

Lecture 1

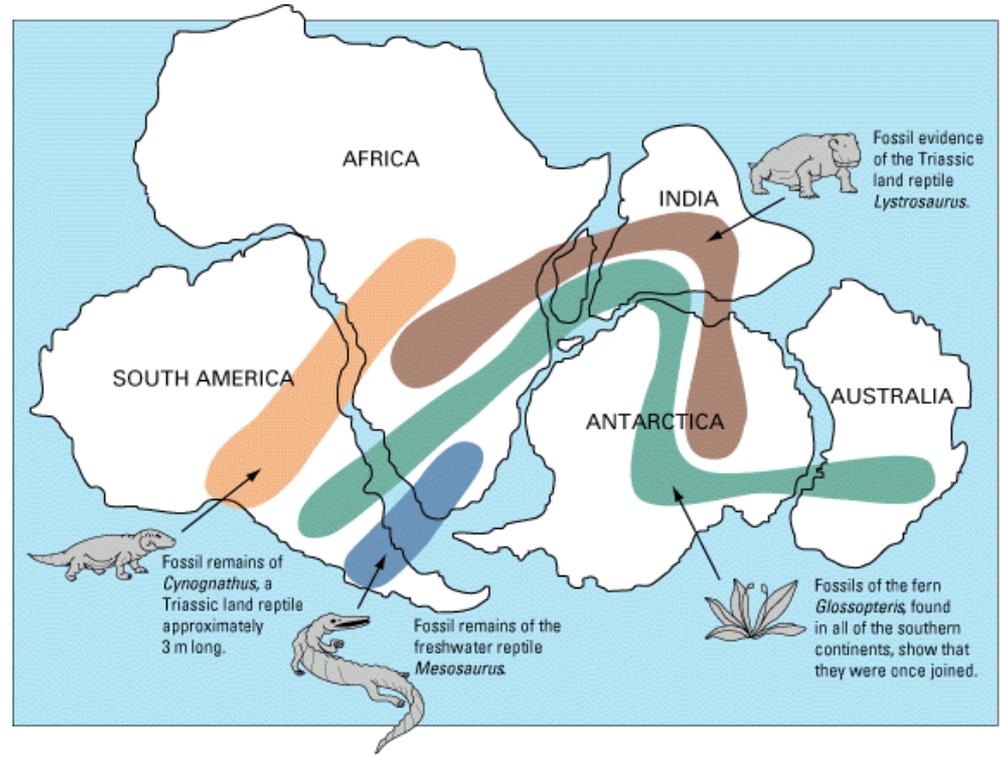
A Brief History of Plate Tectonics

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Earlier Beliefs on the and

► Wegener's continental Drift Theory:

- A meteorologist by training
- He was surprised by how the edges of continents fit geometrically like a jigsaw puzzle.
- Afterwards he learned about fossil evidence (common fossils in continents that are separated by oceans).
- He came up with continental drift theory.
- He came up with Pangea.
- His claim was that continents move around
- The explanation for common fossils was “Land Bridge Theory”
- He explained land bridge was inconsistent with isostasy.



Continental Drift

- ▶ Continental Drift Theory was widely rejected by the earth scientists at the time.
 - Wegener could not offer a physical mechanism of how continents moved over oceanic plates. (What is the driving force).
 - Ocean floors are too rigid to let continents move around
- ▶ In 1929, Arthur Holmes claimed that the physical mechanism for continental drift could be mantle convection (not noticed at the time).
- ▶ Until the end of WWII the issue was put to rest.
 - During Great Depression, not much happened.
 - During WWII many scientists worked in submarines, Sonar, Radar work, has done bathymetry work, worked with magnetometers.
- ▶ Some European Scientists still believed continents moved around, but especially in USA the continental drift was not supported at all.

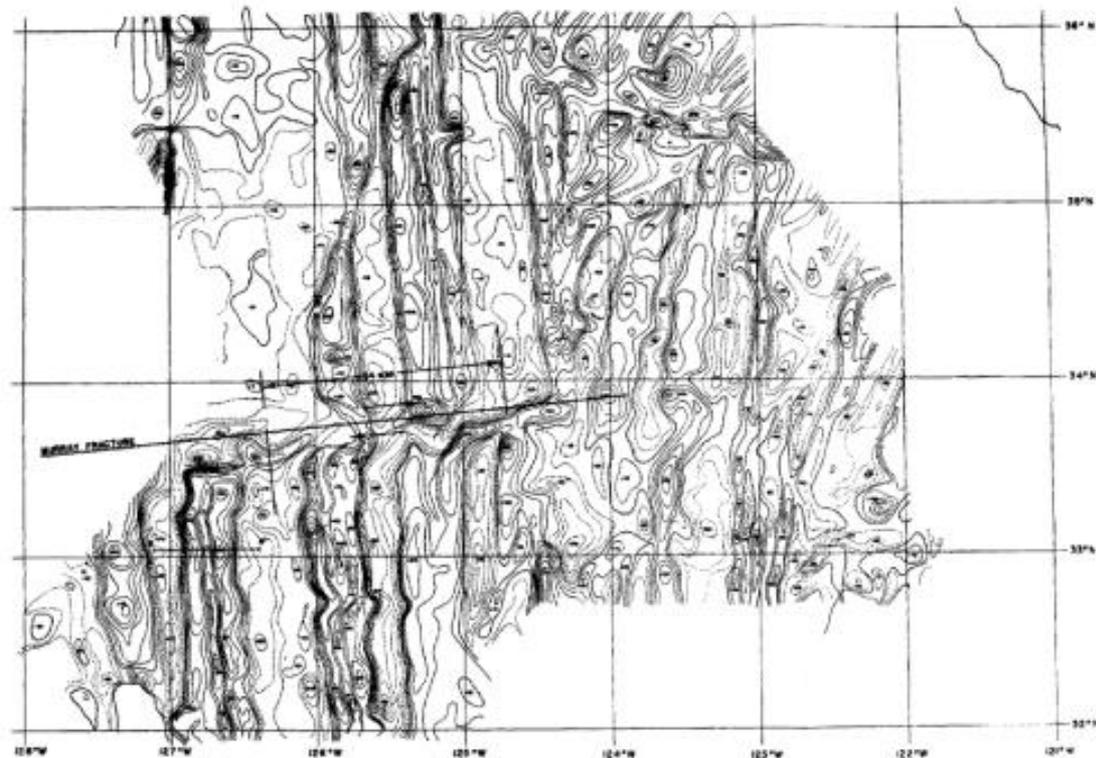
Contraction Theory

- ▶ At this point, the explanation for why there was topography, why there were oceans and continents was made by “contraction theory”.
- ▶ As the earth cooled, it contracted. This created the mountains, continents and oceans. Similar to a drying apple.

Sea Floor Spreading Theory

- ▶ After WWII some bathymetric data became available (it was not public but it was available to some scientists).
- ▶ Radiometric dating was available
- ▶ Due to submarine navigation in WWII, bathymetry studies were done.
- ▶ Radar systems were used so militaries wanted to know more about magnetic field.
- ▶ Princeton geologist Harry Hess:
 - The oldest dated ocean bottom is 180 m.y. old.
 - There are rifts in between the ocean floor
 - Mid-ocean ridges have high heat flow and low seismic velocities.
 - “A more acceptable mechanism is derived for continental drift whereby continents ride passively on convecting mantle instead of having to plow through oceanic crust”

- ▶ Roger Mason and Art Raff of Scripps Institute (UCSD) published magnetic anomaly map of off coast of California.
- ▶ Magnetic anomalies showed an amazing pattern of symmetry. They looked like stripes of equal values.
- ▶ These stripes were parallel to the ridges.
- ▶ Mason and Raff stated in the paper that they don't have an explanation for this.
- ▶ They tried to explain it with topographic undulations.



Initial results of the *Pioneer* survey of rock magnetism off the west coast of North America, after three months' operation. The distinctly linear pattern in the south-west corner of the map area, where we started, persuaded us to continue with the survey. (From Mason, 1958, Figure 2.)

- ▶ Mason and Raff (1961) published another magnetic survey of the off-coast of Western USA. Again same zebra pattern showed up clearly.

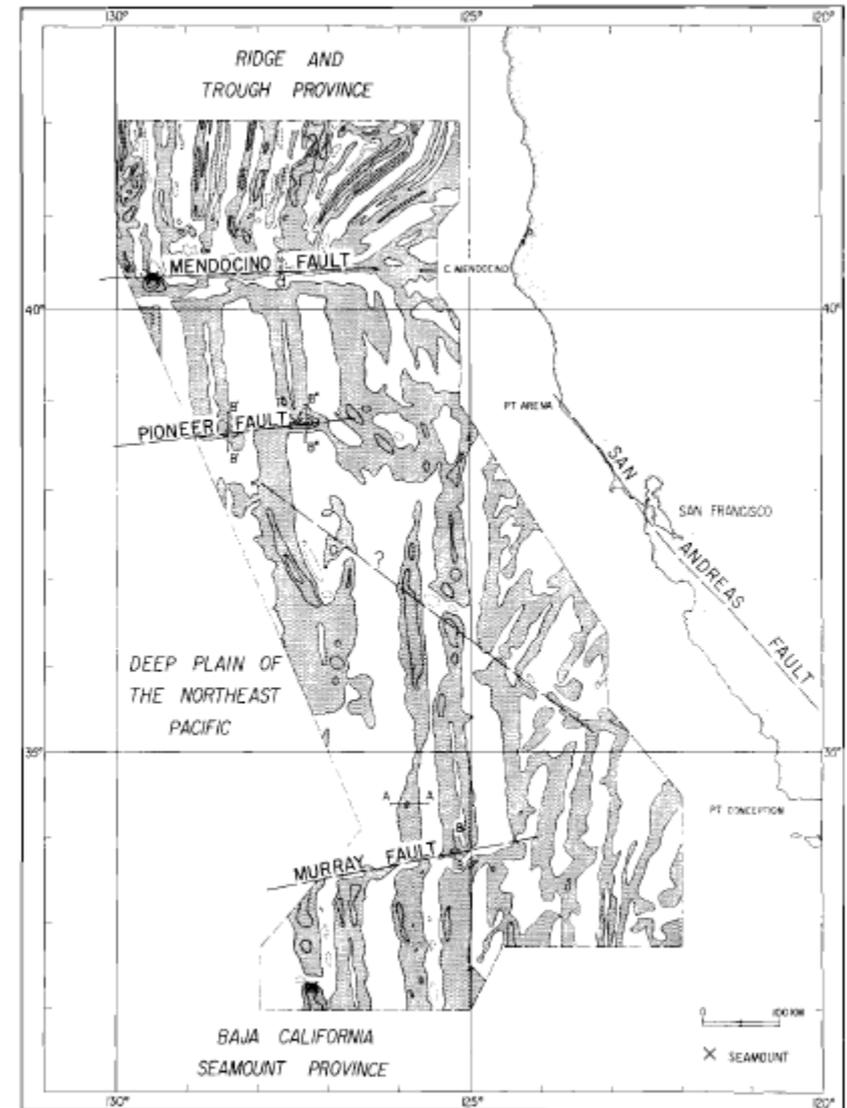
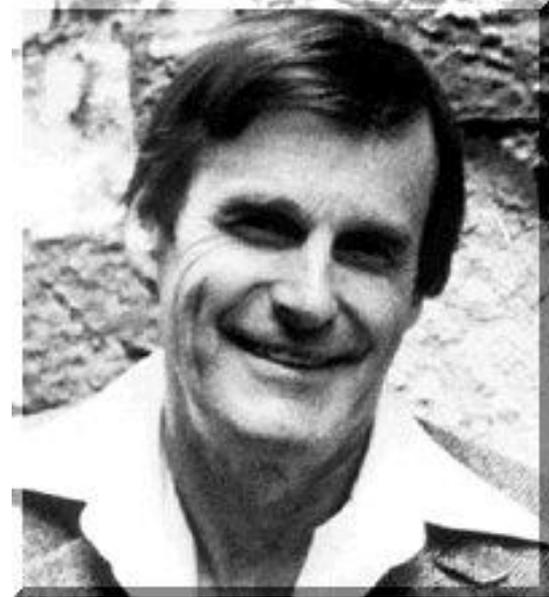


