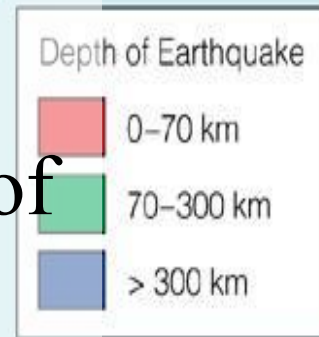


OCN 201: Seafloor Spreading and Plate Tectonics I



Revival of Continental Drift Theory

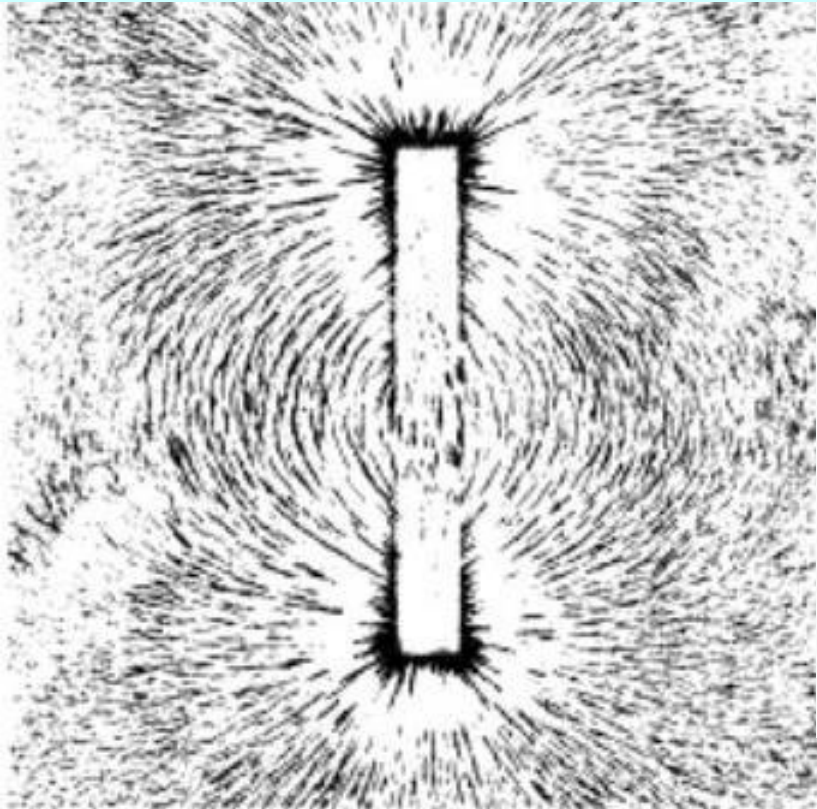
- Kiyoo Wadati (1935) speculated that earthquakes and volcanoes may be associated with continental drift.
- Hugo Benioff (1940) plotted locations of deep earthquakes at edge of Pacific “Ring of Fire”.
- Earthquakes are not randomly distributed but instead coincide with mid-ocean ridge system.
- Evidence of *polar wandering*.



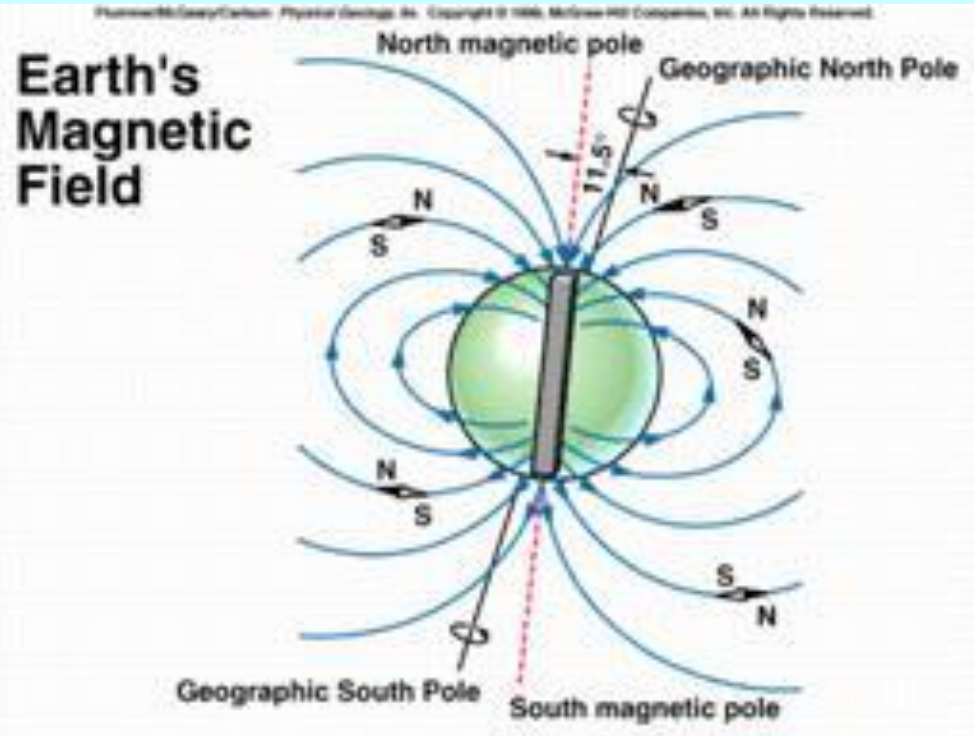
Revival of Continental Drift Theory

Wegener's theory was revived in the 1950's based on paleomagnetic evidence for "Polar Wandering".

Earth's Magnetic Field

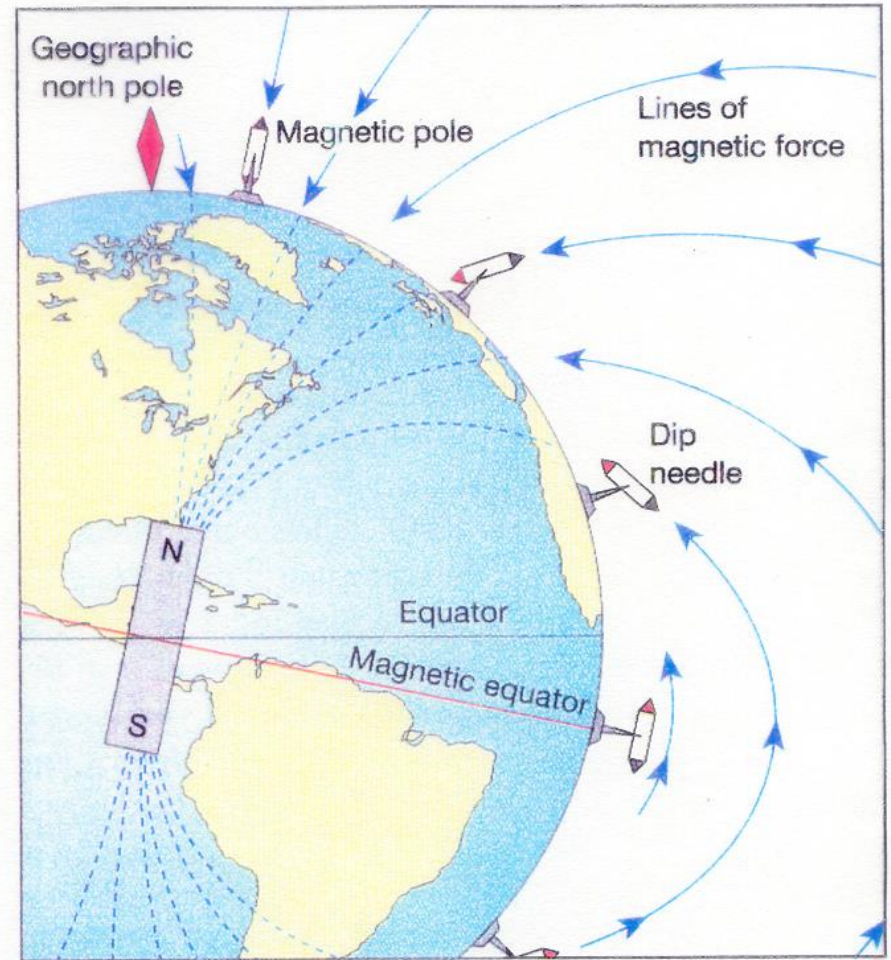
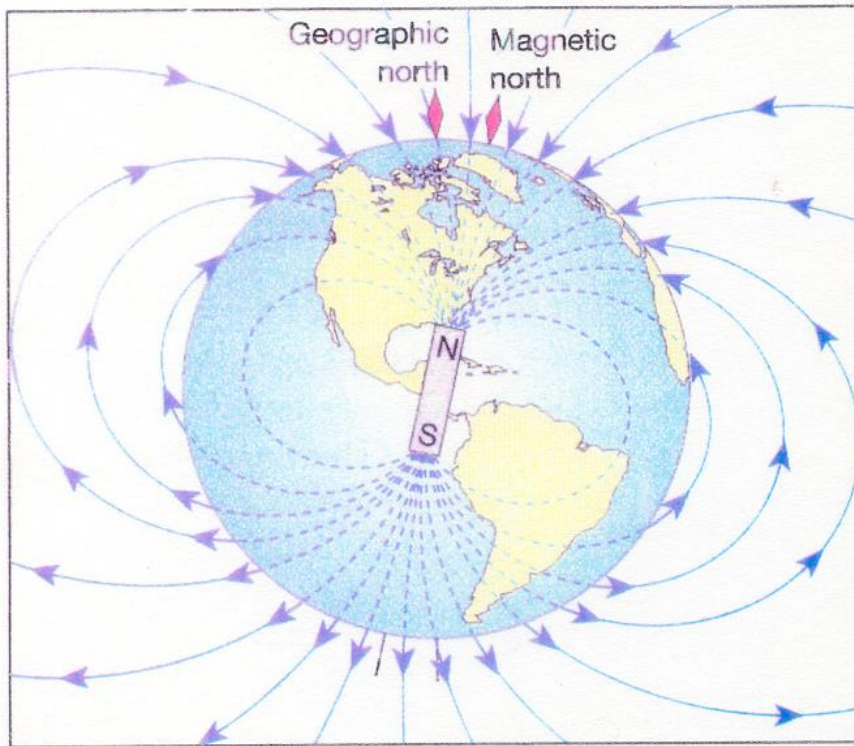


A bar magnet with Fe filings aligning along the “lines” of the magnetic field



Earth's magnetic field simulates a bar magnet, but it is caused by convection of liquid Fe in Earth's outer core: the ***Geodynamo***.
A moving electrical conductor induces a magnetic field.

Earth's magnetic field is toroidal, or “donut-shaped”.

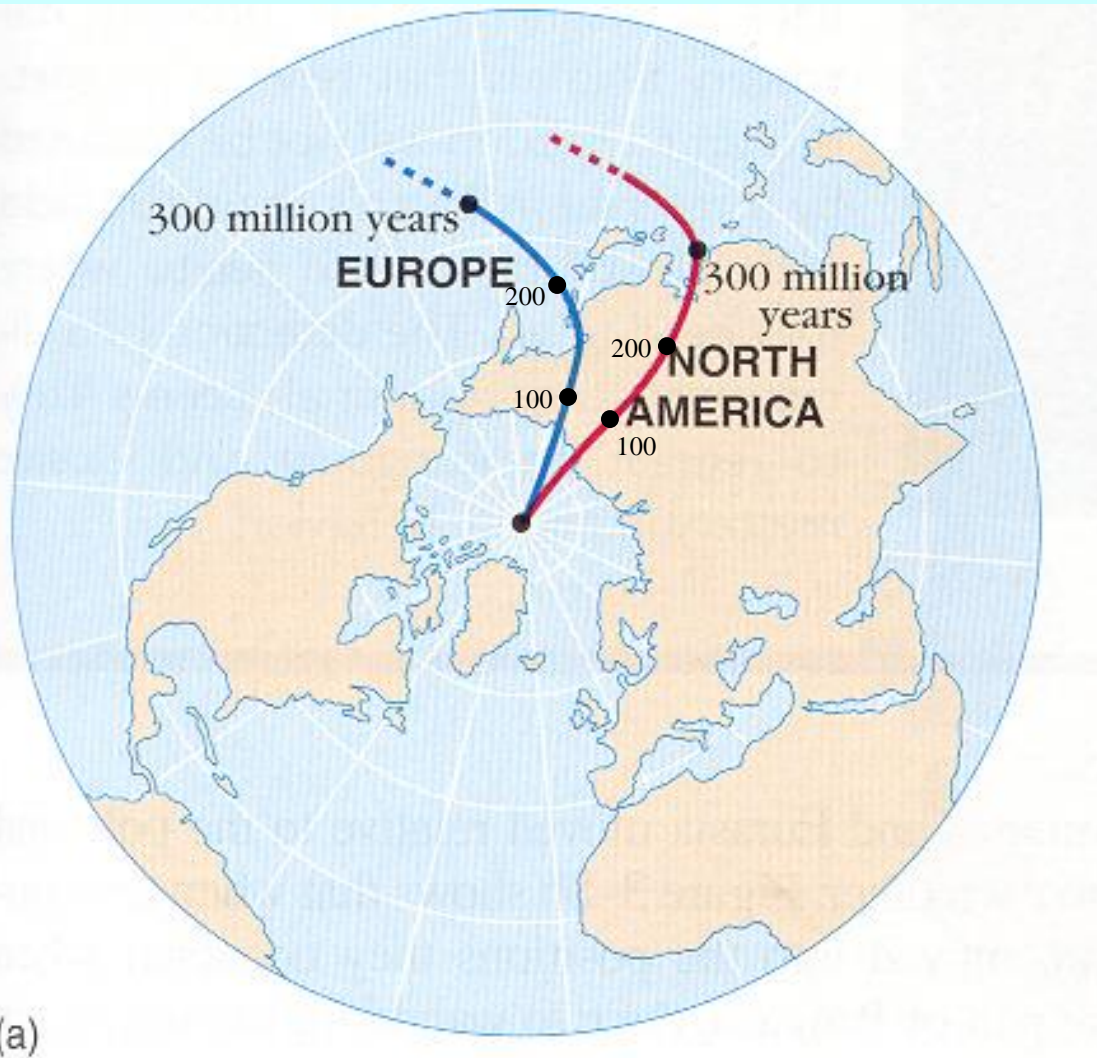


A freely moving magnet lies horizontal at the equator, vertical at the poles, and points toward the “North” pole.

Paleomagnetism in Rocks

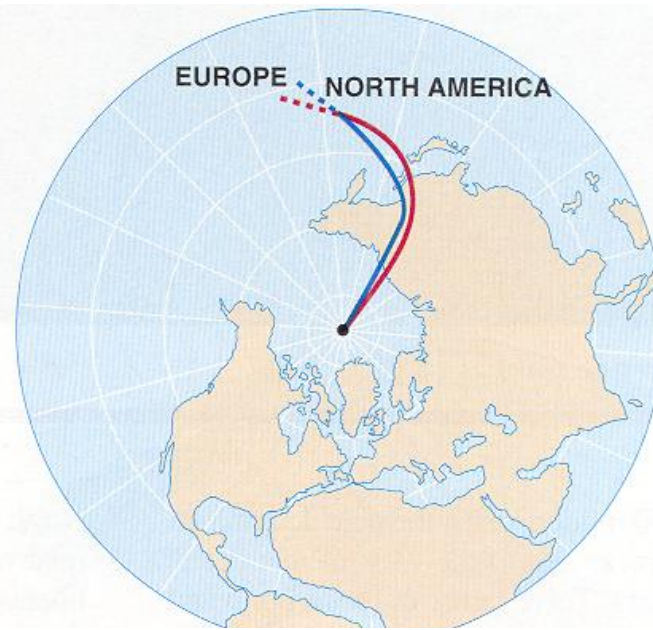
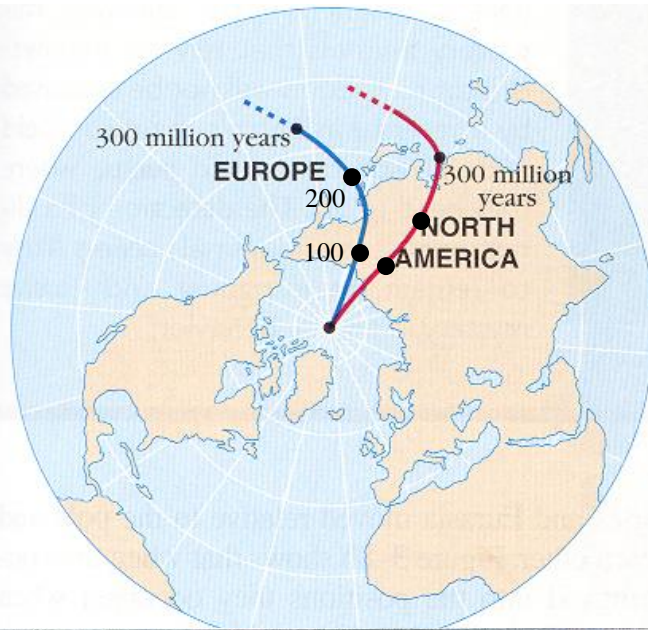
- Magnetic minerals (e.g. Magnetite, Fe_3O_4) in rocks align with Earth's magnetic field when rocks solidify.
- Magnetic alignment is “frozen in” and retained if rock is not subsequently heated.
- Can use paleomagnetism of ancient rocks to determine:
 - direction and polarity of magnetic field
 - paleolatitude of rock
 - apparent position of N and S magnetic poles.

Apparent Polar Wander Paths

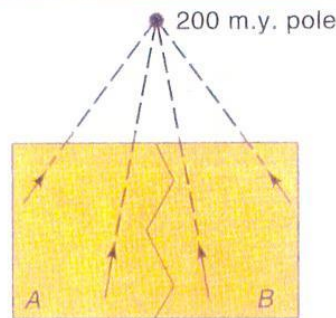


- Geomagnetic poles had apparently “wandered” systematically with time.

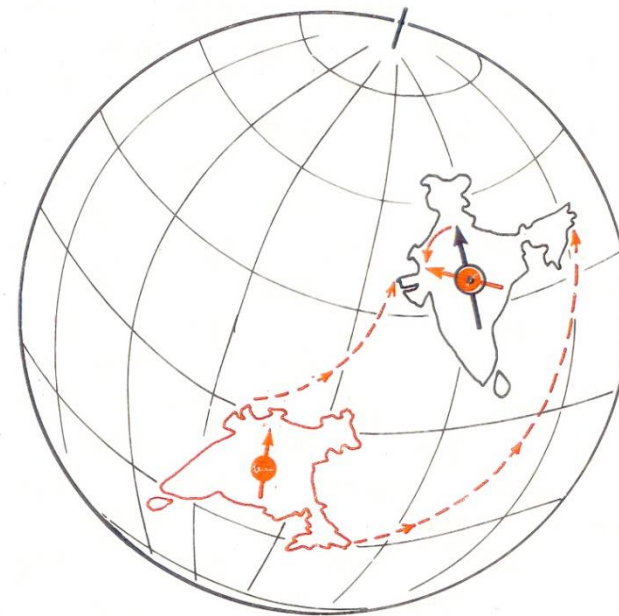
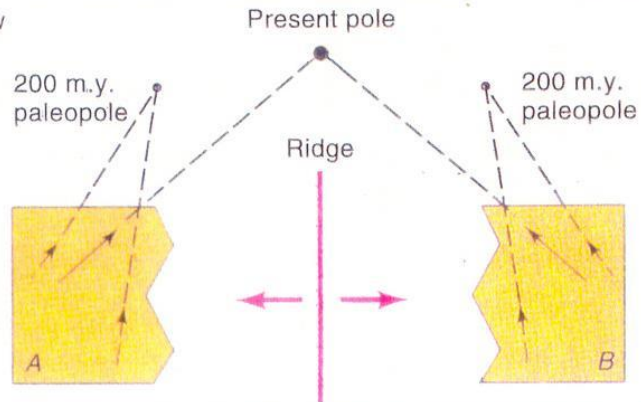
- Rocks from different continents gave different paths! Divergence increased with age of rocks.



