FUNDAMENTALS OF EARTH SCIENCES (ESO 213A)

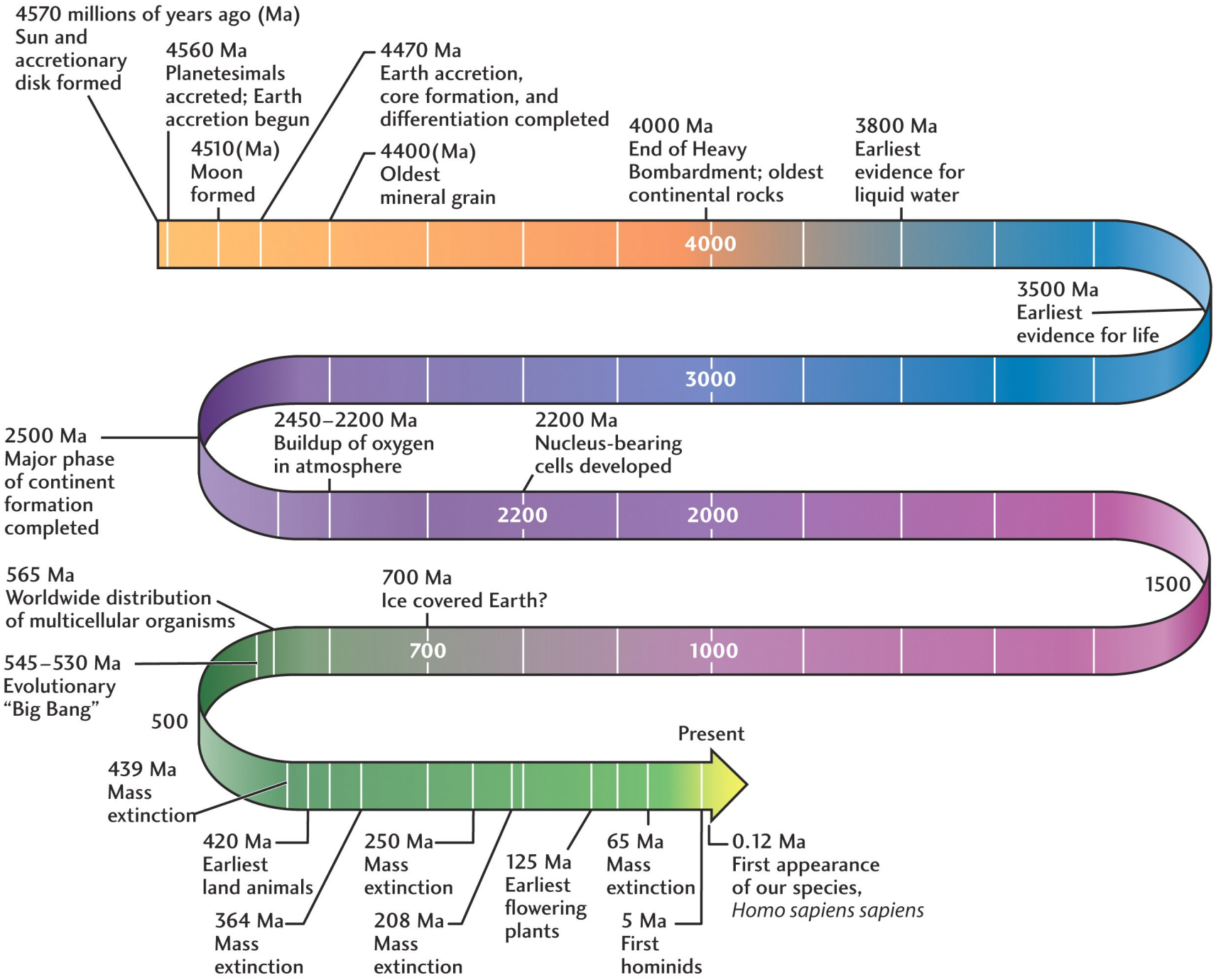
DIBAKAR GHOSAL
DEPARTMENT OF EARTH SCIENCES

Topic: Internal structure of Earth

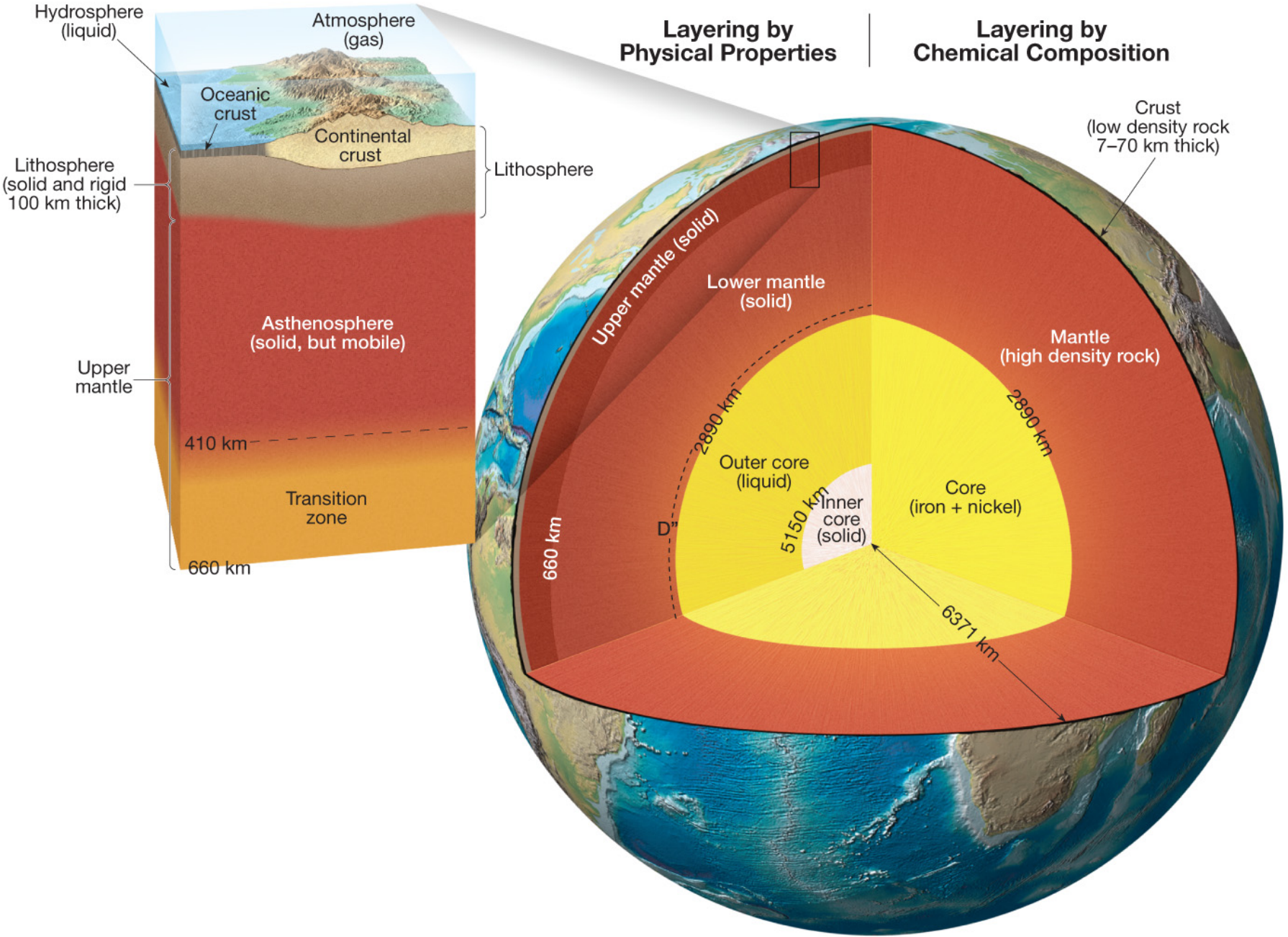
Previous Class: Earth, Moon and Atmosphere

Last Class: Review

- Origin of our Solar System (4.57 Ba)
- Origin of Earth (4.56 Ba)
- Origin of Moon (4.51 Ba)
- Internal Layering (4.47 Ba)
- Water (3.8 Ba)
- Oxygen(3.5 Ba)
- BIF (~3.0 Ba)

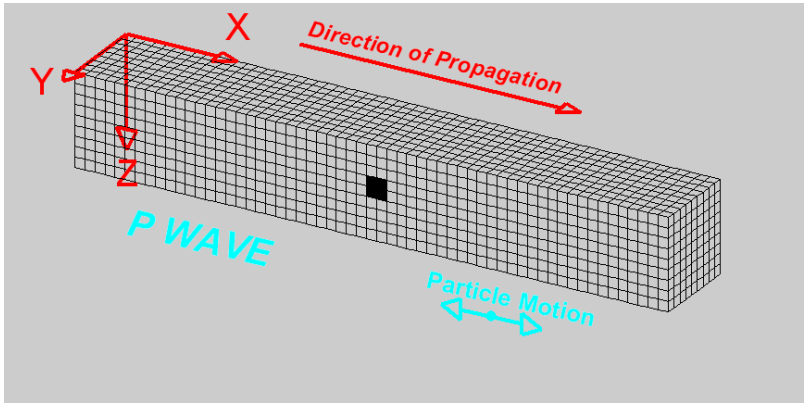

4570 millions of years ago (Ma)
Sun and accretionary disk formed
4560 Ma
Planetesimals accreted; Earth accretion begun
4510(Ma)
Moon formed
4470 Ma
Earth accretion, core formation, and differentiation completed
4400(Ma)
Oldest mineral grain
4000 Ma
End of Heavy Bombardment; oldest continental rocks
3800 Ma
Earliest evidence for liquid water
4000
3500 Ma
Earliest evidence for life
3000
2500 Ma
Major phase of continent formation completed
2450–2200 Ma
Buildup of oxygen in atmosphere
2200 Ma
Nucleus-bearing cells developed
2200
2000
1500
565 Ma
Worldwide distribution of multicellular organisms
700 Ma
Ice covered Earth?
700
1000
545–530 Ma
Evolutionary "Big Bang"
500
Present
439 Ma
Mass extinction
420 Ma
Earliest land animals
364 Ma
Mass extinction
250 Ma
Mass extinction
208 Ma
Mass extinction
125 Ma
Earliest flowering plants
65 Ma
Mass extinction
5 Ma
First hominids
0.12 Ma
First appearance of our species, *Homo sapiens sapiens*

