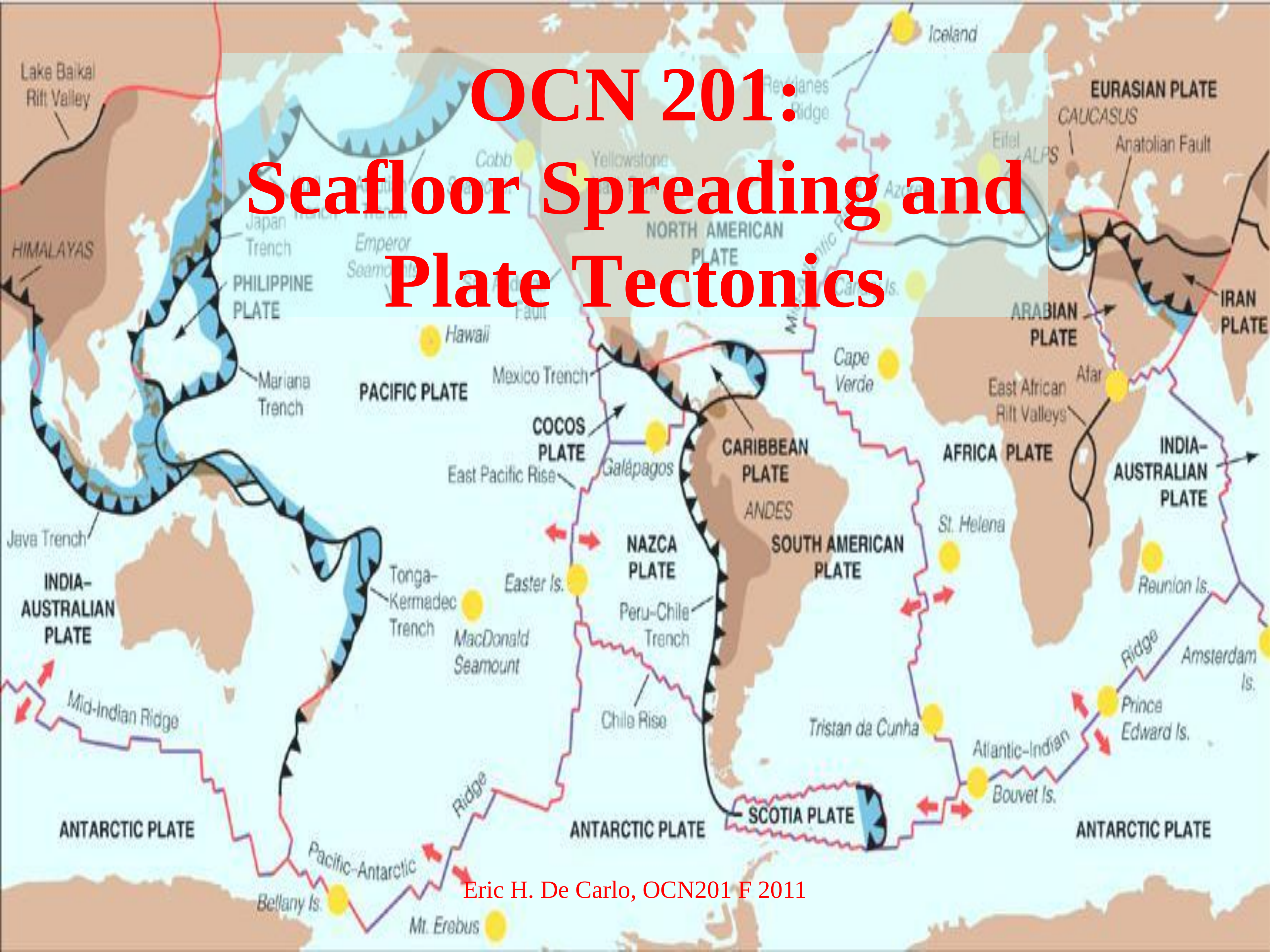
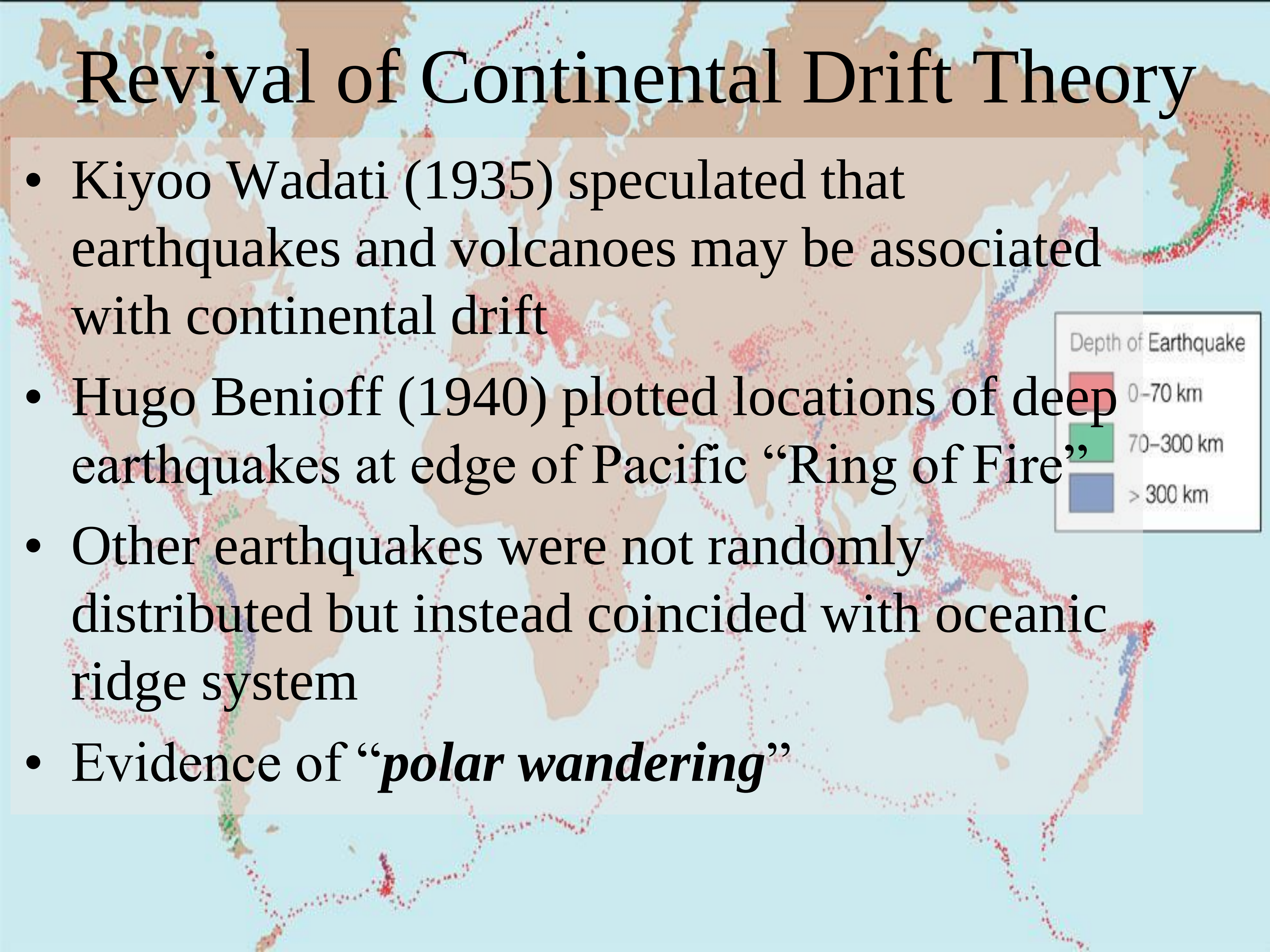
OCN 201: Seafloor Spreading and Plate Tectonics



Eric H. De Carlo, OCN201 F 2011

Revival of Continental Drift Theory

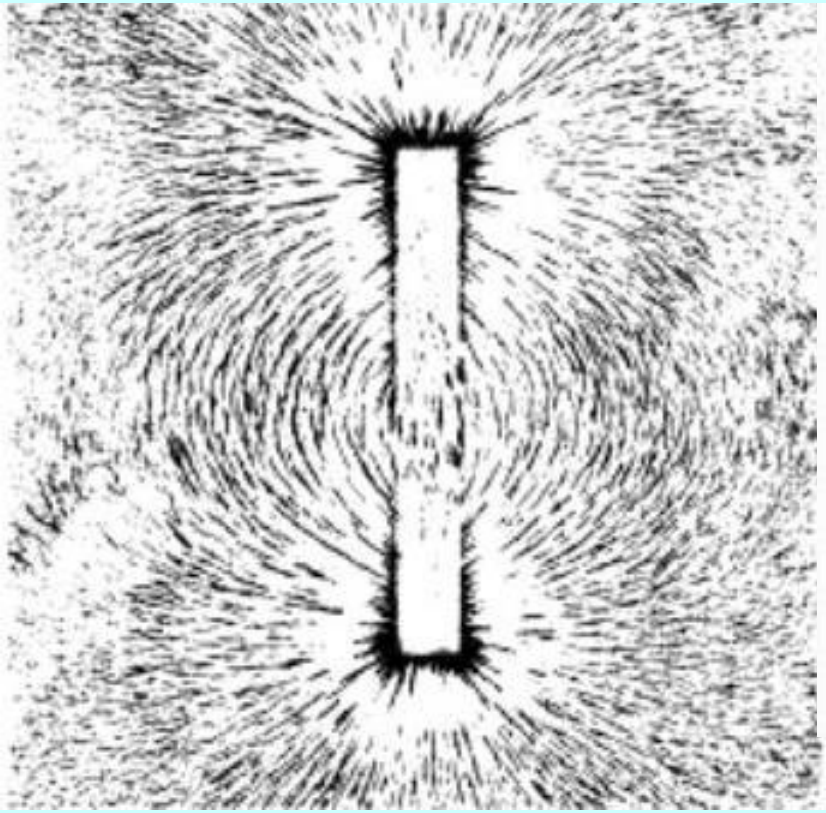
- Kiyoo Wadati (1935) speculated that earthquakes and volcanoes may be associated with continental drift
- Hugo Benioff (1940) plotted locations of deep earthquakes at edge of Pacific “Ring of Fire”
- Other earthquakes were not randomly distributed but instead coincided with oceanic ridge system
- Evidence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



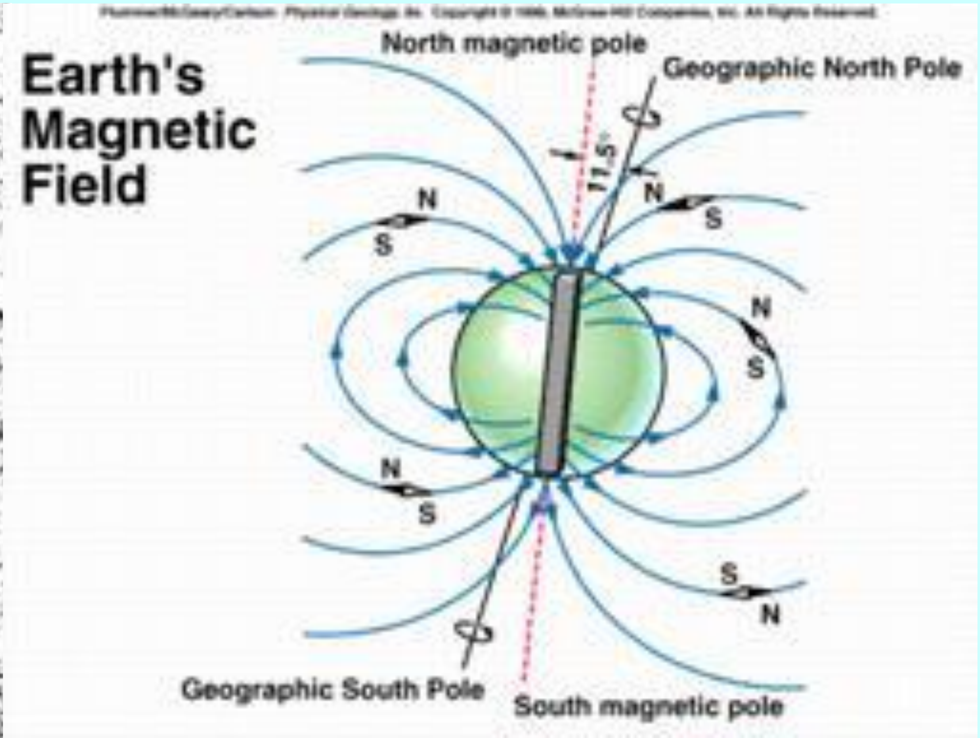
Revival of Continental Drift Theory

Wegener’s theory was revived in the 1950’s based on paleomagnetic evidence of “Polar Wandering”

Earth’s Magnetic Field

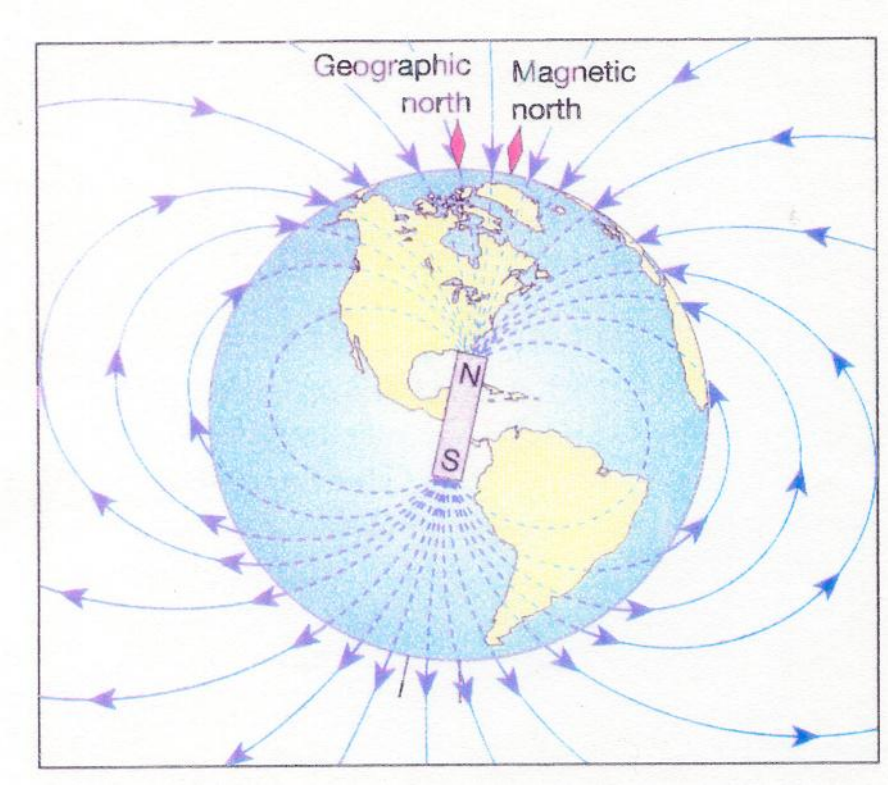


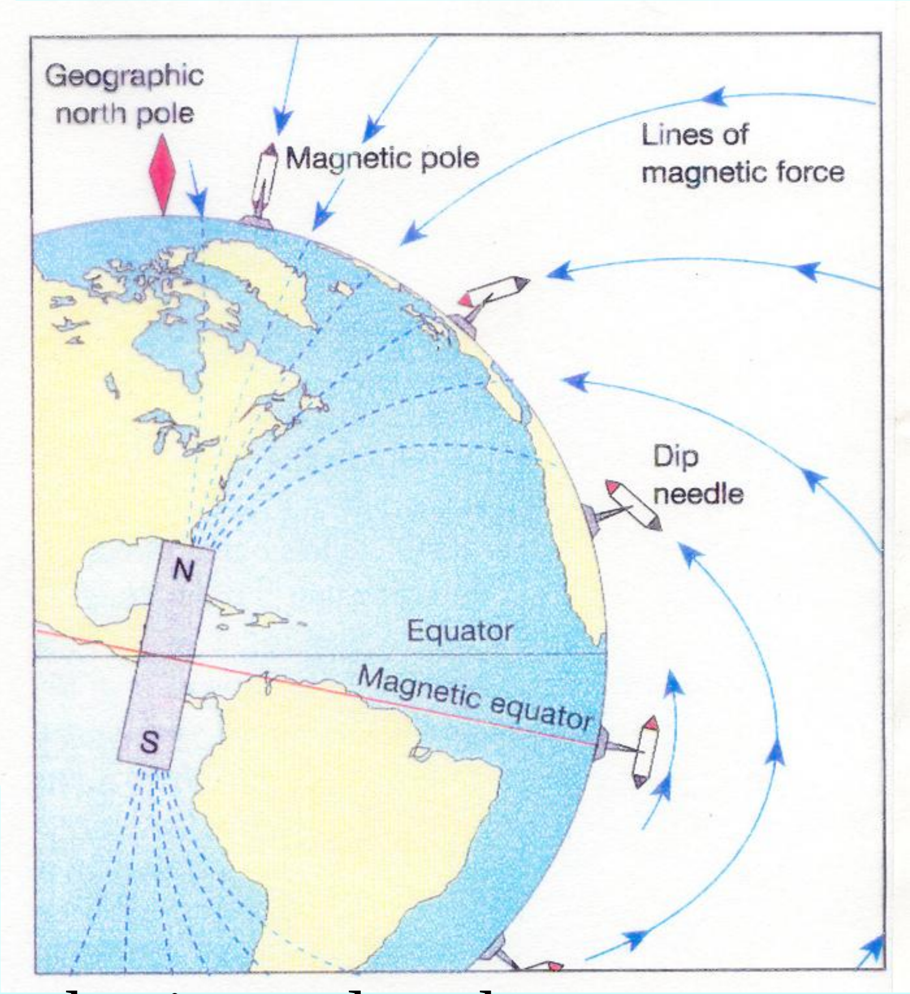
A bar magnet with Fe filings aligning along the “lines” of the magnetic field



