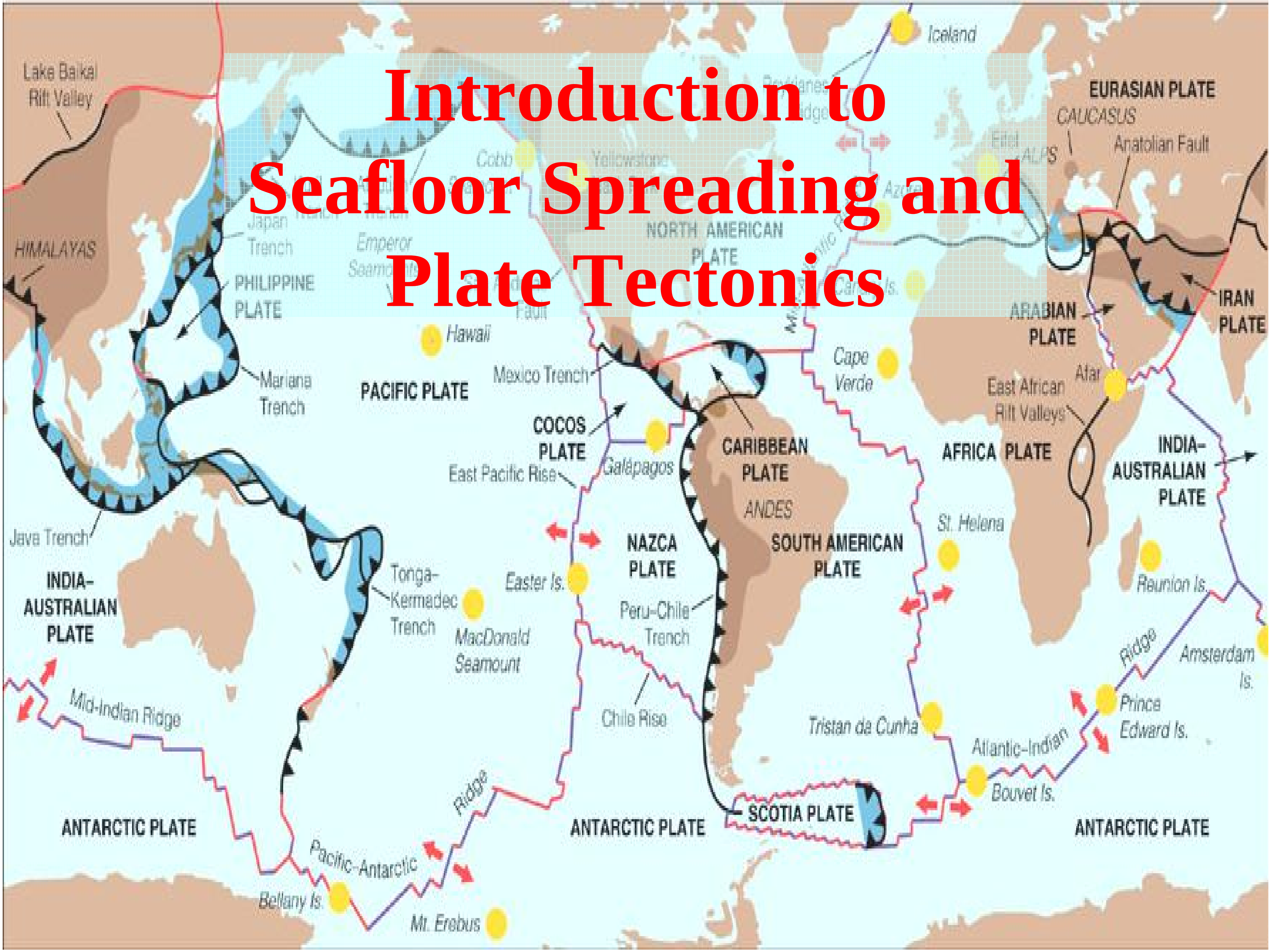
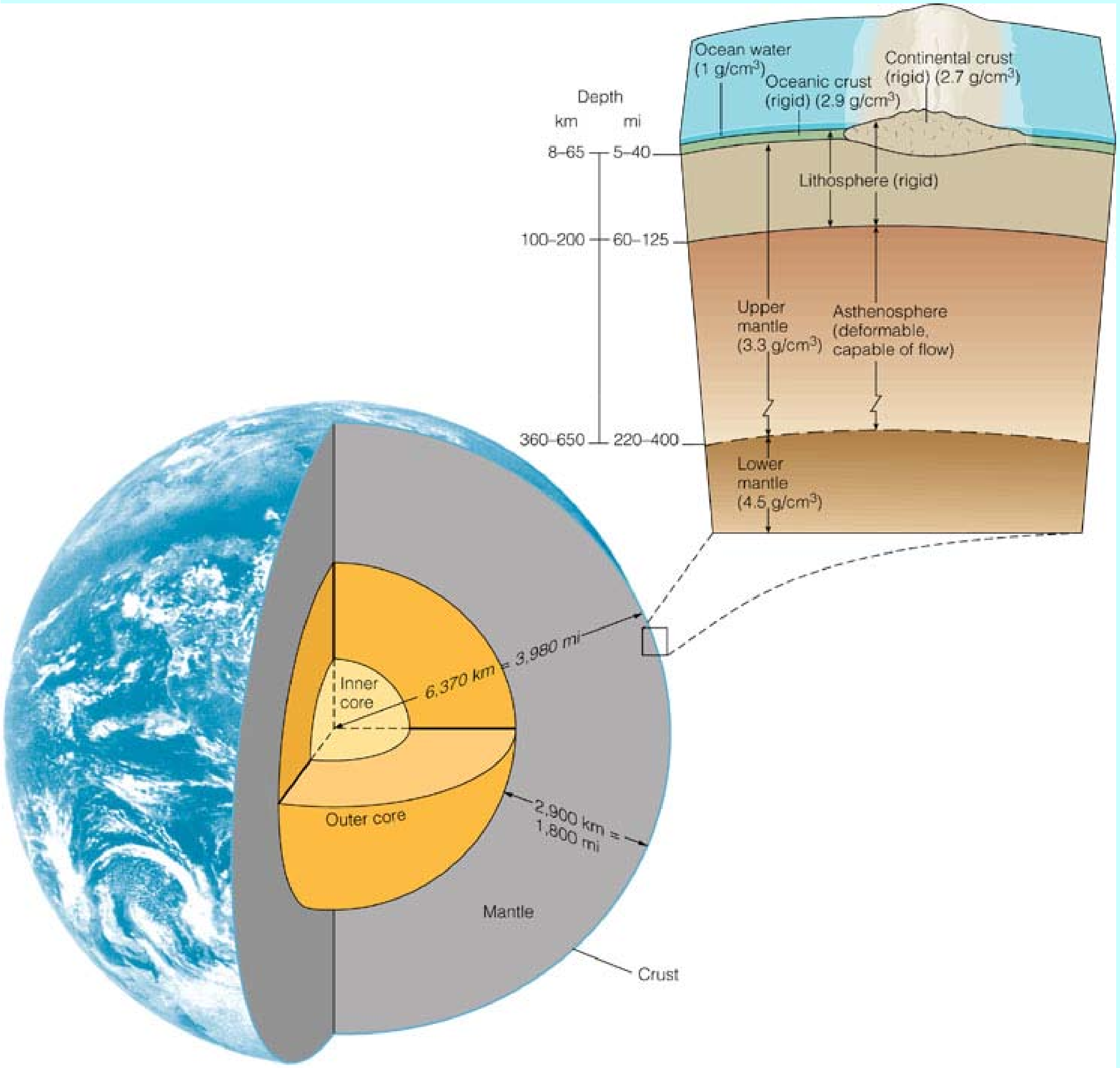
Introduction to Seafloor Spreading and Plate Tectonics



Earth's Lithosphere = Plates



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

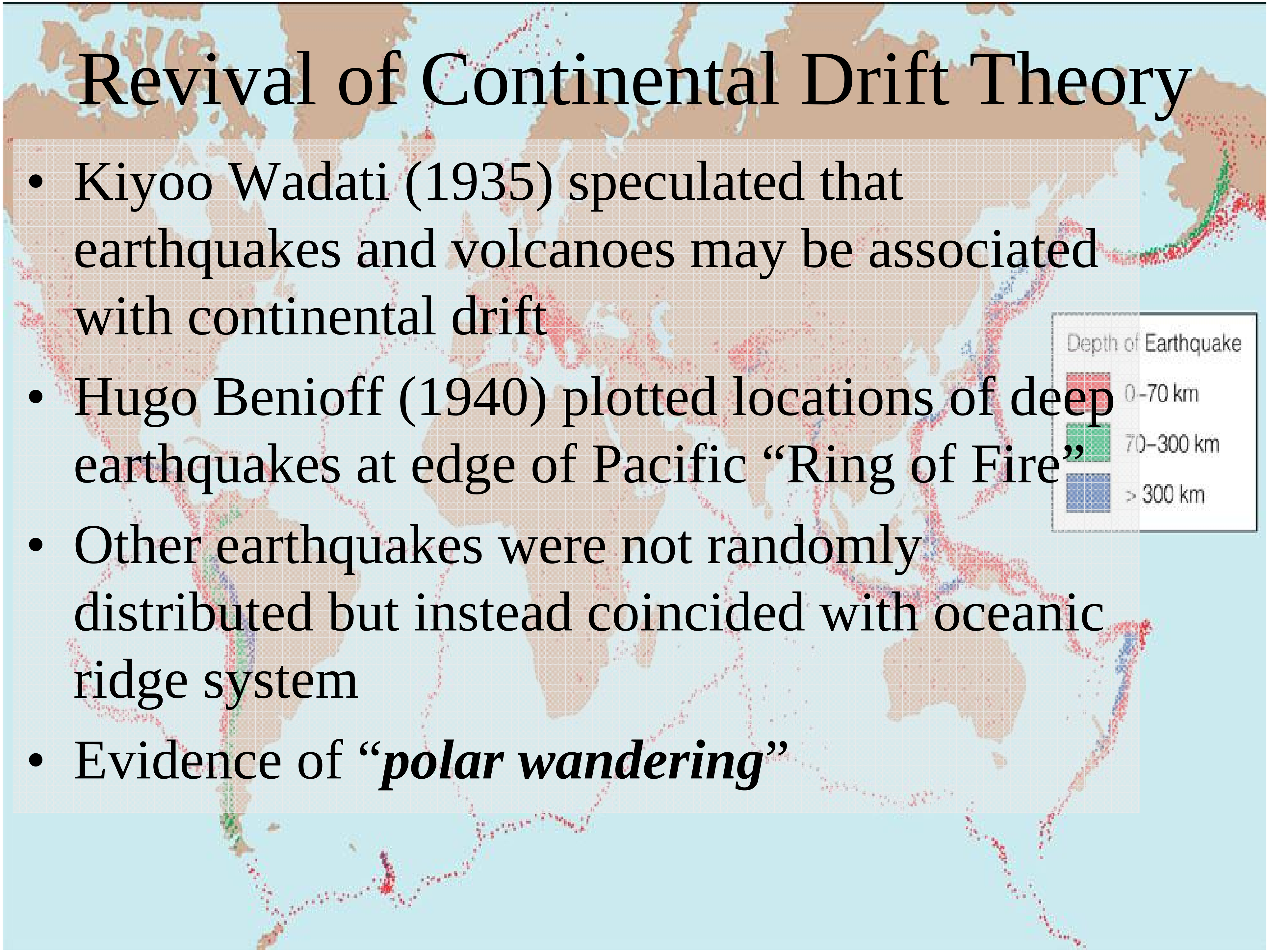
Oceanic crust ~ 6 km thick
Continental crust ~ 35 km
Lithosphere 70-120 km

Revival of Continental Drift Theory

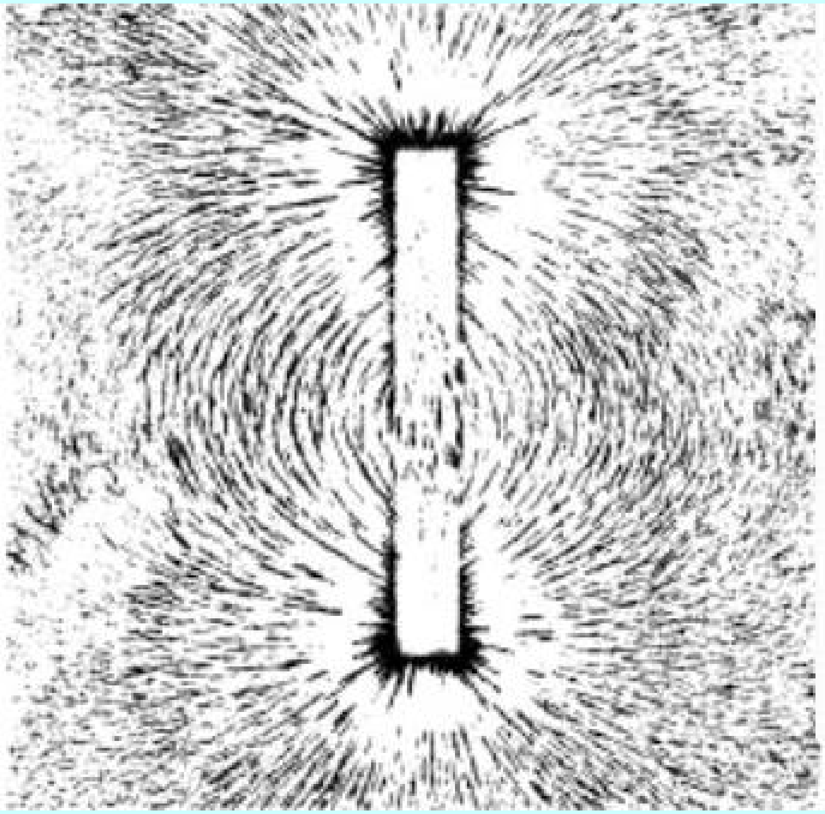
Wegener's theory was revived in the 1950's based on paleomagnetic evidence of "Polar Wandering"

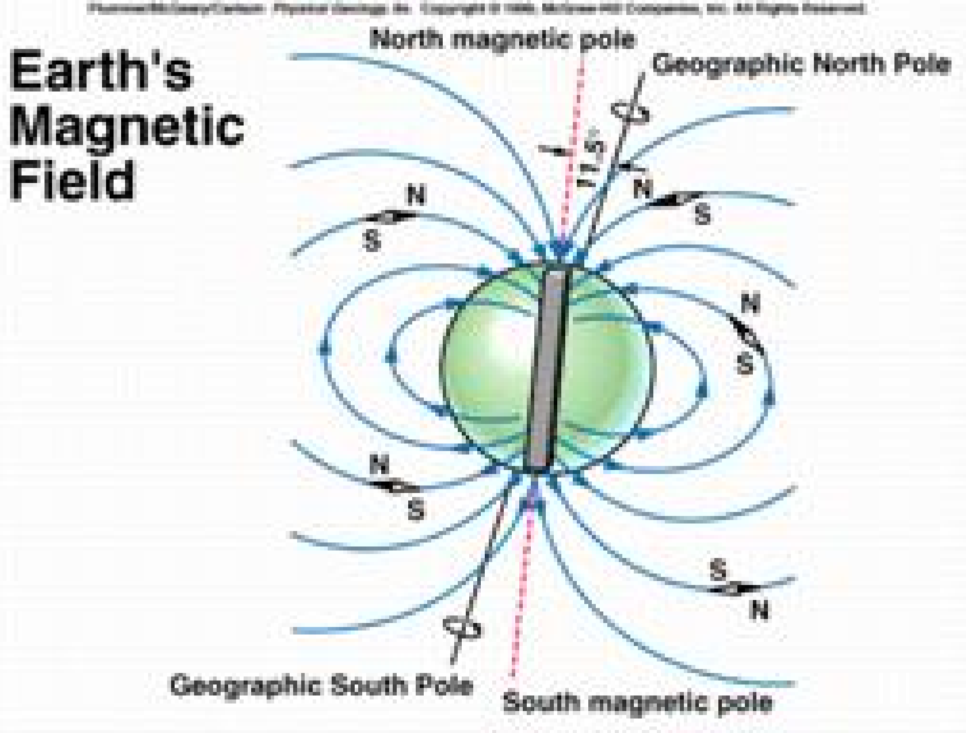
Revival of Continental Drift Theory

- 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***"



Earth’s Magnetic Field

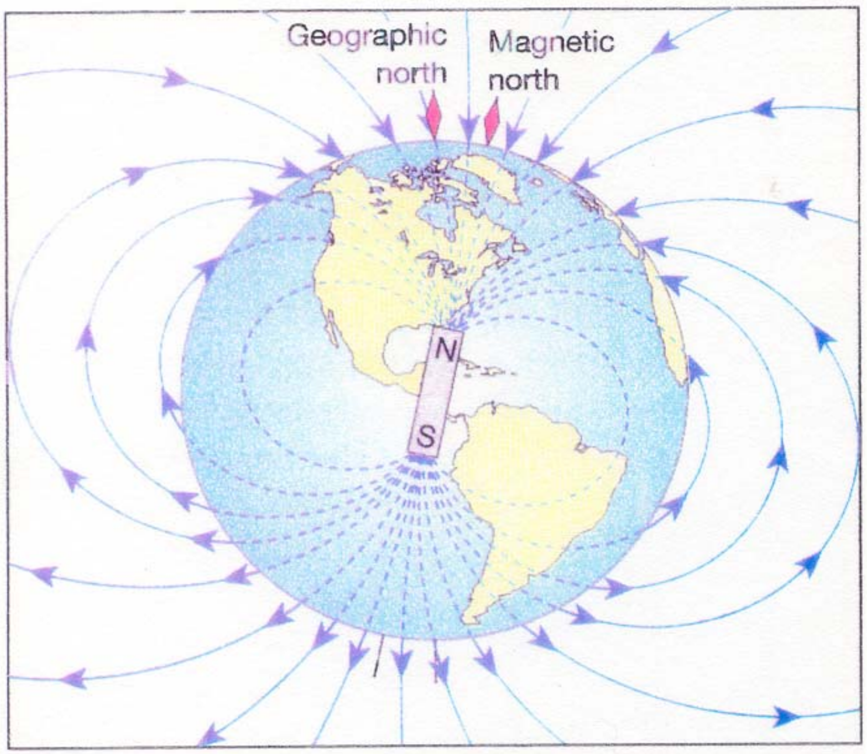


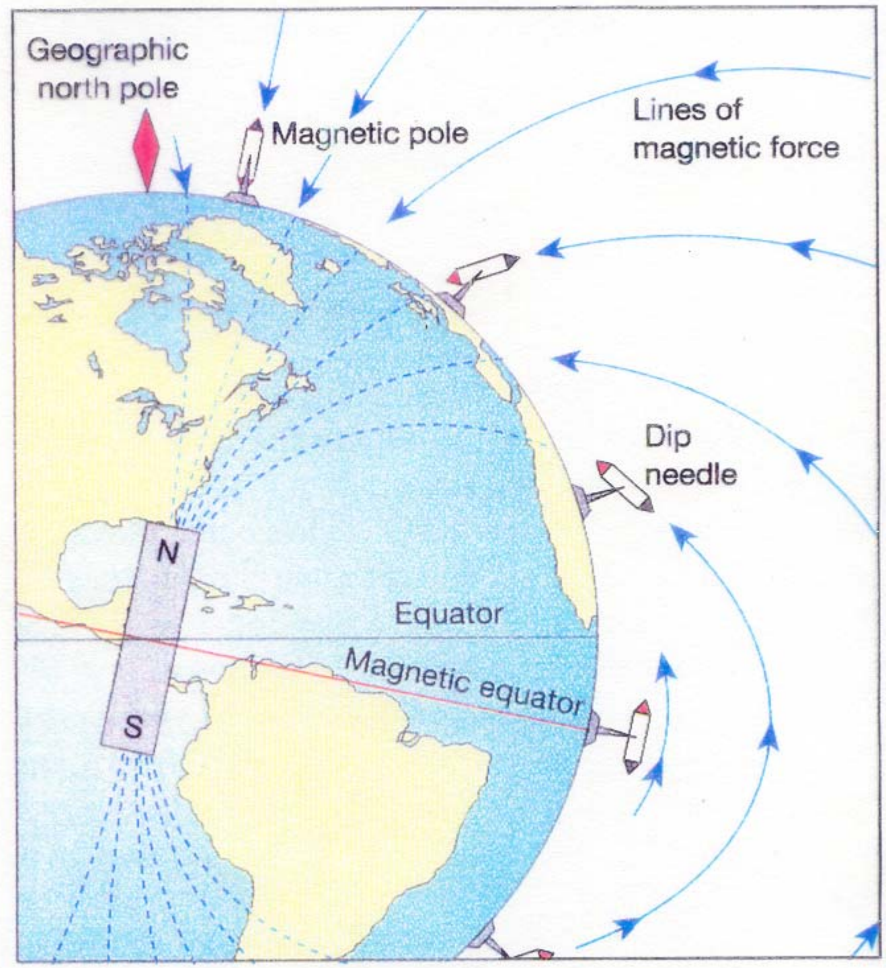


A bar magnet with Fe filings aligning along the “lines” of the magnetic field

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

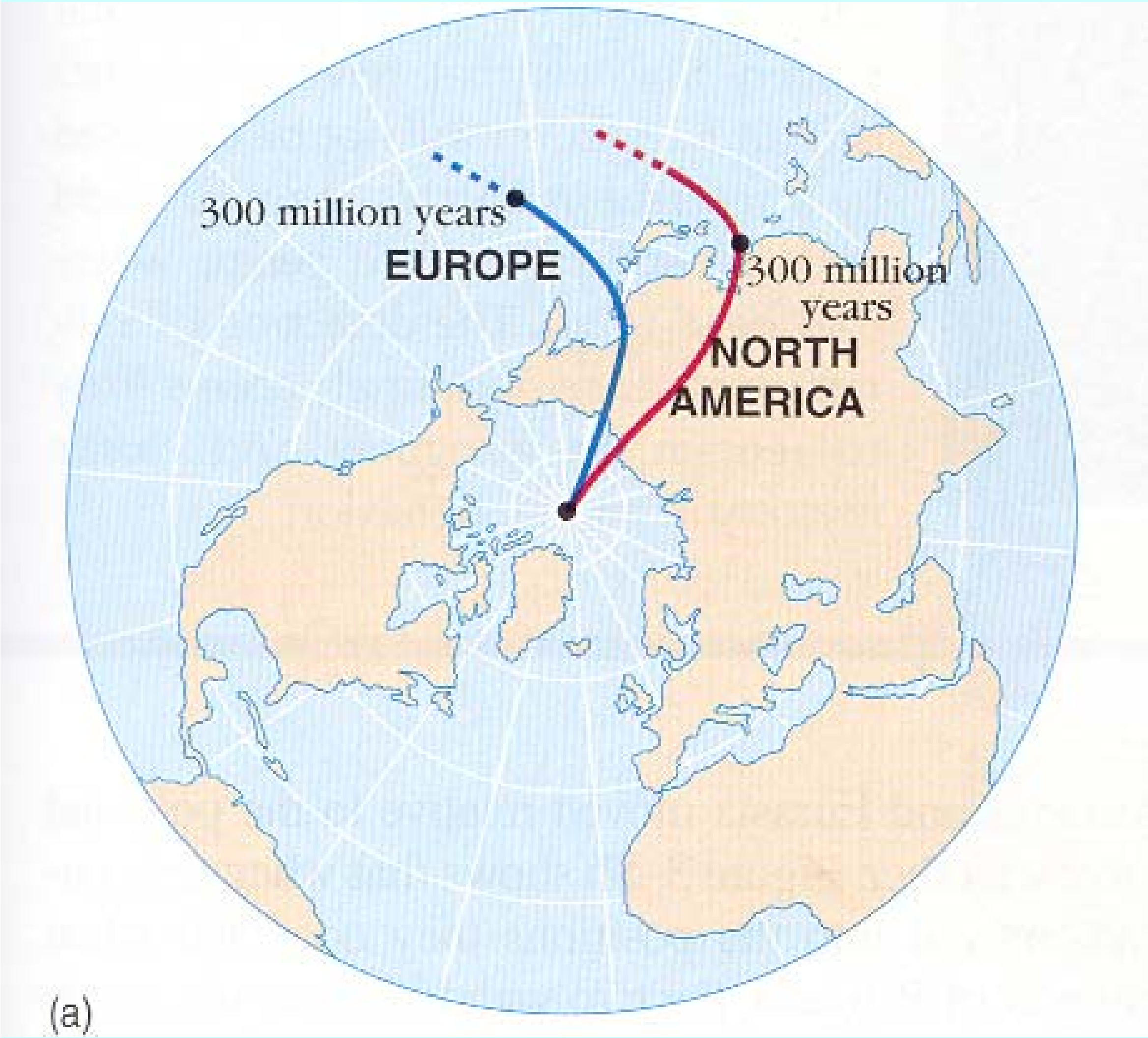
- Magnetic minerals in igneous rocks align themselves with the magnetic field of Earth when rocks solidify
- This magnetic alignment is “frozen” and retained if rock is not subsequently reheated
- Can use paleomagnetism of ancient rocks to determine:

  - direction and polarity of Earth’s magnetic field

  - paleolatitude from inclination (dip)

  - apparent position of N and S magnetic poles

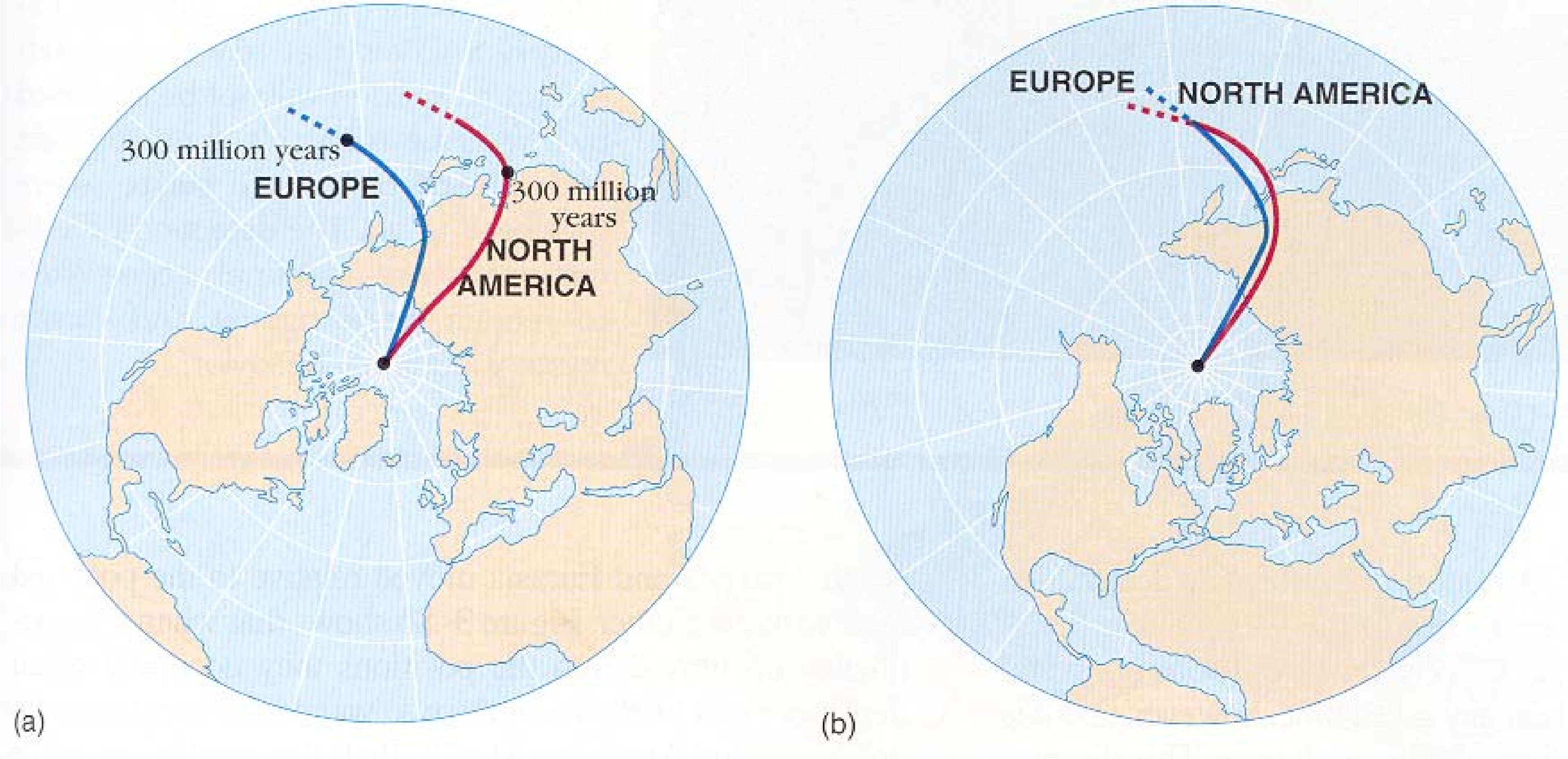
Apparent Polar Wander Paths



- Geomagnetic poles had apparently "wandered" systematically with time.