200 M.Y. Ago

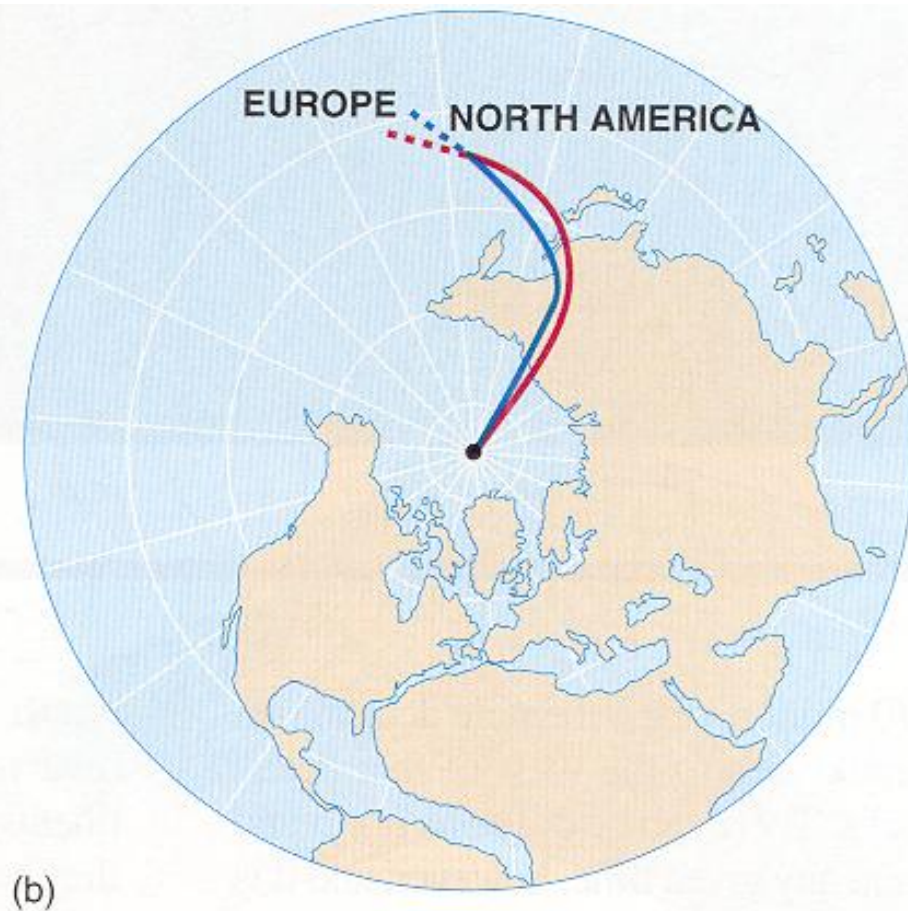
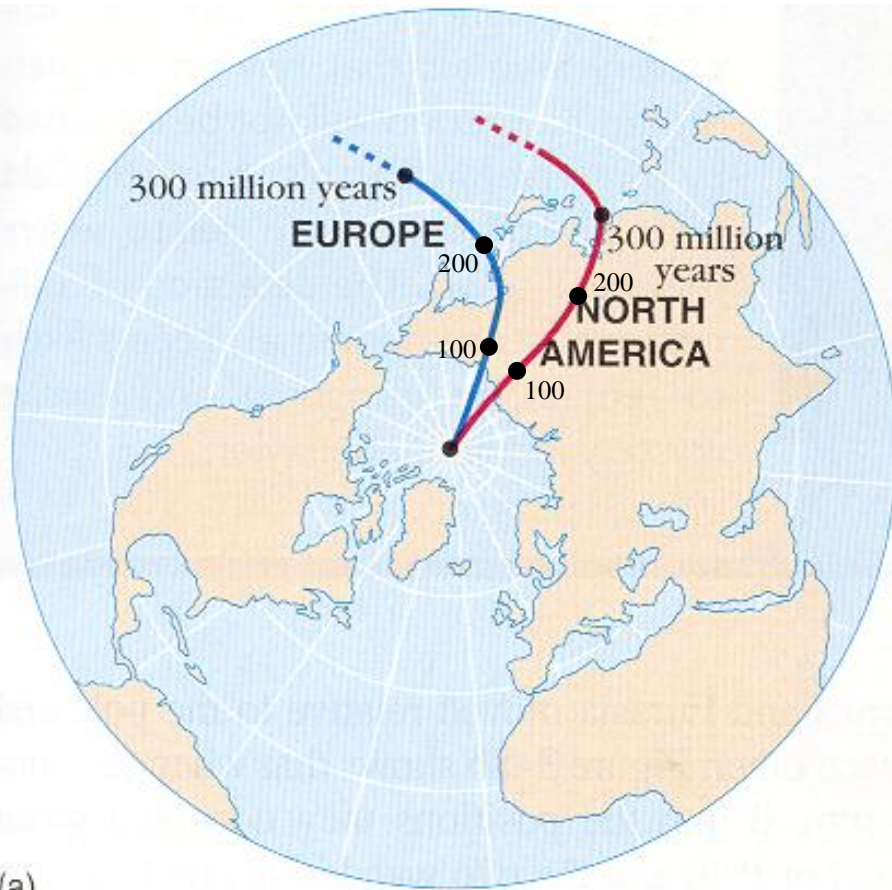


Now



When magnetic minerals crystallize, they align with the geomagnetic field, as in the continent in color. When their crustal plate moves, their old magnetic alignment is preserved and is out of line with the current geomagnetic field, in black.

Apparent Polar Wander Paths



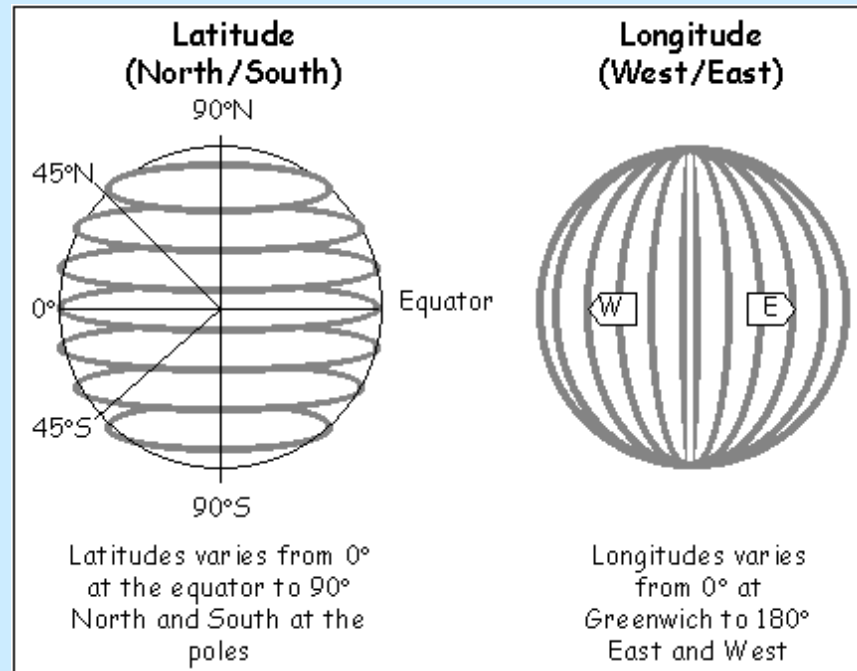
Magnetic poles have never been more than 20° from geographic poles of rotation; rest of apparent wander results from *motion of continents*!

For a magnetic compass, the red end of the needle points to:

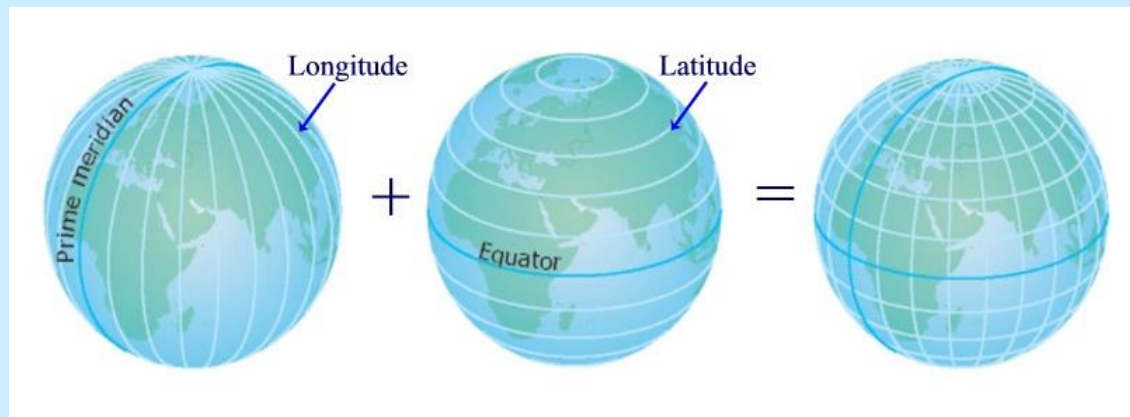
- A. The North Pole
- B. True North
- C. Geographic North
- D. Magnetic North
- E. All of the above.

Parallels of latitude Meridians of longitude

Lines of constant latitude are “small circles”, except for the equator.

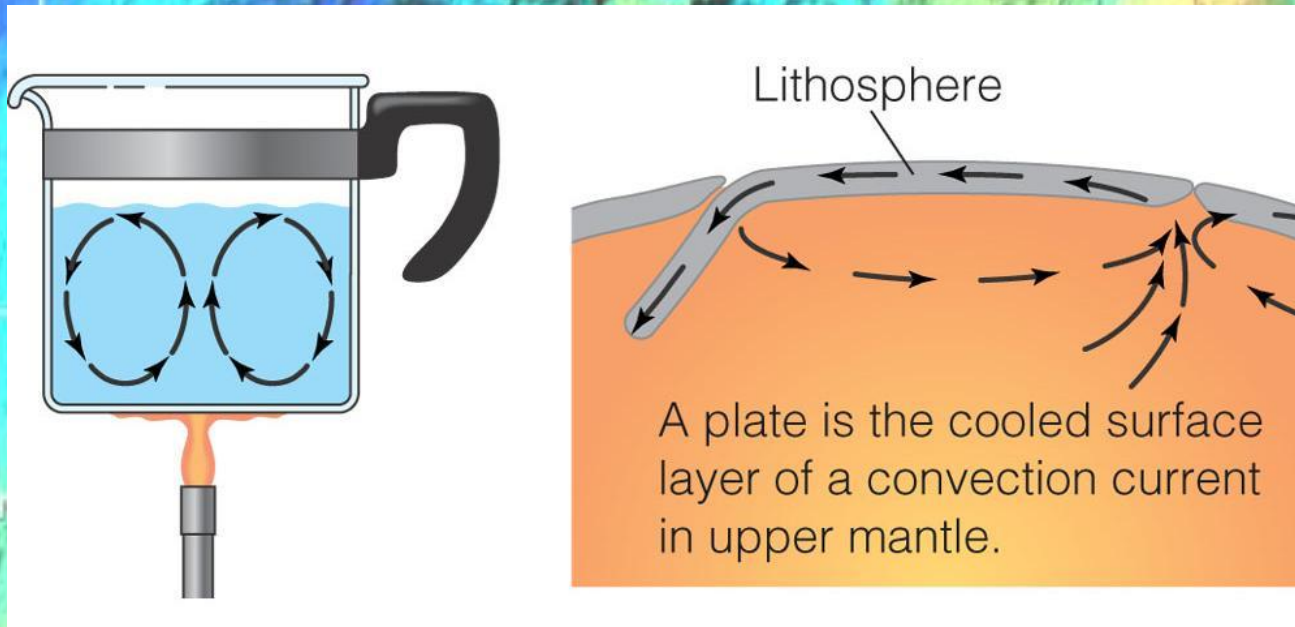


Lines of constant longitude are all “great circles”.



Seafloor Spreading: I

- First suggested by Arthur Holmes (1928) based on concepts of continental drift and convection cells within the mantle.

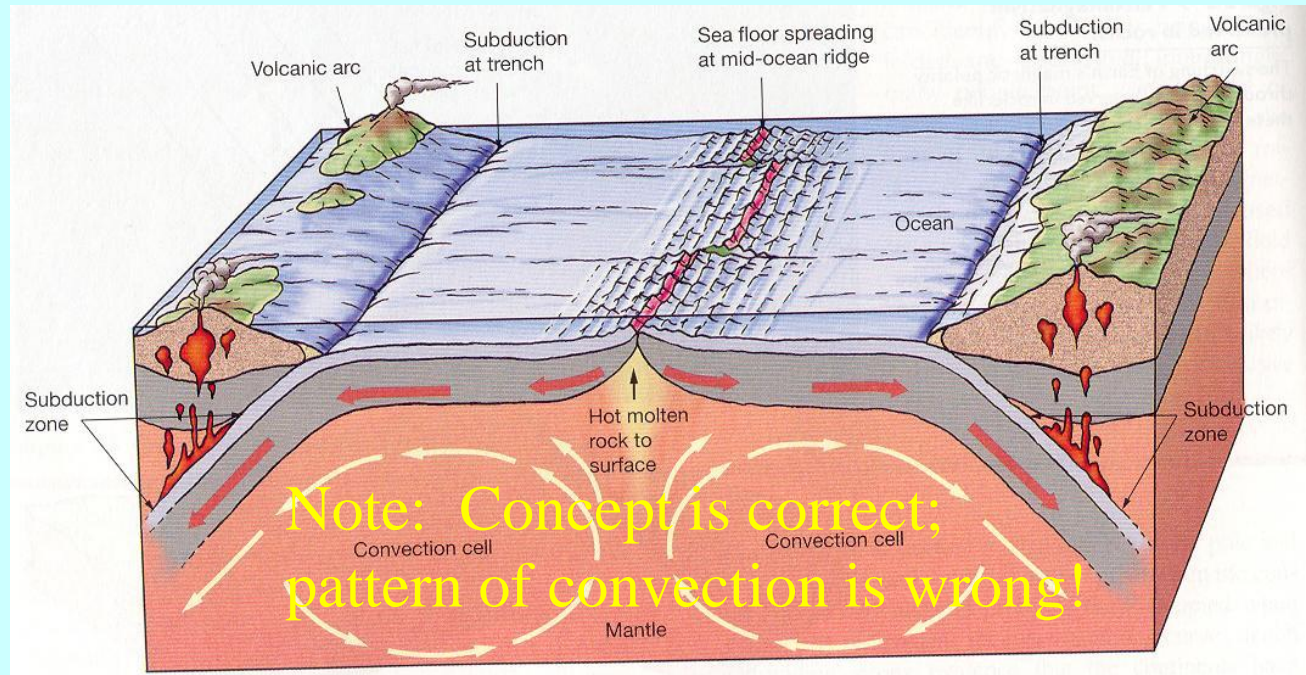


Heat can be transported by conduction, convection, and radiation.

Seafloor Spreading: II

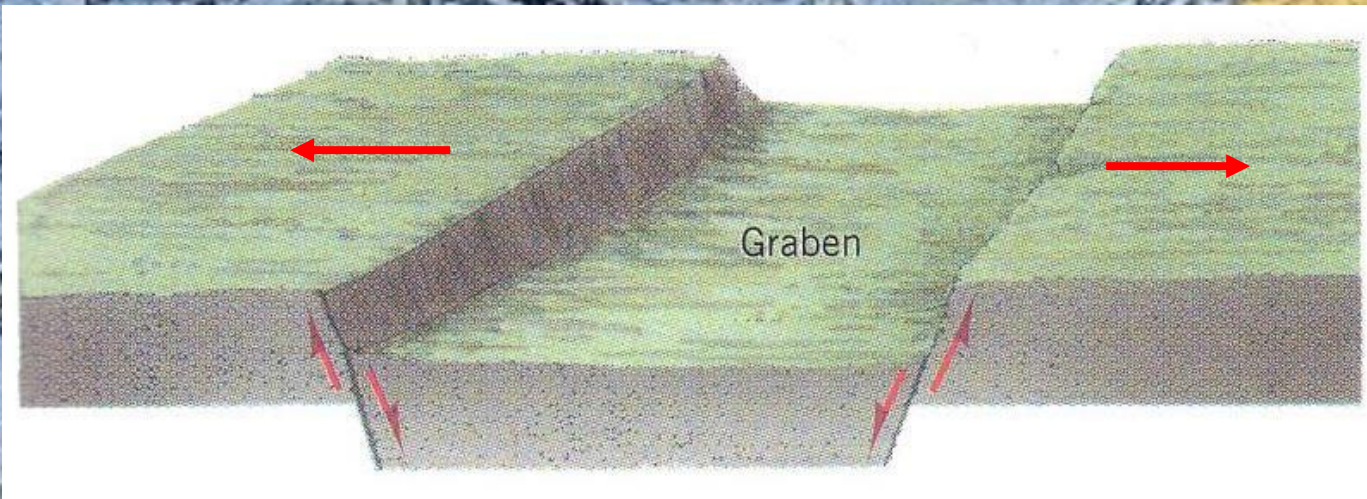
Formally proposed by Dietz (1961) and Hess (1962):

- **Convection cells: Mantle upwells under mid-ocean ridge (MOR).**
- Lithosphere with new oceanic crust is formed at MOR, then spreads laterally as if on conveyor belt.
- **Lithospheric plate with oceanic crust is dragged down at trenches (compression, mountain ranges and volcanic arcs).**
- Continents ride passively between sites of upwelling and downwelling.



