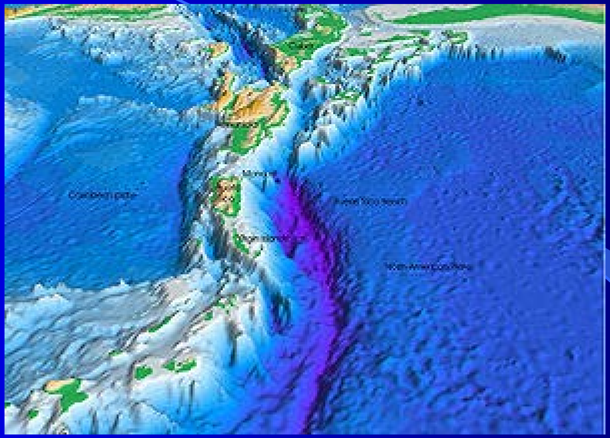
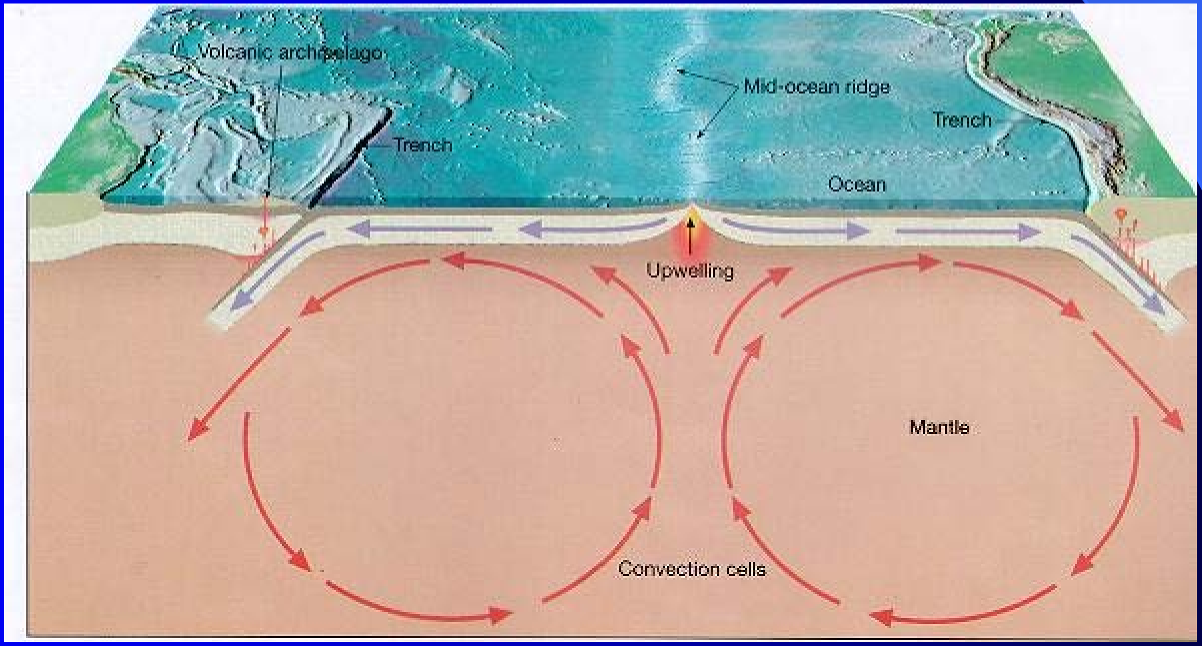
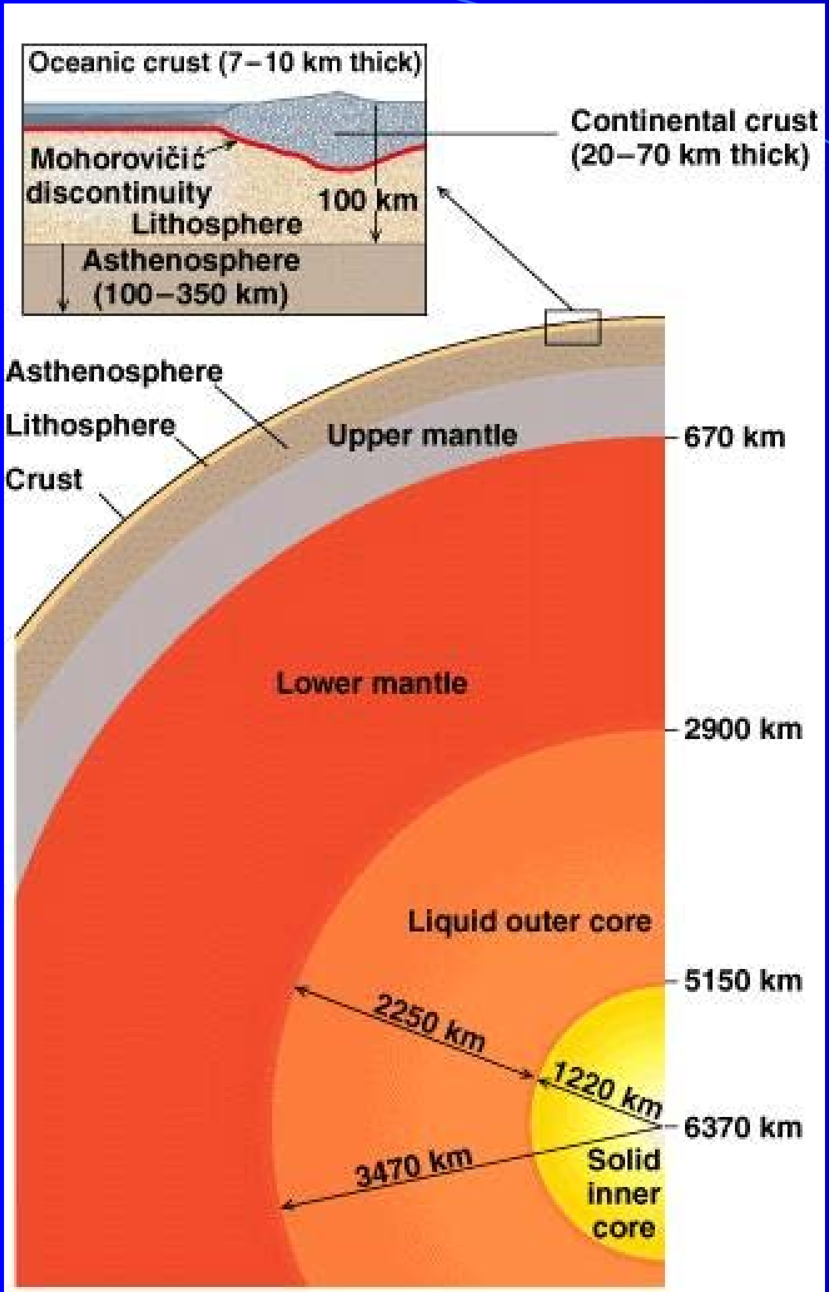
Plate Tectonics – A Geologic Revolution

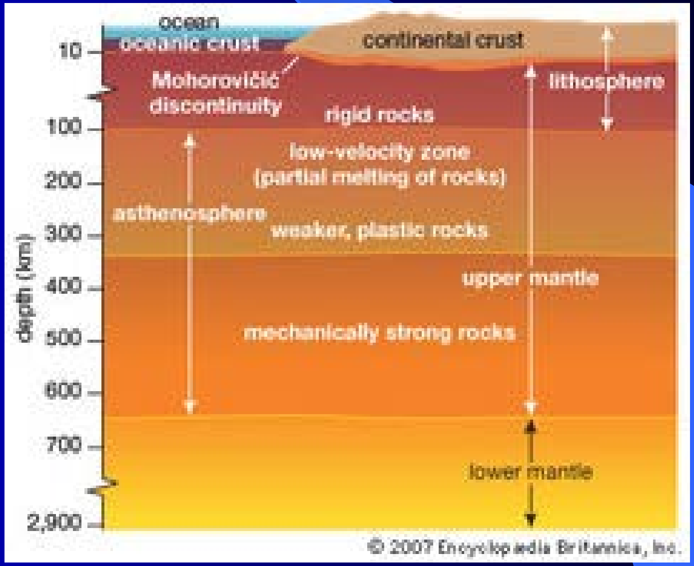






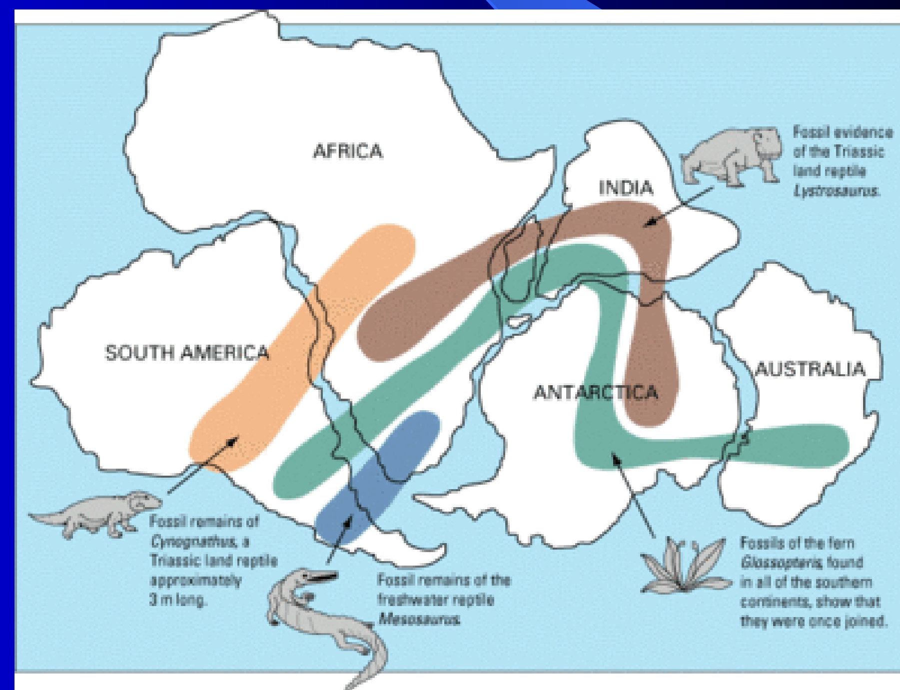
Earth's Structure

- Iron-nickel core
- Silicate Mantle
- Mohorovicic Discontinuity
- Asthenosphere
- Lithosphere

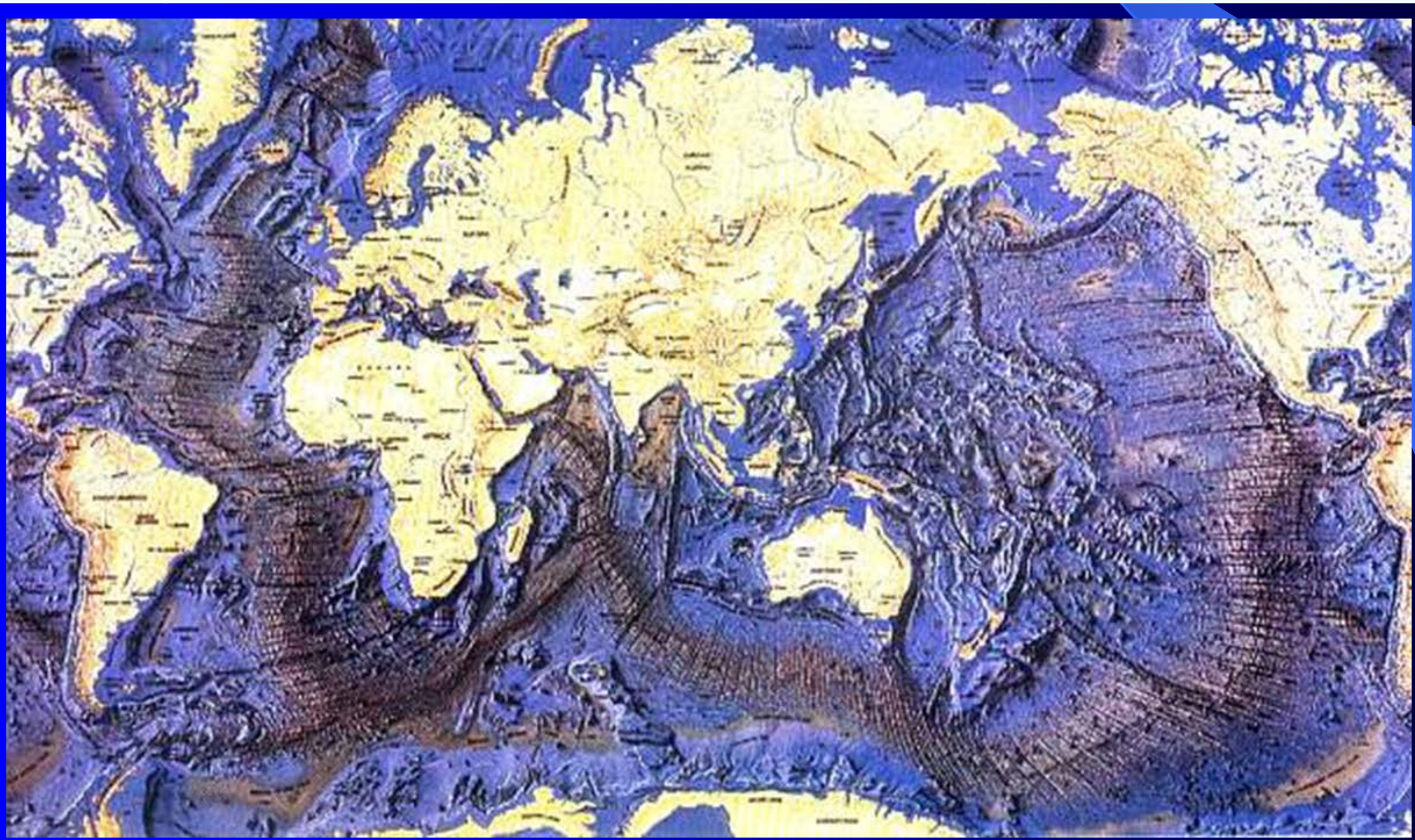


Continental Drift – the Great Debate

Date	Topic or Event	Scientist Involved
1912-1915	Continental Drift proposed	Wegner
1915-1920	Great debate	
1930	Death on Greenland ice sheet	Wegner



Date	Topic or Event	Scientist Involved
1930-1950	Stalemate. A lost cause in the US; debate continued elsewhere	DuToit, Holmes
1950-1960	Revival of interest Exploration of ocean floor Fossil magnetism in rocks and paths of polar wandering	Carey, King, Bullard Ewing, Hezen, Menard Blackett, Runcorn



Precision depth sounding was used to determine the topography of the seafloor. Mid-Atlantic Ridge and trenches.

The Pacific ocean is rimmed with trenches and volcanoes (the “ring-of-fire”) and has volcanic island chains

The Earth’s Magnetic Field

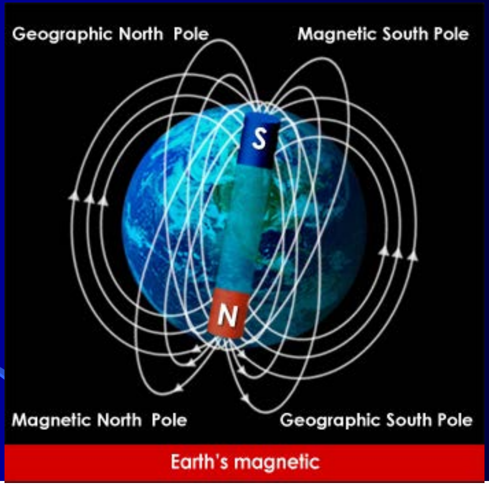
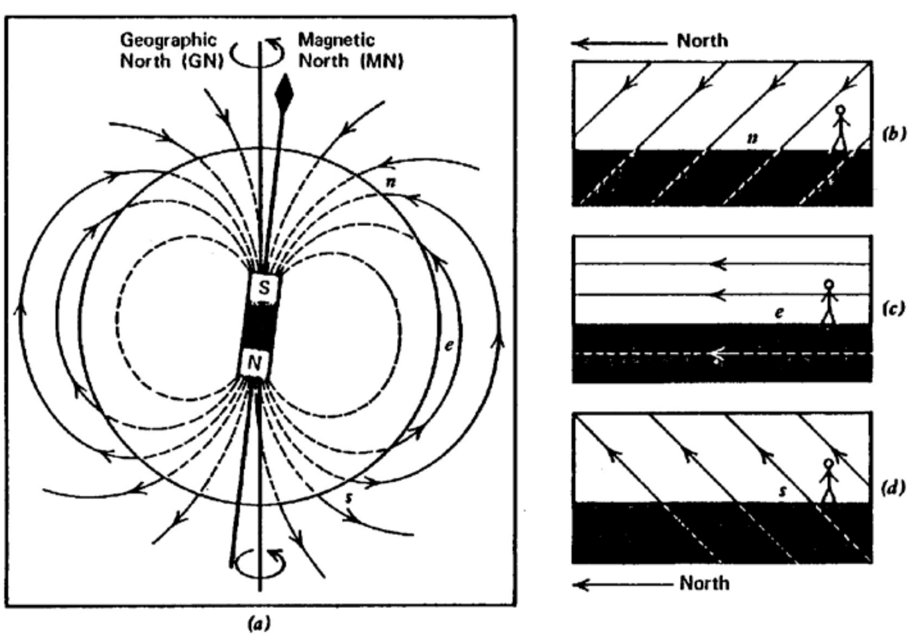


Fig. 8-5 *(a)* Diagrammatic representation of the earth's magnetic field. The directions of the lines of magnetic force at the earth's surface and in space around the earth (measured from satellites) are consistent with the presence of a magnet within the earth in the orientation shown (Figure 8-3). In fact, there is not a magnet within the earth. *(b, c, d)* illustrate in larger scale the lines of magnetic force as they would be measured by a person standing on the earth's surface at points *n*, *e*, and *s*, respectively.



