Earth and Planetary Sciences (ES1101)

(Continental Drift, Sea floor Spreading, and Plate Tectonics)

(Autumn 2023 by Gaurav Shukla)

Book: **1) Understanding Earth by Grotzinger & Jordan (Text Book)**

2) Earth: An introduction to Physical Geology by Tarbuck & Lutgens

3) The Solid Earth: An introduction to global geophysics by Fowler

Continental Drift

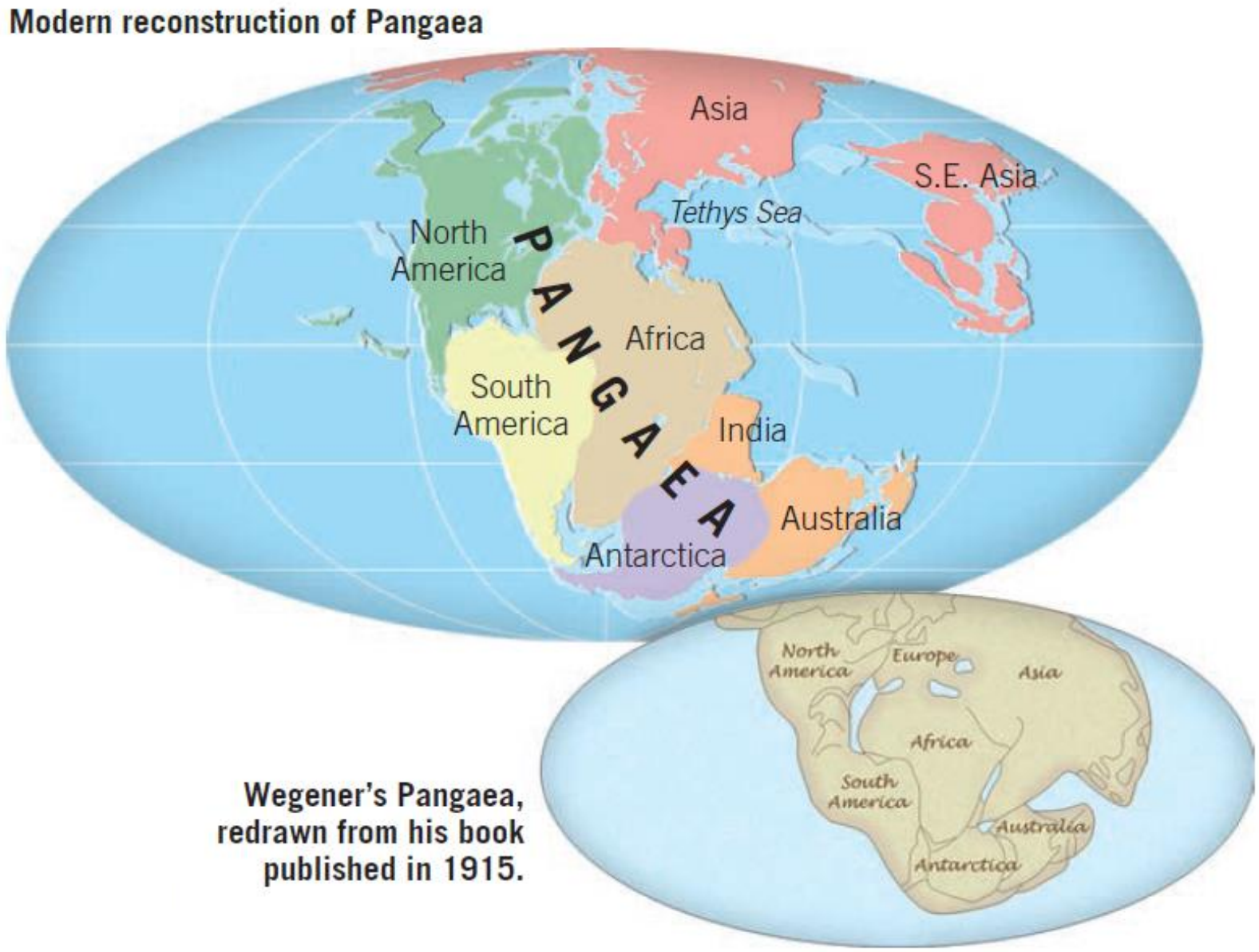
Alfred Wegener

- German meteorologist & geophysicist
- Published "*The Origin of Continents and Oceans*" (1915)

- Hypothesis:
  - A single supercontinent "Pangaea" existed.
  - It began to break in Mesozoic.
  - The fragmented land masses drifted to their present position.

- Observations :
  - Jigsaw like fit of the continents
  - Global distribution of fossils
  - Climatic signature
  - Similar rocks across continents
  - Continuous mountain ranges

Continental Drift



Wegener's Pangaea, redrawn from his book published in 1915.

Continental Drift

Fits of the Continents

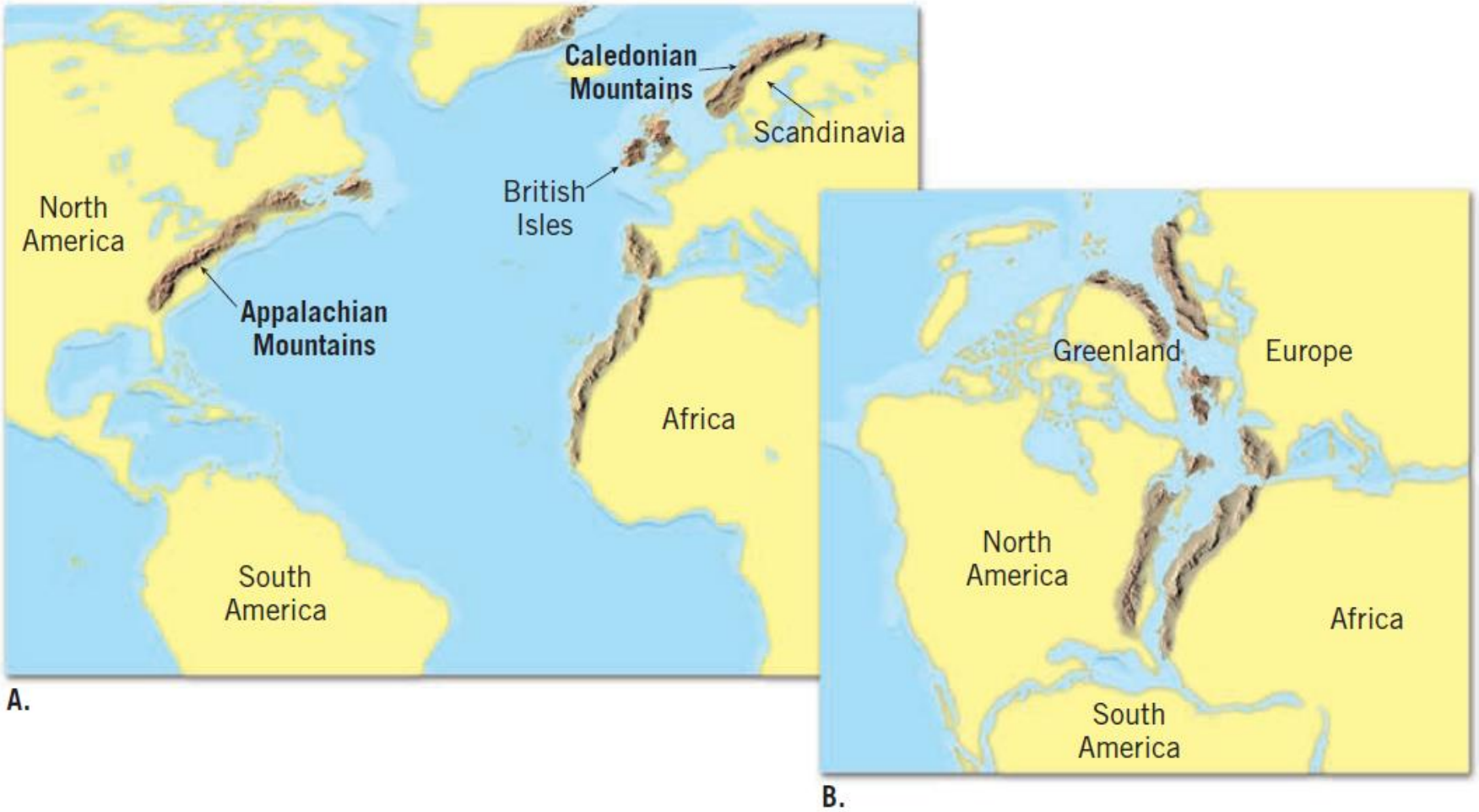
- **Remarkable fit between the coastlines on opposite sides of the Atlantic Ocean**

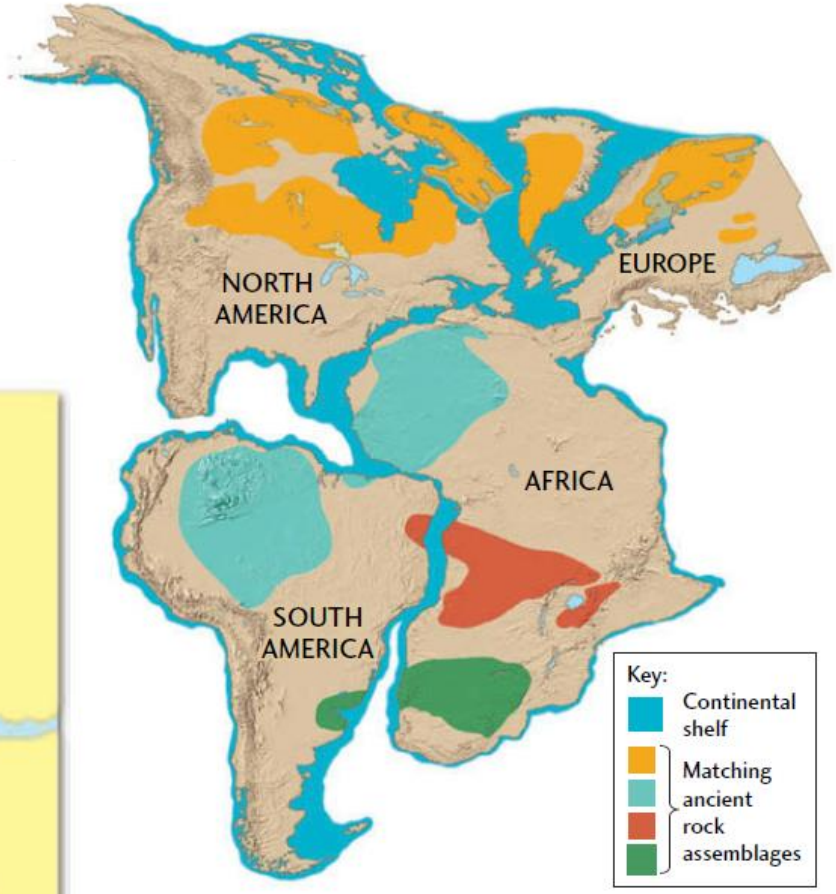
- **Problems: Crude match, Shorelines are affected by erosion and deposition**

- **Advanced mapping of continental shelf in 1960s showed that match is extremely good.**

Continental Drift

Rock Types





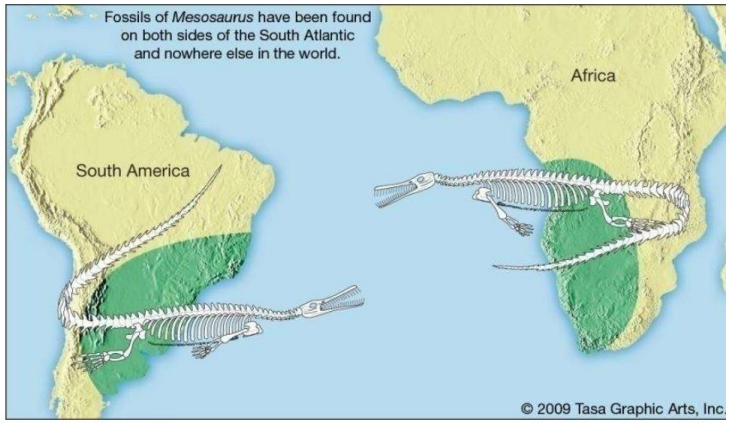
Continental Drift

Rock Types

- **Mountain belts terminate at one coastline and reappear on landmasses across the ocean.**
- **Nearly continuous mountain chain joining North America, Greenland, British Isle, and Africa.**
- **Same rock age**
- **Same structural orientation**
- **Same rock type (igneous rocks)**

Distribution of fossils

• Similar fossil organisms were found in separate continents.



Explanation:
A) "land bridge" existed in past
B) continents moved

1. *Mesosaurus:*
   - Aquatic reptile
   - Permian age
   - Found in S. America and Africa
   - Very limited distribution
   - Can't swim through vast ocean.

2. *Glossopteris*:
   - Fossil fern
   - Late Paleozoic
   - Found in S. America, Africa and Antarctica
   - Not easily transportable seeds

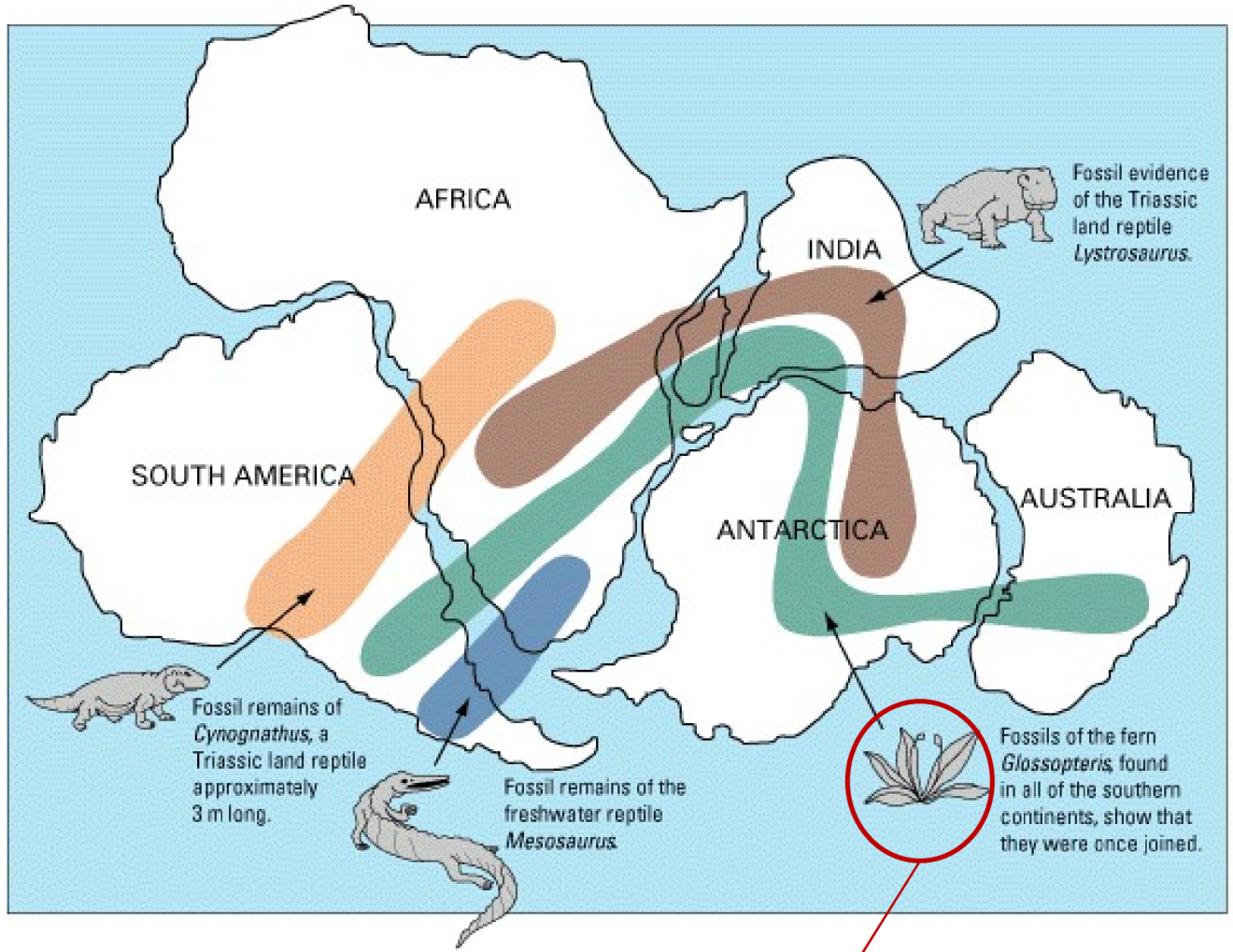
Distribution of fossils: Current knowledge

-Wegener only knew about the previous two examples.

- Later paleontologists discovered two more fossil groups from presently disconnected continents.

- Both of the groups are land reptiles.

- They couldn't have crossed the oceans.



Explanation:

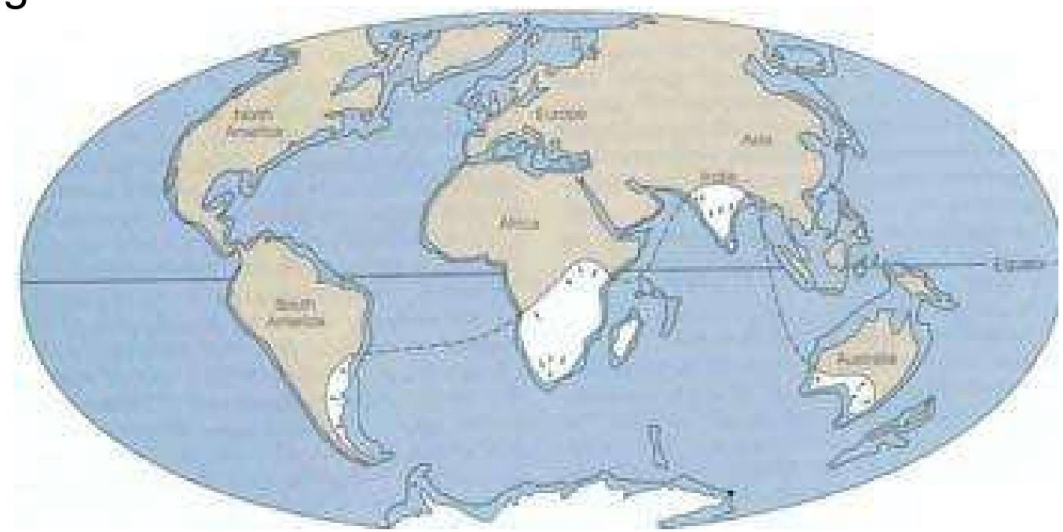
~~A) "land bridge" existed in past~~

B) continents moved

They generally occur only in subpolar climate!!!

Paleoclimatic evidence

Paleo (Past) climate studies including
- Study of ancient glaciers



Evidence of ice sheets from 220-300 my ago, found on
A) Antarctica
B) Southern South America
C) Australia
D) South Africa
E) Madagascar
F) India

Evidence: How do we know about ancient glaciers?

Glacial striations: Scouring caused by the rocks carried by a glacier.

It tells us about
- Presence of glacier
- Direction of flow

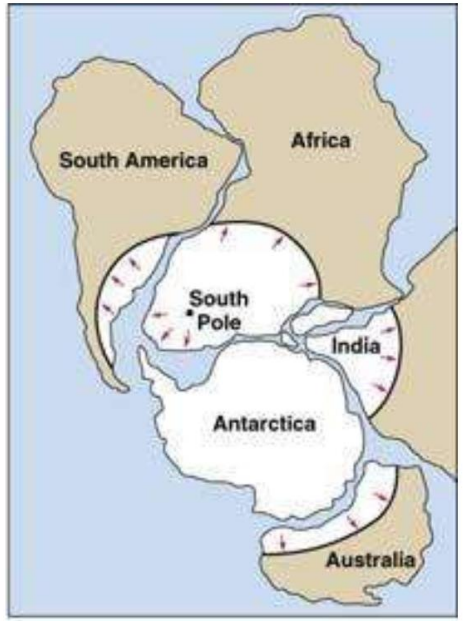
Paleoclimatic evidence

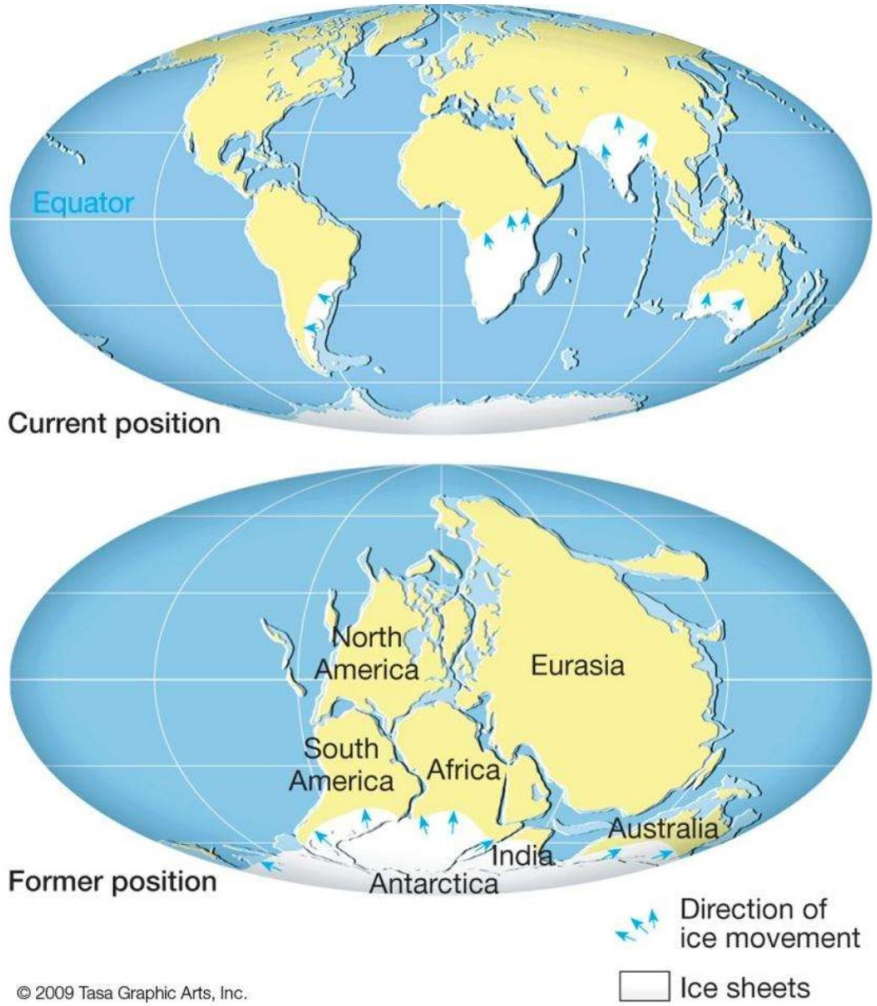
Using the evidence from ancient glaciers

