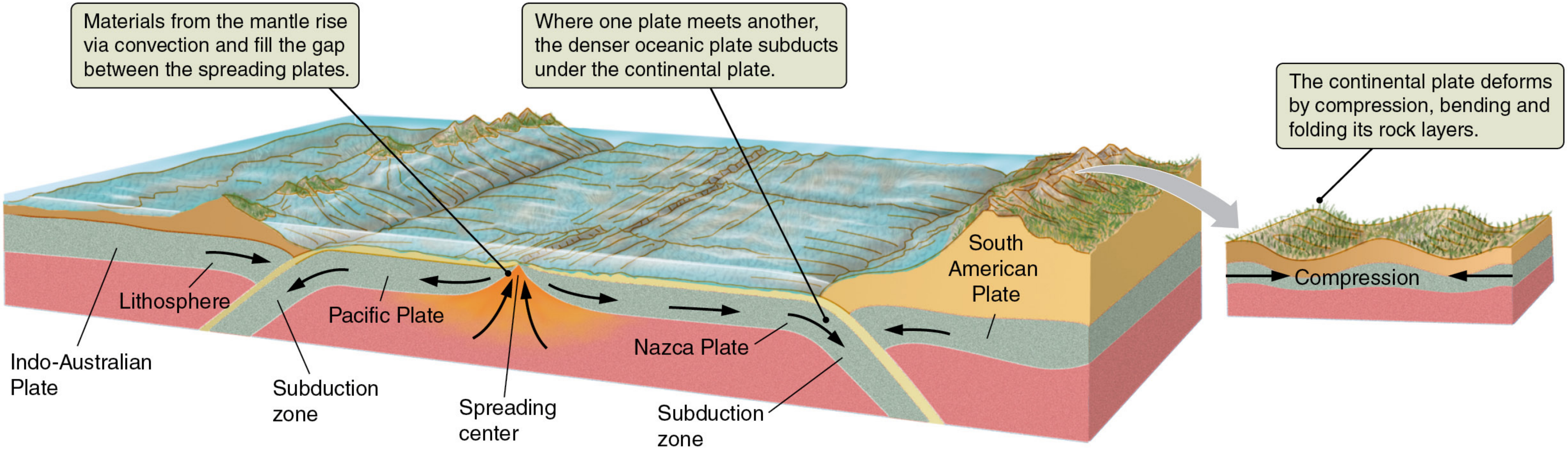
Today

- Terrestrial Planet Geology - Earth
- Terrestrial Planet Atmospheres

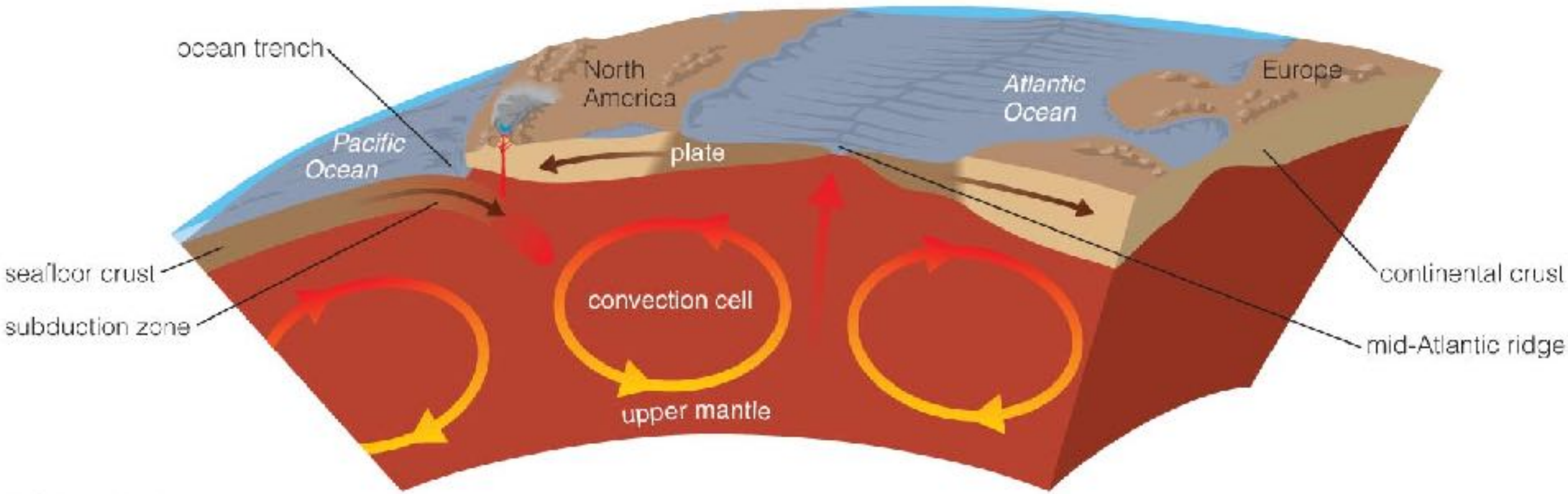
Events

- Spring equinox tomorrow
- Homework DUE next time
- Exam II March 28

Plate tectonics
- **stretches seafloor, creating new crust (e.g., mid-Atlantic ridge)**
- **subducts seafloor beneath continents (e.g., Mariana trench)**

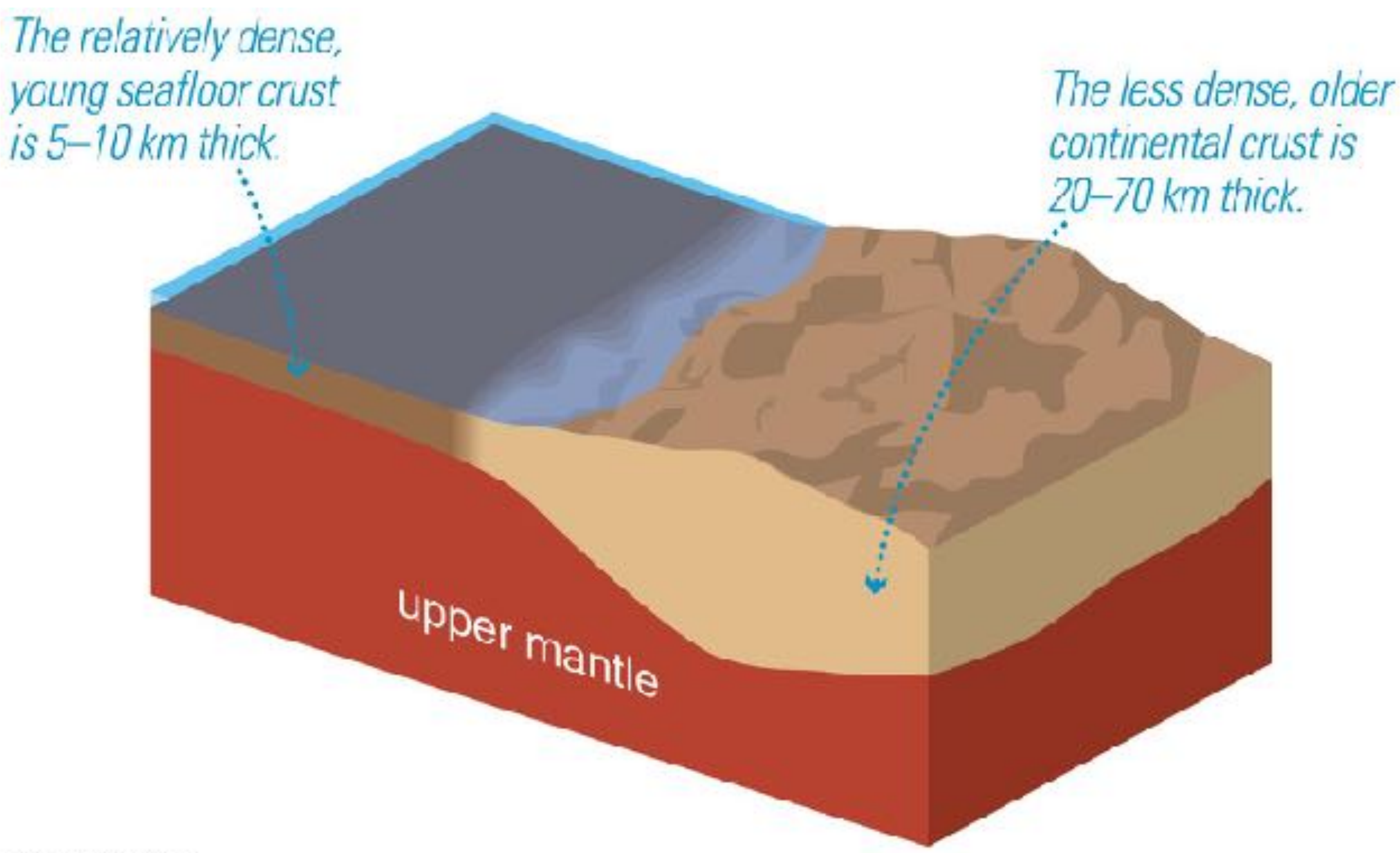


Seafloor Recycling



- Seafloor is recycled through a process known as subduction.

Seafloor Crust



- Thin seafloor crust differs from thick continental crust.
- Dating of the seafloor shows that it is relatively young.

Rifts, Faults, Earthquakes

- The San Andreas fault in California is a plate boundary.
- Motion of plates can cause earthquakes.