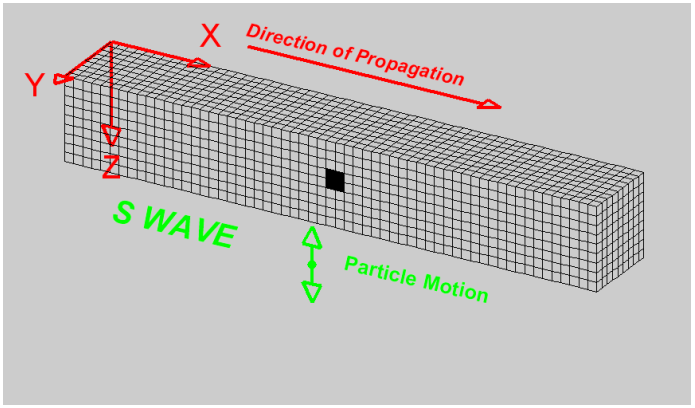
Earth's Layered Structure



Probing Earth's Interior

- *Most of our knowledge of Earth's interior comes from the study of earthquake waves.*
  - **Travel times of P (compressional) and S (shear) waves through the Earth vary depending on the properties of the materials. P waves travel faster than do S waves. S waves cannot travel through liquids**





$$v_p = \sqrt{\frac{\kappa + 4\mu/3}{\rho}}$$

$$v_s = \sqrt{\frac{\mu}{\rho}}$$

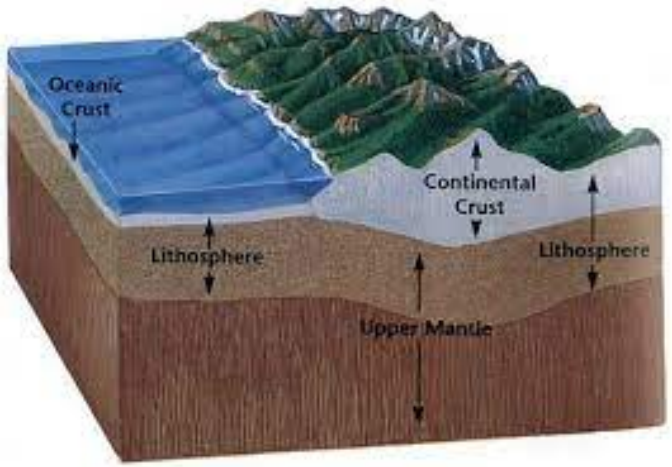
Earth's Layers

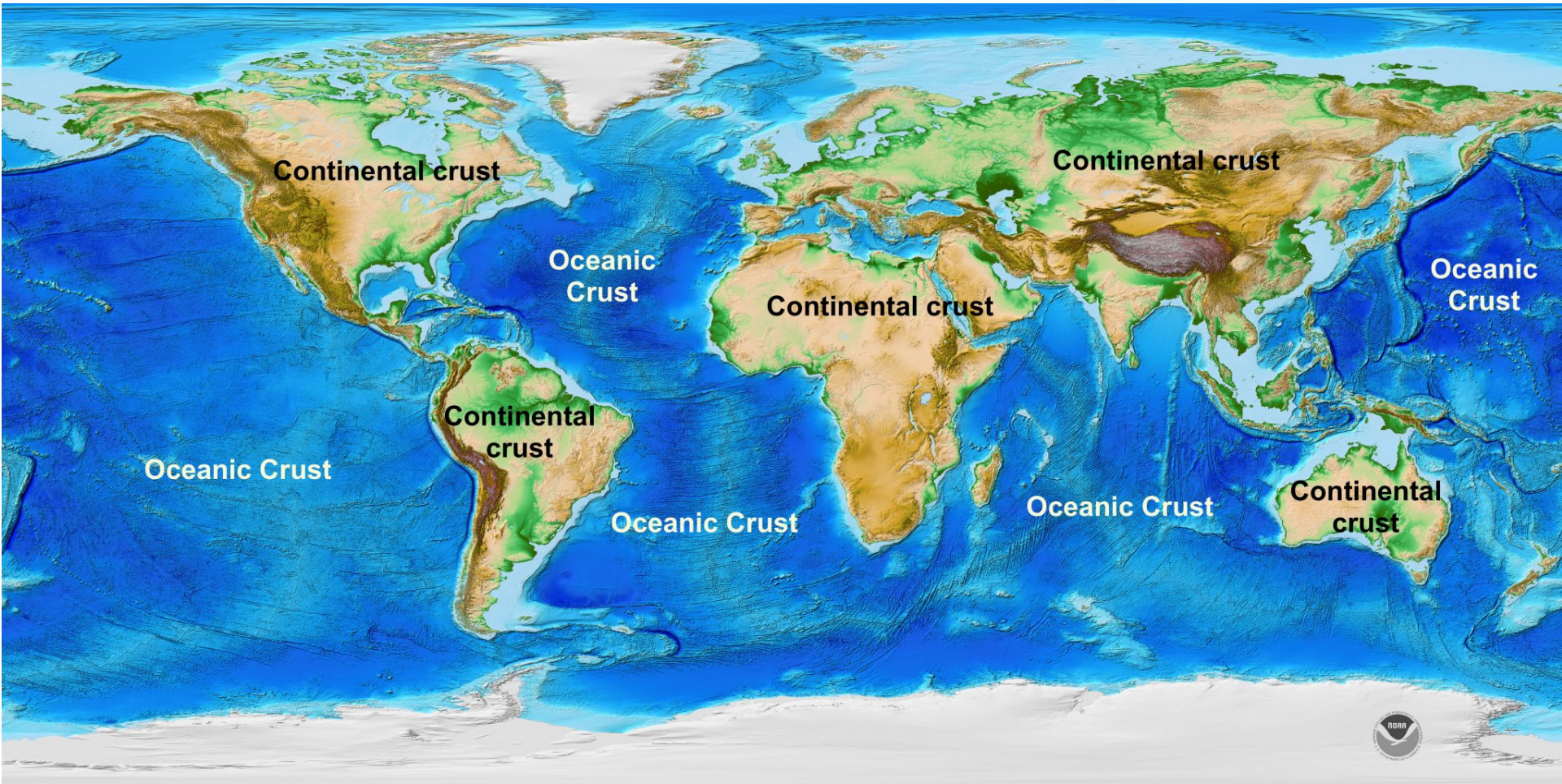
Crust: ***1. oceanic*** **- P wave = 5 – 7 km/s**

- density = 3 g/cm³

2. continental **- seismic velocities vary**

- density = 2.7 g/cm³ **(buoyant)**





Earth's Layers

Crust: ***1. oceanic*** **- P wave = 5 – 7 km/s**

- density = 3 g/cm^3

2. continental **- seismic velocities vary**

- density = 2.7 g/cm^3 **(buoyant)**

Mantle: - 82 % of Earth's volume, ~ 2900 km thick

- between Moho (base of crust) and the liquid core

- silicate minerals rich in Fe and Mg

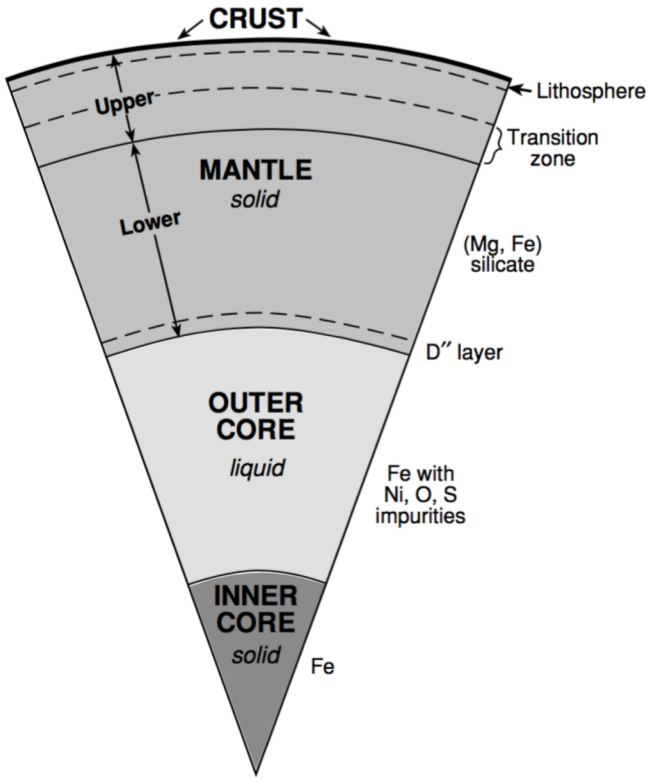
- density = between 3.3 and 5.6 g/cm^3

Core: - at the mantle-core boundary

» P wave velocities drop from ~13.7 km/s to 8.1 km/s

» S wave velocities drop from ~7.3 km/s to 0 km/s

- density = 9.9 g/cm^3



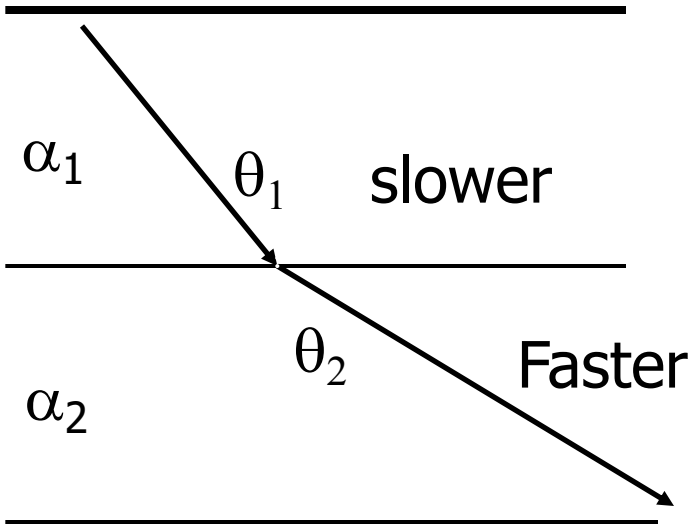
Probing Earth's Interior

- The speed of seismic waves
  - Velocity (speed) depends on the *stiffness* and *compressibility* of the intervening material → information about the composition and temperature
  - Faster in more rigid (stiff) and less compressible rocks
  - Increases with depth (pressure increases and squeezes the rock into a more compact, rigid material) → strongly curved paths

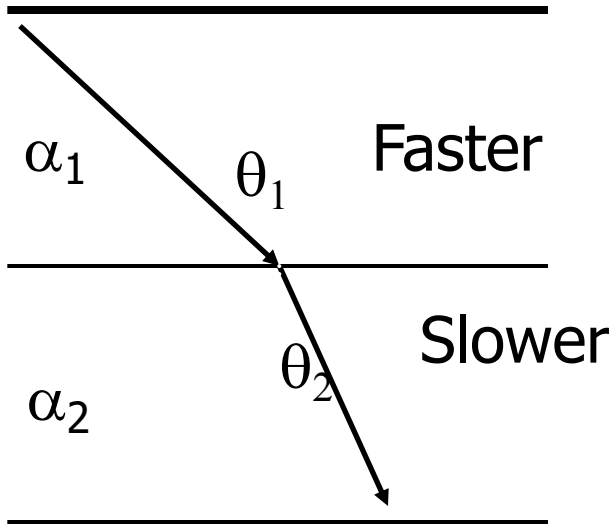
Ray Paths in a Layered Medium

$\sin \theta_1 / \alpha_1 = \sin \theta_2 / \alpha_2 = s_1 \sin \theta_1 = s_2 \sin \theta_2$