Figure 1. Skeleton magnetic map, showing geomorphic provinces, principal known faults, and locations of profiles. The contour interval is 250 gammas. Areas of positive anomaly are stippled. Negative contour lines are broken.

Putting the Pieces Together

- ▶ A Canadian geophysicist called Lawrence Morley, put the whole picture together in 1963.
 - The earth's magnetic field is reversed at various periods.
 - As the new magma forms at the ridges, before they reach Curie temperature they are magnetized in the direction of the magnetic field of the earth at that time.
 - This leads to the stripes that we see that are parallel to the ridge.
 - His paper was rejected by both Nature and JGR.



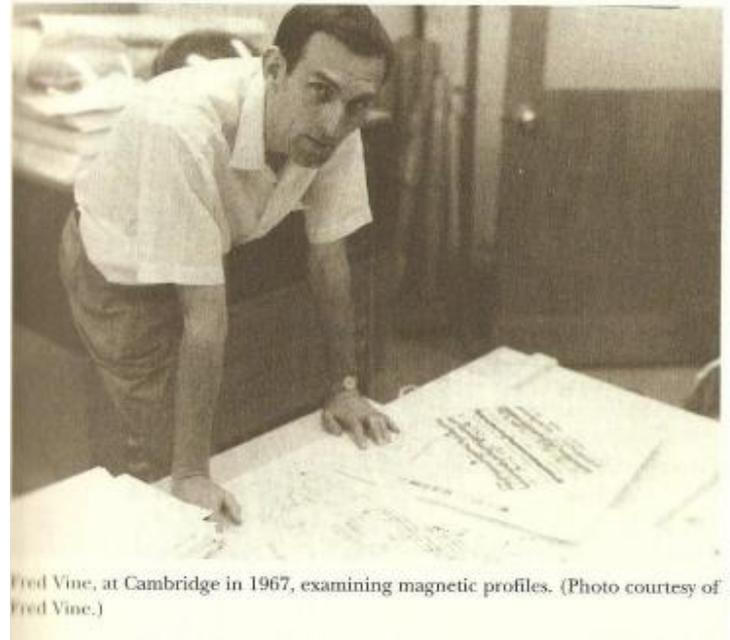
Morley Manuscript

“Several investigators and authors writing on the subject of continental drift and convection currents in the earth’s mantle have referred to the puzzling linear magnetic anomalies in the Eastern Pacific Ocean Basin reported by scientists of the Scripps Institution of Oceanography.

If one accepts in principle, the concept of mantle convection currents rising under the ocean ridges, travelling horizontally under the ocean floor and sinking at the ocean troughs, one cannot escape the argument that the upwelling rock under the ocean ridge, as it rises above the Curie Point geotherm, must become magnetized in the direction of the earth’s prevailing field at the time. If this portion of the rock moves upward and then horizontally to make room for new upwelling material and if, in the mean time, the earth’s field has reversed, and the same process continues it stands to reason that a linear magnetic anomaly pattern of the type observed would result. This explanation has the advantage, over the many others put forward, that it does not require a petrologically, structurally, thermally and strain-banded oceanic crust. It requires a convection cell, whose axis of rotation is at least as long as the linear magnetic anomalies and whose horizontal distance-of-travel, stretches from ocean rise to ocean trough. In addition to this it requires a large number of reversals of the earth’s magnetic field...”

Finally an Accepted Paper

- ▶ A young grad student at Cambridge Fred Vine and his advisor Drum Matthews (without knowing Morley) came up with the same explanation.
- ▶ Harry Hess and Tuzo Wilson were on sabbatical at Cambridge Geophysics Department (then called Madingley Rise, now called Bullard Lab).
- ▶ Tuzo Wilson contributed to the idea by explaining the fracture zones.
- ▶ The paper was poorly received. Vic Vacquier (Scripps), Talwani (most Lamont people).
- ▶ Le Pichon wrote a paper against plate tectonics explaining that the heat flow measurements are not well-explained by this new theory.



Why was it hard to get the Theory Accepted

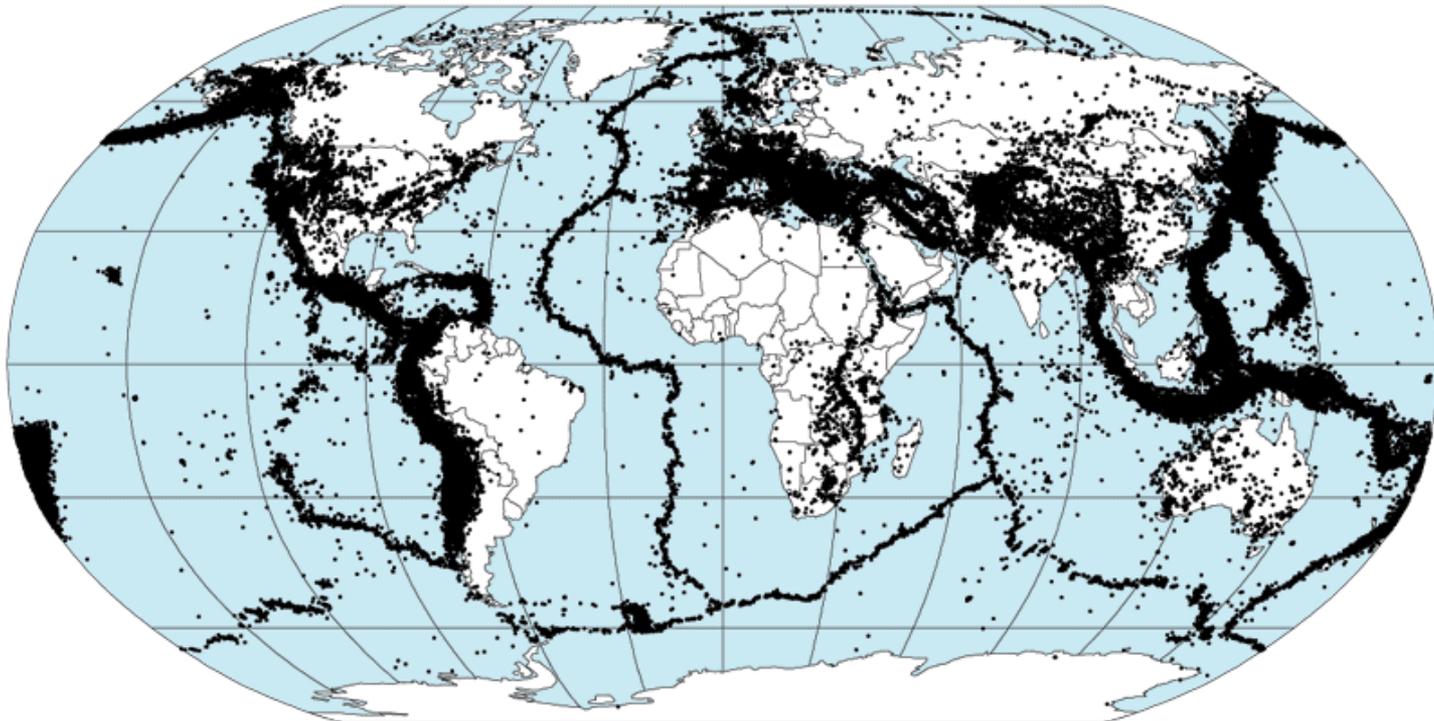
- ▶ It was not widely accepted that the earth's magnetic field goes through reversals.
- ▶ Reversals were suggested by observations of continental rocks, which seemed to have magnetic reversals at different layers.
- ▶ Convection was not widely accepted at the time. There was the question of driving force?
- ▶ So some older generation scientists were skeptical about the paleomagnetic studies of continental rocks and ocean floors.
- ▶ The profiles with stripes did not cover any actual mid-ocean ridge. (Juan de Fuca ridge was not known at the time).
- ▶ Harold Jeffreys: The earth is too strong for such mobility. If it can support mountains and ocean trenches, then the continental drift is out of the question.

Ron Mason: “Vine-Matthews’ hypothesis offered an elegant explanation of how the magnetic lineations of the northeast Pacific could have come about, although at this time there was no obvious connection with an ocean ridge. I was familiar with ideas about sea floor spreading and reversals of the earth’s magnetic field, and I could have kicked myself for not thinking of the idea, particularly because, had I looked more carefully at our map. I would have realized that some of the seamounts might be reverseky magnetized, and this might have headed my thoughts in the right direction. I had absolutely no doubt as to the correctness of their hypothesis. But to my surprise the idea was not universally accepted. One reason for doubt was that no magnetic survey spanning an ocean ridge was thought to be available. Perhaps more importantly, in 1963 neither sea floor spreading, nor geomagnetic field reversals were universally accepted. In that regard, Vine-Matthews hypothesis was built upon two other hypotheses, about which many people still had doubts.