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

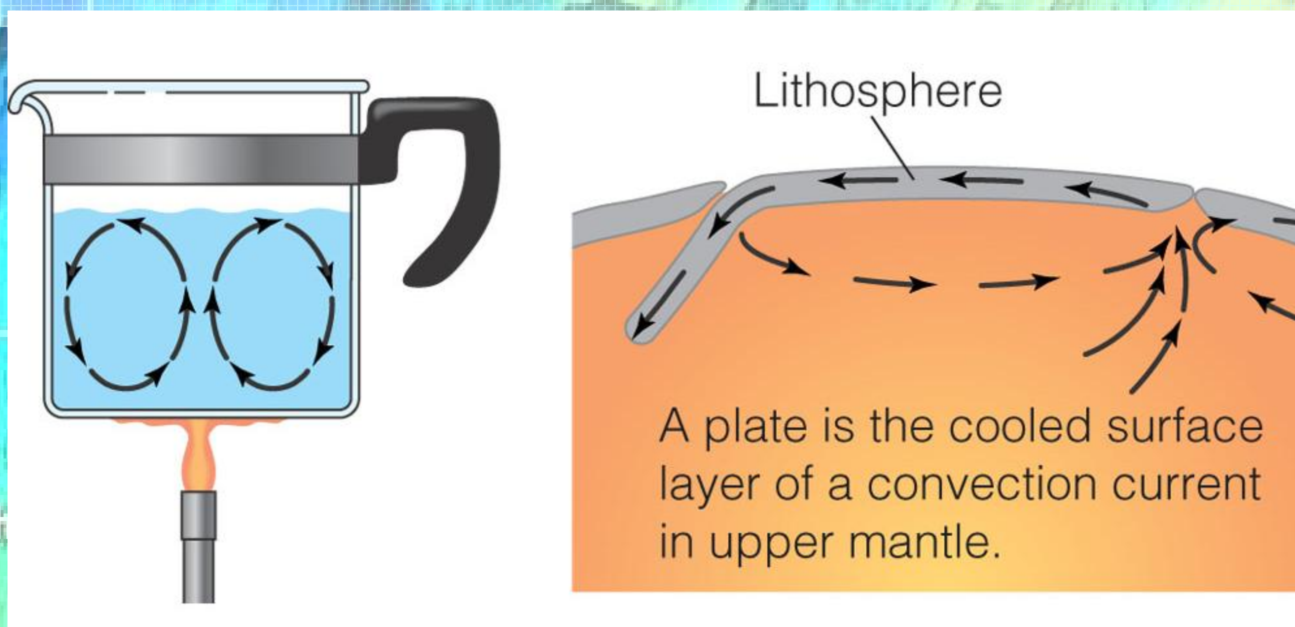
Apparent Polar Wander Paths



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

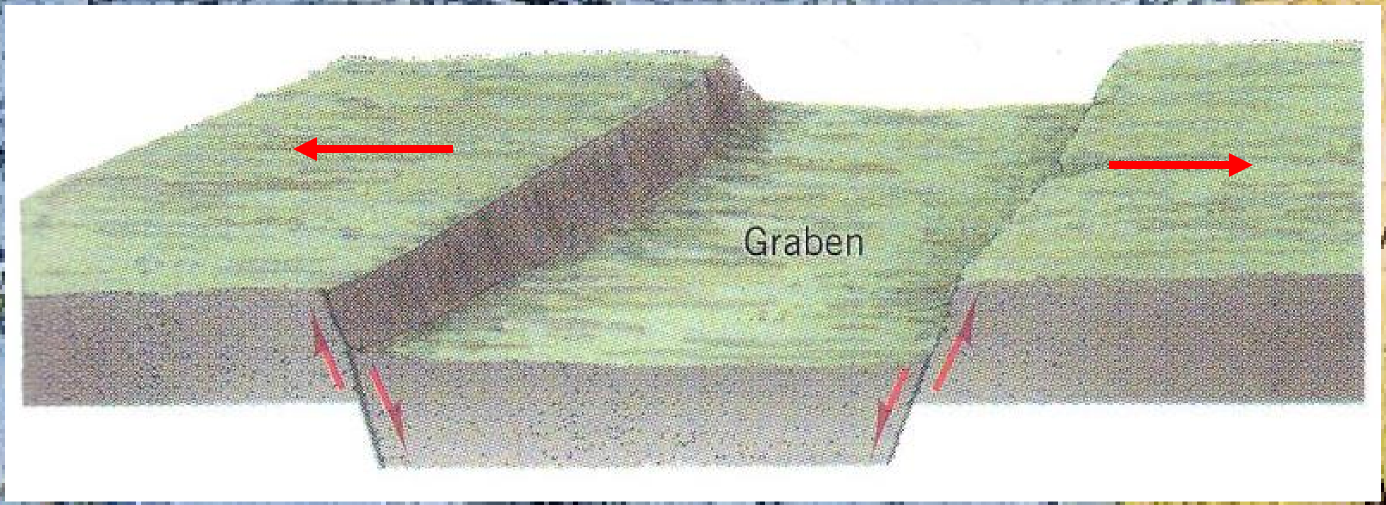
Seafloor Spreading: I

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



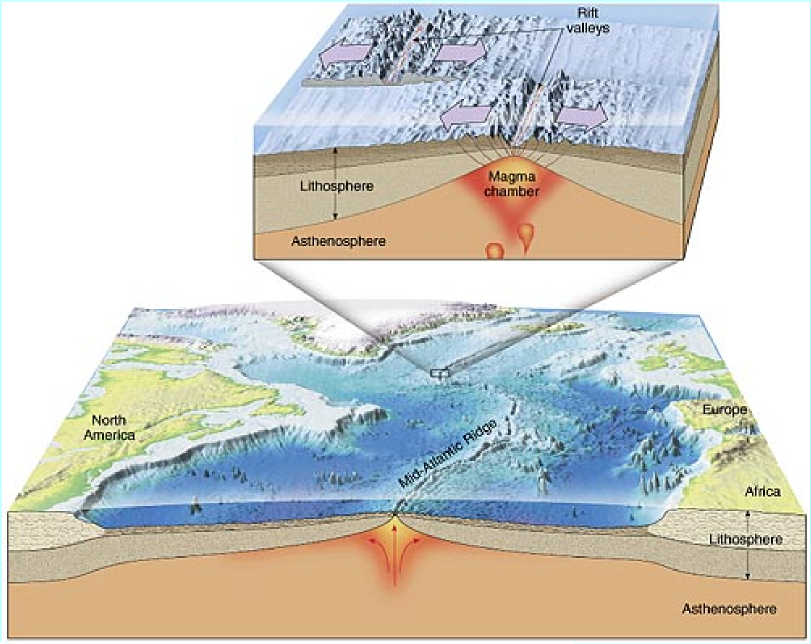
Seafloor Spreading: II

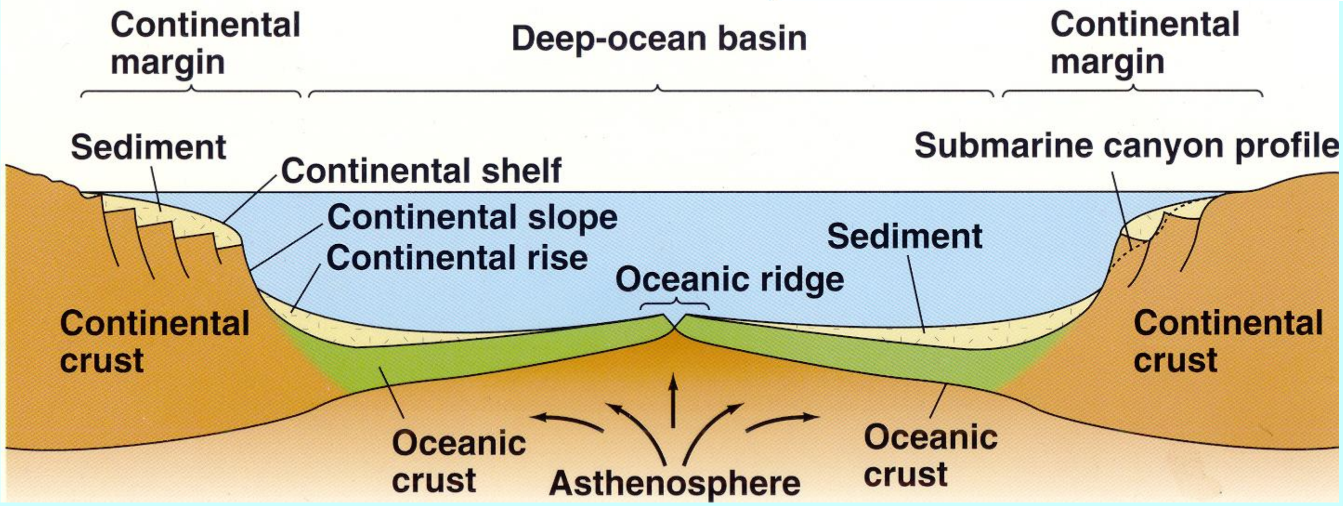
- Suggested by characteristics of **mid-ocean ridge**
  - Topography is elevated
  - Structure: **axial valley** with horst and graben structure formed by normal faulting, implying tension and extension



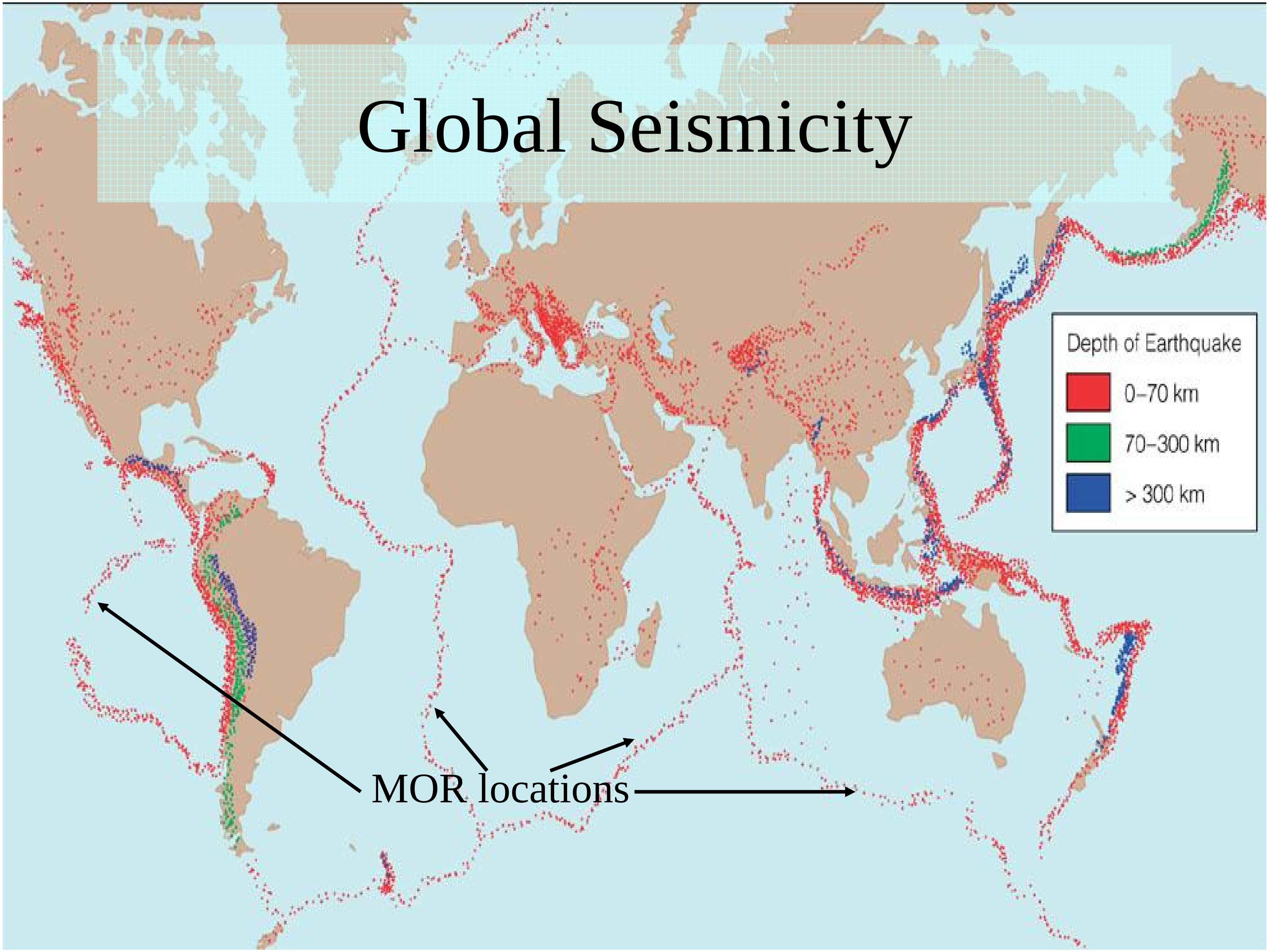
Mid-Ocean Ridges

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





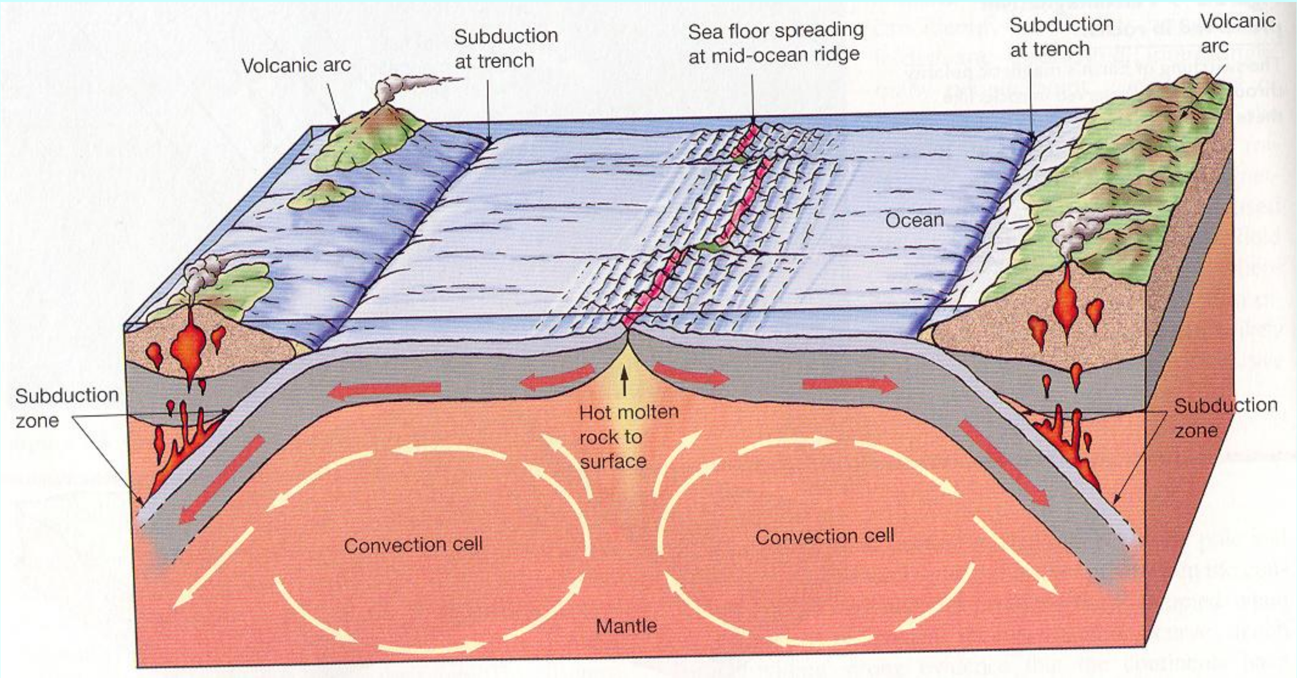
Global Seismicity



Seafloor Spreading: III

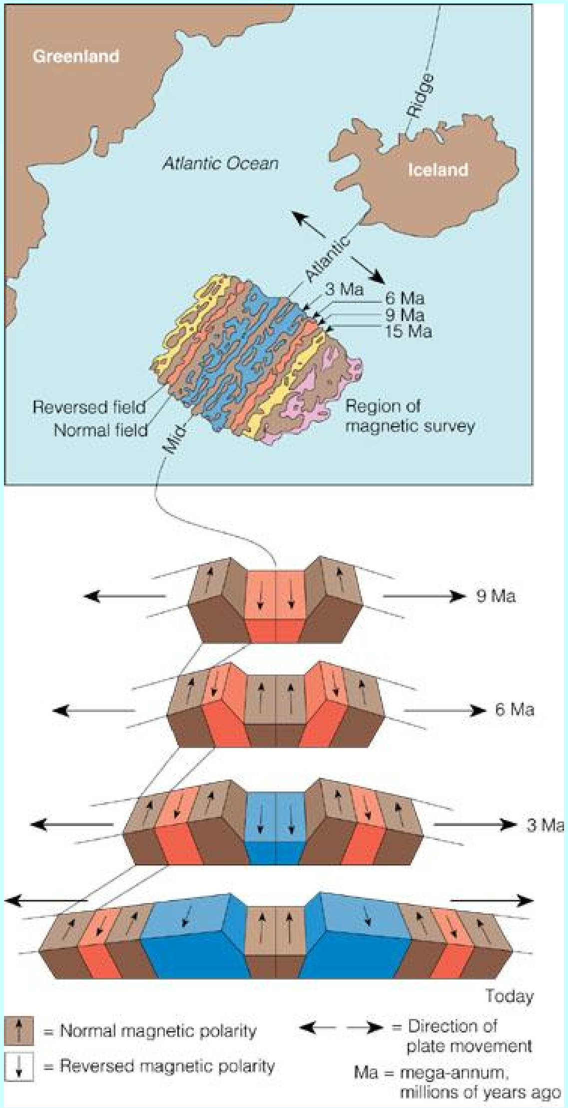
Formally proposed by Dietz (1961) and Hess (1962)

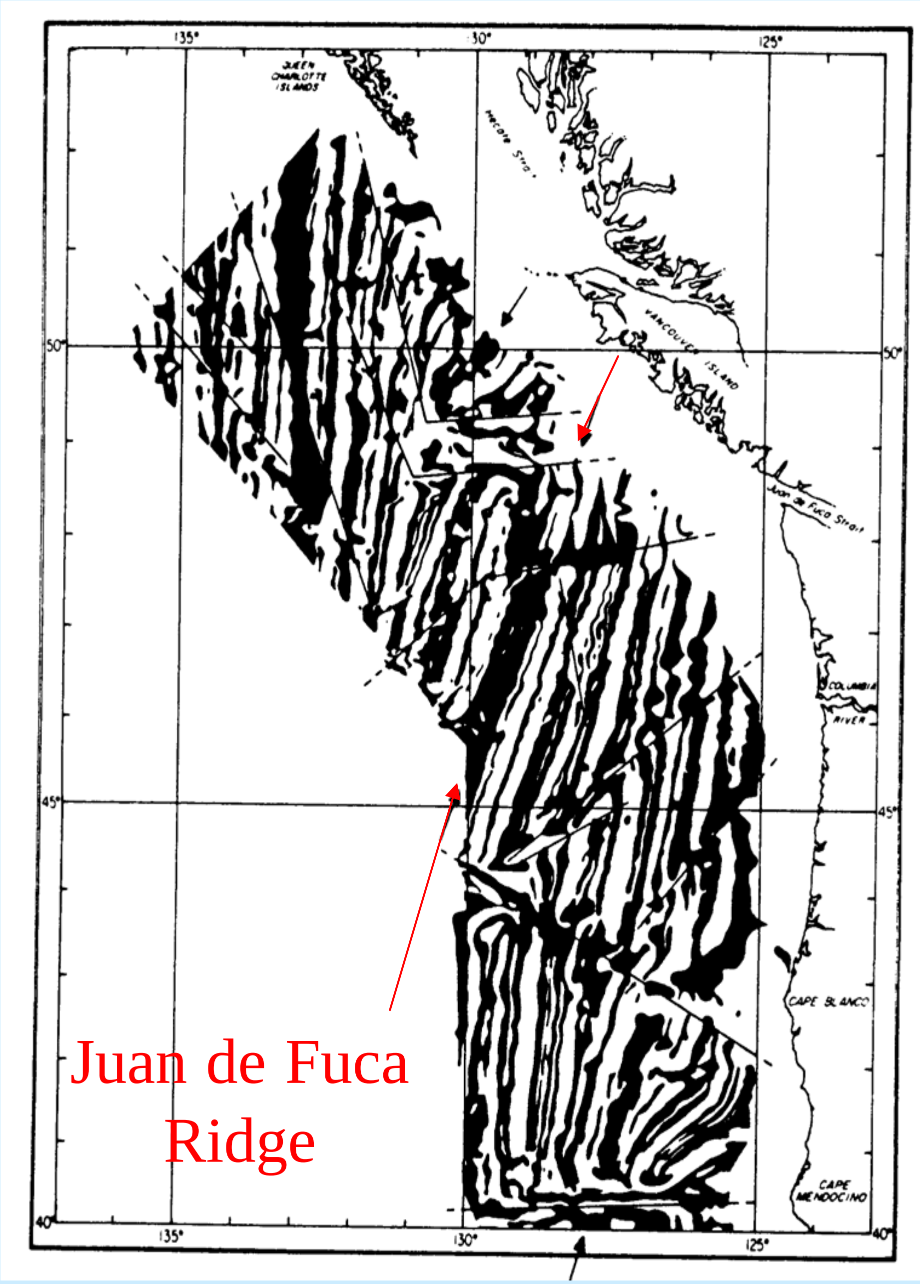
- Convection cells: Mantle upwells under MOR
- New oceanic crust is formed at MOR, then spreads laterally as if on conveyor belt
- Oceanic crust is dragged down at trenches (compression, mountain ranges and volcanic arcs)
- Continents ride passively between sites of upwelling and downwelling



Seafloor Spreading: IV

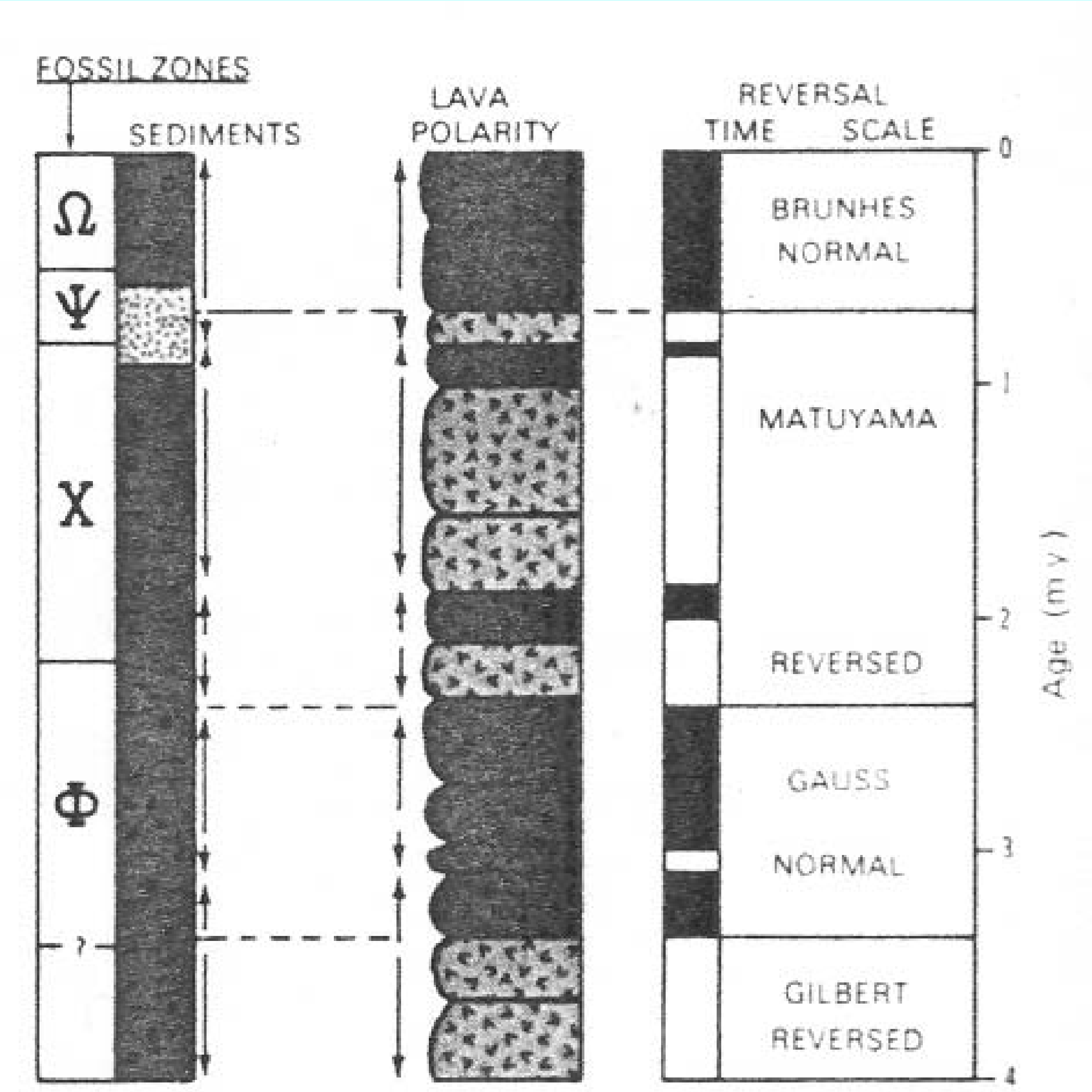
- Confirmed for some by Vine and Matthews (1963) who interpreted linear magnetic anomalies parallel to MOR as result of seafloor spreading
- Magnetic anomalies showed periodic polarity reversals first observed by Brunhes in 1906 on land (where patterns are complex)
- Simple marine sequence of magnetic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

