Introduction to Earth Science (ES1101)

Autumn 2024

Exploring Earth's Interior using Seismic Waves

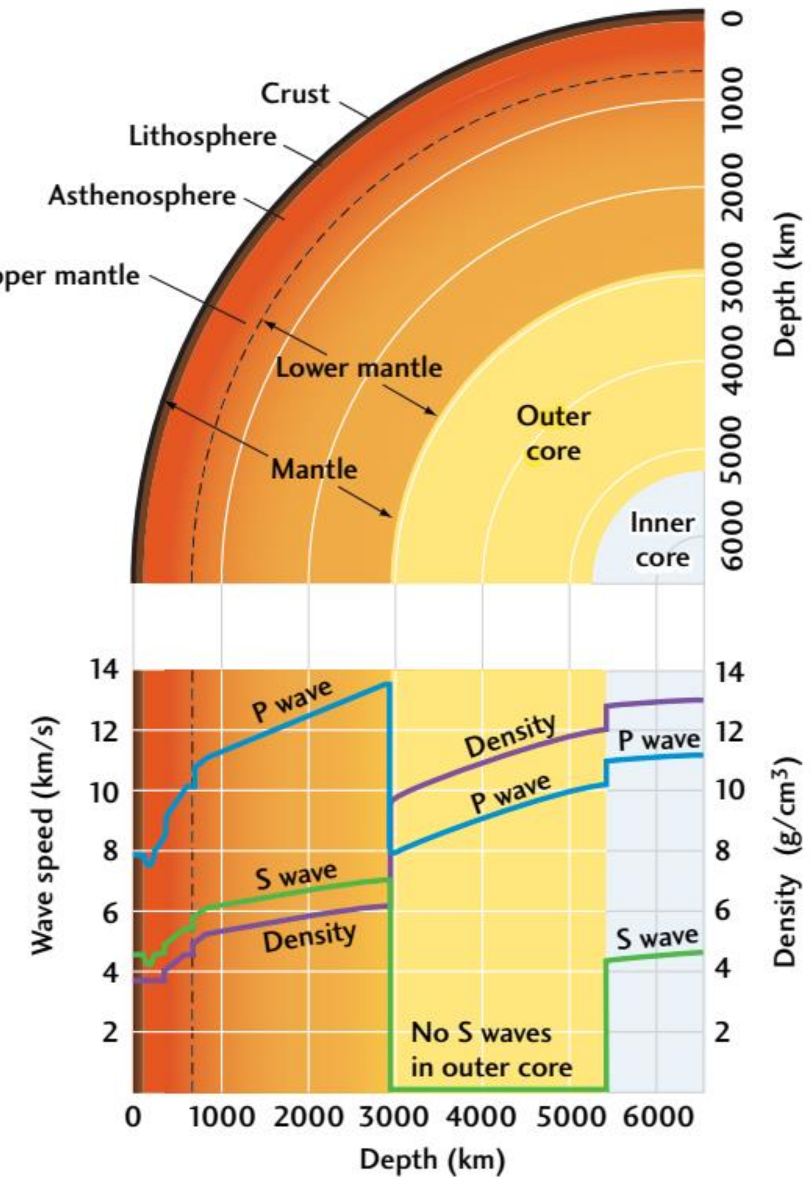


FIGURE 14.7 ■ Earth's layering as revealed by seismology. The lower diagram shows changes in P-wave and S-wave velocities and rock densities with depth. The upper diagram is a cross section through Earth on the same depth scale, showing how those changes are related to the major layers (see also Figure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

Exploring Earth's Interior using Seismic Waves

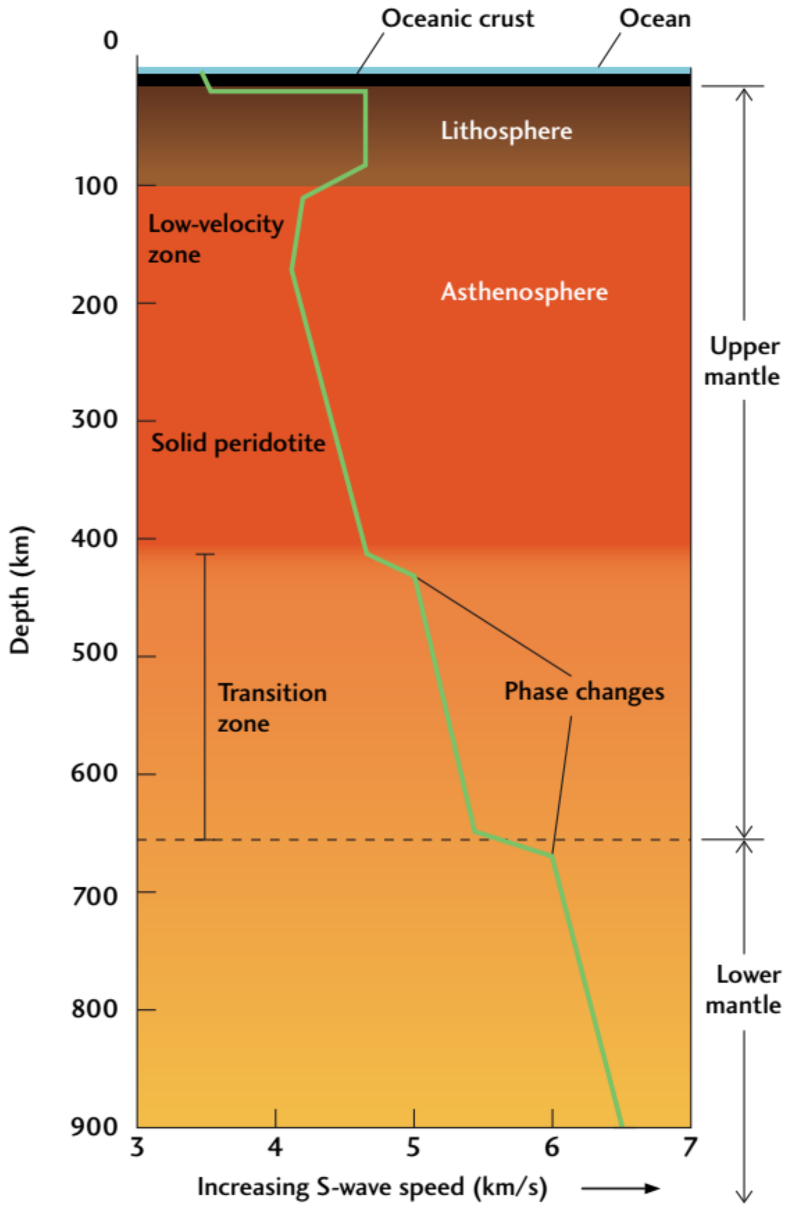
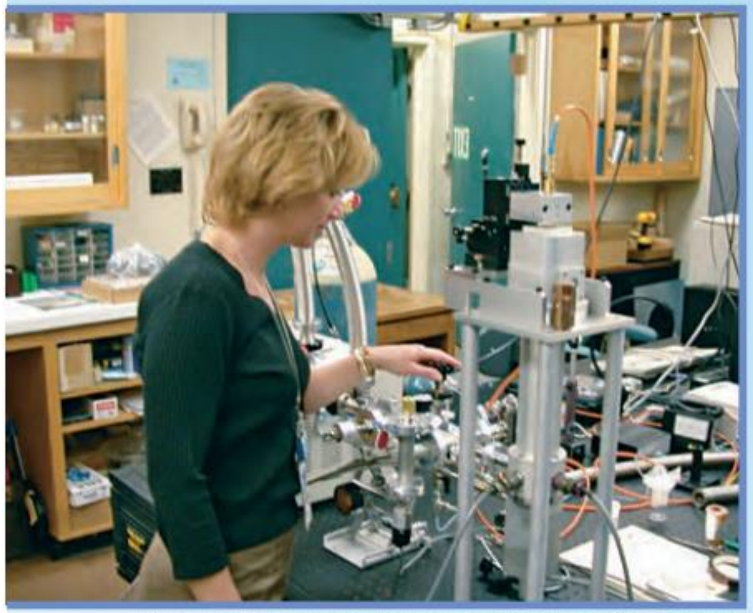


FIGURE 14.8 ■ The structure of the mantle beneath old oceanic lithosphere, showing S-wave velocities to a depth of 900 km. Changes in S-wave velocity mark the strong, brittle lithosphere, the weak, ductile asthenosphere, and a transition zone, in which increasing pressure forces rearrangements of atoms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

GEO GRAPHICS 12.1

Recreating the Deep Earth

Seismology alone cannot determine the nature of the materials deep in Earth's interior. Additional information must be obtained by other techniques. Mineral physics experiments can measure physical properties of rocks and minerals such as stiffness, compressibility, and density while simulating the extreme conditions of the mantle and core.

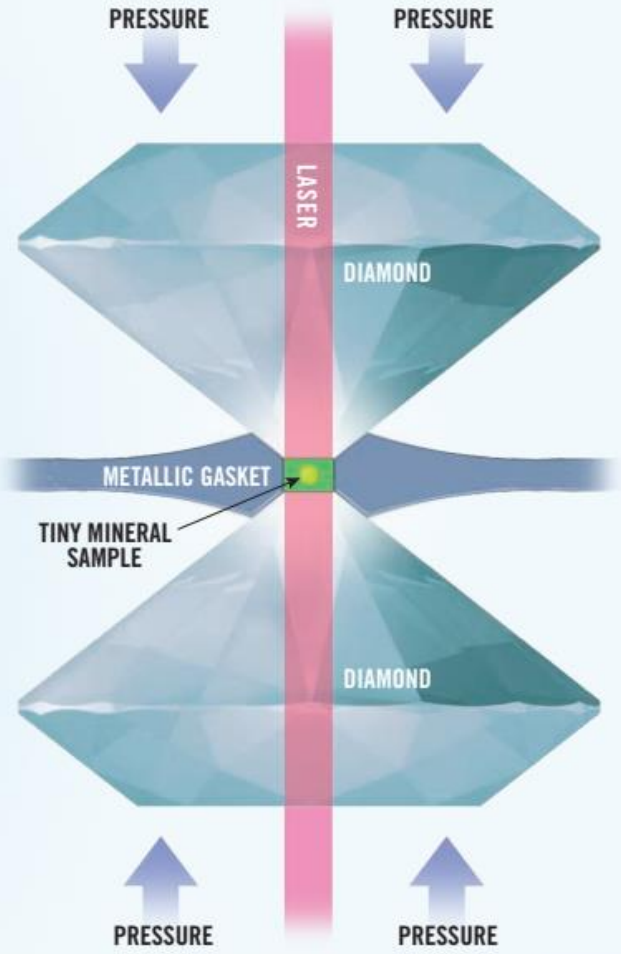


C.Arache, D. Jackson and S.T. Weir/Lawrence Livermore National Laboratory

One experiment examines the temperatures and pressures at which one mineral phase will become unstable and convert into a new "high-pressure" phase. These experiments are useful because they help identify where phase changes take place within Earth.