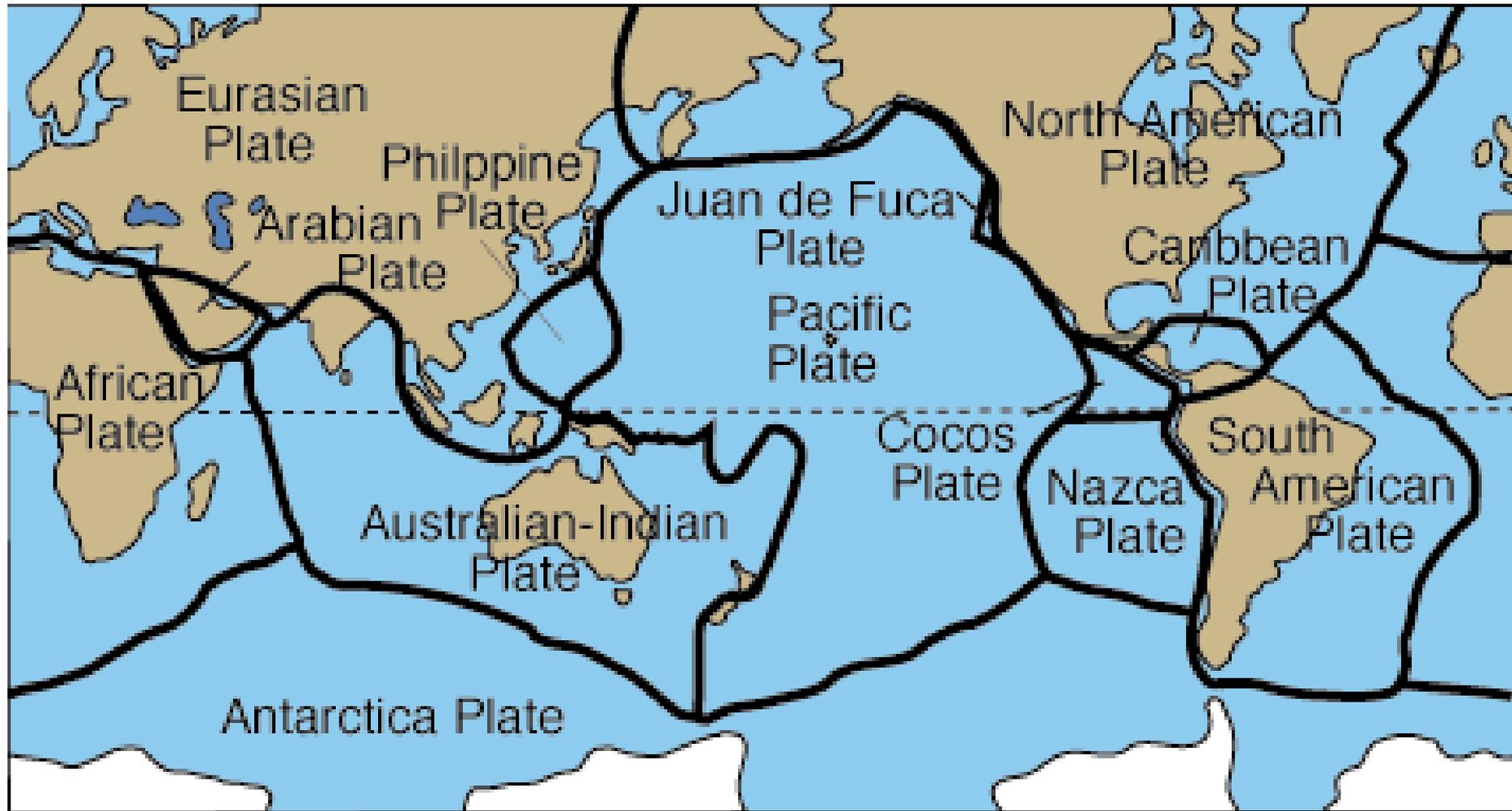
Evidence From Seismology

- ▶ Lynn Sykes (Lamont) has shown in 1967 that earthquakes over the mid ocean ridges are normal fault earthquakes.
- ▶ Earthquake first motion polarity directions were being used for finding out earthquake mechanisms. The focal mechanisms also agreed with the idea of seafloor spreading.

Preliminary Determination of Epicenters
358,214 Events, 1963 - 1998



Plates of the World



Major tectonic plates of the world.

Sea Floor Age

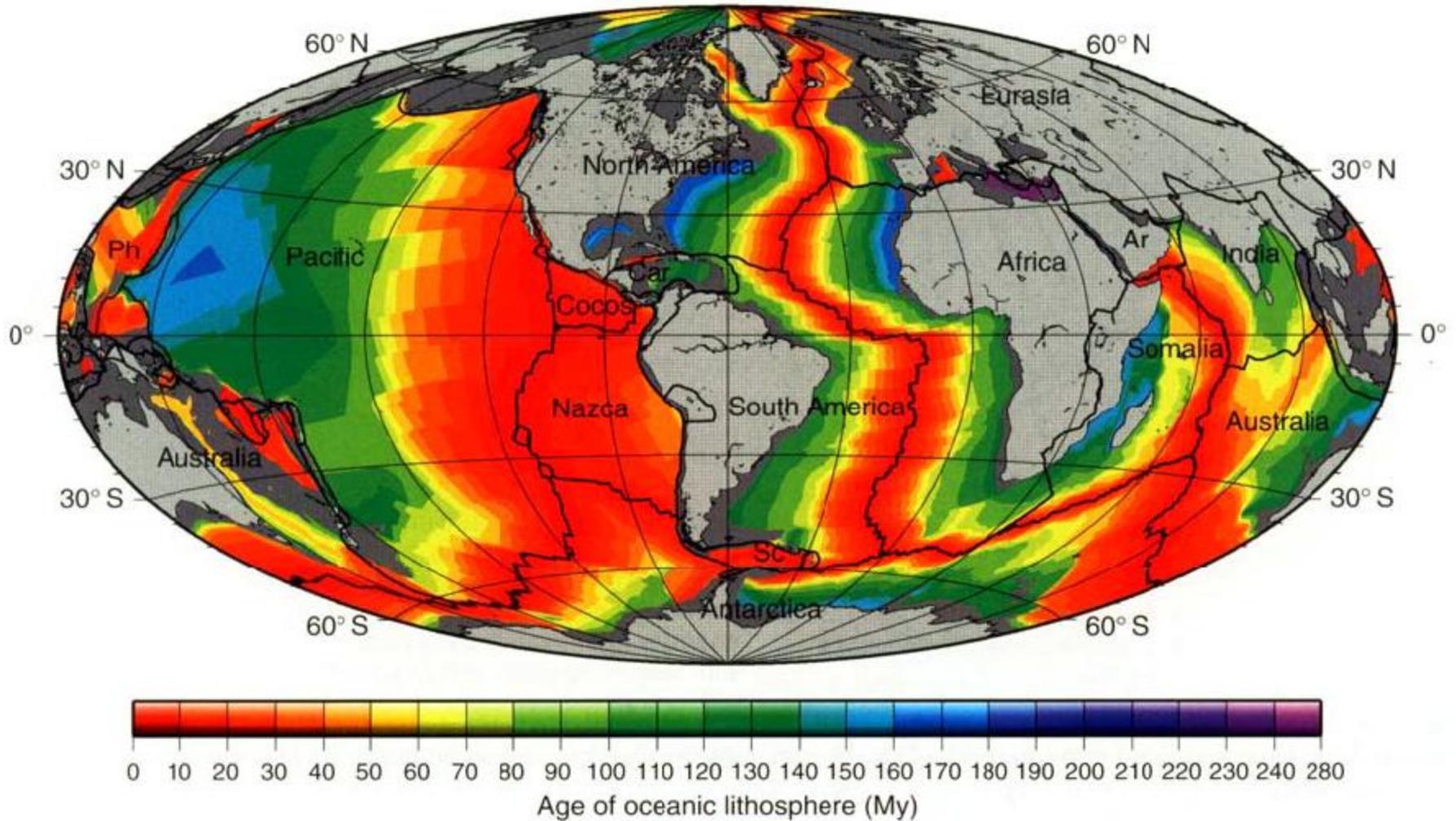
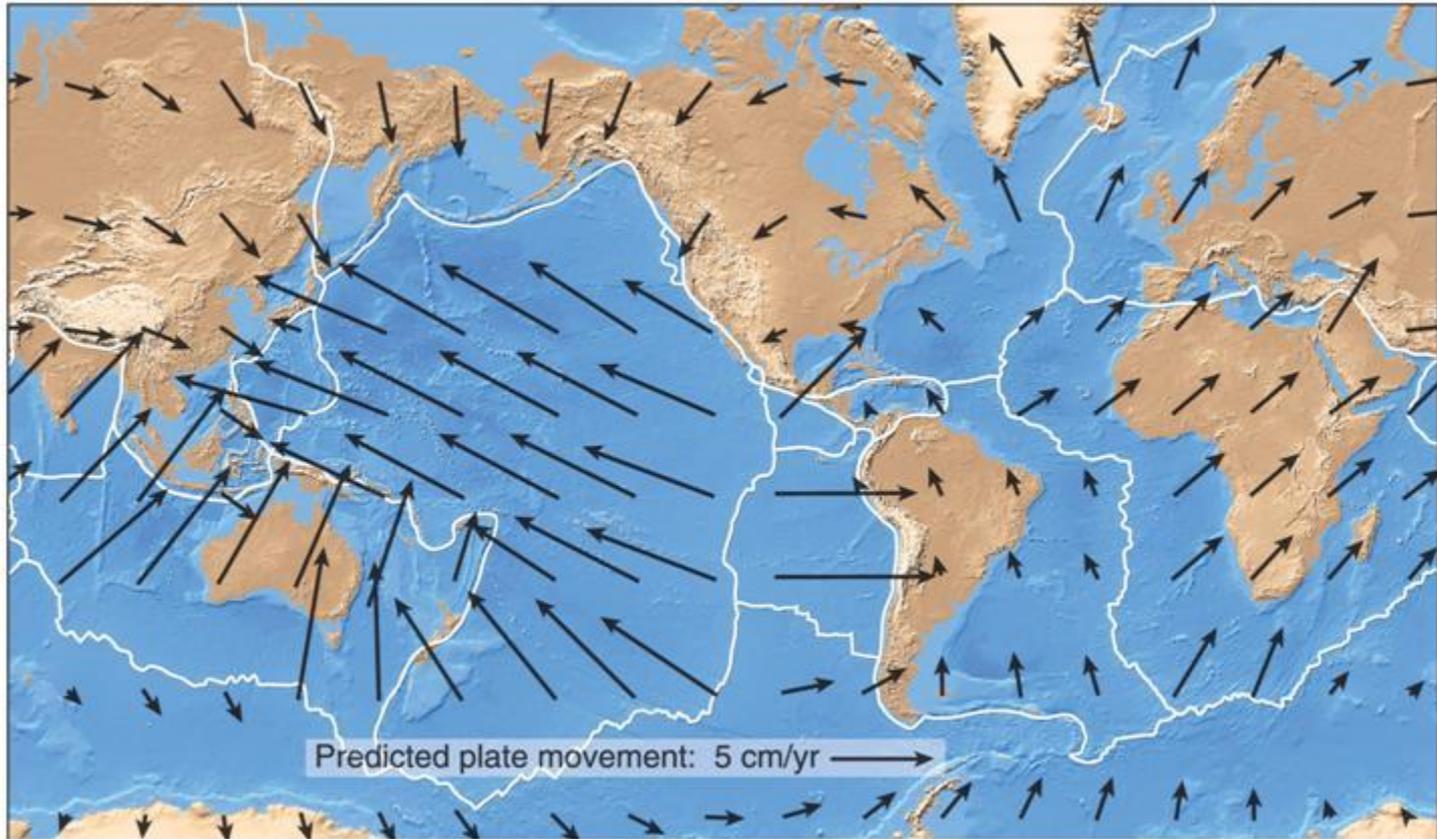


Figure 3 Revised age of the global ocean floor based on Müller *et al.* (1997) with plate boundaries from Bird (2003) overlain.