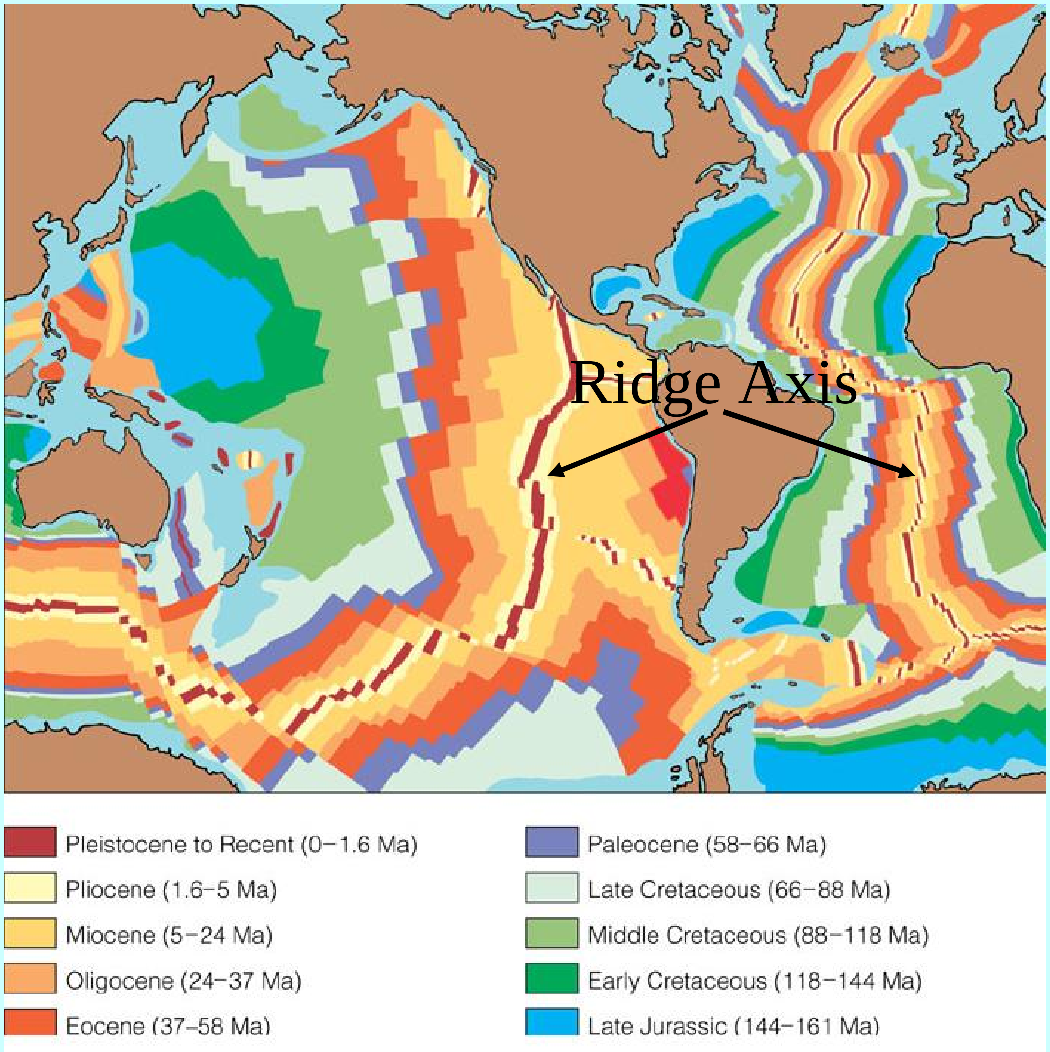


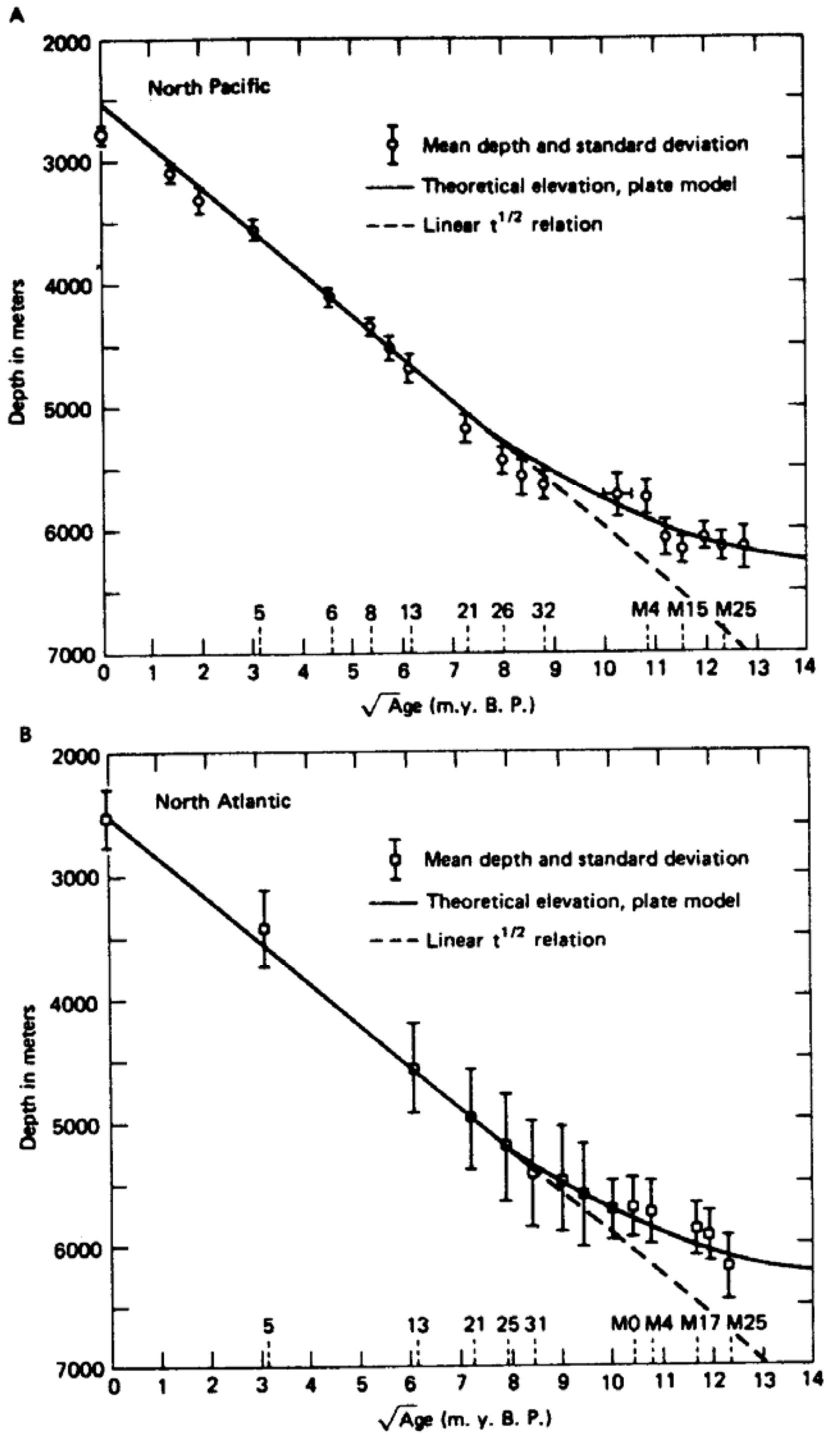
- Magnetic polarity reversals* were first observed by Brunhes (1906) on land.

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

Seafloor Spreading: V

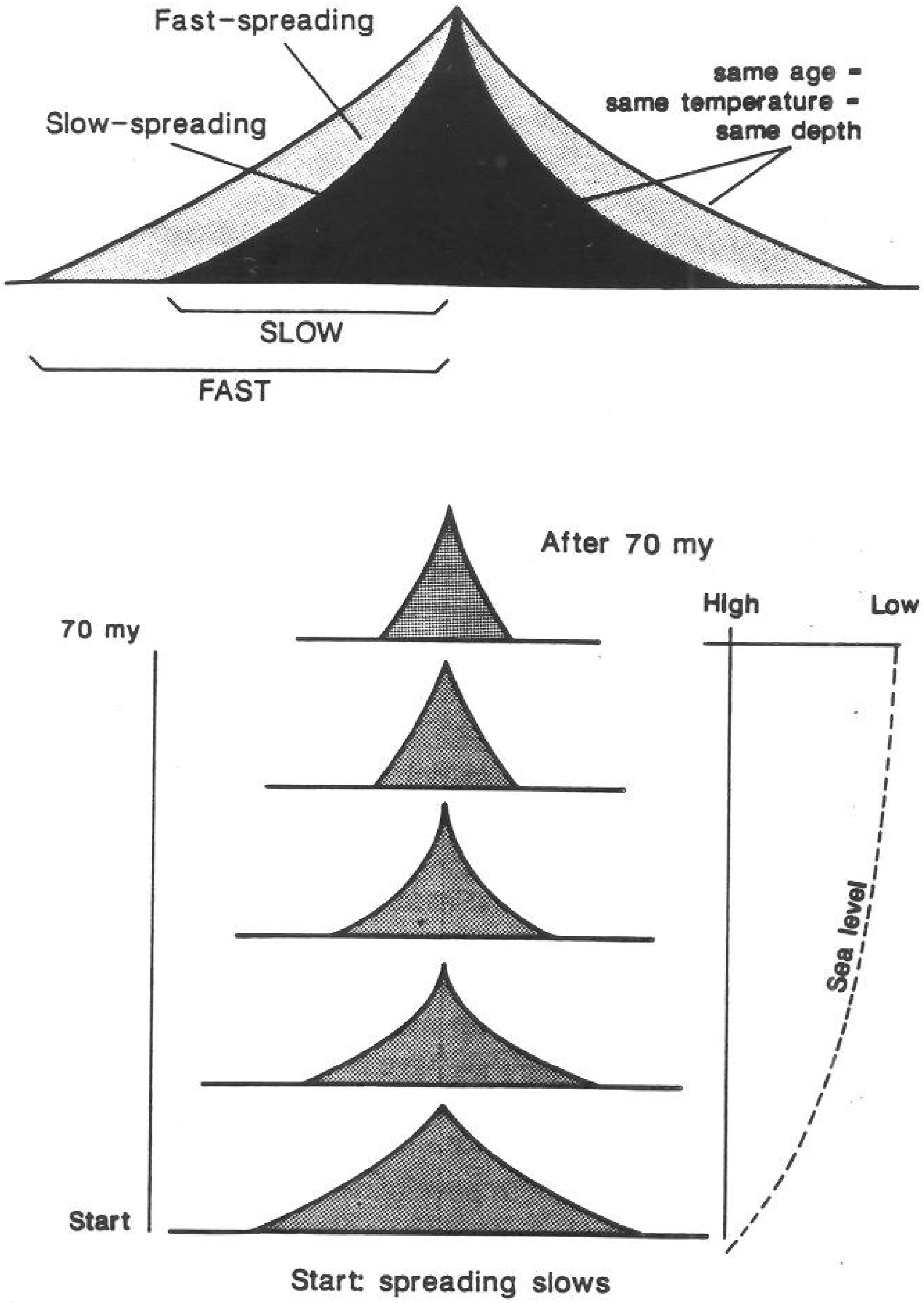
- Confirmed for most geologists by DSDP (1970's): age of sea floor (crust) increases regularly with distance from the ridge axis
- This was a major prediction of the seafloor spreading hypothesis!





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)

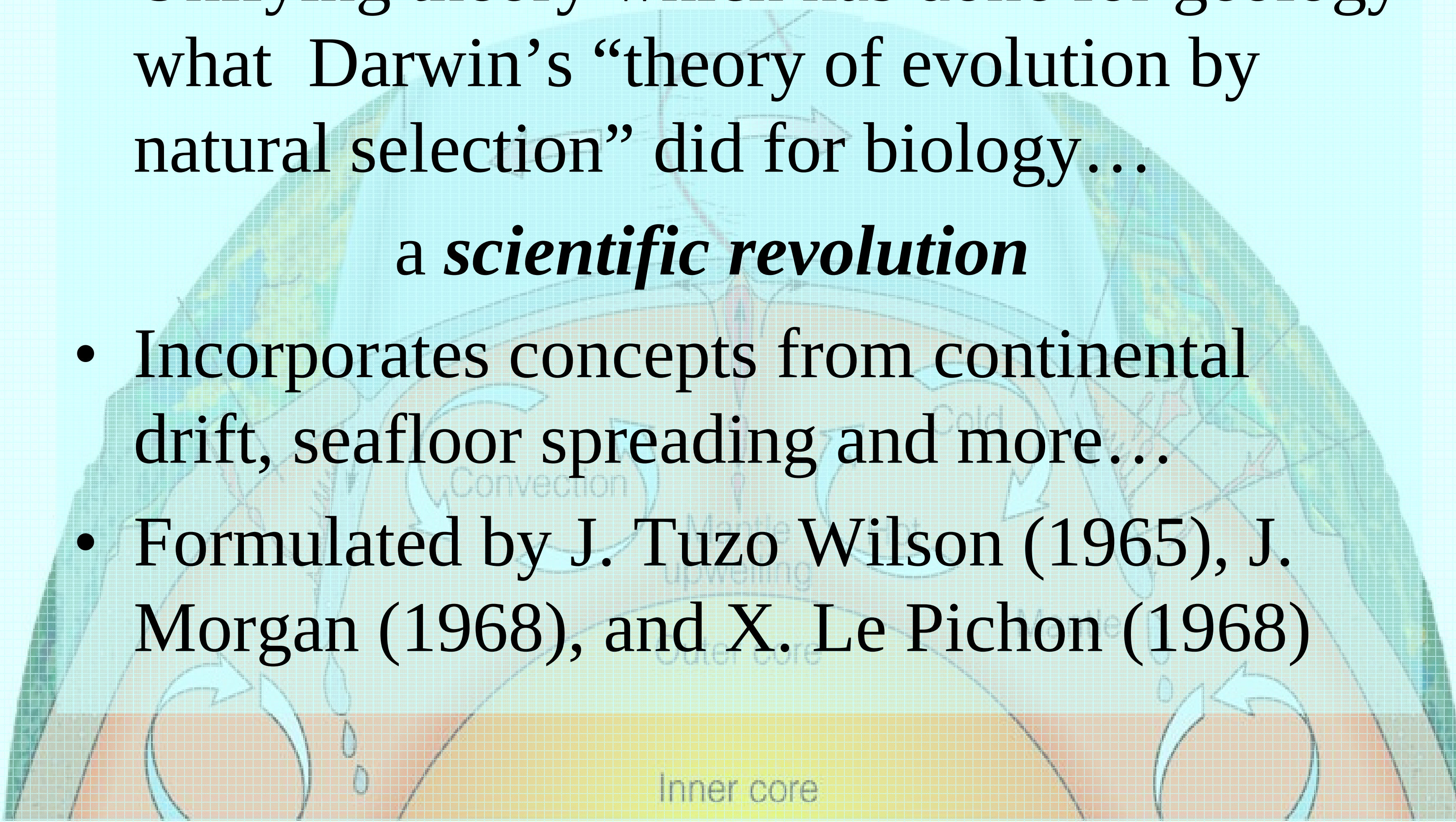
  ➔ ***large sea level change!***

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***

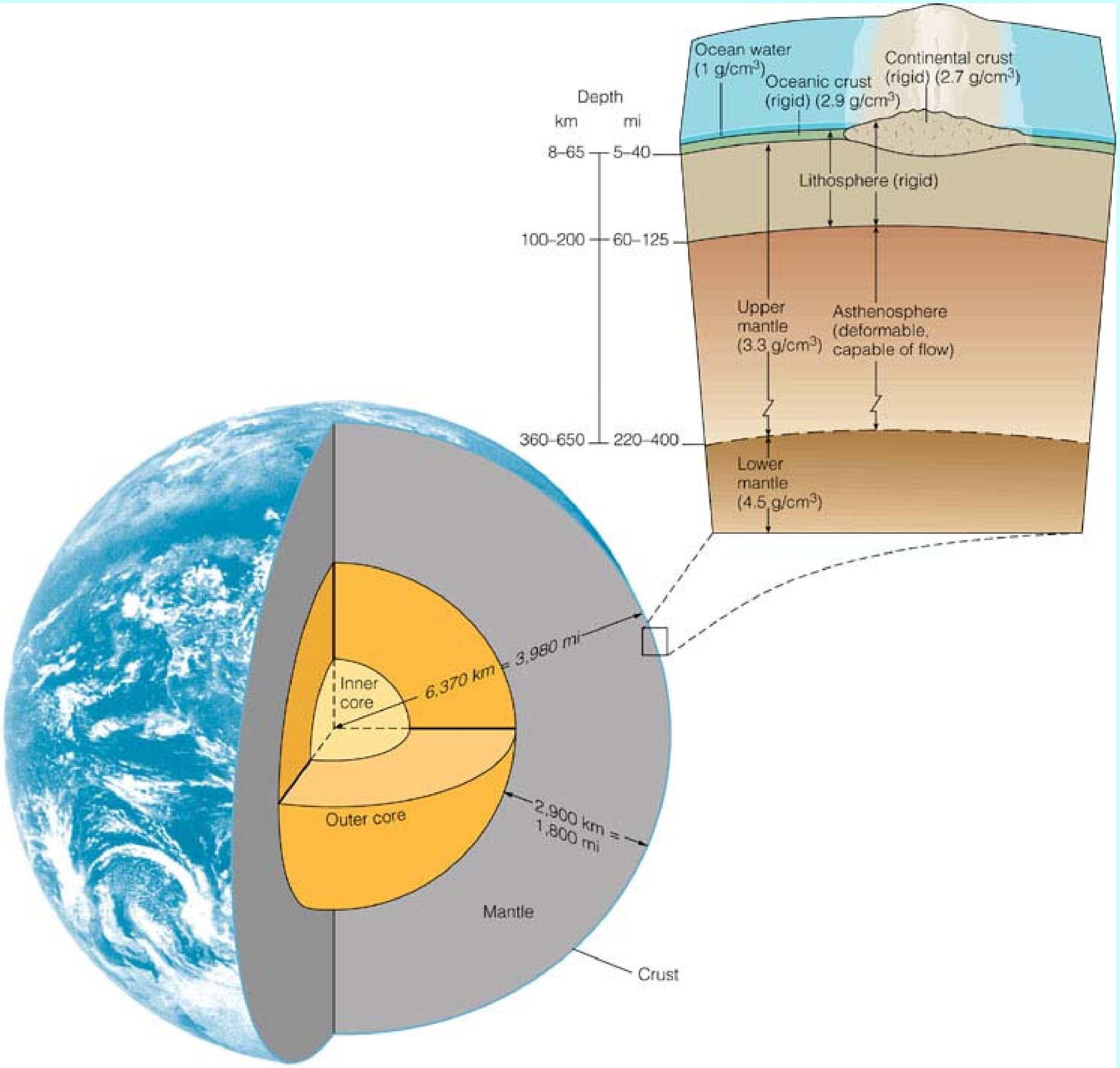
- Incorporates concepts from continental drift, seafloor spreading and more…
- Formulated by J. Tuzo Wilson (1965), J. Morgan (1968), and X. Le Pichon (1968)



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 with one 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: 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 igneous rocks.
- The ***mesosphere*** (most of mantle) extends to the core and is more rigid than the asthenosphere.

Lithospheric Plates

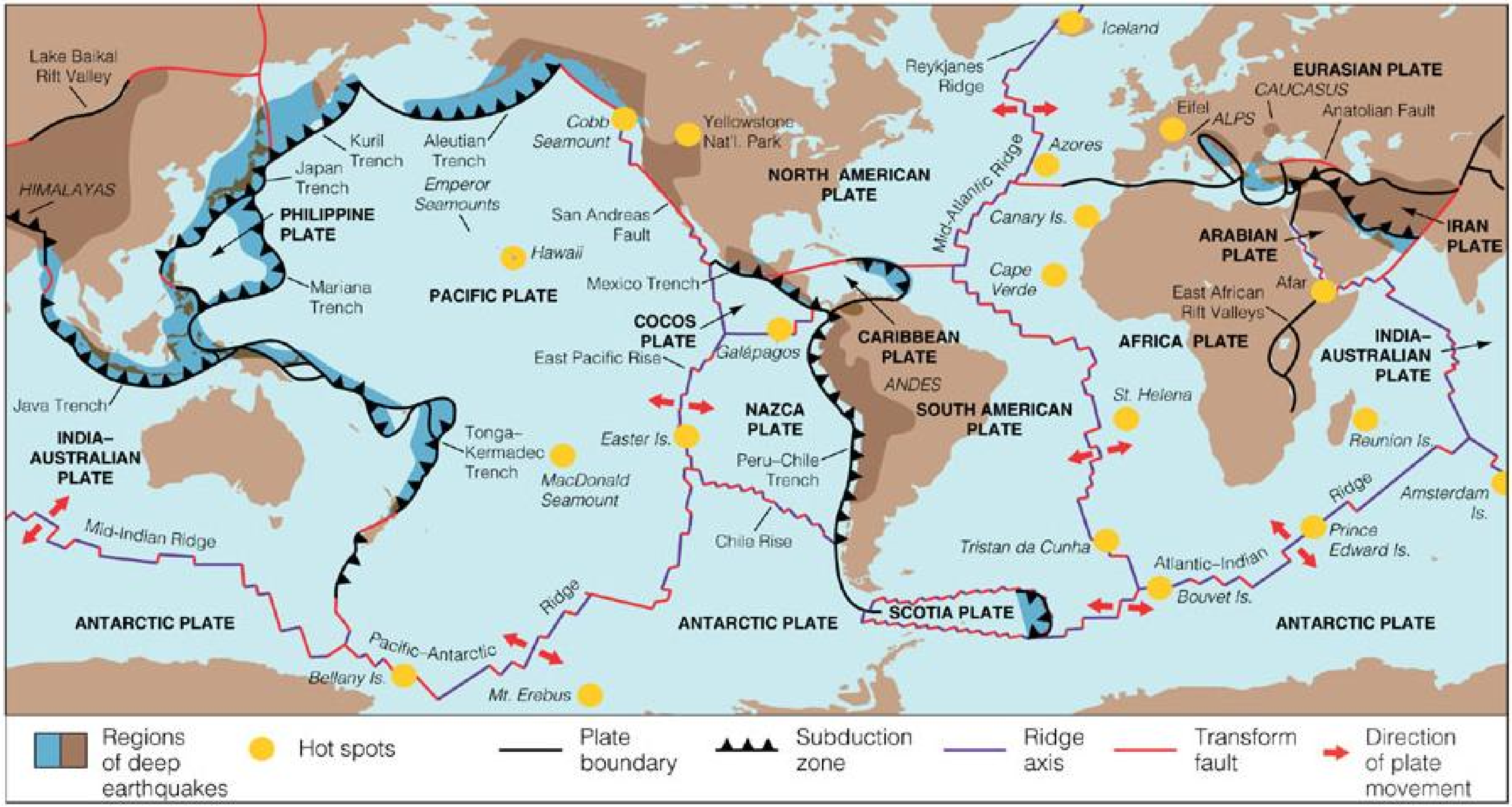
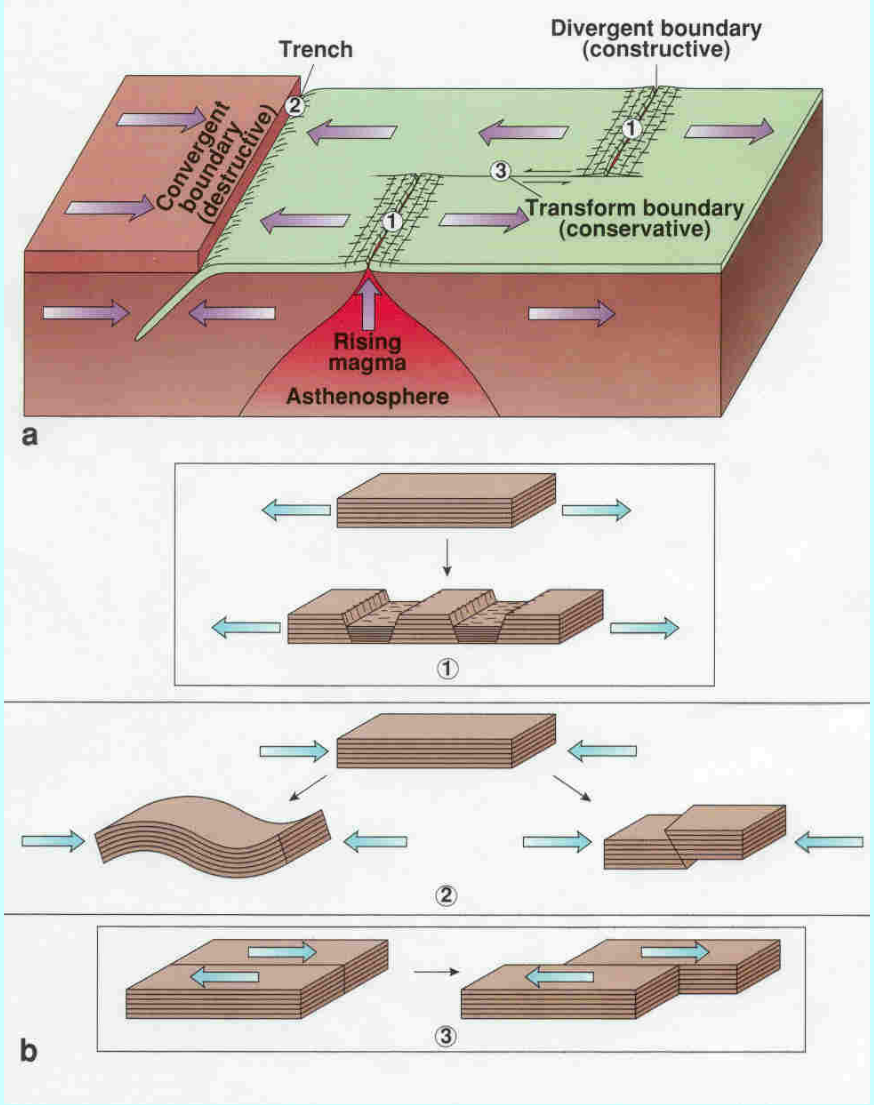


Plate Boundaries

3 types:

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

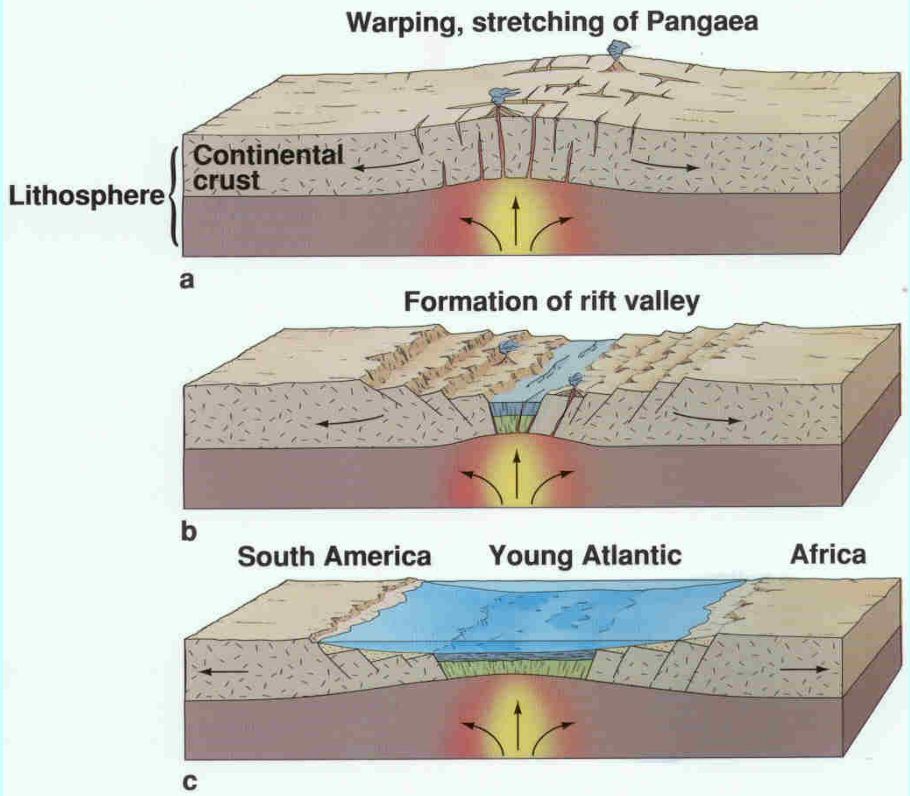
Earth's area is fixed, so construction must balance destruction!