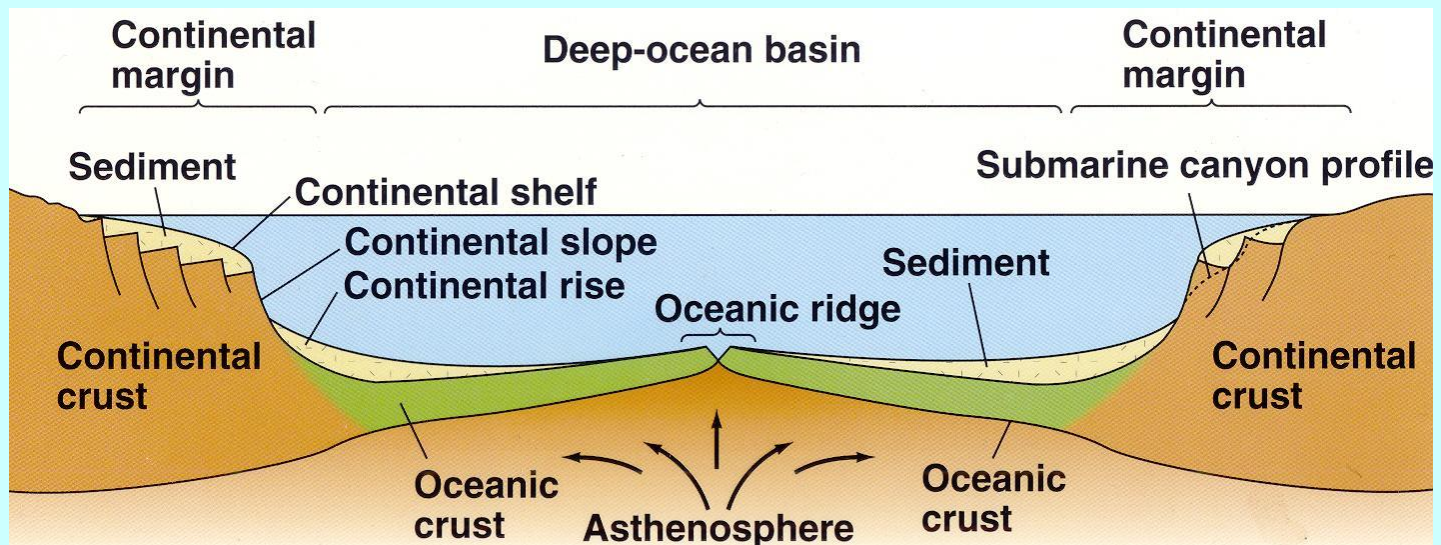
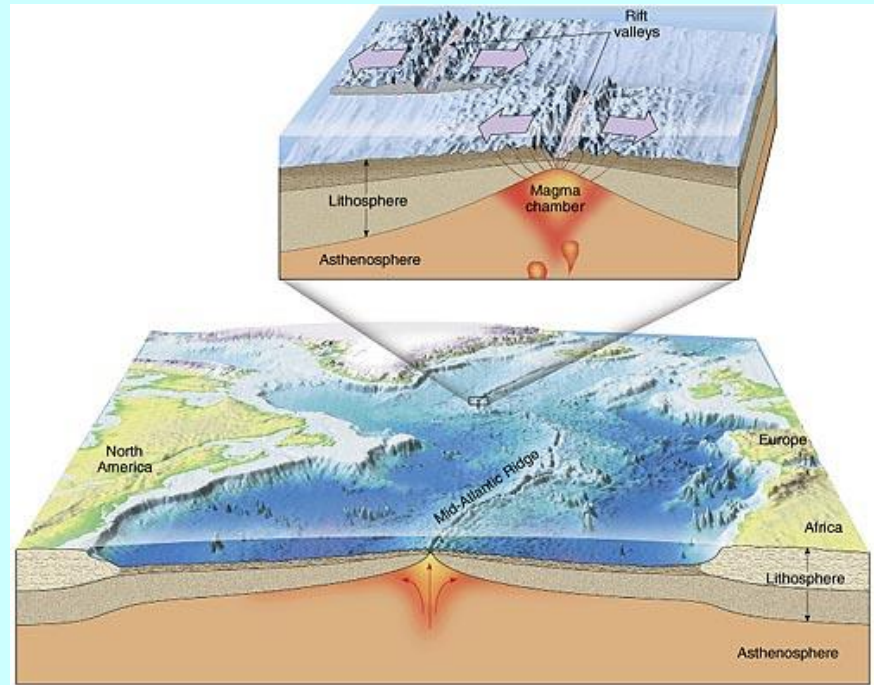
Seafloor Spreading: III

- Suggested by characteristics of **mid-ocean ridge**:
 - Topography is elevated.
 - Structure: **axial valley** formed by normal faulting, implying tension and extension

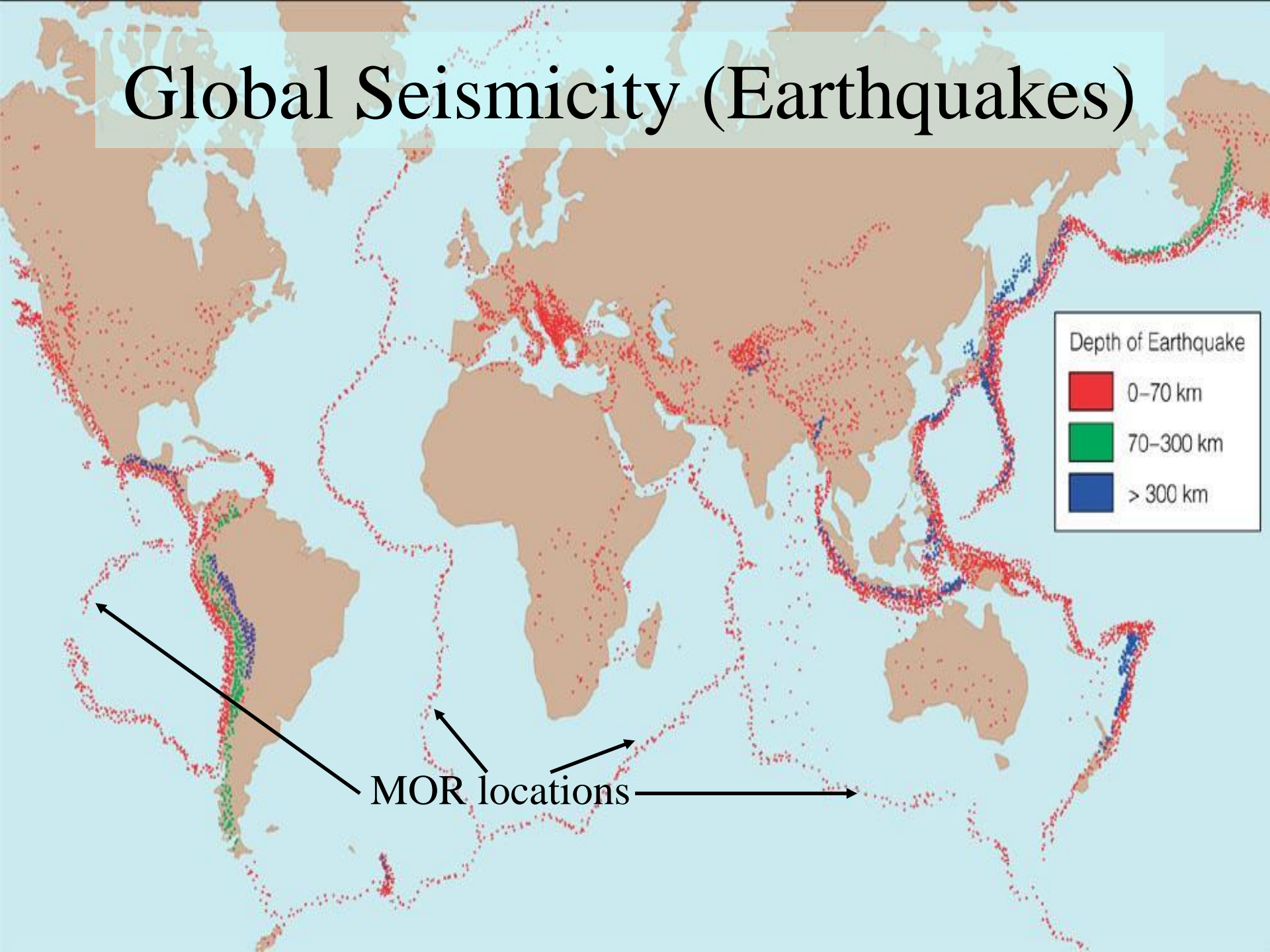


Mid-Ocean Ridges

- High heat flow
- Shallow seismicity (<70 km below MOR).
- Sediment absent or thin
- Basaltic volcanism
- Tensional stress: rifting



Global Seismicity (Earthquakes)



Internal Structure of the Earth

(based on physical properties)

Use viscosity and strength to describe outer layers:

- **Lithosphere:** 0-100 km

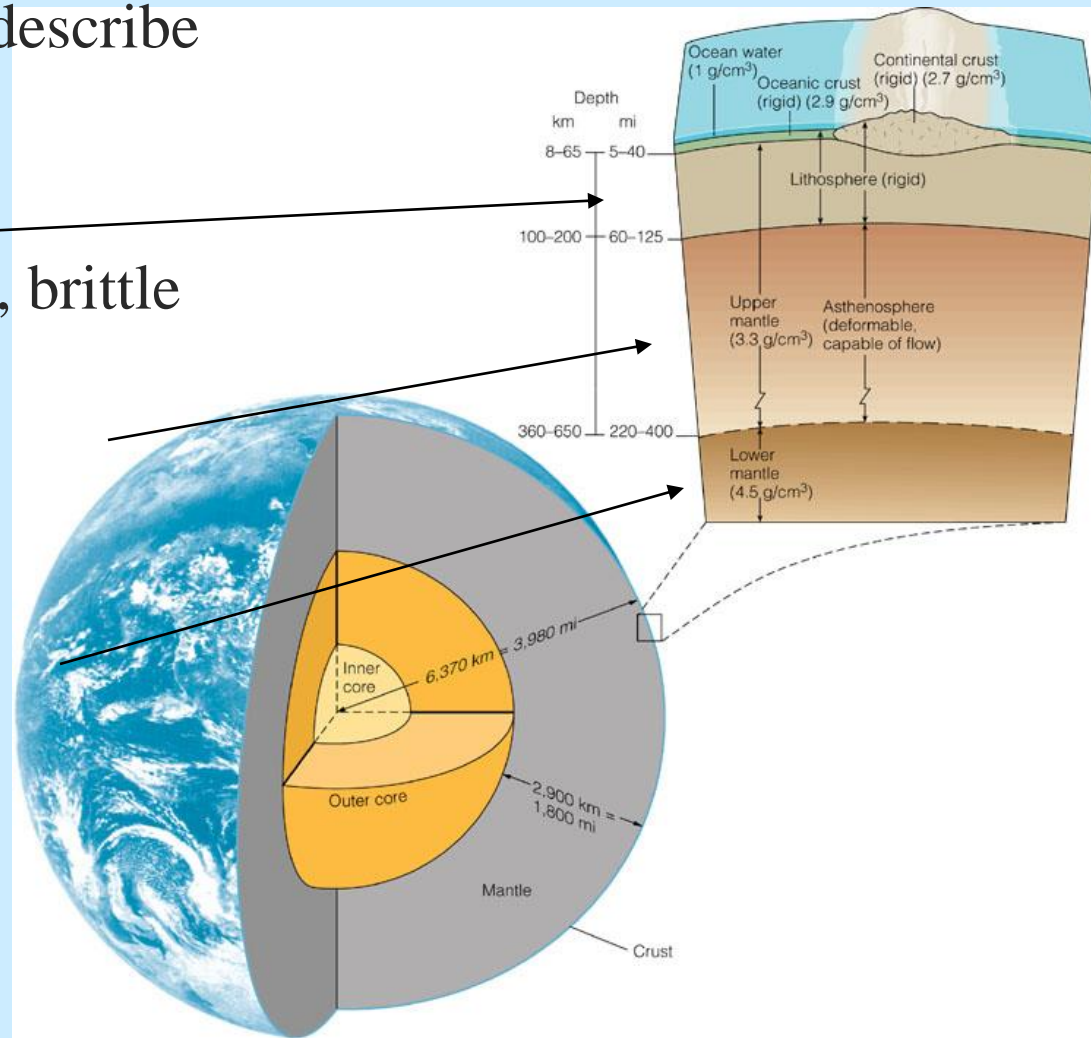
= mantle + crust: rigid, brittle

- **Asthenosphere:** 100-700 km

= mantle: soft, plastic

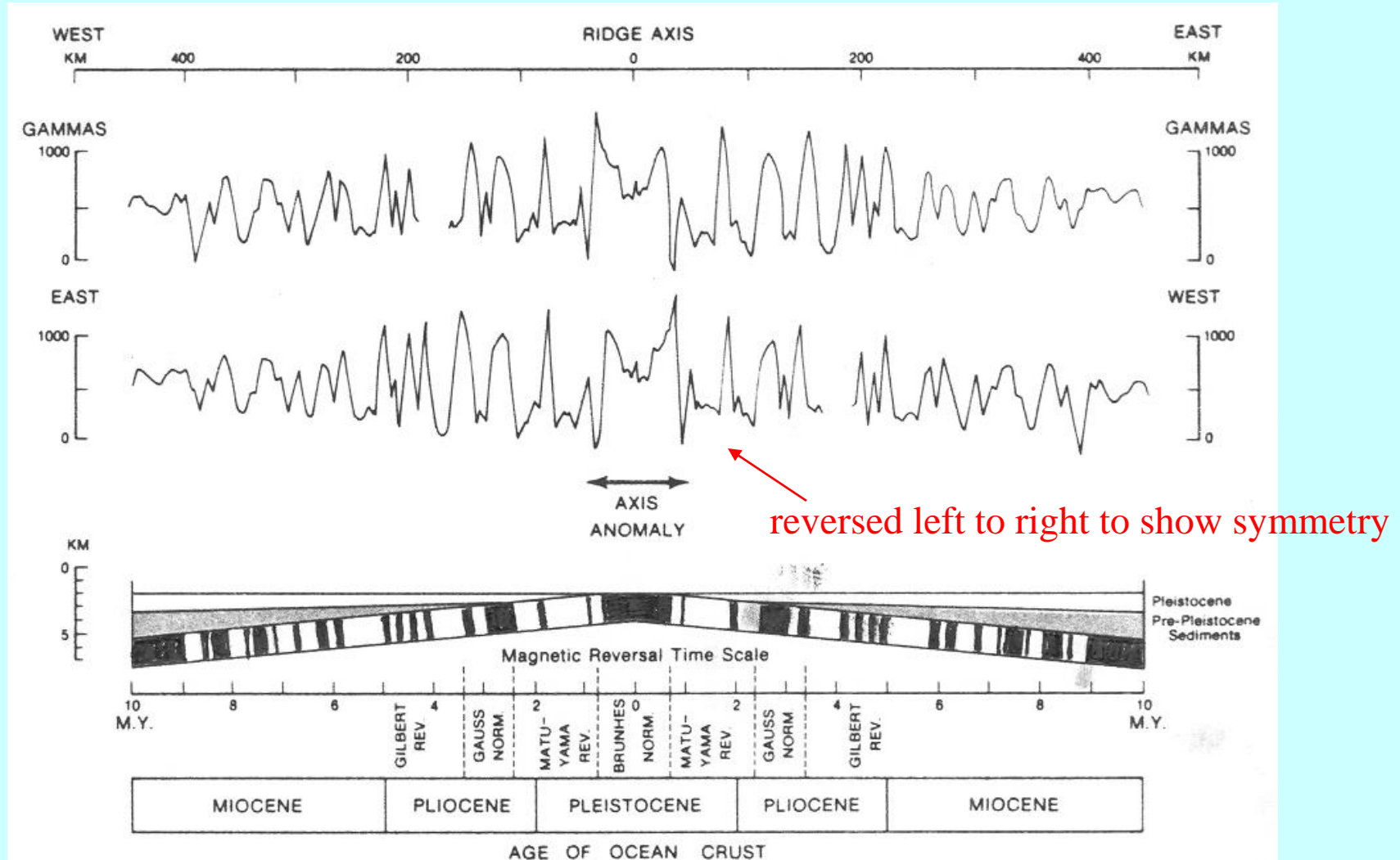
- **Lower Mantle:**

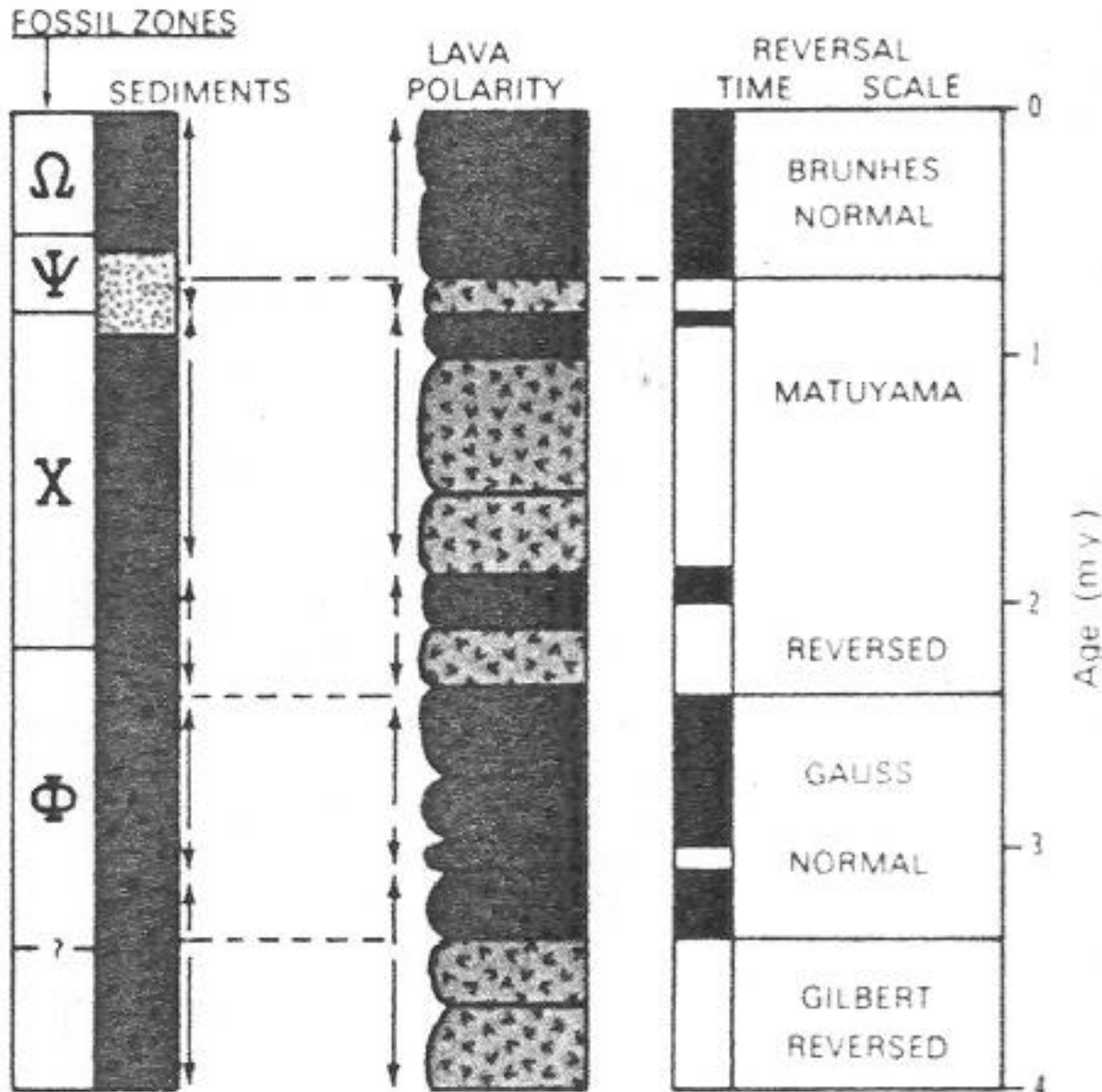
700-2900 km



Seafloor Spreading: IV

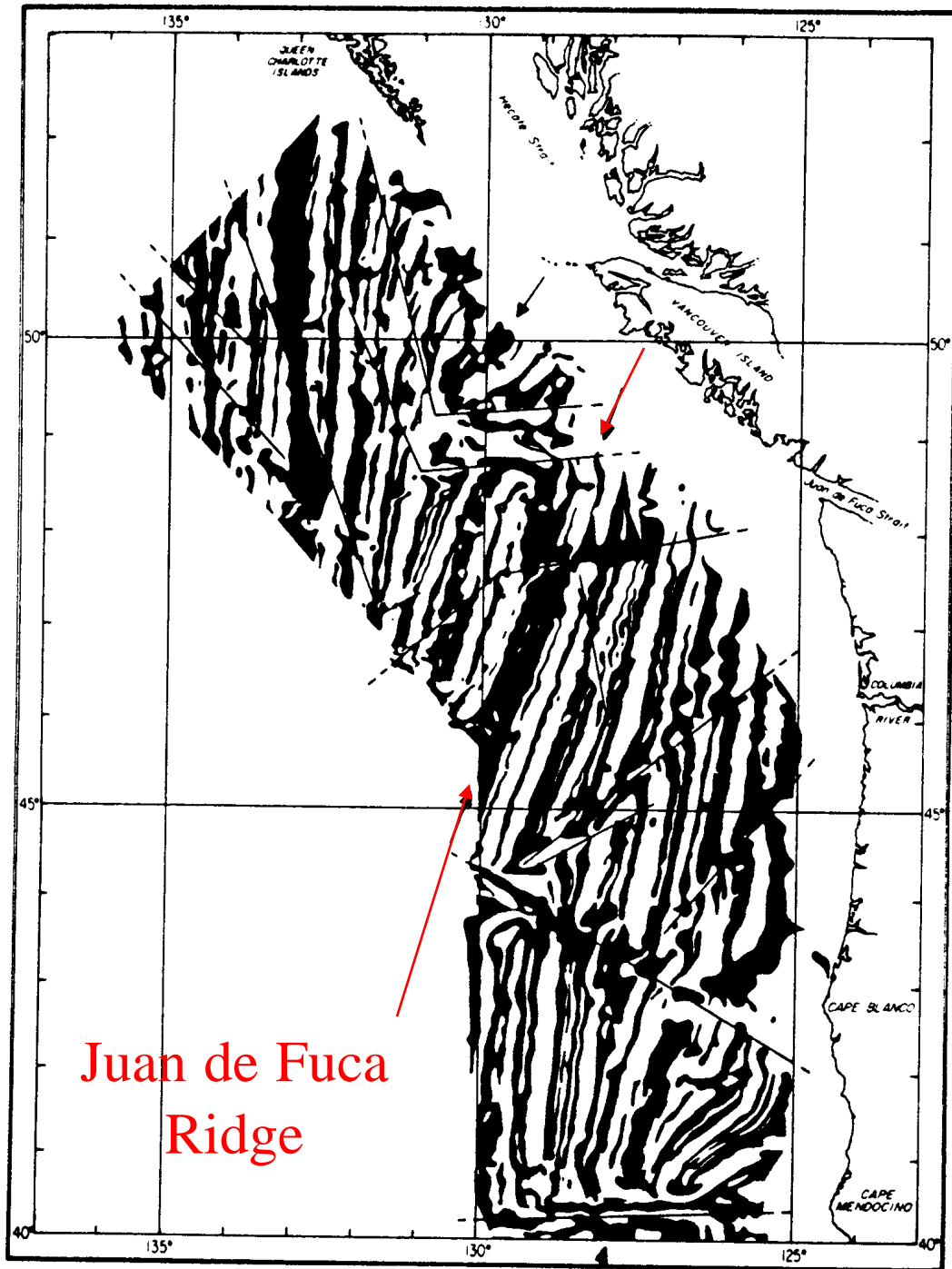
- Confirmed for some by Vine and Matthews (1963): the “*tape recorder*” model:





- Magnetic polarity reversals* were first observed by Brunhes (1906) on land.

*North magnetic pole becomes South magnetic pole and South becomes North!

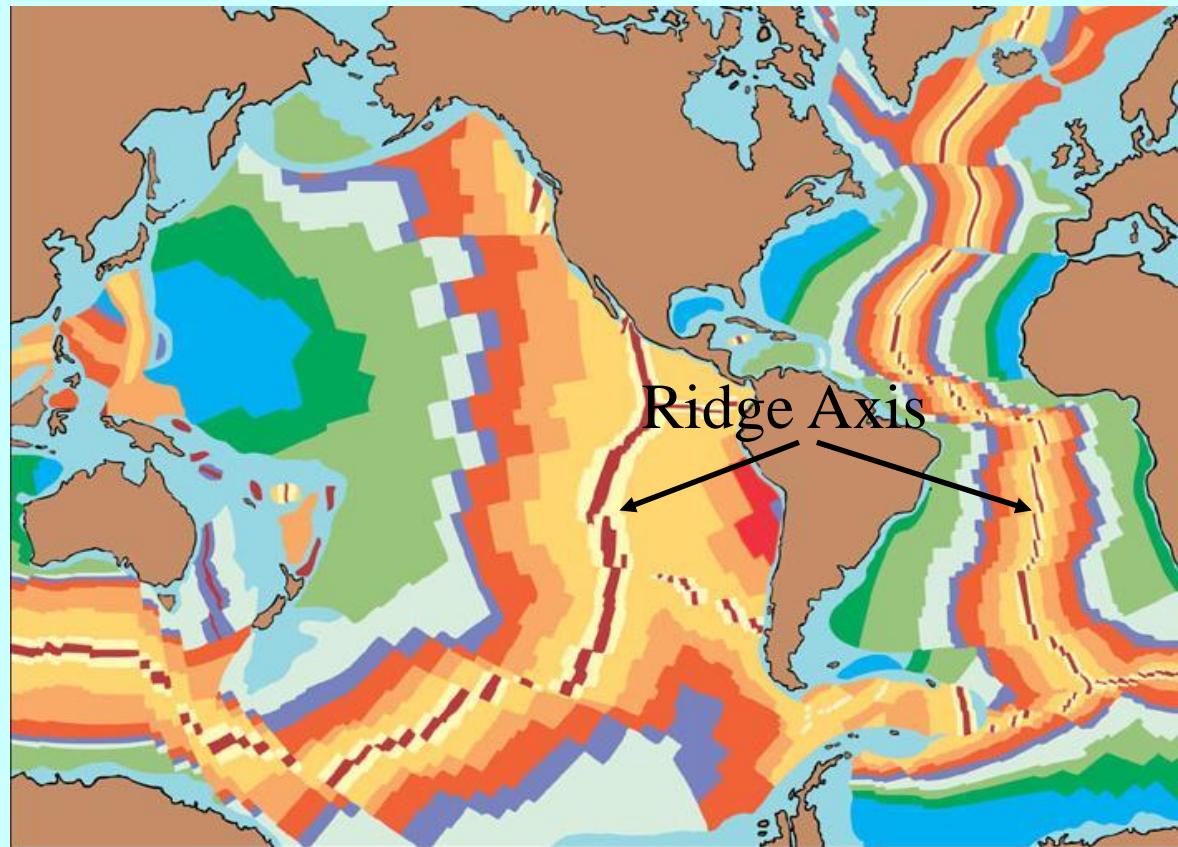


Map of seafloor
magnetic anomalies
off the coast of
Oregon and
Washington

The Juan de Fuca plate is
a small plate off the coast
of the Pacific Northwest.

Seafloor Spreading: V

- Confirmed for most geologists by DSDP (1970's): age of seafloor (crust) increases regularly with distance from the ridge axis:
a major prediction of seafloor spreading hypothesis!



Pleistocene to Recent (0–1.6 Ma)
Pliocene (1.6–5 Ma)
Miocene (5–24 Ma)
Oligocene (24–37 Ma)
Eocene (37–58 Ma)

Paleocene (58–66 Ma)
Late Cretaceous (66–88 Ma)
Middle Cretaceous (88–118 Ma)
Early Cretaceous (118–144 Ma)
Late Jurassic (144–161 Ma)

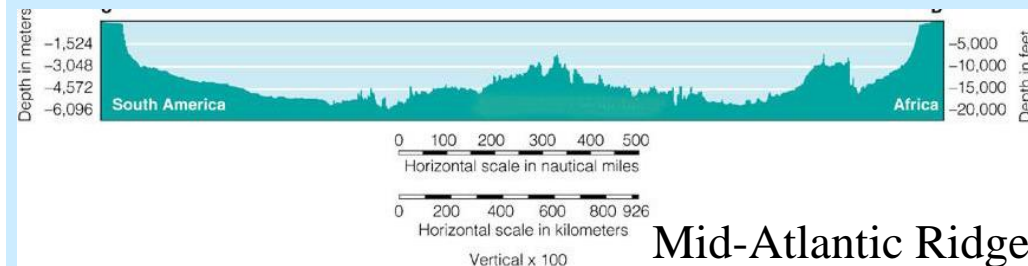
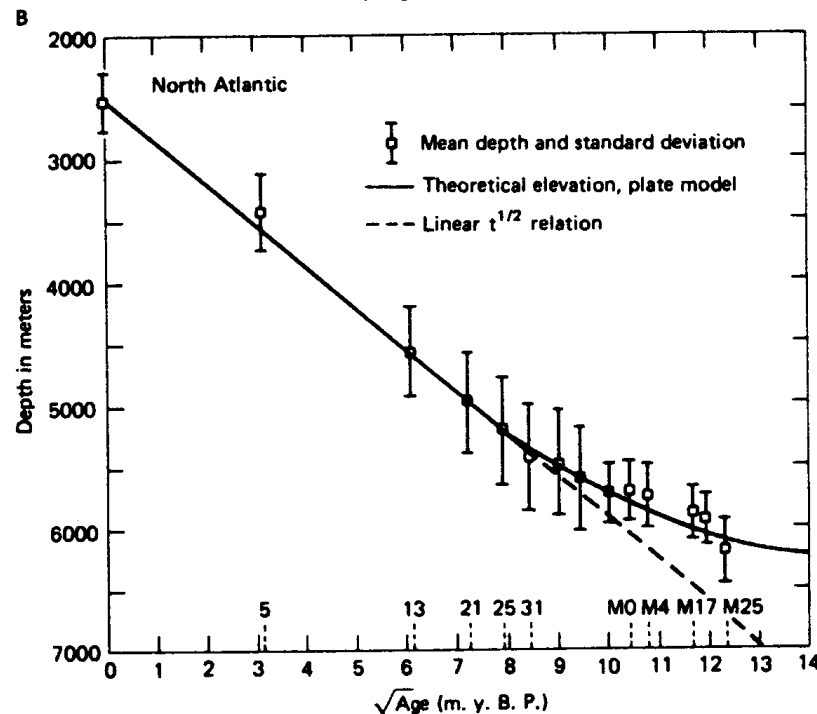
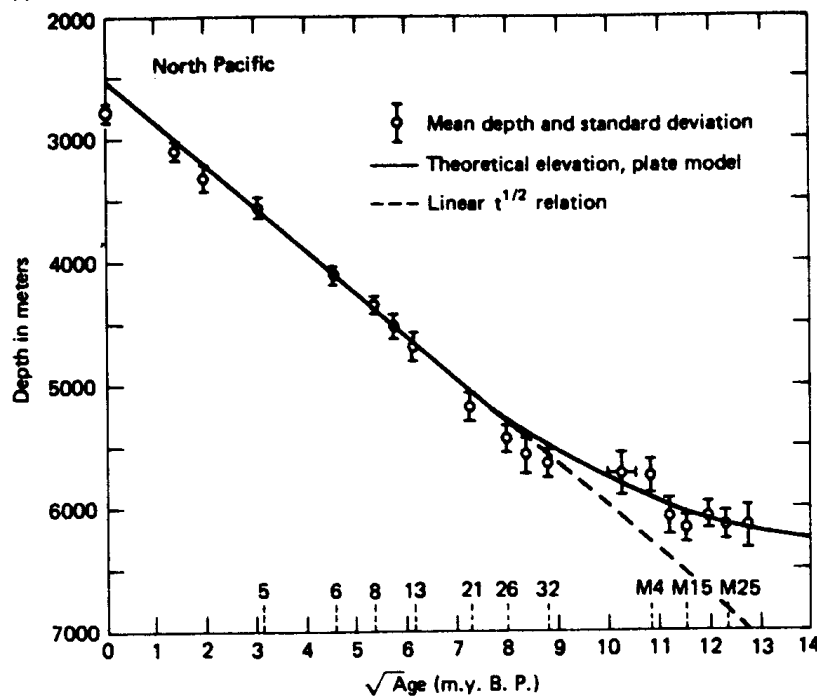
Sediment also thickens.

The major cause of change in global sea level over geologic time has been:

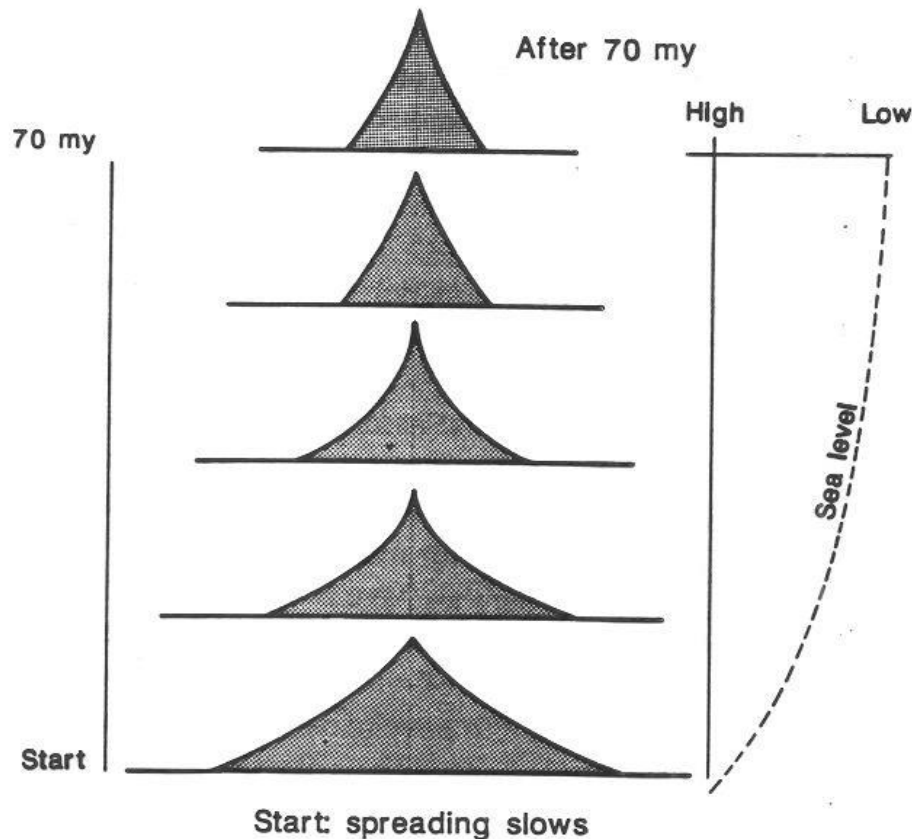
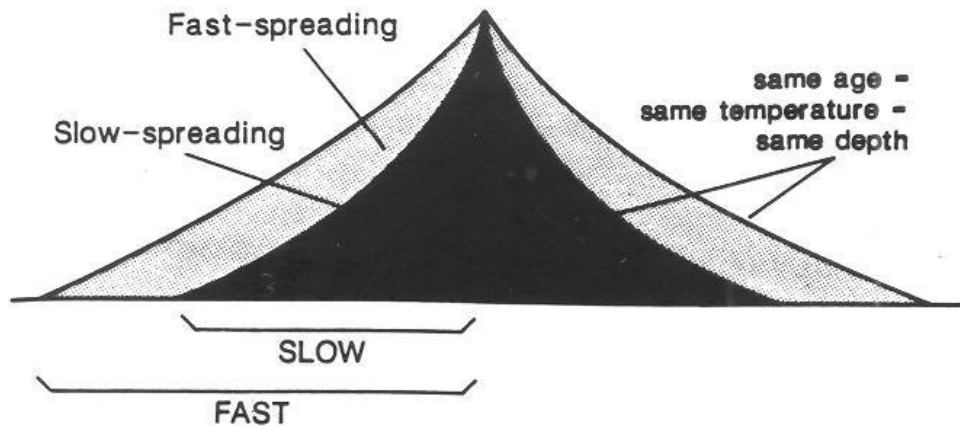
- A. Formation and melting of ice on land (Ice Ages).
- B. All land on Earth bobbing up and down at once.
- C. Change in the volume of the ocean basins.
- D. Degassing of water from Earth's interior.
- E. Noah's flood.

Volume of Ocean Basins

- Ridges are elevated because lithospheric plate is young and hot at the spreading center → thermally expanded!
- As it cools (slowly with time) it contracts, causing depth of seafloor to increase linearly with square root of the crustal age (only to ~80 Ma).



Mid-Atlantic Ridge

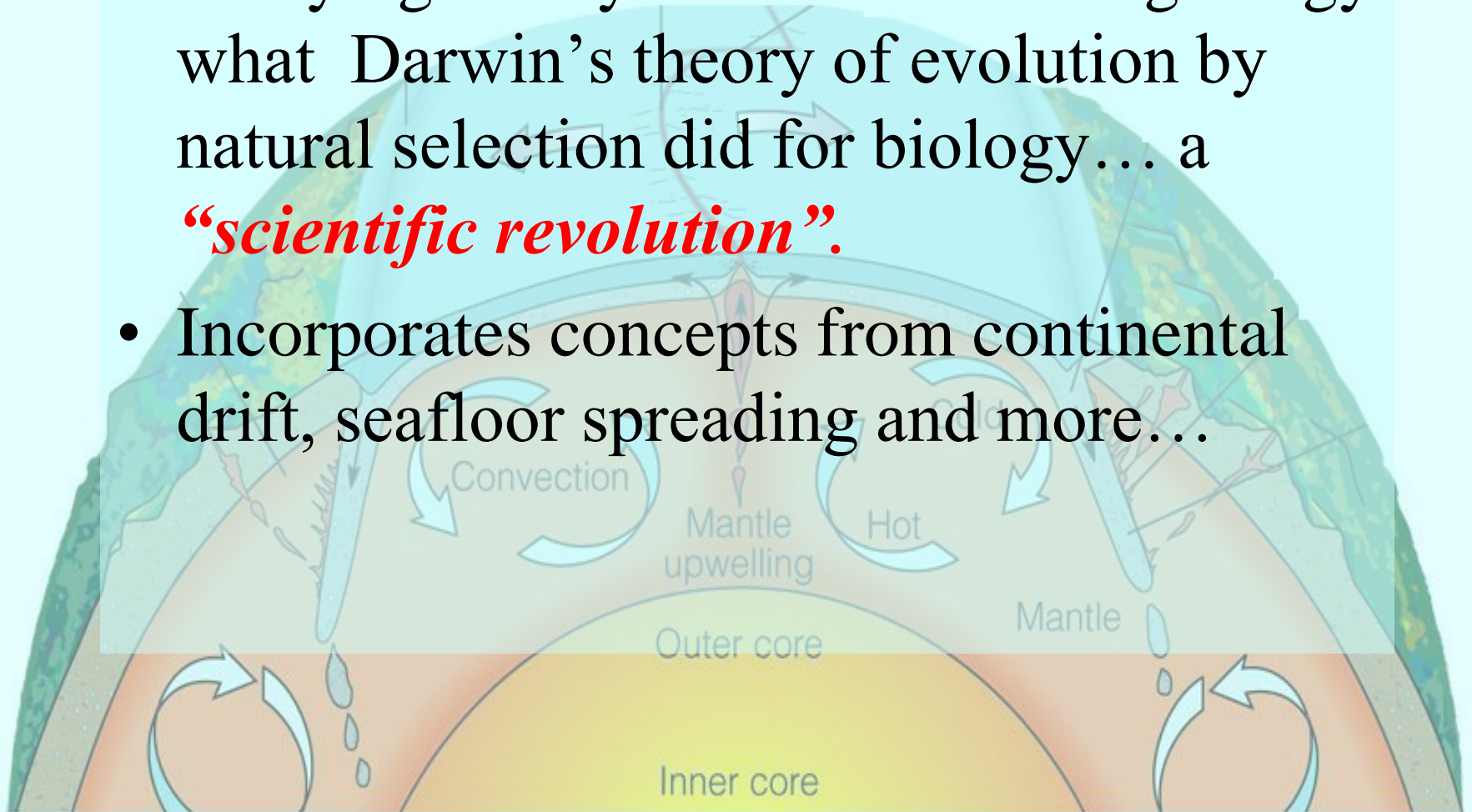


Volume of Ocean Basins

- Fast spreading means larger ridge volume
 → reduces volume of ocean basins
 → increases sea level
 → causes flooding of continents (on time scale of million yrs)
 → *large sea level change!*