Earth’s magnetic field simulates a bar magnet, but is caused by convection of Fe in the outer core: the ***Geodynamo…***

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 in igneous rocks align themselves with the magnetic field of Earth when rocks solidify
- This magnetic alignment is “frozen” and retained if rock is not subsequently reheated
- Can use paleomagnetism of ancient rocks to determine:

  - direction and polarity of Earth’s magnetic field

  - paleolatitude from inclination (dip)

  - apparent position of N and S magnetic poles

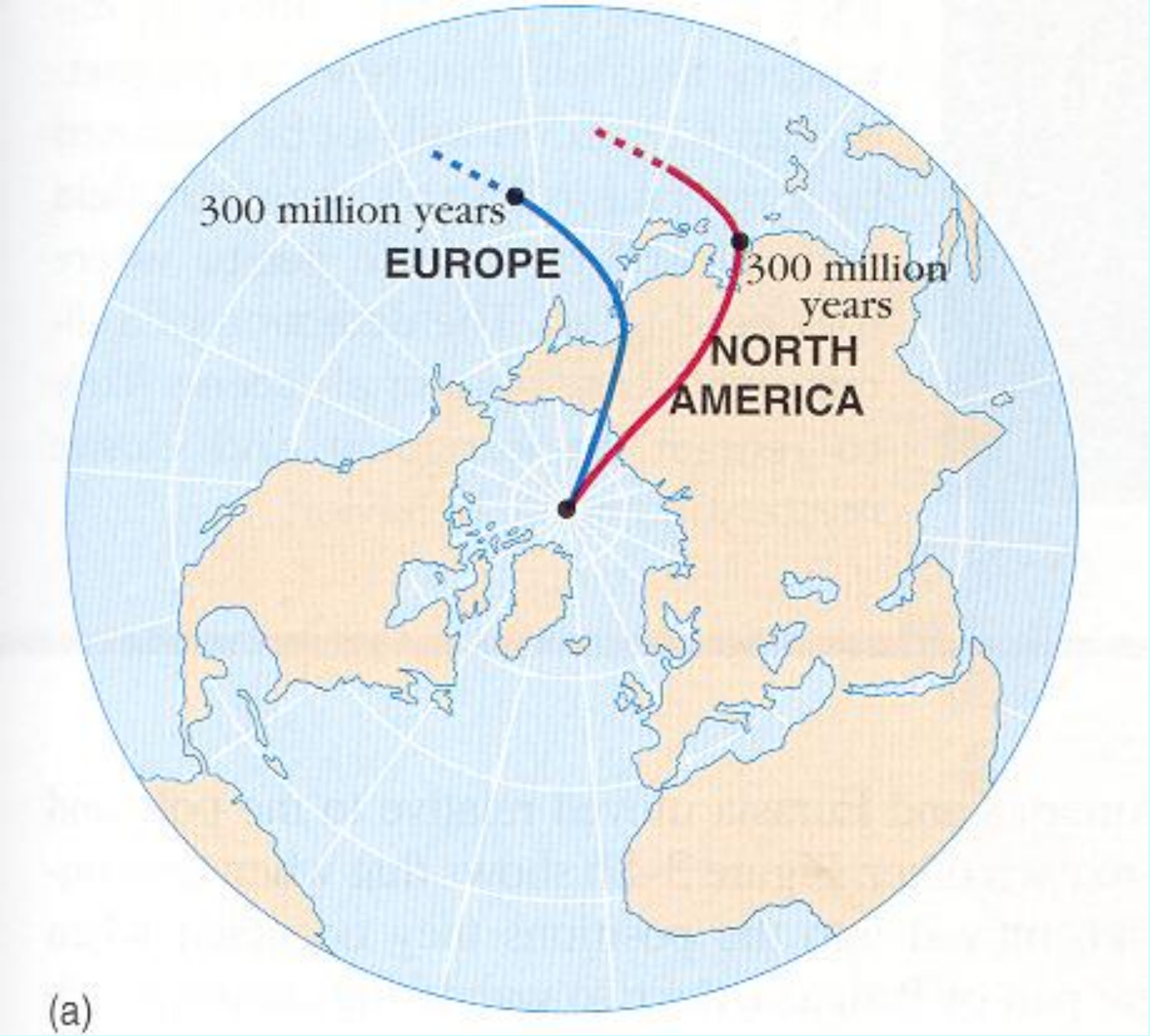
Paleomagnetics

- It was originally thought that Earth's magnetic field was caused by large mass of permanently magnetized material deep in its interior
- Pierre Curie (1900) recognized permanent magnetism is lost from magnetizable matter at ~500-700^{o}C (Curie Pt.)
- Nothing in deep earth (>30 km deep) can be permanently magnetized because of T gradient
- Outer core is likely the cause of Earth's magnetic field because it is in convective motion
- Moving conductor in magnetic field induces electric current (and vice-versa)
- Earth's outer core is like a "dynamo"

Paleomagnetics, cont.

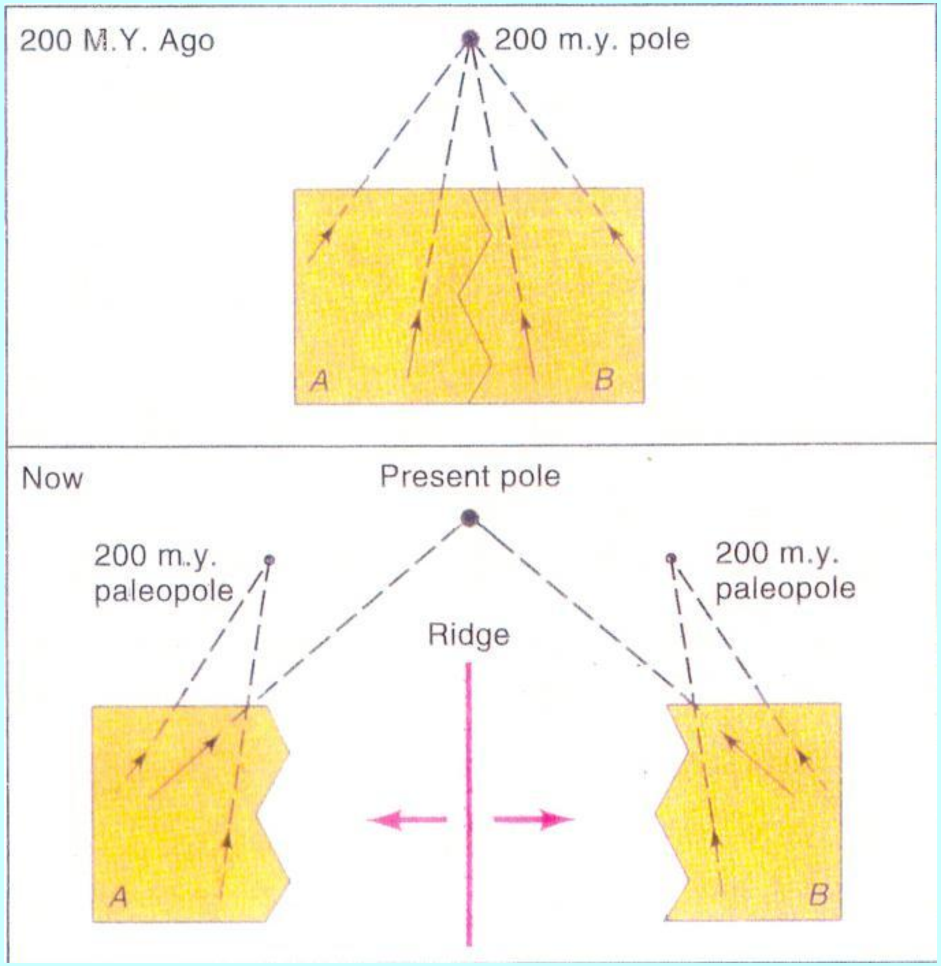
- Current rotational (geographic) poles correspond closely to magnetic poles, especially if averaged over time…
- Paleomagnetic evidence from ancient rocks, however, suggested pole "positions" for given continents had systematically moved across face of the Earth
- Current evidence indicates magnetic poles have never moved more than about 20^{o} from geographic poles, thus apparent polar wandering is due to some other factor…

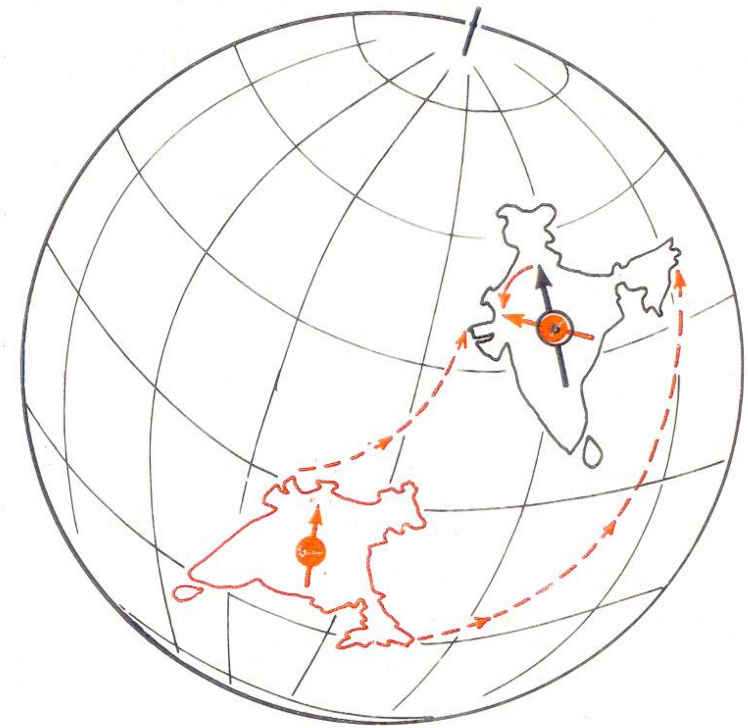
Apparent Polar Wander Paths



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

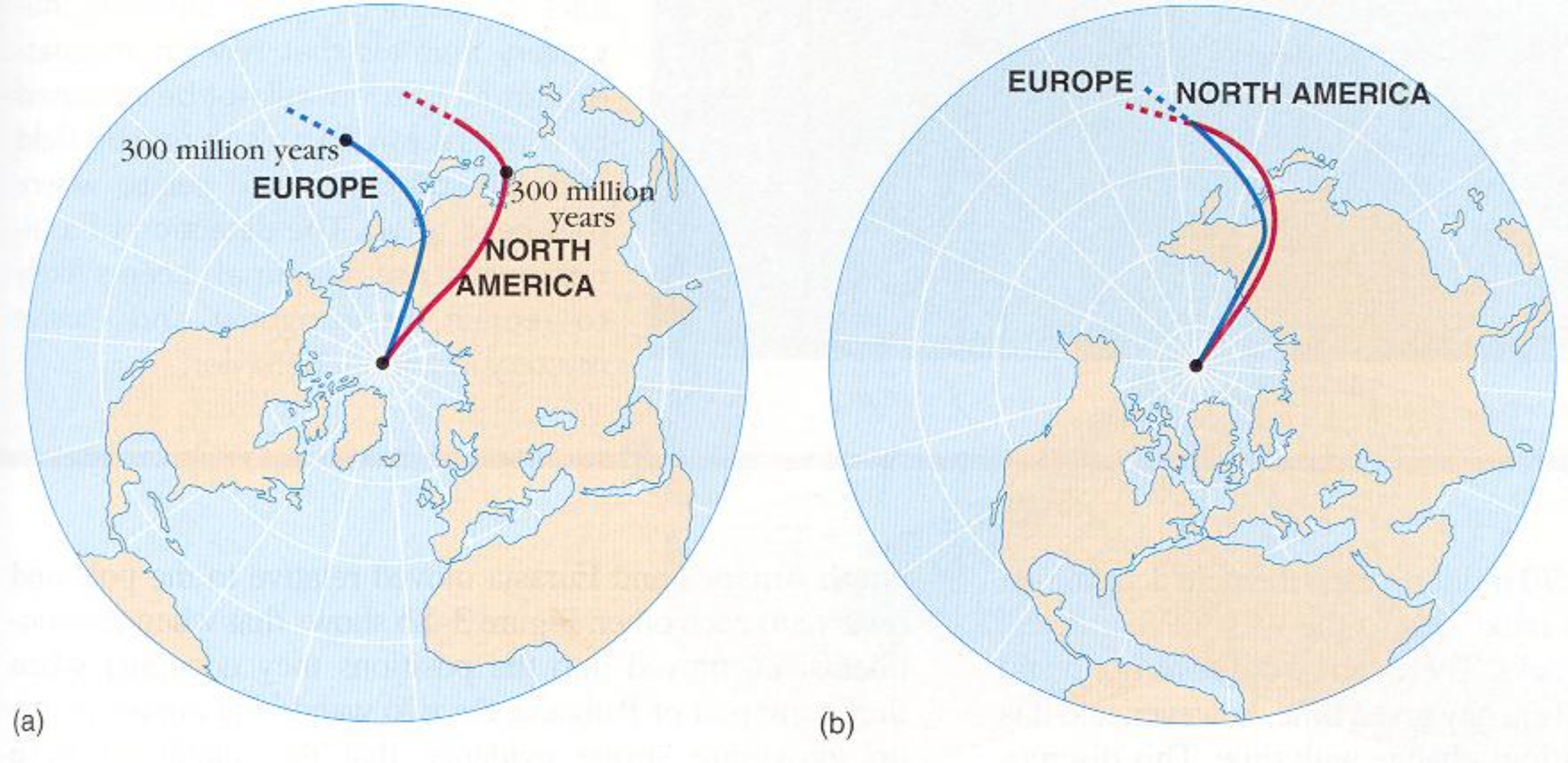
- Rocks from different continents gave different paths! Divergence increased with age of rocks.





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.

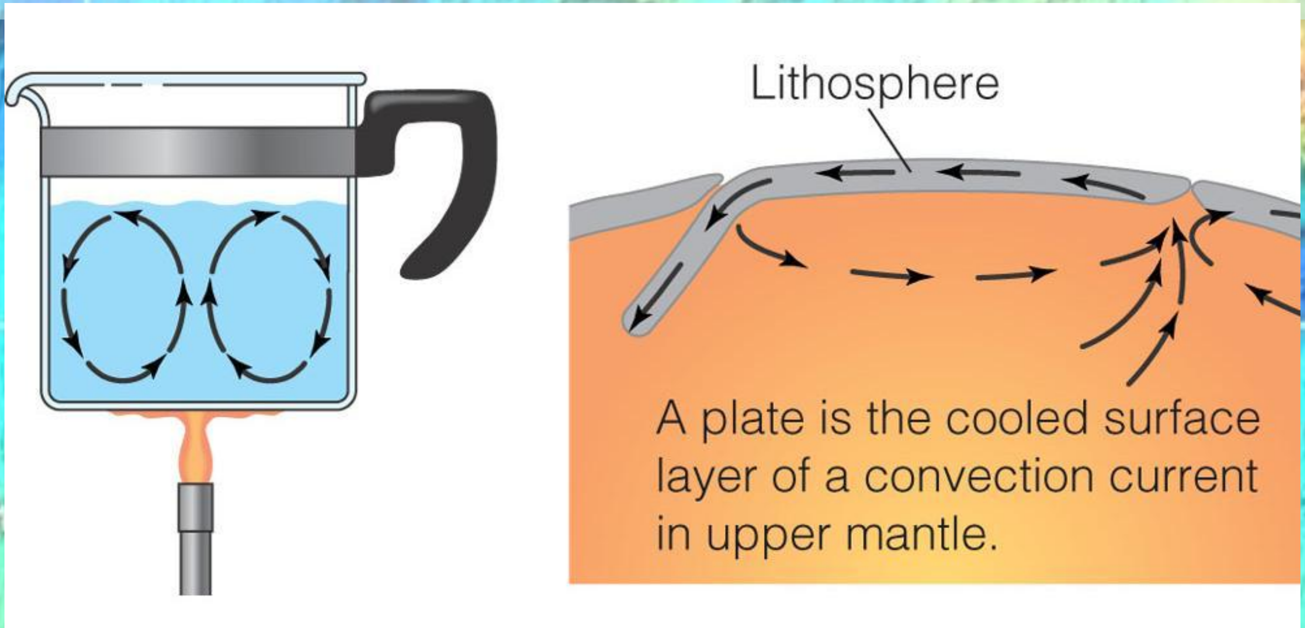
Apparent Polar Wander Paths



Magnetic poles have never been more the 20^{o} from geographic poles of rotation; rest of apparent wander results from ***motion of continents***!