Constructional Plate Boundaries

The *mid ocean ridges*, seafloor spreading axes

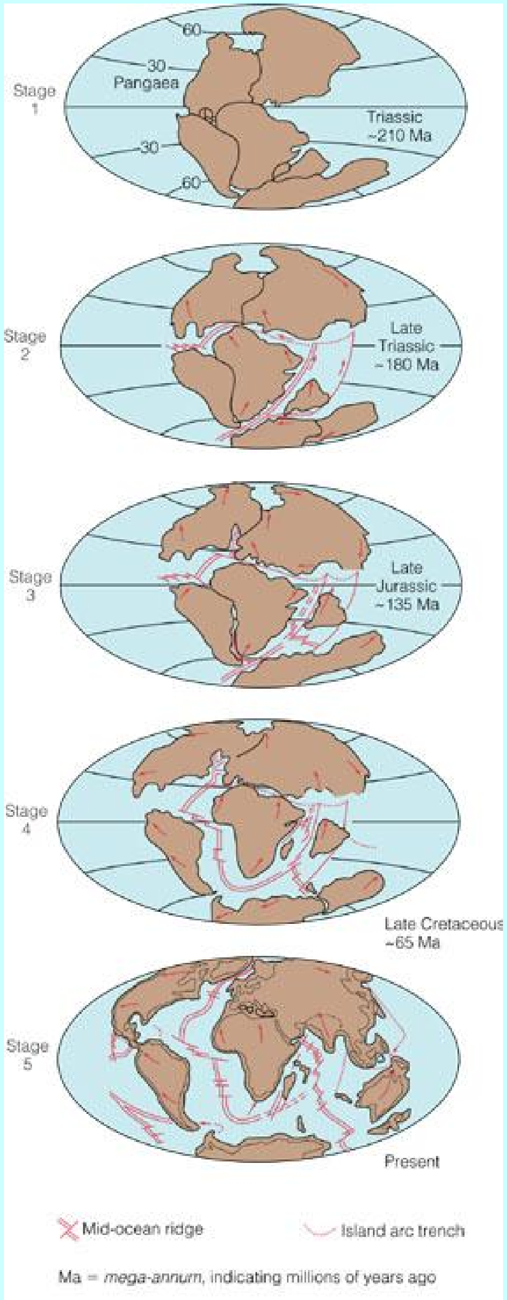
- Shallow seismicity
- Basaltic volcanism
- High heat flow
- Absent to thin sediment cover
- Zero to very young crustal age
- Tensional stress, produces rifting
- ½ Spreading rates: 1-8 cm/yr



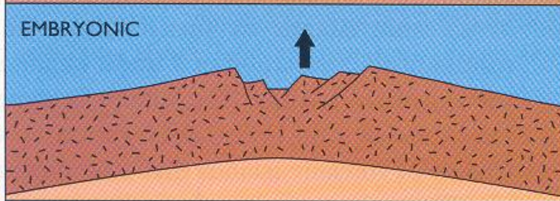
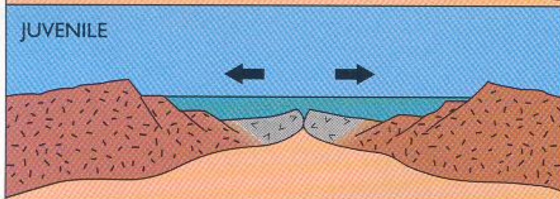
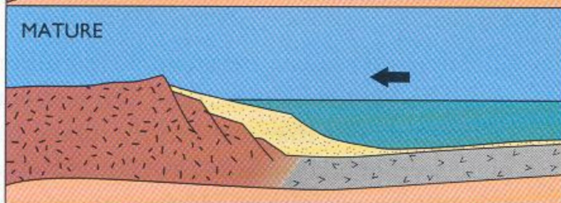
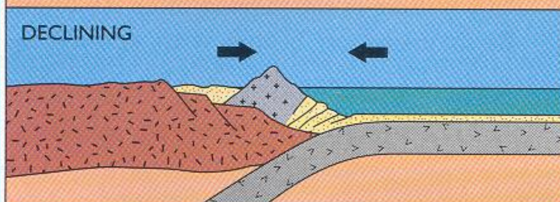
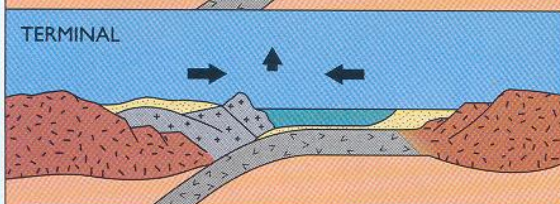
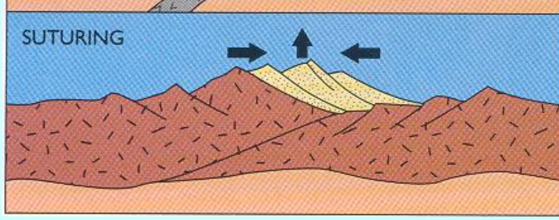
A model for the formation of a new plate boundary

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

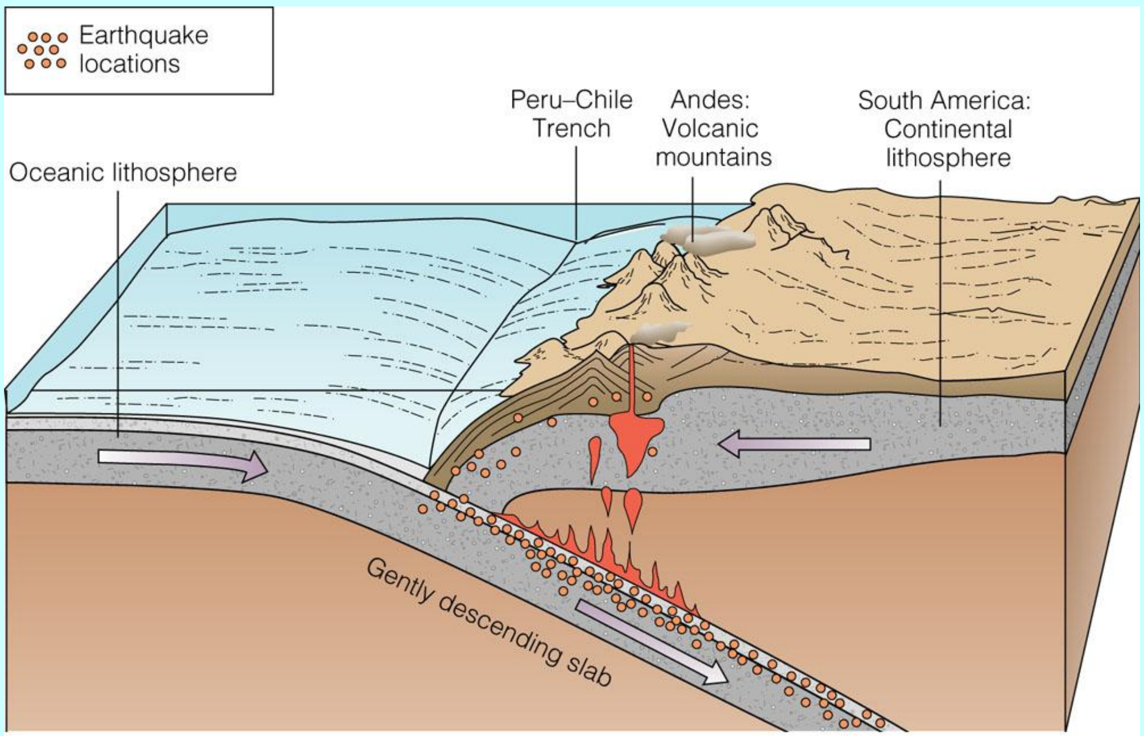


The Supercontinent Cycle

STAGE	MOTION	PHYSIOGRAPHY	EXAMPLE
EMBRYONIC 	Uplift	Complex system of linear rift valleys on continent	East African rift valleys
JUVENILE 	Divergence (spreading)	Narrow seas with matching coasts	Red Sea
MATURE 	Divergence (spreading)	Ocean basin with continental margins	Atlantic, Indian, and Arctic oceans
DECLINING 	Convergence (subduction)	Island arcs and trenches around basin edge	Pacific Ocean
TERMINAL 	Convergence (collision) and uplift	Narrow, irregular seas with young mountains	Mediterranean Sea
SUTURING 	Convergence and uplift	Young to mature mountain belts	Himalayas

Destructional Plate Boundaries: I

1. The deep sea trenches
2. Deep seismicity
3. Andesitic volcanism
4. Low heat flow at trench



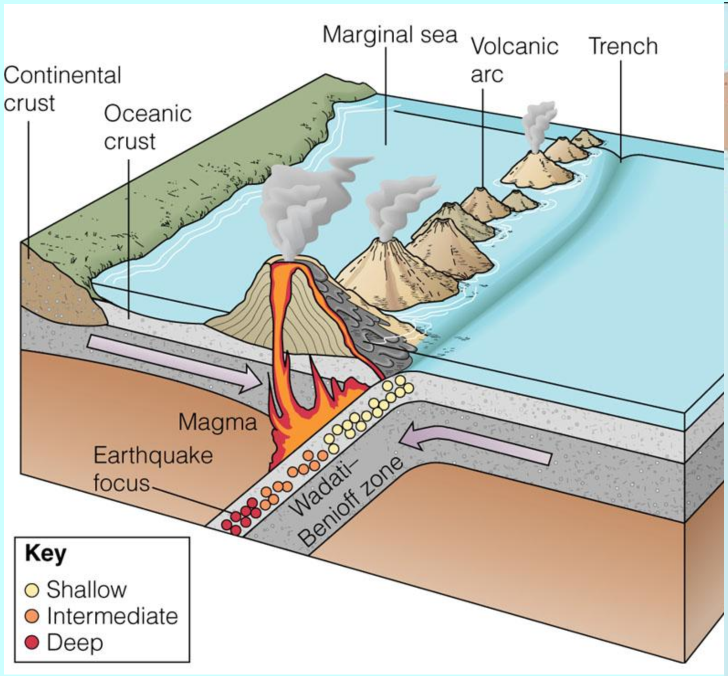
5. High heat flow under volcanic arc
6. Thick sediment cover
7. Old crustal age
8. Compressional stress, produces folding and thrust faulting

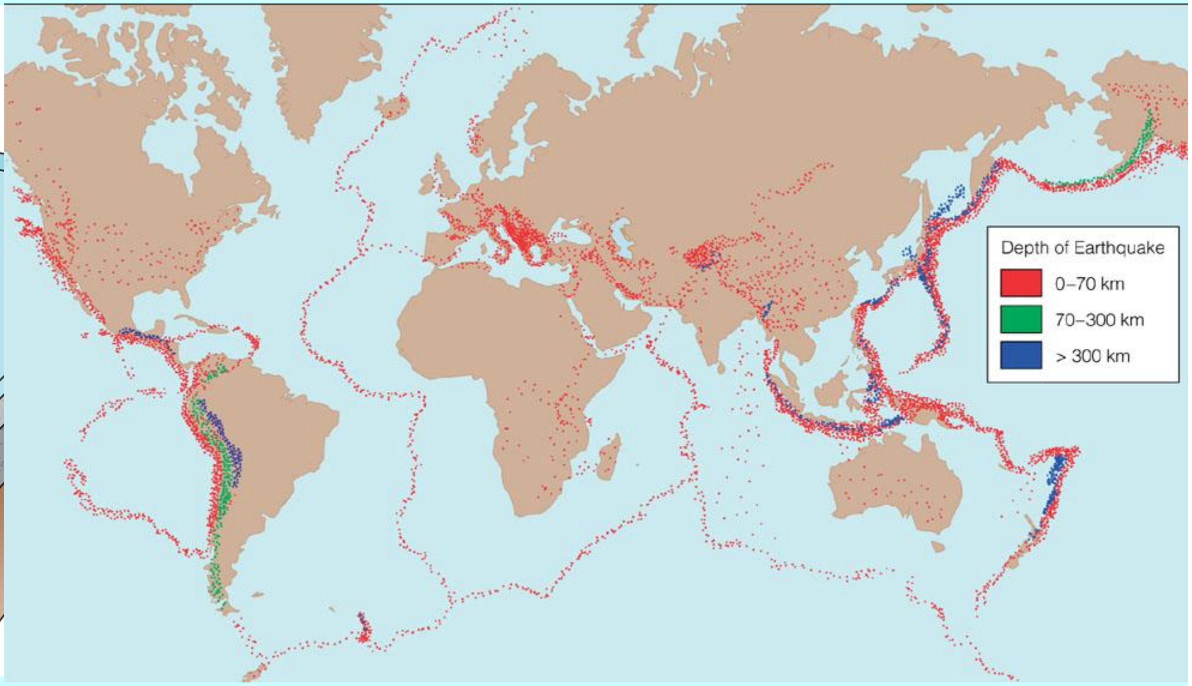
➔

<u>Subduction Zone</u>

Destructional Plate Boundaries: II

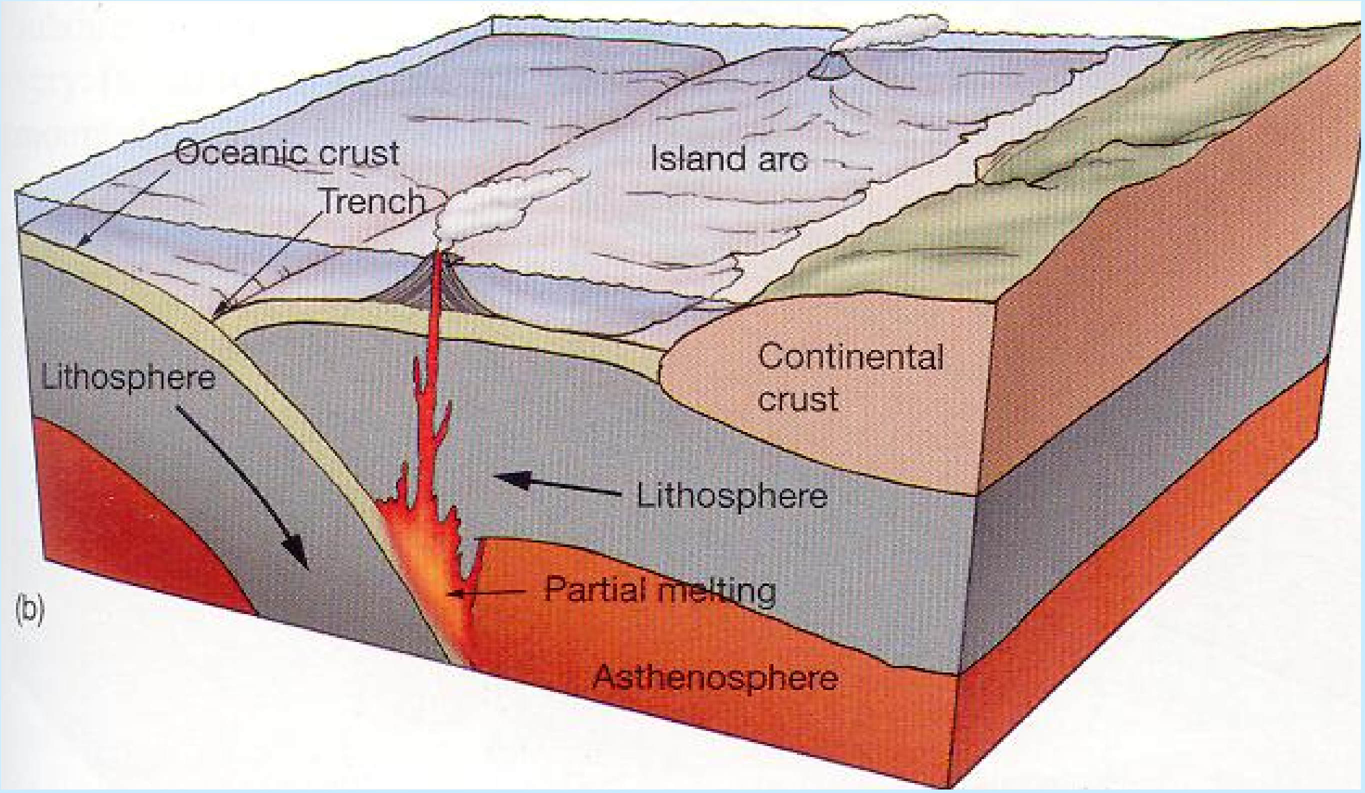
- Oceanic crust is ***subducted*** into the mantle at trenches below continental (e.g., Peru) or oceanic (e.g., Japan) crust
- The downgoing slab is characterized by a zone of earthquakes (Wadati-Benioff zone) that can be very deep





3 Types of Destructional Boundaries

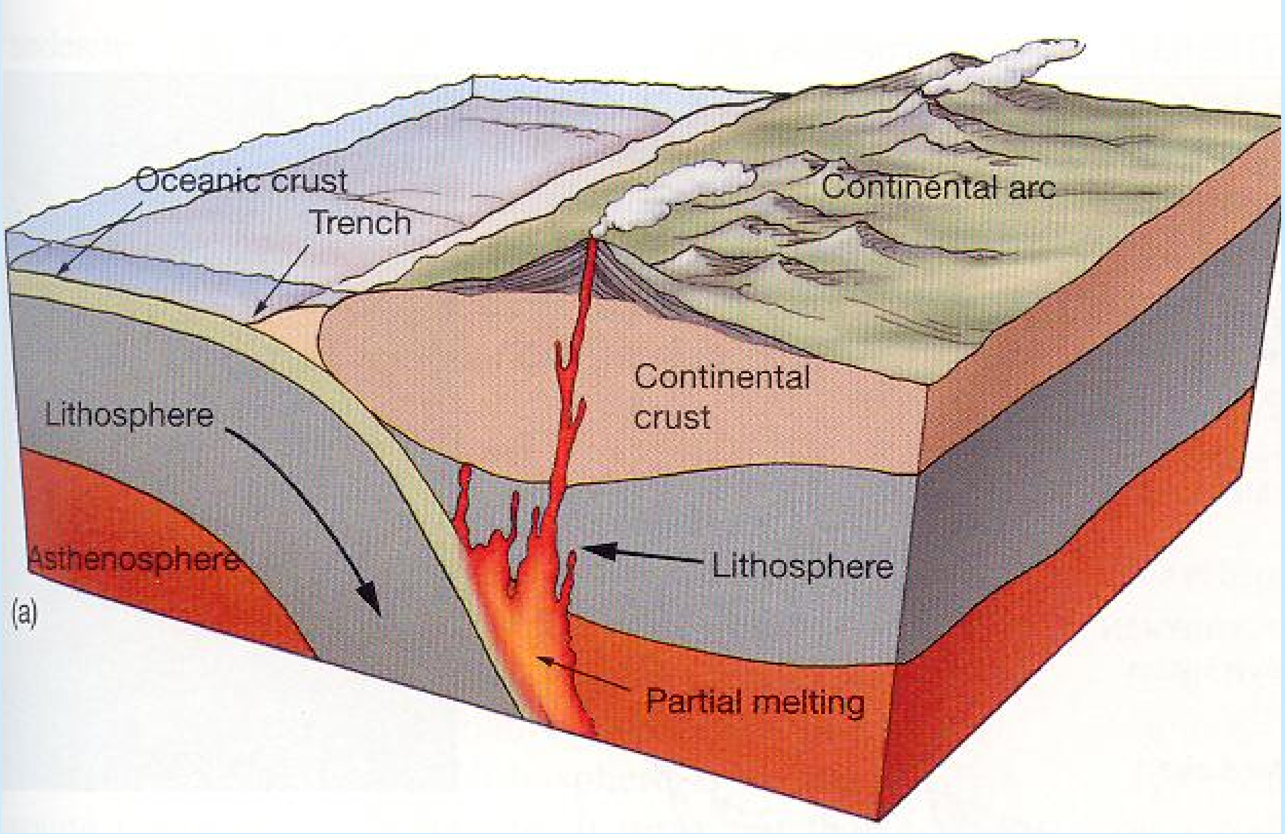
1. ***Oceanic-Oceanic***: volcanic island arc above the downgoing slab (e.g., Aleutians, Indonesia, Marianas)



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

3 Types of Destructional Boundaries

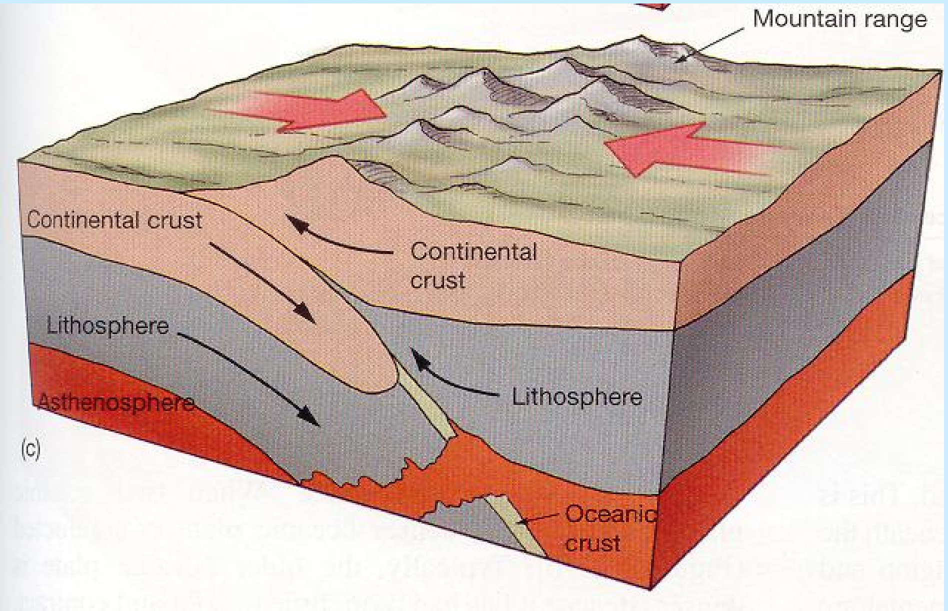
2. Oceanic-Continental: volcanic arc at edge of continent (e.g., Peru-Chile)

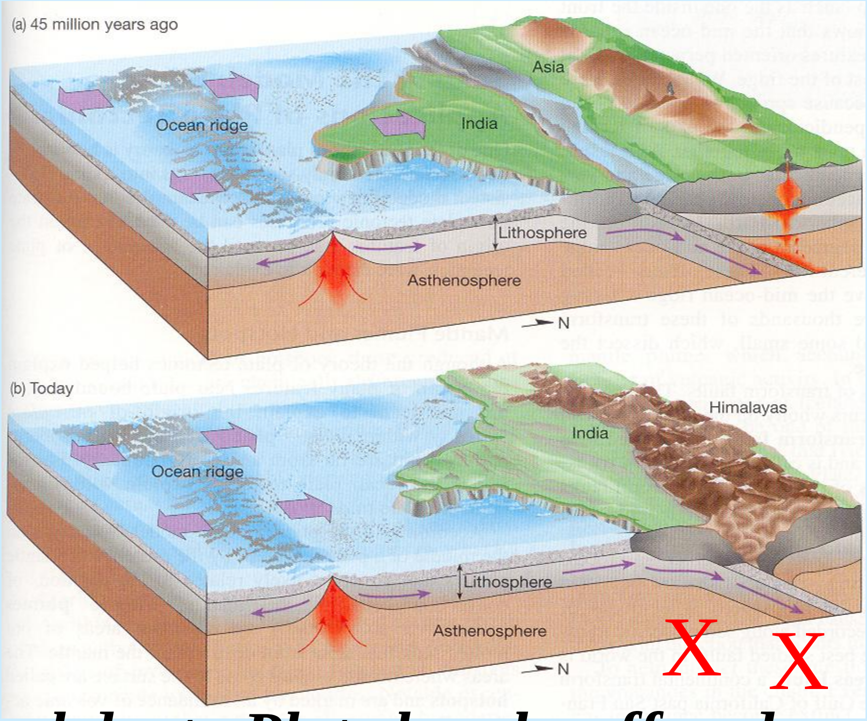


Continental crust is too buoyant to subduct!

3 Types of Destructional Boundaries

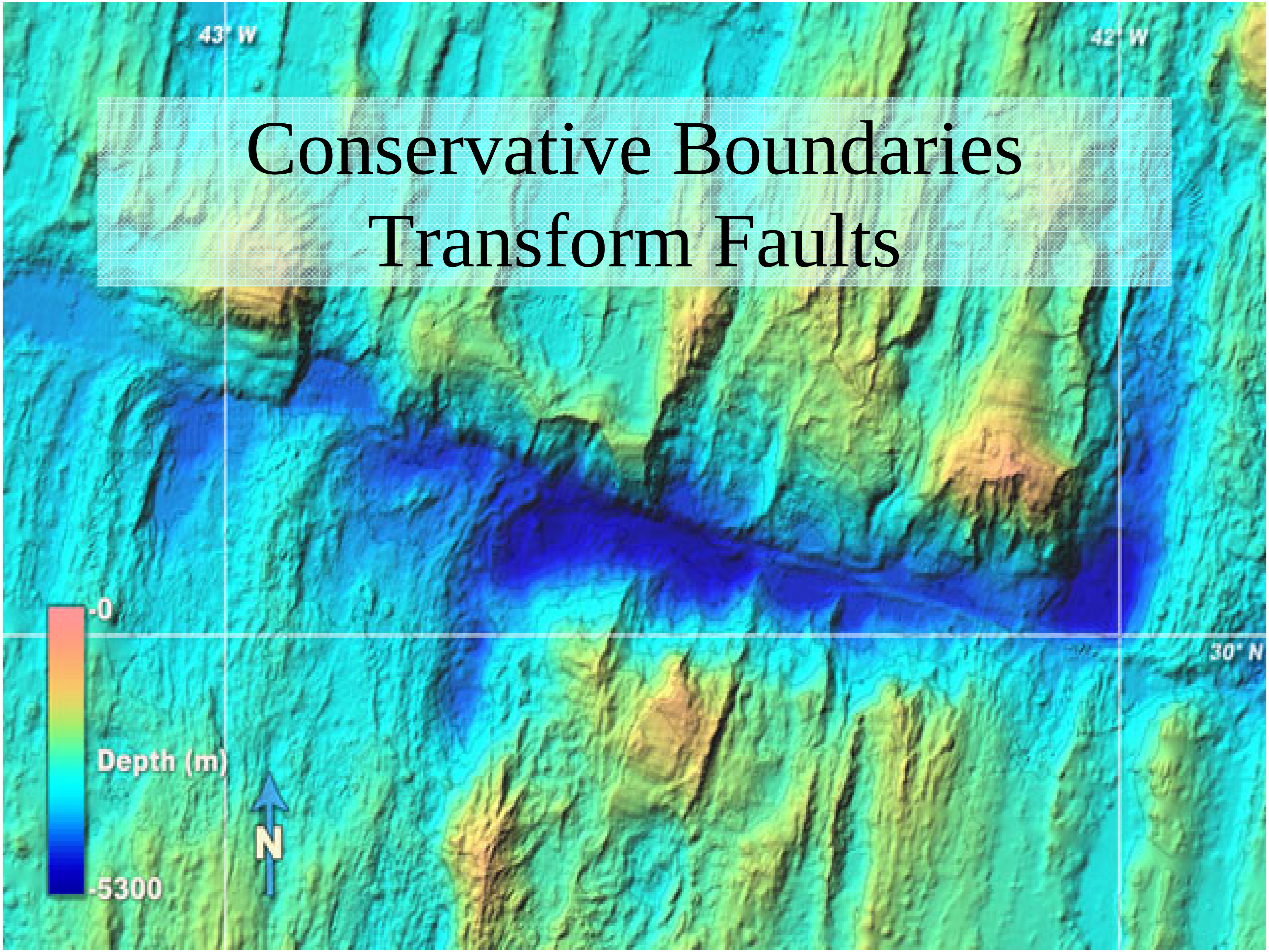
3. Continental-Continental: produces crust up to twice as thick as normal and a correspondingly high mountain plateau (e.g., Tibet, Himalayas).