-We know about the existence of glacier
- Reconstructed the flow of the glacier

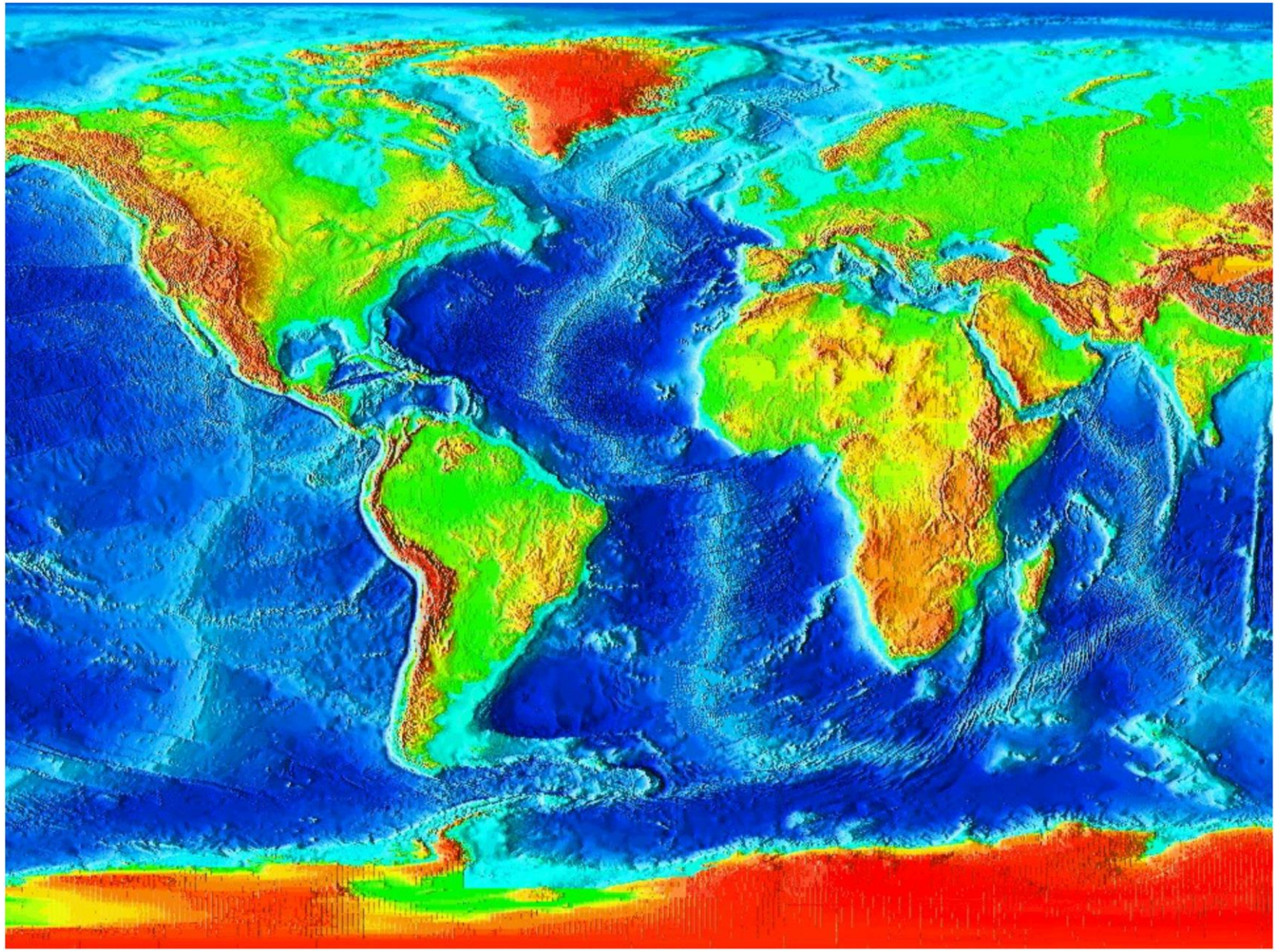
• Both of them indicate that the continents were connected in a specific arrangement.

•They were at much higher latitude than their present location.

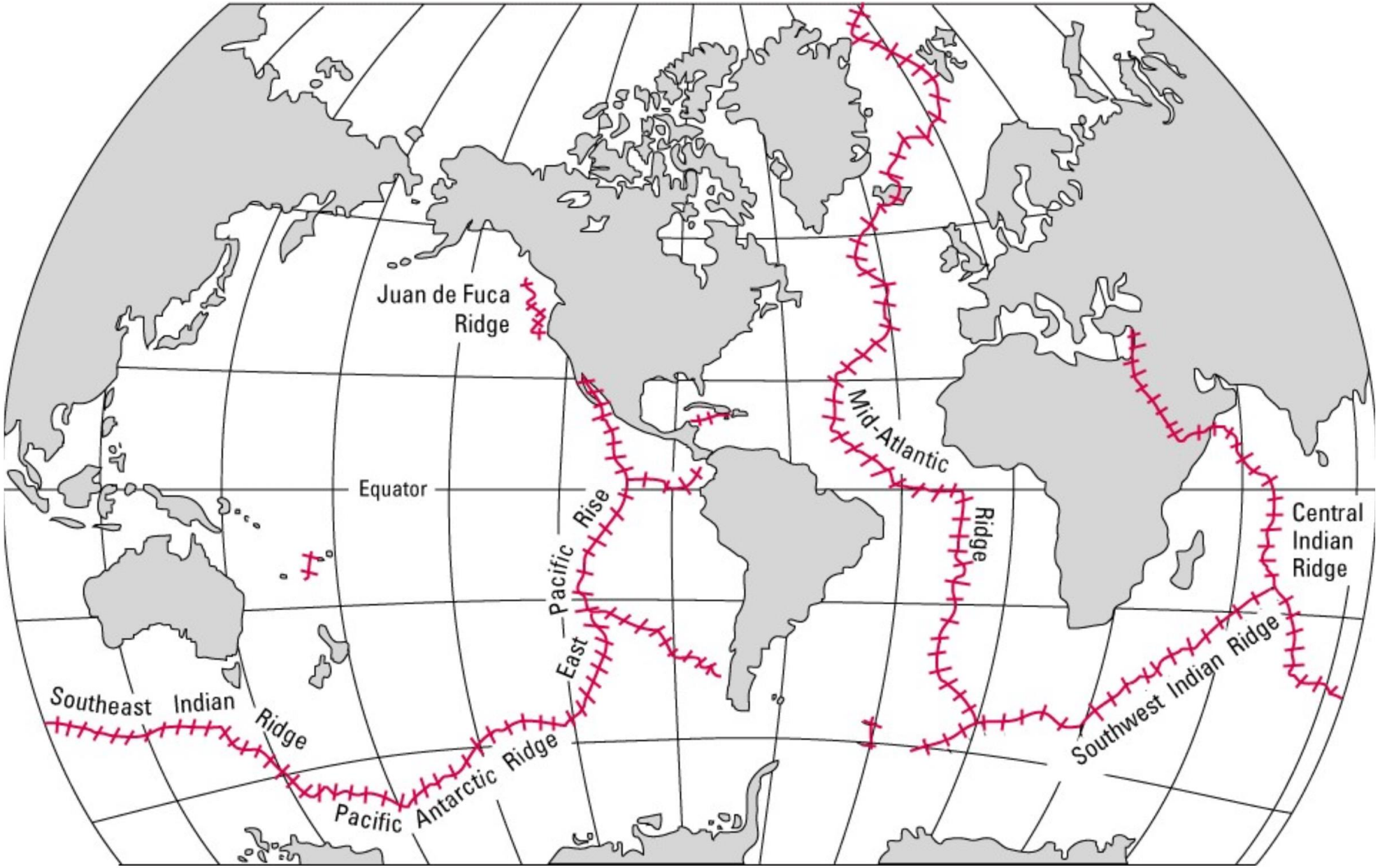




Topography of the Ocean Floor



Topography of the Ocean Floor



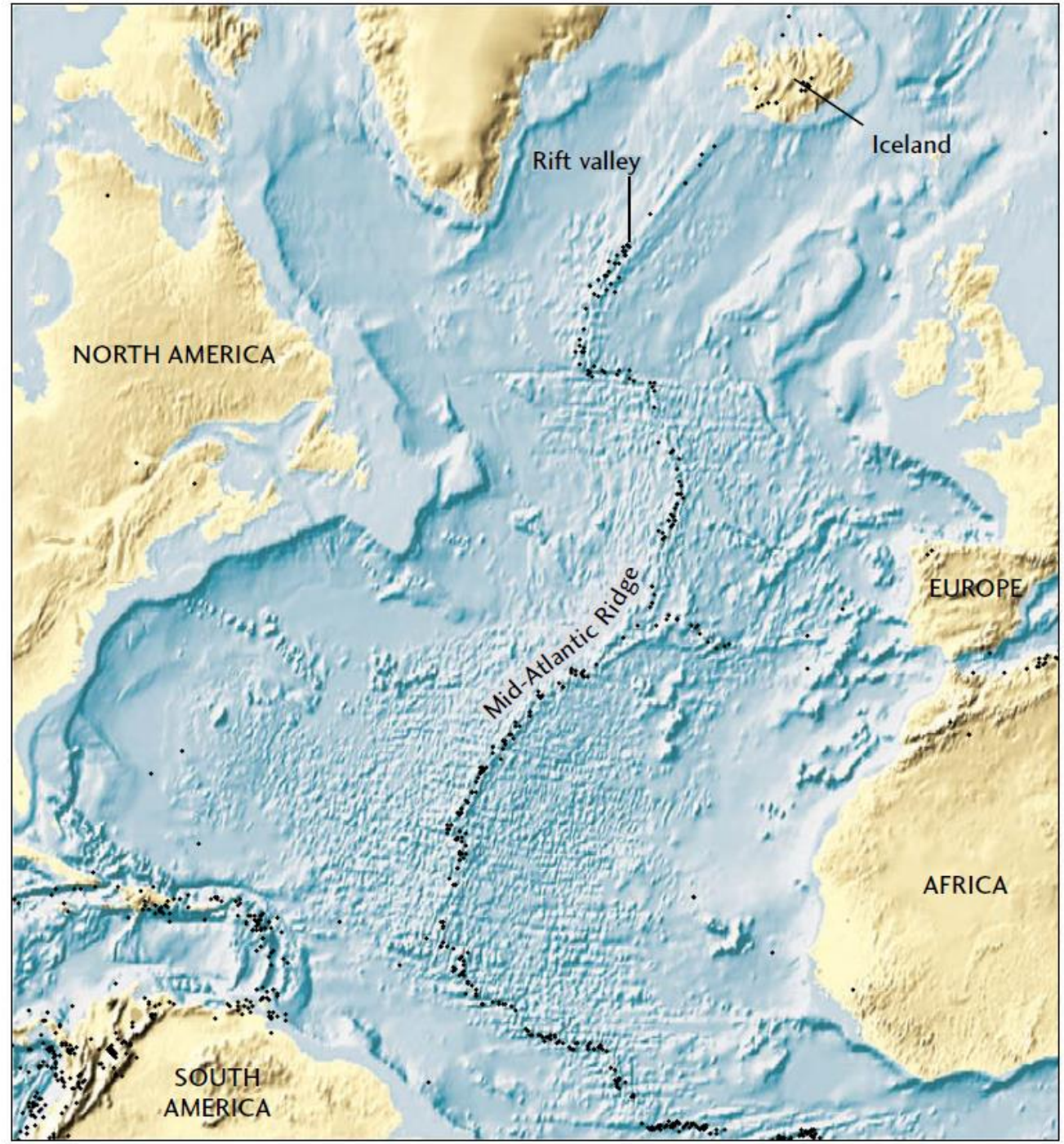


FIGURE 2.4 ■ The North Atlantic seafloor, showing the cracklike rift valley running down the center of the Mid-Atlantic Ridge and the locations of earthquakes (black dots).

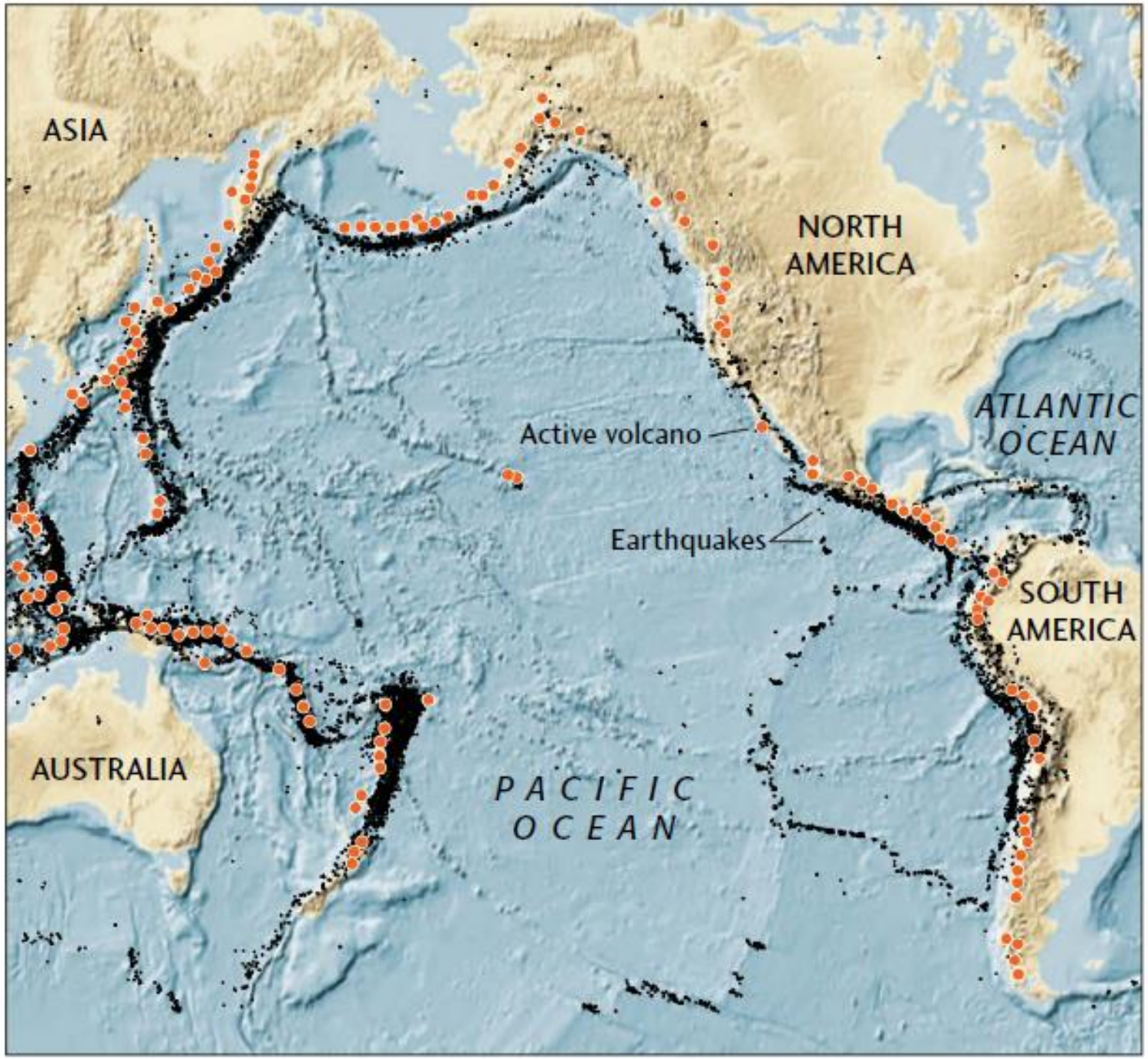
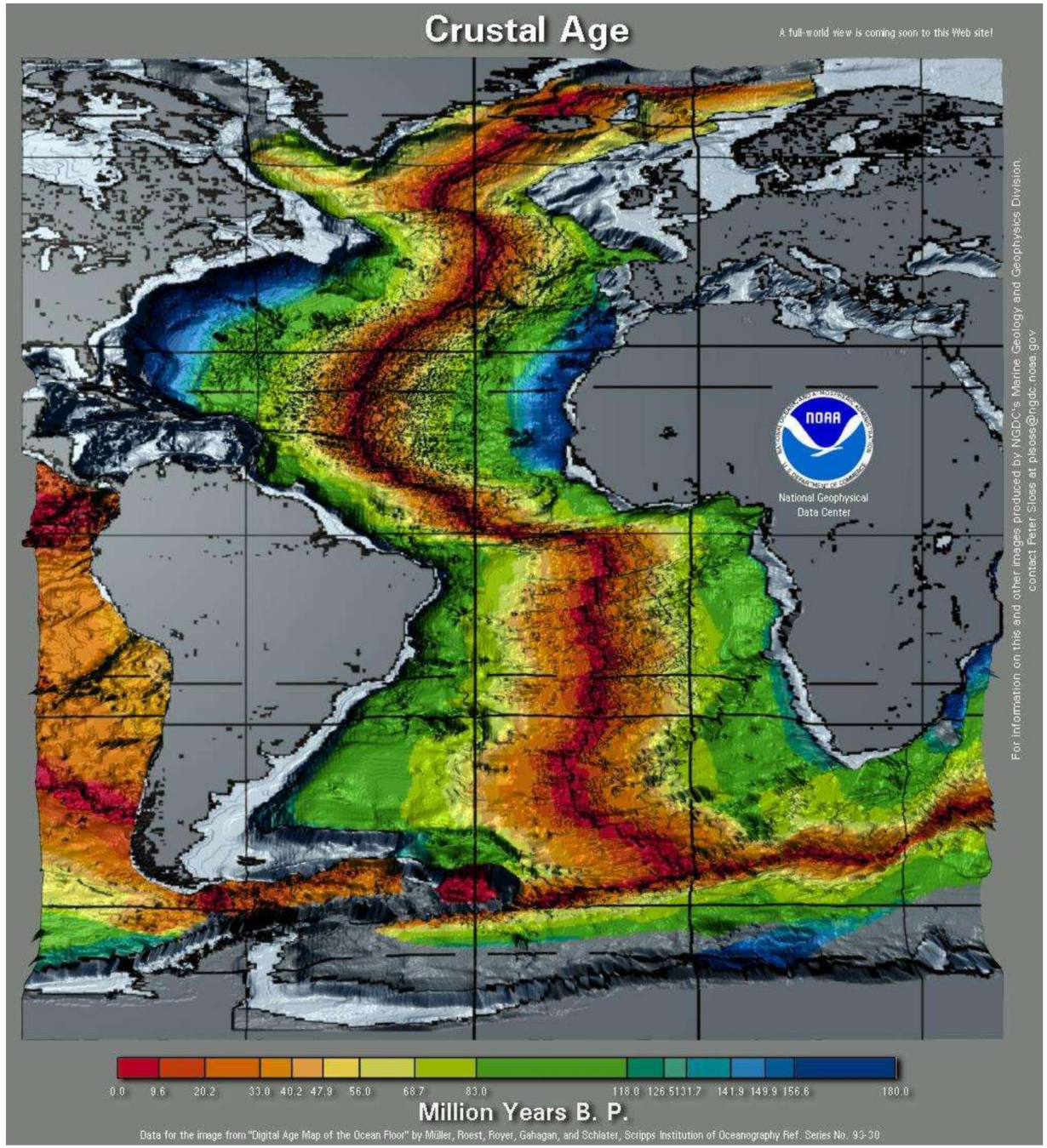
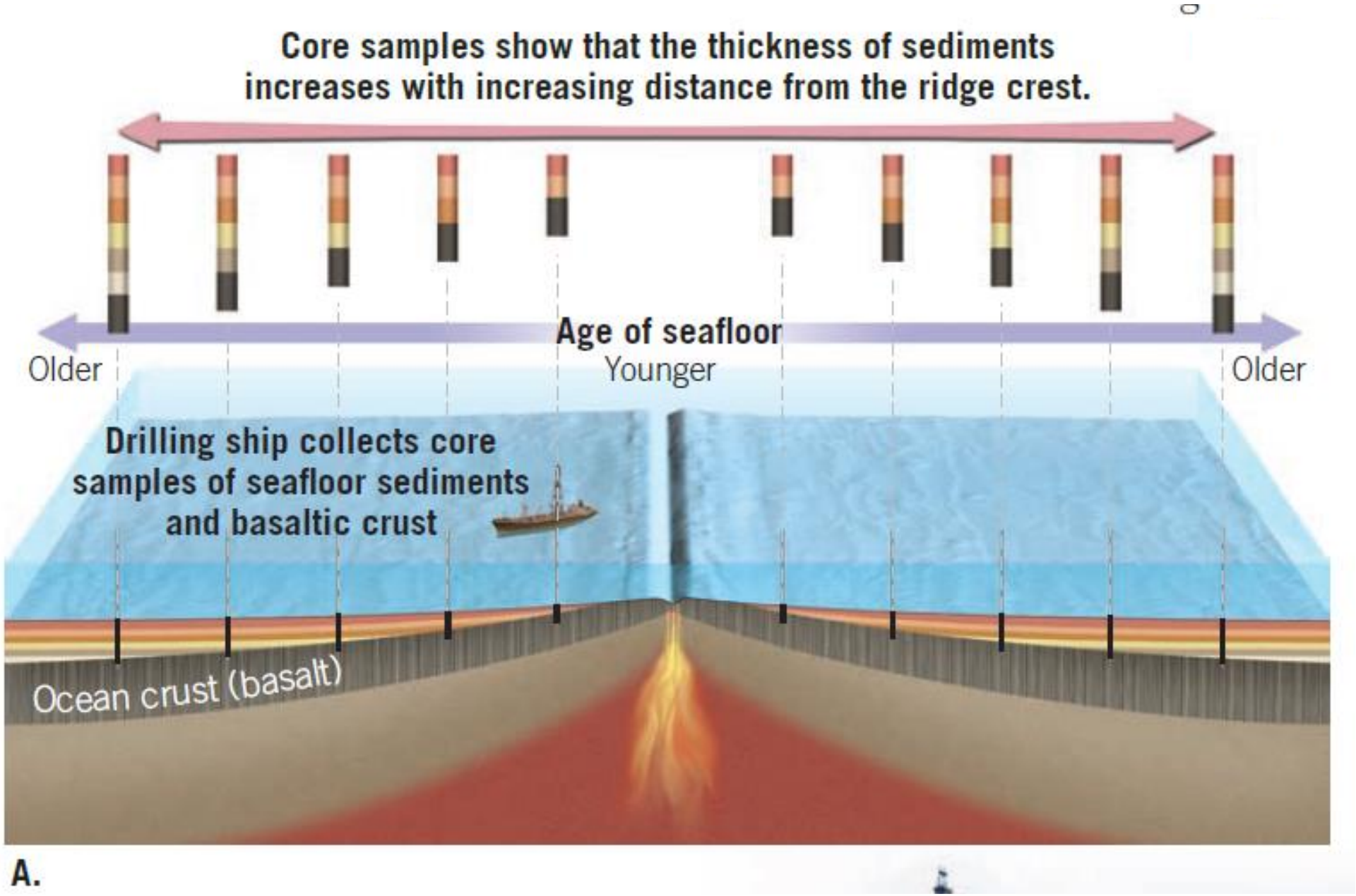


FIGURE 2.6 ■ The Pacific Ring of Fire, with its active volcanoes (large red circles) and frequent earthquakes (small black dots), marks convergent plate boundaries where oceanic lithosphere is being recycled.