$\alpha =$ velocity of seismic energy in the layer

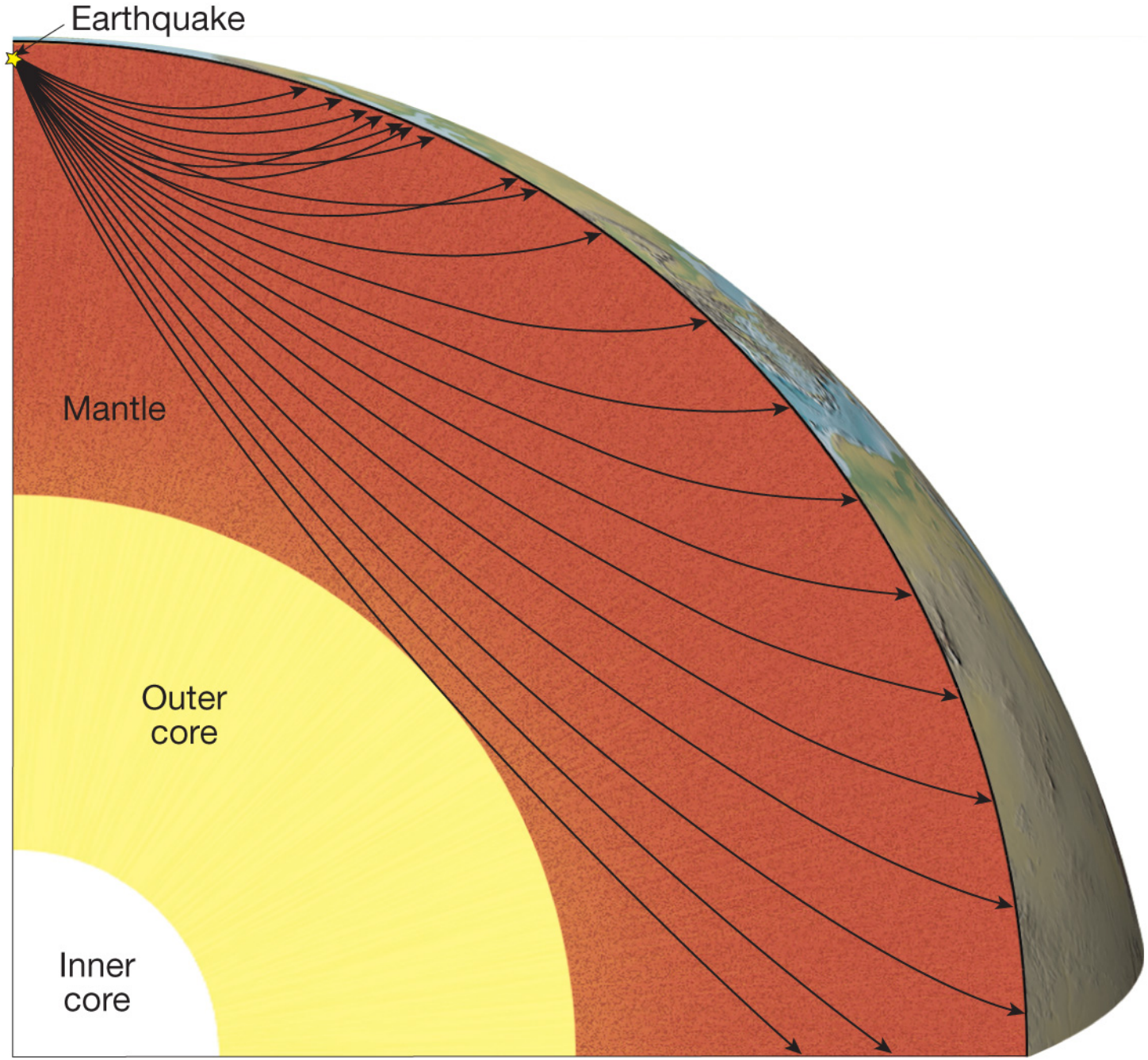


$\alpha_1 < \alpha_2$



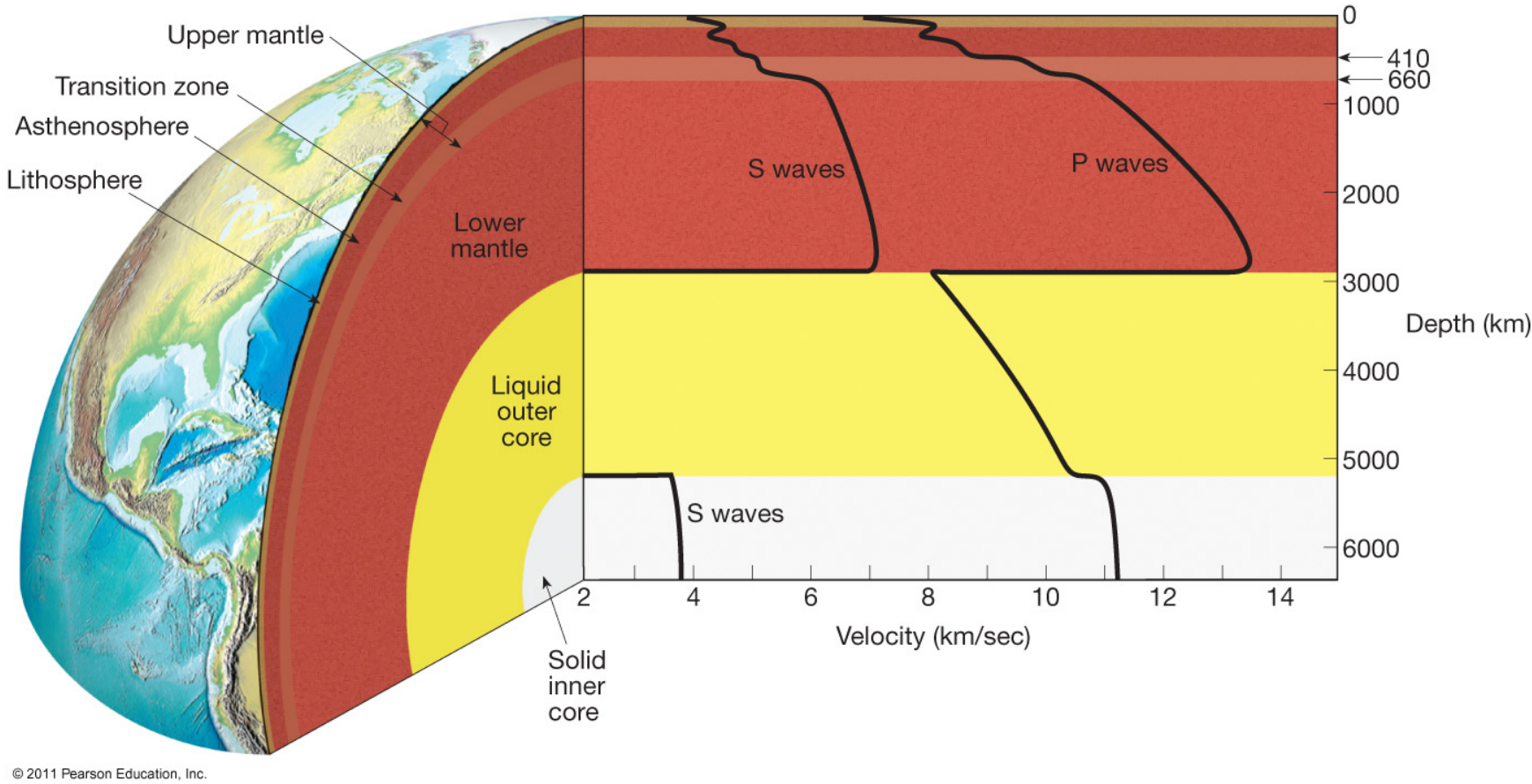
$\alpha_1 > \alpha_2$

USGS
science for a changing world



Seismic Waves and Earth's Structure

- **Abrupt changes in seismic-wave velocities that occur at particular depths helped seismologists to conclude that Earth must be composed of distinct shells.**

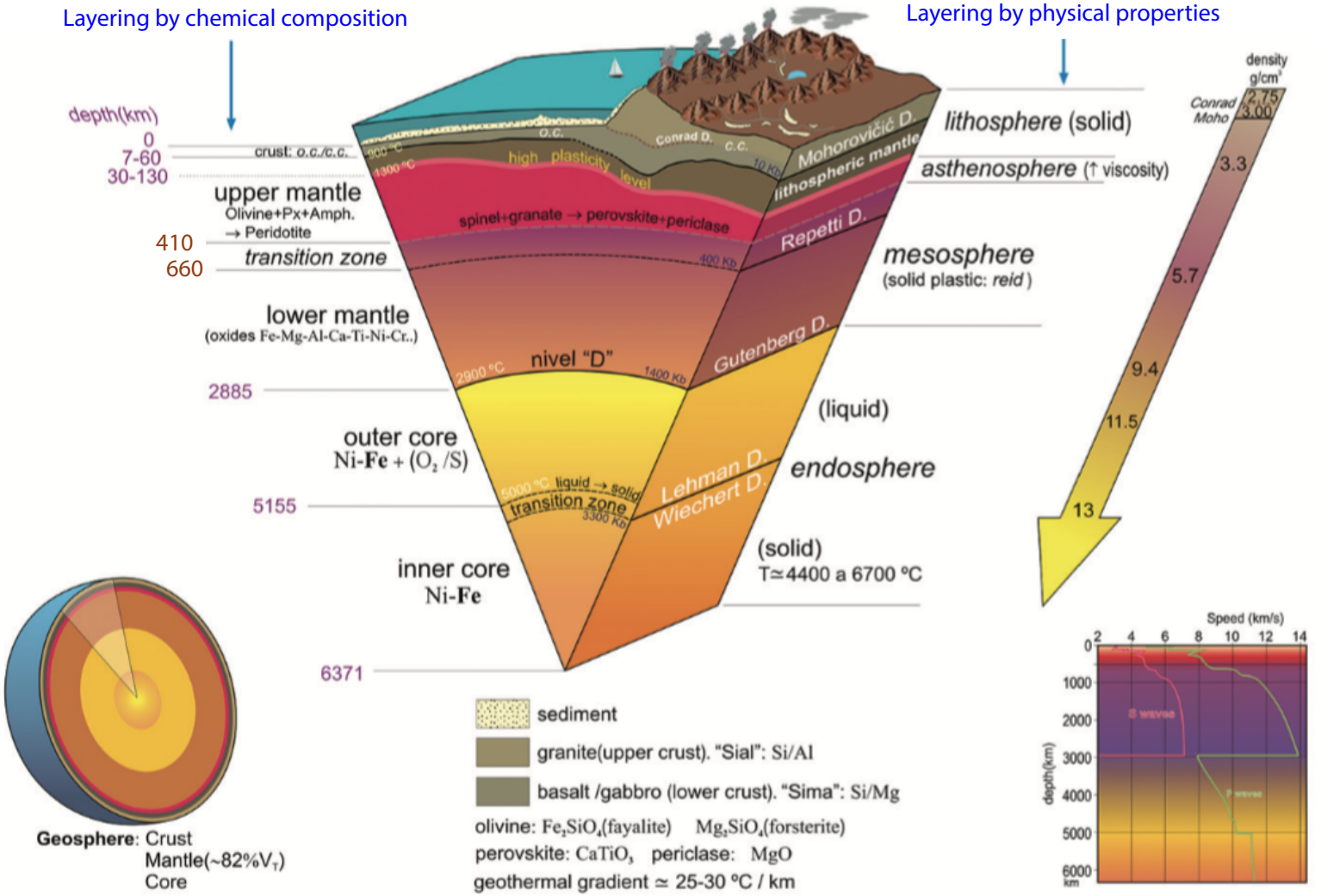


I. Layers are defined by composition.

Earth's Layers

Three principal compositional layers

1. **Crust is the comparatively thin outer skin that ranges from 7 kilometers at the oceanic ridges to 70 kilometers in some mountain belts**
2. **Mantle is a solid rocky (silica-rich) shell that extends to a depth of about 2900 kilometers**
3. **Core is an iron-rich sphere having a radius of about 3500 kilometers**



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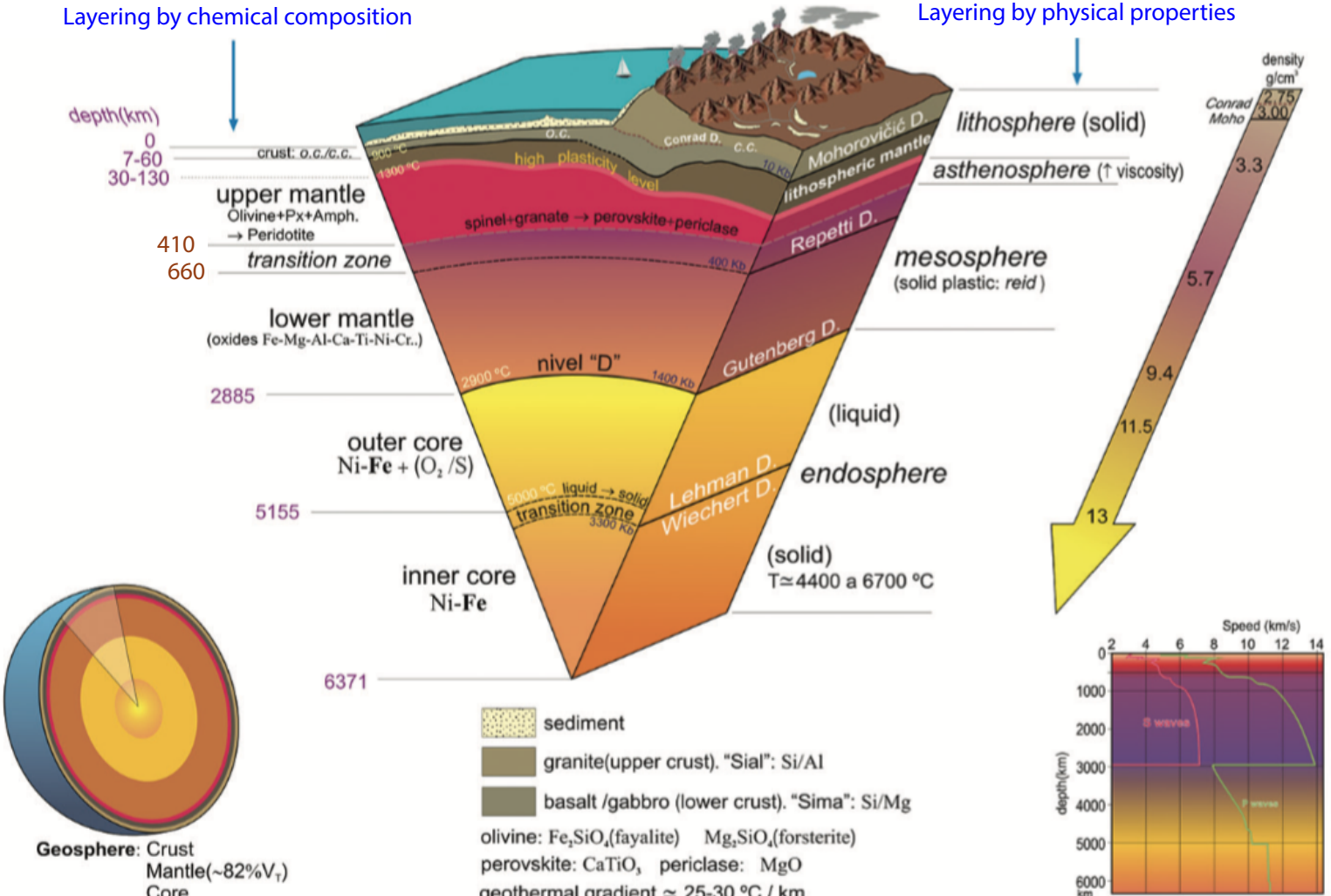
Discovering Earth´s Major Boundaries