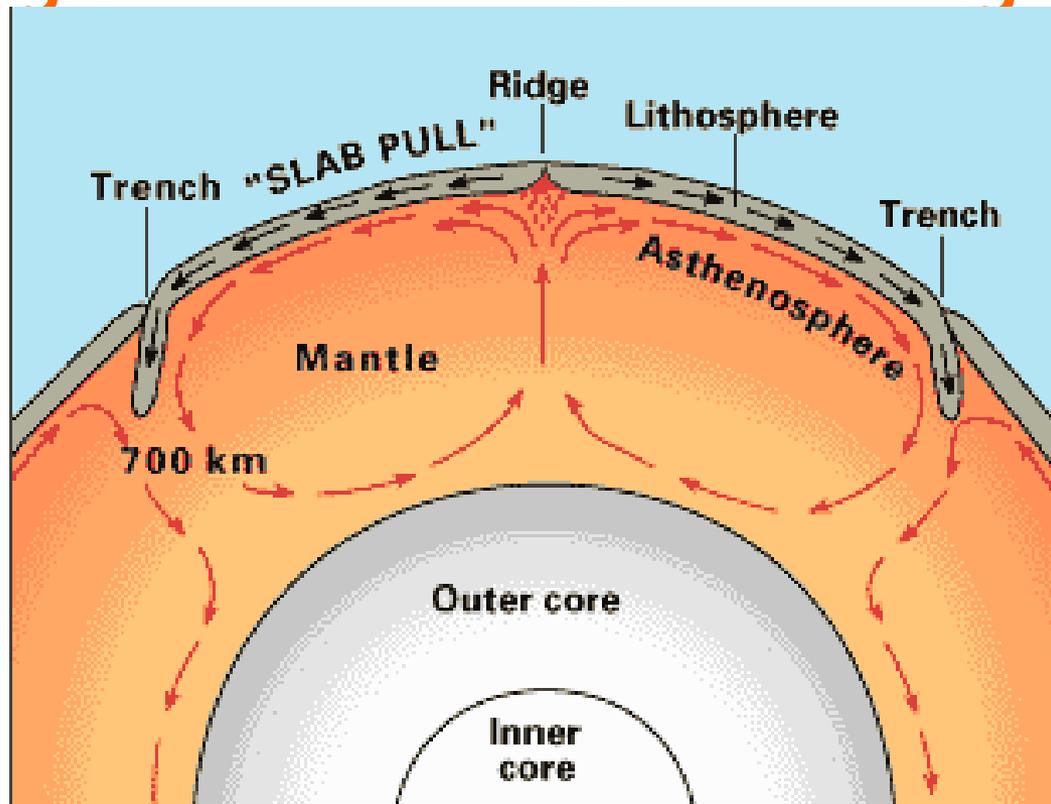
Plate Velocities



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Fig 12.37

Driving Force: Convective Cooling of Mantle

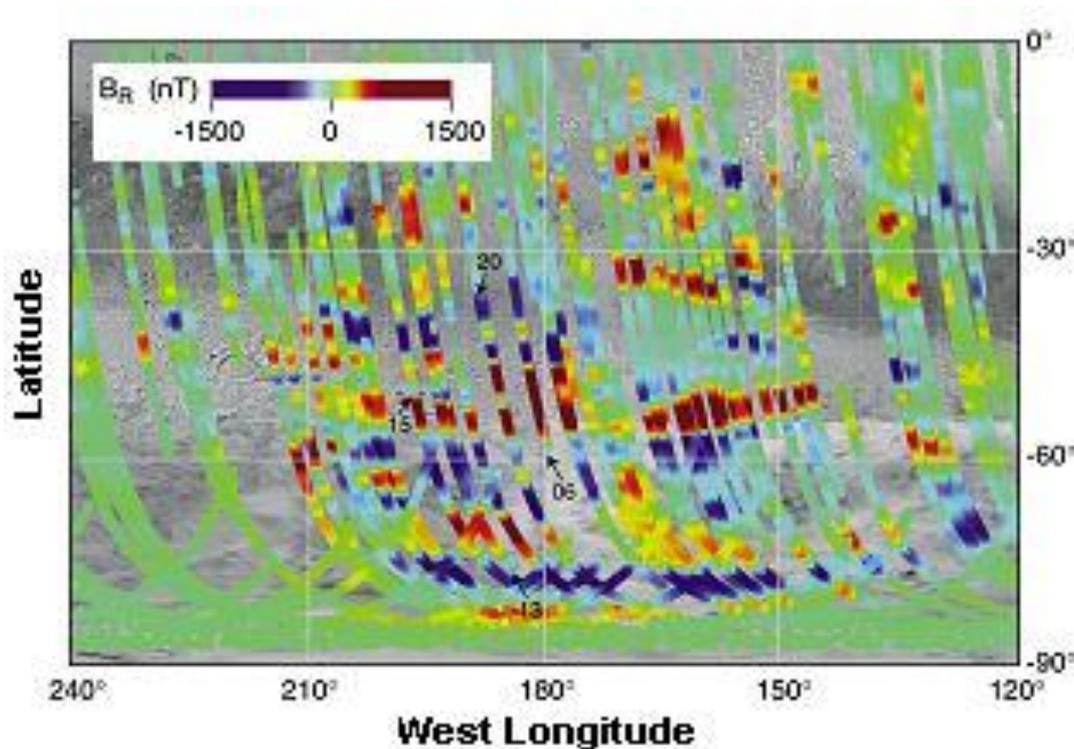


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- ▶ Although mantle convection is probably the driving force, it is not the reason.
- ▶ One could have convection in the mantle and a conductive thermal boundary layer without continental plates as in the case of the earth.
- ▶ Presence of water in the earth (kept on the earth by the atmosphere) possibly also plays a role.

Mars

- ▶ No active plate tectonics but evidence that there was plate tectonics from the magnetic anomaly.
- ▶ Since Mars is smaller, it probably lost its heat sufficiently which stopped plate tectonics.



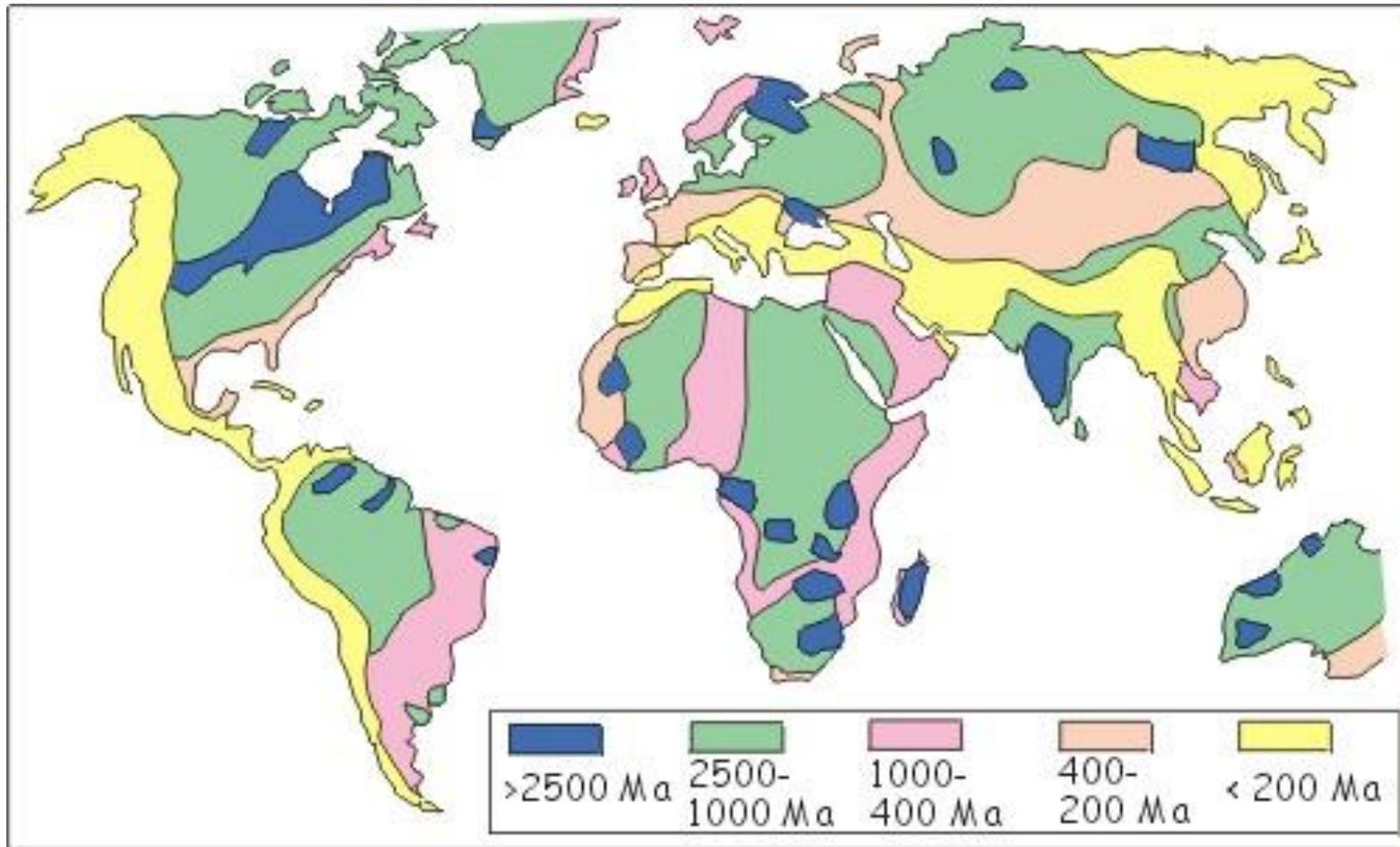
Venus

- ▶ Venus has a thermal boundary layer similar to continental crust of the earth.
- ▶ Surface temperature of Venus is 750 K, so it is certainly bouyant lithosphere.

