Physical Geology

Plummer • McGeary • Carlson

Chapter 17: Earth's Interior

Introduction

- Deep interior of the Earth must be studied *indirectly*
  - Direct access only to crustal rocks and small upper mantle fragments brought up by volcanic eruptions or slapped onto continents by subducting oceanic plates
  - Deepest drillhole reached about 12 km, but did *not* reach the mantle

- *Geophysics* is the branch of geology that studies the interior of the Earth

Earth's Internal Structure

- *Seismic waves* have been used to determine the three main zones within the Earth: the *crust*, *mantle* and *core*
- The *crust* is the outer layer of rock that forms a thin skin on Earth's surface
- The *mantle* is a thick shell of dense rock that separates the crust above from the core below
- The *core* is the metallic central zone of the Earth

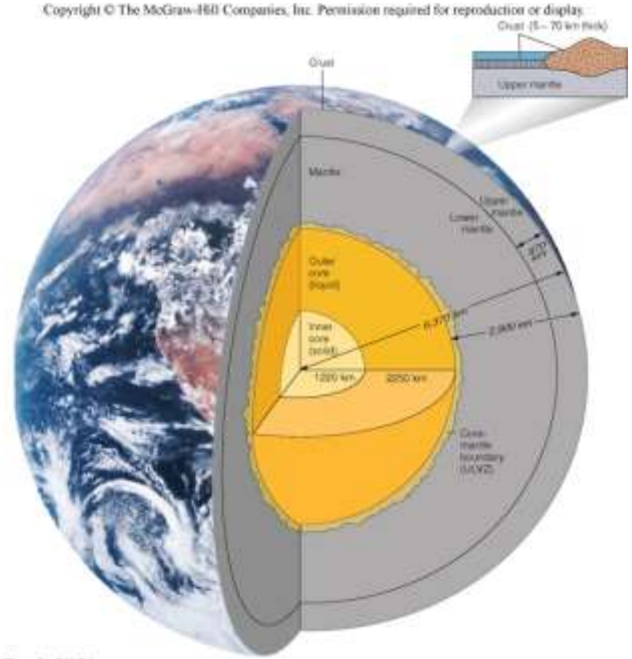


Photo by NASA

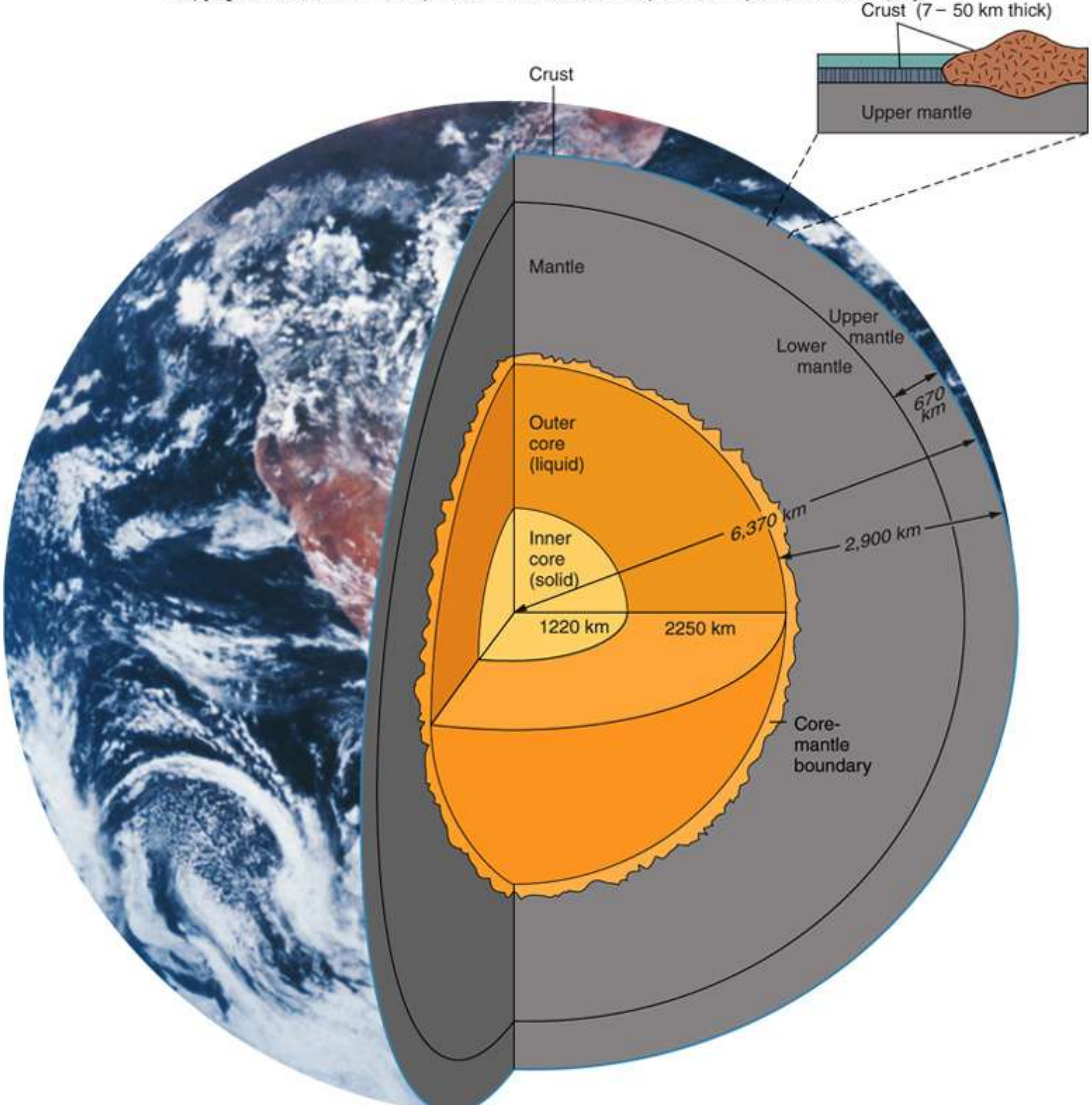
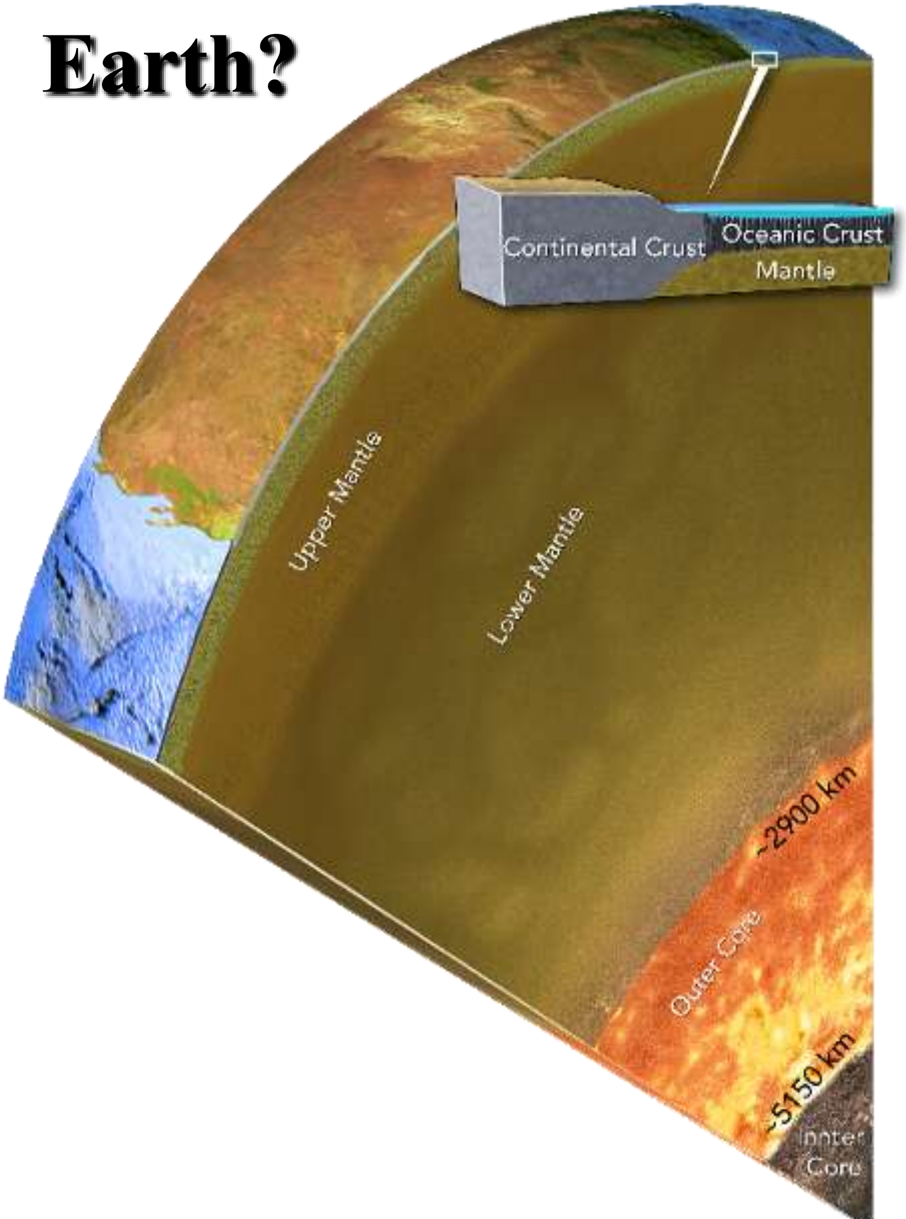


Photo by NASA

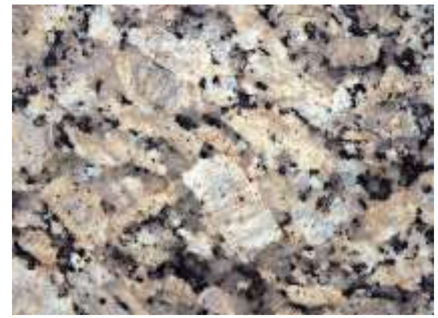
What Is Inside Earth?



01.03.a

Upper layer is *crust;* two types:

continental *oceanic*

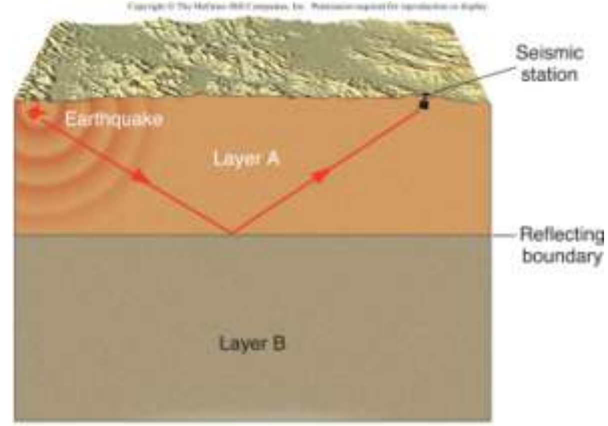


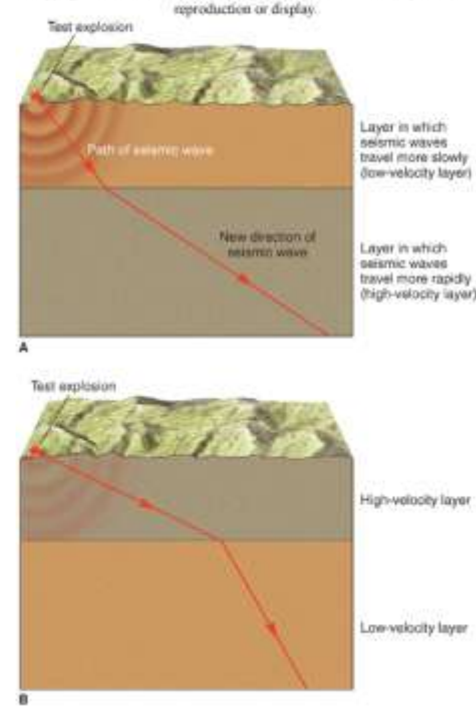
Thickest layer: *mantle*

Lowest layer: iron-nickel core (molten outer core; solid inner core)

Evidence from Seismic Waves

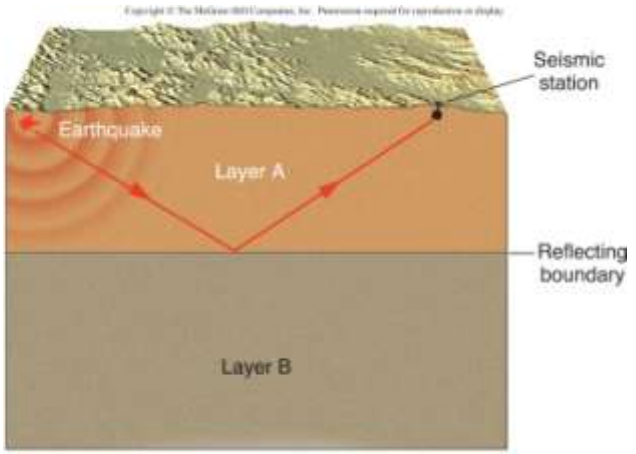
- *Seismic waves* or vibrations from a large earthquake (or underground nuclear test) will pass through the entire Earth
- *Seismic reflection* - the return of some waves to the surface after bouncing off a rock layer boundary
  - Sharp boundary between two materials of different densities will reflect seismic waves
- *Seismic refraction* - bending of seismic waves as they pass from one material to another having different seismic wave velocities