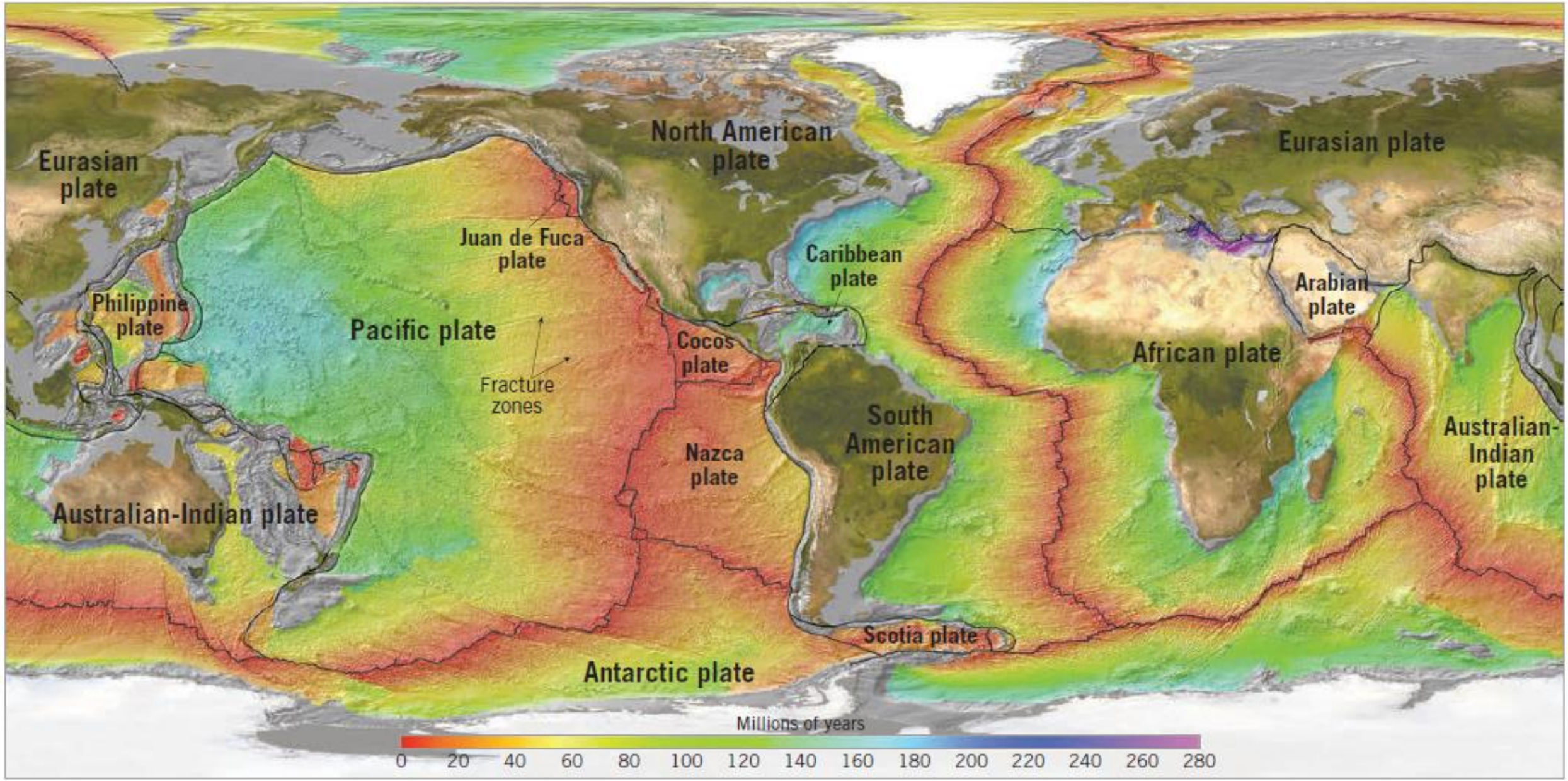


Atlantic Ocean

Crustal Ages


Core samples show that the thickness of sediments increases with increasing distance from the ridge crest.
Age of seafloor
Older
Younger
Older
Drilling ship collects core samples of seafloor sediments and basaltic crust
Ocean crust (basalt)

A.


Eurasian plate
North American plate
Eurasian plate
Juan de Fuca plate
Caribbean plate
Philippine plate
Pacific plate
Arabian plate
African plate
Cocos plate
Fracture zones
South American plate
Australian-Indian plate
Nazca plate
Australian-Indian plate
Scotia plate
Antarctic plate
Millions of years
0 20 40 60 80 100 120 140 160 180 200 220 240 260 280

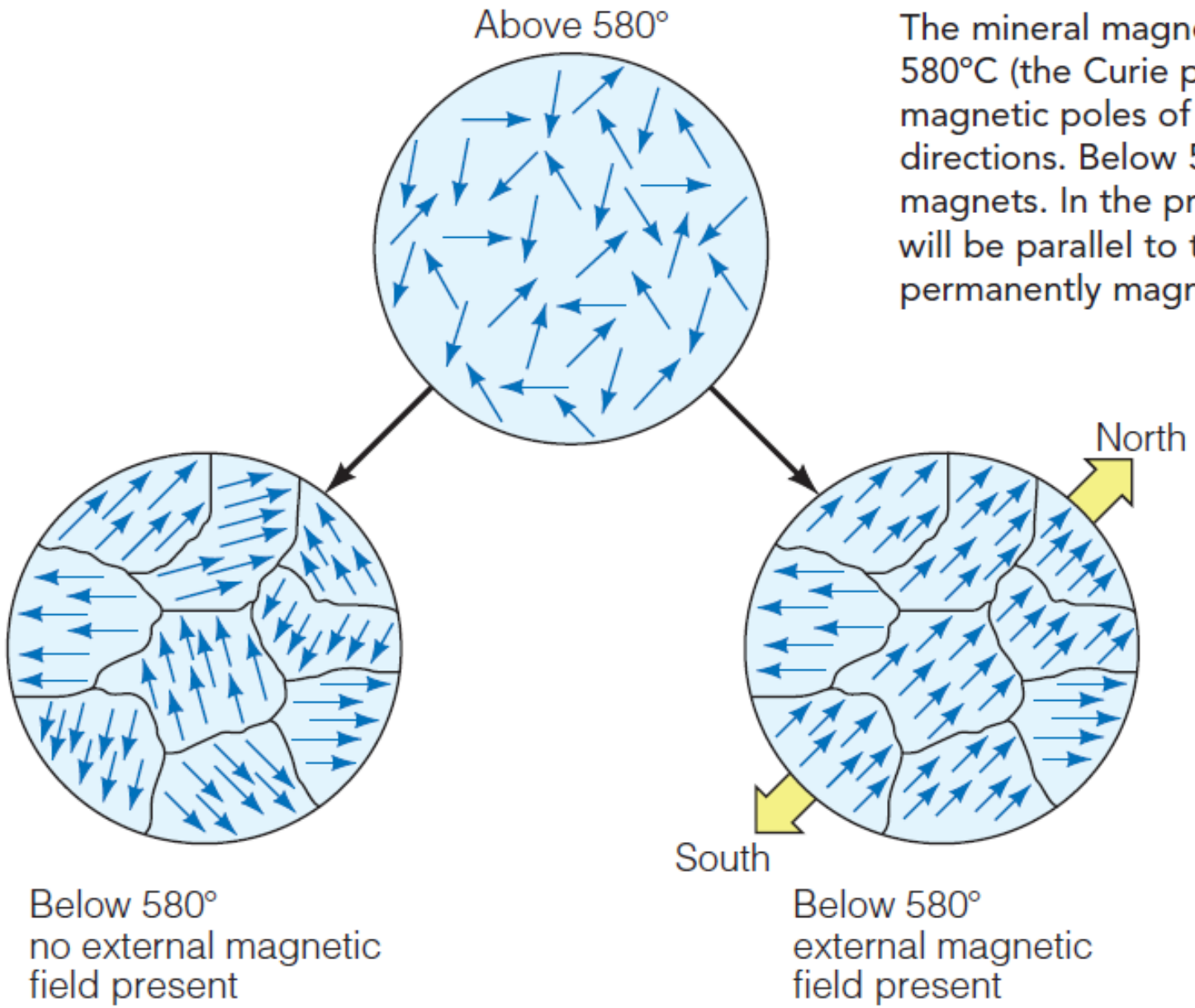
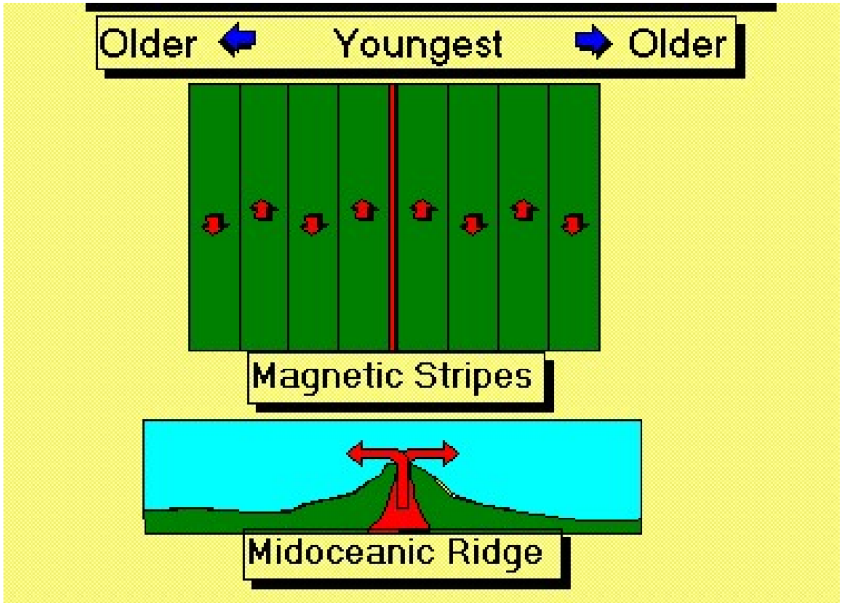


FIGURE B5.2 Magnetic magnetite
The mineral magnetite can acquire permanent magnetism. Above 580°C (the Curie point), the vibration of atoms is so great that the magnetic poles of individual atoms (small arrows) point in random directions. Below 580°C, the atoms begin to align and form tiny magnets. In the presence of an external magnetic field, most domains will be parallel to the external field, and the material becomes permanently magnetized.

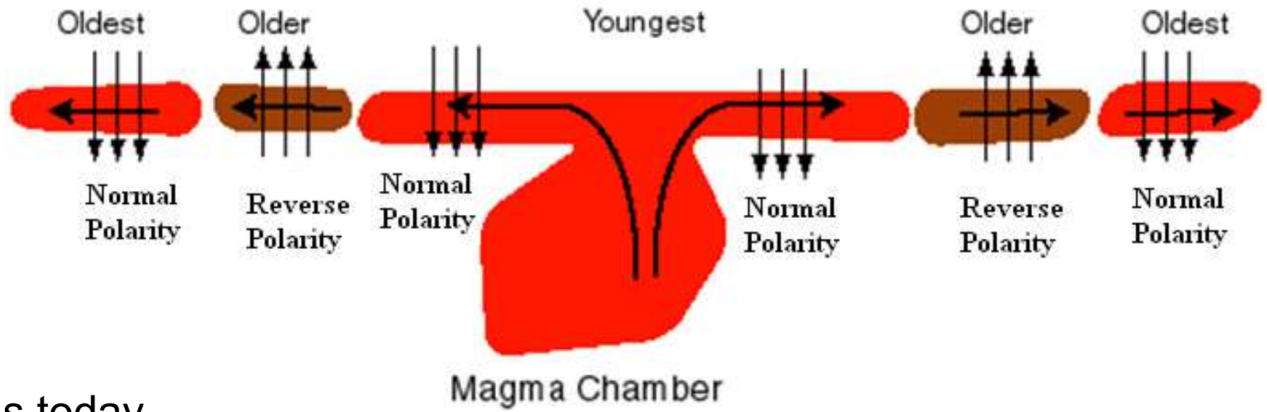
Another piece of the puzzle: Magnetic reversals



• The polarity changed throughout the history of the Earth.

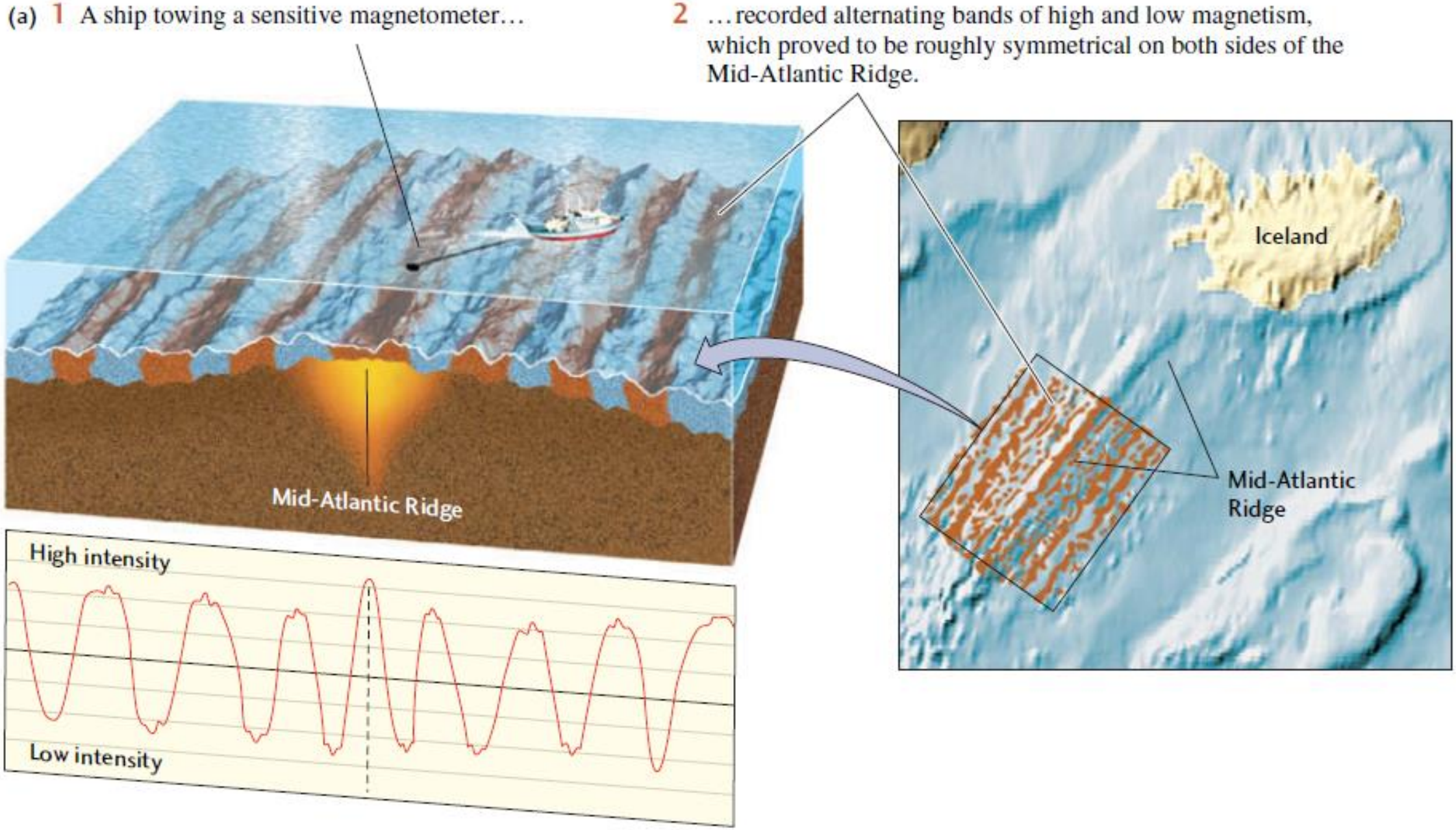
•The polarity gets recorded in the rock when it crystallizes from the magma.

• Since the poles flipped in different times, some of the rocks show normal polarity while others would show reverse polarity.

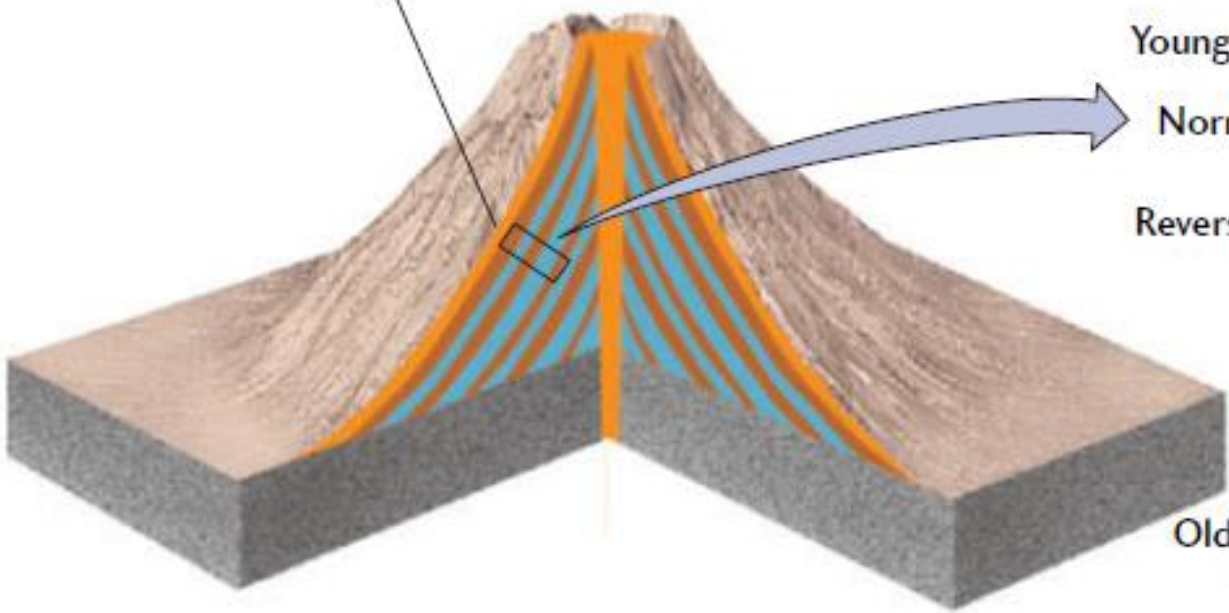


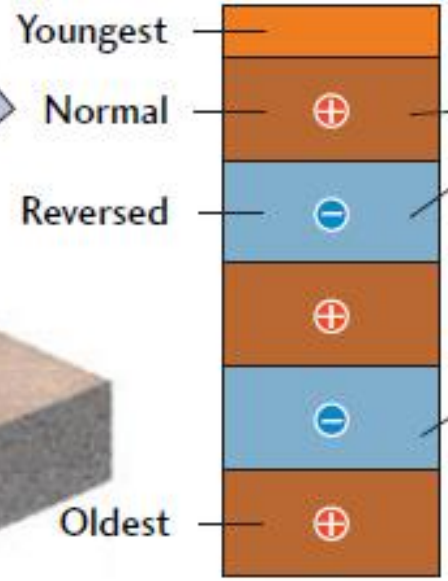
Normal polarity: Same as today.

Reverse polarity: Reverse orientation with respect to today's polarity.


(a) 1 A ship towing a sensitive magnetometer…
2 …recorded alternating bands of high and low magnetism, which proved to be roughly symmetrical on both sides of the Mid-Atlantic Ridge.
Mid-Atlantic Ridge
High intensity
Low intensity
Iceland
Mid-Atlantic Ridge

(b) 3 Volcanic lavas also revealed magnetic anomalies. When iron-rich lava cools, it becomes magnetized in the direction of Earth's magnetic field.





4 Lavas "remember" the magnetic field (thermoremanent magnetization).

5 Older, deeper layers preserve the direction of the magnetic field at earlier times.

6 By determining the ages of magnetic reversals at many volcanoes, scientists constructed a magnetic time scale.

Benioff Zone is an area of increasing seismic activity, inclined from the trench downward in the direction of island arc.