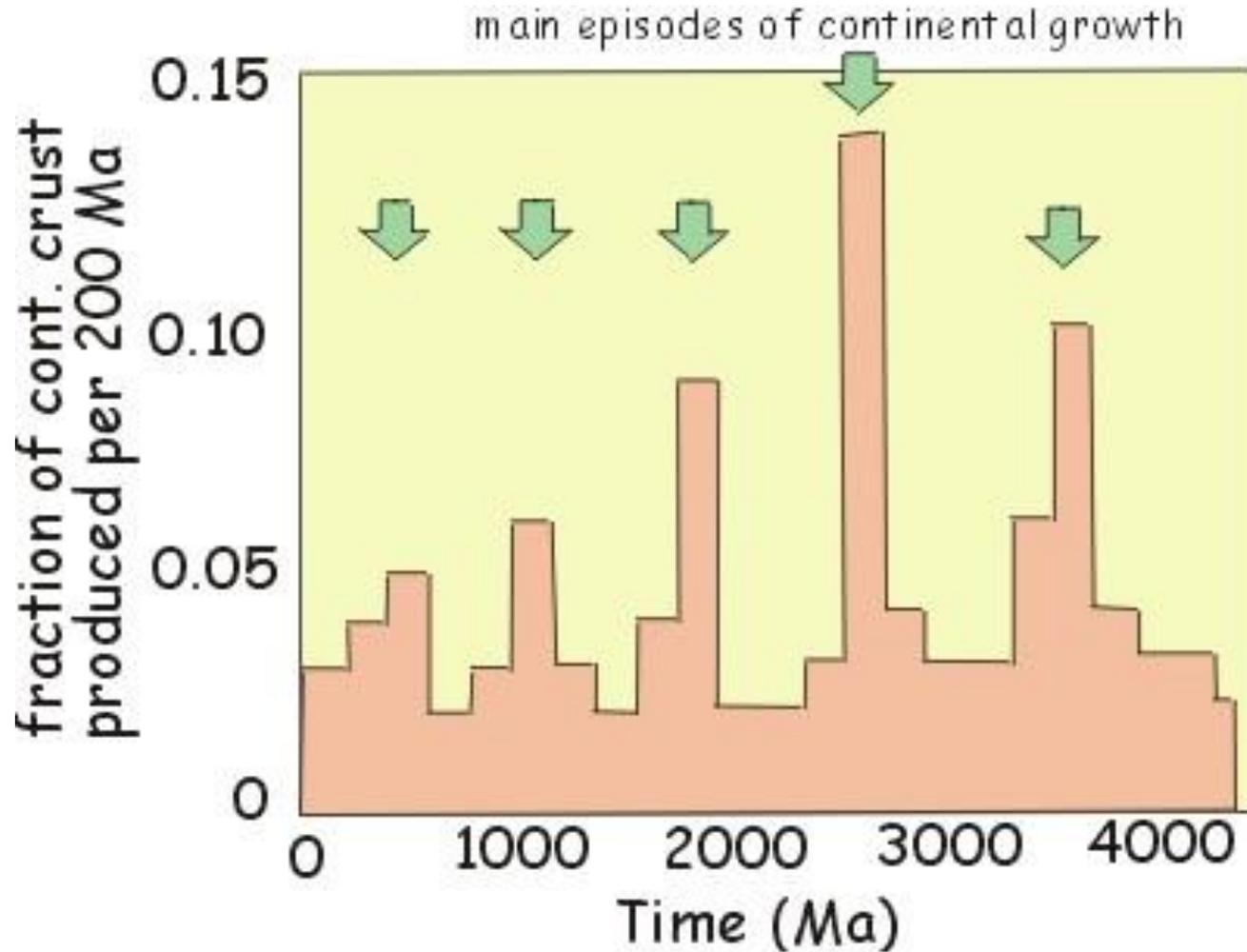
Continental vs. Oceanic Crust

- ▶ It is clear that the oceanic crust and continental crust are very different.
- ▶ Thickness of continental crust is ~ 40 km
- ▶ Thickness of oceanic crust is ~ 5 km
- ▶ The oceanic crust is made up of sediment, basalt and gabbro.
- ▶ Continental crust is more silica rich, thicker and less dense (lower seismic velocities).

Age of Crust



Episodic Growth of Continents



Related to avalanche of subducted slabs that break the 660
When major mass arrives to D'' it causes superplume events.

Geometry of Plate Tectonics

► There are three types of boundaries

1. Convergent boundaries: One plate is overriding another plate. The downgoing plate goes into mantle.

- Here crust is destroyed and recycled back into the interior of the Earth as one plate dives under another. These are known as ***Subduction Zones*** - mountains and volcanoes are often found where plates converge. There are 3 types of convergent boundaries: Oceanic-Continental Convergence; Oceanic-Oceanic Convergence; and Continental-Continental Convergence.

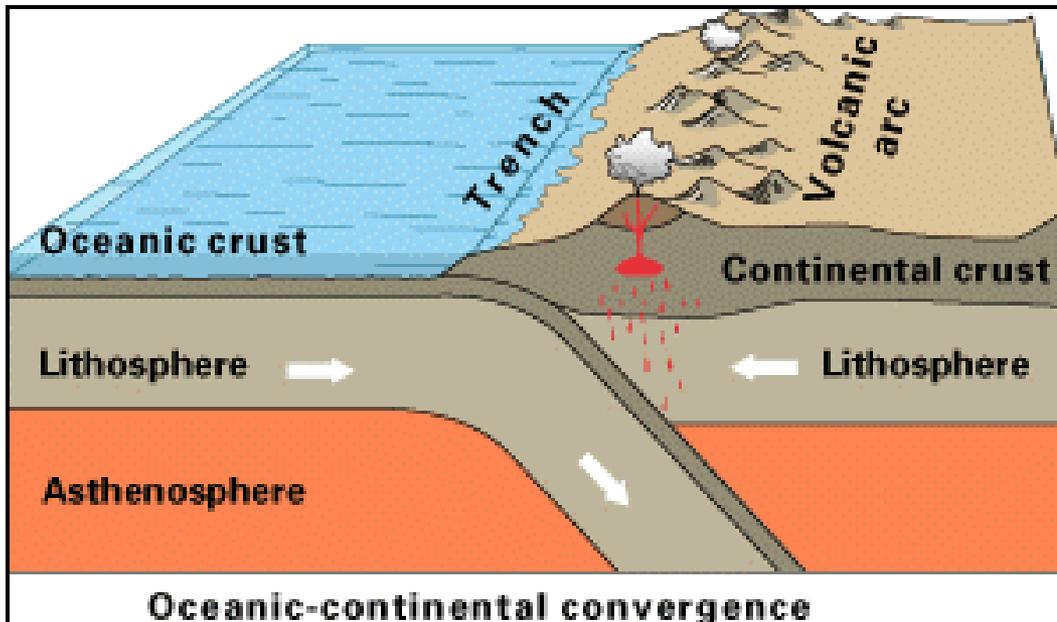
2. Divergent boundaries;

- New material is produce

3. Conservative Boundaries

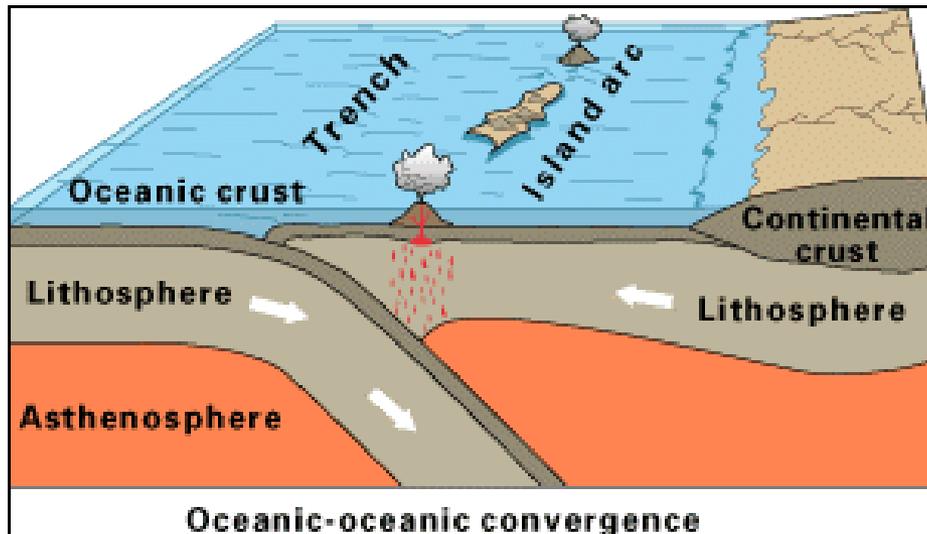
- San Andreas or North Anatolian Fault systems

Oceanic-Continental Convergence



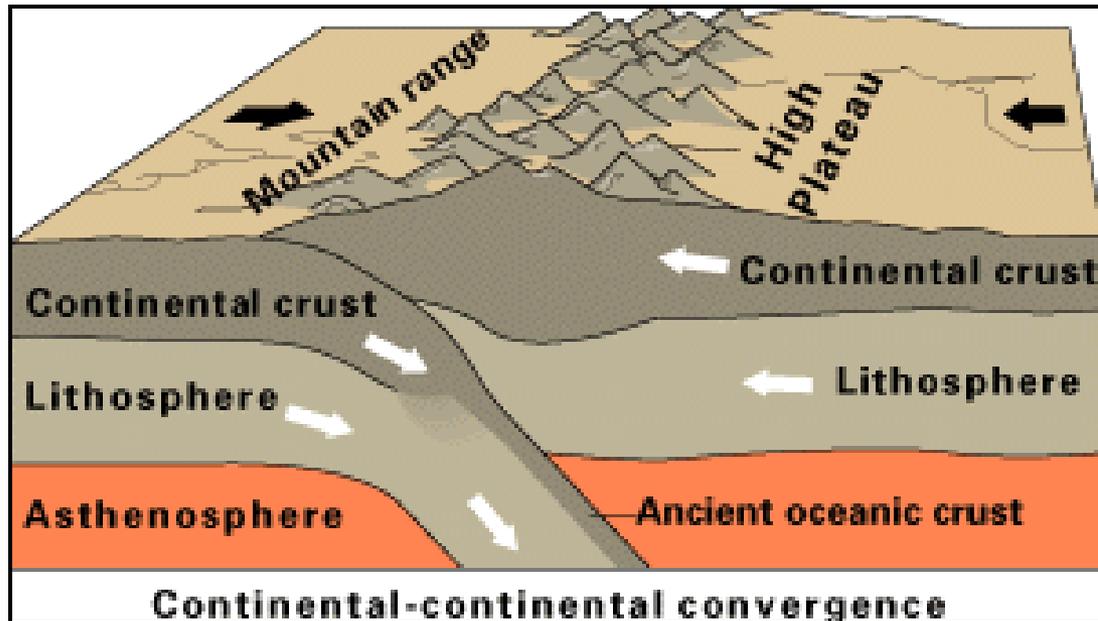
- ▶ Oceanic crust is heavier than the continental crust. So it is always the oceanic crust that subducts under the continental crust.
- ▶ Characterized by deep trenches near the coast
- ▶ Large earthquakes (Sumatra, Chile).