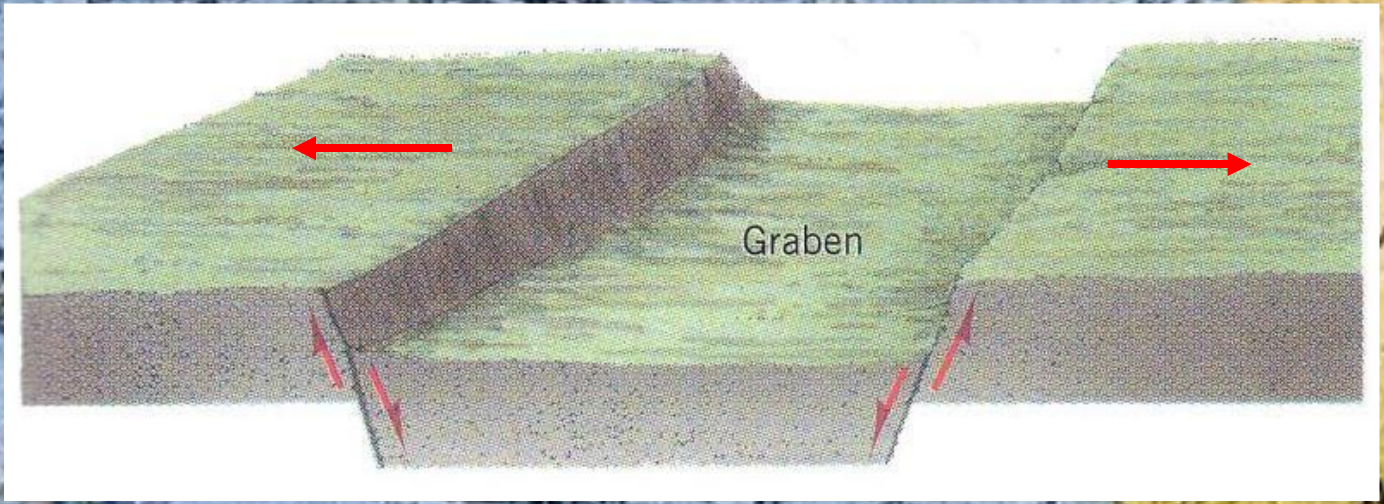
Seafloor Spreading: I

- First suggested by Arthur Holmes (1931) based on concepts of continental drift and convection cells within the mantle



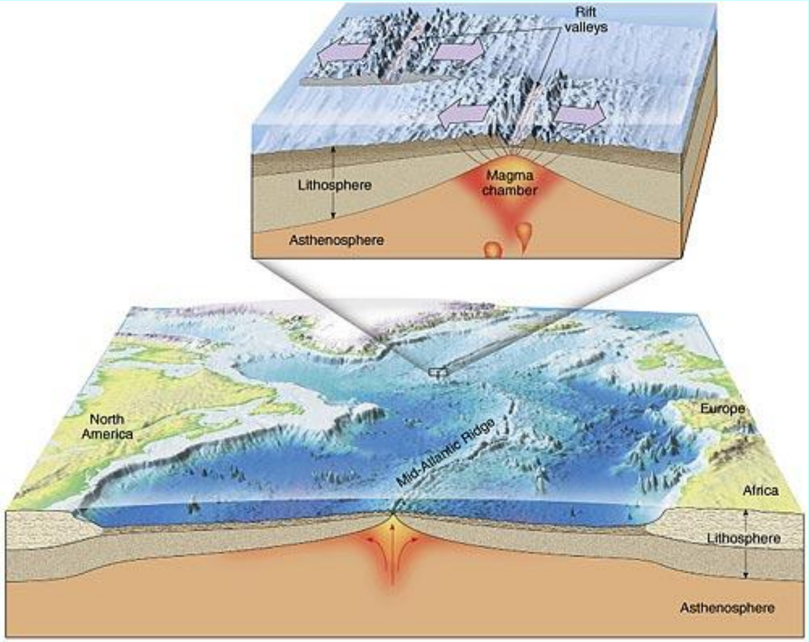
Seafloor Spreading: II

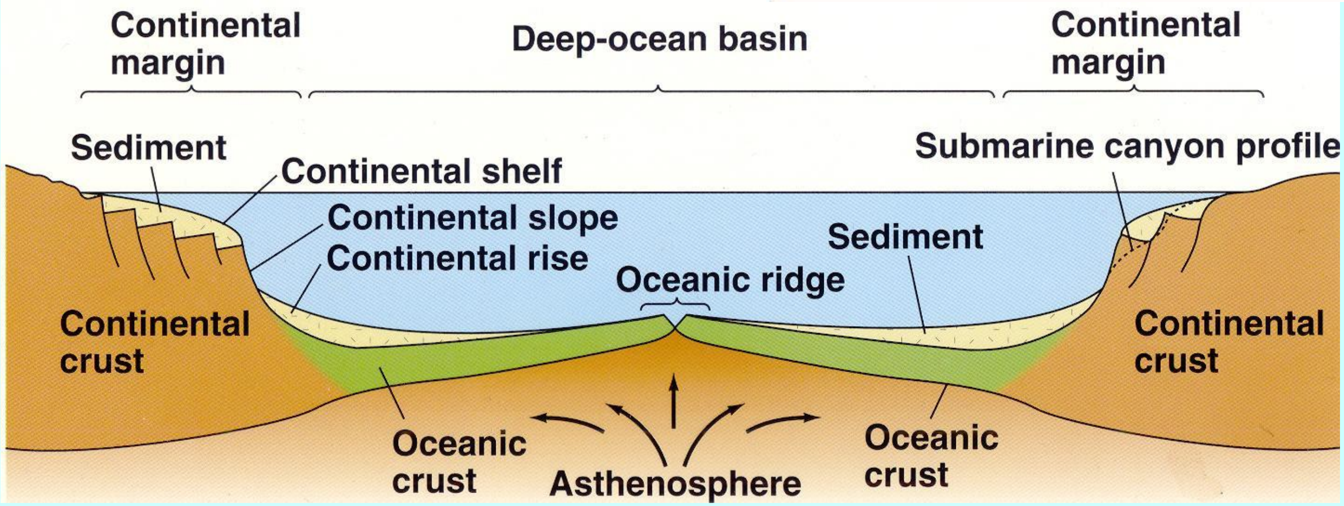
- Suggested by characteristics of **mid-ocean ridge**
  - Topography is elevated
  - Structure: **axial valley** with horst and graben structure formed by normal faulting, implying tension and extension



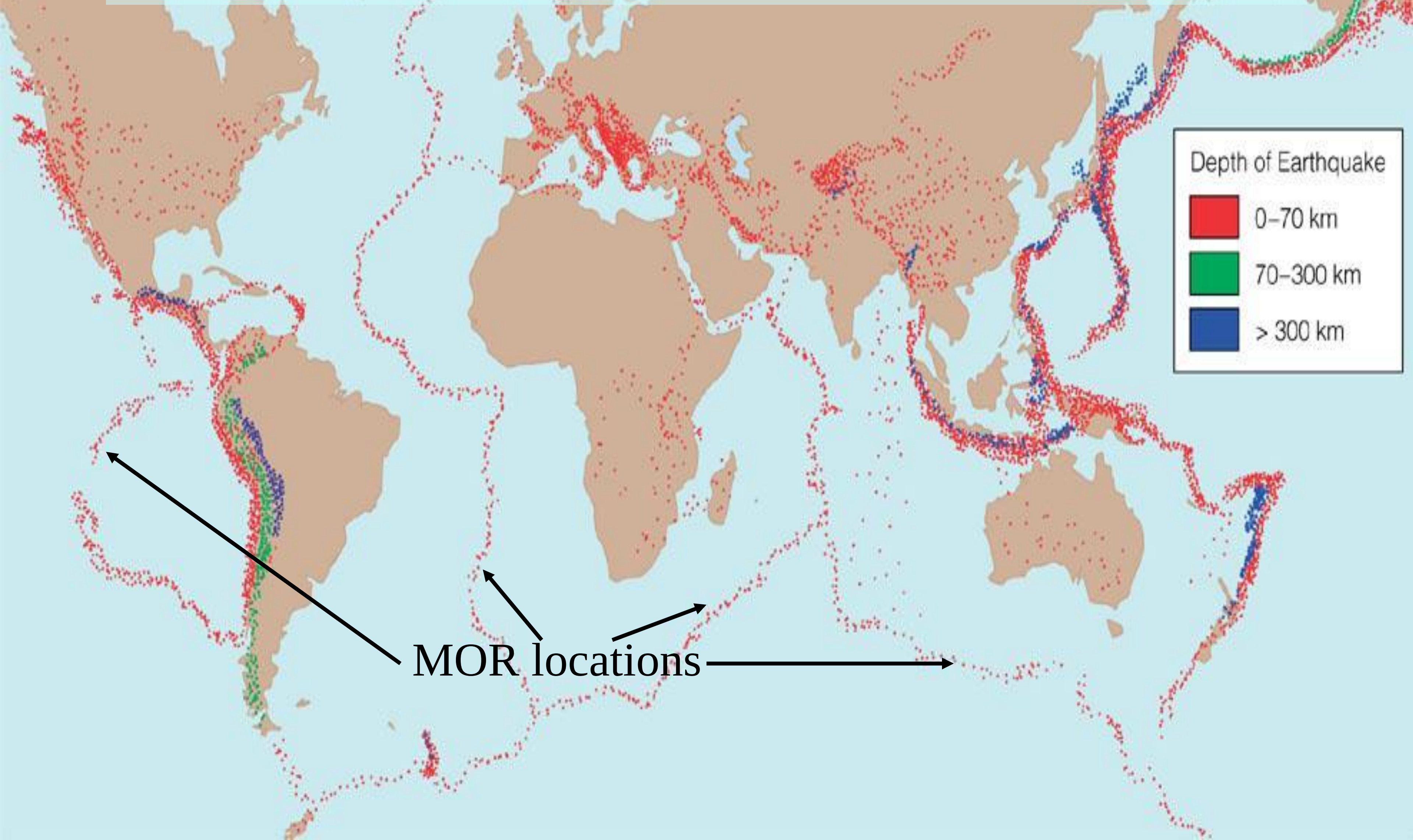
Mid-Ocean Ridges

- High heat flow (from magma)
- Seismicity is shallow (<70 km below MOR)
- Sediment thickness increases with distance away from MOR (age)





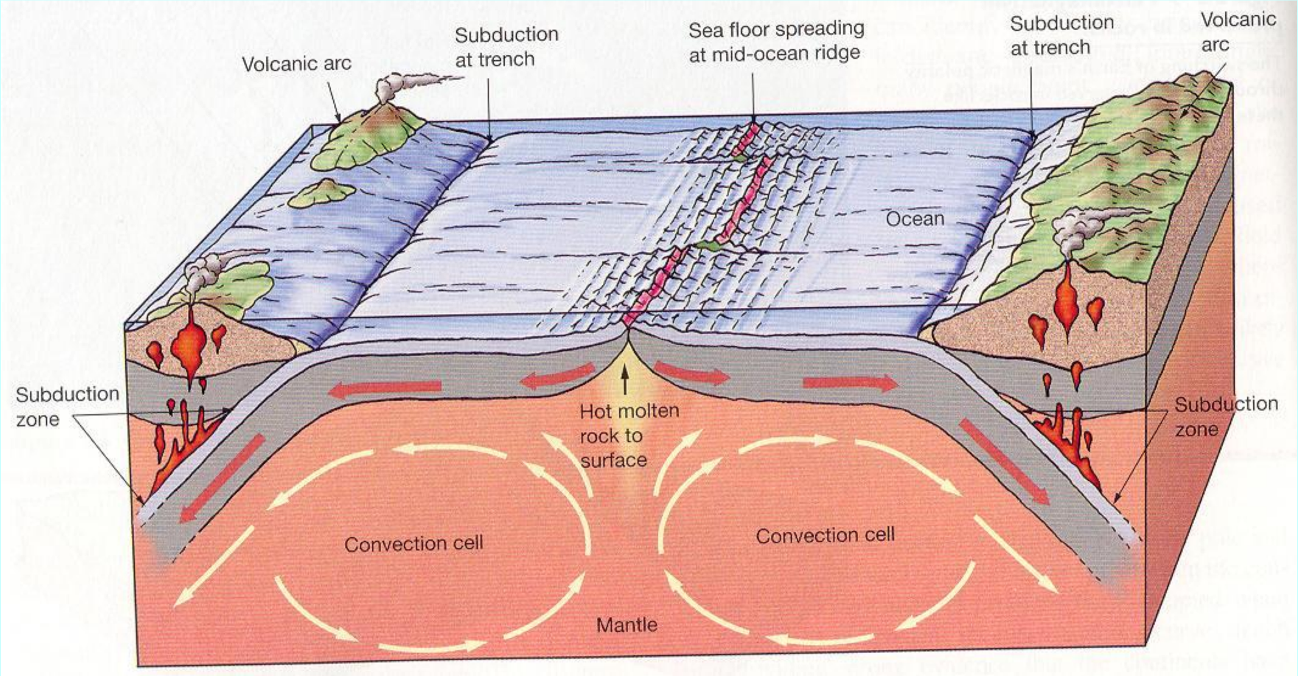
Global Seismicity



Seafloor Spreading: III

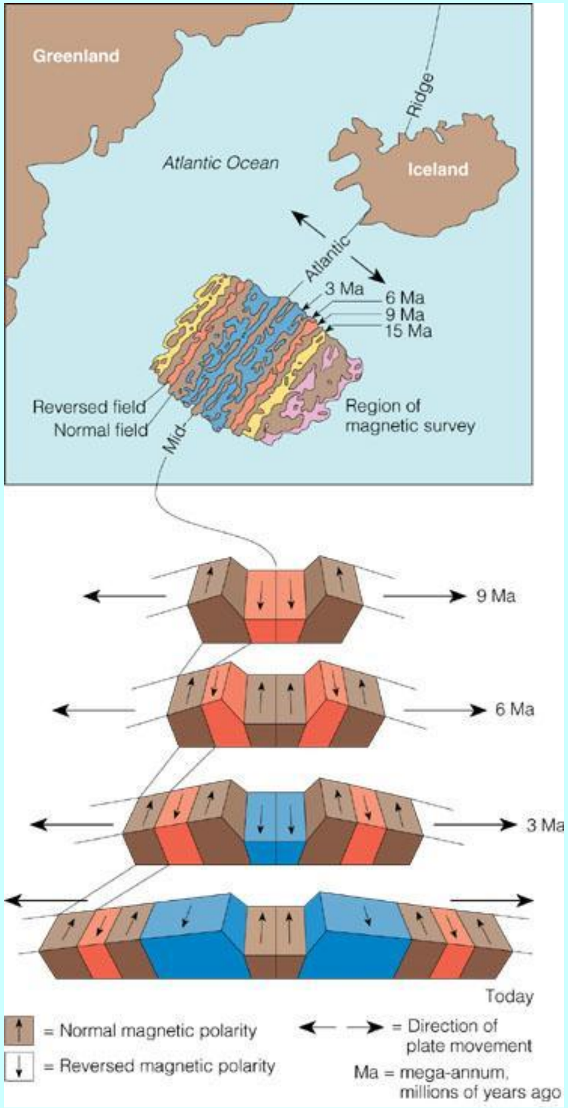
Formally proposed by Dietz (1961) and Hess (1962)

