News and Reminders

Homework 3 is due Monday (Oct. 14)

- we will not cover the material for Problem 3 (4.16 in the textbook + extra questions) in class, but the textbook should be sufficient to do it (grad students only)

Next reading quiz - Monday (Oct. 14) - Chapter 6 (skip 6.1.5)

Interior

- Generally, planet interiors are probed indirectly:
  - bulk density gives a *rough* indication of composition (i.e. gaseous vs. rocky); limiting cases are more useful but rare.
  - distance from the Sun can indicate what elements condensed where the planet formed
  - observations of satellite orbits can inform on the interior mass distribution
  - observations of tidal deformations can inform on the internal structure of moons
  - presence of a magnetic field can indicate the existence of ferromagnetic materials or a fluid core

Hydrostatic equilibrium (again):

To first order, the internal structure of a spherical body is governed by a balance between gravity and pressure.

$$P(r) = \int_r^R g_P(r')\,\rho(r')\,dr'$$

HW3 problem

if ρ is constant, then: $P_{center} = \frac{3GM^2}{8\pi R^4}$

Class: if ρ is not constant, is this result a lower or an upper limit?

This is a lower limit, because ρ (density) usually decreases with increasing r. This works well enough for small, ~uniform density bodies, where we can assume ρ is constant (e.g. the Moon)

An even simpler approximation can be made if we assume g is constant as well. In this case:

$$P_{center} = \frac{6GM^2}{8\pi R^4}$$ ← about accurate for Earth

Class: is this a ~~lower~~ under- or ~~upper limit~~ over-estimate, if g is not constant?

This is an over-estimate, since g is over-estimated for most of r.

Though for a highly centrally condensed planet (i.e. ρ not constant), the pressure above would be an under-estimate (e.g. by a factor of 4 for Jupiter).

Magnetic Fields

How are magnetic fields generated?

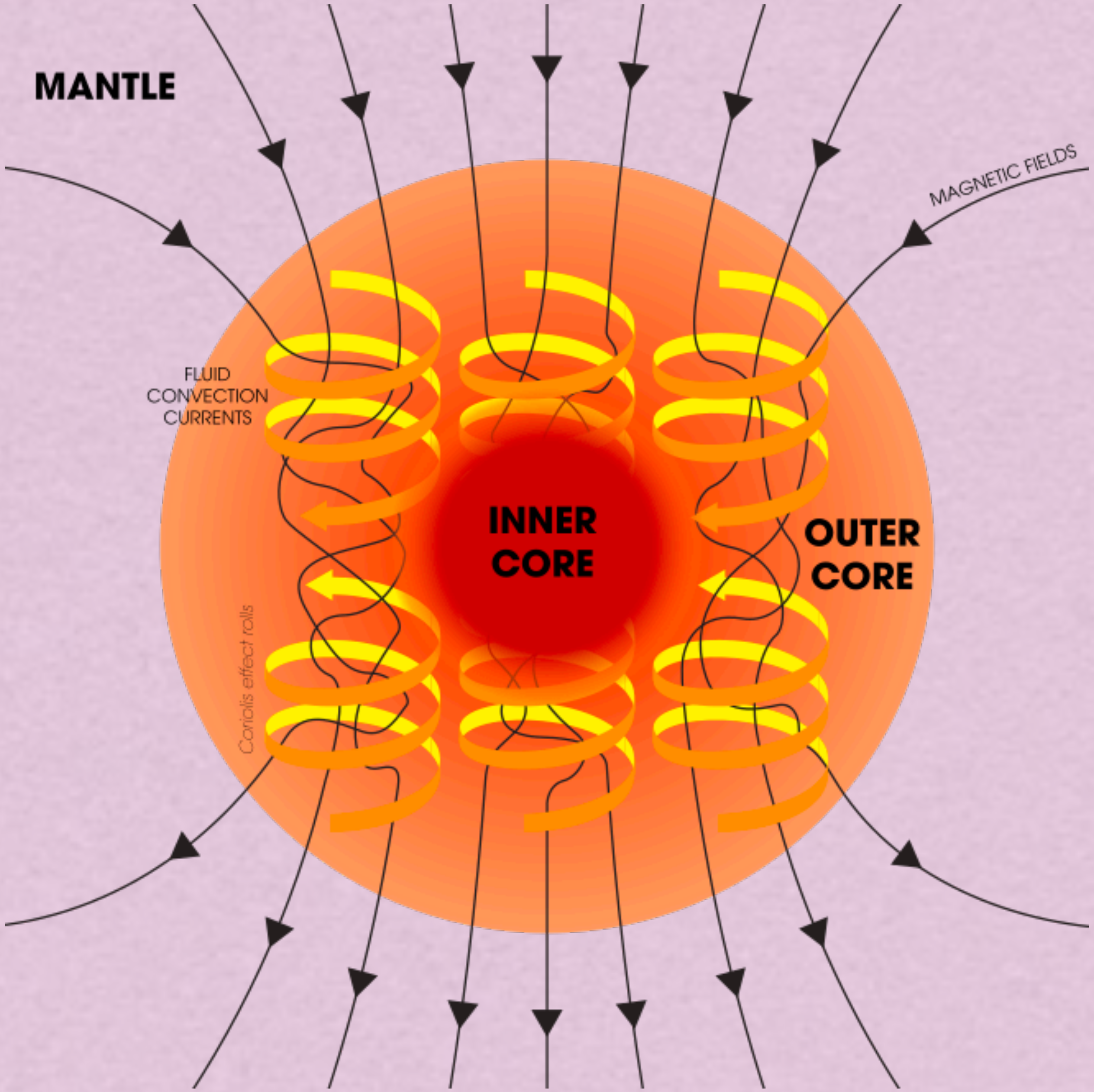
- remanent ferromagnetism (charges bound to atoms of a solid in an aligned configuration): **Mars** (in some parts of its crust)
- interaction between solar wind and conducting regions of the planet: **Venus**
- Dynamo Process:

  -> inner core solid (due to high pressure)

  -> outer core is liquid and in motion (due to convection and Earth's rotation) through the Sun's magnetic field

  -> generates circulating electric currents in outer core

  -> generates and supports magnetic field



So need **convection**, **rotation**, and an **electrically conducting fluid**

Moment of inertia:

$$\text{MoI factor} = \frac{I}{MR^2}$$

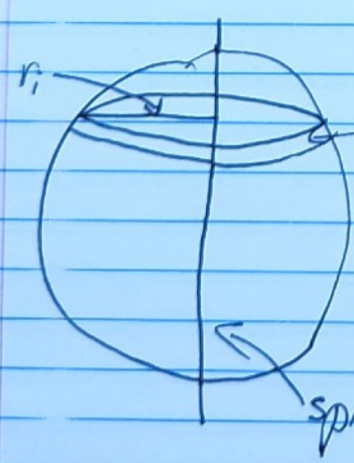
I: measured from the spin precession rate (hard!) or gravitational moments.