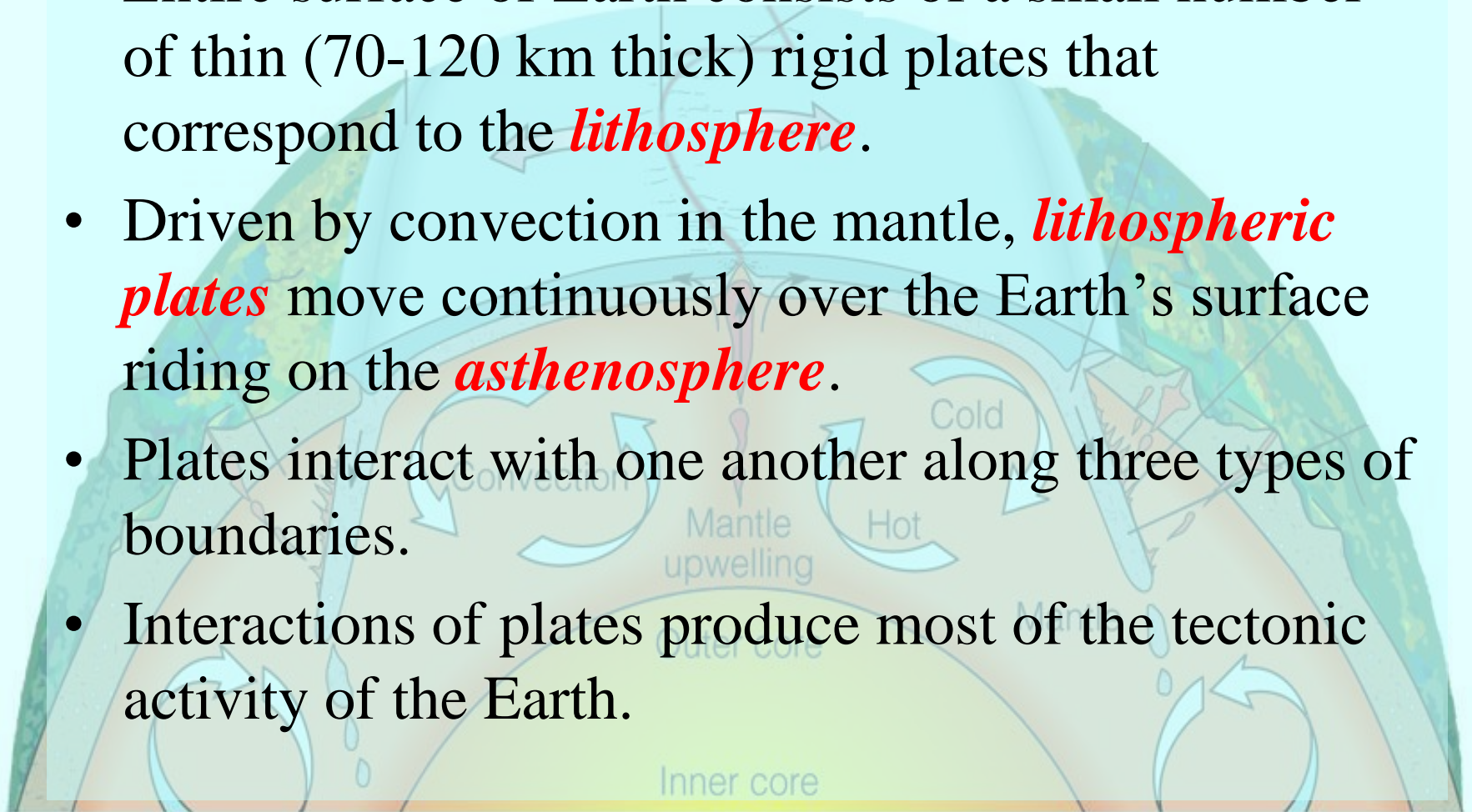
Theory of Plate Tectonics: I

- Unifying theory that has done for geology what Darwin's theory of evolution by natural selection did for biology... a *“scientific revolution”*.
- Incorporates concepts from continental drift, seafloor spreading and more...



Theory of Plate Tectonics: II

- Entire surface of Earth consists of a small number of thin (70-120 km thick) rigid plates that correspond to the *lithosphere*.
- Driven by convection in the mantle, *lithospheric plates* move continuously over the Earth's surface riding on the *asthenosphere*.
- Plates interact with one another along three types of boundaries.
- Interactions of plates produce most of the tectonic activity of the Earth.

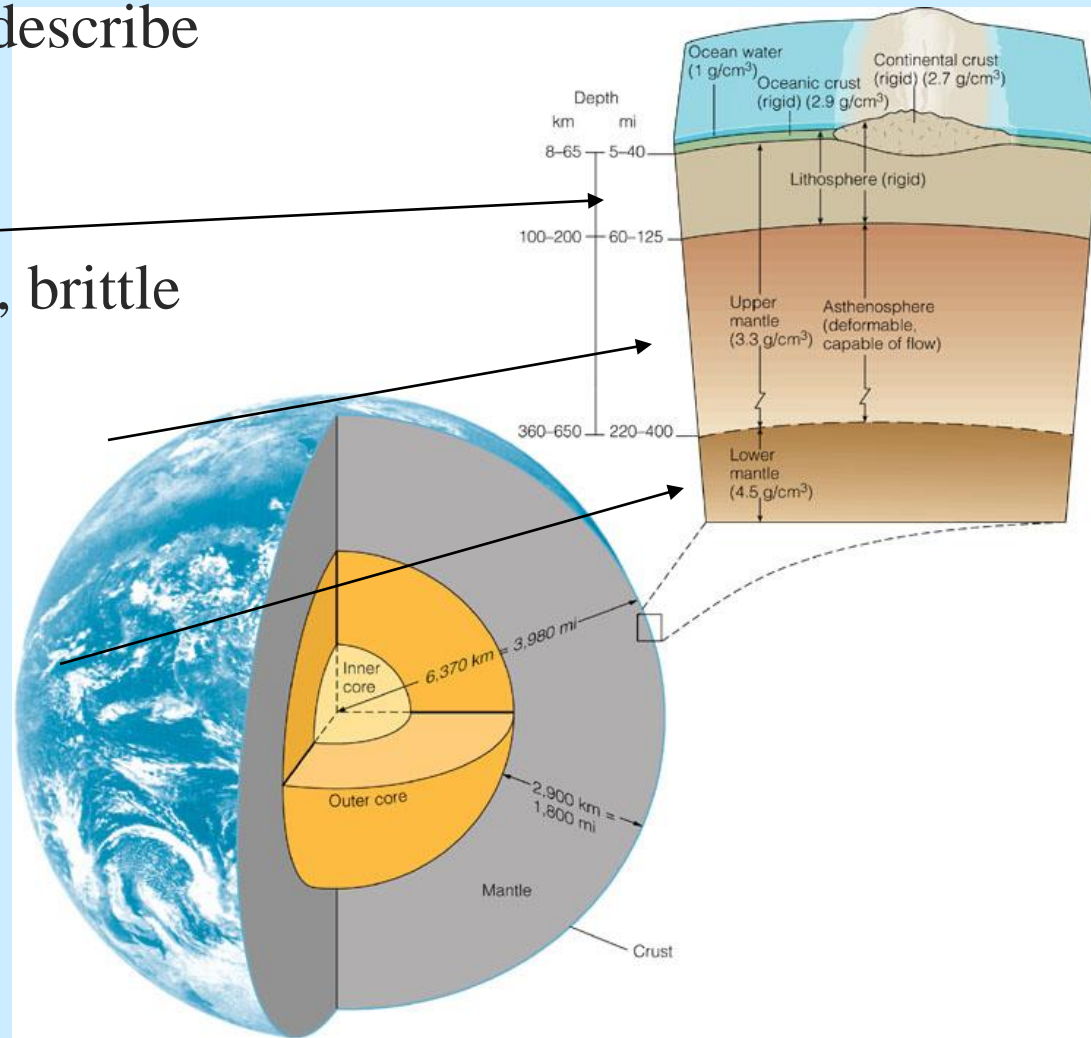


Internal Structure of the Earth

(based on physical properties)

Use viscosity and strength to describe outer layers:

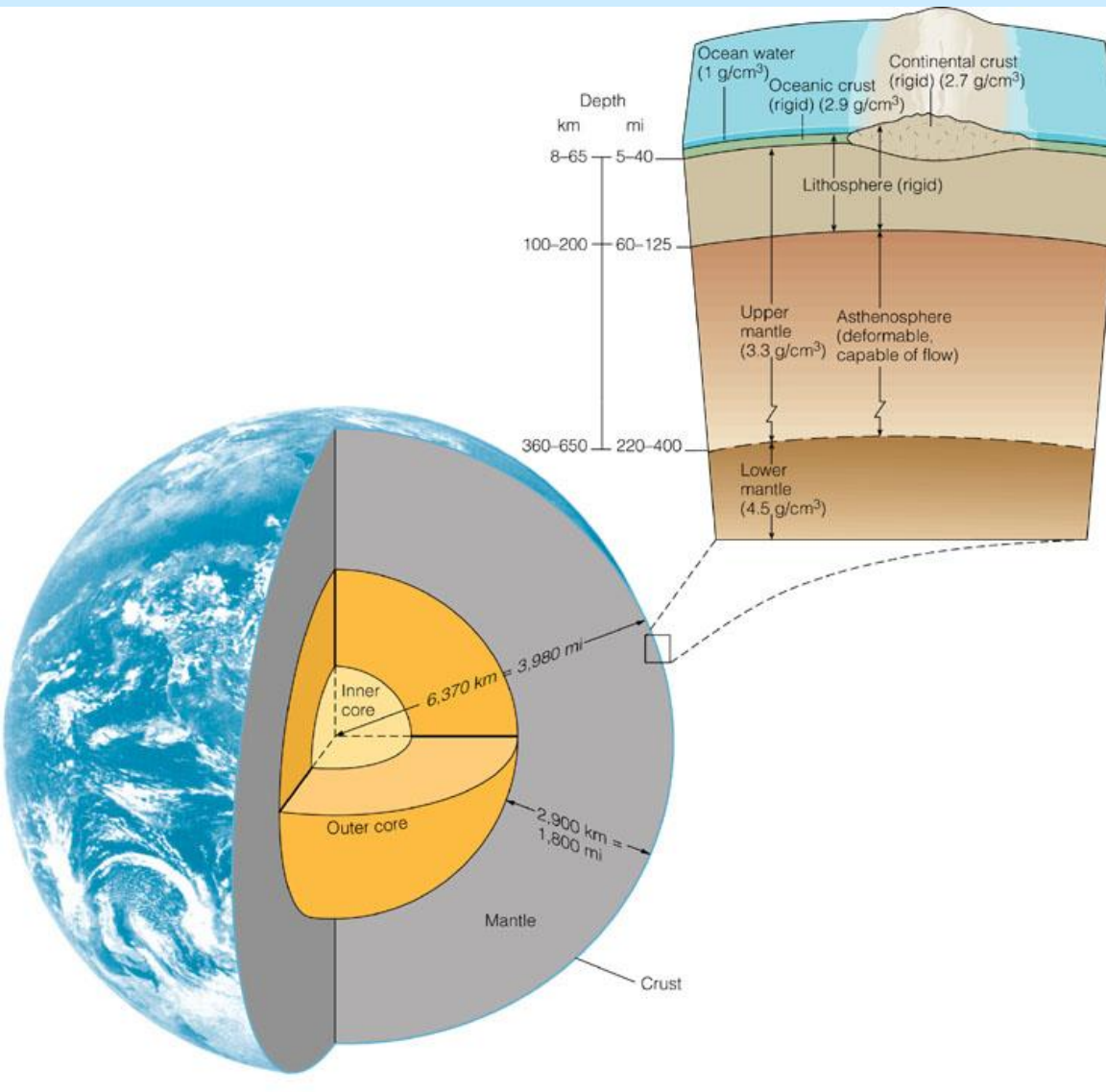
- **Lithosphere:** 0-100 km
= mantle + crust: rigid, brittle
- **Asthenosphere:** 100-700 km
= mantle: soft, plastic
- **Lower Mantle:**
700-2900 km



Internal Structure of the Earth

- The ***lithosphere*** (“rocky sphere”) is cool, rigid, brittle (earthquakes!), can support loads, and includes the crust and uppermost mantle, ~100 km thick: the *Plates* of plate tectonics.
- The ***asthenosphere*** (“soft sphere”) is solid but near its melting point; it deforms plastically (no earthquakes!)
- Upper asthenosphere (100-230 km) is thought to contain ~1% melt.
- Upper asthenosphere is the zone of ***isostatic compensation*** and a zone of melting to produce the oceanic crust.
- The ***lower mantle*** extends to the core and is more rigid than the asthenosphere.

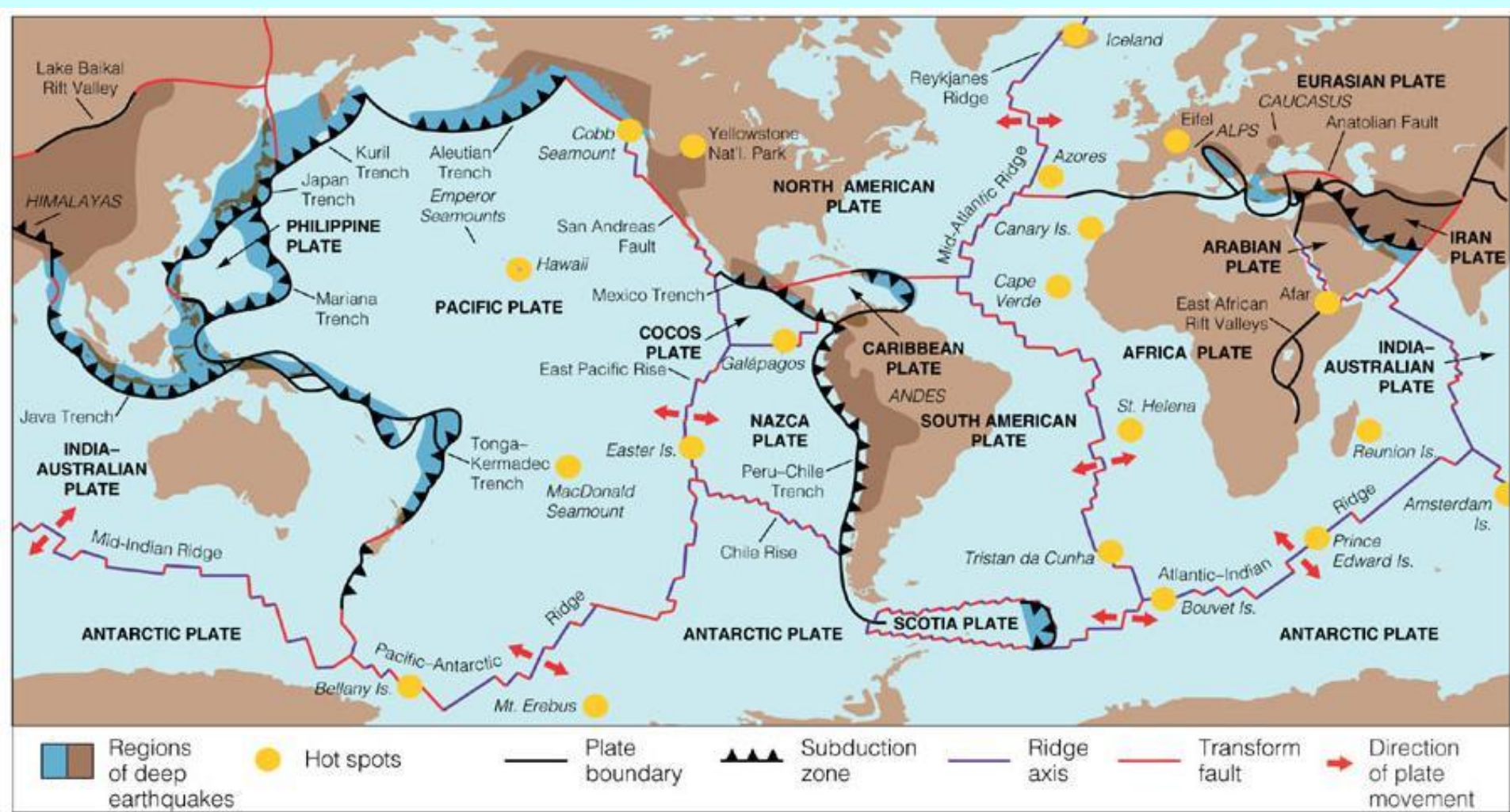
Earth's Lithosphere = Plates



Crust is only the outer part of the lithosphere; most of the lithosphere is upper mantle.