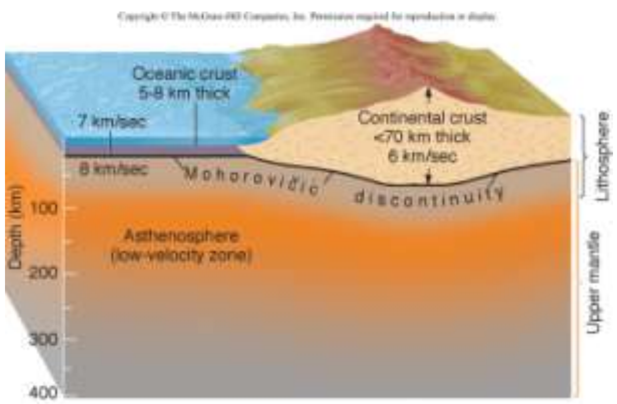


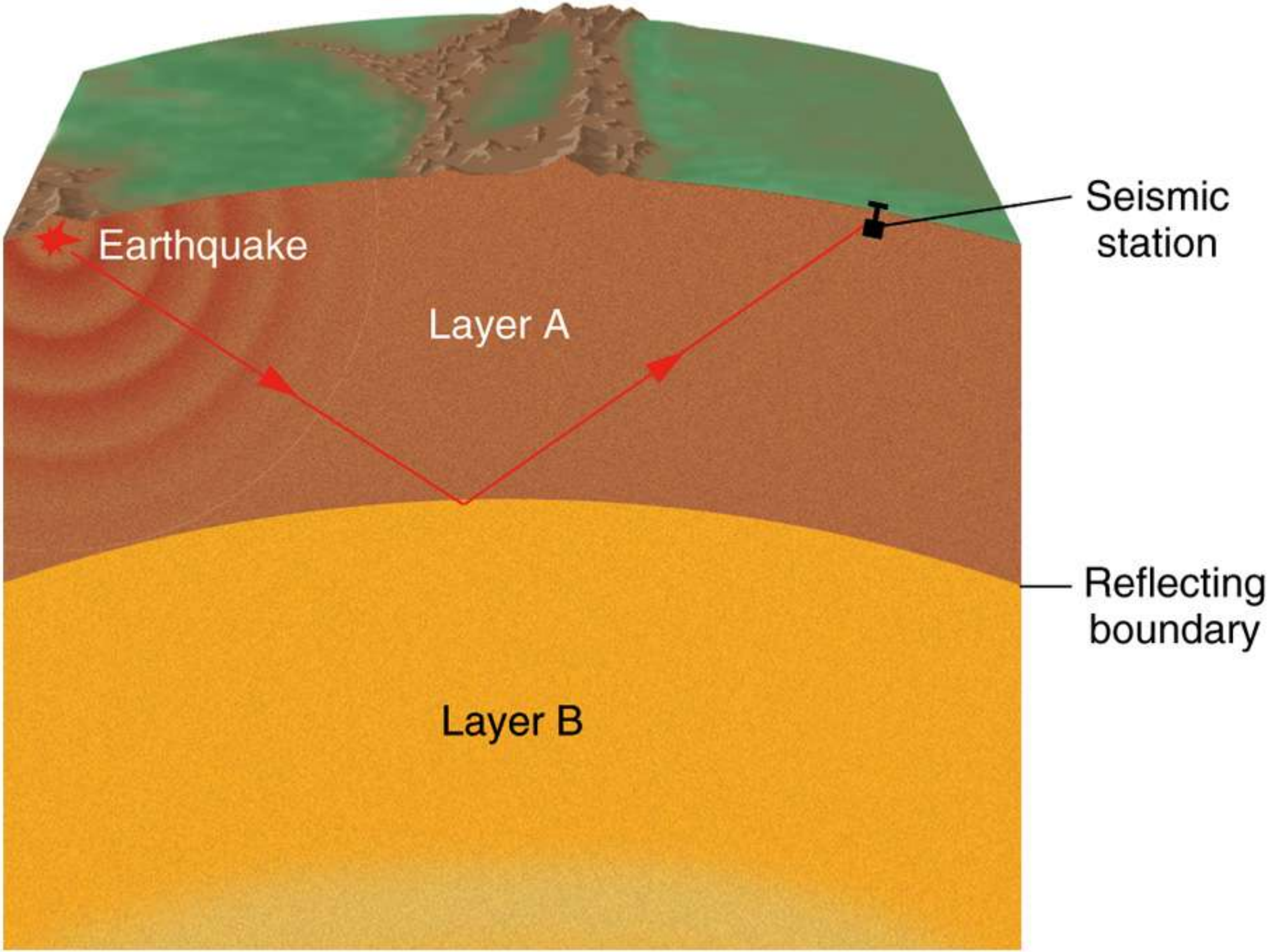


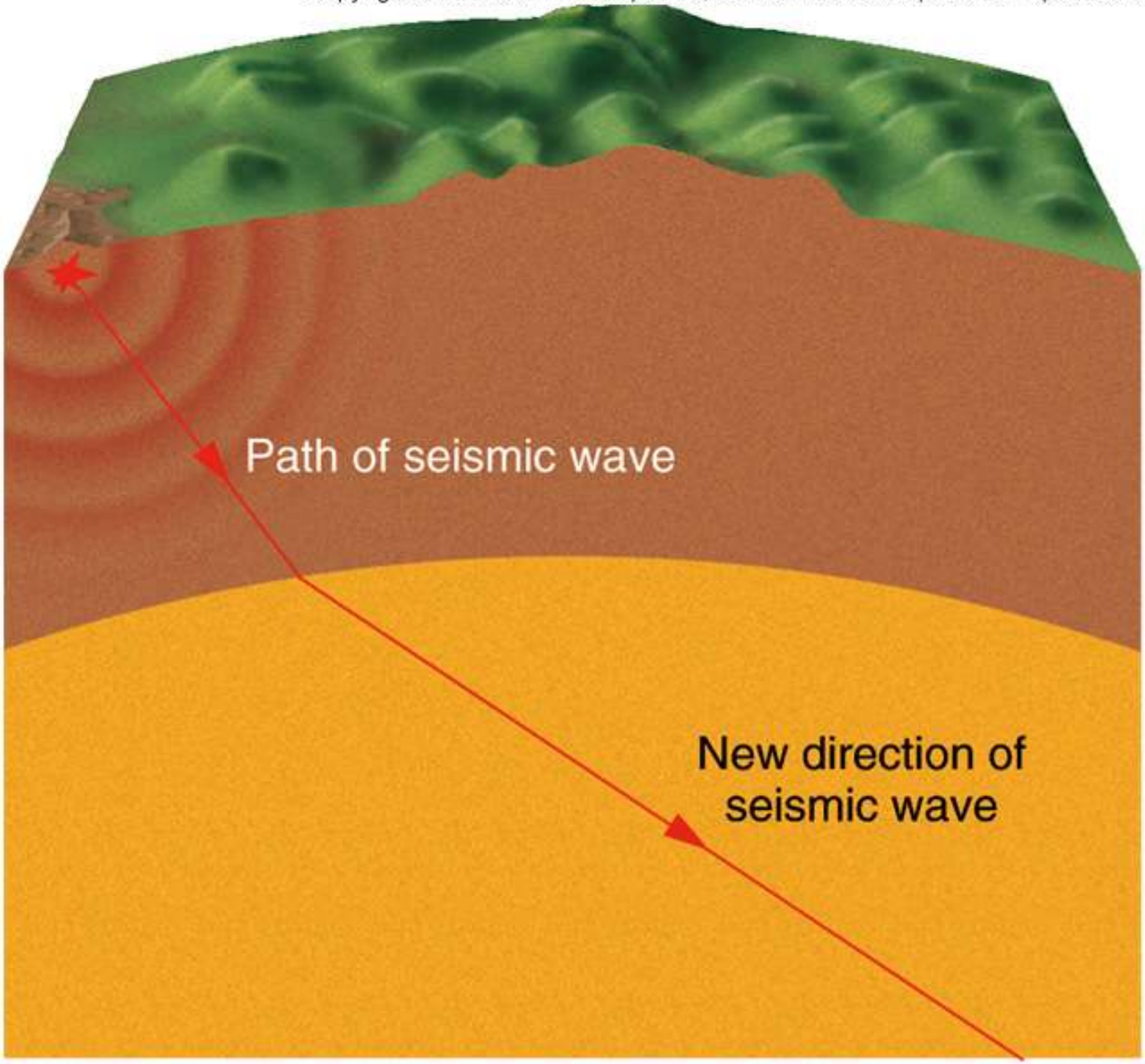
The Crust

- *Seismic wave* studies indicate crust is thinner and denser beneath the oceans than on the continents
- Different seismic wave velocities in oceanic (7 km/sec) vs. continental (~6 km/sec) crustal rocks are indicative of different compositions
- Oceanic crust is *mafic*, composed primarily of basalt and gabbro
- Continental crust is *felsic*, with an average composition similar to granite






Earthquake
Layer A
Seismic station
Reflecting boundary
Layer B


Path of seismic wave
New direction of
seismic wave
Layer in which
seismic waves
travel slowly
(low-velocity layer)
Layer in which
seismic waves
travel rapidly
(high-velocity layer)

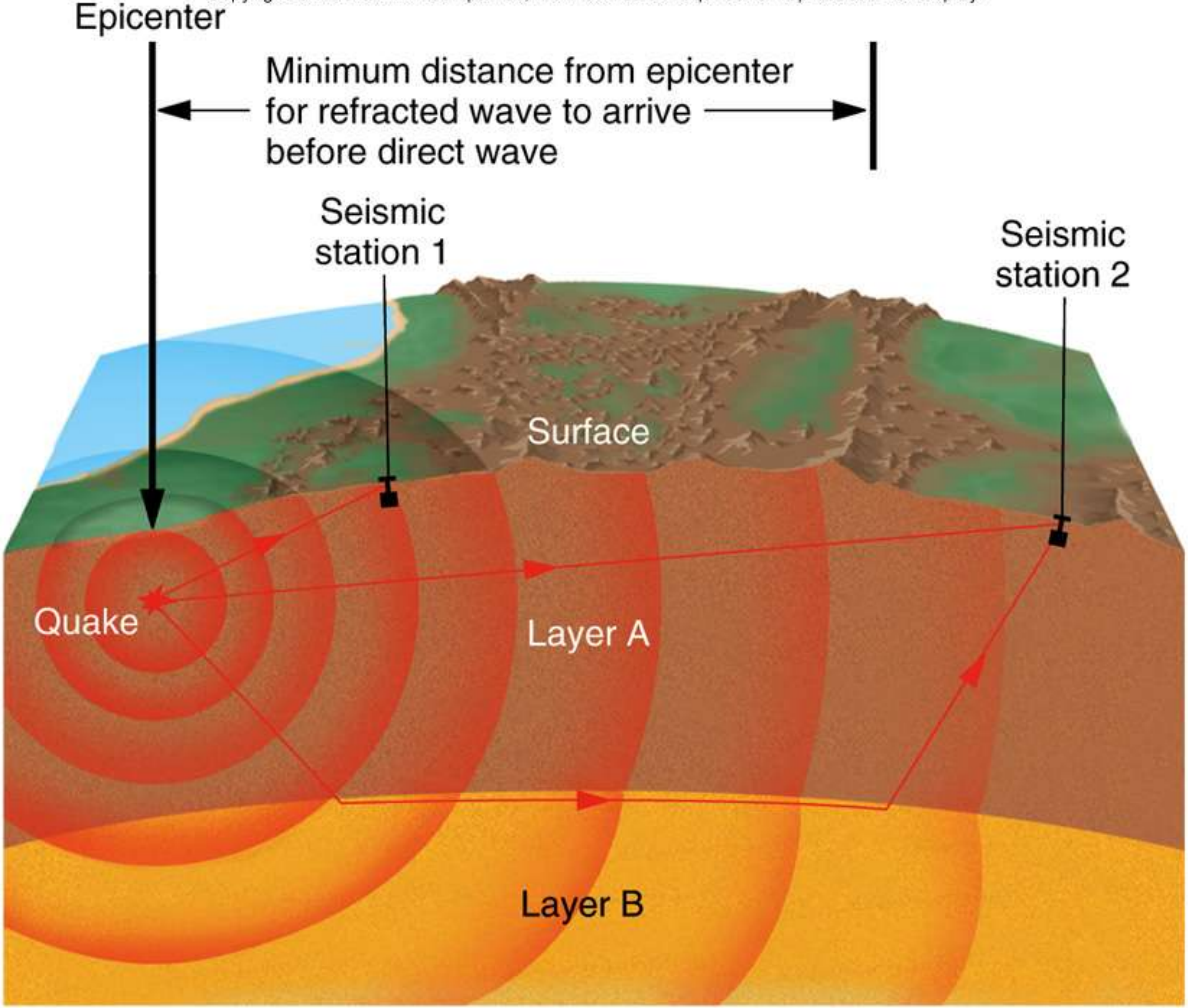
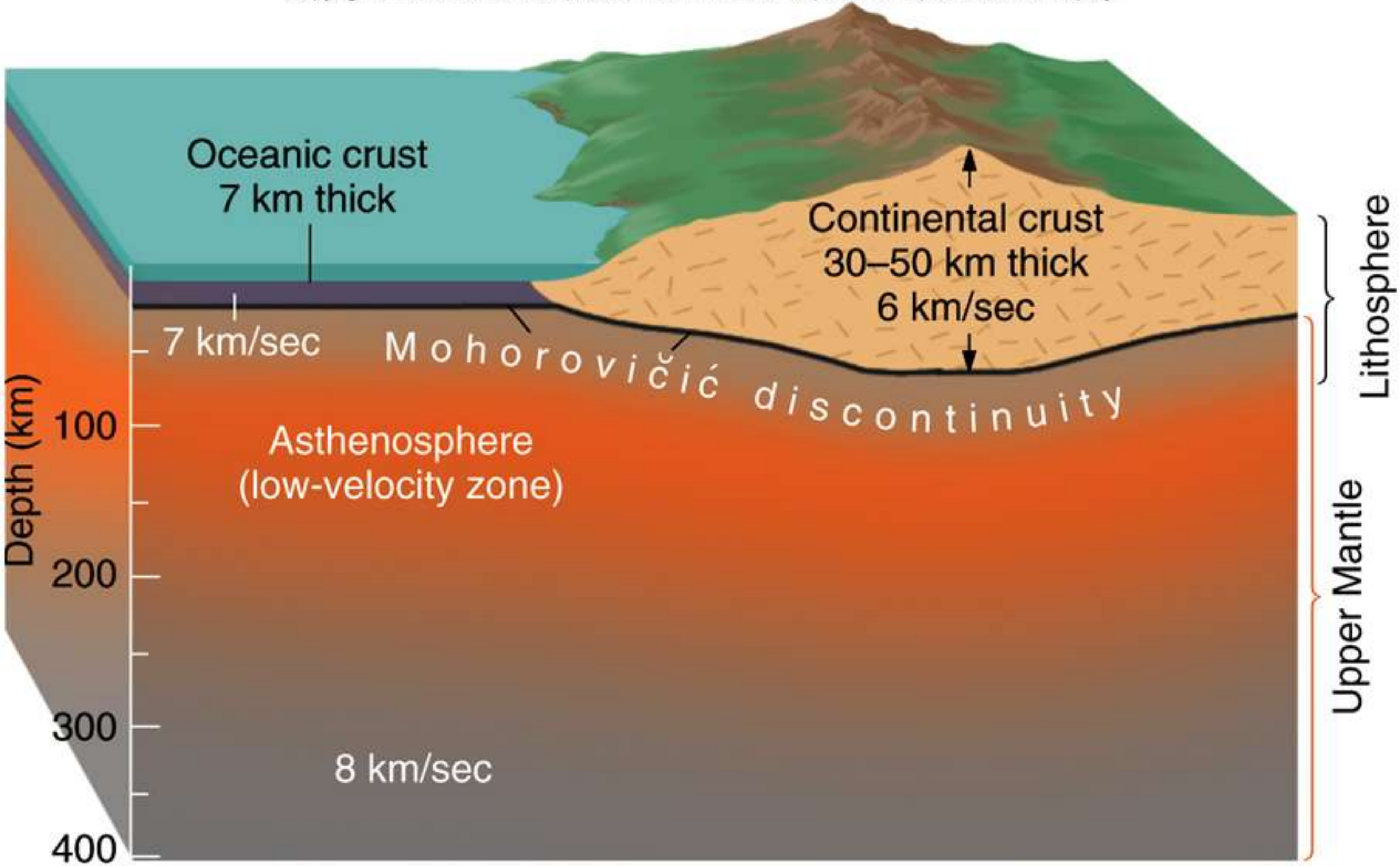
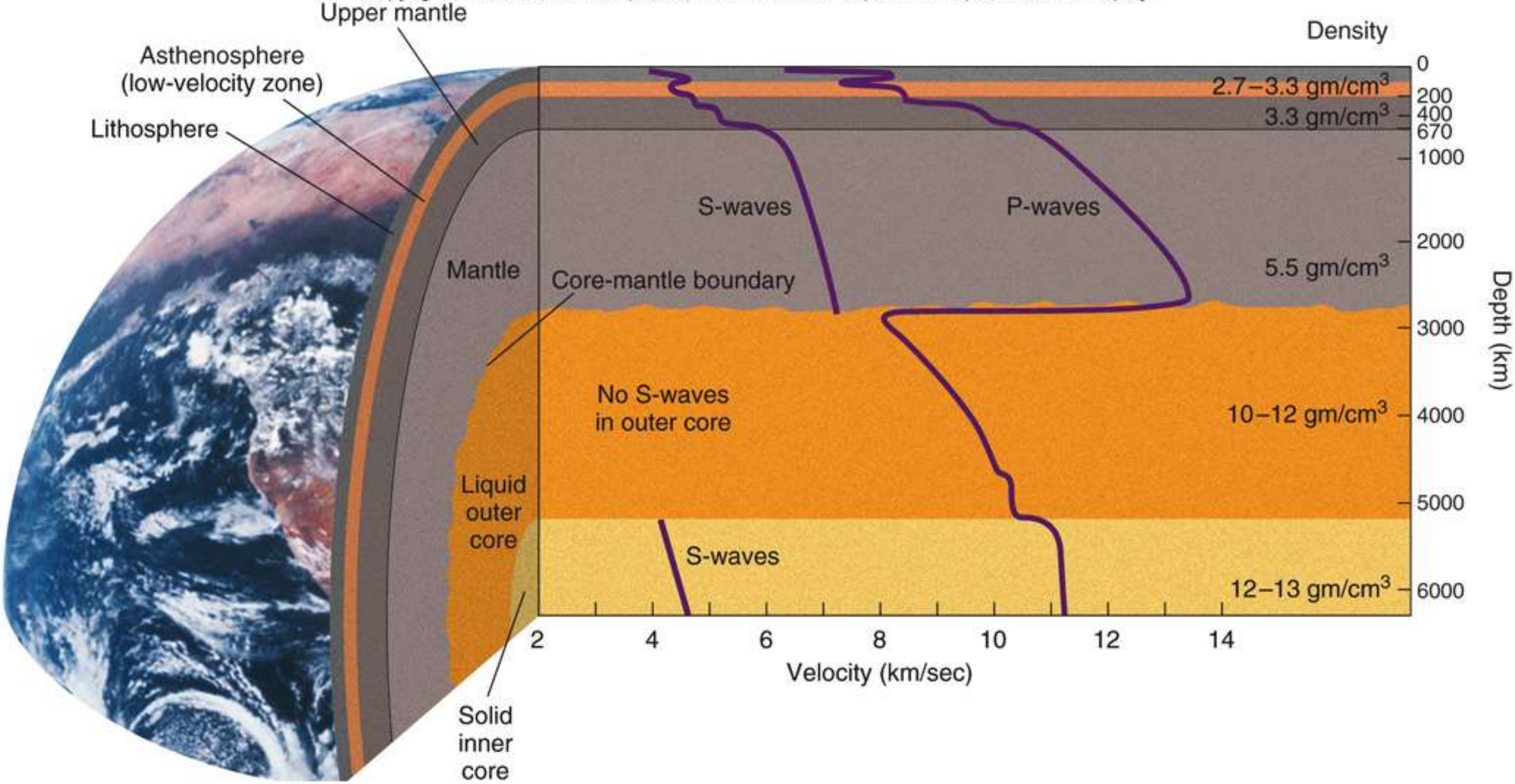

Epicenter
Minimum distance from epicenter for refracted wave to arrive before direct wave
Seismic station 1
Seismic station 2
Surface
Quake
Layer A
Layer B

Table 17.1 Characteristics of Oceanic Crust and Continental Crust

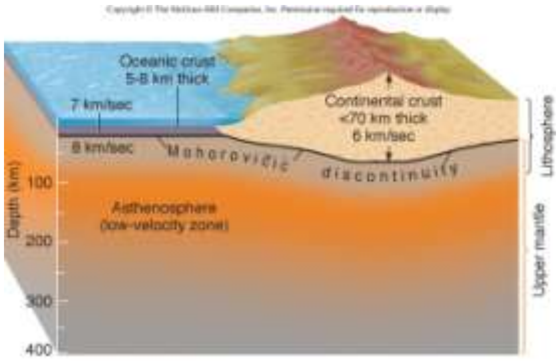
	Oceanic Crust	Continental Crust
Average thickness	7 km	30 to 50 km (thickest under mountains)
Seismic P-wave velocity	7 km/second	6 km/second (higher in lower crust)
Density	3.0 gm/cm^3	2.7 gm/cm^3
Probable composition	Basalt underlain by gabbro	Granite, other plutonic rocks, schist, gneiss (with sedimentary rock cover)