Oceanic-Oceanic Convergence



- ▶ Oceanic crust is being subducted under oceanic crust
- ▶ The subducting oceanic crust is usually quite old
- ▶ Examples are Japan subduction

Continent-Continent Convergence

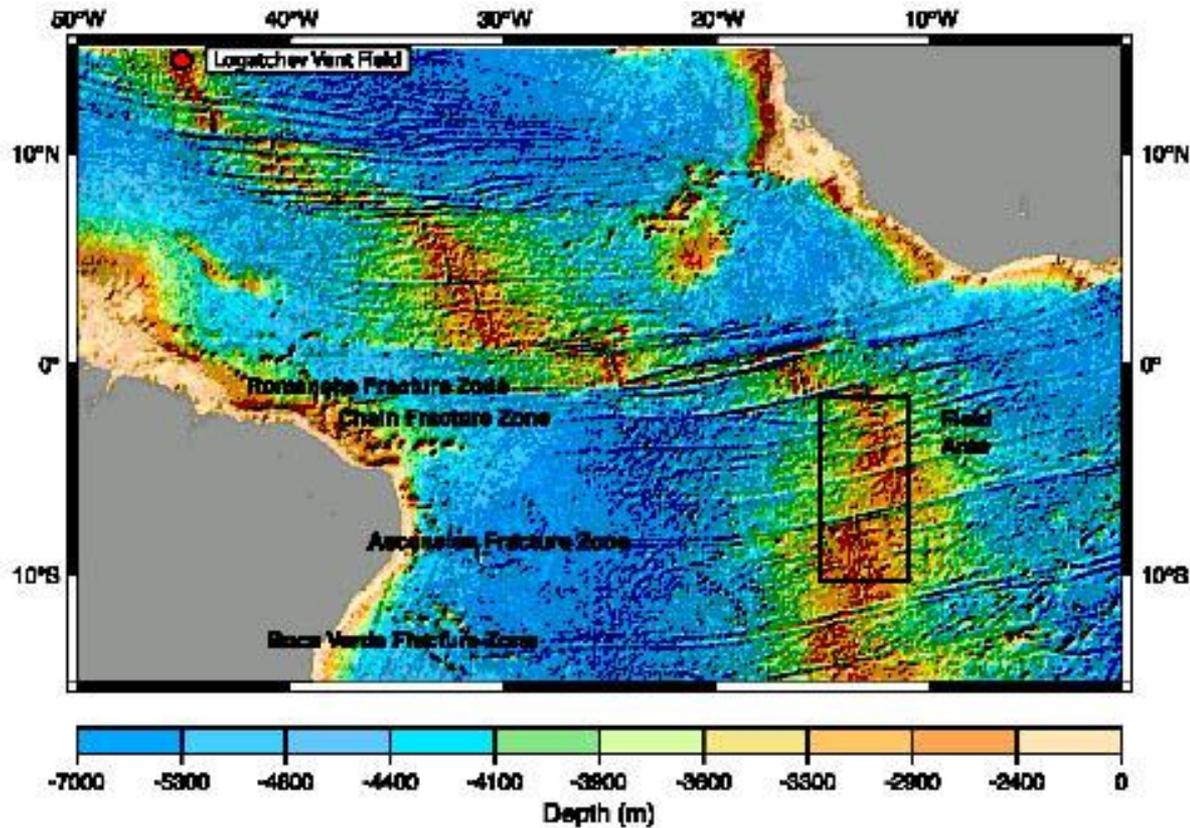


Usually occurs after depletion of the ocean-continent subduction

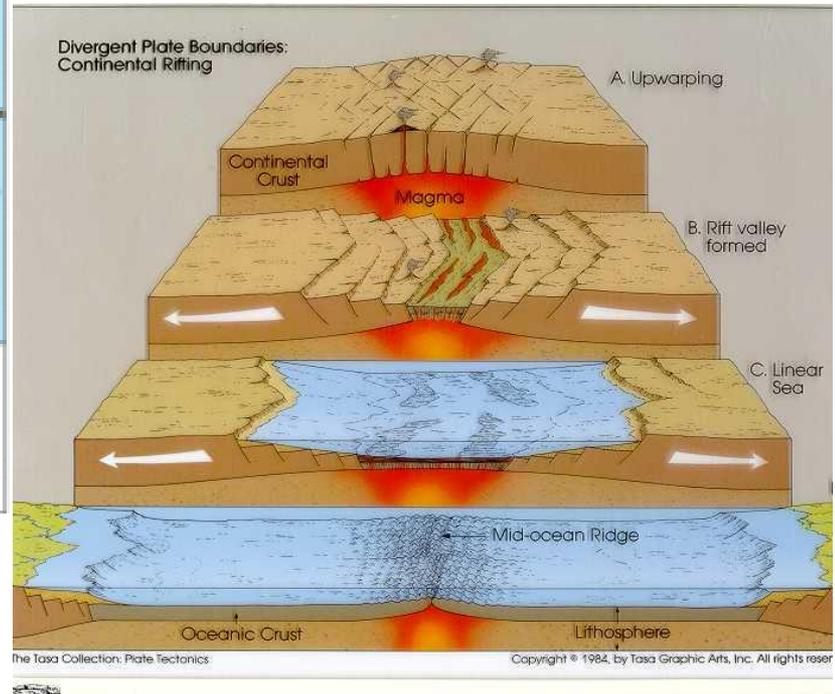
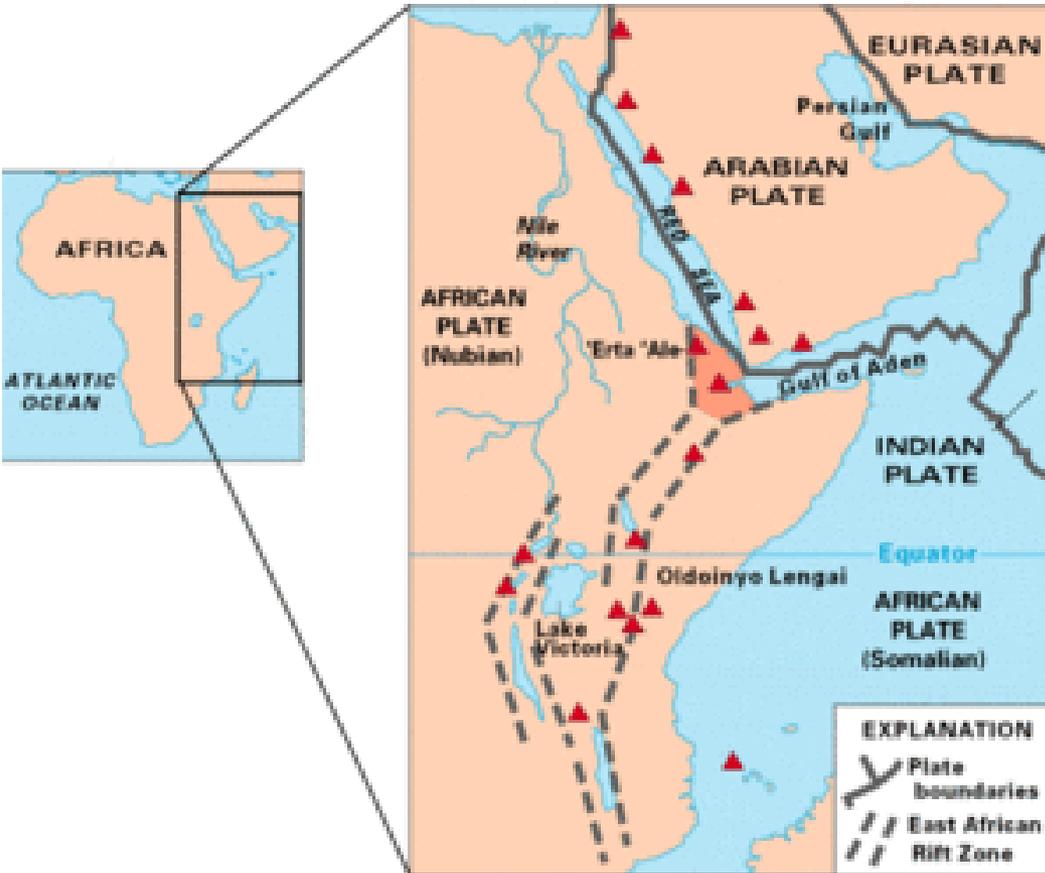
Leads to thickening of crust and large orogenic belts (India-Eurasia collision).