- *The crust-mantle boundary*
- **The Moho (Mohorovicic) discontinuity**
  - **Discovered in 1909 by Andrija Mohorovîčîč**
  - **Identified by an abrupt change in the velocity of P waves at the base of continents (from ~6 km/s to 8 km/s)**



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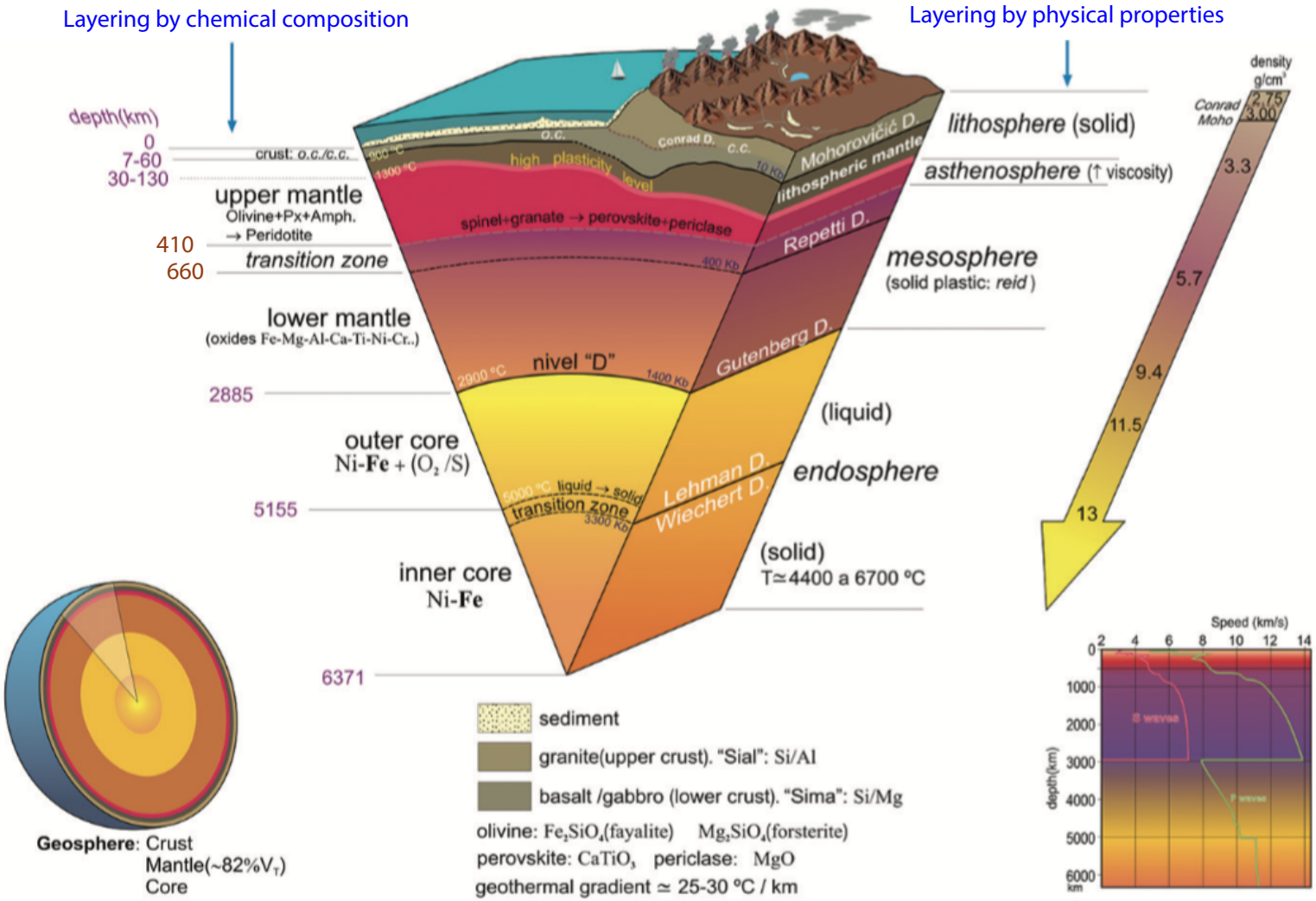
Discovering Earth's Major Boundaries

The mantle-core boundary

- **Discovered in 1906 by Richard Oldham (Gutenberg Discontinuity)**
- **Based on the observation that P waves die out at 100 degrees from the earthquake and reappear at about 140 degrees**
- **35 degree-wide belt is named the P-wave shadow zone.**



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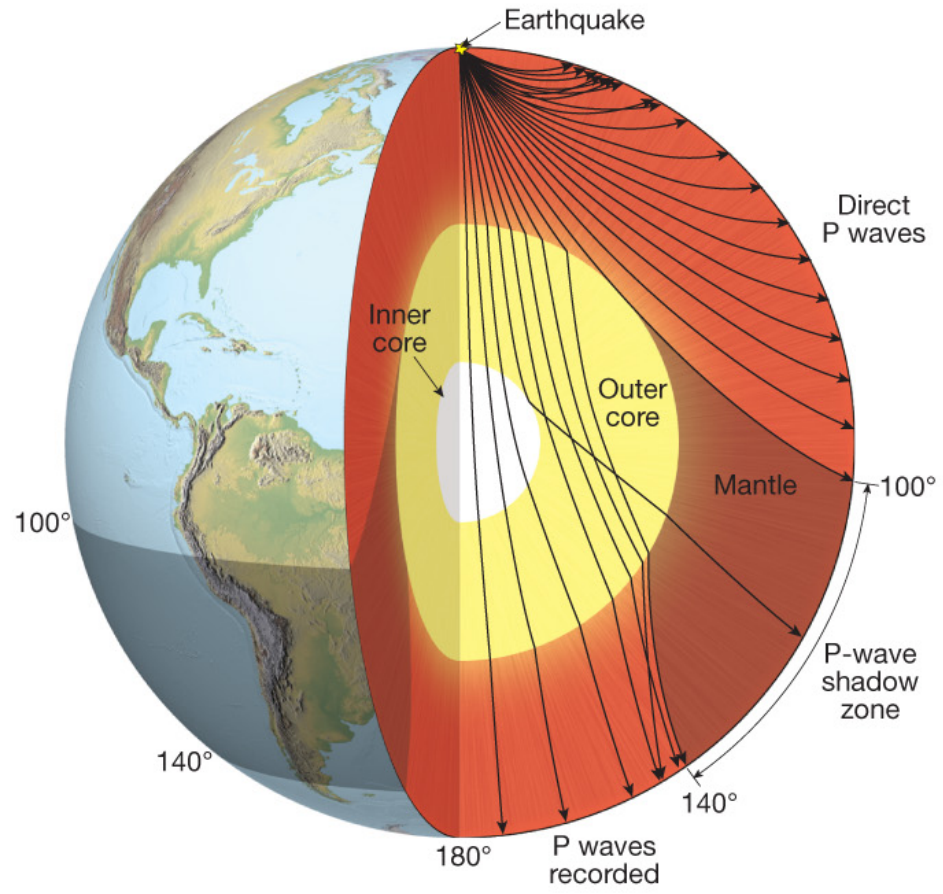
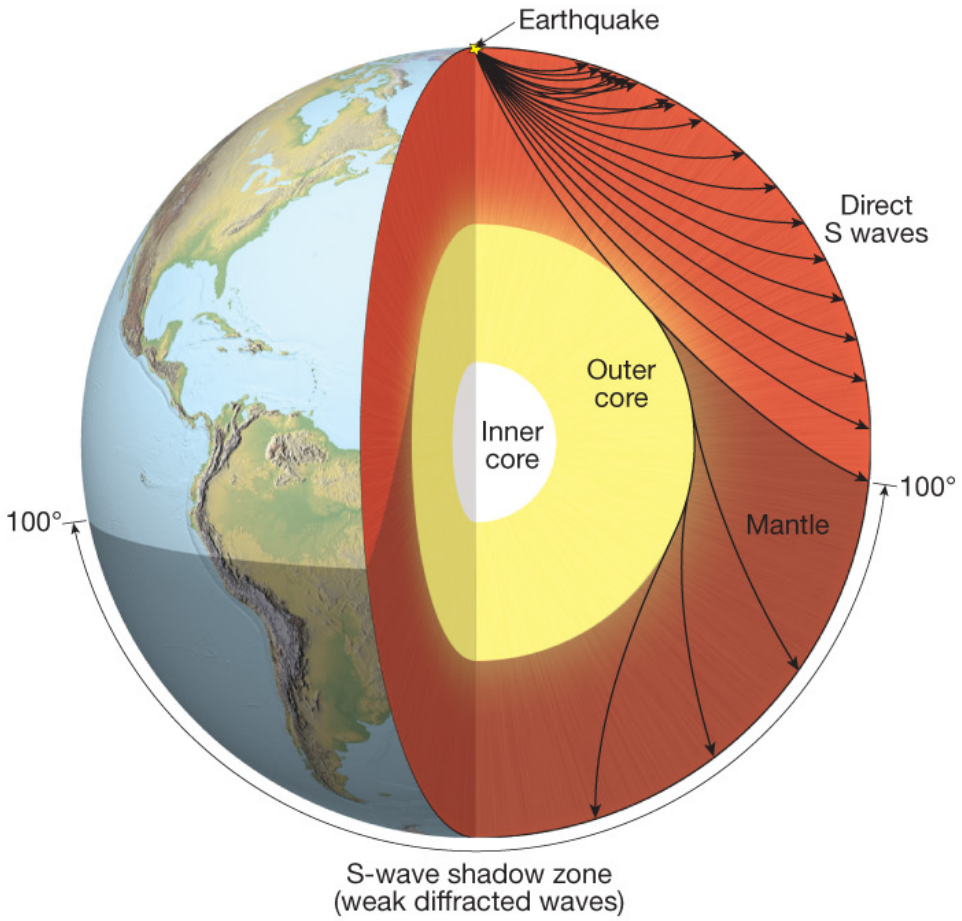
Shadow zones