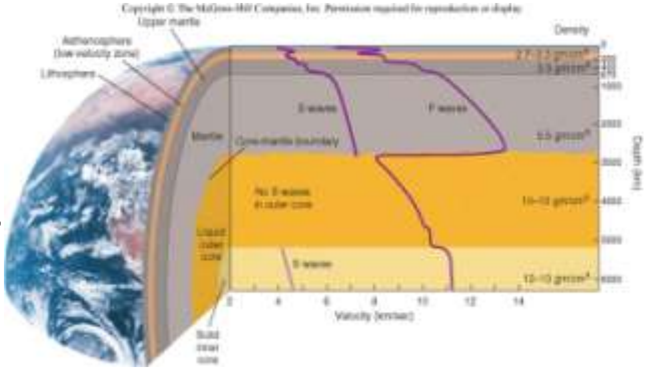

Oceanic crust
7 km thick
7 km/sec
Mohorovičić discontinuity
Continental crust
30–50 km thick
6 km/sec
Asthenosphere
(low-velocity zone)
8 km/sec
Depth (km)
100
200
300
400
Lithosphere
Upper Mantle


Upper mantle
Asthenosphere (low-velocity zone)
Lithosphere
Mantle
Core-mantle boundary
Liquid outer core
Solid inner core
Density
2.7–3.3 gm/cm3
3.3 gm/cm3
5.5 gm/cm3
10–12 gm/cm3
12–13 gm/cm3
S-waves
P-waves
No S-waves in outer core
S-waves
0
200
400
670
1000
2000
3000
4000
5000
6000
Depth (km)
2
4
6
8
10
12
14
Velocity (km/sec)

The Mantle

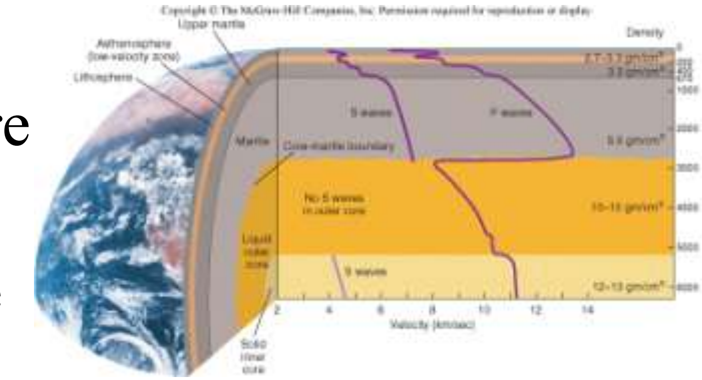
- *Seismic wave* studies indicate the mantle, like the crust, is made of solid rock with only isolated pockets of magma
- Higher seismic wave velocity (8 km/sec) of mantle vs. crustal rocks indicative of denser, *ultramafic* composition
- Crust and upper mantle together form the *lithosphere*, the brittle outer shell of the Earth that makes up the tectonic plates
  - Lithosphere averages 70 km thick beneath oceans and 125-250 km thick beneath continents
- Beneath the lithosphere, seismic wave speeds abruptly decrease in a plastic *low-velocity zone* called the *asthenosphere*

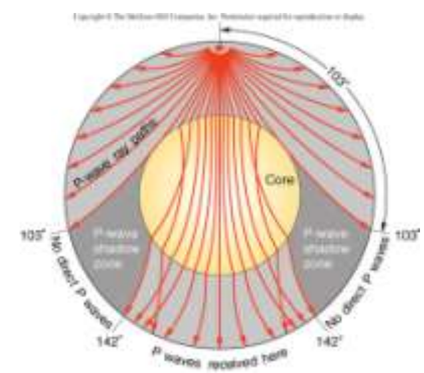


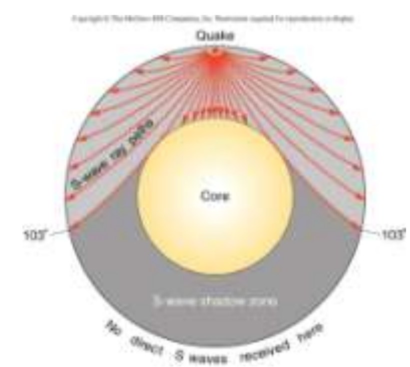


The Core

- *Seismic wave* studies have provided primary evidence for existence and nature of Earth's core
- Specific areas on the opposite side of the Earth from large earthquakes do not receive seismic waves, resulting in *seismic shadow zones*
- *P-wave shadow zone* (103°-142° from epicenter) explained by refraction of waves encountering core-mantle boundary
- *S-wave shadow zone* (≥ 103° from epicenter) suggests outer core is a liquid
- Careful observations of *P-wave* refraction patterns indicate inner core is solid

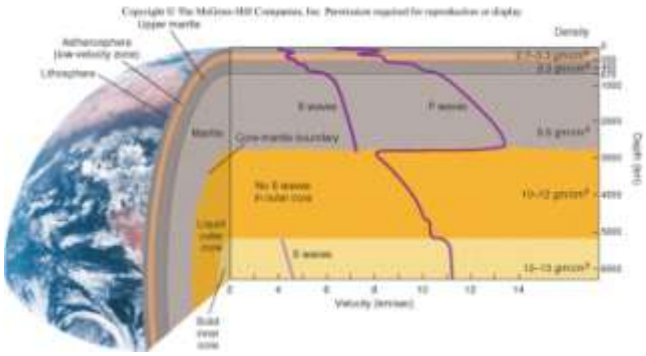


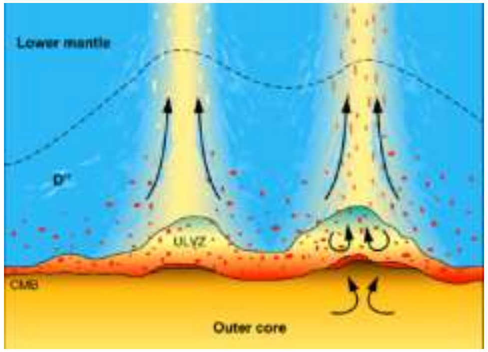


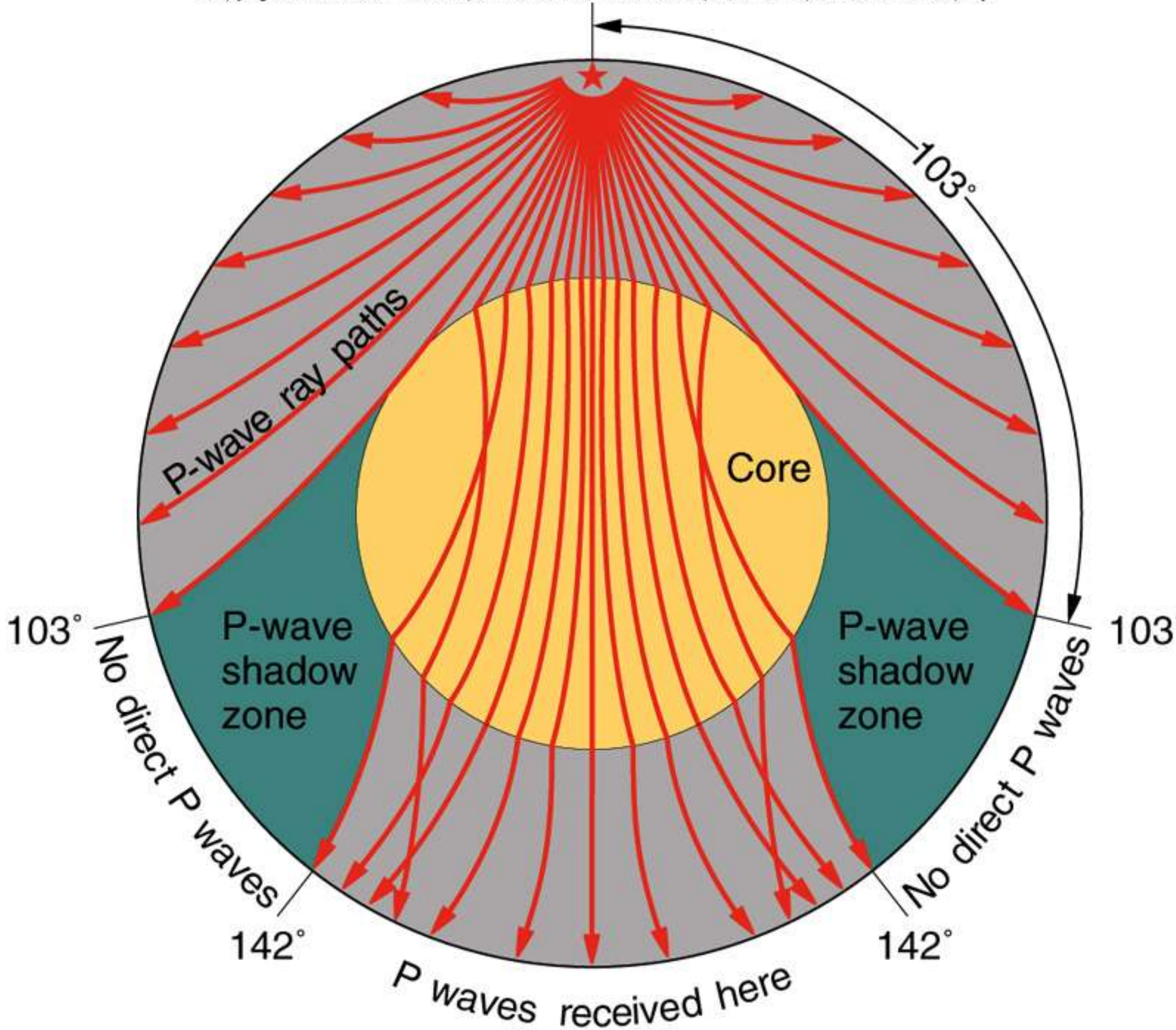


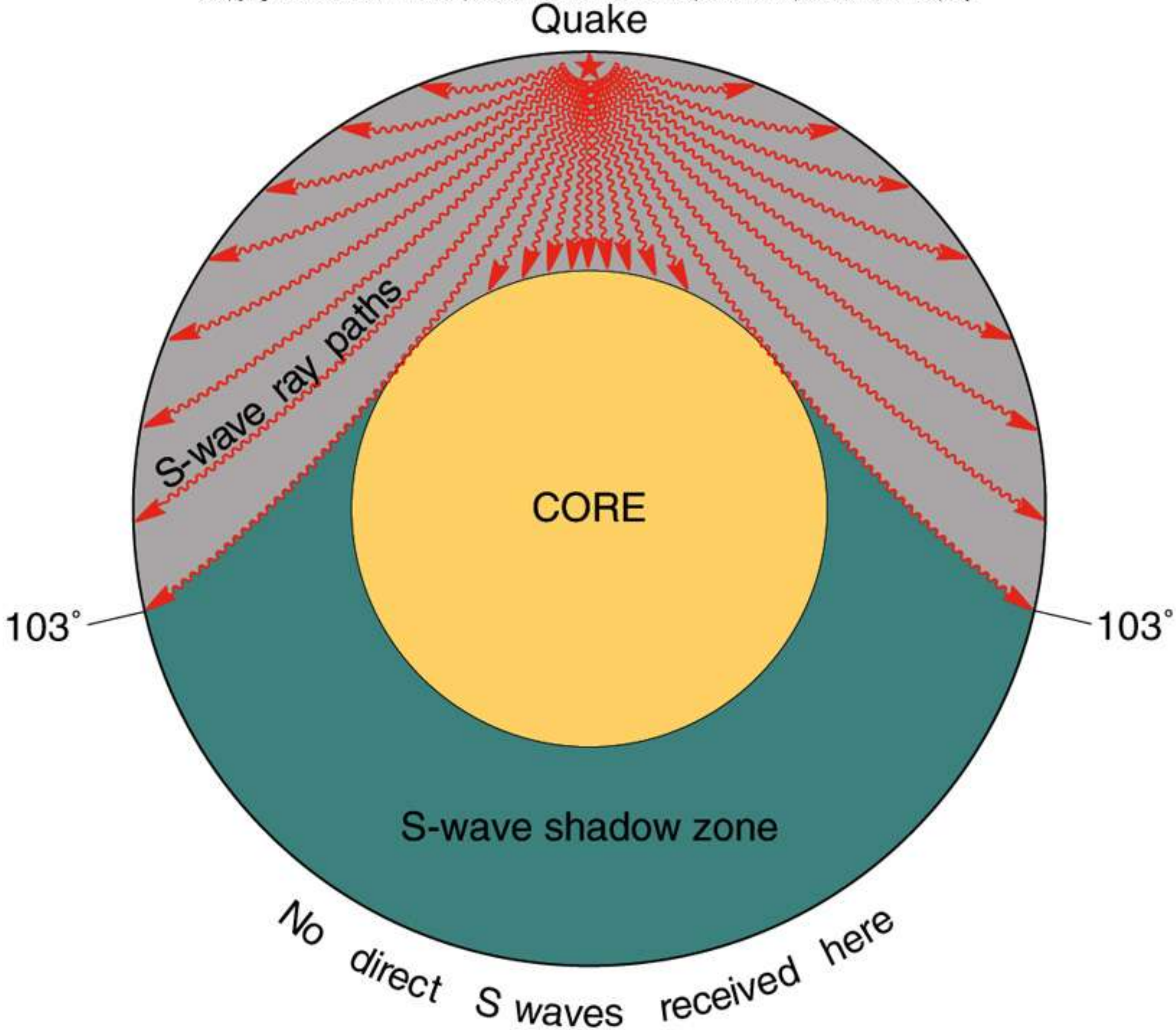
The Core

- Core composition inferred from its calculated density, physical and electro-magnetic properties, and composition of *meteorites*
  - *Iron metal* (liquid in outer core and solid in inner core) best fits observed properties
  - Iron is the only metal common in meteorites
- *Core-mantle boundary* (D” layer) is marked by great changes in seismic velocity, density and temperature
  - Hot core may melt lowermost mantle or react chemically to form iron silicates in this seismic wave *ultralow-velocity zone (ULVZ)*



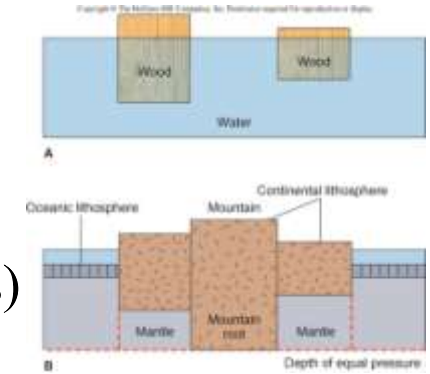


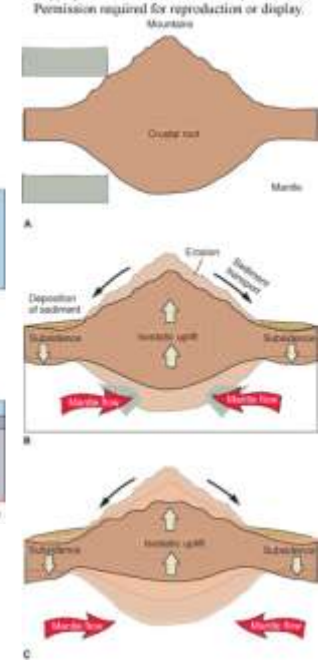

103°
P-wave ray paths
Core
103°
P-wave shadow zone
P-wave shadow zone
103°
No direct P waves
No direct P waves
142°
142°
P waves received here

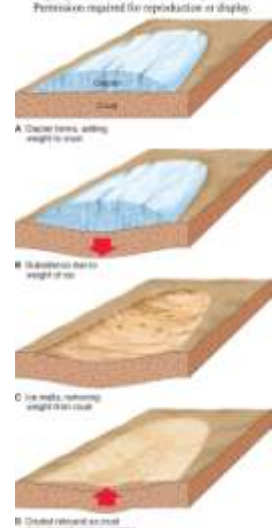

Quake
S-wave ray paths
CORE
103°
103°
S-wave shadow zone
No direct S waves received here

