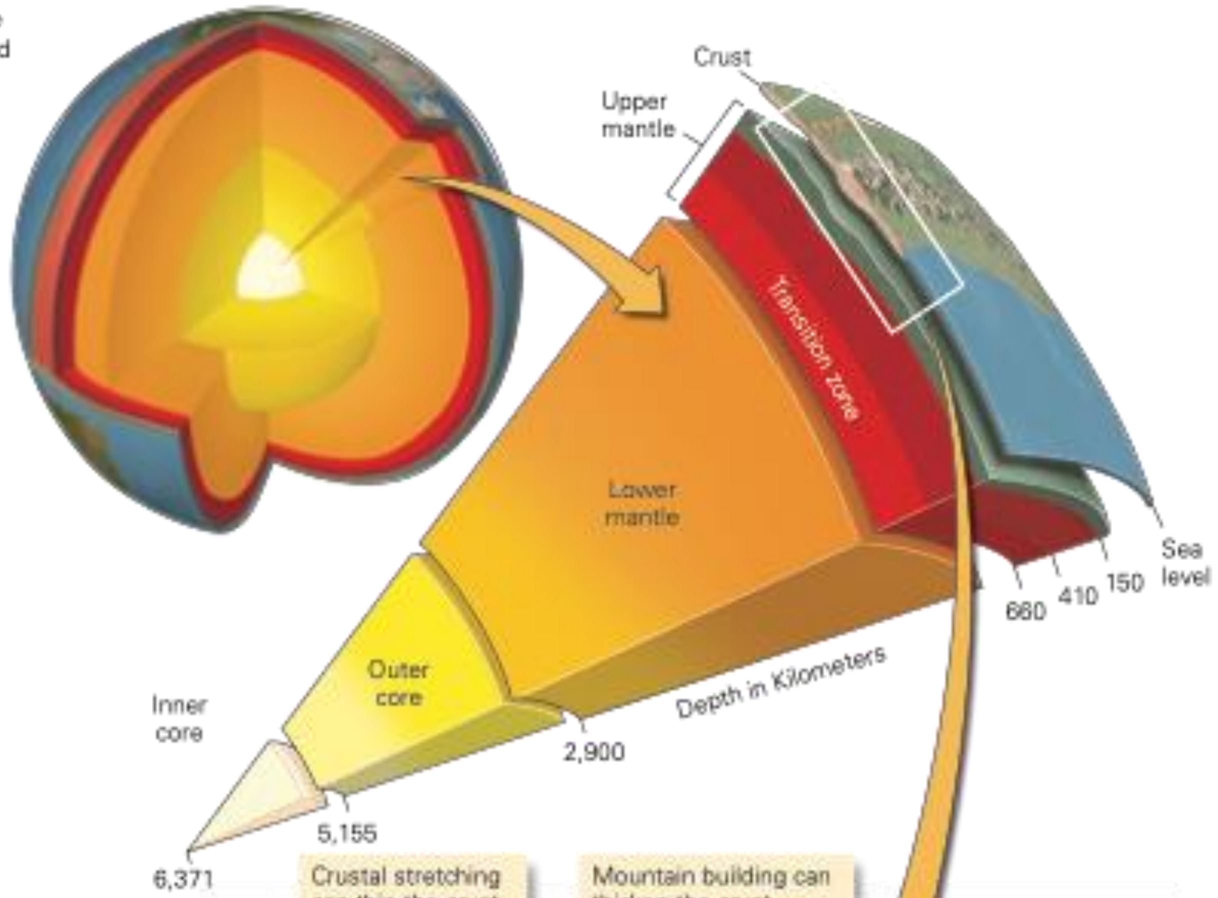
Earth and Planetary Sciences (ES1101)

Autumn 2024

FIGURE 2.14 A modern view of the Earth's interior layers.

(a) By studying earthquake waves, geologists produced a refined image of the Earth's interior, in which the mantle and core are subdivided.



(b) There are two basic types of crust. Oceanic crust is thinner and consists of basalt and gabbro. Continental crust varies in thickness and rock type.

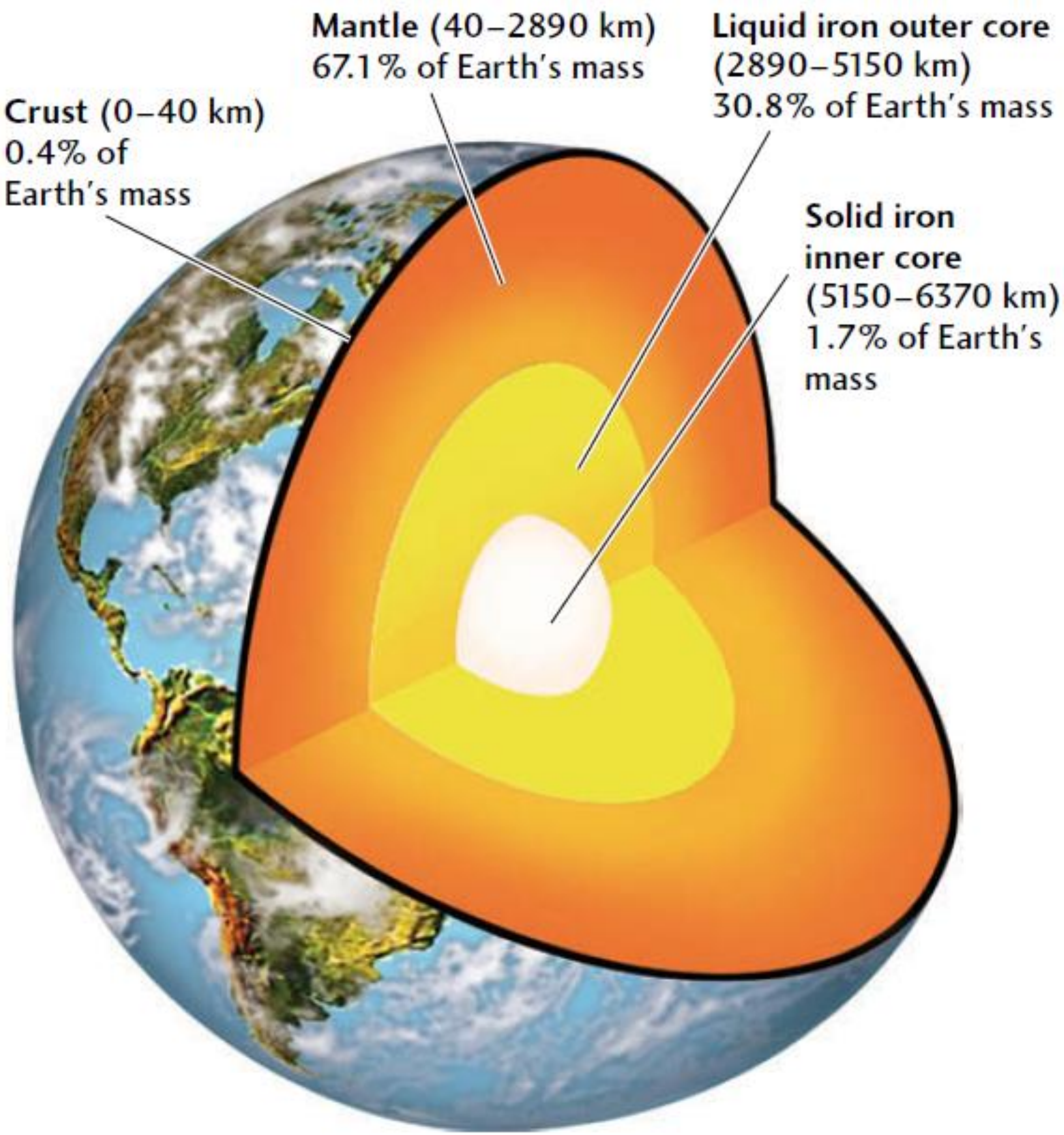
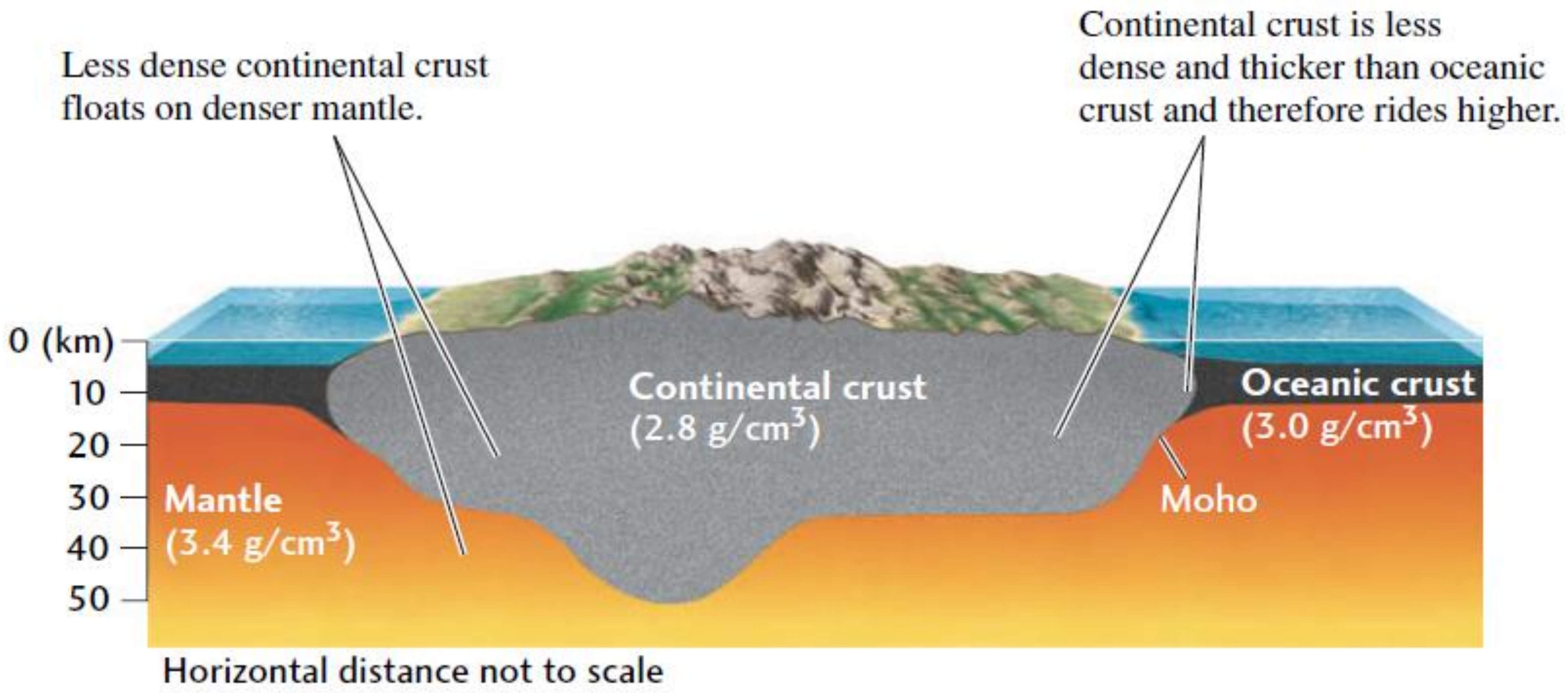


FIGURE 1.9 ■ Earth's major layers, showing their depths and their masses expressed as a percentage of Earth's total mass.


Less dense continental crust floats on denser mantle.
Continental crust is less dense and thicker than oceanic crust and therefore rides higher.
0 (km)
10
20
30
40
50
Continental crust
(2.8 g/cm³)
Oceanic crust
(3.0 g/cm³)
Mantle
(3.4 g/cm³)
Moho
Horizontal distance not to scale

Abundance of elements in different parts of the Earth

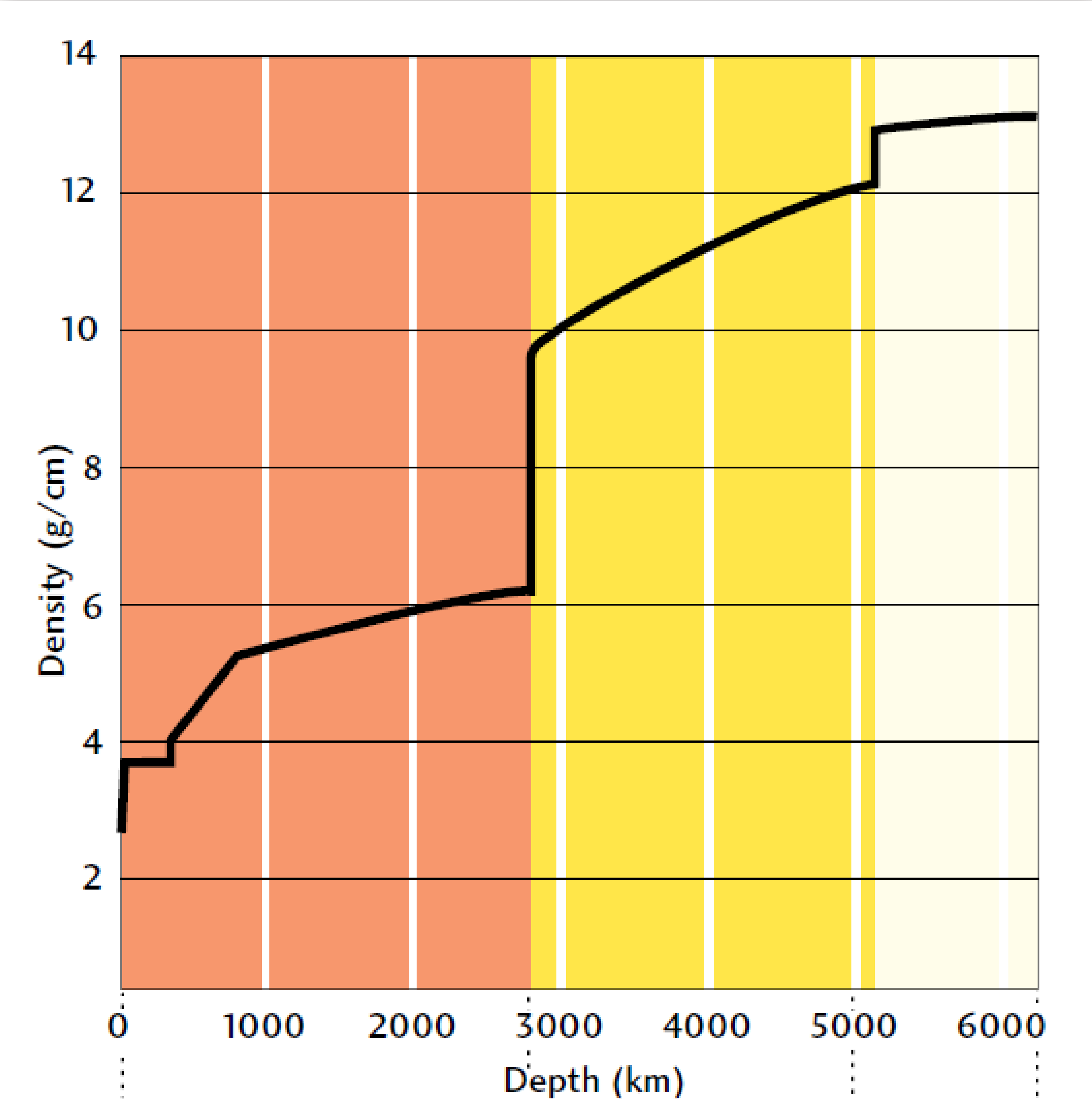


TABLE 3.1 The Most Abundant Chemical Elements in the Continental Crust

Element	Ion	Percent by Weight
Oxygen (O)	O^{2-}	45.20
Silicon (Si)	Si^{4+}	27.20
Aluminum (Al)	Al^{3+}	8.00
Iron (Fe)	Fe^{2+} and Fe^{3+}	5.80
Calcium (Ca)	Ca^{2+}	5.06
Magnesium (Mg)	Mg^{2+}	2.77
Sodium (Na)	Na^{+}	2.32
Potassium (K)	K^{+}	1.68
Titanium (Ti)	Ti^{4+}	0.86
Hydrogen (H)	H^{+}	0.14
Manganese (Mn)	Mn^{2+} and Mn^{4+}	0.10
Phosphorus (P)	P^{3+}	0.10
All other elements		0.77
	TOTAL	100.00