~~MoI~~

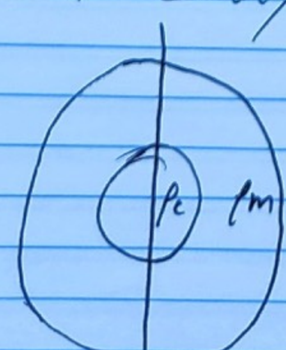
I can be used to learn about planetary (and satellite) interiors.

For a solid uniform sphere: $I = \frac{2}{5} MR^2$

recall: $I = \sum m_i r_i^2 = \int r^2 \, dm$



take a 2-layer sphere (same density ρ as uniform sphere):



$\rho_c > \rho_m$: more mass is closer to the spin axis (relative to the uniform case)

$\Rightarrow$ more mass is ~~at smaller r~~ closer to spin axis

$\Rightarrow$ sum of $m_i r_i^2$ is smaller

so $I_{2\text{-layer}} < 0.4 MR^2$

Solar System Interiors

For small bodies, a density $\rho \lesssim 1$ g/cm^3 implies an icy or porous interior. For large bodies, it implies a primarily hydrogen/helium composition.

$\rho \approx 3$ g/cm^3 -> rocky body

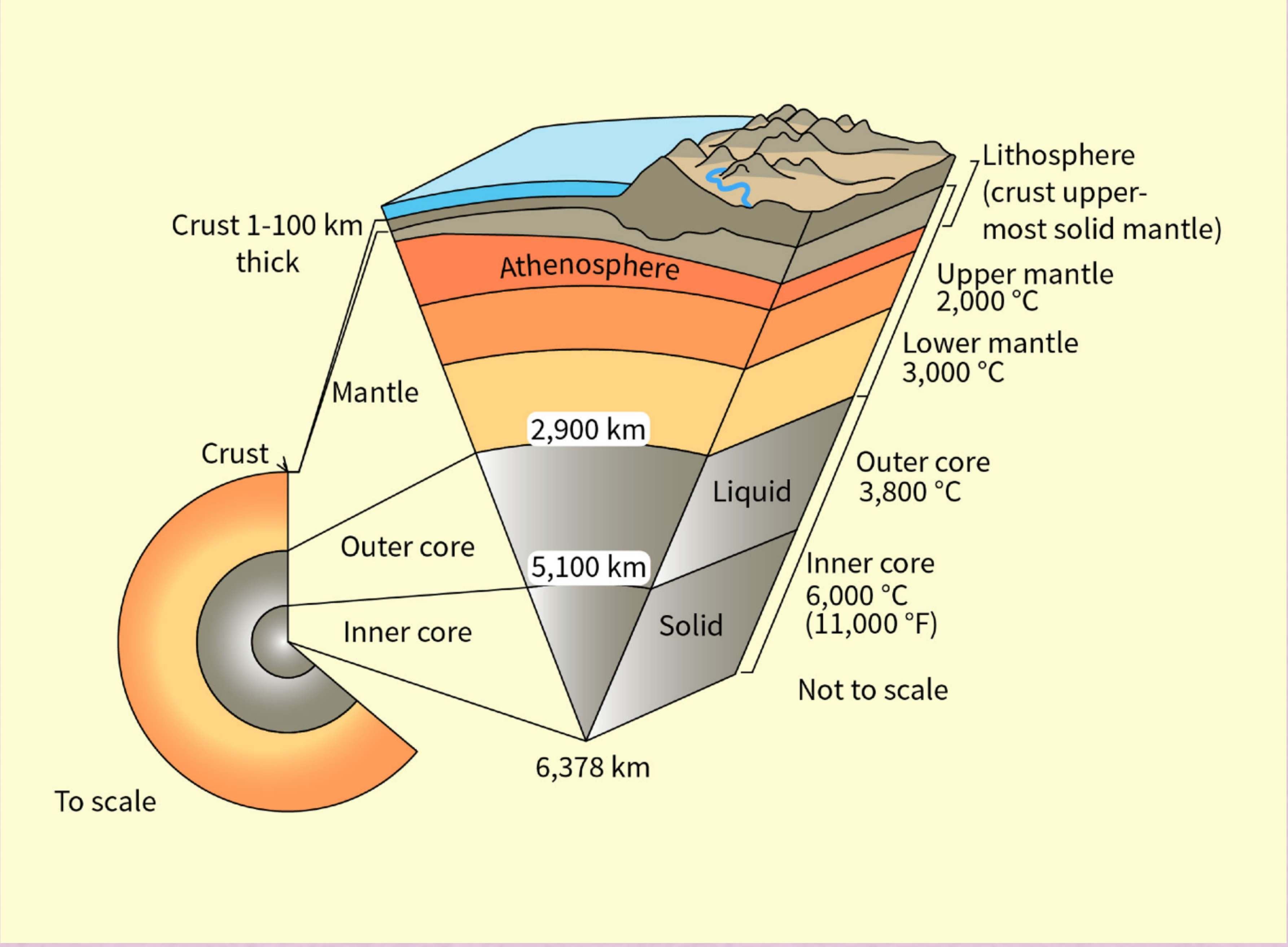
$\rho > 3$ g/cm^3 -> iron (or other heavier elements) must be present