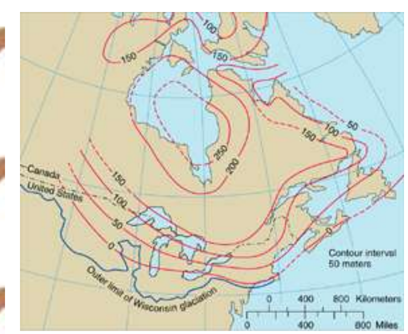
Isostasy

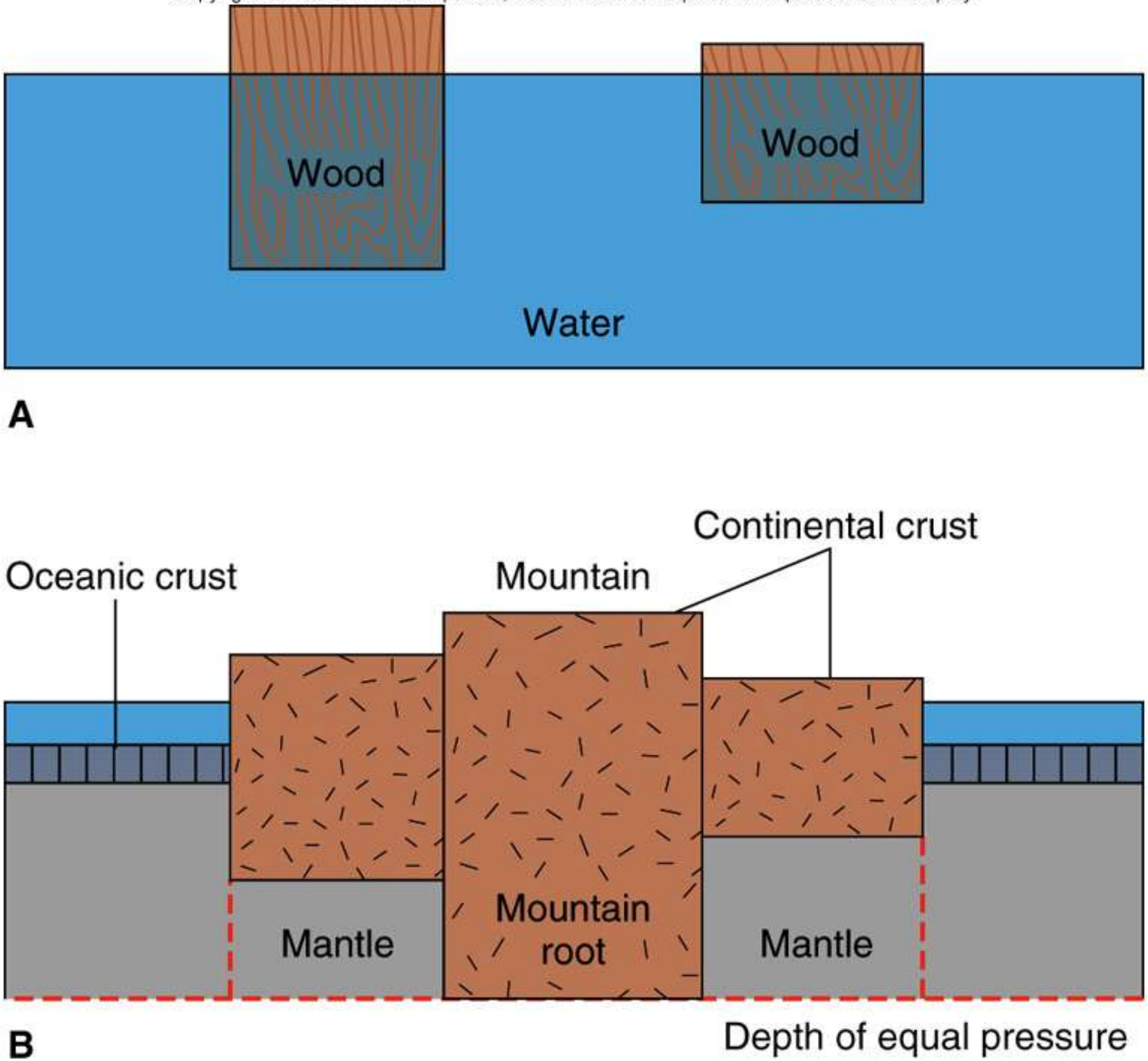
- *Isostasy* - equilibrium of adjacent blocks of brittle crust "floating" on upper mantle
  - Thicker blocks of lower density crust have deeper *"roots"* and float higher (as mountains)
- *Isostatic adjustment* - rising or sinking of crustal blocks to achieve isostatic balance
  - Crust will rise when large mass is rapidly removed from the surface, as at end of ice ages
  - Rise of crust after ice sheet removal is called *crustal rebound*
    - Rebound still occurring in northern Canada and northern Europe





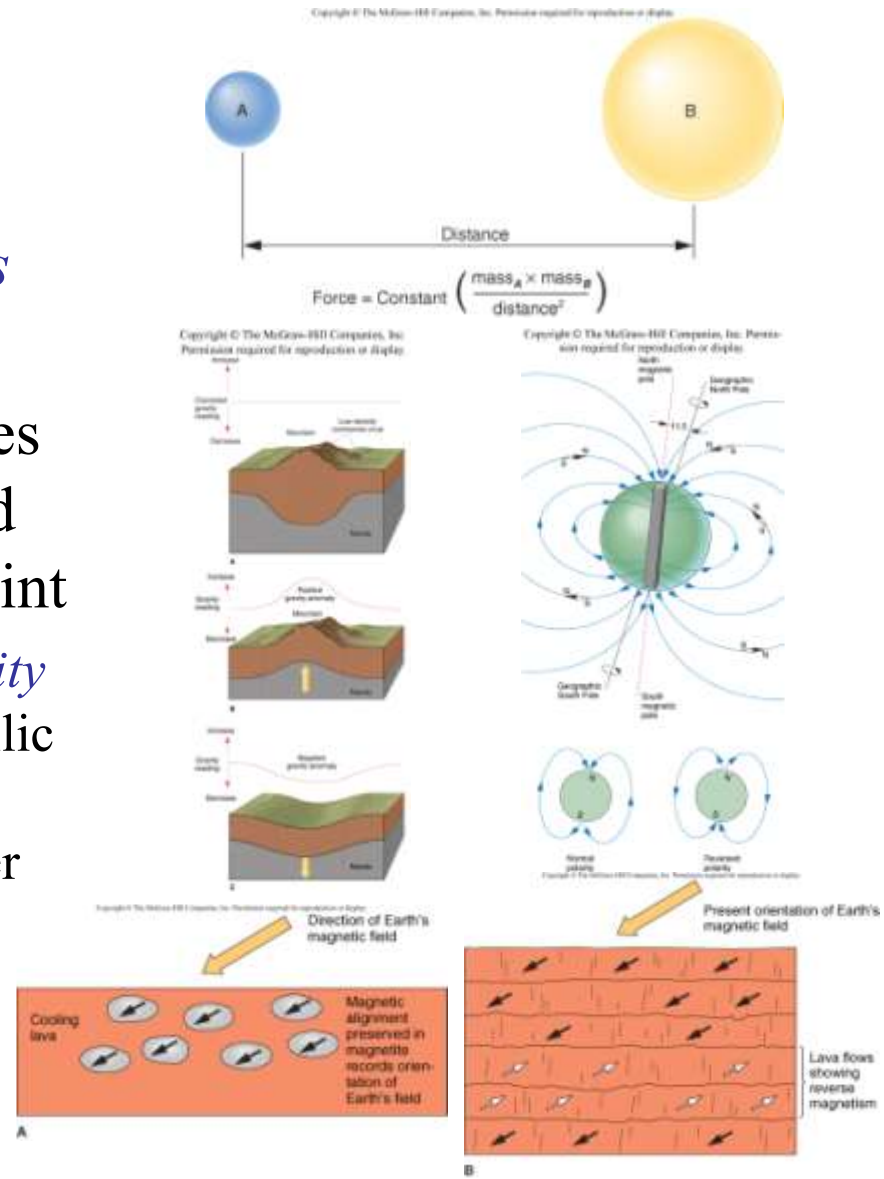


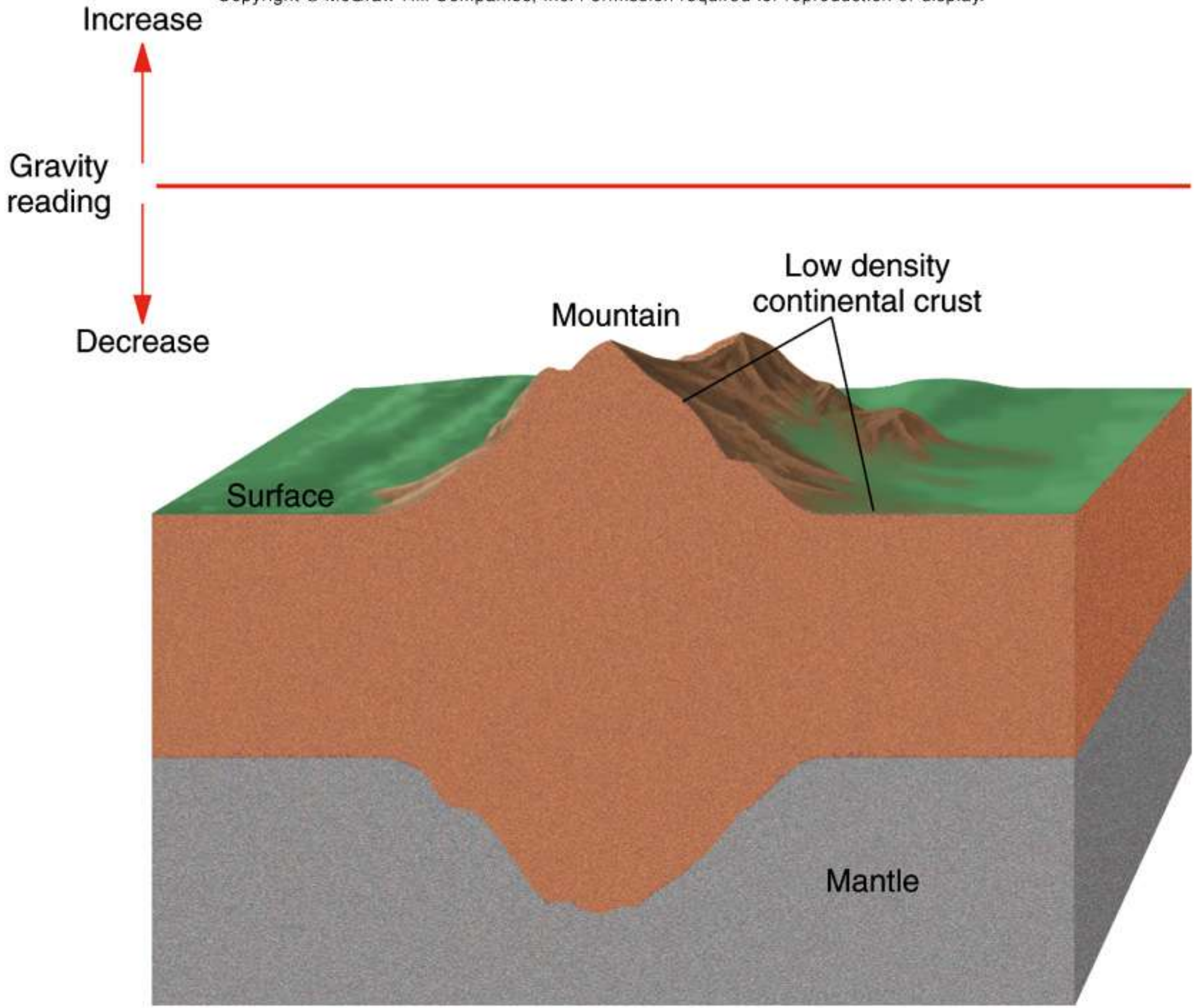


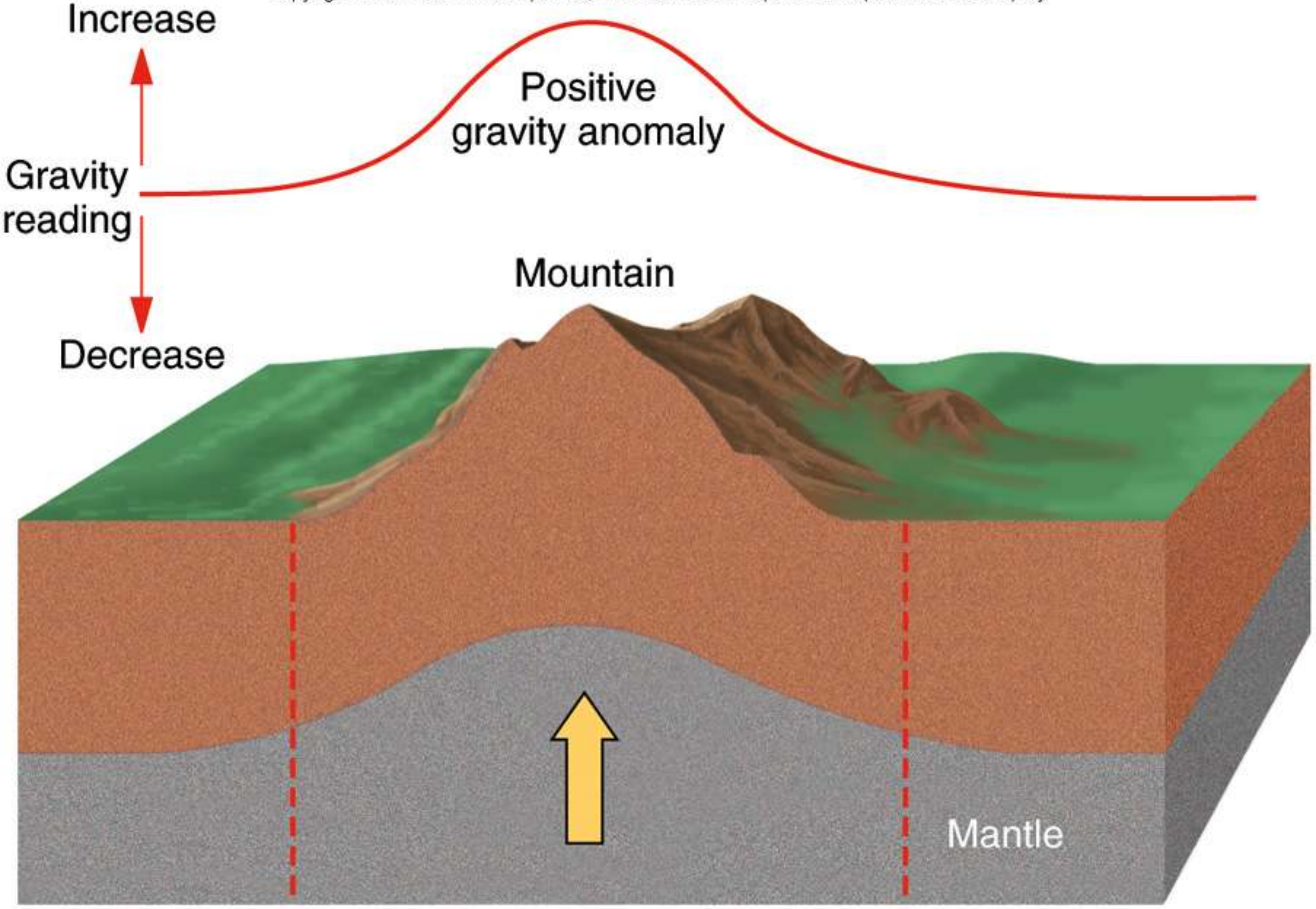

Wood
Wood
Water
A
Continental crust
Oceanic crust
Mountain
Mantle
Mountain root
Mantle
Depth of equal pressure
B