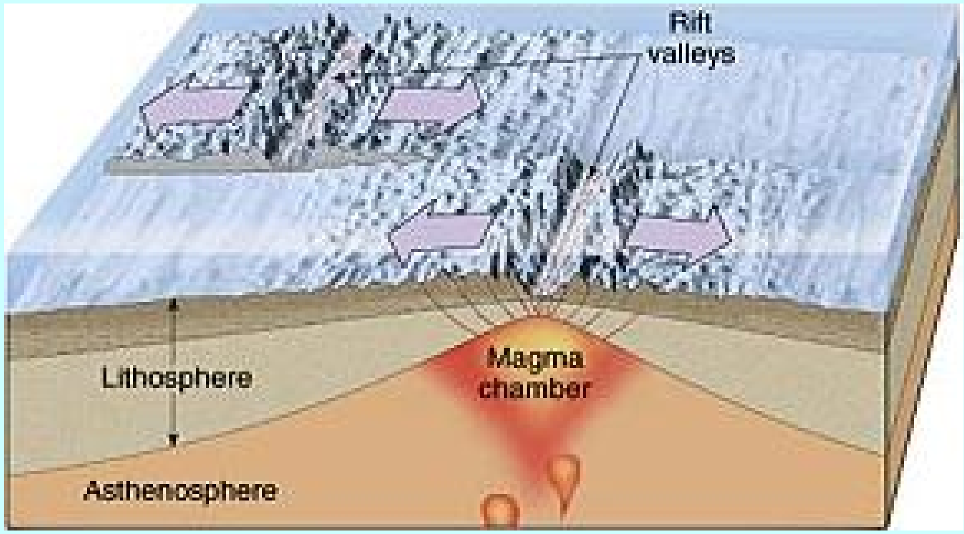
Continental crust is too buoyant to subduct. Plate breaks off and subduction stops, causing a global change in plate motions.

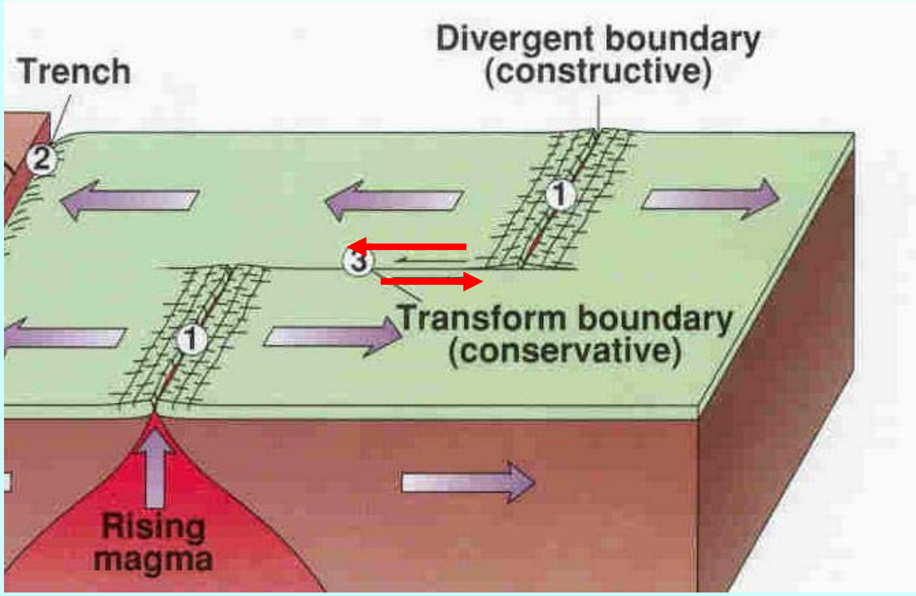
Conservative Boundaries
Transform Faults



Conservative Boundaries: Transform Faults

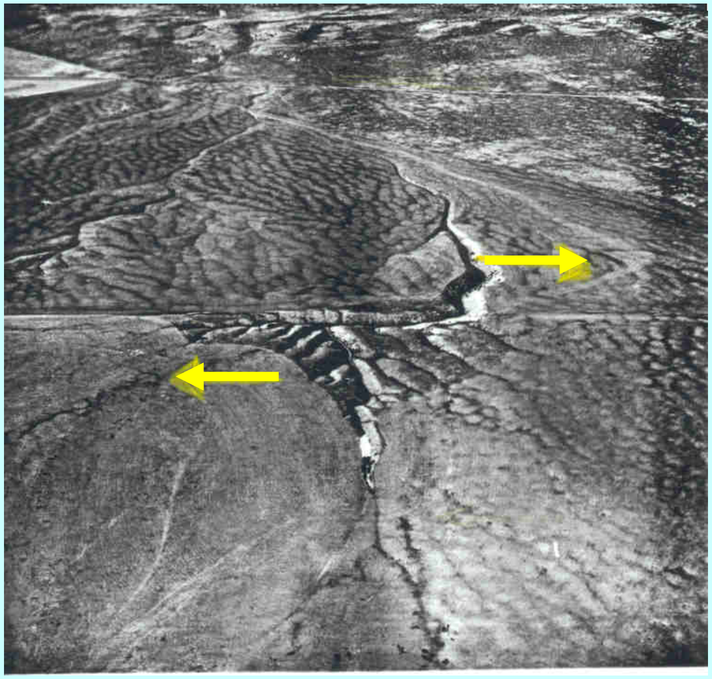
- Active zone of movement along a vertical fault plane located between two offset segments of ridge axis
- Relative motion is in opposite direction to that which would have produced such an offset in the absence of seafloor spreading.

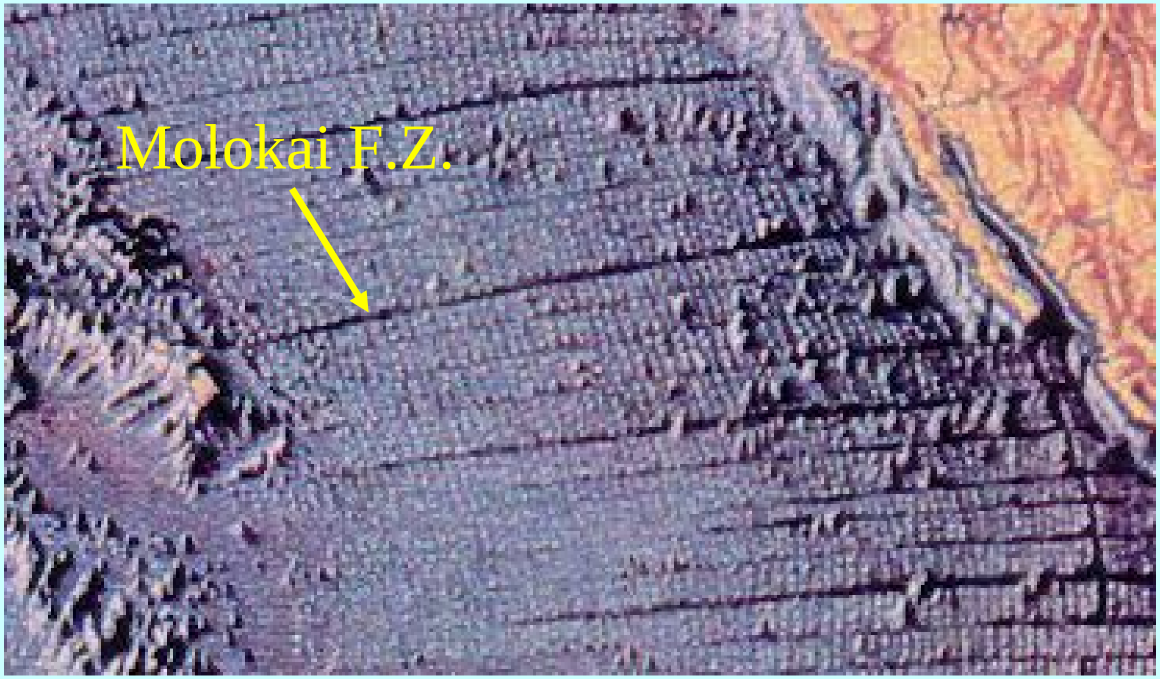




Conservative Boundaries: Transform Faults

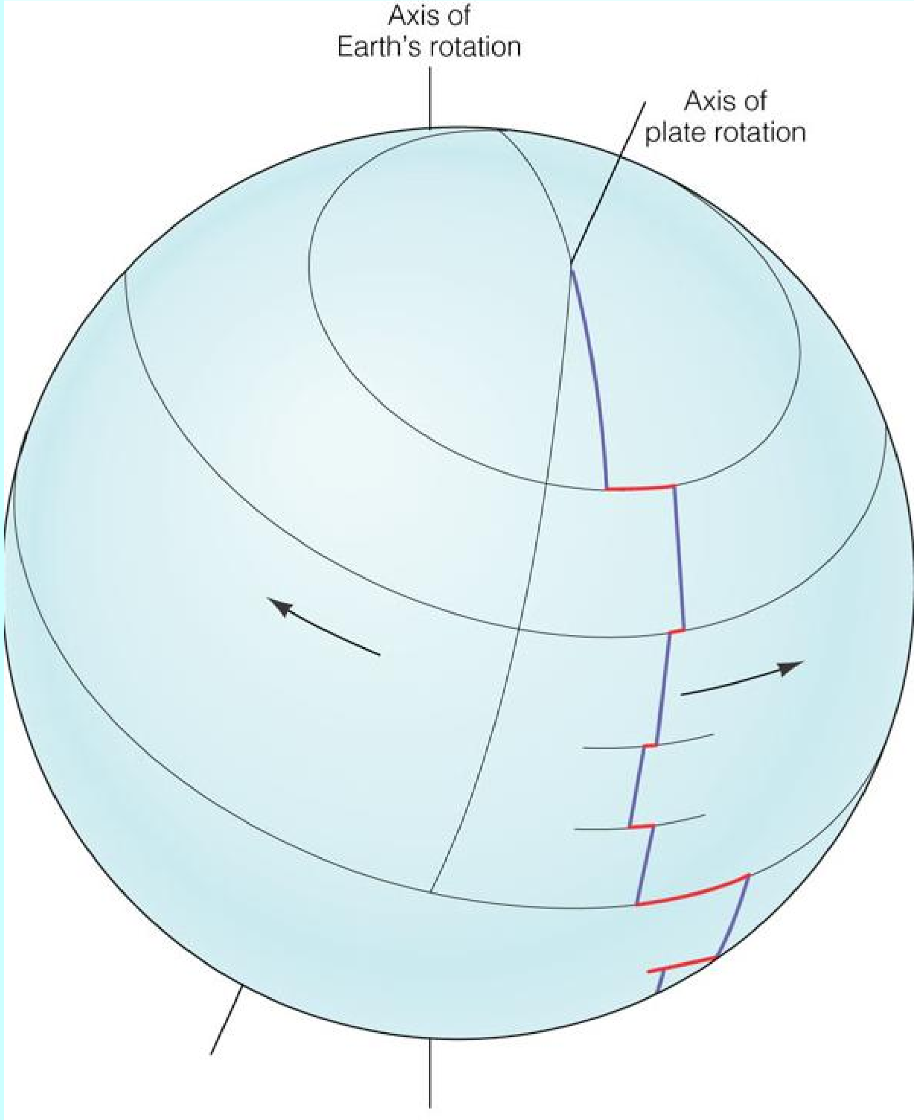
- Outside active transform region (not part of plate boundary), crust formed by offset segments becomes welded together to form the ***trace*** of the transform fault. Entire structure is called a ***Fracture zone***.





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.

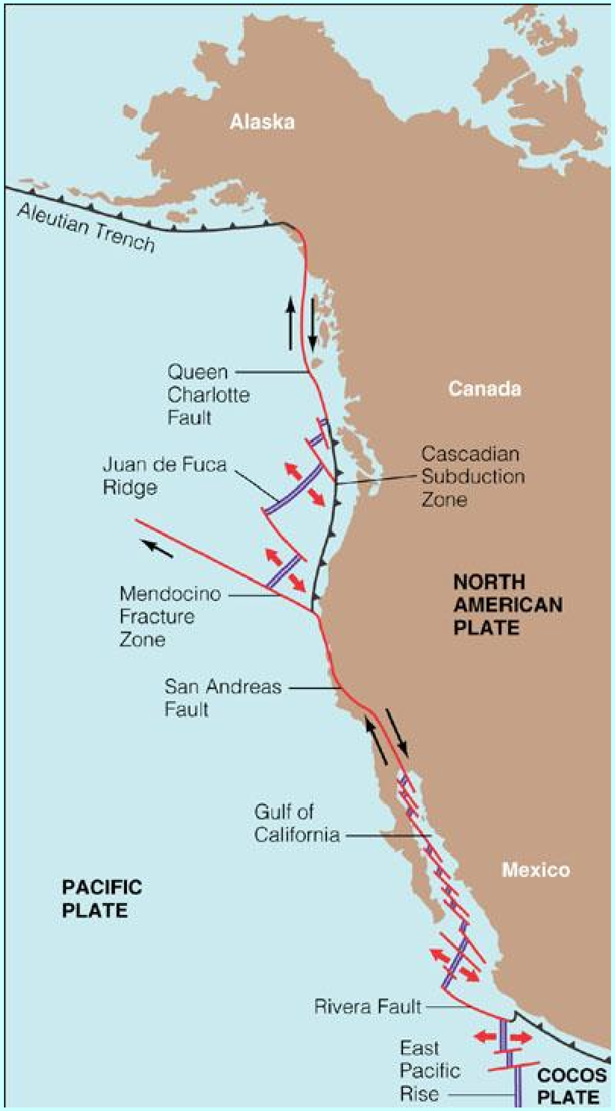
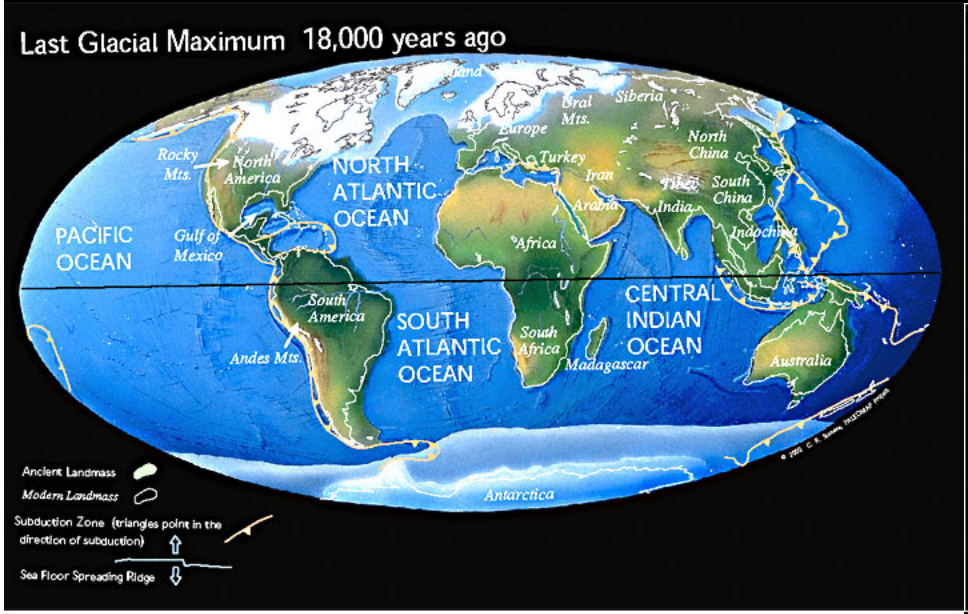


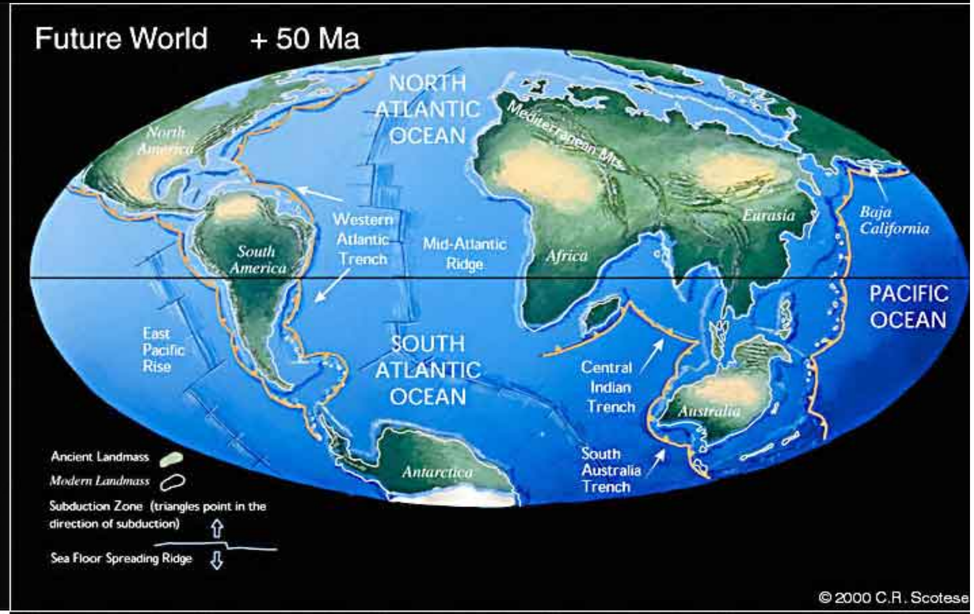
Plate Boundary Summary

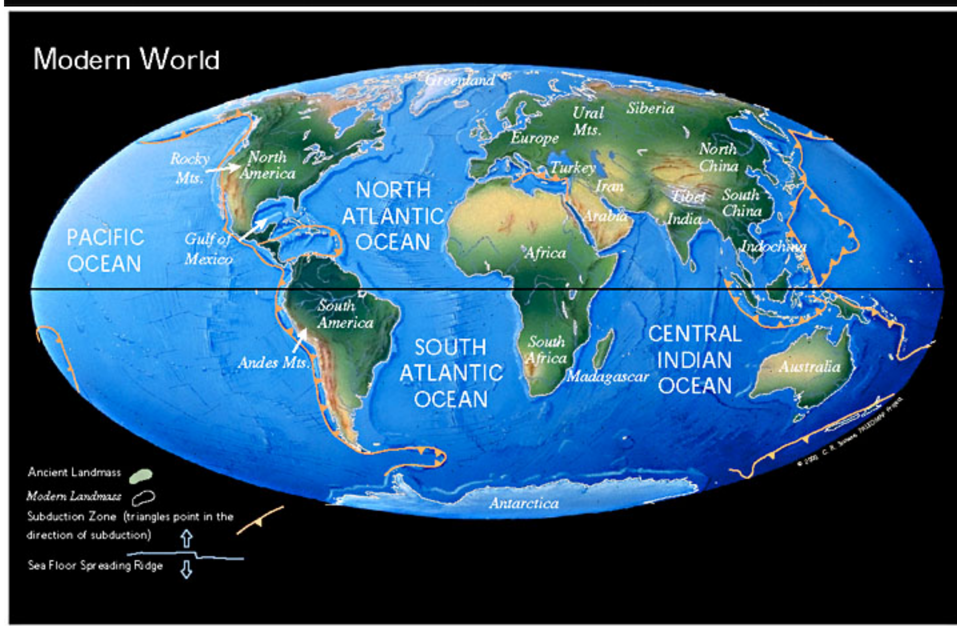
Table 3.1 Characteristics of Plate Boundaries

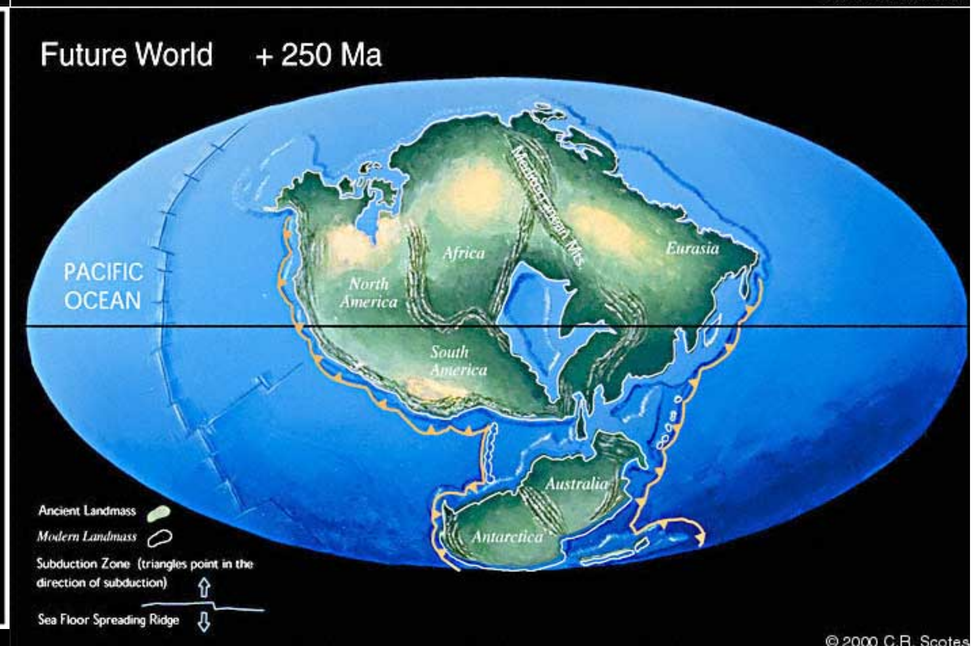
Plate Boundary		Plate Movement	Seafloor	Events Observed	Example Locations
Divergent plate boundaries	Ocean-ocean	Apart	Forms by seafloor spreading.	Ridge forms at spreading center. Ocean basin expands, plate area increases. Many small volcanoes and/or shallow earthquakes.	Mid-Atlantic Ridge, East Pacific Rise
	Continent-continent		New ocean basin may form as continent splits.	Continent spreads, central rift collapses, ocean fills basin.	East African Rift Valley, Red Sea
Convergent plate boundaries	Ocean-continent	Together	Destroyed at subduction zones.	Dense oceanic lithosphere plunges beneath less dense continental. Earthquakes trace path of down-moving plate as it descends into asthenosphere. A trench forms. Subducted plate partially melts. Magma rises to form continental volcanoes.	Western South America, Cascade Mountains in western United States
	Ocean-ocean			Older, cooler, denser crust slips beneath less dense crust. Strong quakes. Deep trench forms in arc shape. Subducted plate heats in upper mantle, magma rises to form curving chains of volcanic islands.	Aleutians, Marianas
	Continent-continent		Closure of Ocean Basins.	Collision between masses of granitic continental lithosphere. Neither mass is subducted. Plate edges are compressed, folded, uplifted; one may move beneath the other.	Himalayas, Alps
Transform plate boundaries		Past each other	Neither created nor destroyed.	A line (fault) along which lithospheric plates move past each other. Strong earthquakes along fault.	San Andreas Fault; South Island, New Zealand
				Transform faults across spreading center.	Mid-ocean ridges

Changing Continent Configurations



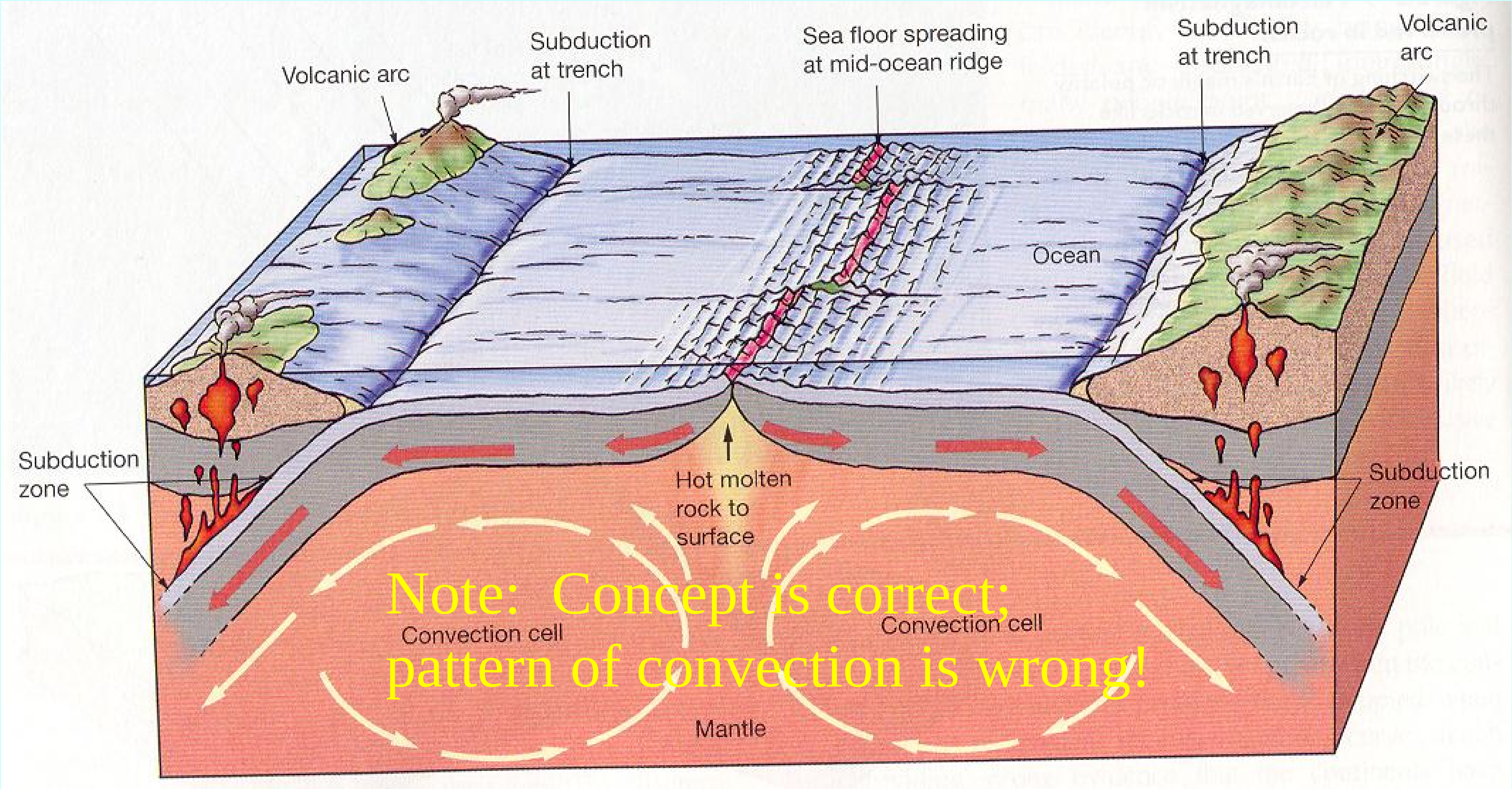






Tectonic Model

- 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.