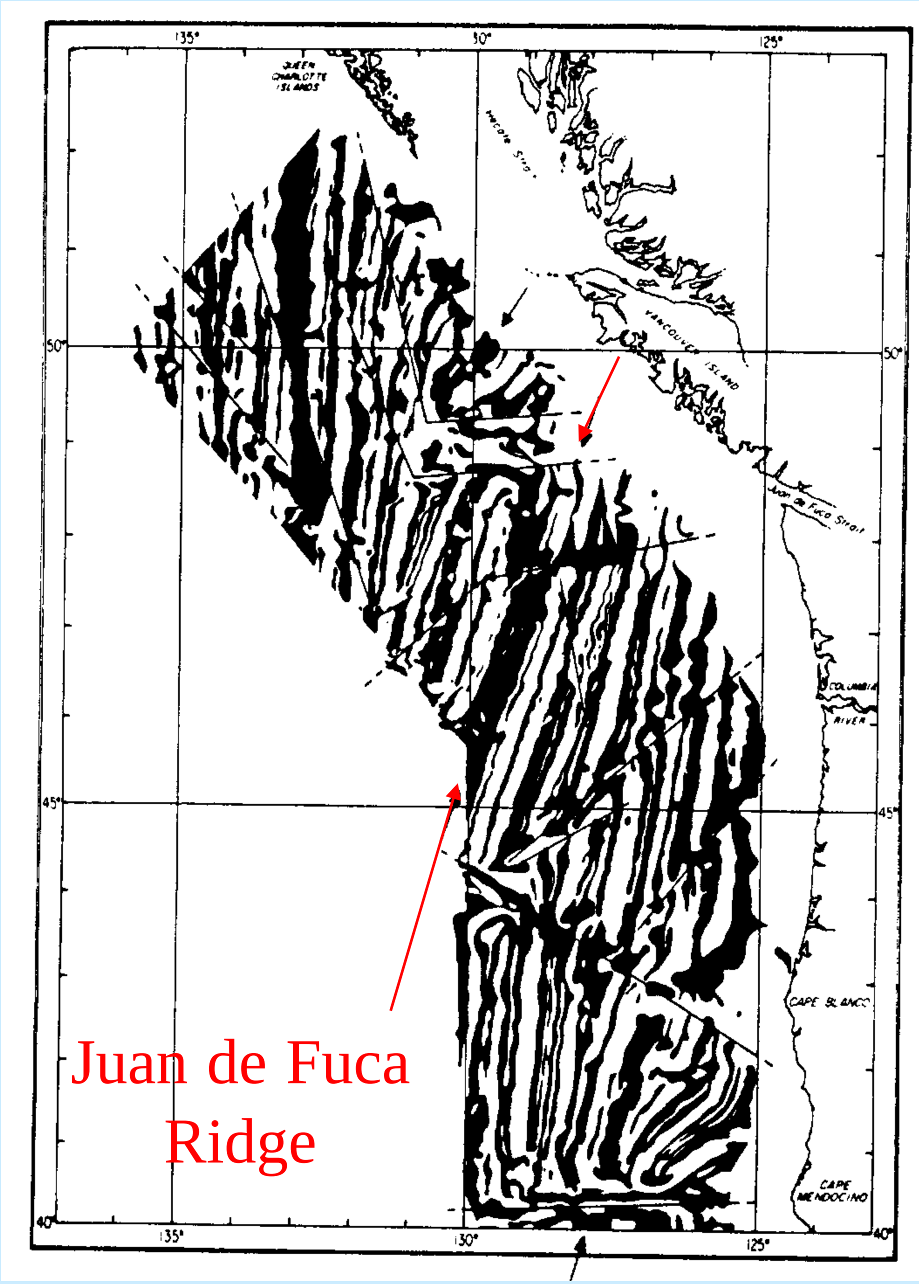
- Convection cells: Mantle upwells under MOR
- New oceanic crust is formed at MOR, then spreads laterally as if on conveyor belt
- Oceanic crust is dragged down at trenches (compression, mountain ranges and volcanic arcs)
- Continents ride passively between sites of upwelling and downwelling



Seafloor Spreading: IV

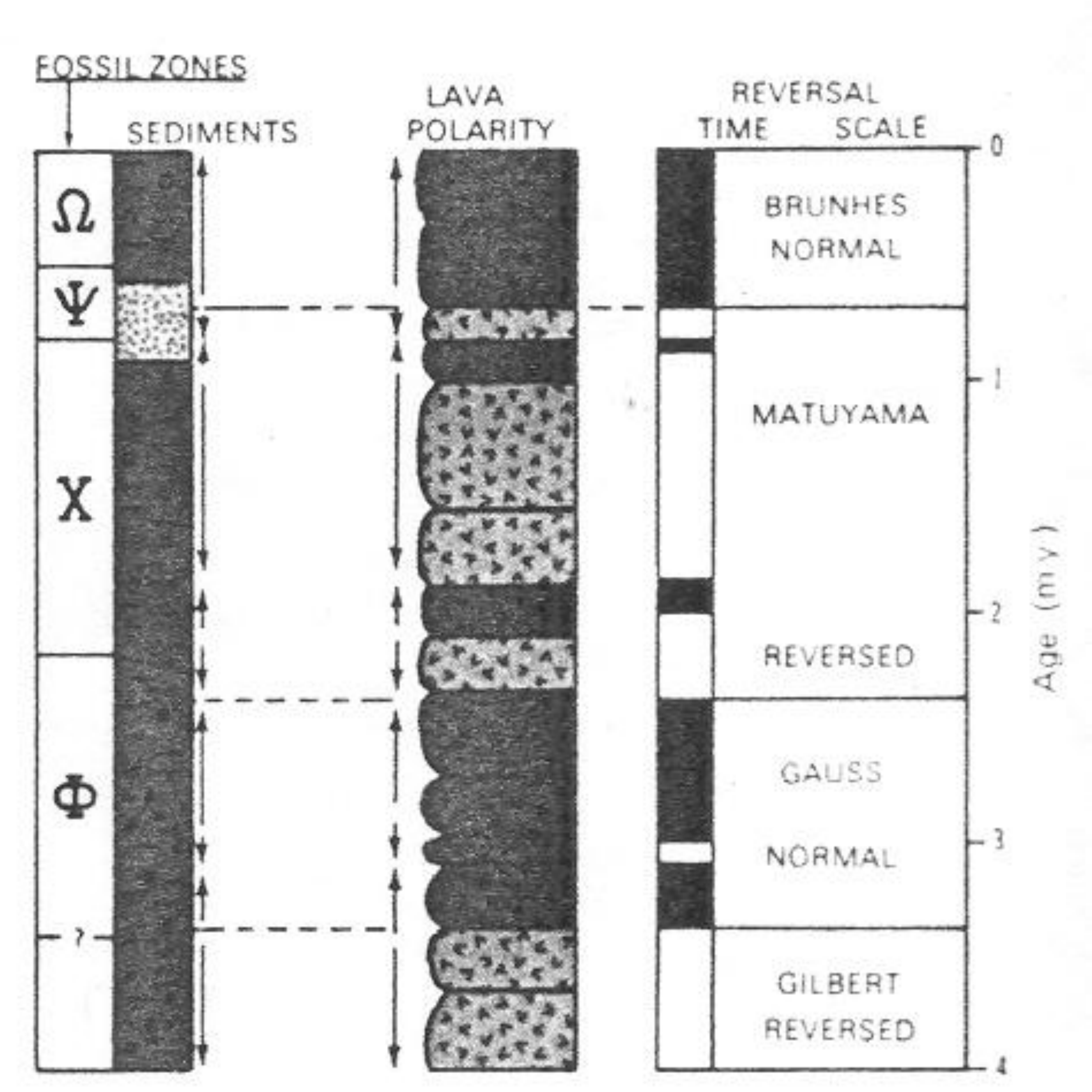
- Confirmed for some by Vine and Matthews (1963) who interpreted linear magnetic anomalies parallel to MOR as result of seafloor spreading
- Magnetic anomalies showed periodic polarity reversals first observed by Brunhes in 1906 on land (where patterns are complex)
- Simple marine sequence of magnetic reversals was labeled the "tape recorder" model





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.

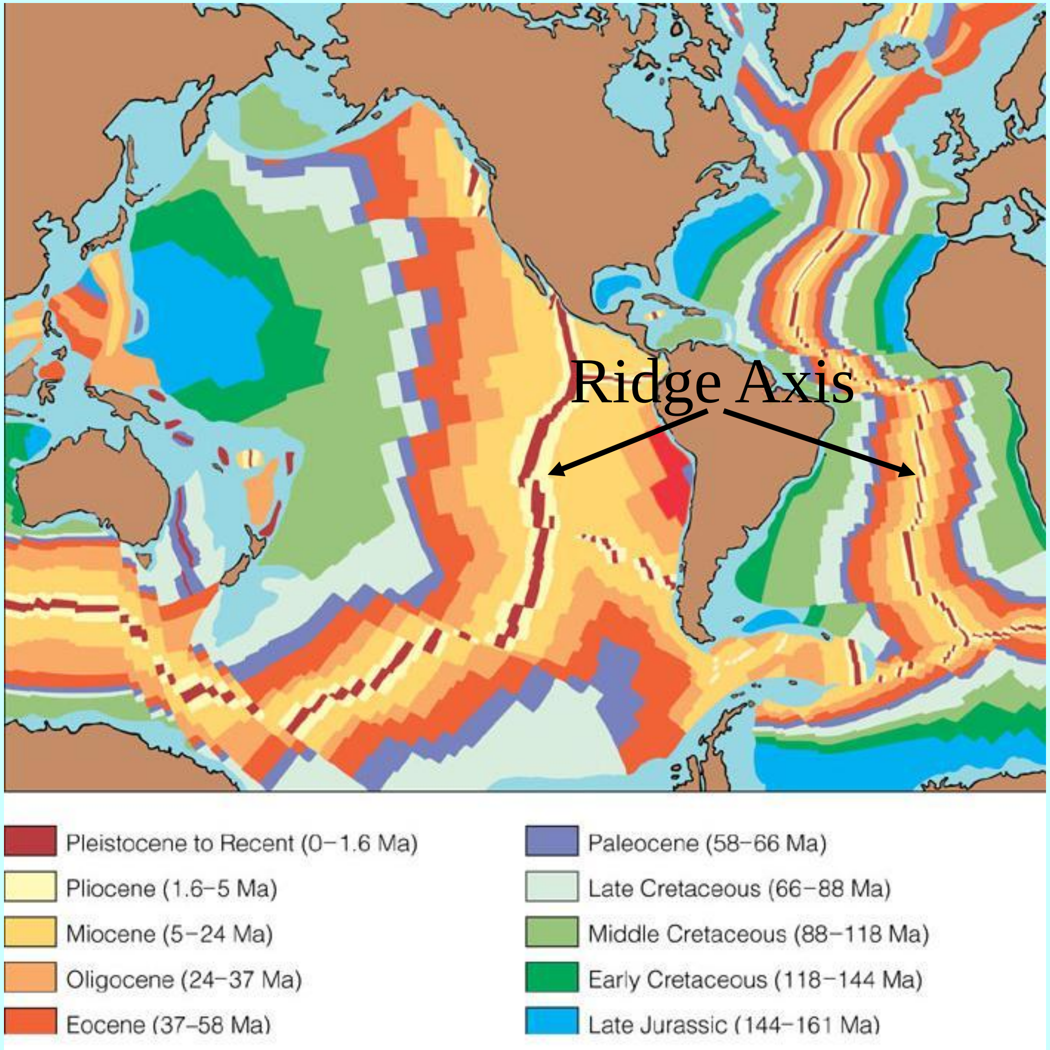


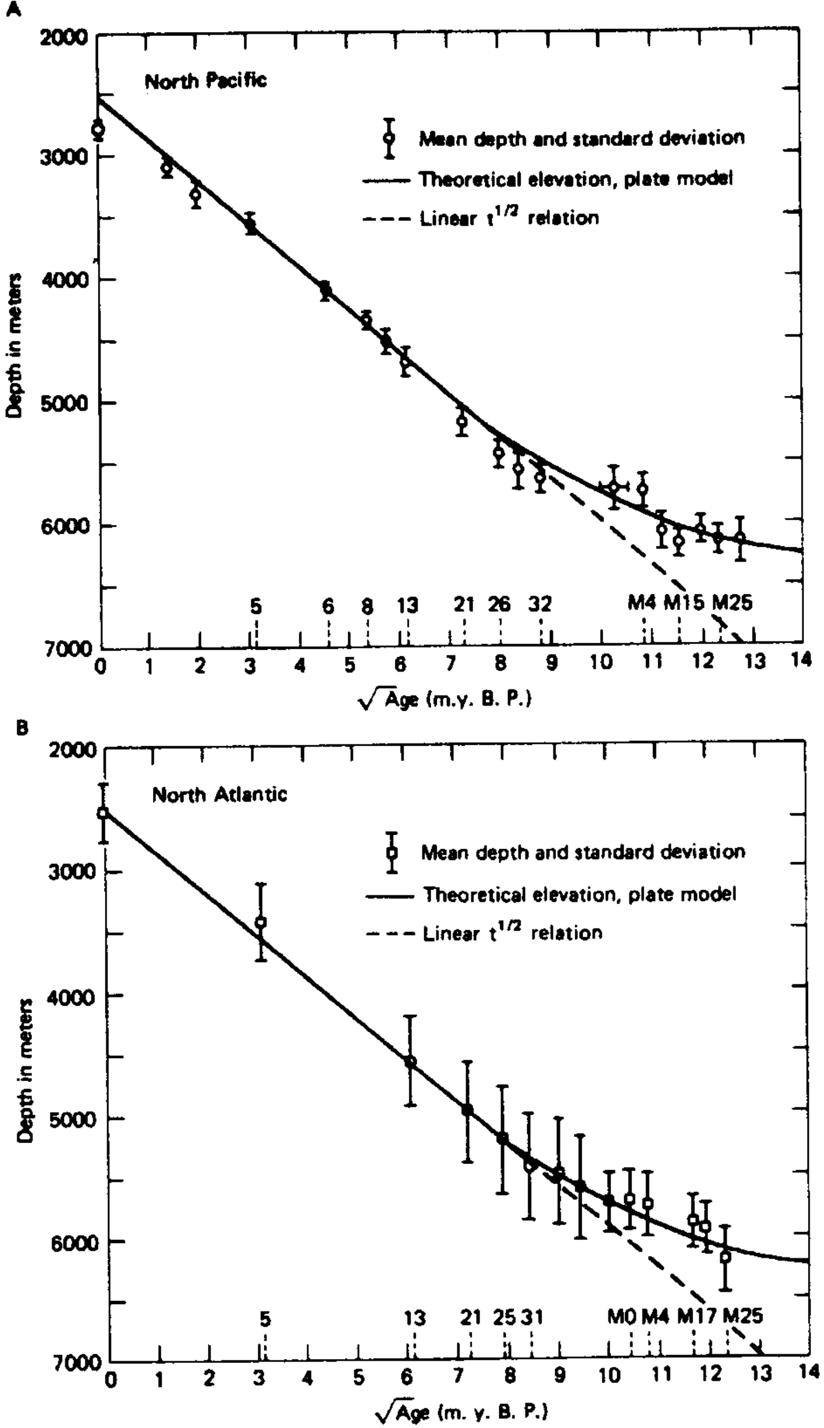
- Magnetic polarity reversals* were first observed by Brunhes (1906) on land.