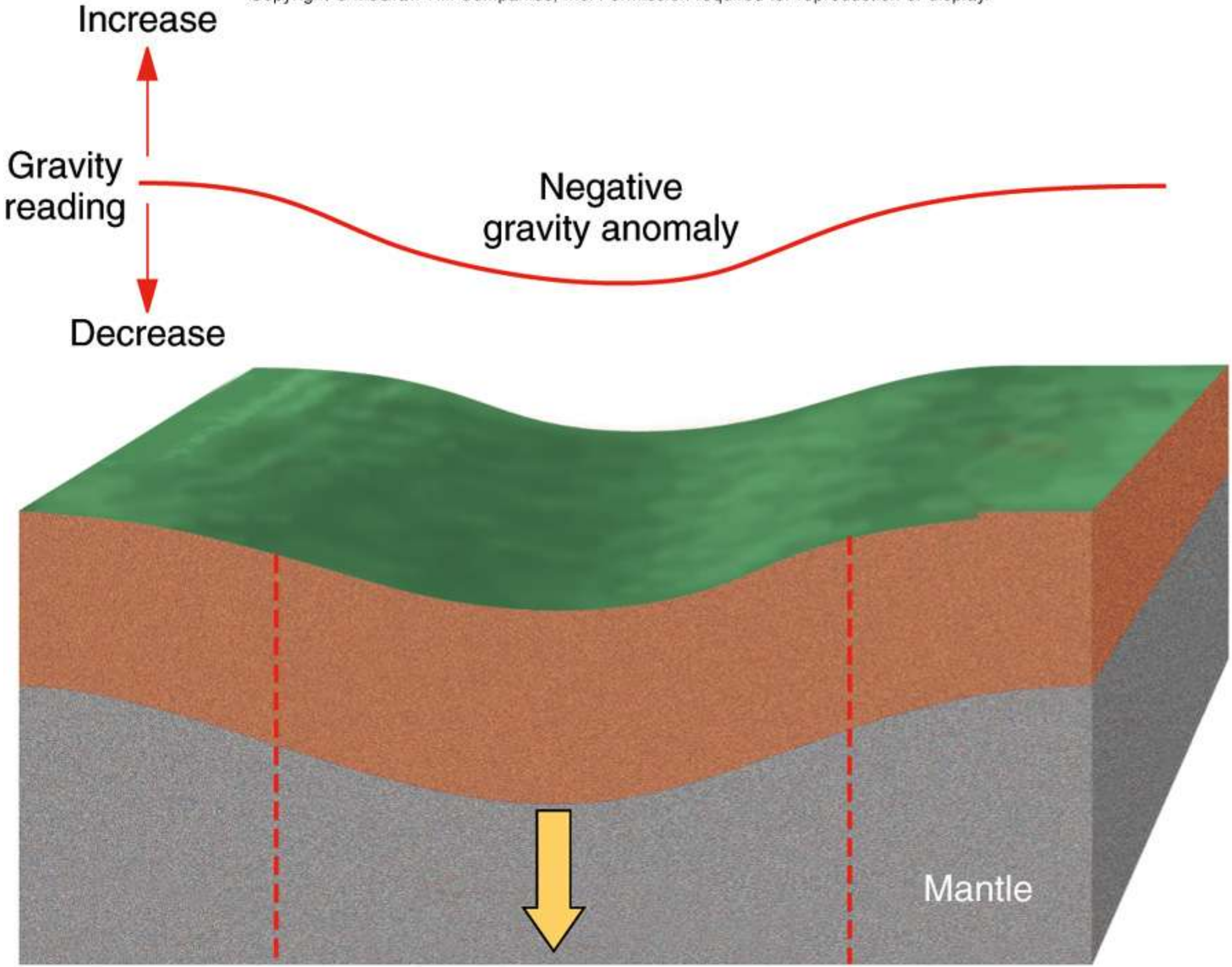
Gravity Measurements

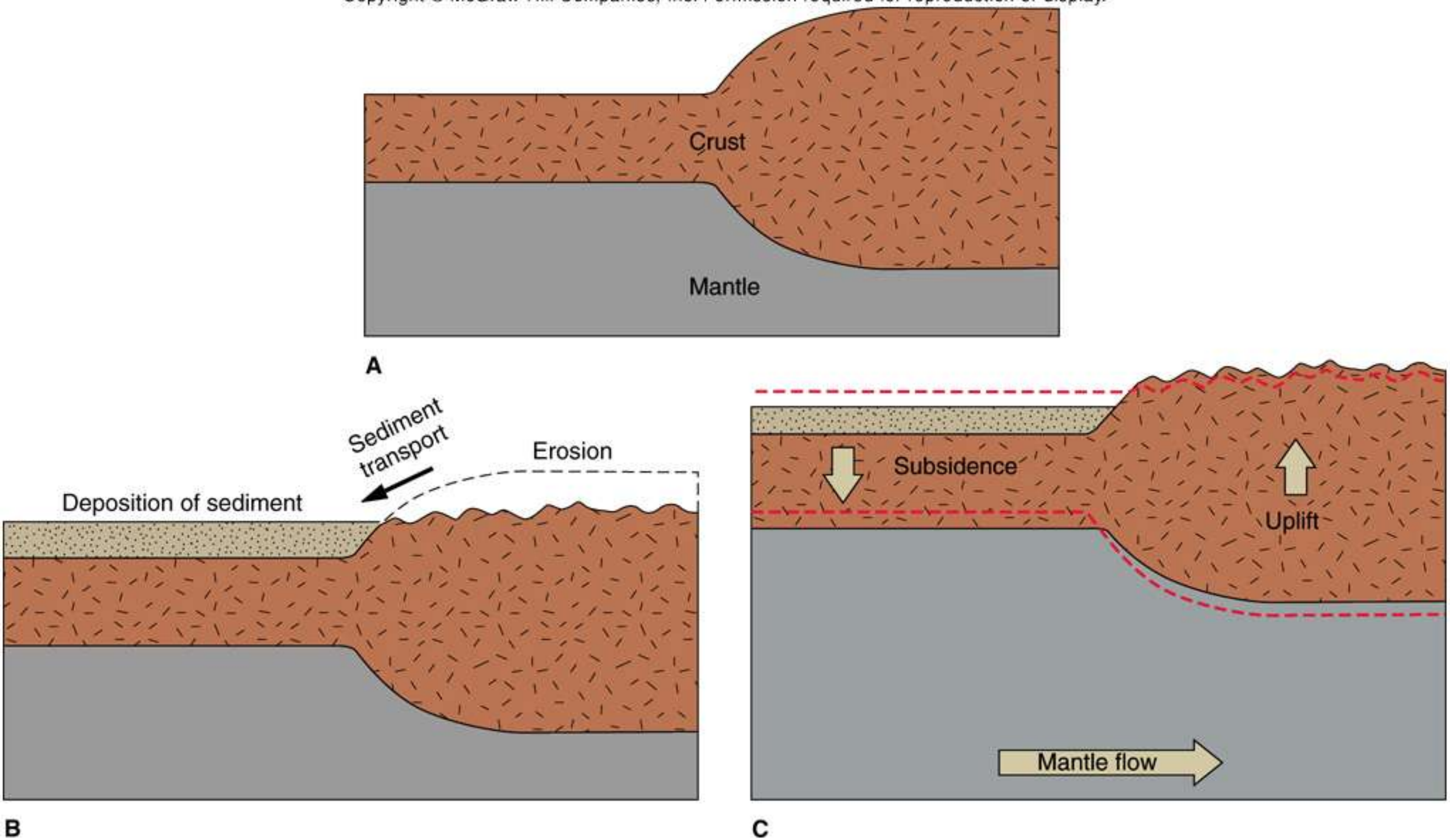
- *Gravitational force* between two objects determined by their *masses* and the *distance* between them
- *Gravity meters* - detect tiny changes in gravity at Earth's surface related to total mass beneath any given point
  - Gravity slightly higher (*positive gravity anomaly*) over dense materials (metallic ore bodies, mafic rocks) and slightly lower (*negative gravity anomaly*) over less dense materials (caves, water, magma, sediments, felsic rocks)

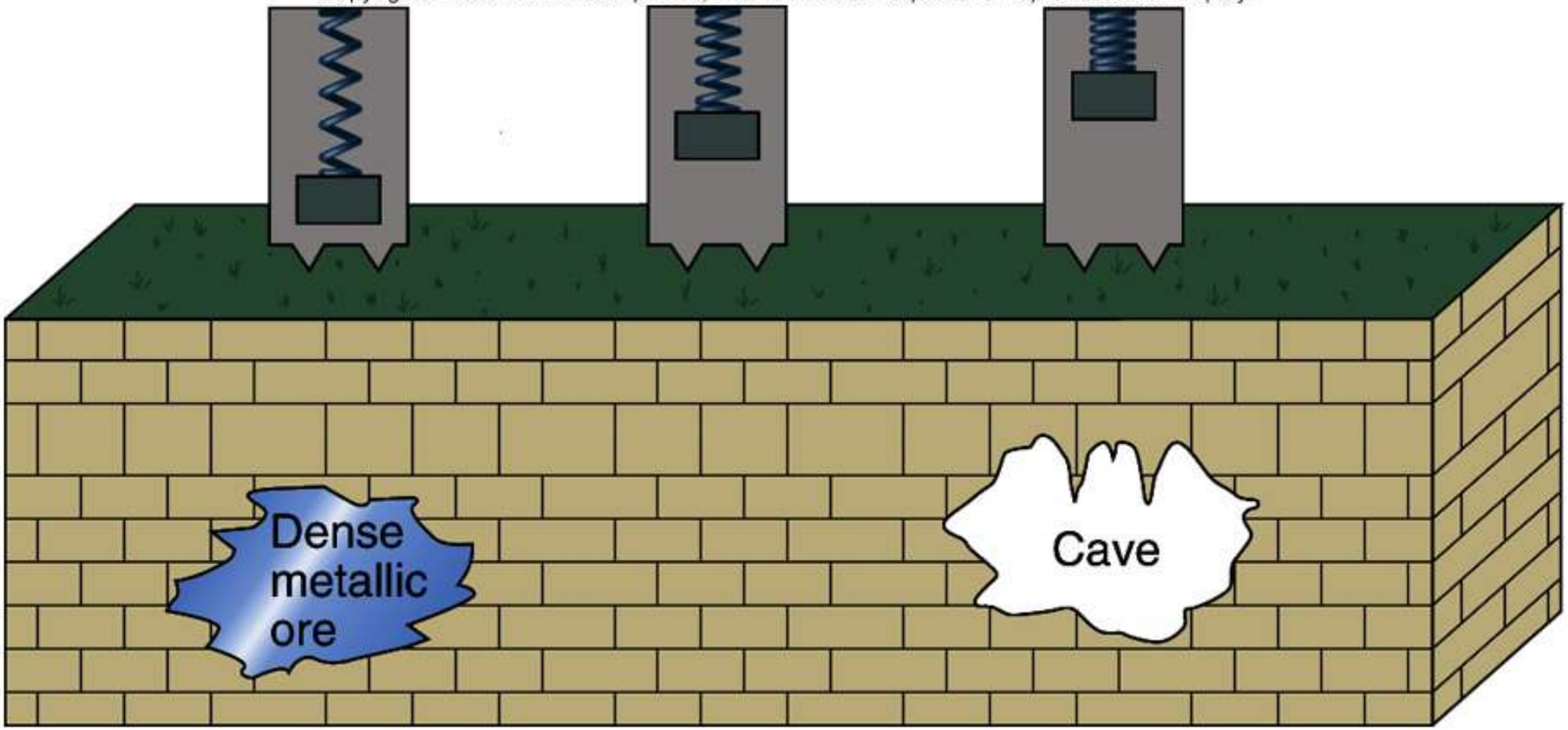


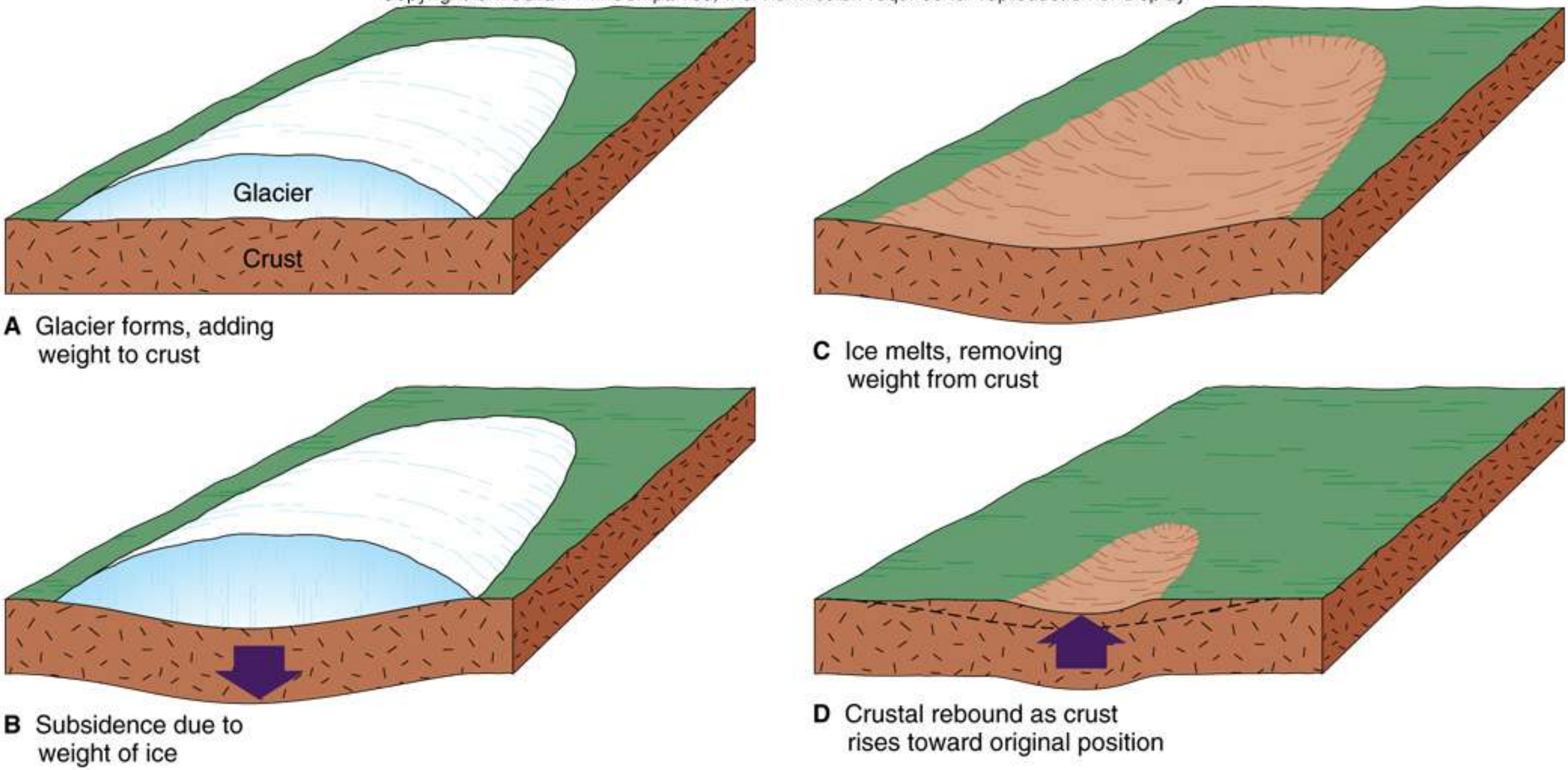

Increase
Gravity
reading
Decrease
Low density
continental crust
Mountain
Surface
Mantle

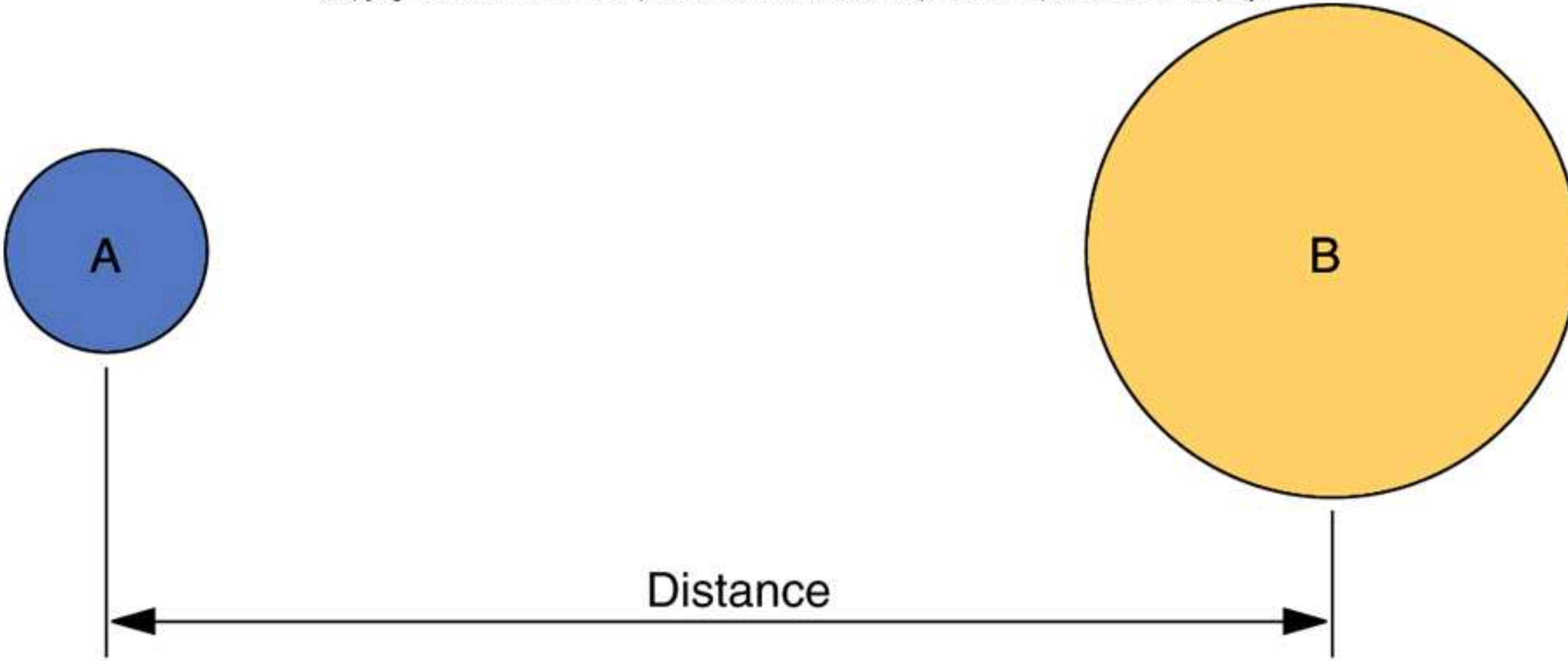

Increase
Gravity reading
Decrease
Positive gravity anomaly
Mountain
Mantle


Increase
Gravity
reading
Decrease
Negative
gravity anomaly
Mantle

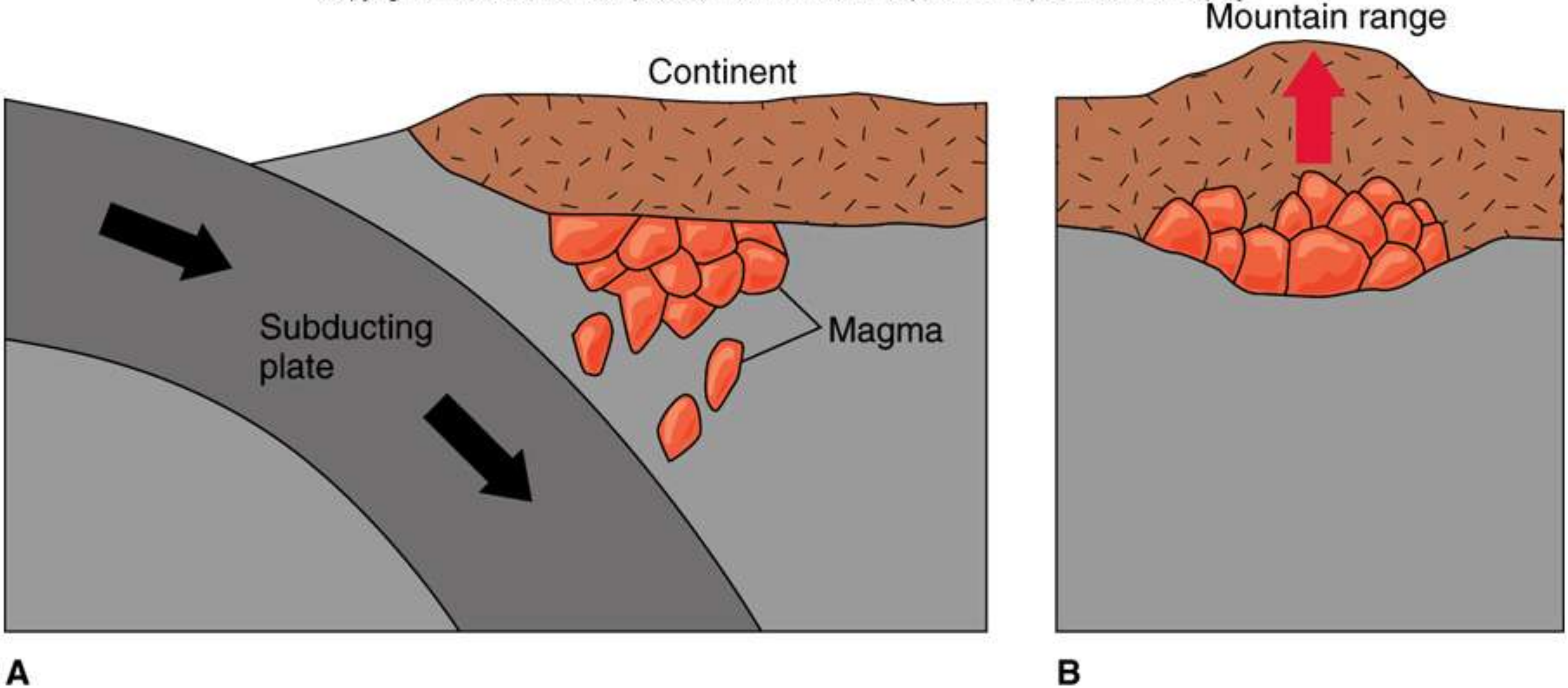

Crust
Mantle
A
Sediment transport
Erosion
Deposition of sediment
B
Subsidence
Uplift
Mantle flow
C