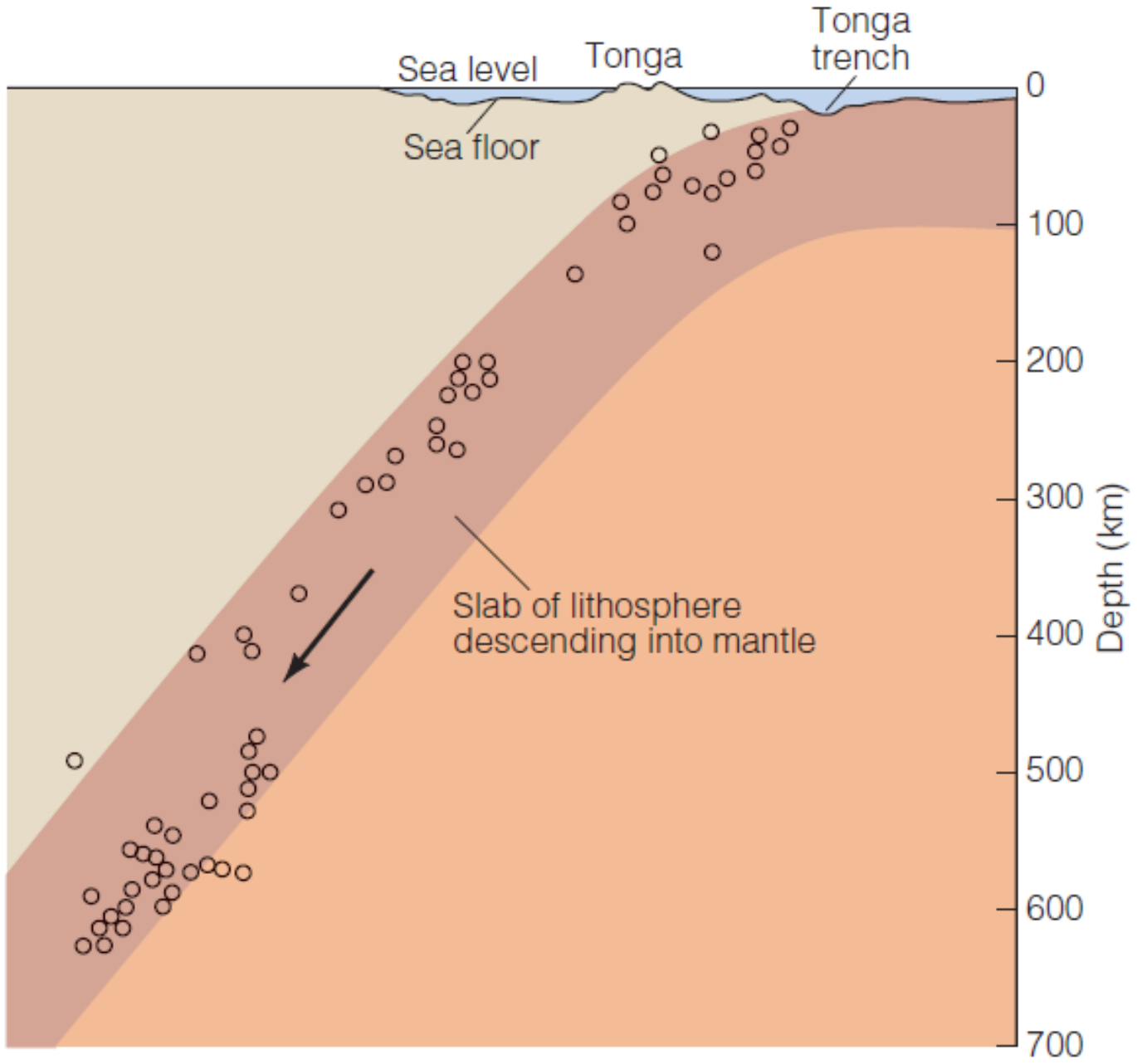
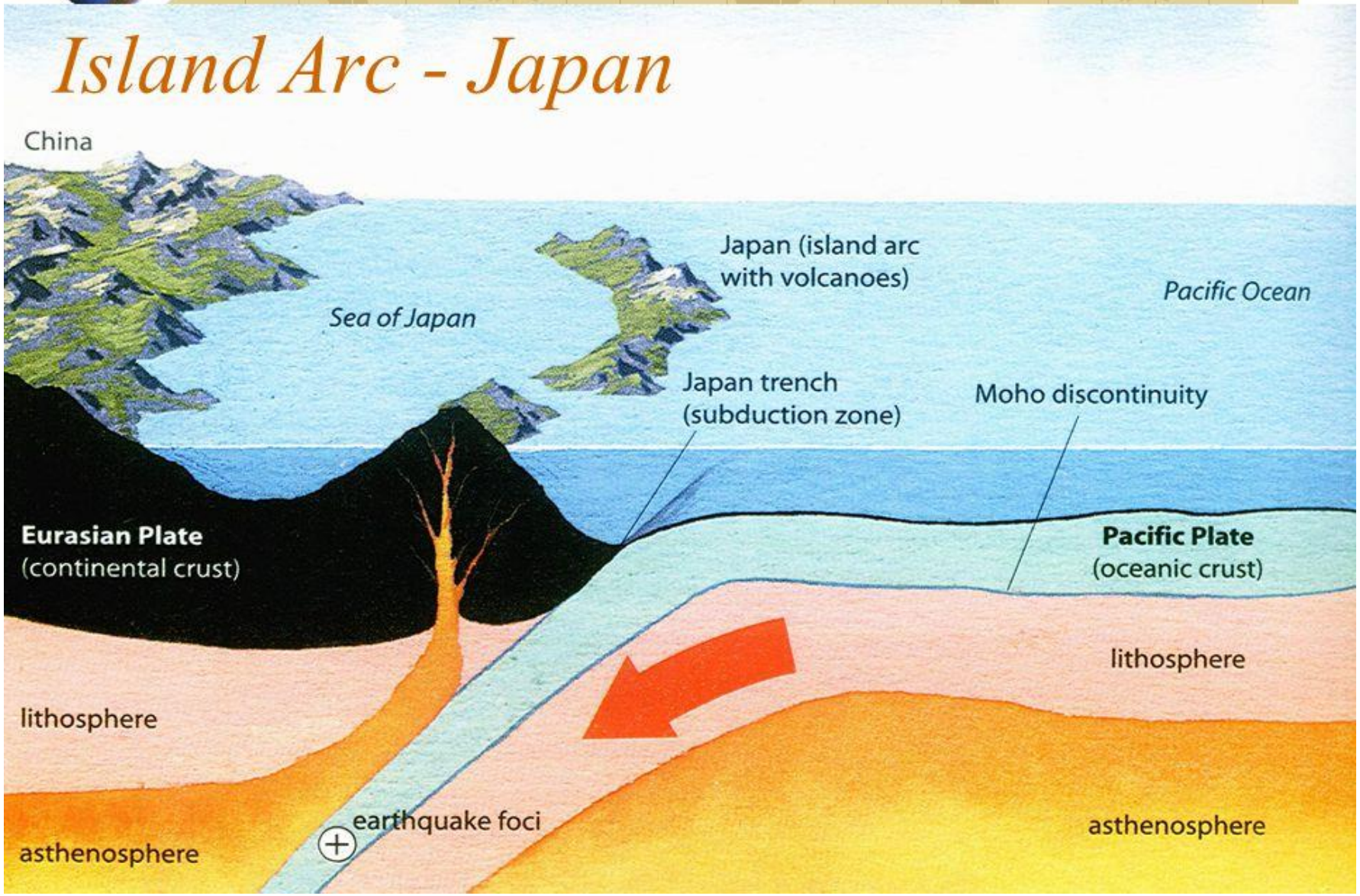


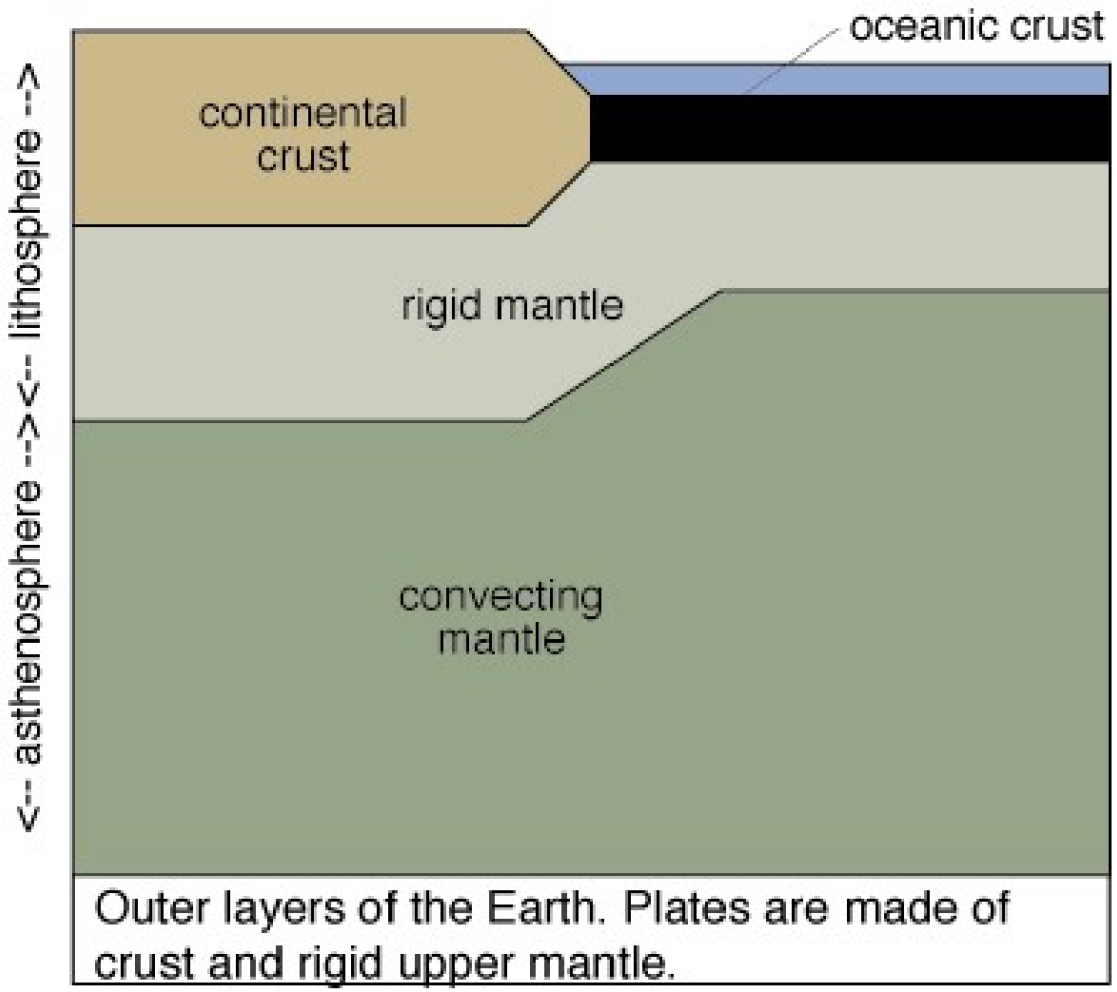
FIGURE 5.19 **Benioff zone**
Deep earthquakes define the dimensions of a downgoing slab of oceanic lithosphere in a Wadati-Benioff zone located in the Pacific Ocean near the island of Tonga. Each circle represents a single earthquake in a given year. The earthquakes are generated by the downward grinding movement of the comparatively cold slab of lithosphere.

Island Arc - Japan



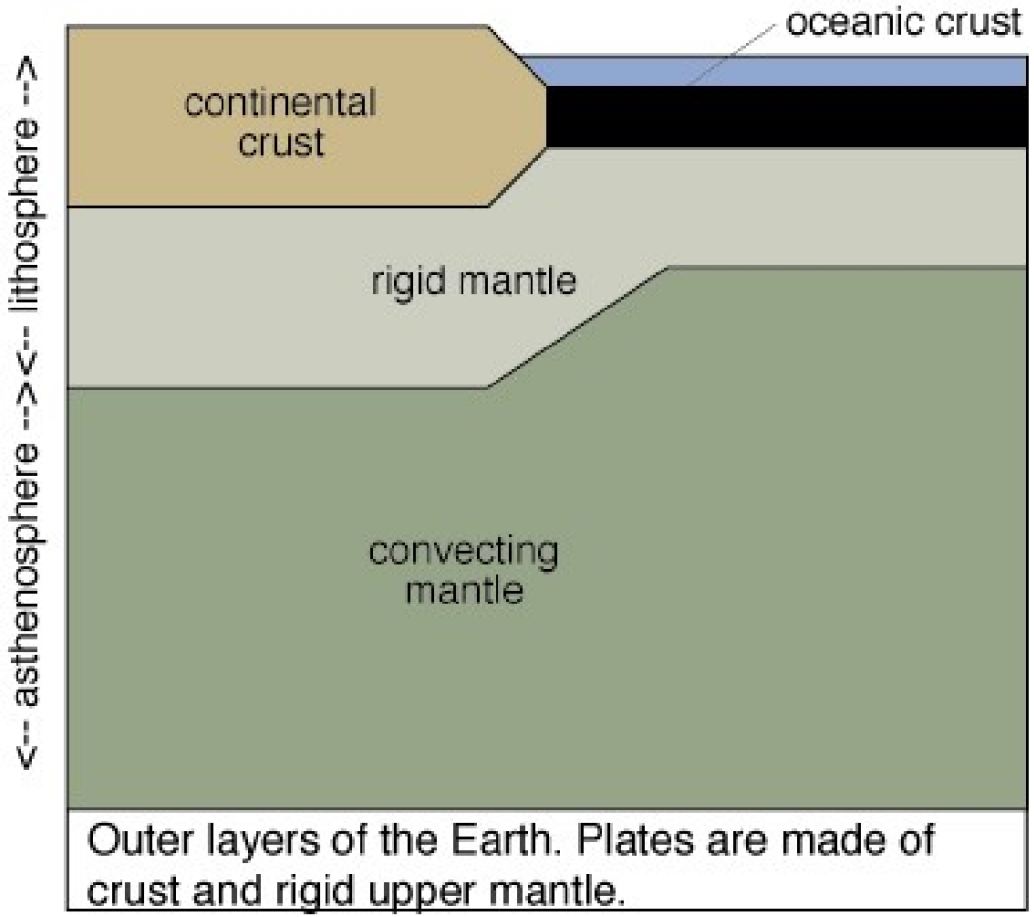
LITHOSPHERE

- The lithosphere (from the Greek, lithos, stone) is the rigid outermost layer made of crust and uppermost mantle
- The lithosphere is the "plate" of the plate tectonic theory



ASTHENOSPHERE

- The asthenosphere (from the Greek, asthenos, devoid of force) is part of the mantle that flows, a characteristic called plastic behavior.
- The flow of the asthenosphere is part of mantle convection, which plays an important role in moving lithospheric plates.



Mantle Plume and Hot Spots

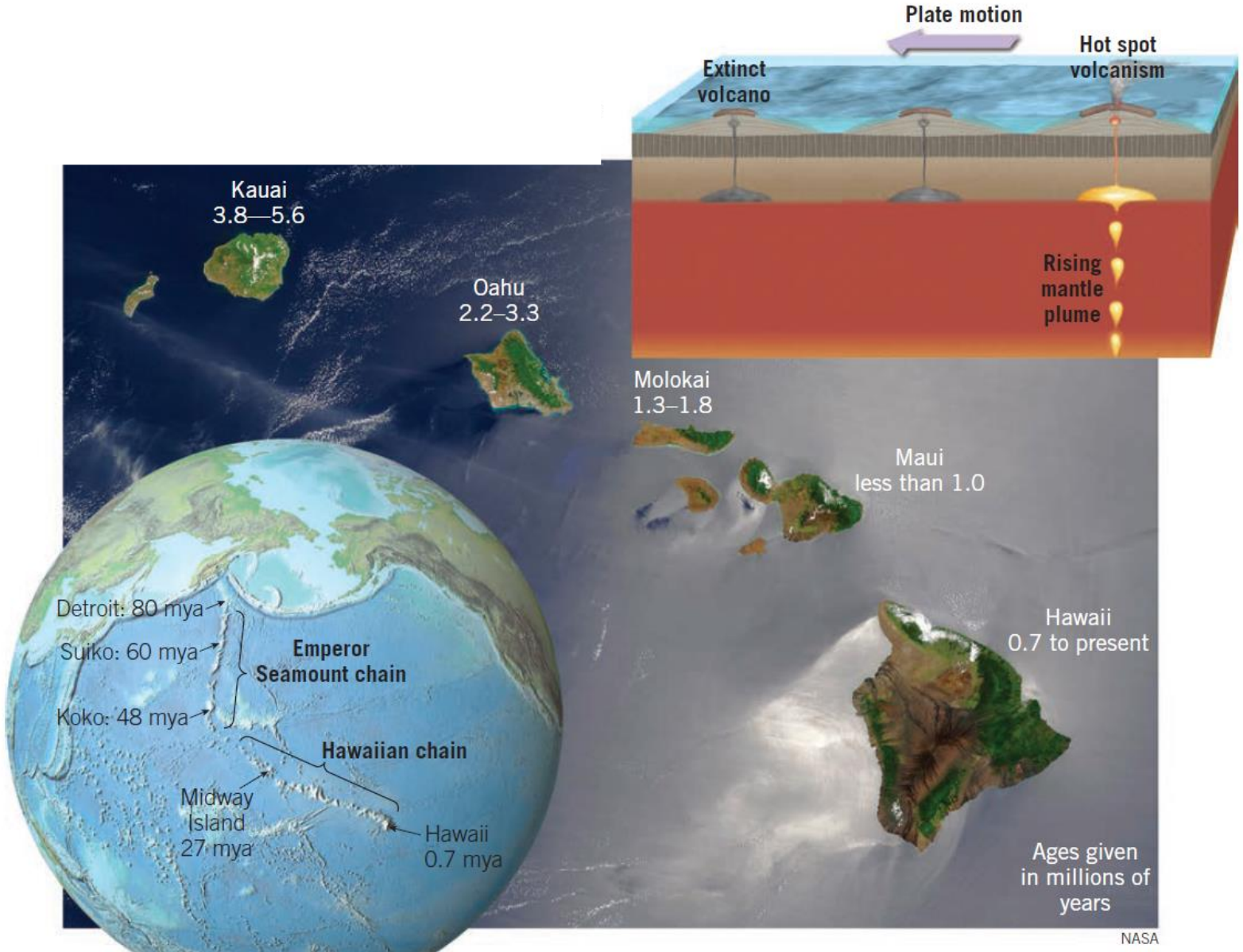
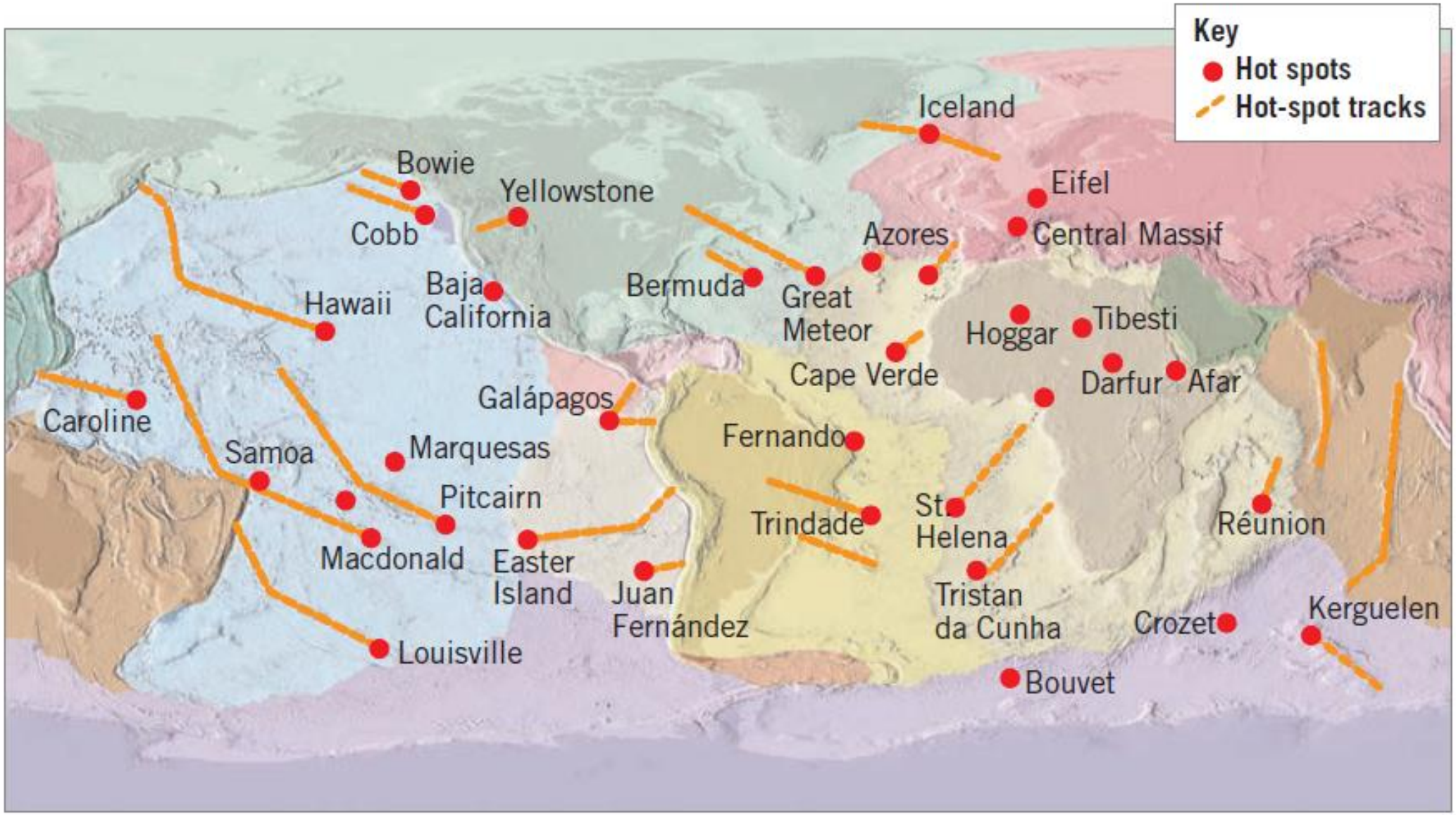


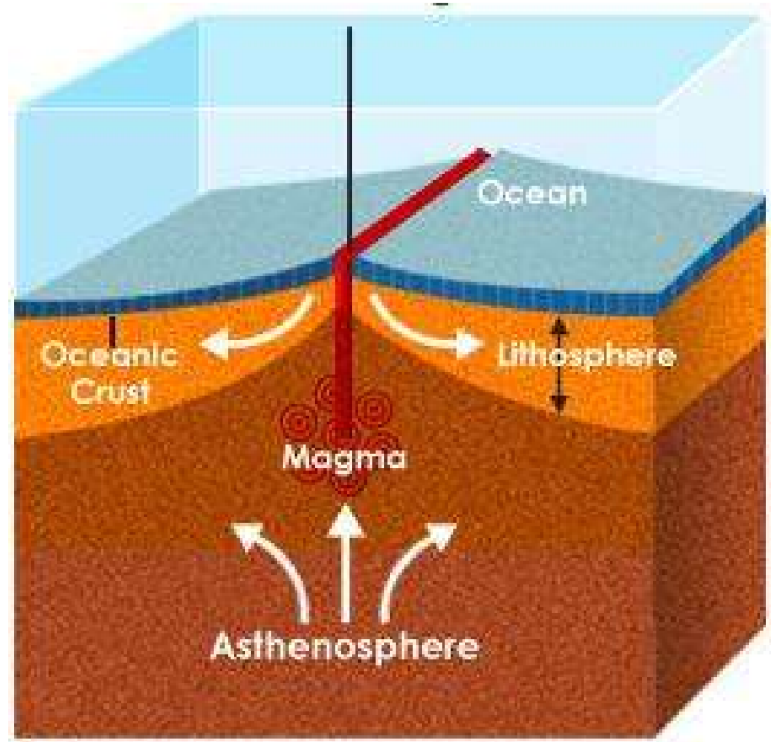
Figure 2.27
Hot-spot volcanism and the formation of the Hawaiian chain
Radiometric dating of the Hawaiian Islands shows that volcanic activity increases in age moving away from the Big Island of Hawaii.