Abundance of elements in different parts of the Earth

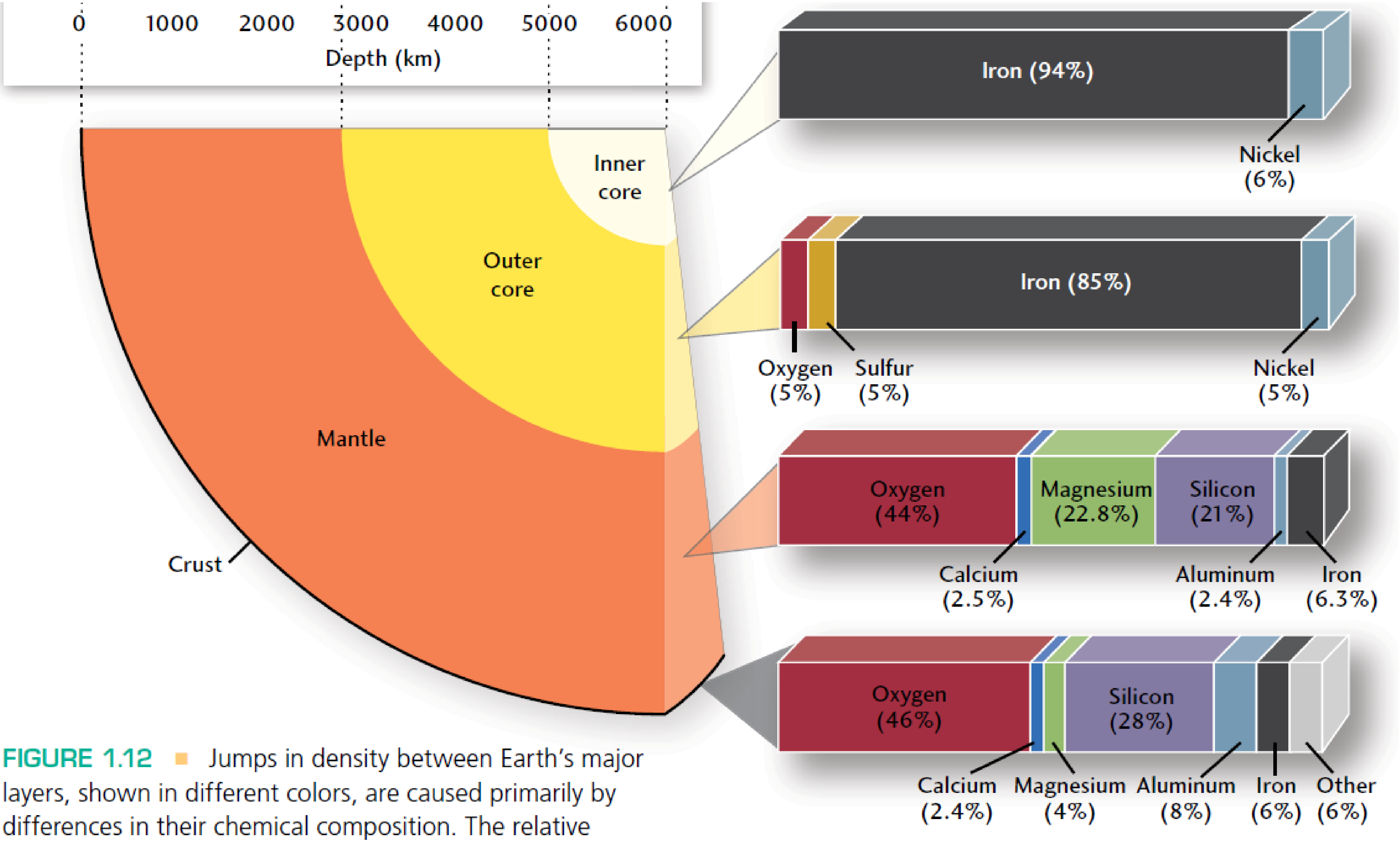
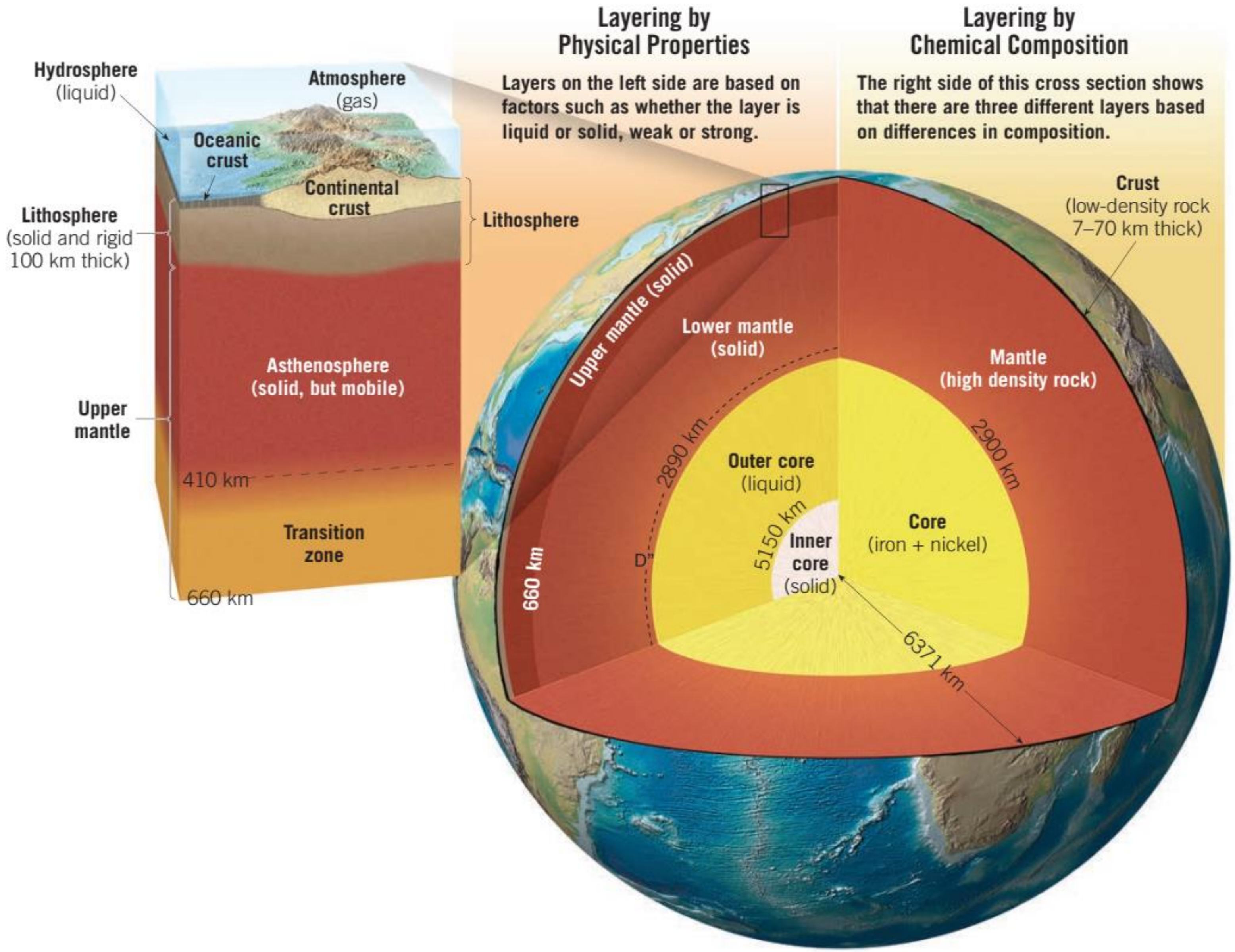


FIGURE 1.12 ■ Jumps in density between Earth's major layers, shown in different colors, are caused primarily by differences in their chemical composition. The relative amounts of the main elements are depicted in the bars on the right.

Internal Structure of the Earth (Chemical & Physical)



Exploring the Earth’s interior

- **Earthquake seismology:** A principal technique to investigate the interior of the Earth.

- **Geothermal gradient:** Exploring the various heat sources and understanding the thermal variations inside the Earth.

- **Pressure gradient:** Pressure variation within the Earth.

- **Constituents of Earth Materials:** Study of minerals and melts, Phase changes of minerals with pressure and their correlations with seismically observed layers of the Earth.

- **Continental Drift and Plate tectonics**

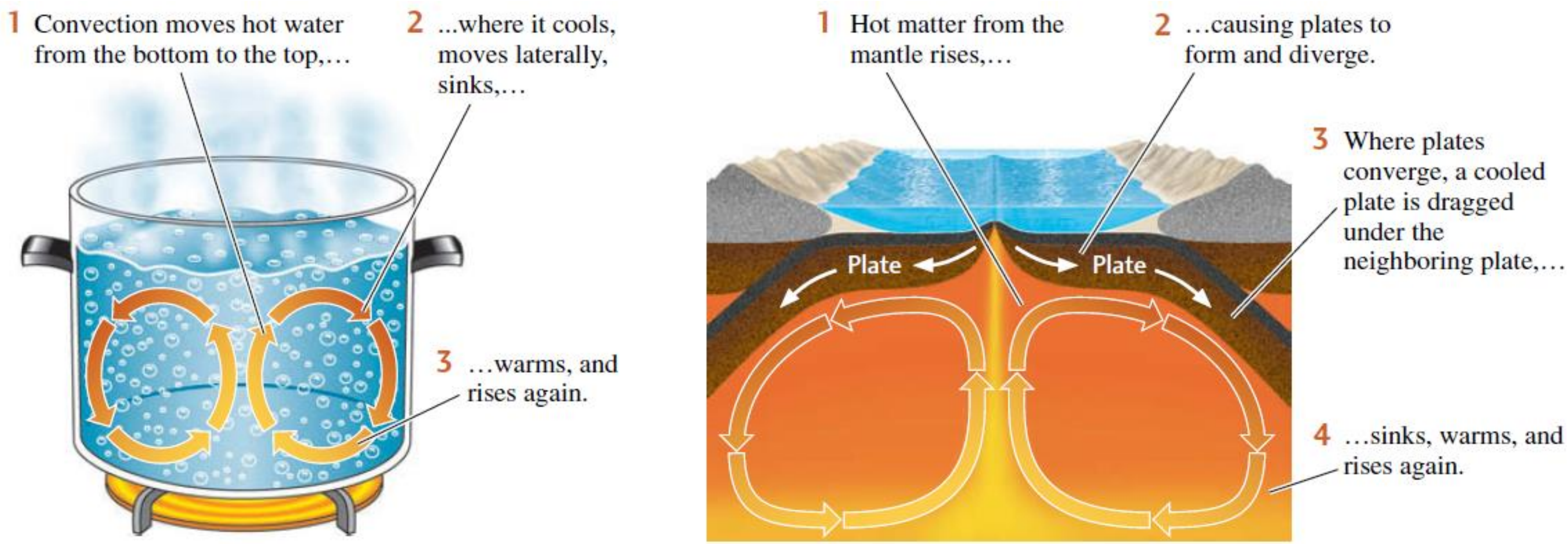


FIGURE 1.16 ■ Convection in Earth's mantle can be compared to the pattern of movement in a pot of boiling water. Both processes carry heat upward through the movement of matter.

Earthquake Seismology

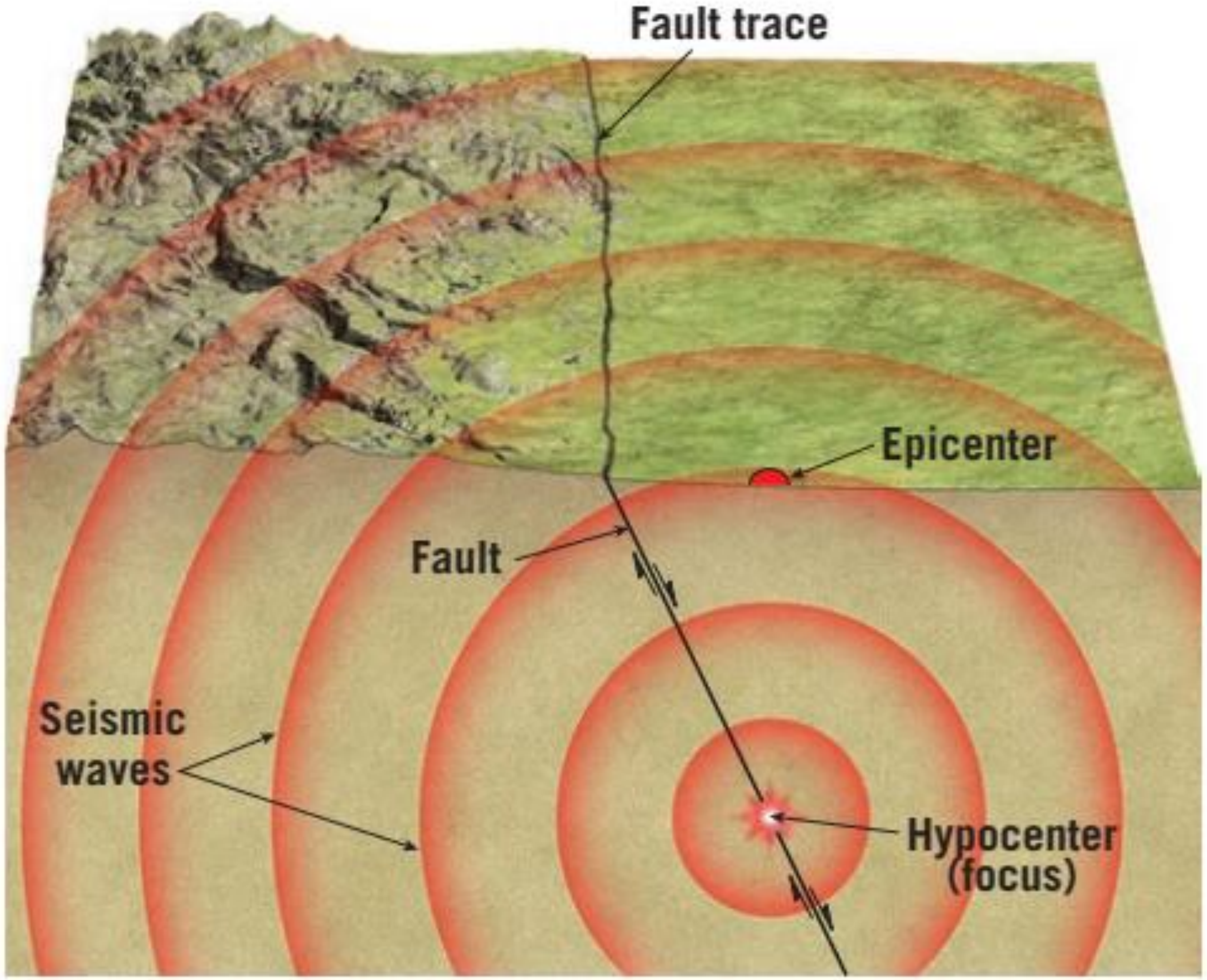


Figure 11.2
Earthquakes hypocenter and epicenter The *hypocenter* is the zone at depth where the initial displacement occurs. The *epicenter* is the surface location directly above the hypocenter.

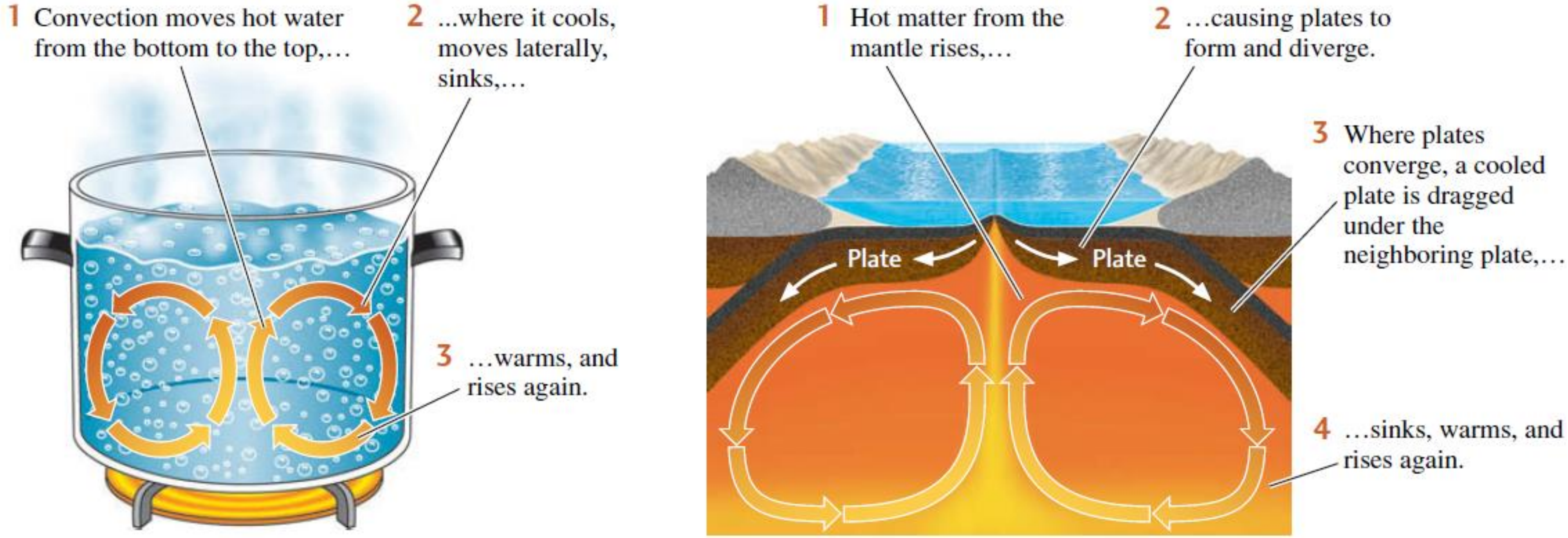


FIGURE 1.16 ■ Convection in Earth's mantle can be compared to the pattern of movement in a pot of boiling water. Both processes carry heat upward through the movement of matter.

Mantle Convection and Plate Theory

https://www.youtube.com/watch?v=ryrXAGY1dmE

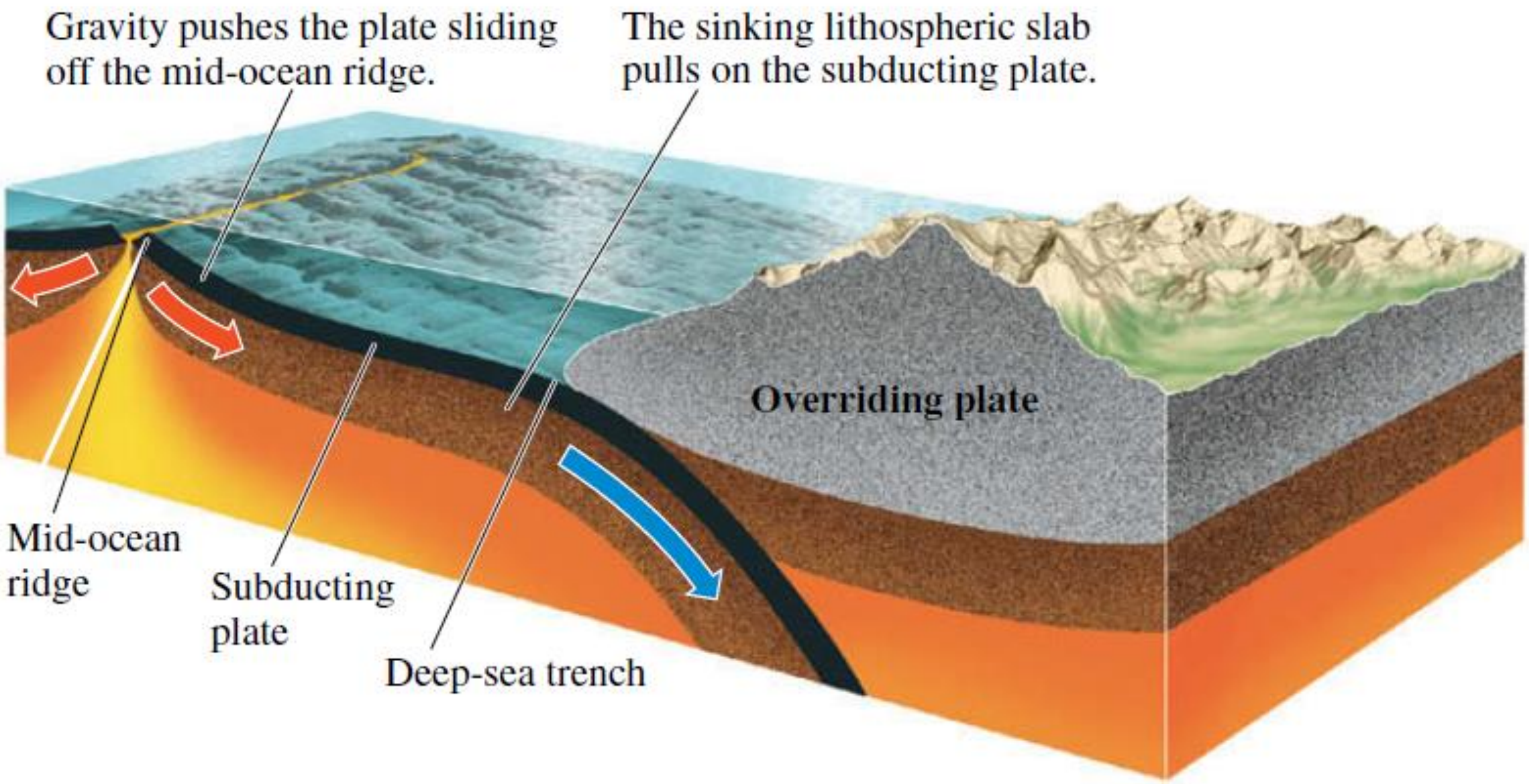
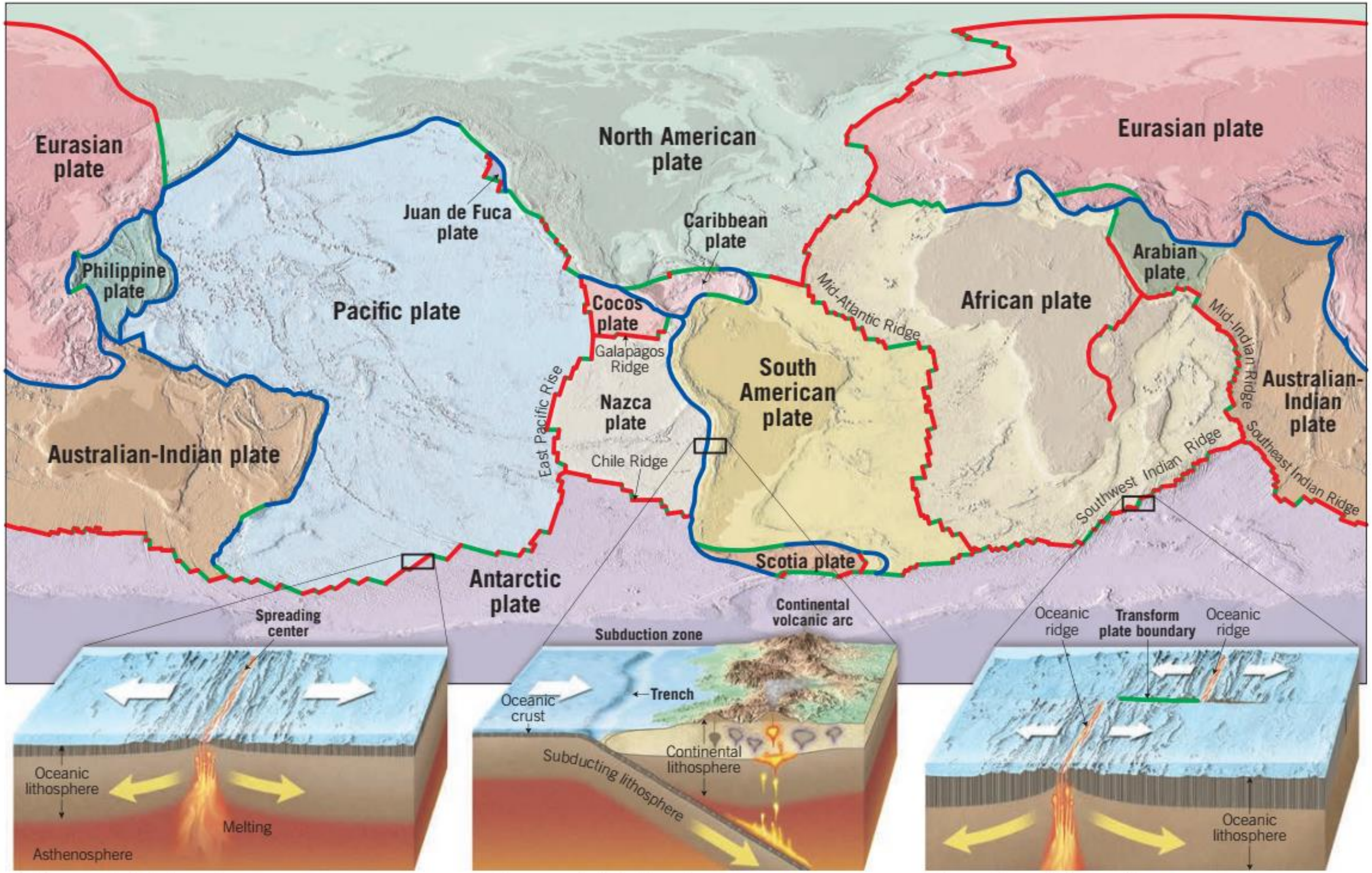