Ring of Fire

- Boundaries of plates traced by Earthquakes and Volcanos

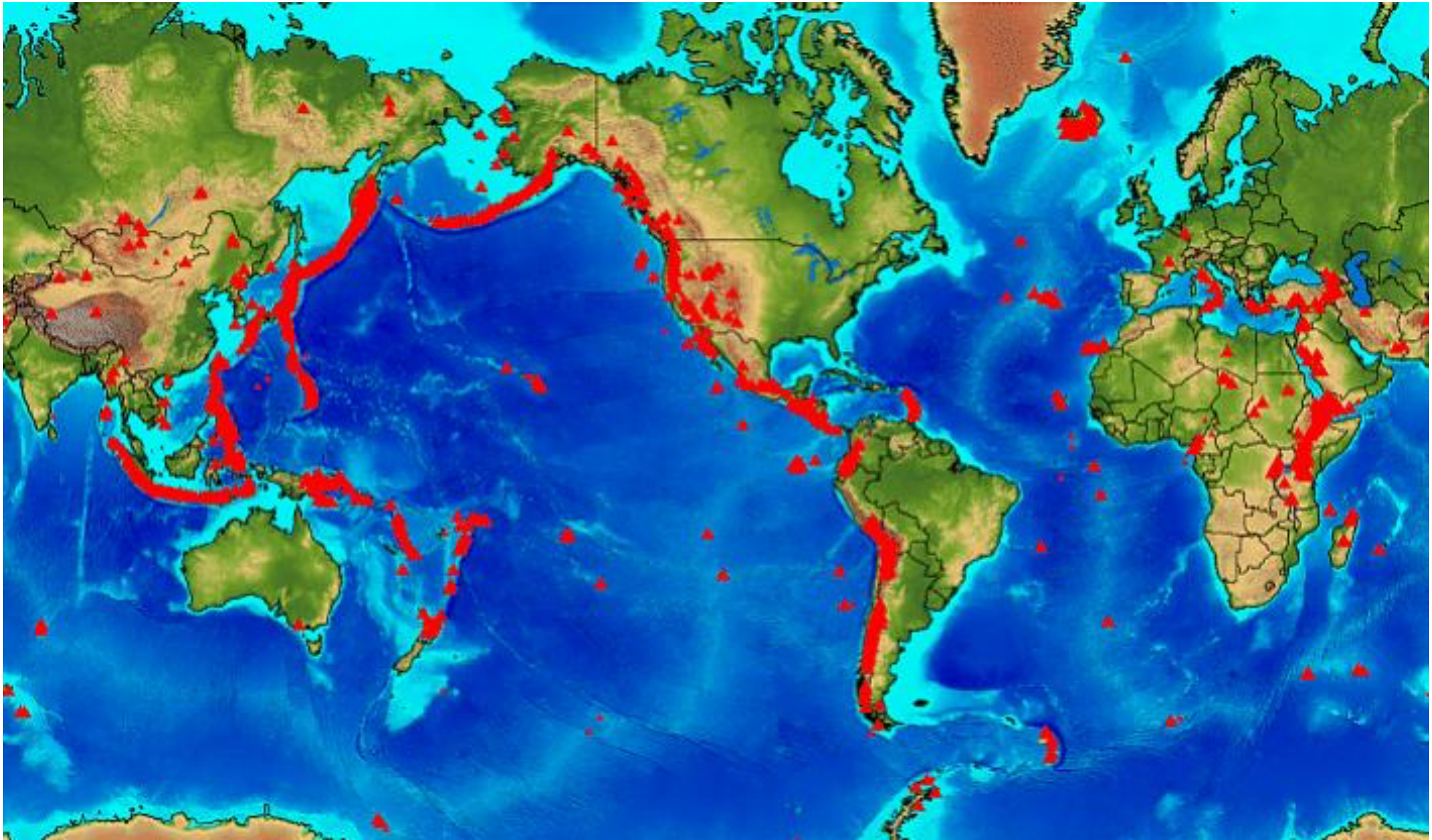
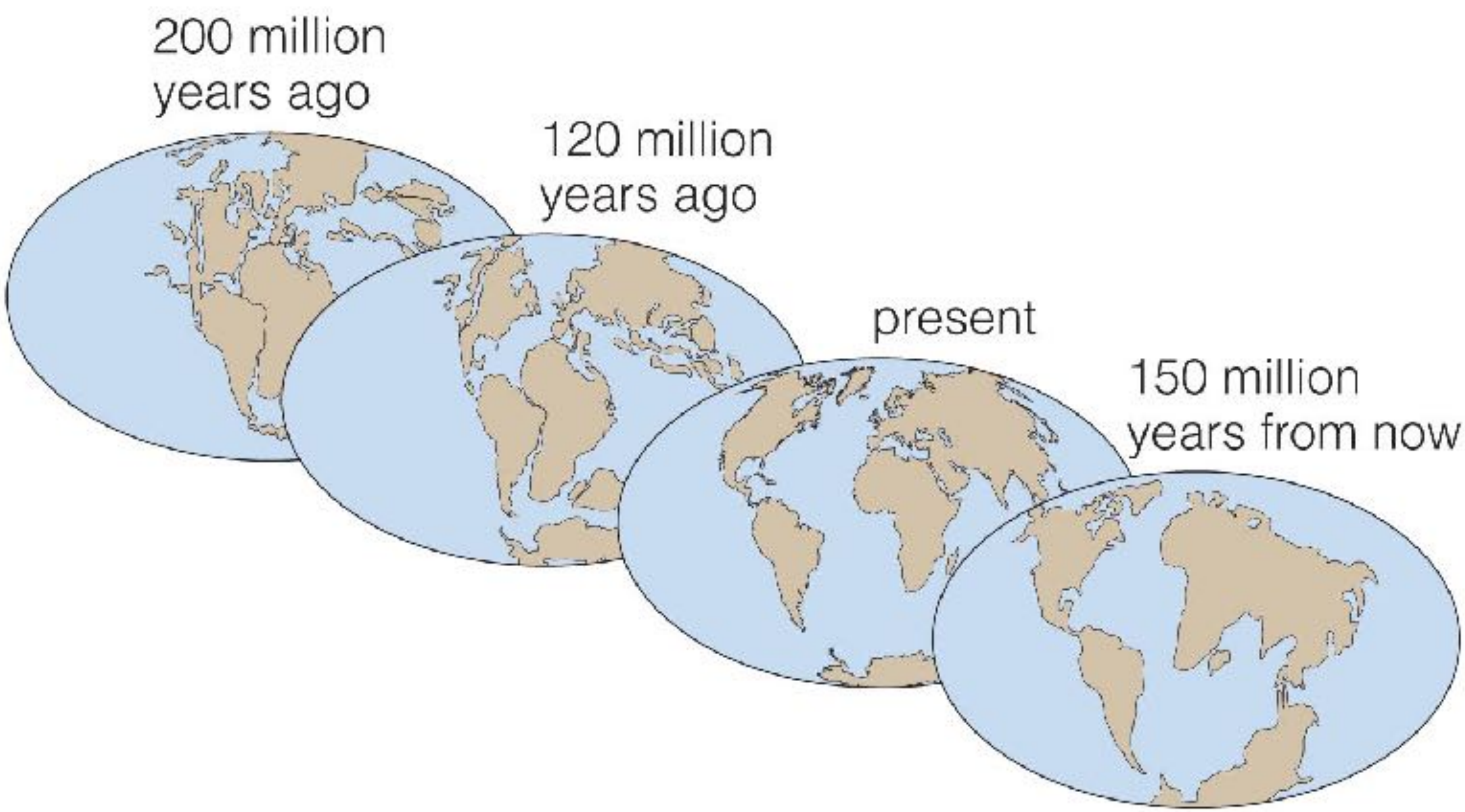


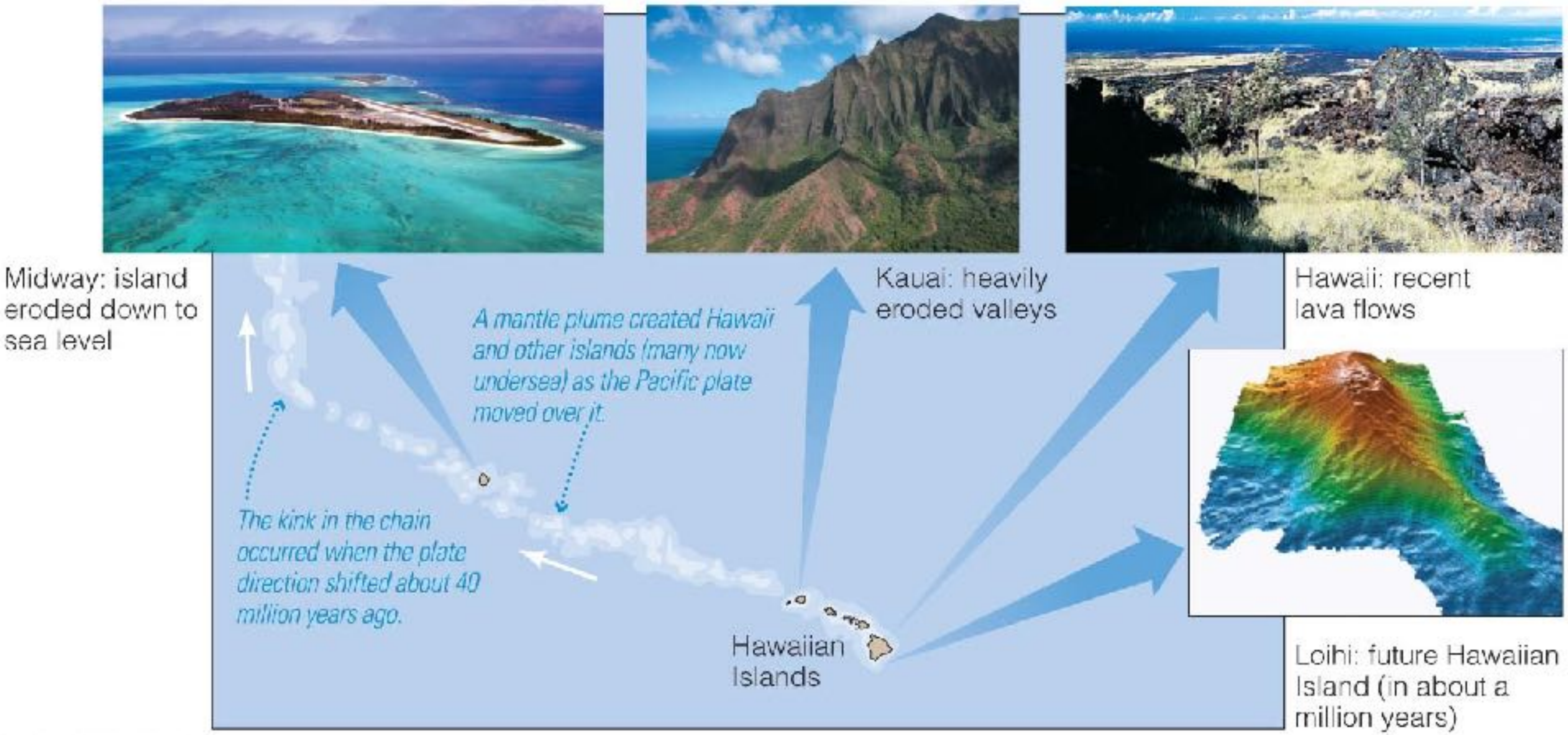
Plate Motions

- Measurements of plate motions tell us past and future layout of the continents.

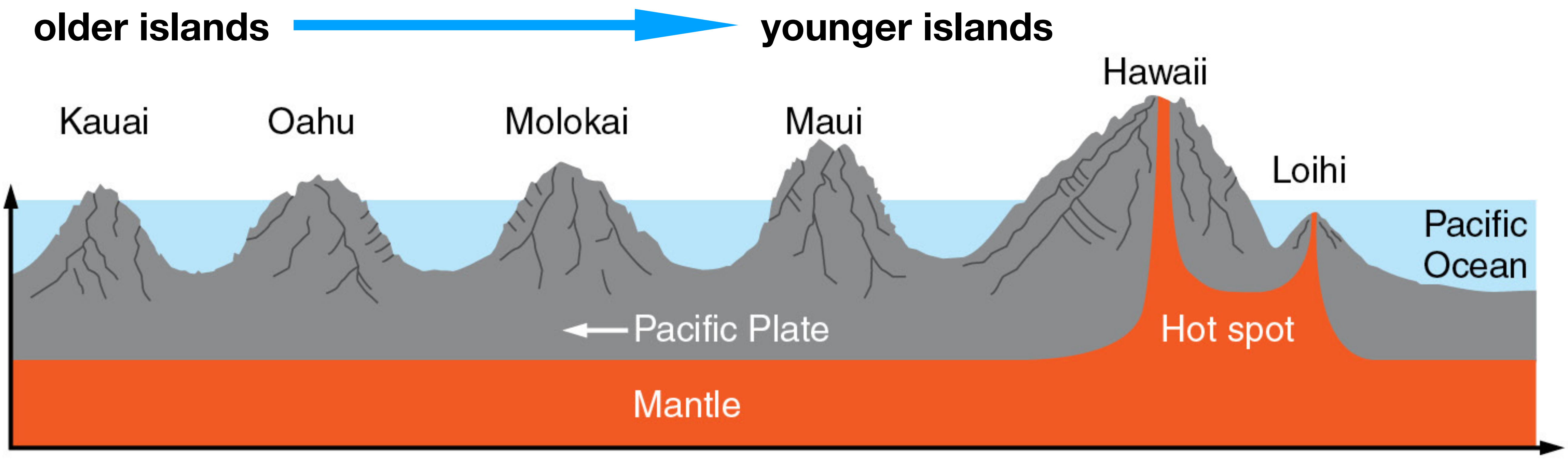


https://www.youtube.com/watch?v=cQVoSyVu9rk

Hot Spots



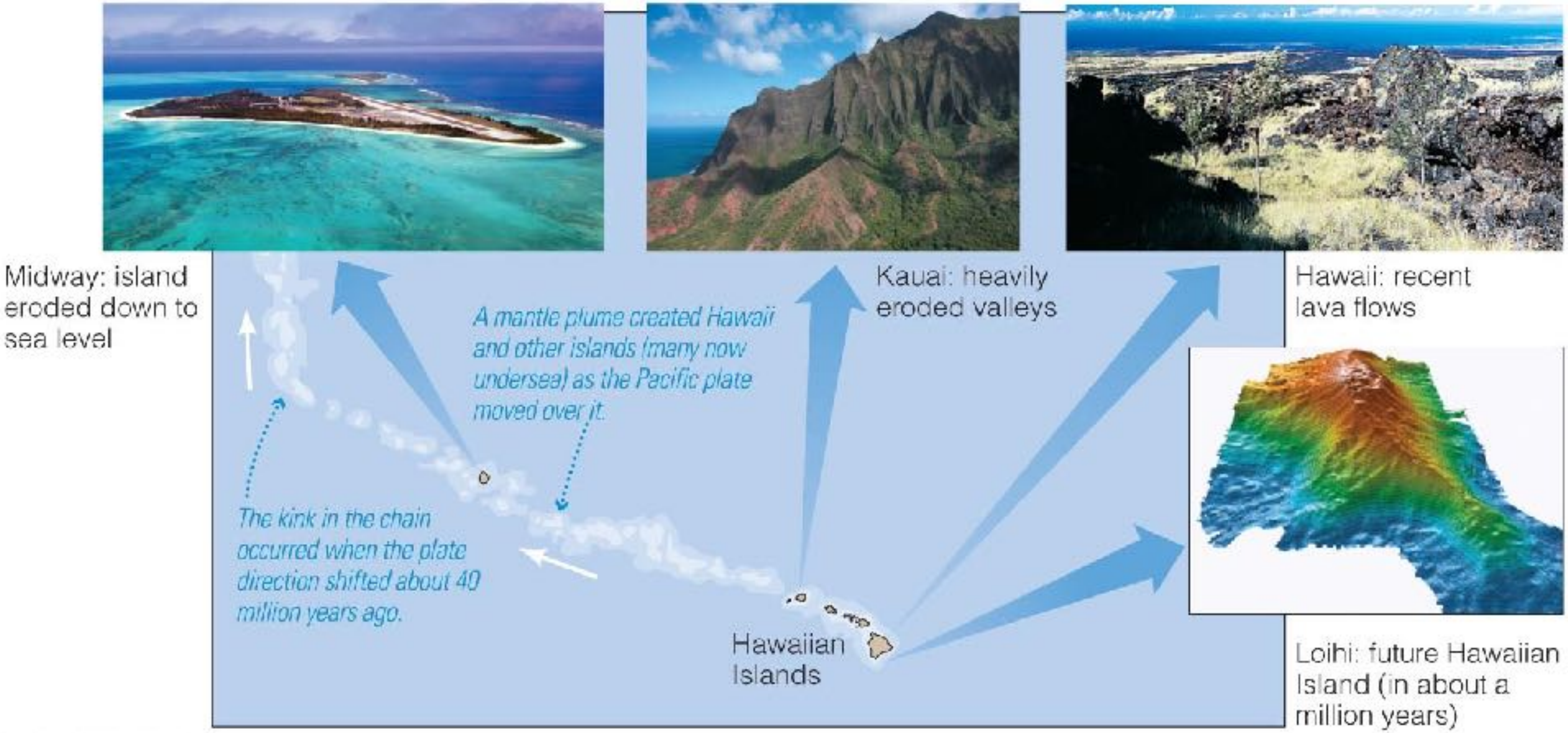
- The Hawaiian islands have formed where a plate is moving over a volcanic hot spot.