Magnetic Inclination

- Magnetic inclination can be related to magnetic latitude.
- If one can determine the magnetic inclination at some time in the past this information can be used to determine paleolatitude.
- Magnetite becomes magnetic at 580^{o}C (the Curie temperature).

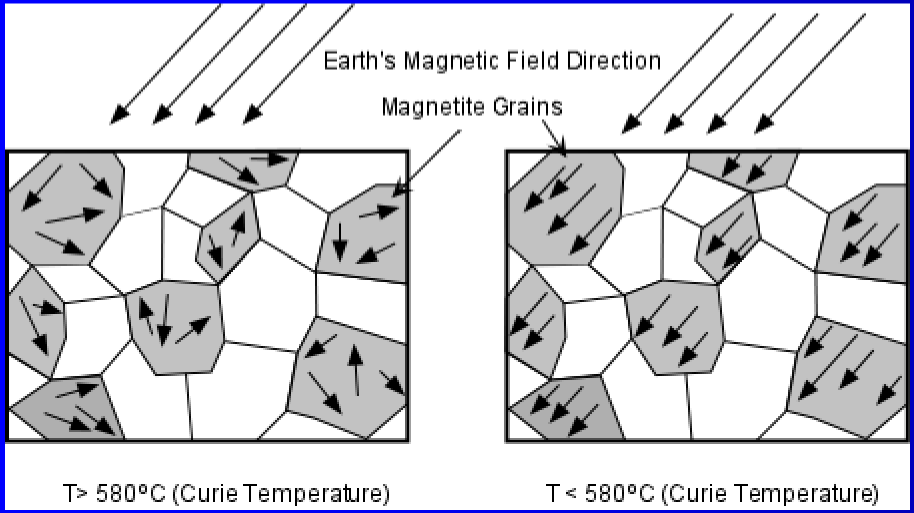
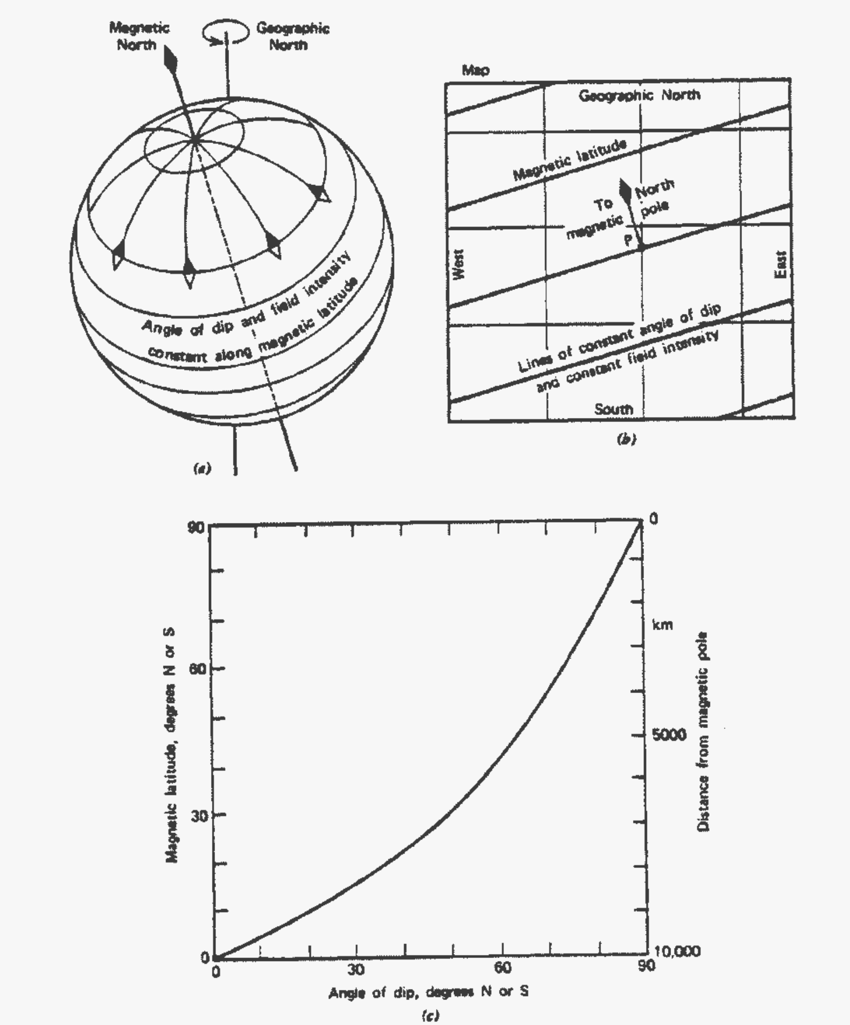
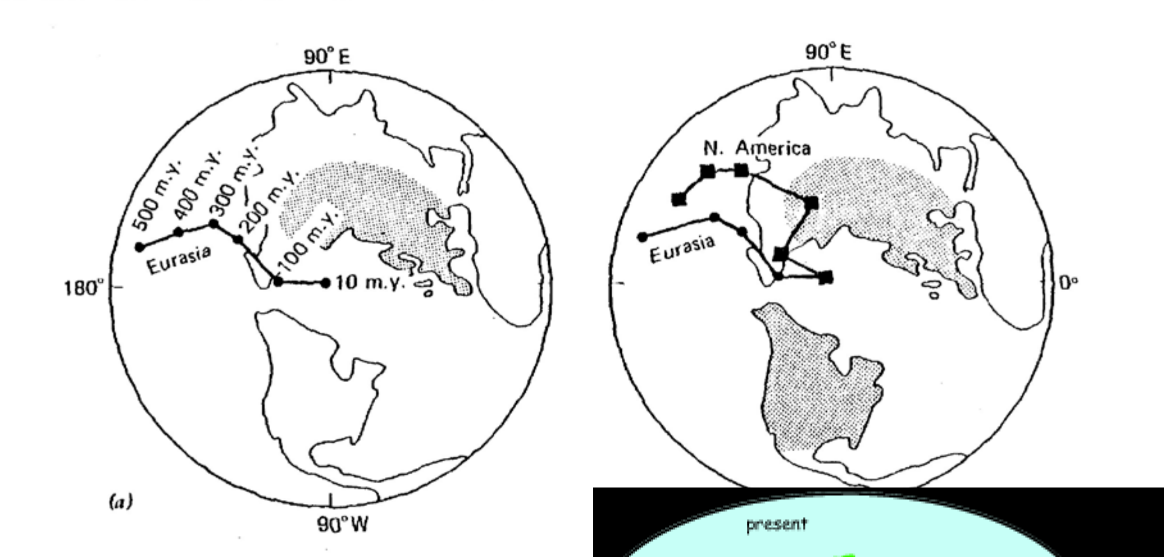


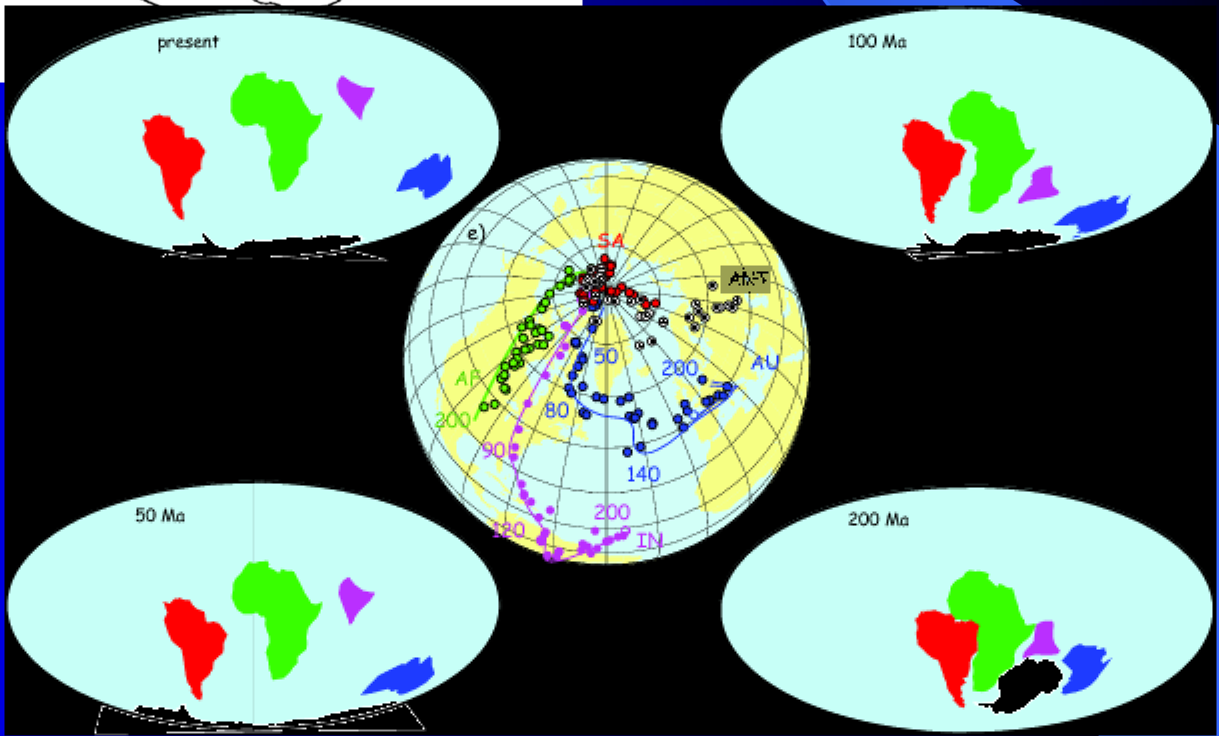
Fig. 8-8 *(a)* Compare Figures 8-5a and 8-6. For an idealized model of the earth's magnetic field, there are lines of magnetic latitude in concentric circles about the magnetic poles. Angles of dip and magnetic field intensities are constant along each of these lines. *(b)* Lines of magnetic latitude compared with geographic latitude and longitude lines on a map. *(c)* The angle of dip is 90° at the magnetic poles, and 0° at the magnetic equator (Figure 8-5). At any magnetic latitude between these limits the angle of dip is given by the graph. For a point with measured angle of dip, the graph gives the magnetic latitude and also the distance to the magnetic pole.



Measuring Paleomagnetism (Remnant Magnetism)

Fig. 12-2 *(a)* Apparent polar wandering path for Eurasia, determined as shown in Figure 12-1, using rocks from Eurasia. *(b)* Comparison of apparent polar wandering paths for North America and Eurasia.





Polar wandering curves. Did the magnetic poles shift or did the continents shift?

Date	Topic or Event	Scientist Involved
1960-1962	Sea-floor spreading - geopoetry	Dietz, Hess
1963	Oceanic magnetic anomalies associated with sea-floor spreading; the magnetic tape recorder	Matthews, Morley, Vine
1963-1966	Polarity reversals of earth's magnetic field; fossil magnetism and accurate rocks dating for lavas on land and for deep-sea sediment cores	Cox, Dalrymple, Doell, Foster, McDougall, Opdyke
1965-1966	Transform faults and earthquake studies	Sykes, Wilson
1966-1967	Revolution procalaimed after it all came together at the Goddard Symposium	
1967-1968	Plate tectonics incorporated spreading and drift Earthquake synthesis Polarity reversal time-scale extrapolated, giving sea-floor isochrons	LePichon, McKenzie, Morgan, Parker, Isacks, Oliver, Sykes, Heirtzler, Pitman
1968-1970	Deep-sea drilling by *Glomar Challenger*	Maxwell and others
1970	Revolution over (it only took a decade)	

Now for some really bizarre stuff. Measurements of the magnetic polarity of magnetite as a function of age revealed that the Earth's magnetic polarity was reversed at different times in the past.