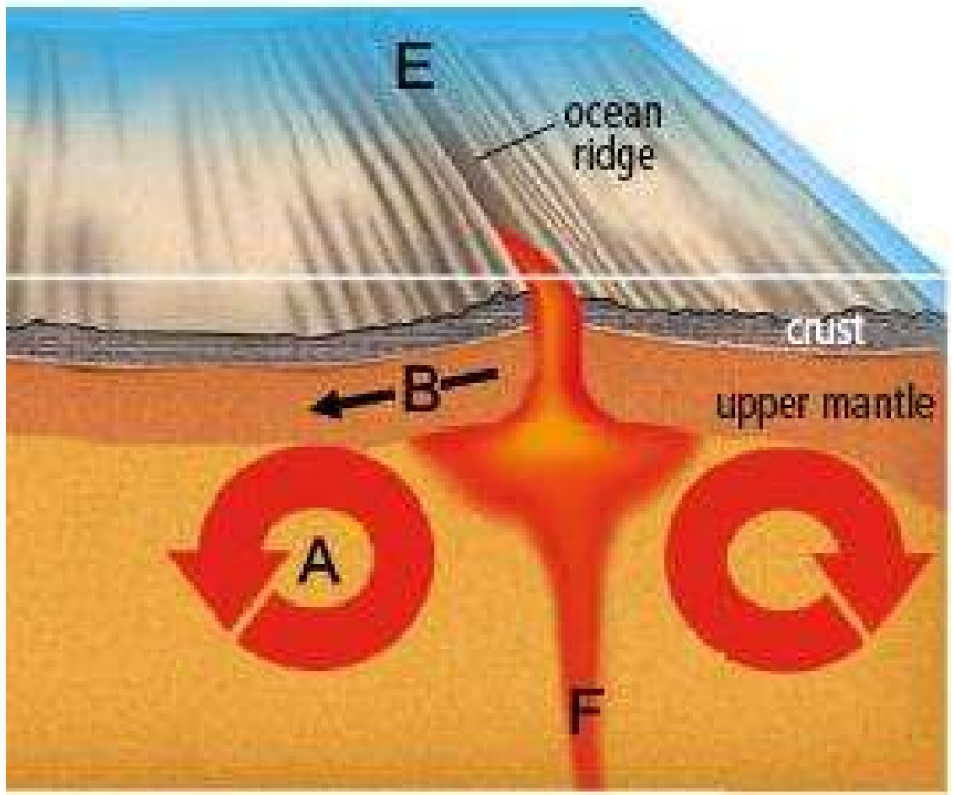
Mantle Plume and Hot Spots



How does it work??

- All starts at the mantle.
- Magma comes from the mantle.
- The motion of the magma is guided by the convection cycle.
- As it comes to the surface, it pushes the oceanic plates apart.





- Problem:

-If we constantly generate oceanic plates, the would eventually push the continents.

- After a time there won't be enough space because the surface of the earth is not expanding.

- Where does it all go?

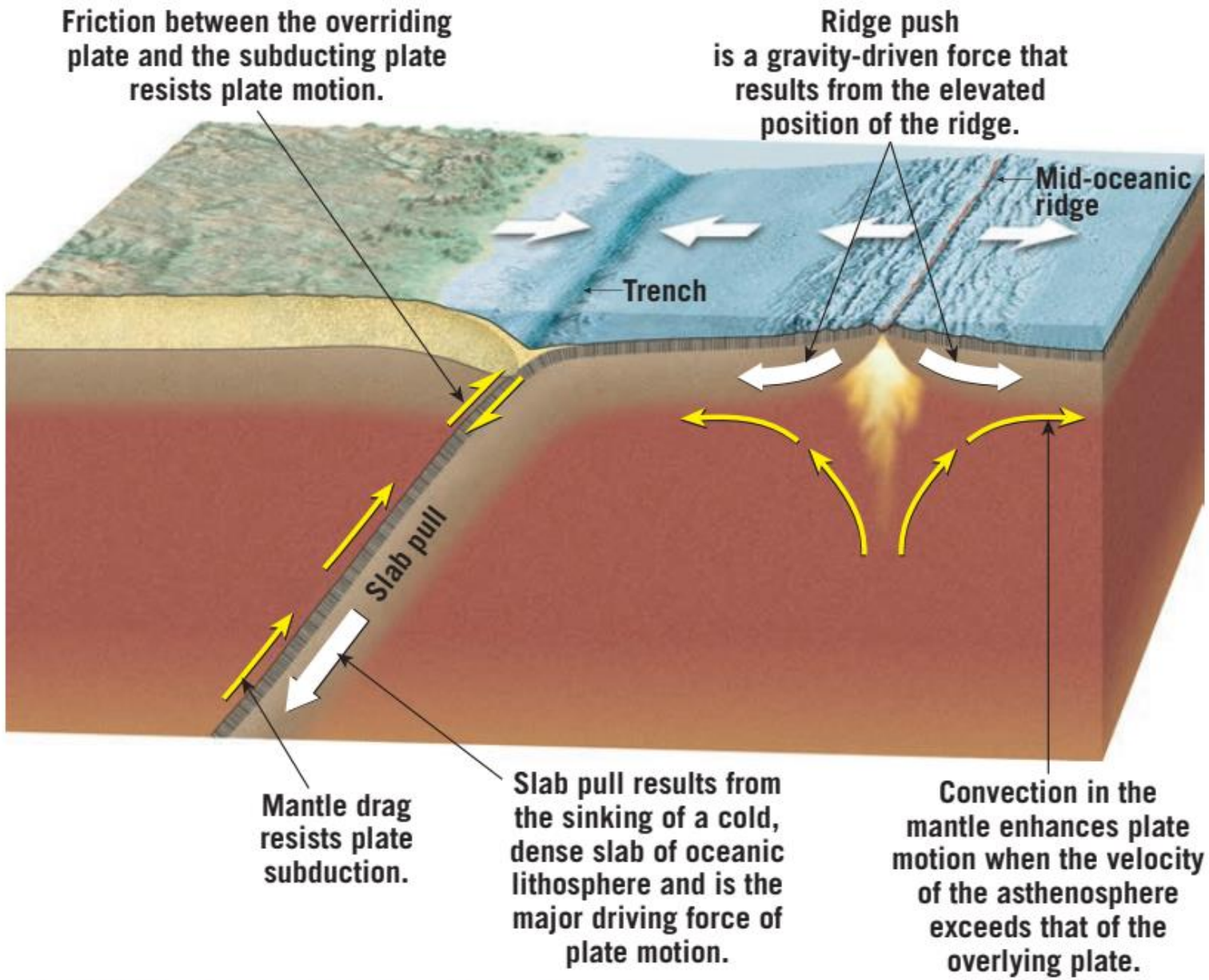
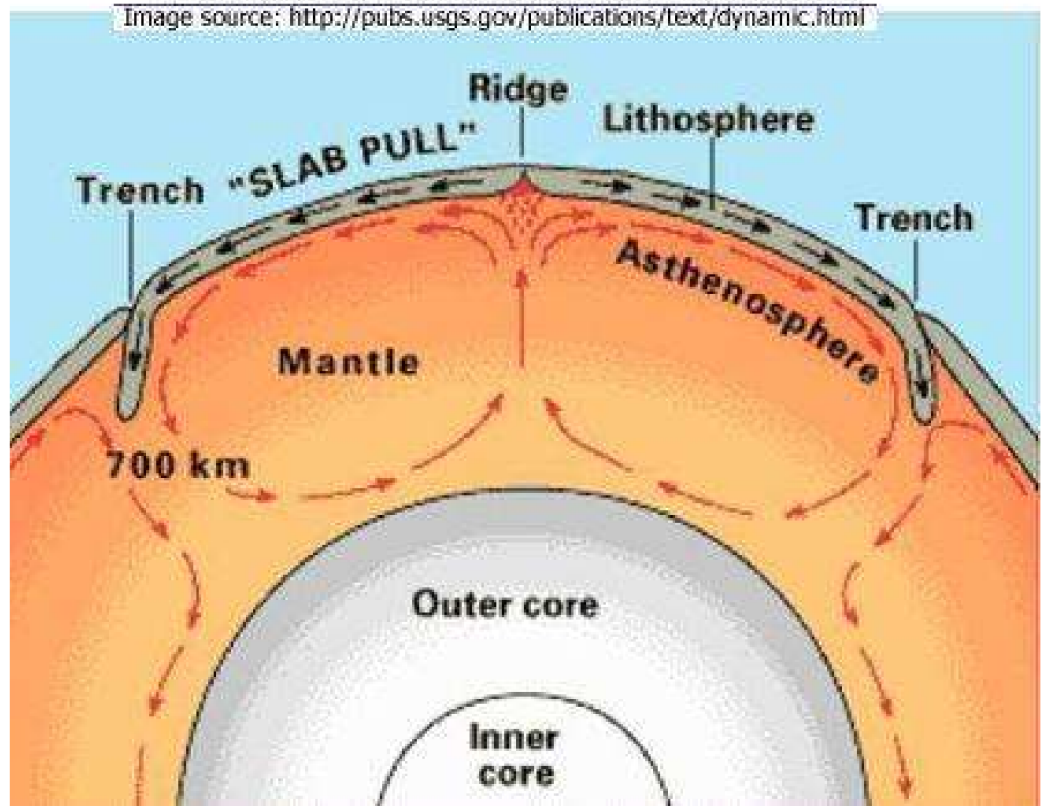


Figure 2.37 Forces that act on lithospheric plates

The Forces That Cause Plate Tectonics

Image source: http://pubs.usgs.gov/publications/text/dynamic.html



The lithosphere is the crust and the upper mantle. The lithosphere is divided into plates. The plates move because of convection currents (shown above). **Convection is the major mechanism of energy transfer in the oceans, atmosphere, and Earth's interior.**

Convection currents are when hot, less dense material rises, cools, becomes more dense and sinks.

Why don’t we see any oceanic crust older than 200 my ?

-They must be consumed somewhere.
- That’s where the trenches are. It is called subduction zone.
- When oceanic crust hits the continental crust, heavy oceanic crust goes under the continental crust.

- As it moves down due to increasing Temperature, it starts melting.

-All the oceanic crust older than 200my has already gone down and remelted.

-So we don’t have any record of those old oceanic crusts.

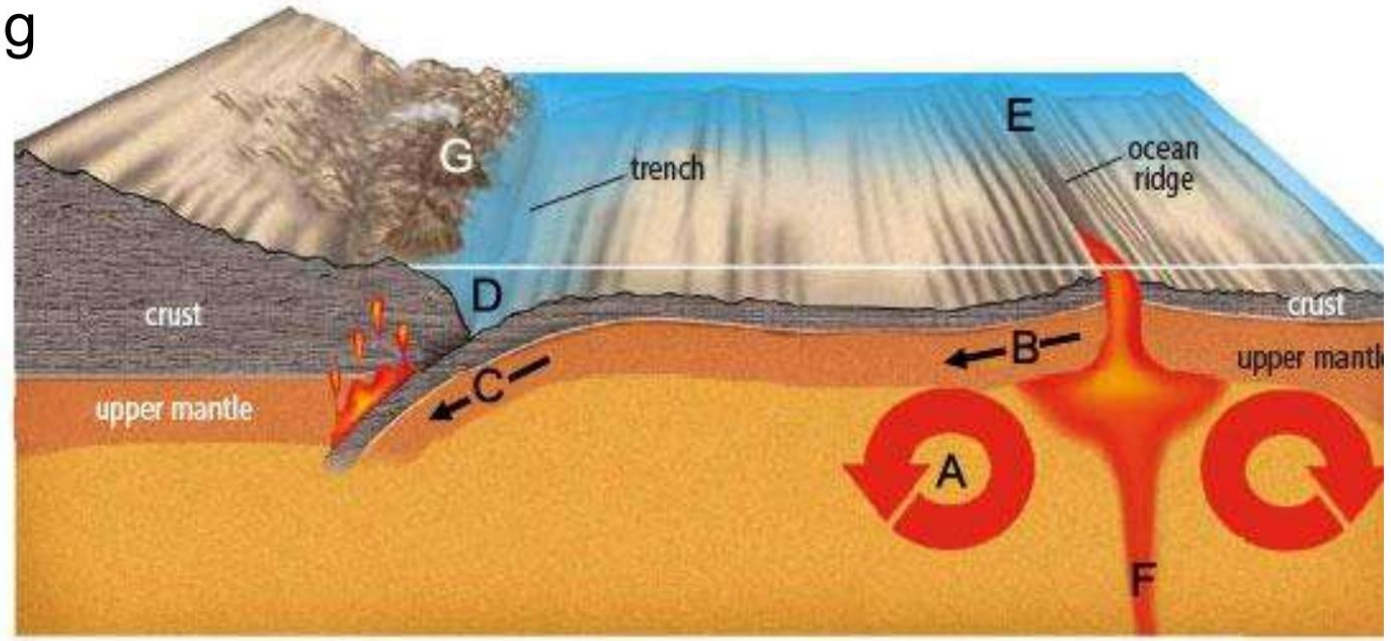
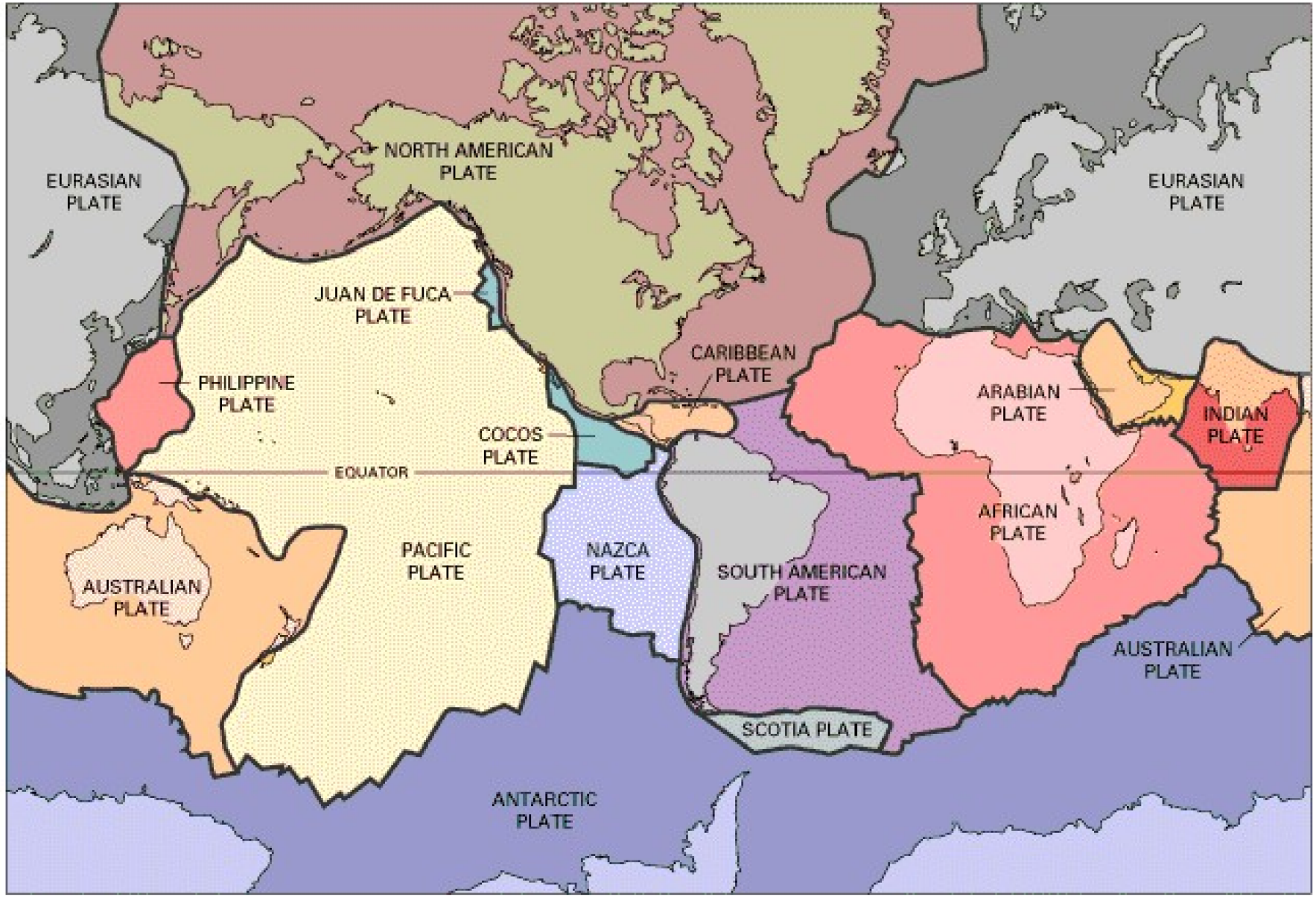


Plate Boundaries on Earth



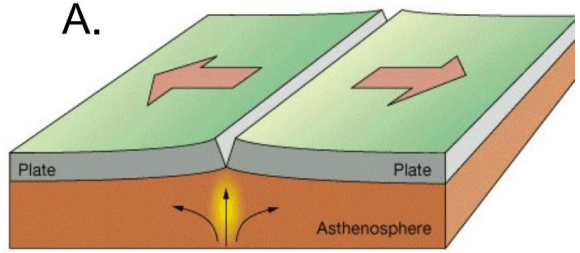
Types of Plate Boundaries

Types of plates: Continental plate (Light)
Oceanic plate (Heavy)

Three main types of boundaries:

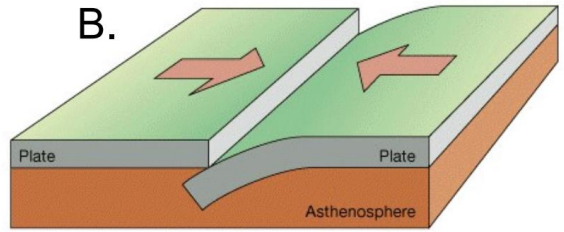
A. Divergent Boundaries
(where the plates are going away from each other.
Example: Mid Atlantic Ridge).

A.



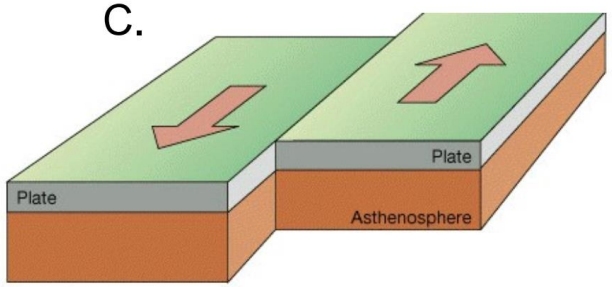
B. Convergent Boundaries
(where the plates are coming towards each other)

B.



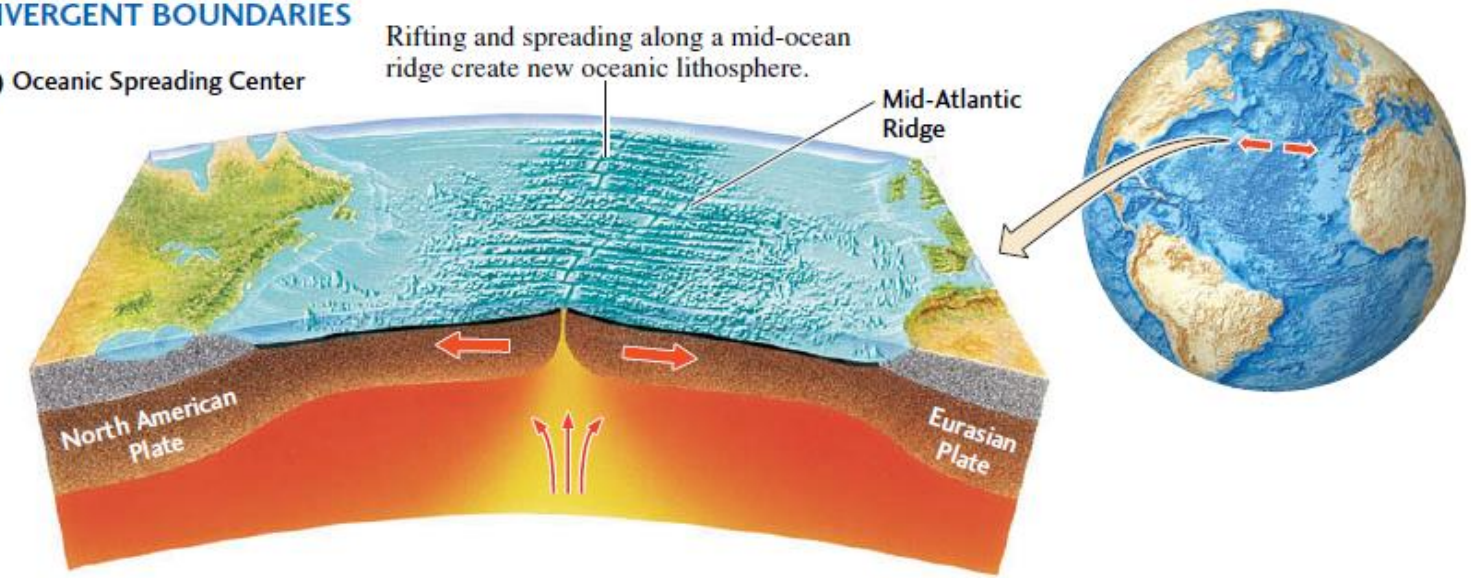
C. Transform Boundary
(where plates are going past each other.
Exam: San Andreas Fault)

C.