older islands
younger islands
Hawaii
Kauai
Oahu
Molokai
Maui
Loihi
Pacific
Ocean
Pacific Plate
Hot spot
Mantle

Hot Spots

Each Hawaiian Island starts as a growing volcano, goes extinct as the plate slides across the hot spot, then erodes back into the sea.



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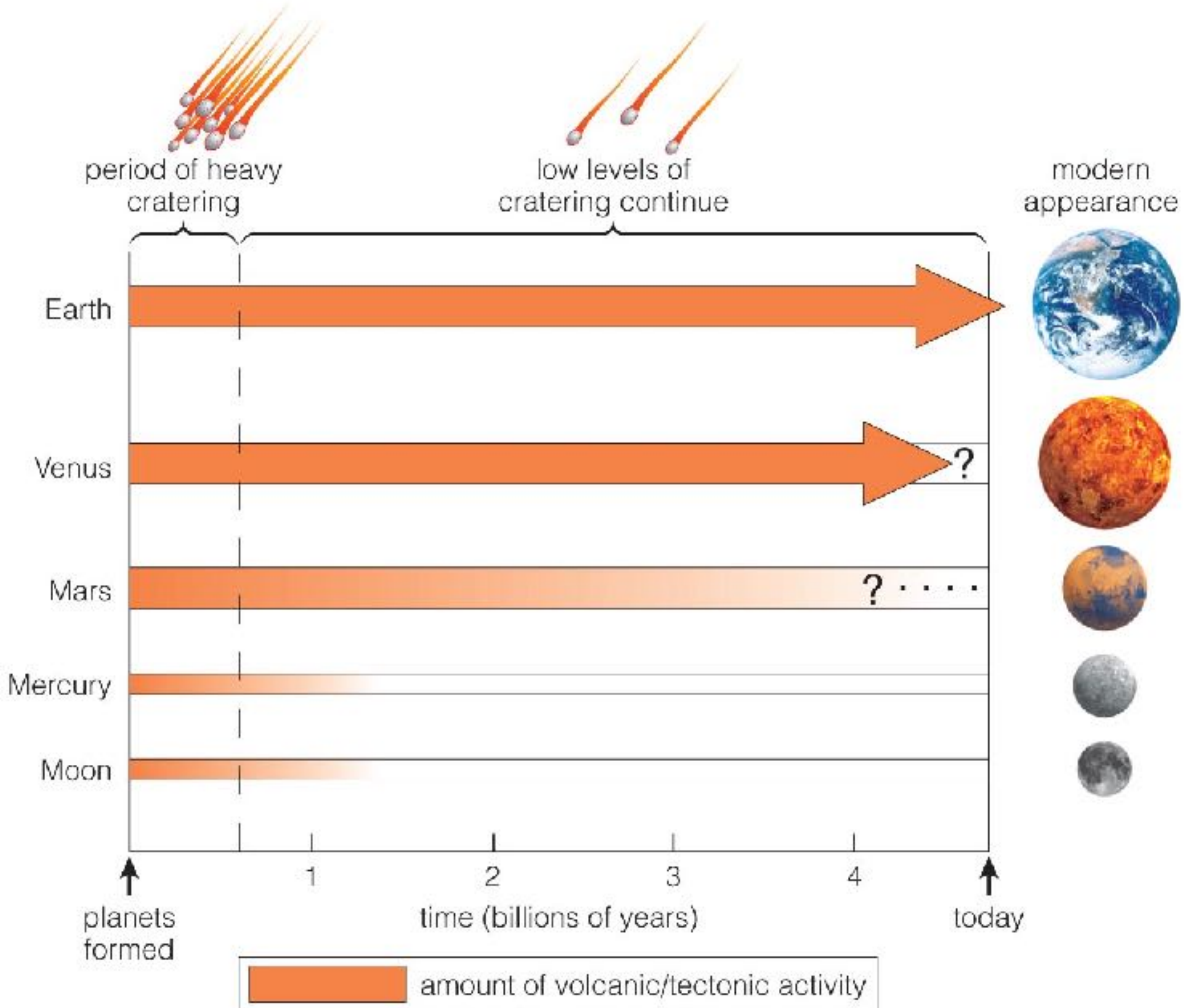
Earth remains geology active thanks to its size

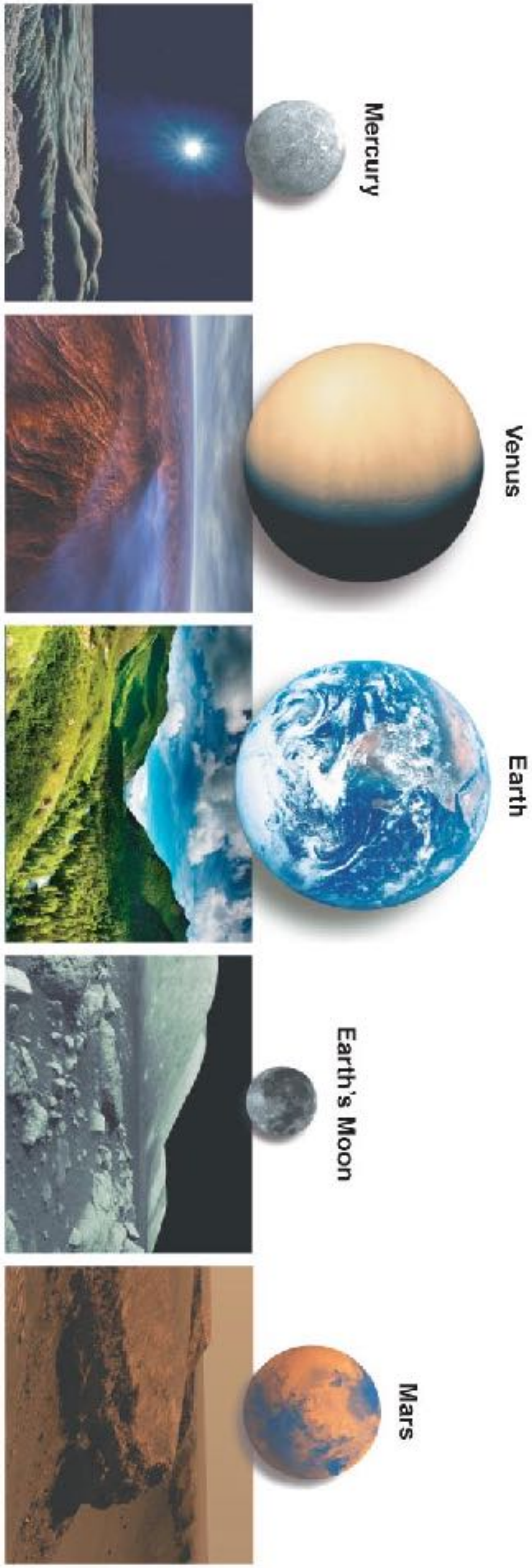


What is an atmosphere?

- An atmosphere is a layer of gas that surrounds a planet.
  - Terrestrial planet atmospheres are a very thin veil of gas between the solid surface and the vacuum of space

	Composition	Pressure	Temperature
Mercury	N/A	0	797 (day) -283 (night)
Venus	96% CO_2 3.5% N_2 <1% SO_2	90 (equivalent to 900m deep in the ocean)	878
Earth	78% N_2 21% O_2 <1% H_2O, CO_2	1	59 (global ave)
Moon	N/A	0	257 -283
Mars	95% CO_2 2.7% N_2	0.007	-58

Earth Atm | Farenheit

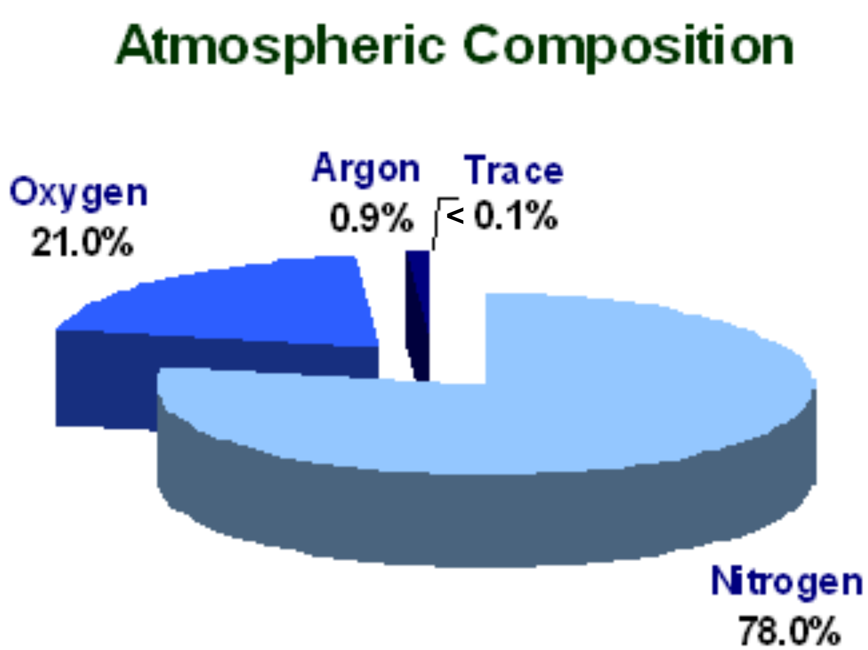


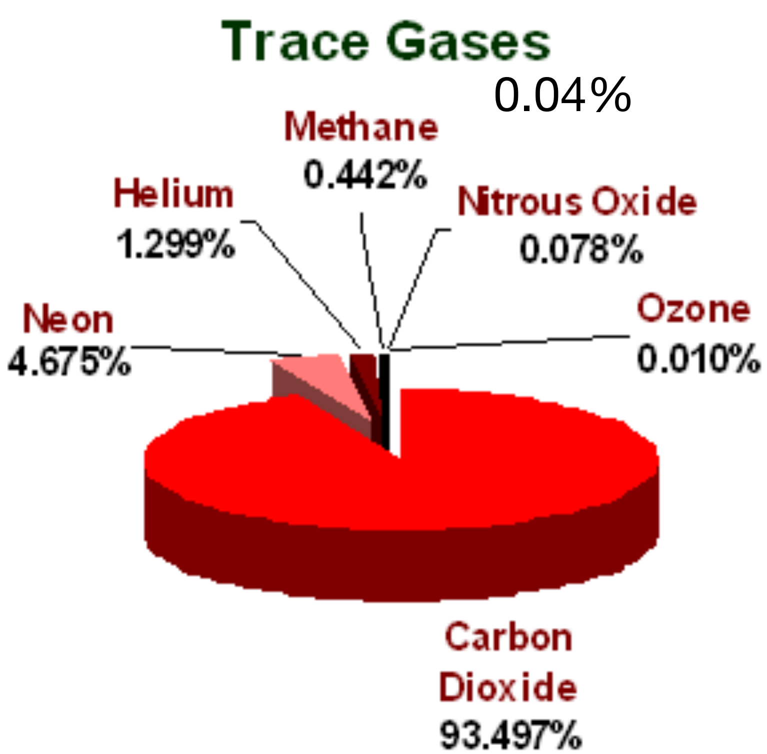
	Composition	Breathing?	Result
Mercury	N/A	nothing to breathe	death
Venus	96% CO_2 3.5% N_2 <1% SO_2	poisonous	death
Earth	78% N_2 21% O_2 <1% H_2O, CO_2	oxygen	life
Moon	N/A	nothing to breathe	death
Mars	95% CO_2 2.7% N_2	very little to breathe	death