FIGURE 2.17 ■ A schematic cross section through the outer part of Earth, illustrating two of the forces thought to be important in driving plate tectonics: the pulling force of a sinking lithospheric slab and the pushing force of plates sliding off a mid-ocean ridge. [After D. Forsyth and S. Uyeda, *Geophysical Journal of the Royal Astronomical Society* 43 (1975): 163–200.]



A. Divergent plate boundary

B. Convergent plate boundary

C. Transform plate boundary

Figure 11.33
Global earthquake belts Distribution of nearly 15,000 earthquakes with magnitudes equal to or greater than 5 for a 10-year period. (Data from USGS)

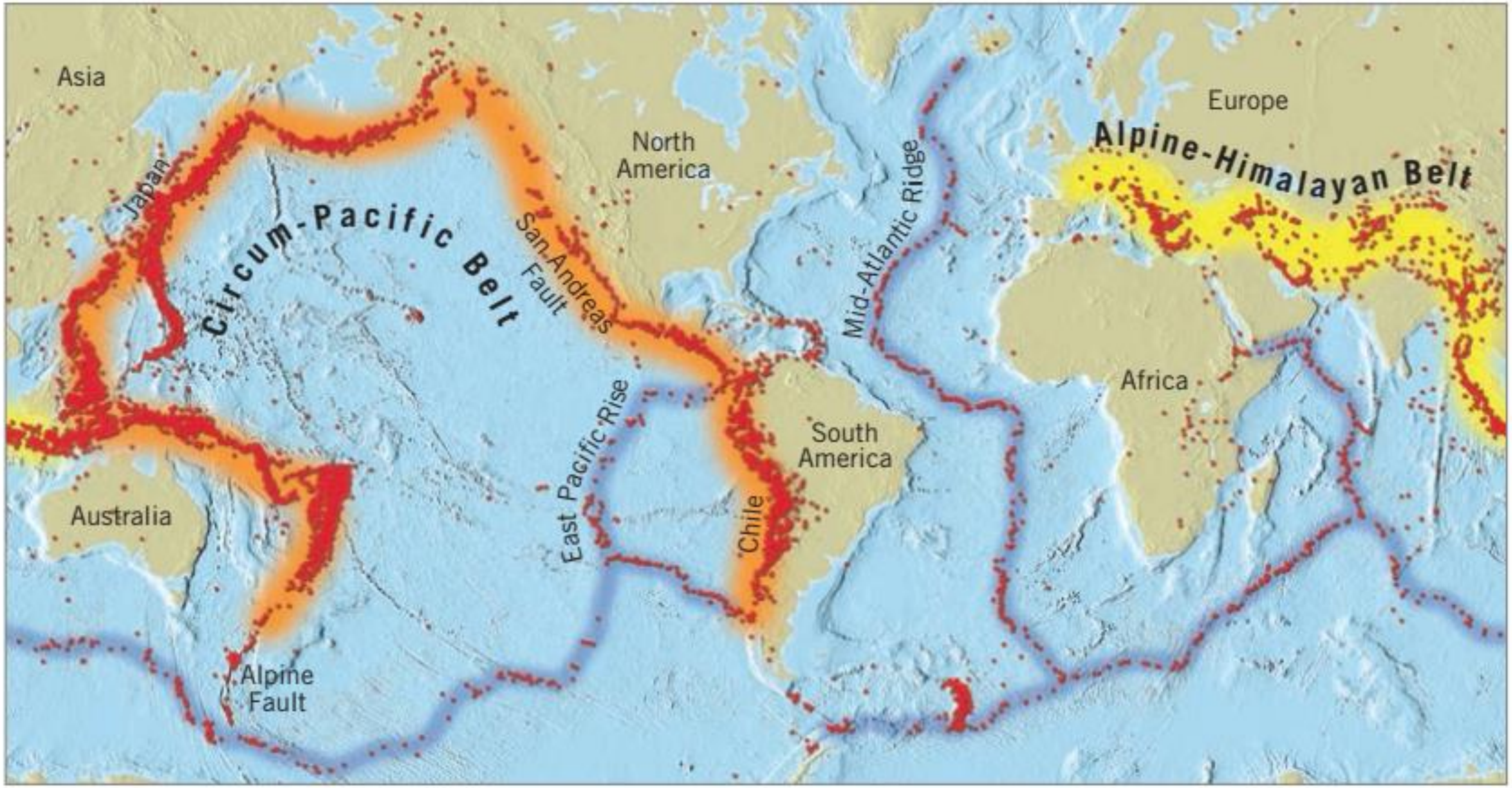
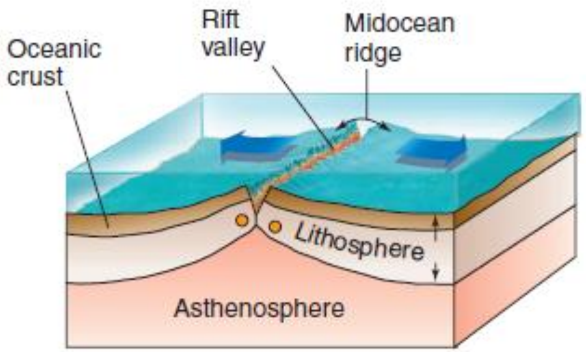
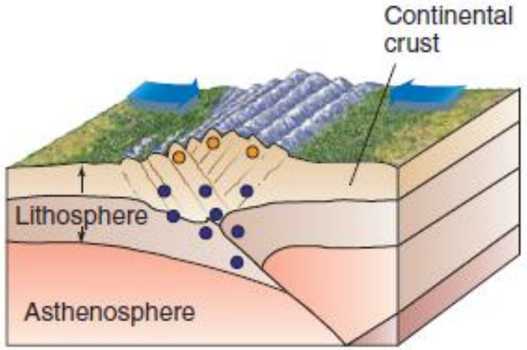


Plate Boundary



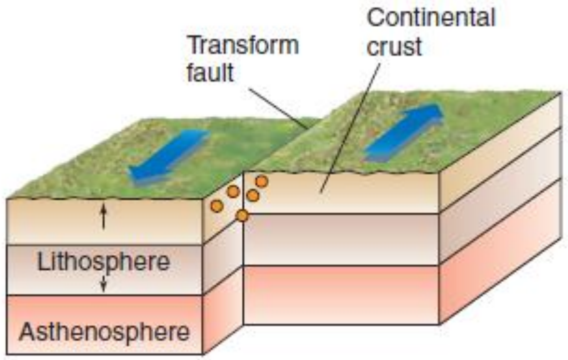
DIVERGENT BOUNDARY

At divergent margins, earthquakes tend to be fairly weak and shallow. Earthquakes can only occur in rock that is cold and brittle enough to break; at a midocean ridge, this means they cannot be very deep.



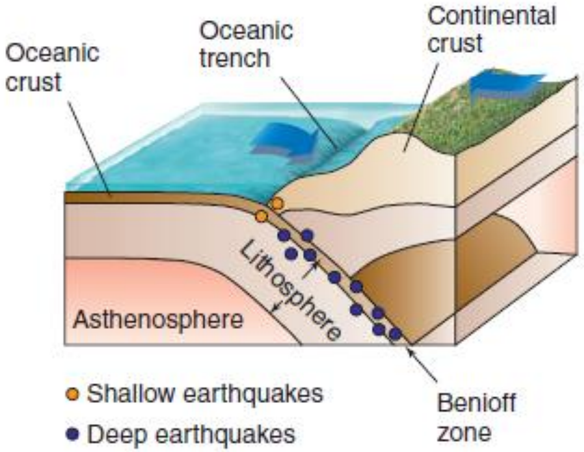
CONTINENTAL COLLISION BOUNDARY

In collision zones the earthquakes can be deep and also very powerful.



TRANSFORM FAULT BOUNDARY

Transform fault margins have shallow earthquakes, but they can be very powerful.



SUBDUCTION ZONE BOUNDARY

The deepest and most powerful quakes occur in subduction zones. Here, an oceanic plate moves downward relative to a continental plate. The earthquake foci are shallow near the oceanic trench but become deeper along the descending edge of the subducting plate. These zones of shallow- and deep-focus earthquakes, called *Benioff zones*, first alerted scientists to the phenomenon of *subduction*.

Earthquake Seismology

FIGURE 7.7 ■ View of the San Andreas fault, showing the northwestward movement of the Pacific Plate with respect to the North American Plate. The map shows a formation of volcanic rocks 23 million years old that has been displaced by 315 km. The fault runs from top to bottom (dashed line) near the middle of the photograph. Note the offset of the stream (Wallace Creek) by 130 m as it crosses the fault. [University of Washington Libraries, Special Collections, John Shelton Collection, KCN7-23.]

Earthquake Seismology

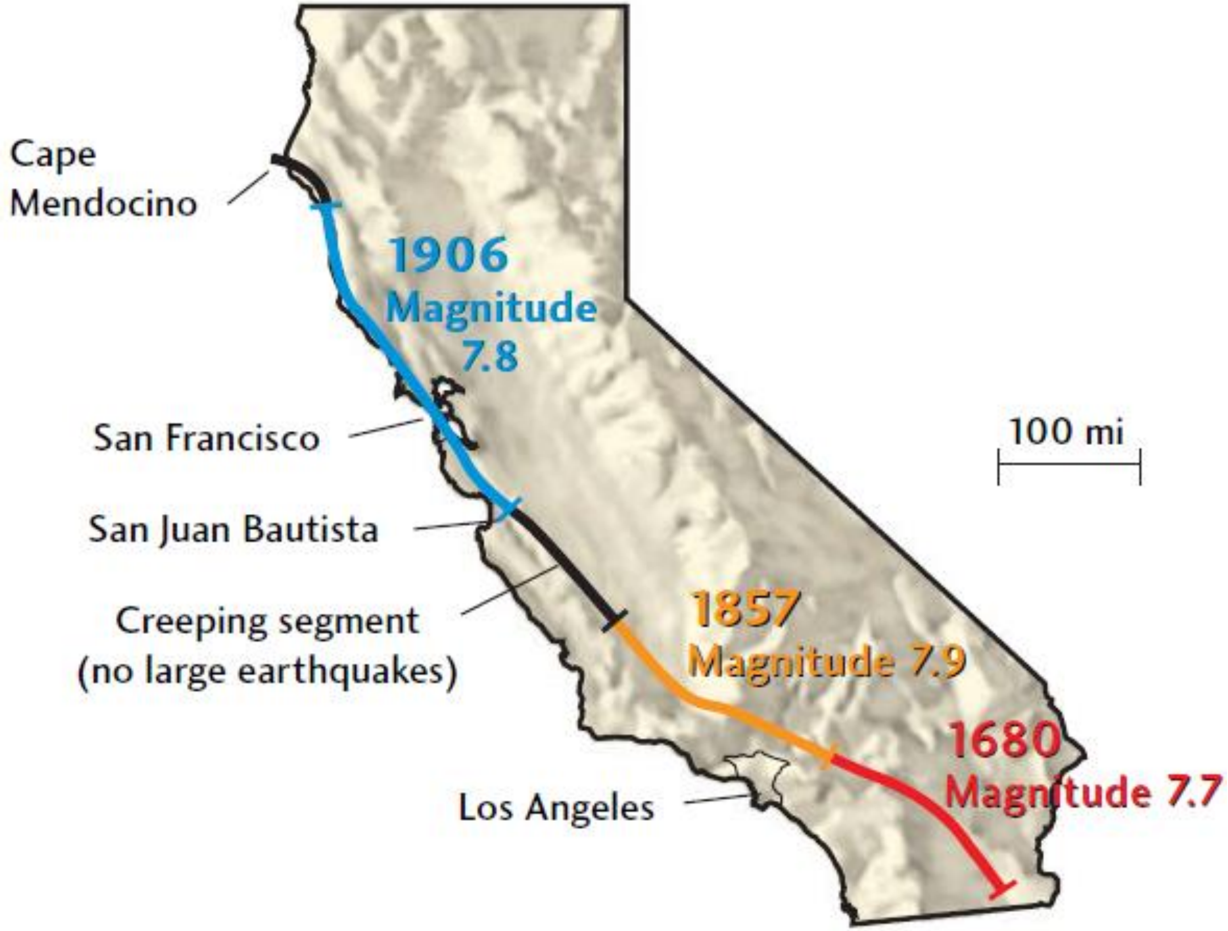
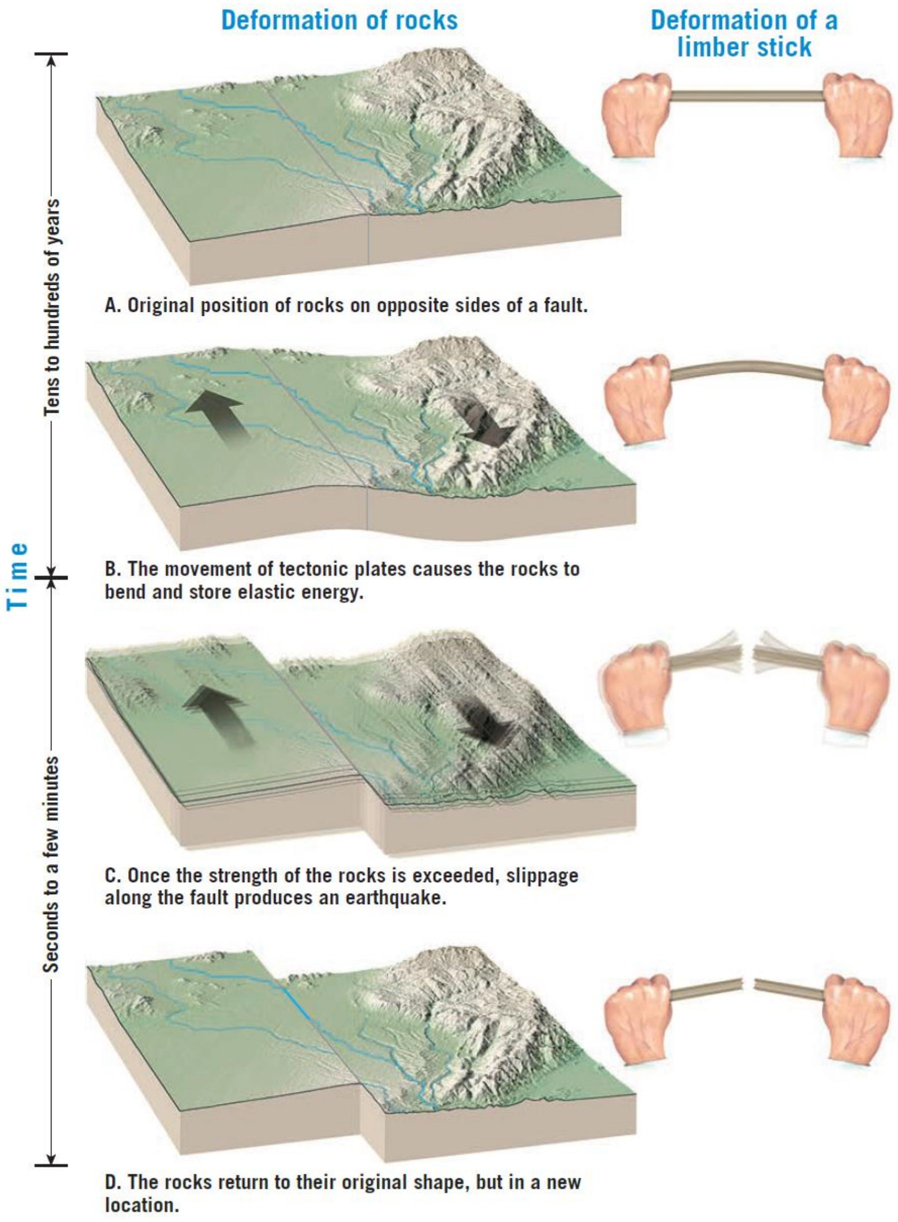
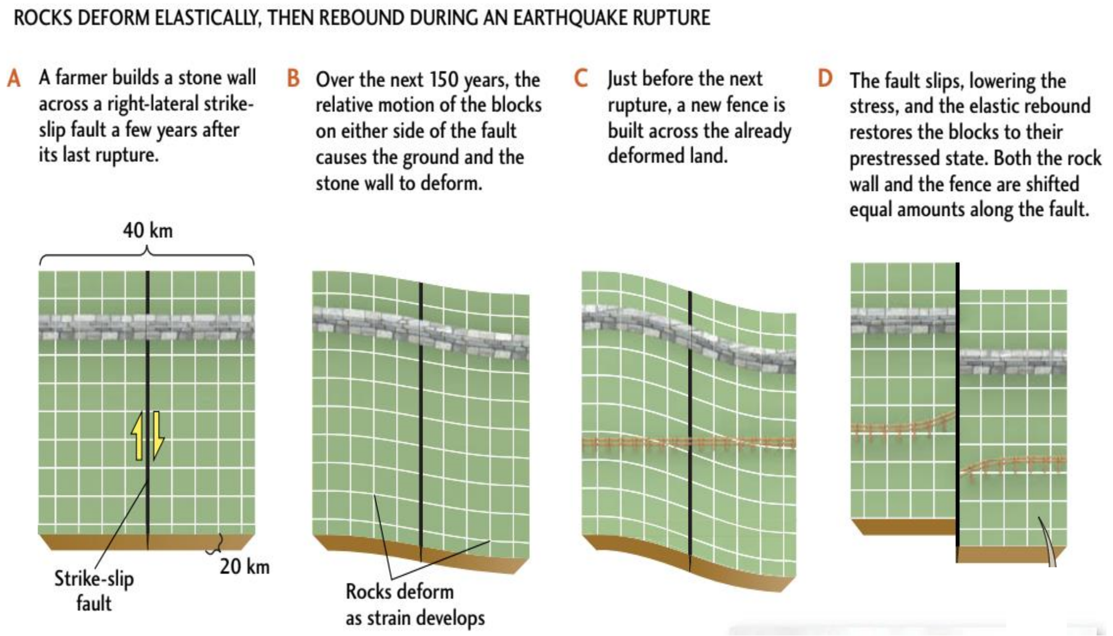