Interior of the Earth

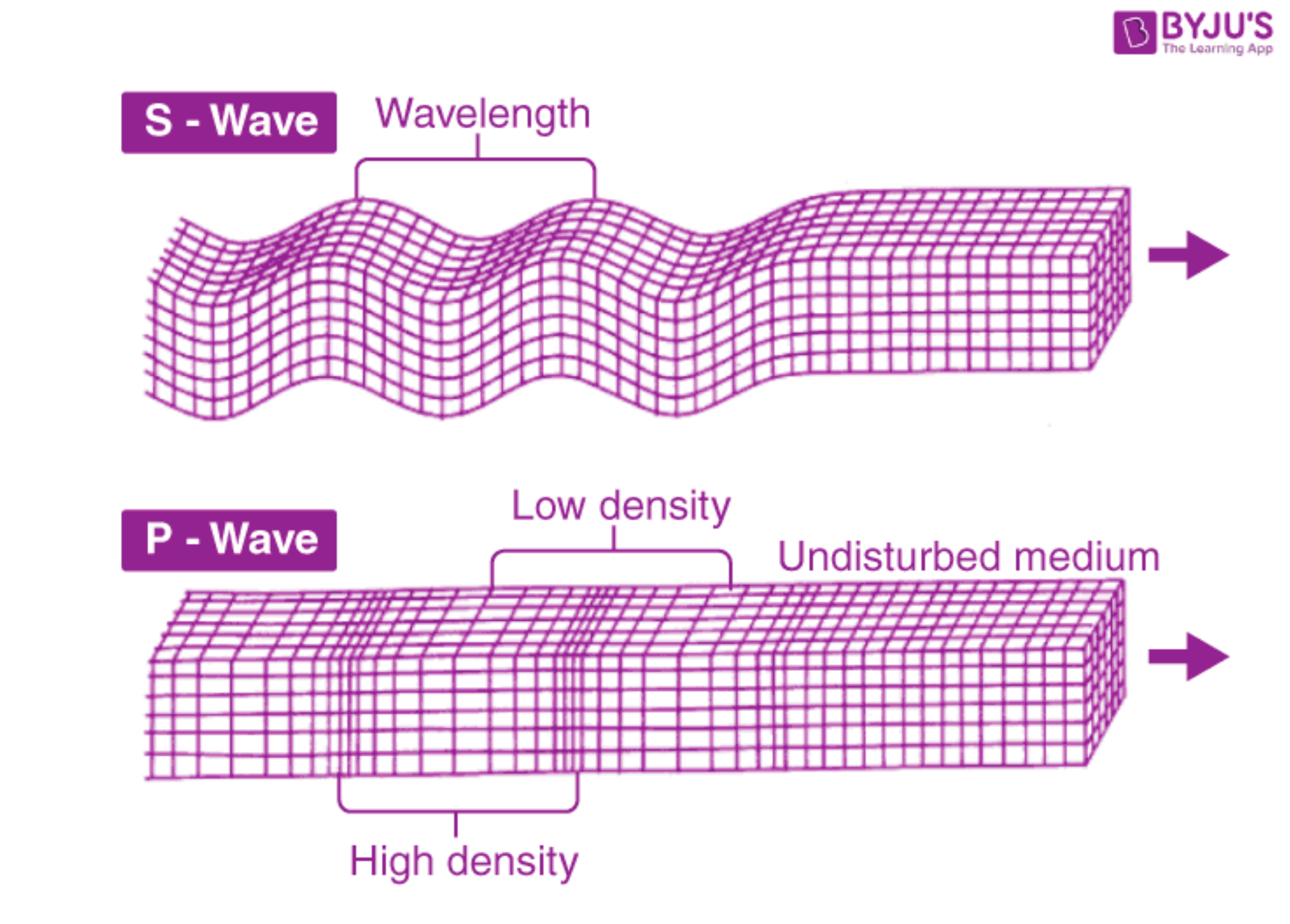
$I/(MR^2) = 0.33$

$\rho \approx 5.5$ g/cm^3

Densities of typical surface rocks ≈ 3 g/cm^3



P and S waves



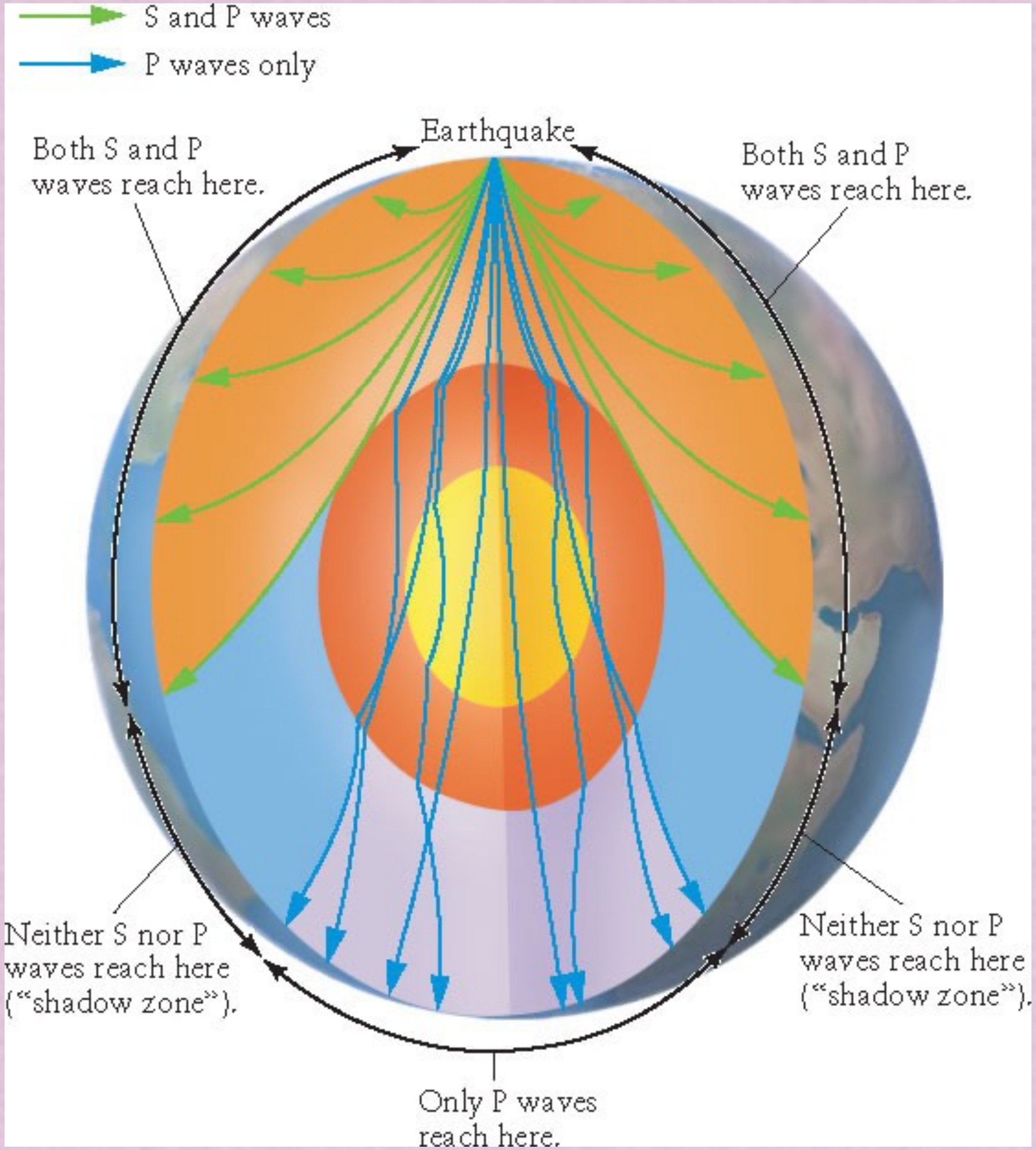
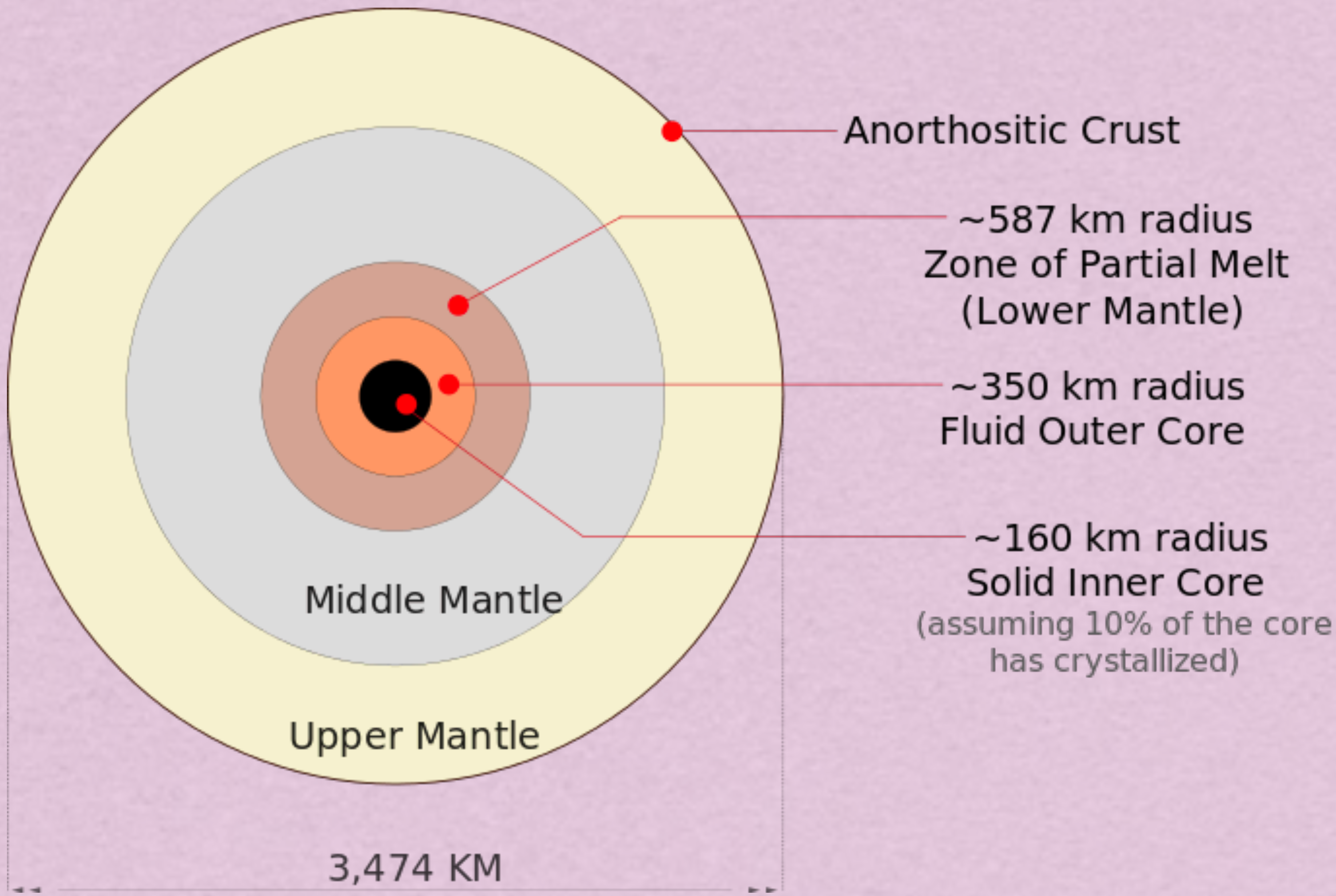