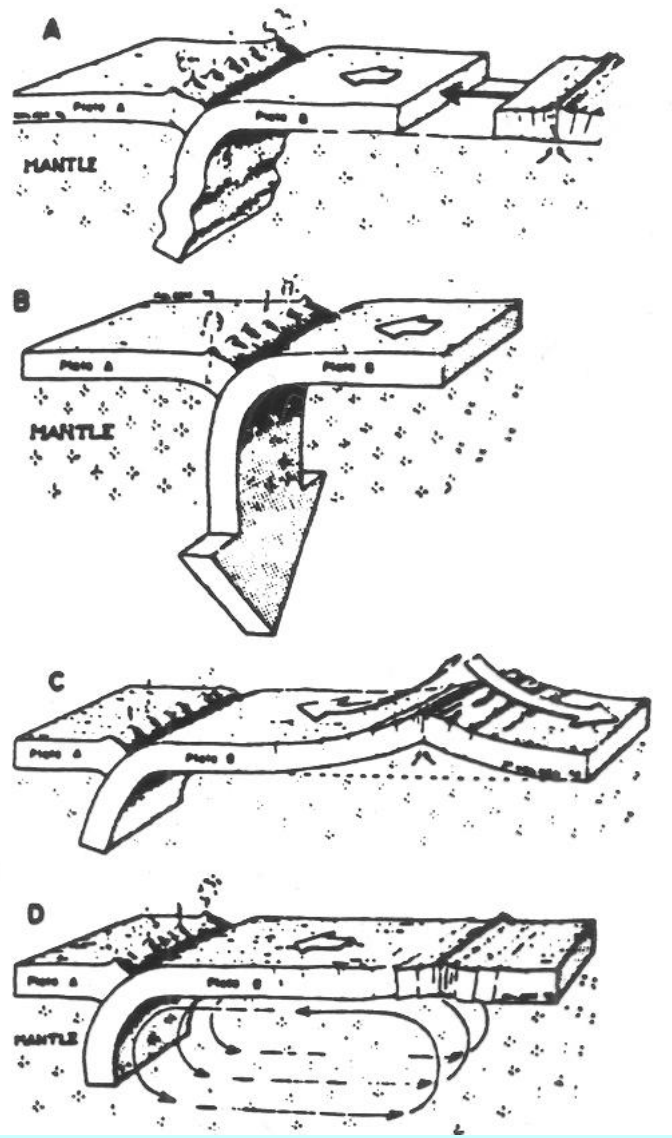


Note: Concept is correct; pattern of convection is wrong!

Driving Forces of Plate Tectonics

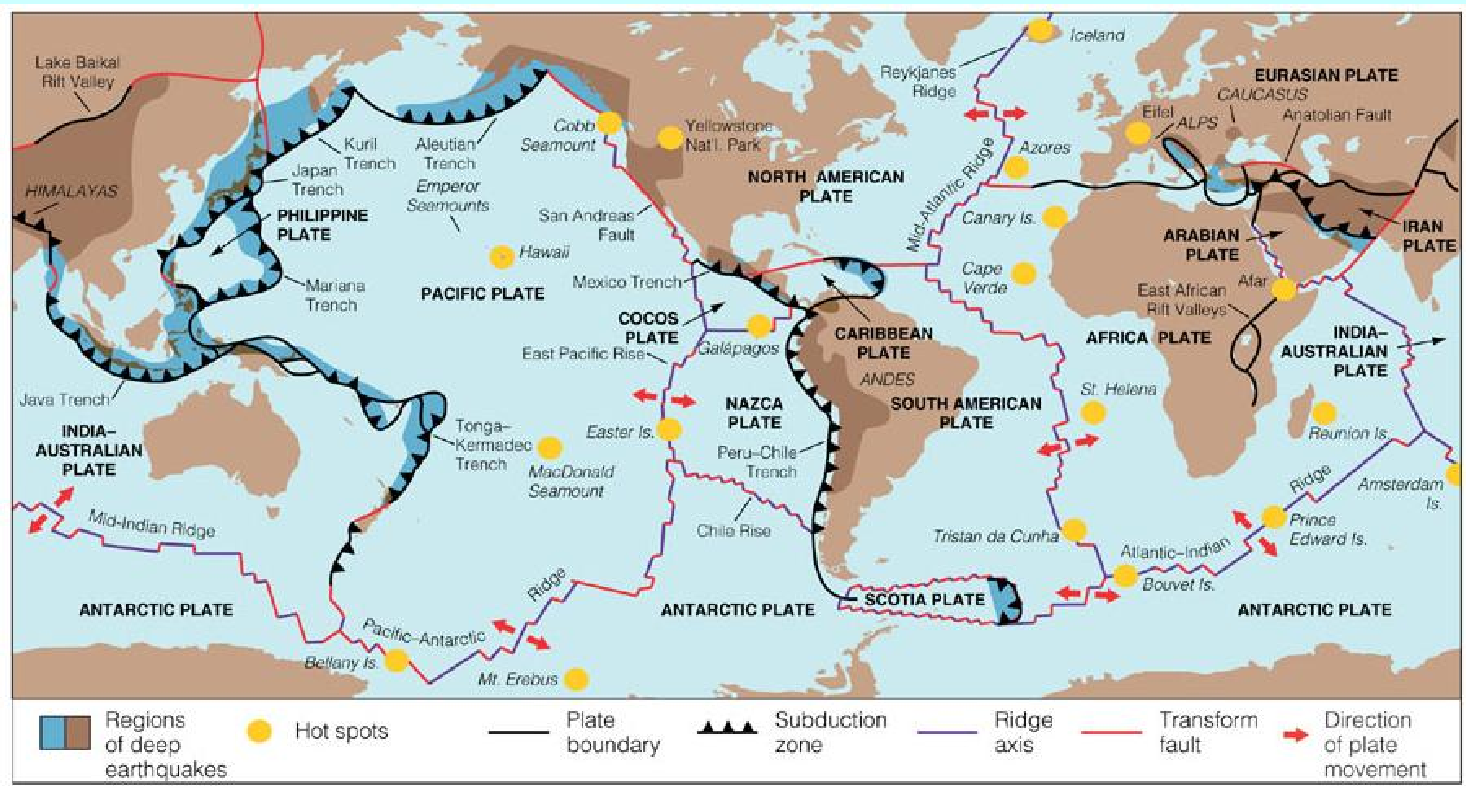
Immediate mechanism is more controversial: 4 possibilities . . .

- **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.

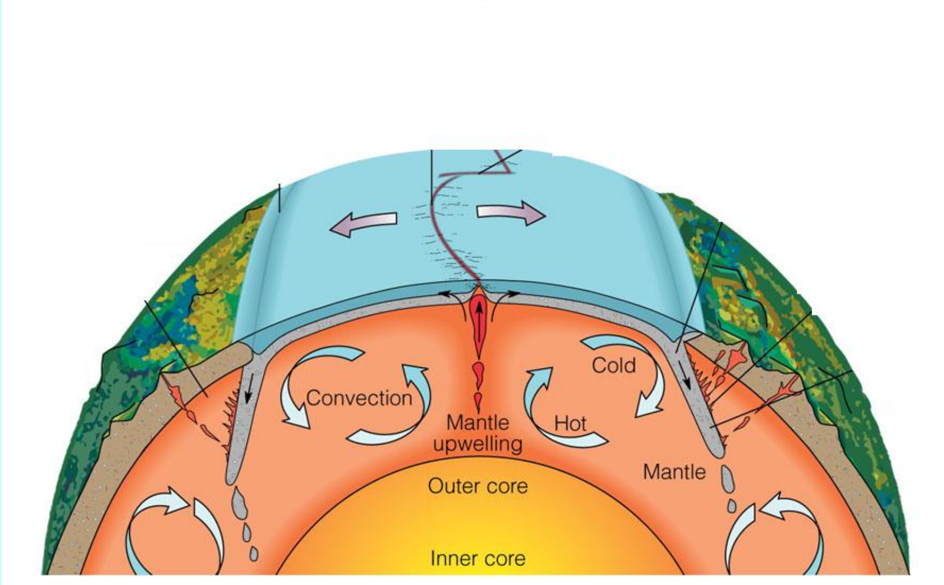


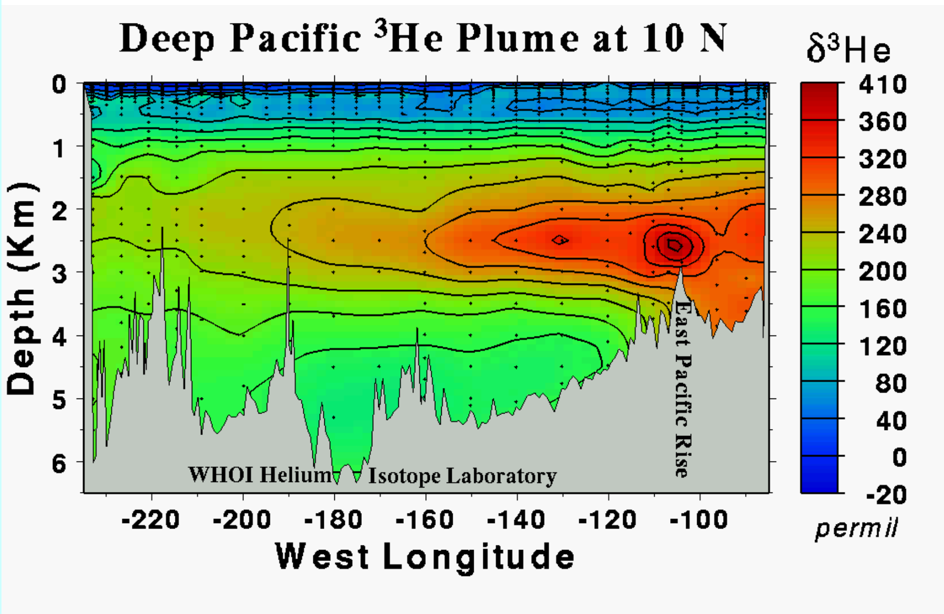
Implications for Oceanography

- **Theory of plate tectonics has important implications for geochemical oceanography. It provides mechanisms for chemical interaction between deeper reservoirs in the Earth and those at the surface.**

Implications for Oceanography: II

- Creation of oceanic and continental crust by differentiation from mantle ➔ manifested as volcanism at MOR and volcanic arcs
- Injection of primordial gases (^3He) from Earth interior into oceans and atmosphere by volcanism

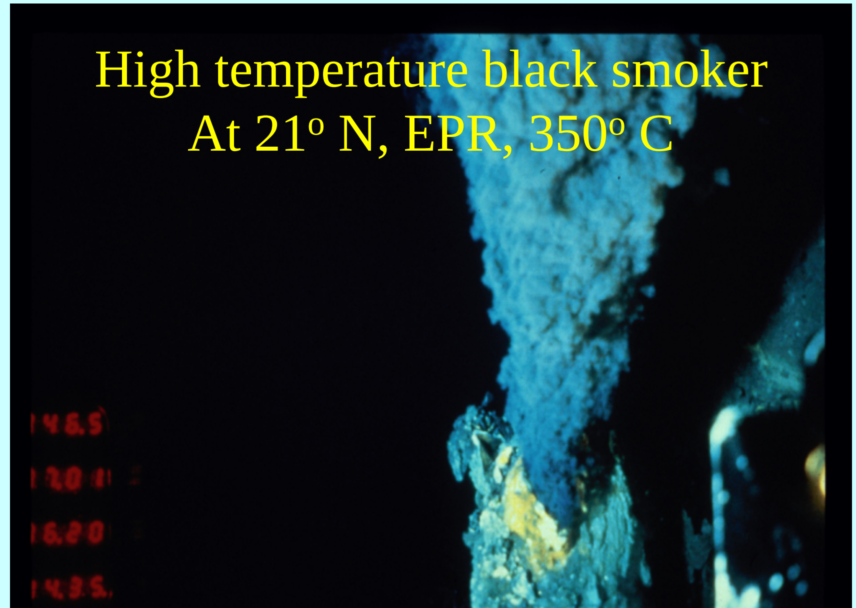


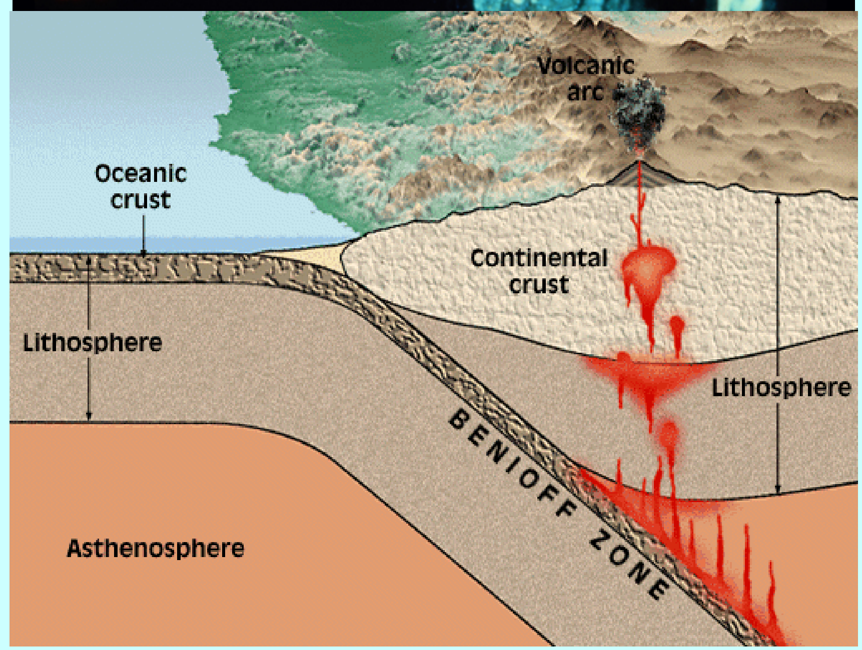


Implications for Oceanography: III

- Interaction of seawater with igneous oceanic crust (hydrothermal circulation) driven by heat of formation of new lithospheric plate

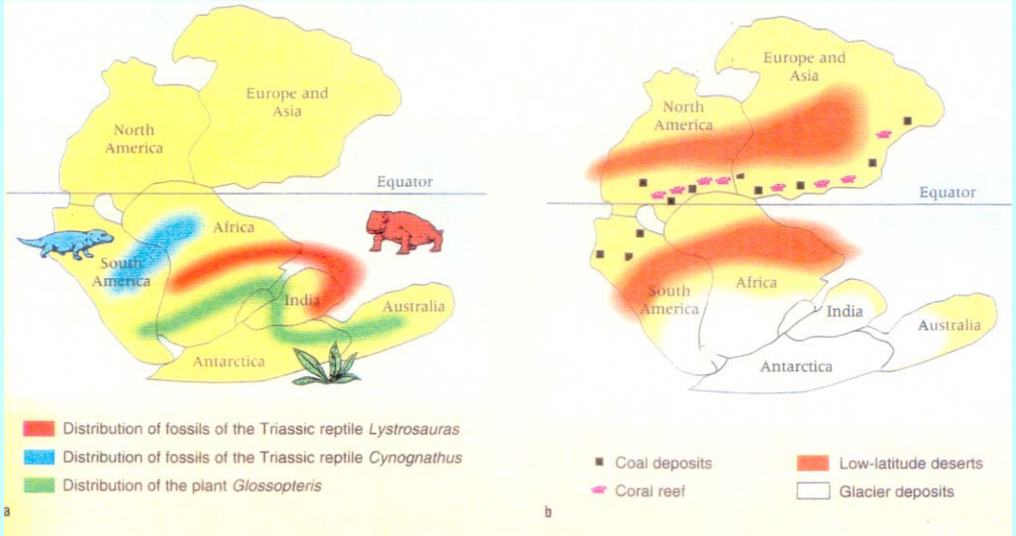
- Recycling of oceanic sediments and basalt back into mantle at subduction zones





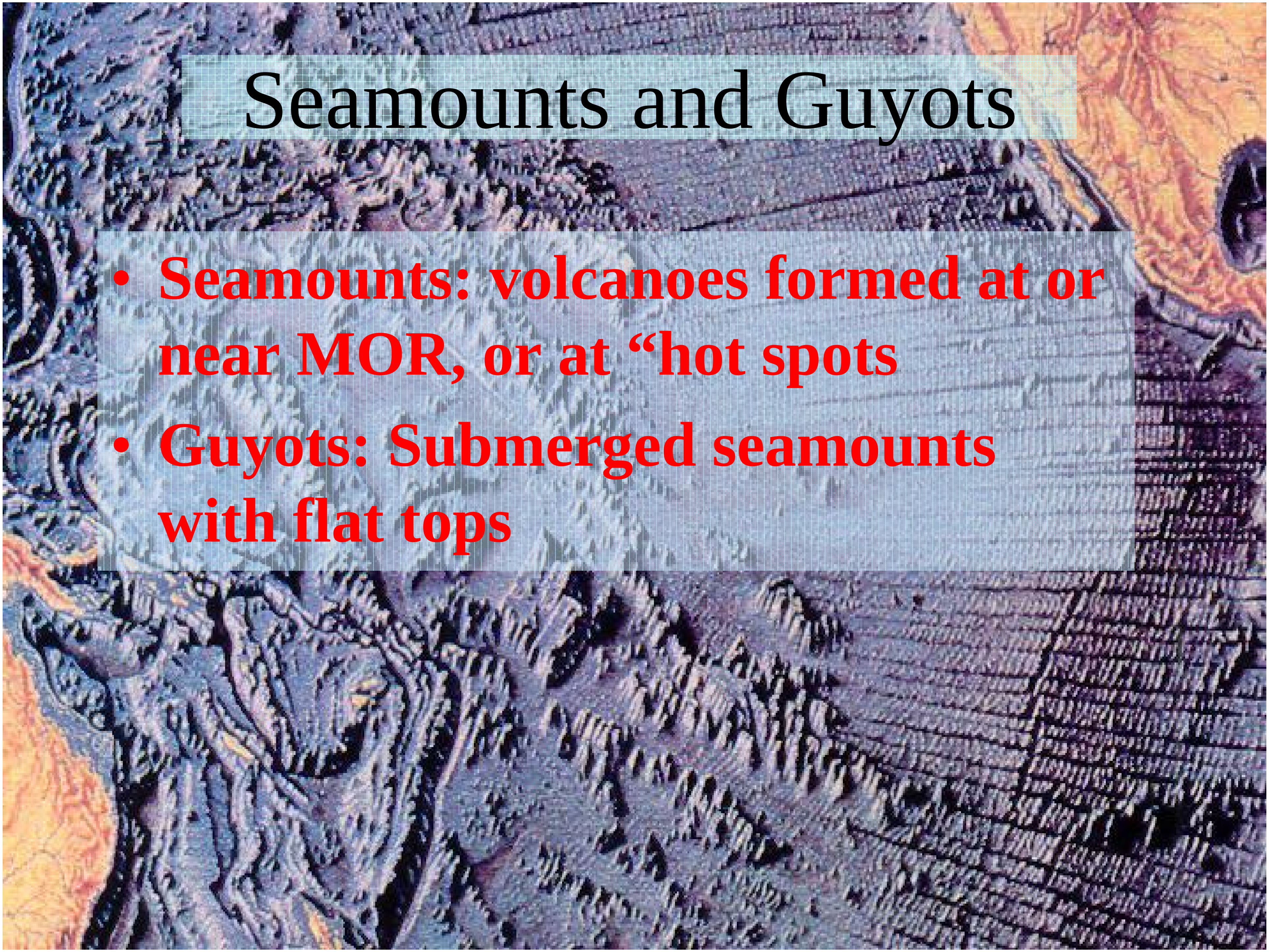
Implications for Oceanography: V

- Global climate: heat flux affects ocean T, volcanic ash blocks sun
- Distribution of organisms (land mass connections, paleolatitudes)



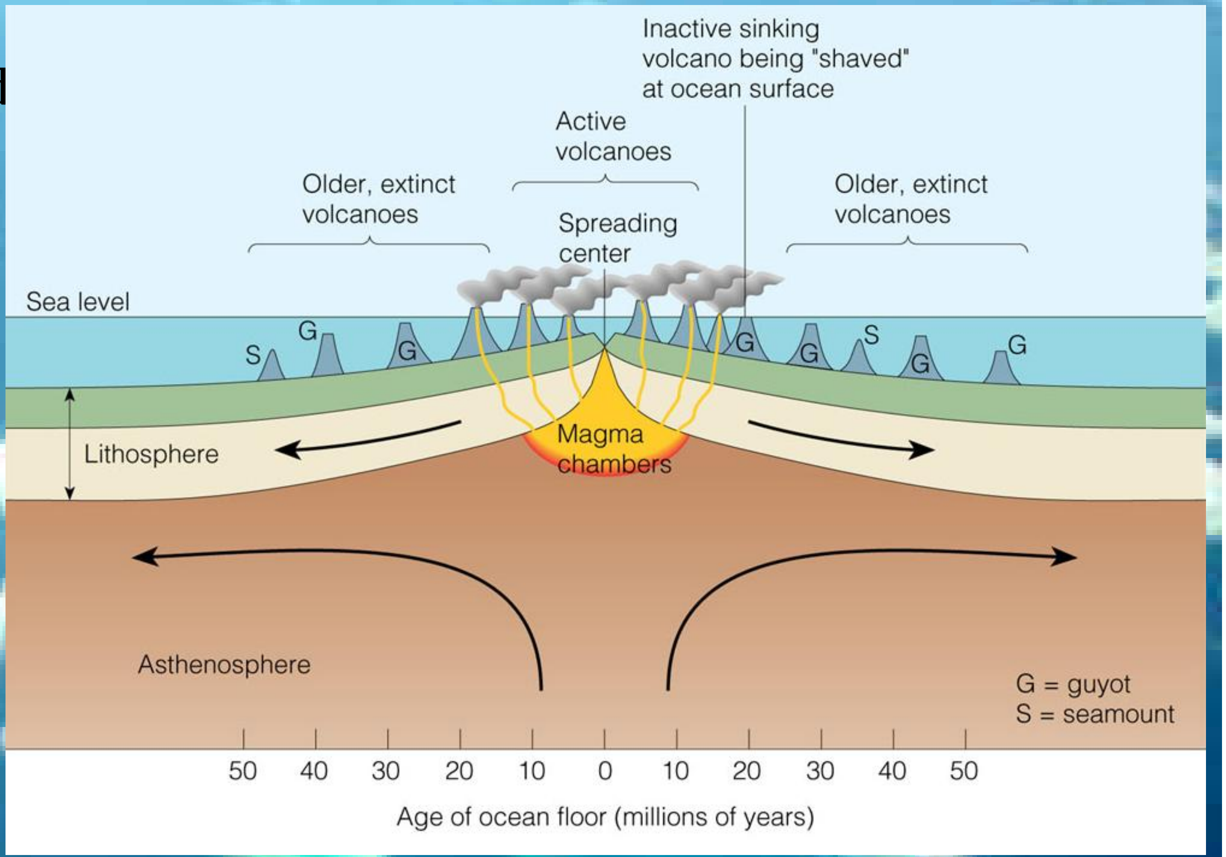
Seamounts and Guyots

- **Seamounts: volcanoes formed at or near MOR, or at “hot spots**
- **Guyots: Submerged seamounts with flat tops**



Seamounts and Guyots…

- **Seamounts that form at MOR become inactive and subside with seafloor as they move away from the ridge axis.**
- **Guyots formed from volcanic islands that are planed off at sea level by erosion, then subside as seafloor travels away from the ridge axis.**

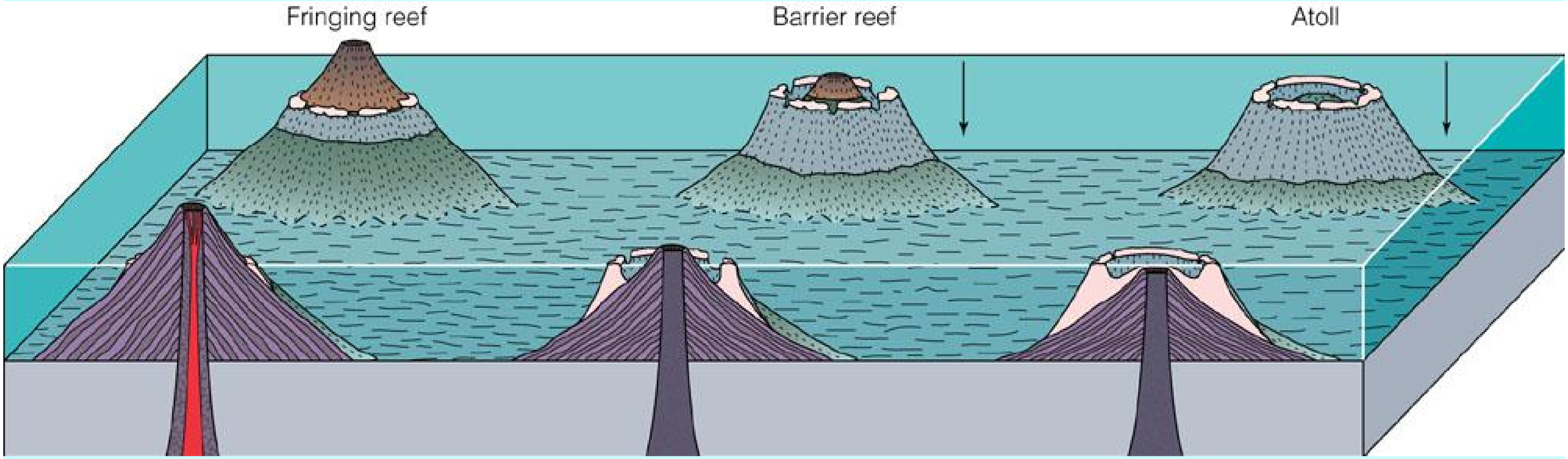


Atolls

- Ring shaped islands or coral reefs centered over submerged, inactive volcanic seamounts
- Corals can only live within the photic zone, in tropical regions.
- Coral reefs build upward ~1cm/yr.
- If volcanic islands sink sufficiently slowly, coral growth can keep up, producing an atoll.

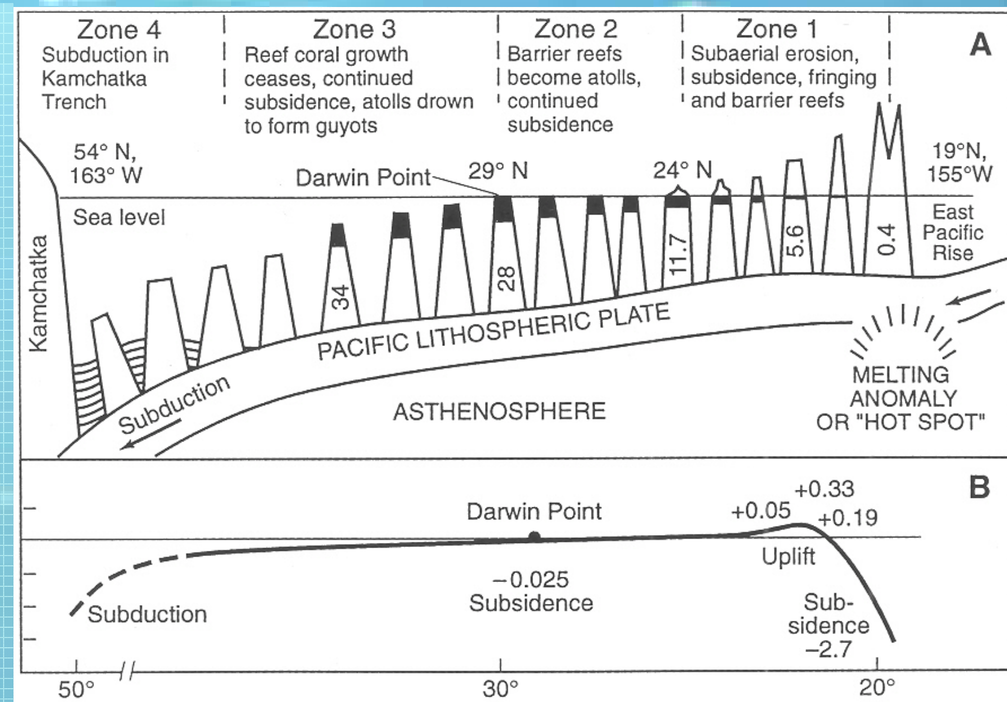
Darwin's Theory of Atoll Formation

- Fringing reef grows upward around a young island.
- Barrier reef develops as corals grow upward, but the subsiding island is eroded and a lagoon forms.
- Atoll develops fully as island subsides further; "motu" form from accretion/consolidation of storm debris at barrier.