A. P-wave shadow zone

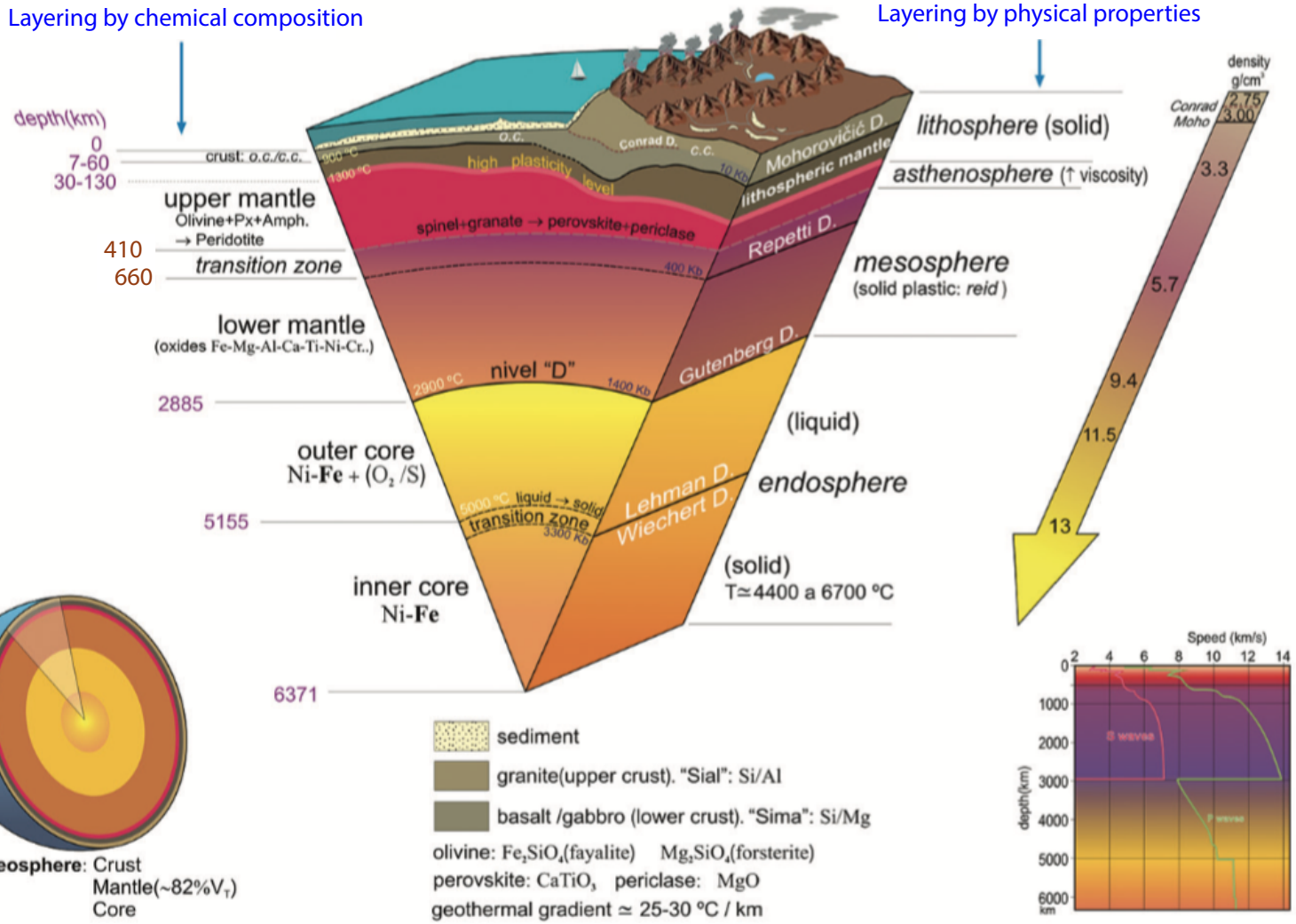


B. S-wave shadow zone

II. Layers are defined by physical properties.

Earth's Layers

- With increasing depth, Earth's interior is characterized by gradual increases in temperature, pressure, and density.
- Depending on the temperature and depth, a particular Earth material may behave like a brittle solid, deform in a plastic–like manner, or melt and become liquid.
- Main layers of Earth's interior are based on physical properties and hence, mechanical strength.



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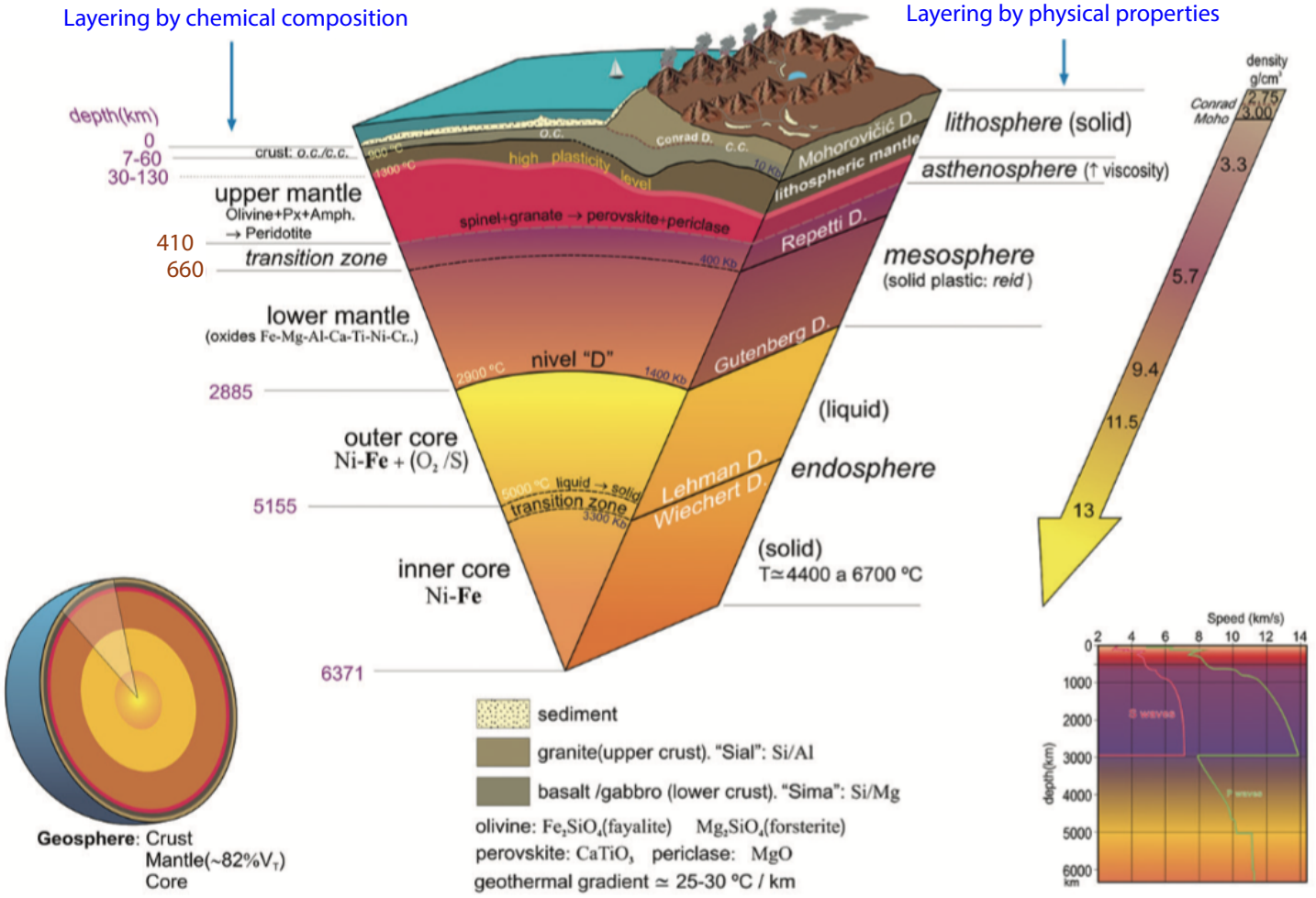
Earth's Structure

I. The Upper Mantle (Moho → 660 km)

- **A. Lithosphere (sphere of rock)**
  - **Earth's outermost layer**
  - **Consists of the crust and uppermost mantle**
  - **Relatively cool, rigid shell**
  - **Averages about 100 kilometers in thickness, but may be 250 kilometers or more thick beneath th older portions of the continents.**



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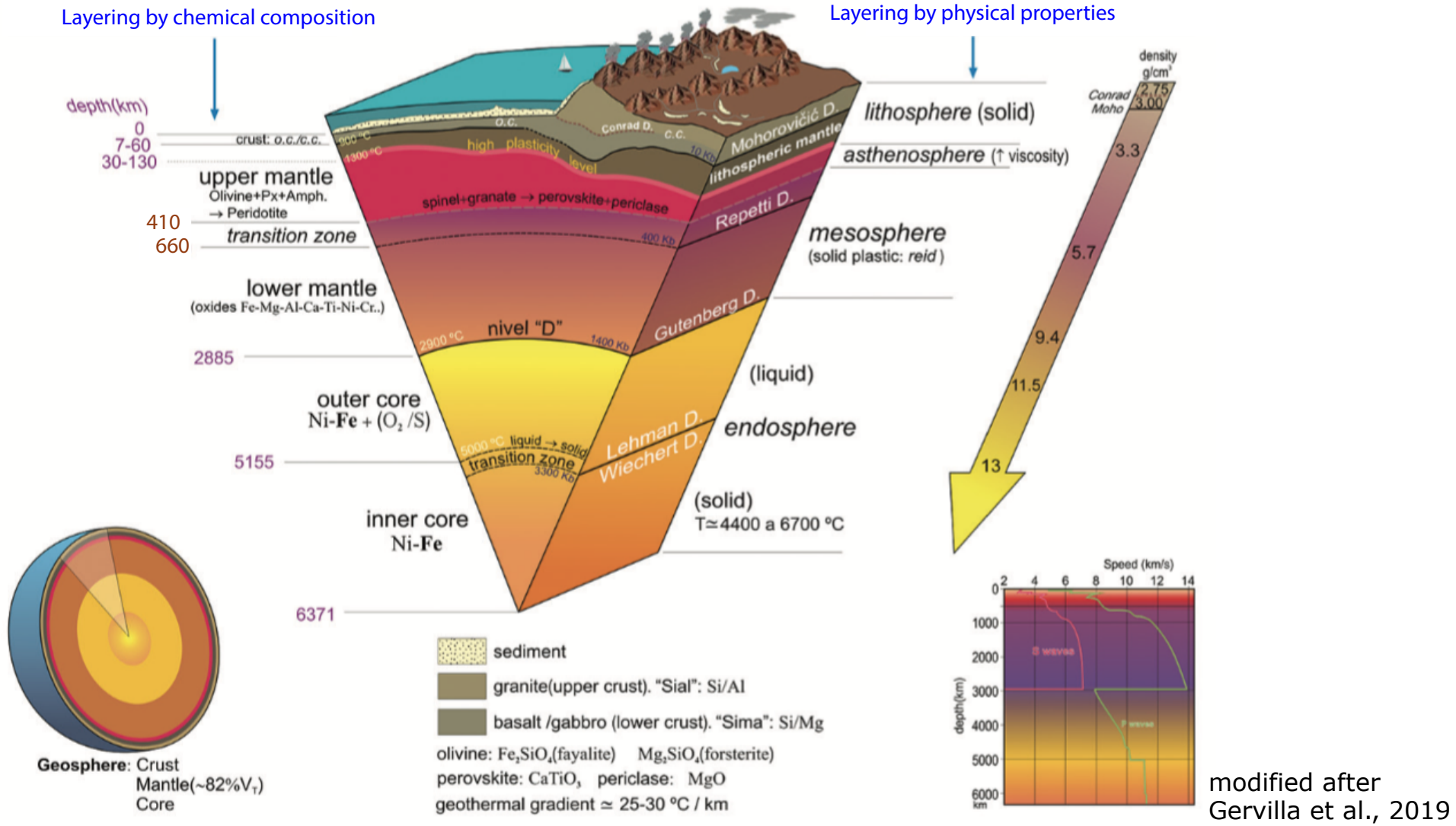
The Upper Mantle

Earth's Structure

- **B. Asthenosphere (weak sphere)**
  - **Beneath the lithosphere, in the upper mantle to a depth of about ~410 kilometers**
  - **A small amount of melting in the upper portion mechanically detaches the lithosphere from the layer below, allowing the lithosphere to move independently of the asthenosphere.**