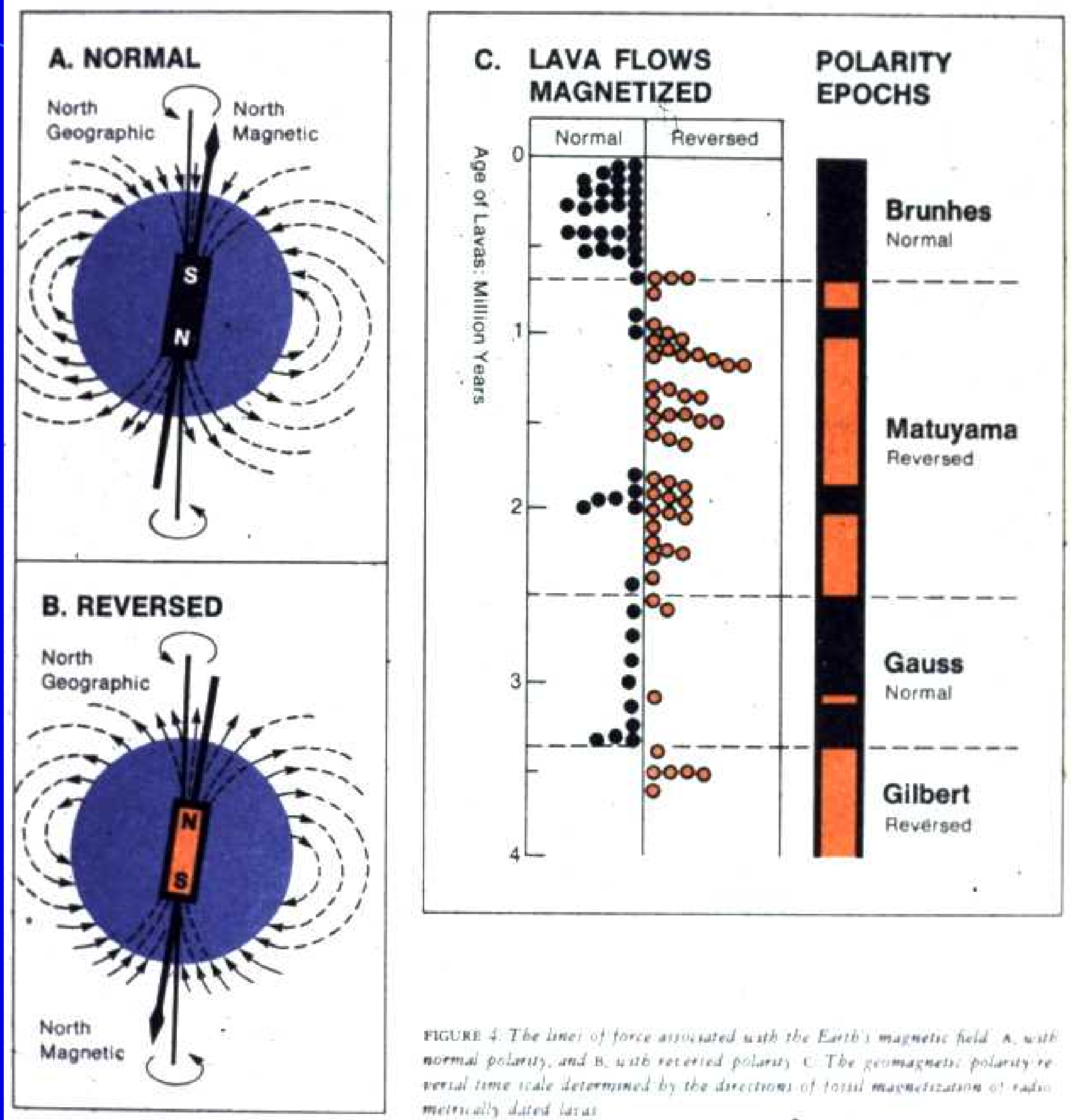


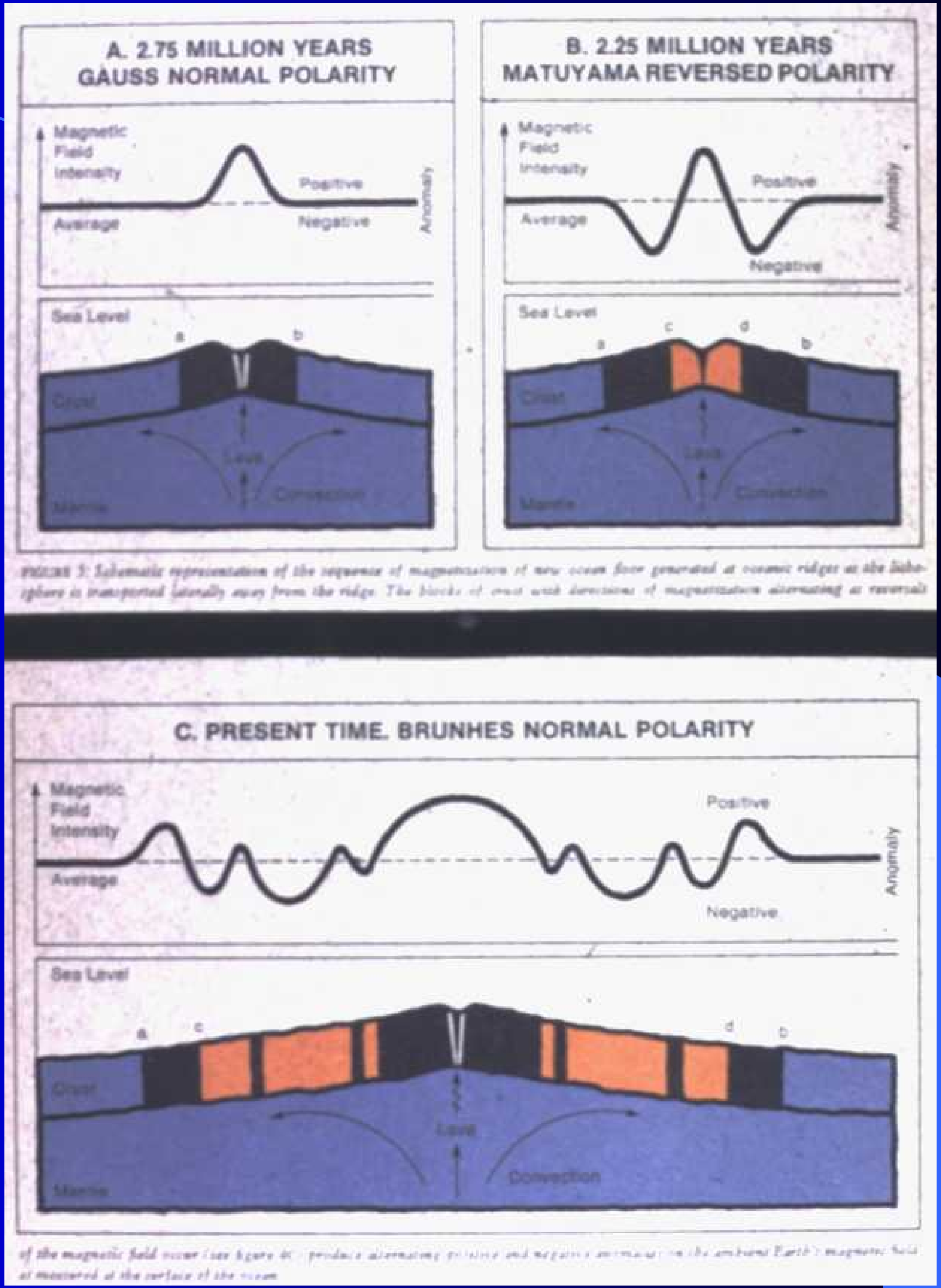
FIGURE 4. *The lines of force associated with the Earth's magnetic field: A, with normal polarity, and B, with reversed polarity. C, The geomagnetic polarity reversal time scale determined by the directions of total magnetization of radiometrically dated lavas.*

Oceanic Magnetic Anomalies (1963)

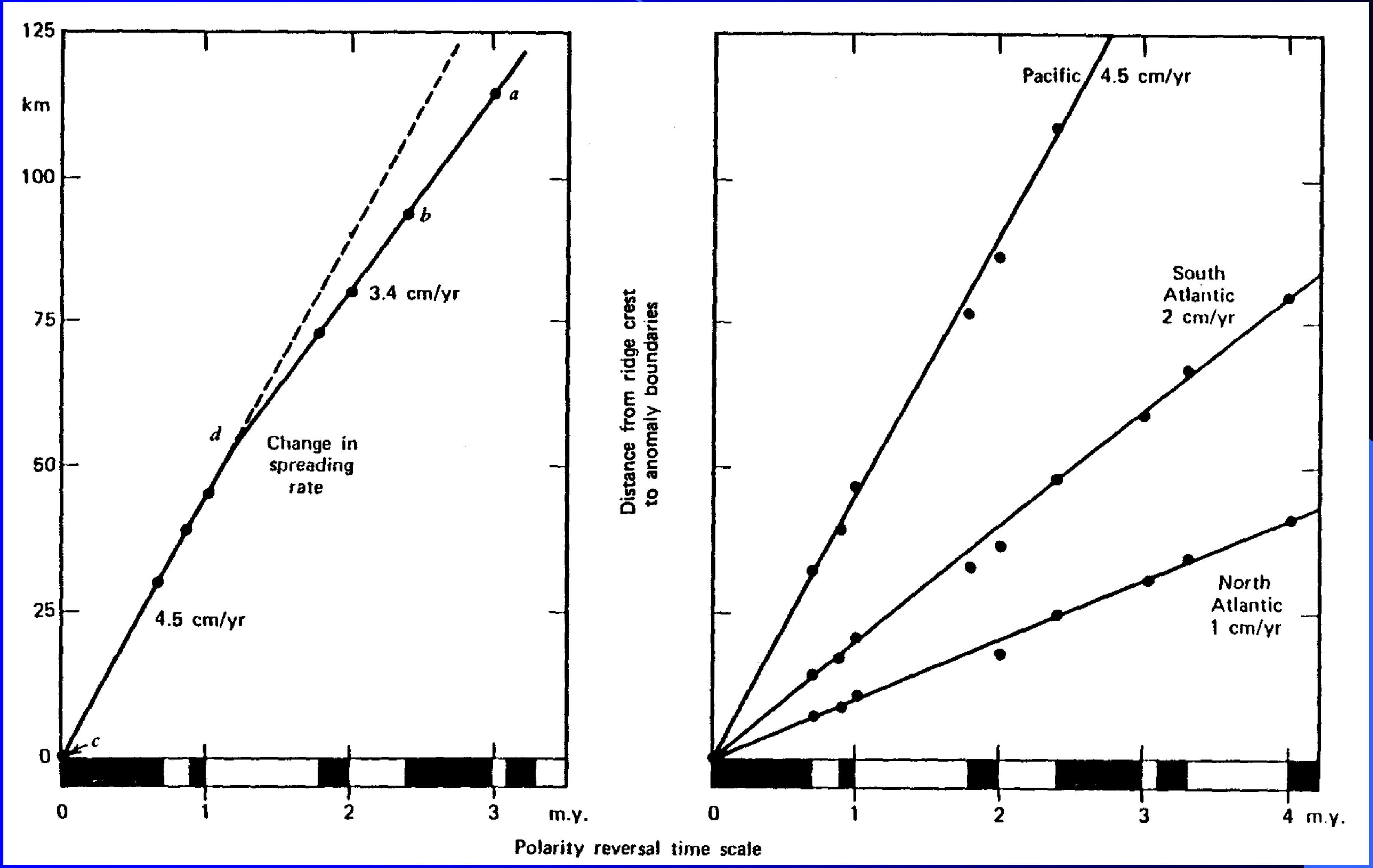
Measurements of magnetism in the ocean basin revealed that magnetic intensity varied as one moved across the ocean basin. This variation was more or less symmetrically distributed around mid-ocean ridge systems. How might this happen?

Figure 7.8 Evidence of sea-floor spreading. The Reykjanes Ridge south of Iceland is an active center of sea-floor spreading, where reversals in the polarity of the geomagnetic field have been recorded in new sea floor as it was emplaced and spread away from fissures at the crest of the ridge. Each colored stripe maps a band of rock laid down when the earth's magnetic field was pointing in its present direction, and the white stripes outline sea floor formed while the magnetic field was reversed. Note that these patterns are not perfect stripes any more than they are perfectly symmetrical about the ridge crest. The asymmetries suggest the complicated nature of sea-floor spreading and the incompleteness of our understanding of it.

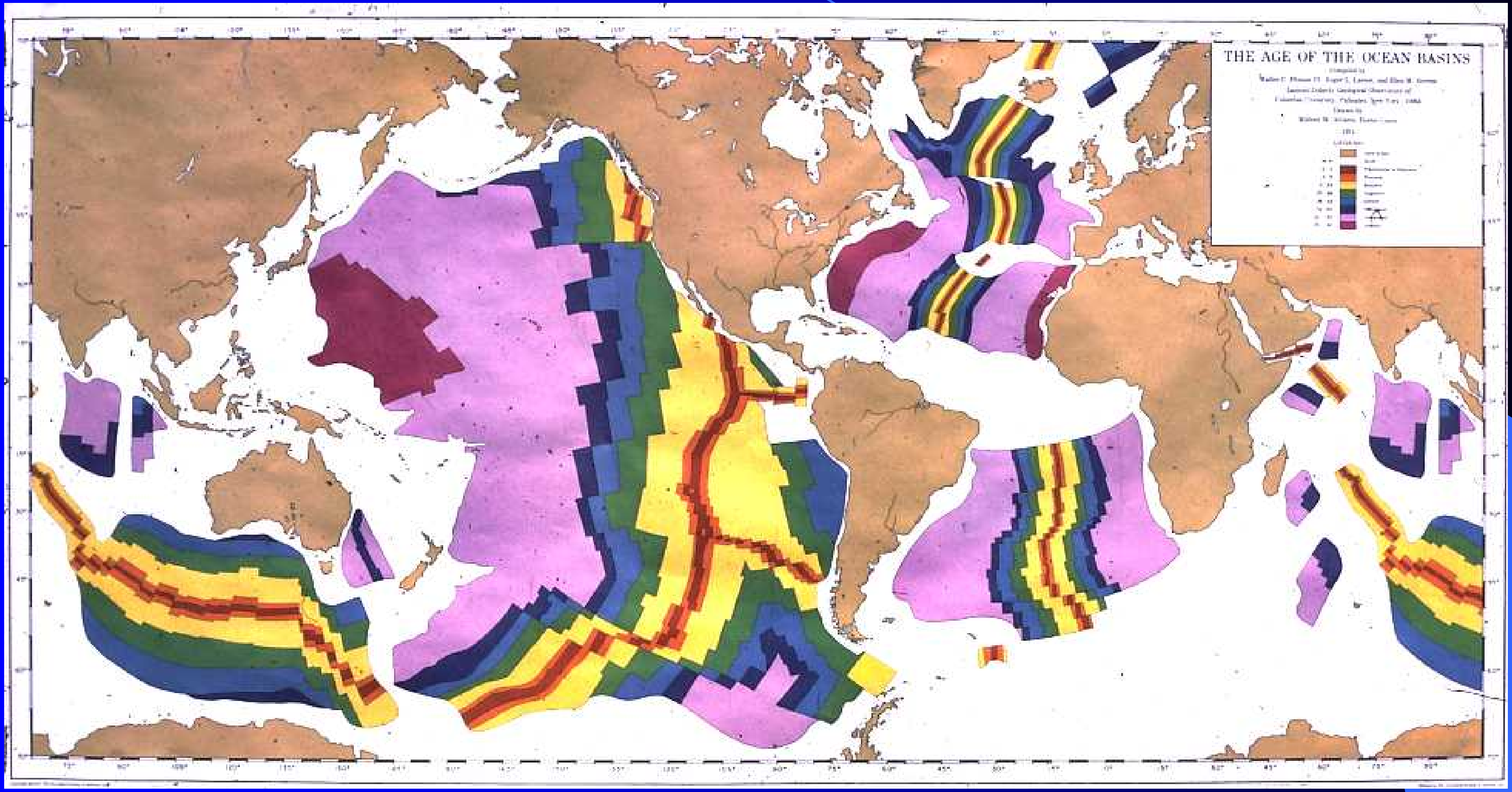
One possible interpretation is that material was added to the seafloor at the mid-ocean ridge system (basaltic magmatism) at different times in the past and then moved away from the mid-ocean ridge. This was referred to as *seafloor spreading* and the idea was very controversial.



Based on the relationship between geologic age and magnetic reversal, spreading rates were calculated for the various ocean basins.

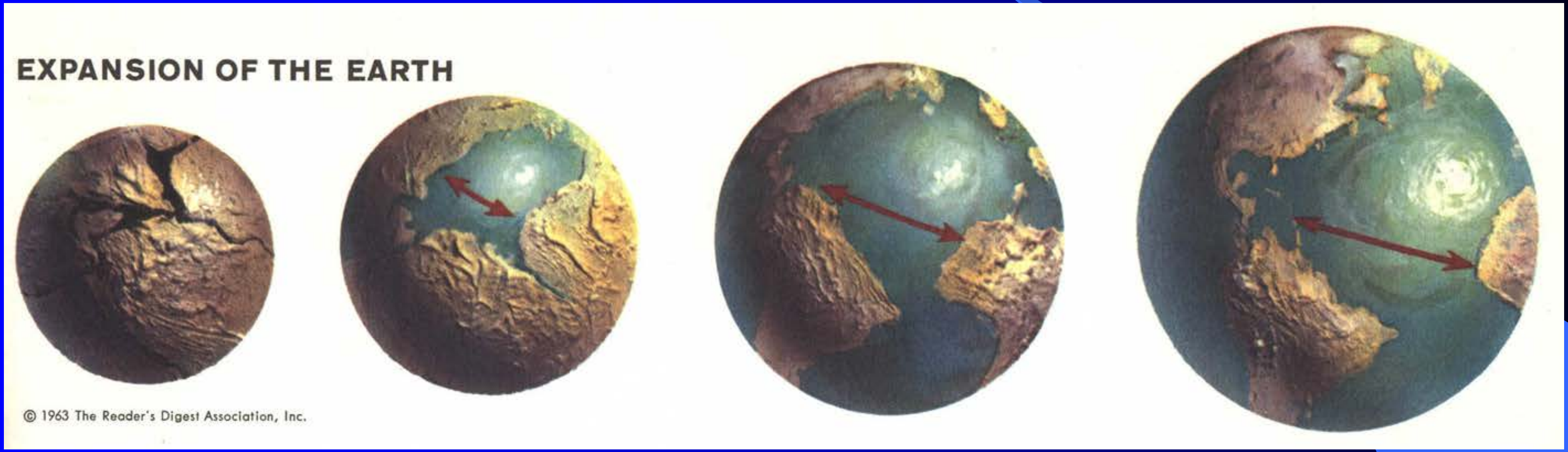


Using the calculated spreading rate for each ocean basin, the age of the various magnetic reversals was determined. The result was a map showing the age of the seafloor. It turned out the oldest rocks in the ocean were about 200 Ma old, much younger than the oceans.



We now have all kinds of problems:

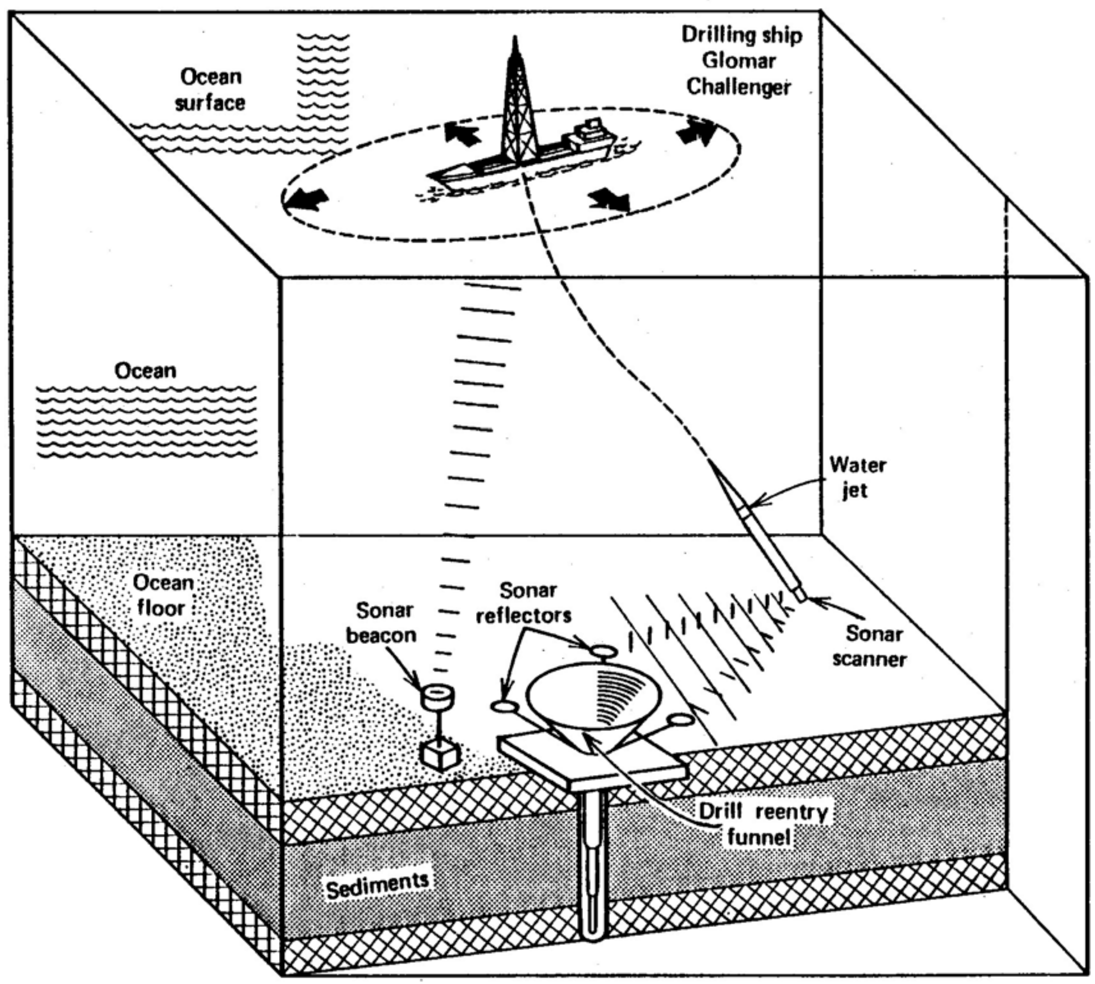
- The ocean basins are younger than the ocean
- The oceans basins are getting bigger with time. What's happening to the size of the Earth?