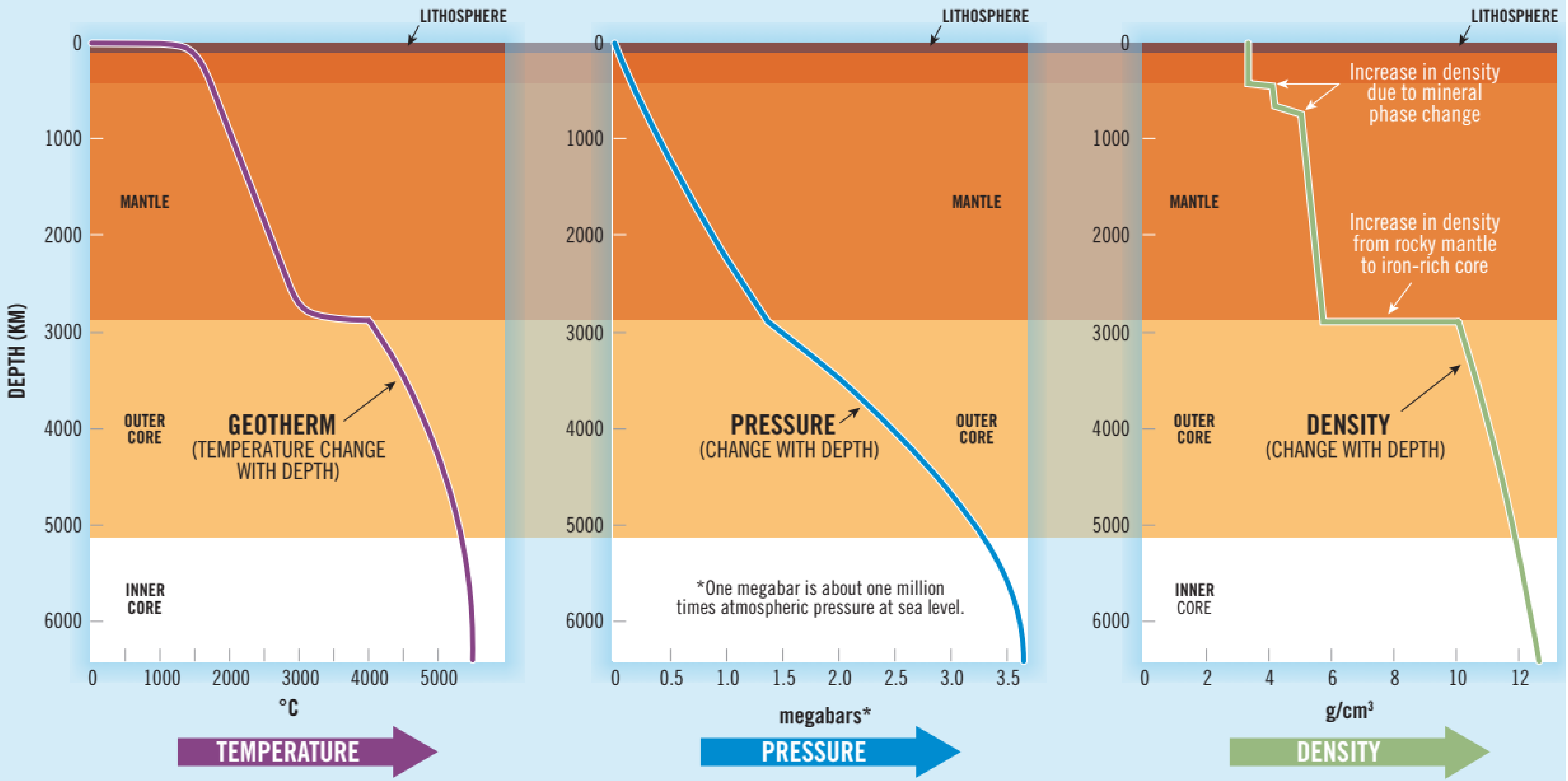
Most mineral physics experiments are conducted using diamond-anvil presses like the one shown here. These take advantage of two important properties of diamonds—hardness and transparency. The tips of two diamonds are cut off, and a small mineral sample is placed between them. By squeezing two diamonds together, pressures as high as our planet's interior have been simulated. High temperatures are achieved by firing a laser beam through the diamond and into the mineral sample.

Douglas L. Peck Photography



Question:
What two properties of diamonds make them ideal for use in a diamond-anvil press?

These experiments have also helped identify where changes in temperature, pressure, and density occur in Earth's interior, as shown in the graphs below.



Heat Sources in the Earth

- **Heat from the early accretion and differentiation of Earth:**
  - **Kinetic energy released by impacts with the planetesimals heated its outer regions.**
  - **Gravitational energy released by differentiation of the core heated its deep interior.**

- **Heat released by the radioactive decay of unstable nuclei.**

Heat transfer

- **Radiation**
- **Conduction**
- **Convection**

Heat Sources in the Earth

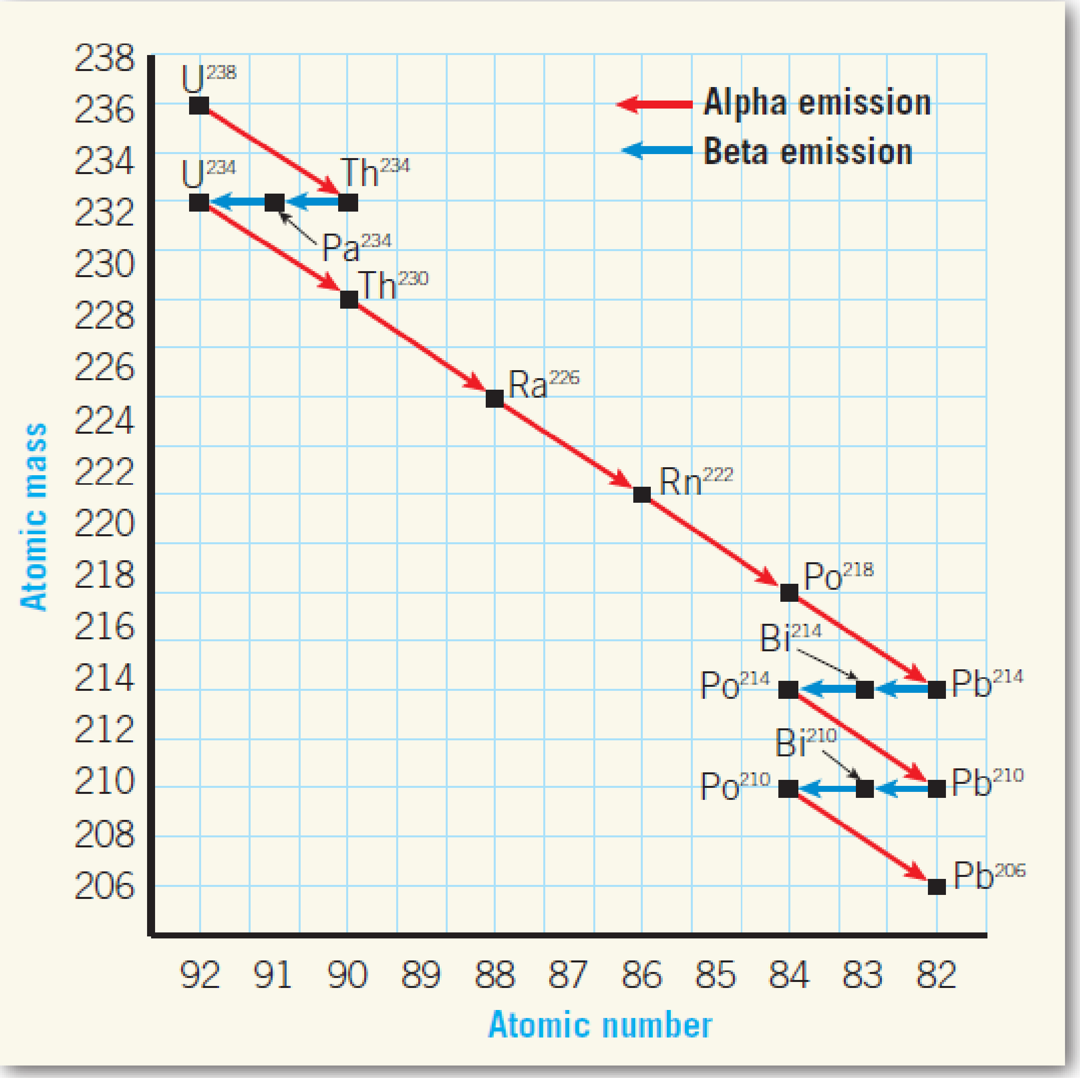


TABLE 9.1 Isotopes Frequently Used in Radiometric Dating

Radioactive Parent	Stable Daughter Product	Currently Accepted Half-Life Values
Uranium-238	Lead-206	4.5 billion years
Uranium-235	Lead-207	704 million years
Thorium-232	Lead-208	14.1 billion years
Rubidium-87	Strontium-87	47.0 billion years
Potassium-40	Argon-40	1.3 billion years

Heat Sources in the Earth

Table 7.2 *Relative abundances of isotopes and crustal heat generation in the past relative to the present*

	Relative abundance					Heat generation	
Age (Ma)	^{238}U	^{235}U	U[a]	Th	K	Model A[b]	Model B[c]
Present	1.00	1.00	1.00	1.00	1.00	1.00	1.00
500	1.08	1.62	1.10	1.03	1.31	1.13	1.17
1000	1.17	2.64	1.23	1.05	1.70	1.28	1.37
1500	1.26	4.30	1.39	1.08	2.22	1.48	1.64
2000	1.36	6.99	1.59	1.10	2.91	1.74	1.98
2500	1.47	11.4	1.88	1.13	3.79	2.08	2.43
3000	1.59	18.5	2.29	1.16	4.90	2.52	3.01
3500	1.71	29.9	2.88	1.19	6.42	3.13	3.81

[a] This assumes a present-day isotopic composition of 99.2886% ^{238}U and 0.7114% ^{235}U.