Earth's Atmosphere

- About 10 km thick, crudely speaking

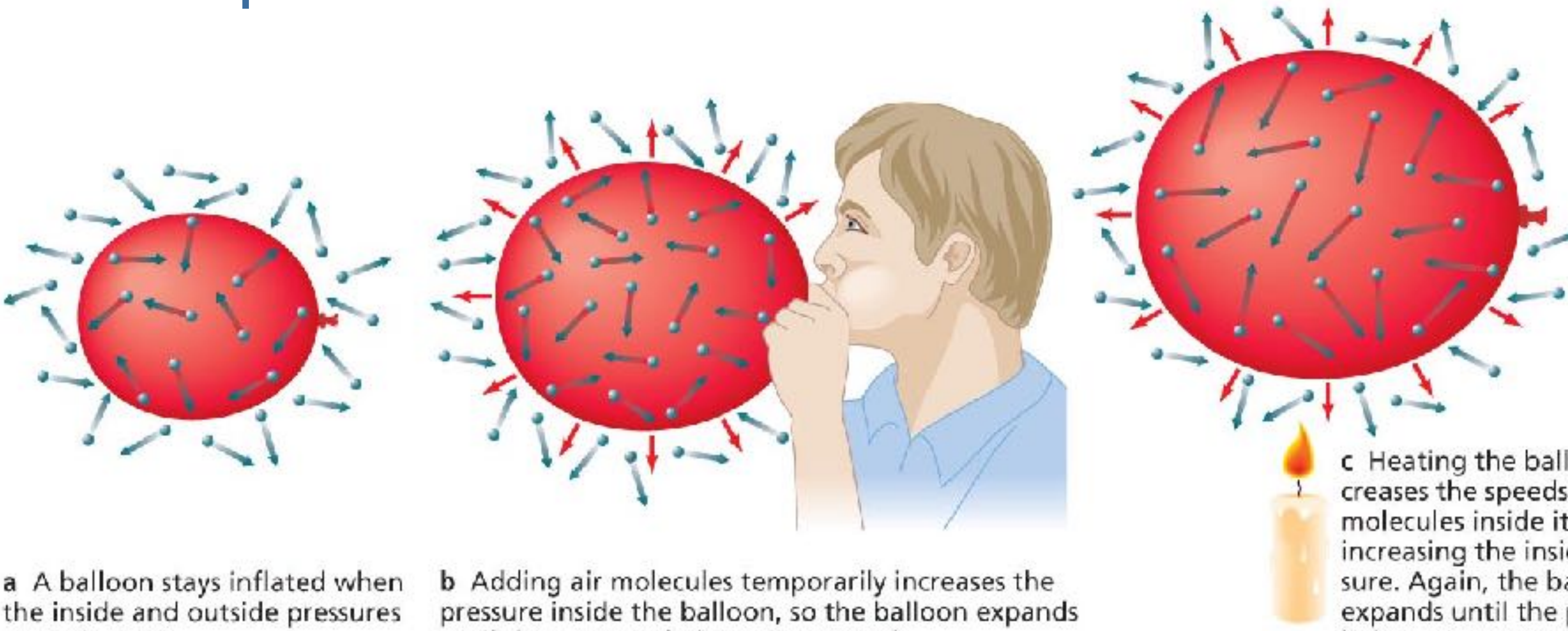
- 78% N_2
- 21% O_2
- 1% Argon
- 0.4% H_2O (variable)
  - “humidity”
- 0.04% CO_2 (increasing)
- 0.00018% CH_4





Not always like this. Oxygen appeared “only” ~2 billion years ago as a byproduct of photosynthesis

Atmospheric Pressure



a A balloon stays inflated when the inside and outside pressures are balanced.

b Adding air molecules temporarily increases the pressure inside the balloon, so the balloon expands until the pressure balance is restored.

c Heating the balloon increases the speeds of air molecules inside it, thereby increasing the inside pressure. Again, the balloon expands until the pressure balance is restored.

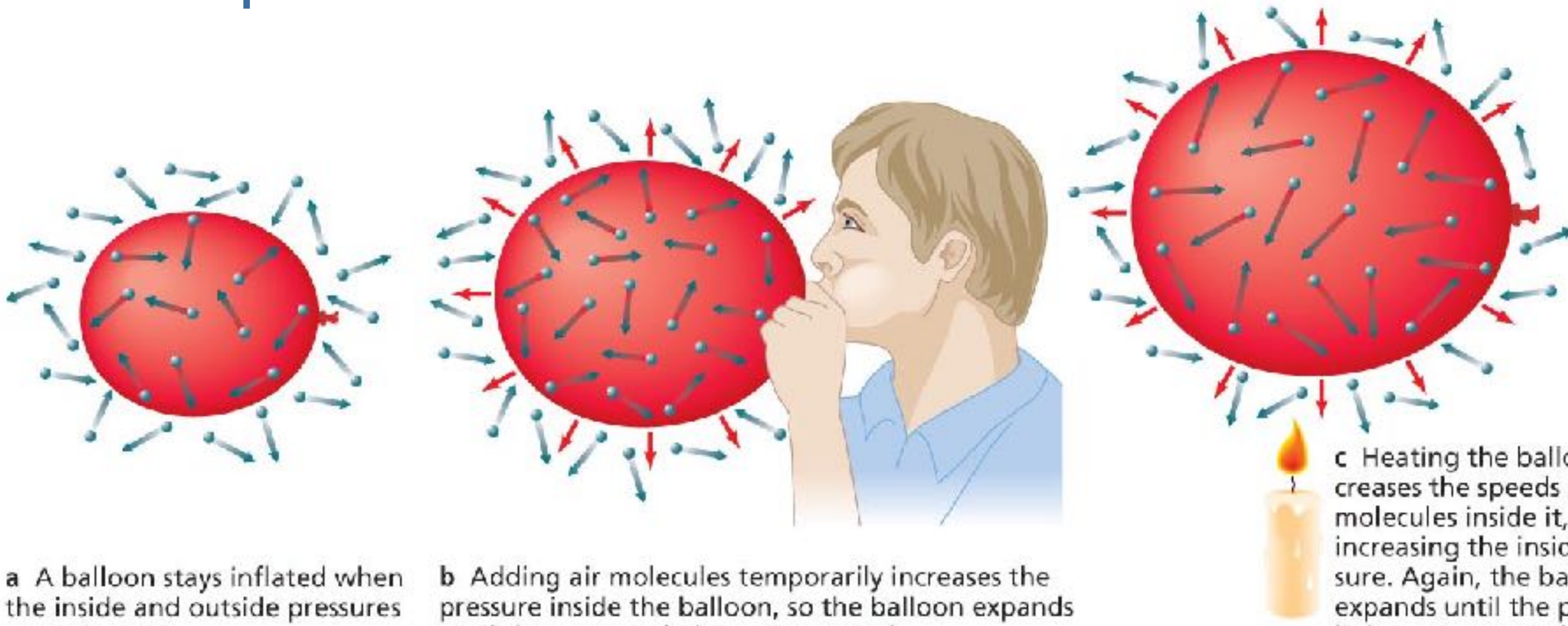
$$P = NkT$$

- P → Pressure
- N → Number density (# molecules per cubic centimeter)
- T → Temperature

More stuff → higher pressure

Higher temperature → higher pressure

Atmospheric Pressure



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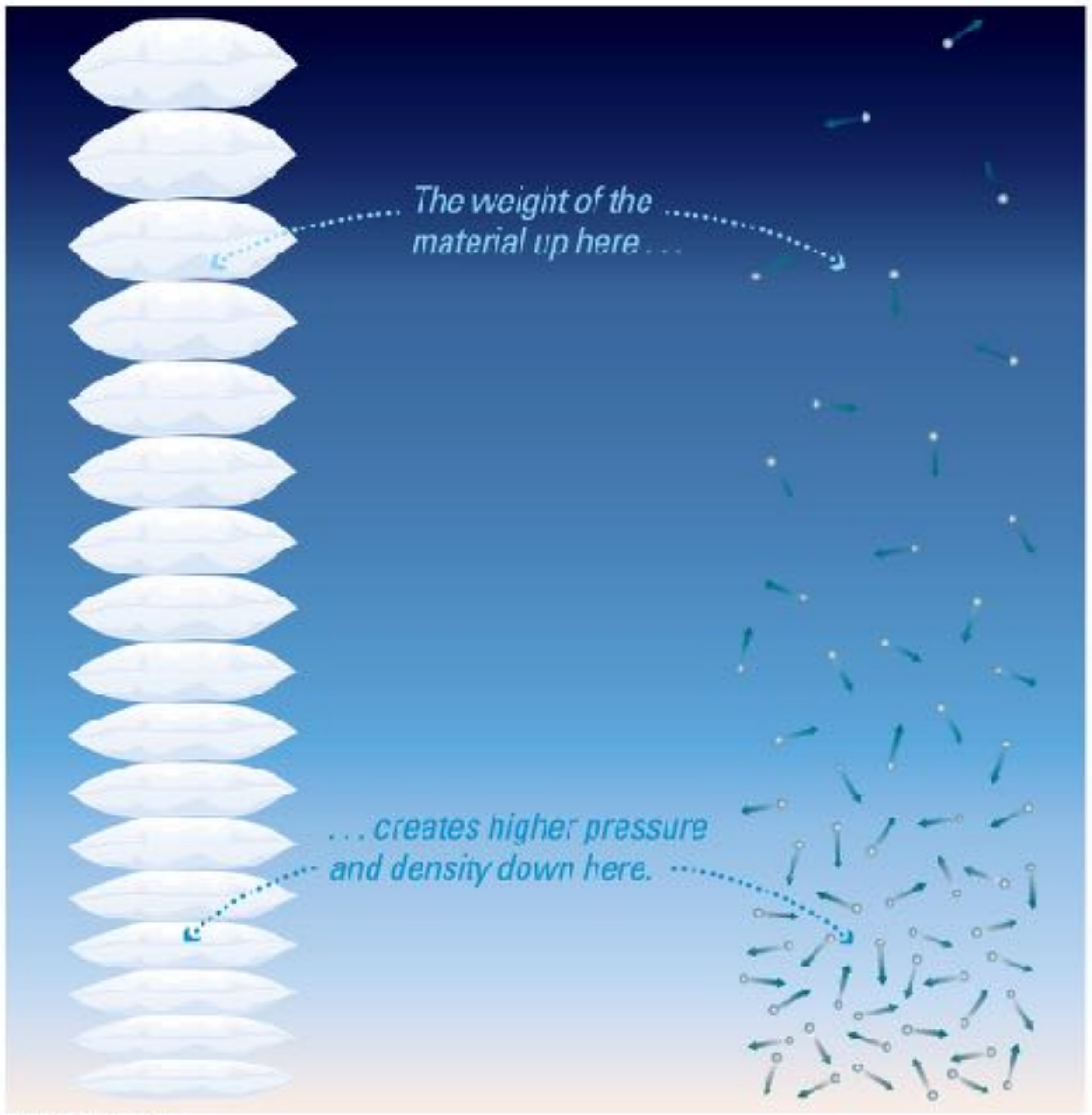
Things exist in pressure equilibrium with their surroundings:

- balloons
- sea level
- people (that’s why your ears pop at high altitude,
  or you get the bends if you come up too fast from a deep dive)

