Introduction to Earth Science (ES1101)

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

(Autumn 2024 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:

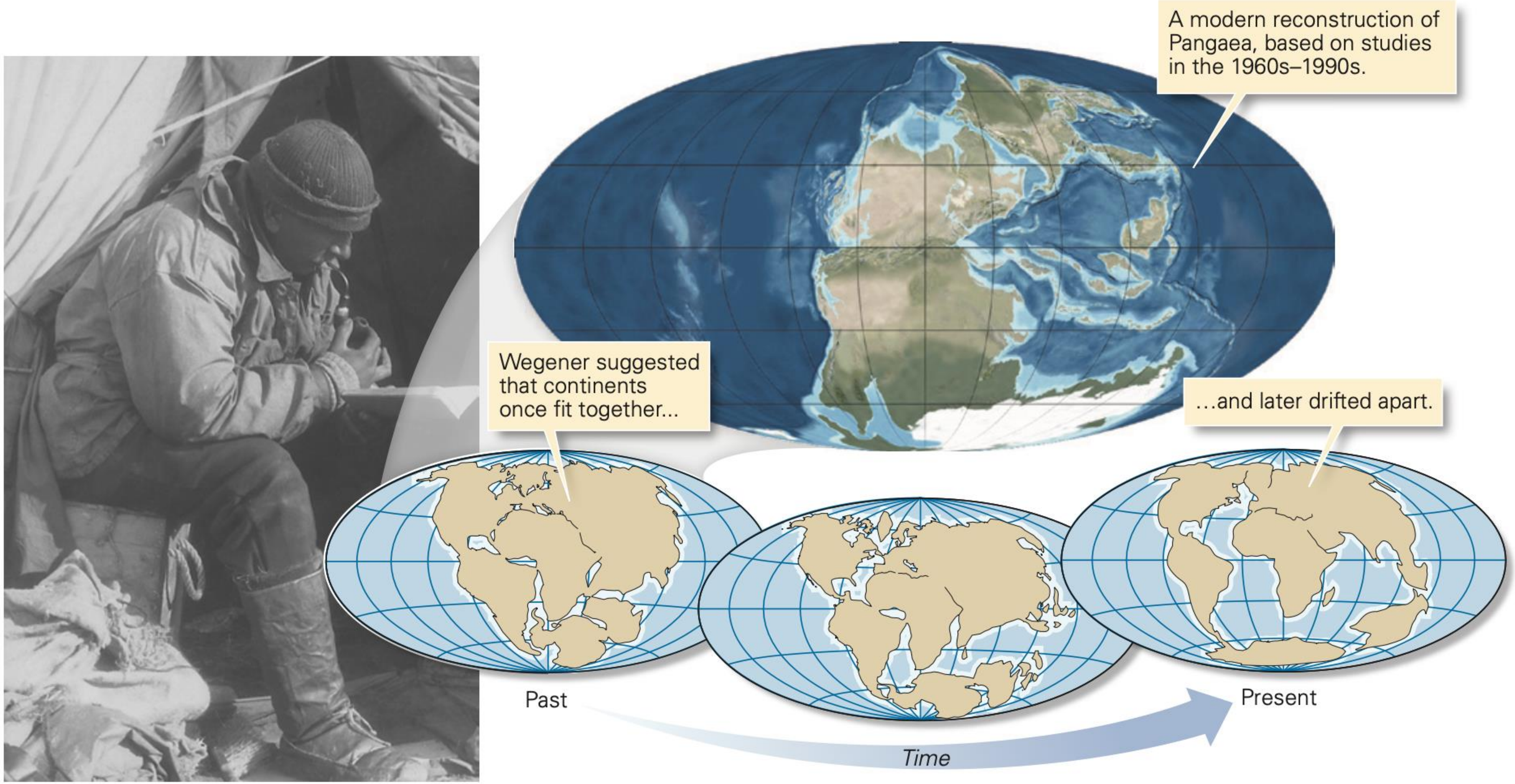
- A single supercontinent "Pangaea" existed.
- It began to break in Mesozoic.
- The fragmented land masses drifted to their present position.

• Observations :

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

Continental Drift

FIGURE 3.1 Alfred Wegener and his model of continental drift.



(a) Wegener in Greenland.

(b) Wegener's maps illustrating continental drift.

Continental Drift

Modern reconstruction of Pangaea

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

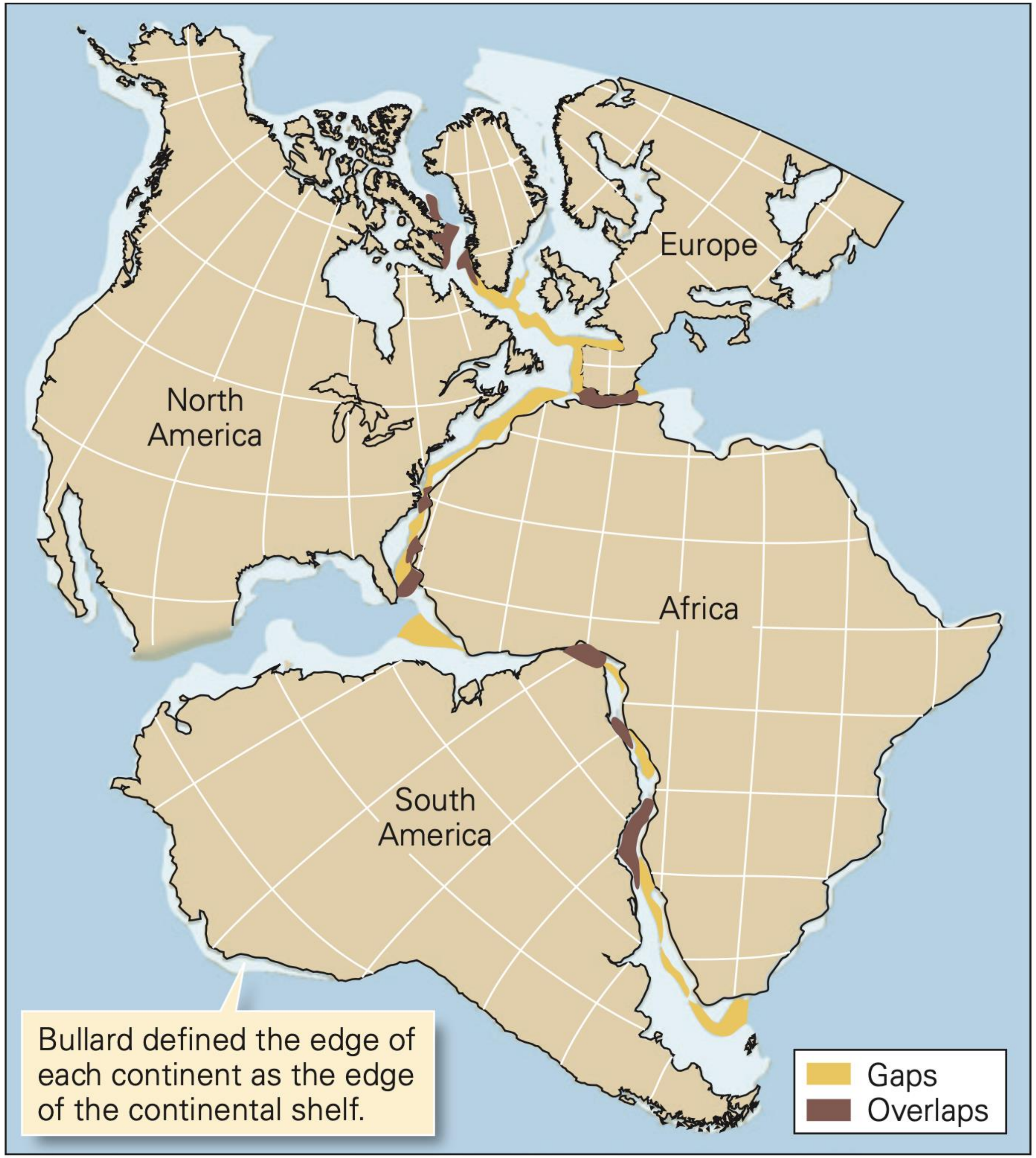
Continental Drift

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.**

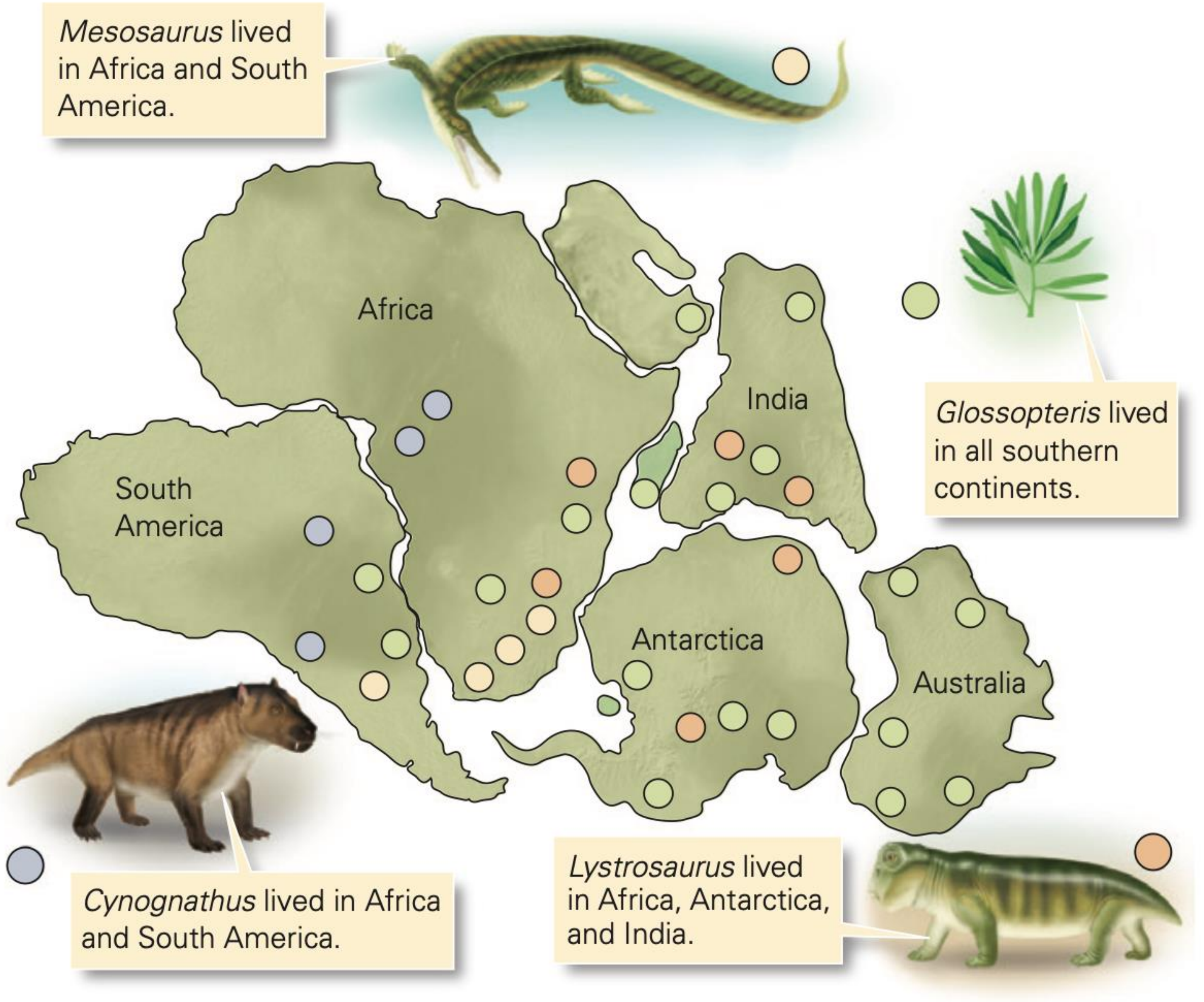


Distribution of Fossils

- **Similar fossil organisms were found in separate continents**

- **Explanation:**
  (A) Land bridge existed in past?
  (B) Continents moved?

➢ **Mesosaurus:**
- **Aquatic reptile**
- **Can't swim through vast ocean**



(a) The distribution of fossil localities shows that Mesozoic land-dwelling or coastal organisms occur on continents that were adjacent in Pangaea.

Distribution of Fossils

- Glassoteris is fossil fern
- Found in South America, Africa, Antarctica
- Not easily transportable seeds

(b) Fossils of *Glossopteris*, a land plant from Australia. Such fossils have been found on other continents.

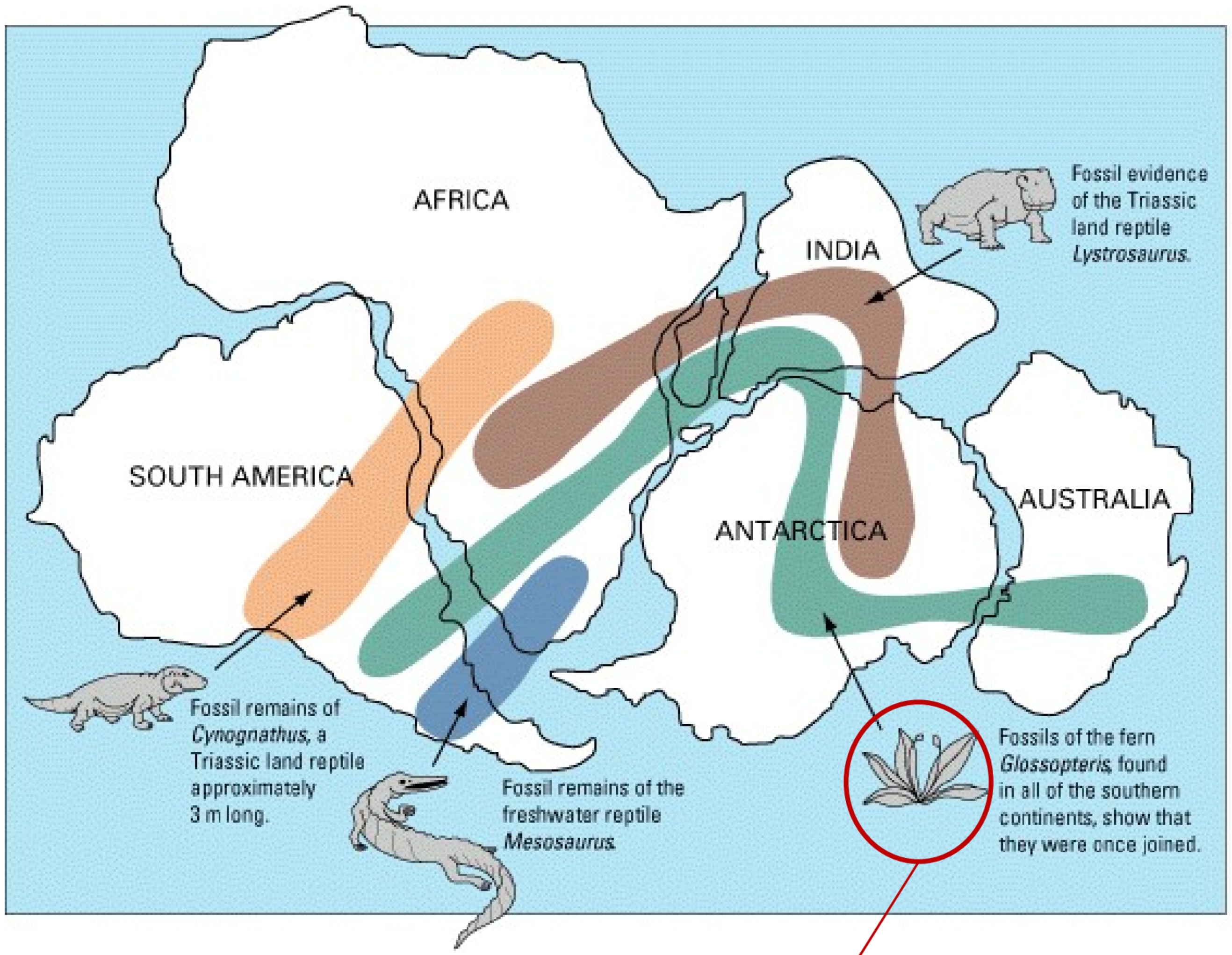
Distribution of fossils: Current knowledge

-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.



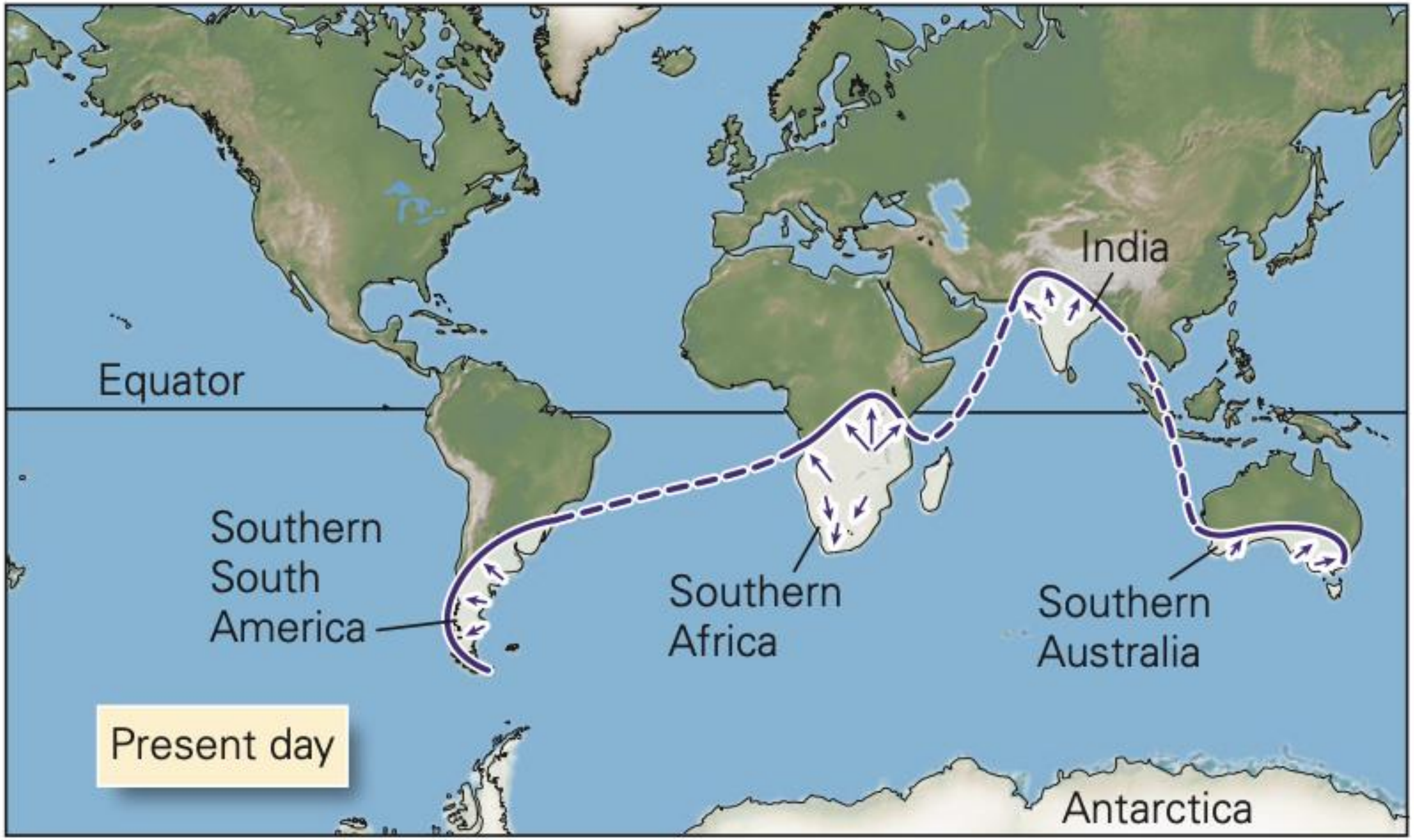
Explanation:
~~A) "land bridge" existed in past~~
B) continents moved

They generally occur only in subpolar climate!!!

Paleoclimatic Evidence of Pangaea

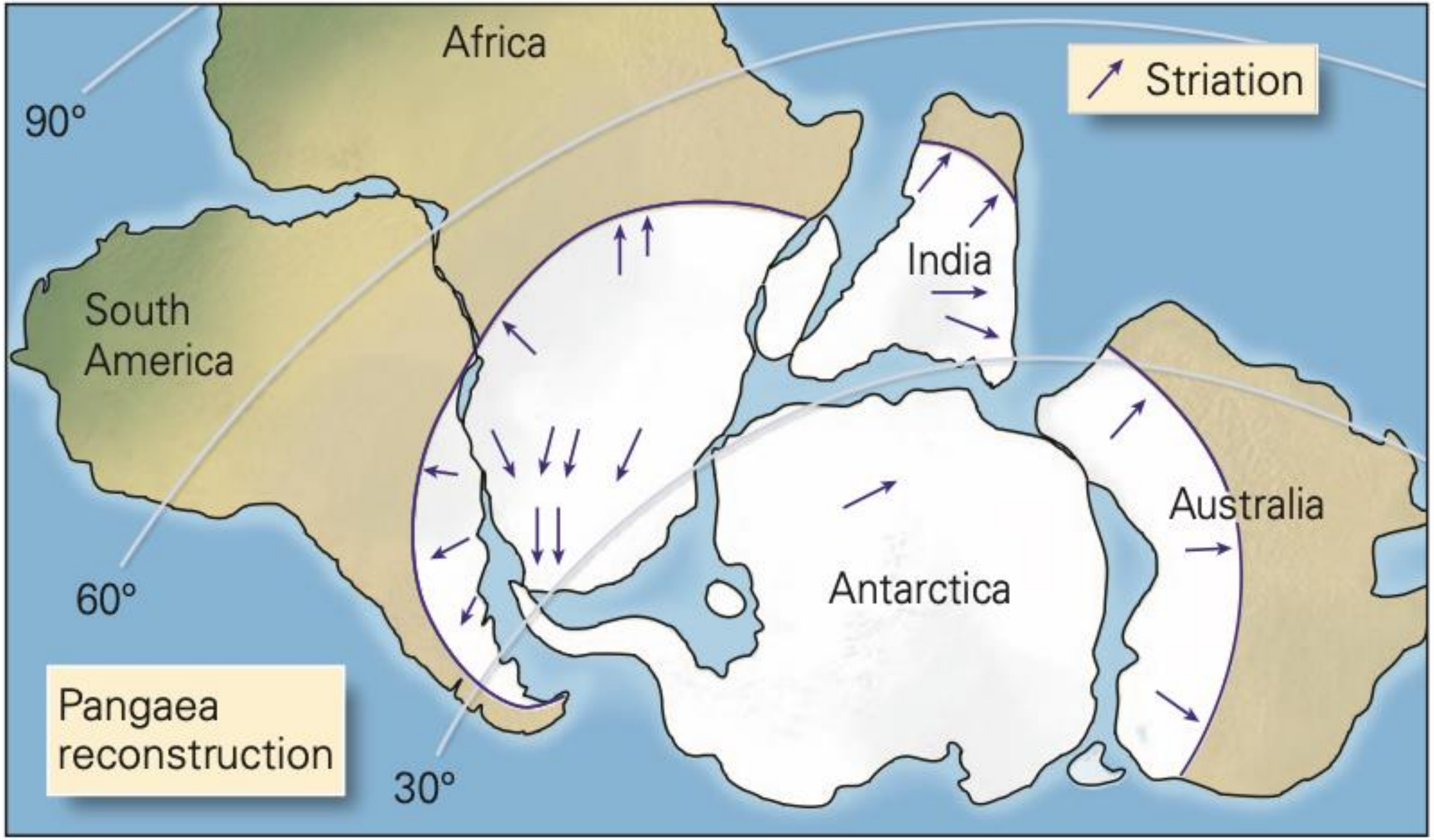
(a) Glacial striations of late Paleozoic age on the surface of bedrock along the southern coast of Australia.

Paleoclimatic Evidence of Pangaea



(b) A map showing the distribution of late Paleozoic glacial deposits and the orientation of associated striations.

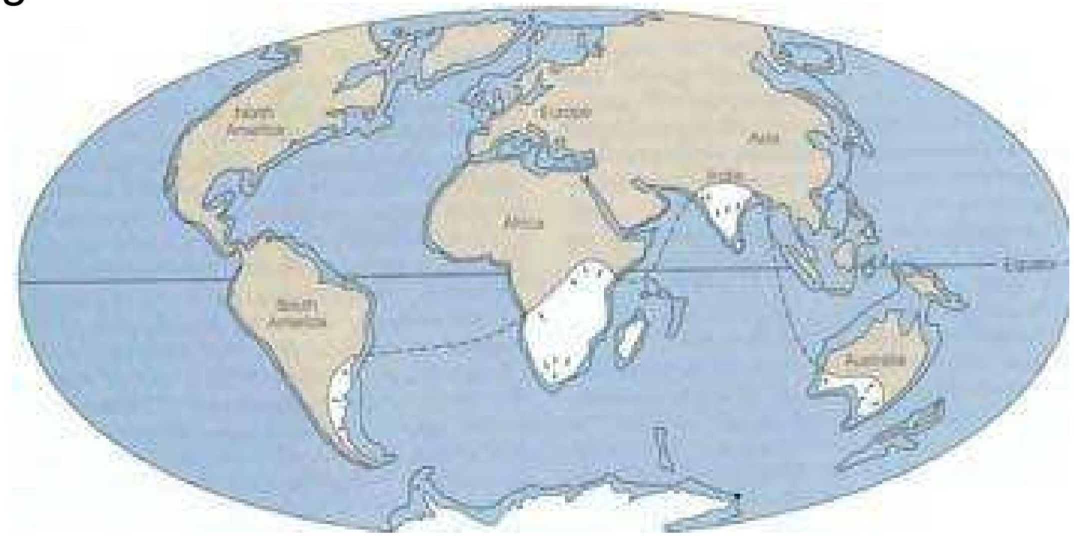
Paleoclimatic Evidence of Pangaea



(c) In Wegener's reconstruction of Pangaea, the glaciated areas connect to outline a region of late Paleozoic southern polar ice caps.

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

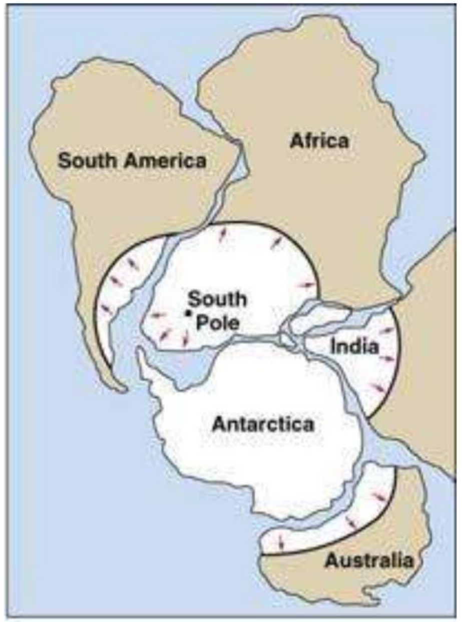
Paleoclimatic evidence

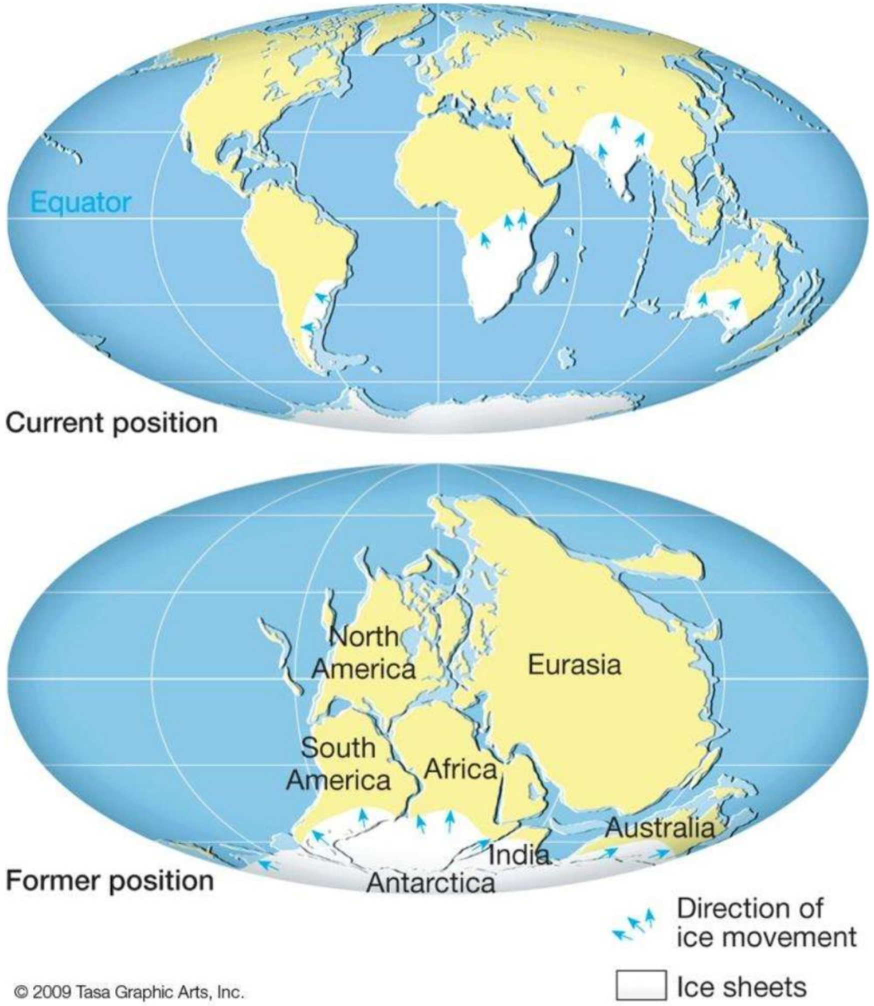
Using the evidence from ancient glaciers

-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.