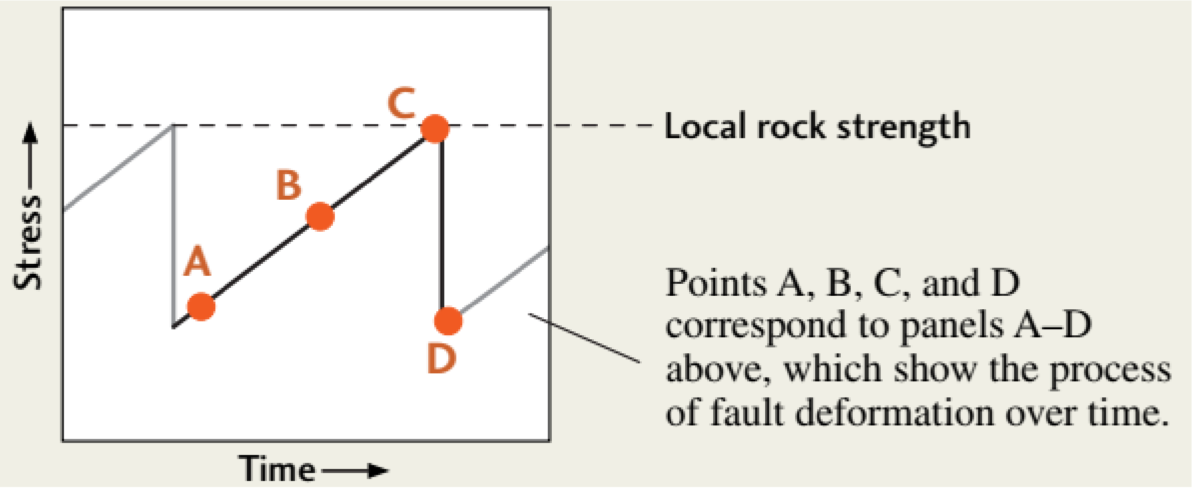
FIGURE 13.2 ■ Map of California, showing the segments of the San Andreas fault that ruptured in 1680, 1857, and 1906. [Southern California Earthquake Center.]

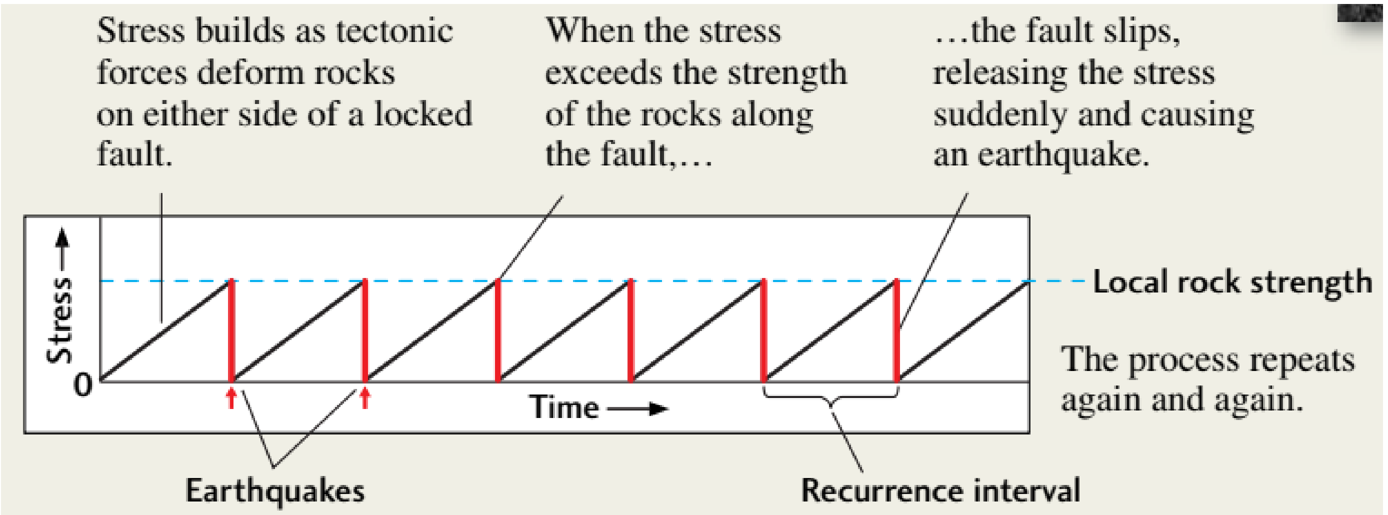
Earthquake Seismology: Elastic Rebound Theory



Earthquake Seismology: Elastic Rebound Theory







- Based on elastic rebound theory it seems one can predict future Earthquakes nicely? The answer is NO because of in reality the pattern is irregular (see the next slide)

Earthquake Seismology: Elastic rebound theory

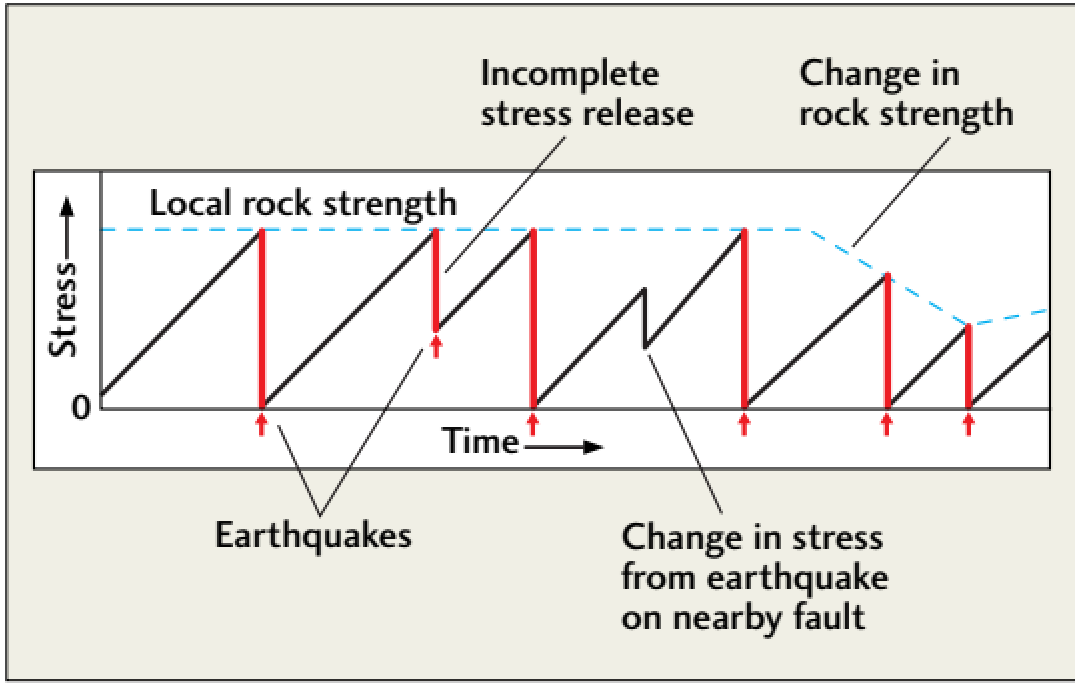


FIGURE 13.4 ■ Irregularities in the earthquake cycle can be caused by incomplete stress release, changes in stress caused by earthquakes on nearby faults, and local variations in rock strength.

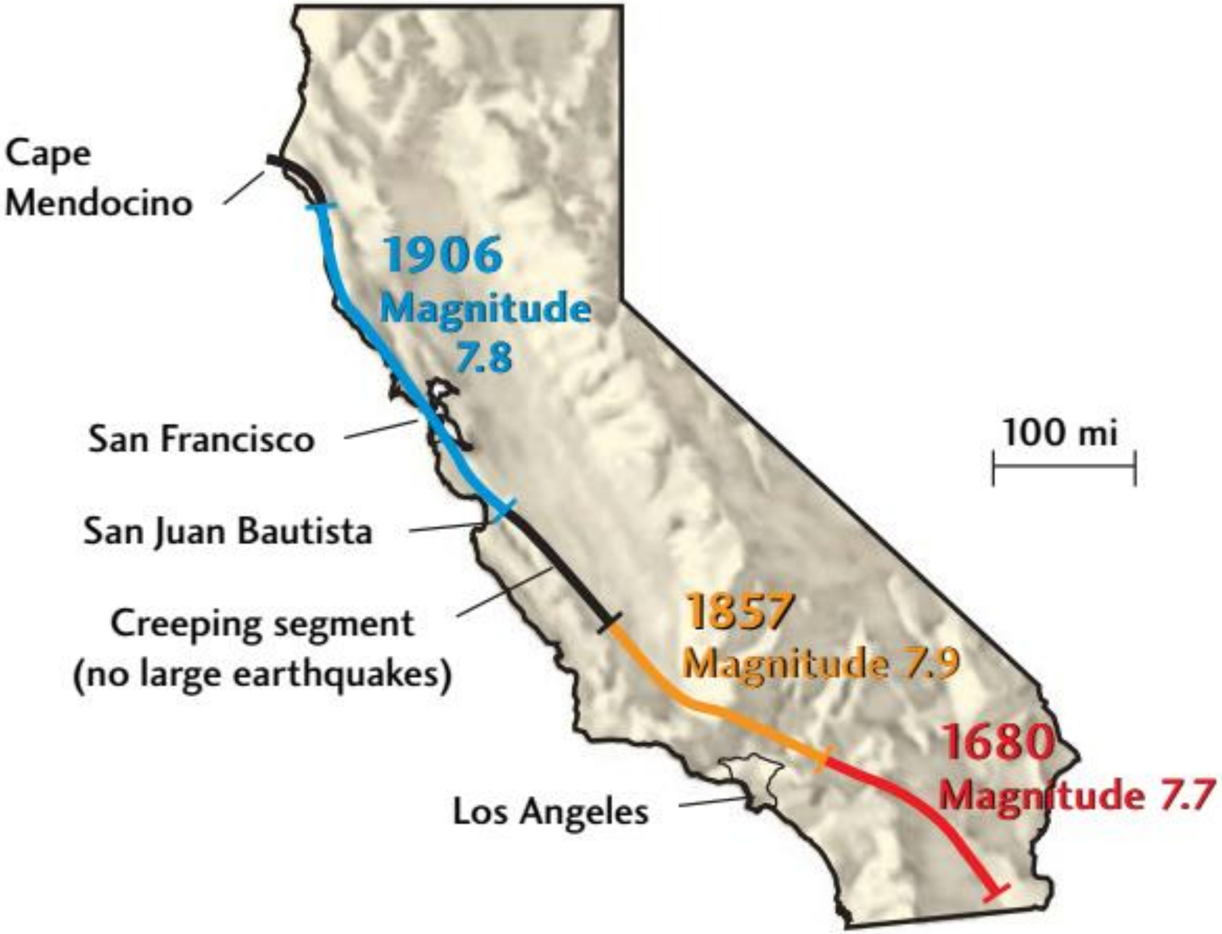


FIGURE 13.2 ■ Map of California, showing the segments of the San Andreas fault that ruptured in 1680, 1857, and 1906. [Southern California Earthquake Center.]

Earthquake Seismology: Fault slipping progression

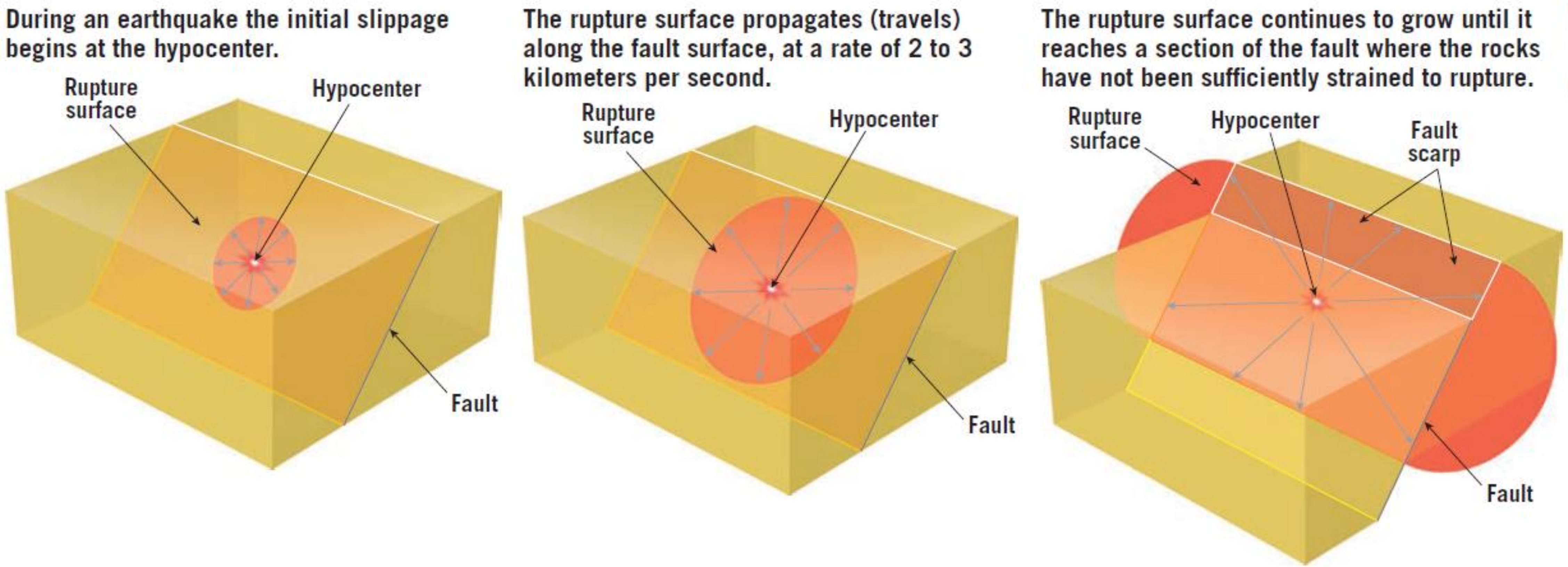


Figure 11.8 Fault propagation

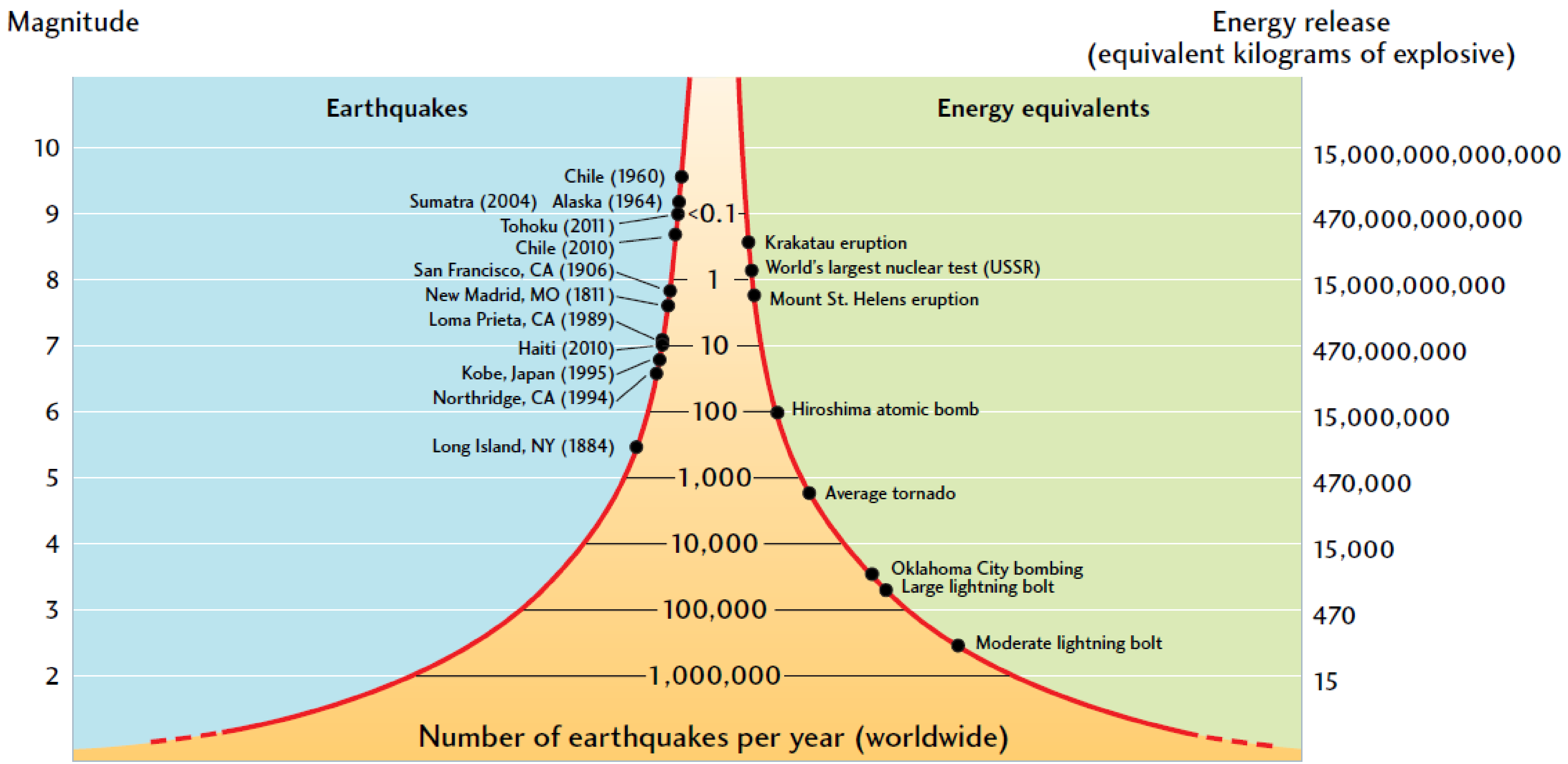


FIGURE 13.12 ■ Relationship between moment magnitude, seismic energy release, and number of earthquakes per year worldwide. Examples of earthquakes of various magnitudes and of other large sources of sudden energy release are included for comparison. [Adapted from IRIS Consortium, http://www.iris.edu.]