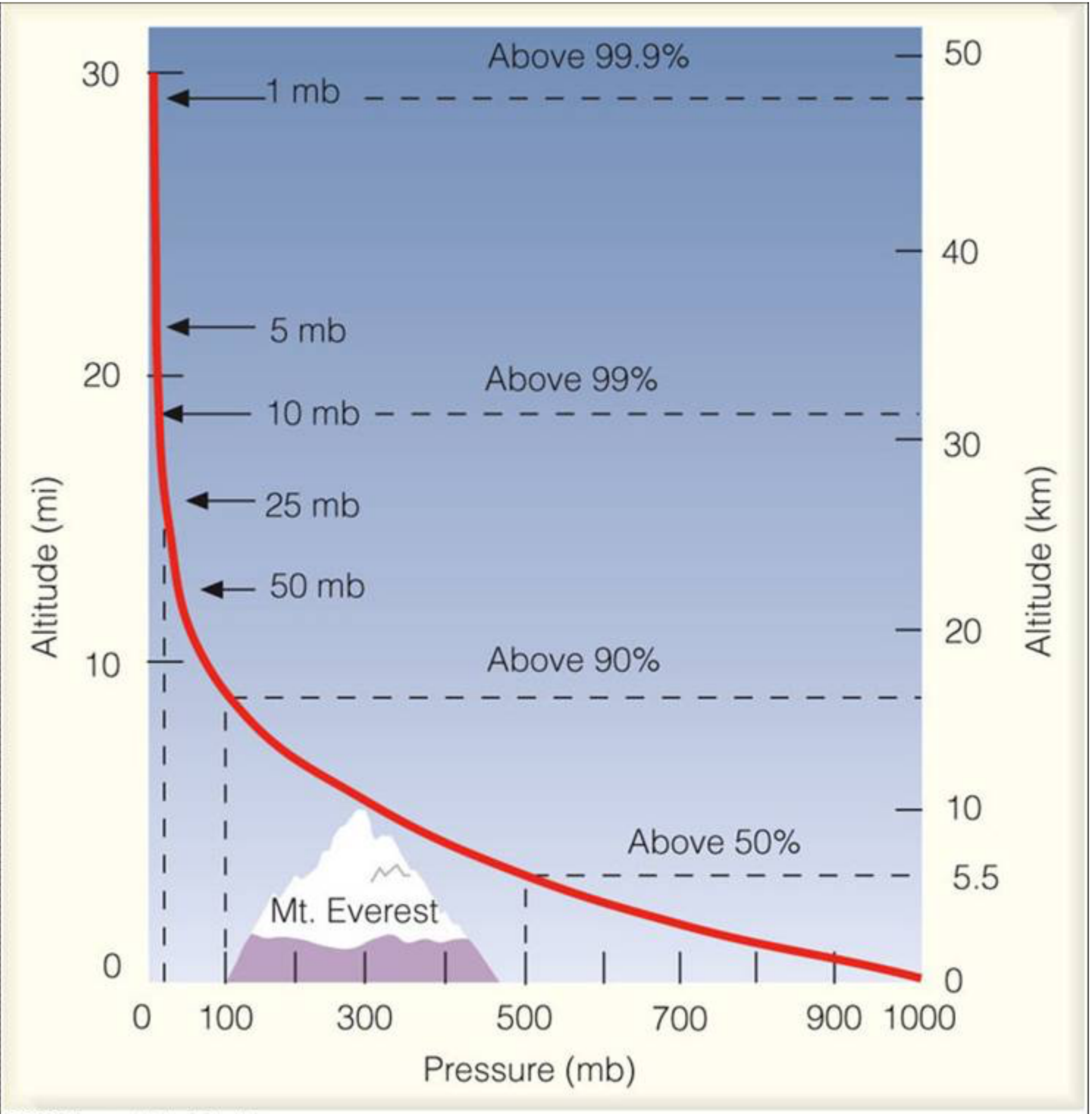
Atmospheric Pressure



- Pressure and density decrease with altitude because the weight of overlying layers is less.

- Earth's pressure at sea level is:
  – 1.03 kg per sq. meter
  – 14.7 lb per sq. inch
  – 1 bar / 1 Atmosphere

Barometers measure variations in atmospheric pressure;
cold fronts are typically associated with low pressure.
These are P-waves in the atmosphere.



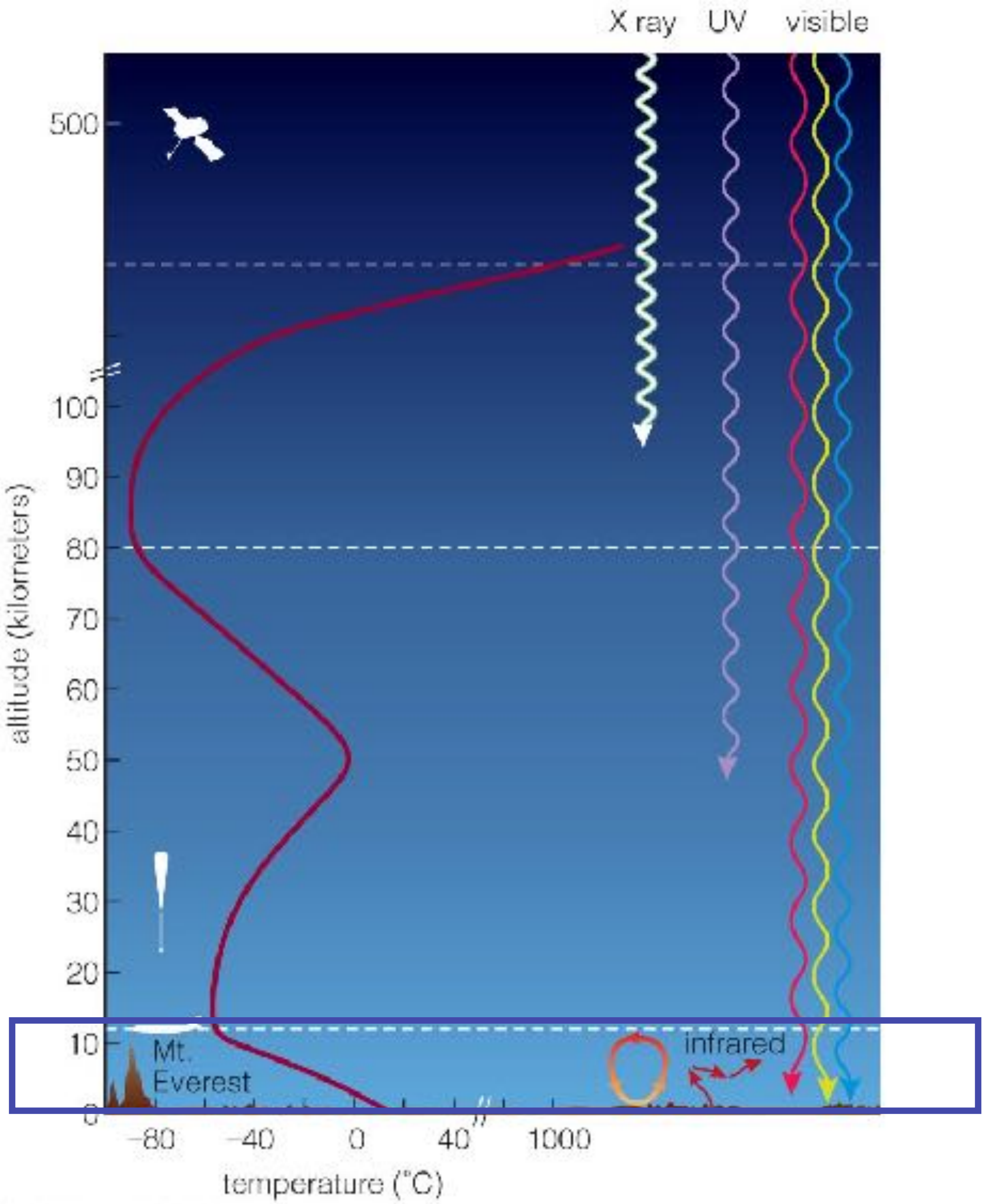
Atmospheric density and pressure decline with increasing altitude.

There is no clear "edge" to the atmosphere - just an exponential attenuation.

Jet cruising altitude ~ 10 km

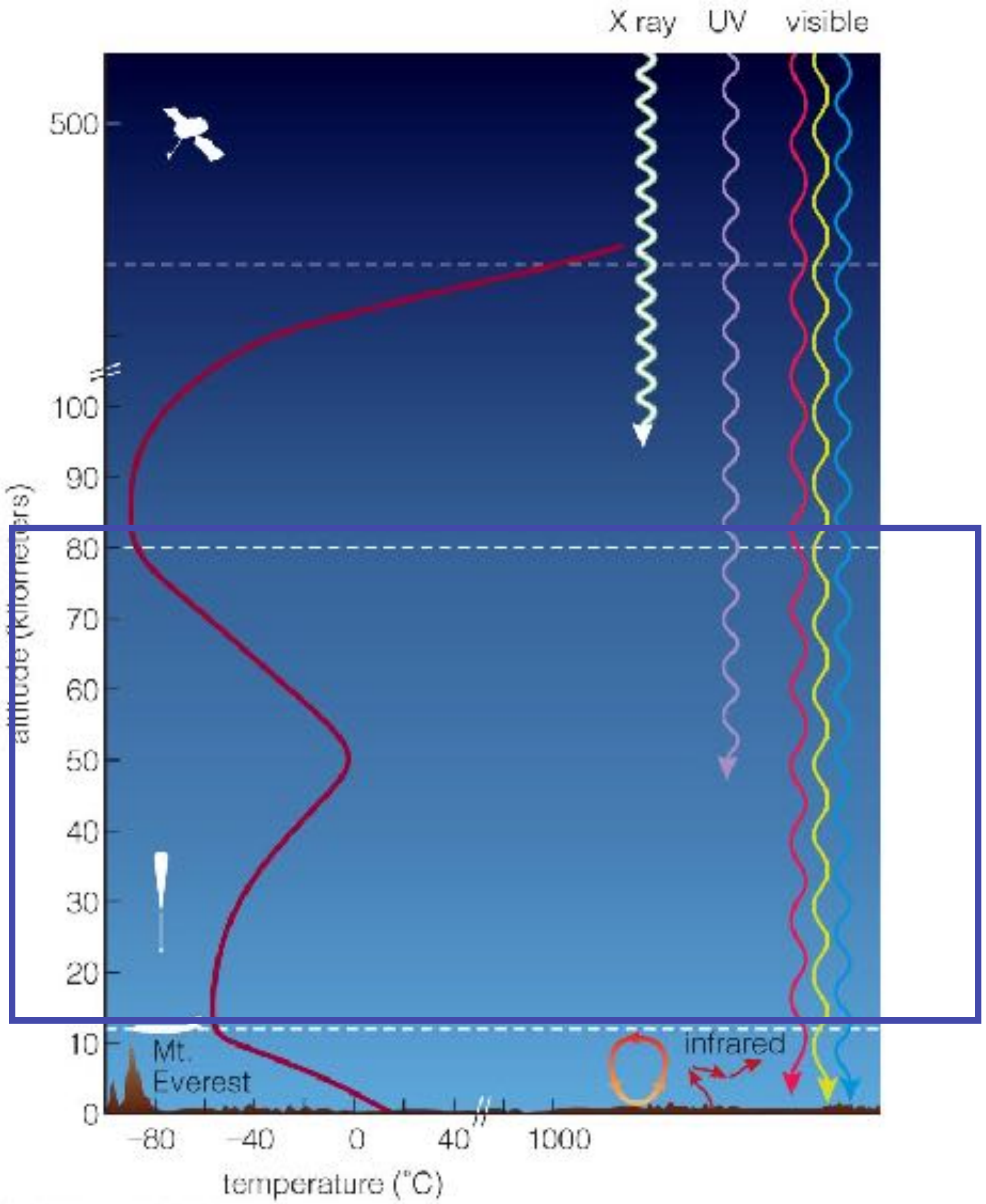
Death zone: > 8 km
not enough oxygen to breathe