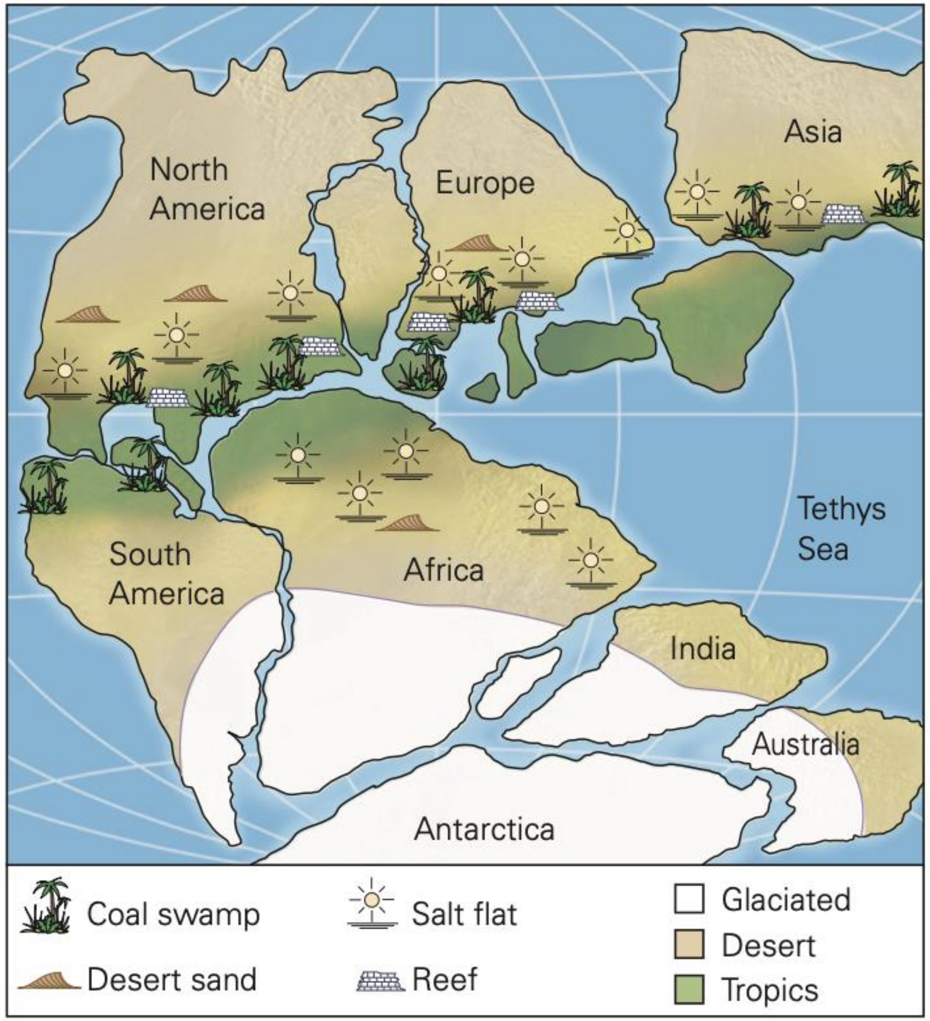
•They were at much higher latitude than their present location.





Distribution of Climate Belts: Evidence of Pangaea

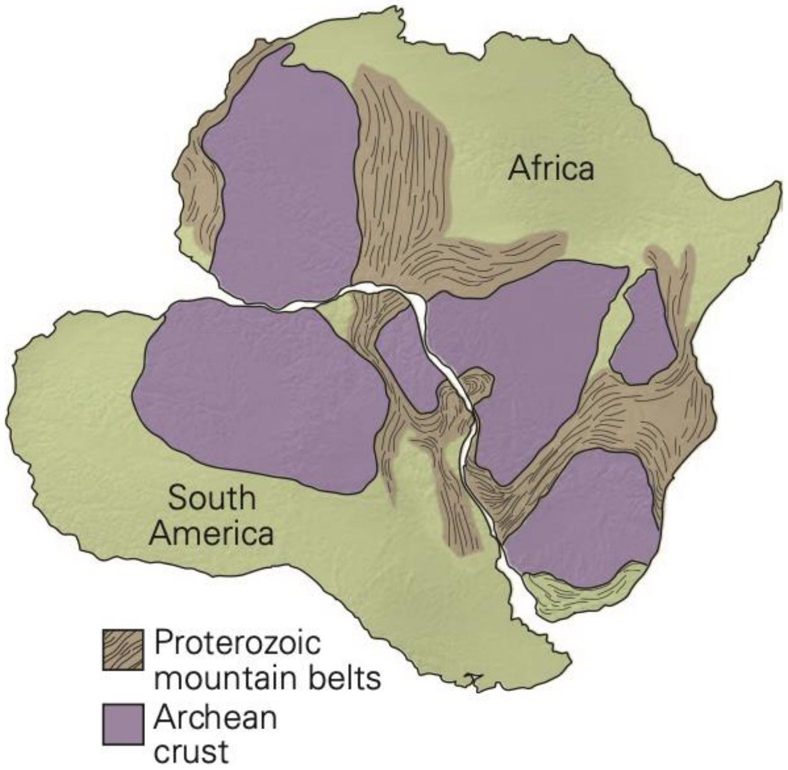
FIGURE 3.4 Each symbol shows the location of an environment in which a distinctive type of sediment accumulates. The locations lie in belts, at appropriate latitudes, on a map of Pangaea.



Continental Drift

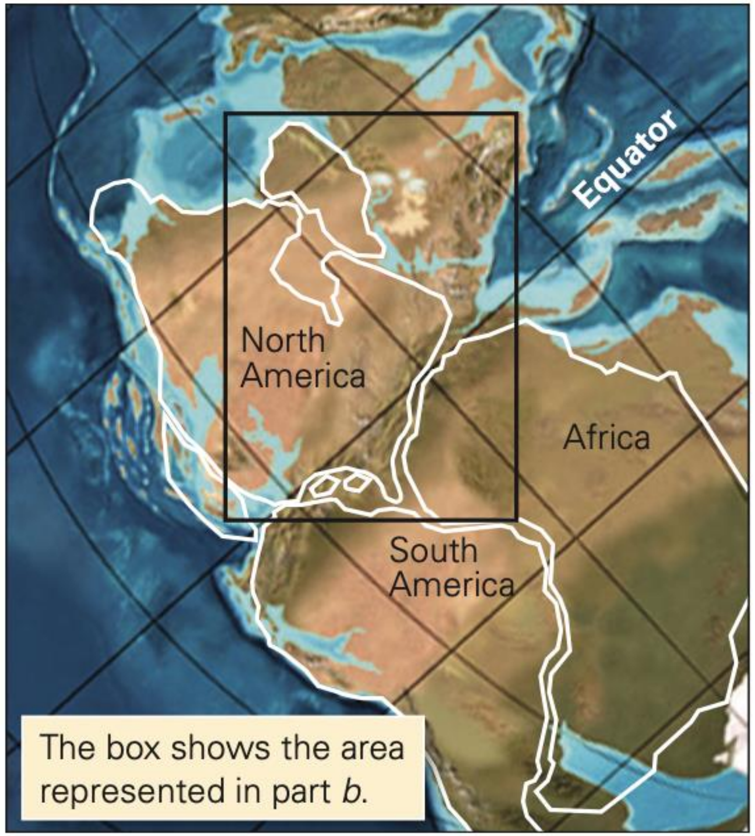
Rock Types

FIGURE 3.6 Further evidence of continental drift: rocks on different sides of the ocean match.



(a) Distinctive belts of rock in South America would align with similar ones in Africa if the Atlantic Ocean didn't exist.

(b) If the Atlantic didn't exist, Paleozoic mountain belts on both coasts would be adjacent.



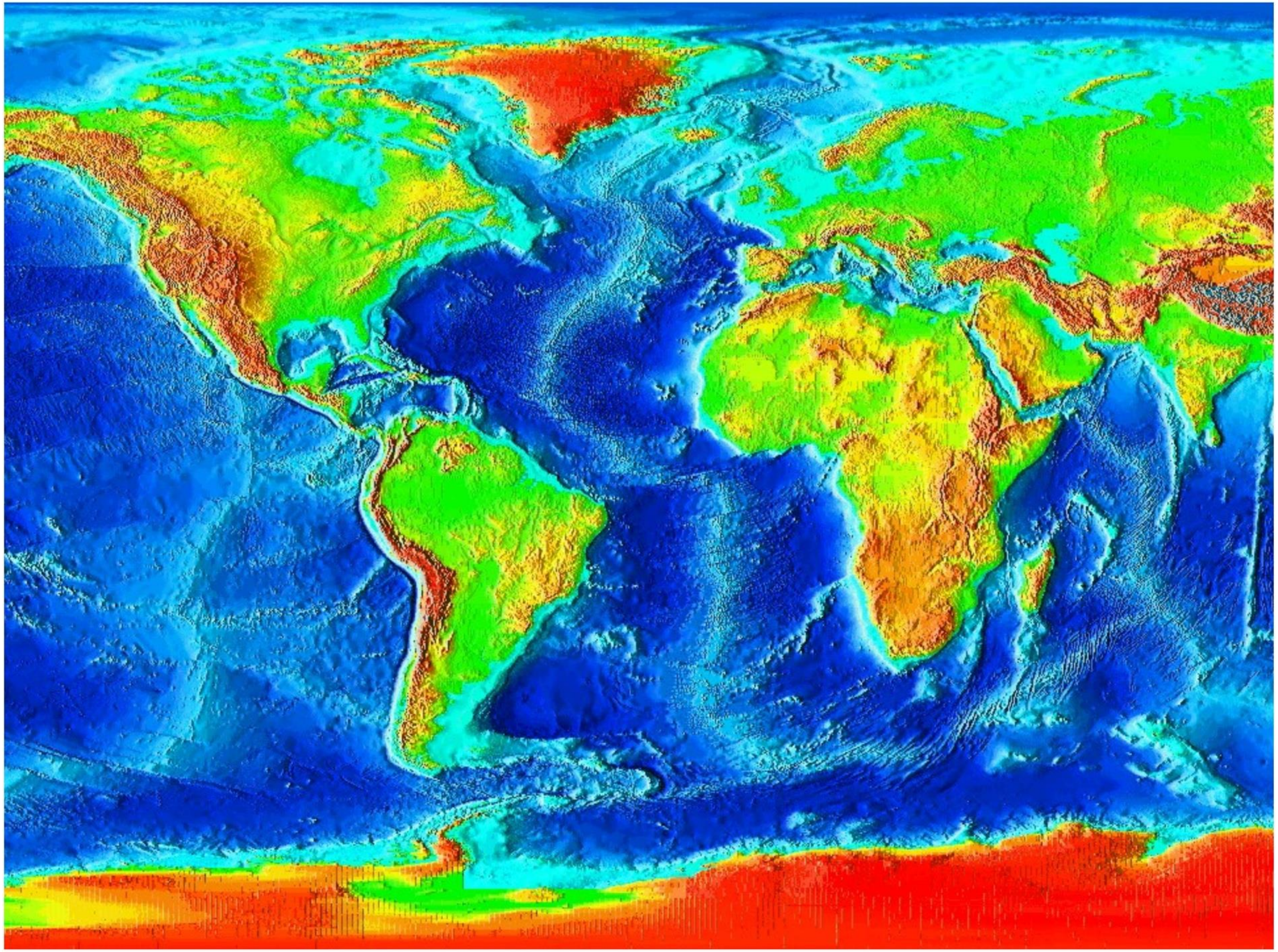
(c) A modern reconstruction showing the positions of mountain belts in Pangaea. Modern continents are outlined in white.

Continental Drift

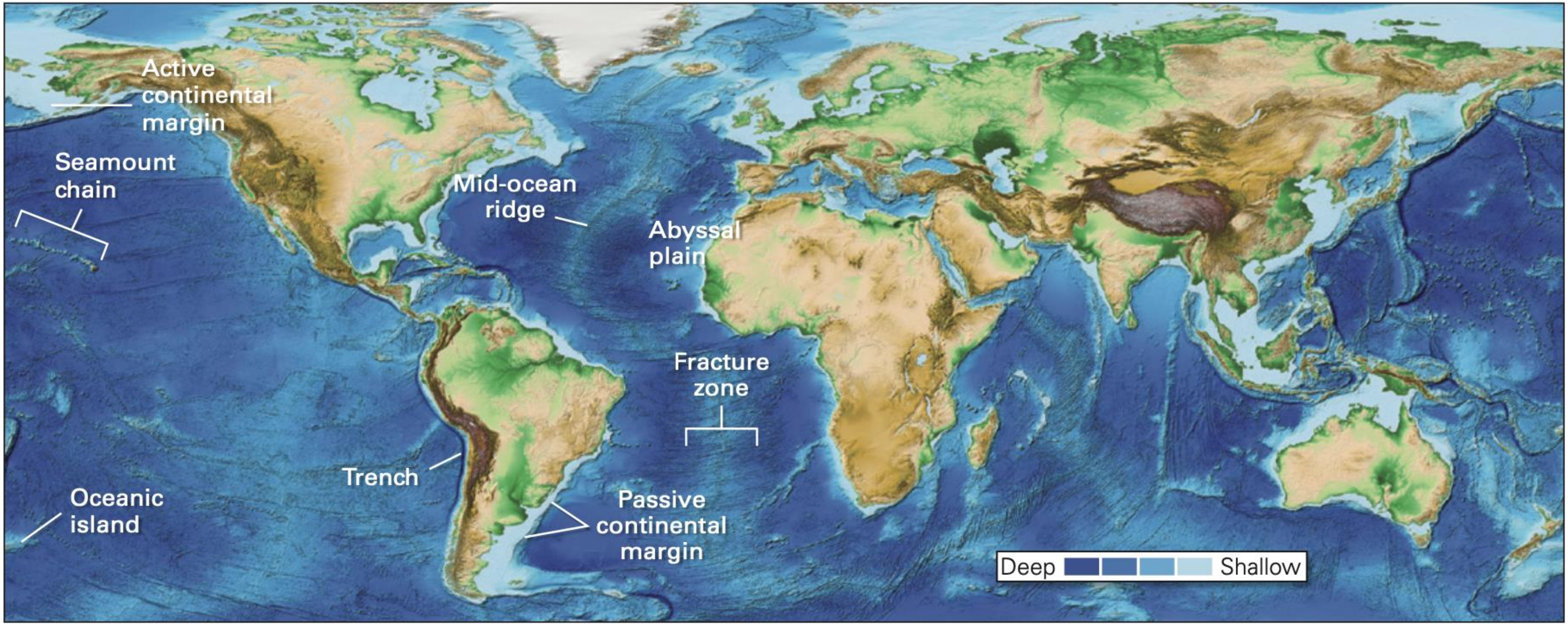
Rock Types

- 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)

Topography of the Ocean Floor

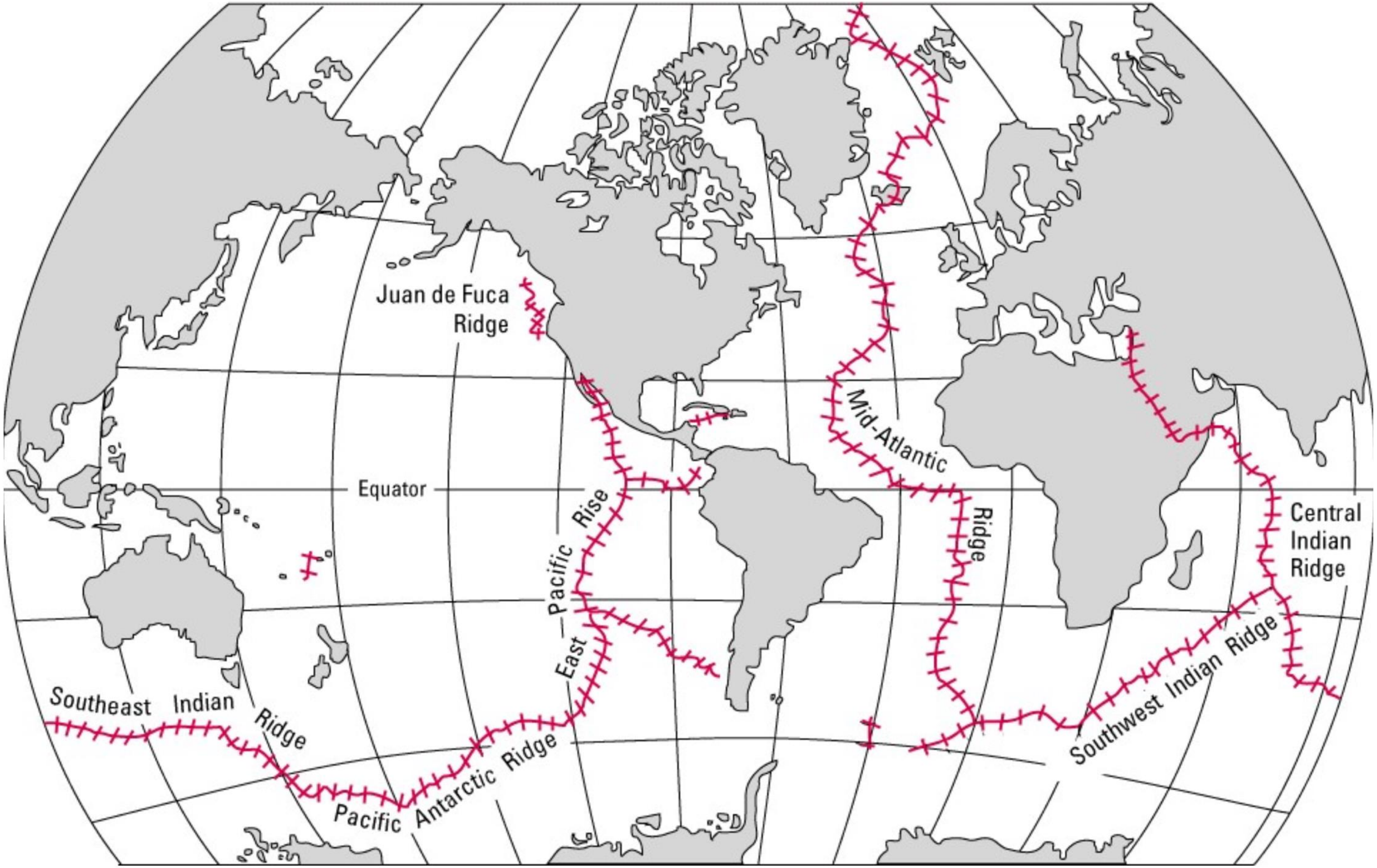


Topography of the Ocean Floor



(a) A modern image of seafloor bathymetry. (Older versions were based on sonar studies; this one uses satellite data.) The colors indicate water depth.

Topography of the Ocean Floor



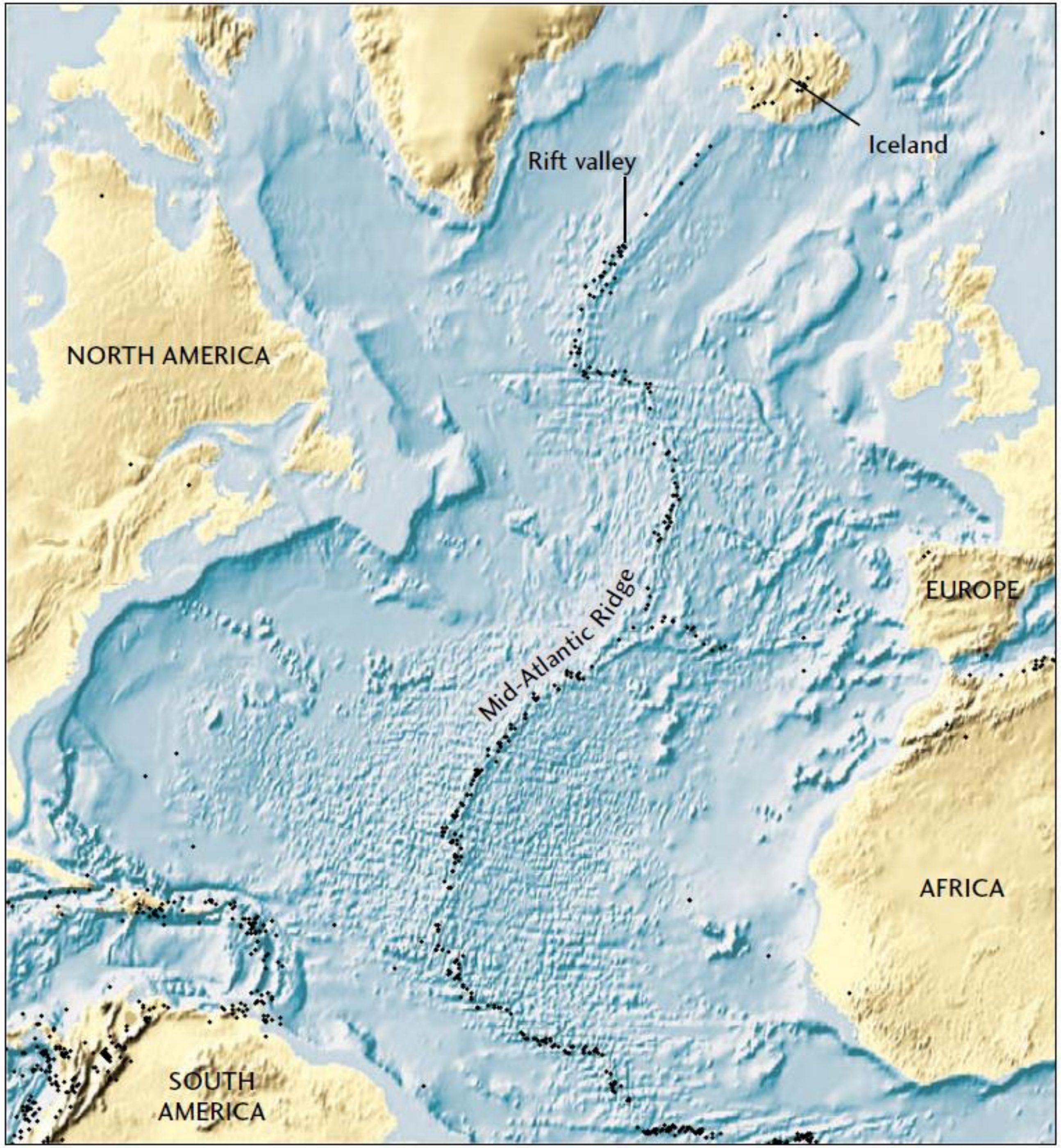
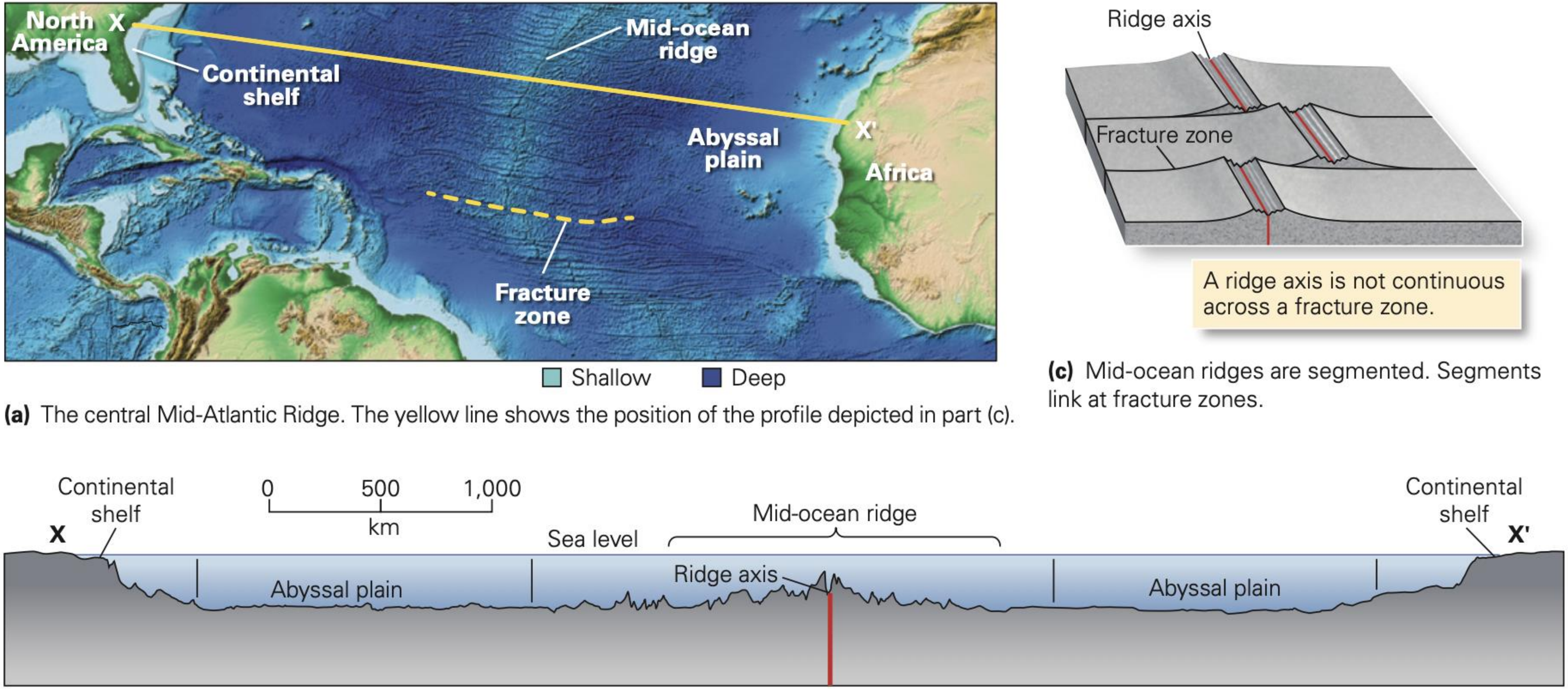


FIGURE 2.4 ■ The North Atlantic seafloor, showing the cracklike rift valley running down the center of the Mid-Atlantic Ridge and the locations of earthquakes (black dots).

Topography of the Ocean Floor

FIGURE 3.9 Bathymetric characteristics of mid-ocean ridges.

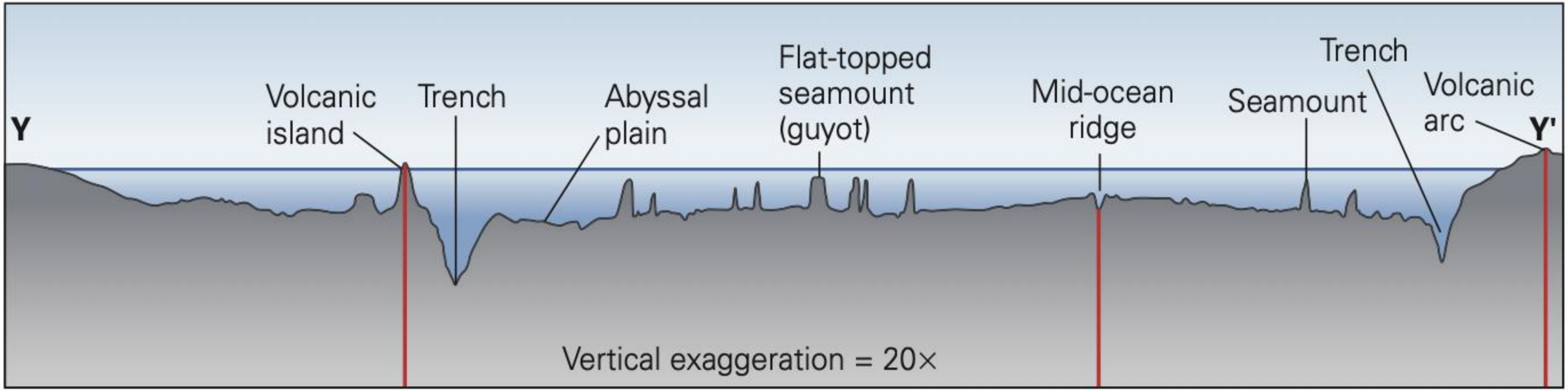


(a) The central Mid-Atlantic Ridge. The yellow line shows the position of the profile depicted in part (c).

(c) Mid-ocean ridges are segmented. Segments link at fracture zones.