Plate tectonics cause Earthquakes (motion along fault lines)

Interior of the Moon

$I/(MR^2) = 0.3932$

$\rho \approx 3.3\ g/cm^3$



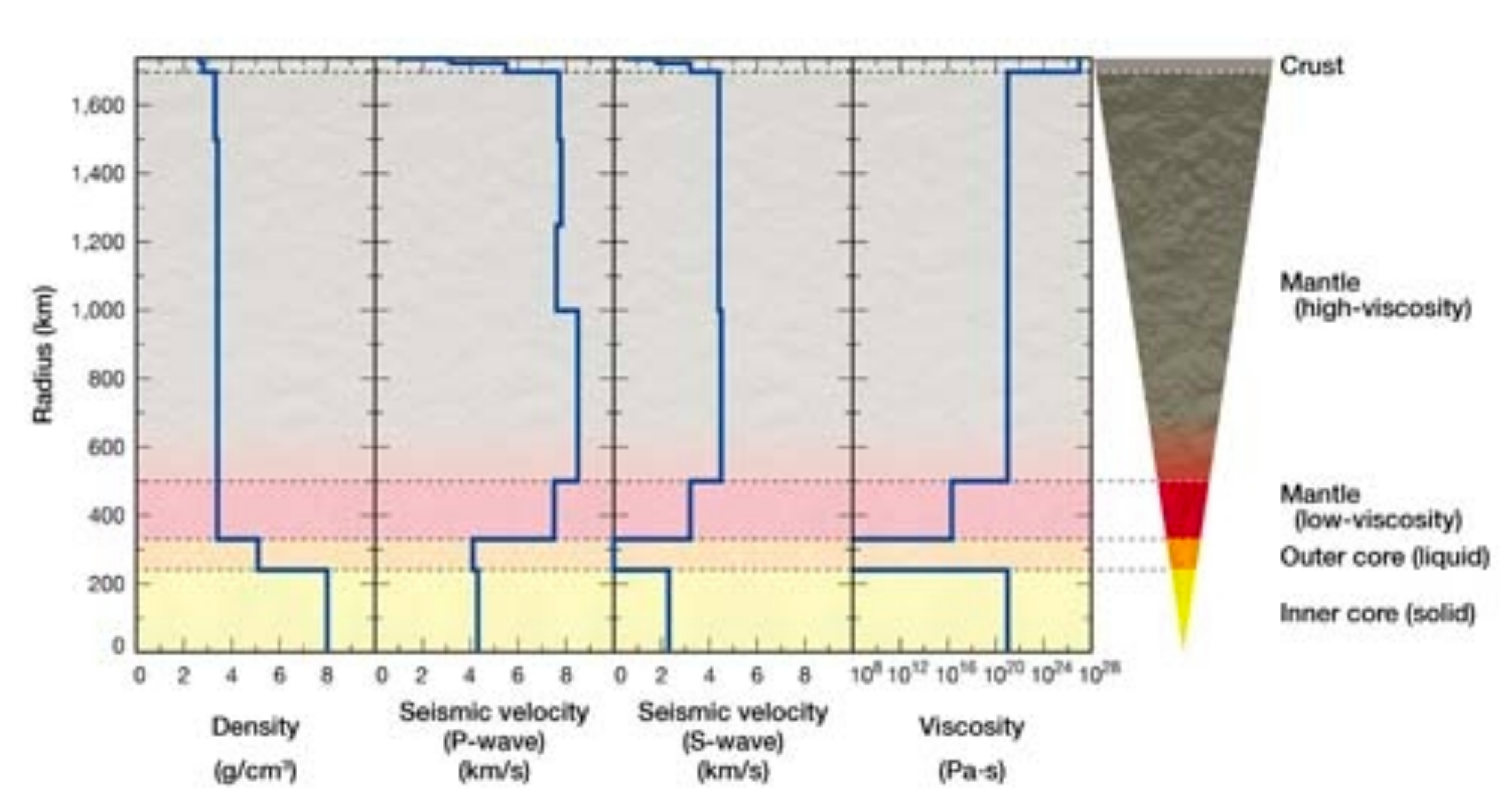
upper mantle: olivine

middle mantle: olivine+pyroxene

Interior of the Moon from seismology

No plate tectonics, but moonquakes can originate:

- near the surface (like on Earth, but due to meteorite impacts);
- from deep in the Moon's interior, as a result of the tidal force exerted by Earth;
- thermally, by expansion of the crust illuminated by the Sun after two weeks in the dark and cold.