Earth's Atmospheric Structure



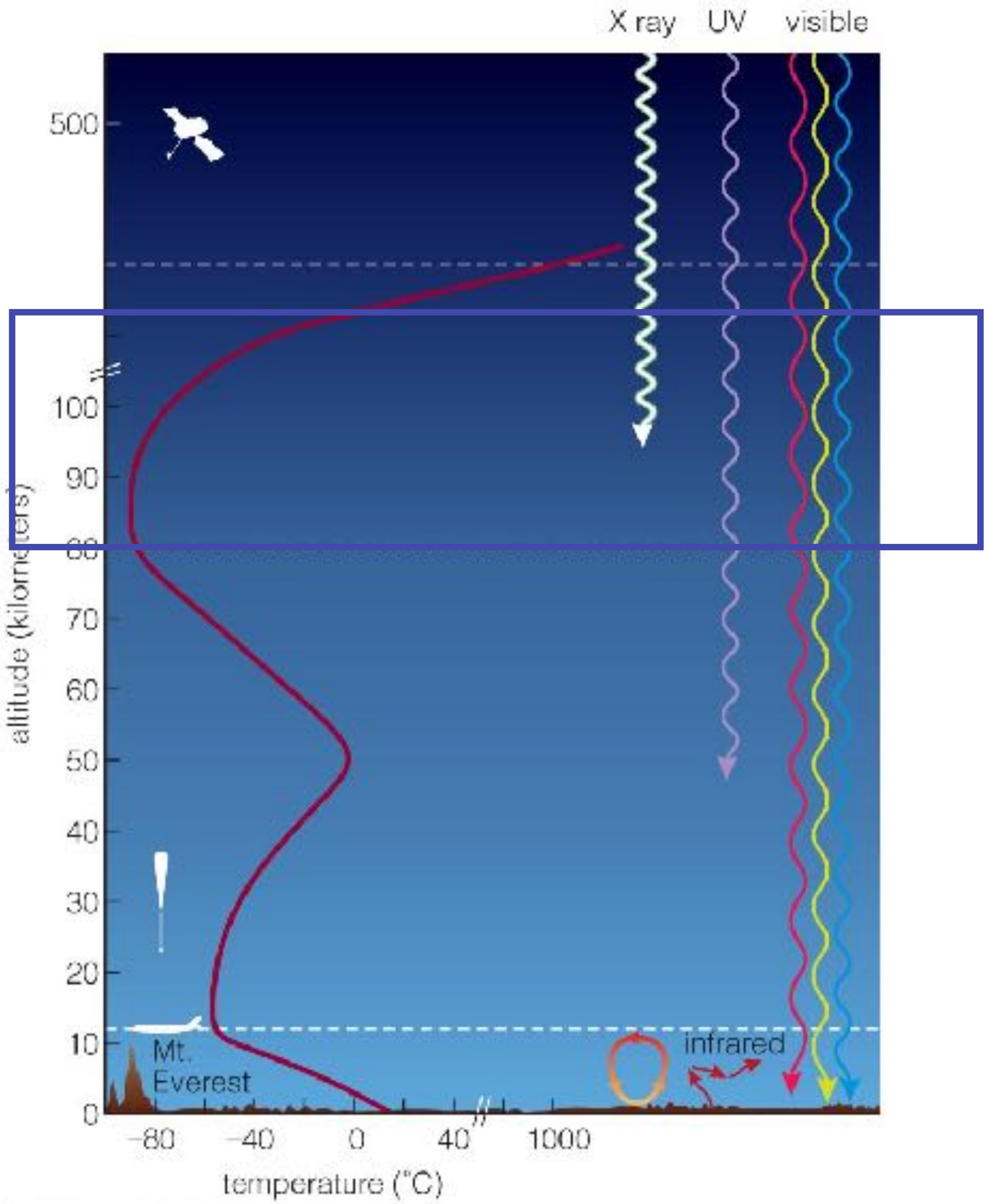
- Troposphere: lowest layer of Earth's atmosphere
- Temperature drops with increasing altitude.
- Warmed by infrared light from surface and convection

Earth's Atmospheric Structure



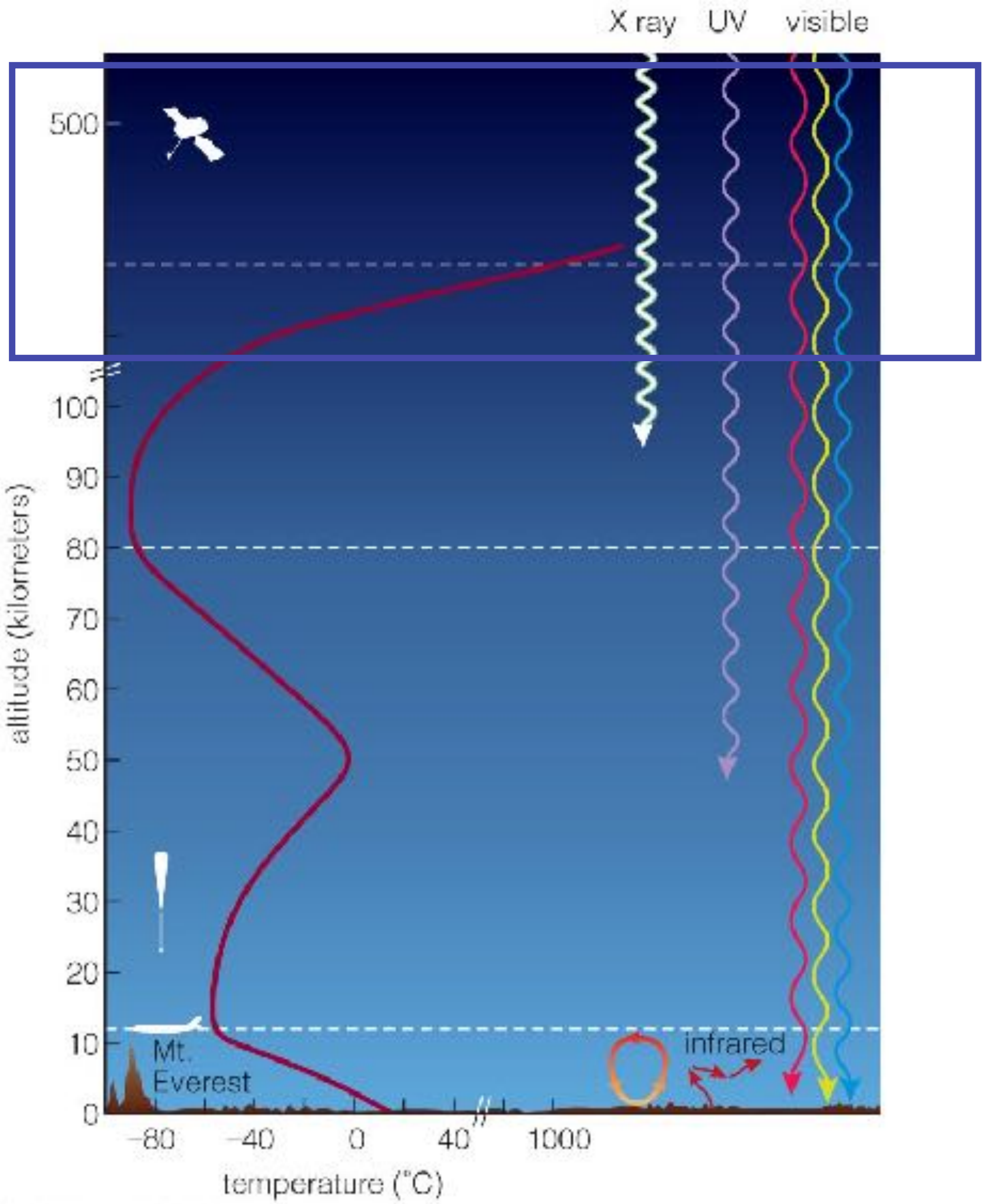
- Stratosphere: layer above the troposphere
- Temperature rises with altitude in lower part, drops with altitude in upper part.
- Warmed by absorption of ultraviolet sunlight

Earth's Atmospheric Structure



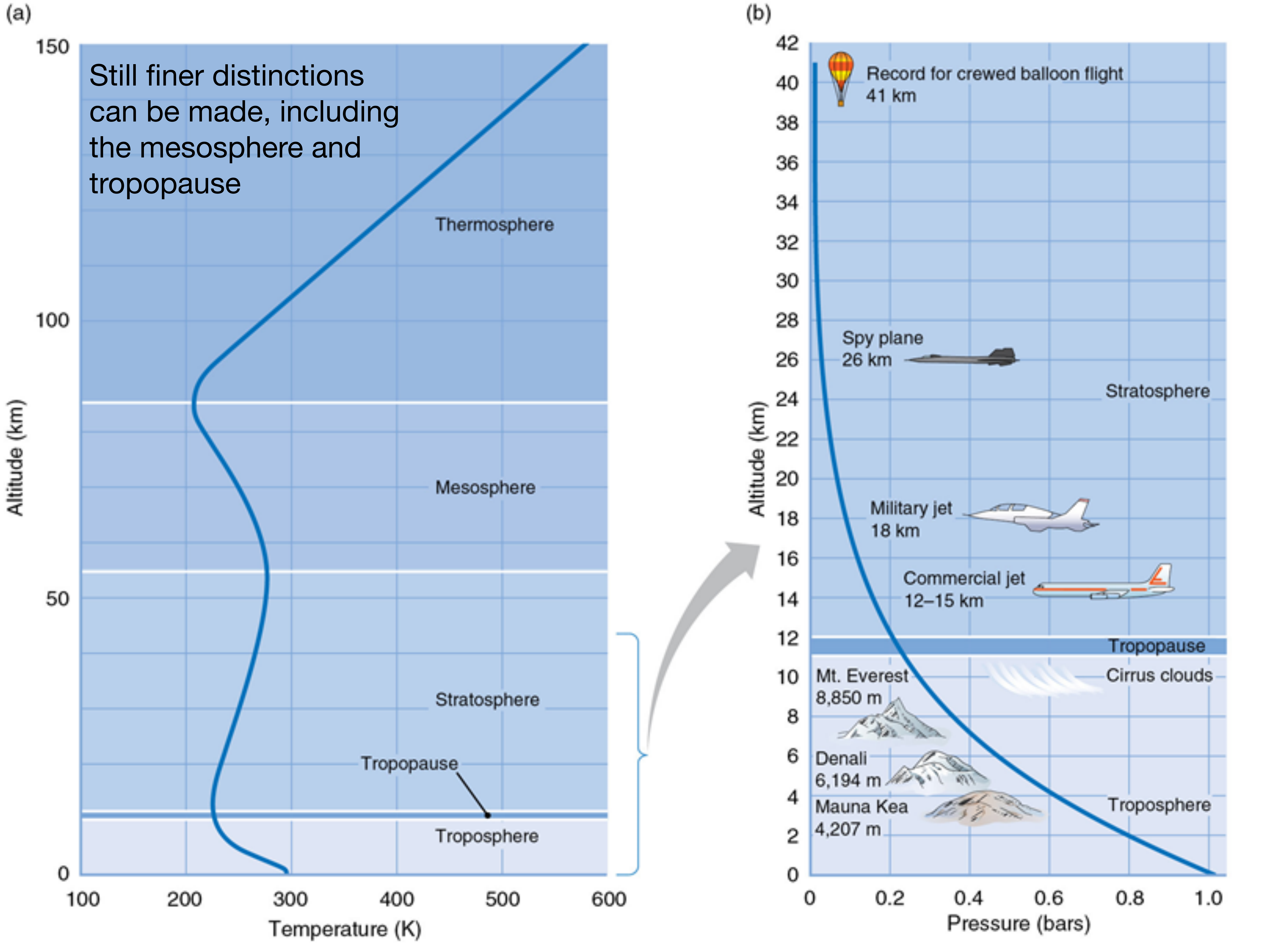
- Thermosphere: layer at about 100 kilometers altitude
- Temperature rises with altitude.
- X rays and ultraviolet light from the Sun heat and ionize gases.

Earth's Atmospheric Structure



- Exosphere: highest layer in which atmosphere gradually fades into space
- Temperature rises with altitude; atoms can escape into space.
- Warmed by X rays and UV light

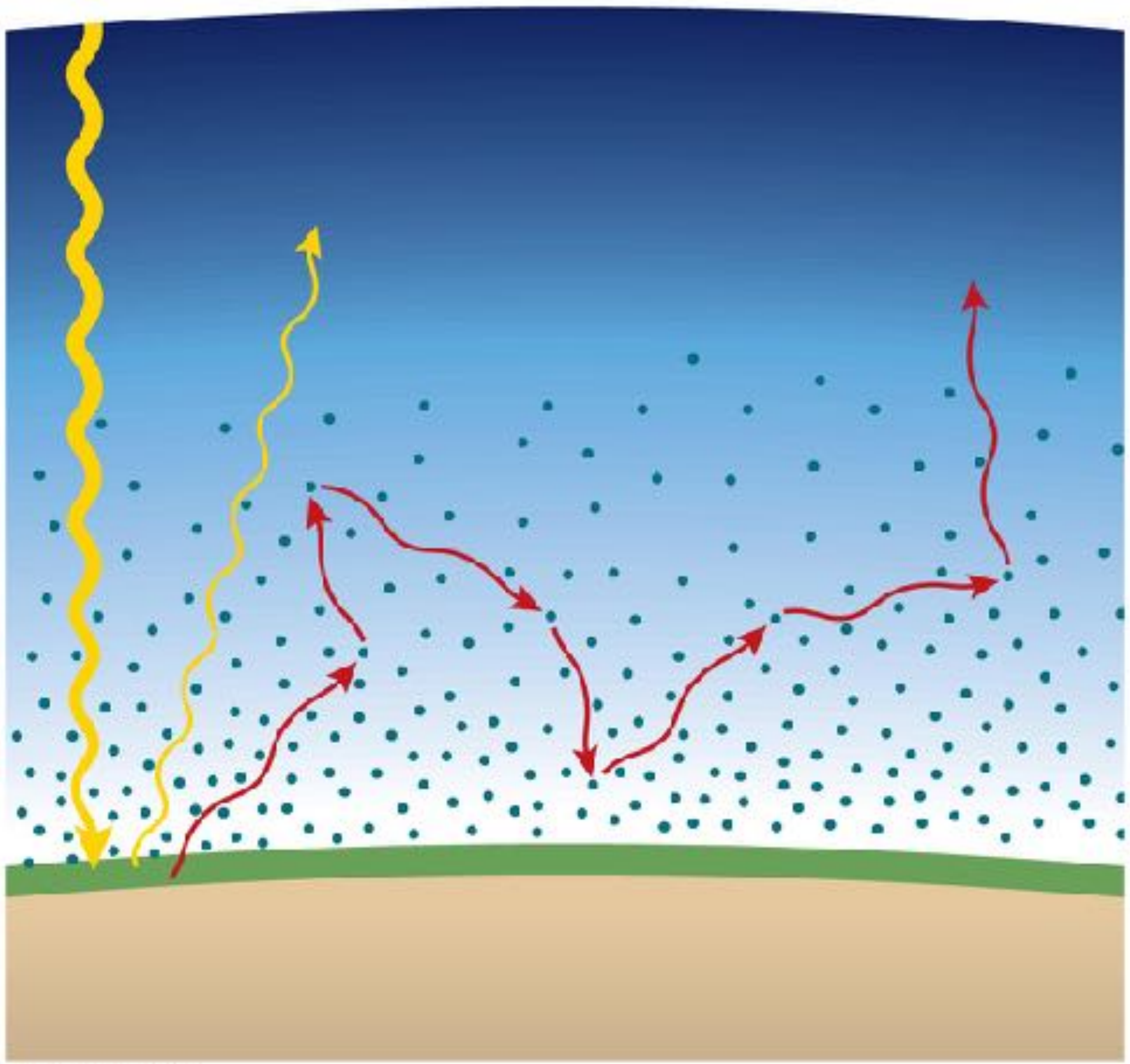
Still finer distinctions can be made, including the mesosphere and tropopause