[b] Model A, based on Th/U = 4 and K/U = 20 000.

[c] Model B, based on Th/U = 4 and K/U = 40 000.

Source: Jessop and Lewis (1978).

Geothermal Gradient

- **Heat is transported in the lithosphere by conduction mainly.**
- **Measurement of heat flow shows that continental areas have lower heat flows than ocean basins.**
- **Consequently, the continental geotherm is located at relatively lower temperature side of the oceanic geotherm in the lithosphere.**
- **From the asthenosphere downwards in the mantle, heat transport is primarily by convection, which should theoretically homogenize the temperature distribution, and the two geotherms should merge.**
- **There are various estimates of geothermal gradients in the lithosphere, but The continental geotherm is always at lower temperatures than the oceanic geotherm.**

Geothermal Gradient

~15°C/km to 75 °C/km in lithosphere

~0.5°C/km in convective mantle

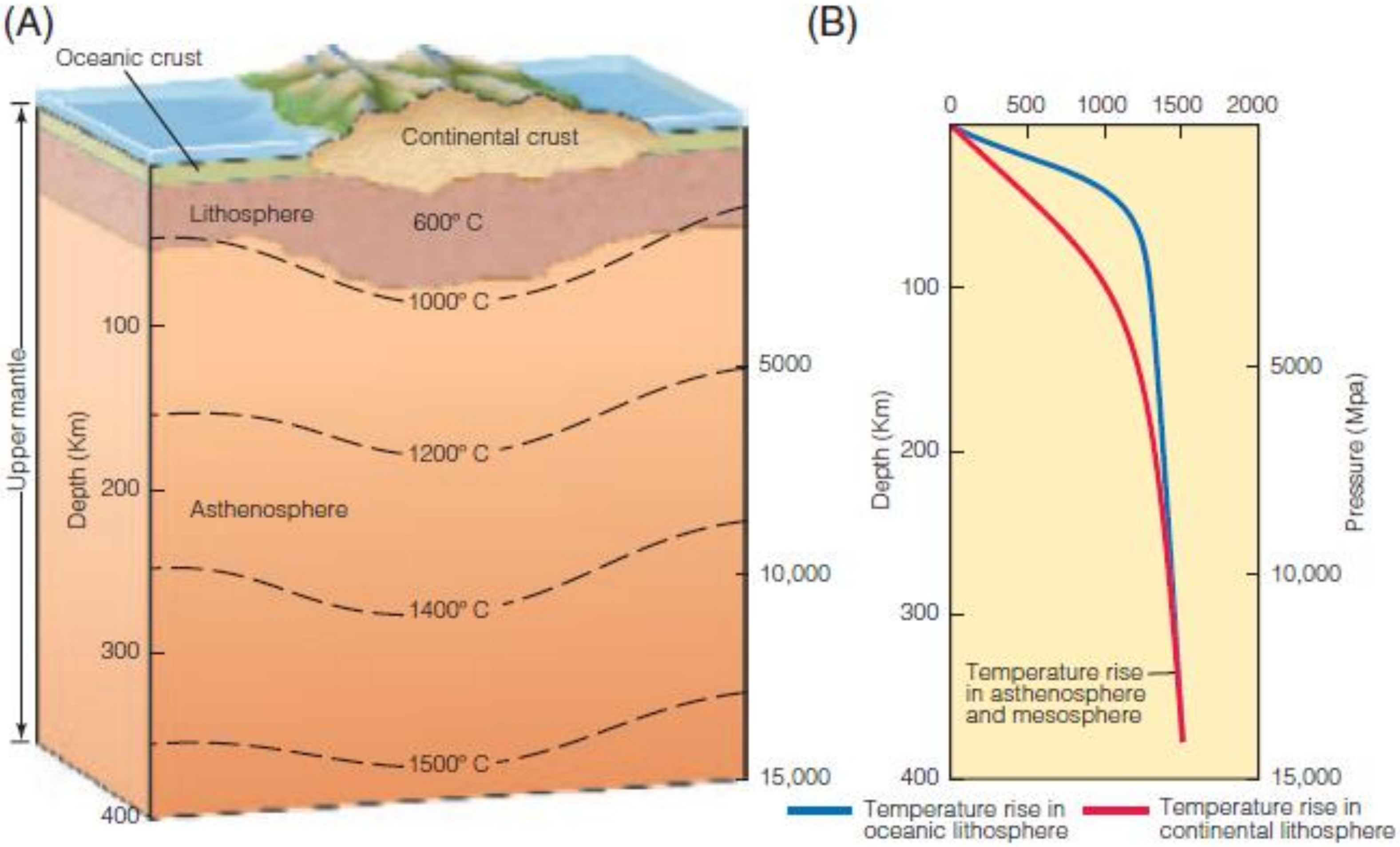


FIGURE 2.11 Geothermal gradient
Temperature increases with depth. (A). The dashed lines are *isotherms*, lines of equal temperature. Temperature increases more slowly under the continents than under the oceans. The lithosphere is thicker under the continents, so heat flows more slowly to the surface in those areas. (B). This is the same information as shown in (A) but in graph form. Earth's surface is at the top, so depth (and corresponding pressure) increases downward. Temperature increases from left to right.

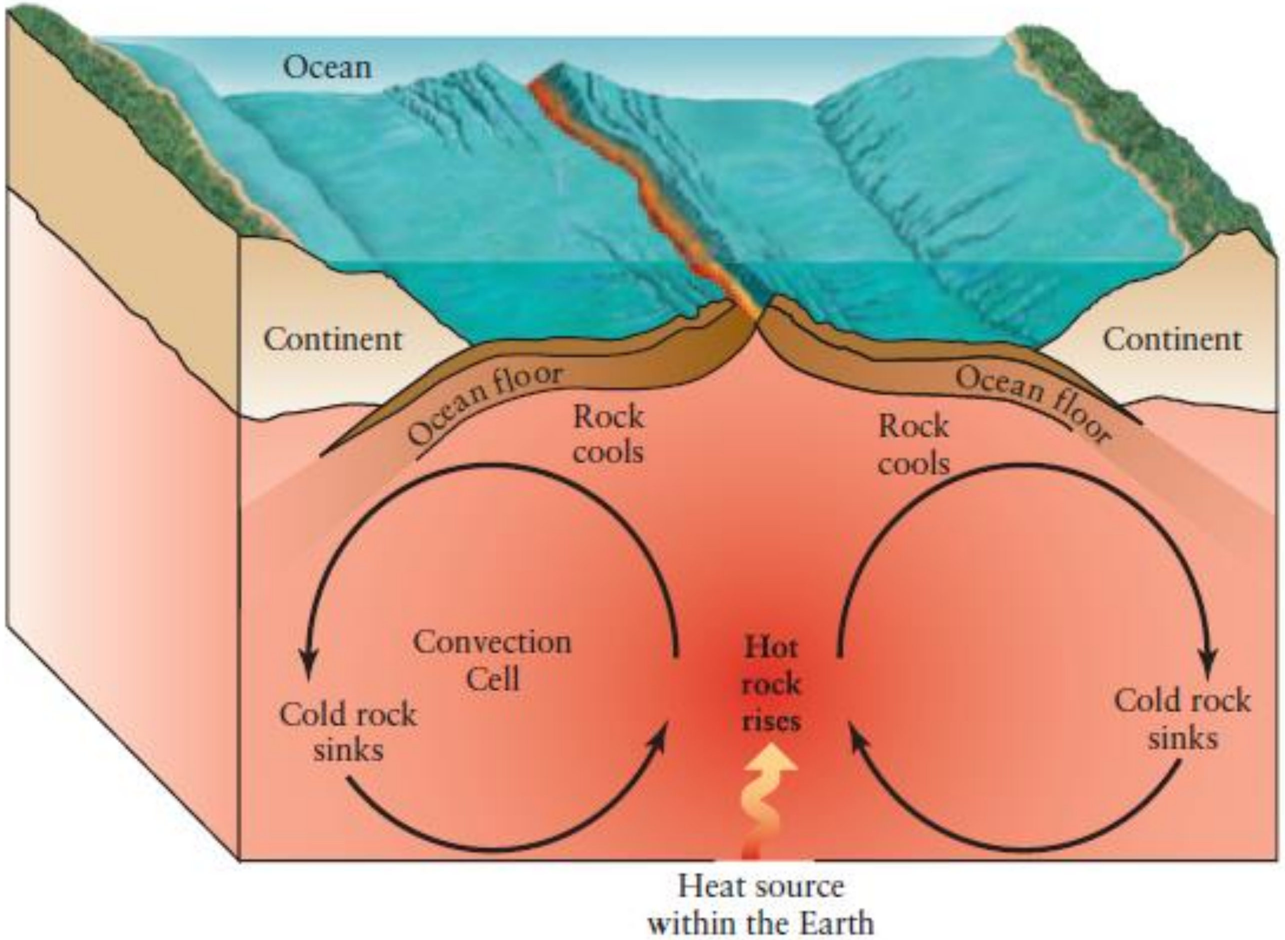


FIGURE 2.10 Convection in Earth's interior
Hot rock rises slowly from deep inside Earth, cools, flows sideways, and sinks. The rising hot rocks and sideways flow are the source of plate tectonic motion, and have an enormous influence on the shapes and distribution of land masses and ocean basins on Earth's surface.