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

Seafloor Spreading: V

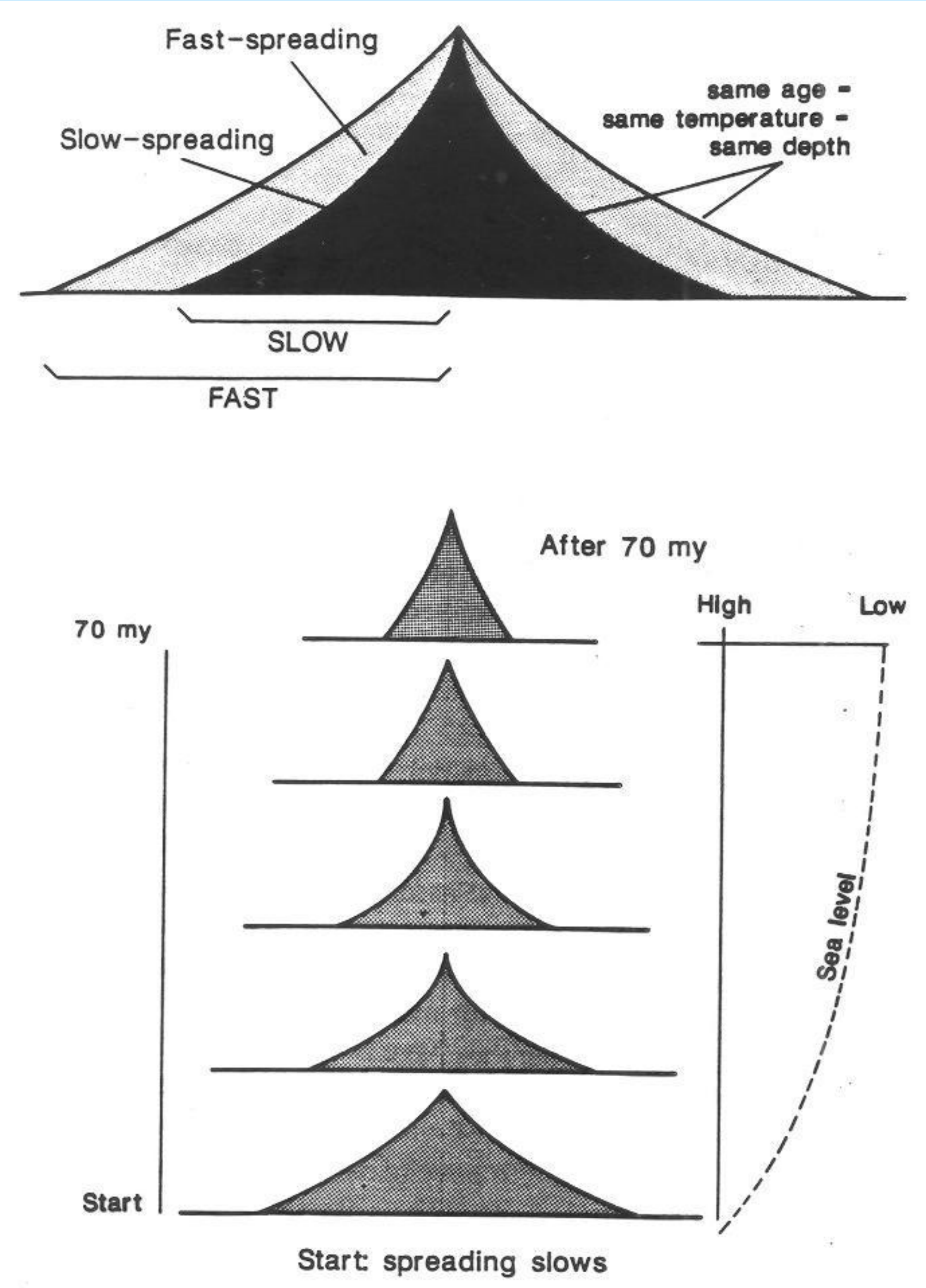
- Confirmed for most geologists by DSDP (1970's): age of sea floor (crust) increases regularly with distance from the ridge axis
- This was a major prediction of the seafloor spreading hypothesis!





Volume of Ocean Basins

- Ridges are elevated because lithospheric plate is young and hot at the spreading center ➔ thicker!
- 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).



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 tens of millions of yrs)

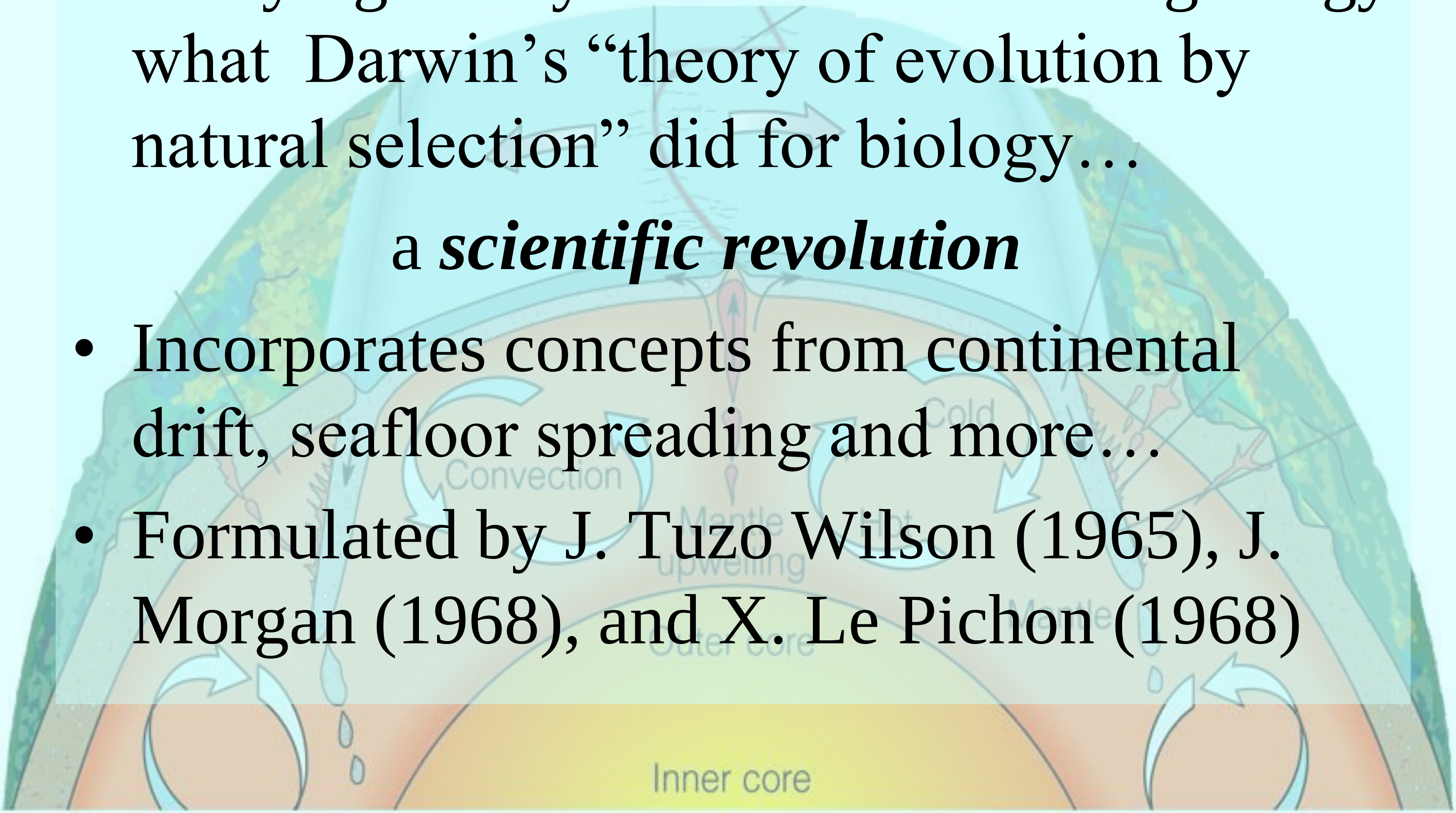
  ➔ ***large sea level change!***

The Theory of Plate Tectonics: I

- Unifying theory which has done for geology what Darwin's "theory of evolution by natural selection" did for biology…

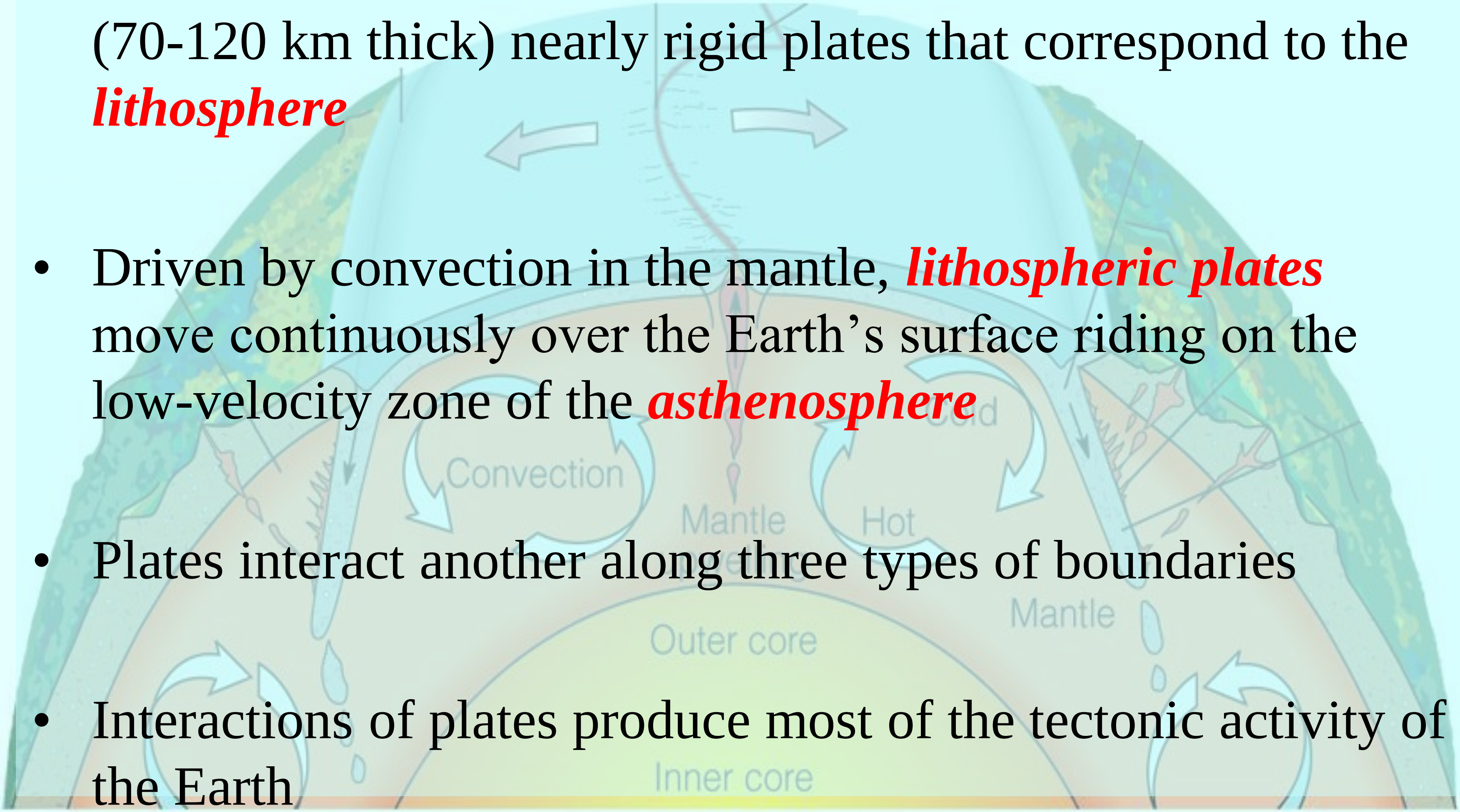
  a ***scientific revolution***

- Incorporates concepts from continental drift, seafloor spreading and more…
- Formulated by J. Tuzo Wilson (1965), J. Morgan (1968), and X. Le Pichon (1968)

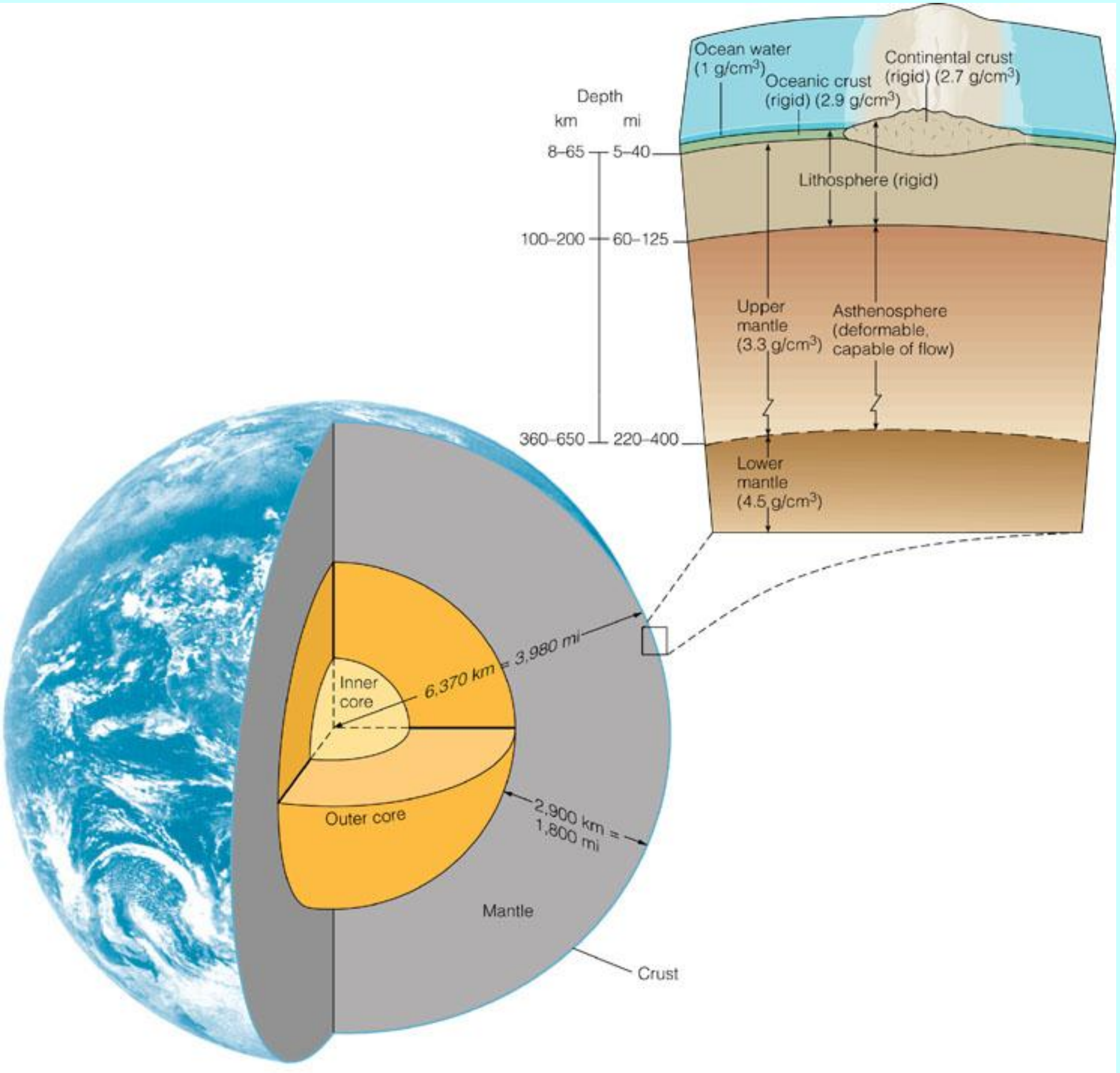


The Theory of Plate Tectonics: II

- Entire surface of Earth consists of a small number of thin (70-120 km thick) nearly 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 low-velocity zone of the ***asthenosphere***
- Plates interact another along three types of boundaries
- Interactions of plates produce most of the tectonic activity of the Earth



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 70-120 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: it forms 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 melting to produce igneous rocks.
- The ***mesosphere*** (most of the mantle) extends to the core and is more rigid than the asthenosphere.