The Darwin Point

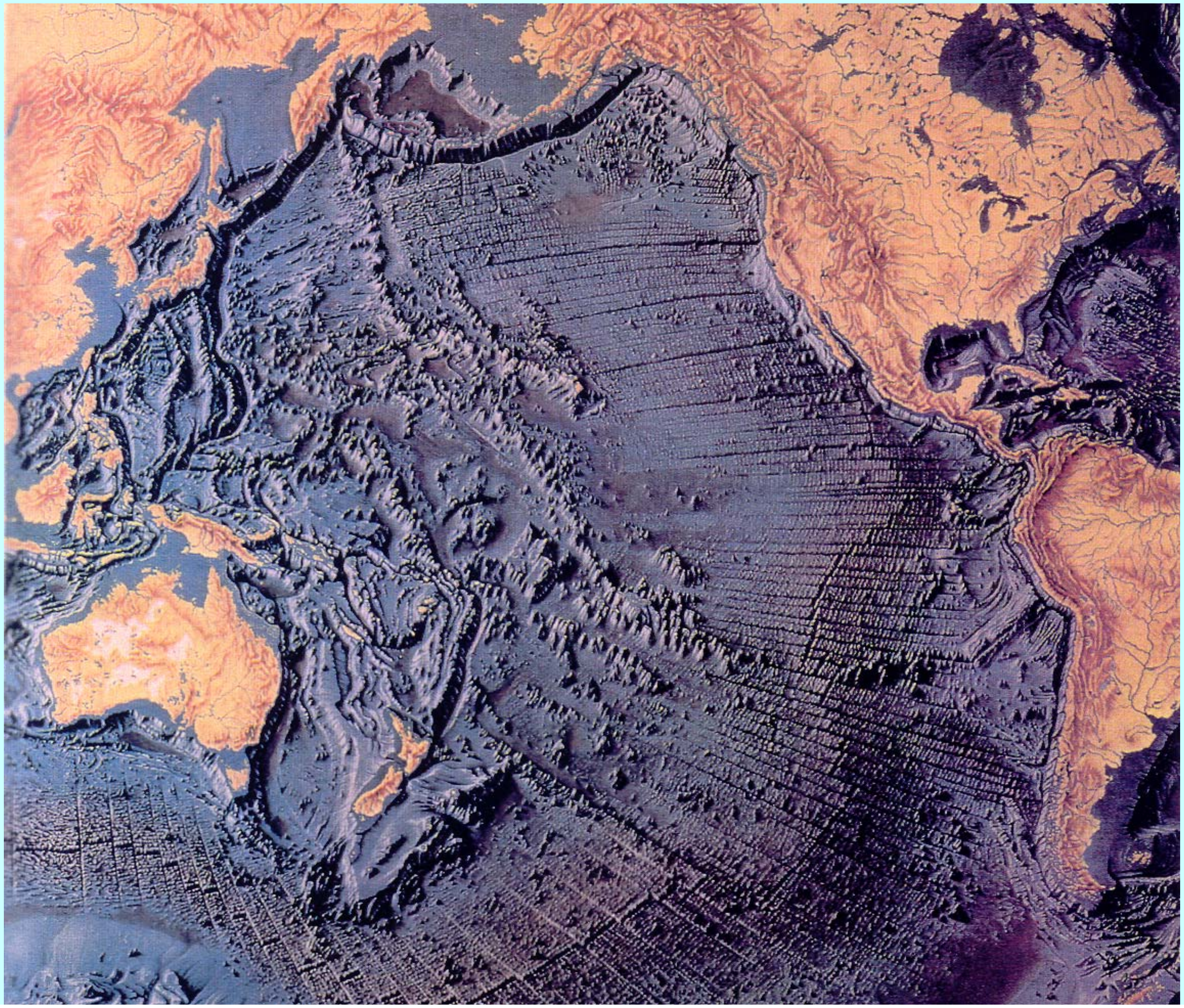
- Darwin Point: where atolls “drown” because coral growth can no longer keep up with subsidence.
- When temp. becomes too low for coral to grow efficiently…



- Rate of subsidence of the volcanic edifice becomes greater than (upward) coral growth rate…
- In Hawaii this occurs ~ 29^{o}N (i.e., just N. of Kure Atoll).

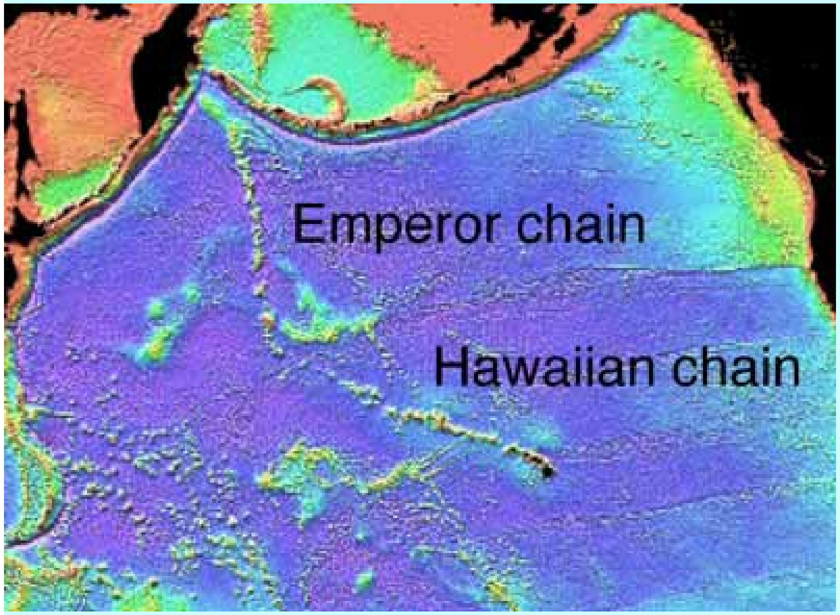
Mantle Plumes or "Hot Spots"

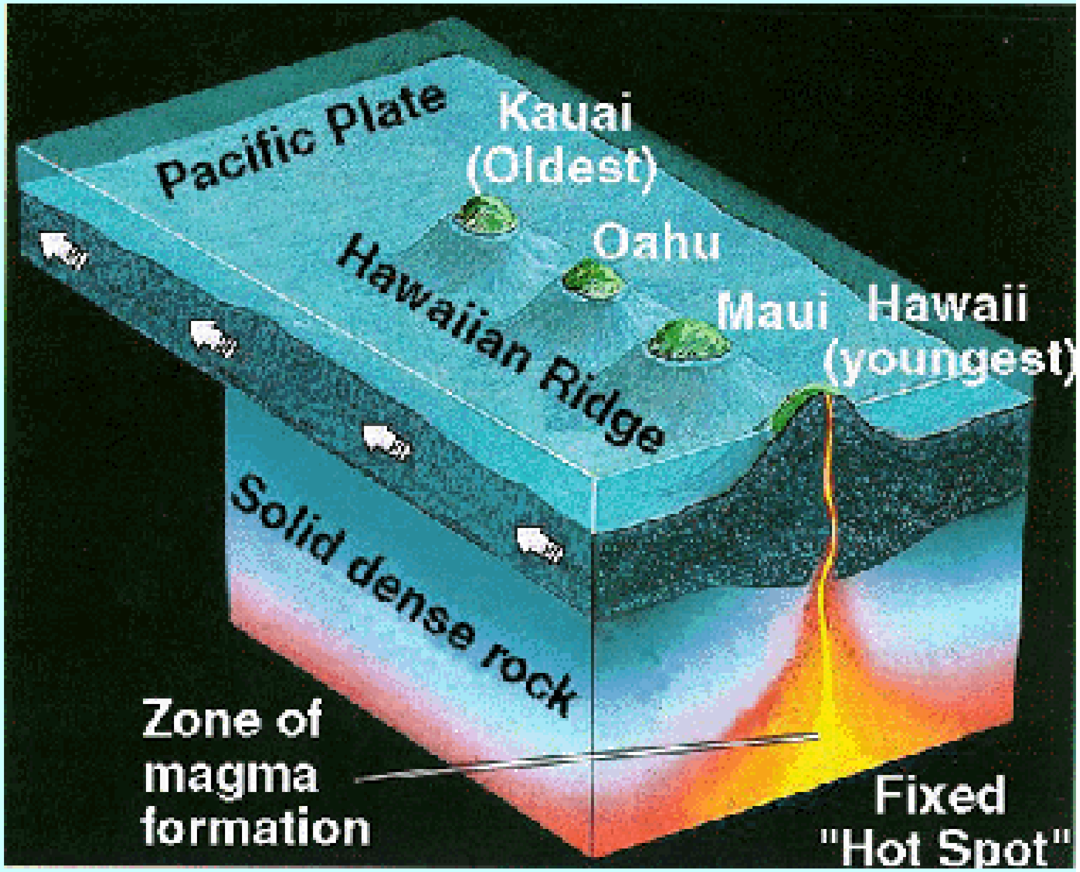
- First hypothesized by J. Tuzo Wilson (1963) to explain linear island chains in the Pacific.

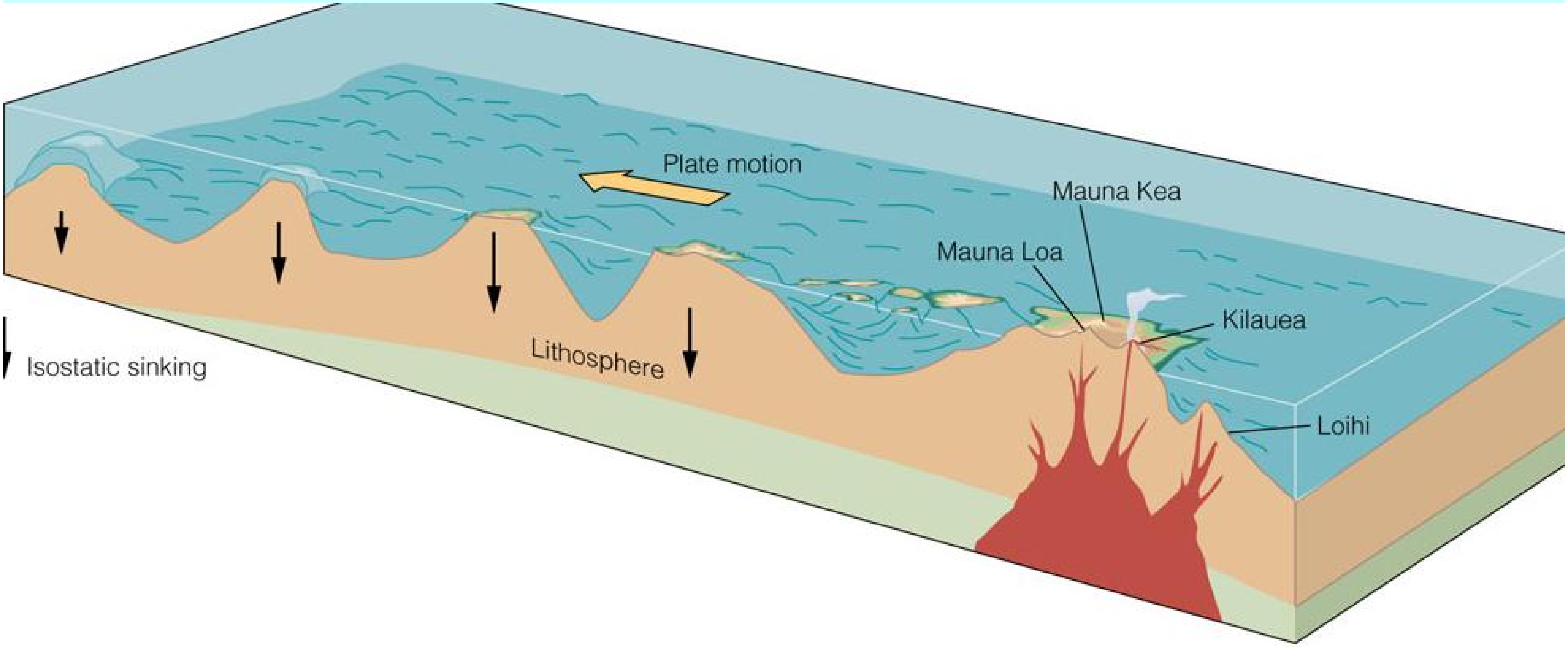


Mantle Plume or "Hot Spot" Theory

- Proposes that "hot spots" are point sources of magma that have apparently remained fixed in one spot of the Earth's mantle for long periods of time.

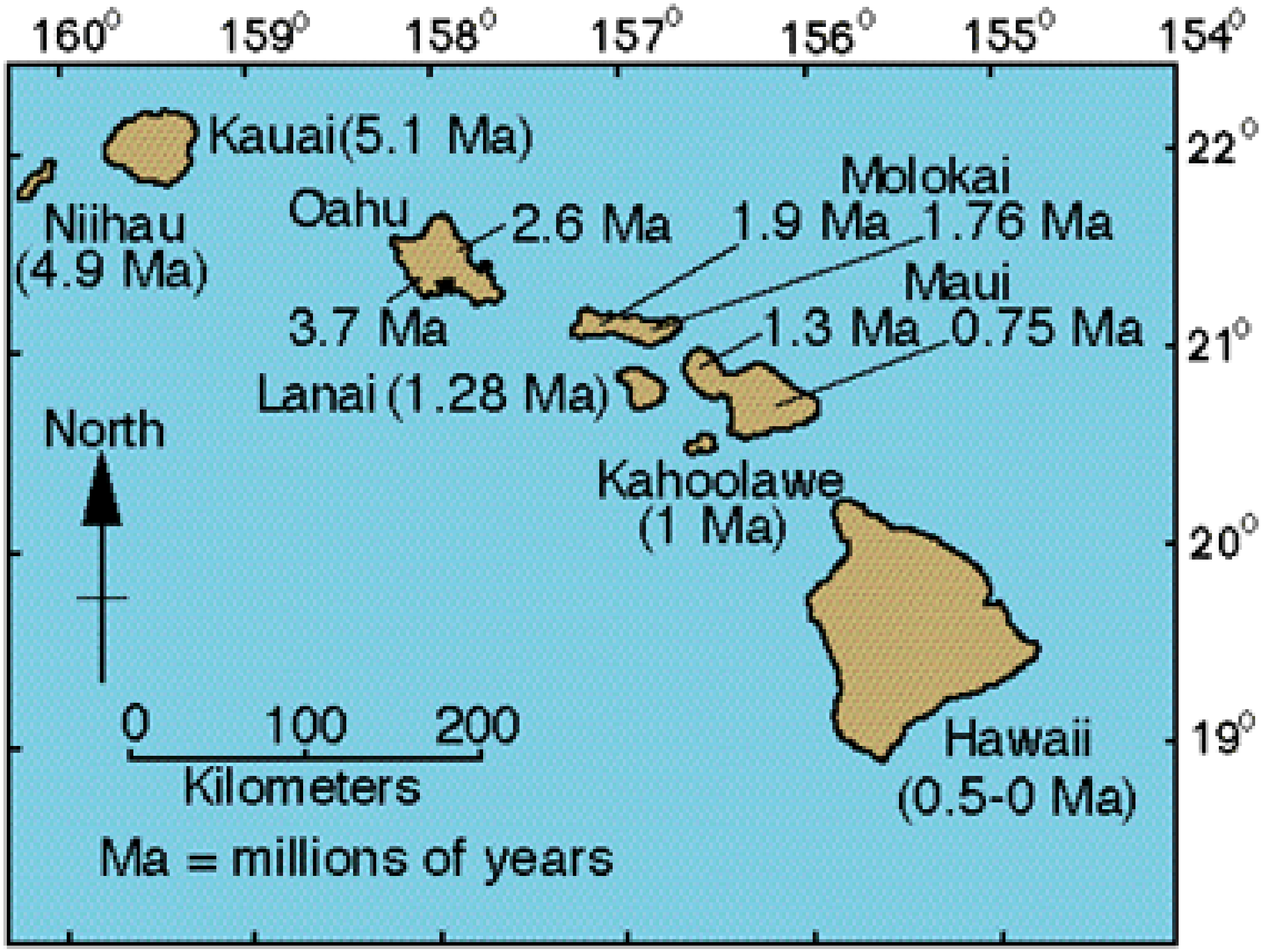






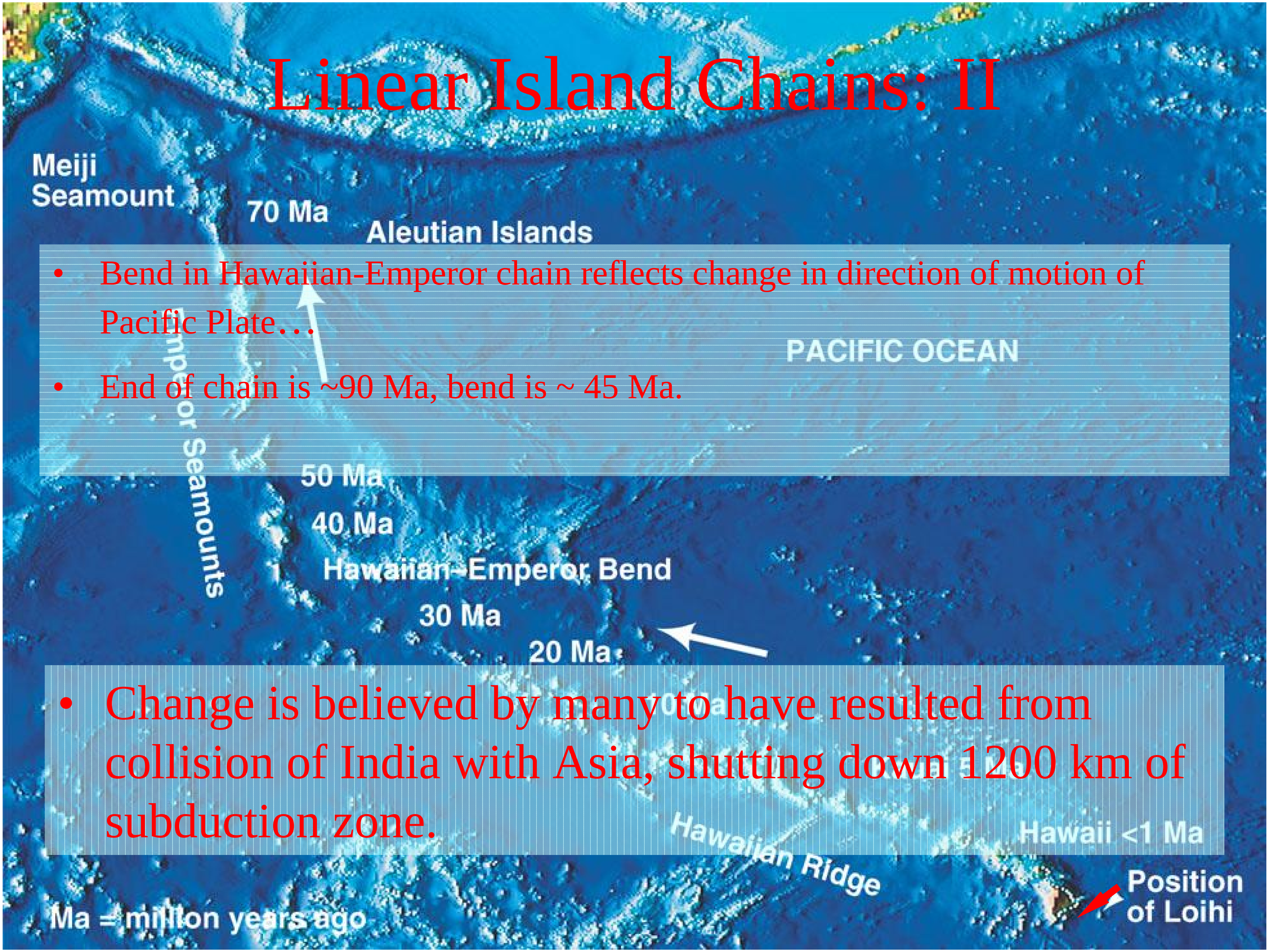
The Hawaiian hot spot presently lies beneath the Big Island of Hawaii.

Age of the Hawaiian Islands increases with distance from Kilauea



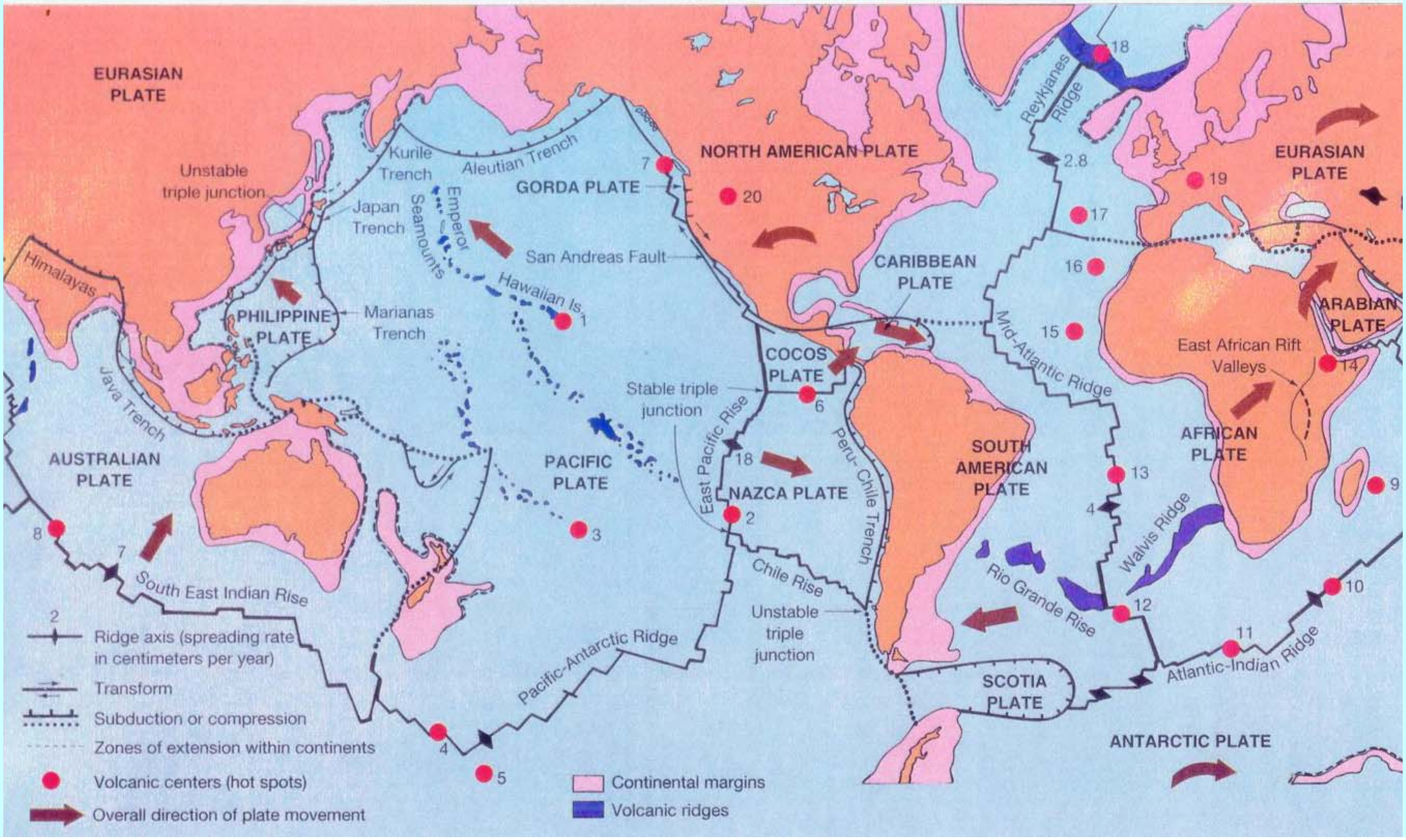
Linear Island Chains: II

- Bend in Hawaiian-Emperor chain reflects change in direction of motion of Pacific Plate…
- End of chain is ~90 Ma, bend is ~ 45 Ma.



- Change is believed by many to have resulted from collision of India with Asia, shutting down 1200 km of subduction zone.