Oceanic crust ~ 6 km thick
Continental crust ~ 35 km
Lithosphere ~ 100 km

Lithospheric Plates



~8 large plates and ~6 smaller plates

The motion of lithospheric plates across Earth's surface is caused by:

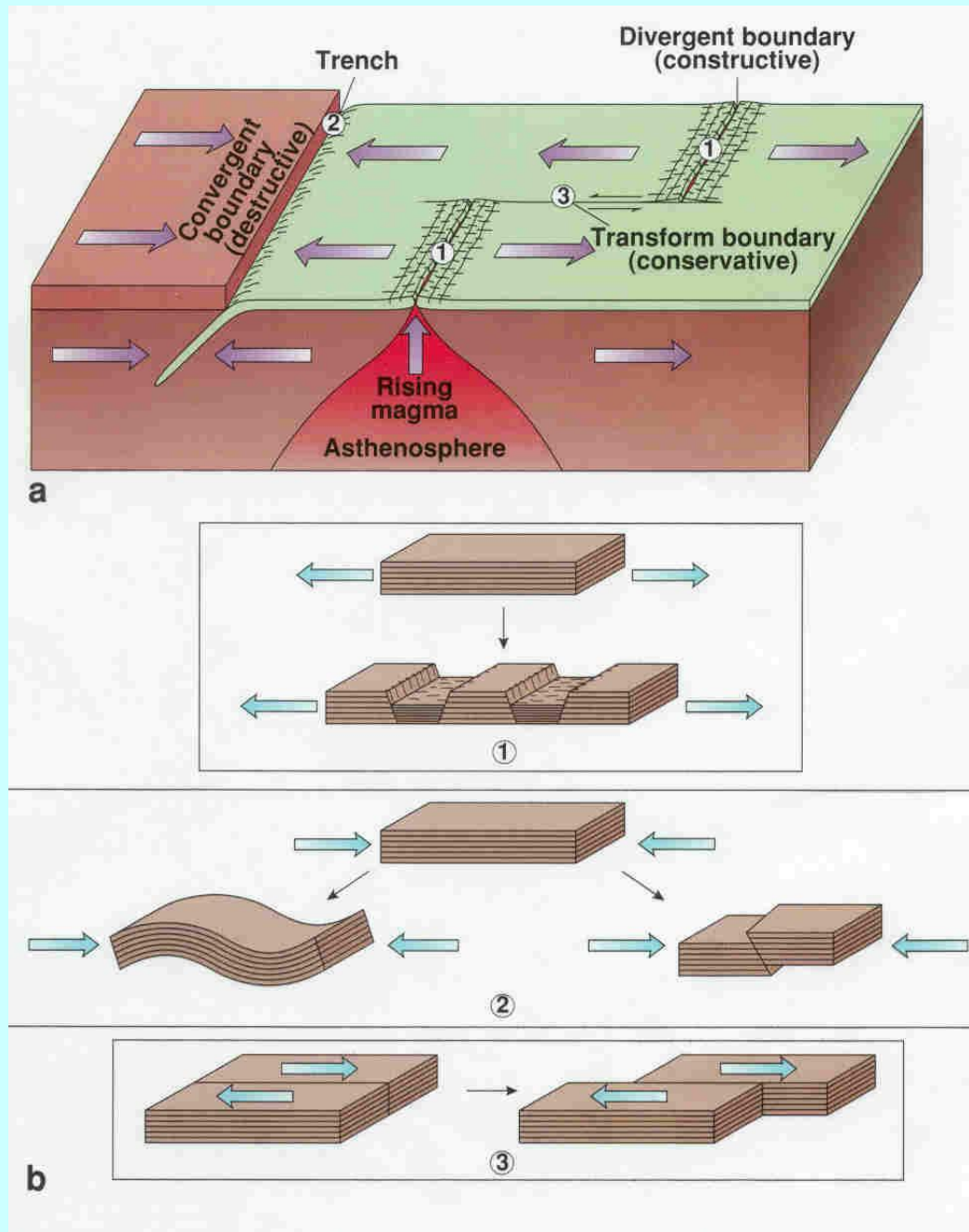
- A. The Geodynamo
- B. Polflucht: centrifugal force and Earth's rotation
- C. Convection in Earth's mantle
- D. The shrinking Earth
- E. Continental drift.

Plate Boundaries:

3 types:

1. Constructional or divergent
(*mid-ocean ridges*)
2. Destructional or convergent
(*subduction zones*)
3. Conservative
(*transform faults*)

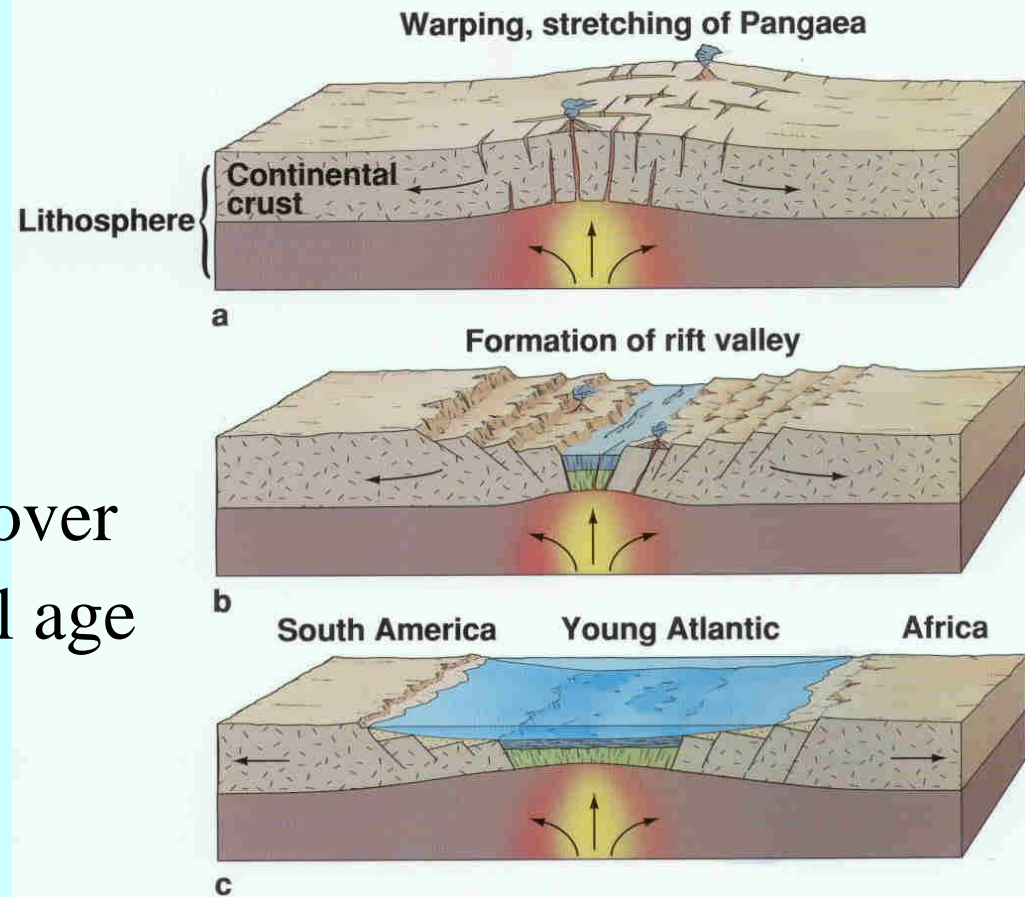
Earth's area is fixed, so construction must balance destruction!



Constructional Plate Boundaries

The *mid-ocean ridges*,
seafloor spreading axes:

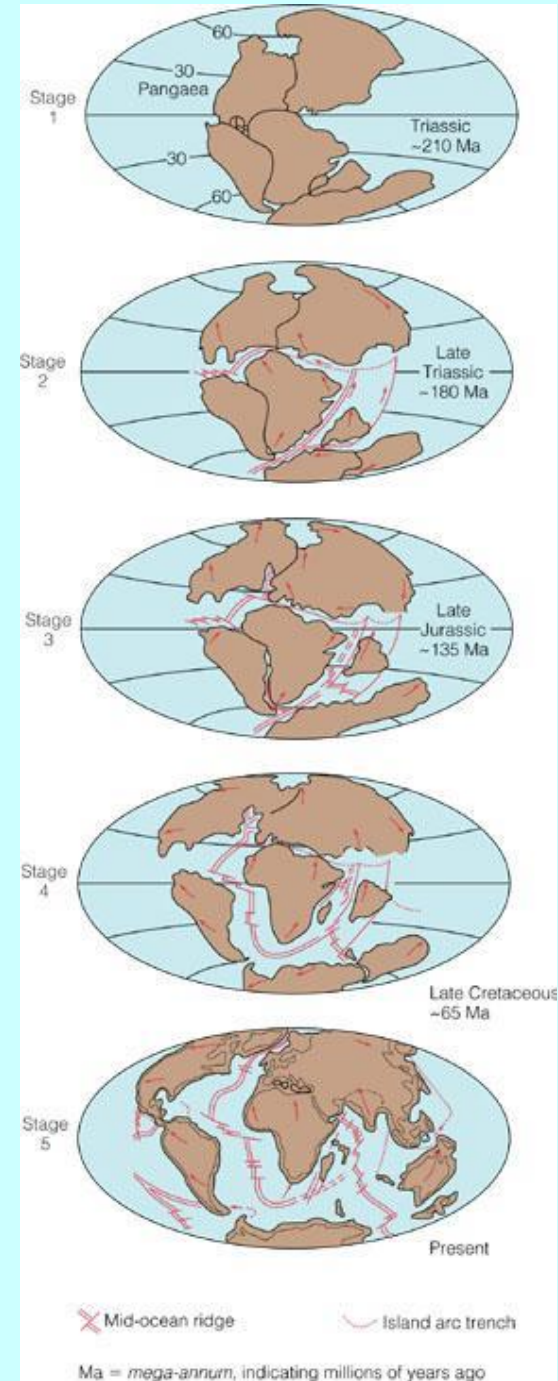
- Shallow seismicity
- Basaltic volcanism
- High heat flow
- Absent to thin sediment cover
- Zero to very young crustal age
- Tensional stress, produces rifting
- $\frac{1}{2}$ spreading rates
= plate velocities = 1-8 cm/yr



Breakup of Pangaea

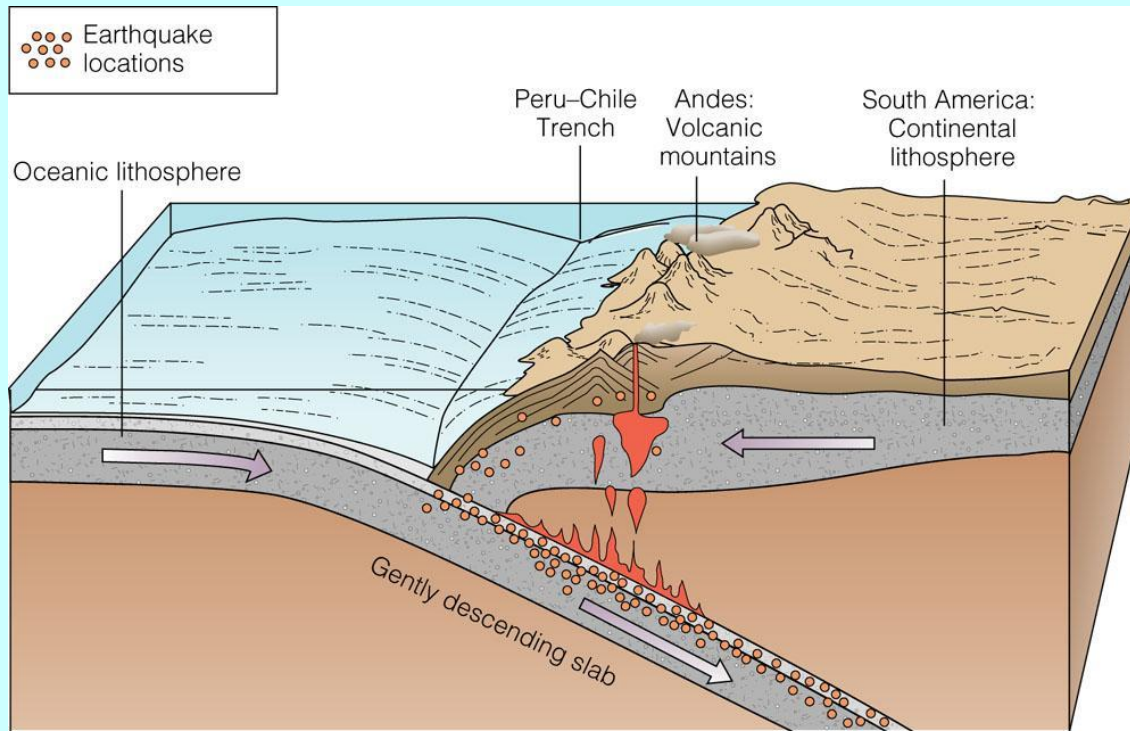


- Comparable to current day situation in East African Rift.
- Demonstrates how initiation of seafloor spreading leads to formation of new ocean basins.



Destructive Plate Boundaries: I

1. Deep sea trench
2. Deep earthquakes
3. Andesitic volcanism
4. Low heat flow at trench
5. High heat flow under volcanic arc
6. Thick sediment cover
7. Old crustal age
8. Compressional stress, produces folding and thrust faulting

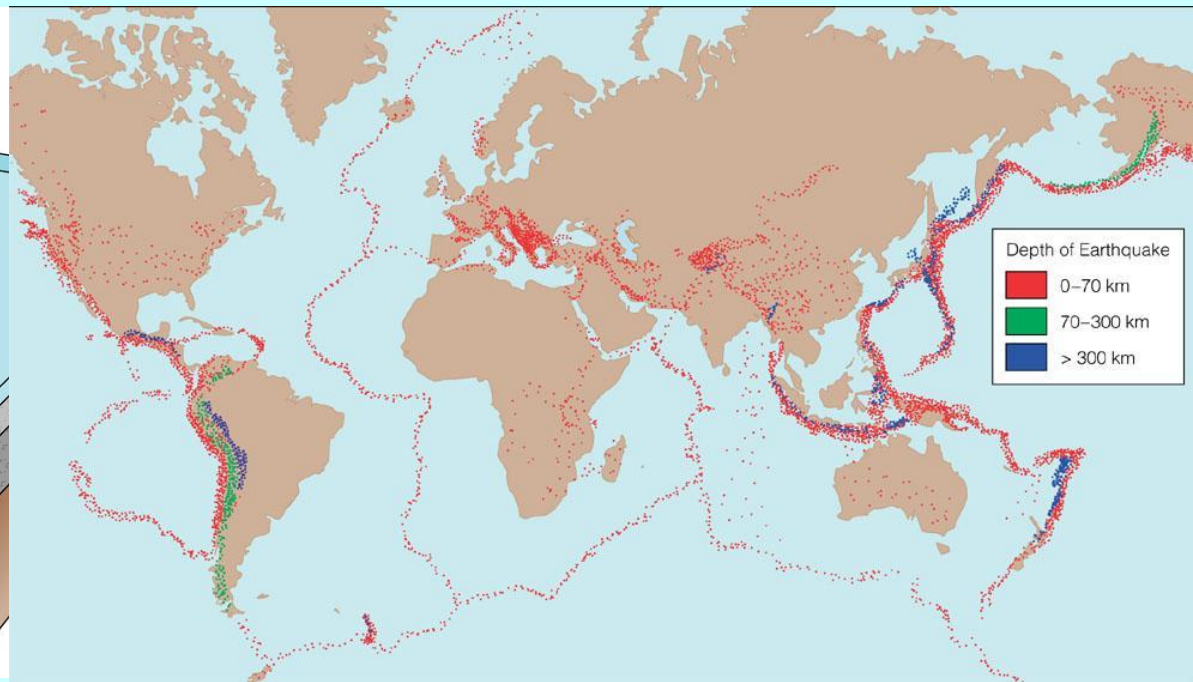
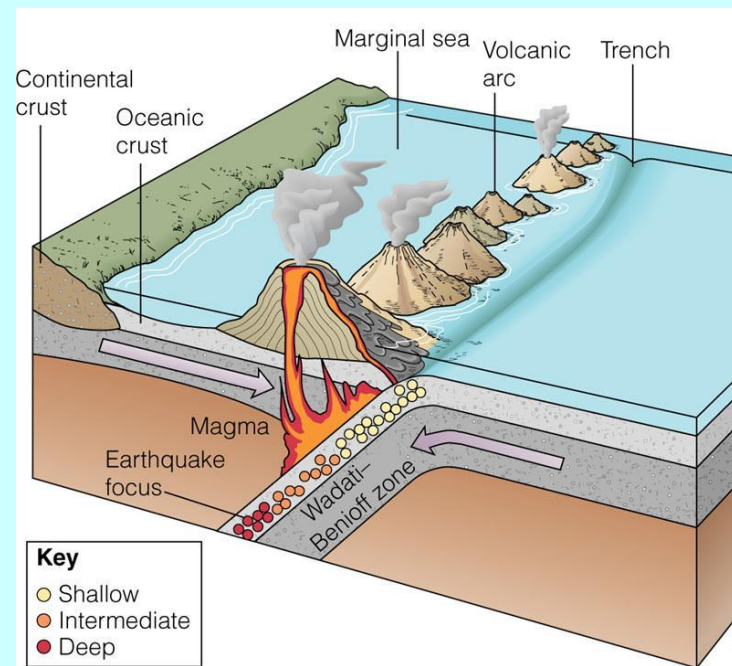


=

Subduction Zone

Destructive Plate Boundaries: II

- Oceanic plate is *subducted* into the mantle at trenches below continental (e.g. Peru) or oceanic (e.g. Tonga) plate.
- The downgoing plate is characterized by a zone of earthquakes (Wadati-Benioff zone) that can be very deep.



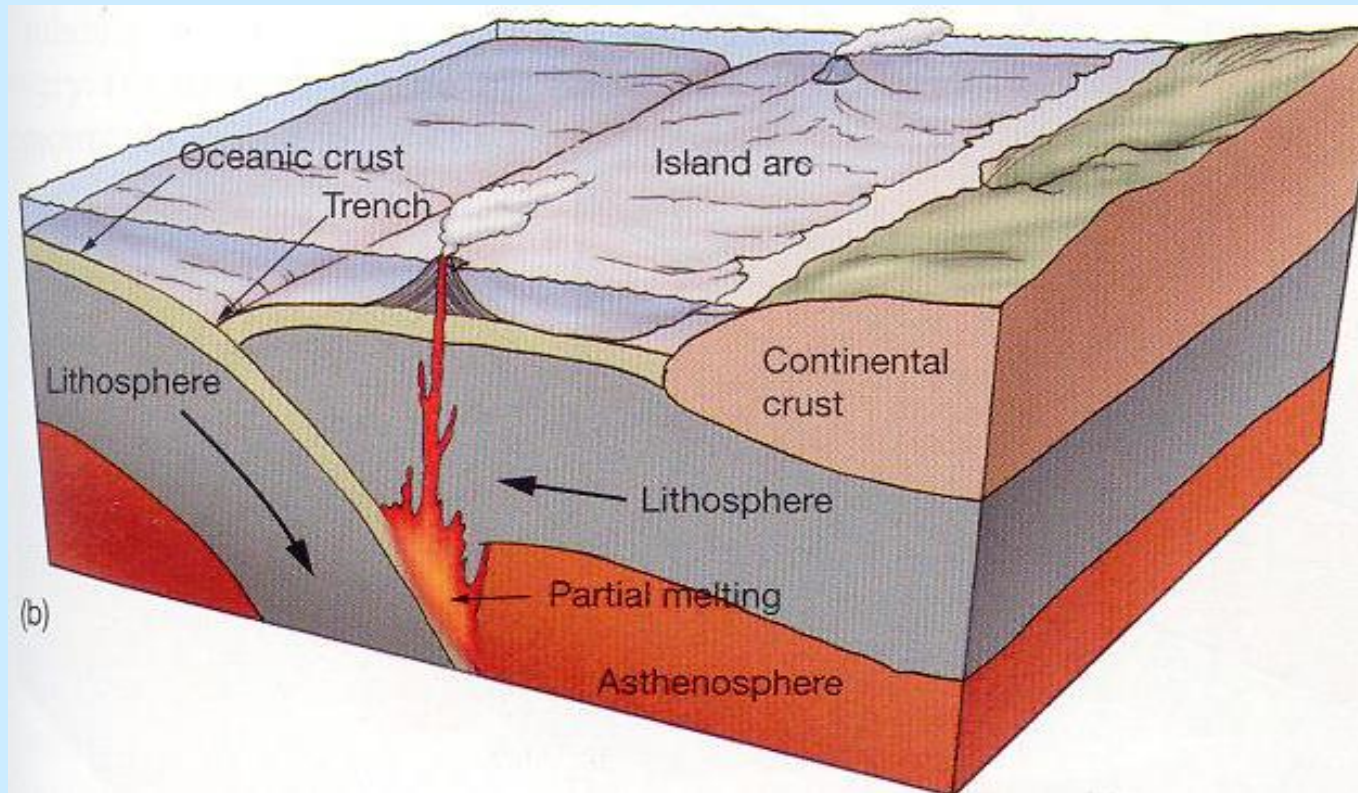
3 Types of Destructive Boundaries

(based on two kinds of crust surfacing the plates)