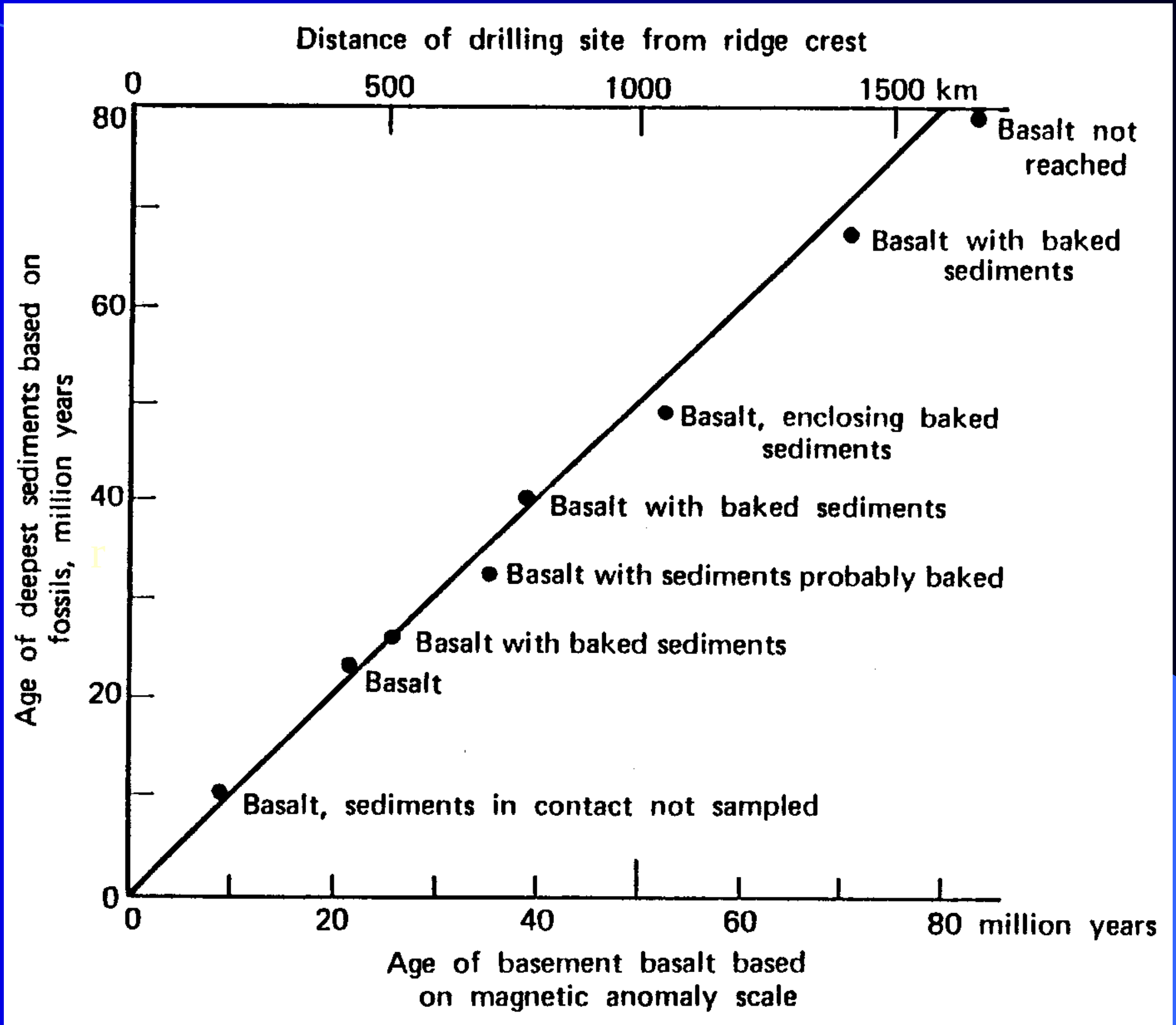
Before we go any further, is there any way to independently verify the age of the ocean basins?

Enter the Deep Sea Drilling Project. Sediment cores were collected from the deep ocean. The cores reached the seafloor basalts, hence we could determine the age of the sediments lying directly on the basalts.

Fig. 14-1 Sketch of the *Glomar Challenger* lowering its drill stem through the ocean toward the drill reentry funnel that has been secured in the ocean-floor sediments. (Based on a National Science Foundation report.)

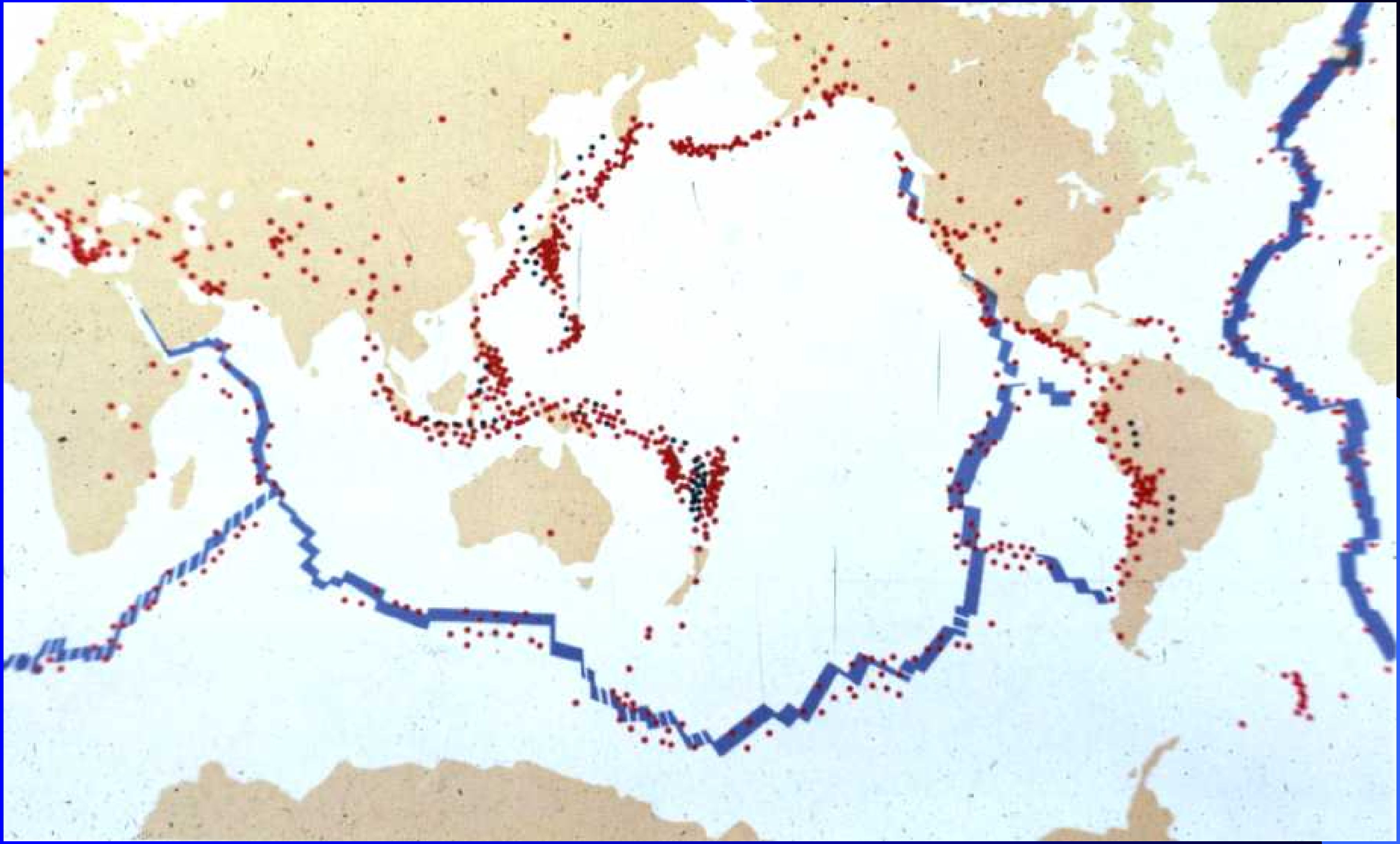


Fossils in the sediments just above the seafloor basalts verified the ages determined using the magnetic anomaly scale.



Earthquake Studies (1965-1966)

Earthquakes are not randomly distributed



Earthquakes associated with oceanic trenches extended to great depths. This was a puzzle because for earthquakes to occur rocks must behave as elastic solids. At depths below 70 km rocks ***do not*** behave as elastic solids.

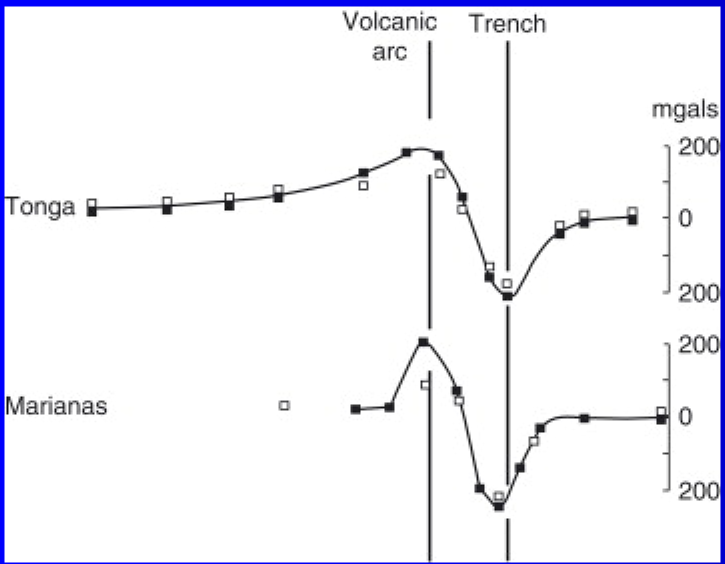


Fig. 4-9 Schematic map of distribution of earthquake epicenters for deep-focus earthquakes between the Tonga trench and the Fiji Islands, north of New Zealand. Locate this on Figures 3-12 and 4-7. (Based on data of L. R. Sykes, 1966, *Jour. Geophys. Res.*, *71*, 2981-3006.)

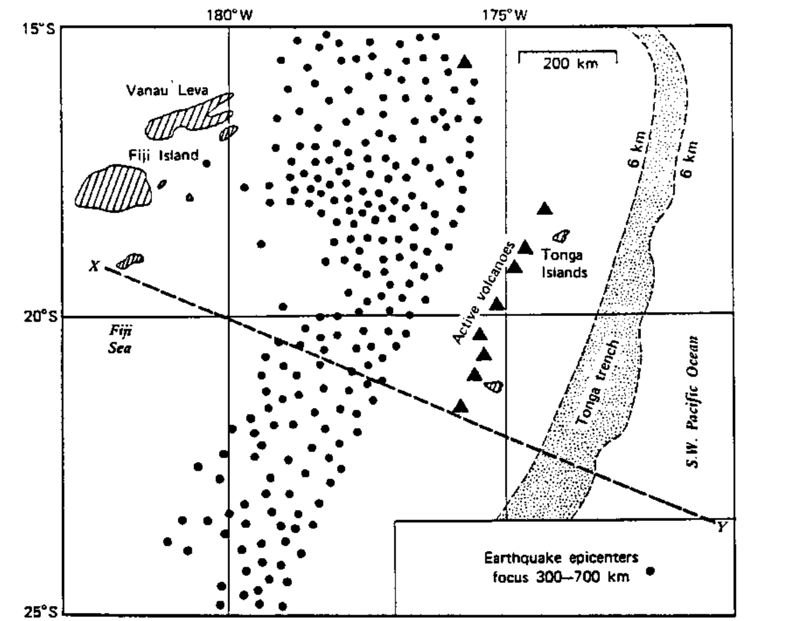
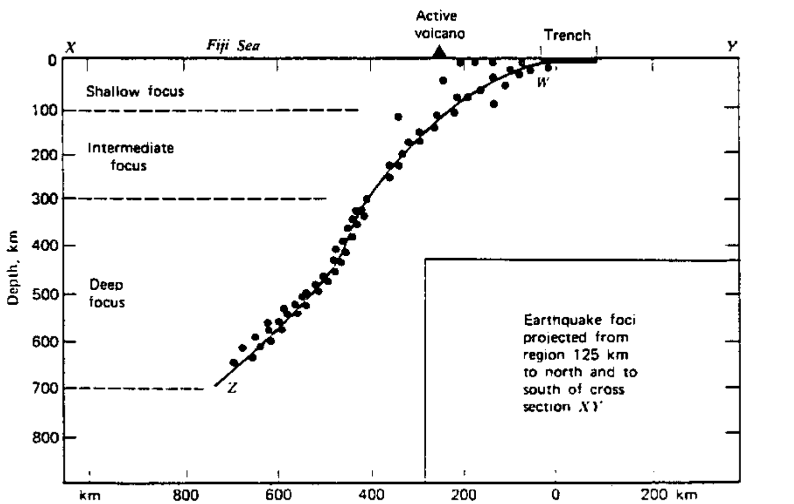


Fig. 4-10 Vertical cross section through line *XY* in Figure 4-9, showing schematically the distribution of earthquake foci down to depths of 700 km. The foci lie close to line *WZ* extending downward from the ocean trench. (Based on data of L. R. Sykes, 1966, see Figure 4-9.)