Planetary climates

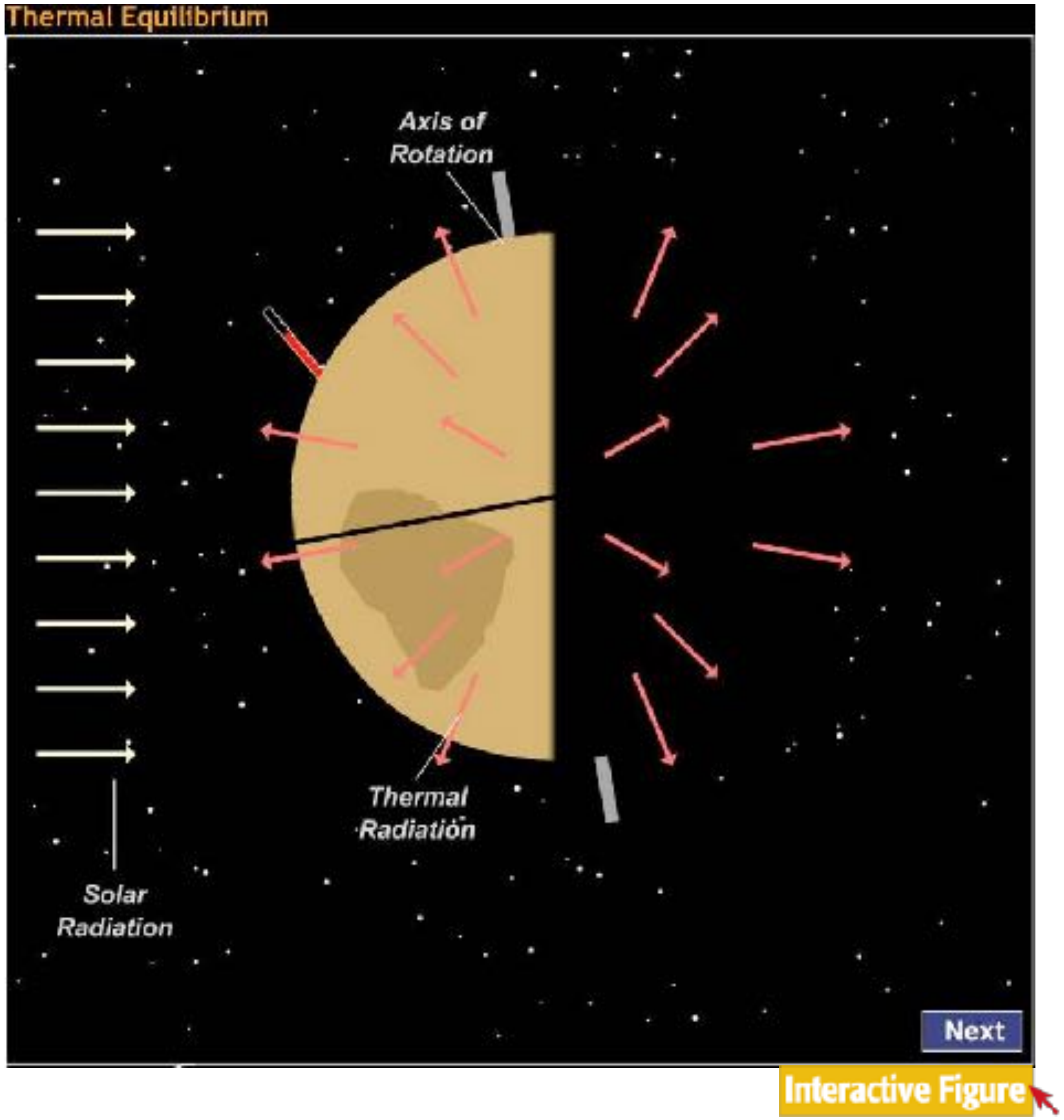
- Temperature depends on balance between
- Heat input from sun
  - distance dependent
  - albedo dependent (reflection vs. absorption)
- Heat loss to space
  - atmosphere dependent (natural greenhouse effect)
  - heat trapping "greenhouse" gases (e.g., H_2O, CO_2) important even if only present in trace quantities
    - they are the like a thin, black shade to the thick transparent glass of the more abundant atmospheric gases (N_2, O_2)

Greenhouse Effect



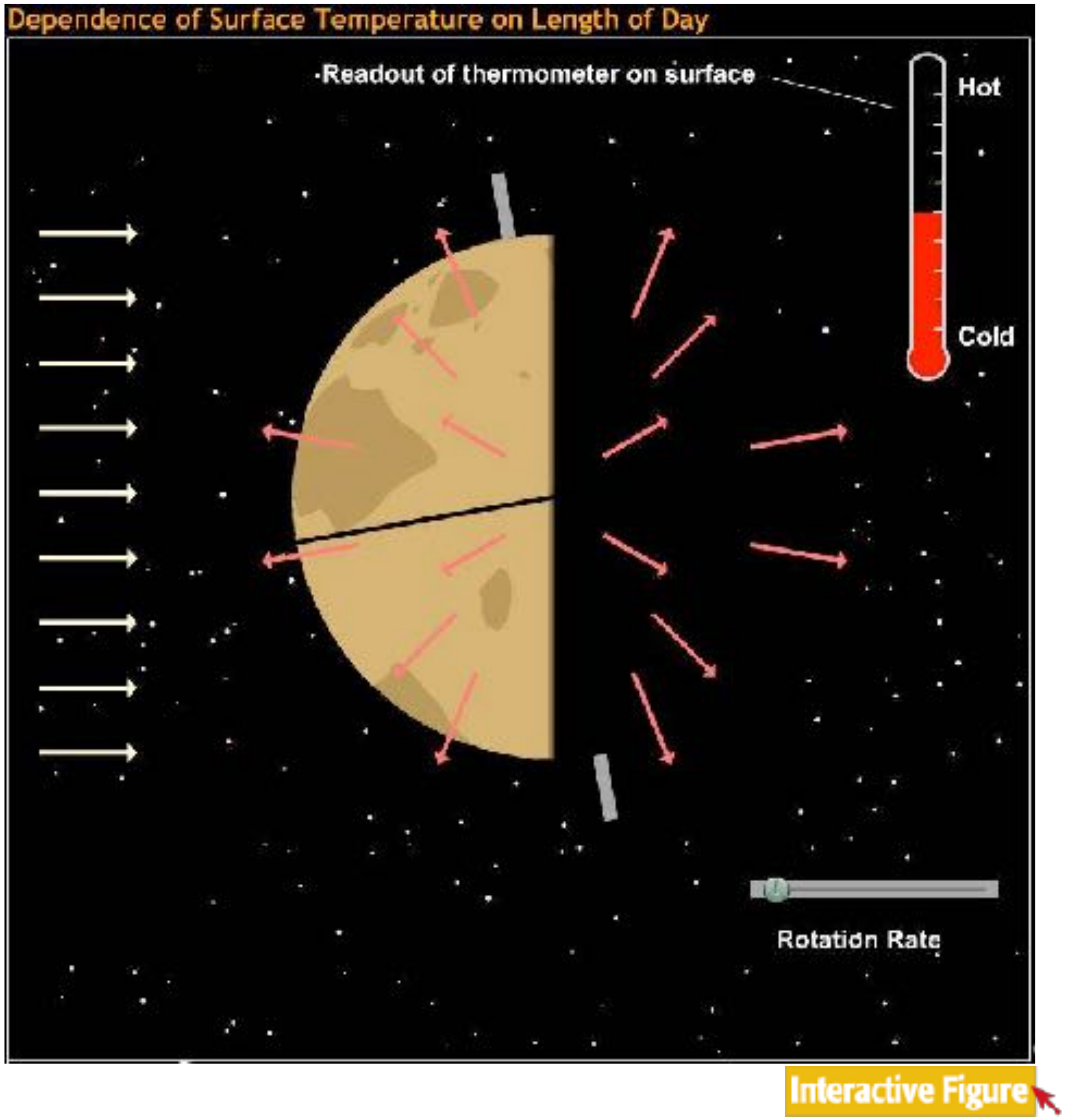
- Visible light passes through the atmosphere and warms a planet's surface.
- The atmosphere absorbs infrared light from the surface, trapping heat.

Planetary Temperature



- A planet's surface temperature is determined by the balance between energy from sunlight it absorbs and energy of outgoing thermal radiation.

Temperature and Rotation



- A planet's rotation rate affects the temperature differences between day and night.
- Rapid rotation evens out temperature variations
- Slow rotation exaggerates temperature variations

Temperature and Reflectivity

- A planet's reflectivity (or albedo) is the fraction of incoming sunlight it reflects.
- Planets with low albedo absorb more sunlight, leading to hotter temperatures.
- On planets without an atmosphere, like Mercury and the moon, that’s it
  – the surface heats up during the day
  – cools off at night

"No Greenhouse" Temperatures

Atmospheres act like blankets, trapping heat.

TABLE 10.2 The Greenhouse Effect on the Terrestrial Worlds

World	Average Distance from Sun (AU)	Reflectivity	"No Greenhouse" Average Surface Temperature*	Actual Average Surface Temperature	Greenhouse Warming (actual temperature minus "no greenhouse" temperature)
Mercury	0.387	12%	163°C	day: 425°C night: −175°C	—
Venus	0.723	75%	−40°C	470°C	510°C
Earth	1.00	29%	−16°C	15°C	31°C
Moon	1.00	12%	−2°C	day: 125°C night: −175°C	—
Mars	1.524	16%	−56°C	−50°C	6°C

*The "no greenhouse" temperature is calculated by assuming no change to the atmosphere other than lack of greenhouse warming. For example, Venus has a lower "no greenhouse" temperature than Earth even though it is closer to the Sun, because the high reflectivity of its bright clouds means that it absorbs less sunlight than Earth.

- Venus would be 510°C colder without greenhouse effect.
- Earth would be 31°C colder (below freezing on average).