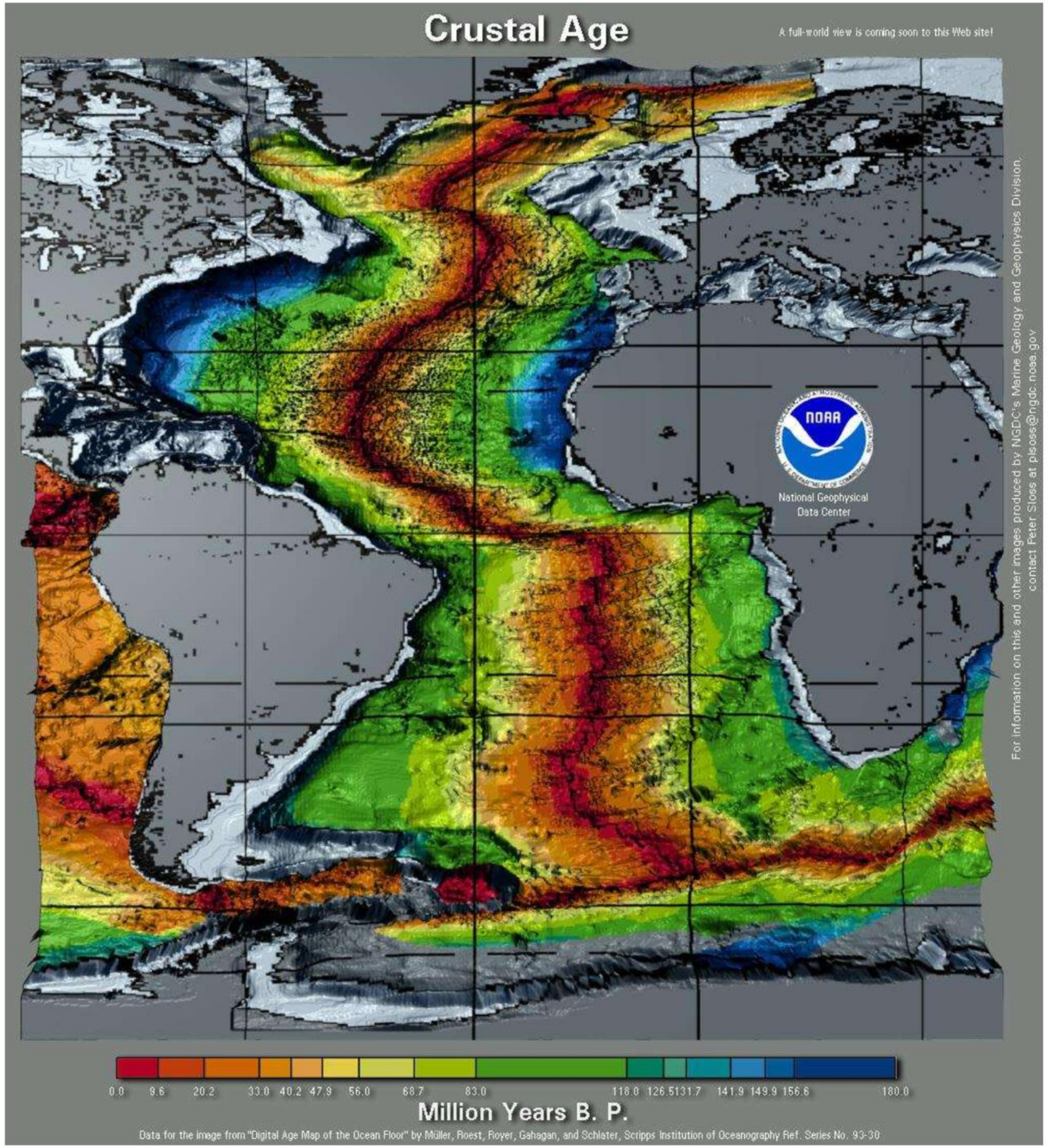
(b) A profile of the Mid-Atlantic Ridge, showing how the ridge rises above the abyssal plains.

Topography of the Ocean Floor



(b) A bathymetric profile of the Pacific (see Figure 3.8b for the location). Note that trenches can have ocean floor on either side, or can have a continent on one side. All trenches border volcanic arcs. Seamounts can rise to shallow depths.

Crustal Age

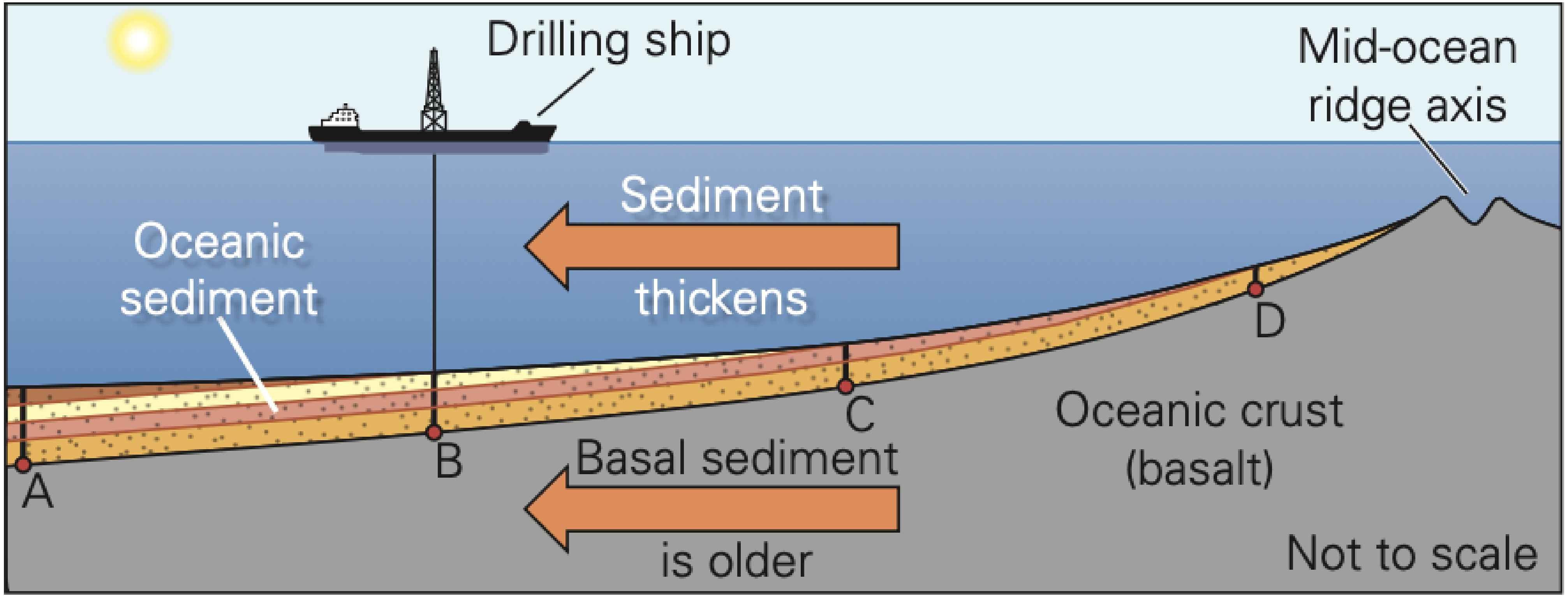


Atlantic Ocean

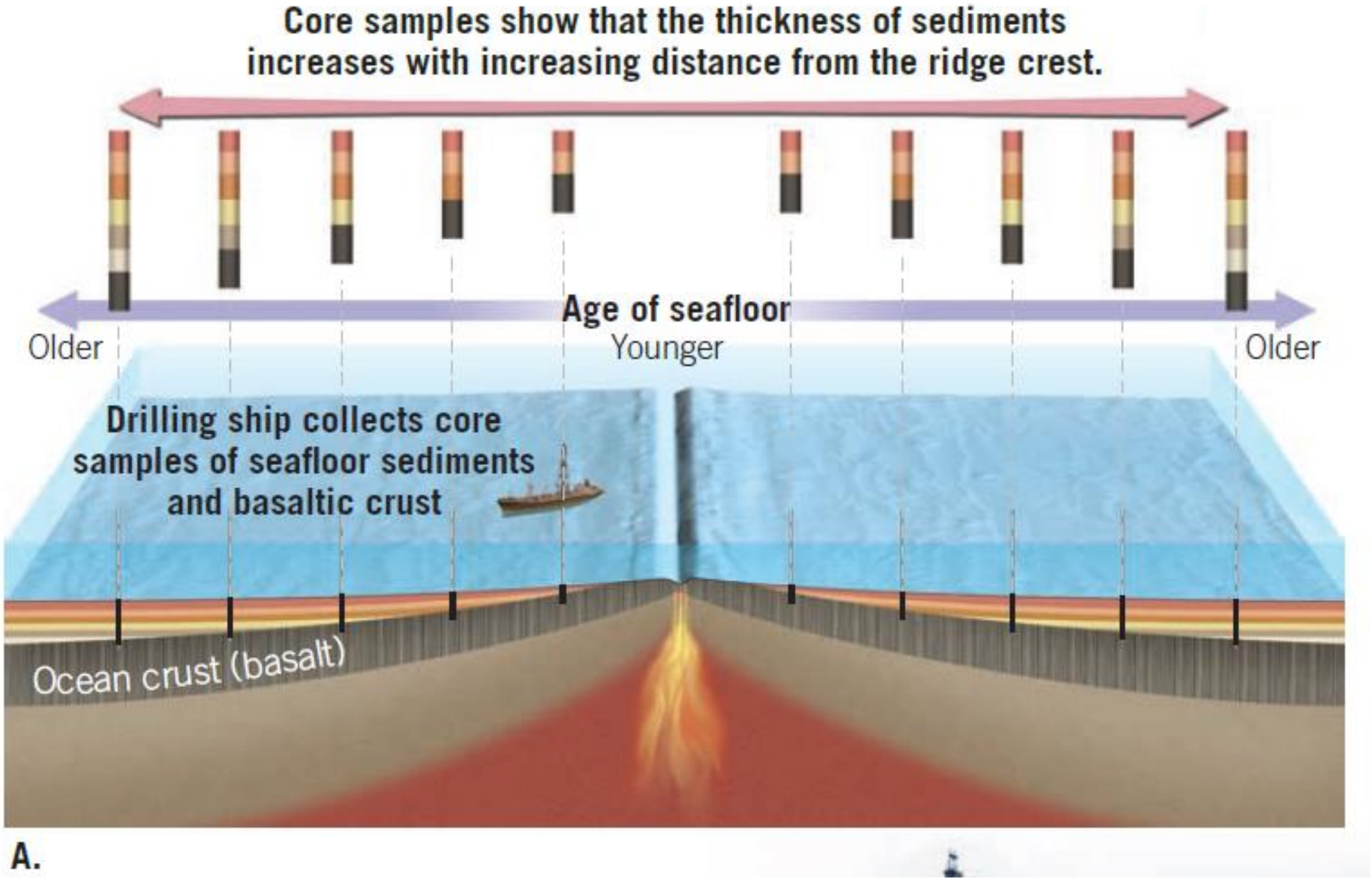
Crustal Ages

Crustal Age

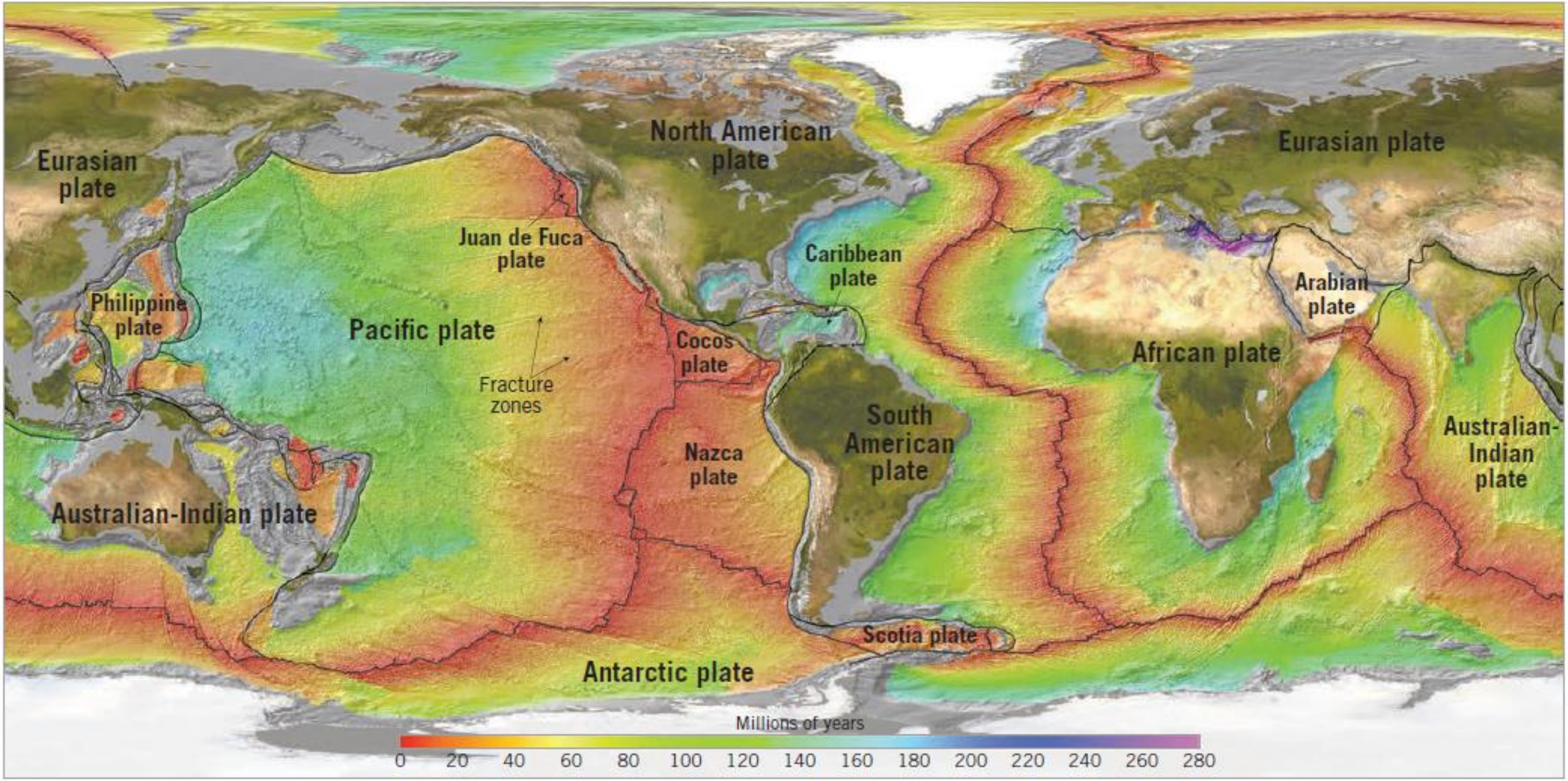
FIGURE 3.11 Drilling into the sediment layer of the ocean floor confirms that the basal sediment in contact with basalt gets older the farther away it is from the ridge. The sediment at location A is older than the sediment at location D.



Crustal Age


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.

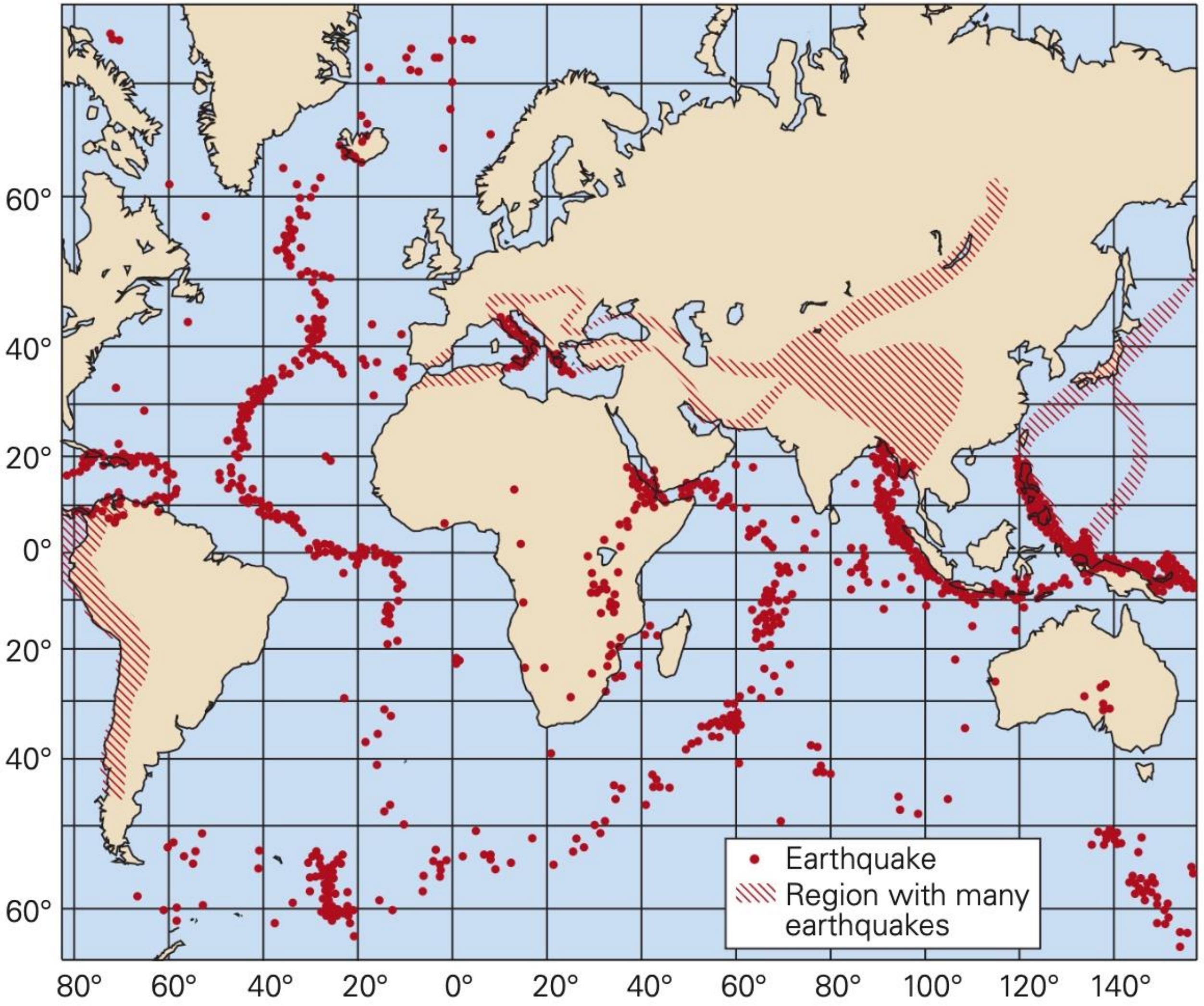
Crustal Age

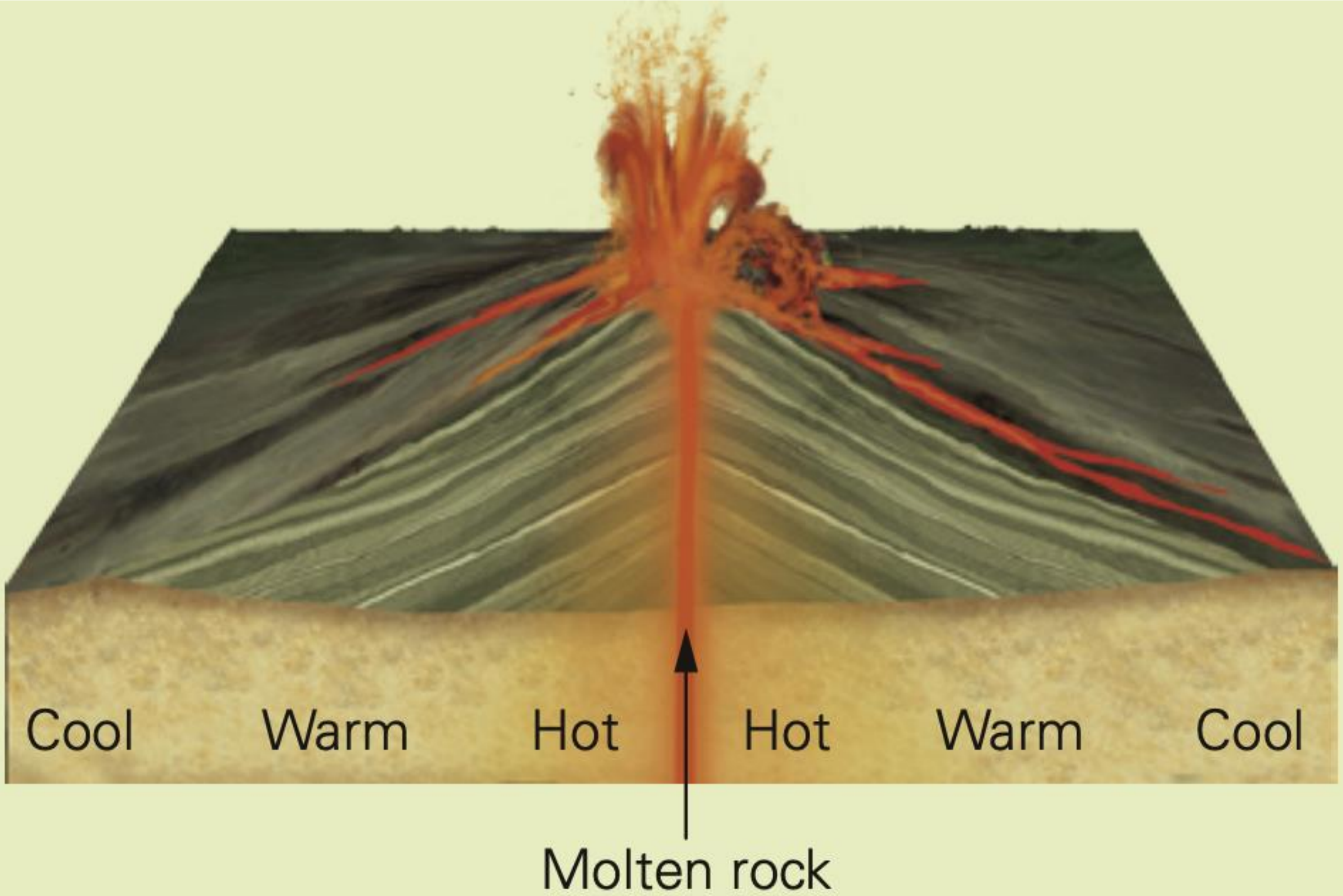


Eurasian plate
North American plate
Eurasian plate
Juan de Fuca plate
Caribbean plate
Philippine plate
Pacific plate
Cocos plate
Arabian plate
African plate
Fracture zones
South American plate
Nazca plate
Australian-Indian plate
Australian-Indian plate
Scotia plate
Antarctic plate
Millions of years
0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

Earthquake Distribution

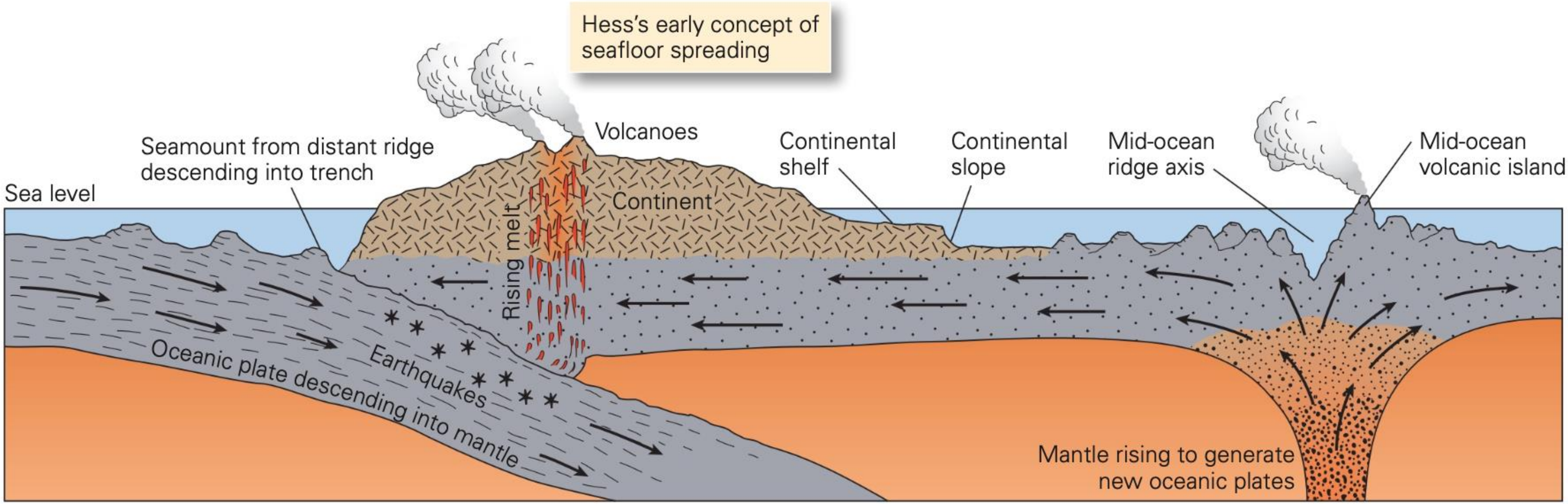
FIGURE 3.12 A 1953 map showing the distribution of earthquake locations in the ocean basins. Note that earthquakes occur in belts.





(d) During advection, a hot liquid (such as molten rock) rises into cooler material, and heat then conducts from the hot liquid into the cooler material.