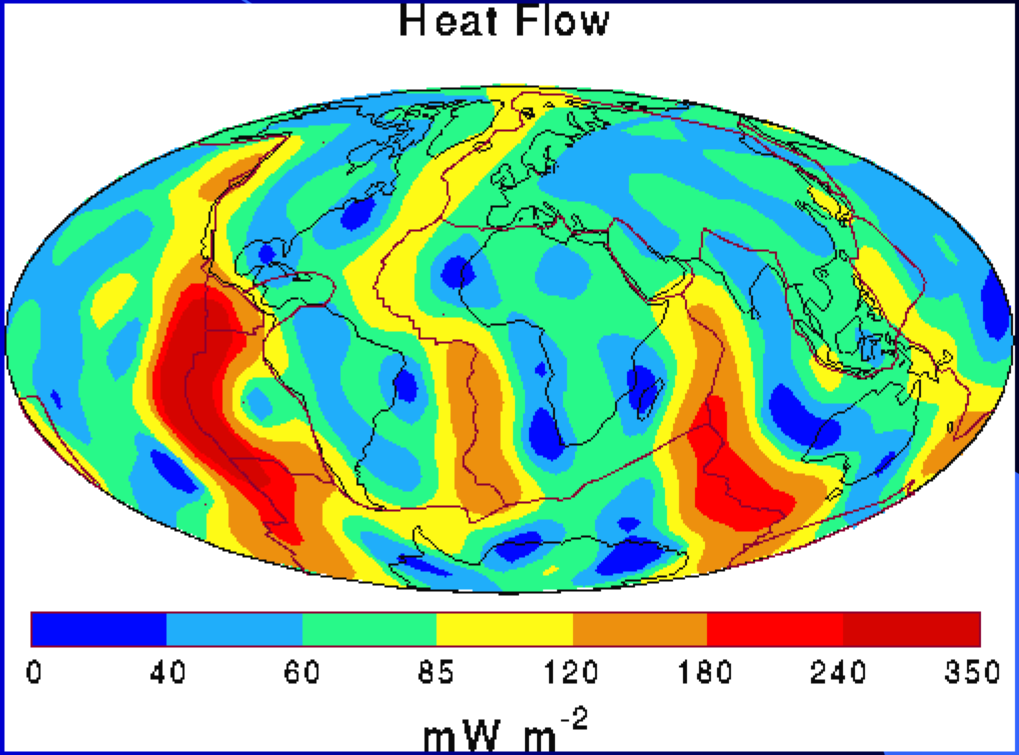


Heat Flow varies across the Earth's surface

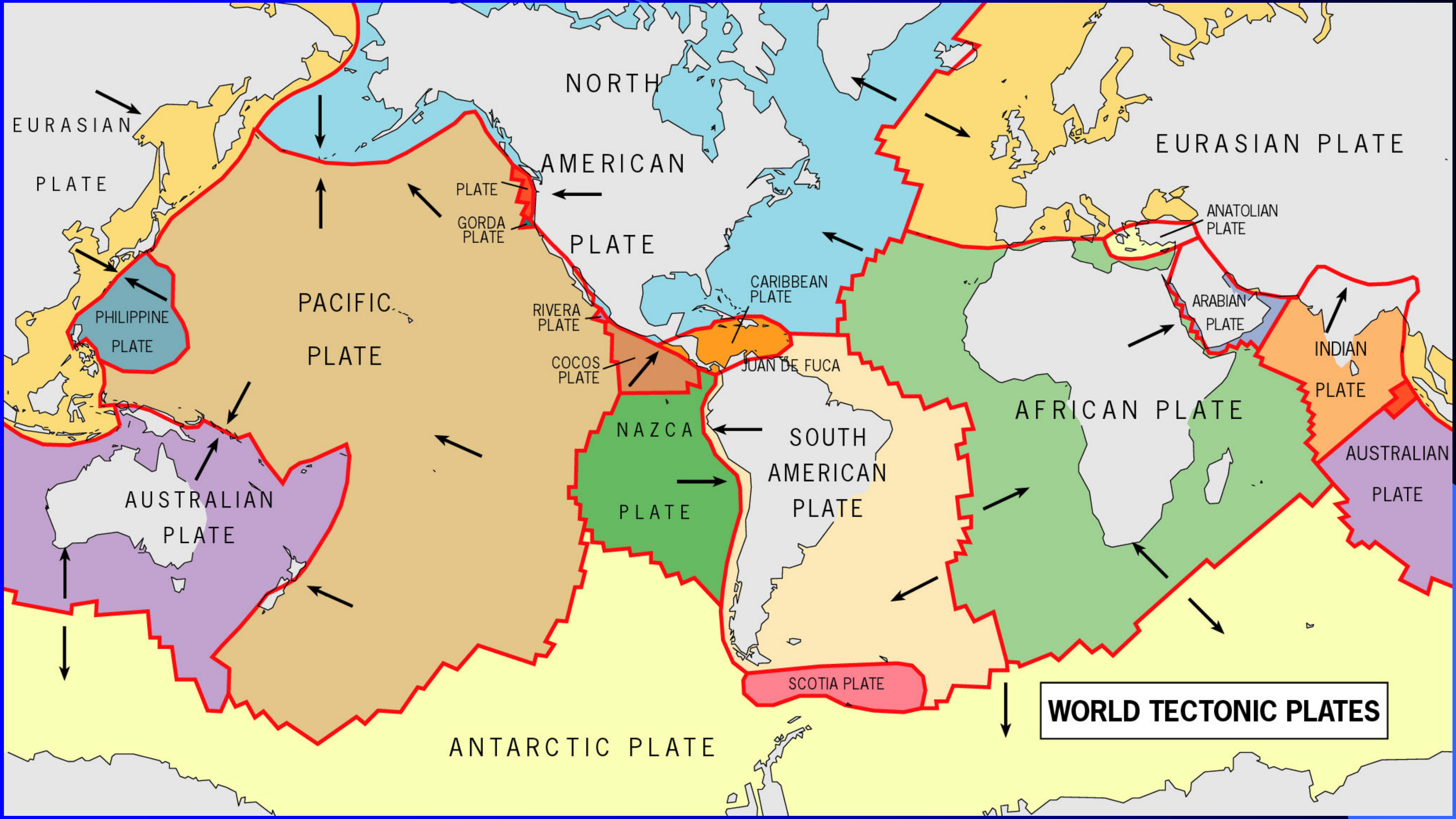
HFU = Heat Flow Unit = 1 x 10^{-6} cal/cm^2 · min = 41.86 mW/m^2 · min

Heat flow variations:

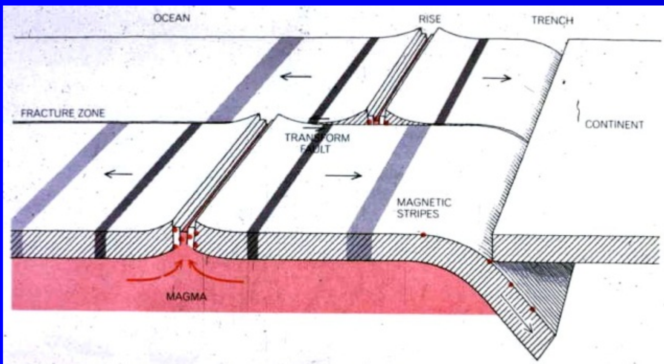
- 1-2 HFU over trenches
- 2-3 HFU ocean average
- 4-6 HFU over ocean ridge



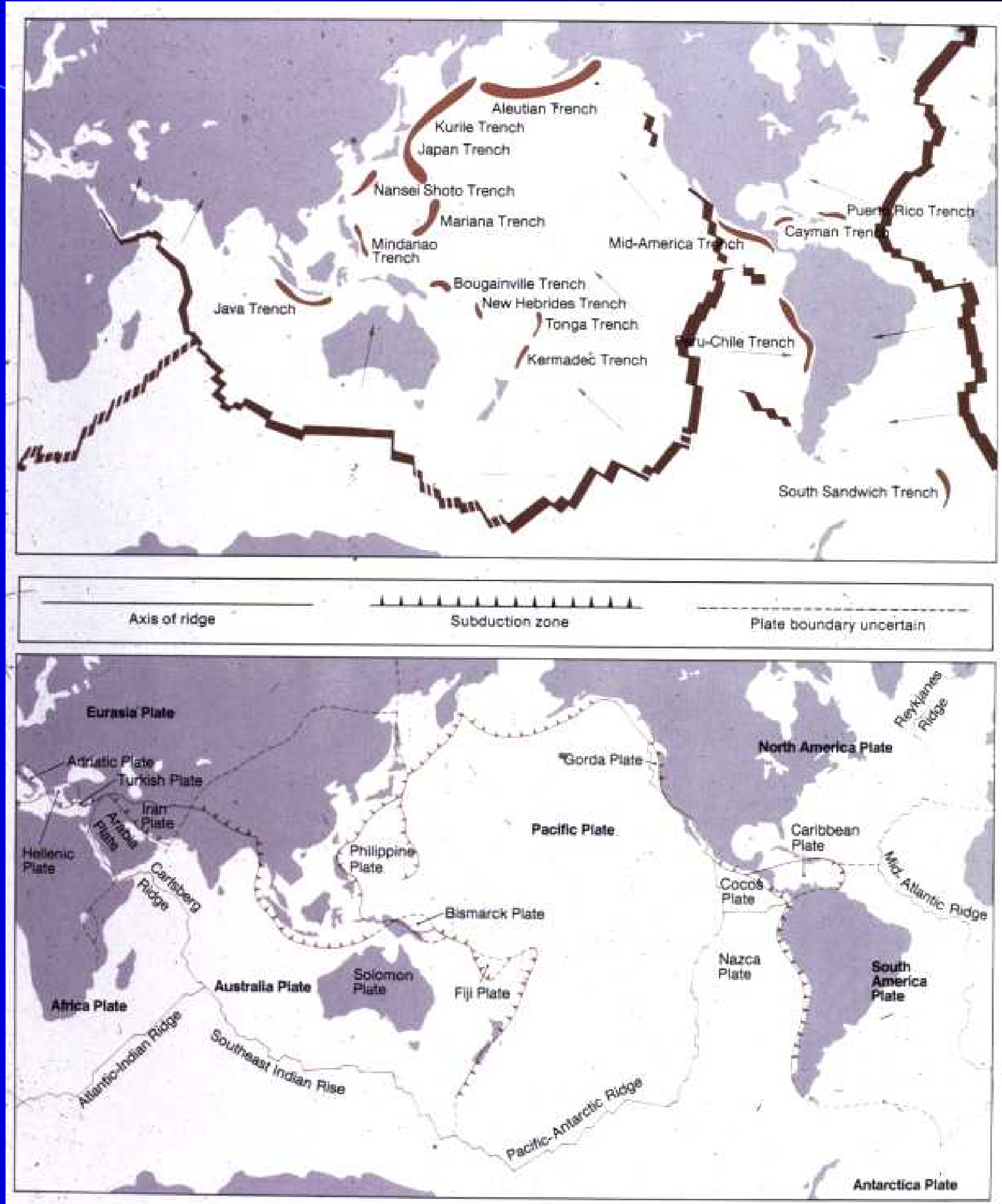
Earth's Tectonic Plates



The lithosphere of the Earth was divided into about a dozen large pieces called *plates*. Plate boundaries are marked by spreading centers, subduction zones, and faults.



RIFT IN OCEAN FLOOR (*color*) initiates three major features of oceanic plate tectonics. The rift is bordered by a rise or ridge created by magma pushed up from the mantle below. The magma solidifies with a magnetic polarity corresponding to that of the earth. When, at long intervals, the earth's polarity reverses, the polarity of newly formed crust reverses too, resulting in a sequence of magnetic "stripes." A trench results when an oceanic plate meets a continental plate. A fracture zone and transform fault result when two plates move past each other. Earthquakes (*dots*) accompany these tectonic processes. The earthquakes in the vicinity of a rise and along a transform fault are shallow. Deep-focus earthquakes occur where a diving oceanic plate forms a trench.



Fault boundaries (transform faults)

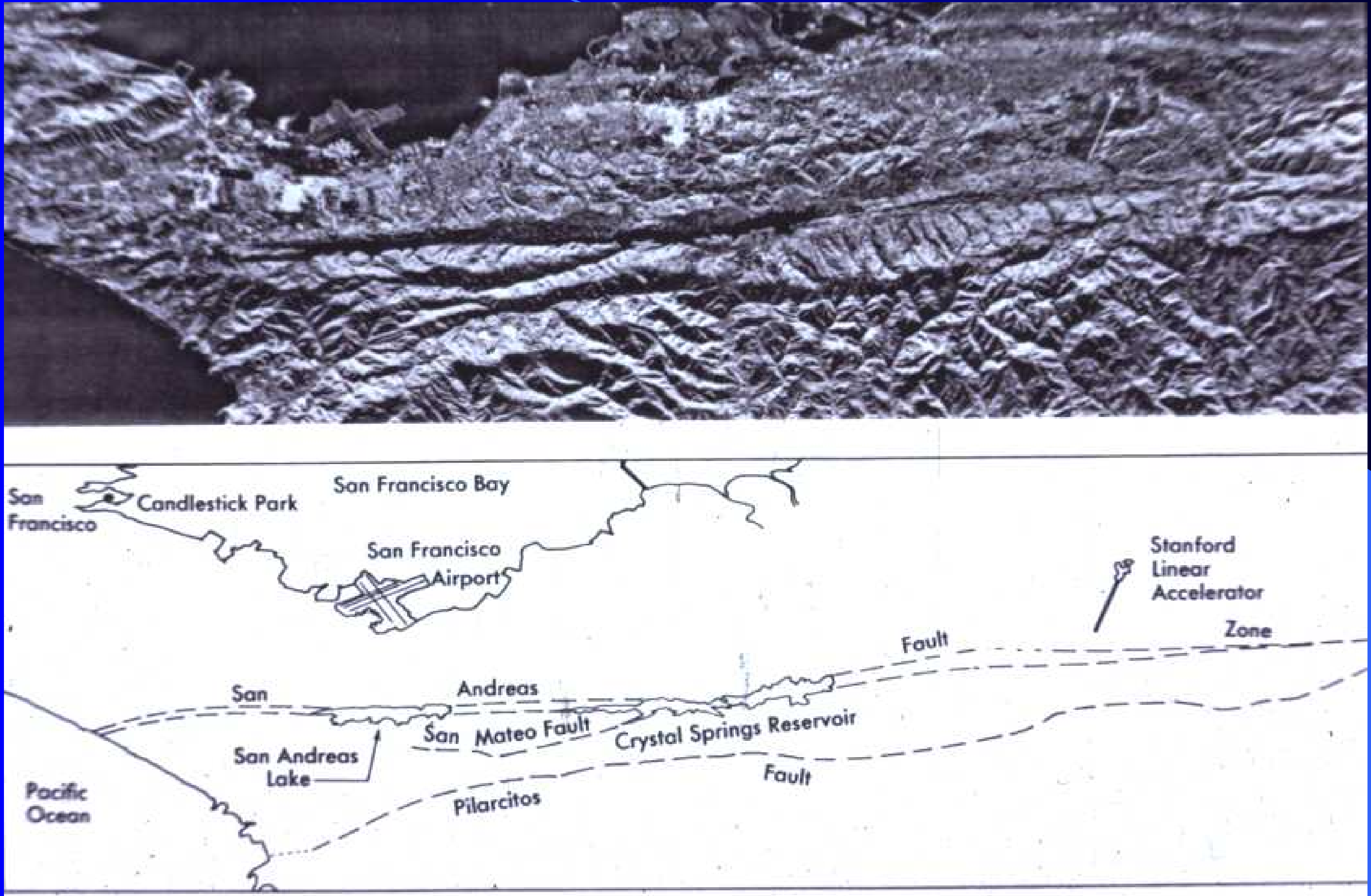
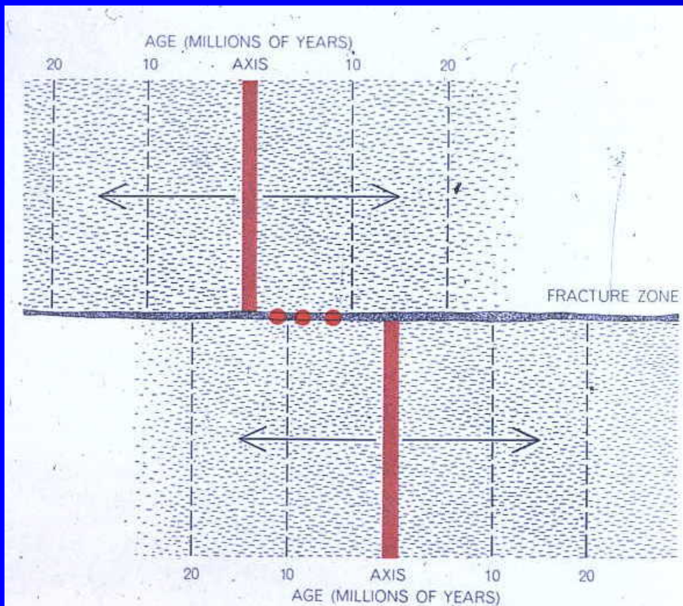
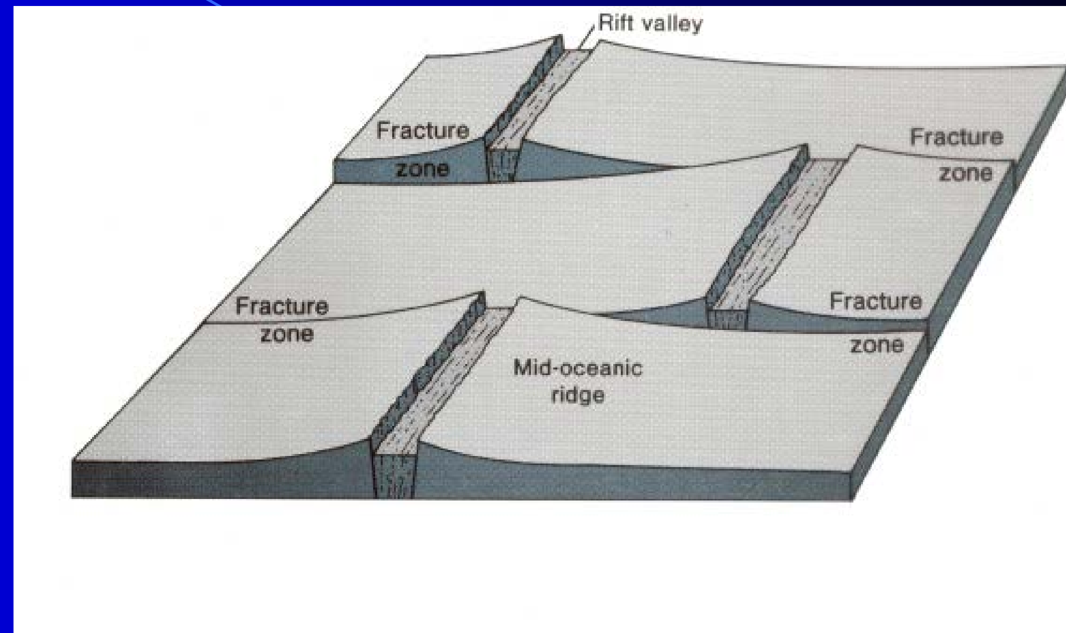


FIG. 1-5. Radar images. A. San Francisco Peninsula. Unlike conventional aerial photos, radar images can be obtained in cloudy weather or even at night. The radar penetrates the vegetation and reveals the actual surface. The bottom (west) part of this area has thick redwood forests. From U. S. Geological Survey in cooperation with NASA and Westinghouse Electric Co.