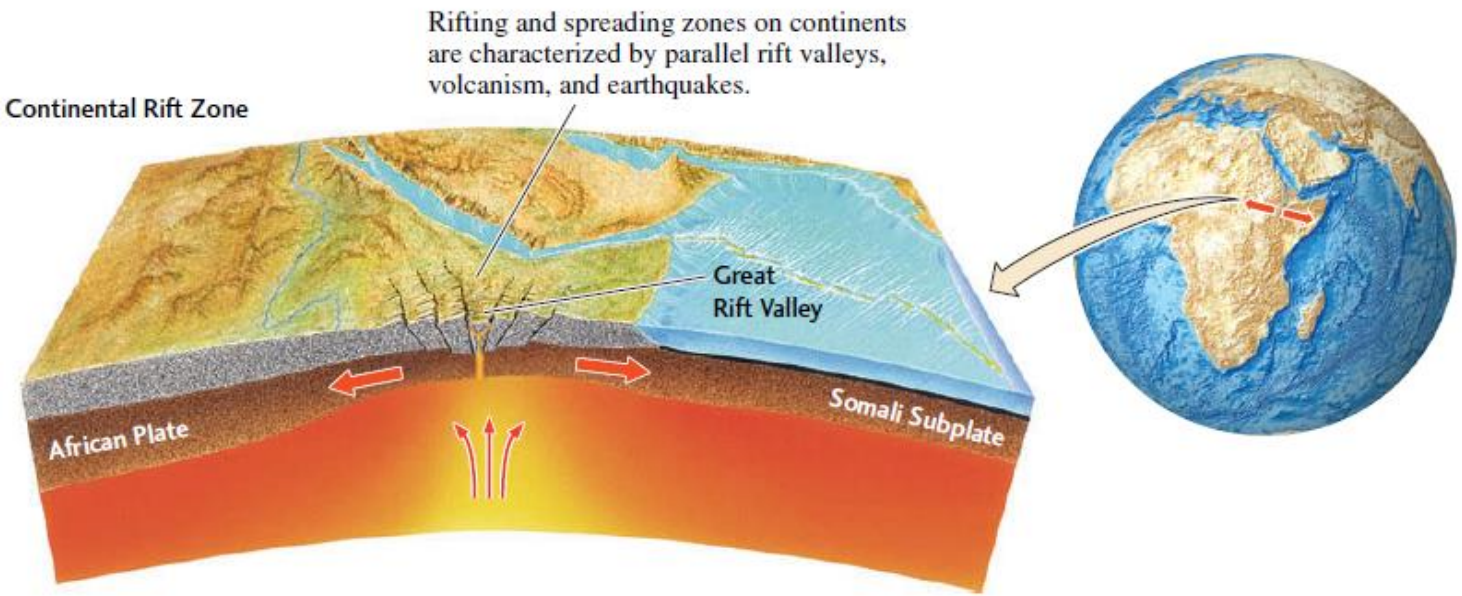


DIVERGENT BOUNDARIES

(a) Oceanic Spreading Center



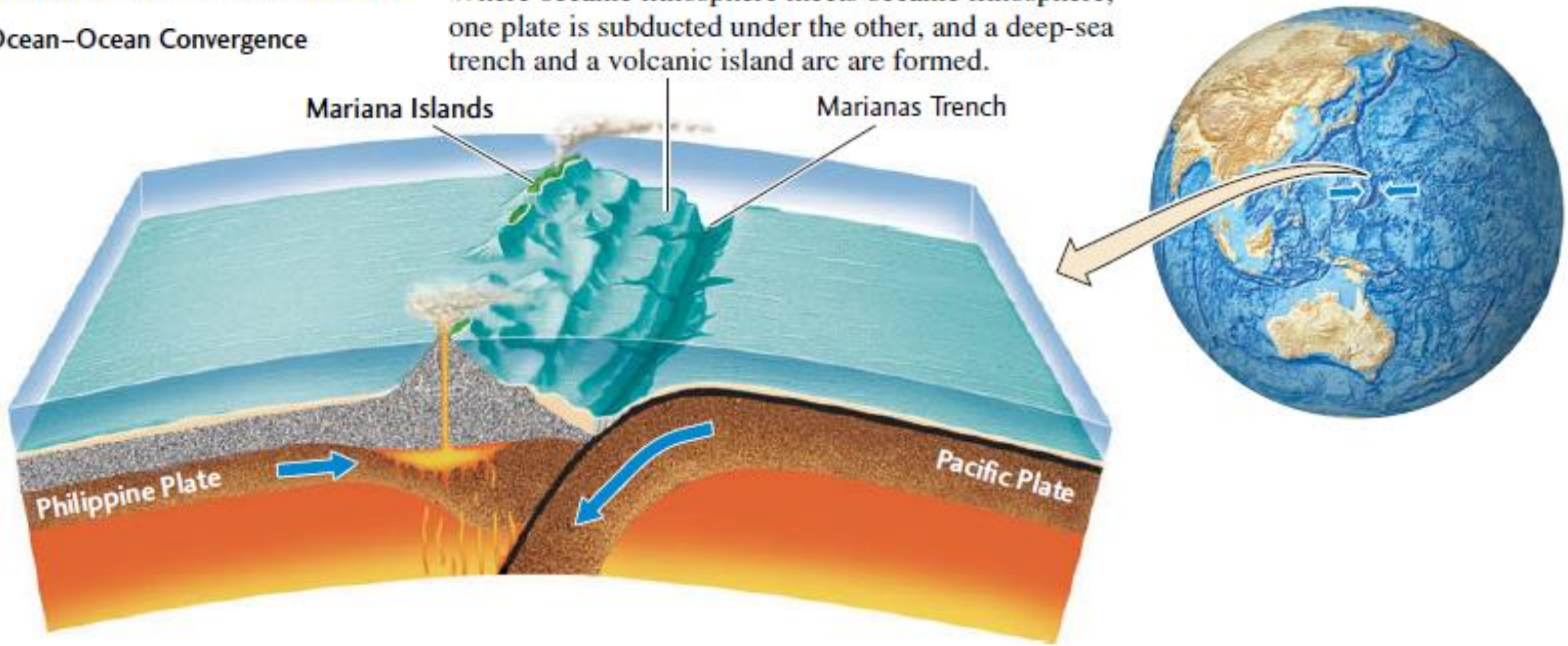
(b) Continental Rift Zone



CONVERGENT BOUNDARIES

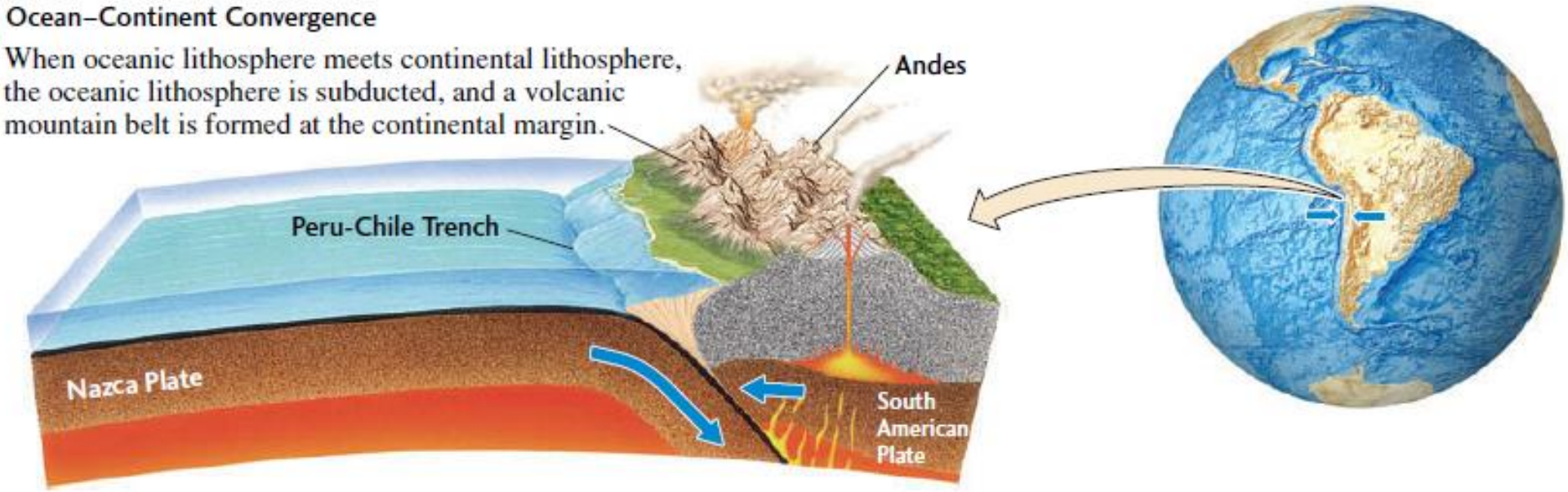
(c) Ocean–Ocean Convergence

Where oceanic lithosphere meets oceanic lithosphere, one plate is subducted under the other, and a deep-sea trench and a volcanic island arc are formed.



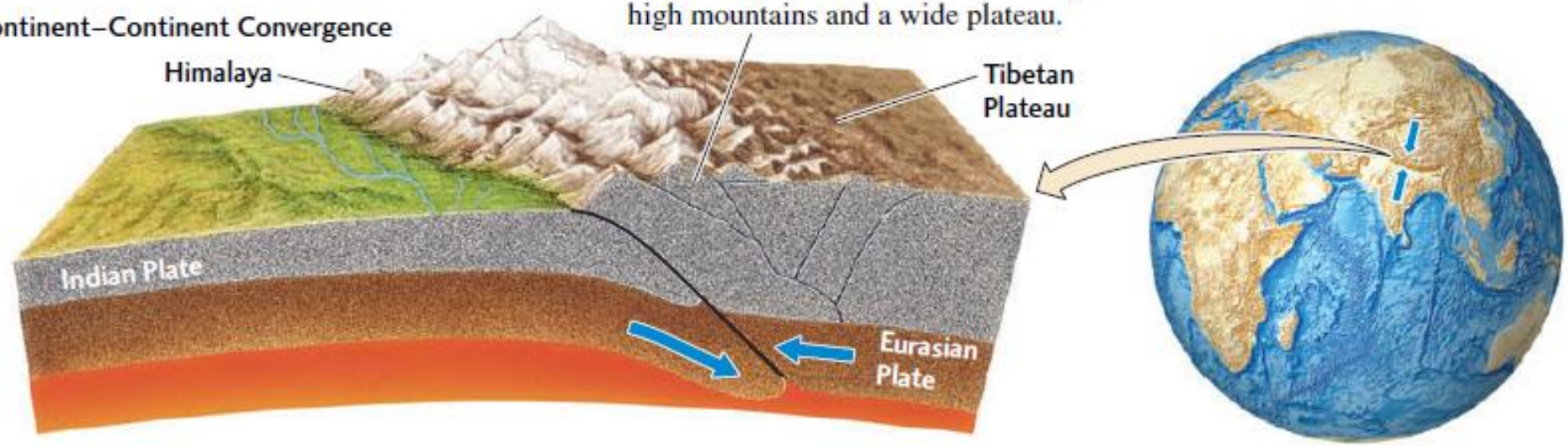
(d) Ocean–Continent Convergence

When oceanic lithosphere meets continental lithosphere, the oceanic lithosphere is subducted, and a volcanic mountain belt is formed at the continental margin.



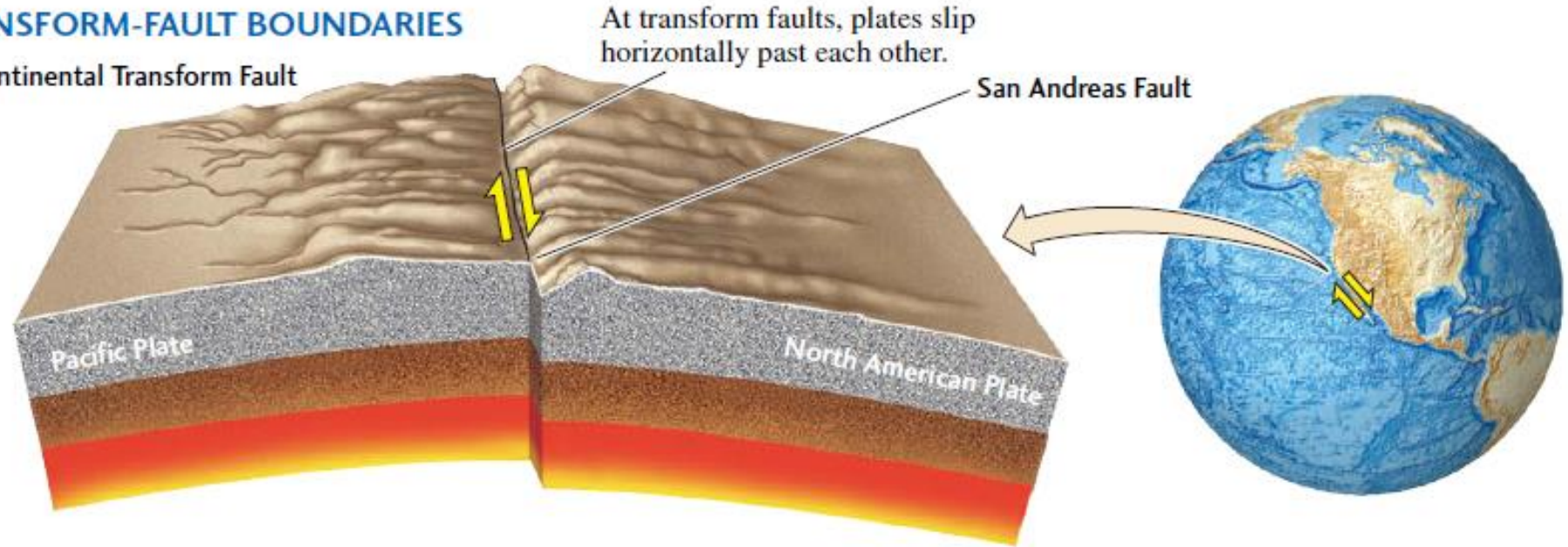
(e) Continent–Continent Convergence

Where two continents converge, the crust crumples and thickens, creating high mountains and a wide plateau.

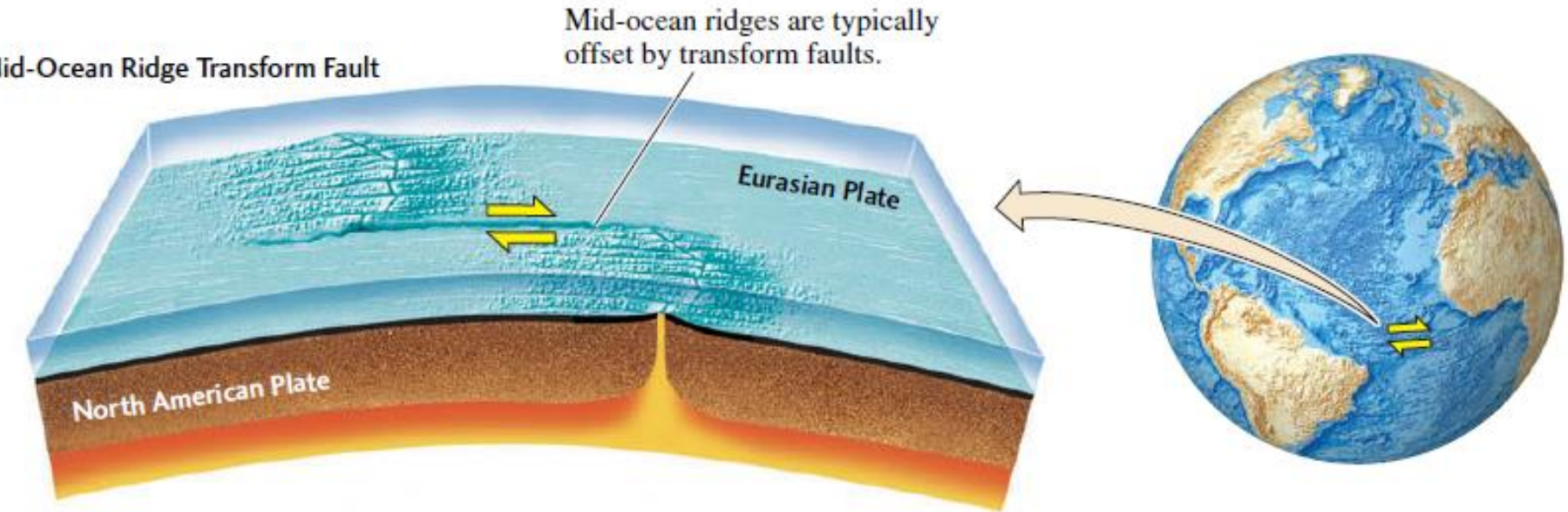


TRANSFORM-FAULT BOUNDARIES

(f) Continental Transform Fault



(g) Mid-Ocean Ridge Transform Fault

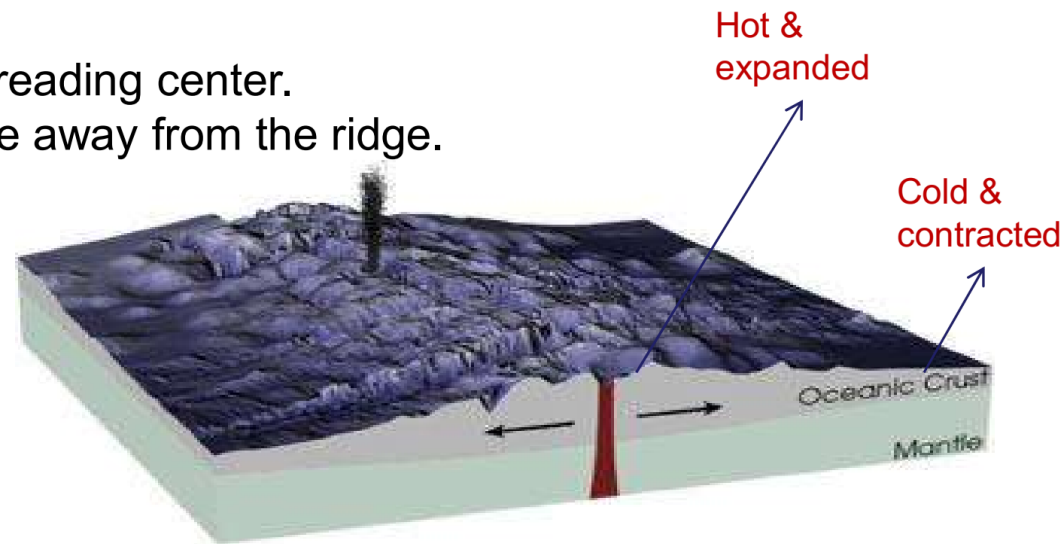


Divergent Boundaries

1. Continental rifts: Continent breaks apart

2. Mid Oceanic ridges:
• The mechanism that operates along the oceanic ridge system to create new seafloor is called seafloor spreading.
• Typical spreading rate -- 2 inches/ year

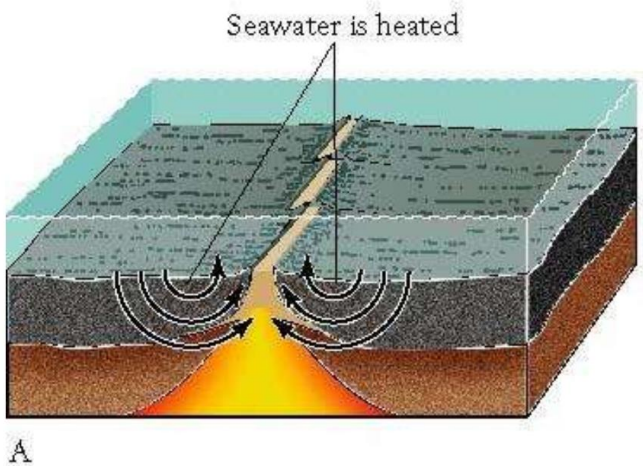
Shape of the ridge:
- It has maximum height at the spreading center.
- Gradually decreases as we move away from the ridge.

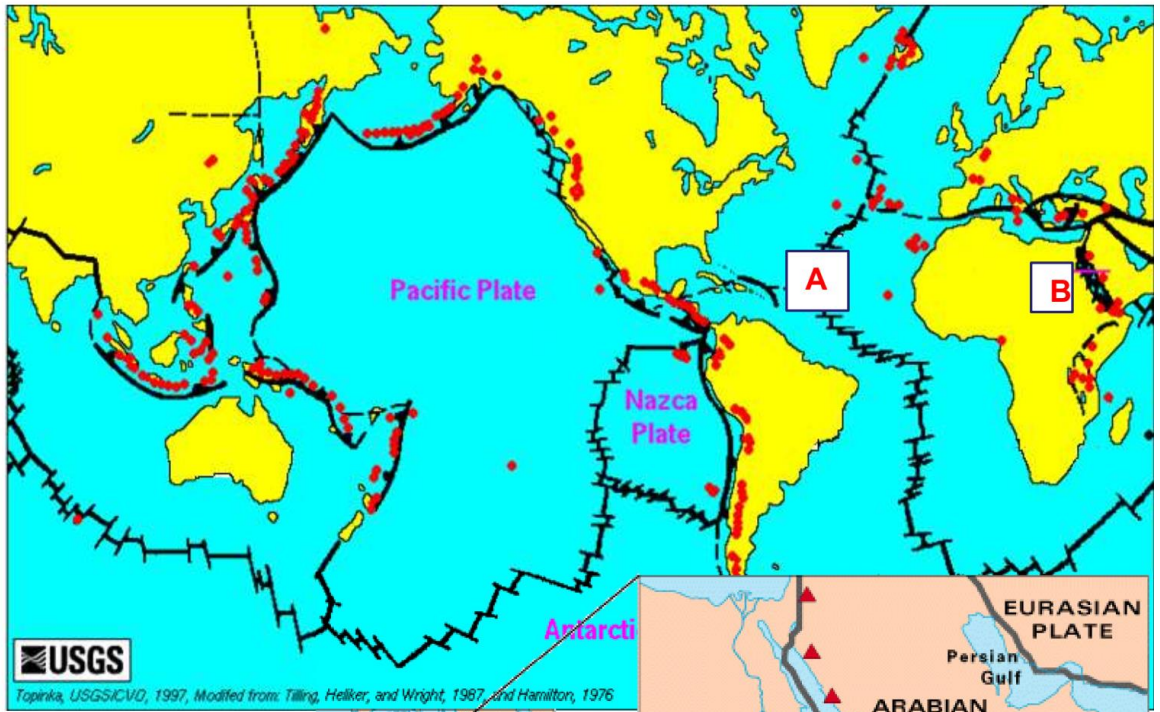


What causes this particular shape of the ridge?
-At the spreading center, the newly formed crust is hottest --- occupies more volume --- less dense.
- As it move away from the center, it cools down ---- contracts ---becomes more dense.