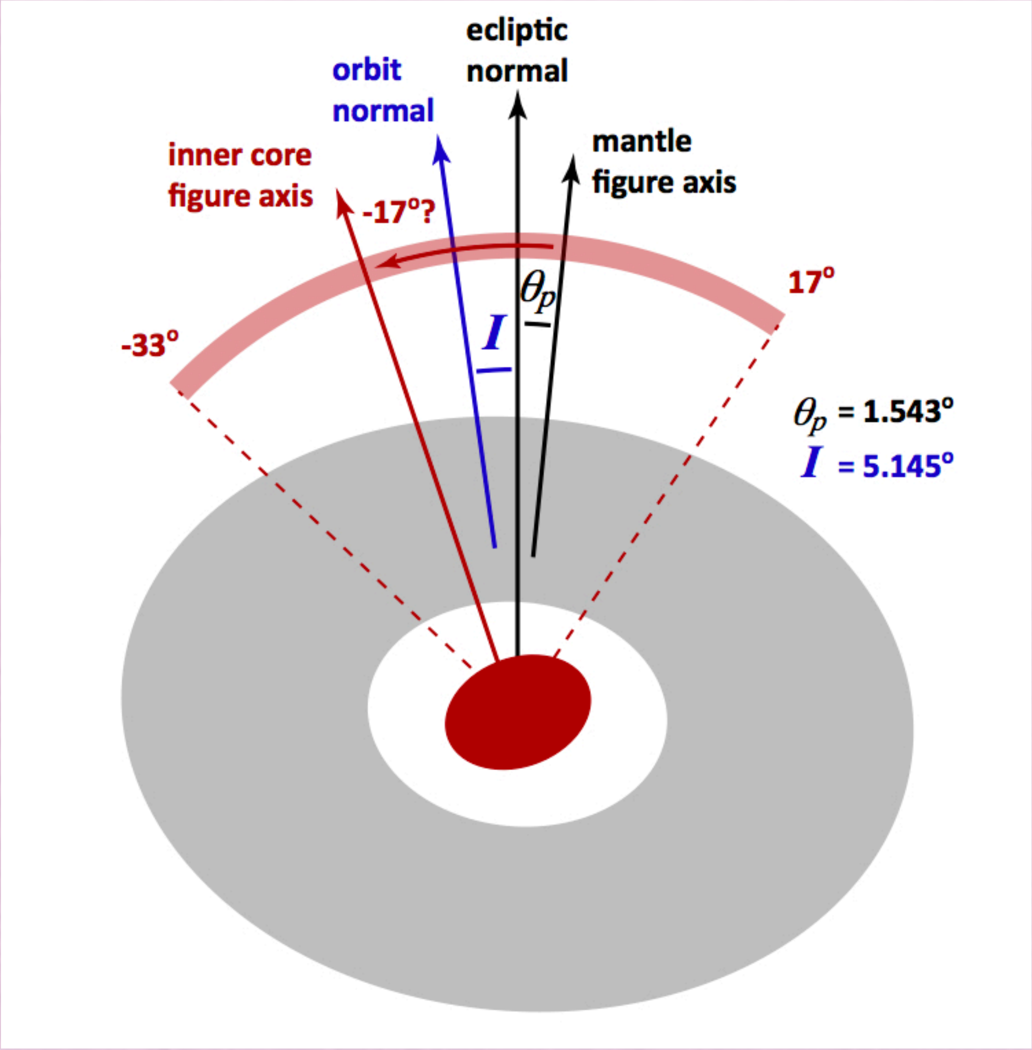


Moon’s past magnetic field

The presence of an iron core and magnetized lunar samples show evidence of a past magnetic field.

Possible sources:

- mantle and core rotate around slightly different axes, and the boundary between them is not quite spherical, so their relative motion causes the fluid to mix around;
    - but as distance from Earth has increased, the angle has decreased and eventually these forces became insufficient to generate a dynamo
- impacts by meteorites or comets (since recently it was found that not all lunar samples were magnetized; Tarduno et al. 2021).