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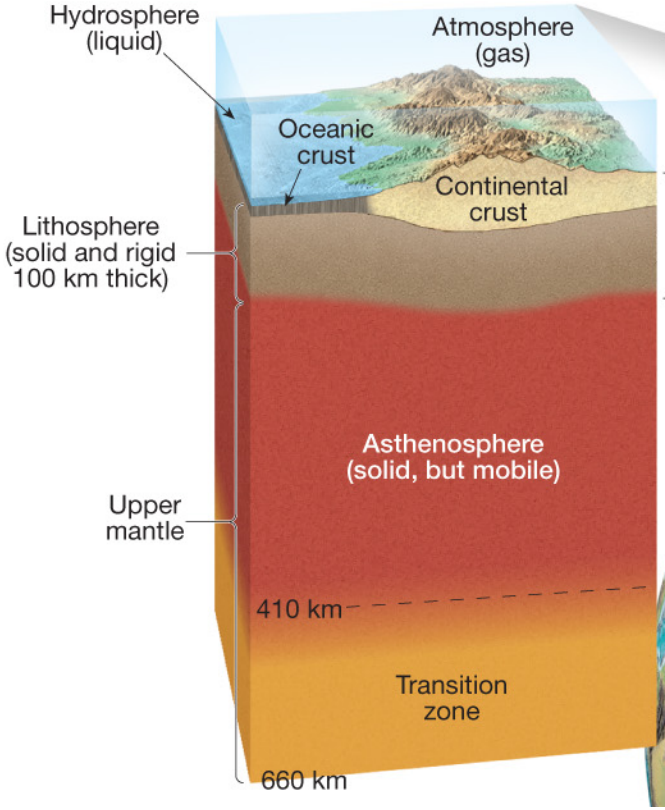
Earth's Structure

The Upper Mantle

- **C. Transition Zone (410 – 660 km)**
  - **Beneath the asthenosphere, in the upper mantle, to a depth of about 660 kilometers**
  - **Top of TZ identified by sudden increase in density from 3.5 to 3.7 g/cm^3**
  - **Change in mineral phase:**

    Olivine → β-spinel → Ringwoodite



PERIDOTITE – mainly olivine and pyroxene

II. The Lower Mantle (Mesosphere)

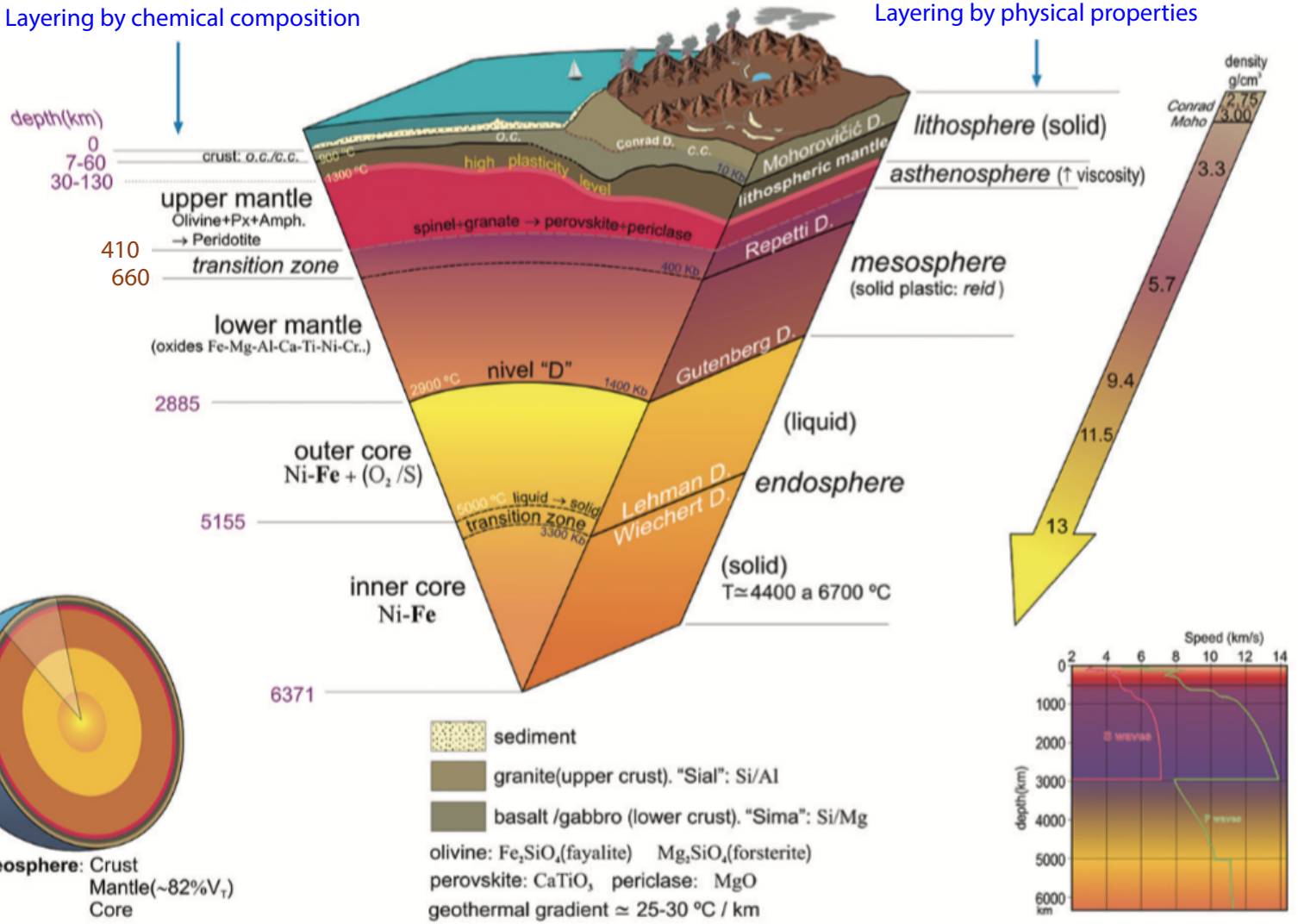
Earth's Structure

Rigid layer between the depths of 660 kilometers and 2900 kilometers

Largest by volume (56%)

Rocks are very hot and capable of very gradual flow

Olivine and Pyroxene→ Perovskite



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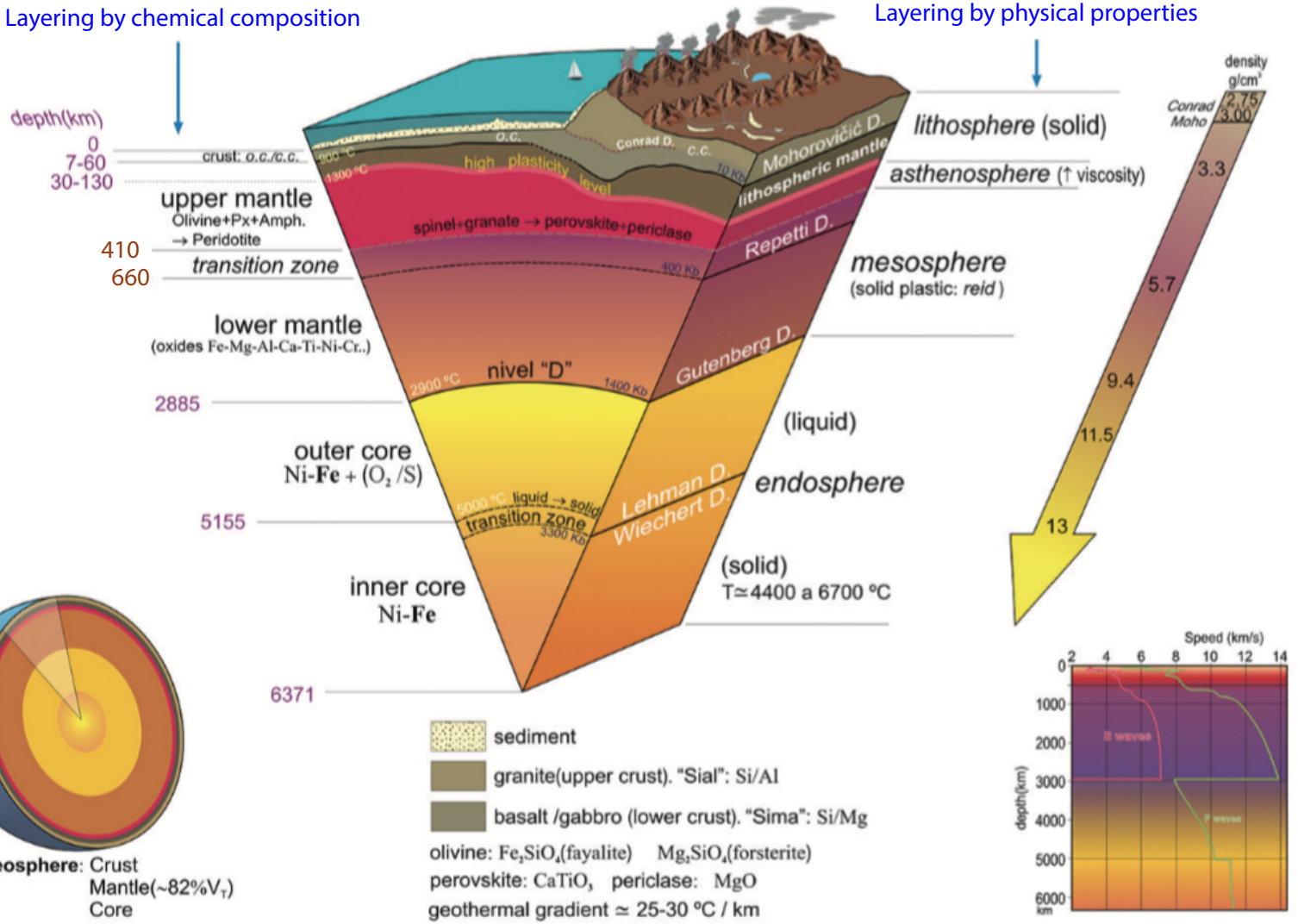
III. The D" Layer

Earth's Structure

Boundary layer between the rocky mantle and the liquid outer core

- "Graveyard" of some subducted oceanic lithosphere and "birthplace" of some mantle plumes