Harry Hess's Hypothesis of Seafloor Spreading



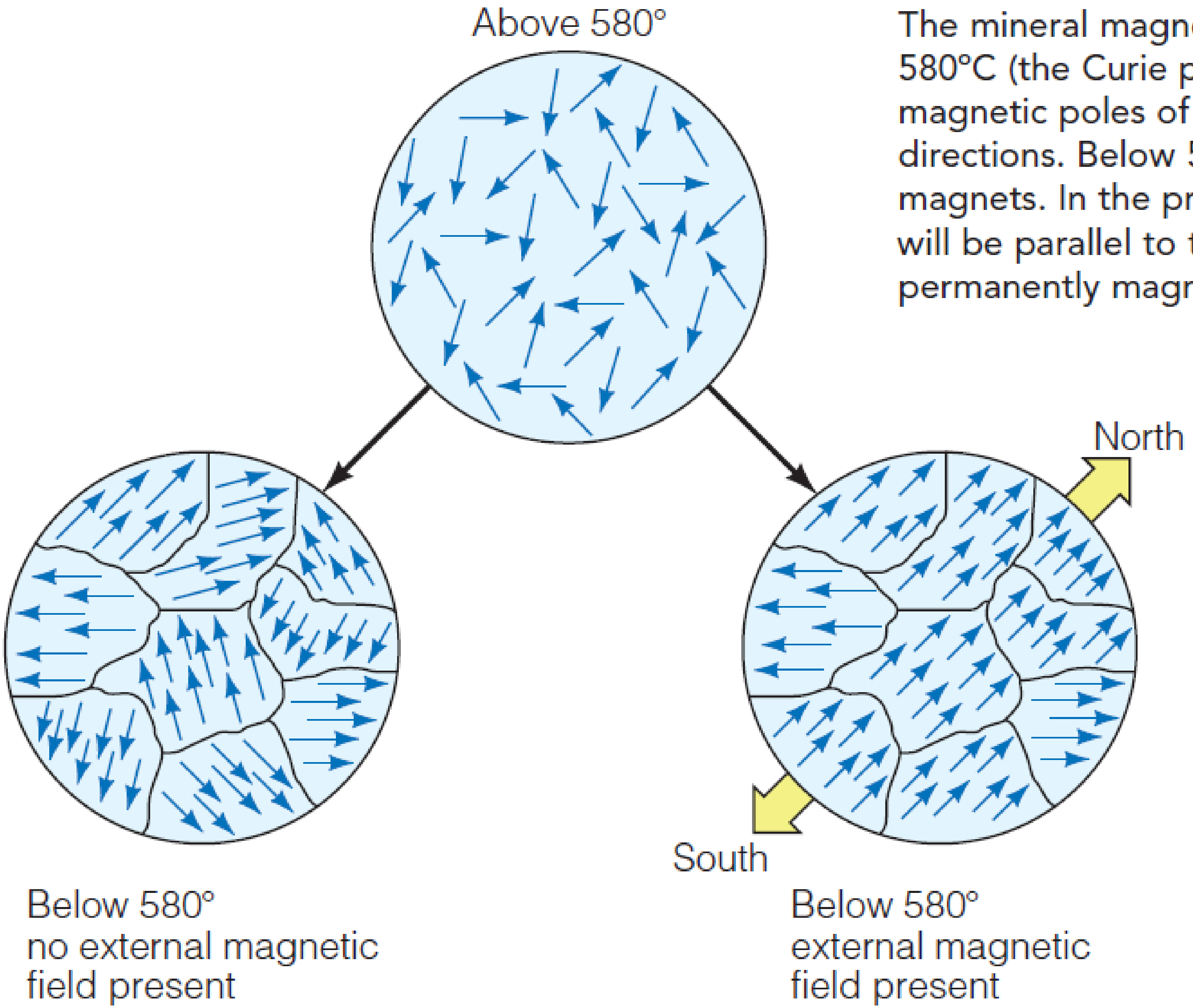
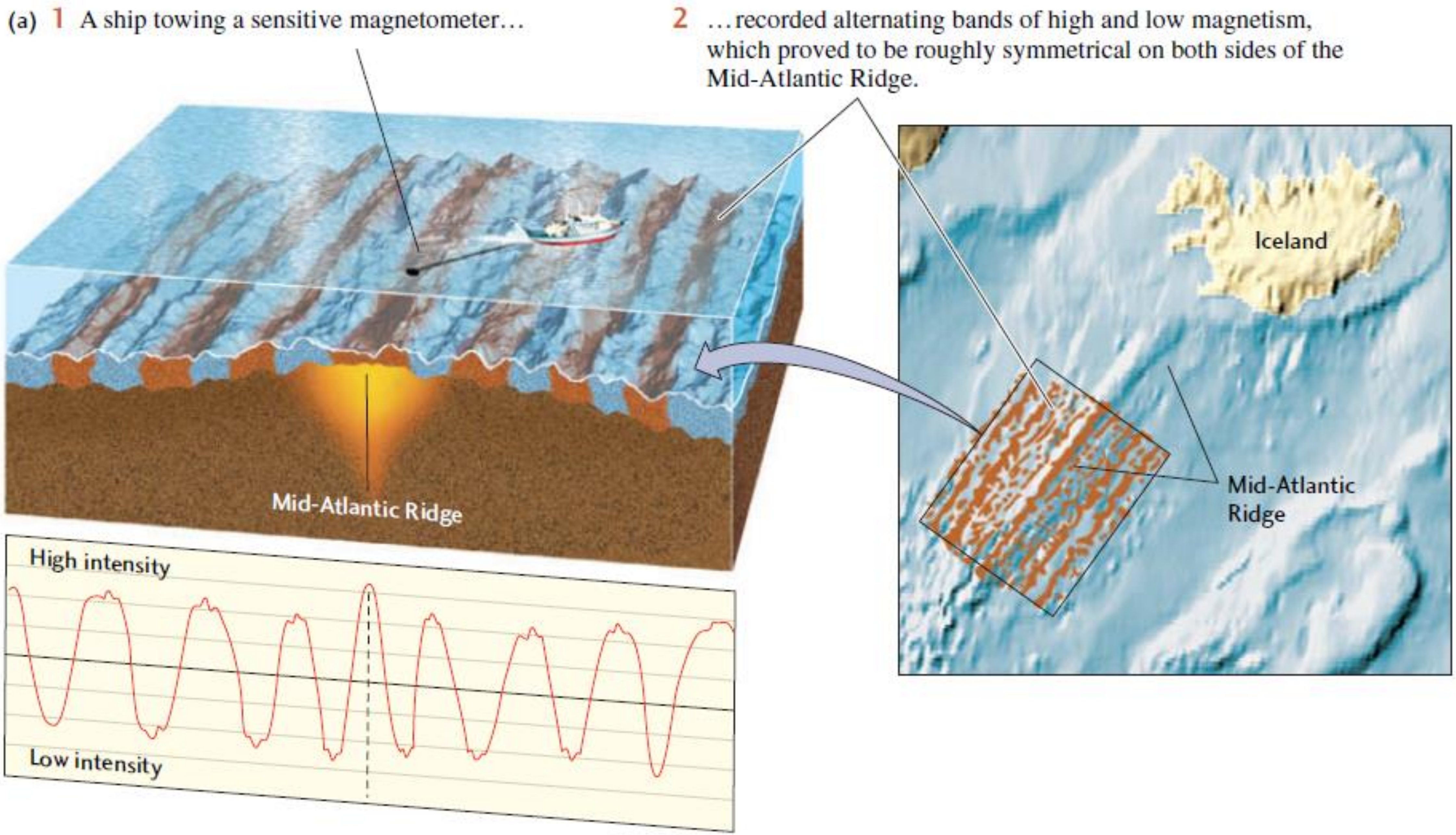


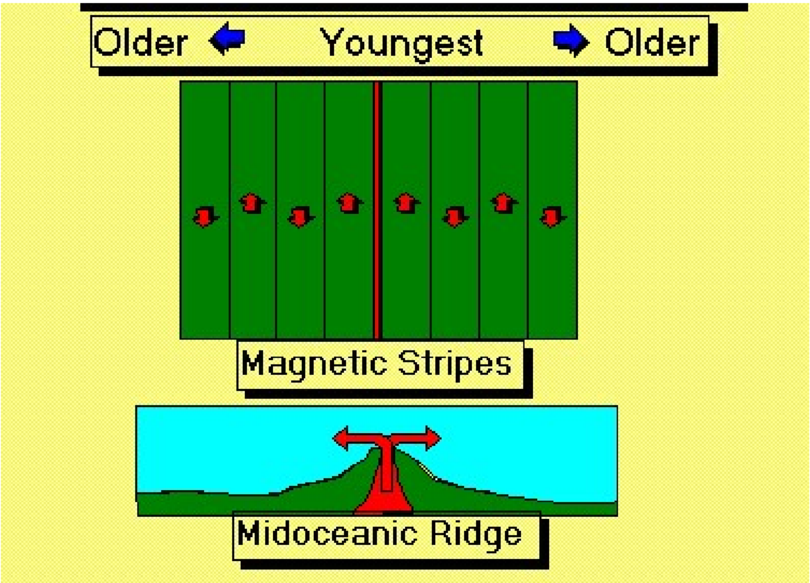
FIGURE B5.2 Magnetic magnetite
The mineral magnetite can acquire permanent magnetism. Above 580°C (the Curie point), the vibration of atoms is so great that the magnetic poles of individual atoms (small arrows) point in random directions. Below 580°C, the atoms begin to align and form tiny magnets. In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

Magnetic Reversals



Magnetic Reversals

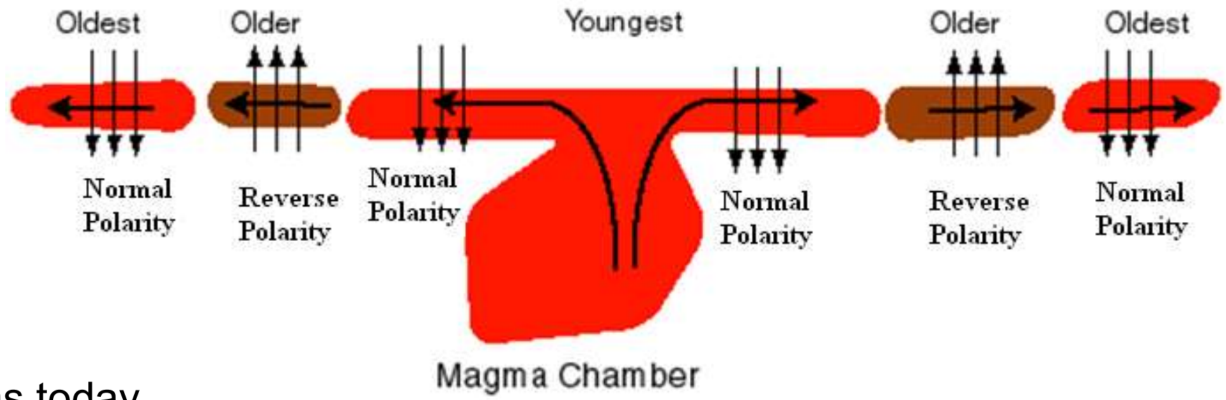
Another piece of the puzzle: Magnetic reversals



• The polarity changed throughout the history of the Earth.

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

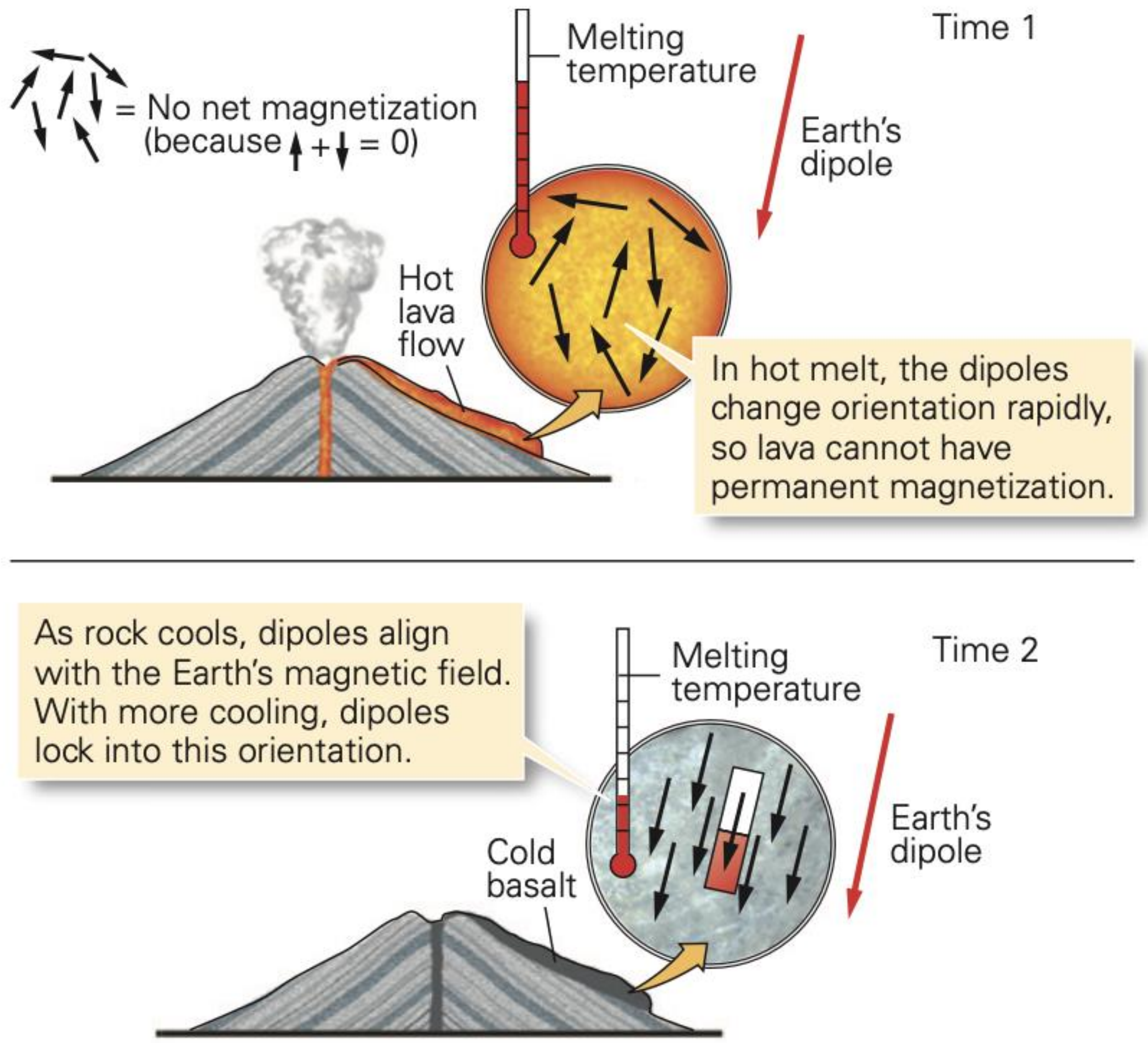
• Since the poles flipped in different times, some of the rocks show normal polarity while others would show reverse polarity.



Normal polarity: Same as today.

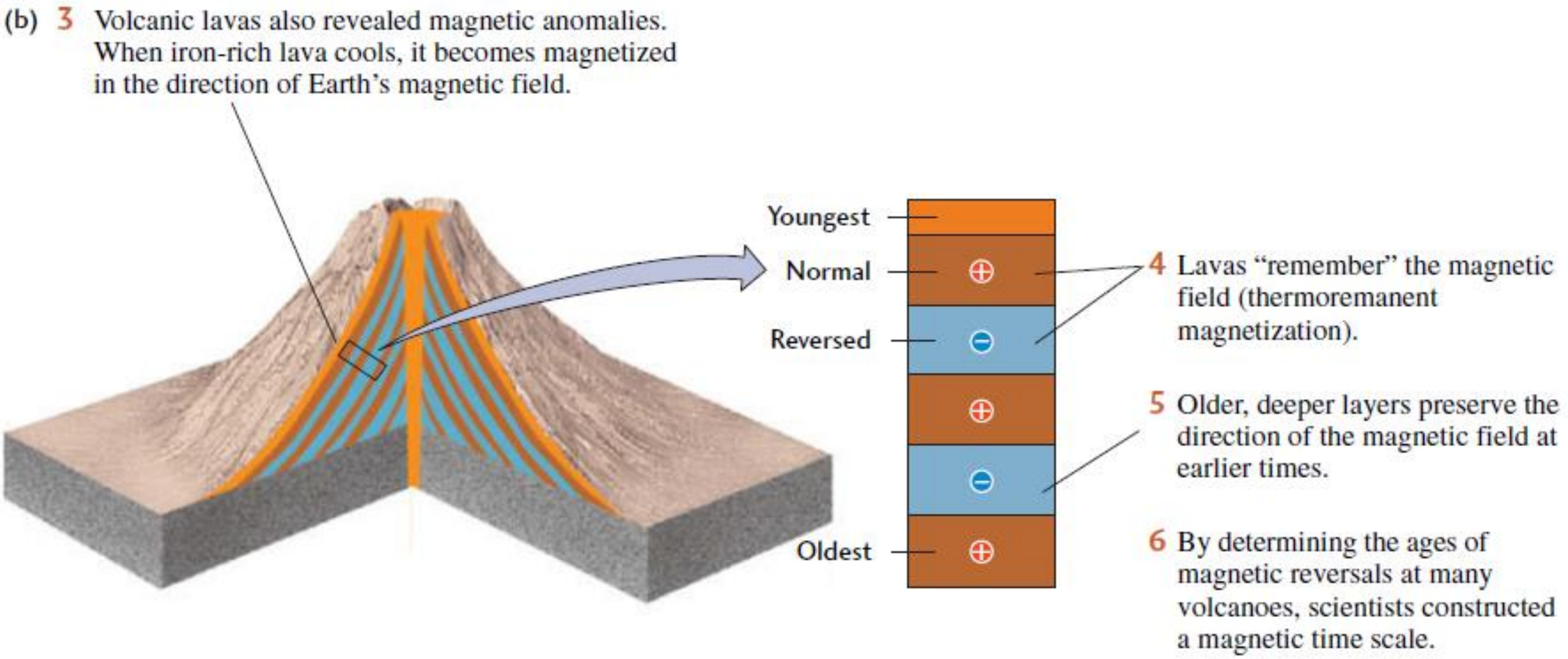
Reverse polarity: Reverse orientation with respect to today’s polarity.

Magnetic Reversals

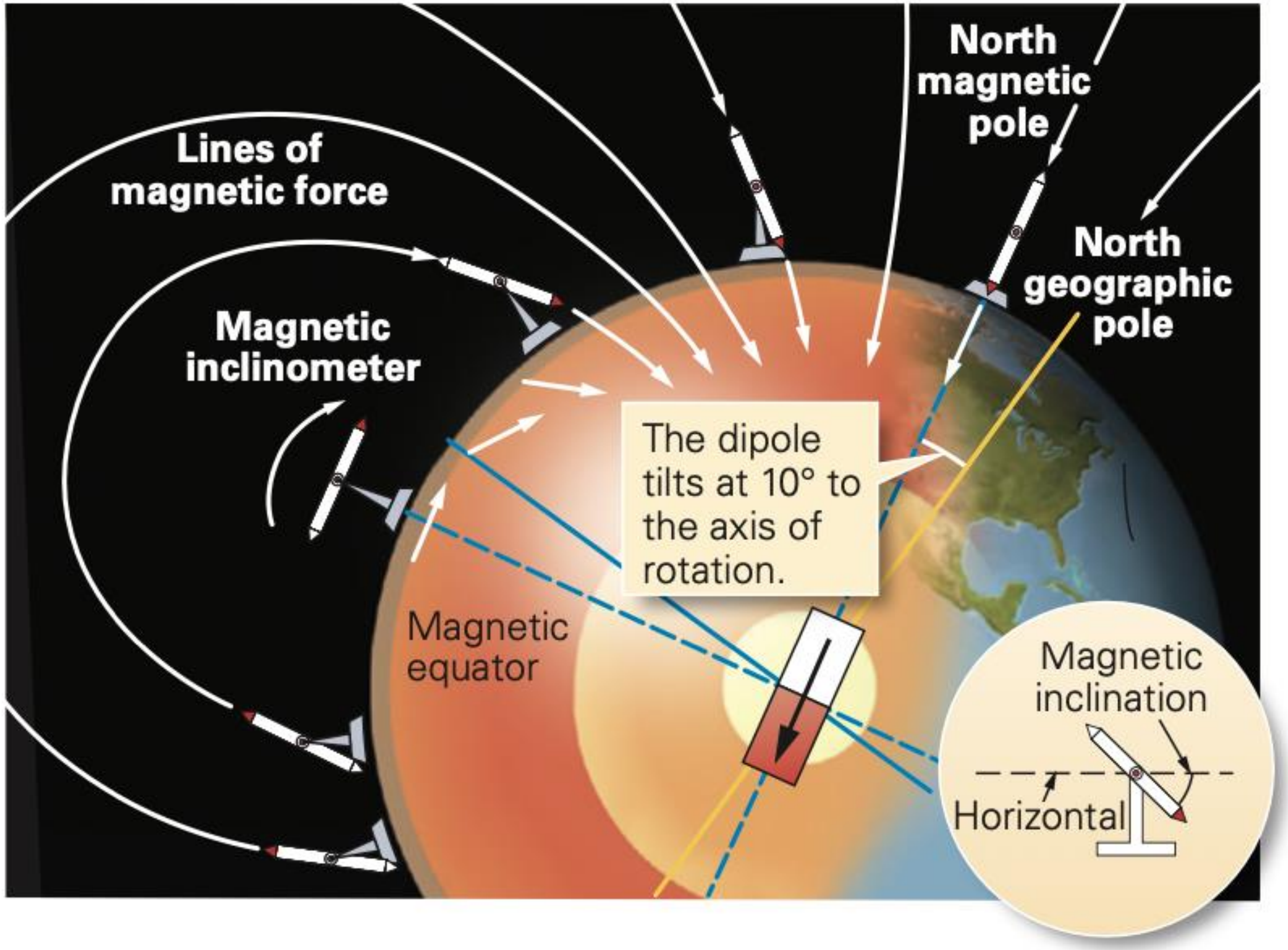


(b) Paleomagnetism can form when melt cools and becomes solid rock.

Magnetic Reversals

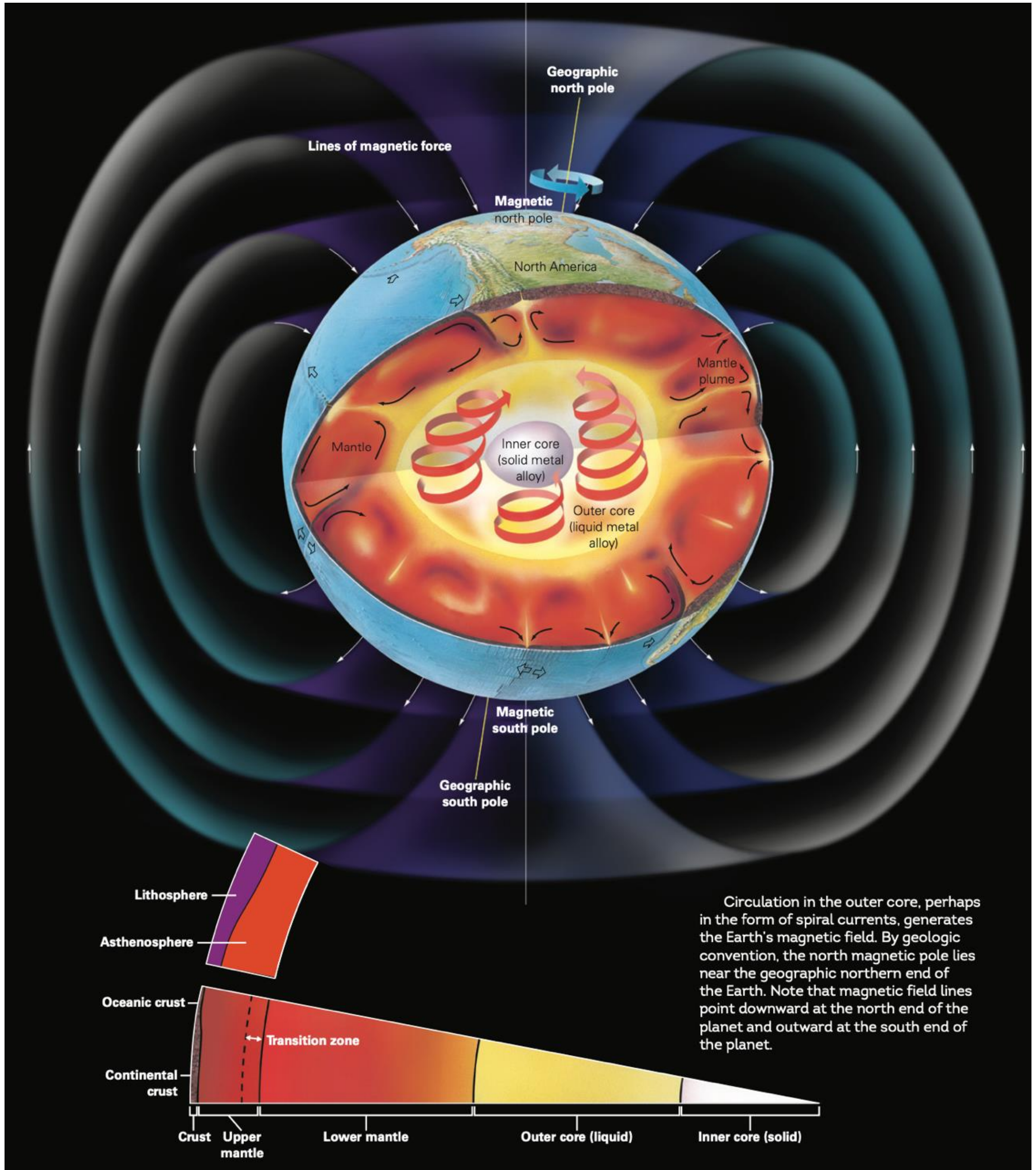


Earth's Magnetic Field

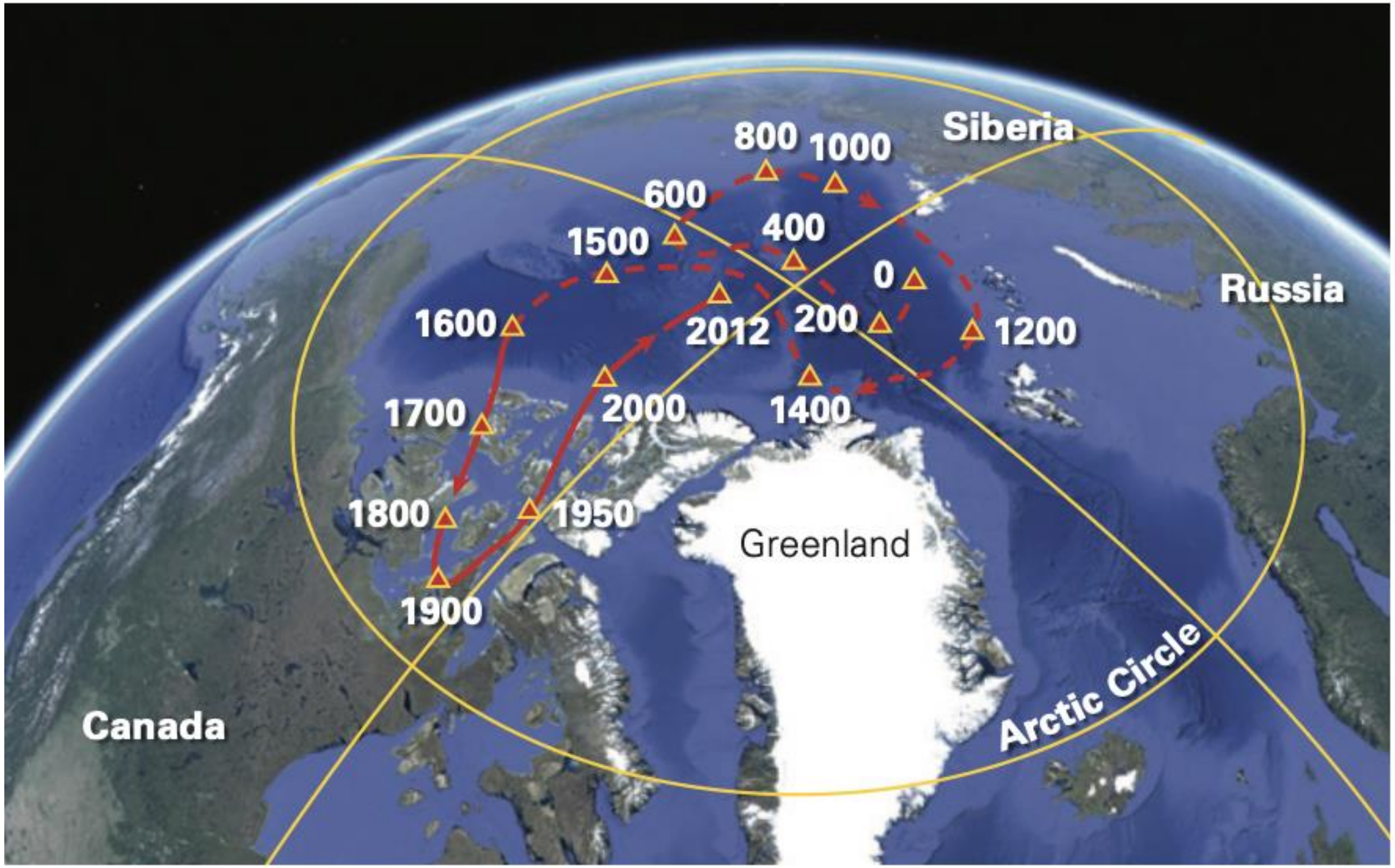


(d) The Earth's magnetic field lines curve, so the tilt of a magnetic needle changes with latitude. This tilt is the magnetic inclination.

Earth’s Magnetic Field



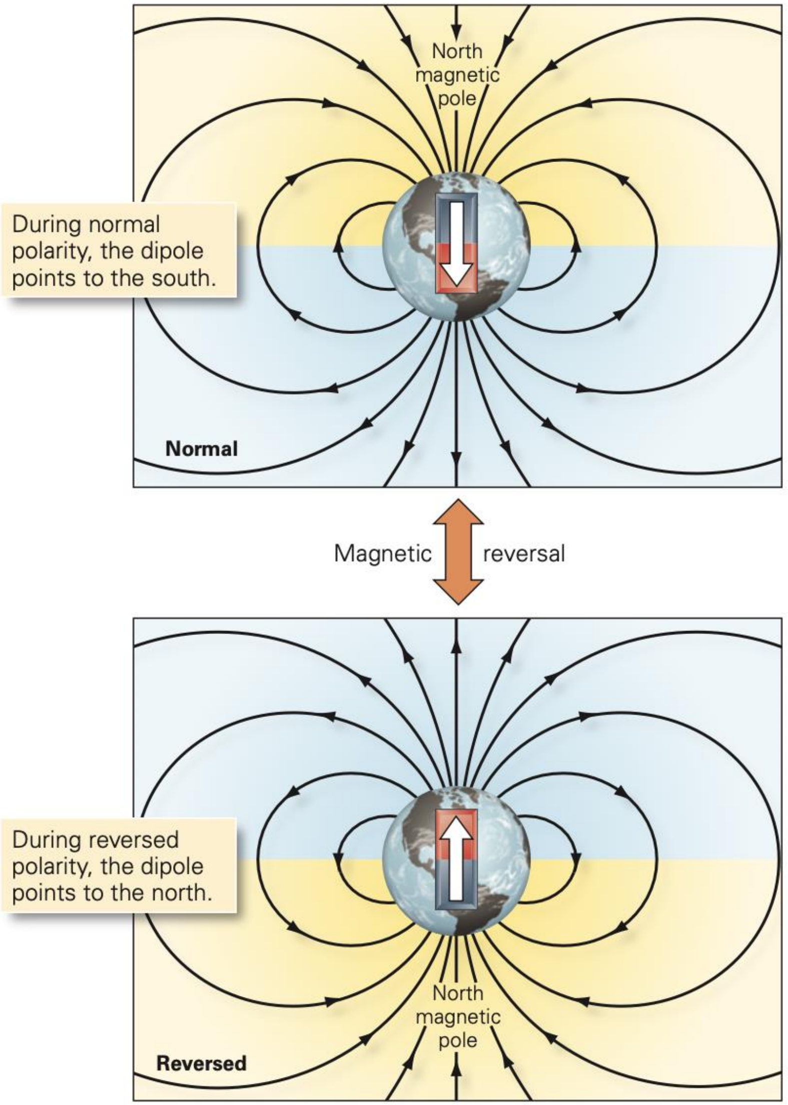
Earth’s Magnetic



(c) A simplified map showing the changing position of the north magnetic pole over the past 2,000 years. Before about 1600, the position was not as well constrained, so the path is dashed.