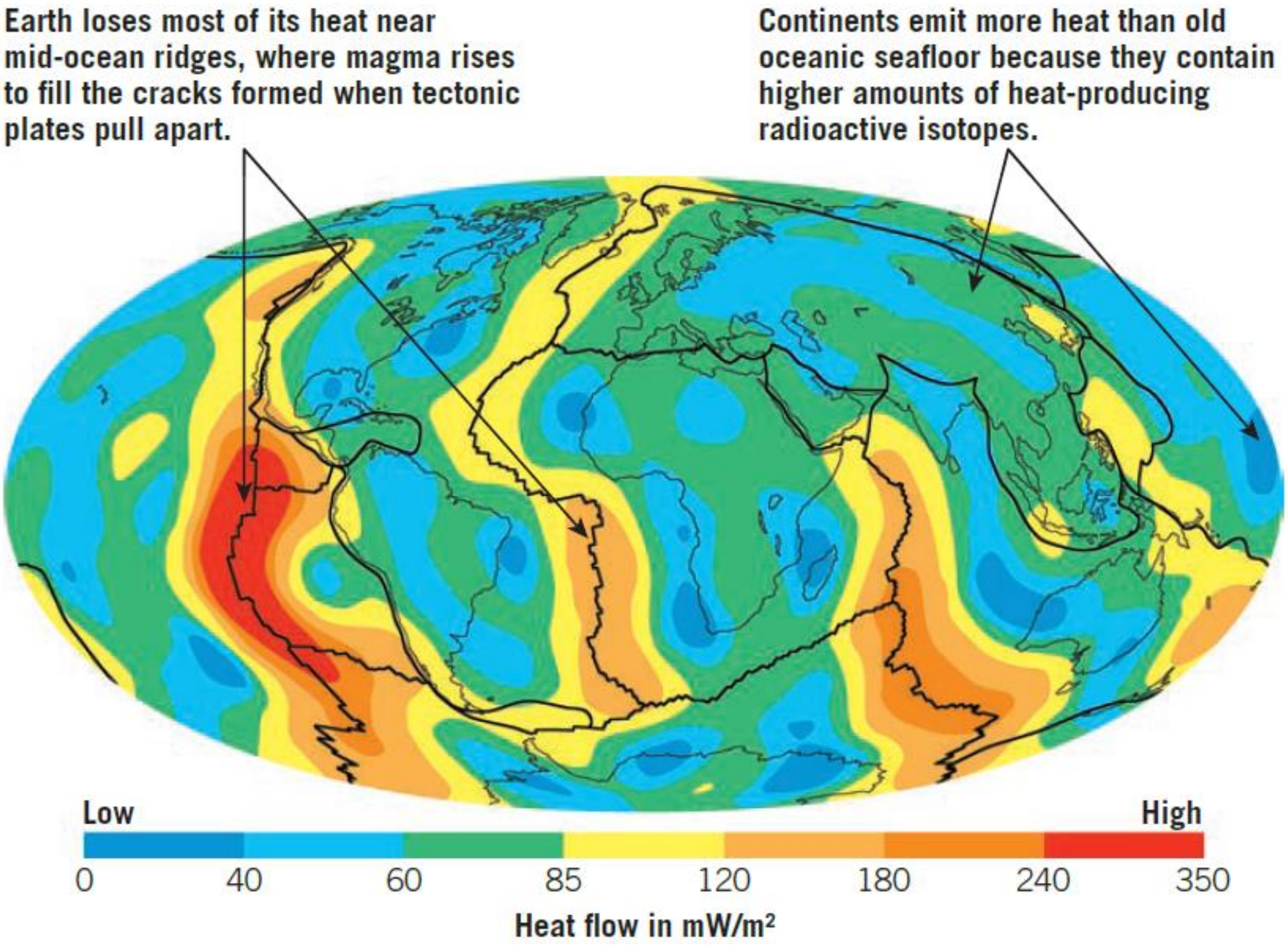
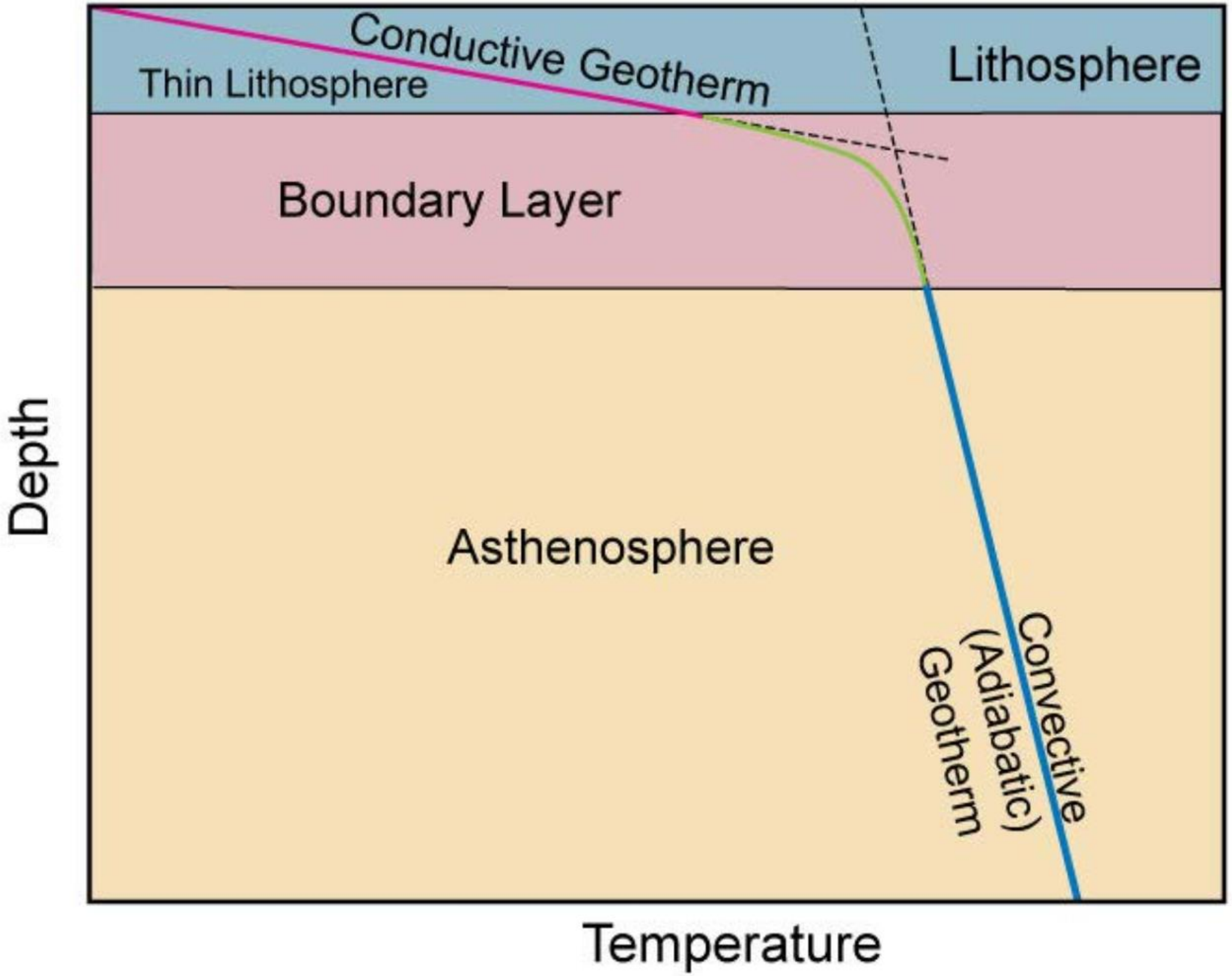


Figure 12.12

Rate of heat flow at Earth's surface A map of the rate of heat flow out of Earth as it gradually cools over time, measured in milliwatts per square meter.

Geothermal Gradient

Figure 1.9 Diagrammatic cross-section through the upper 200-300 km of the Earth showing geothermal gradients reflecting more efficient adiabatic (constant heat content) convection of heat in the mobile asthenosphere (steeper gradient in blue)) and less efficient conductive heat transfer through the more rigid lithosphere (shallower gradient in red). The boundary layer is a zone across which the transition in rheology and heat transfer mechanism occurs (in green). The thickness of the boundary layer is exaggerated here for clarity: it is probably less than half the thickness of the lithosphere.