Dense
metallic
ore
Cave


Glacier
Crust
A Glacier forms, adding weight to crust
B Subsidence due to weight of ice
C Ice melts, removing weight from crust
D Crustal rebound as crust rises toward original position



$$\text{Force} = \text{Constant}\left(\frac{\text{mass}_A \times \text{mass}_B}{\text{distance}^2}\right)$$


Mountain range
Continent
Subducting
plate
Magma
A
B

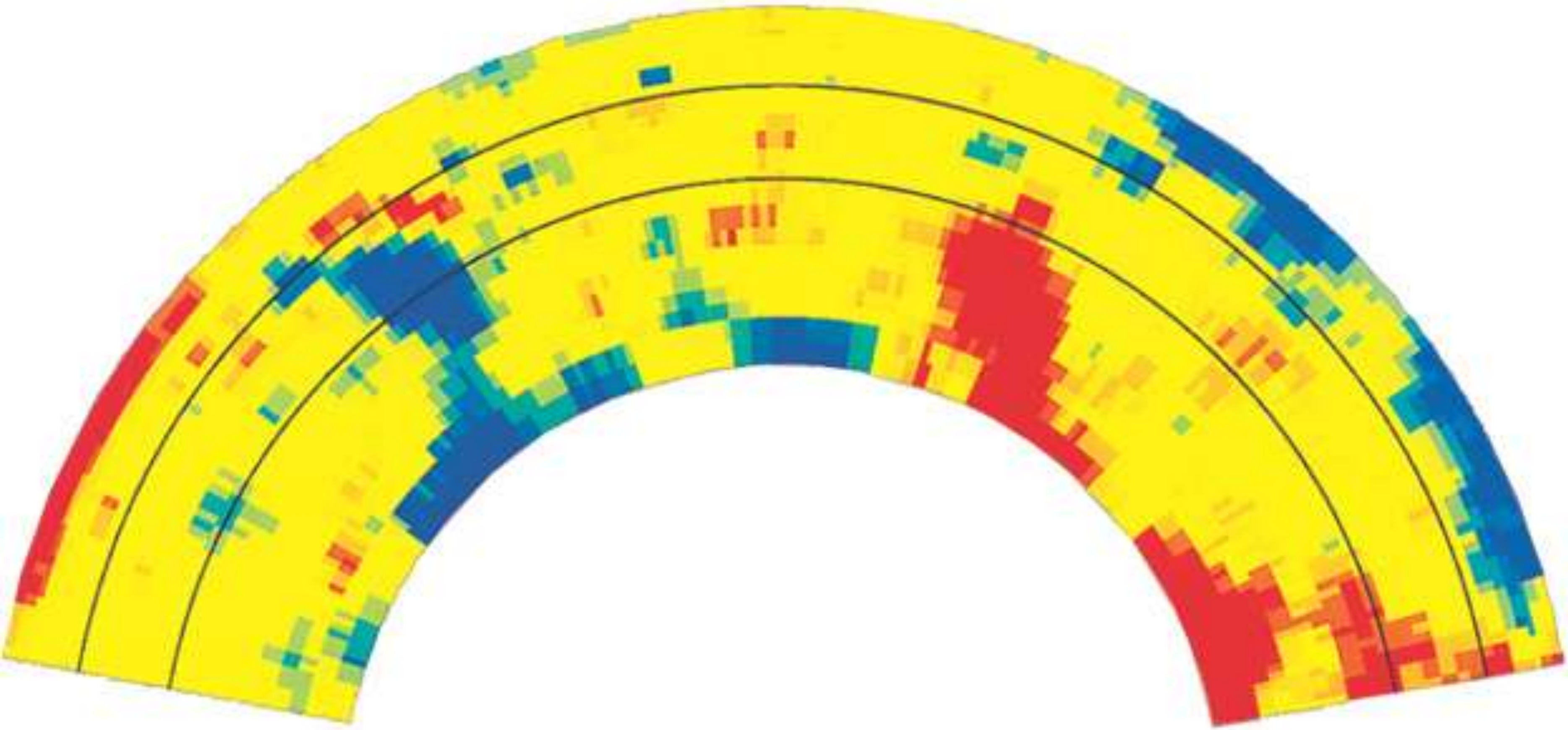
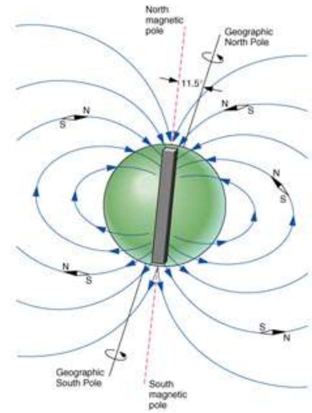
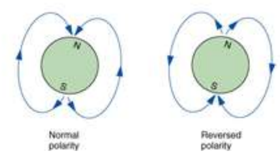


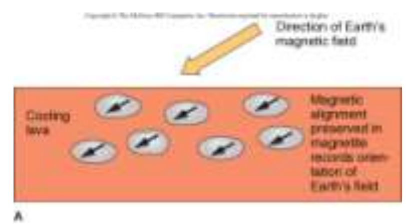
Photo courtesy of Stephen Grand, University of Texas at Austin

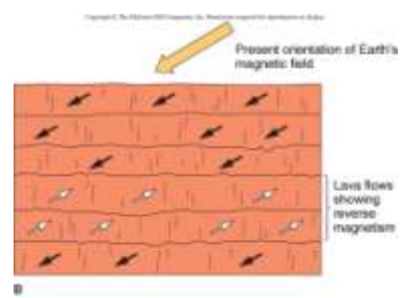
Earth's Magnetic Field

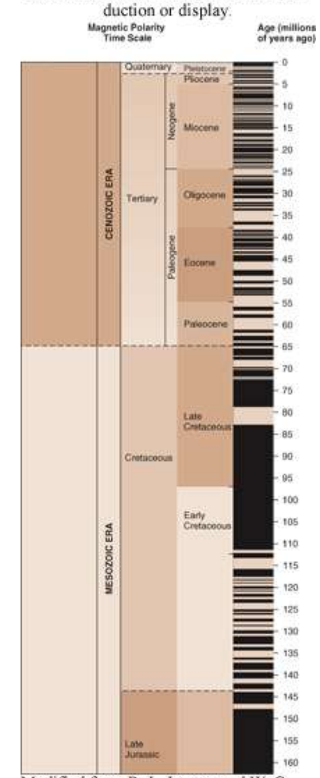
- A *magnetic field* (region of magnetic force) surrounds the Earth
  - Field has north and south *magnetic poles*
  - Earth's magnetic field is what a compass detects
  - Recorded by magnetic minerals (e.g., magnetite) in igneous rocks as they cool below their *Curie Point*
- *Magnetic reversals* - times when the poles of Earth's magnetic field switch
  - Recorded in magnetic minerals
  - Occurred many times; timing appears chaotic
  - After next reversal, a compass needle will point toward the south magnetic pole
- *Paleomagnetism* - the study of ancient magnetic fields in rocks
  - allows reconstruction of plate motions over time



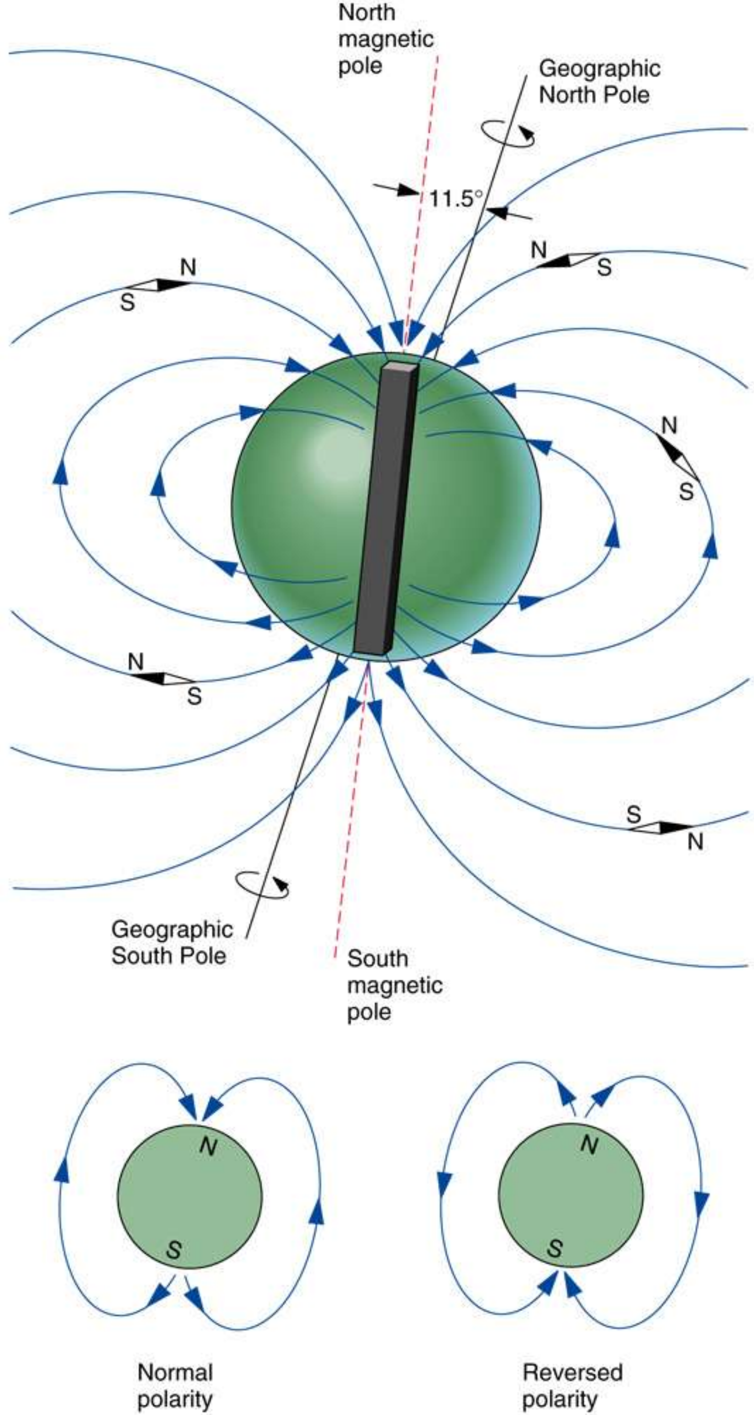


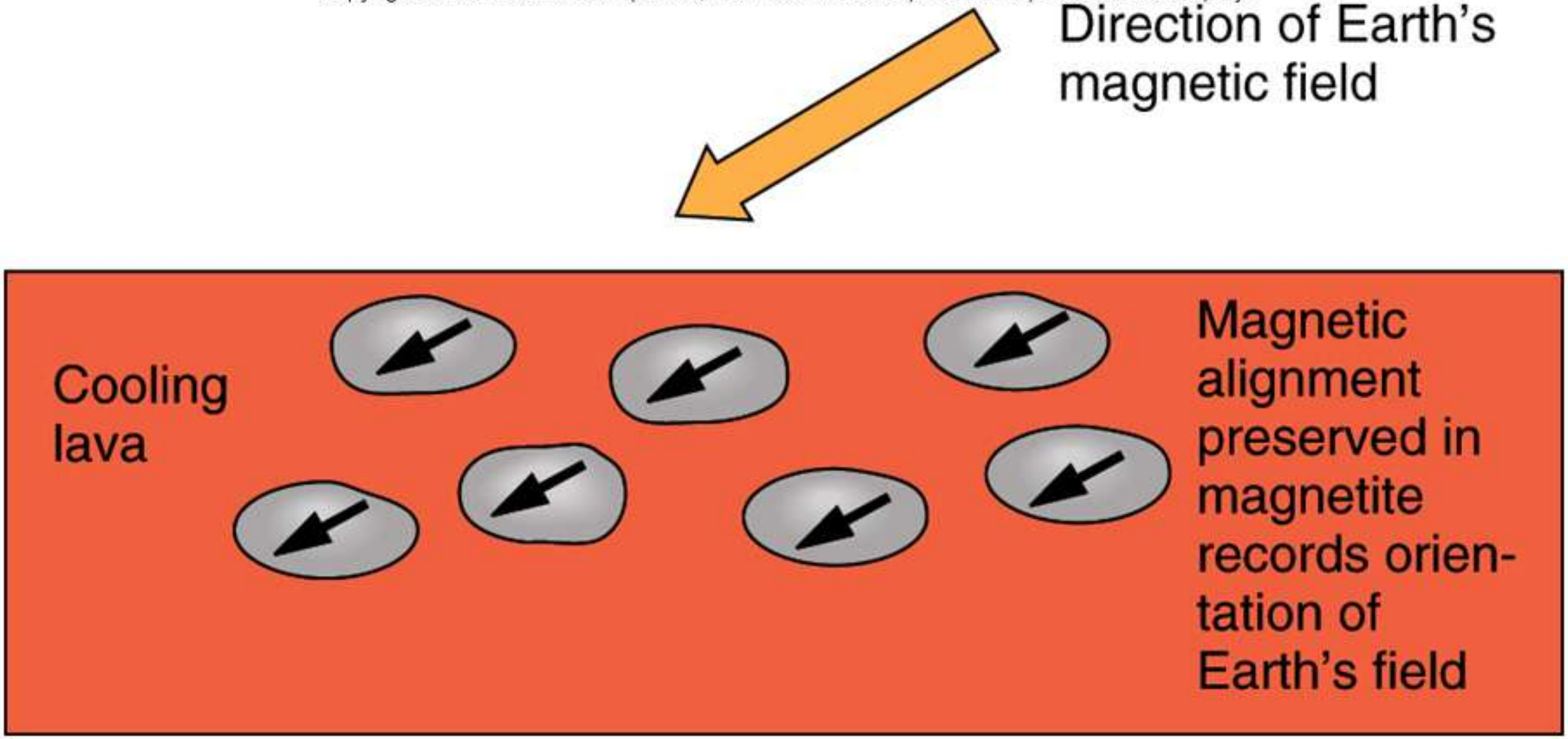


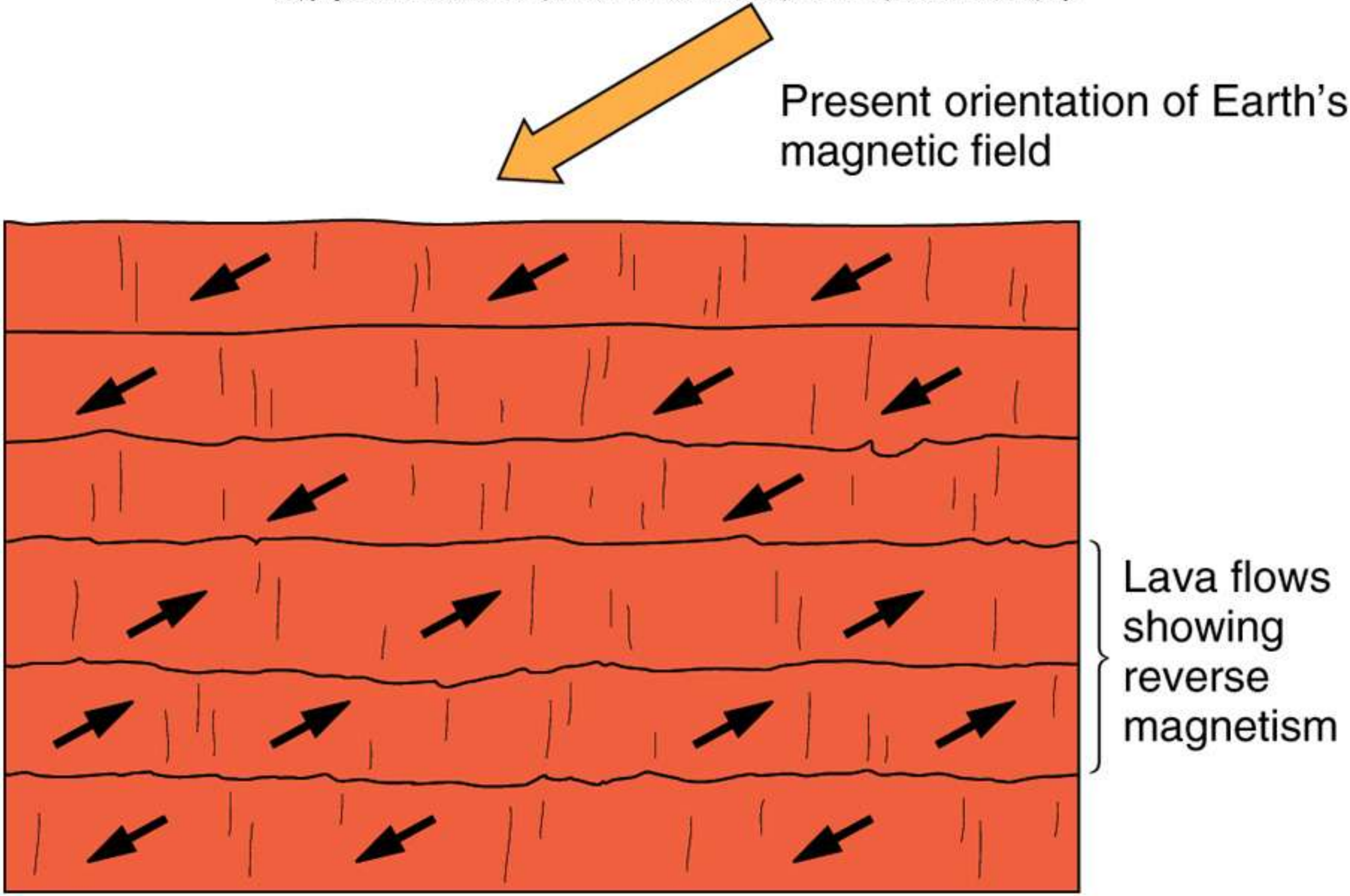


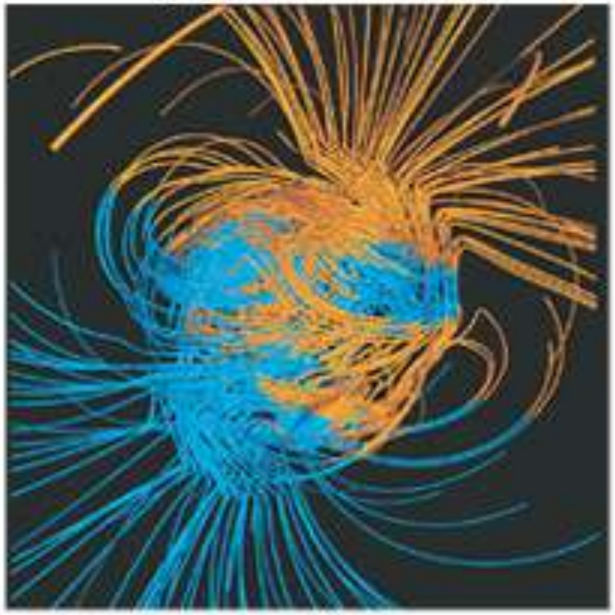


Modified from R. L. Larson and W. C.