Lithospheric Plates

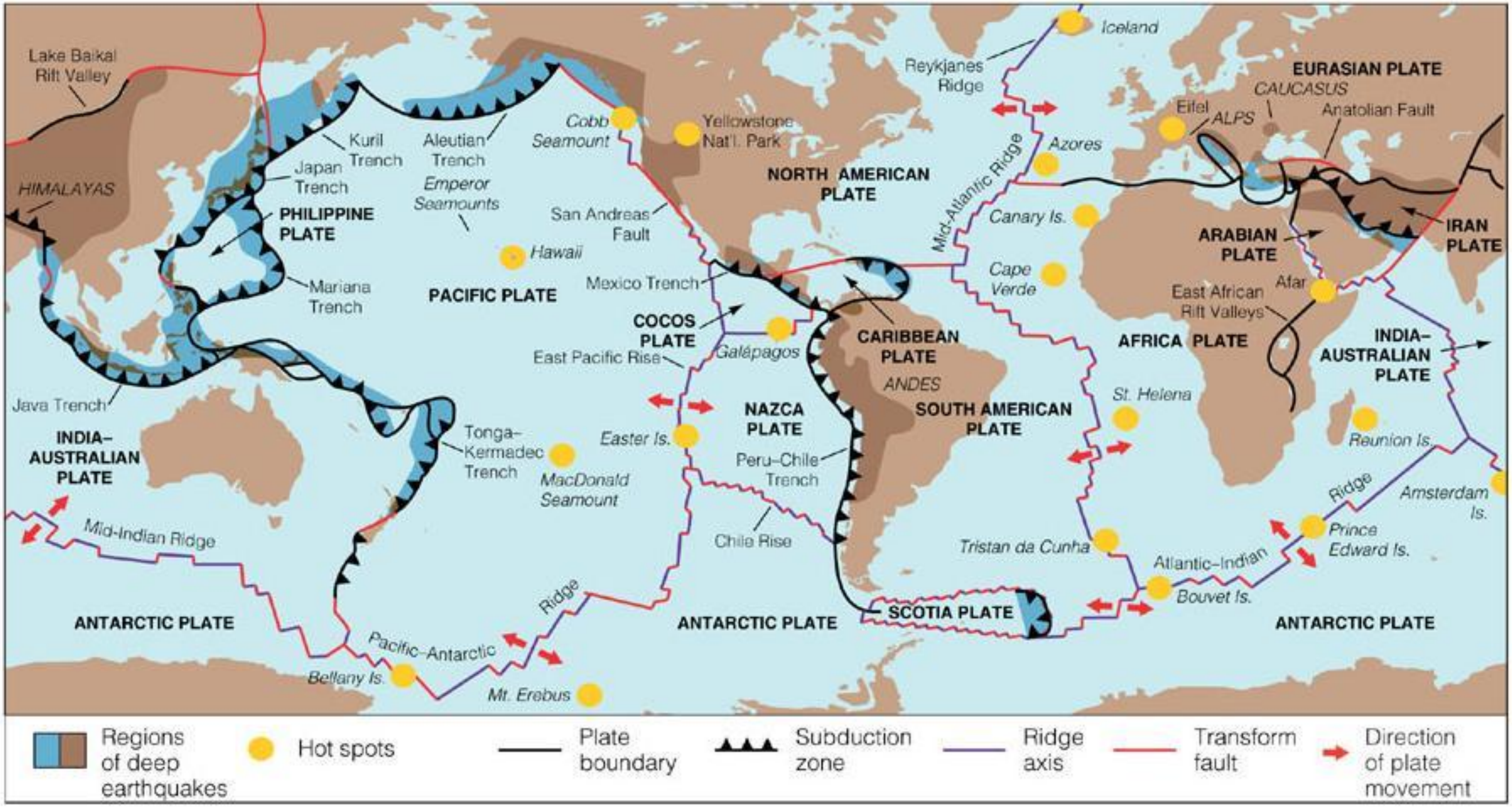
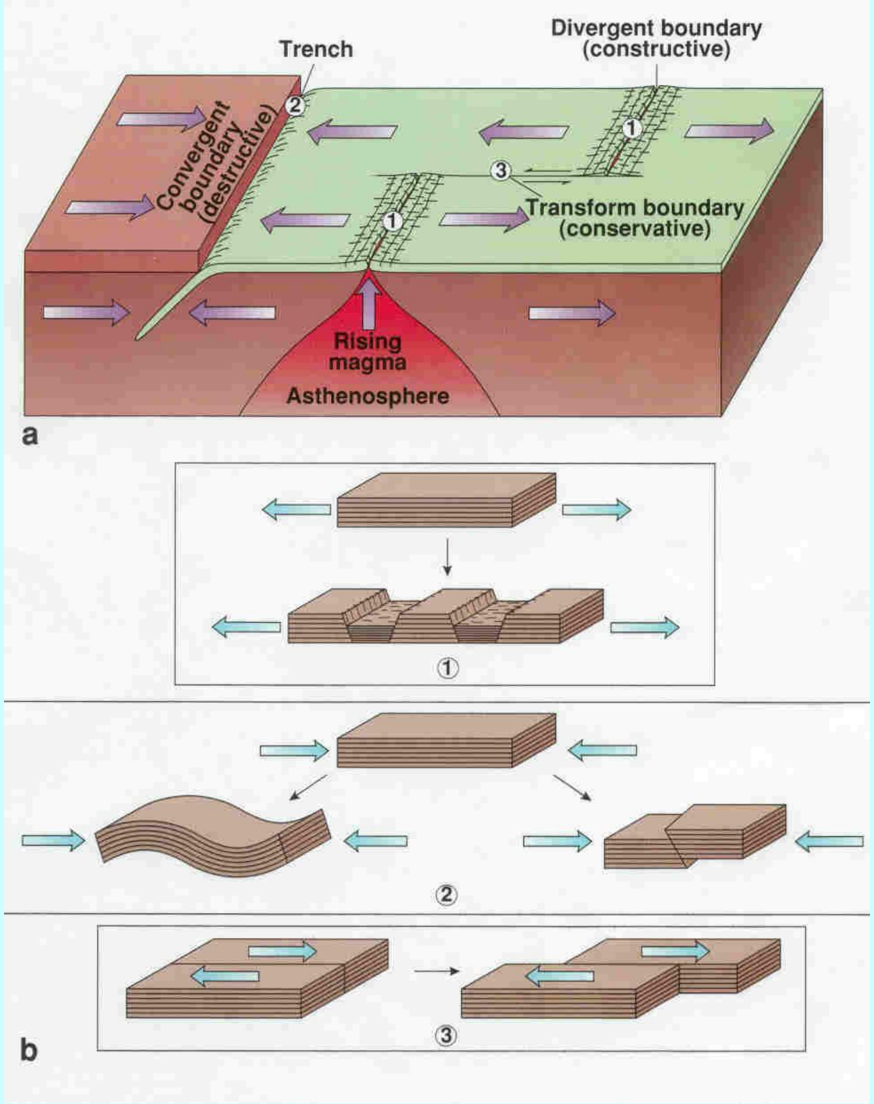


Plate Boundaries

3 types:

- Constructional or divergent
- Destructional or convergent
- Conservative or transform faults

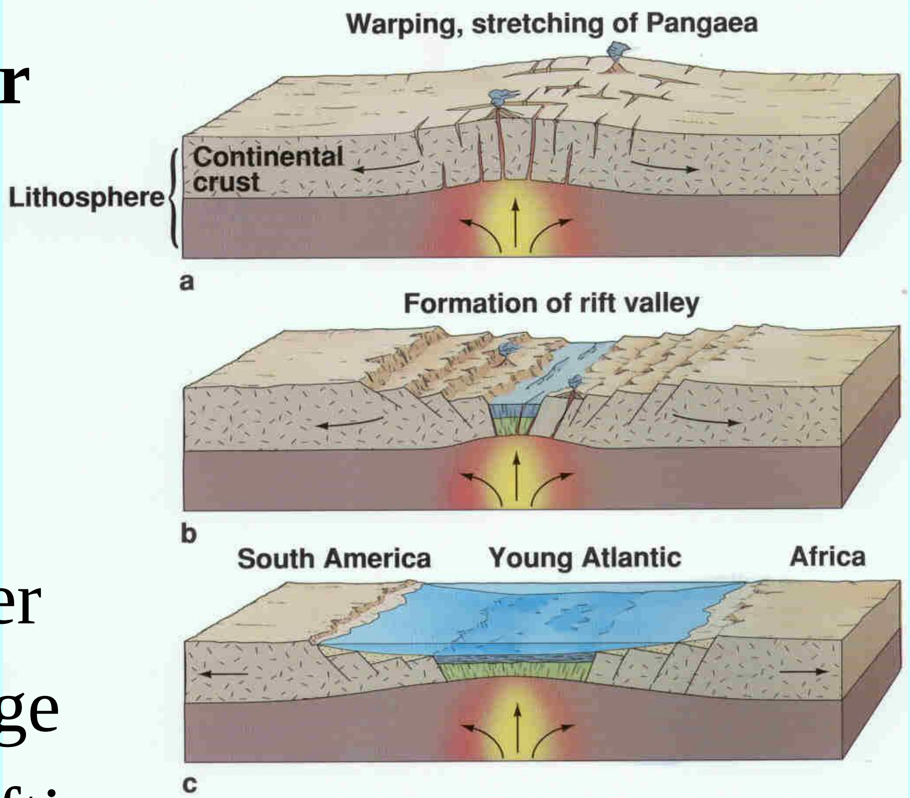
Earth's area is fixed, so construction must balance destruction!



Constructional Plate Boundaries

The *mid ocean ridges*, seafloor spreading axes

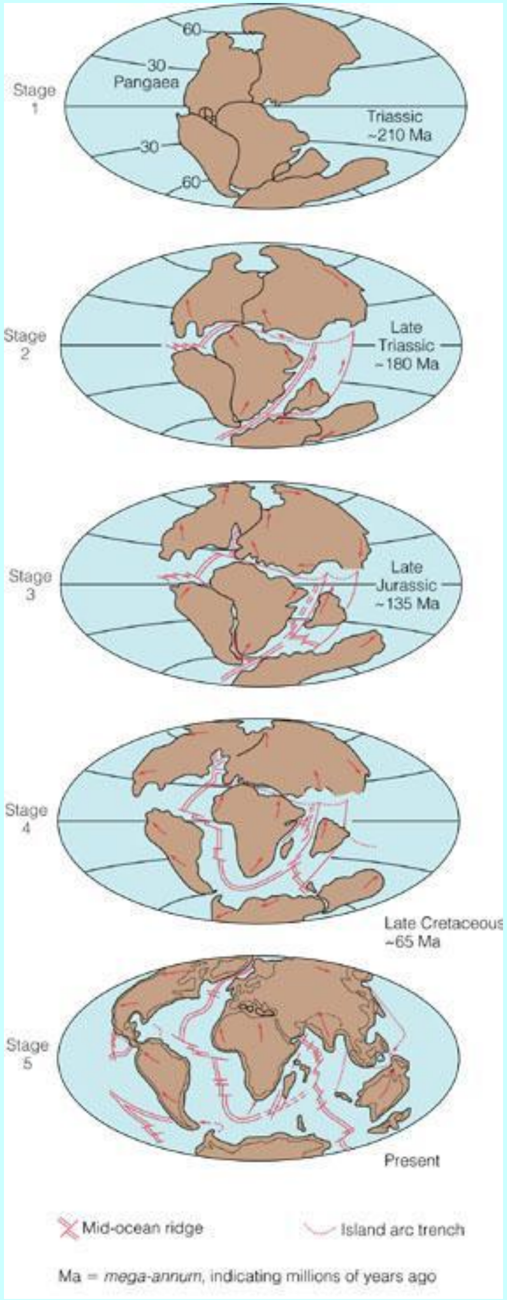
- Shallow seismicity
- Basaltic volcanism
- High heat flow
- Absent to thin sediment cover
- Zero to very young crustal age
- Tensional stress, produces rifting
- ½ Spreading rates: 1-8 cm/yr