Earth's Magnetic Field: Polarity Reversals

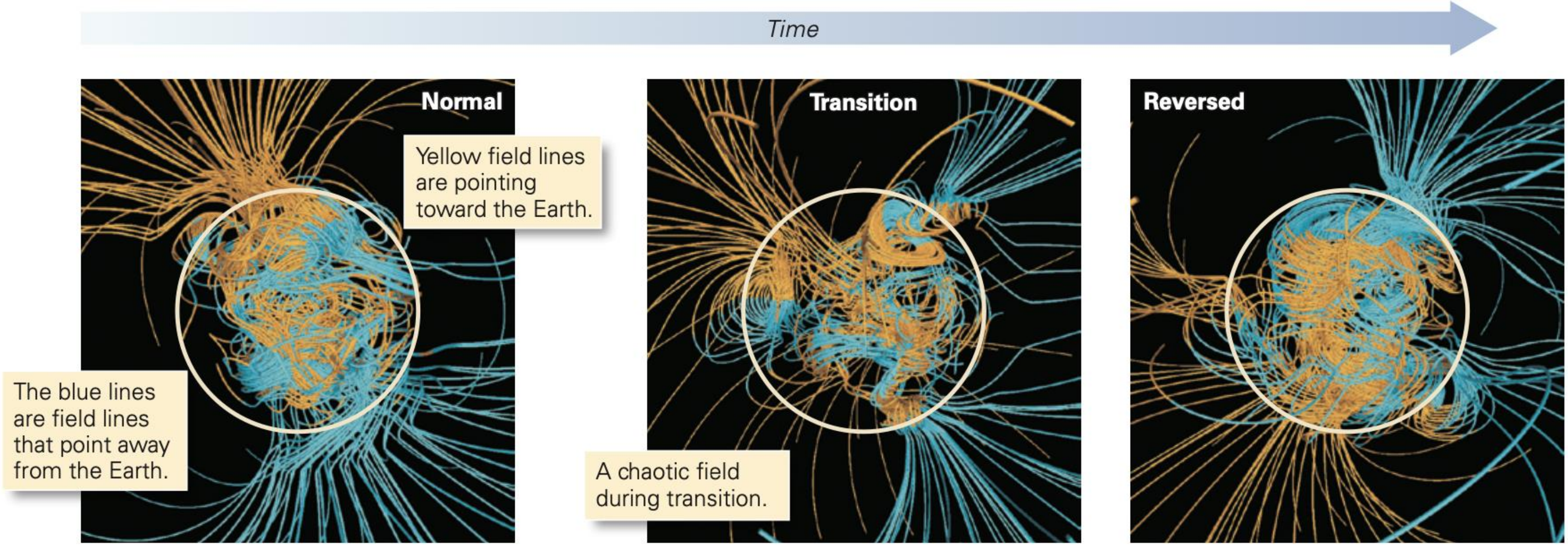
FIGURE 3.19 Magnetic polarity reversals and the chronology of reversals.



(a) Geologists proposed that the Earth's magnetic field reverses polarity every now and then.

Earth's Magnetic Field: Polarity Reversals

FIGURE 3.20 A supercomputer model simulating the reversal of the Earth's magnetic field. In nature, the transition probably takes thousands of years.



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

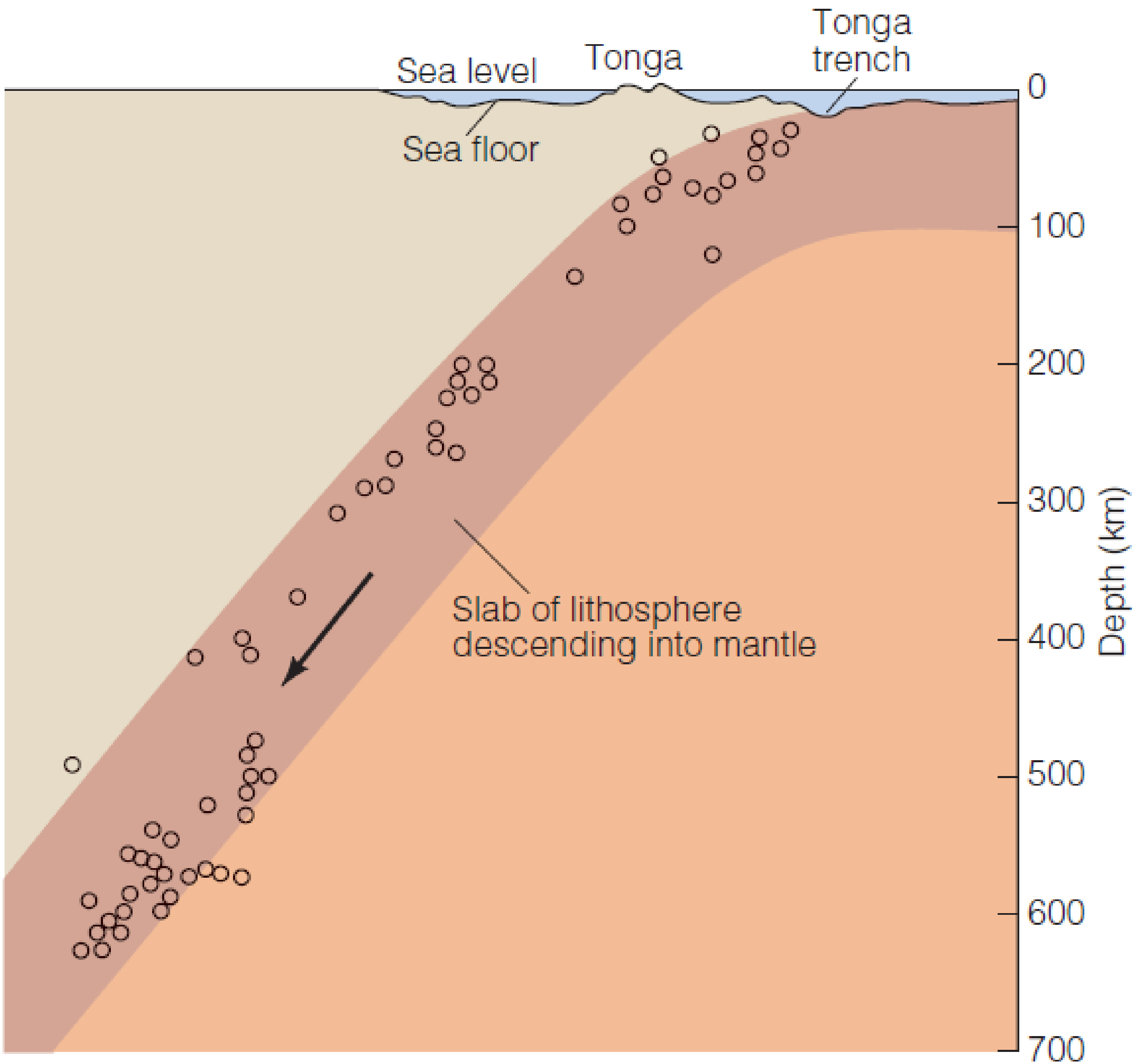
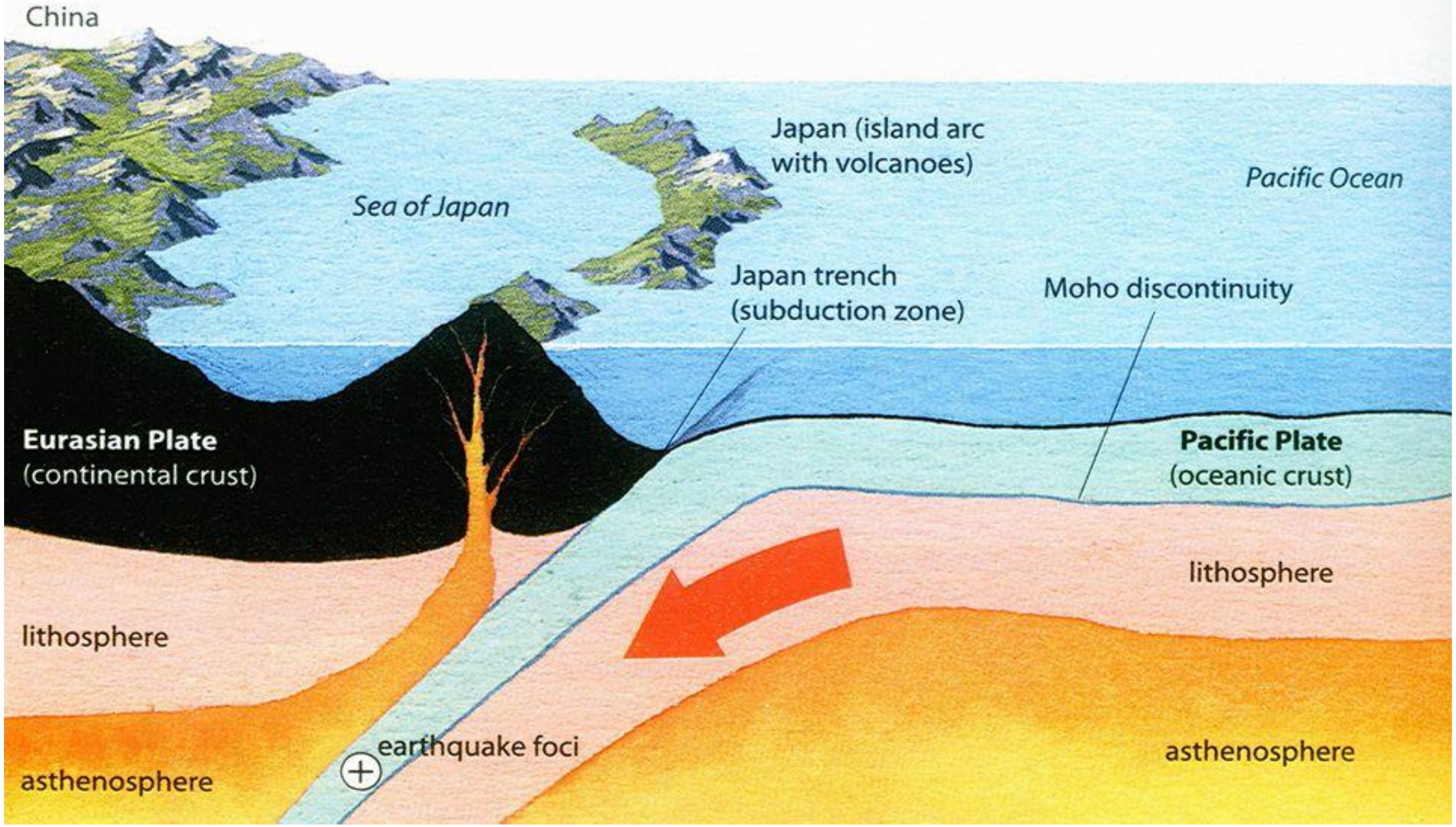


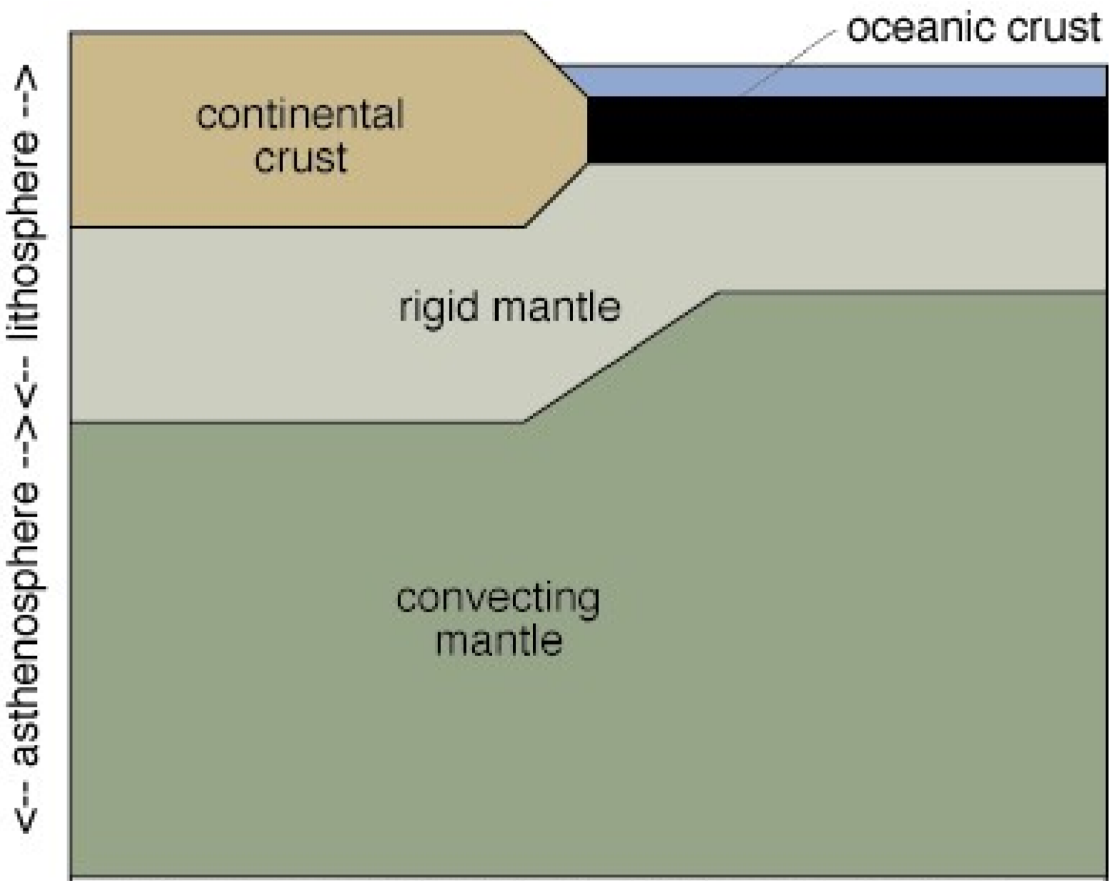
FIGURE 5.19 **Benioff zone**
Deep earthquakes define the dimensions of a downgoing slab of oceanic lithosphere in a Wadati-Benioff zone located in the Pacific Ocean near the island of Tonga. Each circle represents a single earthquake in a given year. The earthquakes are generated by the downward grinding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

Island Arc - Japan



LITHOSPHERE

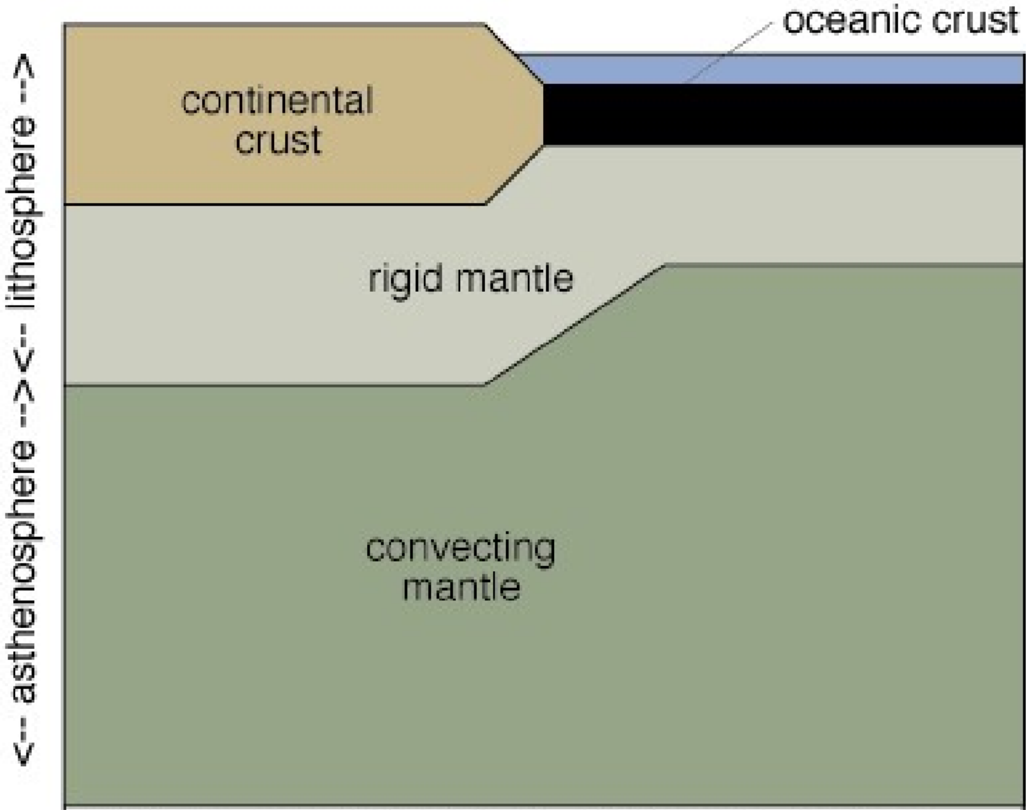
- The lithosphere (from the Greek, lithos, stone) is the rigid outermost layer made of crust and uppermost mantle
- The lithosphere is the "plate" of the plate tectonic theory



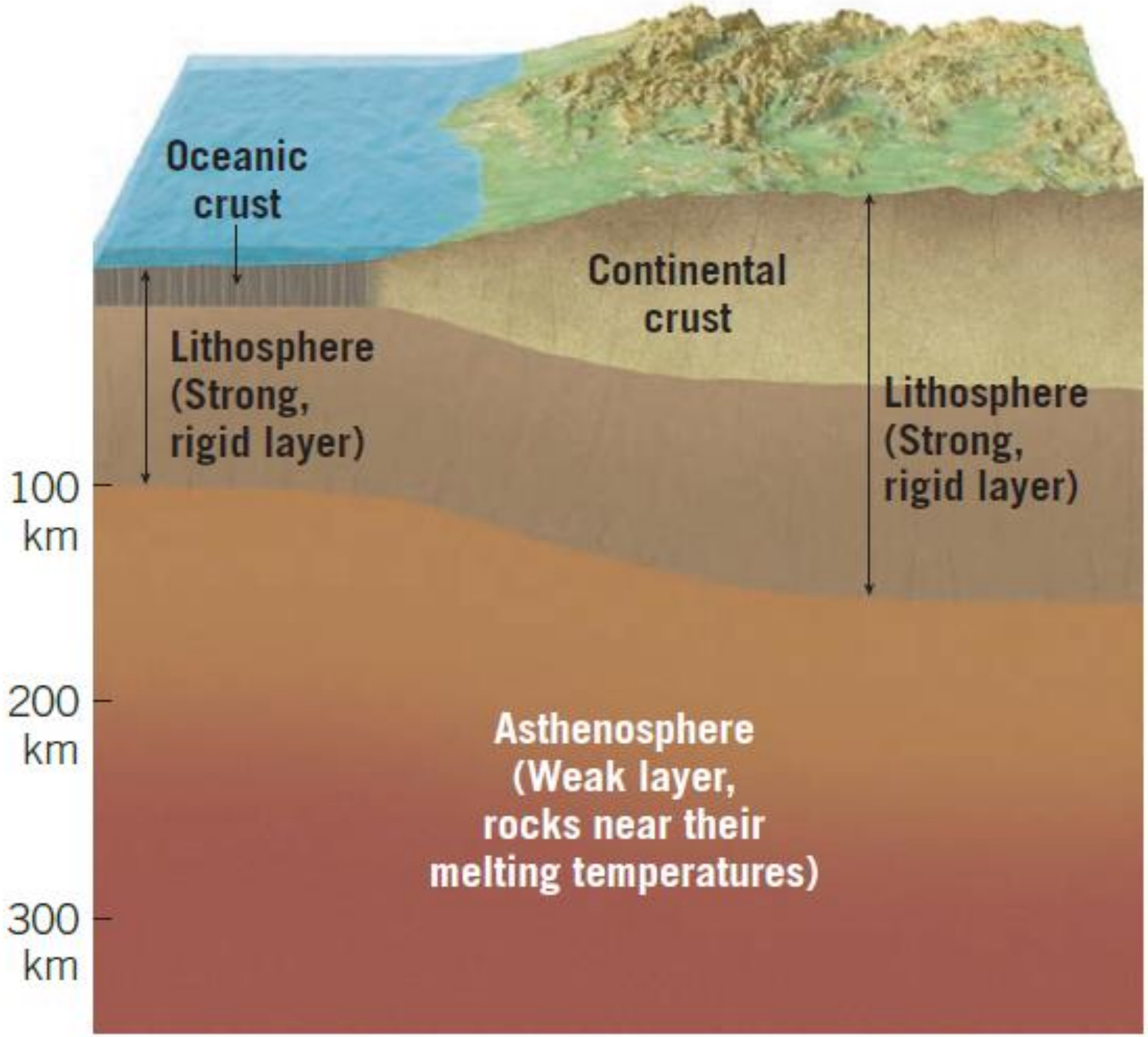
Outer layers of the Earth. Plates are made of crust and rigid upper mantle.

ASTHENOSPHERE

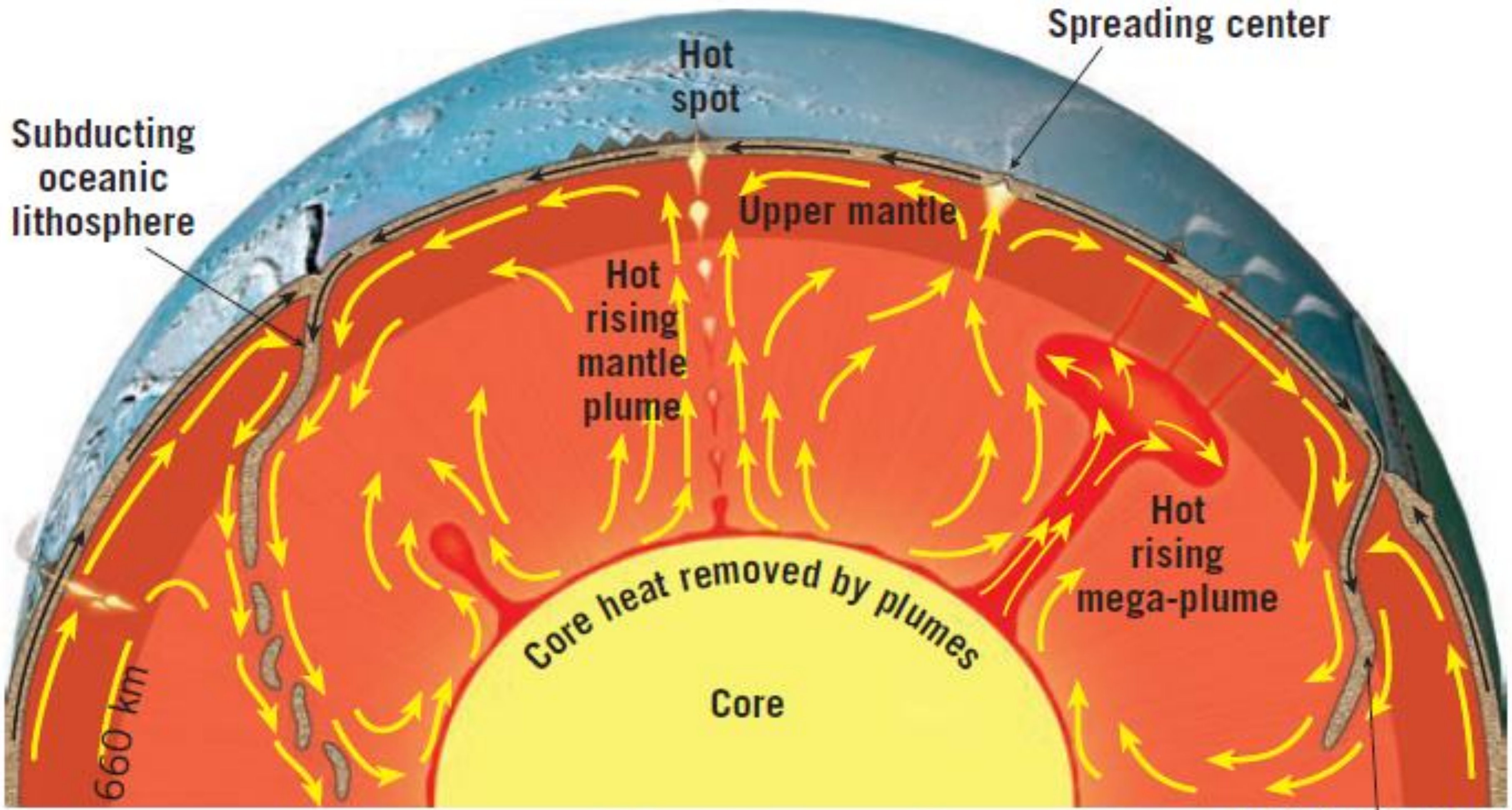
- The asthenosphere (from the Greek, asthenos, devoid of force) is part of the mantle that flows, a characteristic called plastic behavior.
- The flow of the asthenosphere is part of mantle convection, which plays an important role in moving lithospheric plates.



Outer layers of the Earth. Plates are made of crust and rigid upper mantle.


Oceanic crust
Continental crust
Lithosphere (Strong, rigid layer)
Lithosphere (Strong, rigid layer)
100 km
200 km
300 km
Asthenosphere (Weak layer, rocks near their melting temperatures)

Mantle Plume and Hot Spots



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.

Mantle Plume and Hot Spots

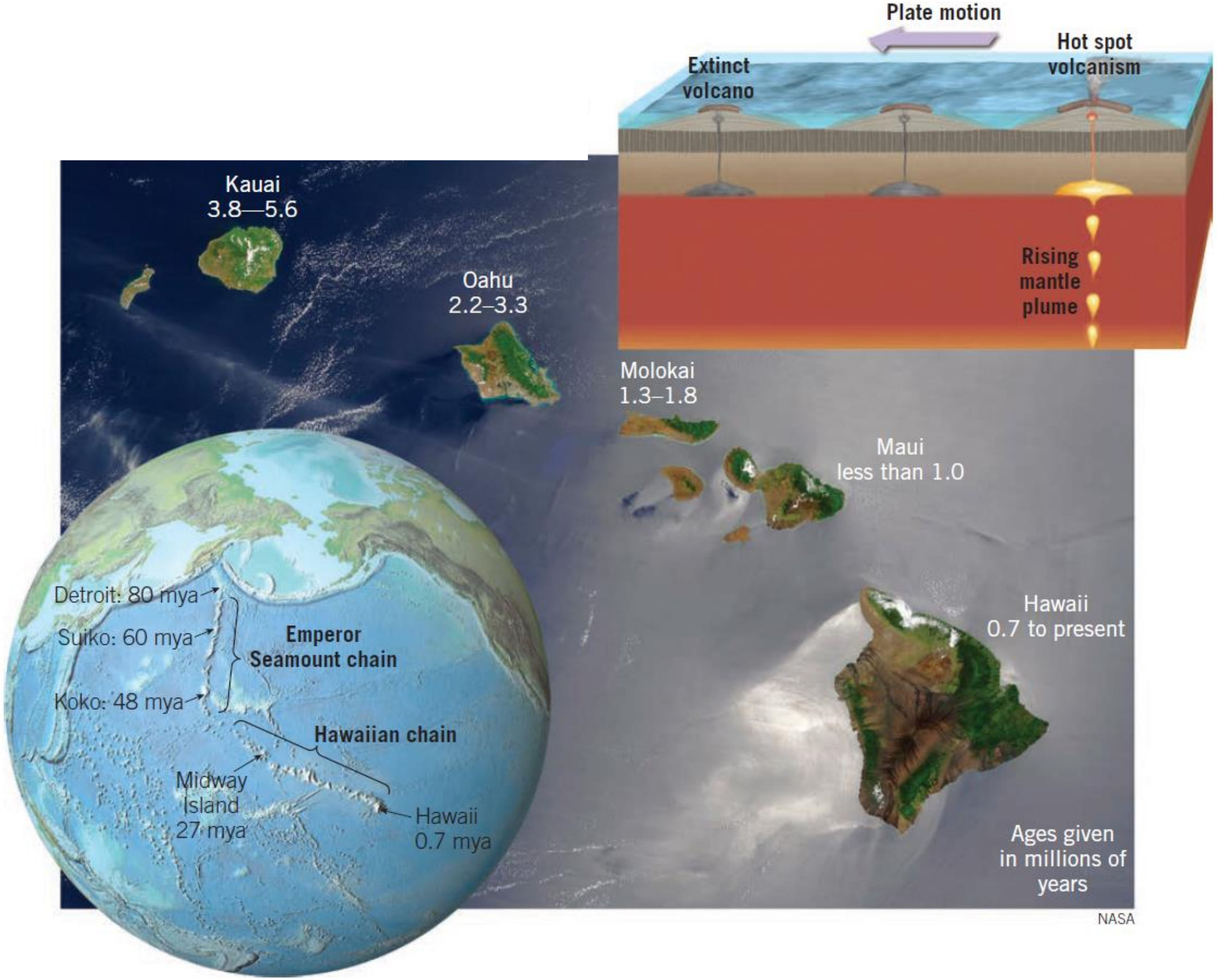
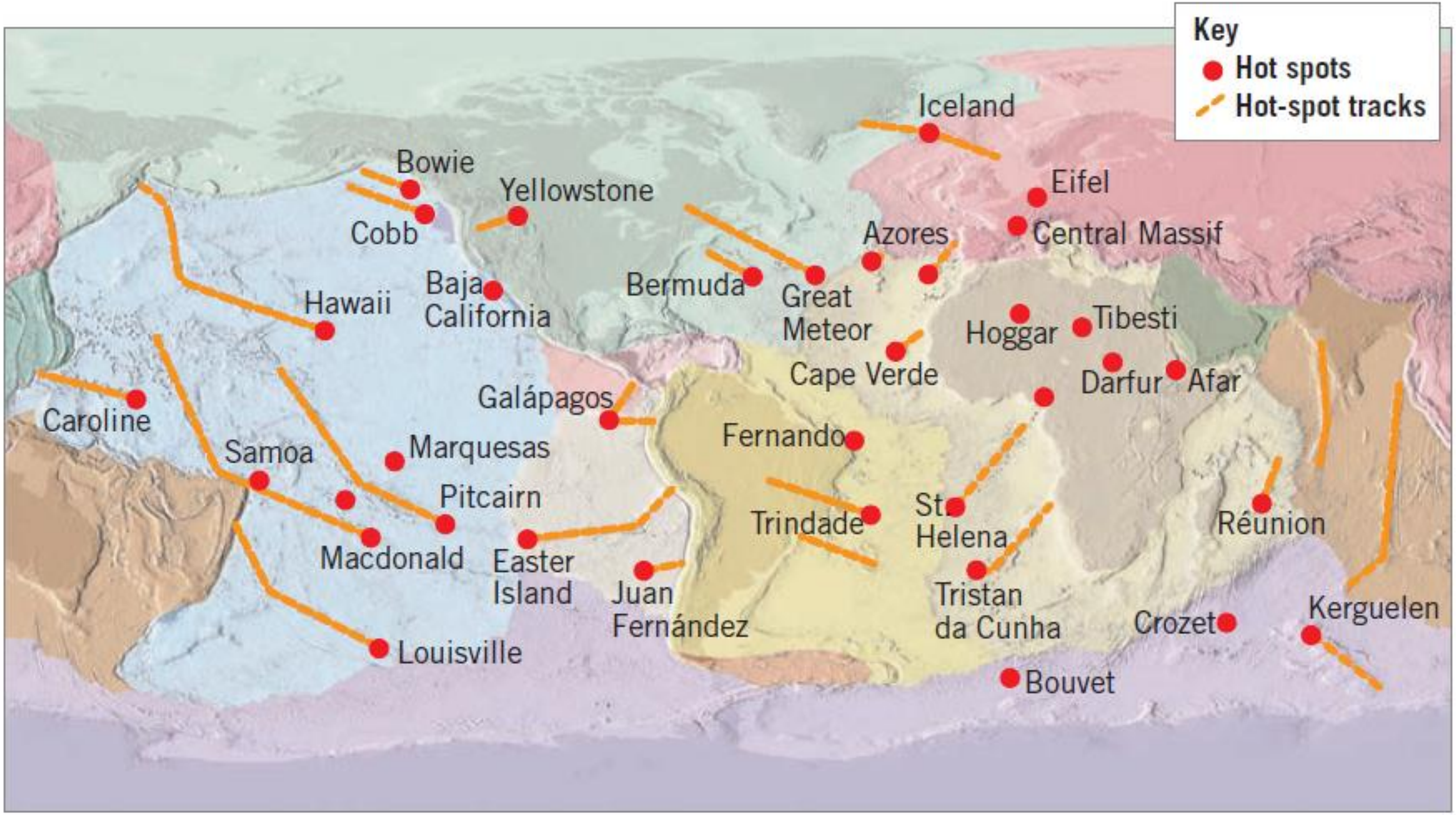