Interior of Mercury

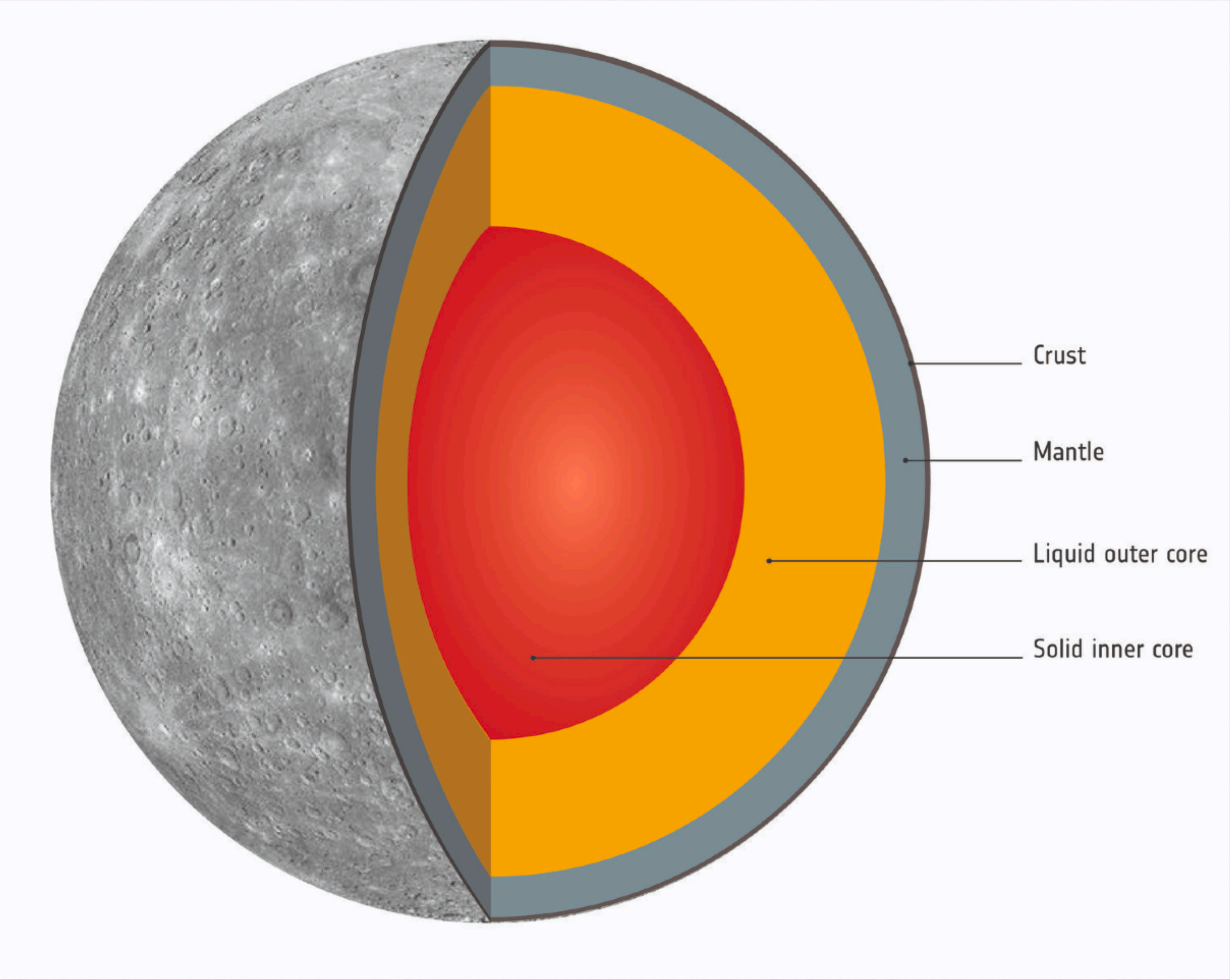
$I/(MR^2) = 0.325$

$\rho \approx 5.3\ g/cm^3$

-> 60% of its mass is made of iron (i.e. 2x the chondritic meteorite percentage)

past volcanic activity suggested by old lava flows

-> lack of basaltic iron suggests last volcanic activity was ~3.5 Gyr ago



Like on Earth, the solidification of the inner core releases enough energy to keep outer core convective -> dynamo! (though magnetic field strength is just 1% that of Earth)

Interior of Venus

$I/(MR^2) = 0.337$

Margot et al. (2021)

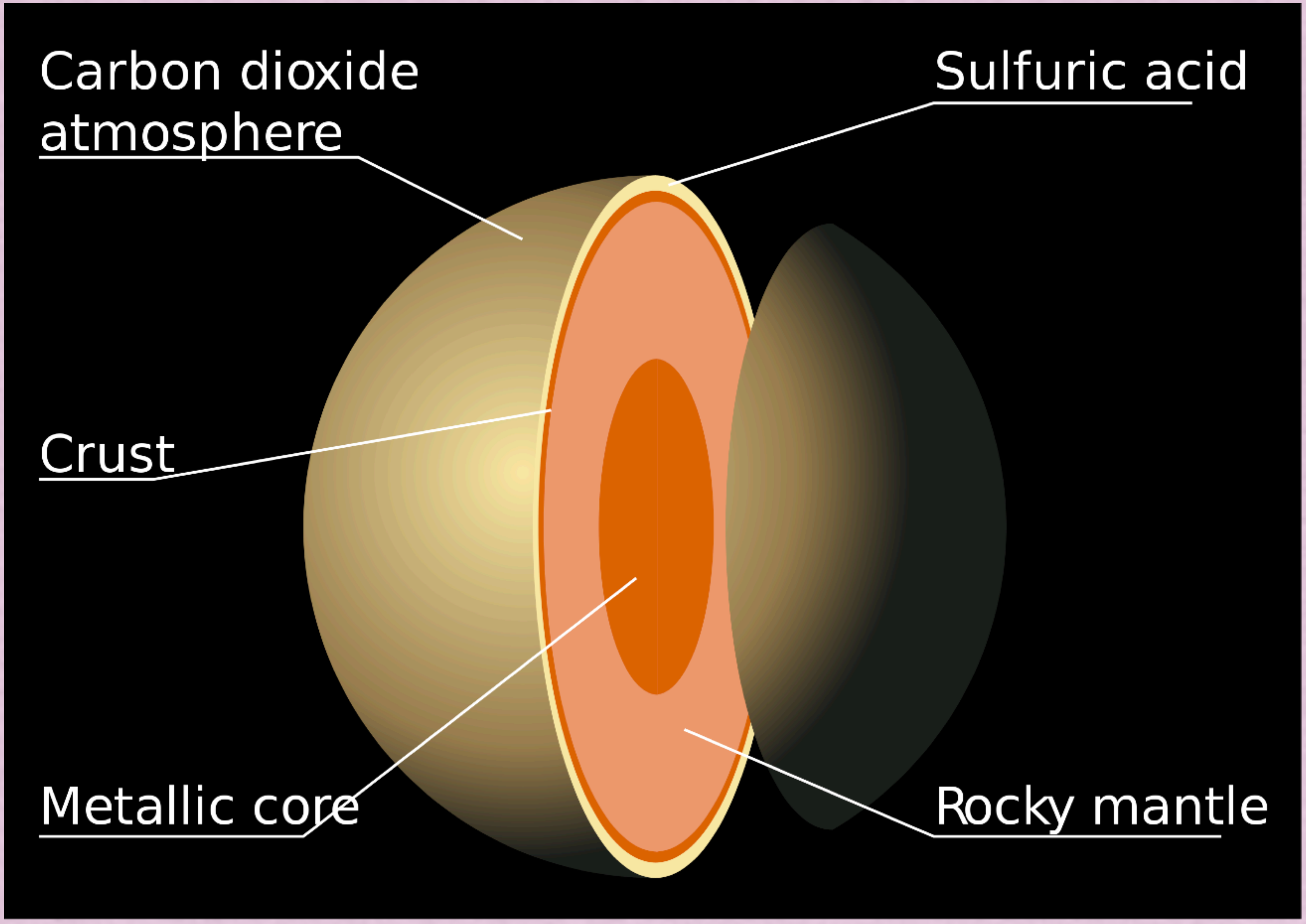
-> core radius is 58% of Venus radius

$\rho \approx 5.24\ g/cm^3$

-> only 5% less than Earth

Landers found the surface is basaltic.

-> suggests recent or ongoing volcanic activity



No magnetic field:

- less FeS than on Earth -> higher melting point -> frozen core

OR

- entire core is liquid -> no convection to drive the dynamo

OR

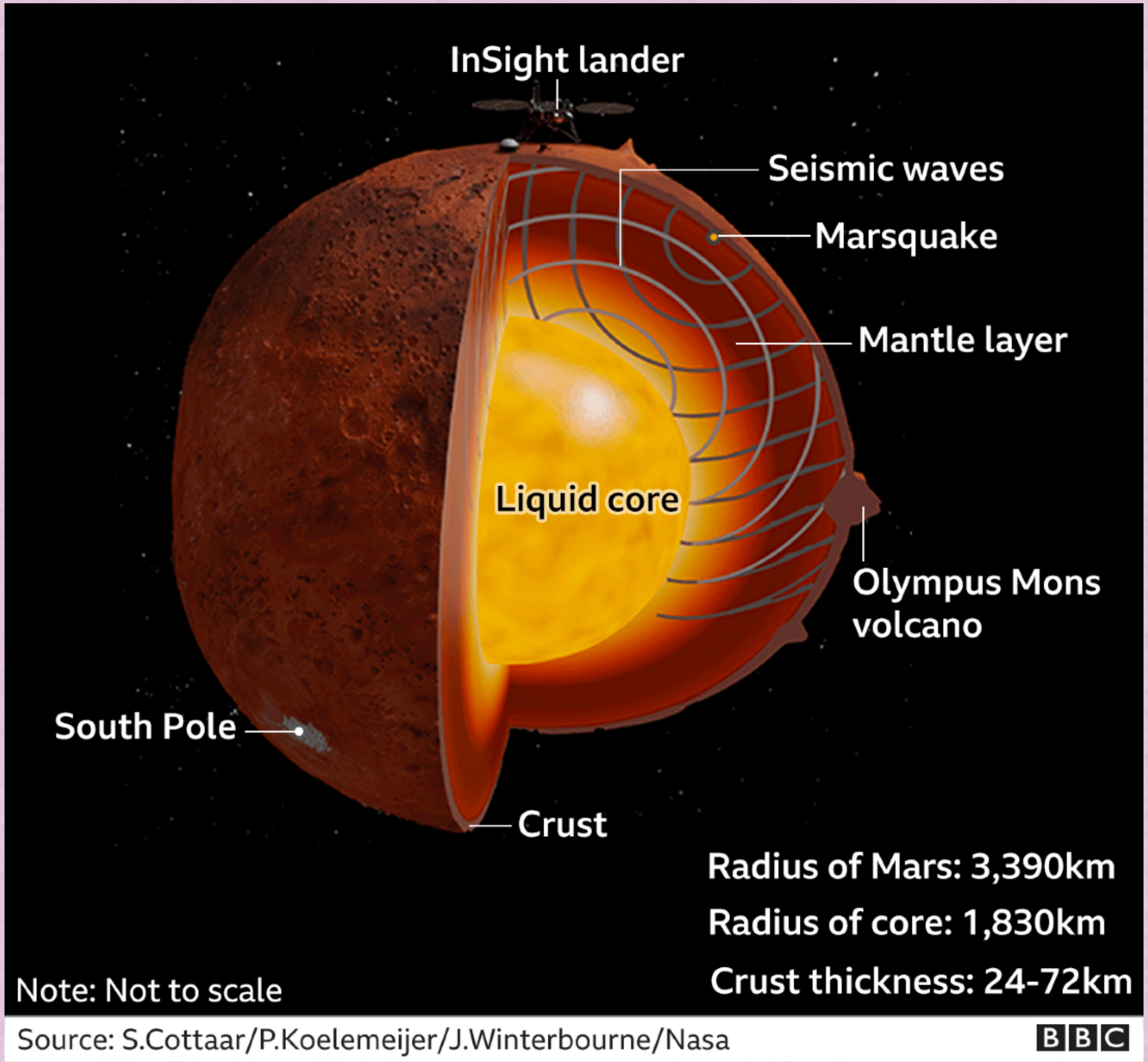
- hot, rigid (from being dry) mantle keeps heat from escaping fast enough from outer core to drive convection

Interior of Mars

$I/(MR^2) = 0.377$

$\rho \approx 3.74$ g/cm^3

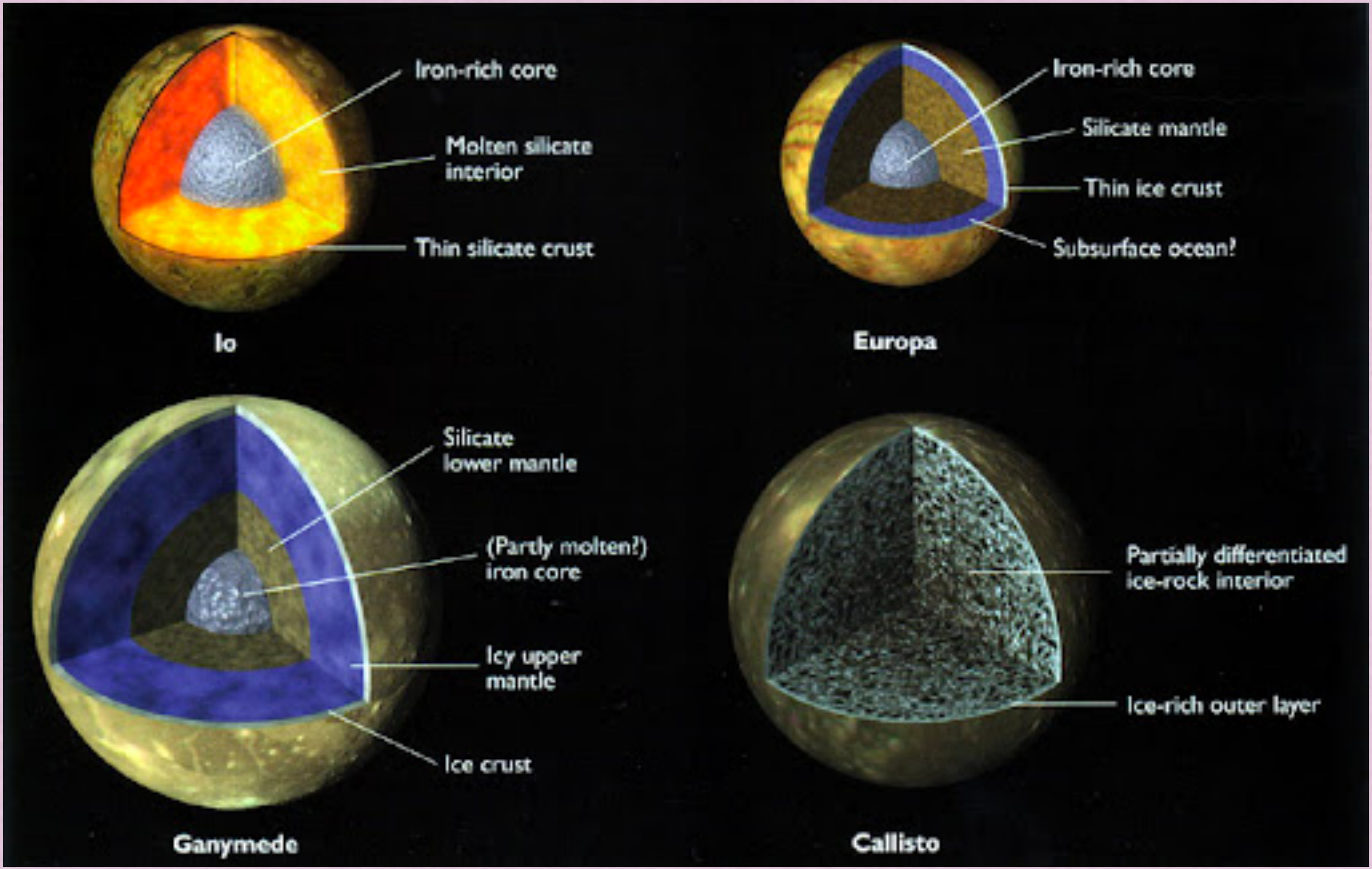
mantle is 18% FeO (by weight) -> rust (Fe_2O_3)



Volcanoes are present, indicating past volcanism (through which the planet likely lost its heat early on).