Divergent Boundaries

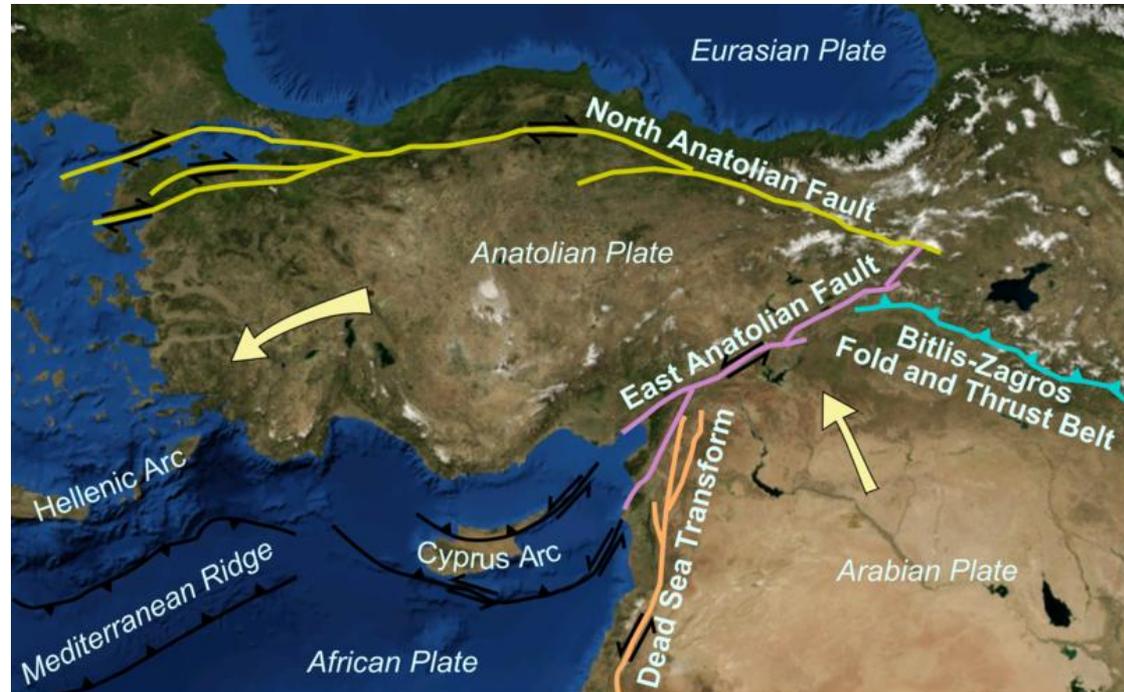
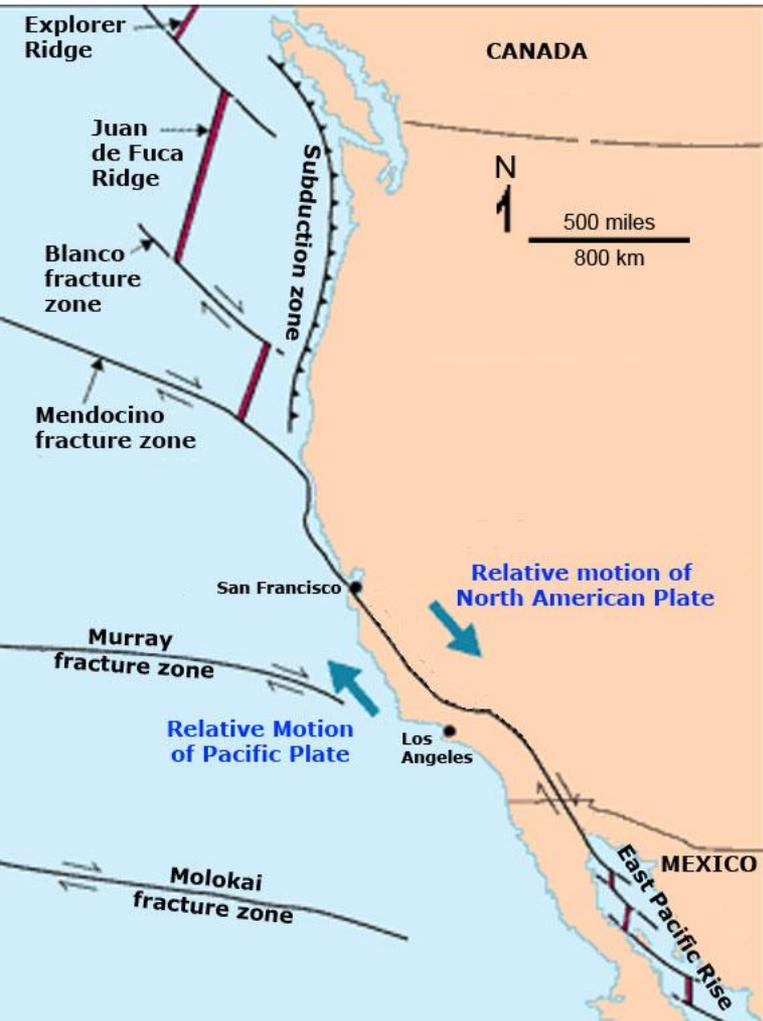
- ▶ Plates are moving apart
- ▶ New crust is created by magmatic intrusion.
- ▶ For oceanic rifts, they are characterized by topographic highs.
- ▶ They are called Mid Ocean Ridges.
- ▶ One example is the Mid-Atlantic Ridge

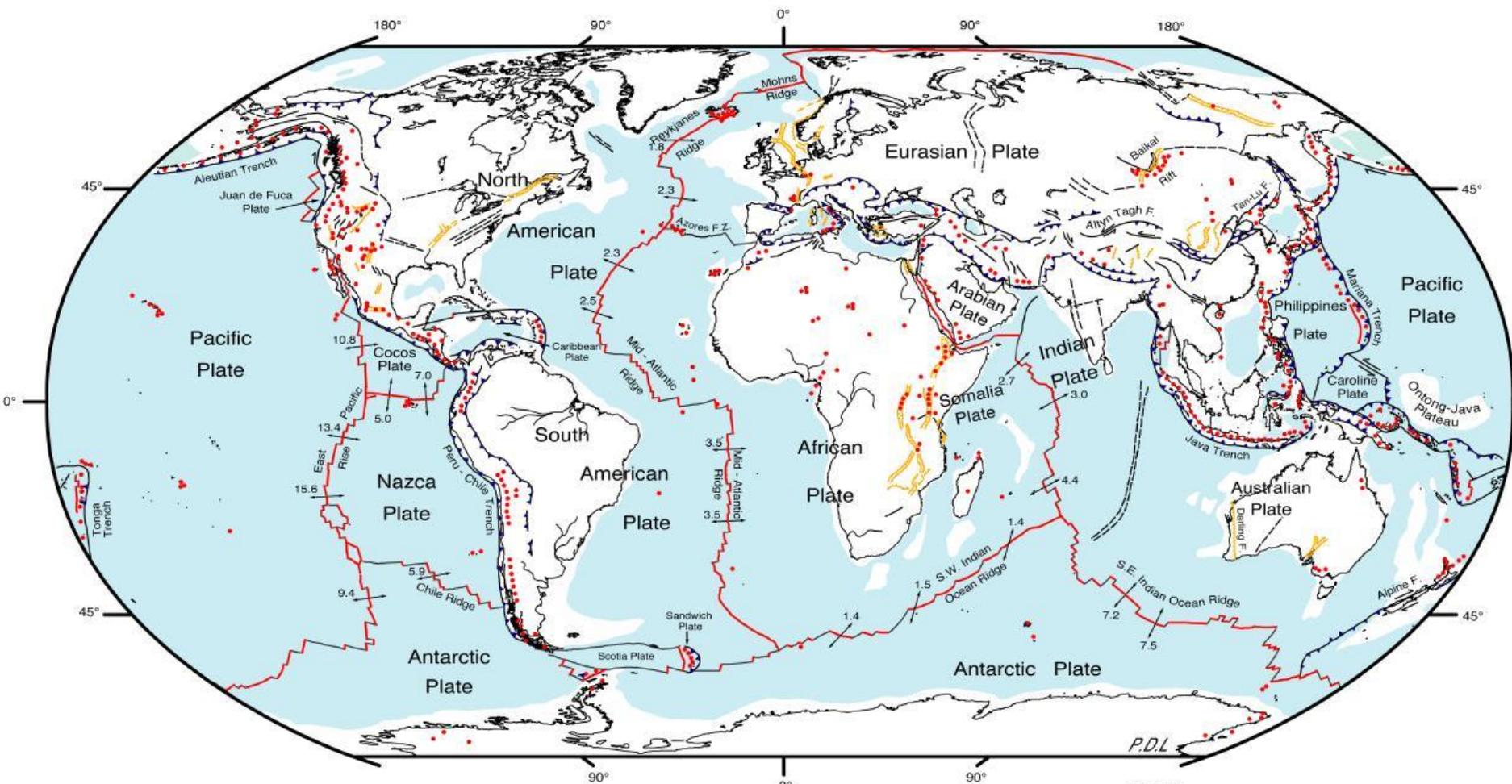


East African Rift



Conservative Boundaries





DIGITAL TECTONIC ACTIVITY MAP OF THE EARTH
Tectonism and Volcanism of the Last One Million Years

DTAM

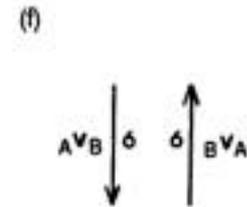
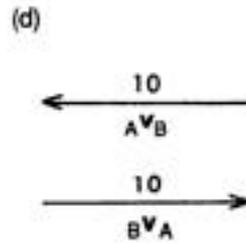
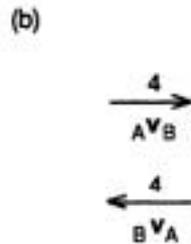
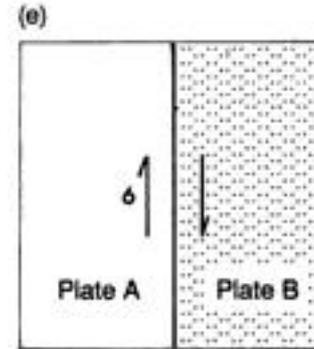
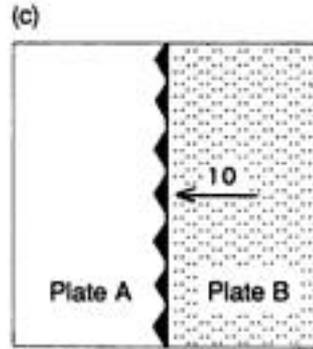
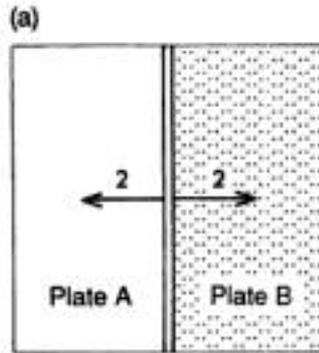