Figure 2.27

Hot-spot volcanism and the formation of the Hawaiian chain

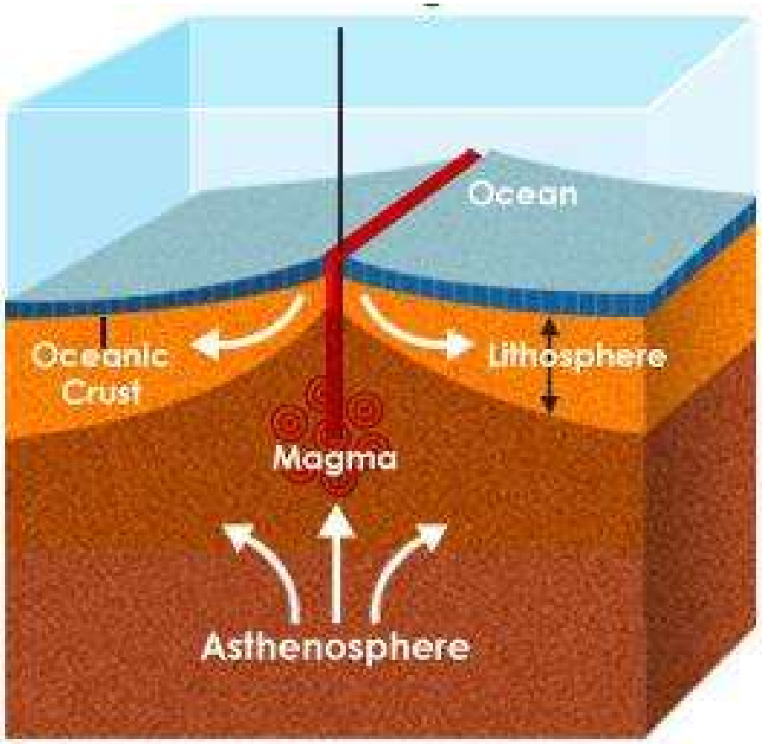
Radiometric dating of the Hawaiian Islands shows that volcanic activity increases in age moving away from the Big Island of Hawaii.

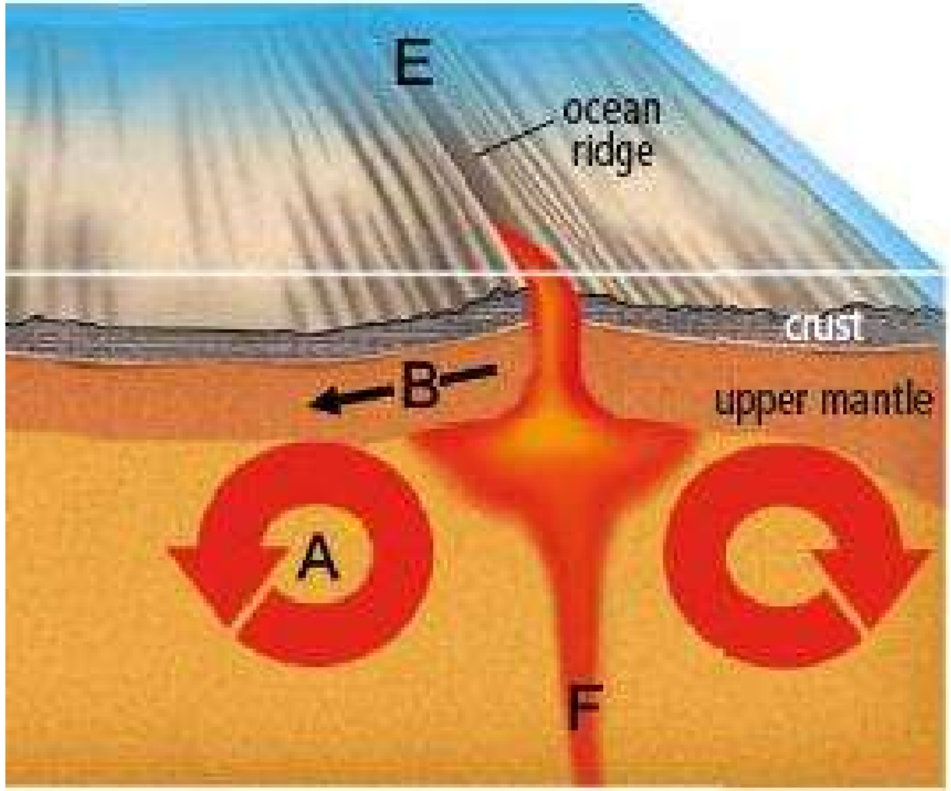
Mantle Plume and Hot Spots



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?

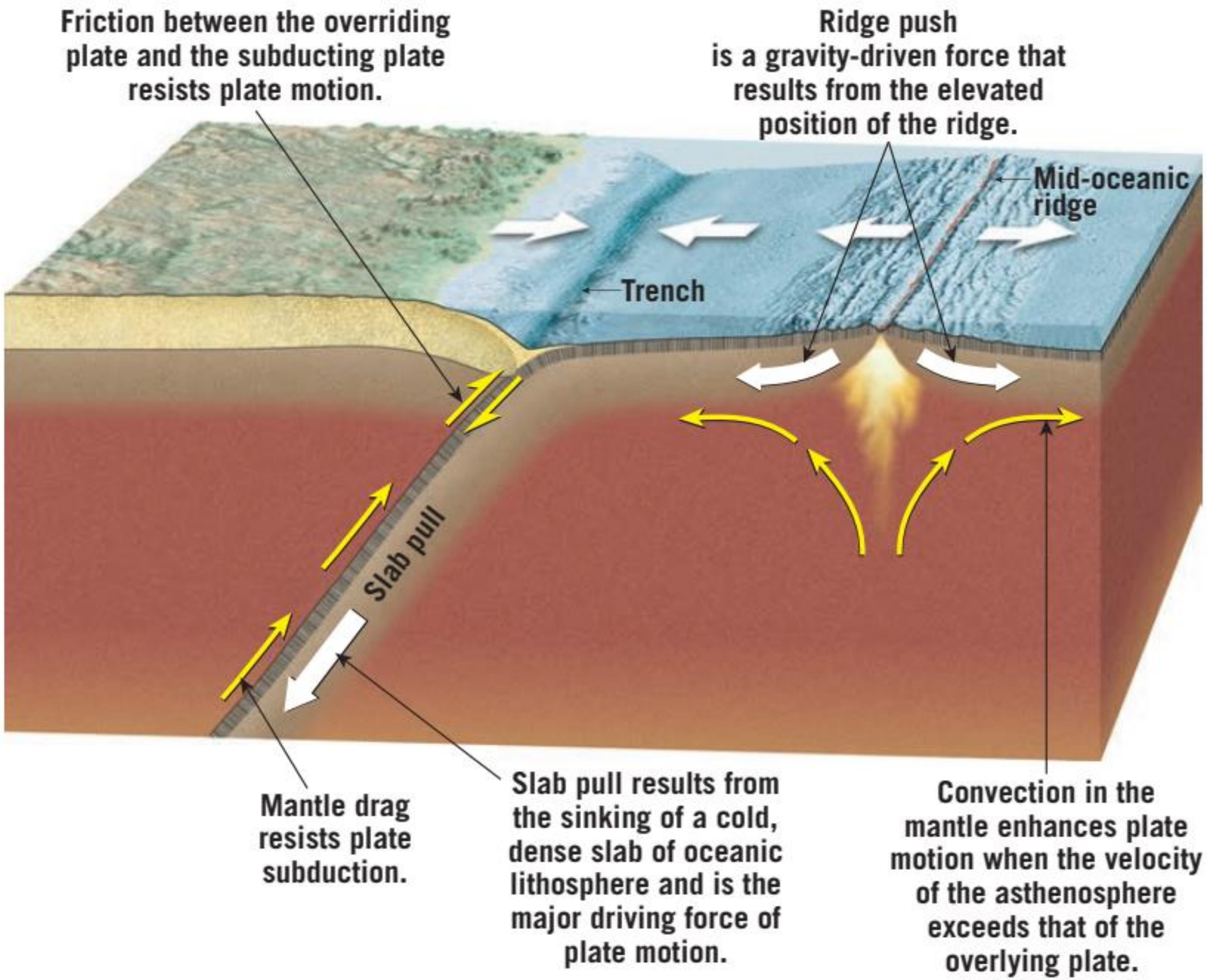
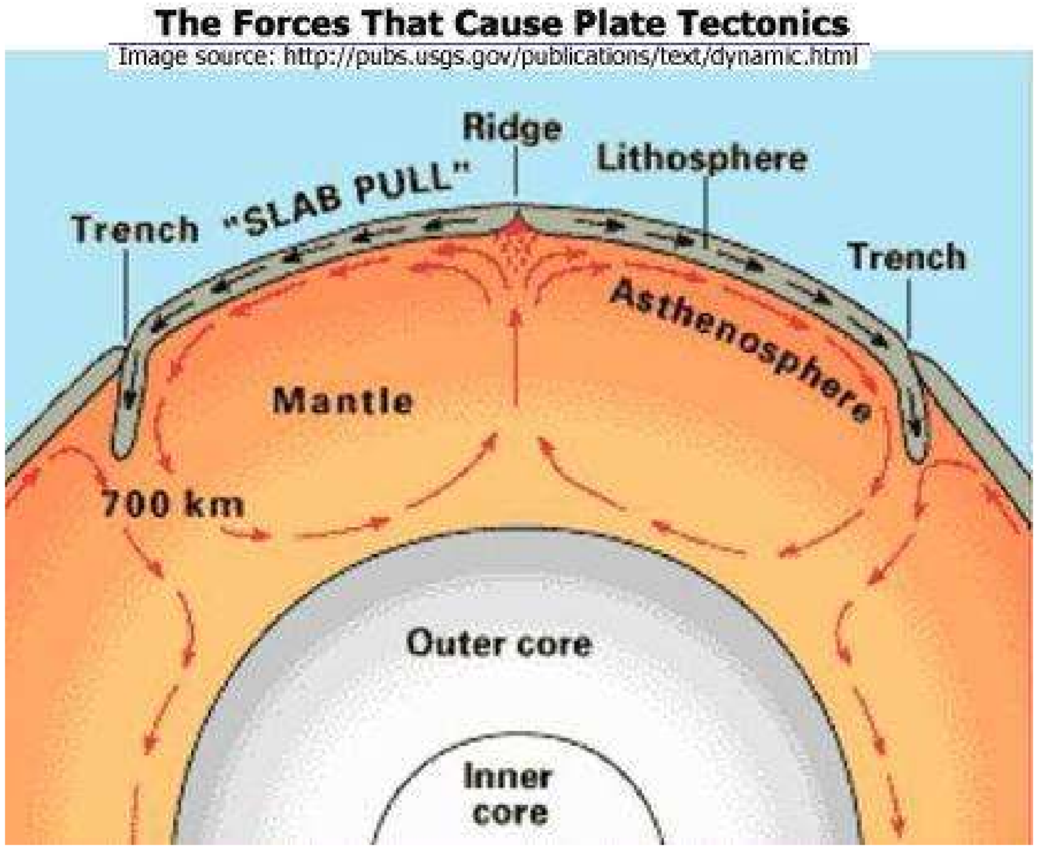


Figure 2.37 Forces that act on lithospheric plates



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

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

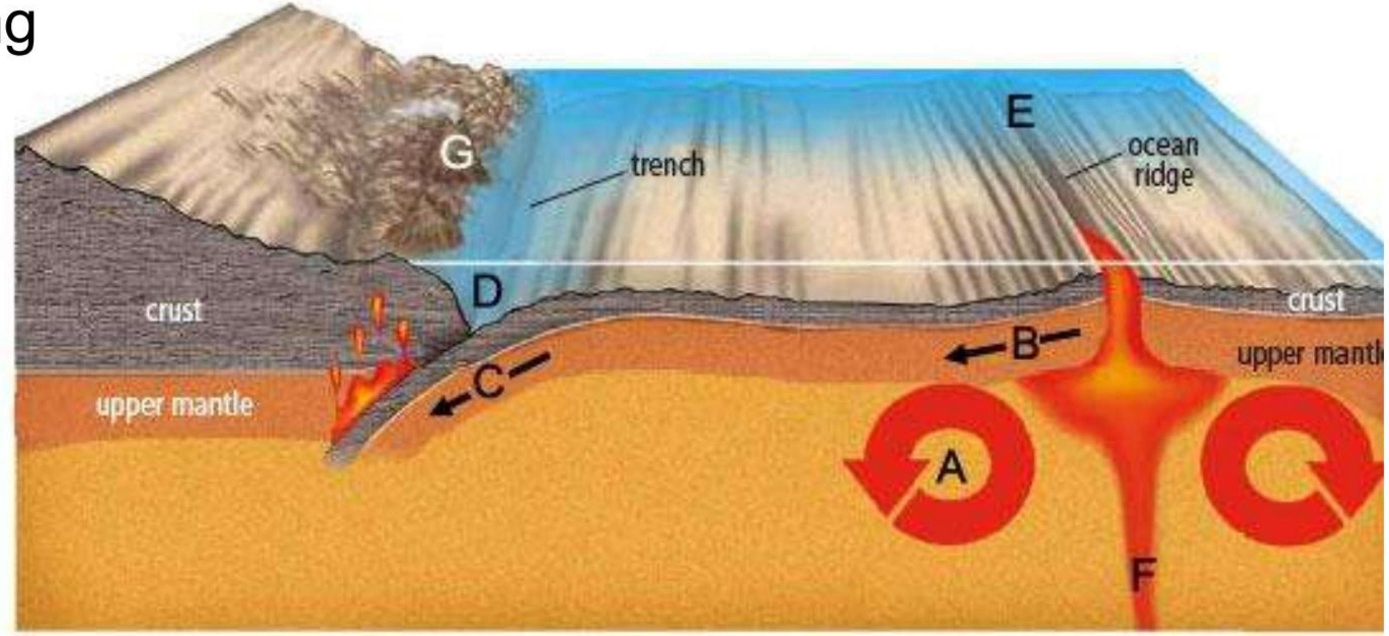
Why don't we see any oceanic crust older than 200 my ?

-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.

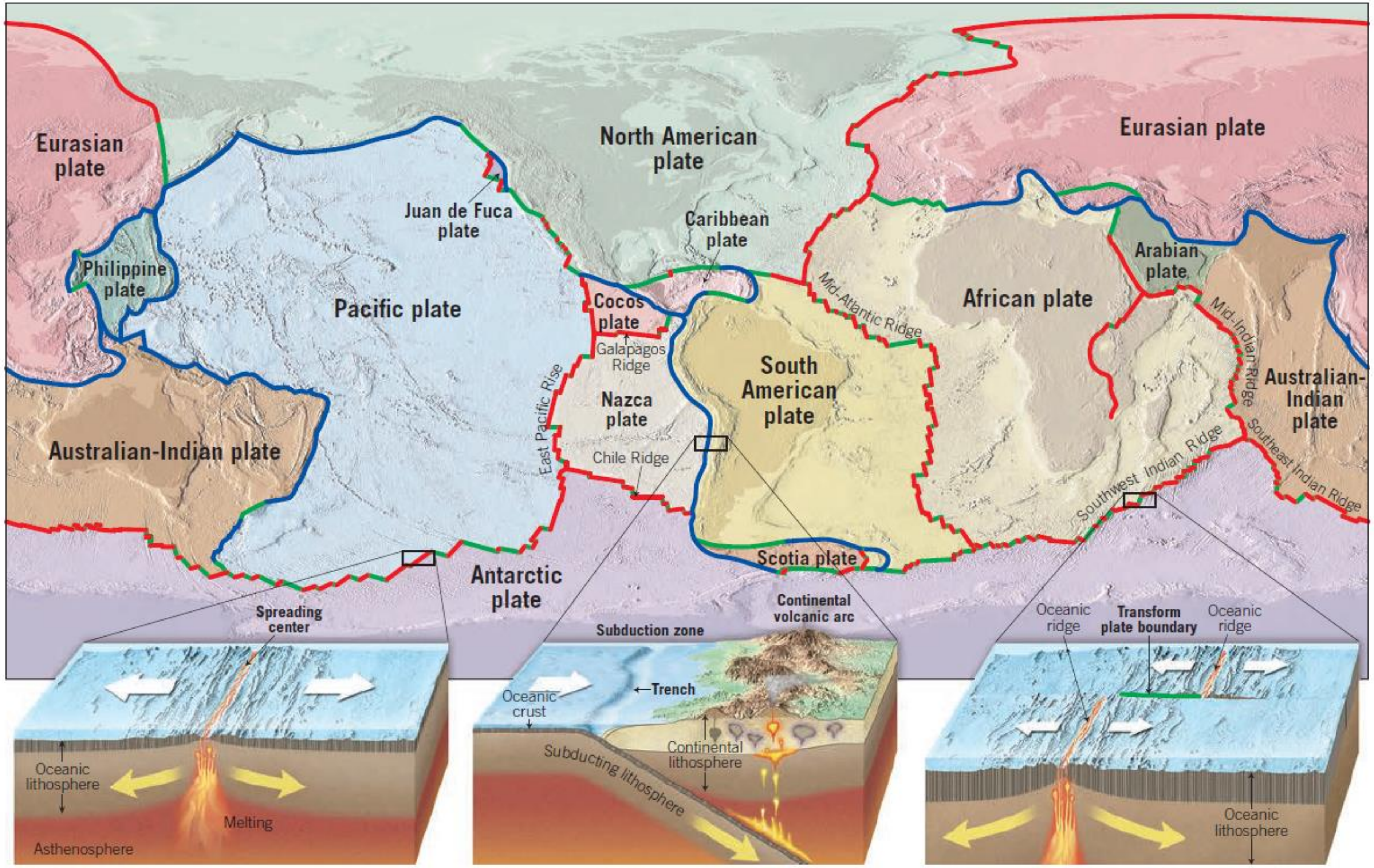
- As it moves down due to increasing Temperature, it starts melting.

-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.



Plates Boundaries

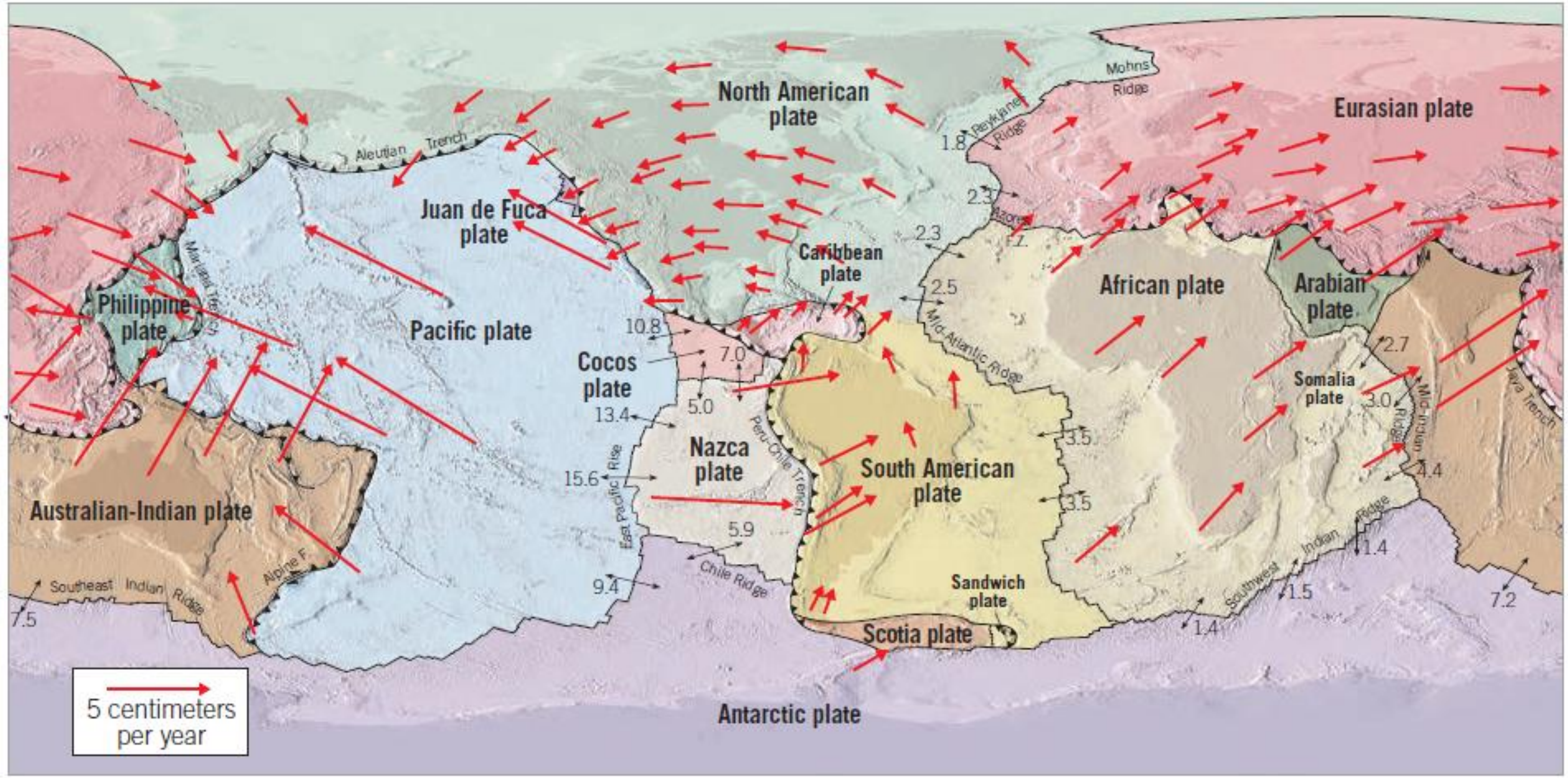


A. Divergent plate boundary B. Convergent plate boundary C. Transform plate boundary

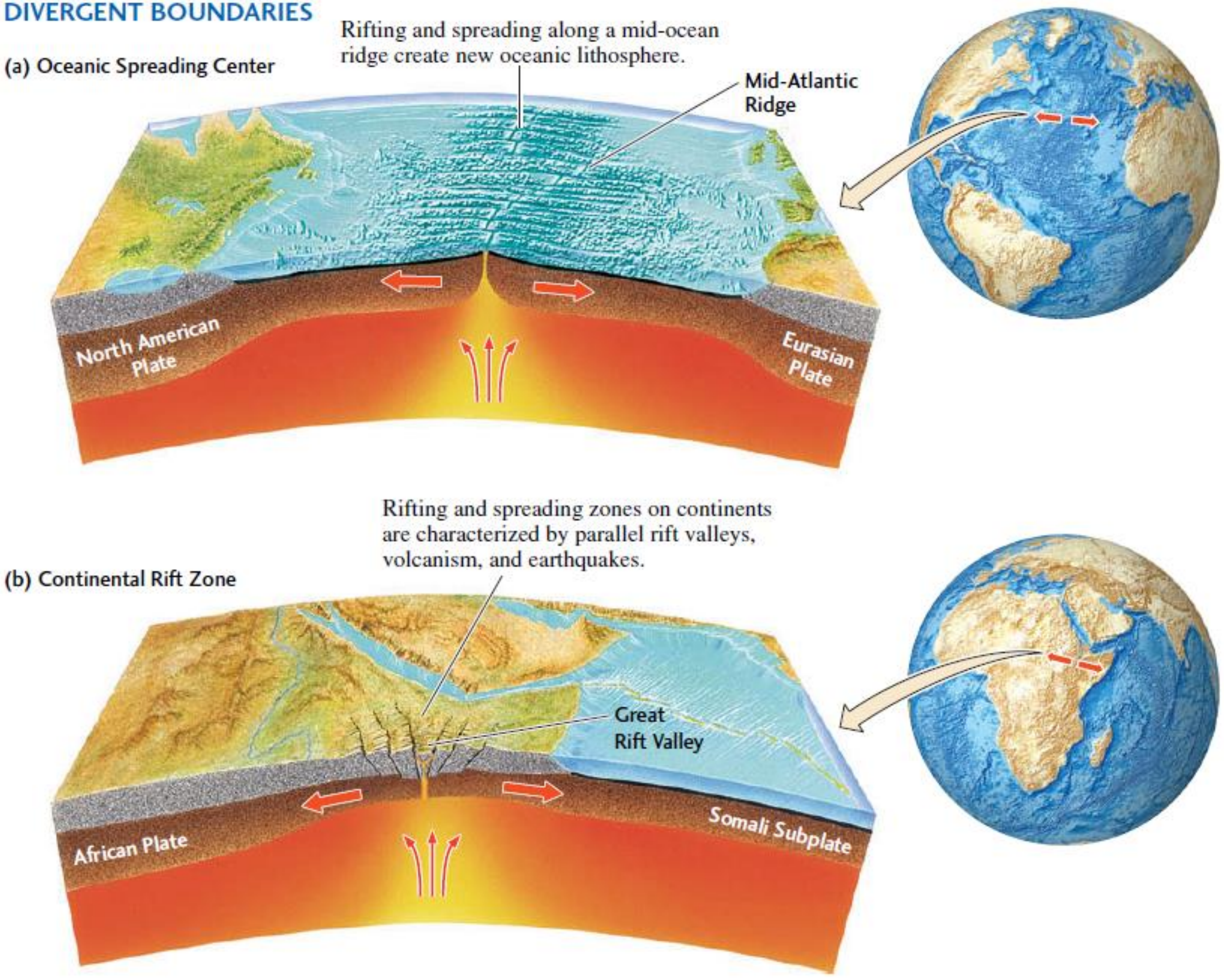
Plates and their relative velocities

Figure 2.35
Rates of plate motion
The red arrows show plate motion at selected locations based on GPS data. Longer arrows represent faster spreading rates. The small black arrows and labels show seafloor spreading velocities based mainly on paleomagnetic data. (Seafloor data from DeMets and others; GPS data from Jet Propulsion Laboratory)