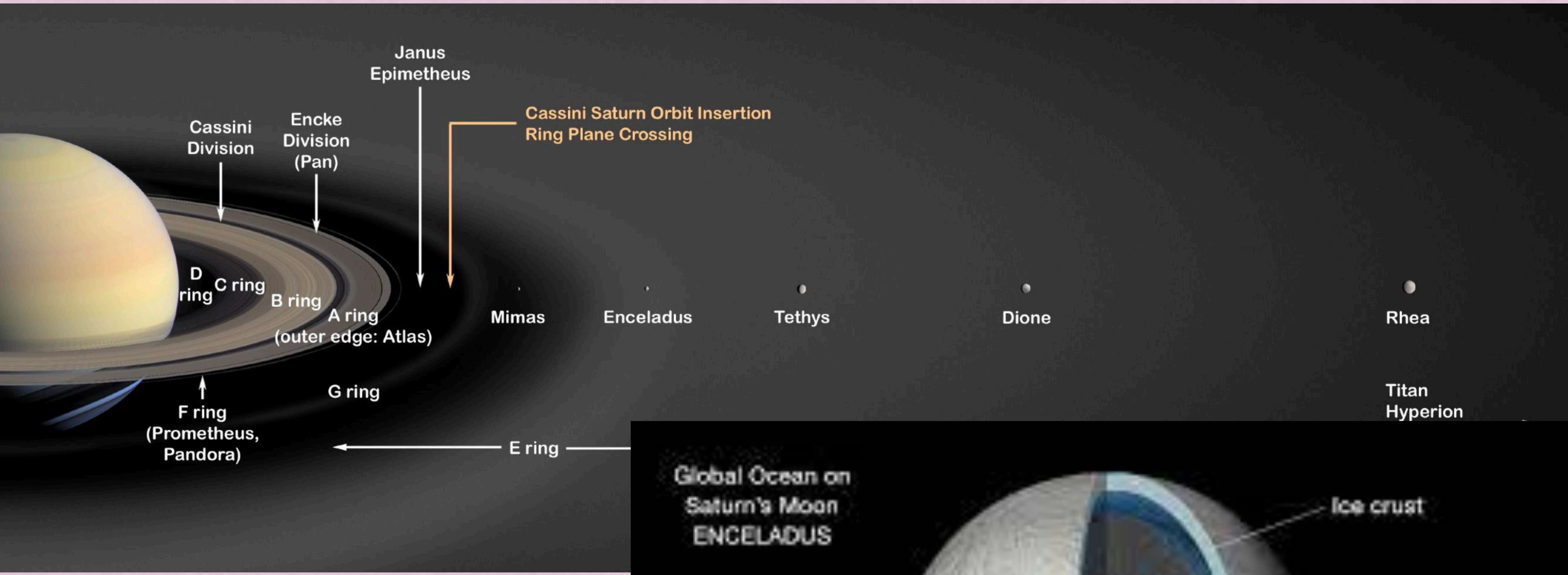
InSight lander gathered seismic data: **Mars is seismically active!** published in Feb. 2020

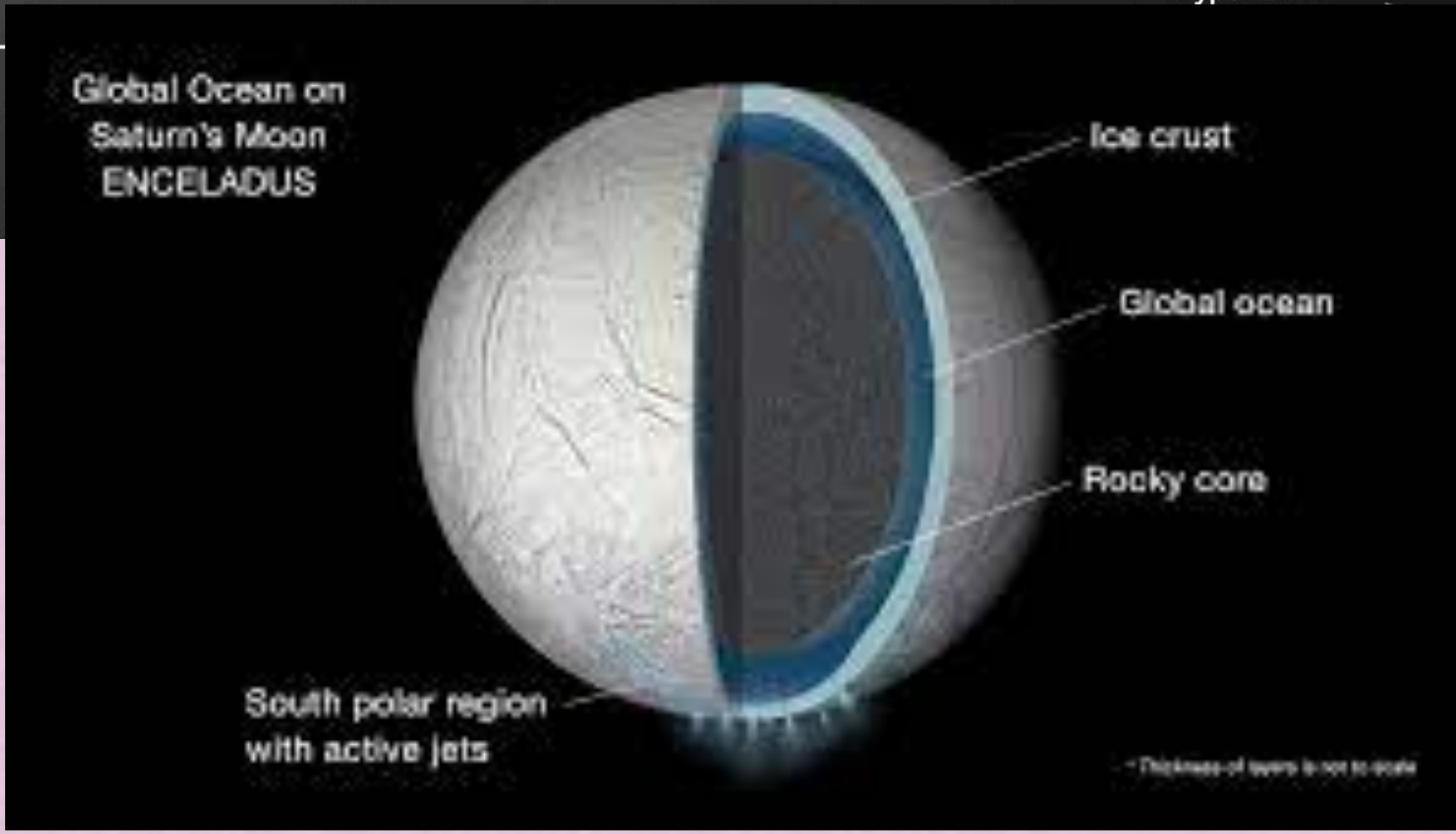
Interior of Jupiter's satellites



density decreases from inner to outermost, indicating increasing ice fractions

Interior of Saturn's satellites





Density does not decrease from inner to outer (like Jupiter's moons):

-> Titan is densest, then Enceladus.