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Earth's Structure

IV. The Outer Core

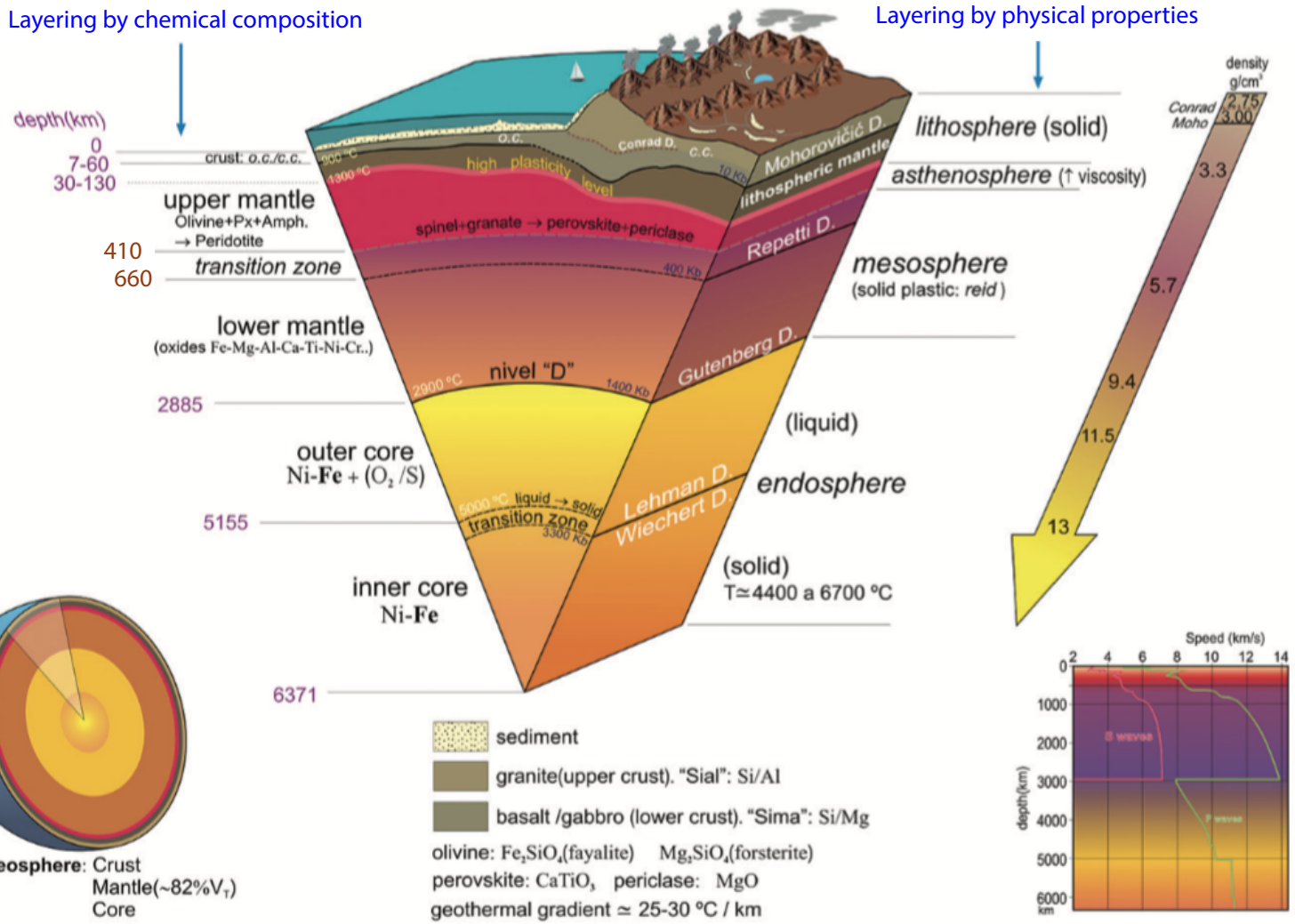
Composed mostly of an iron-nickel alloy

Lower amounts of S, O, Si, H Liquid layer

Density of ~ 9.9 g/cm^3

Around 2300 kilometers

A convective flow within generates Earth's magnetic field



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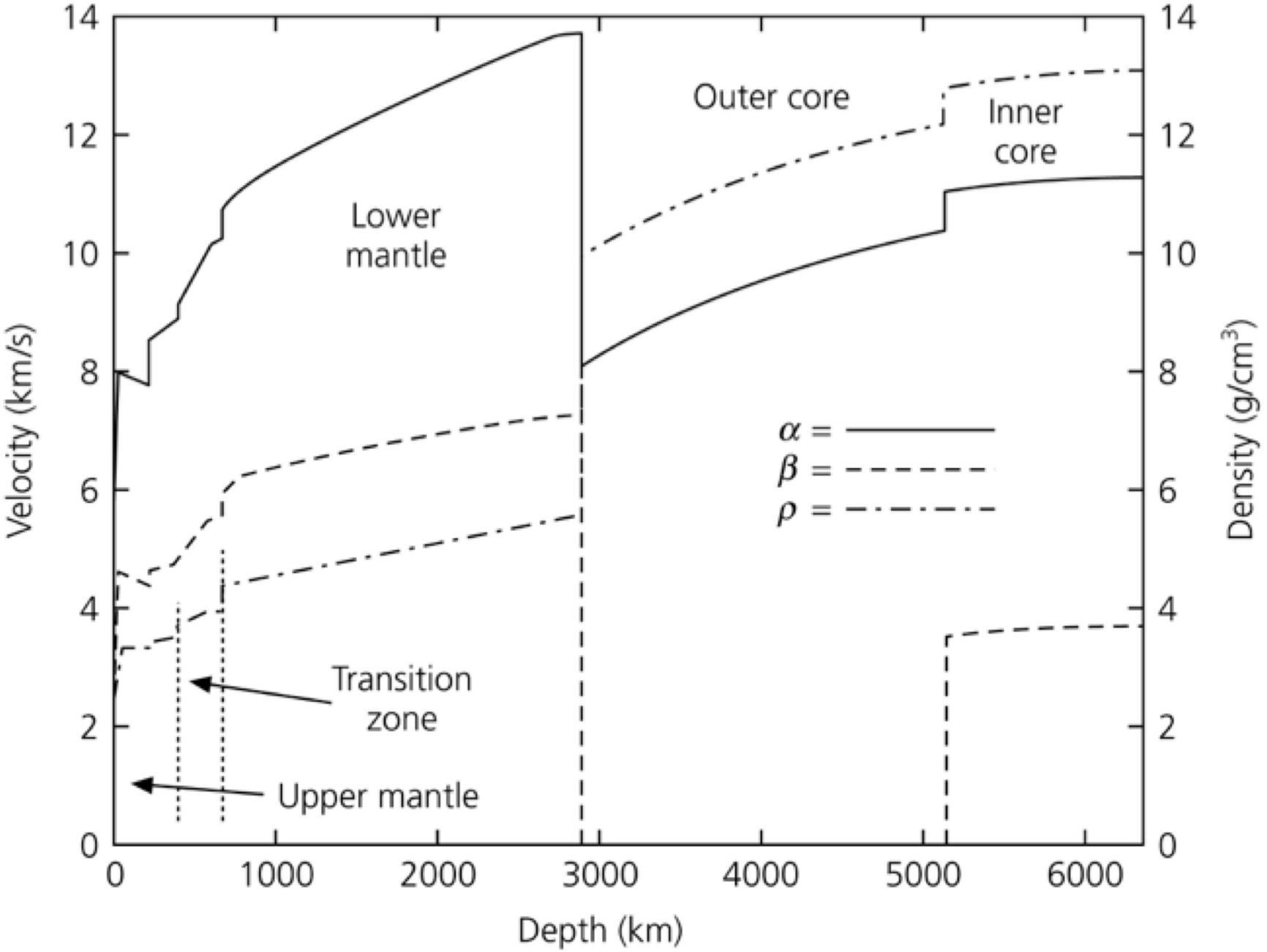
Earth's Structure

IV. The Inner Core

- Sphere of Fe with a radius of around 1200 kilometers
- Stronger than the outer core
- Behaves like a solid
- Did not exist early in Earth's history
- Started to form as Earth cooled and Fe began to crystallize at the center
- P waves passing through the inner core show increased velocity, suggesting that the inner core is solid

Figure 3.8-4: Preliminary Reference Earth Model.



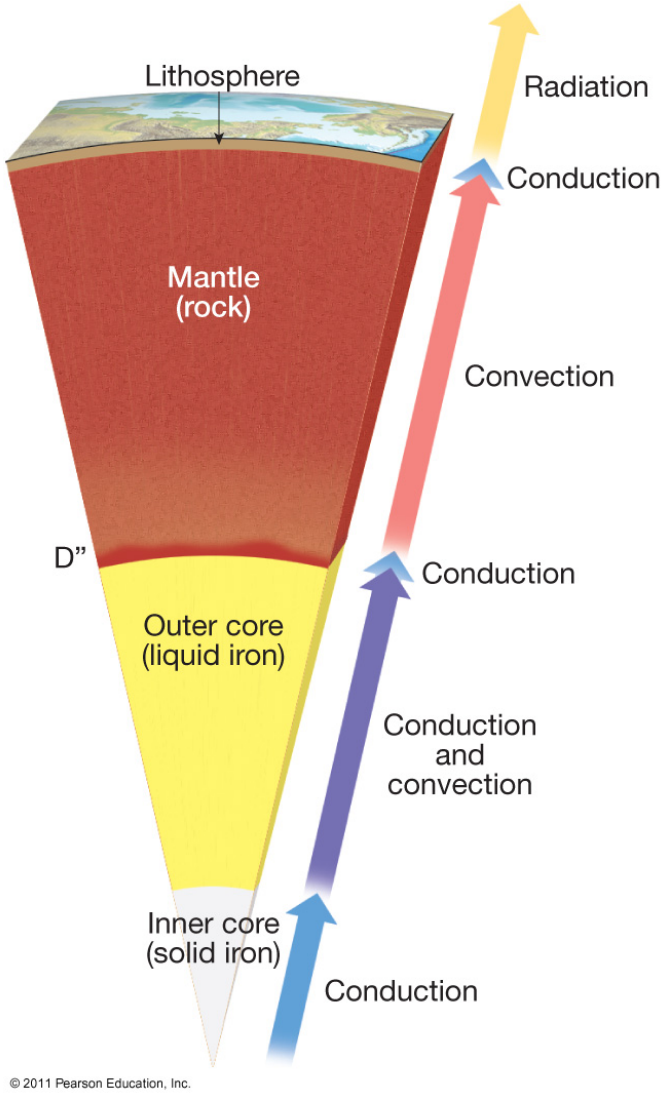
Earth's Temperature

Major processes that have contributed to Earth's internal heat

- **Heat emitted by radioactive decay of isotopes of uranium (U), thorium (Th), potassium (K), aluminum (Al), calcium (Ca), etc.**
- **Heat released as iron crystallized to form the solid inner core**
- **Heat released by collisions of countless planetesimals ("baby planets") during the formation of Earth (kinetic energy → thermal energy)**

Earth's Temperature

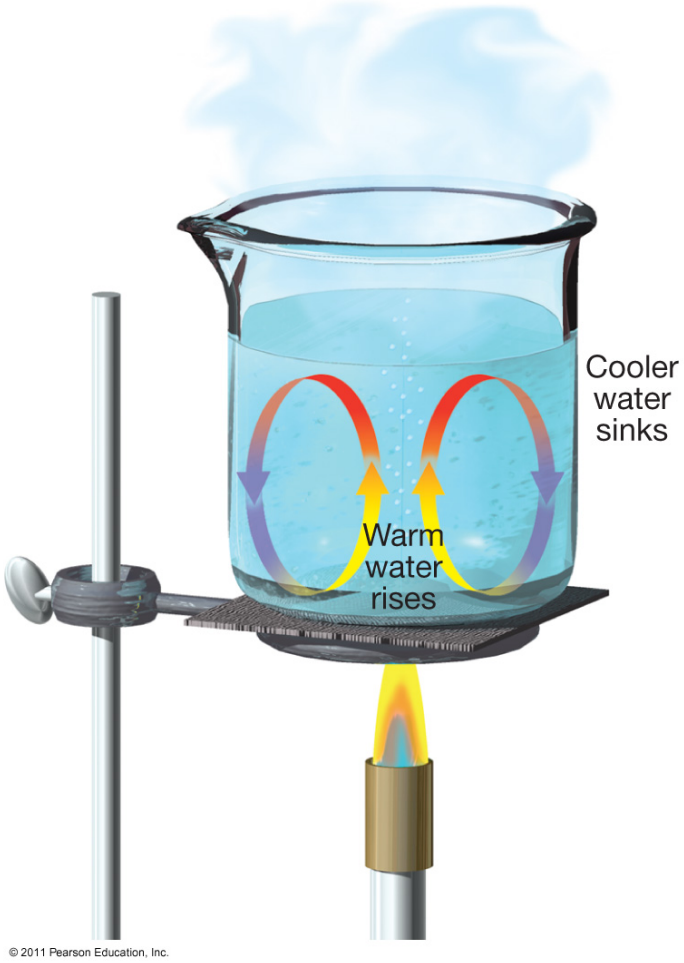
- **Heat flow**
  - **Two main processes operate within Earth's interior:**
  - ***Convection*: the *transfer of heat by moving material* in a fluid-like manner in which hot materials displace those that are cooler (or vice-versa)**
  - ***Conduction*: the *flow of heat through a material***