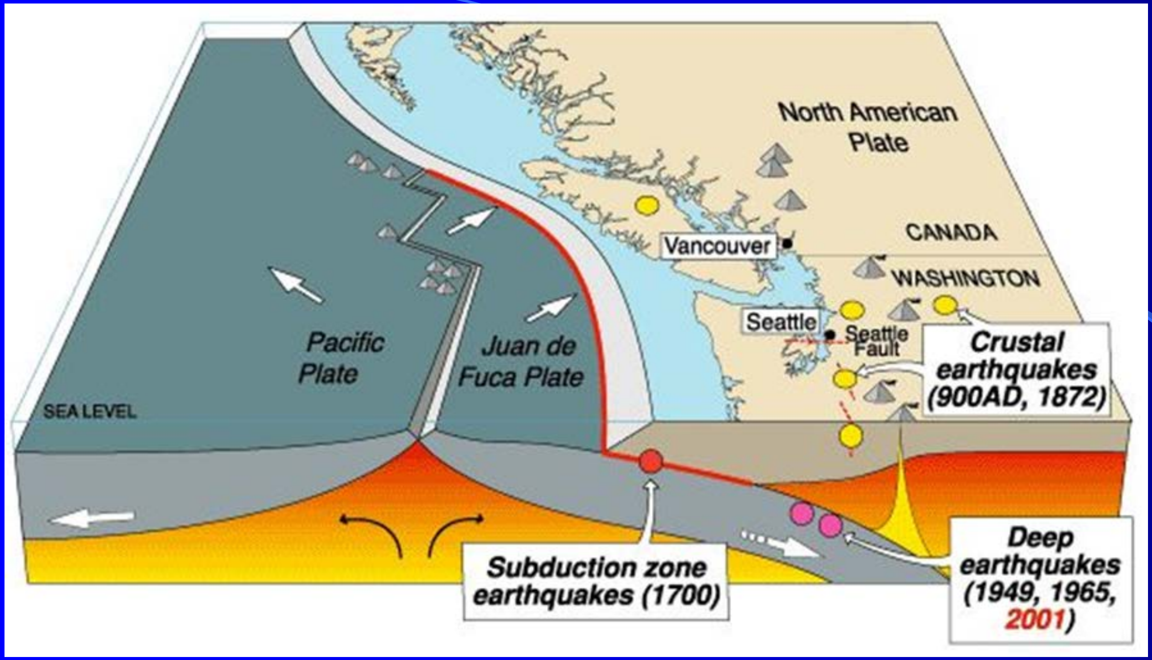
Transform Faults Offsetting the Mid-Ocean Ridge System



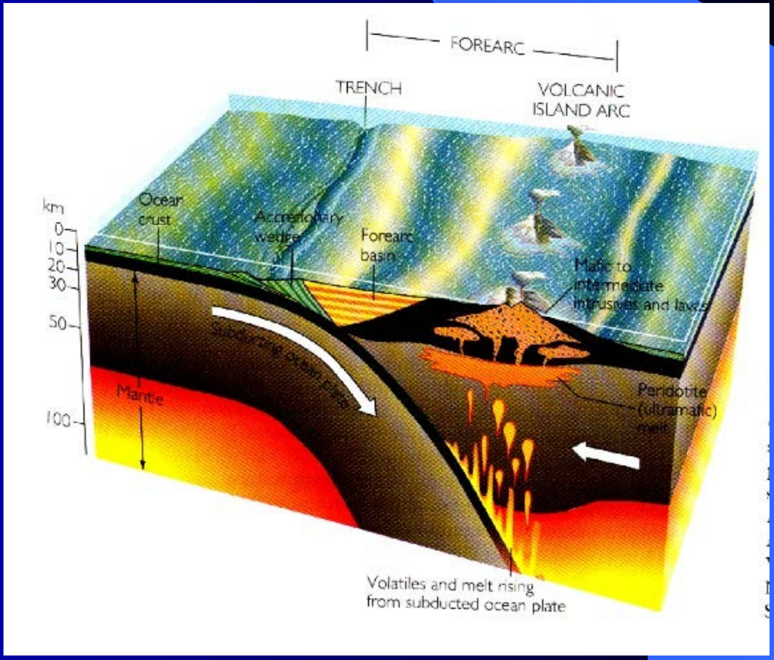
MOLTEN ROCK wells up from the deep earth along a spreading axis, solidifies and is pushed out (*arrows*) by subsequent upwelling. The axis is offset by a fracture zone. Between two offset axes material on each side of the fracture zone moves in opposite directions and the friction between two blocks of the crust causes shallow earthquakes (*colored disks*).



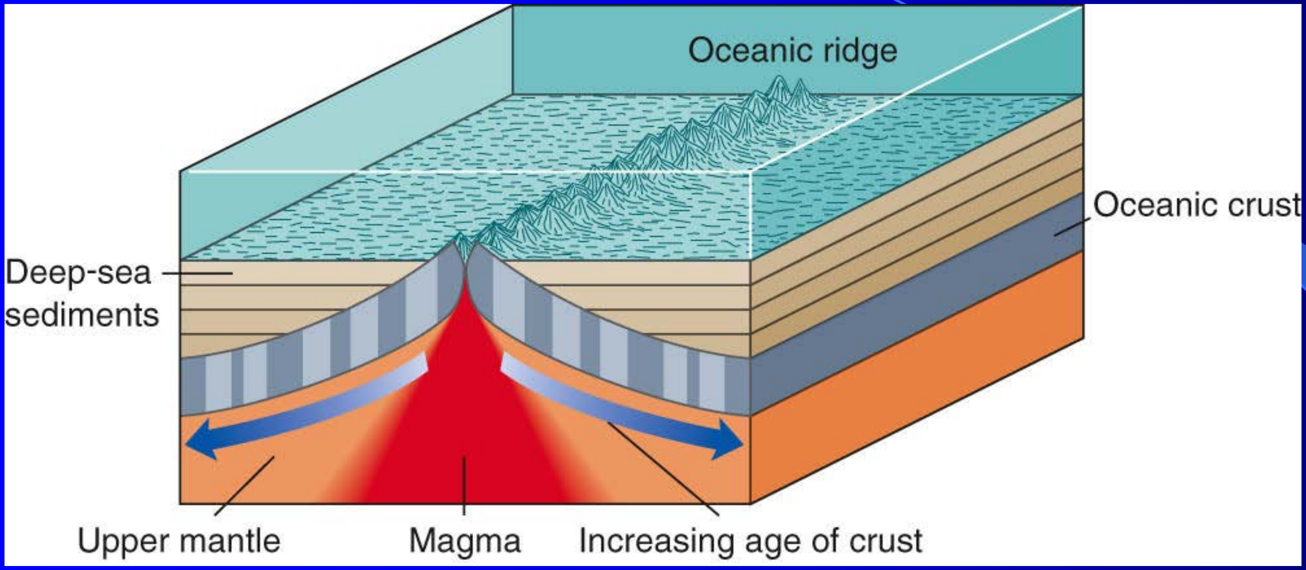
83 Fracture Zones
Figure 18.18

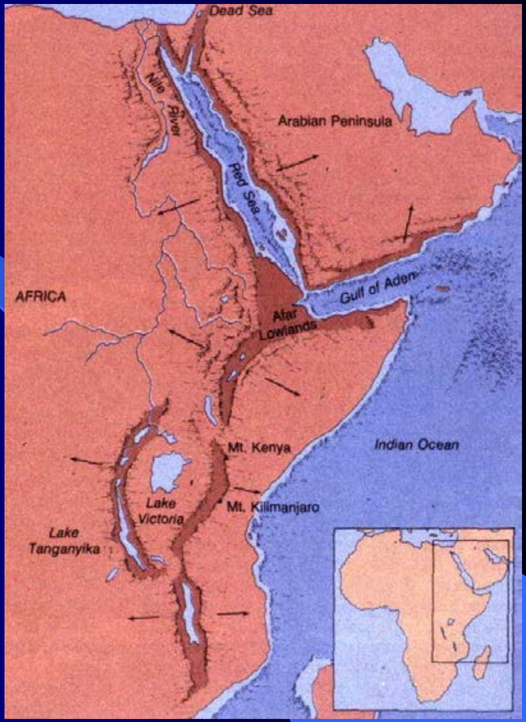


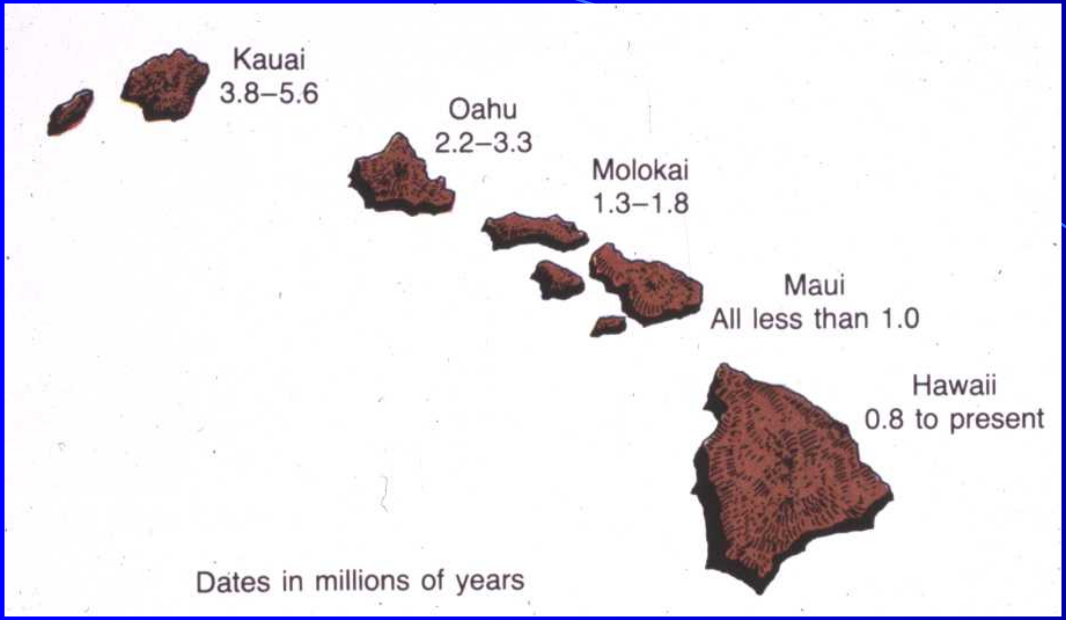
Types of Subduction Zones



Oceanic and Continental Spreading Centers







There is a regular age progression for the Hawaiian volcanoes. Similarly for the entire Hawaii-Emperor Seamount chain.

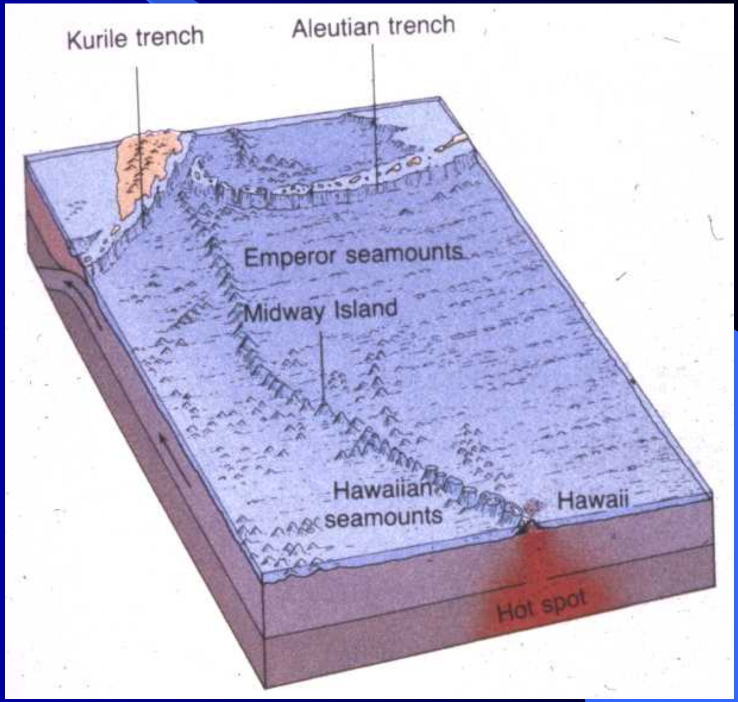
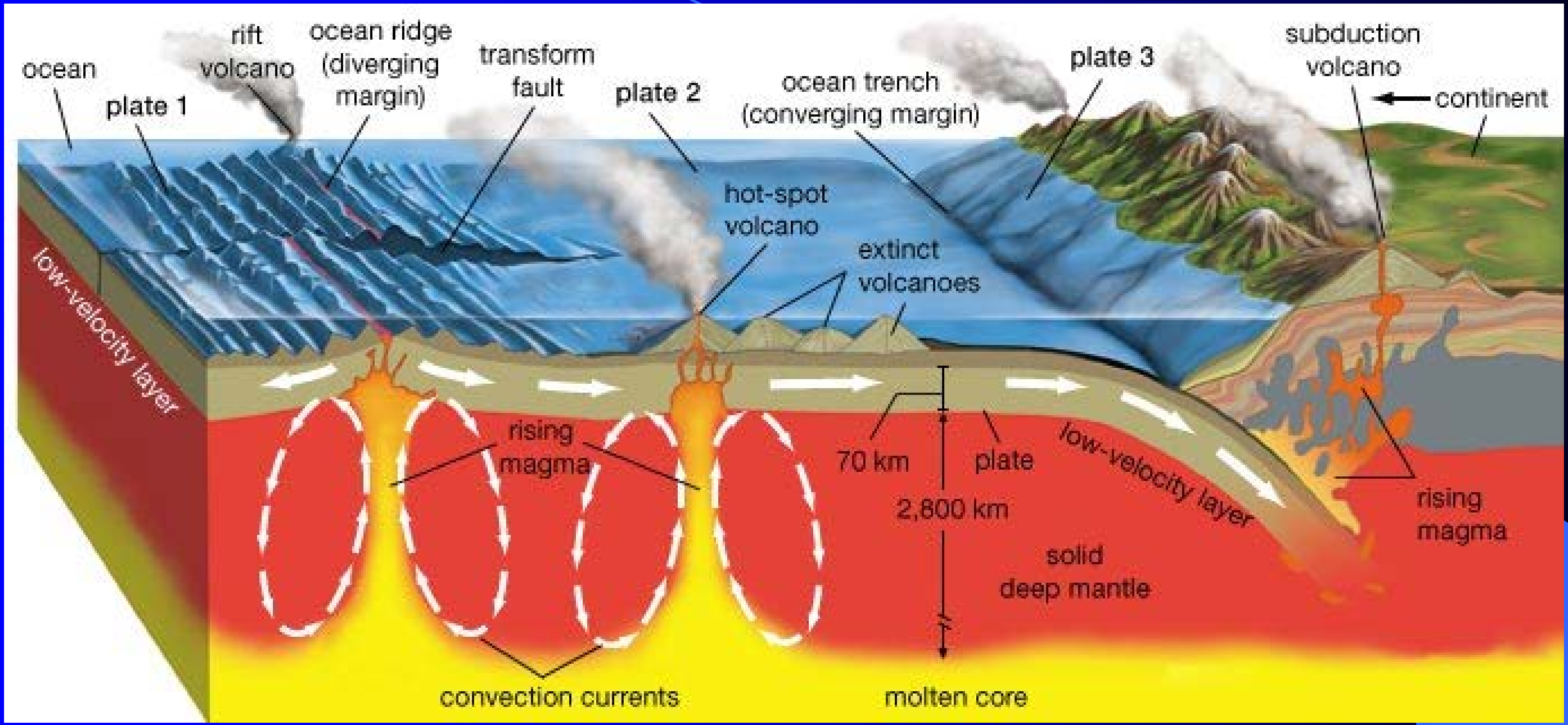
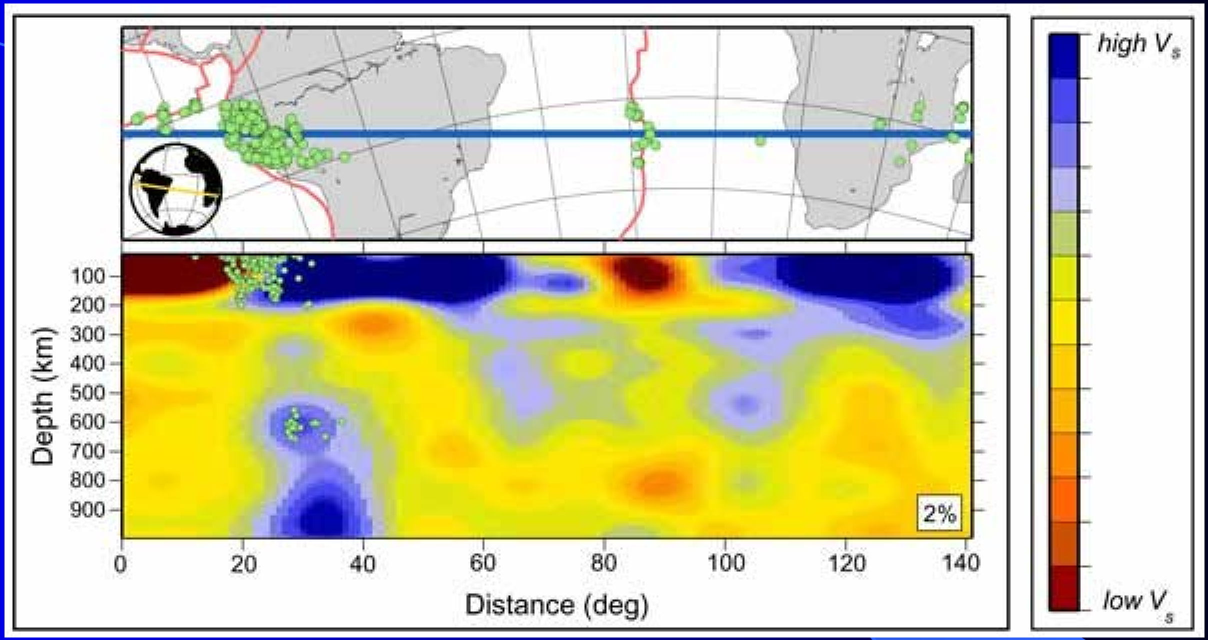
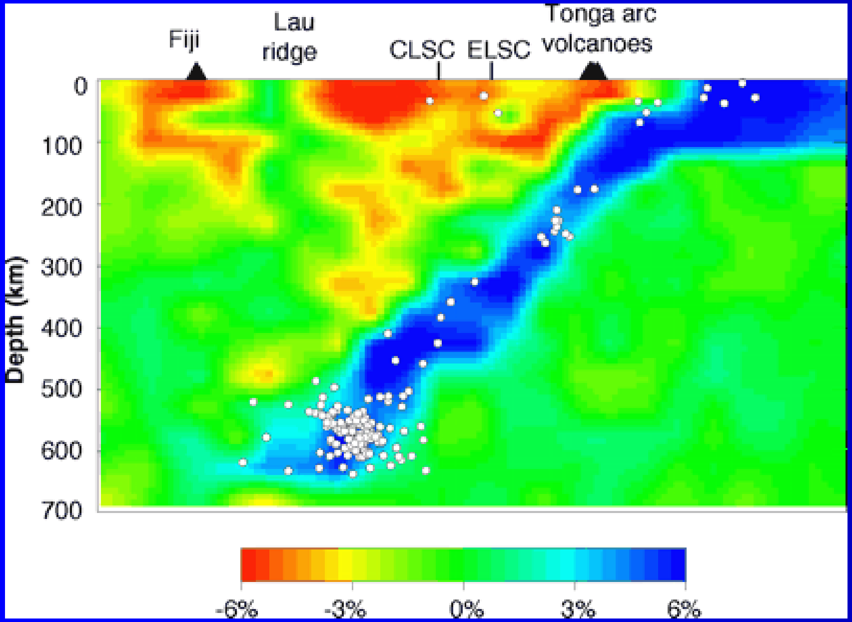