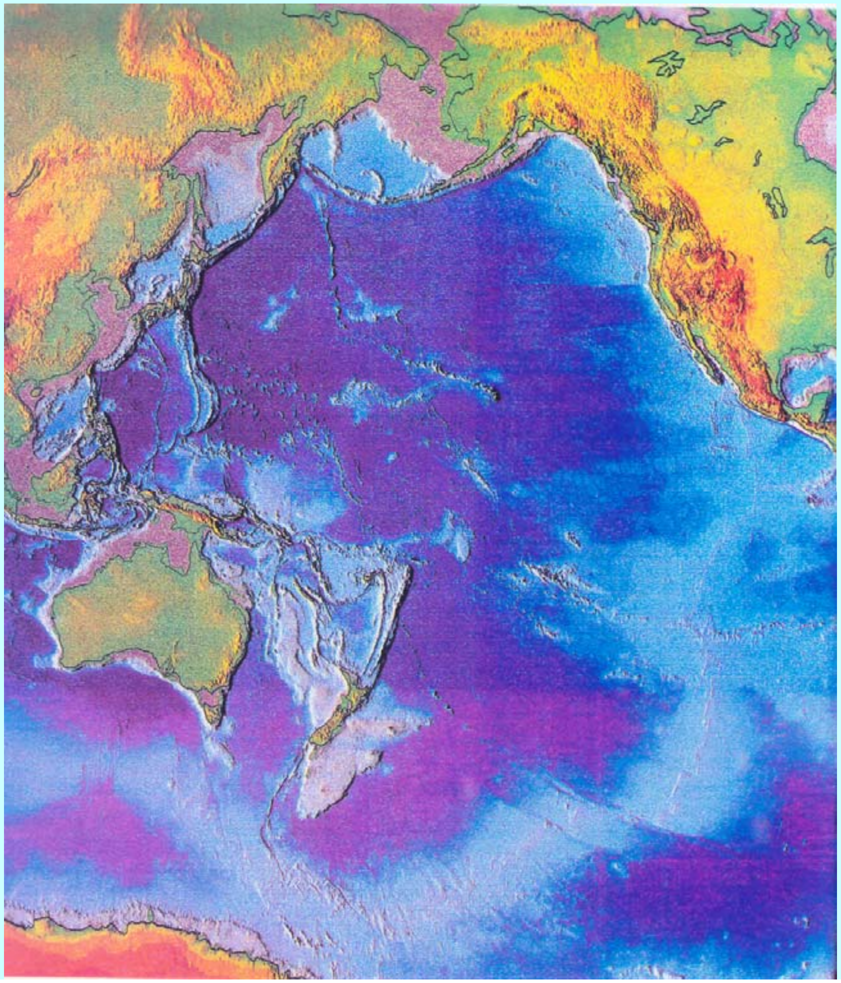
- Hot spots represent major zones of upwelling in overall pattern of mantle convection.
- Downwelling, however, is not so localized as upwelling that occurs at hot spots…

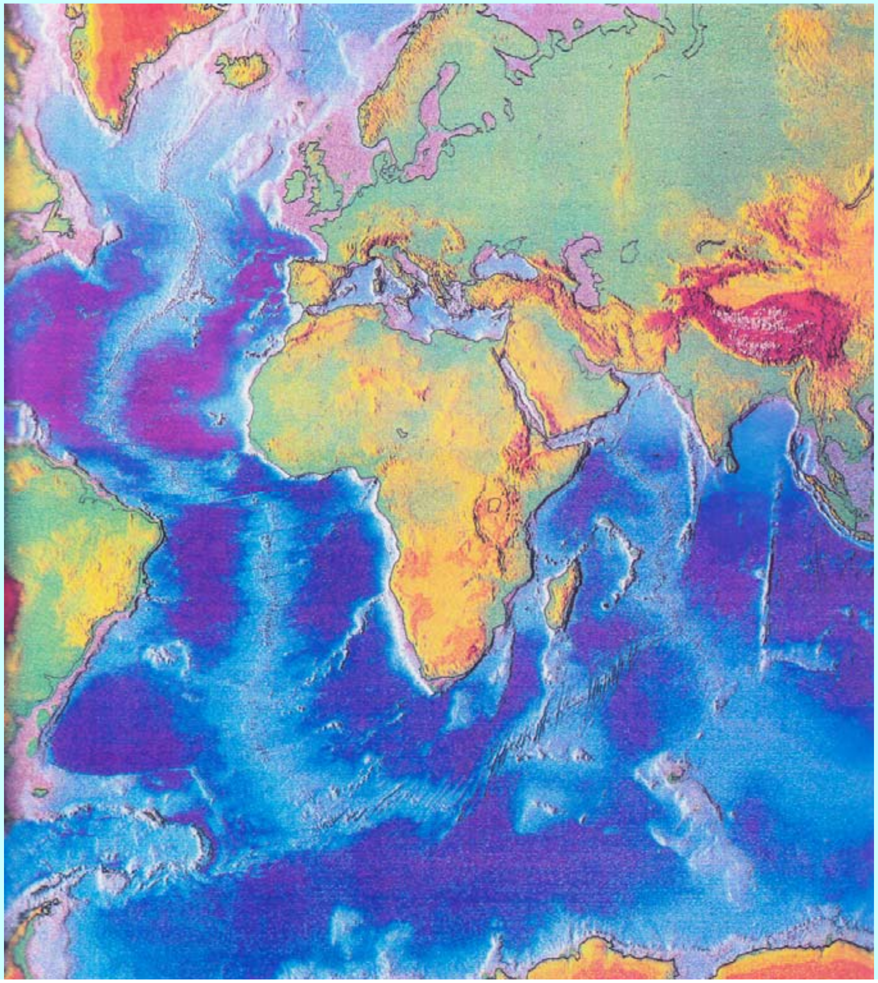


Mantle Plumes: II

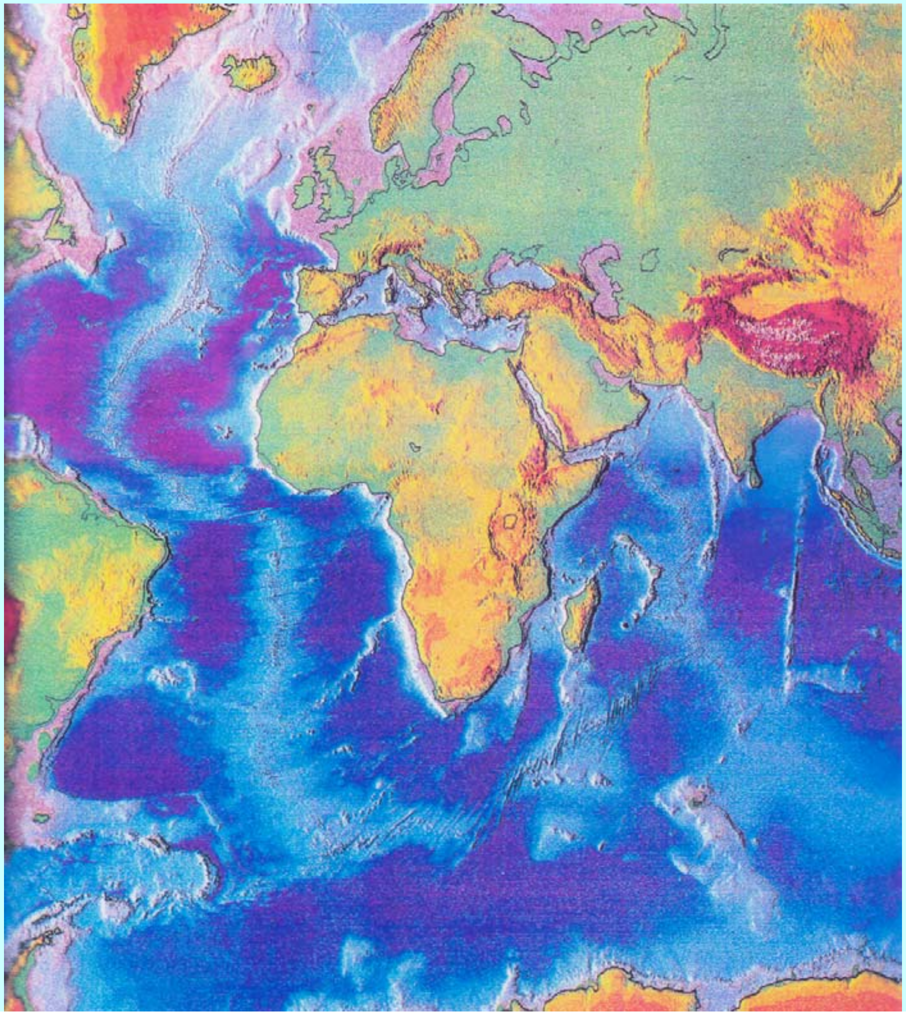
- Mantle plumes may be derived from near the core-mantle boundary, as demonstrated in this simulation from the Minnesota supercomputing lab.
- They may be the major mechanism that cools the core.
- Note the bulbous *plume heads*, and the narrow *plume tails.*
- Plume heads flatten as they impinge on the outer sphere (the base of the lithosphere).

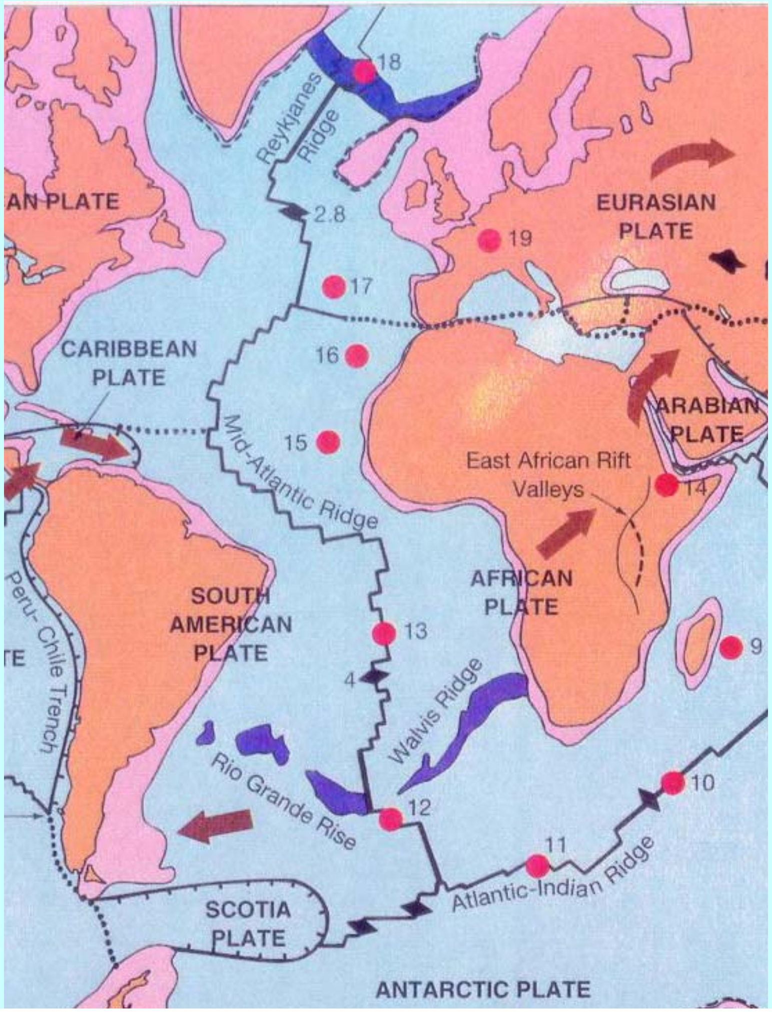
- Hot spots commonly occur on or near the MOR (Easter Island, Iceland, St. Helena, Tristan da Cunha).
- This led Morgan (1972) to suggest hot spots play an important role in driving plate motion…



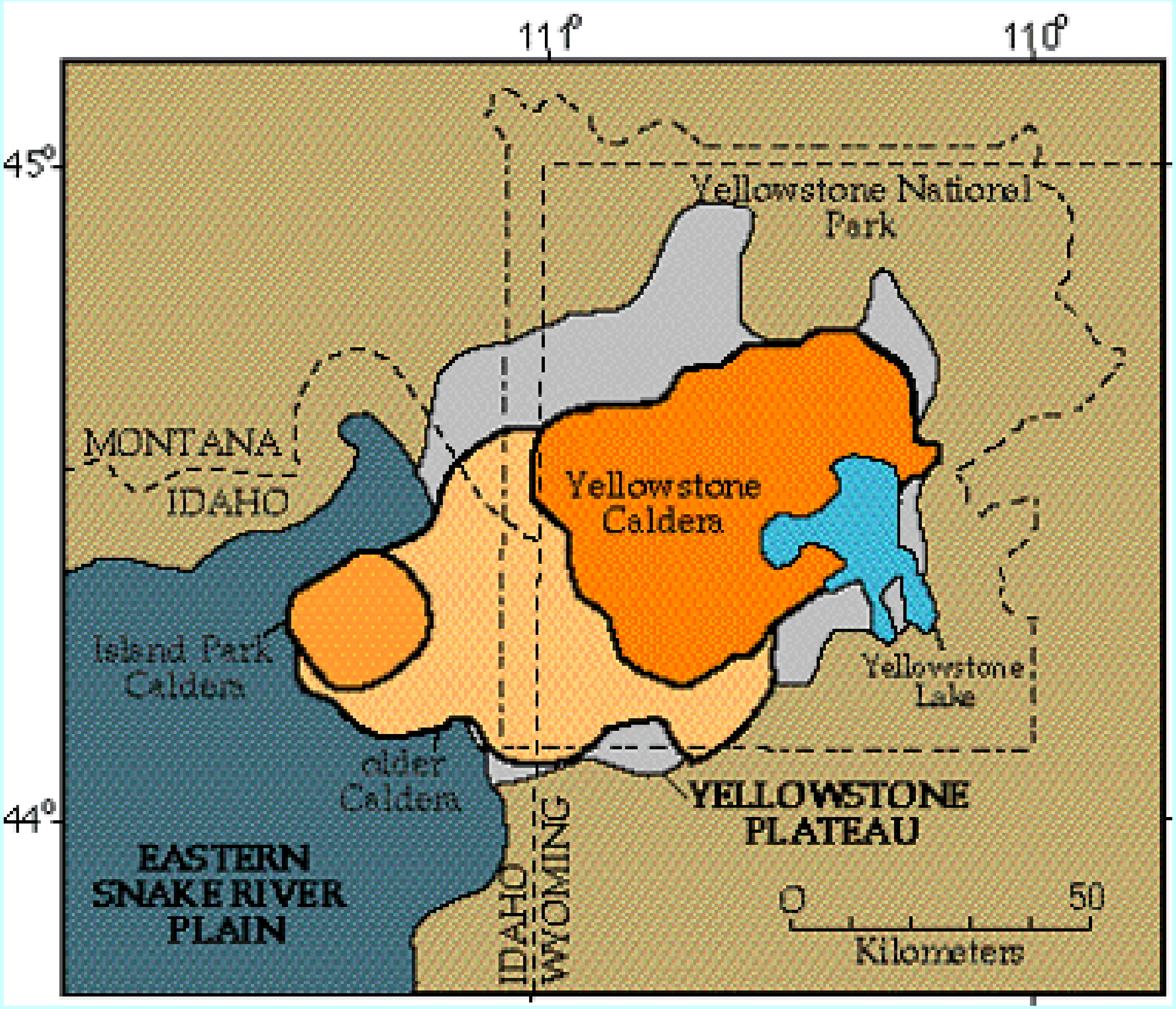


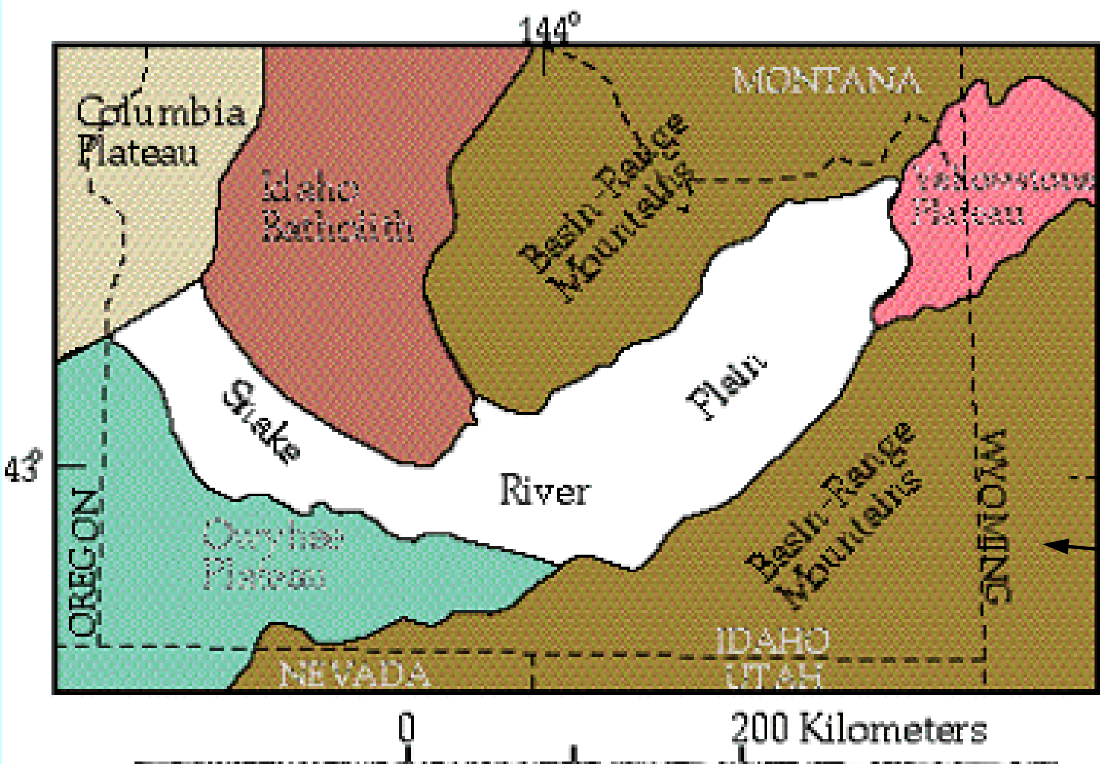
- Hot spots near MOR create aseismic ridges that extend outward from spreading axis (e.g., Tristan da Cunha, which produced the Walvis Ridge and Rio Grande Rise in the S. Atlantic).





- Hot spots also occur in middle of oceanic plates (e.g., Hawaii, Reunion) and under continental crust (e.g., Yellowstone).





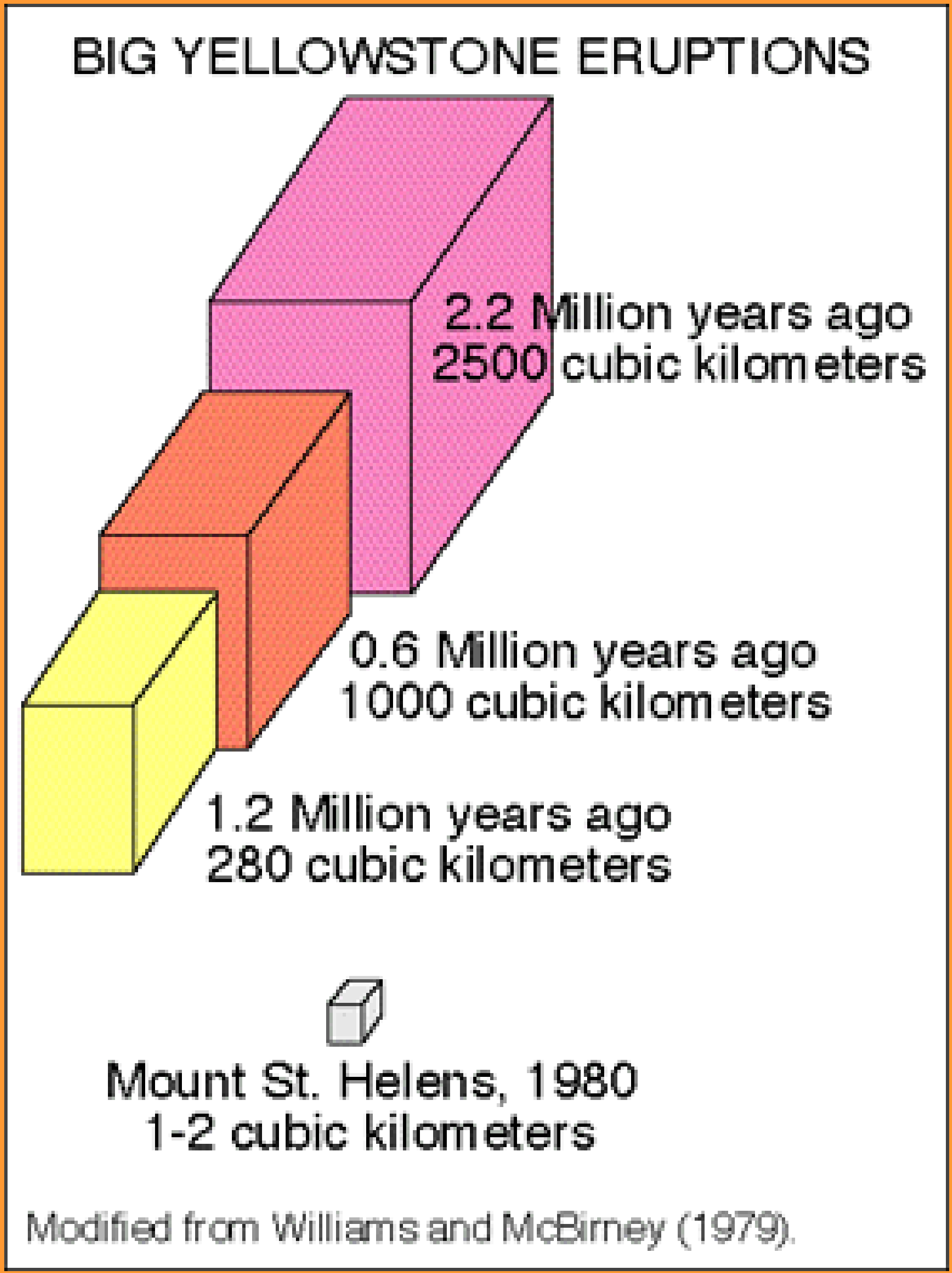
Trace of the Yellowstone hot spot:

the Snake River Plain, Oregon to Wyoming

Southern Idaho

The Snake River Plain from space

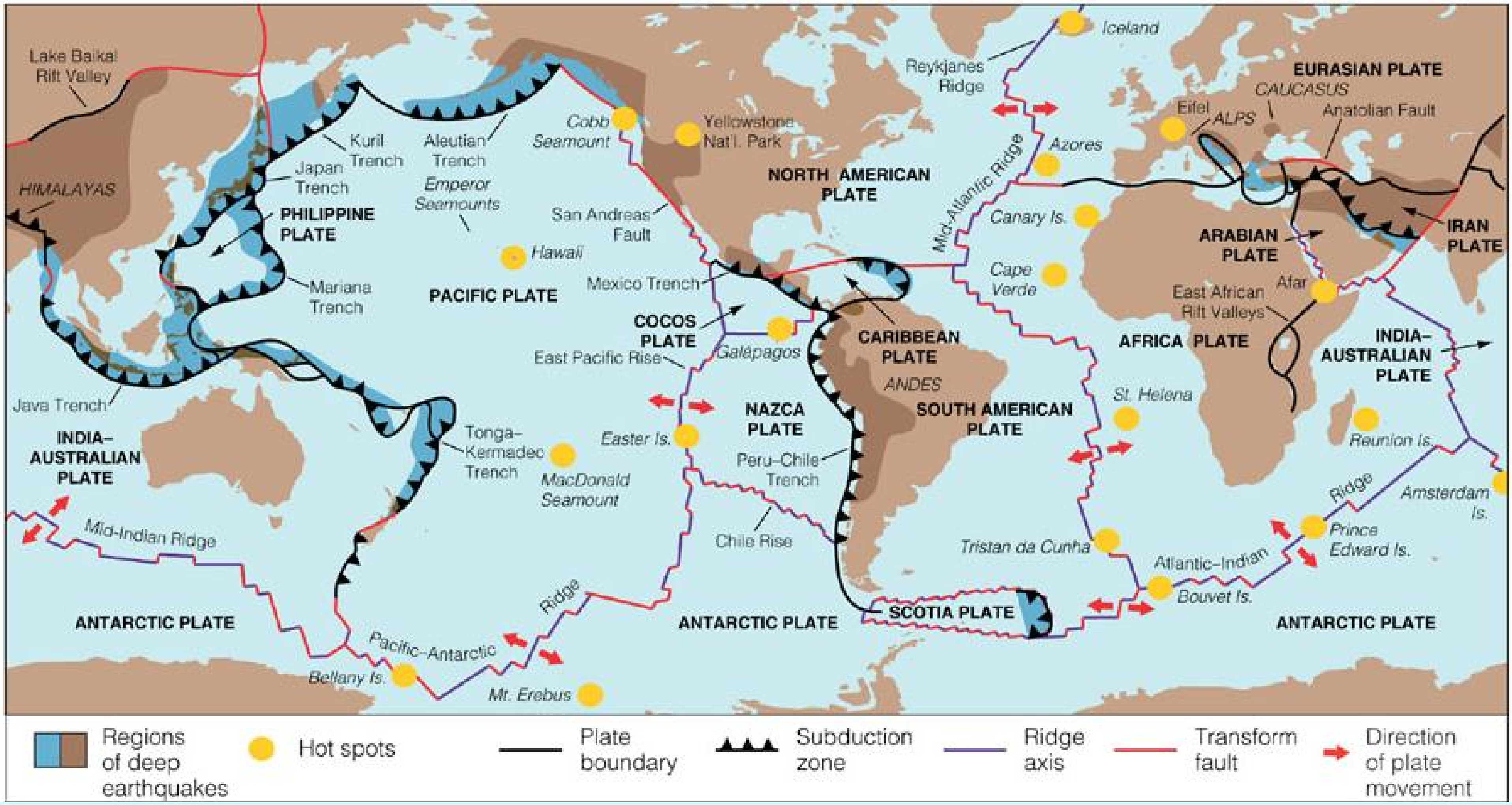
The Yellowstone hot spot: beautiful . . .



But ***dangerous***!

(Mt. Pinatubo, Philippines, 1991: 3-5 km^3)

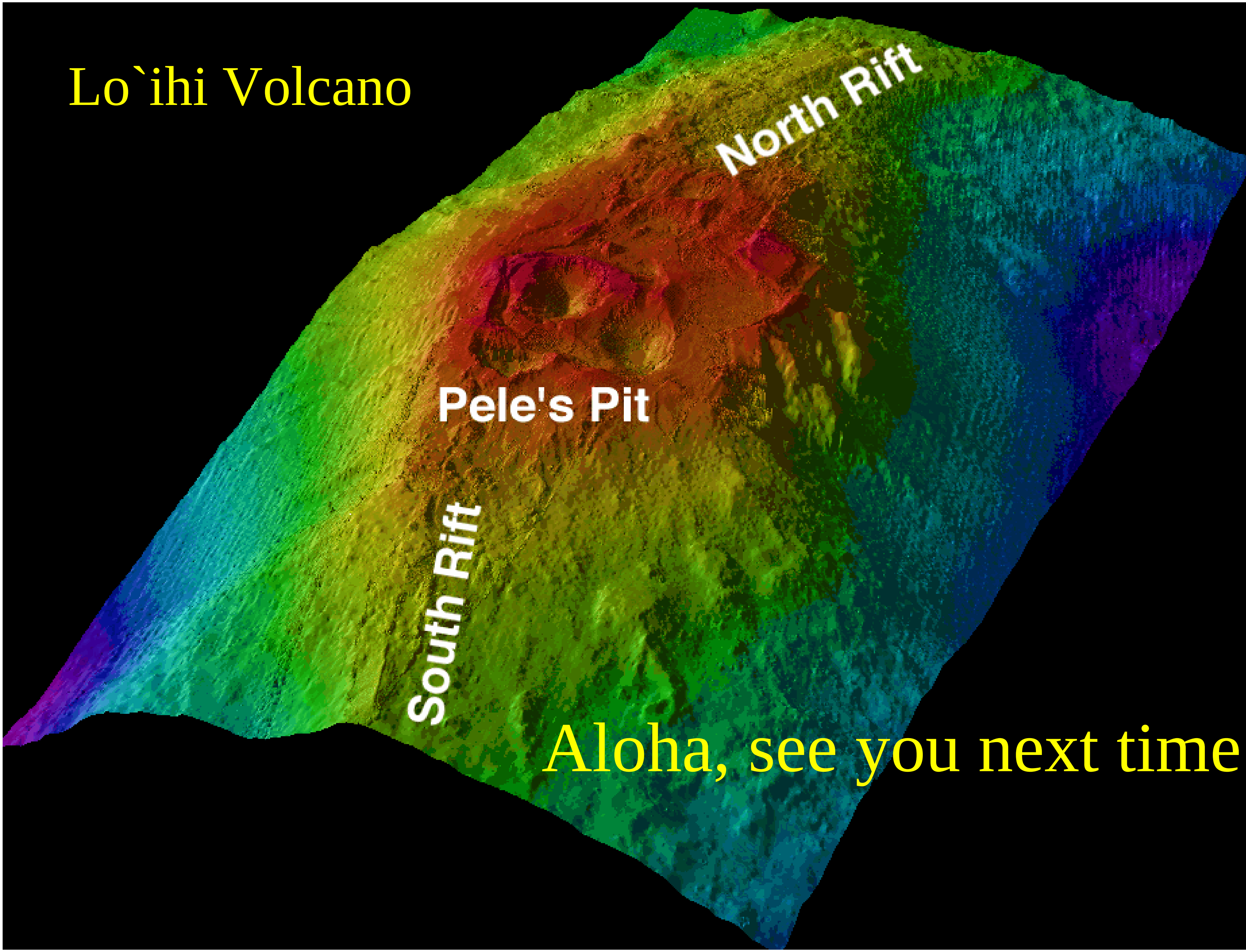
- Because they remain more or less fixed in mantle, hot spots lead to linear track of volcanism that can be used to trace absolute plate motion.



Hot Spots: Mantle Plumes?

- Important because they represent:
  - Third type of volcanism on Earth (MOR: basalt, Volcanic Arc: andesite, Hot spot: basalt)
  - A major mode of mantle upwelling (focused point sources) that may cool the core
  - A measure of absolute plate motion (motion with respect to fixed point in mantle rather than relative to other plates).

Lo`ihi Volcano



Aloha, see you next time