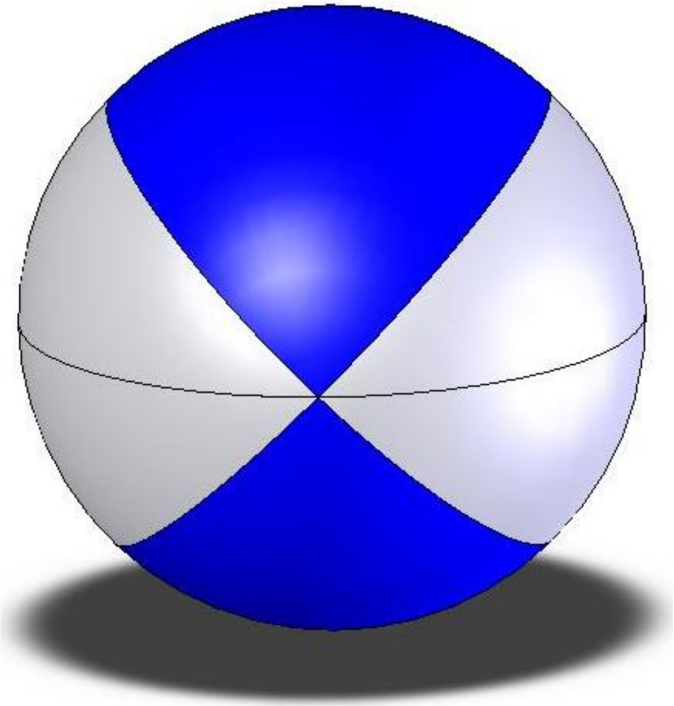
3-Dimensional view
For visualization



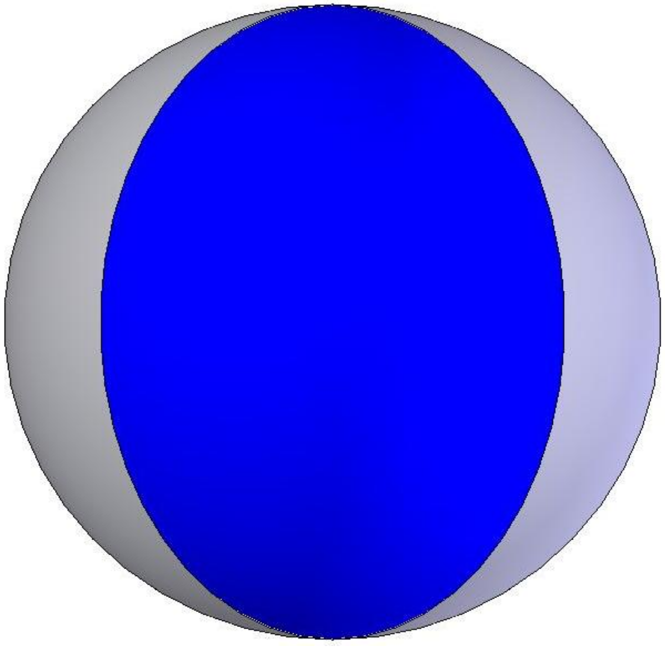
Focal mechanism

Graphics by Tracey Becker



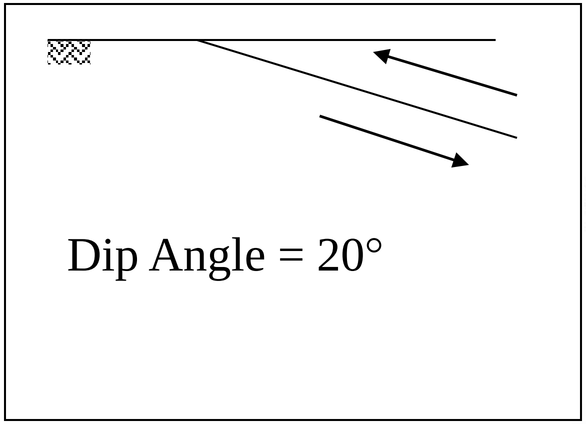


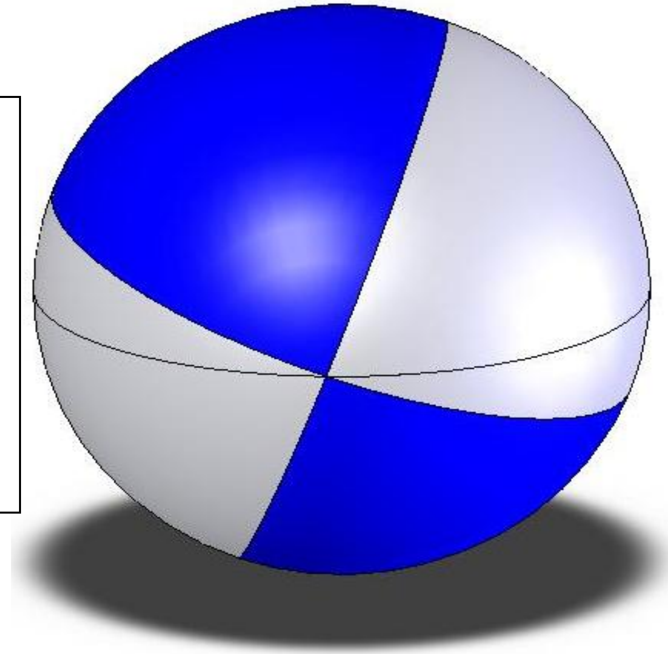
3-Dimensional view
For visualization



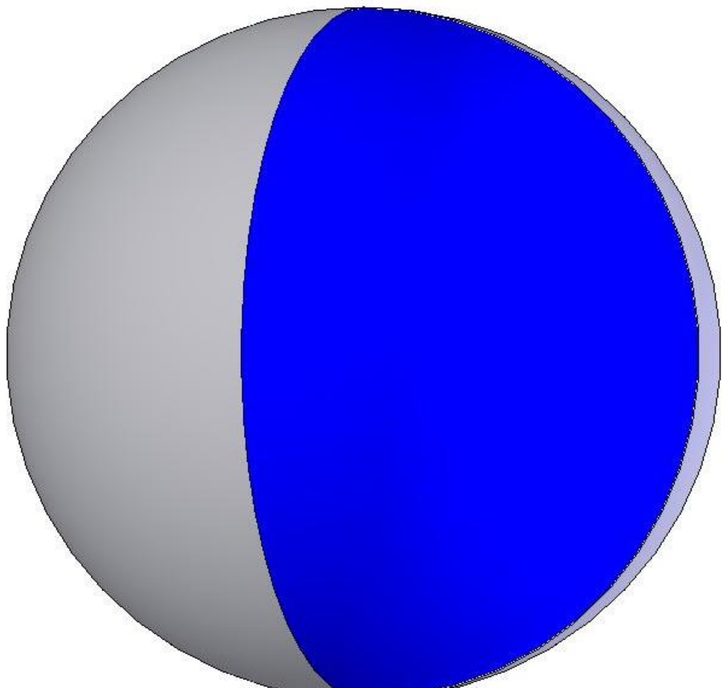
Focal mechanism

Graphics by Tracey Becker





3-Dimensional view
For visualization



Focal mechanism

Graphics by Tracey Becker