Earth's Temperature

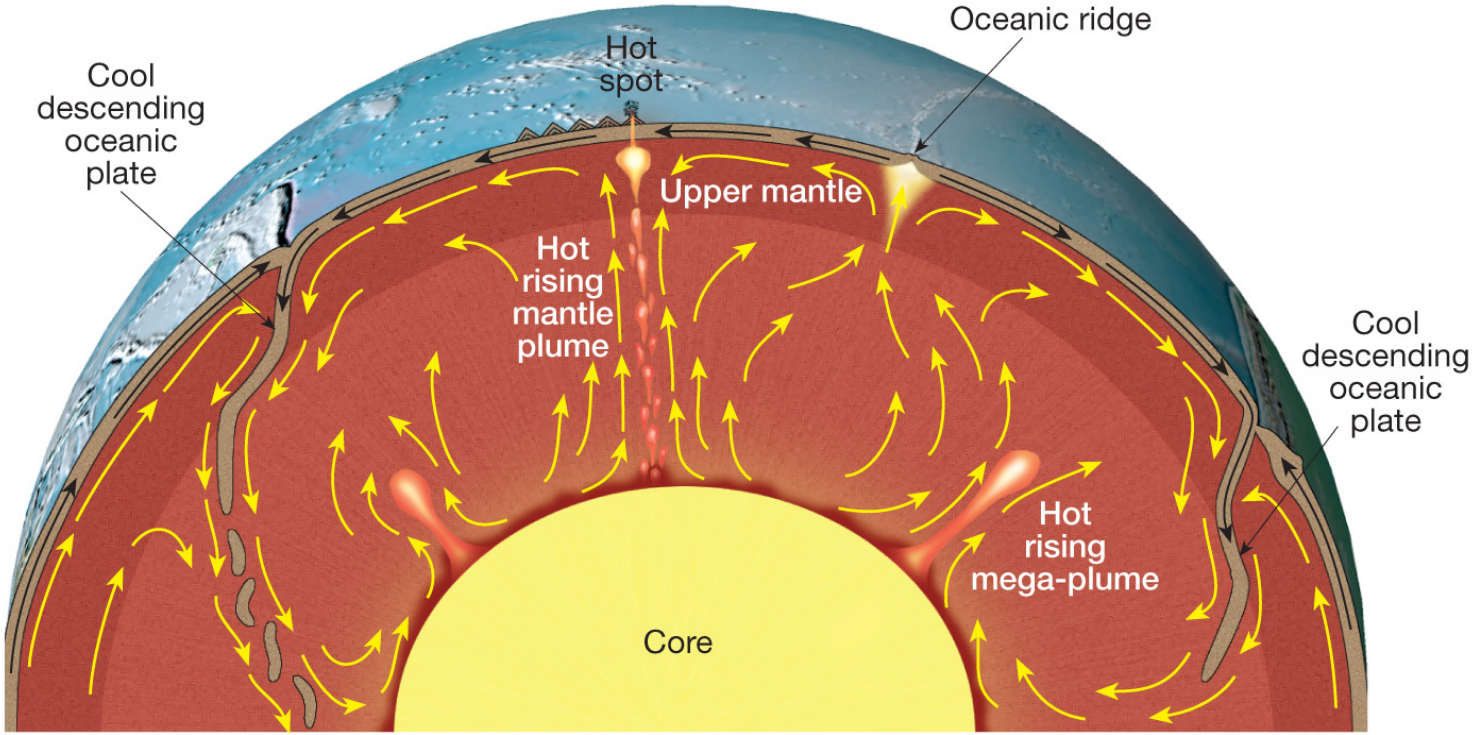
I. Convection

- Gravity is the driving force for convection, leading to gravity induced buoyancy
- Materials must also be weak enough to flow
- Resistance to flow = viscosity



Earth's Internal Heat Engine

- Mantle convection
  - Important process in Earth's interior
  - Provides the force that propels the rigid lithospheric plates across the globe.



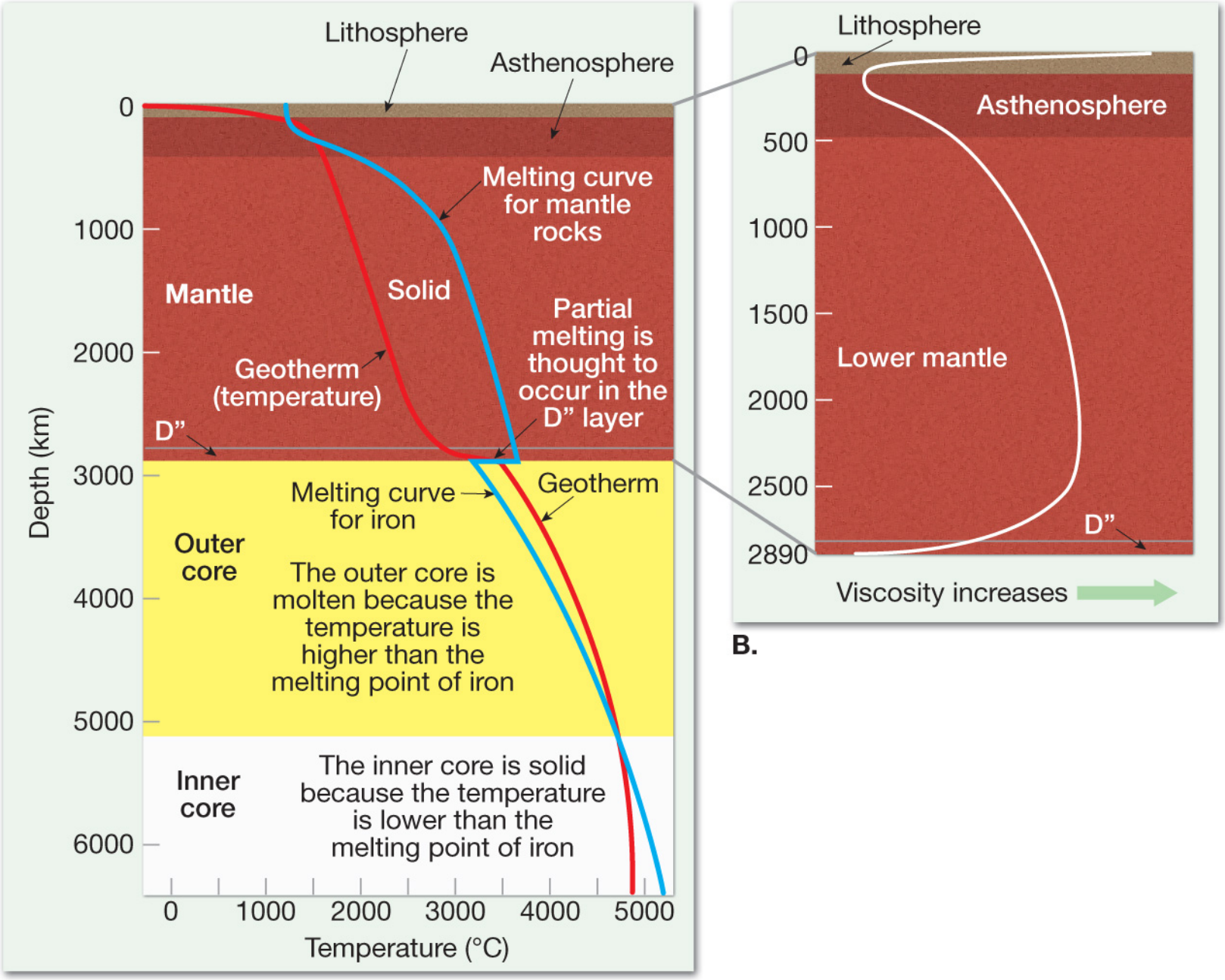
Earth's Temperature

II. Conduction

- Occurs much more quickly in metals than rocky substances
- Not an efficient way to move heat through most of Earth
- However, important mechanism in the core, D" layer, and lithosphere

Earth's Temperature Profile

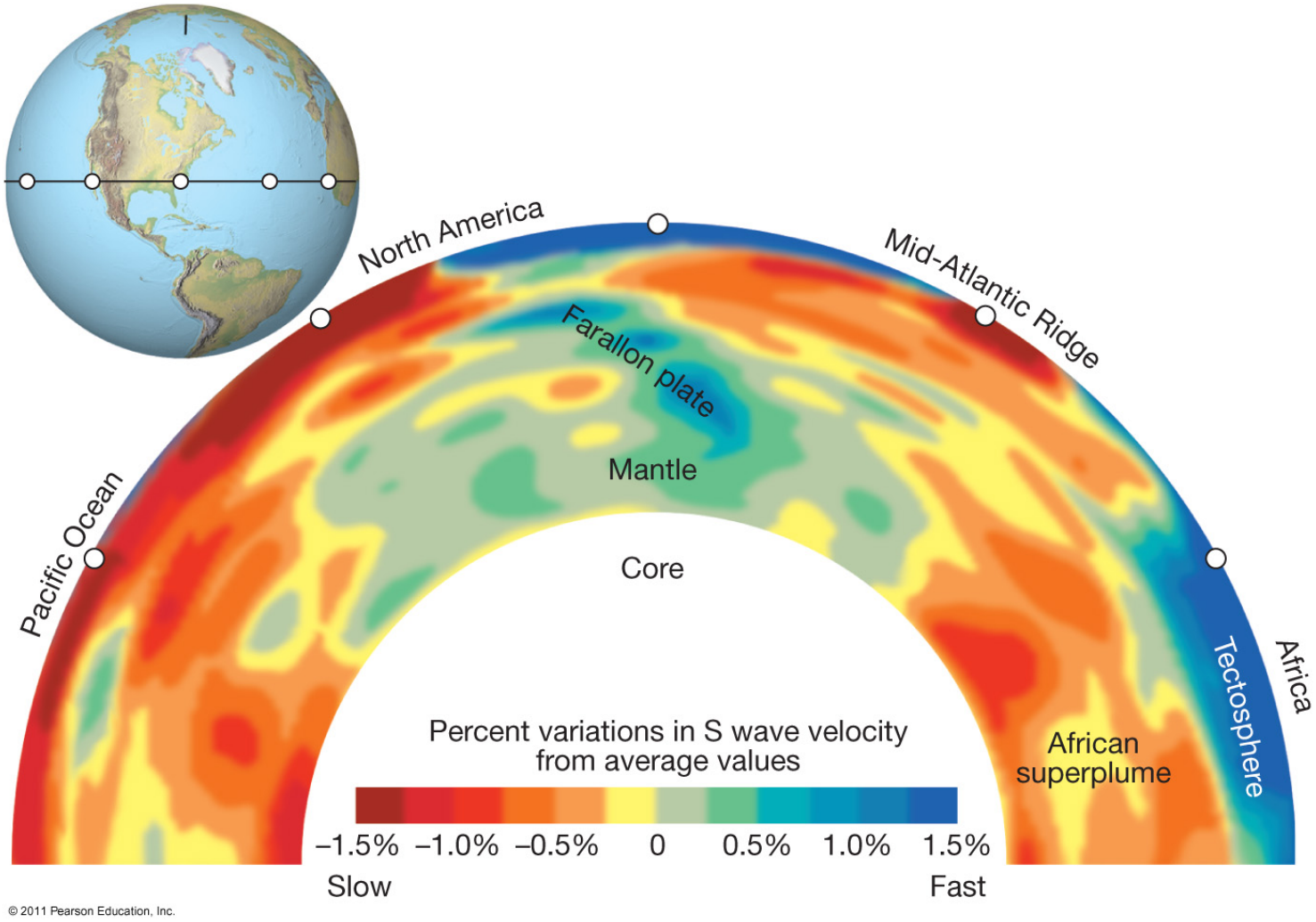
- Earth's temperature gradually increases with an increase in depth at a rate known as the **geothermal gradient.**
  - Varies considerably from place to place
  - Averages between about 20 ° and 30 °C / km in the crust (rate of increase is much less in the mantle and core)



Earth's Three-Dimensional Structure

- **Seismic tomography**
  - **Three-dimensional changes in composition and density in all parts of Earth's interior can be viewed using seismic waves.**
    - **The continental lithosphere can extend hundreds of kilometers into the mantle.**
    - **Cold, subducted oceanic lithosphere sinks to the base of the mantle, while mega-plumes rise upward from the core–mantle boundary.**

Seismic Tomographic Slice Through the Earth



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