Recording the Seismic Waves: Seismograph

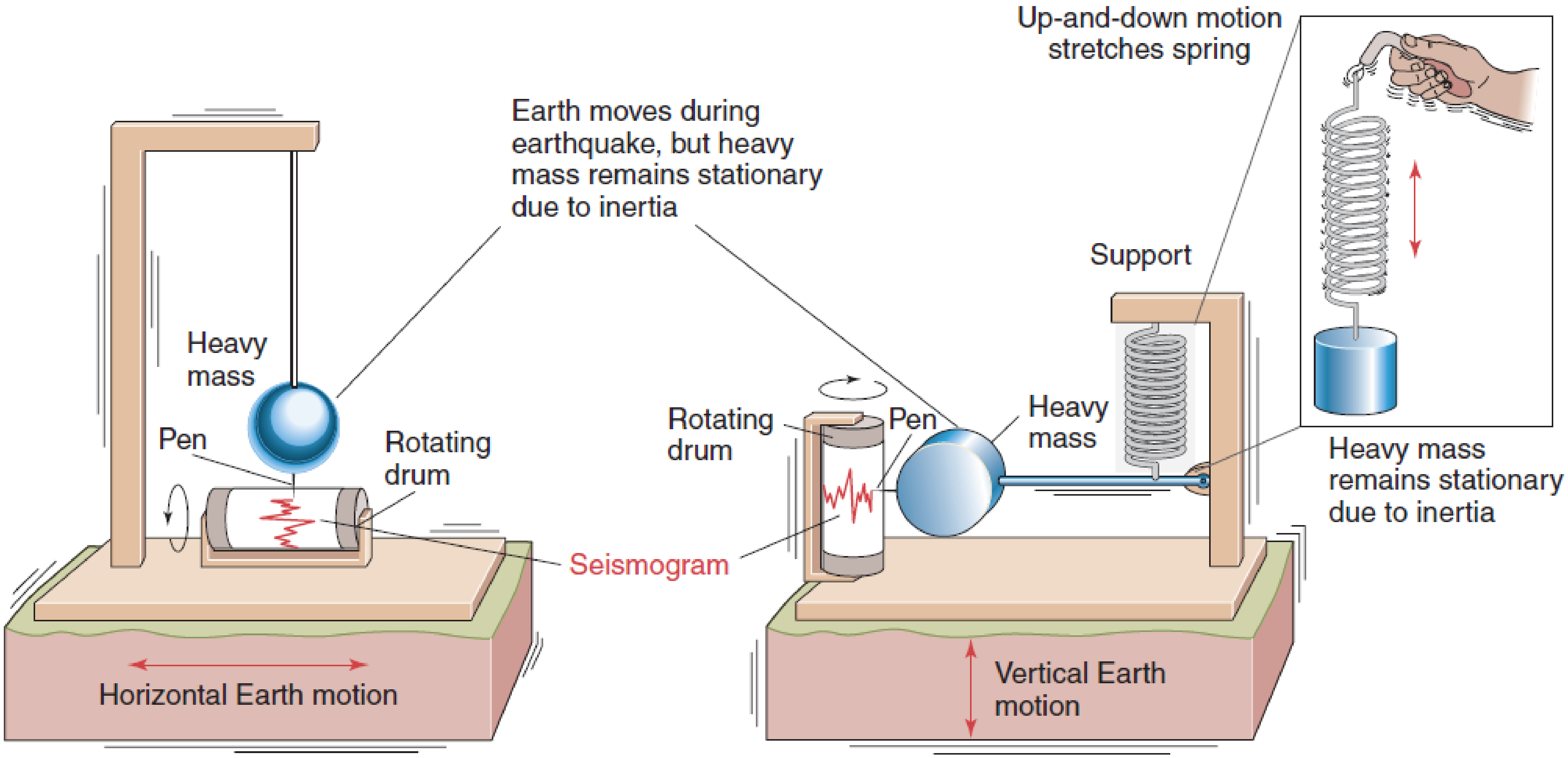


FIGURE 6.3 Seismograph
Seismographs measure and record the vibrations associated with earthquakes. Modern seismographs use the principle of inertia—the resistance of a heavy mass to motion. In this schematic diagram, seismic waves cause the support post and the roll of paper to vibrate back and forth, but the large mass attached to the pendulum and the pen attached to it barely move at all.

Recording the Seismic Waves: Seismograph

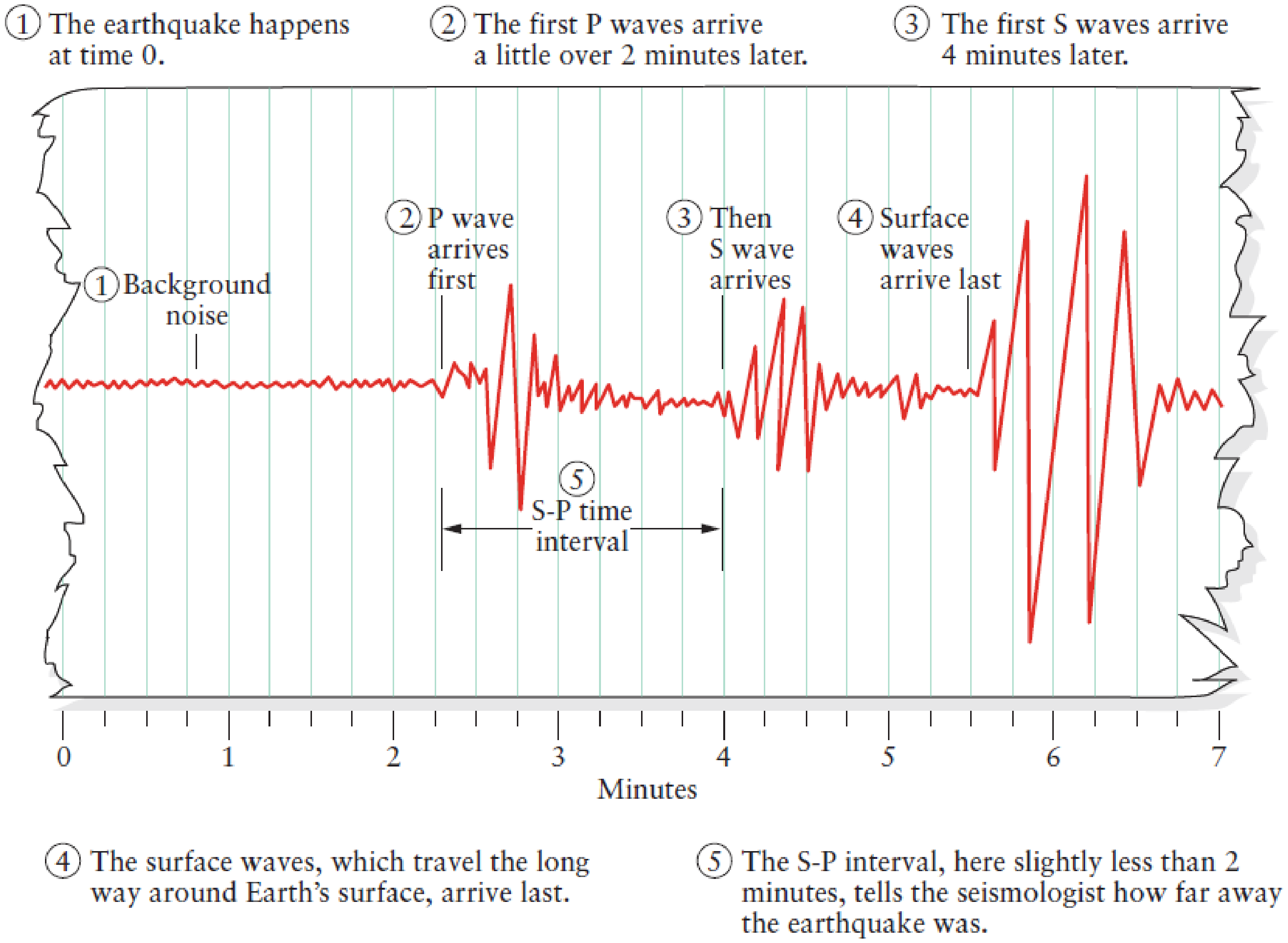
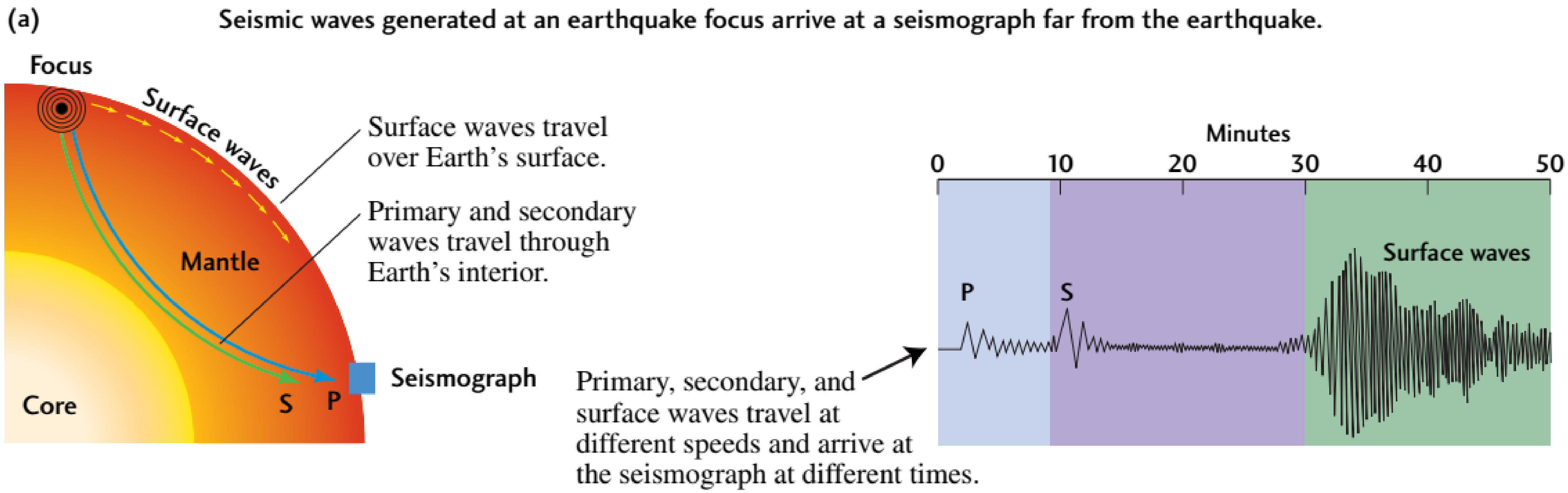


FIGURE B6.2 Seismogram of a typical earthquake
This is a typical seismogram, made by a seismograph. All three types of seismic waves leave the earthquake's focus at the same time. The P waves travel the fastest and arrive at the seismic station first, followed by the S waves. The surface waves travel even more slowly around the outside of Earth rather than through the interior, and they arrive last at the seismic station. The lag times between the arrivals of the different types of seismic waves are a measure of how far they have traveled.

Earthquake Seismology: Seismic Waves

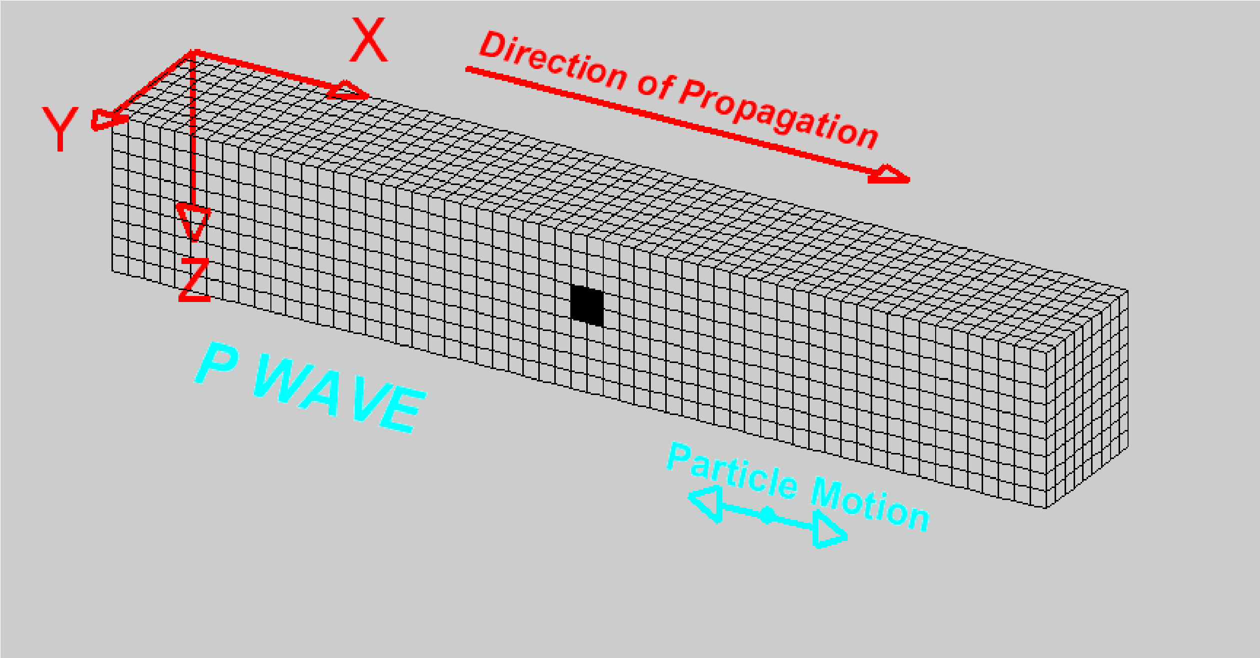


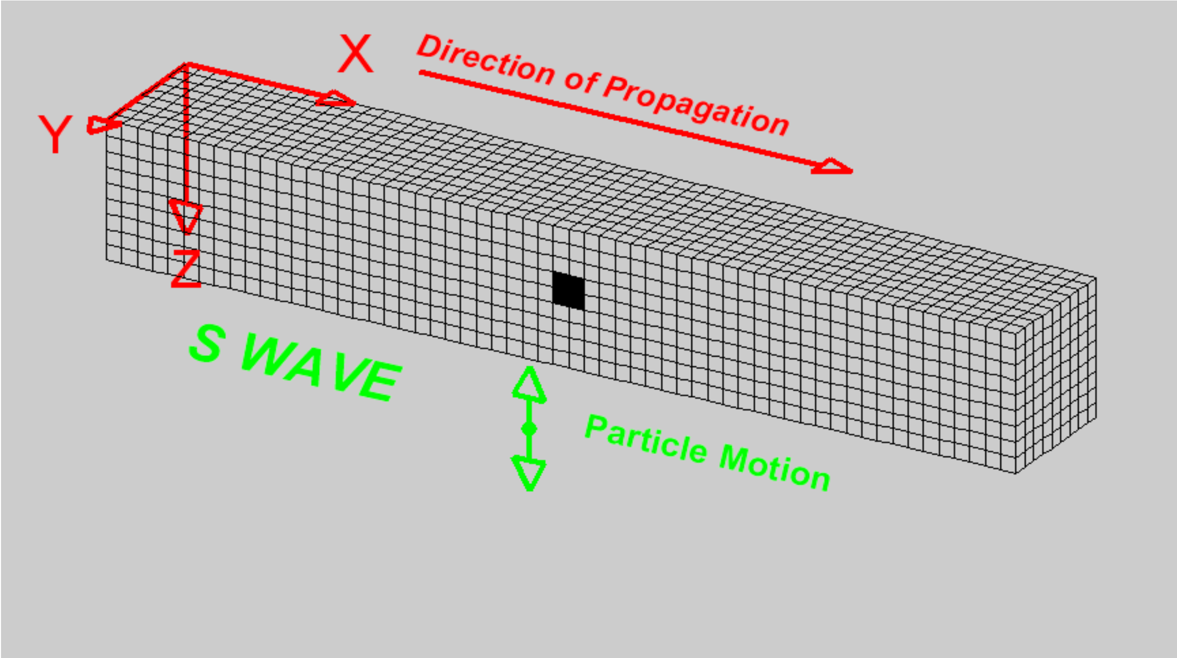
Body Waves: P-wave or Compressional wave
S-wave or Shear wave