Conductive Heat Flow

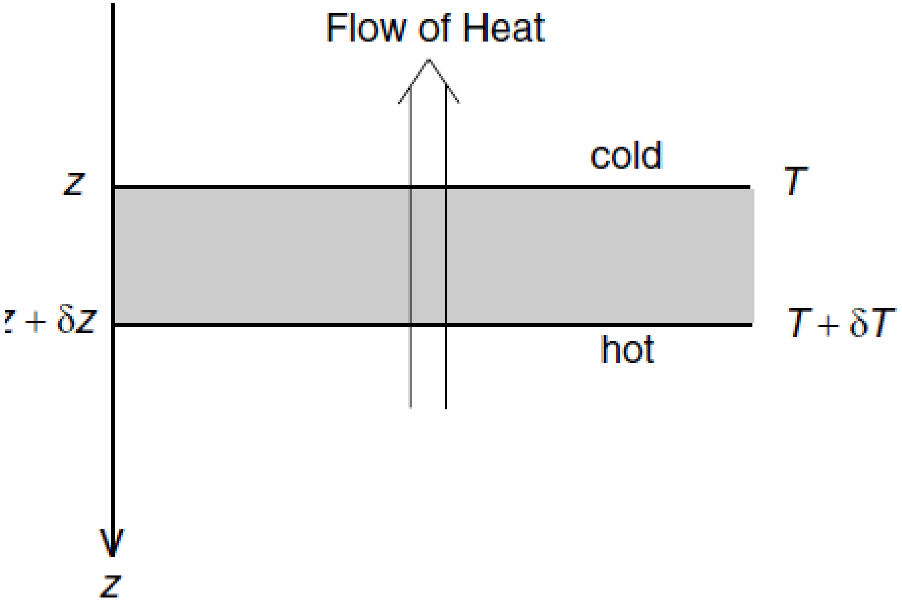
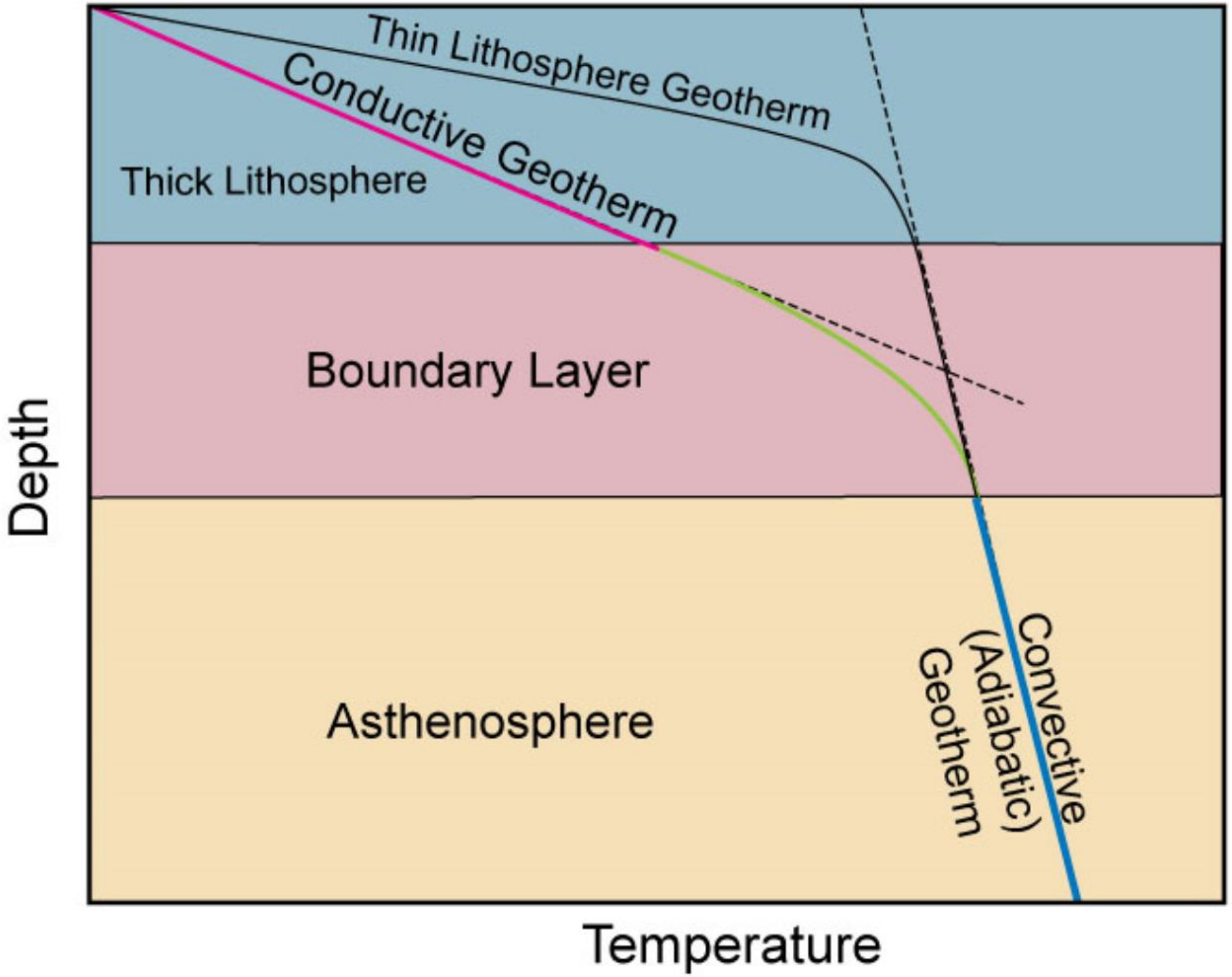


Figure 7.1. Conductive transfer of heat through an infinitely wide and long plate δz in thickness. Heat flows from the hot side of the slab to the cold side (in the negative z direction).

$$Q(z) = -k\frac{\partial T}{\partial z}$$

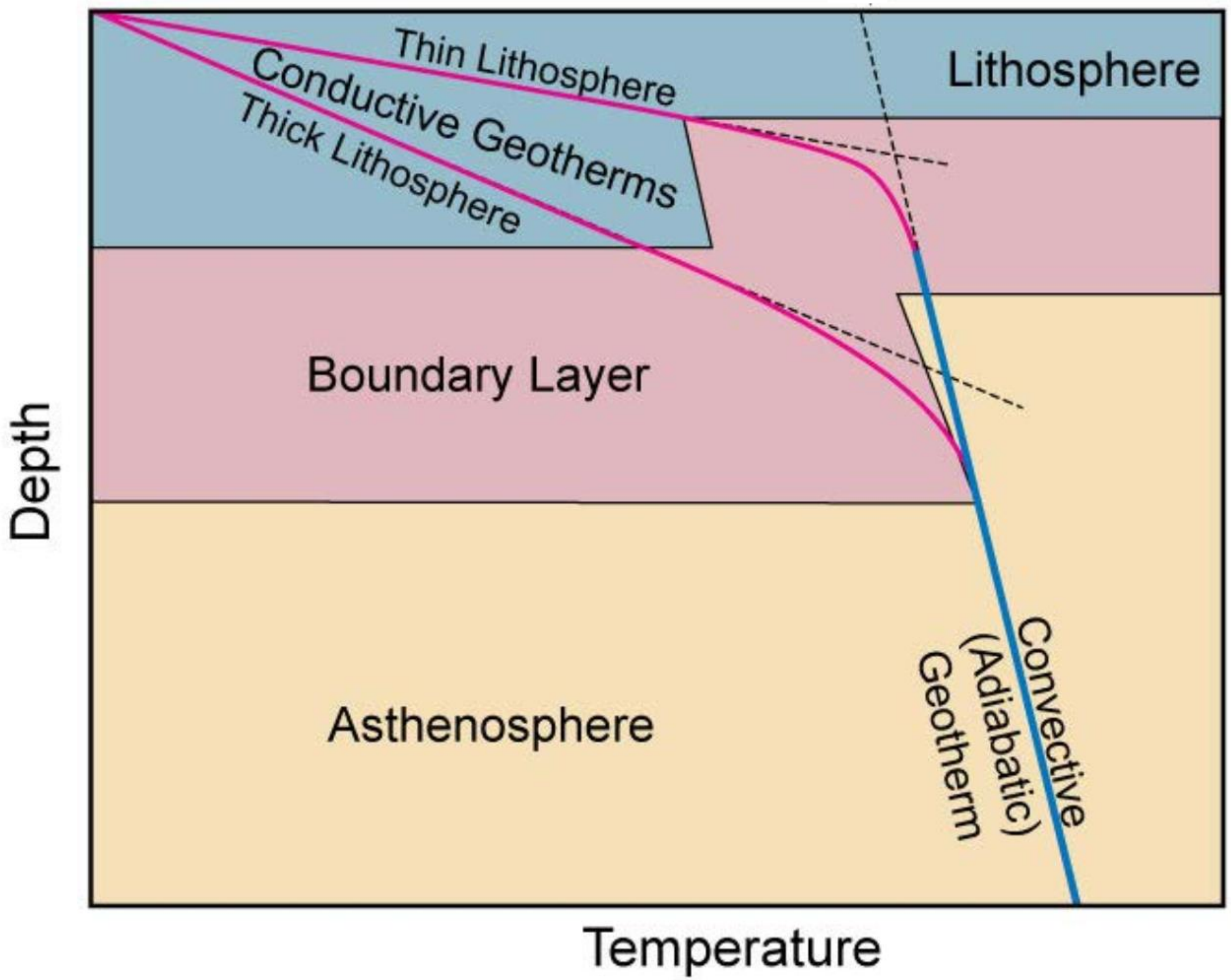
Geothermal Gradient

Figure 1.9 A similar example for **thick** (continental) lithosphere.



Geothermal Gradient

Figure 1.9 Notice that thinner lithosphere allows convective heat transfer to shallower depths, resulting in a **higher** geothermal gradient across the boundary layer and lithosphere.