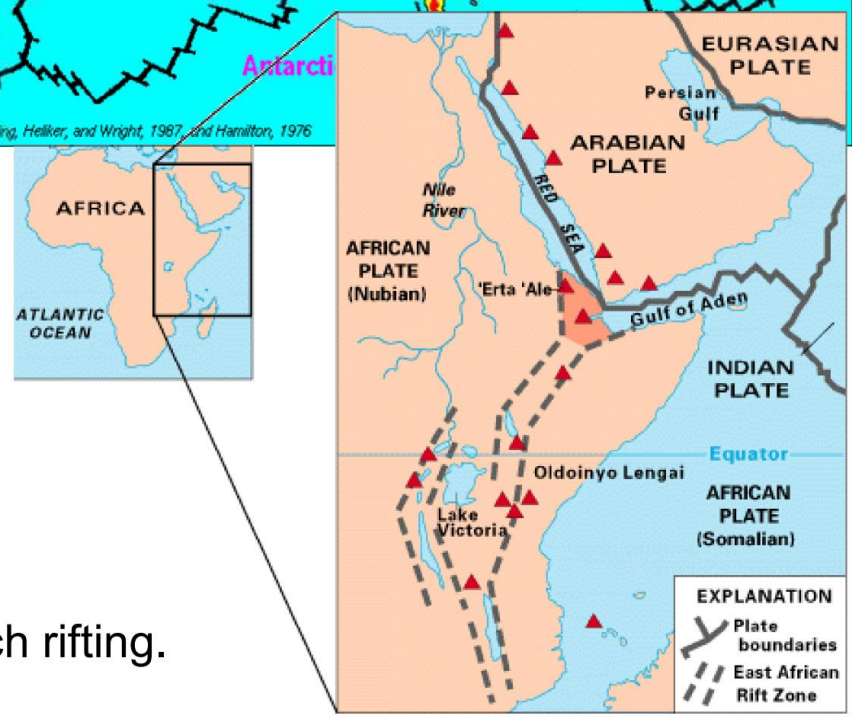
Divergent Boundaries

A. Mid Atlantic ridge:
   - Pillow lava
   - Hydrothermal vent





Life at divergent boundaries:
http://www.youtube.com/watch?v=4LoiInUoRMQ&feature=related

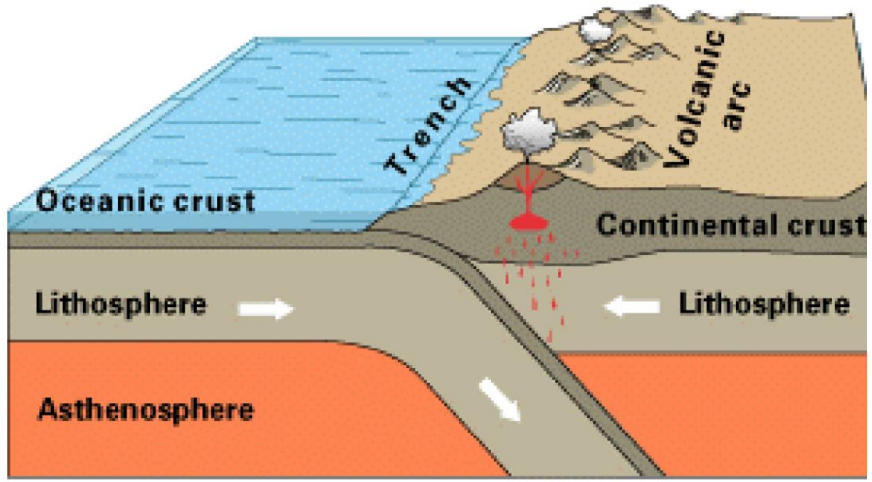


B. East African rift
   - Continental rift
   - Continental crust becoming thinner.
   - Red sea is the most recent result of such rifting.

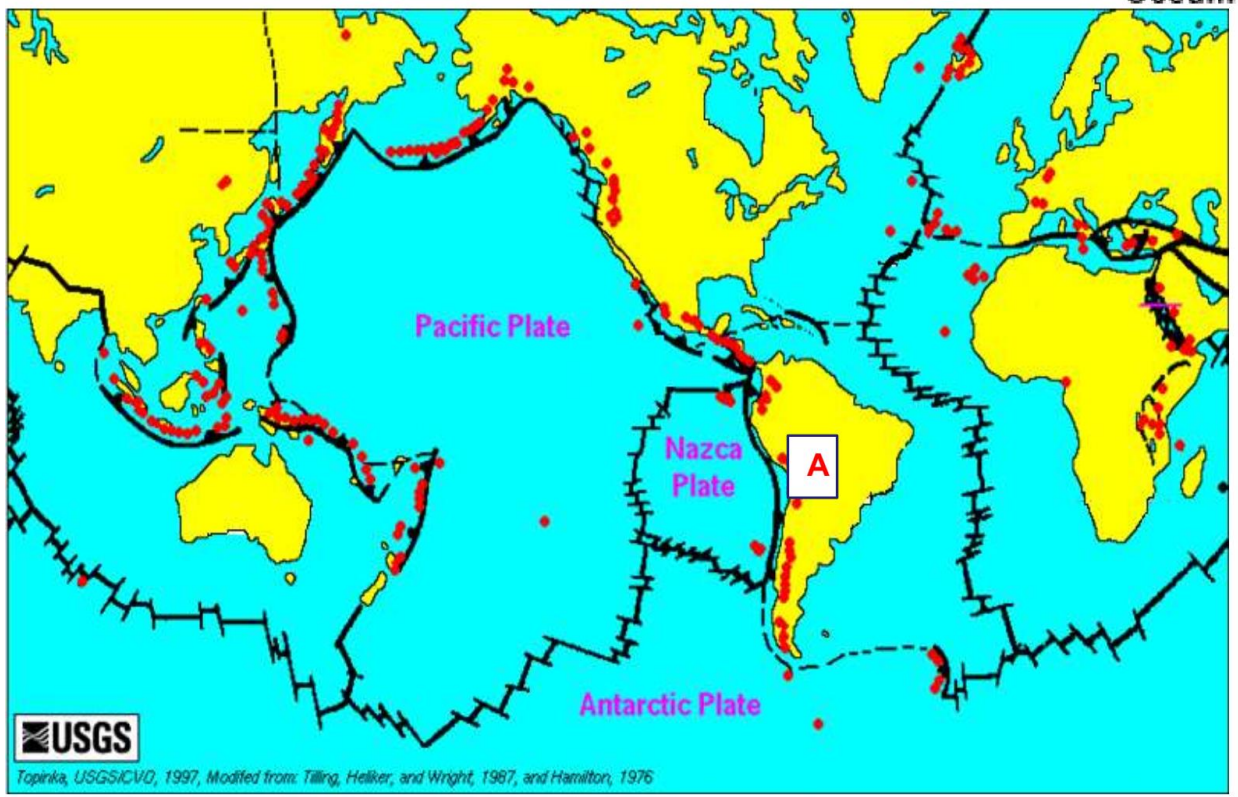
Types of Convergent Boundaries

Oceanic- Continental convergence:

- Oceanic plate would go down since it is heavy.
- When the oceanic plate goes deep down and reaches the mantle, it starts to melt.
- This melting often causes volcanism.
- Most of them are associated with very deep earthquakes.



Oceanic-continental convergence



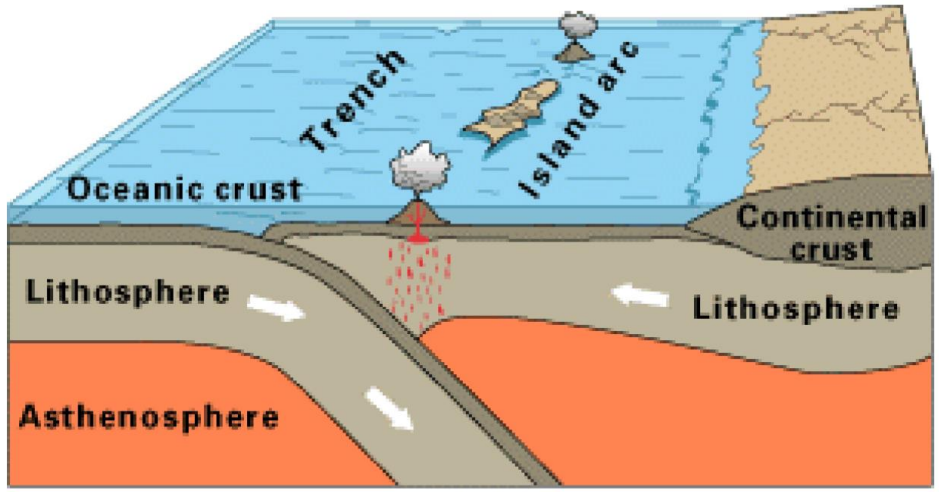
Subduction Zone

Example:
Andes Mountain.
Oceanic plate going under South American continental plate.

Types of Convergent Boundaries

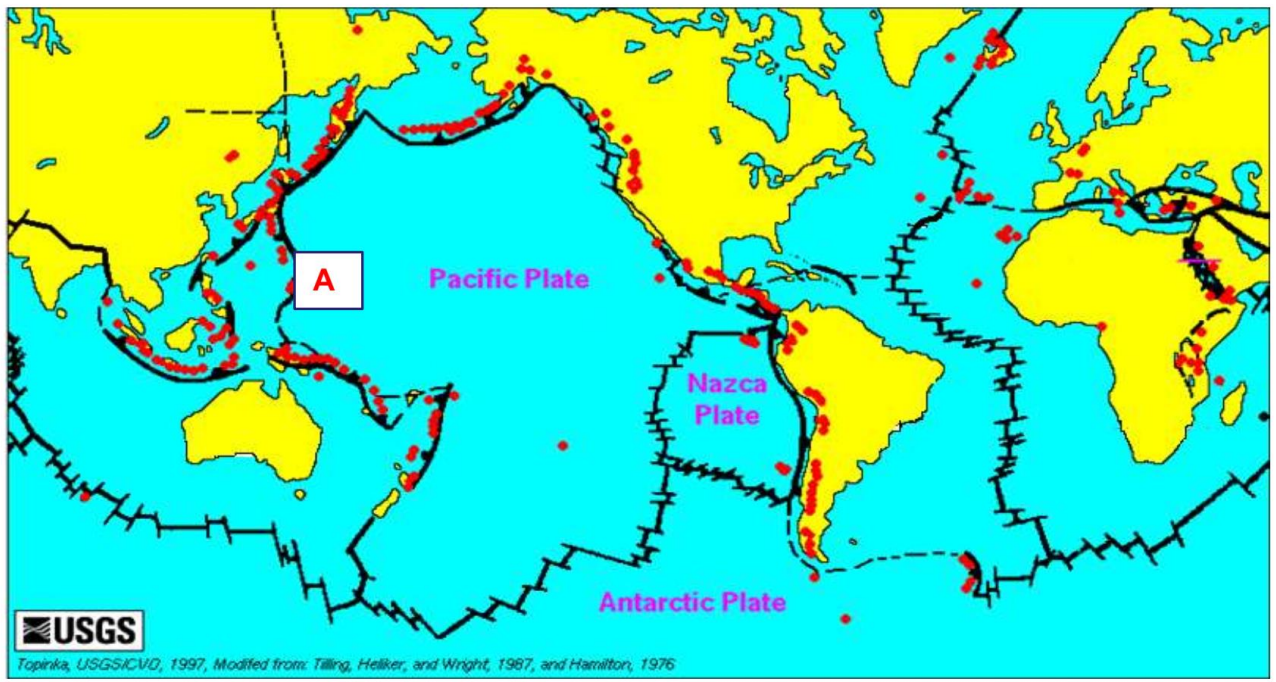
Oceanic – Oceanic convergence

- Older plate would go down
- When the oceanic plate goes deep down and reaches the mantle, it starts to melt.
- This melting causes volcanism.
- These volcanoes would be on the ocean floor. Sometimes they form an volcanic island chain. This volcanic island chain is called “Island arc”.



Oceanic-oceanic convergence

Subduction Zone

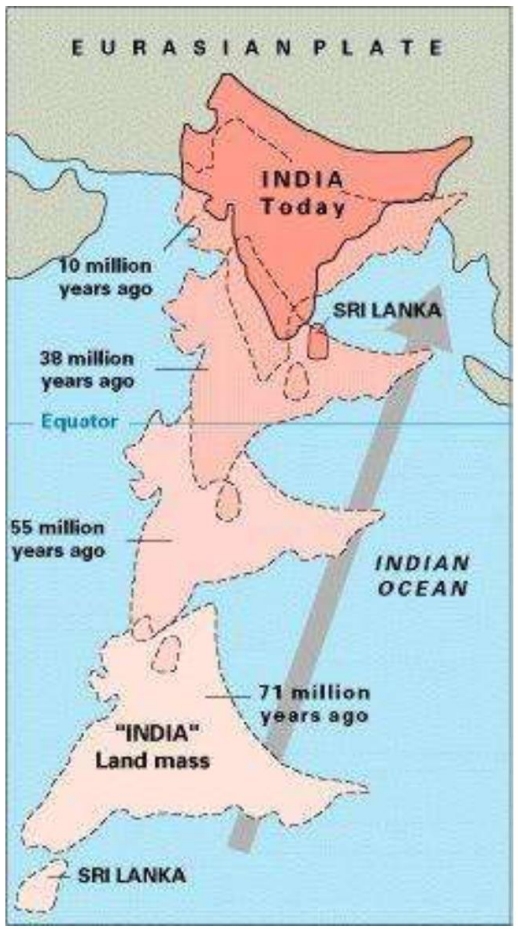


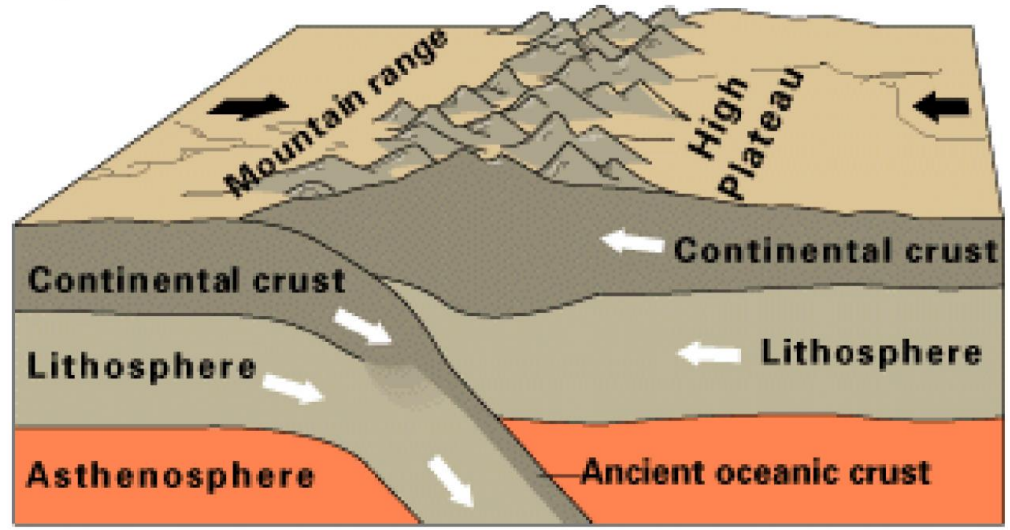
Example:
Numerous islands in the Pacific like Mariana, Tonga etc.

Types of Convergent Boundaries

Continental – Continental Convergence

- They both have similar density and it is lighter than the mantle.
- It does not sink; it floats up.
- The result is a collision.



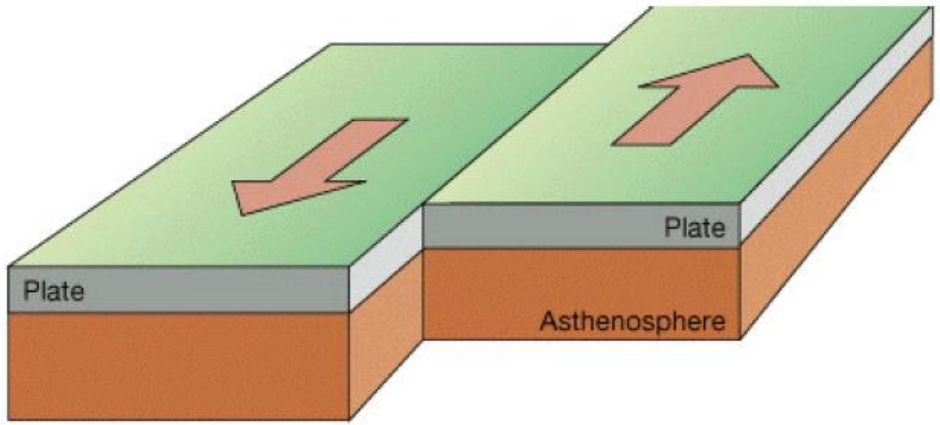


Continental-continental convergence

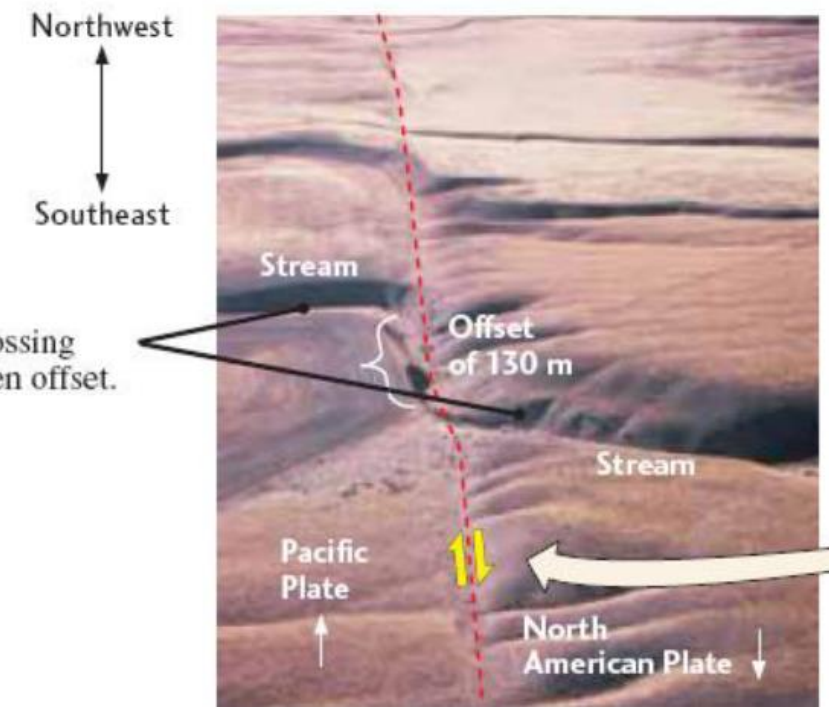
Example:
Collision between Indian subcontinent and Asia producing Himalayan mountain chain.