Surface Waves: Love wave
Rayleigh wave

Earthquake Seismology: Seismic Waves

Body waves: **Compressional (P-wave) Shear (S-wave) wave**

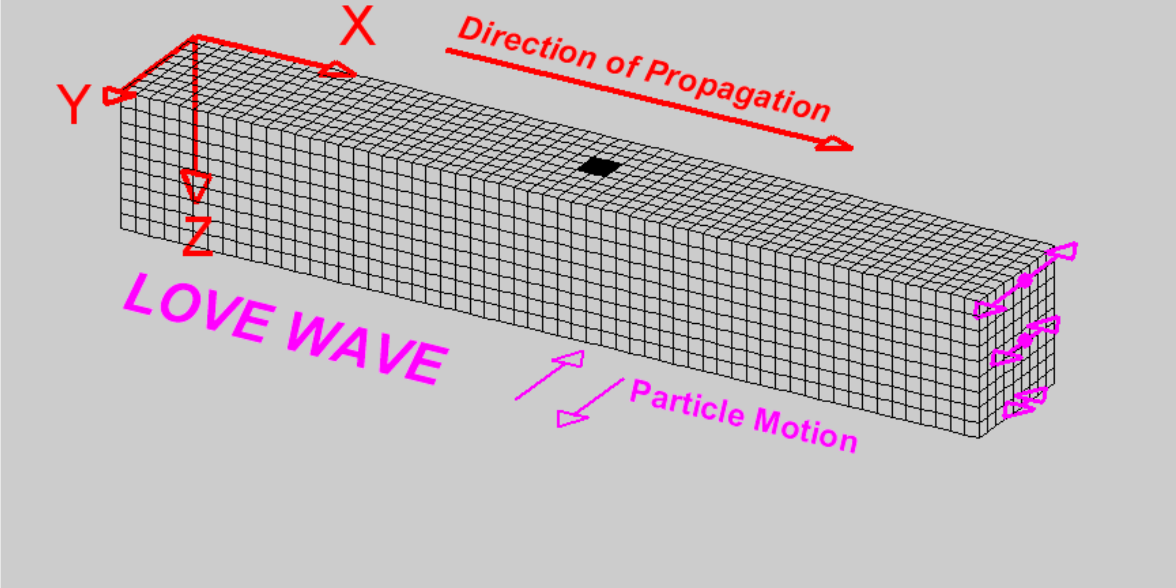


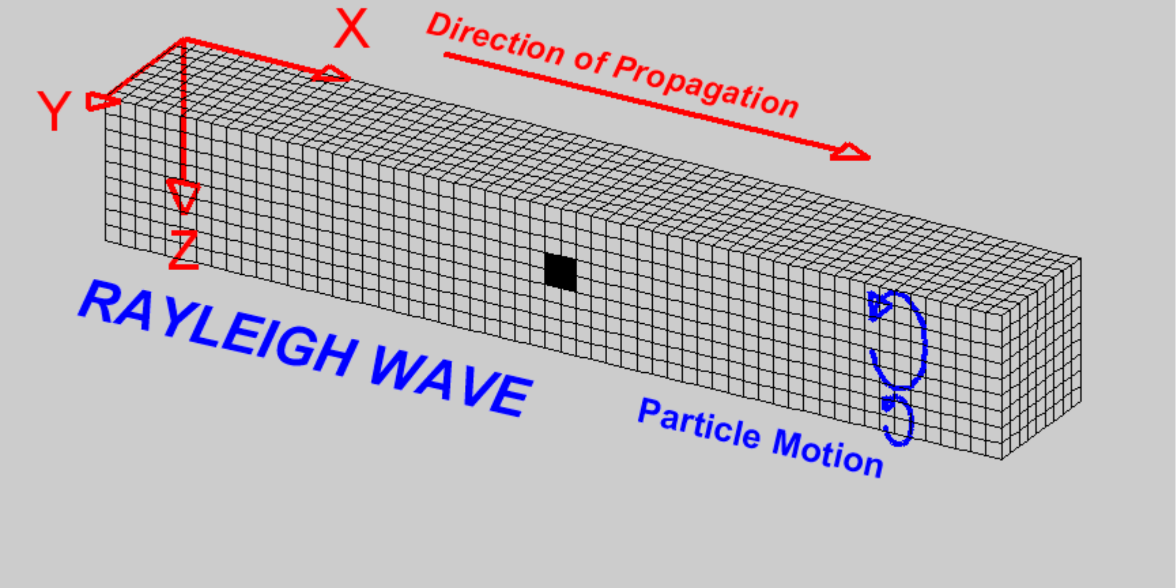


http://www.geo.mtu.edu/UPSeis/waves.html

Earthquake Seismology: Seismic Waves

Surface waves: Love wave and Rayleigh wave





http://www.geo.mtu.edu/UPSeis/waves.html

Earthquake Seismology: Seismic Waves

- **Propagation of seismic wave depends on the physical properties of the material through which they propagate.**

- **The specific properties are**
  - **Bulk modulus (K): The ability of material to resist being <u>compressed</u>.**
  - **Shear modulus (μ): The ability of material to resist being <u>sheared</u>.**
  - **Density (ρ)**

Body wave velocities:

$$V_P = \sqrt{\frac{\left(\frac{4}{3}\mu + K\right)}{\rho}} \quad \text{and} \quad V_s = \sqrt{\frac{\mu}{\rho}}$$

Locating the Earthquake's Focus

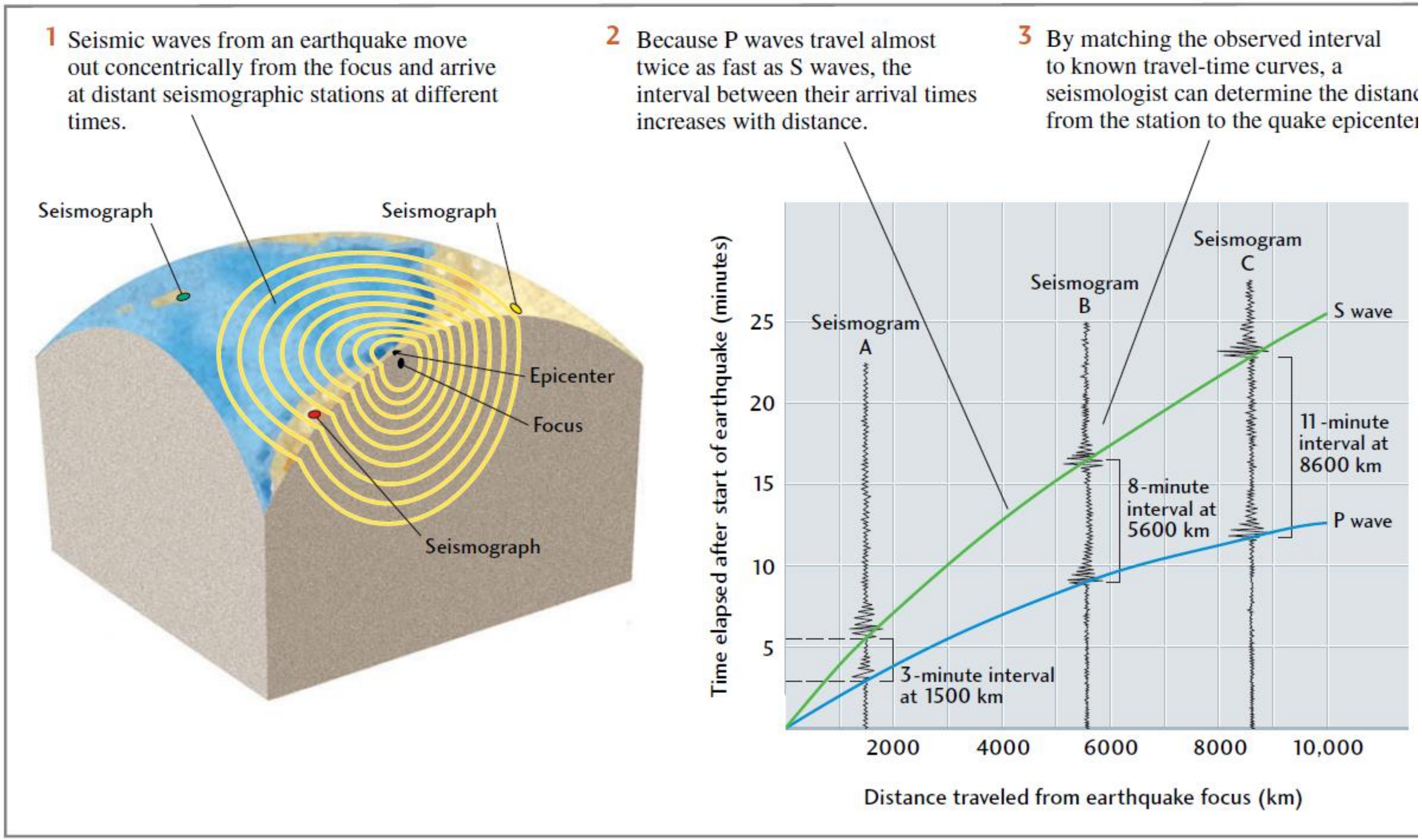


FIGURE 13.10 ■ Readings from three or more seismographic stations can be used to determine the location of an earthquake's focus.

Locating the Earthquake's Focus

The location of an earthquake's epicenter can be calculated from seismic wave measurements at three seismic stations. The time interval between the arrival of the first P wave and the first S wave depends on the distance from the seismic station to the epicenter. Let's say that seismic station 1 calculates a distance of 2000 km to the earthquake's point of origin, on the basis of the time lag between P and S wave arrivals. Seismic station 2 calculates a distance of 4000 km, and seismic station 3 calculates a distance of 6000 km. On a map, a circle of appropriate radius (equal to the distance) is drawn around each station; it has to be a circle because the arrival times indicate the distance traveled by the waves, but not the direction from which they came. The epicenter is where the three circles intersect on the map.

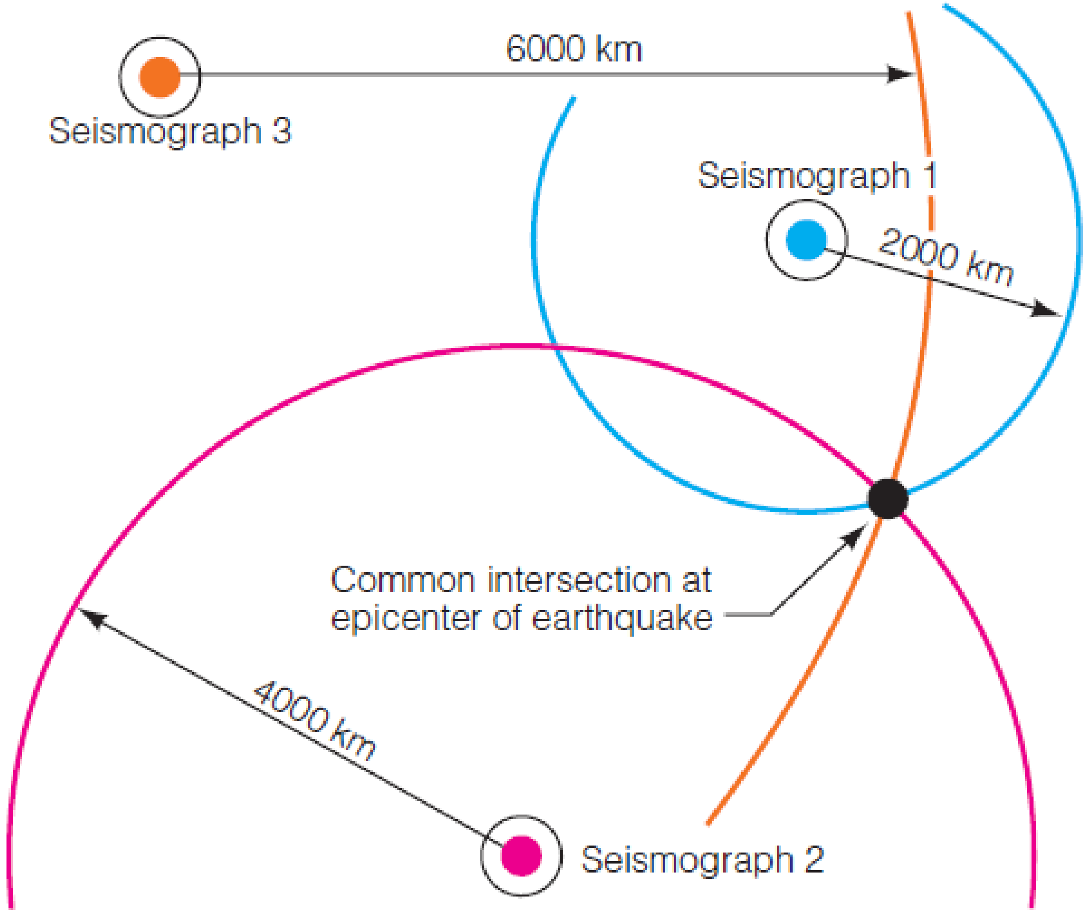


FIGURE 6.5 **Locating an earthquake**

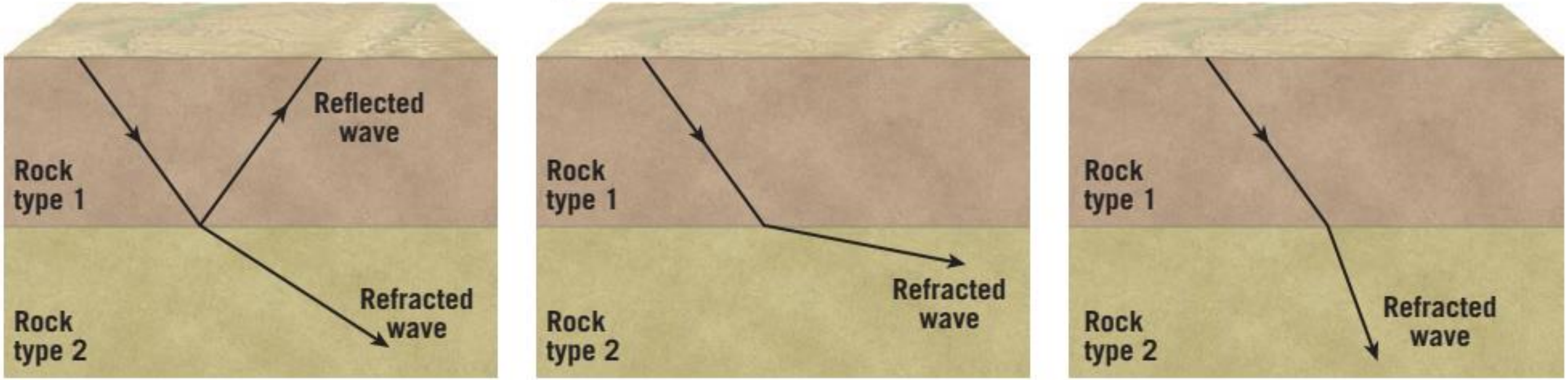
Exploring Earth’s Interior using Seismic Waves

- **Reflection and Refraction of the seismic waves as they pass through different material inside the Earth.**

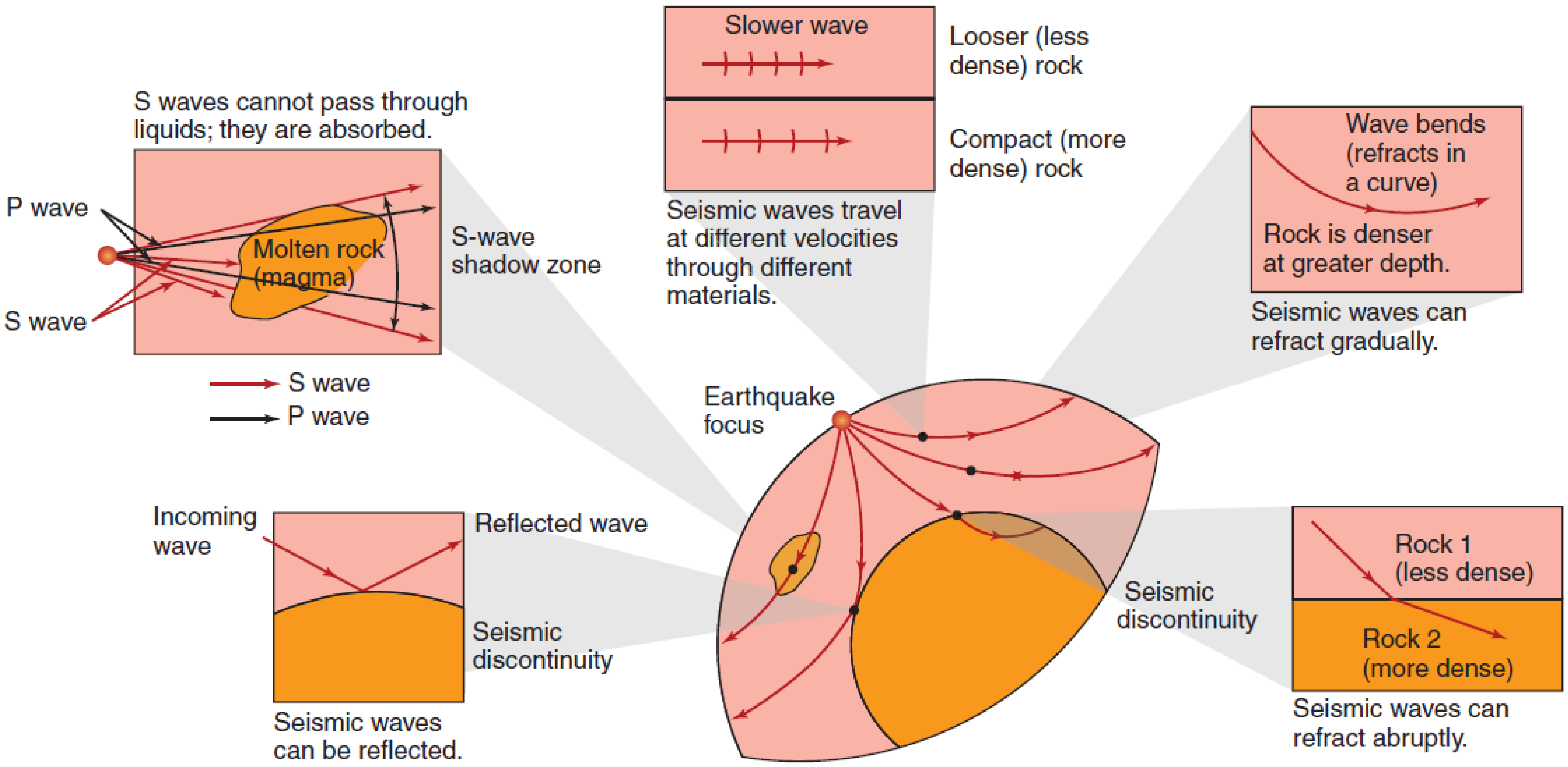
When seismic waves (rays) encounter a boundary between materials with different properties, such as air and water, the energy splits into reflected and refracted (bent) waves.

When the velocity of seismic waves increases as they pass from one layer into another, the waves refract (bend) toward the boundary separating the layers.

When the velocity of seismic waves decreases as they pass from one layer into another, the waves refract (bend) away from the boundary separating them.