Geothermal Gradient: an estimate

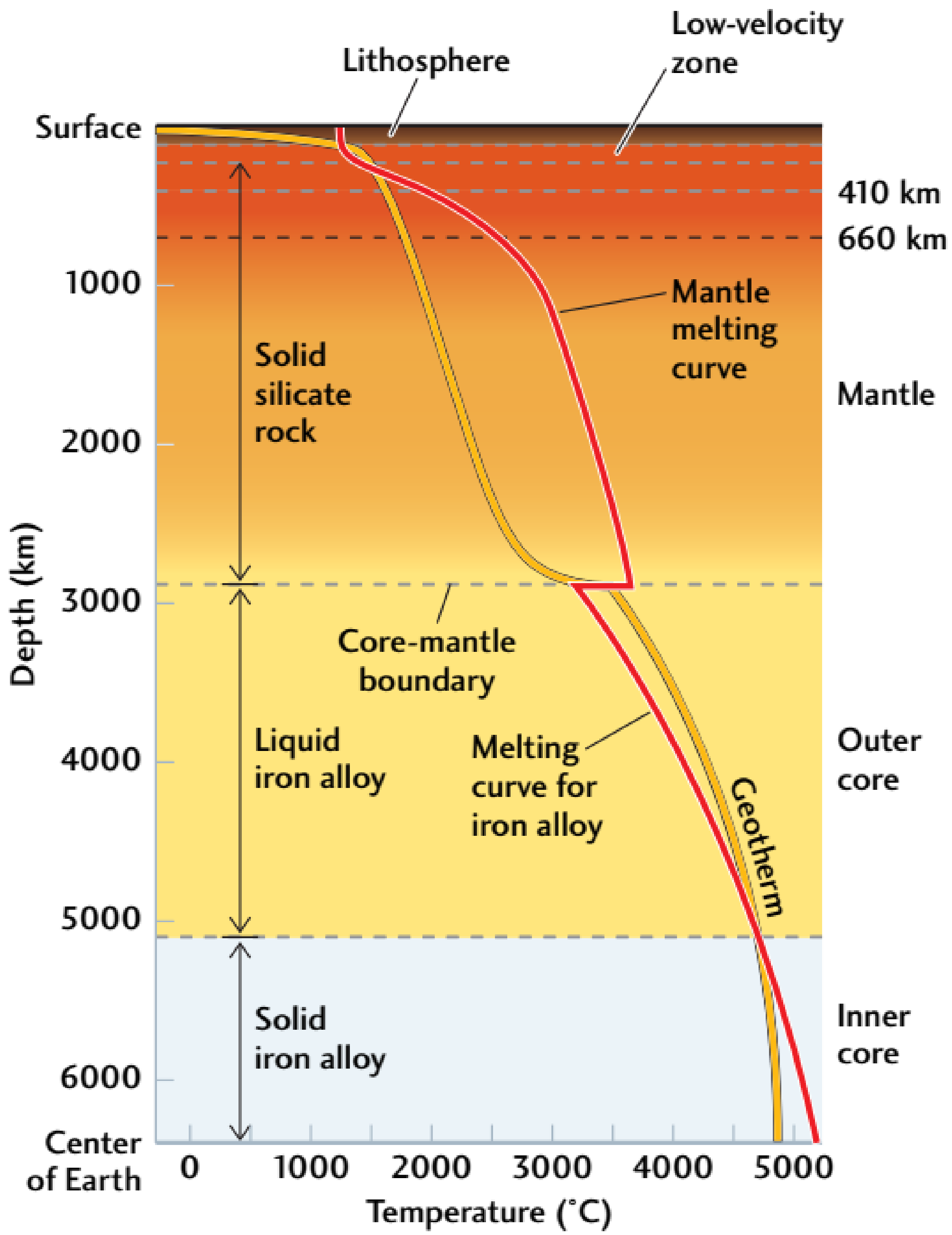
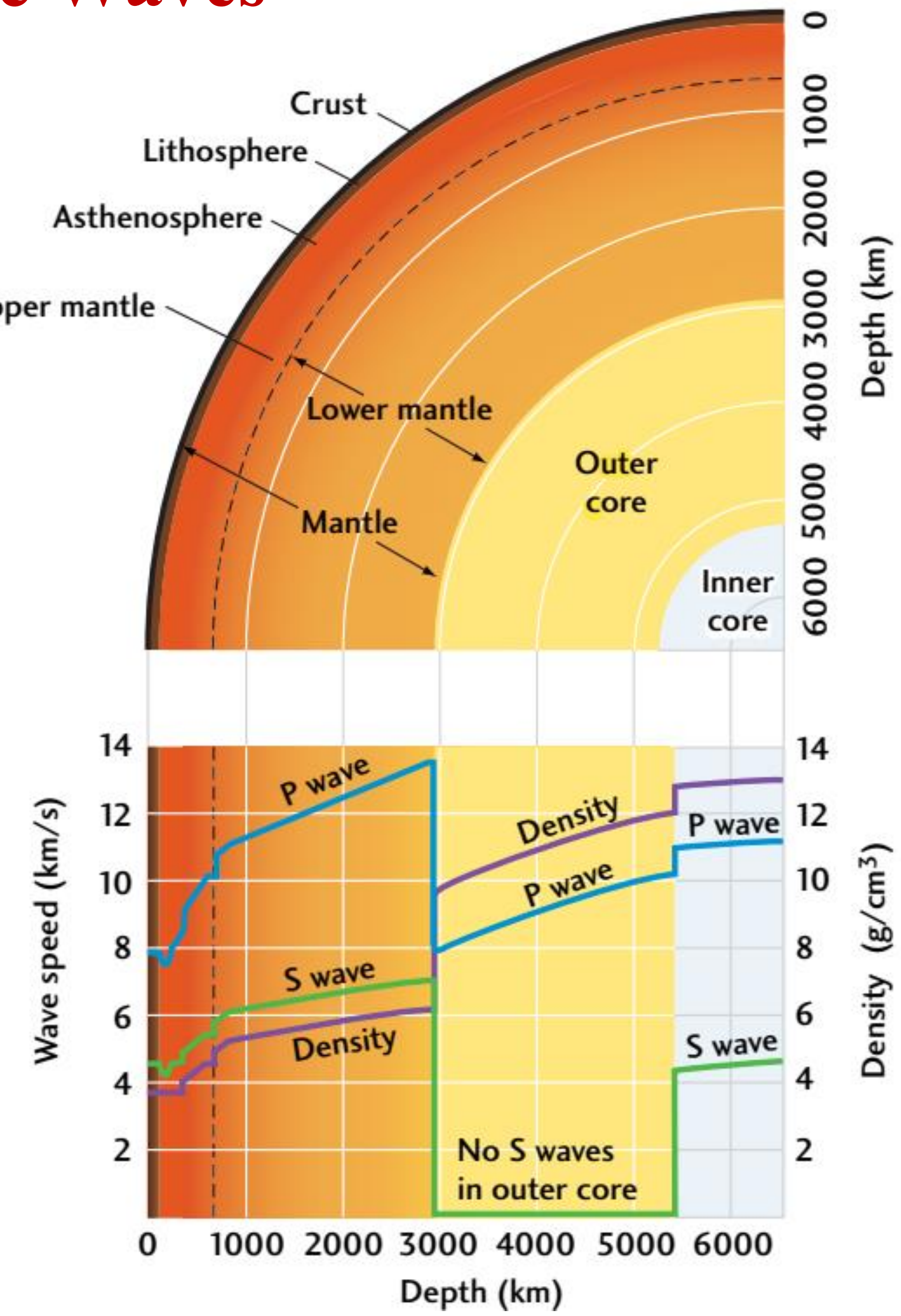


FIGURE 14.10 ■ An estimate of Earth's geotherm, which describes the increase in temperature with depth (yellow line). The geotherm first rises above the melting curve—the temperature at which peridotite begins to melt (red line)—in the upper mantle, forming the partially molten low-velocity zone. It does so again in the outer core, where the iron-nickel alloy is in a liquid state. The geotherm falls below the melting curve throughout most of the mantle and in the solid inner core.

Exploring Earth's Interior using Seismic Waves



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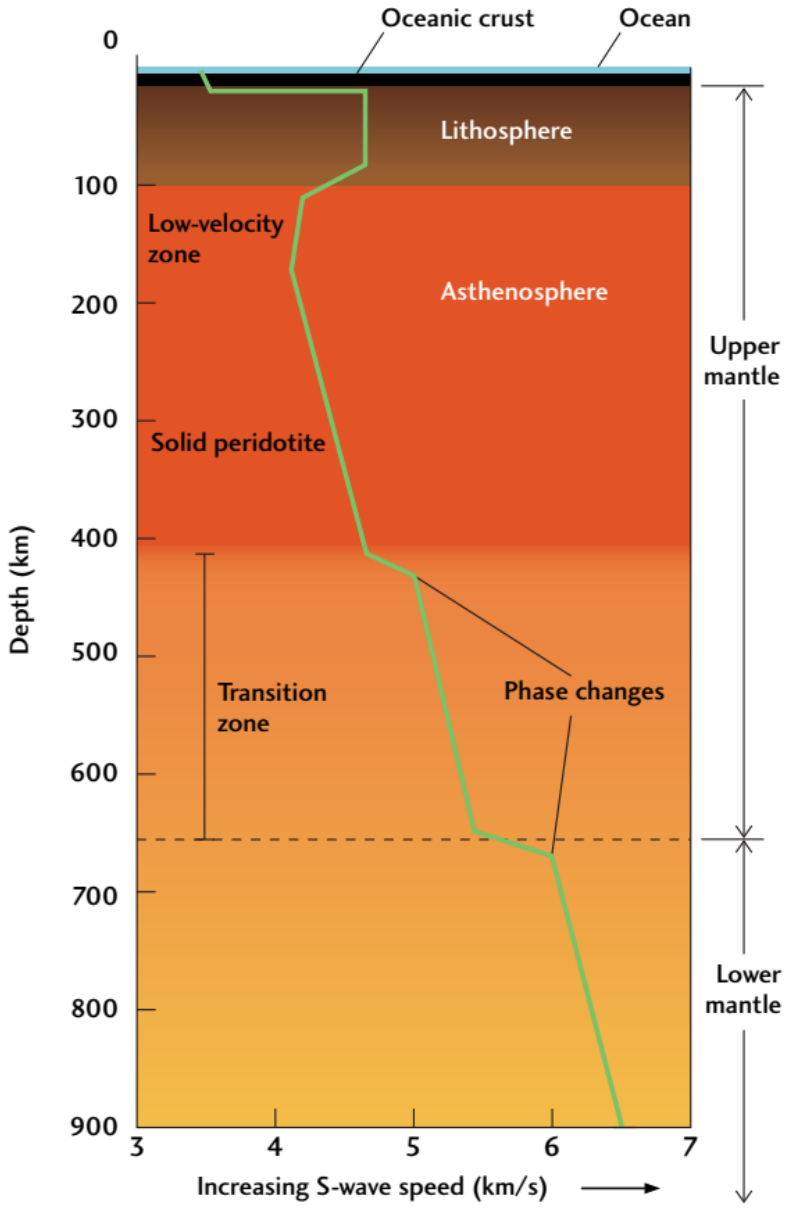
Exploring Earth’s Interior using Seismic Waves