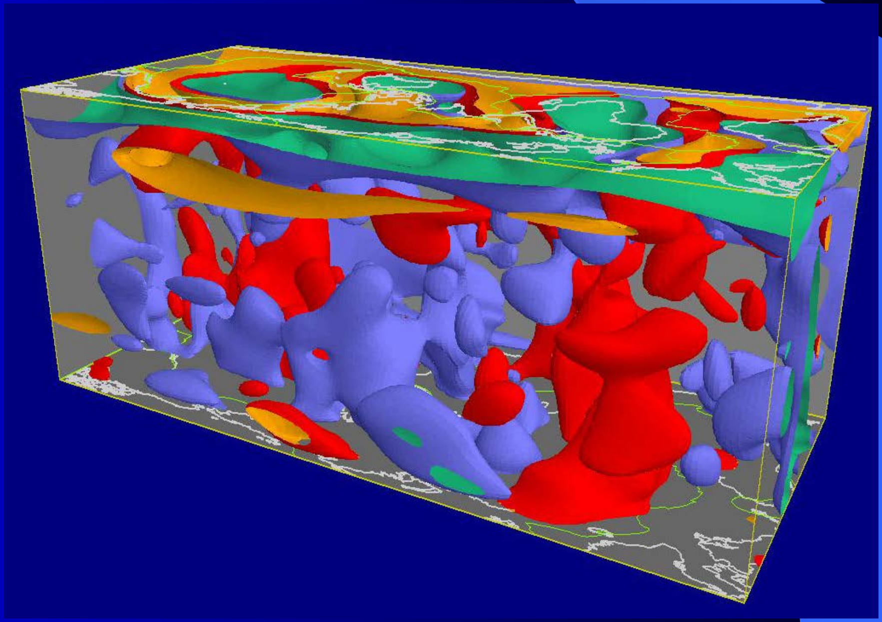
Plate Tectonics Dynamics



Seismic Tomography

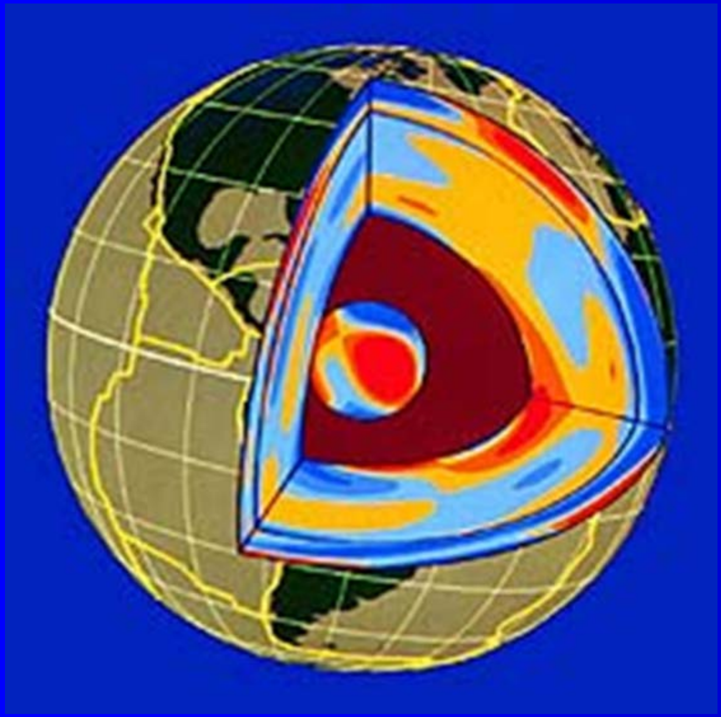


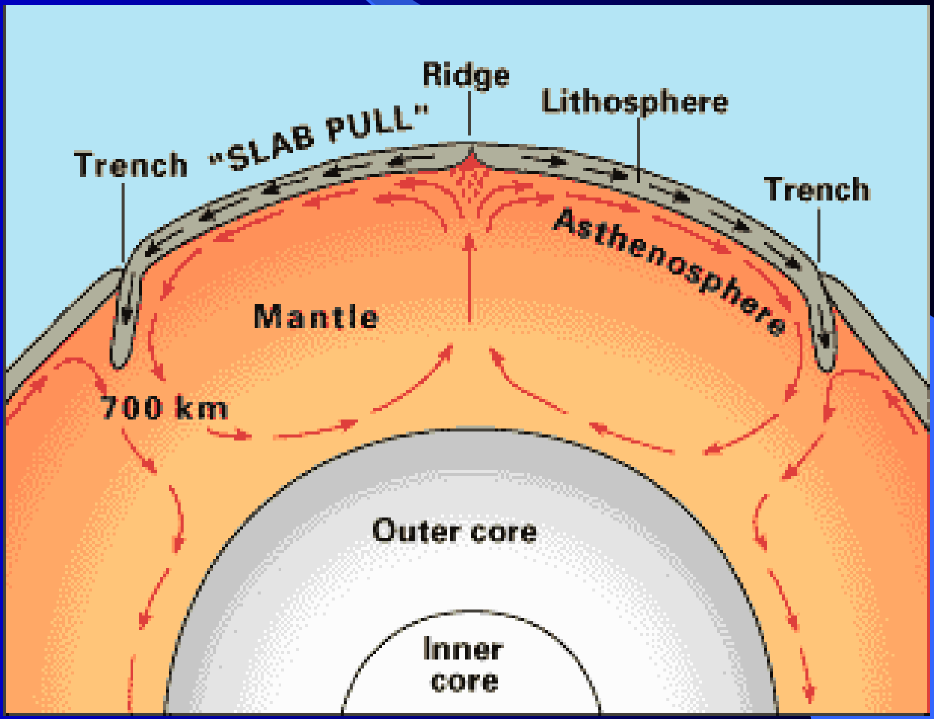




What Drives Plate Tectonics?

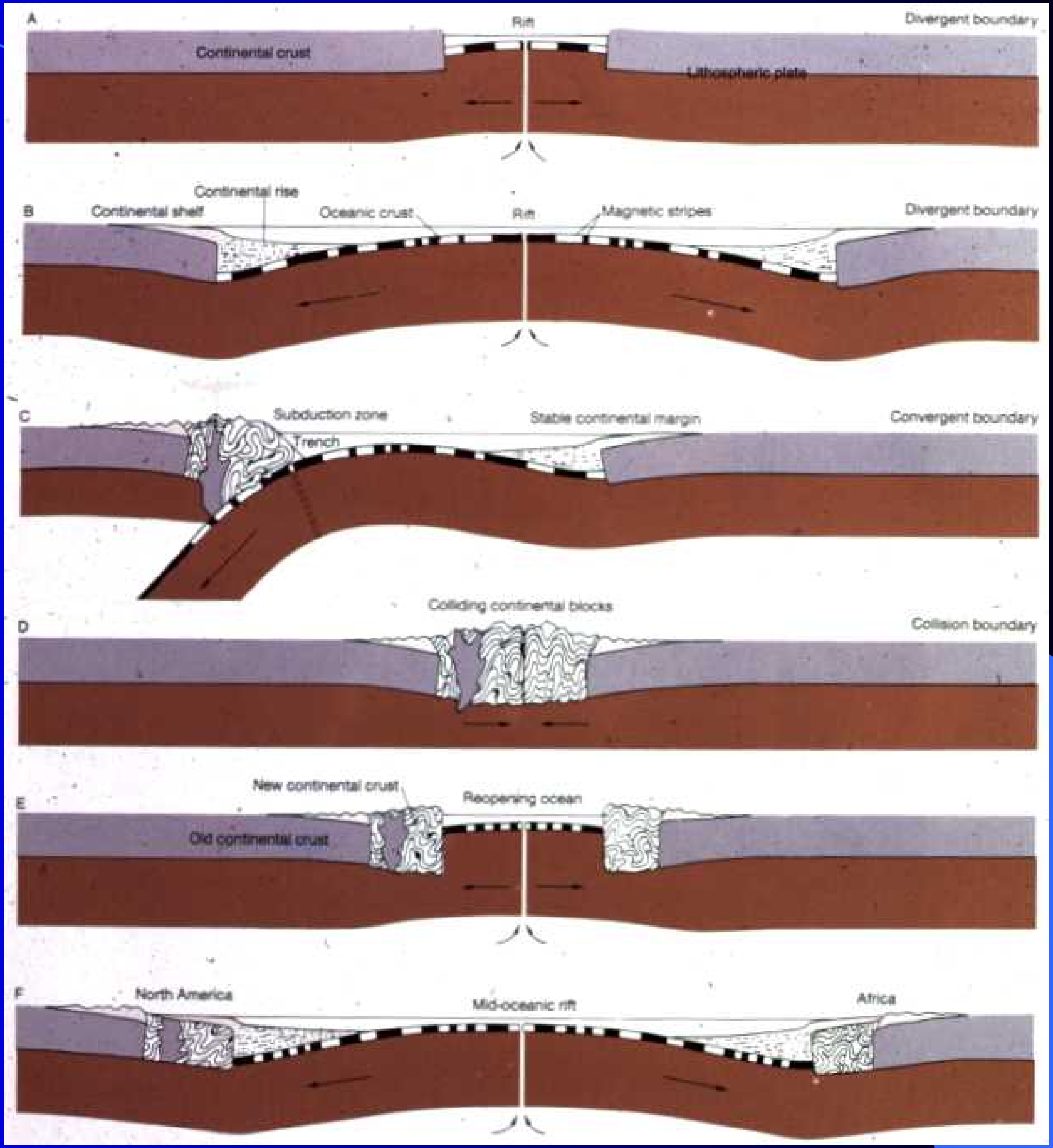
- Heat transfer from the core to the surface via convection currents
- Incremental heat addition occurs due to decay of radioactive elements
- Cooling of the earth will eventually lead to the cessation of plate tectonics and the Earth will become a geologically dead planet



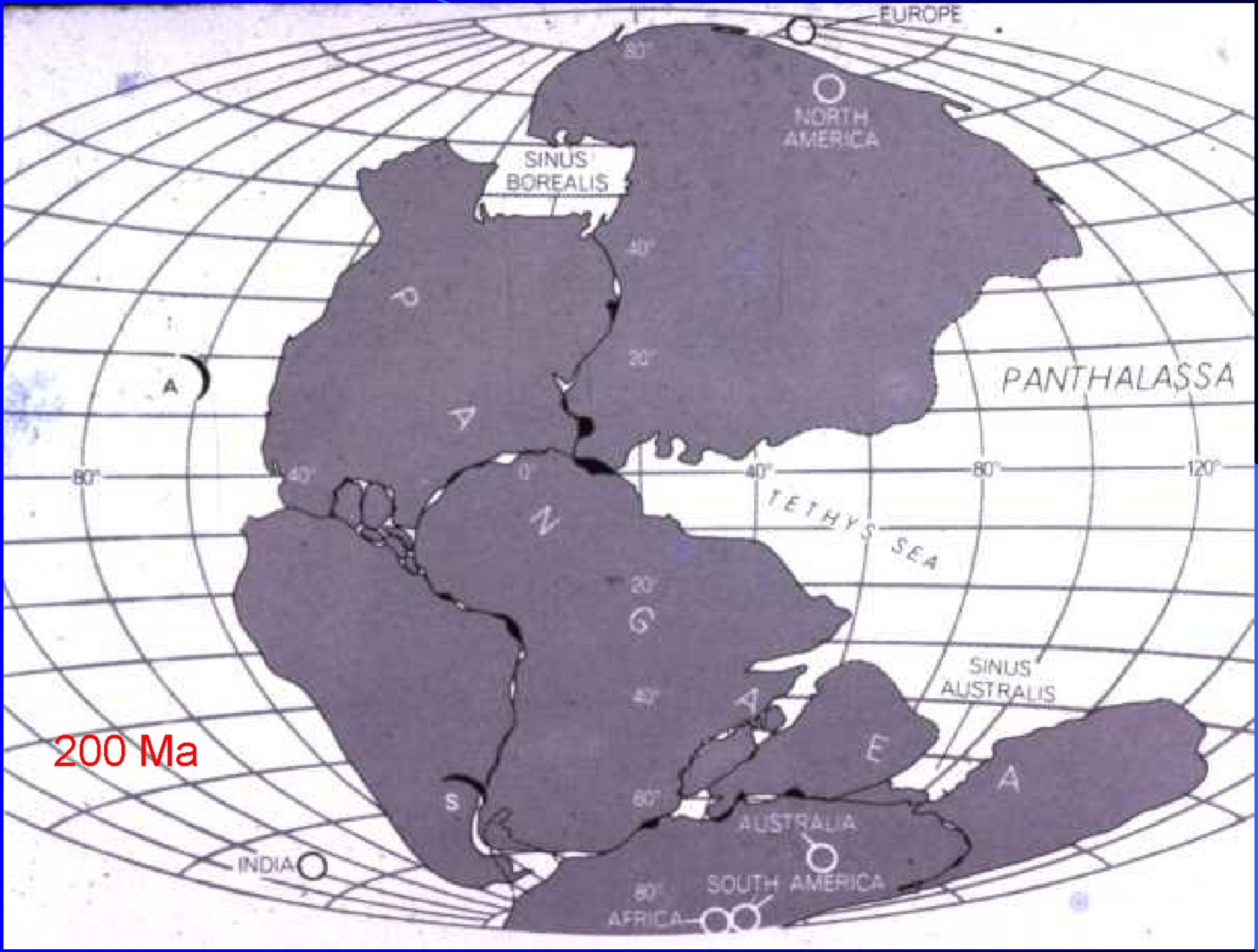


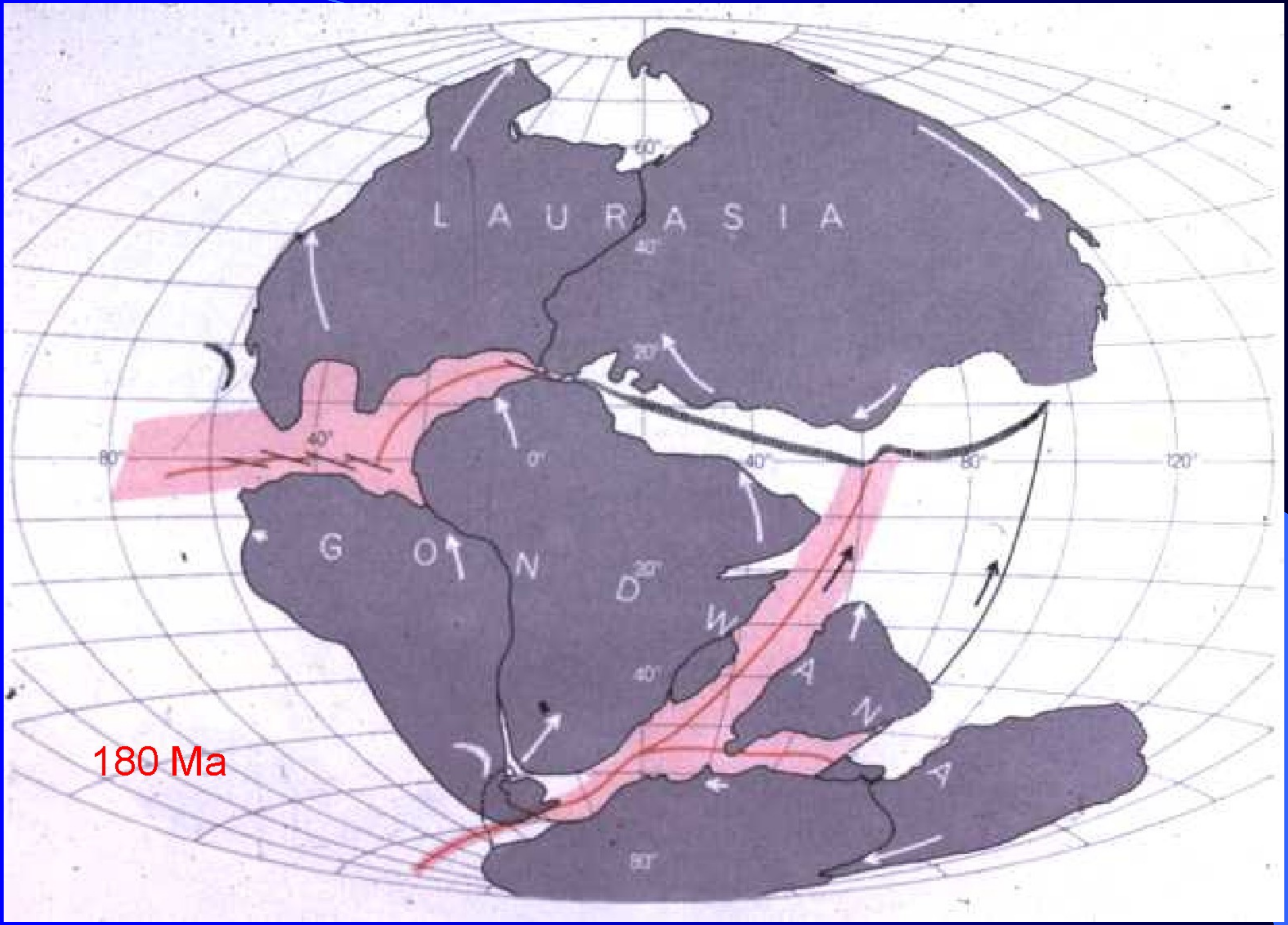
The Wilson Cycle

Opening and closing of ocean basins. Continent-continent collision leads to thickening of the crust and the formation of relief. The European block provided the sediment for the Appalachian mountains. Horizontal tectonics with a vertical component.