Exploring Earth's Interior using Seismic Waves



Exploring Earth's Interior using Seismic Waves

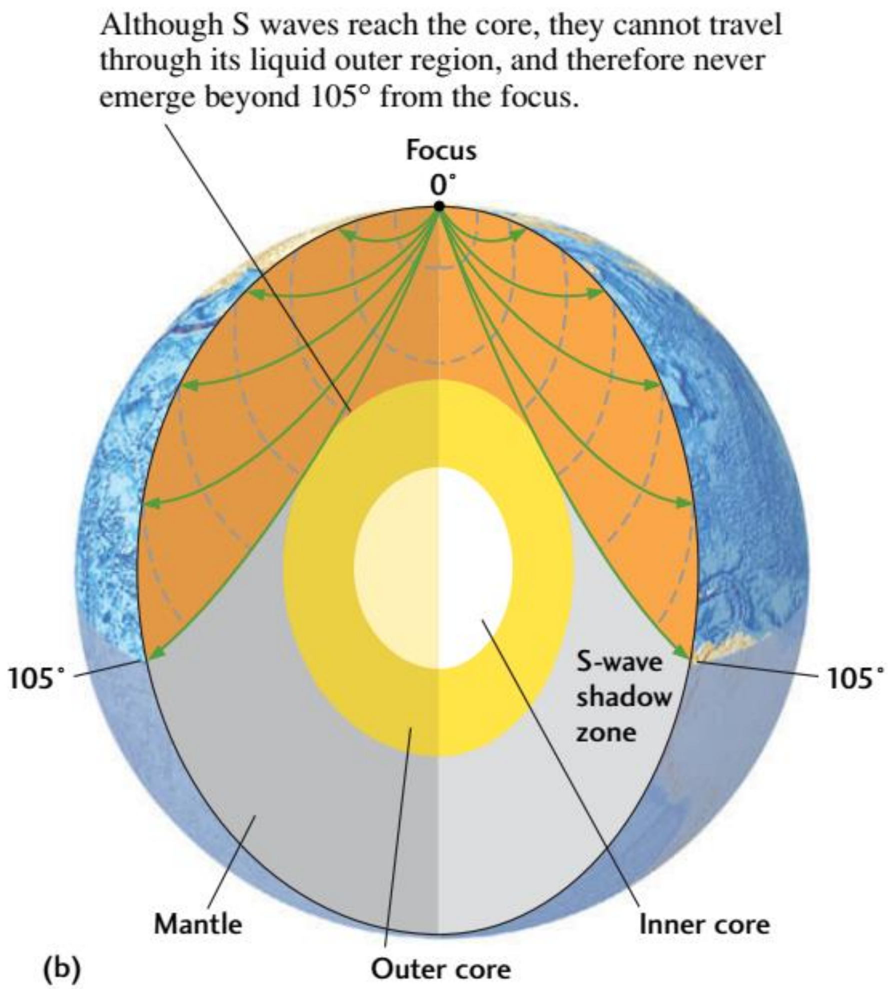
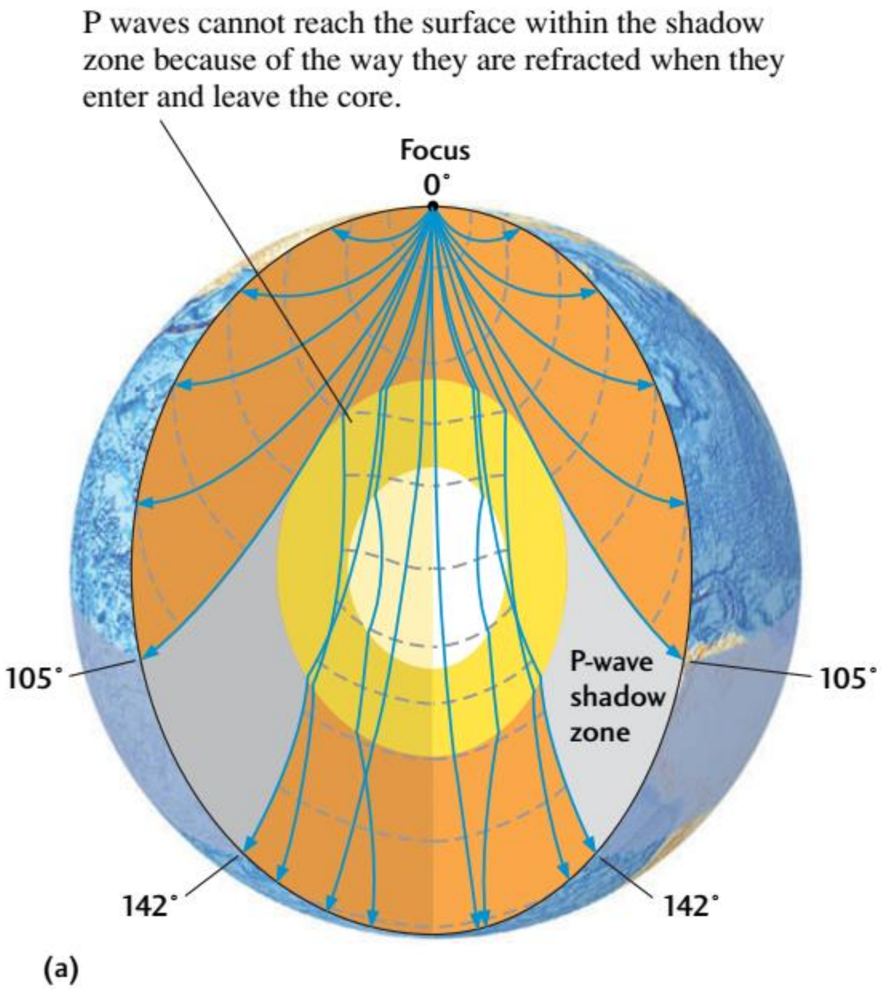


FIGURE 14.2 ■ Earth's core creates P-wave and S-wave shadow zones. The ray paths of the seismic waves from an earthquake focus through Earth's interior are shown by solid lines (blue for P-waves, green for S-waves). The dashed lines show the progress of the waves at 2-minute intervals. Distances are measured in angular degrees from the earthquake focus. (a) The P wave shadow zone extends from 105° to 142°. (b) The larger S-wave shadow zone extends from 105° to 180°.

Exploring Earth's Interior using Seismic Waves



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Exploring Earth's Interior using Seismic Waves

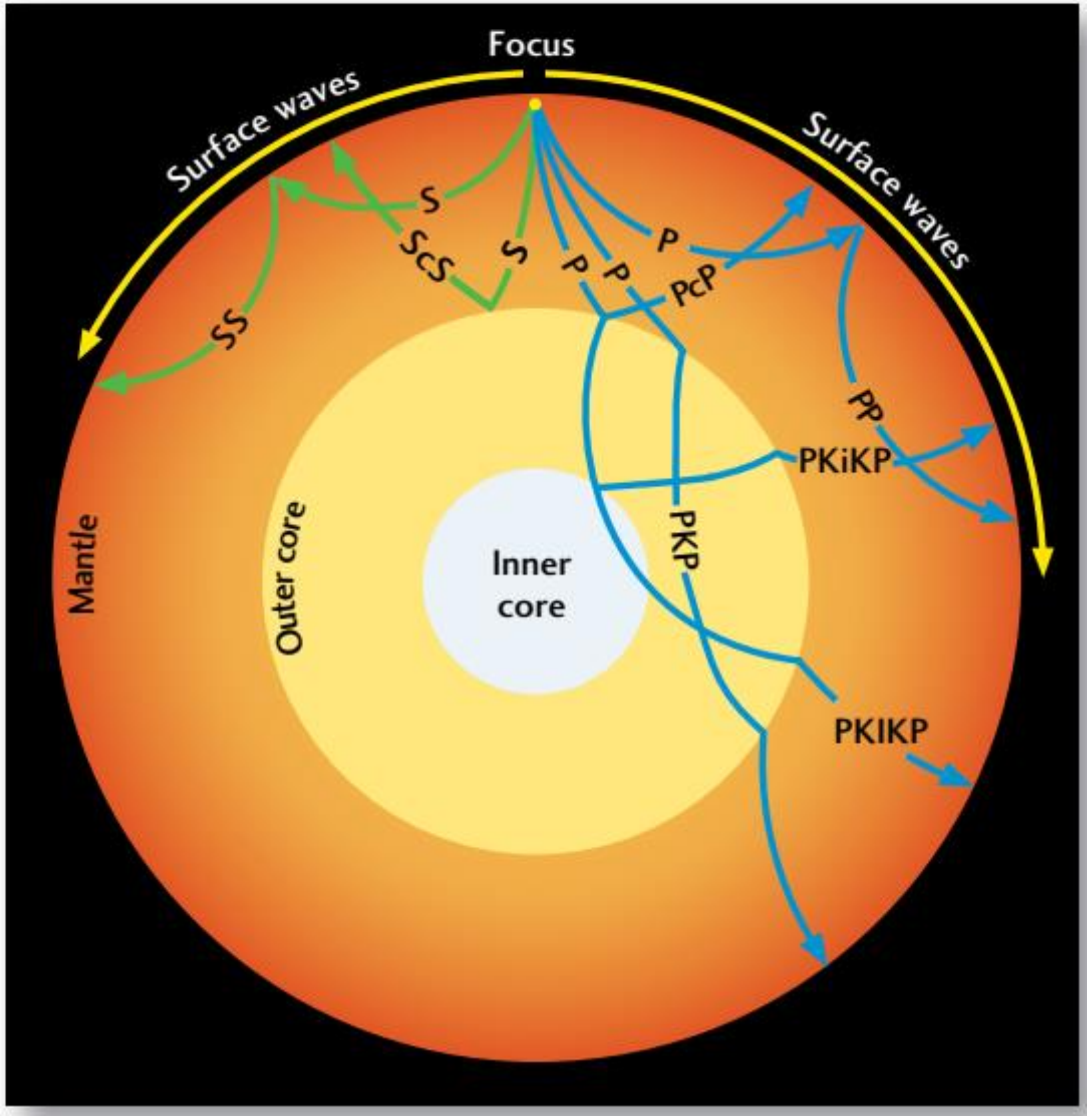


FIGURE 14.3 ■ Seismologists use a simple labeling scheme to describe the various ray paths taken by seismic waves. PcP and ScS are compressional and shear waves, respectively, that are reflected by the core. PP and SS waves are internally reflected from Earth's surface. A PKP wave travels through the liquid outer core, a PKIKP wave travels through the solid inner core, and a PKiKP wave is reflected by the inner core. Surface waves propagate along Earth's outer surface, like waves on the surface of a pond.

Exploring Earth's Interior using Seismic Waves

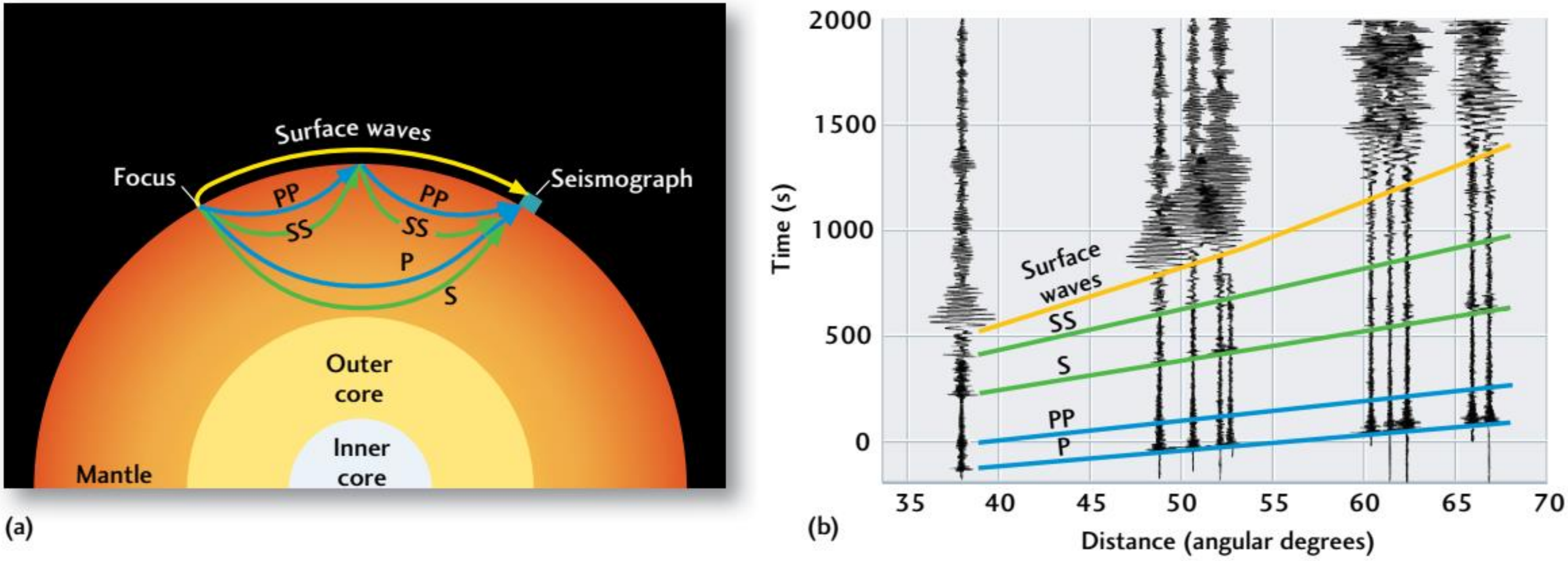


FIGURE 14.4 ■ (a) P and S waves are refracted upward in the mantle and also can be reflected from Earth's surface. A seismic wave that has been reflected once from Earth's surface is labeled with a double letter (PP or SS). (b) Seismograms recorded at various distances from an earthquake focus in the Aleutian Islands, Alaska. The colored lines identify the arrival times of the P and S waves, the surface waves, and the PP and SS waves reflected from Earth's surface.

Exploring Earth's Interior using Seismic Waves

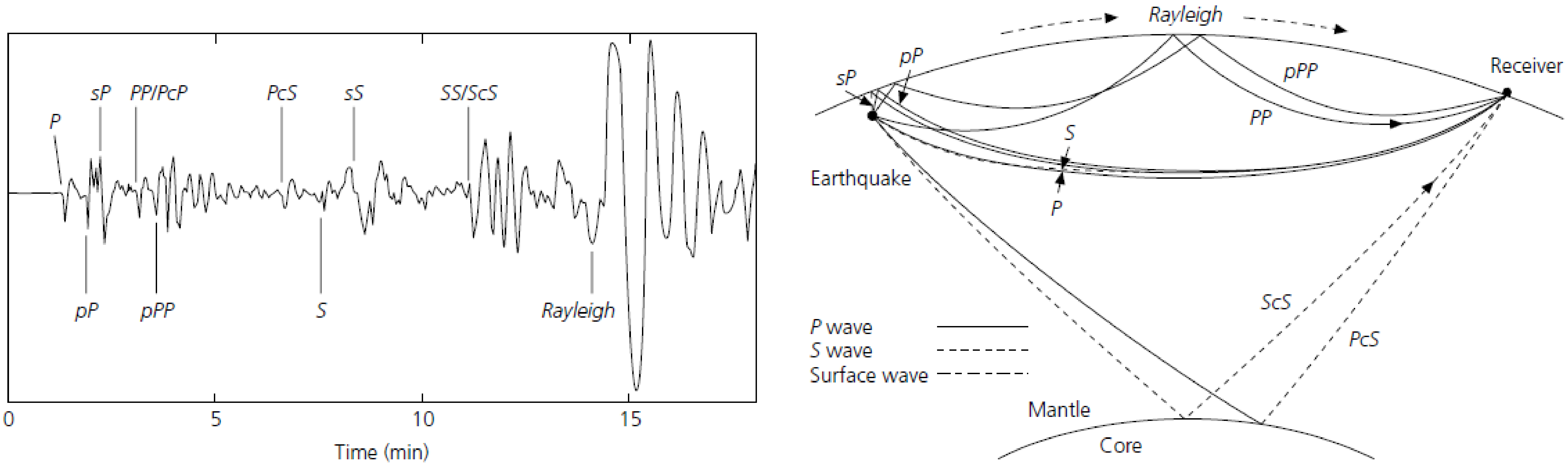


Fig. 1.1-3 *Left*: Long-period vertical component seismogram at Golden, Colorado, from an earthquake in Colombia (July 29, 1967), showing various seismic phases. The distance from earthquake to station is 44°. *Right*: Ray paths for the seismic phases labeled on the seismogram.

Exploring Earth's Interior using Seismic Waves

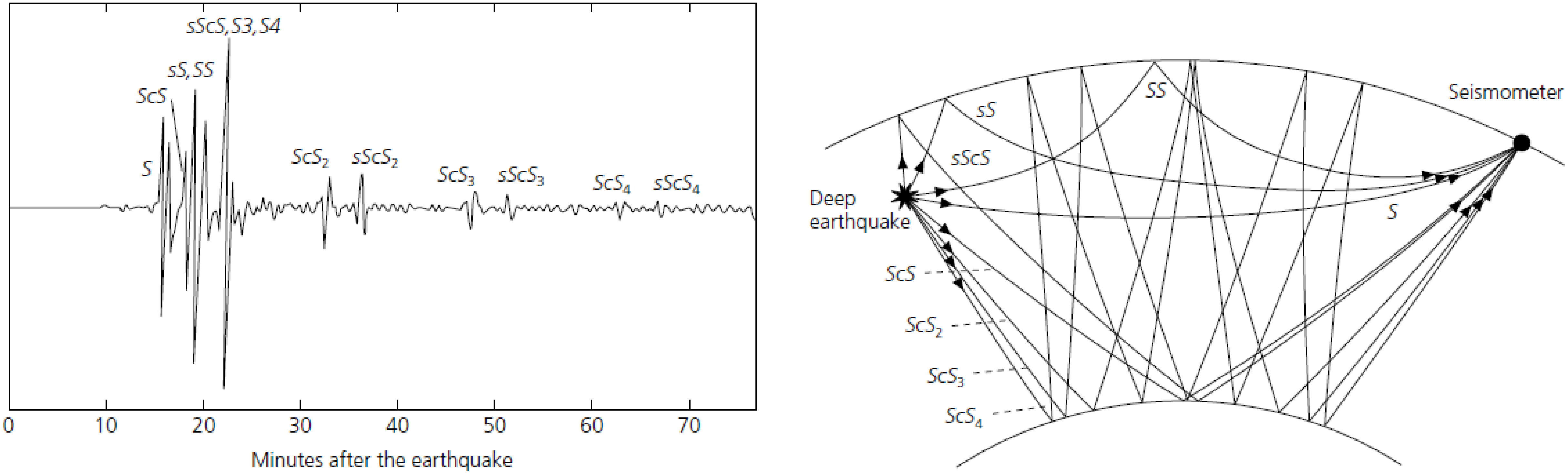
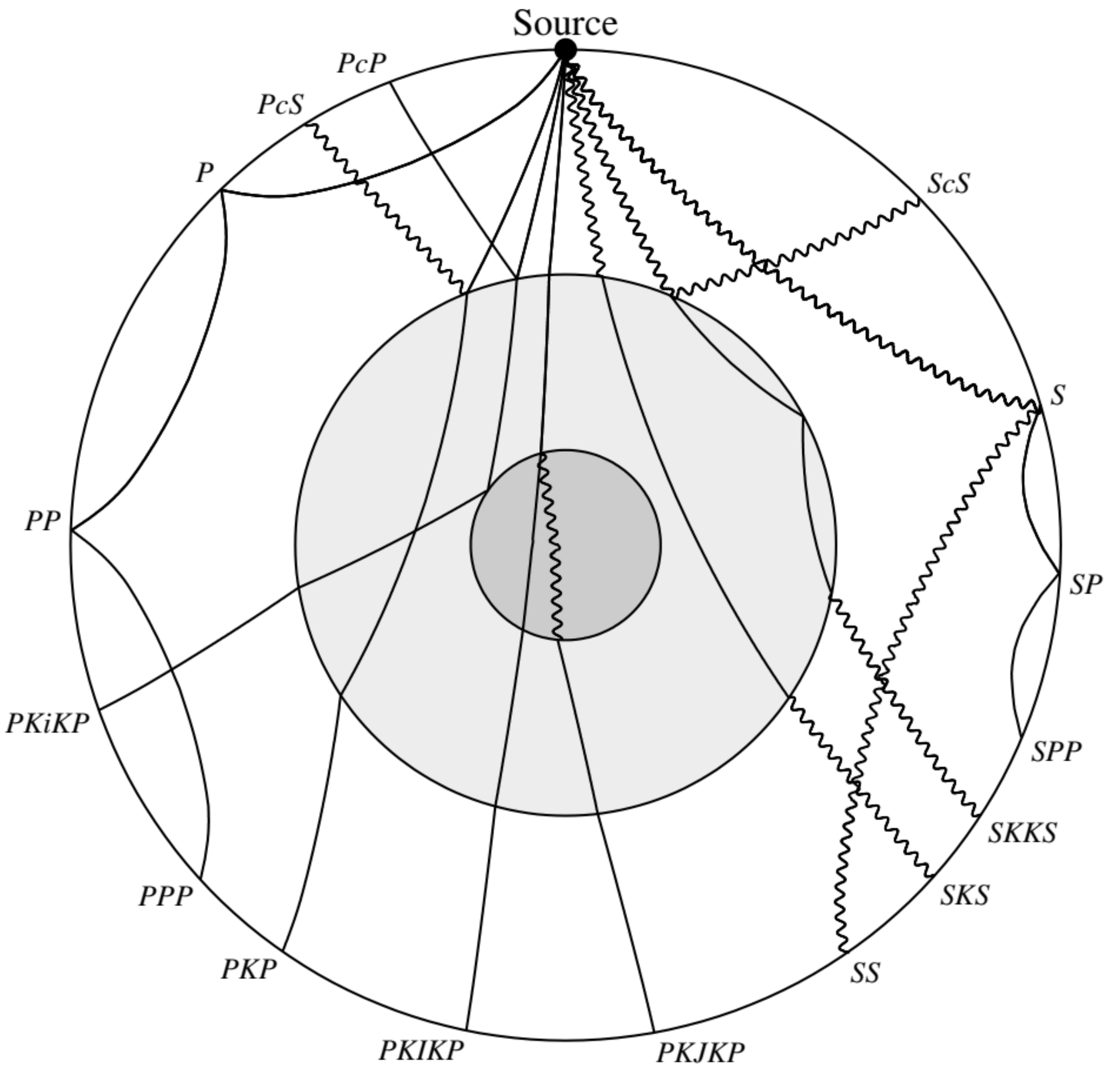


Fig. 1.1-4 Seismogram (*left*) and ray paths (*right*) for a deep focus earthquake in Tonga, recorded at Oahu (Hawaii), showing multiple core reflections.