Directions and rates of plate motions measured in centimeters per year



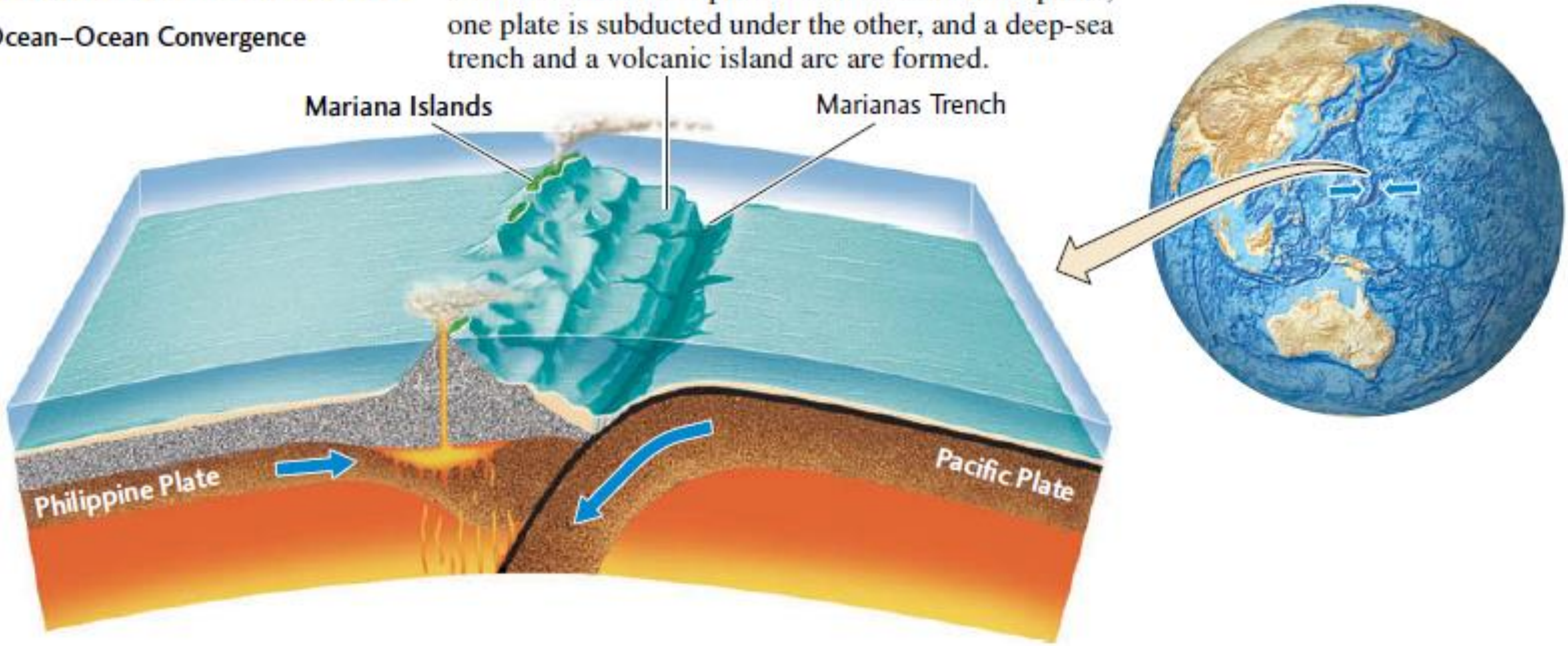
DIVERGENT BOUNDARIES



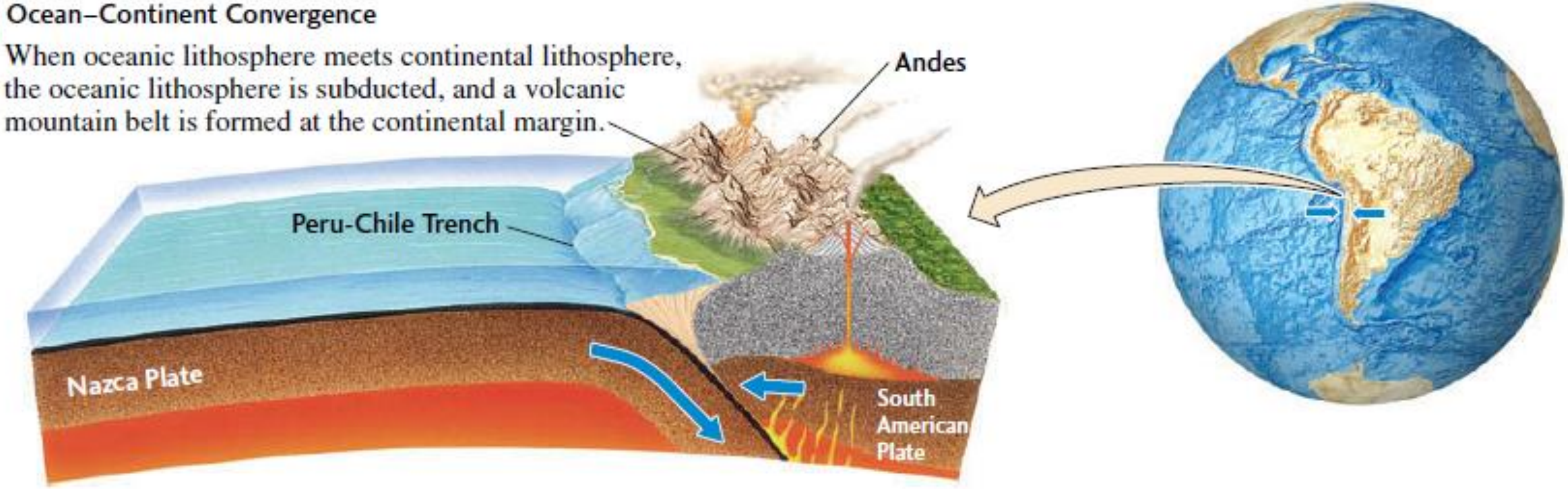
CONVERGENT BOUNDARIES

(c) Ocean–Ocean Convergence

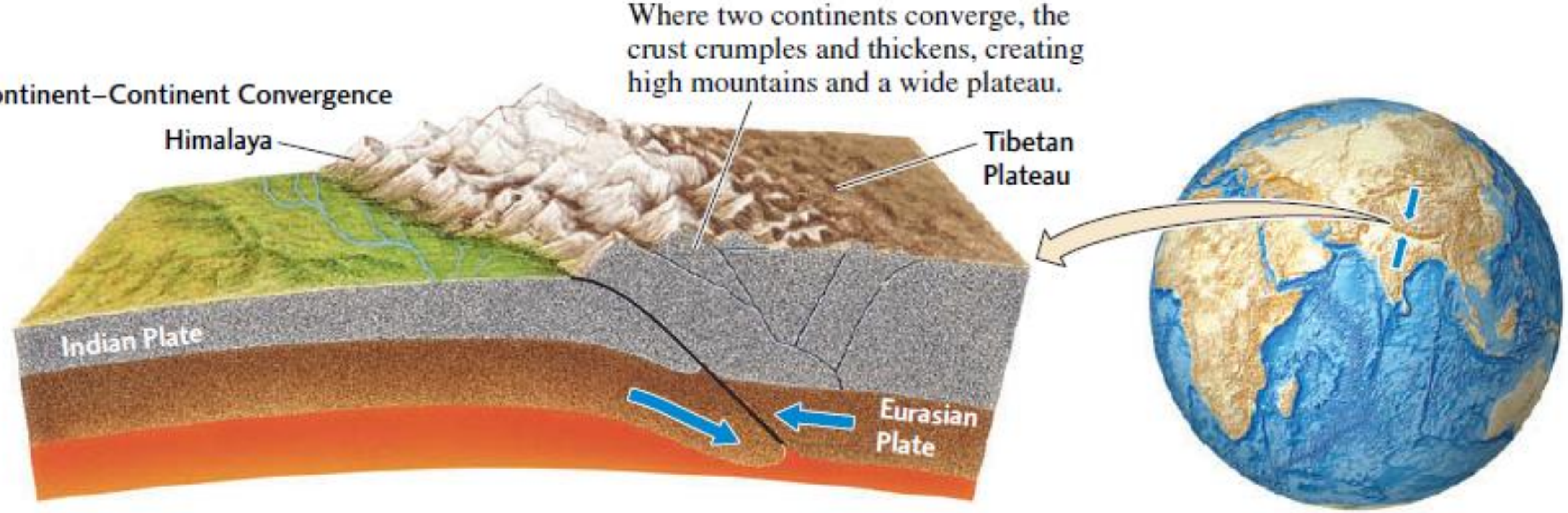
Where oceanic lithosphere meets oceanic lithosphere, one plate is subducted under the other, and a deep-sea trench and a volcanic island arc are formed.



(d) Ocean–Continent Convergence

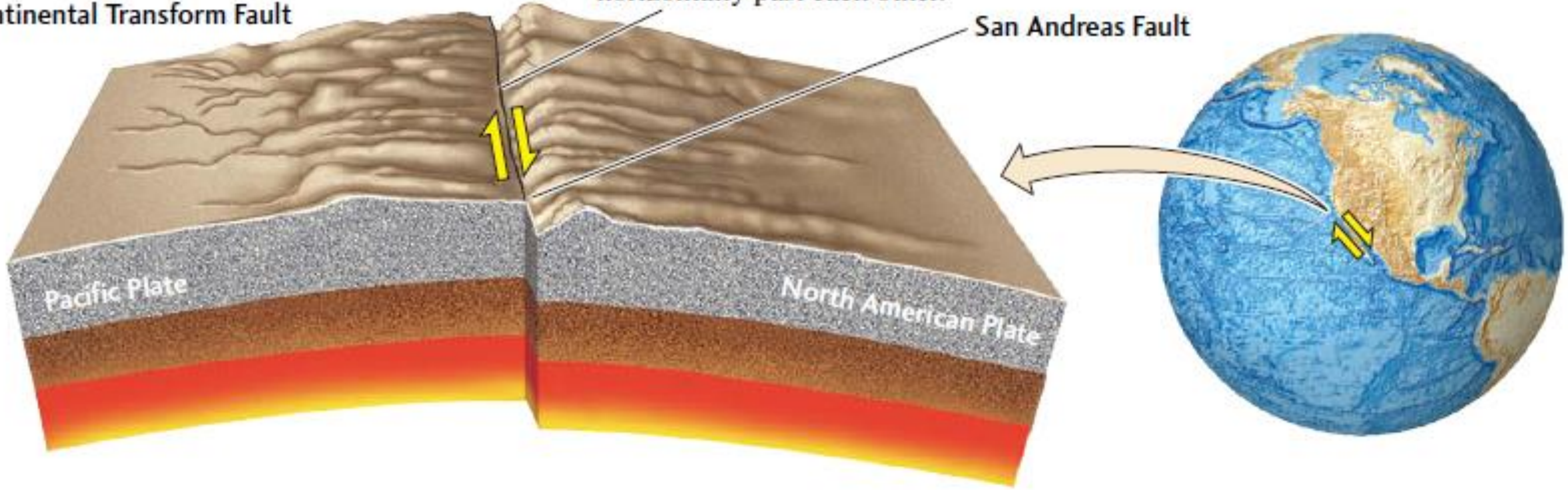


(e) Continent–Continent Convergence

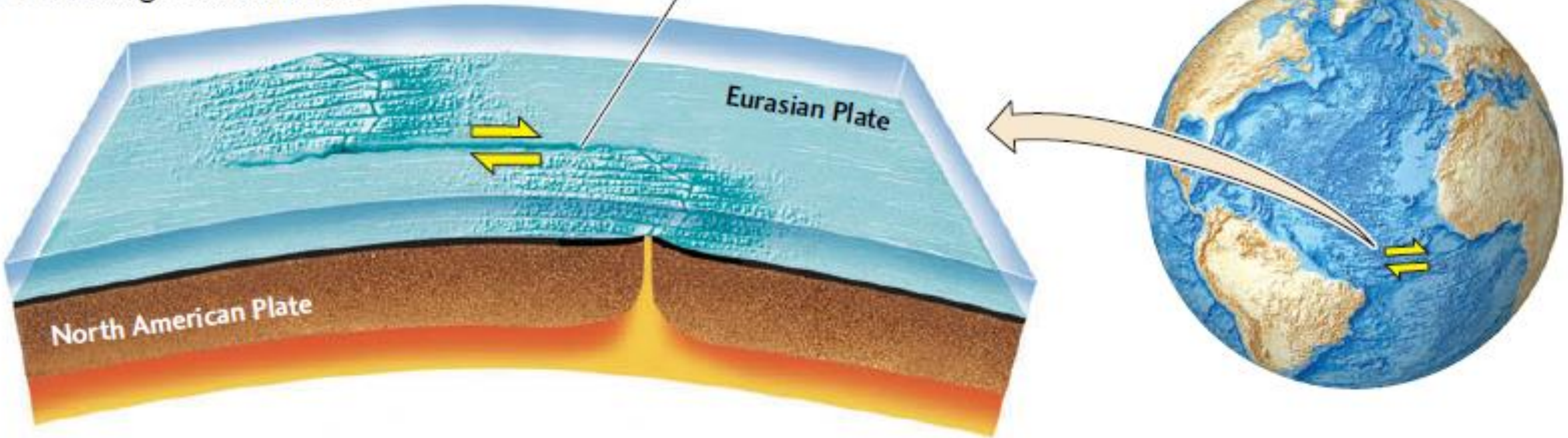


TRANSFORM-FAULT BOUNDARIES

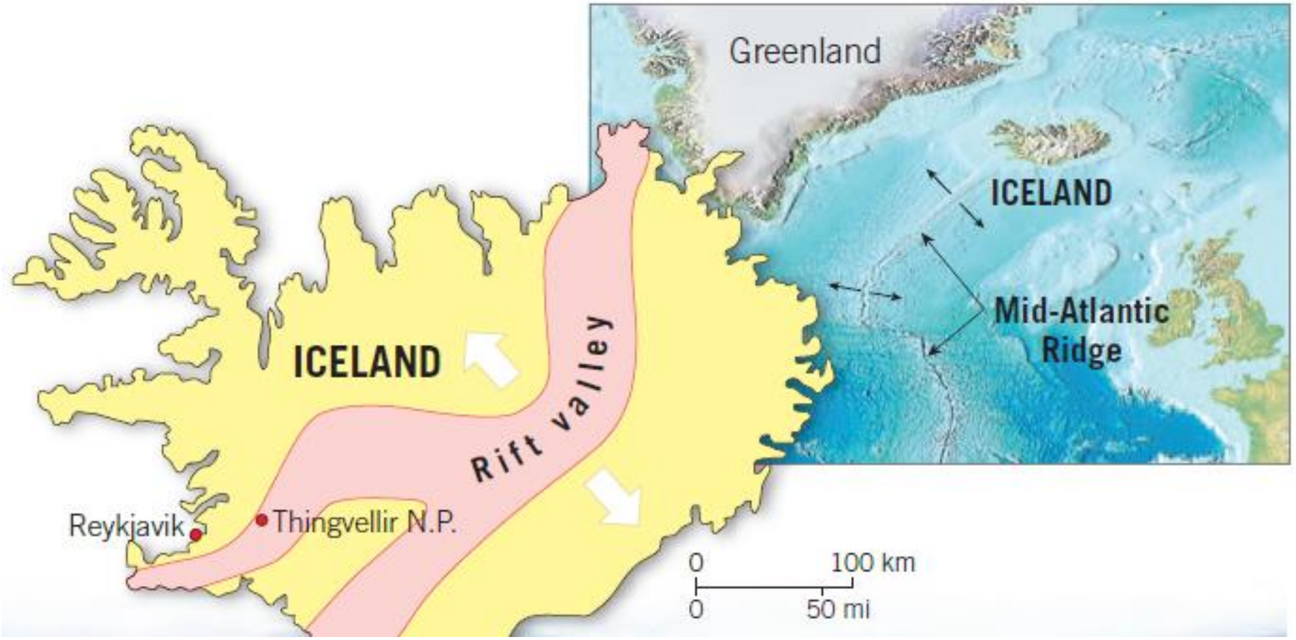
(f) Continental Transform Fault



(g) Mid-Ocean Ridge Transform Fault



Divergent Plate Boundaries (examples)



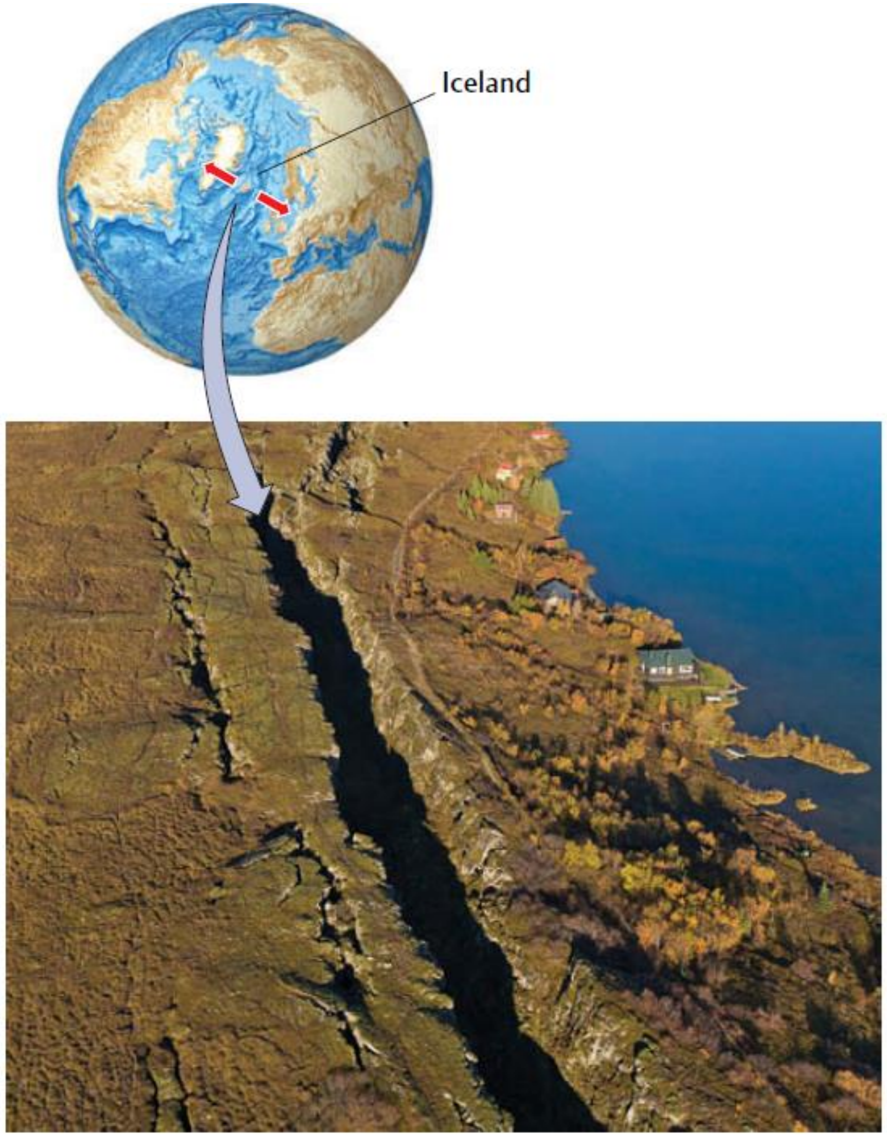
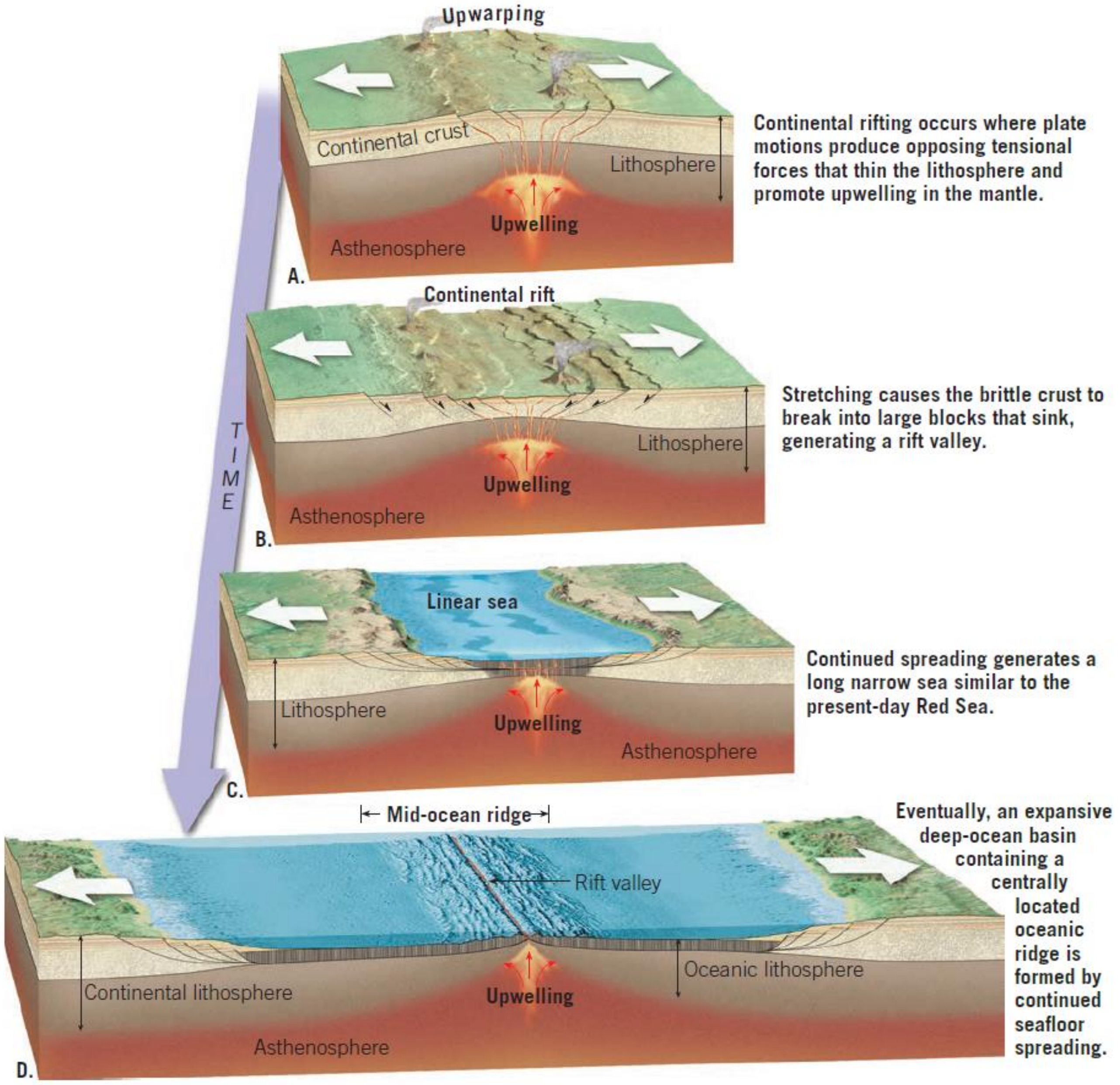


FIGURE 2.9 ■ The Mid-Atlantic Ridge, a divergent plate boundary, rises above sea level in Iceland. This cracklike rift valley, filled with newly formed volcanic rock, indicates that plates are being pulled apart. [Ragnar Th Sigurdsson © ARCTIC IMAGES/Alamy.]

Divergent Plate Boundaries (examples)



Divergent Plate Boundaries (examples)

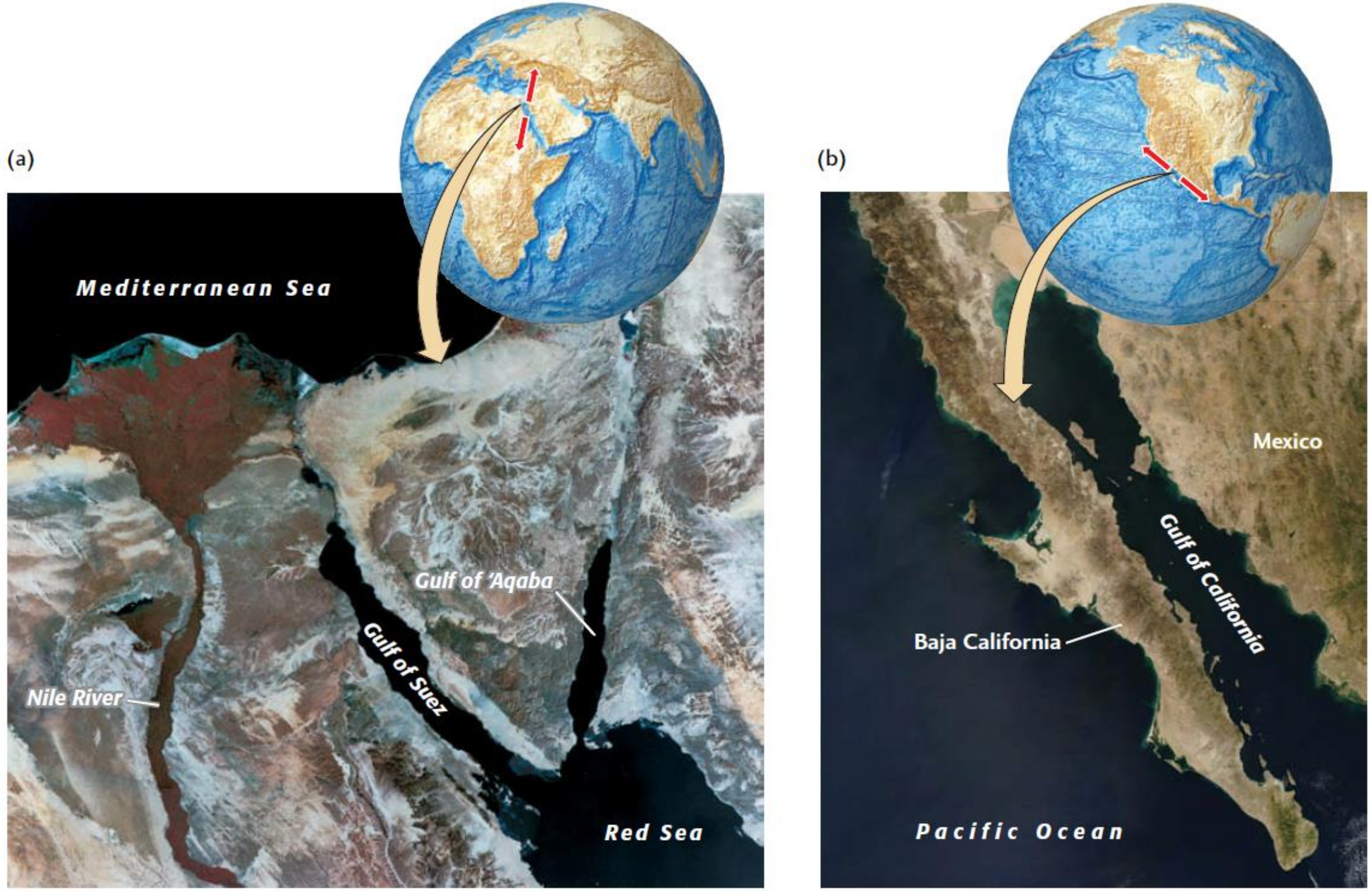
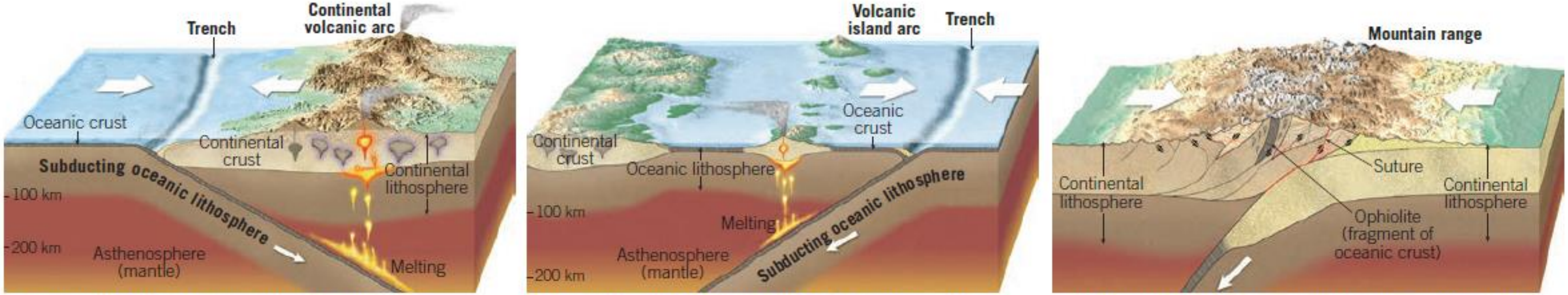


FIGURE 2.10 ■ Rifting of continental crust. (a) The Arabian Plate, on the right, is moving northeastward relative to the African Plate, on the left, opening the Red Sea (lower right). The Gulf of Suez is a failed rift that became inactive about 5 million years ago. North of the Red Sea, most of the plate motion is now taken up by rifting and transform faulting along the Gulf of 'Aqaba and its northward extension. (b) Baja California, on the Pacific Plate, is moving northwestward relative to the North American Plate, opening the Gulf of California between Baja and the Mexican mainland. [(a) Courtesy MDA Information Systems LLC; (b) Jeff Schmaltz, MODIS Rapid Response Team, NASA/GSFC.]