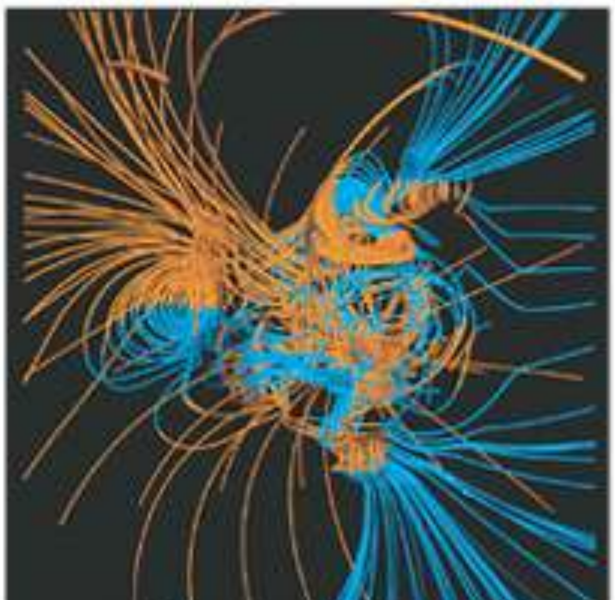

North magnetic pole
Geographic North Pole
11.5°
N
S
N
S
N
S
N
S
S
N
Geographic South Pole
South magnetic pole
N
S
N
S
Normal polarity
Reversed polarity


Direction of Earth's magnetic field
Cooling lava
Magnetic alignment preserved in magnetite records orien-tation of Earth's field

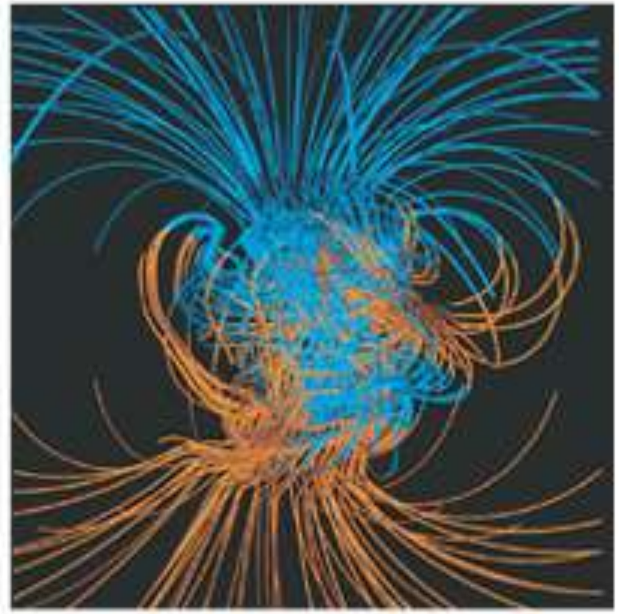

Present orientation of Earth's magnetic field
Lava flows showing reverse magnetism



A

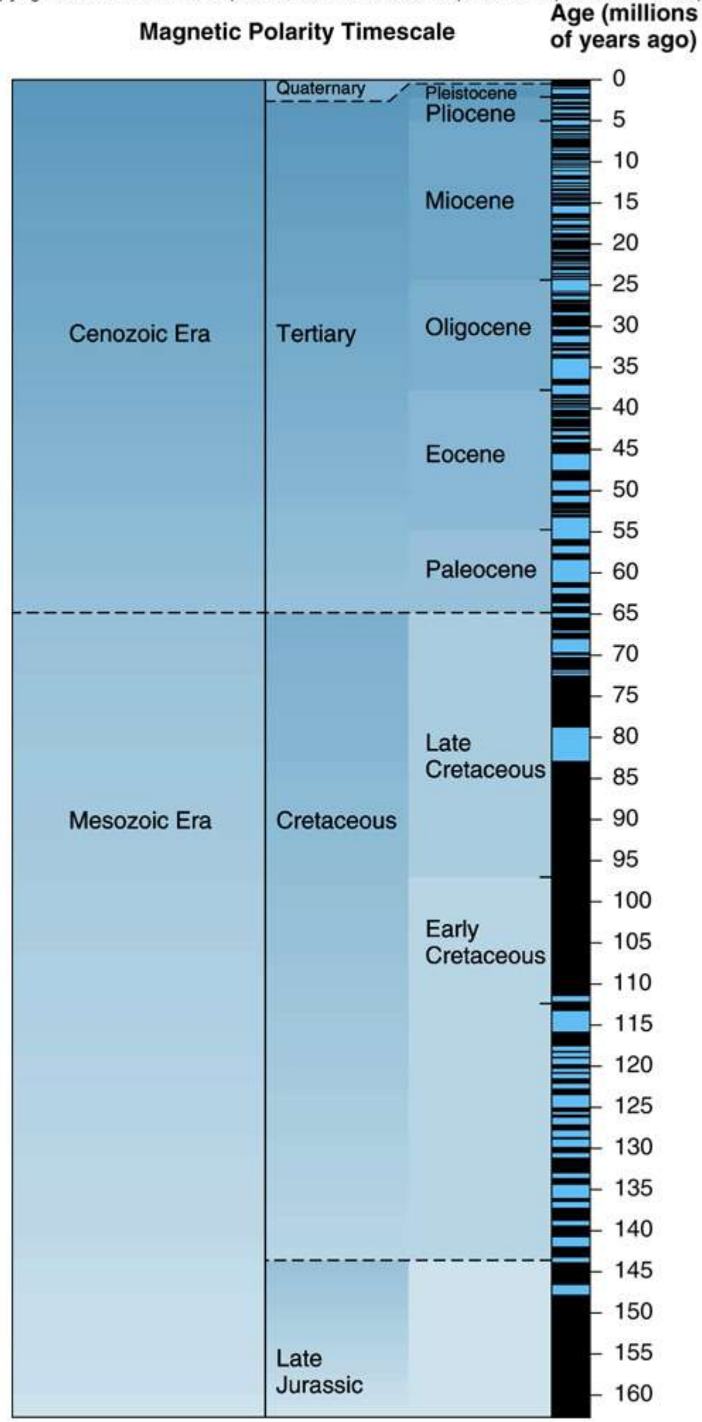


B



C

Photos from the Geodynamo Computer Simulation, courtesy of G. A. Glatzmaier, Los Alamos National Laboratory, and P. H. Roberts, University of California, Los Angeles


Magnetic Polarity Timescale
Age (millions of years ago)
Cenozoic Era
Mesozoic Era
Quaternary
Tertiary
Cretaceous
Late Jurassic
Pleistocene
Pliocene
Miocene
Oligocene
Eocene
Paleocene
Late Cretaceous
Early Cretaceous
0
5
10
15
20
25
30
35
40
45
50
55
60
65
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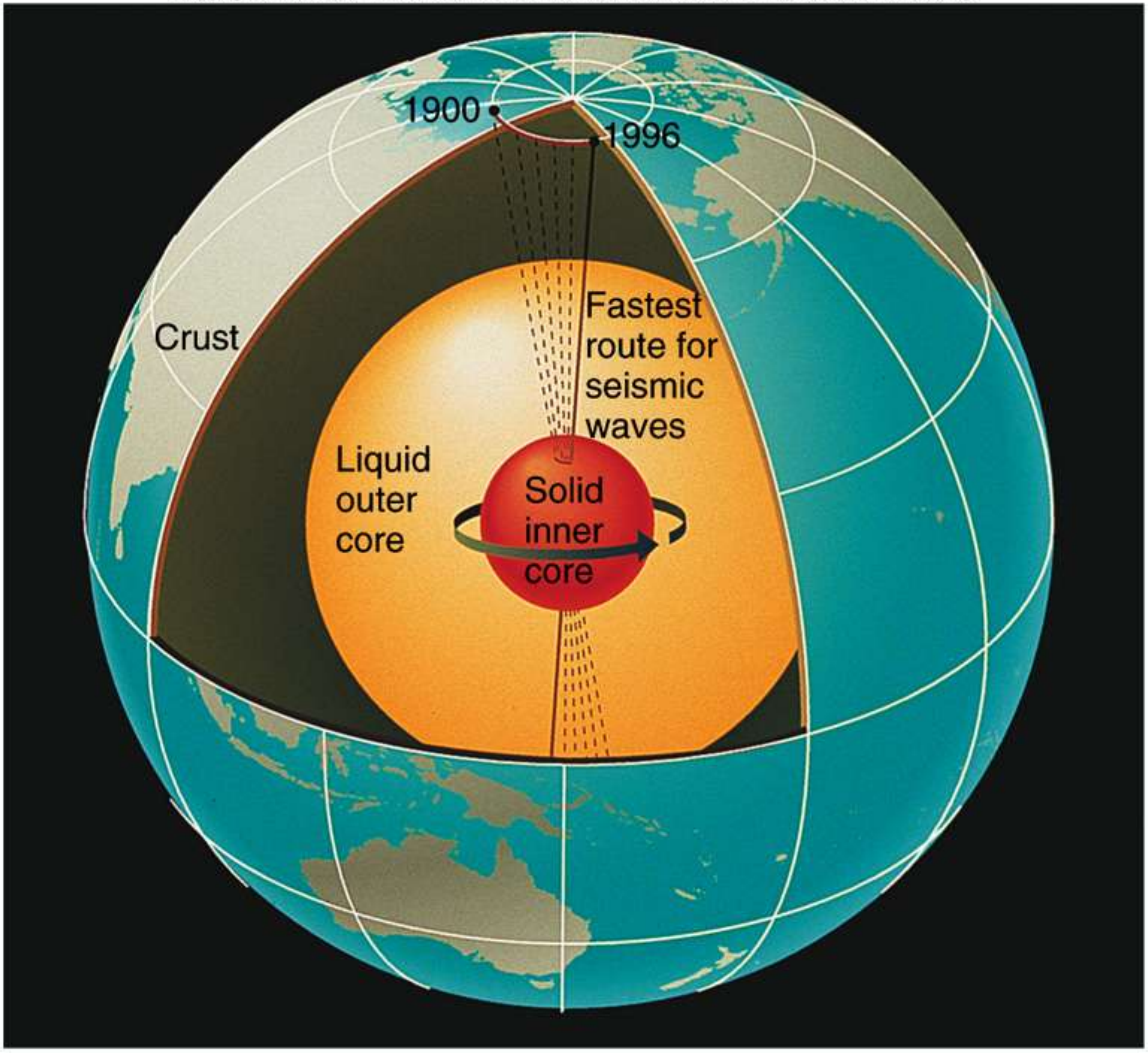
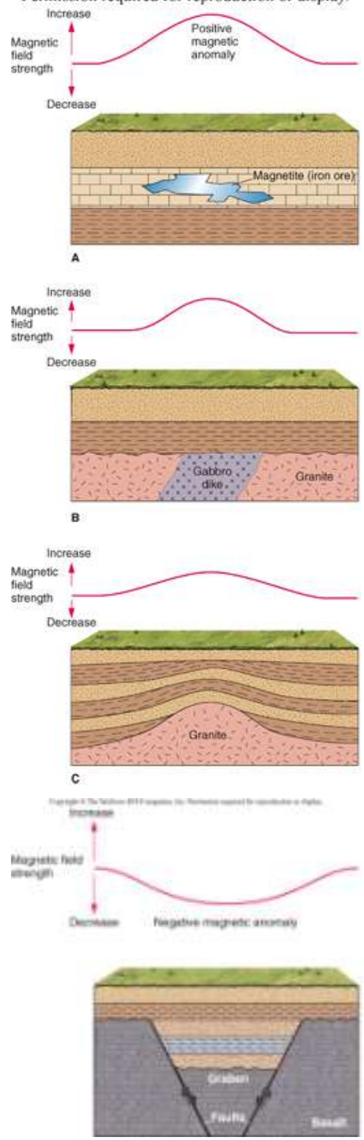
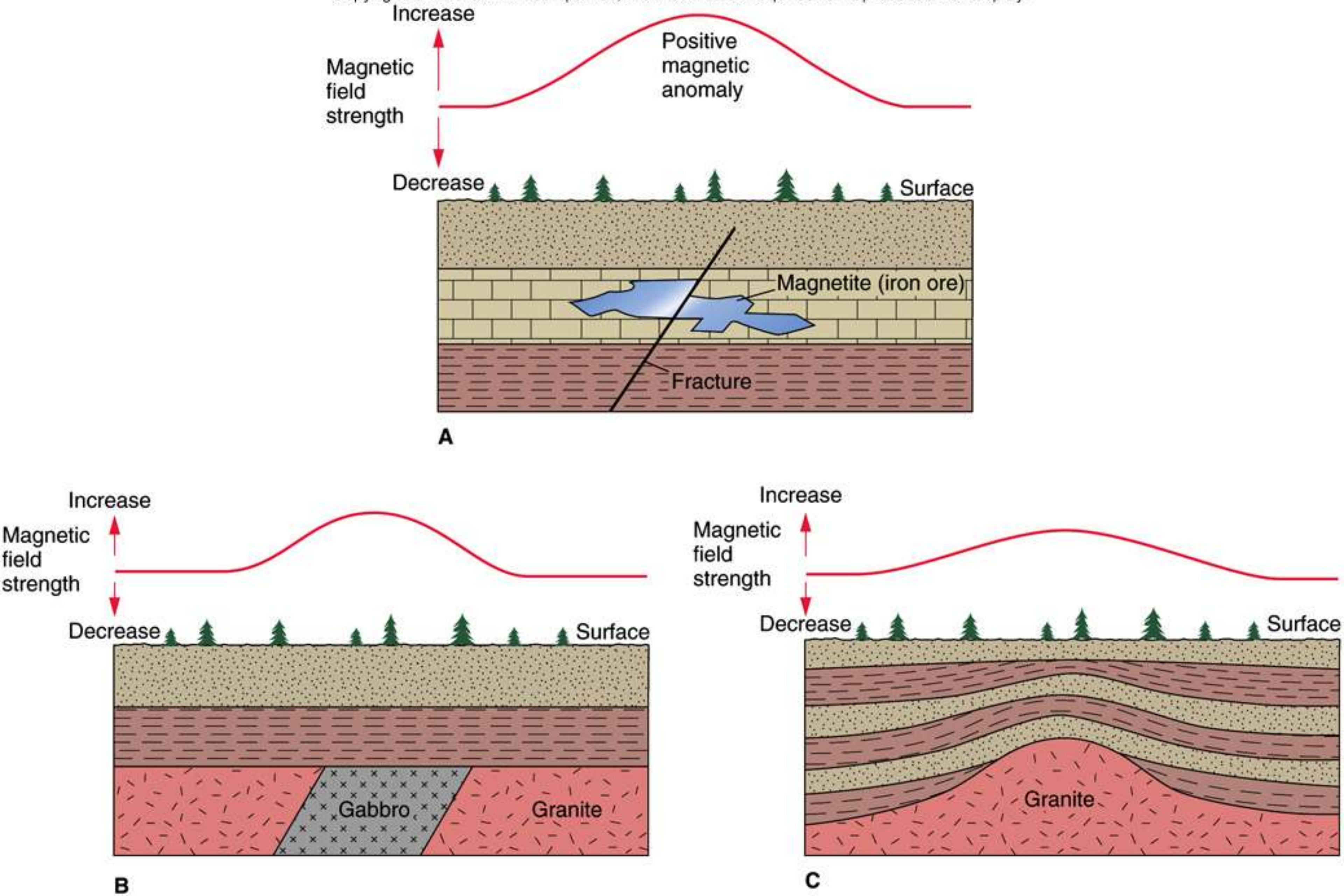
140
145
150
155
160