A model for the formation of a new plate boundary

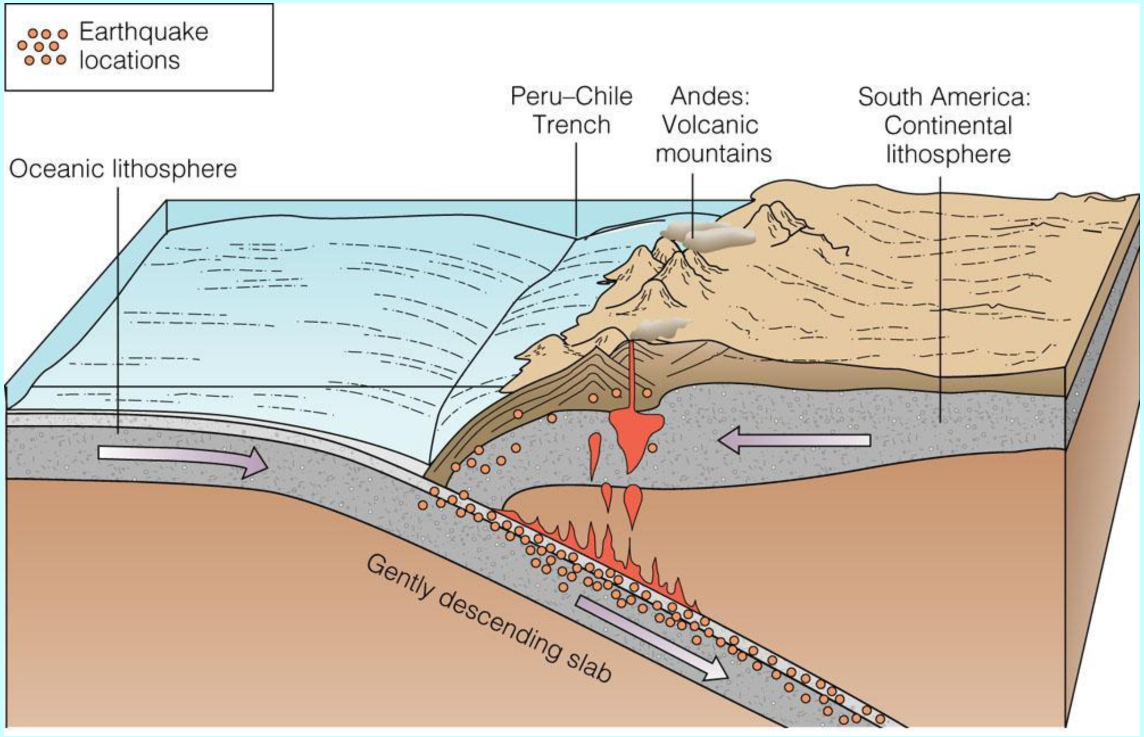
Breakup of Pangaea

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



Destructional Plate Boundaries: I

1. The deep sea trenches
2. Deep seismicity
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

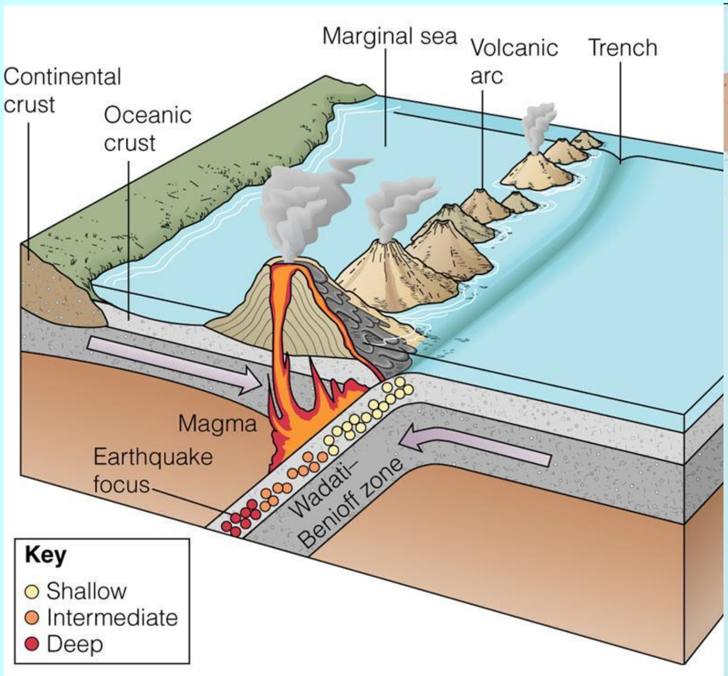


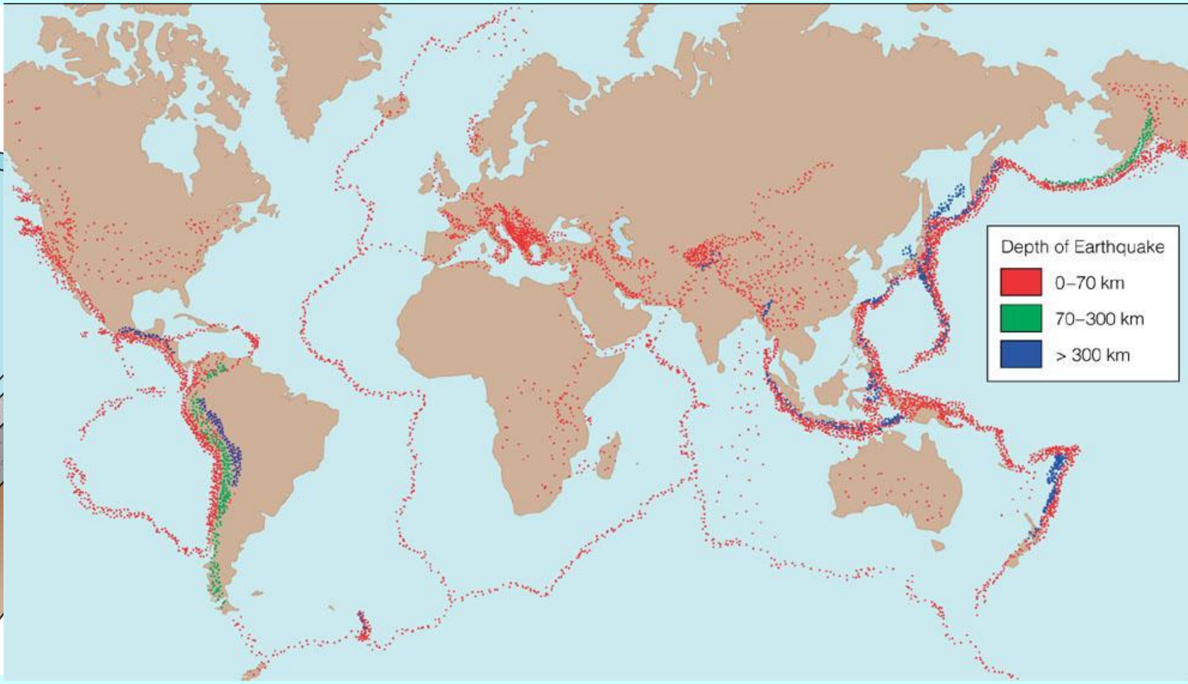
➔

Subduction Zone

Destructional Plate Boundaries: II

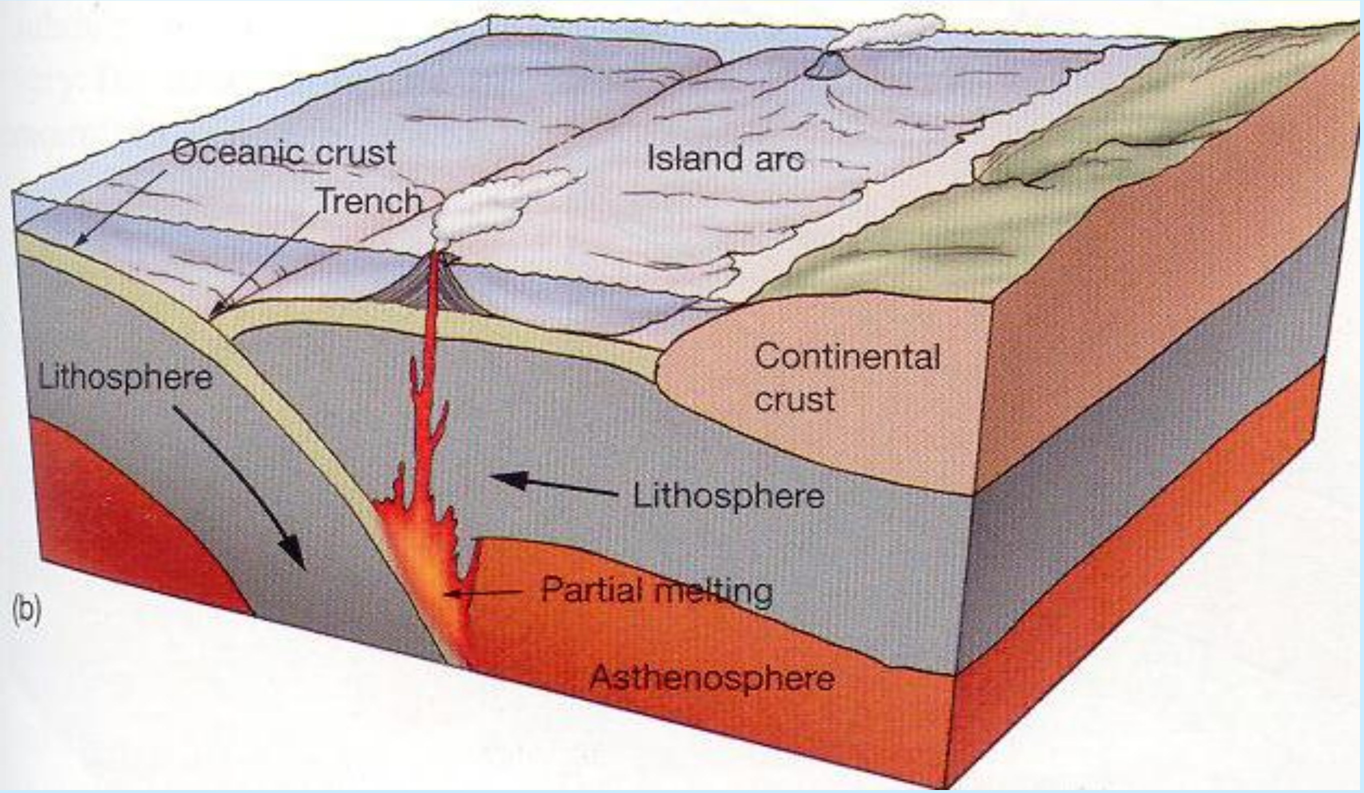
- Oceanic crust is ***subducted*** into the mantle at trenches below continental (e.g., Peru) or oceanic (e.g., Japan) crust
- The downgoing slab is characterized by a zone of earthquakes (Wadati-Benioff zone) that can be very deep





3 Types of Destructional Boundaries

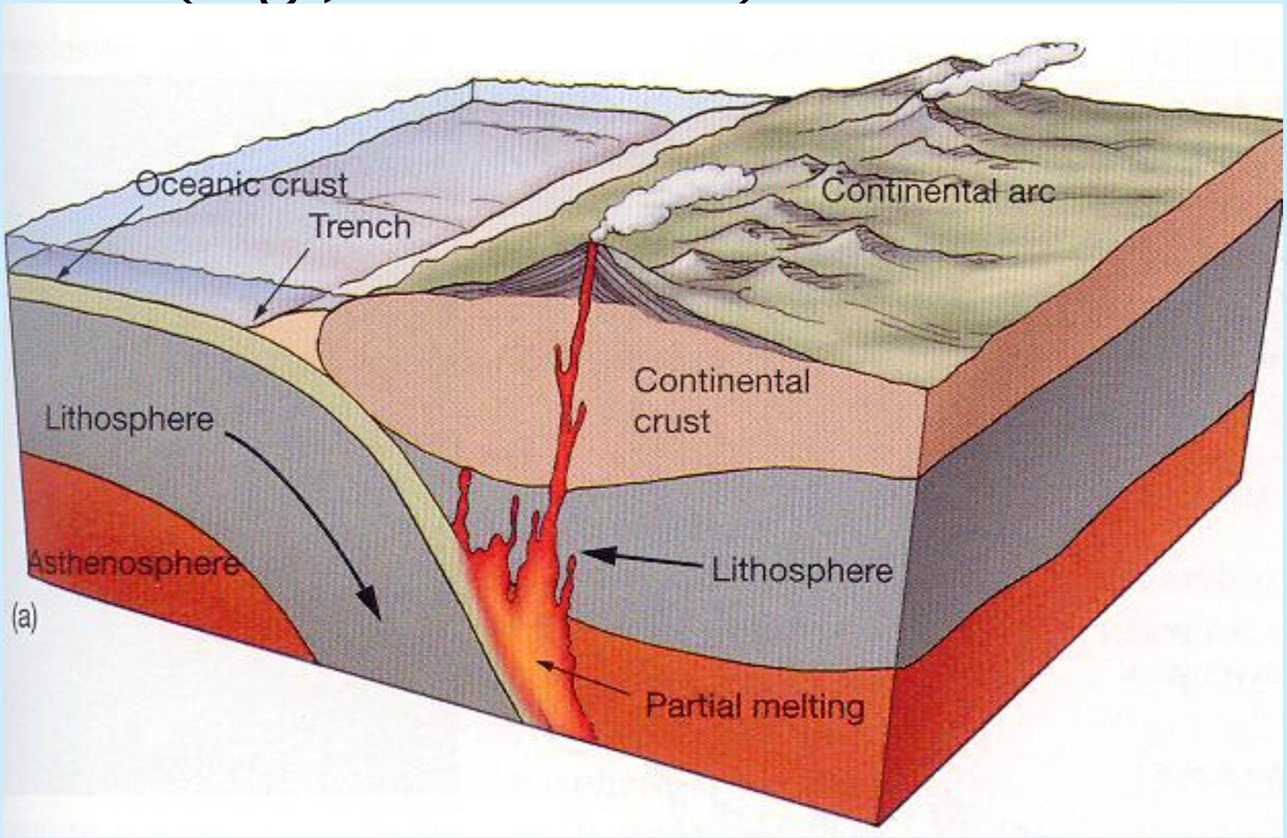
1. ***Oceanic-Oceanic***: volcanic island arc above the downgoing slab (e.g., Aleutians, Indonesia, Marianas)



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

3 Types of Destructional Boundaries

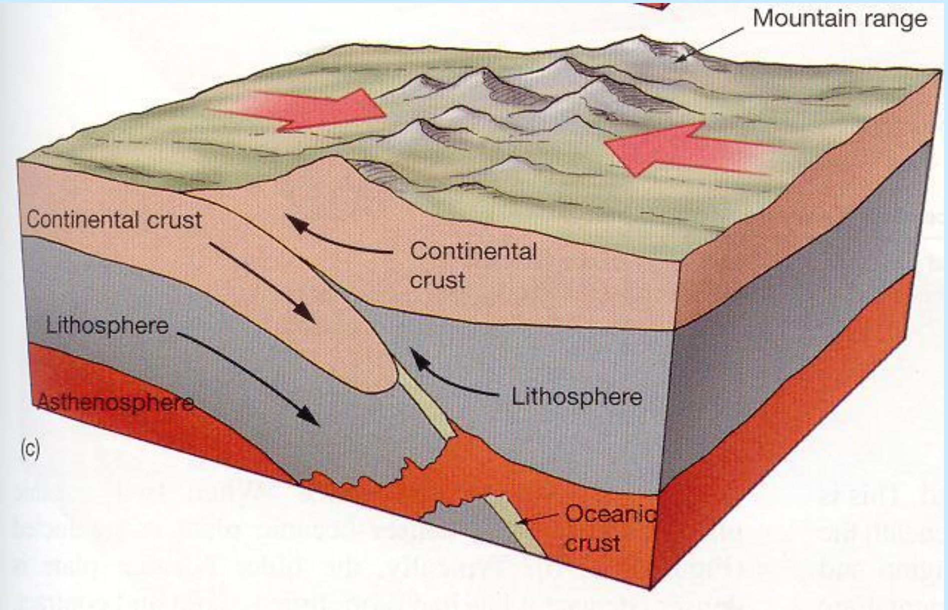
2. ***Oceanic-Continental***: volcanic arc at edge of continent (e.g., Peru-Chile)

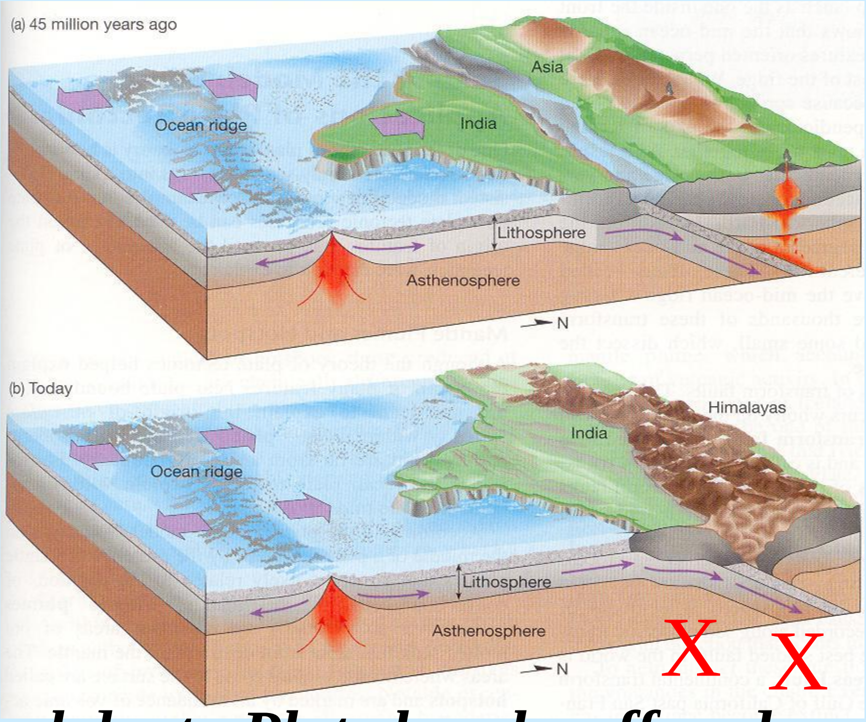


Continental crust is too buoyant to subduct!

3 Types of Destructional Boundaries

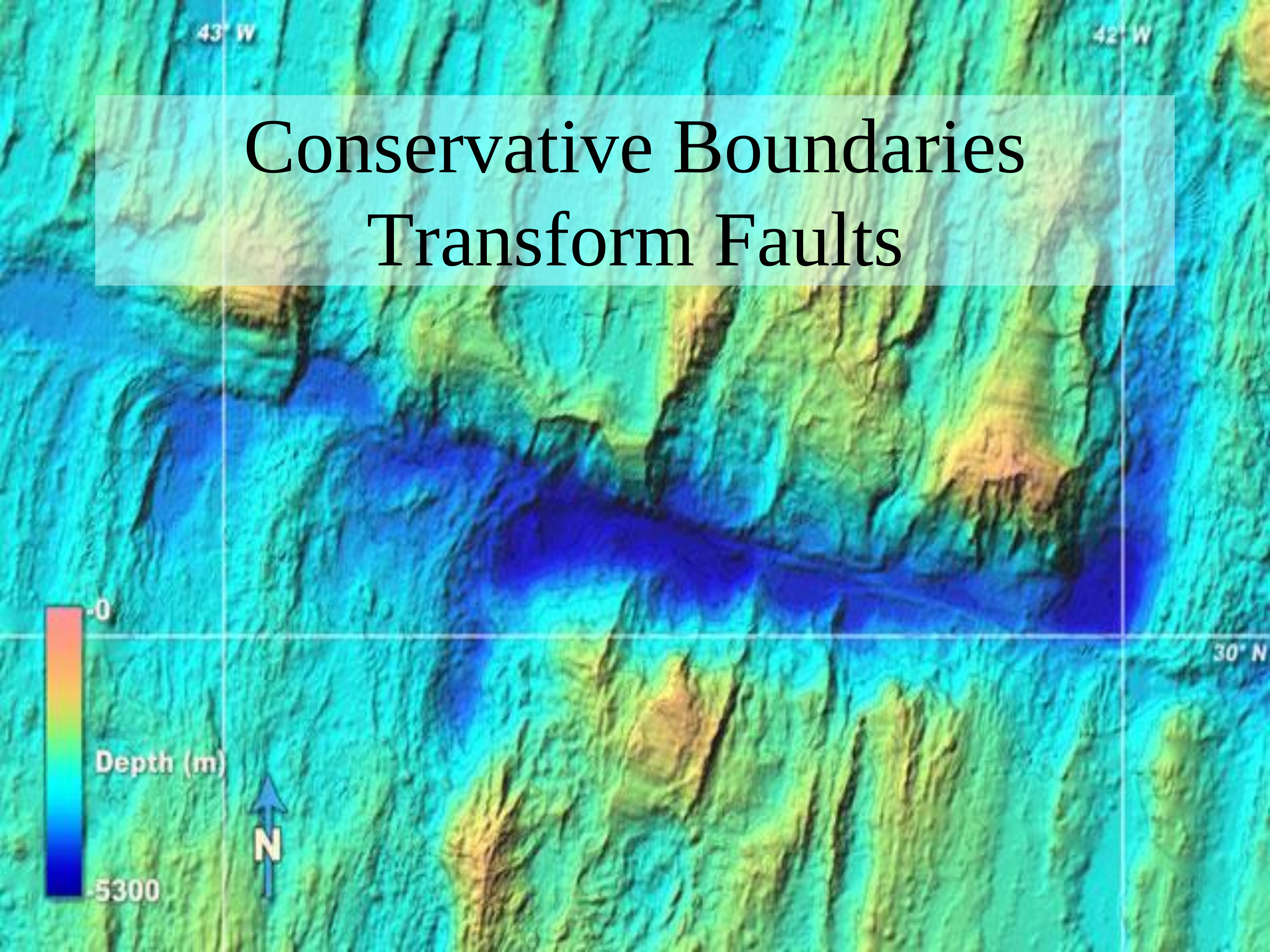
3. Continental-Continental: produces crust up to twice as thick as normal and a correspondingly high mountain plateau (e.g., Tibet, Himalayas).





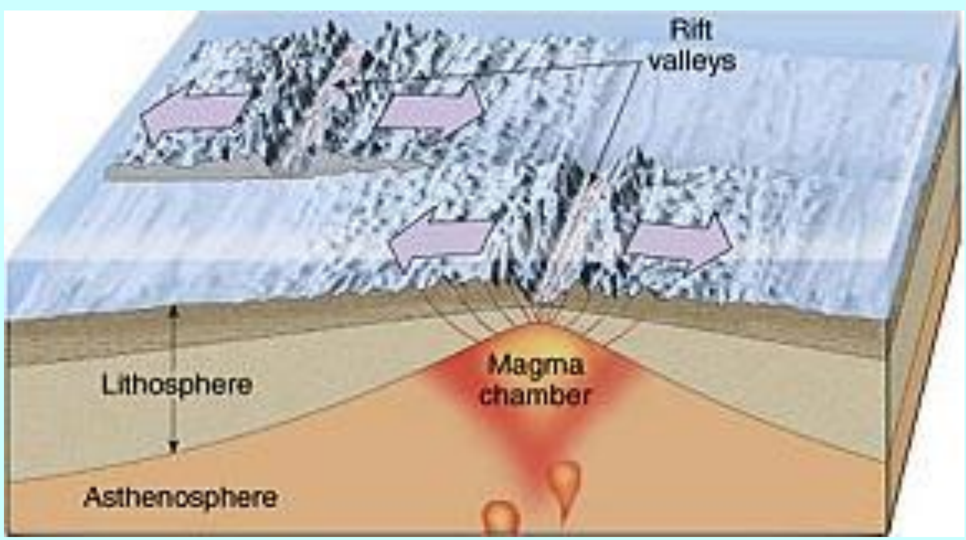
Continental crust is too buoyant to subduct. Plate breaks off and subduction stops, causing a global change in plate motions.