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Phase Transitions in Olivine

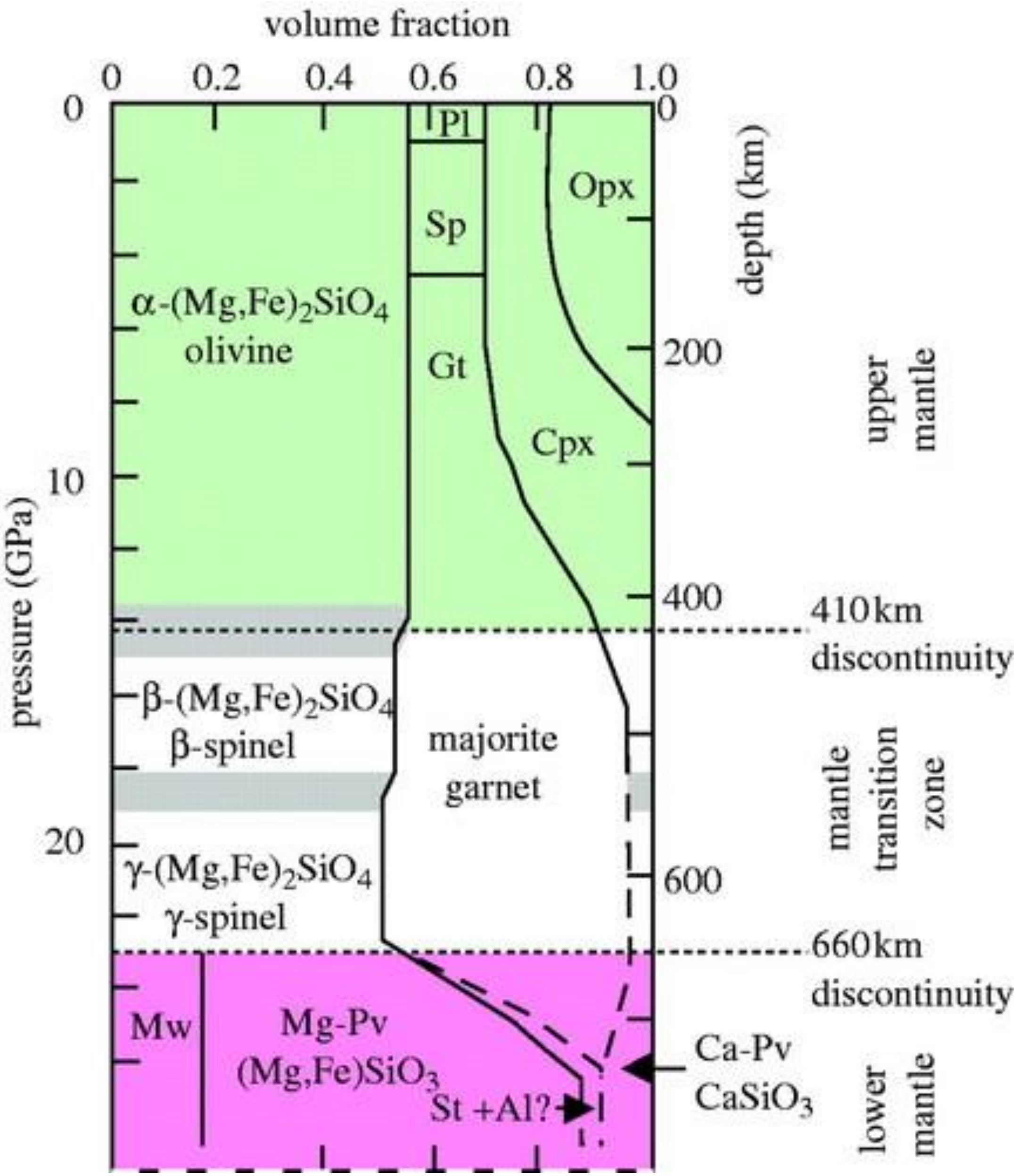


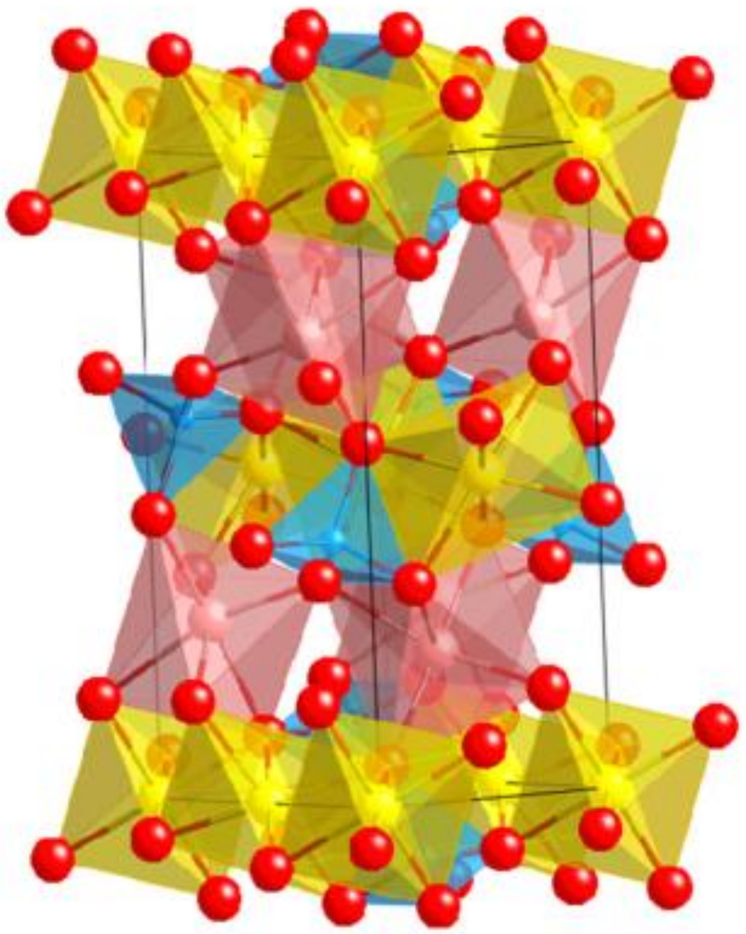
Figure 1. Schematic of the volumetric mineral constitution of a peridotite mantle down to the lower mantle (modified after Ito & Takahashi 1987). Peridotite is a dense coarse-grained igneous rock consisting mainly of olivine and pyroxene. It is high in Fe and Mg and contains less than 45% Si. Peridotite 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–$SiO_2$.

https://royalsocietypublishing.org/doi/10.1098/rsta.2005.1675

Some interesting facts about Olivine

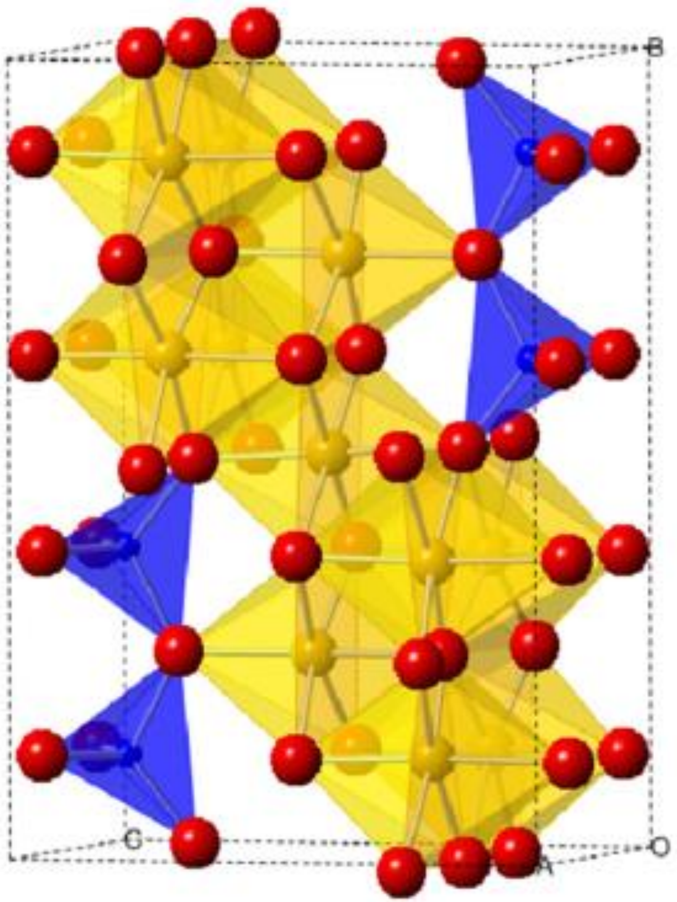
- **Nesosilicate: Isolated SiO_4 tetrahedra**
- **Most common mineral in the Earth's upper mantle.**
- **Chemical Formula: $(Mg, Fe)_2SiO_4$**
- **Mg, and Fe forms MO_6 octahedra that link SiO_4 tetrahedra**
- **Olivine is orthorhombic near surface conditions and usually called α −olivine.**
- **At higher P-T, olivine changes to β −olivine which is also called wadsleyite. β −olivine contains sites having OH.**
- **The wadsleyite structure is currently of great interest because it is being invoked as a reservoir of water (as chemically bound OH) in the Earth's mantle.**
- **At more higher pressure P-T conditions, β −olivine changes to γ −olivine which also contains OH.**
- **At even more higher P-T conditions, γ −olivine changes to bridgmanite (perovskite structure).**