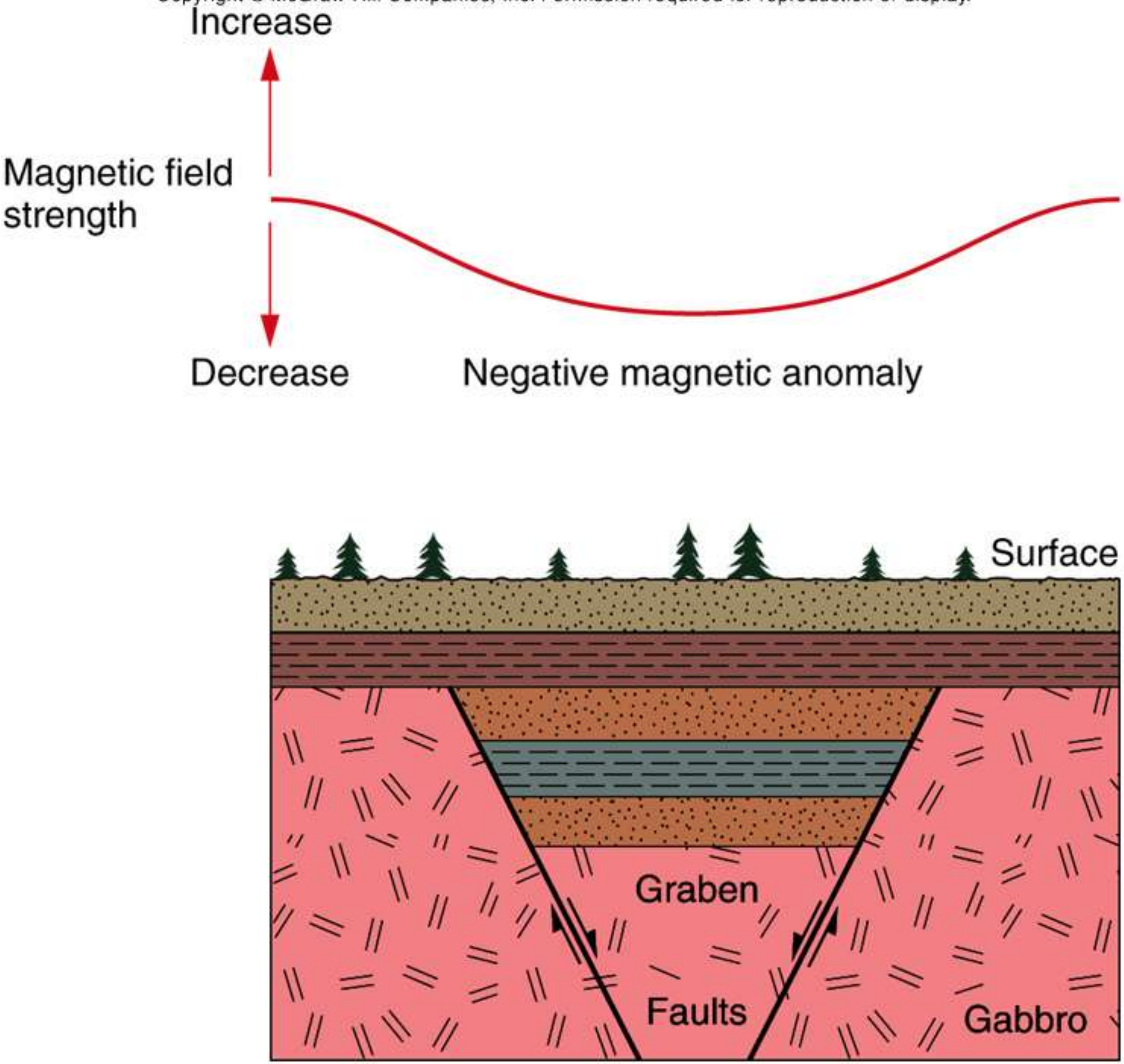

1900
1996
Crust
Fastest
route for
seismic
waves
Liquid
outer
core
Solid
inner
core

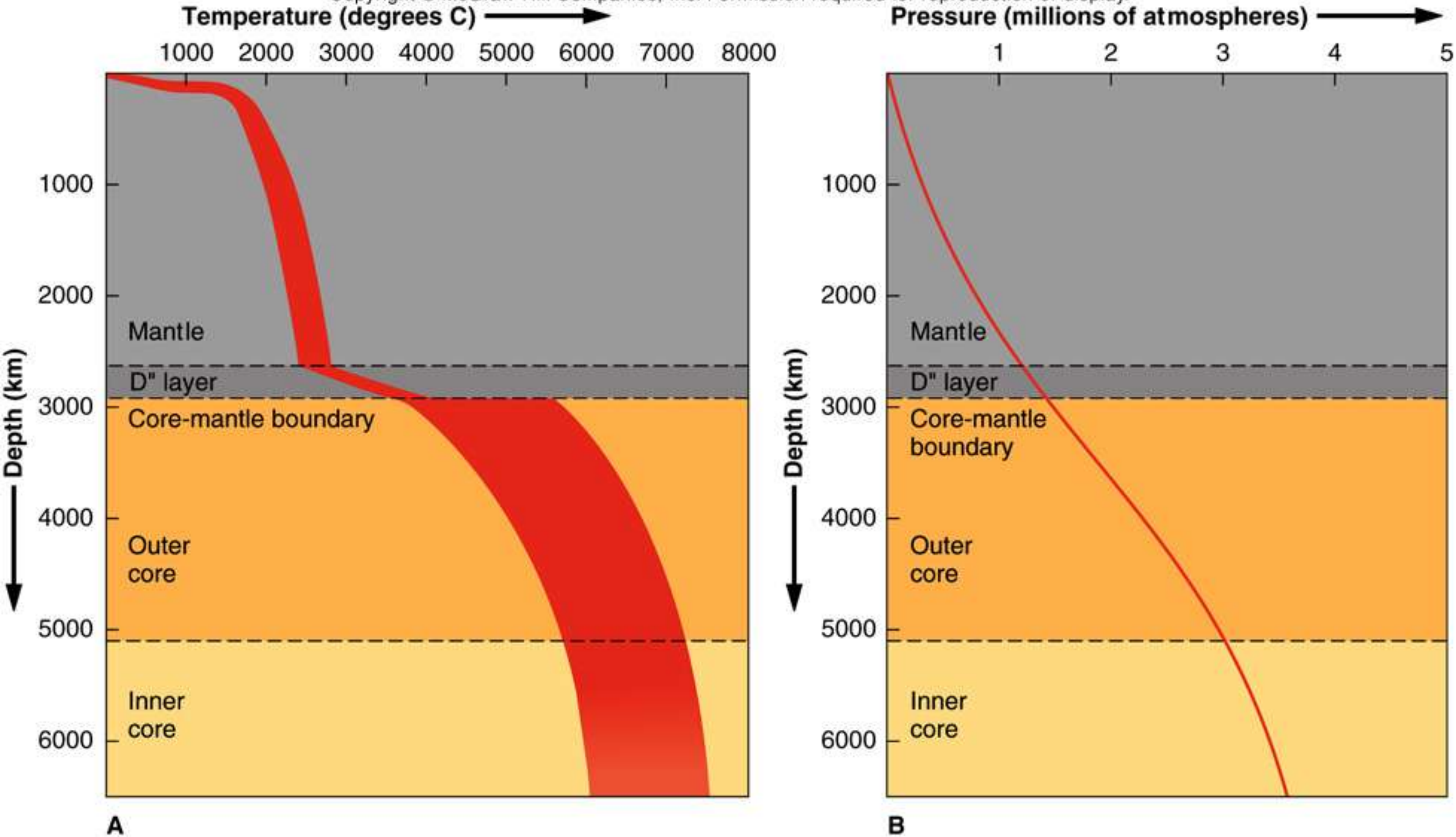
Magnetic Anomalies

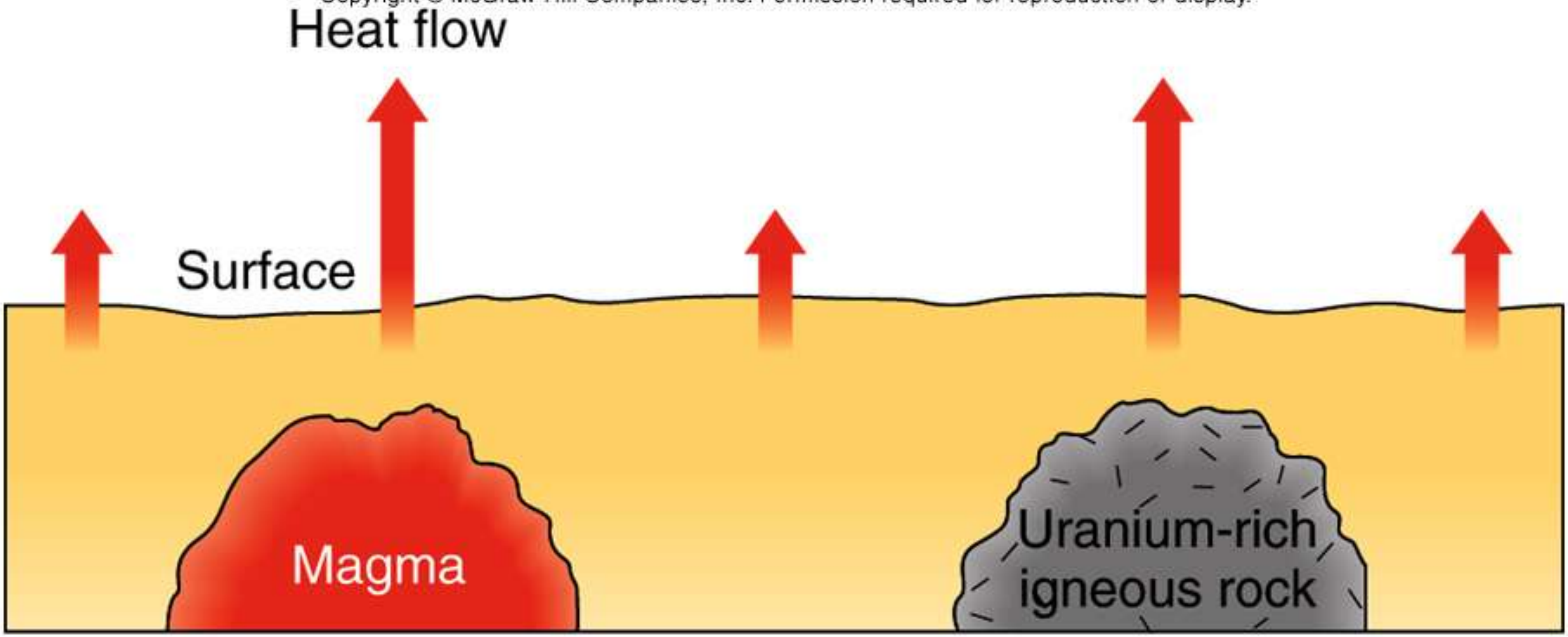
- Local increases or decreases in the Earth's magnetic field strength are known as *magnetic anomalies*
  - Positive and negative magnetic anomalies represent larger and smaller than average local magnetic field strengths, respectively
- *Magnetometers* are used to measure local magnetic field strength
  - Used as metal detectors in airports
  - Can detect metallic ore deposits, igneous rocks (positive anomalies), and thick layers of non-magnetic sediments (negative anomaly) beneath Earth's surface

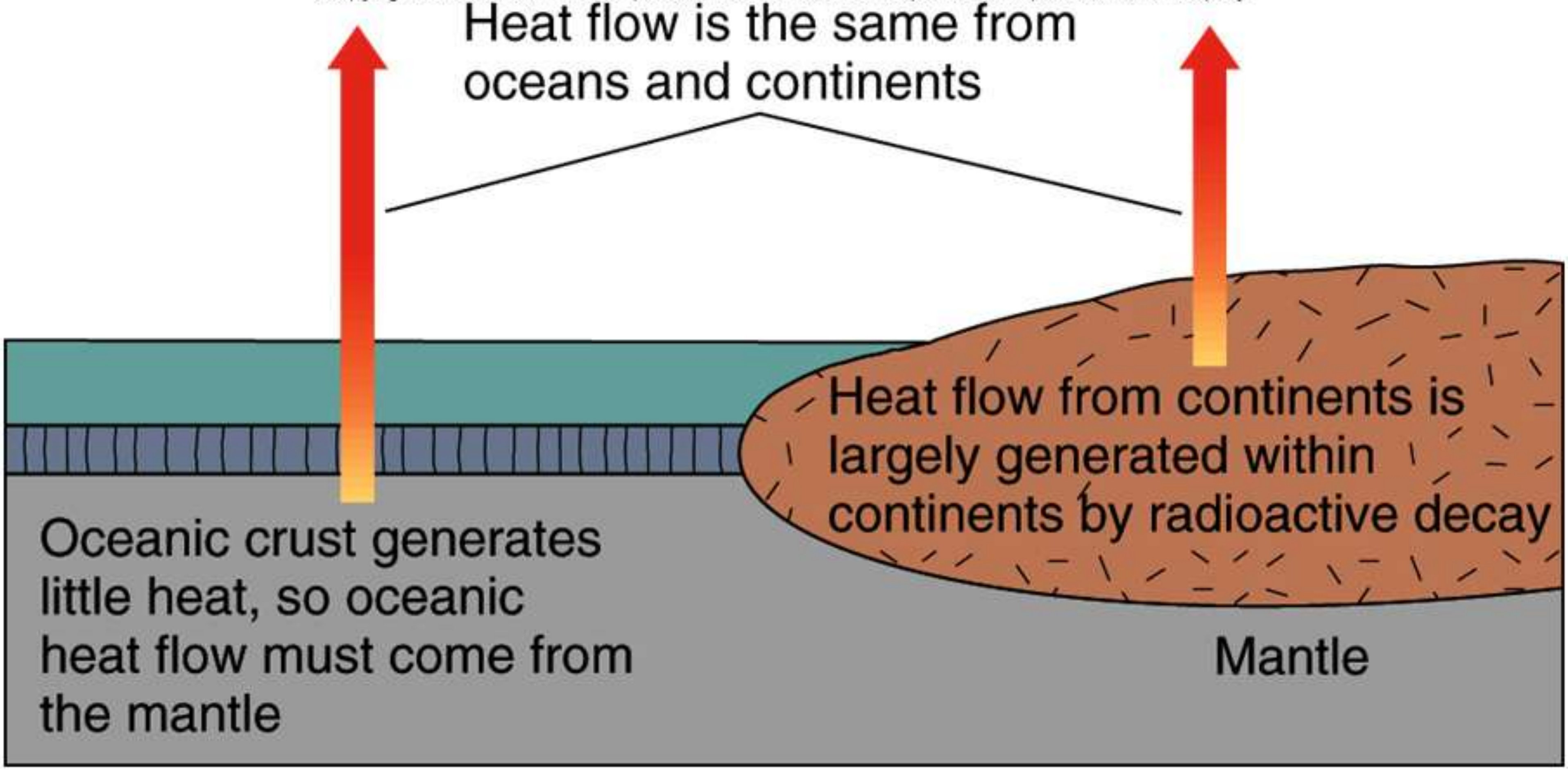



Increase
Magnetic field strength
Decrease
Positive magnetic anomaly
Surface
Magnetite (iron ore)
Fracture
A
Increase
Magnetic field strength
Decrease
Surface
Gabbro
Granite
B
Increase
Magnetic field strength
Decrease
Surface
Granite
C


Increase
Magnetic field strength
Decrease
Negative magnetic anomaly
Surface
Graben
Faults
Gabbro

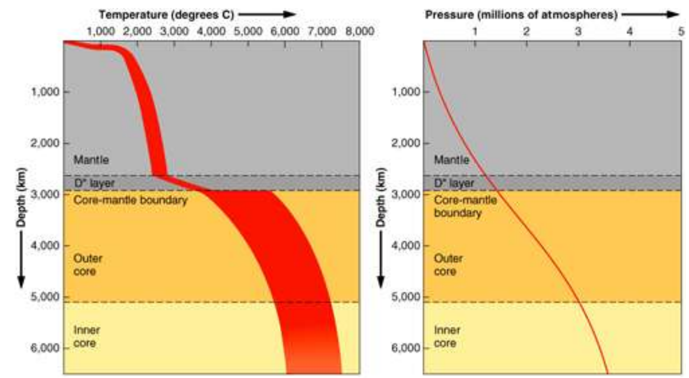

Temperature (degrees C)
1000
2000
3000
4000
5000
6000
7000
8000
Depth (km)
1000
2000
3000
4000
5000
6000
Mantle
D" layer
Core-mantle boundary
Outer core
Inner core
A
Pressure (millions of atmospheres)
1
2
3
4
5
Depth (km)
1000
2000
3000
4000
5000
6000
Mantle
D" layer
Core-mantle boundary
Outer core
Inner core
B


Heat flow
Surface
Magma
Uranium-rich
igneous rock


Heat flow is the same from
oceans and continents
Heat flow from continents is
largely generated within
continents by radioactive decay
Oceanic crust generates
little heat, so oceanic
heat flow must come from
the mantle
Mantle

Heat Within the Earth

- *Geothermal gradient* - temperature increase with depth into the Earth
  - Tapers off sharply beneath lithosphere
  - Due to steady pressure increase with depth, increased temperatures produce little melt (mostly within asthenosphere) except in the outer core



- *Heat flow* - the gradual loss of heat through Earth's surface
  - Major heat sources include original heat (from accretion and compression as Earth formed) and radioactive decay
  - Locally higher where magma is near surface
  - Same magnitude, but with different sources, in the oceanic (from mantle) and continental crust (radioactive decay within the crust)