1. *Oceanic-Oceanic*
2. *Oceanic-Continental*
3. *Continental-Continental*

3 Types of Destructive Boundaries

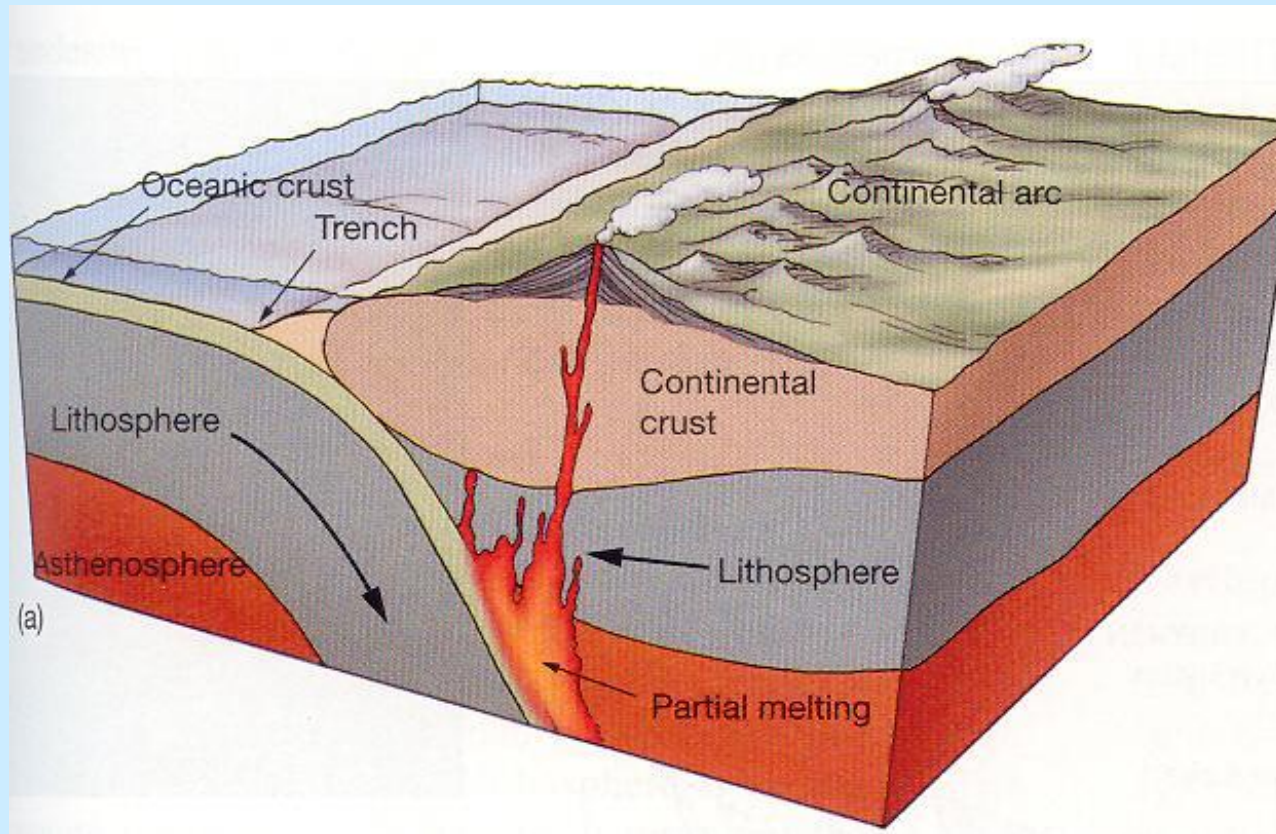
1. *Oceanic-Oceanic*: volcanic island arc above the downgoing slab (e.g., Aleutians, Indonesia, Marianas)



Subduction could go either way; volcanic arc lies above *subducting* plate.

3 Types of Destructive Boundaries

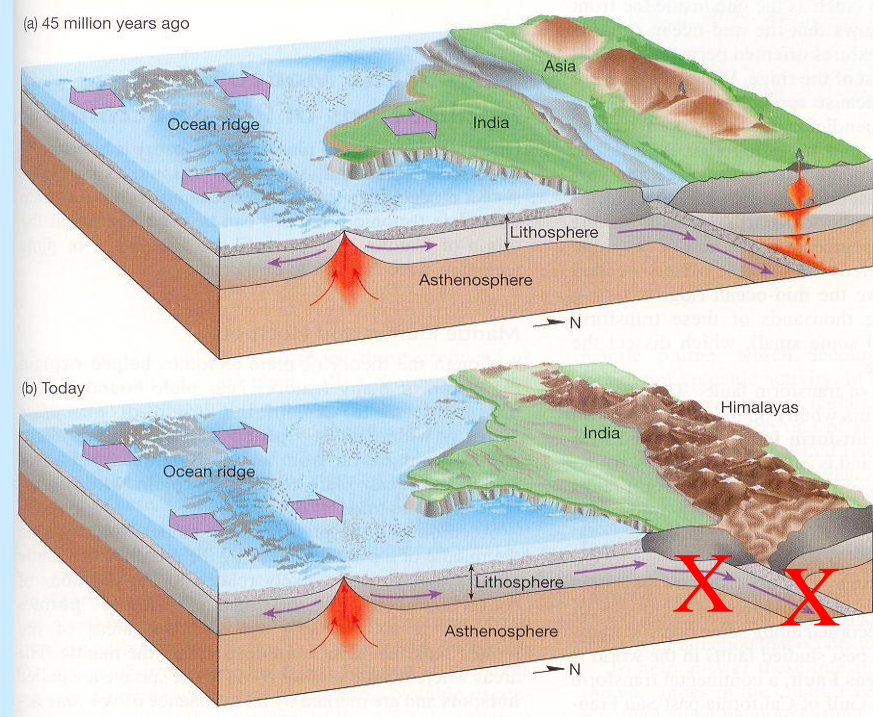
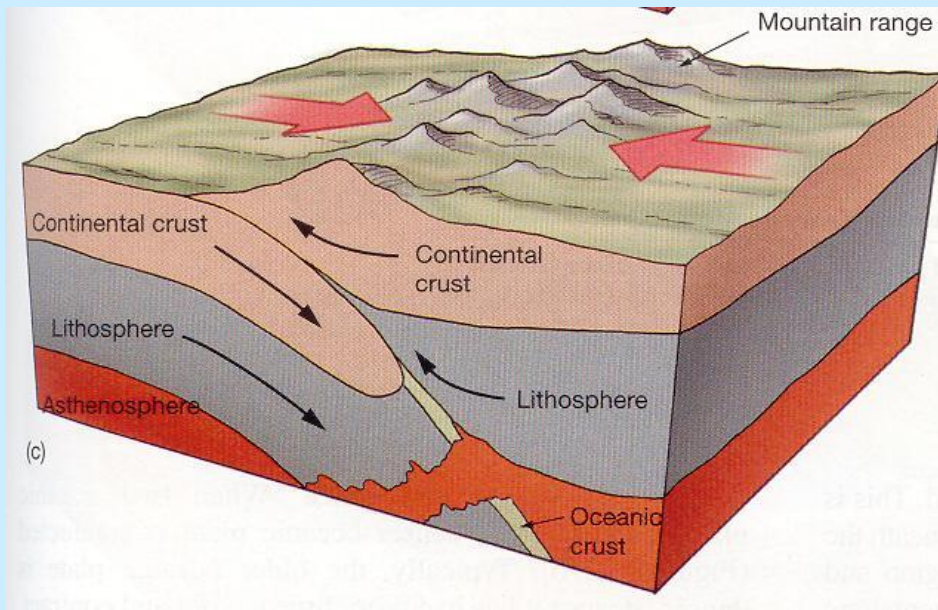
2. ***Oceanic-Continental***: volcanic arc at edge of continent (e.g., Peru-Chile)



Continental crust is too buoyant to subduct!

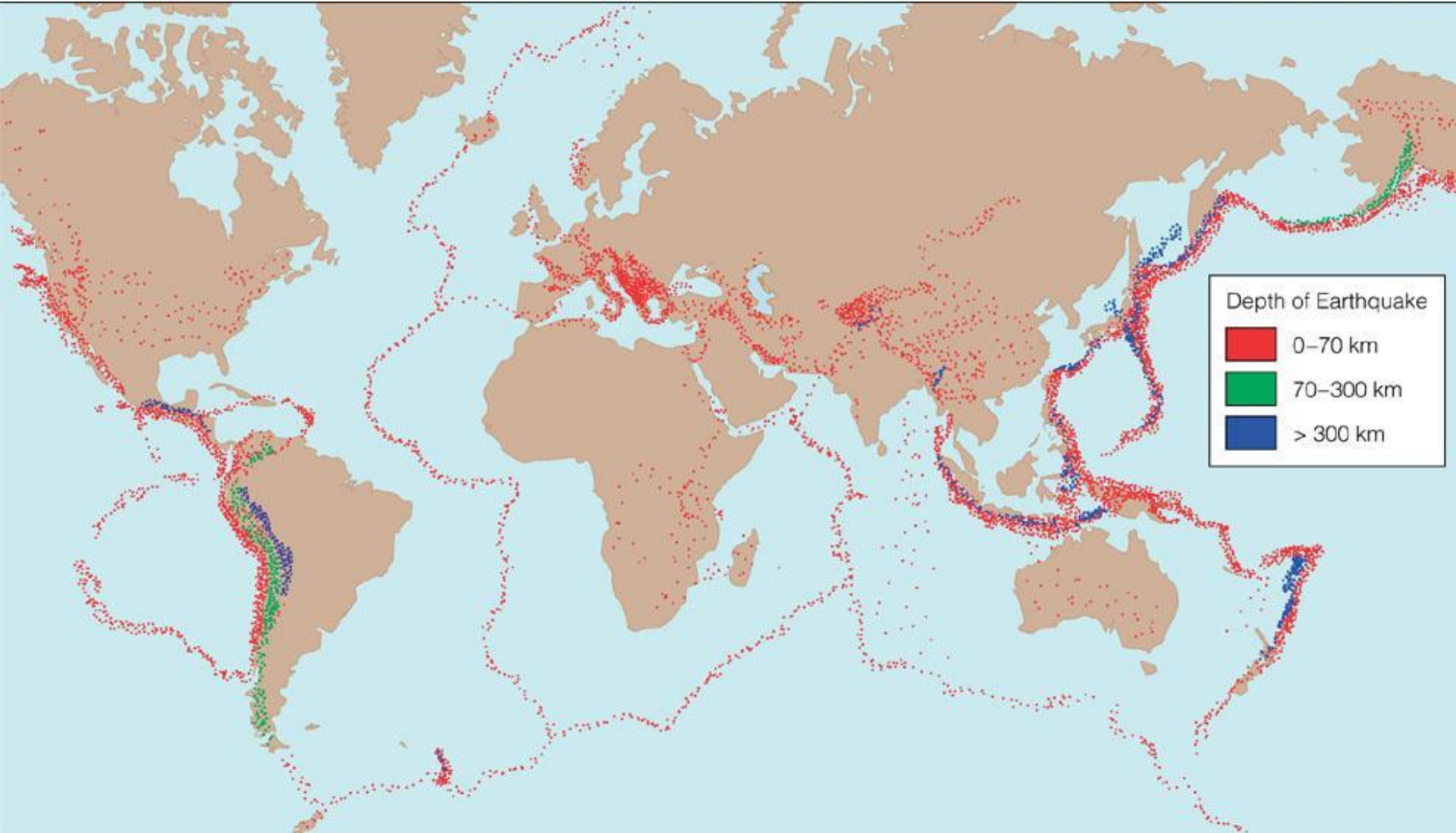
3 Types of Destructive Boundaries

3. Continental-Continental: produces crust up to twice as thick as normal and a correspondingly high mountain plateau (e.g., Tibet, Himalayas).



Continental crust is too buoyant to subduct. Plate breaks off and subduction stops, causing a global change in plate motions.

Global Earthquake Distribution



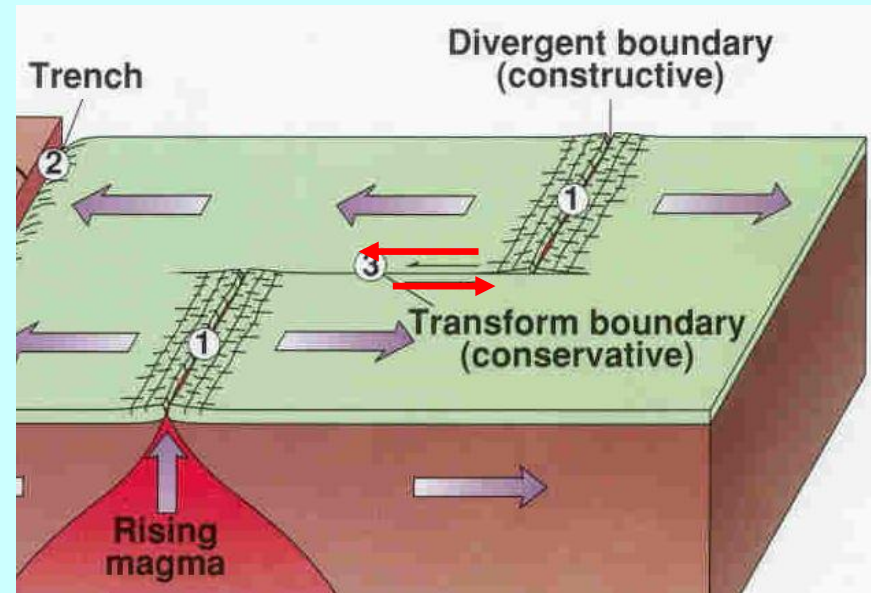
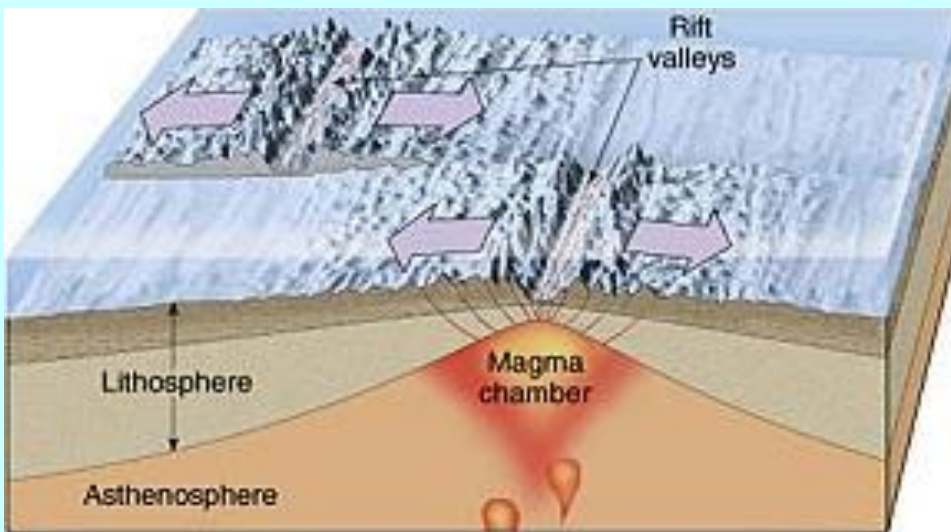
Not all earthquakes occur along plate boundaries.

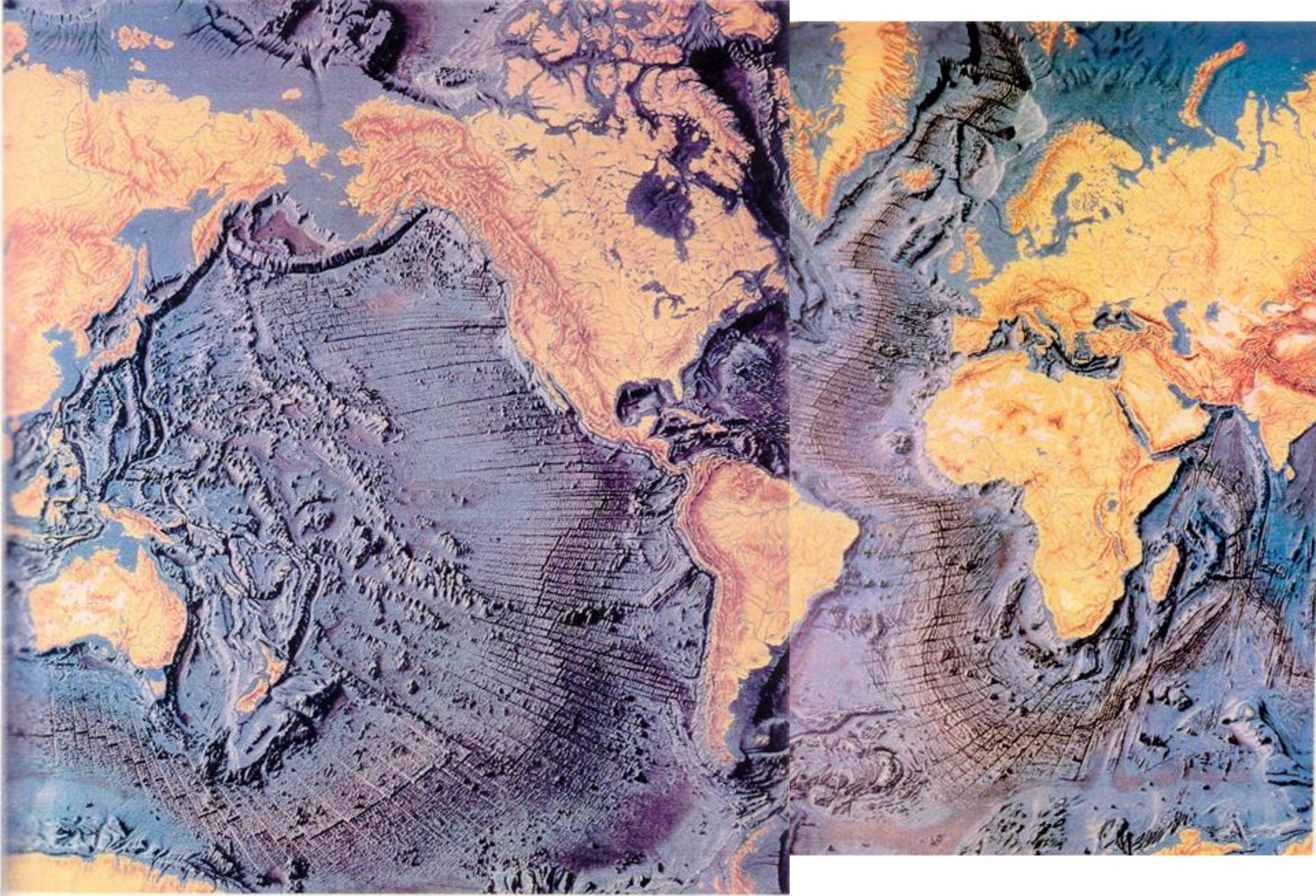
Deep earthquakes occur:

- A. Only in brittle material.
- B. Within the lithosphere and not within the asthenosphere.
- C. To a maximum depth of ~700 km.
- D. Within subduction zones.
- E. All of the above.