Phase Transitions in Olivine



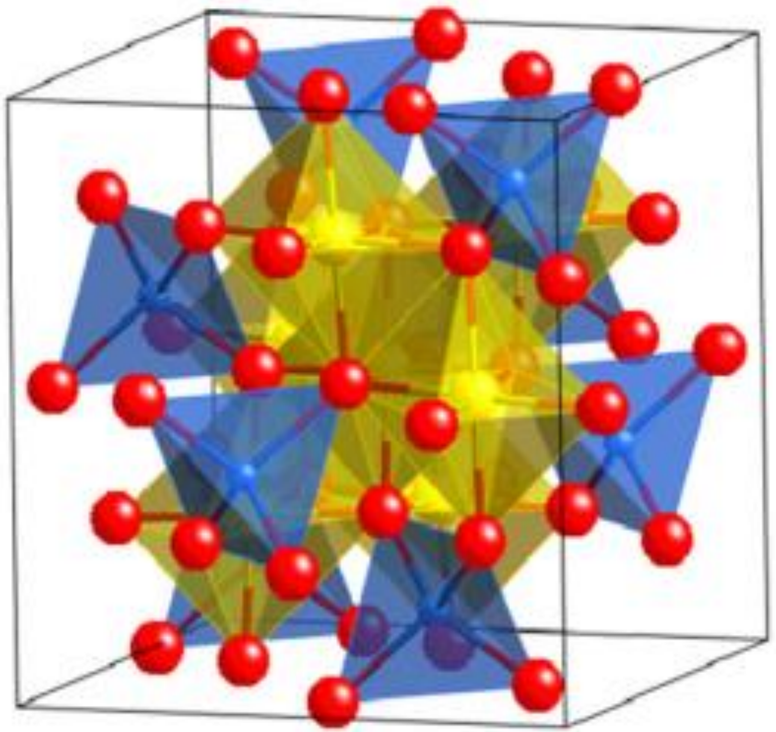
olivine

α –Olivine



wadsleyite

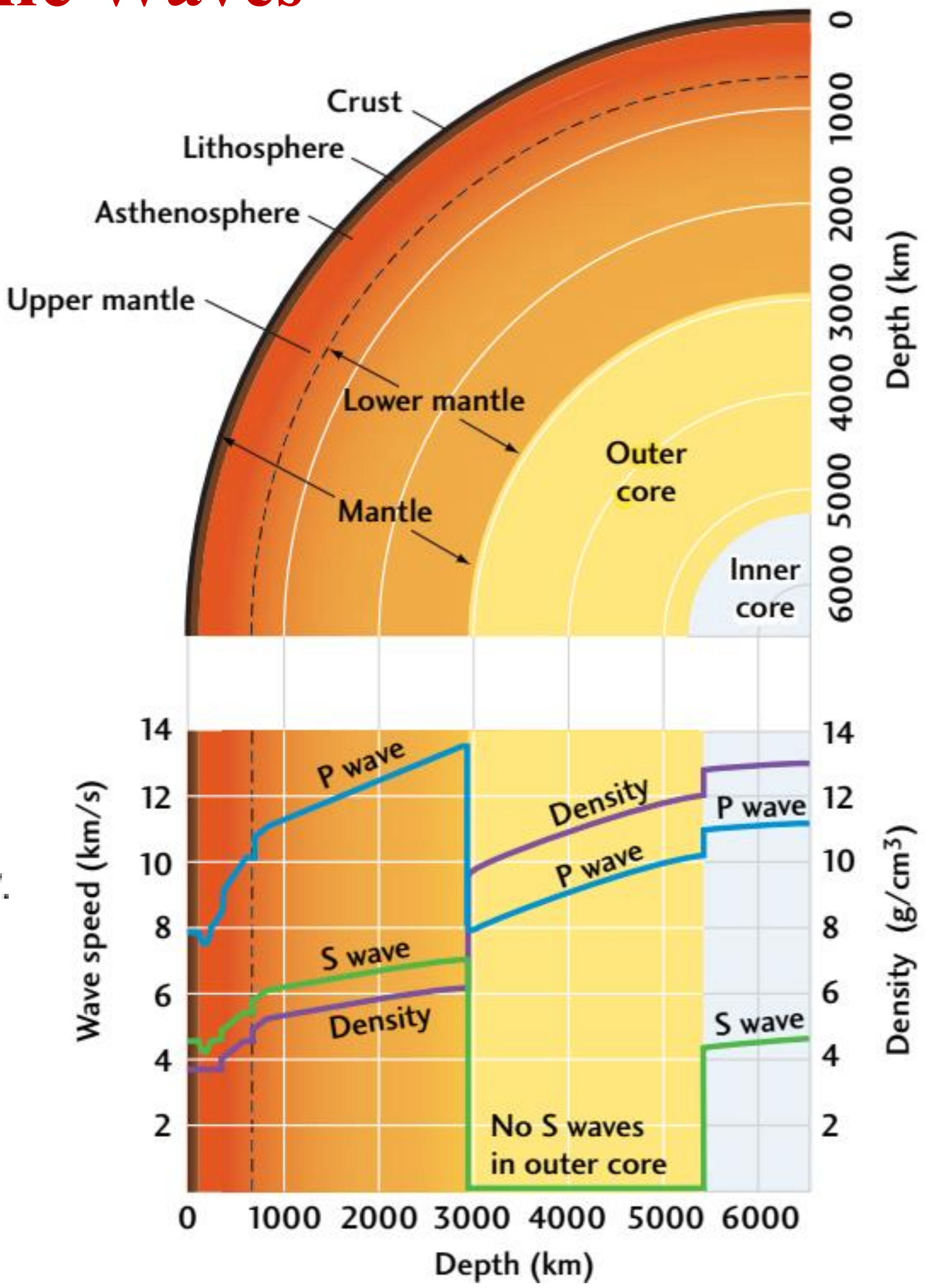
β –Olivine



ringwoodite

γ –Olivine

Exploring Earth's Interior using Seismic Waves



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

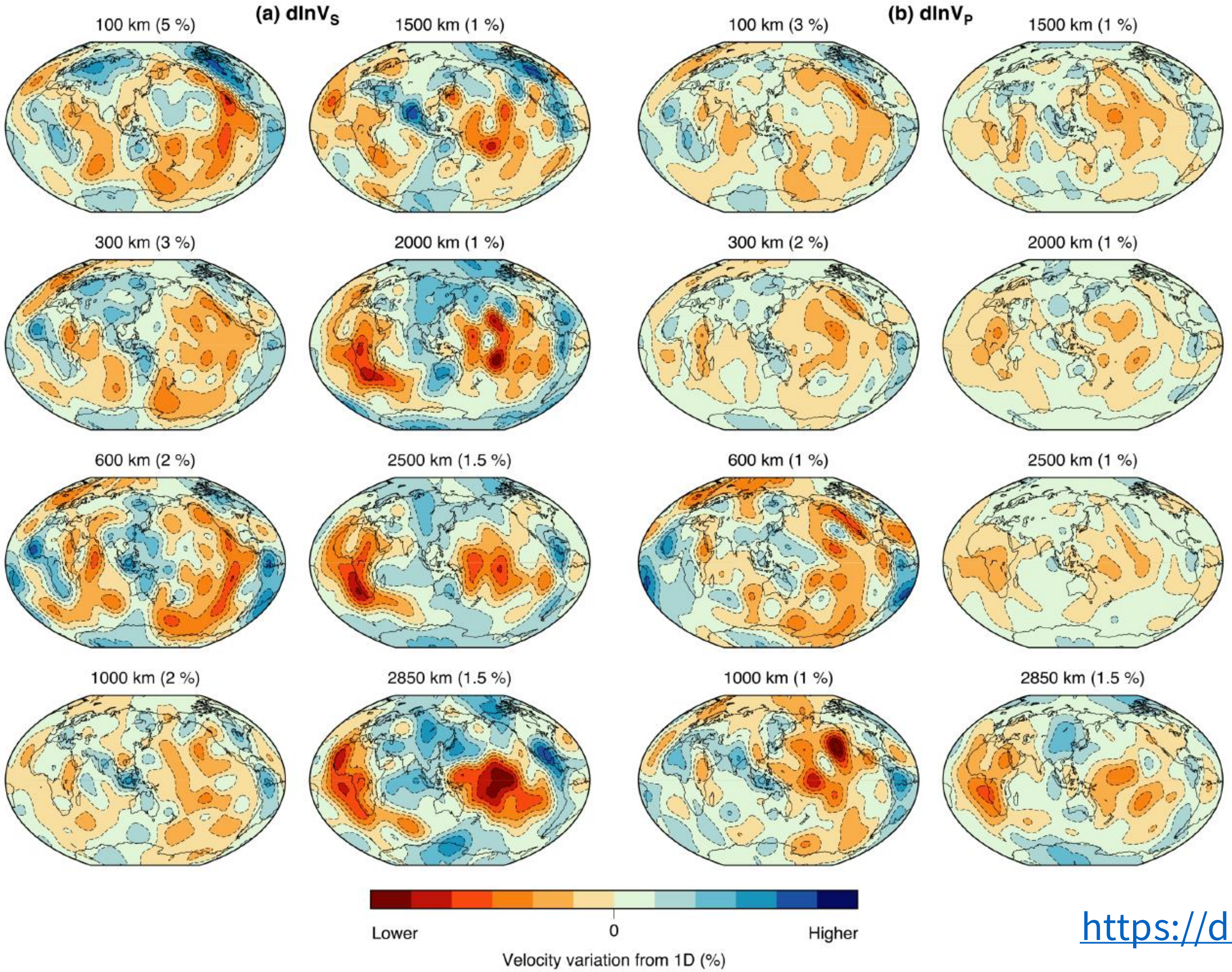

Figure 6. Maps of (a) shear-wave velocity variations dlnV_S and (b) compressional-wave velocity variations dlnV_P according to model SP12RTS at 100, 300, 600, 1000, 1500, 2000, 2500 and 2850 km depth. Velocity is higher (lower) than the radially averaged value at each depth in blue (red) regions and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

https://doi.org/10.1093/gji/ggv481