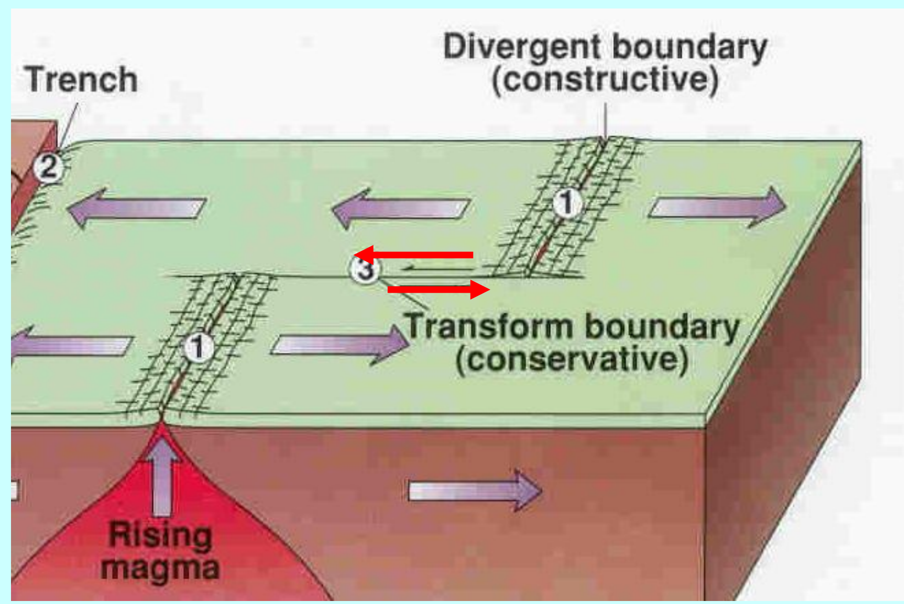
Conservative Boundaries
Transform Faults



Conservative Boundaries: Transform Faults

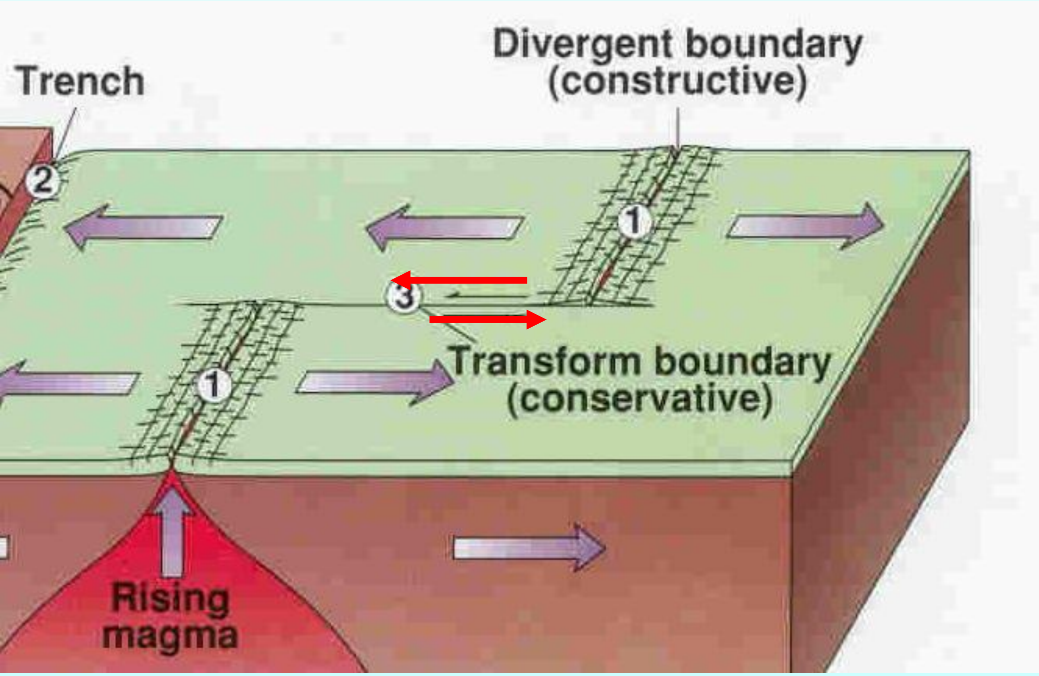
- Active zone of movement along a vertical fault plane located between two offset segments of ridge axis
- Relative motion is in opposite direction to that which would have produced such an offset in the absence of seafloor spreading.

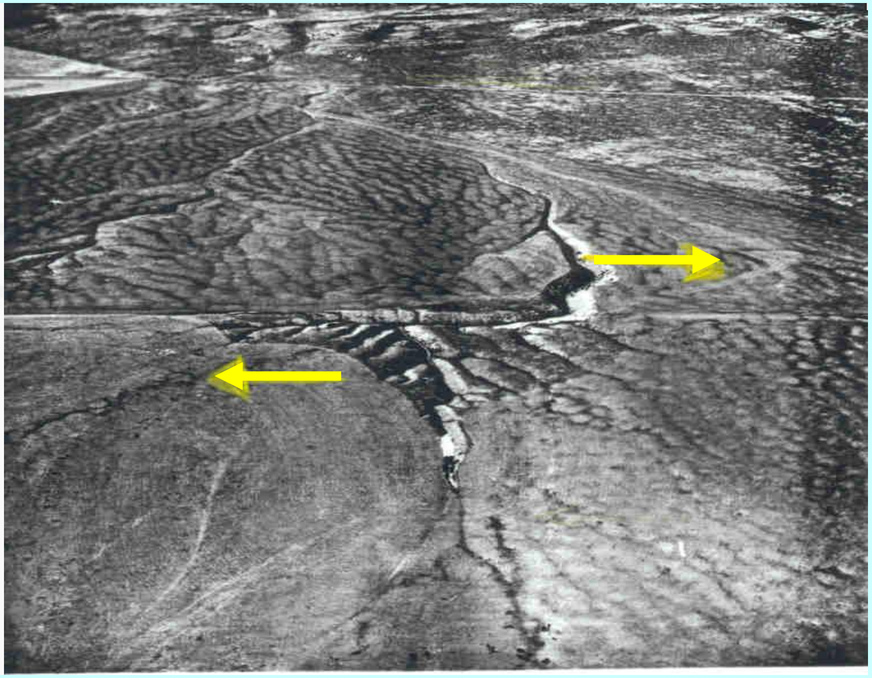




Relative Motions at Transform Faults

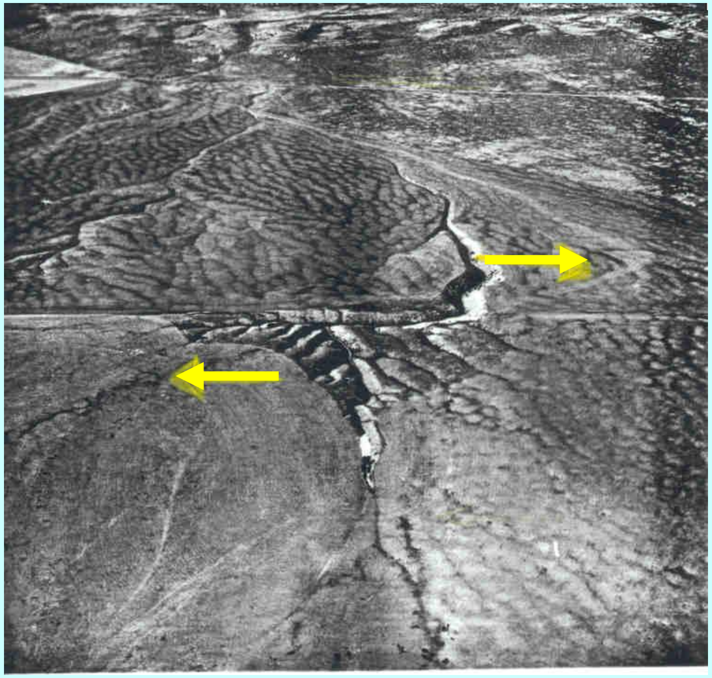
- Note: relative motion between two displaced features is in opposite direction to that which would have produced such an offset in the absence of seafloor spreading
- Compare direction of red arrows on left panel to yellow arrows on right panel (San Andreas Fault)

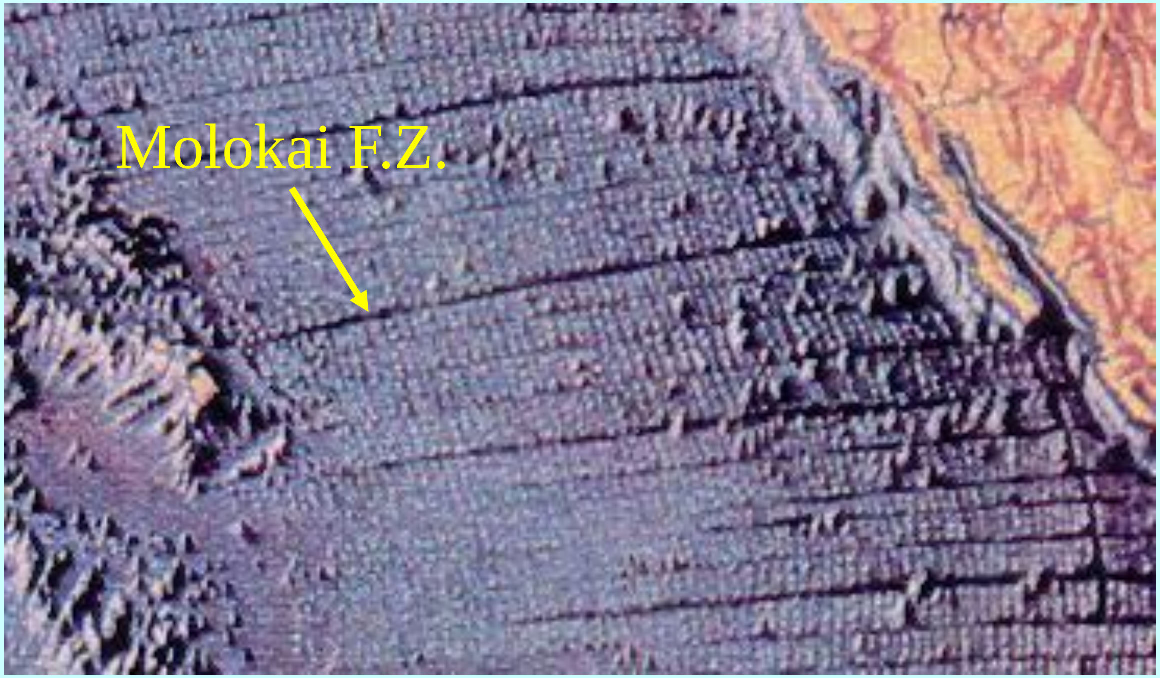




Conservative Boundaries: Transform Faults

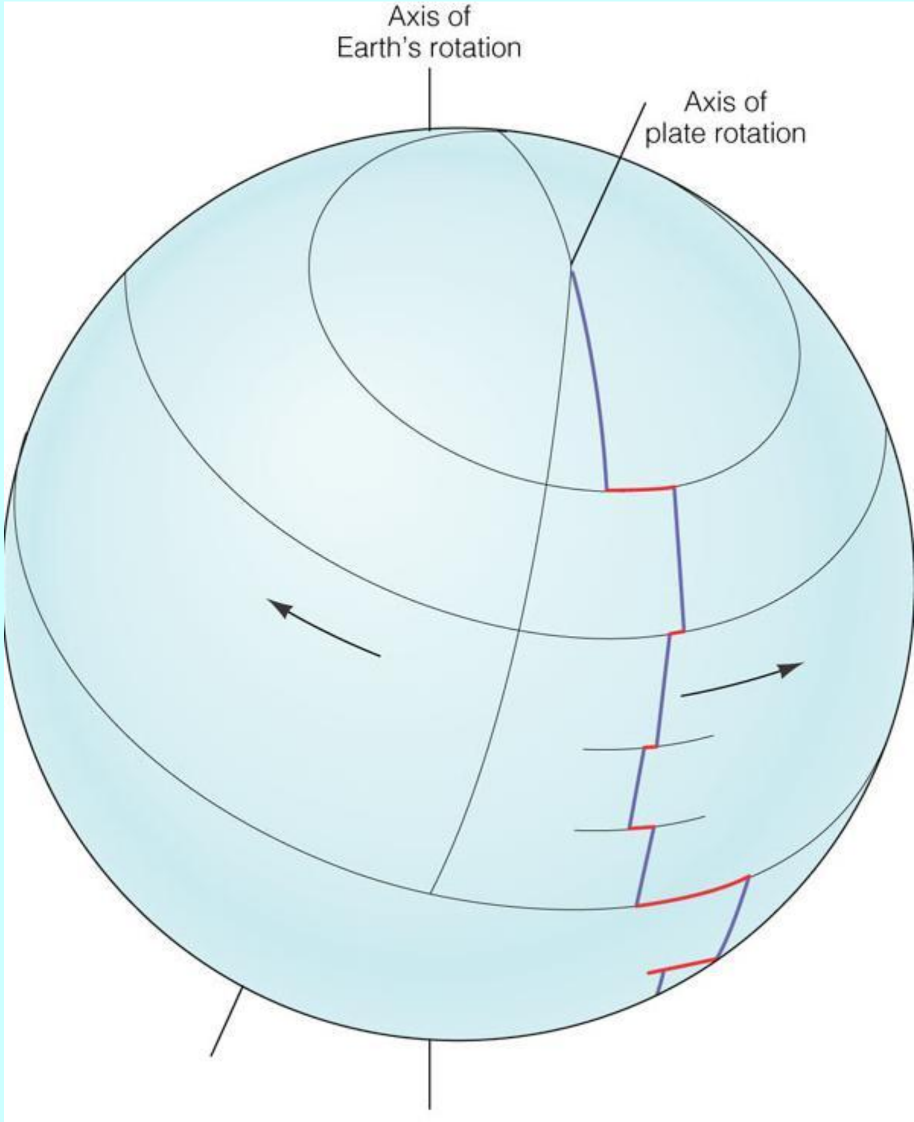
- Outside active transform region (not part of plate boundary), crust formed by offset segments becomes welded together to form the ***trace*** of the transform fault. Entire structure is called a ***Fracture zone***.





Fracture Zones and Poles of Rotation

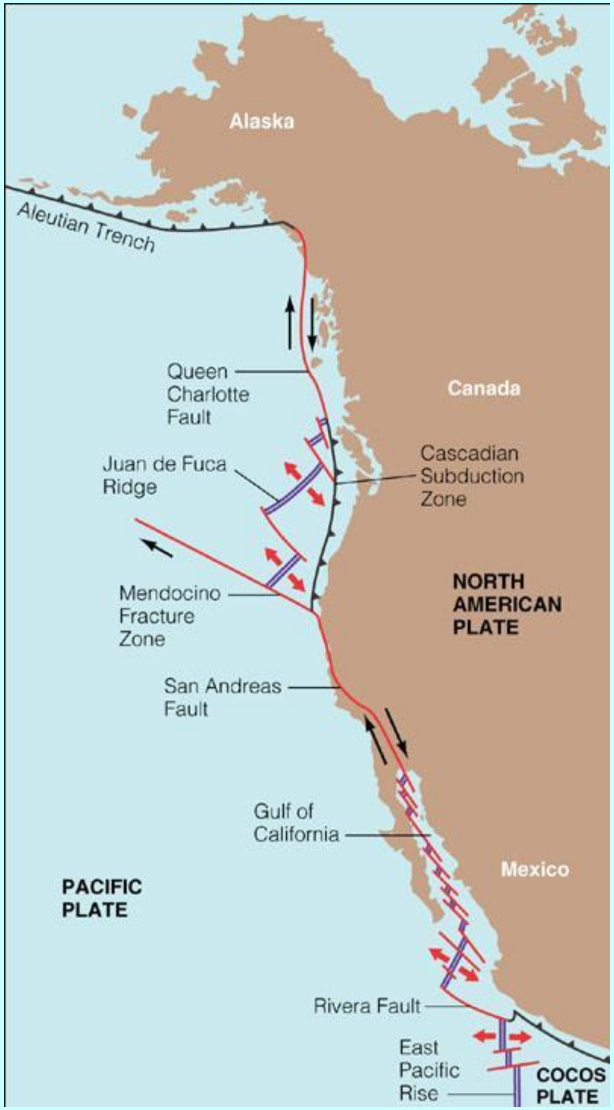
- Fracture zones lie on “small circles” on the Earth’s surface (analogous to circles of latitude)
- These circles are located about the pole of rotation for the relative motion of two plates
- The pole of rotation is located at the intersection of the “great circles” (analogous to lines of longitude)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



Fracture Zones and Poles of Rotation

•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.



Time for the next set of slides…