Convergent Plate Boundaries

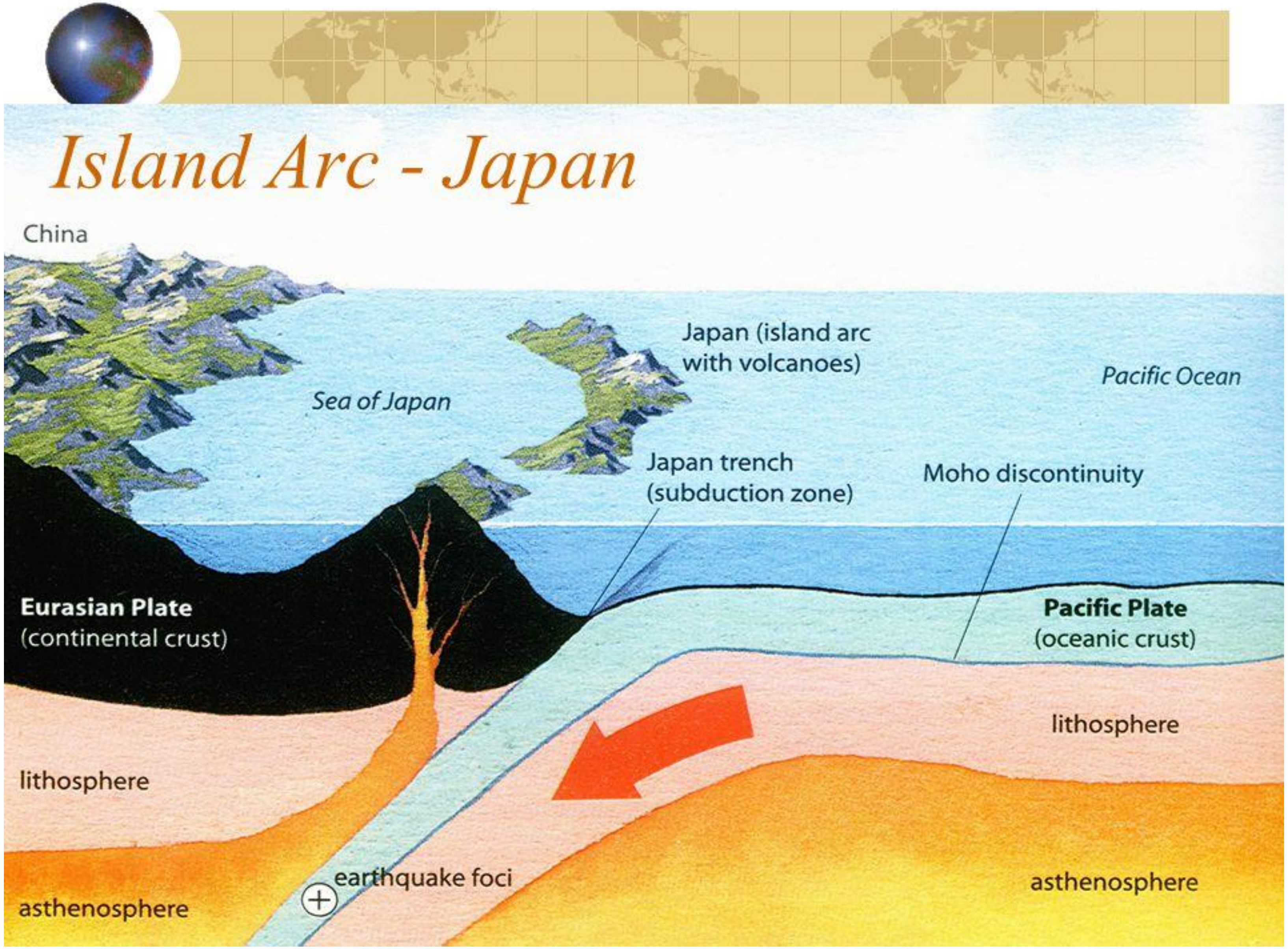


A. Convergent plate boundary where oceanic lithosphere is subducting beneath continental lithosphere.

B. Convergent plate boundary involving two slabs of oceanic lithosphere.

C. Continental collisions occur along convergent plate boundaries when both plates are capped with continental crust.

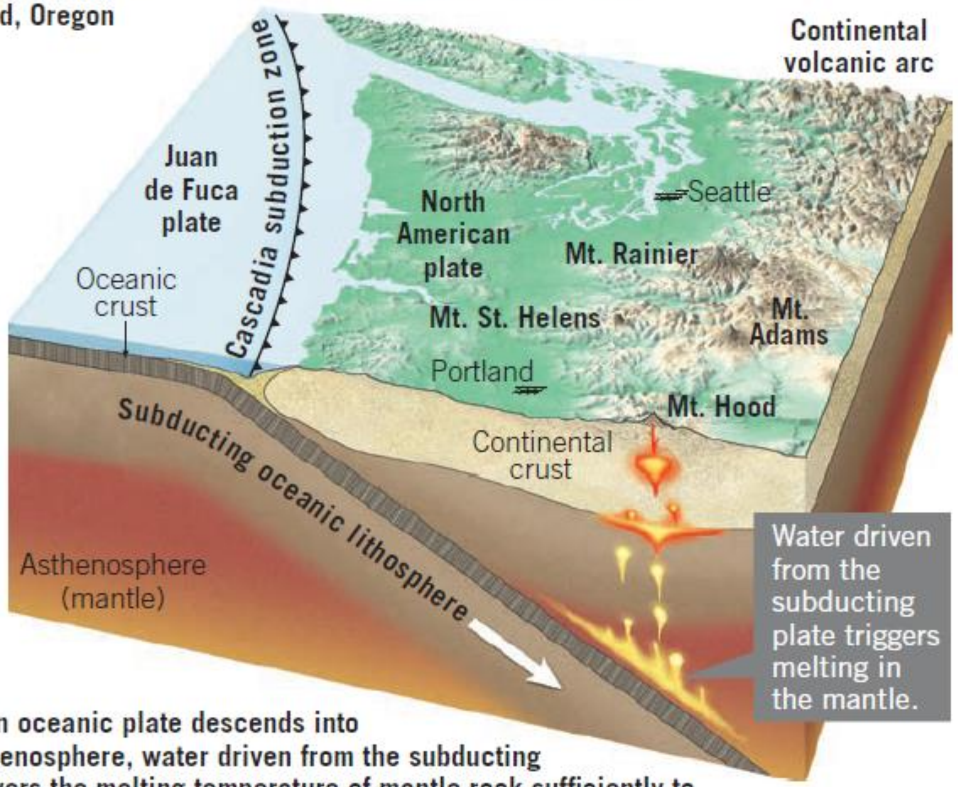
Convergent Plater Boundaries



Convergent Plate Boundaries

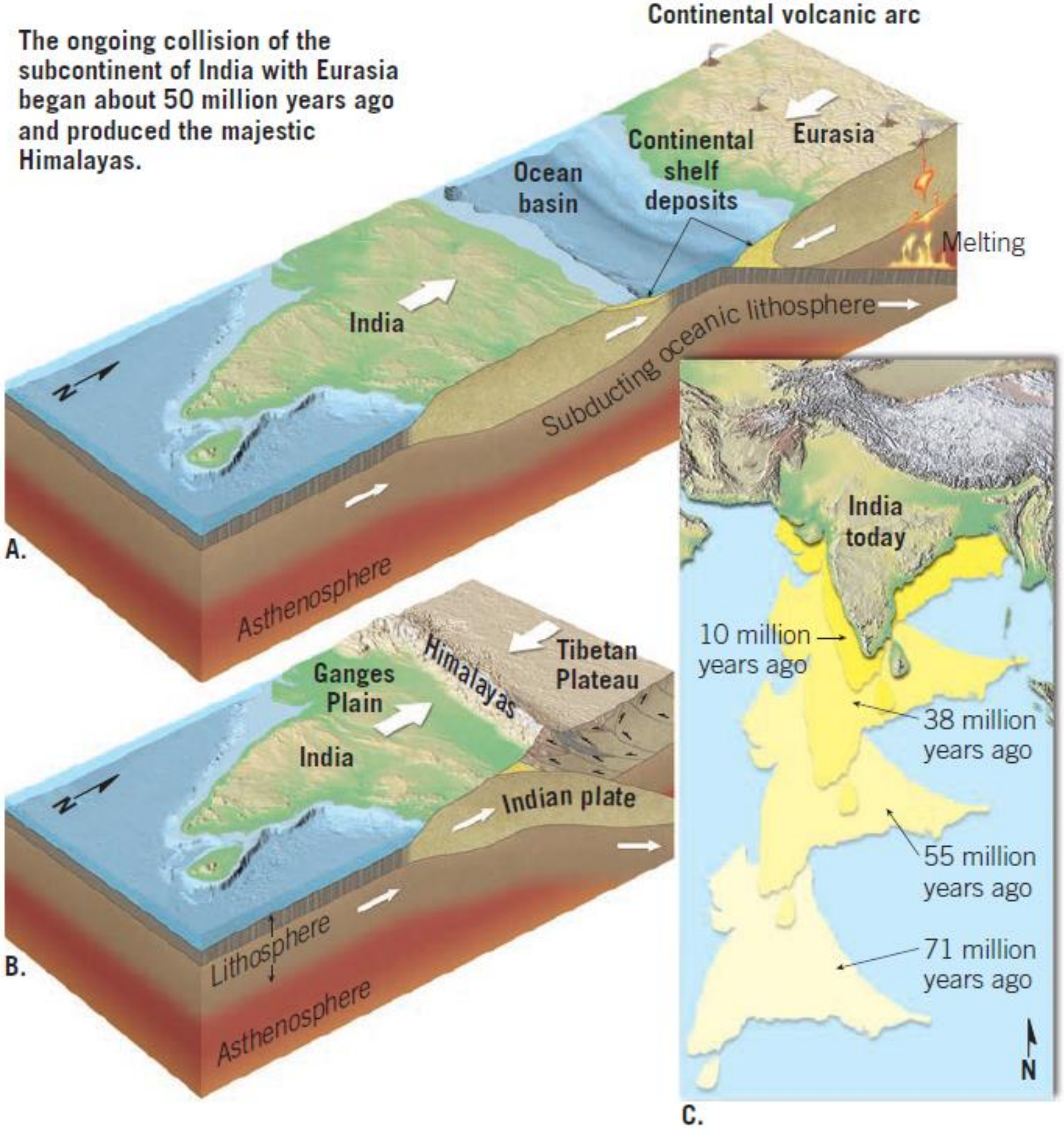
Mt. Hood, Oregon

Figure 2.17
Oceanic–continental convergent plate boundary
Mount Hood, Oregon, is one of more than a dozen large composite volcanoes in the Cascade Range, a continental volcanic arc.

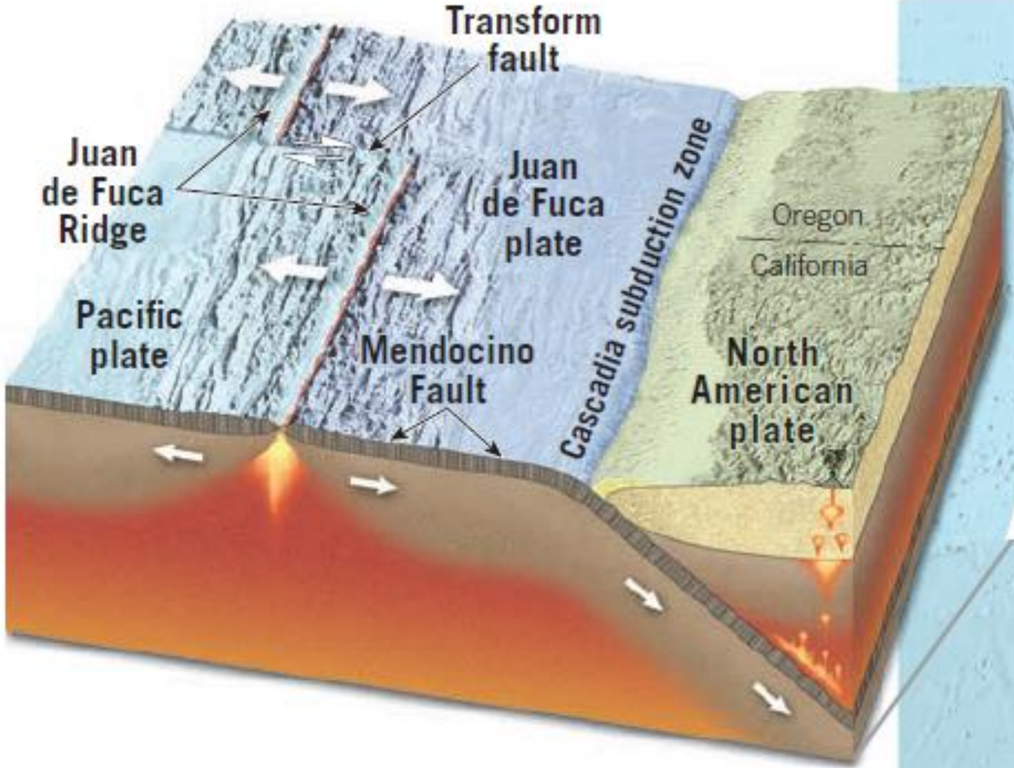


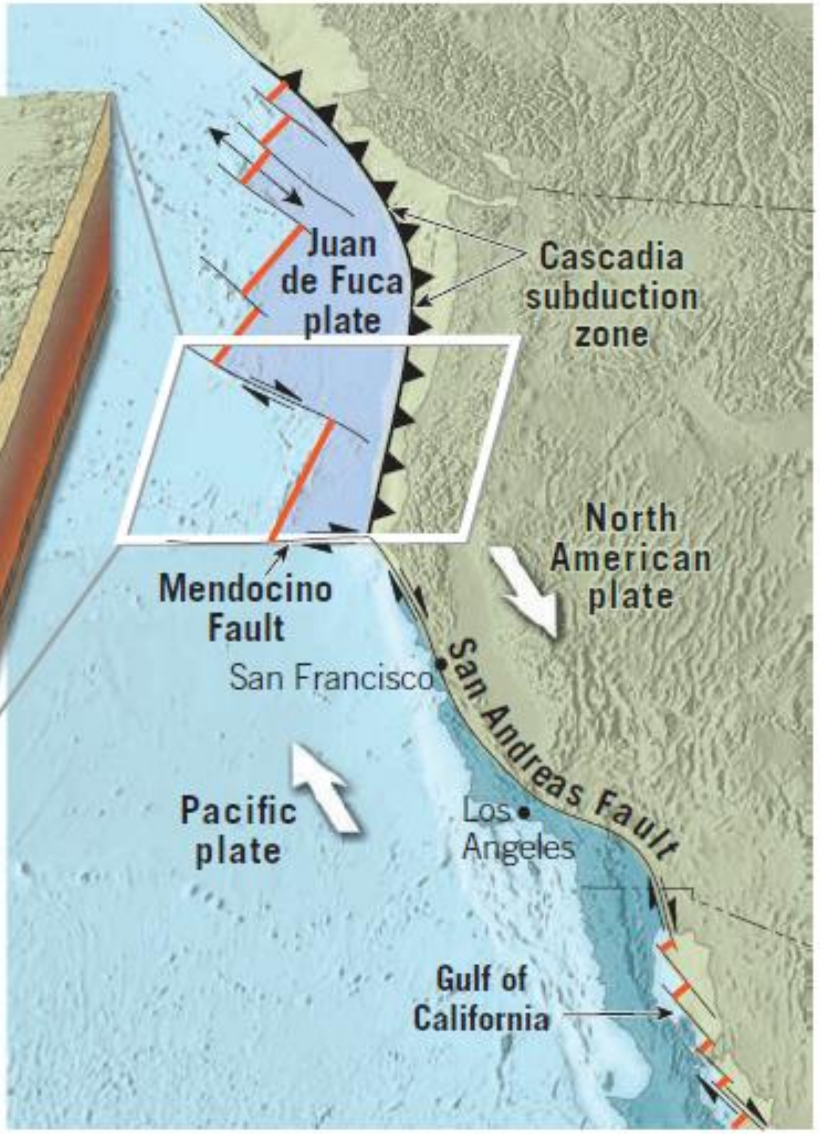
When an oceanic plate descends into the asthenosphere, water driven from the subducting slab lowers the melting temperature of mantle rock sufficiently to generate magma. The Cascade Range is a continental volcanic arc formed by the subduction of the Juan de Fuca plate under the North American plate.

Convergent Plate Boundaries



Transform Plate Boundaries





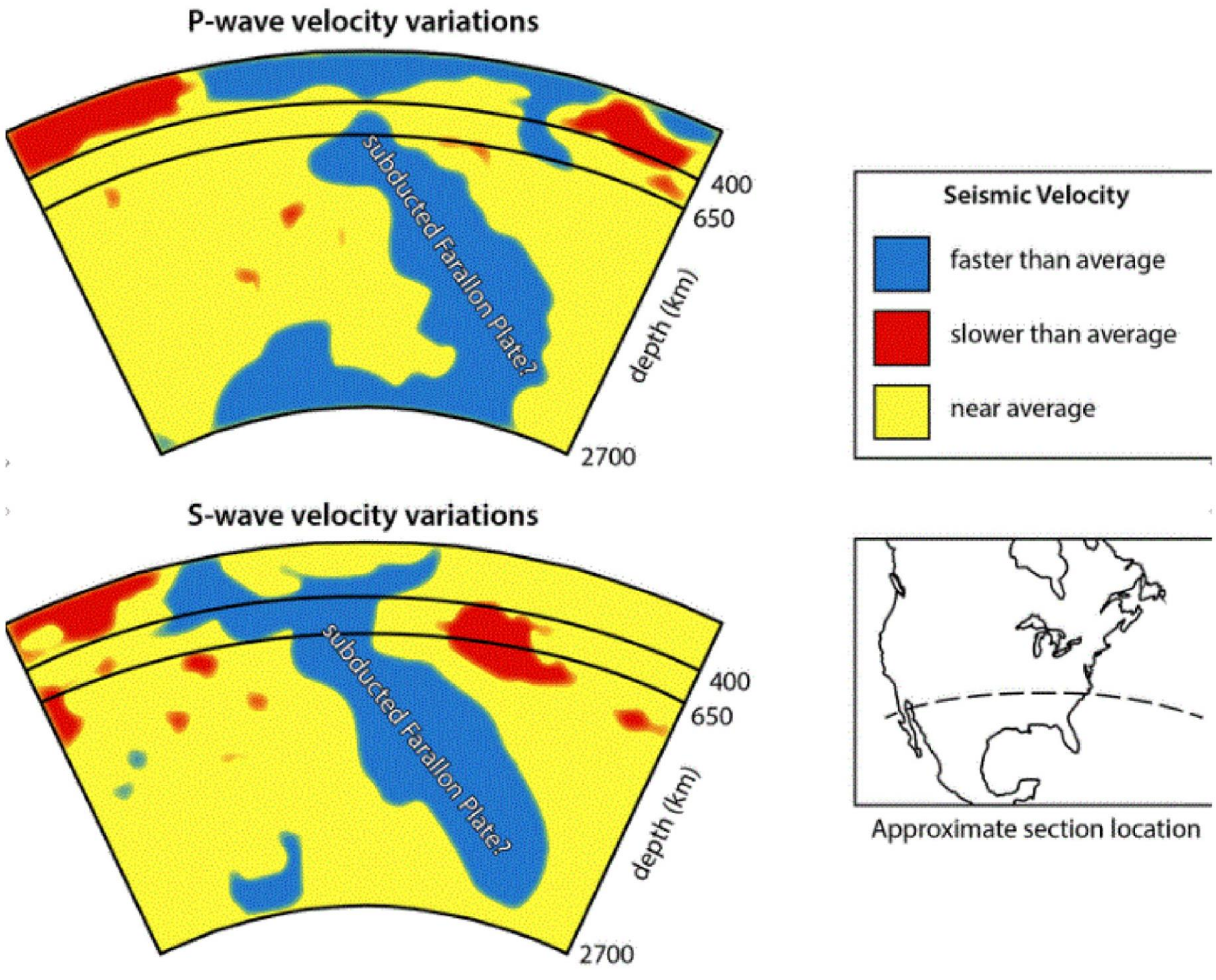
The Mendocino transform fault facilitates the movement of seafloor generated at the Juan de Fuca Ridge by allowing it to slip southeastward past the Pacific plate to its site of destruction beneath the North American plate.

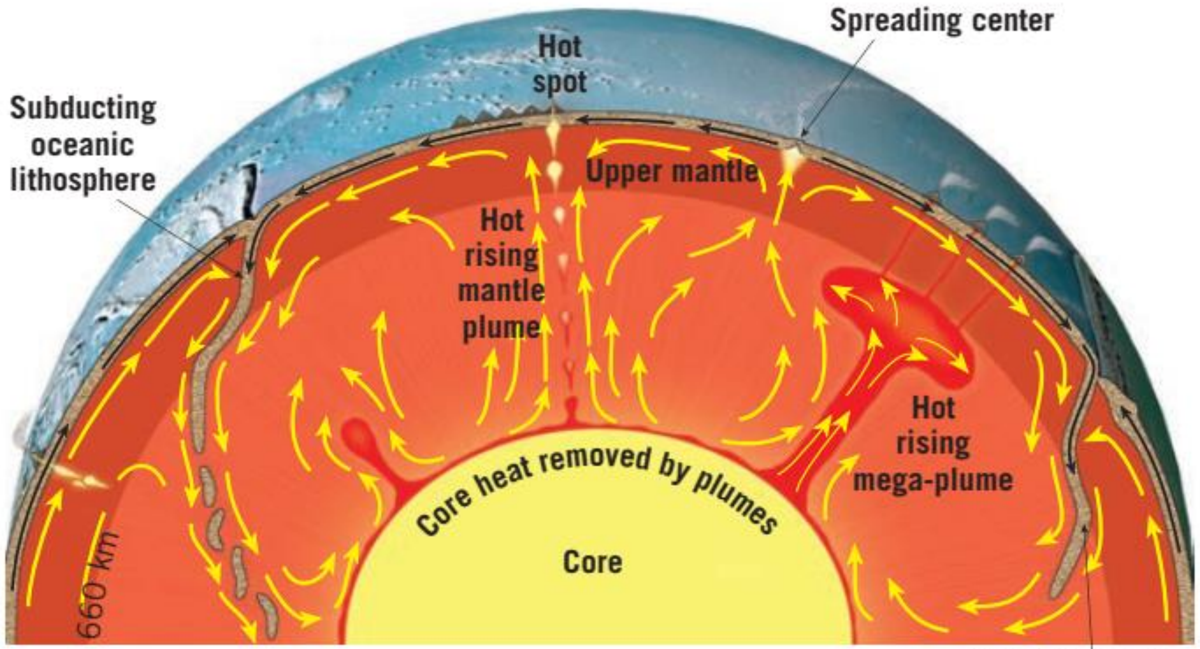
How far the Plates descend?

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

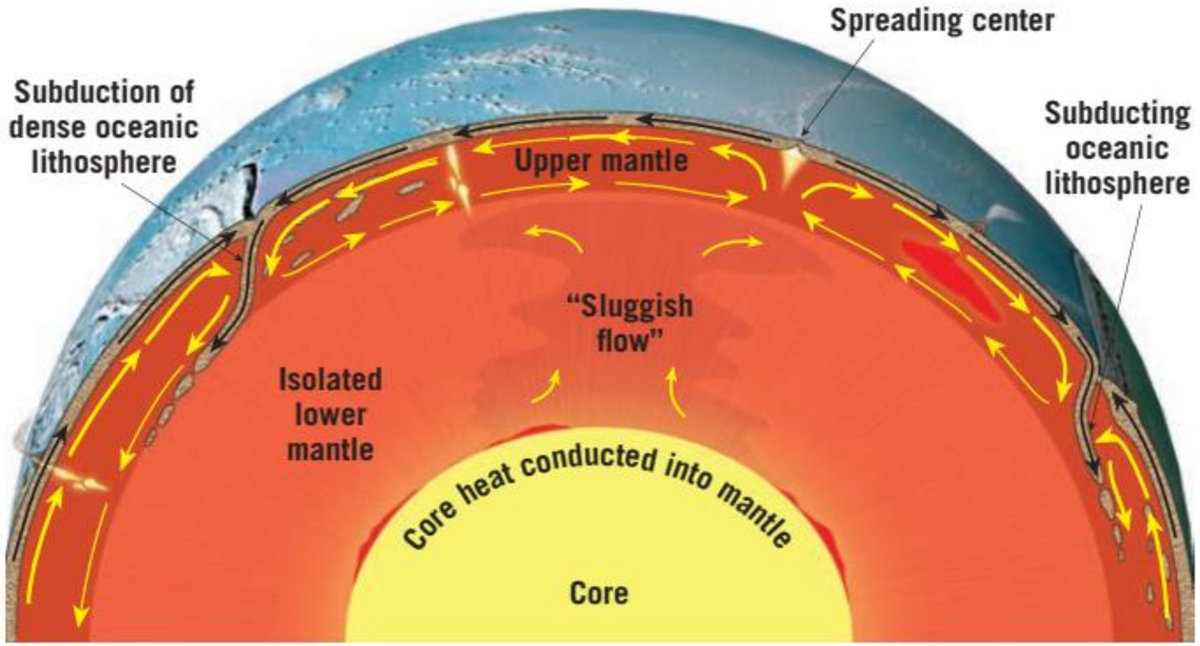
- Seismic imaging allows tracking of subducting plates: Remember that the relatively cold and hence dense subducting plate stands out in imaging
- When the plate reaches 660 Km depth, it becomes plastic and flows- unable to descend further
- Commonly held view is thus the maximum depth of subduction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

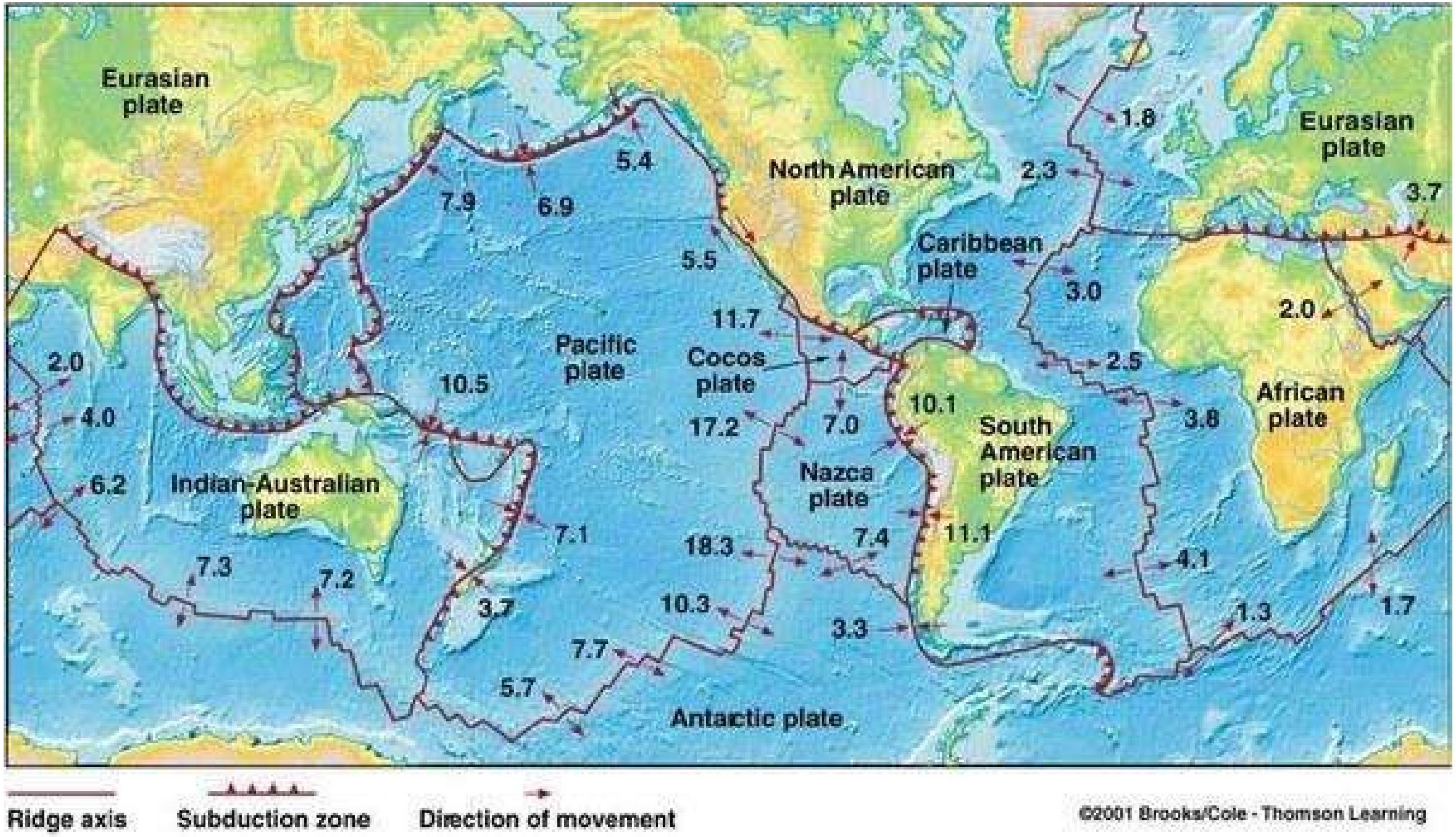


A. In the "whole-mantle model," sinking slabs of cold oceanic lithosphere are the downward limbs of convection cells, while rising mantle plumes carry hot material from the core–mantle boundary toward the surface.



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.

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

(i) PRESENT-DAY 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.

(j) 50 million years in the future