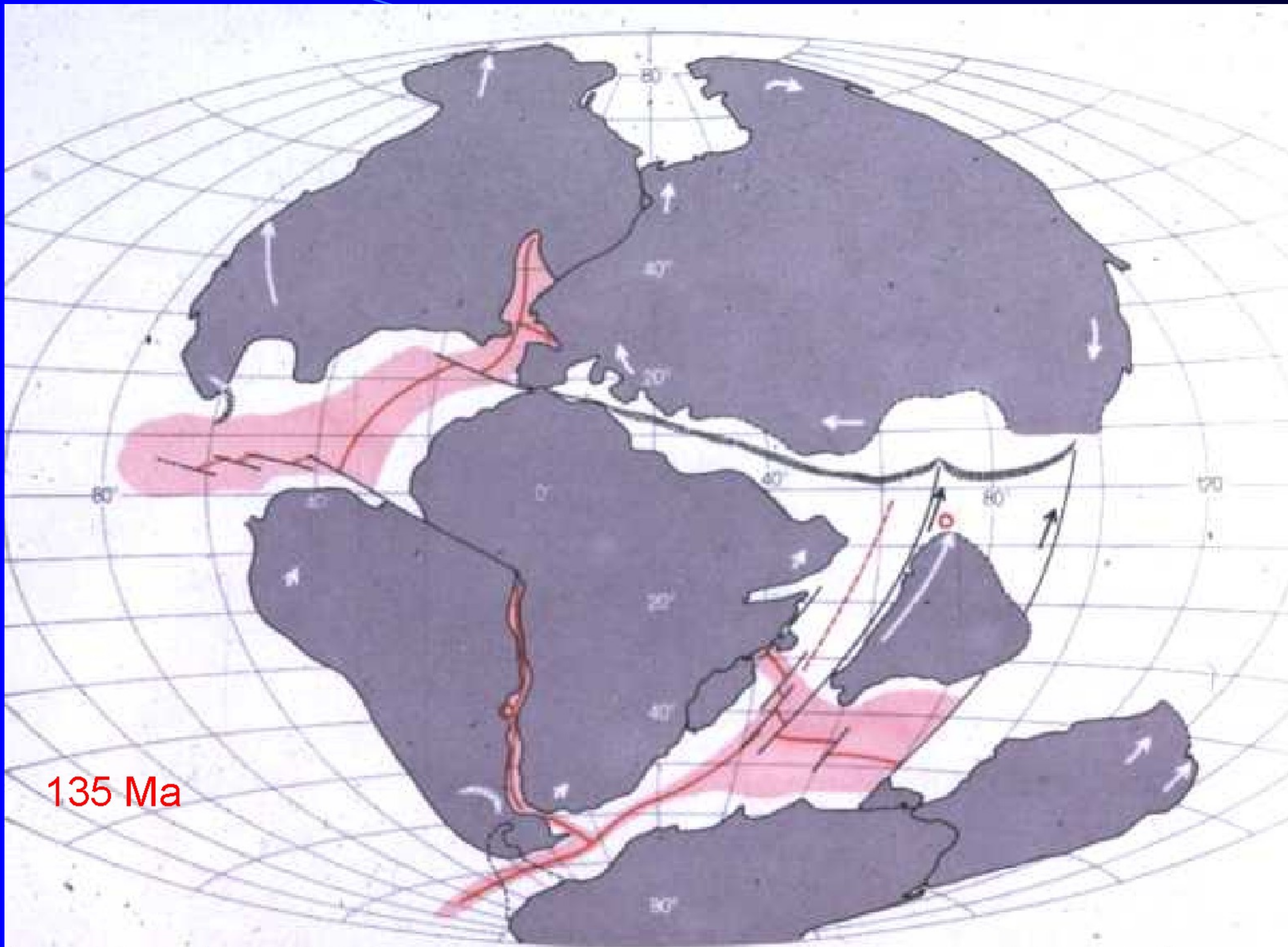


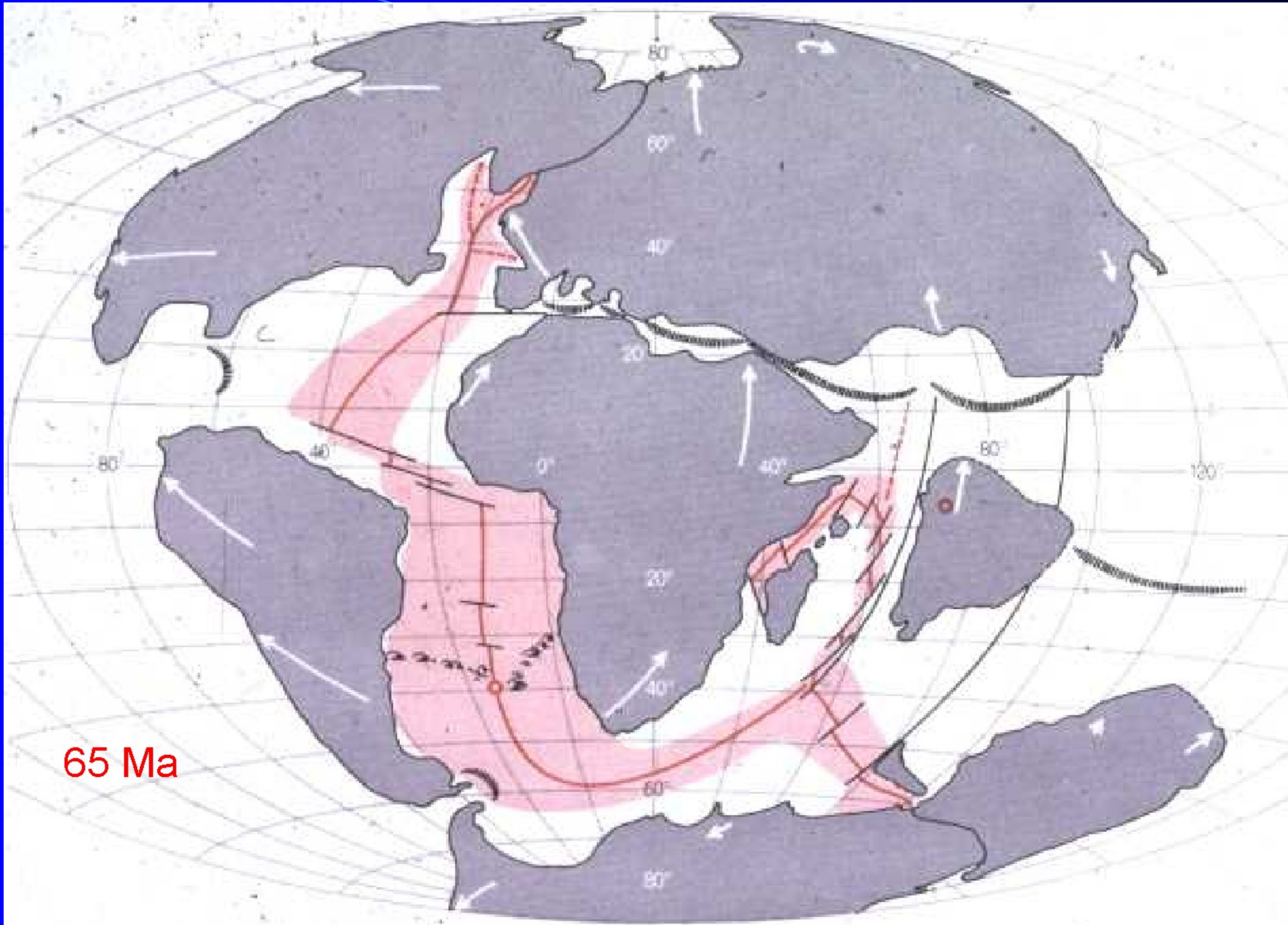
The past 200 Ma of Continental drift

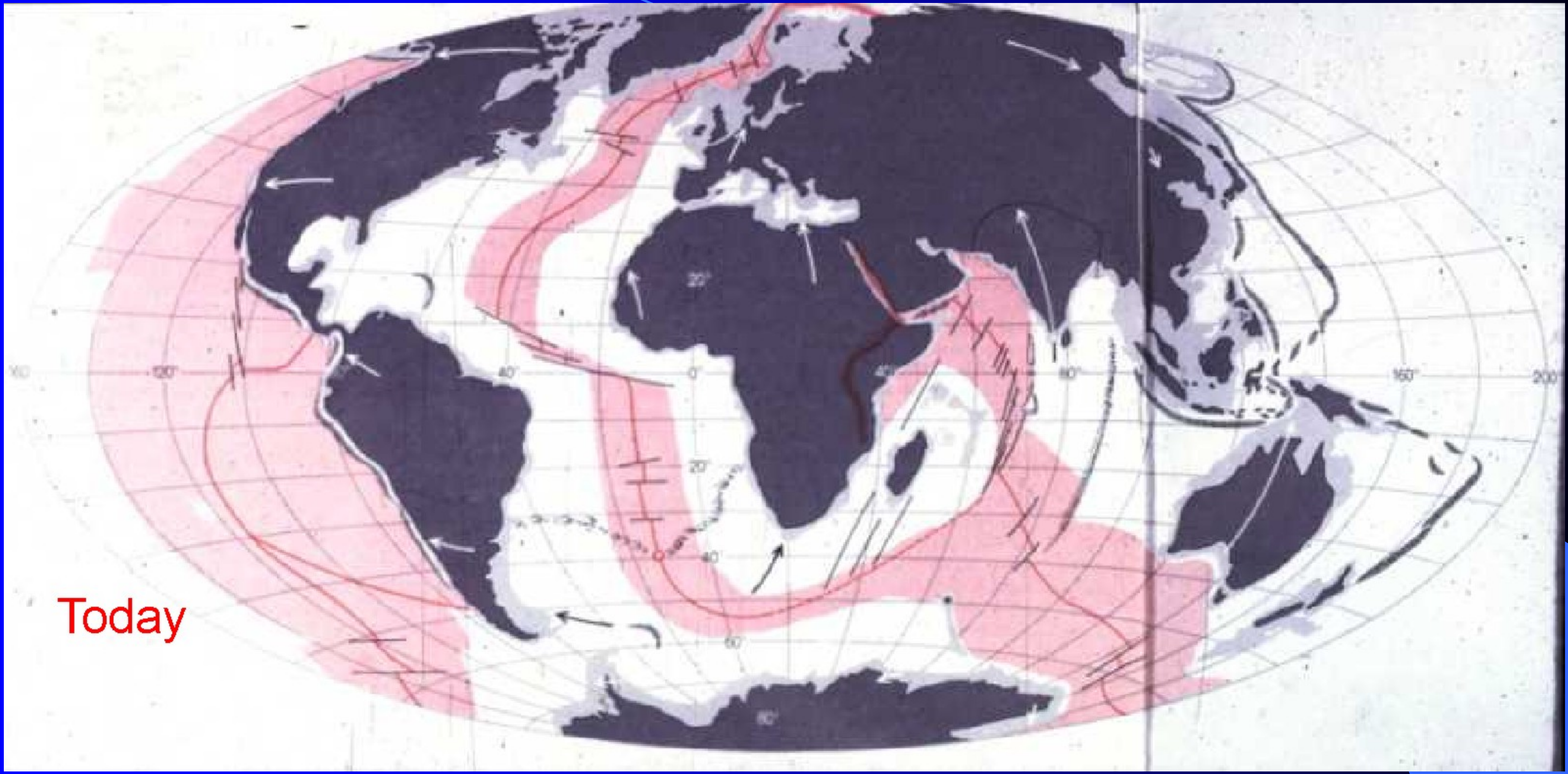


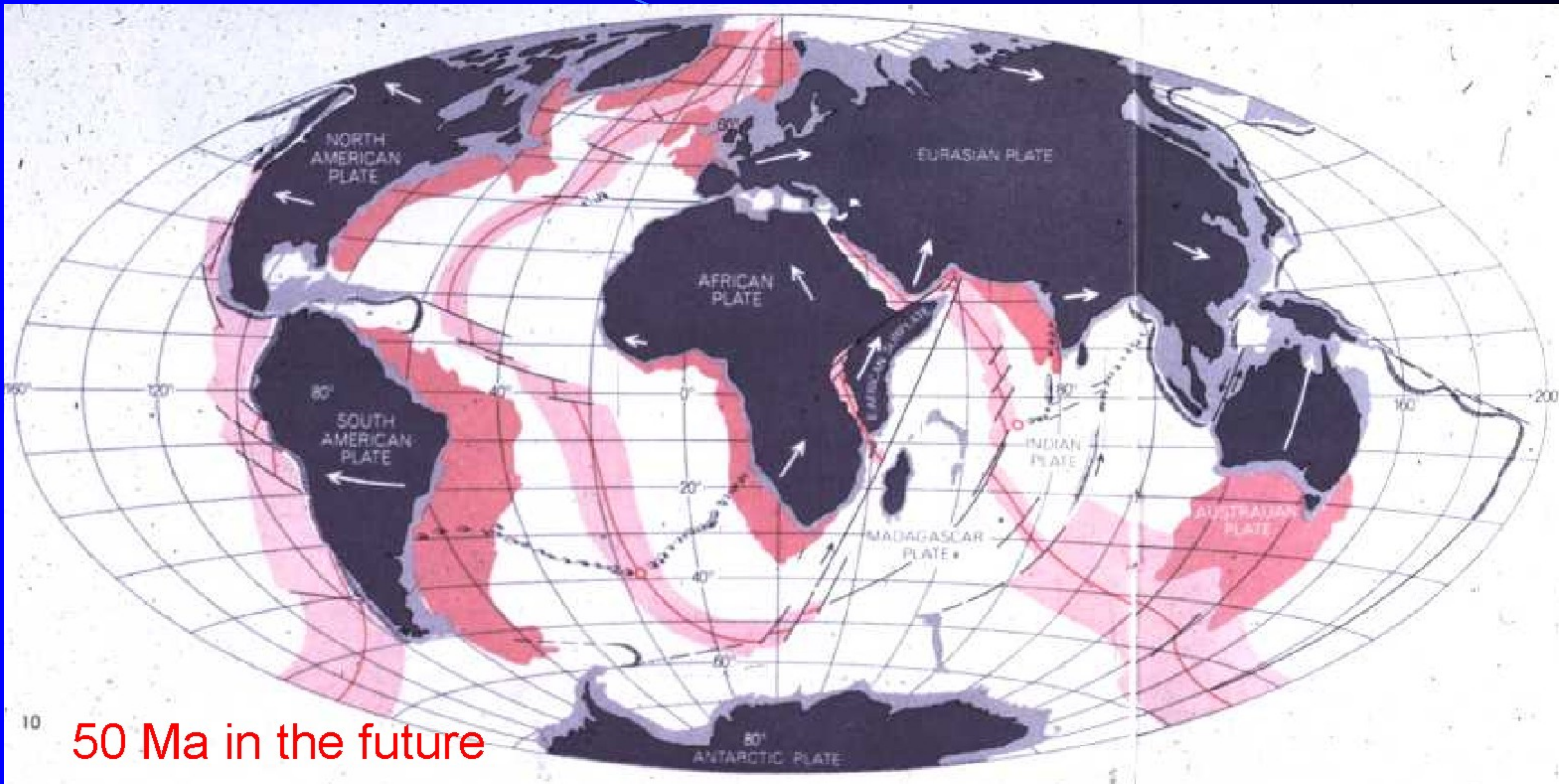


LAURASIA
GONDWANA
60°
40°
20°
0°
80°
40°
80°
120°
180 Ma


135 Ma


65 Ma
80°
60°
40°
20°
0°
120°


Today
20°
120°
40°
0°
40°
80°
160°
200°
20°
40°
60°
80°



50 Ma in the future