Transform Boundaries

-No volcanism
- Lots of shallow earthquake

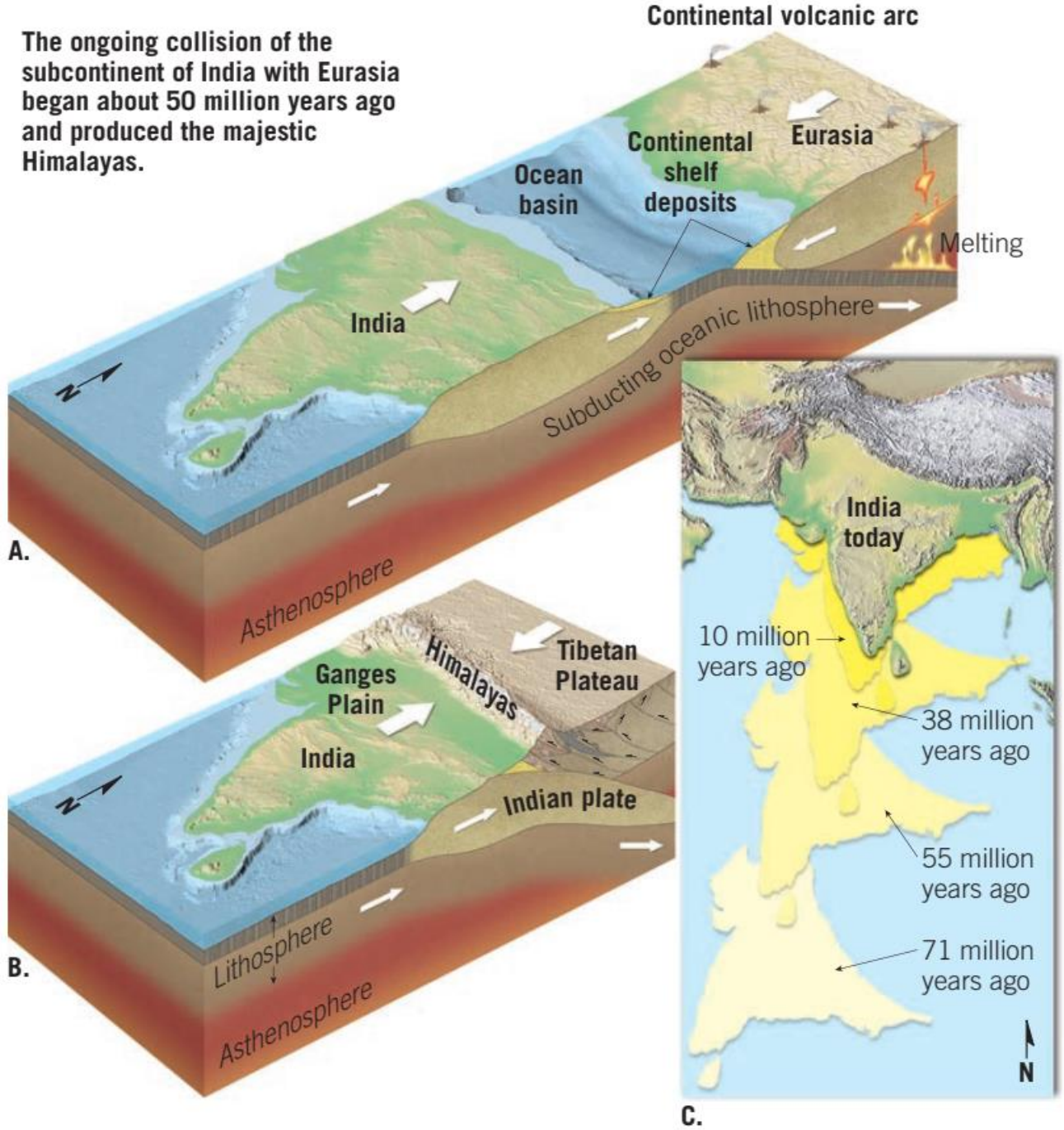


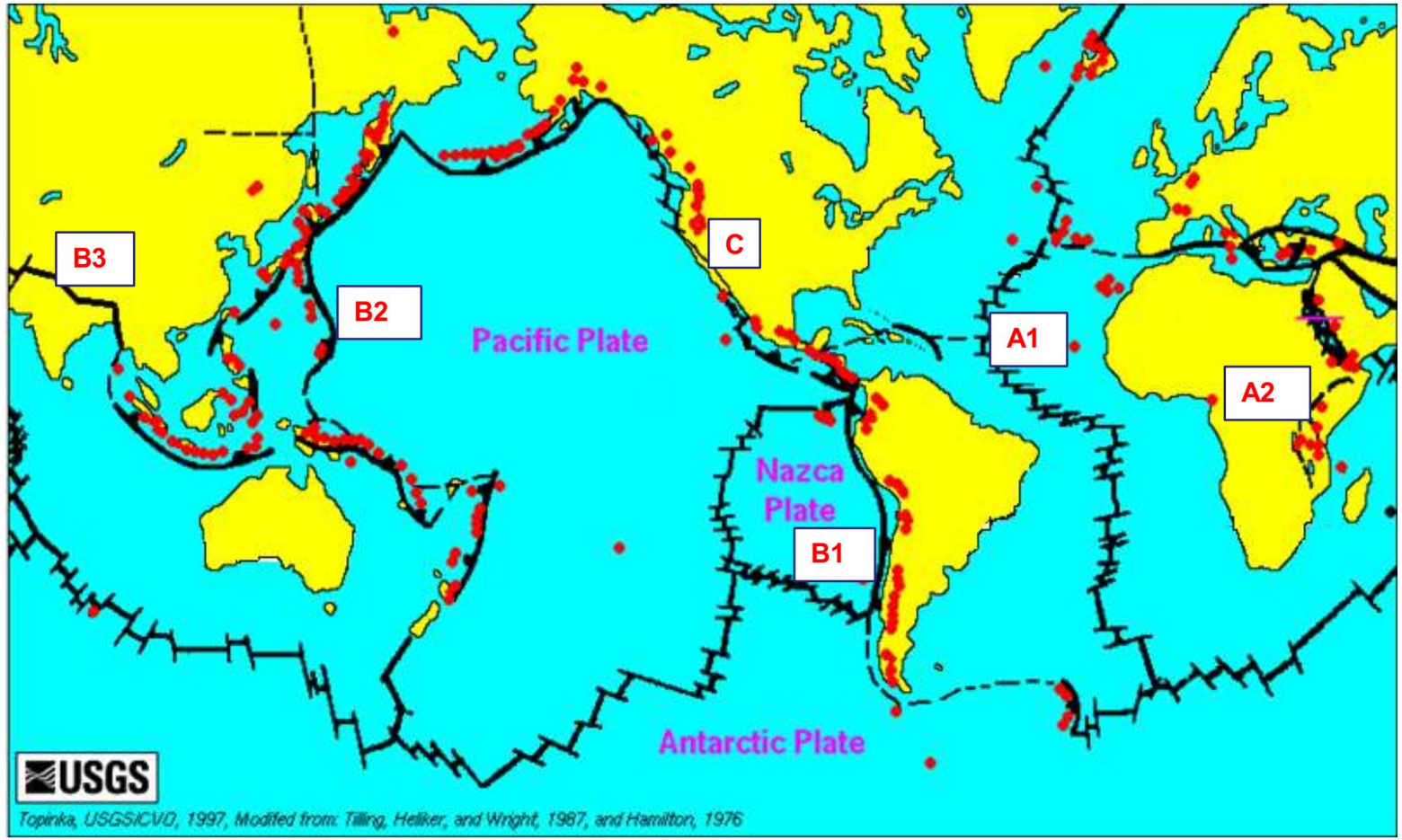
1 As the Pacific Plate and North American Plate move past each other in opposite directions,…



2 …streambeds crossing the fault have been offset.

The ongoing collision of the subcontinent of India with Eurasia began about 50 million years ago and produced the majestic Himalayas.





A1: Mid Oceanic Ridge
A2: Continental Rift

} Divergent Boundary

B1: Oceanic- Continental Convergence
B2: Oceanic-Oceanic Convergence
B3: Continental- Continental Convergence

} Convergent Boundary

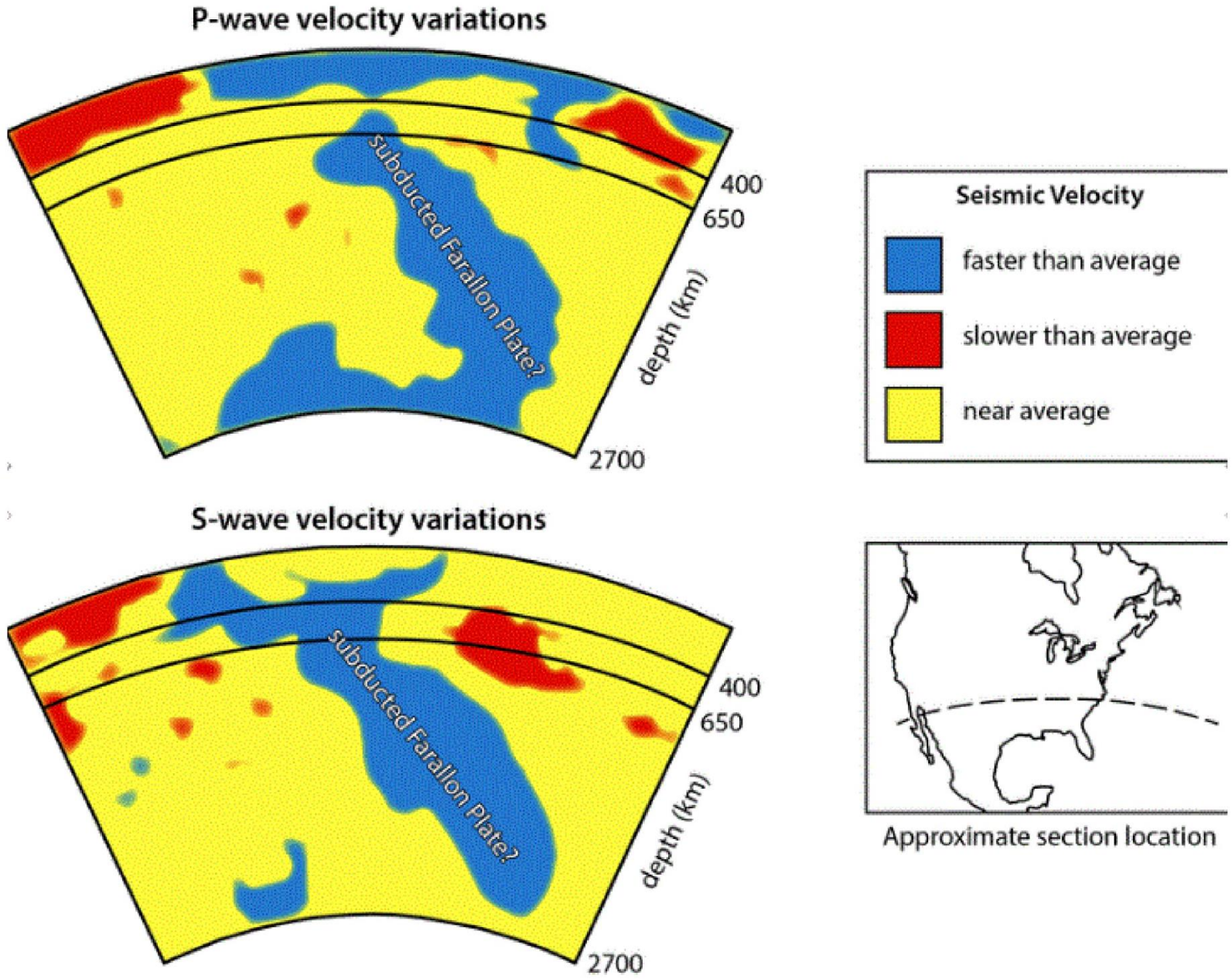
C: Transform Boundary

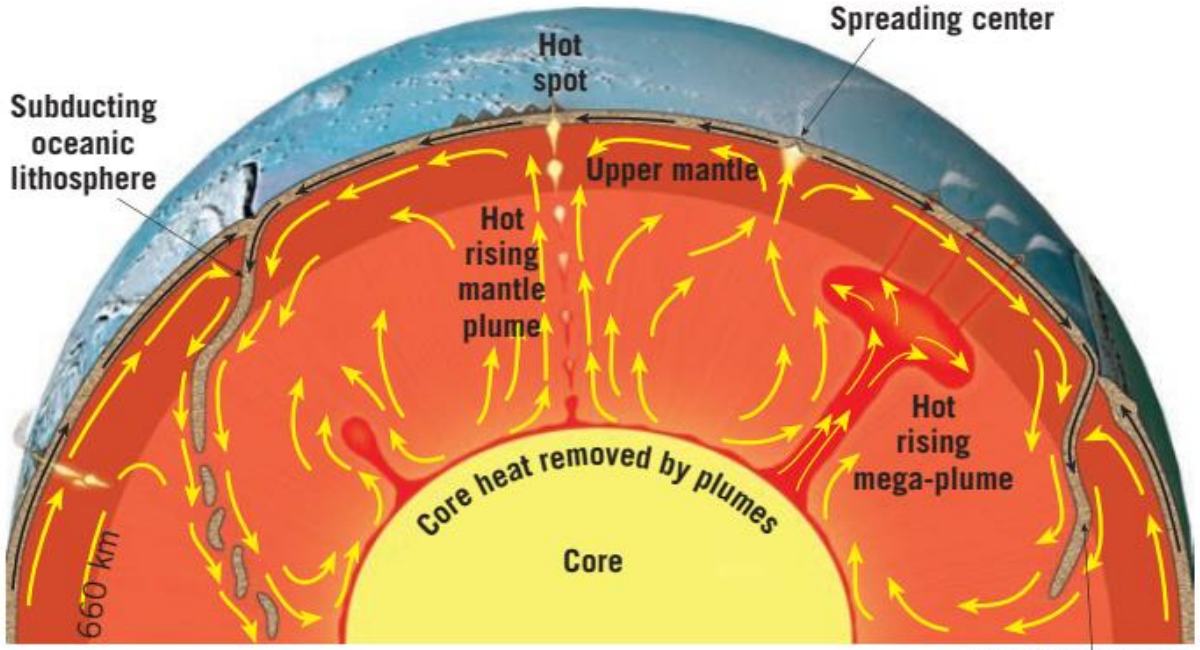
How far the Plates descend?

- For oceanic plate- oceanic plate subduction: Earthquakes are common upto 300 km depth, but usually does not occur at depths below 660Km

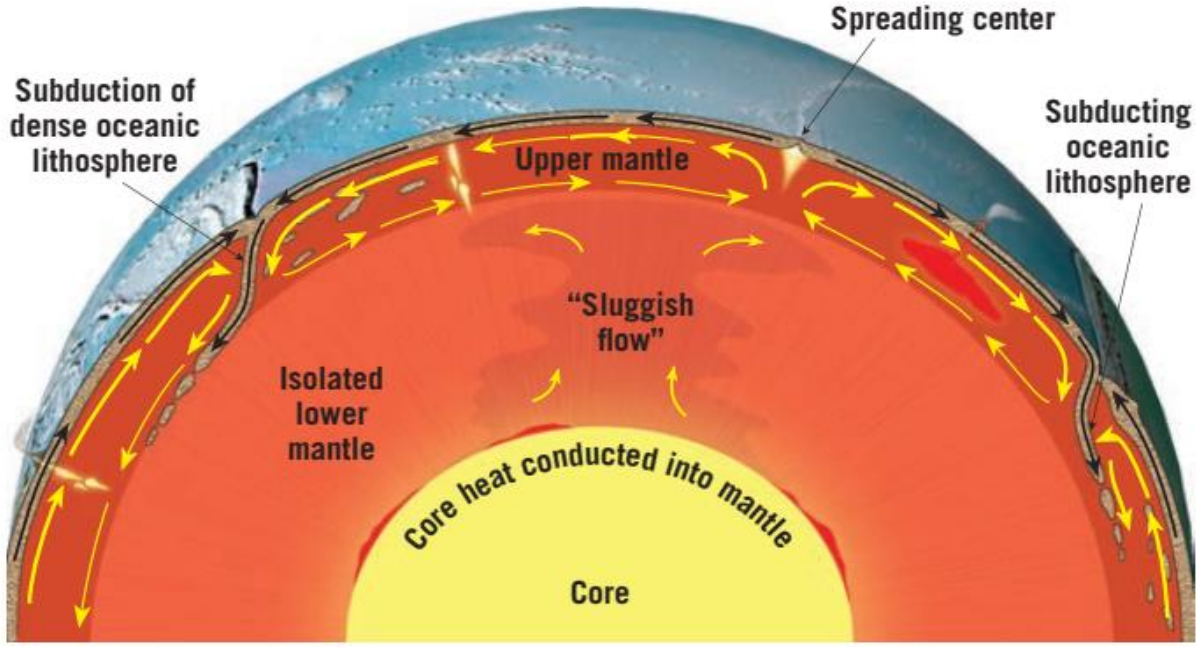
- Seismic imaging allows tracking of subducting plates: Remember that the relatively cold and hence dense subducting plate stands out in imaging
- When the plate reaches 660 Km depth, it becomes plastic and flows- unable to descend further
- Commonly held view is thus the maximum depth of subduction to be 660 Km

However,……..


P-wave velocity variations
Subducted Farallon Plate?
400
650
depth (km)
2700
S-wave velocity variations
Subducted Farallon Plate?
400
650
depth (km)
2700
Seismic Velocity
faster than average
slower than average
near average
Approximate section location



A. In the "whole-mantle model," sinking slabs of cold oceanic lithosphere are the downward limbs of convection cells, while rising mantle plumes carry hot material from the core–mantle boundary toward the surface.



B. The "layer cake model" has two largely disconnected convective layers. A dynamic upper layer driven by descending slabs of cold oceanic lithosphere and a sluggish lower layer that carries heat upward without appreciably mixing with the layer above.

Measuring plate movement

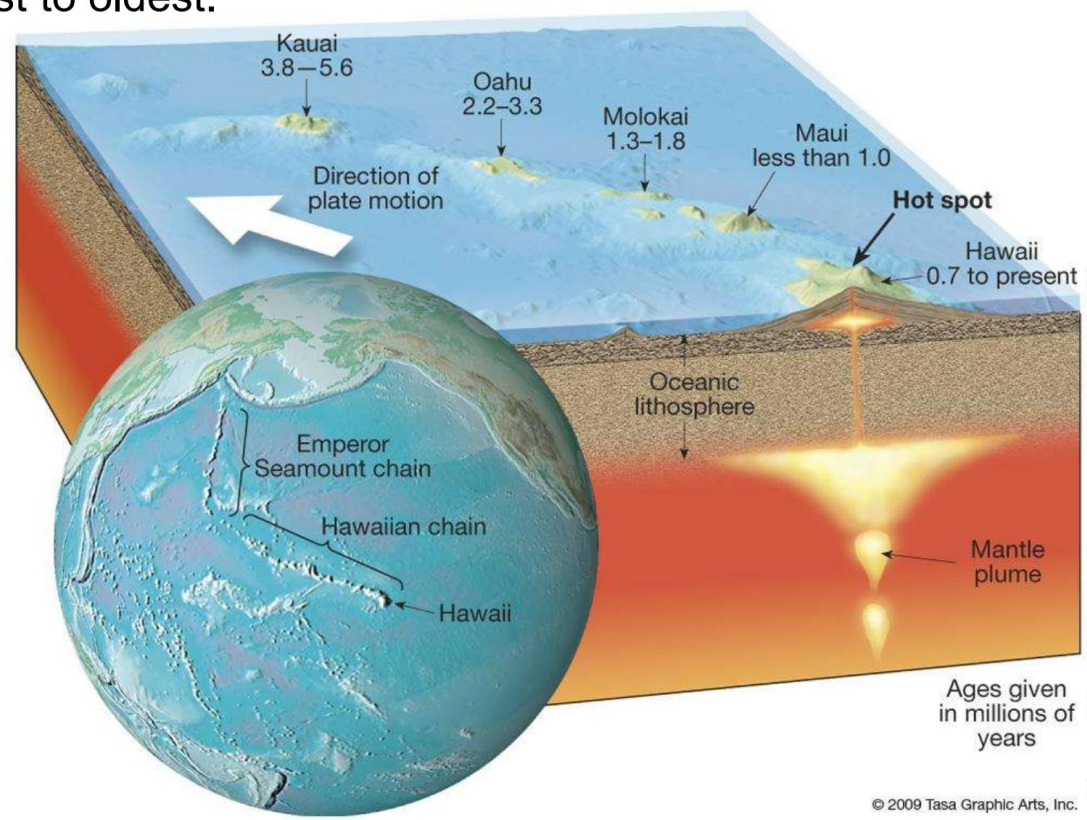
• Pacific plate is moving over a fixed magma plume generating a chain of volcanoes.

• Hawaii is currently on the top of the plume, so youngest island.

• The oldest island Kauai.

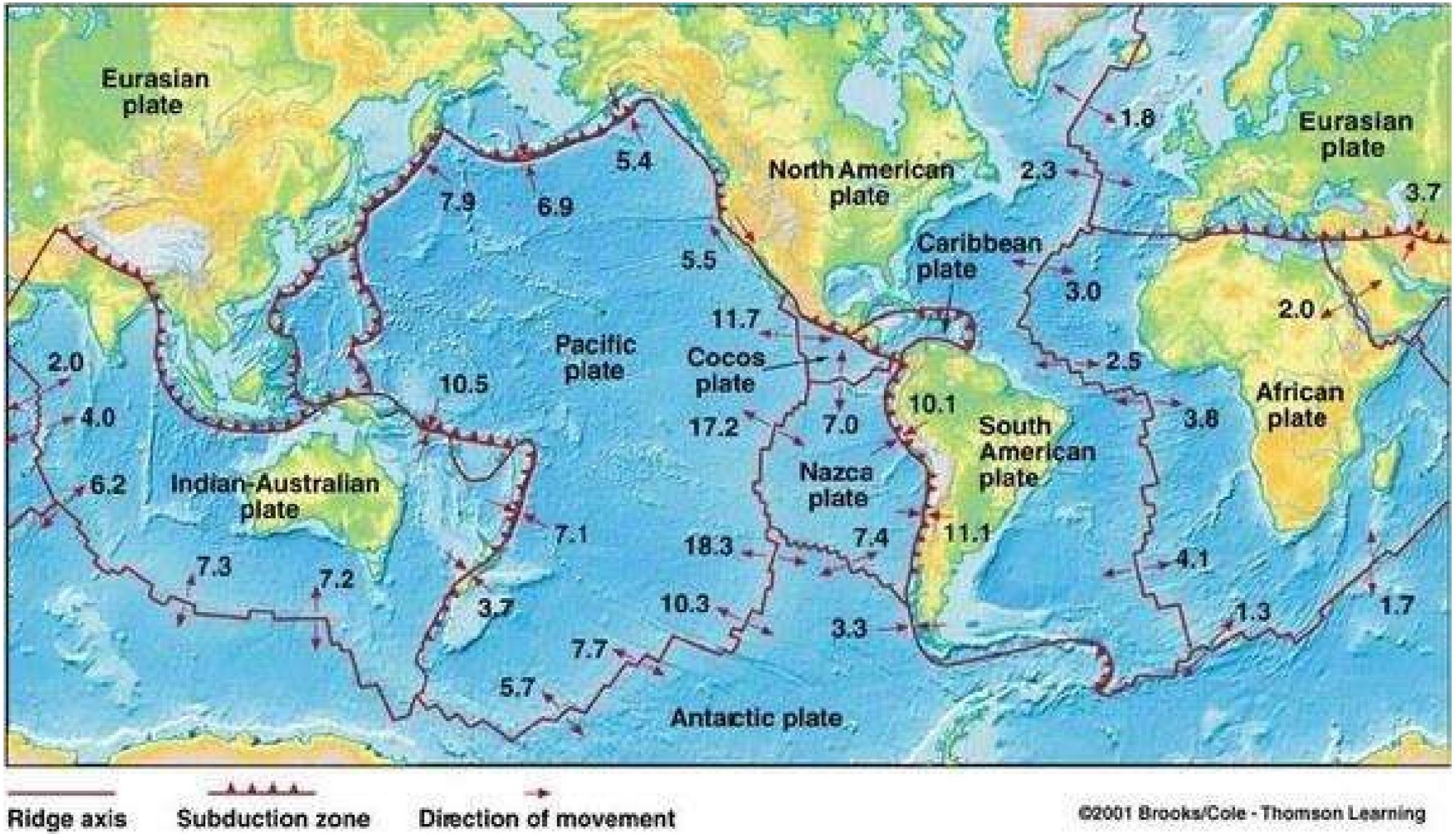
• Plate motion is from youngest to oldest.

Which way is the Pacific plate moving?



GPS measurements show continuous movement of the plates.

Plate velocity



BREAKUP OF PANGAEA

(f) Early Jurassic, 195 Ma

3 The breakup of Pangaea was signaled by the opening of rifts from which lava poured. Rock assemblages that are relics of this great event can be found today in 200-million-year-old volcanic rocks from Nova Scotia to North Carolina.

(g) Late Jurassic, 152 Ma

4 By about 150 million years ago, Pangaea was in the early stages of breakup. The Atlantic Ocean had partially opened, the Tethys Ocean had contracted, and the northern continents (Laurasia) had all but split away from the southern continents (Gondwana). India, Antarctica, and Australia began to split away from Africa.

(h) Late Cretaceous, Early Tertiary, 66 Ma

5 By 66 million years ago, the South Atlantic had opened and widened. India was well on its way northward toward Asia, and the Tethys Ocean was closing to form the Mediterranean.

THE PRESENT-DAY AND FUTURE WORLD

6 The modern world has been produced over the past 65 million years. India collided with Asia, ending its trip across the ocean, and is still pushing northward into Asia. Australia has separated from Antarctica.

(i) PRESENT-DAY WORLD

(j) 50 million years in the future