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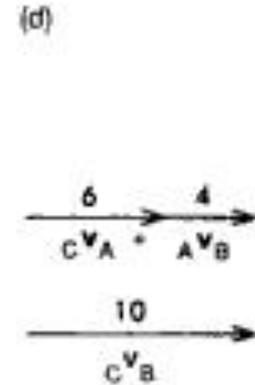
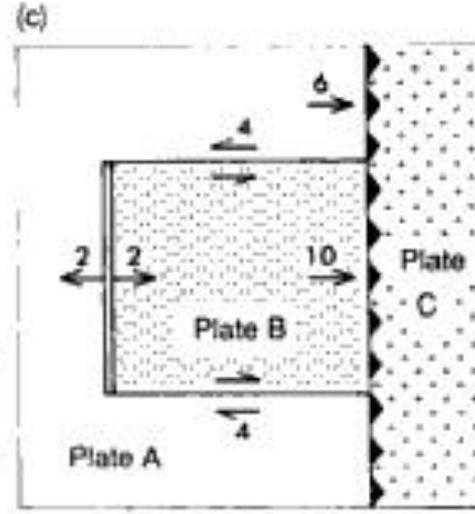
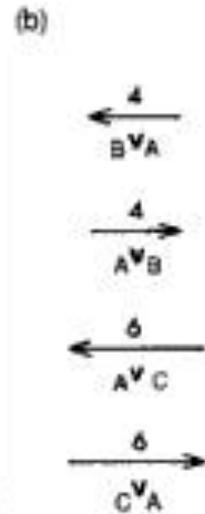
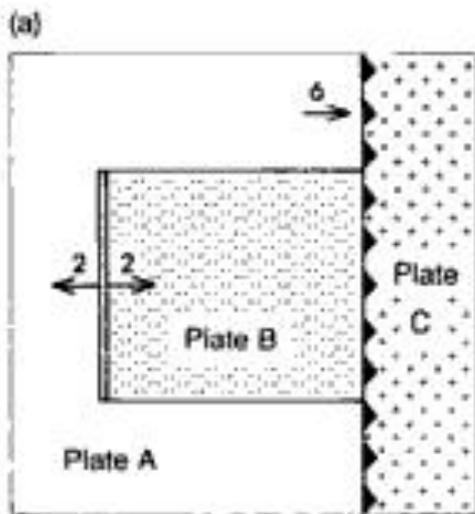
Robinson Projection
 Mainly oceanic crust
 October 1998

- LEGEND**
- Actively-spreading ridges and transform faults
 - Total spreading rate, cm/year, NUVEL-1 model (DeMets et al., Geophys. J. International, 101, 425, 1990)
 - Major active fault or fault zone; dashed where nature, location, or activity uncertain
 - Normal fault or rift; hachures on downthrown side
 - Reverse fault (overthrust, subduction zones); generalized; bars on upthrown side
 - Volcanic centers active within the last one million years; generalized. Minor basaltic centers and seamounts omitted.

Plate Velocities on a Flat Earth



► C:



► $B \nabla A = 4$

$A \nabla B = 4$

$C \nabla A = 6$

$C \nabla B = 6$



Figure 2.5. (a) A two-plate model on a flat planet. Plate B is shaded. The western boundary of plate B is a ridge from which sea floor spreads at a half-rate of 2 cm yr^{-1} . (b) Relative velocity vectors ${}_A\mathbf{v}_B$ and ${}_B\mathbf{v}_A$ for the plates in (a). (c) One solution to the model shown in (a): The northern and southern boundaries of plate B are transform faults, the eastern boundary is a subduction zone with plate B overriding plate A. (d) Alternative solution for the model in (a): The northern and southern boundaries of plate B are transform faults, the eastern boundary is a subduction zone with plate A overriding plate B.

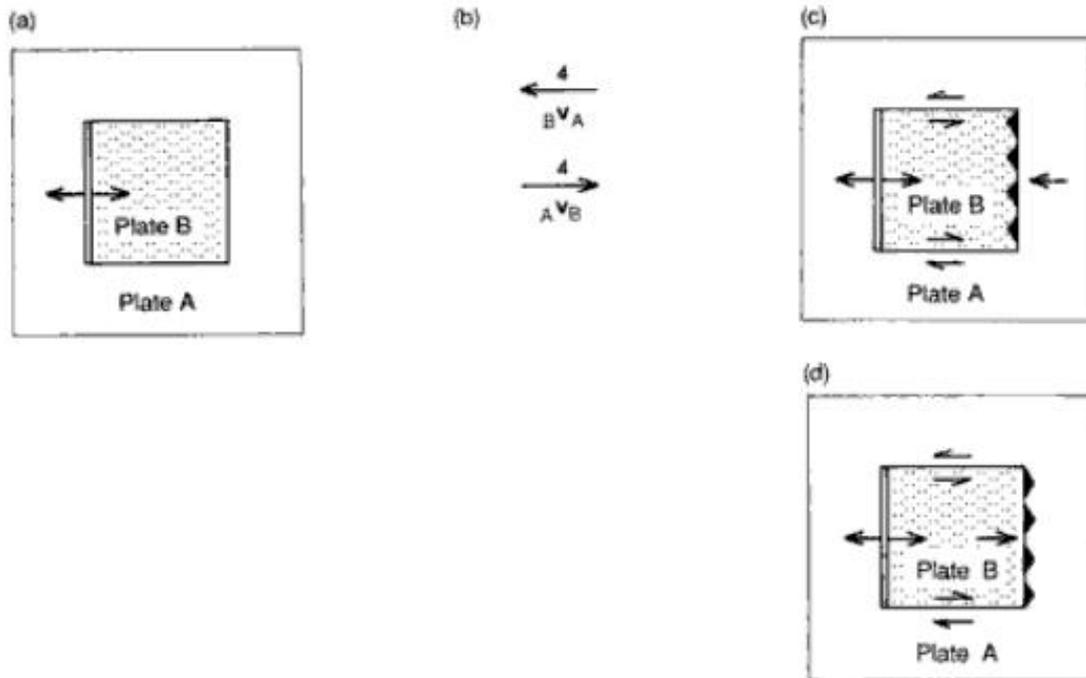
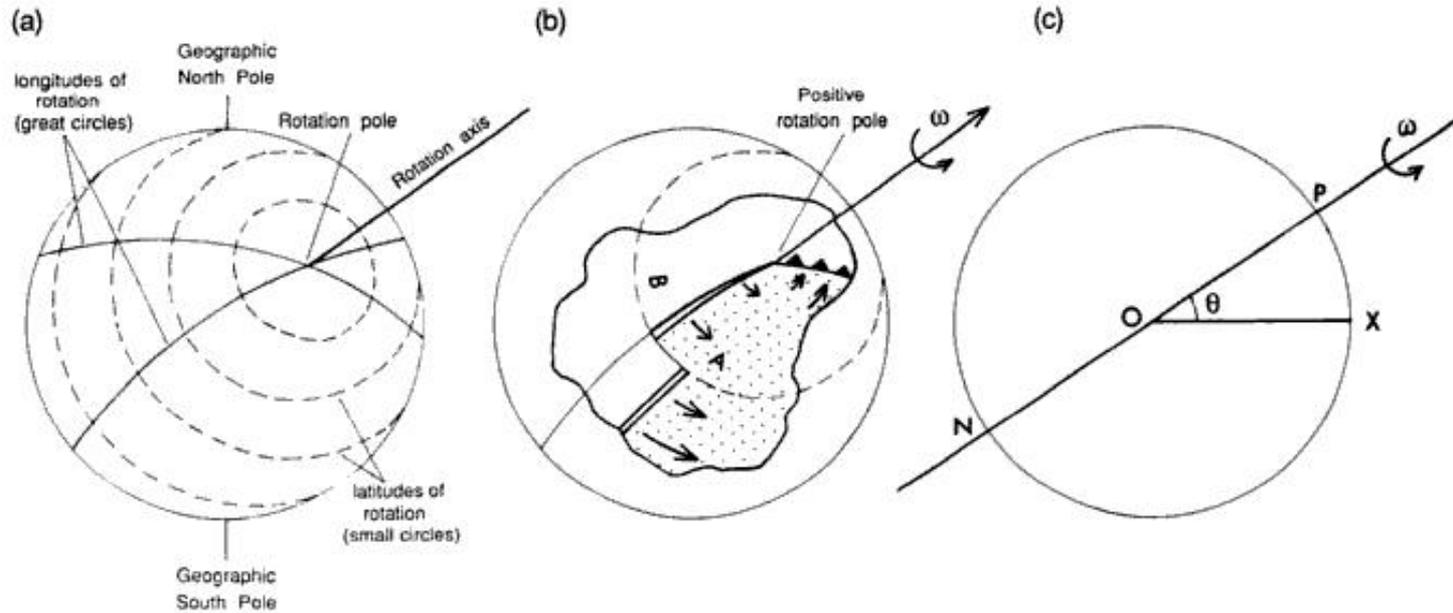


Plate Velocities on a Spherical Earth



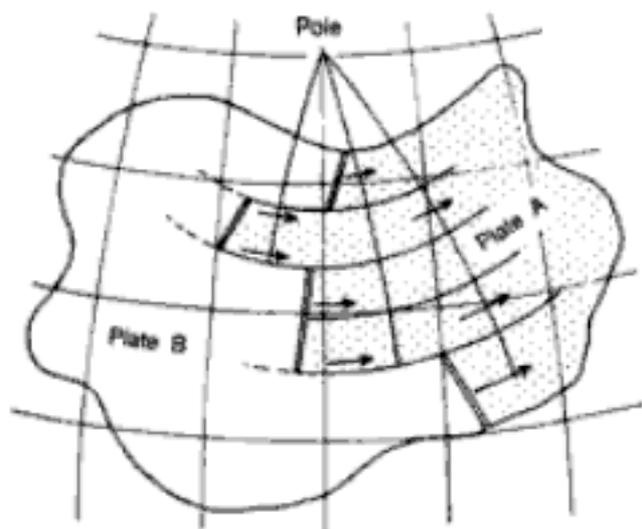


Figure 2.9. On a spherical earth the motion of plate A relative to plate B must be a rotation about some pole. All the transform faults on the boundary between plates A and B must be small circles concentric about the pole. Transform faults can be used to locate the pole: It lies at the intersection of the great circles which are perpendicular to the transform faults. Although ridges are generally perpendicular to the direction of spreading, this is not a geometrical requirement, so it is not possible to determine the relative motion or locate the pole from the ridge itself. (After Morgan 1968.)

Table 2.2. Symbols used in calculations involving rotation poles

Symbol	Meaning	Sign convention
λ_P	Latitude of rotation pole P	$^{\circ}$ N positive $^{\circ}$ S negative $^{\circ}$ W negative $^{\circ}$ E positive
λ_X	Latitude of point X on plate boundary	
ϕ_P	Longitude of rotation pole P	
ϕ_X	Longitude of point X on plate boundary	
v	Velocity at point X on plate boundary	
v	Amplitude of velocity	
β	Azimuth of the velocity with respect to north N	Clockwise positive
R	Radius of the earth	
ω	Angular velocity about rotation pole P	