Conservative Boundaries: Transform Faults

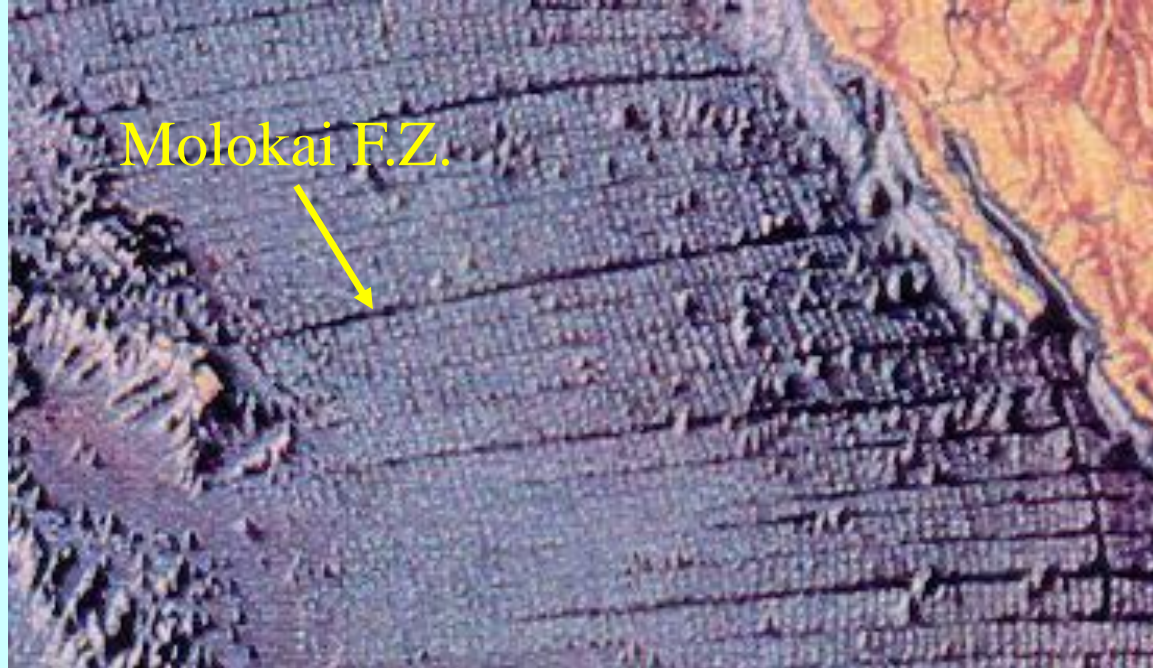
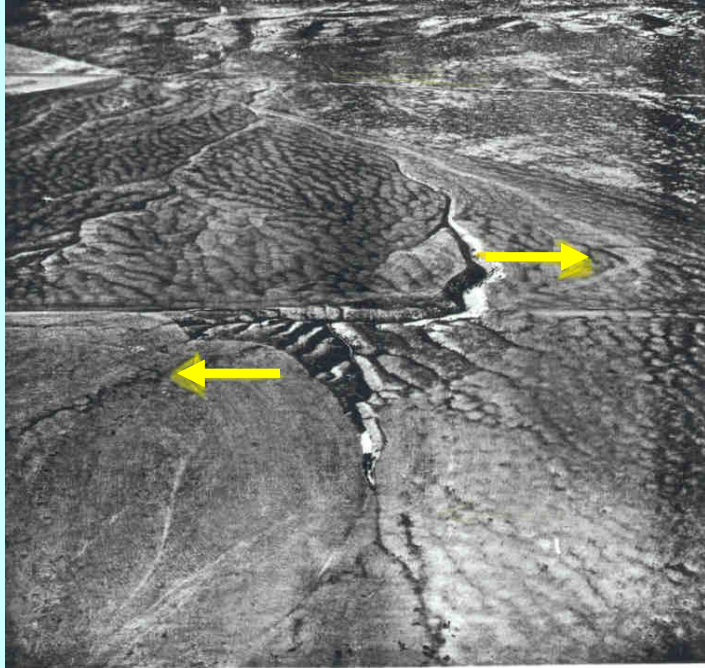
- Active zone of movement along a vertical fault plane located between two offset segments of ridge axis
- Relative motion is in opposite direction to that which would have produced such an offset in the absence of seafloor spreading.





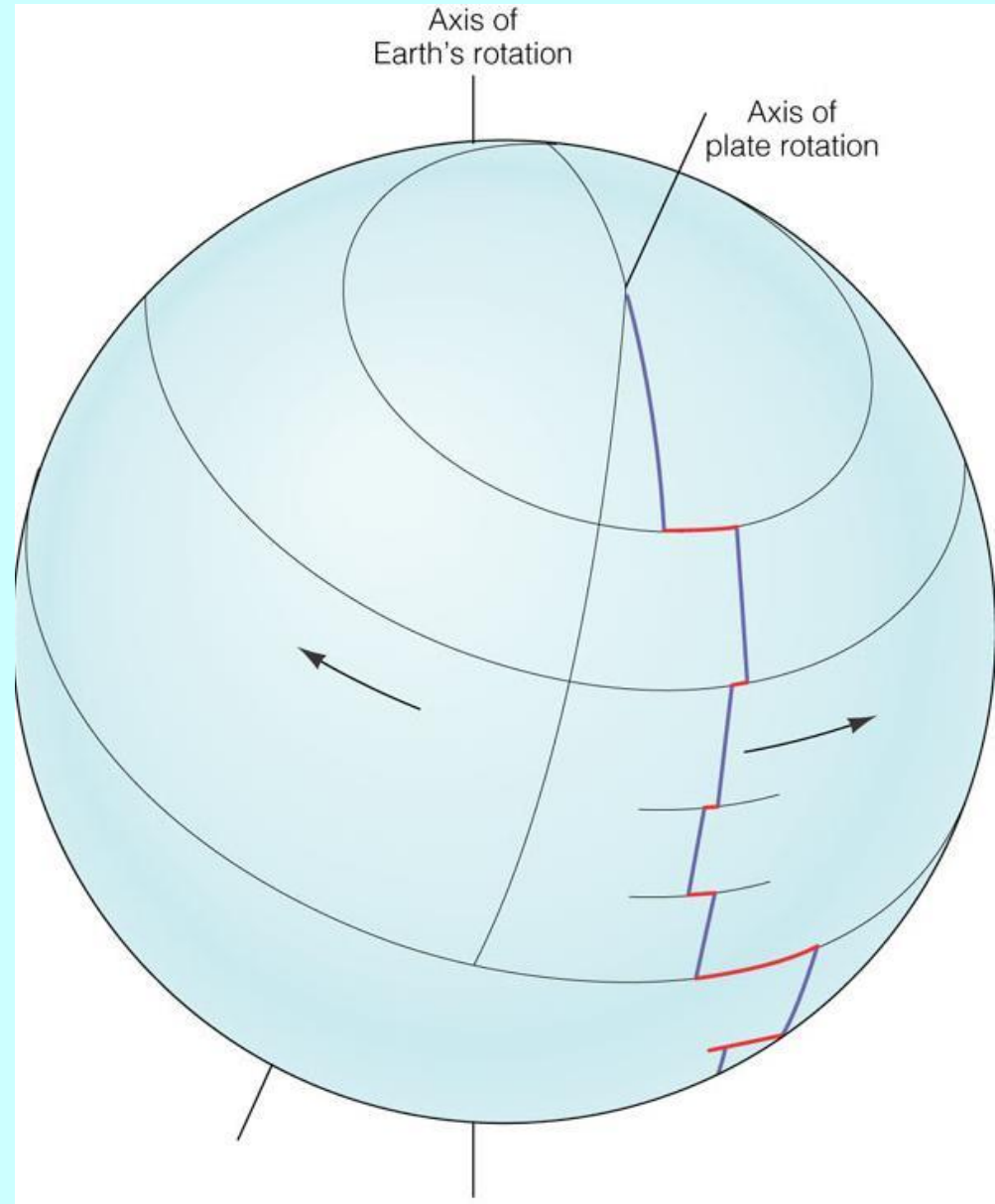
Conservative Boundaries: Transform Faults

- Outside active transform region (not part of plate boundary), crust formed by offset segments becomes welded together to form the *trace* of the transform fault. Entire structure is called a *Fracture zone*.



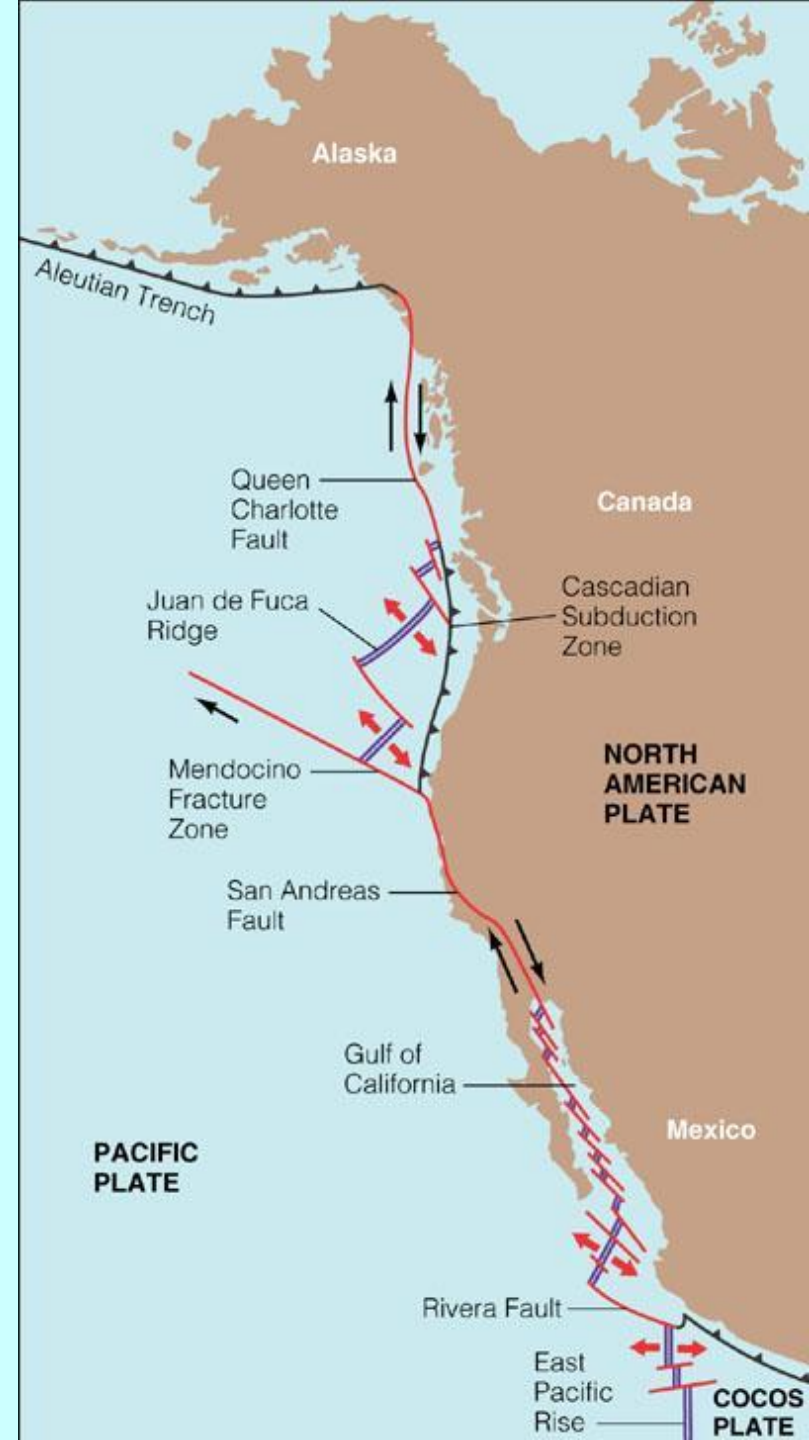
Fracture Zones and Poles of Rotation

- Fracture zones lie on “small circles” on the Earth’s surface (analogous to circles of latitude).
- These circles are located about the pole of rotation for the relative motion of two plates.
- The pole of rotation is located at the intersection of the “great circles” (analogous to lines of longitude) drawn perpendicular to the transform faults along the boundary of the two plates.



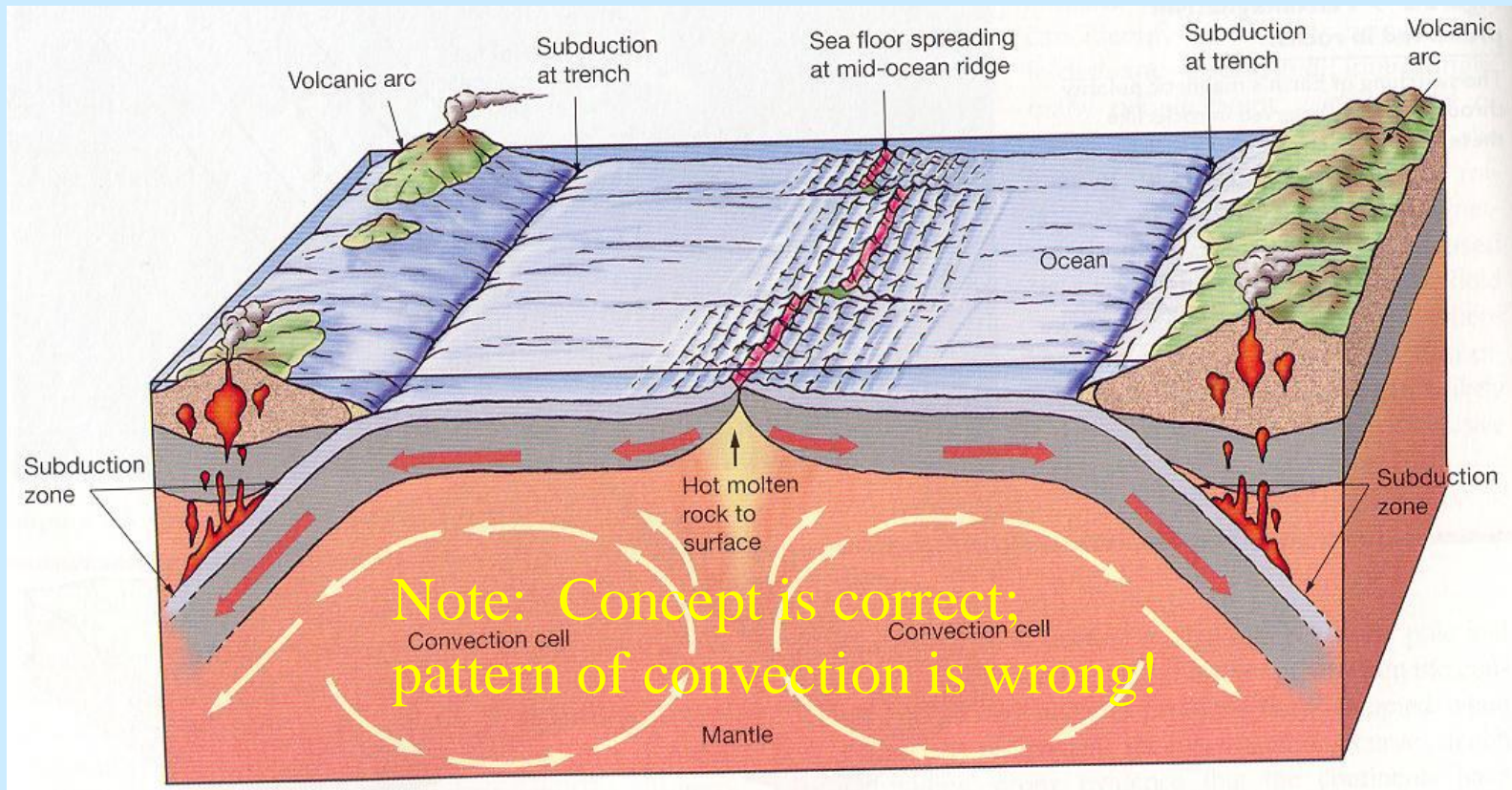
Transform Fault Plate Boundaries

- One of the best known transform faults is the *San Andreas Fault* in California.
- It marks the boundary between the North American Plate, moving westward at ~ 1 cm/yr, and the Pacific Plate, moving northwestward at ~ 8 cm/yr.



What drives Plate Tectonics?

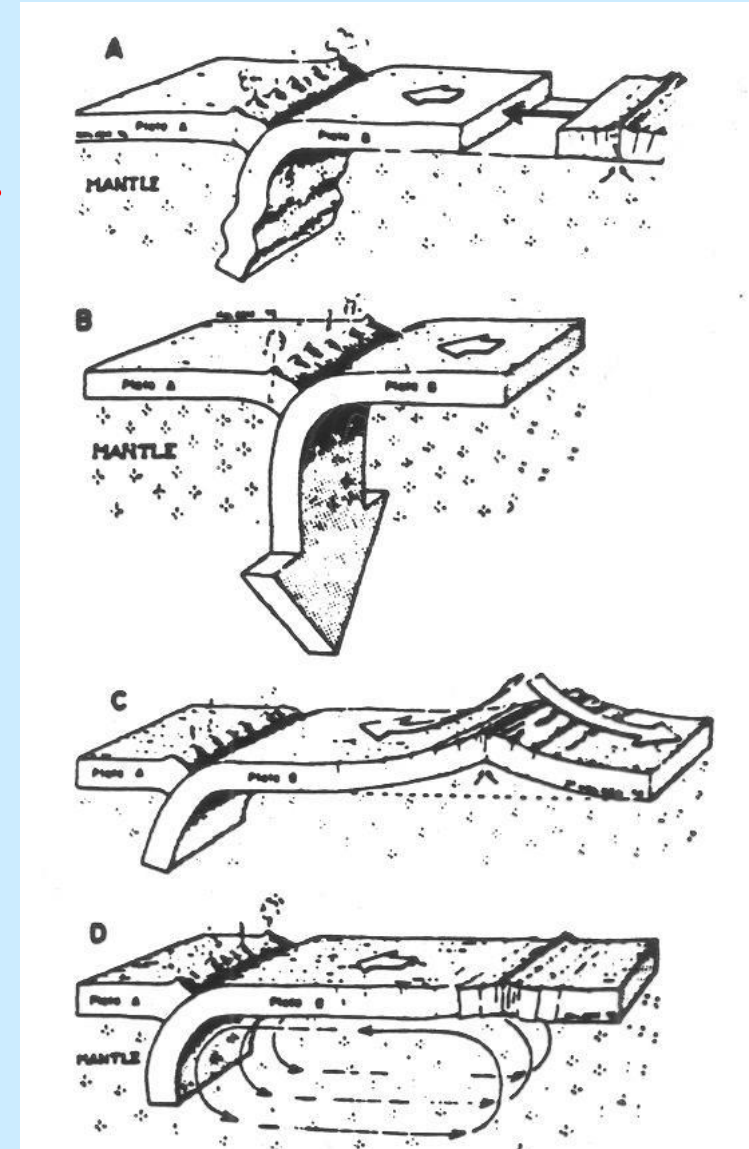
- Ultimate driving force: *Convection of Earth's mantle*
- New crust is formed at MOR, spreads laterally “on conveyor belt”.
- Oceanic plate subducts at trenches.
- Continents ride passively on the moving plates.



Driving Forces of Plate Tectonics

Immediate mechanism is more controversial: 4 possibilities . . .

- **Pushing** from ridges → compressional stress in plate
- **Pulling** by downgoing slab → tensional stress in plate
- Gravity **sliding** from height of MOR to abyssal plain/trench
- **Dragging** by convection cells acting on base of the plate



And the winner is . . .

- **Slab pull** is now considered the most viable mechanism
- *But some plates (S. American) have no subducting slab...*
- In such cases, mantle drag may provide the necessary force to move the plate along.