Exploring Earth's Interior using Seismic Waves



P – *P* wave in the mantle
K – *P* wave in the outer core
I – *P* wave in the inner core
S – *S* wave in the mantle
J – *S* wave in the inner core
c – reflection off the core–mantle boundary (CMB)
i – reflection off the inner-core boundary (ICB)

Figure 4.15 Global seismic ray paths and phase names, computed for the PREM velocity model. *P* waves are shown as solid lines, *S* waves as wiggly lines. The different shades indicate the inner core, the outer core, and the mantle.

Exploring Earth's Interior using Seismic Waves

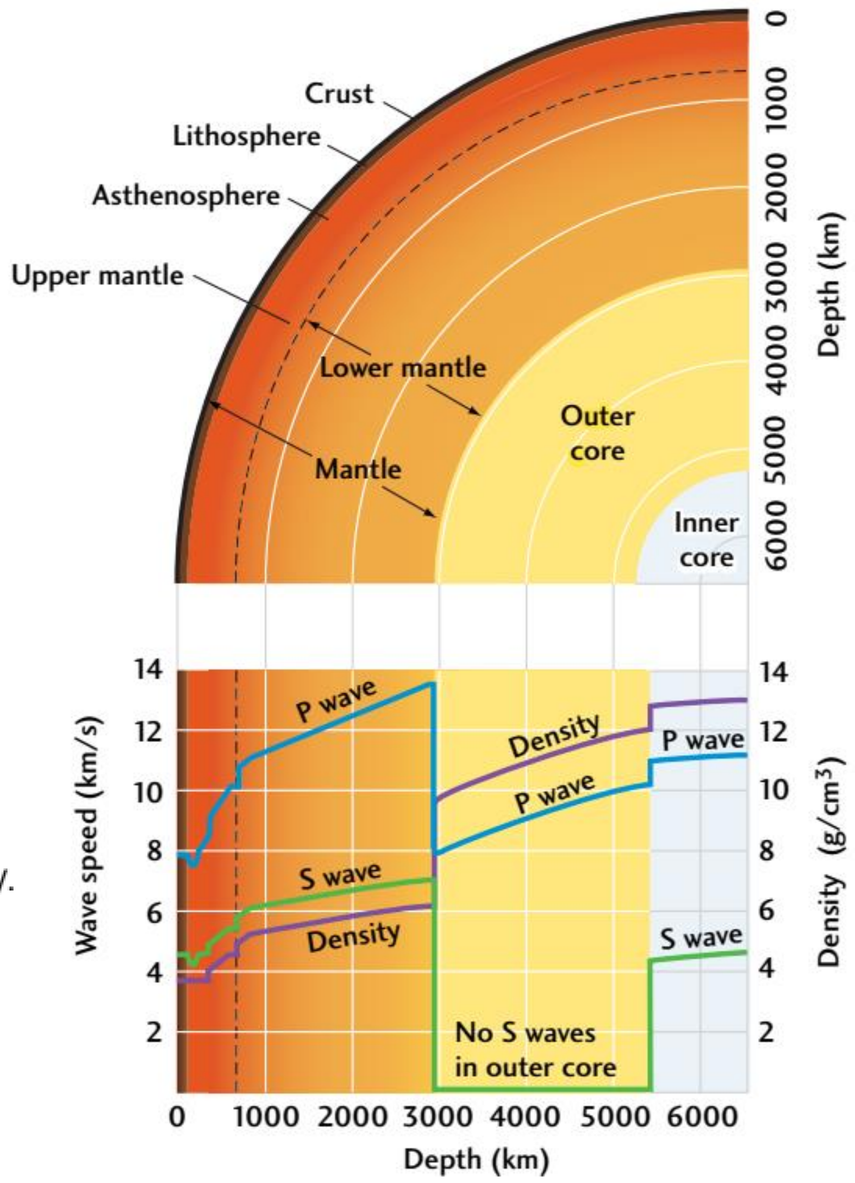


FIGURE 14.7 ■ Earth's layering as revealed by seismology. The lower diagram shows changes in P-wave and S-wave velocities and rock densities with depth. The upper diagram is a cross section through Earth on the same depth scale, showing how those changes are related to the major layers (see also Figure 1.12).

Exploring Earth's Interior using Seismic Waves

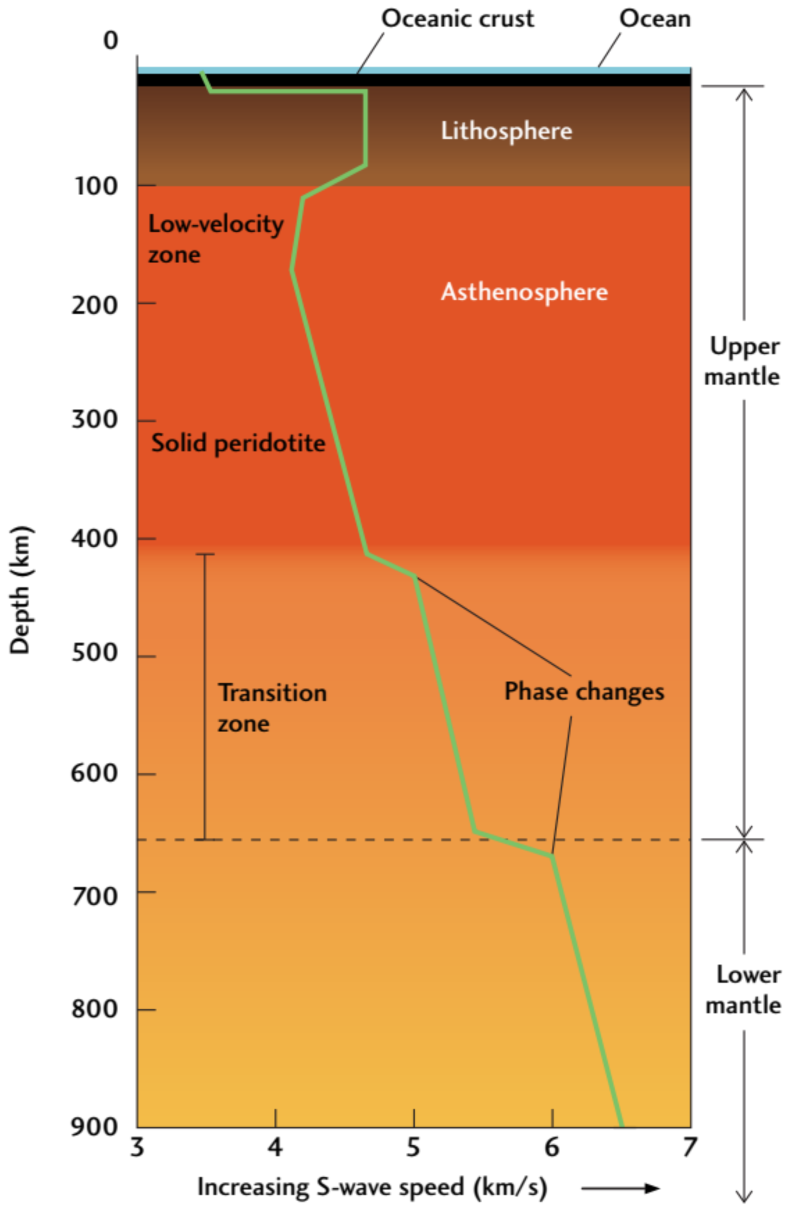


FIGURE 14.8 ■ The structure of the mantle beneath old oceanic lithosphere, showing S-wave velocities to a depth of 900 km. Changes in S-wave velocity mark the strong, brittle lithosphere, the weak, ductile asthenosphere, and a transition zone, in which increasing pressure forces rearrangements of atoms into denser and more compact crystal structures (phase changes).

Phase Transitions in Olivine

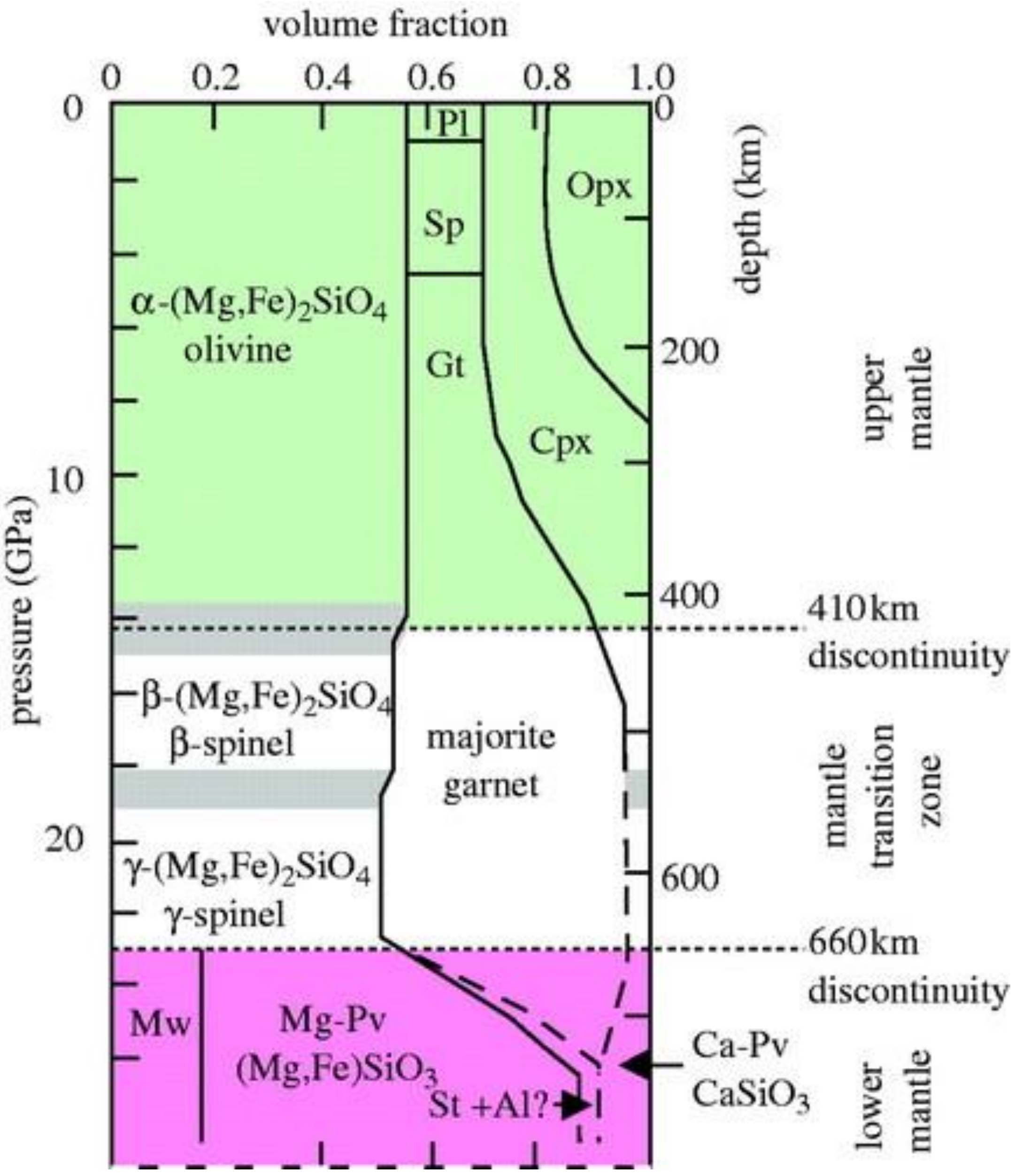


Figure 1. Schematic of the volumetric mineral constitution of a peridotite mantle down to the lower mantle (modified after Ito & Takahashi 1987). Peridotite is a dense coarse-grained igneous rock consisting mainly of olivine and pyroxene. It is high in Fe and Mg and contains less than 45% Si. Peridotite can be found in xenoliths (rock fragments) brought to the surface by magma deriving from the upper mantle. Pl=plagioclase–$CaAl_2Si_2O_8$; Sp=spinel–$MgAl_2O_4$; Gt=garnet–$(Mg,Fe,Ca)_3Al_2Si_3O_{12}$; majorite garnet–$Mg_3(Mg,Si)_2Si_3O_{12}$; Cpx=clinopyroxene–(Ca,Fe,Mg)SiO_3; Opx=orthopyroxene–(Mg,Fe)SiO_3; Mg-Pv=Mg-perovskite–(Mg,Fe)SiO_3; olivine–$(Mg,Fe)_2SiO_4$; Mw=magnesiowüstite–(Mg,Fe)O; Ca-Pv=Ca-perovskite–$CaSiO_3$; St=stishovite–SiO_2.

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Exploring Earth's Interior using Seismic Waves (lateral variation)

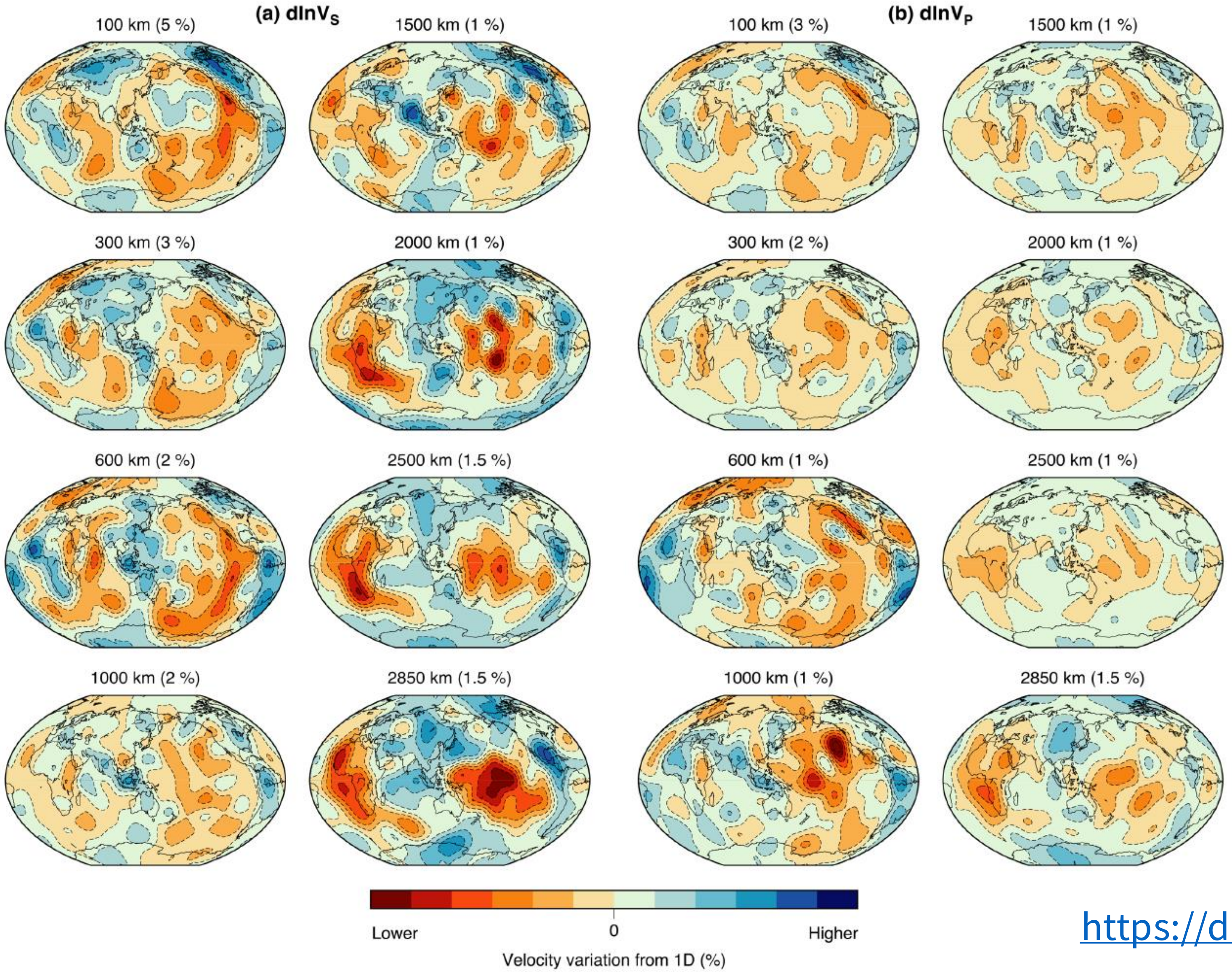

Figure 6. Maps of (a) shear-wave velocity variations dlnV_S and (b) compressional-wave velocity variations dlnV_P according to model SP12RTS at 100, 300, 600, 1000, 1500, 2000, 2500 and 2850 km depth. Velocity is higher (lower) than the radially averaged value at each depth in blue (red) regions and the colour intensity is proportional to the amplitude of the variations up to the maximum (in per cent) indicated above each map.

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