Planetary climates

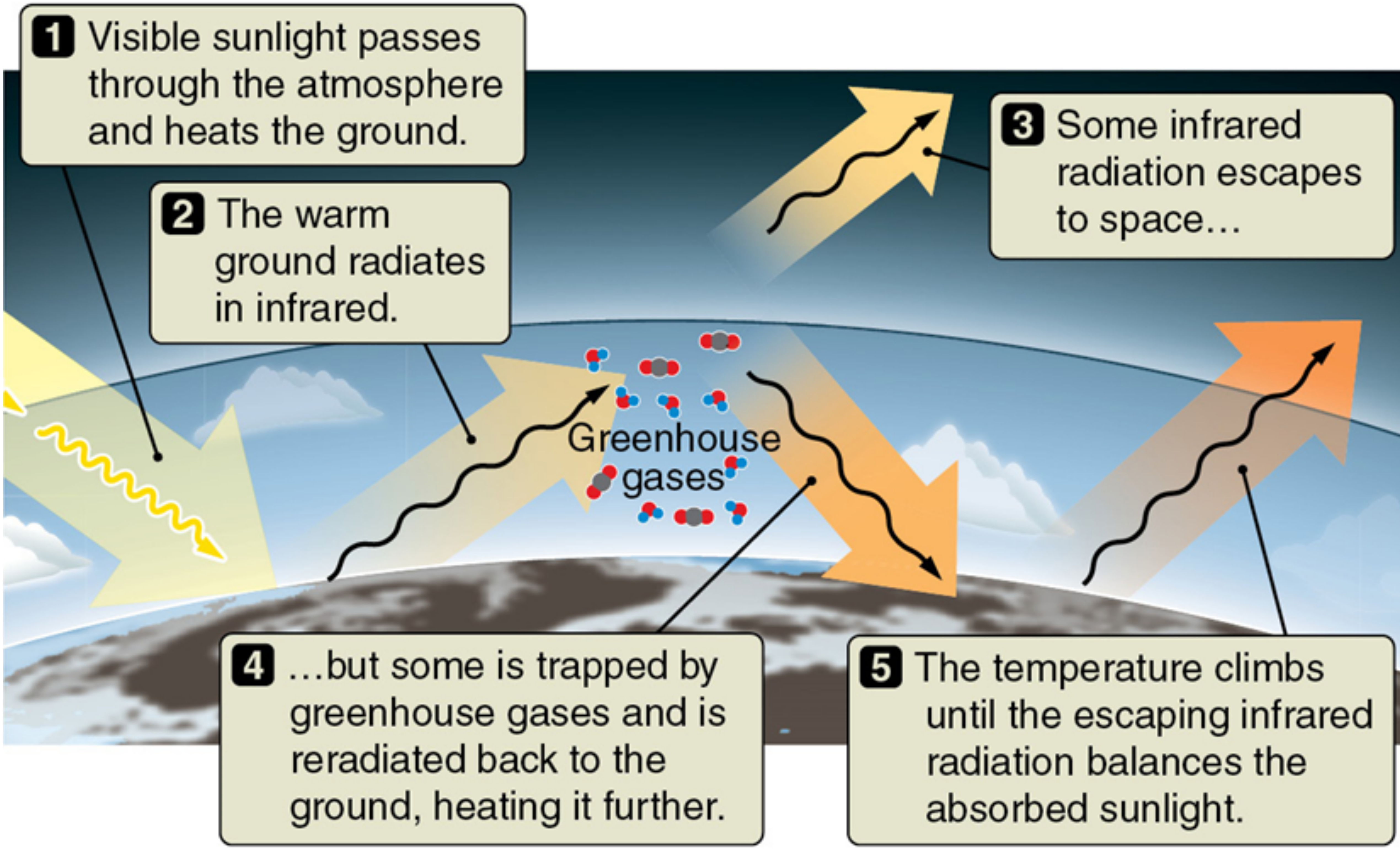
close to sun

- Mercury (no atmosphere)
  - Hot on day side, cold on night side
- Venus (thick atmosphere)
  - Hot all the time (hotter than Mercury!)
- Earth ("nice" atmosphere)
  - "just right"
- Moon (no atmosphere)
  - Hot on day side, cold on night side
- Mars (thin atmosphere)
  - colder now than in past

same distance from sun

far from sun

The Greenhouse Effect



Greenhouse Gas

- Any gas that absorbs infrared
- Greenhouse gas: molecules with two different types of elements (H_2O, CO_2, CH_4)
  - though a minority of the atmosphere, they provide the bulk of the infrared opacity
- Not a greenhouse gas: diatomic molecules with two atoms of the same element (O_2, N_2)
  - Though oxygen and nitrogen compose the bulk of the atmosphere, they do not absorb in the infrared so don’t contribute to the greenhouse effect

Main greenhouse gases
(on the Earth)

– all are < 1% of atmosphere, but provide

- Water (H_2O) ~60% of infrared opacity
- Carbon dioxide (CO_2) ~22%
- Methane (CH_4) ~7%
- Others (ozone, CFCs, nitrous oxide) ~11%

Note: water vapor absorbs more IR than CO_2!

Methane would seem negligible by number, yet contributes noticeably to the IR opacity.

Greenhouse Effect: Bad?

Just talking about the *natural* Greenhouse effect, not any man-made addition to it.

The Earth is much warmer than it would be without an atmosphere because of the greenhouse effect. That's good!

(cf. the moon)

…the same can be said for Venus, only more so...

Why is Venus so hot?

The greenhouse effect on Venus keeps its surface temperature at 470°C (878°F). That's higher than Mercury, even though it is farther from the sun.

The difference is the greenhouse effect.

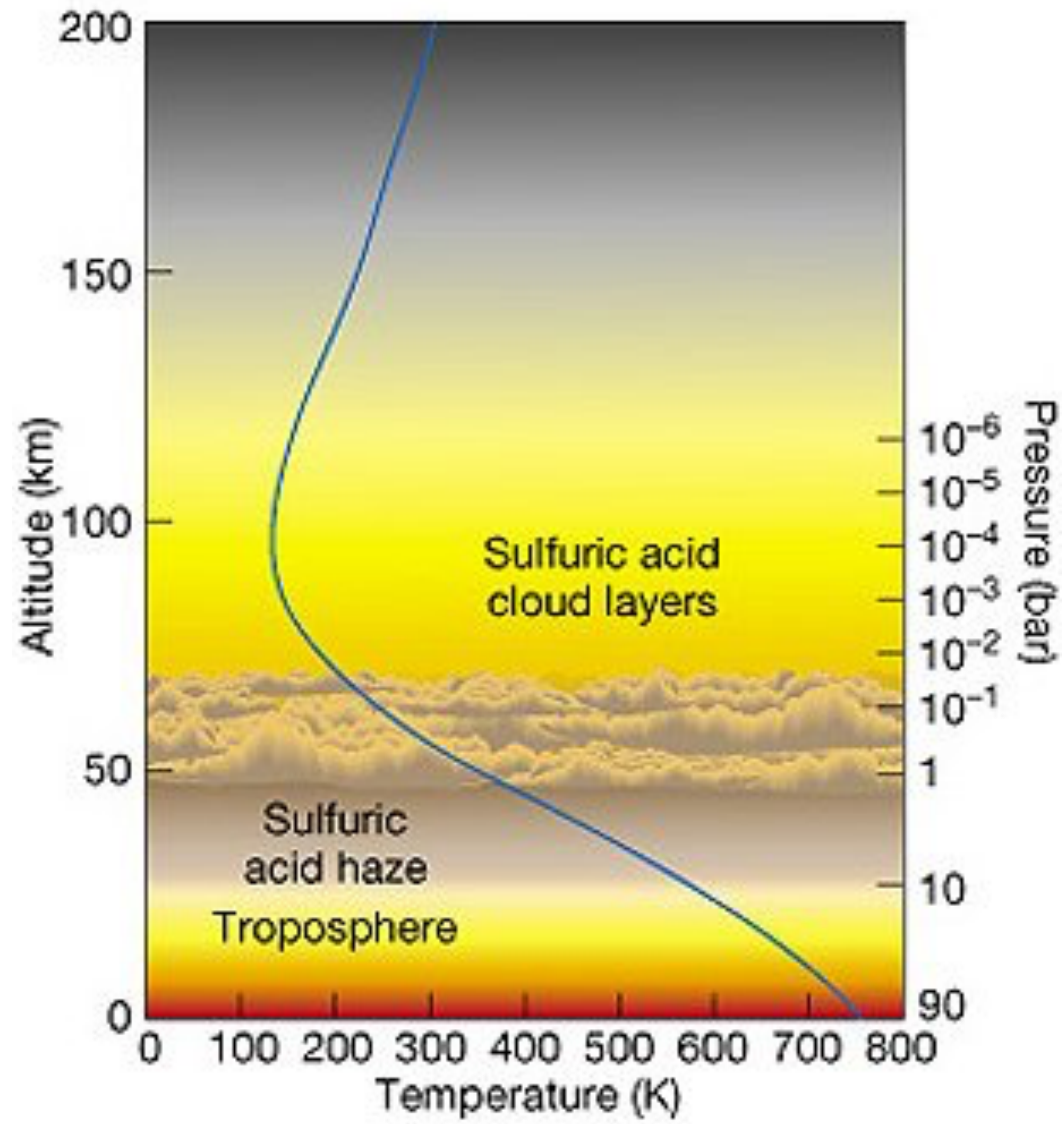
Why is the greenhouse effect on Venus so much stronger than on Earth?

Atmosphere of Venus

- Venus has a very thick carbon dioxide atmosphere with a surface pressure 90 times that of Earth.
- That’s equivalent to nearly a kilometer beneath the surface of the ocean.

Venus

- Permanently shrouded in clouds of sulfuric acid
- Albedo of clouds high
  - little sunlight absorbed
  - yet temperature high
- Earth-like temperature and pressure about 50 km altitude

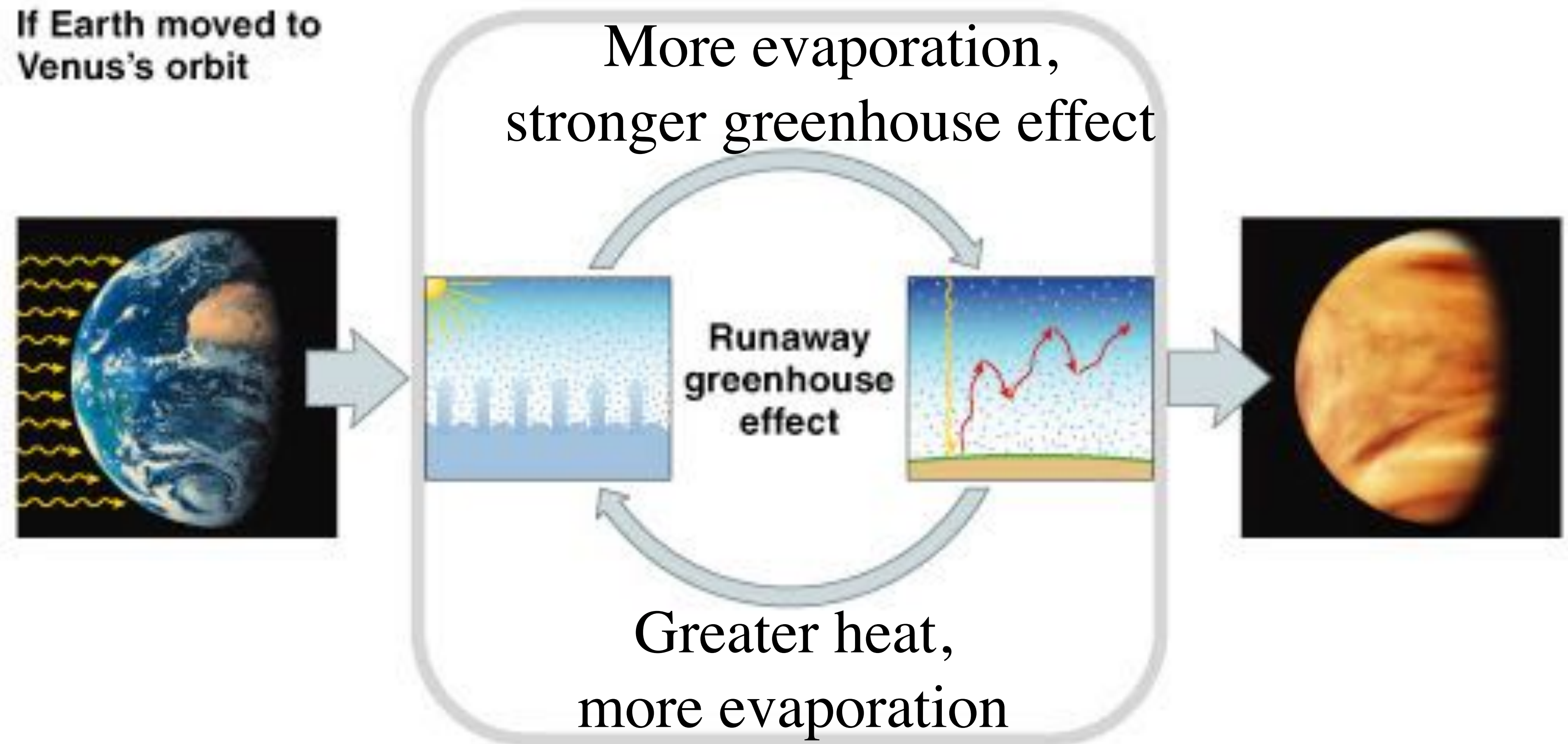


Greenhouse Effect on Venus

- Thick carbon dioxide atmosphere produces an extremely strong greenhouse effect.

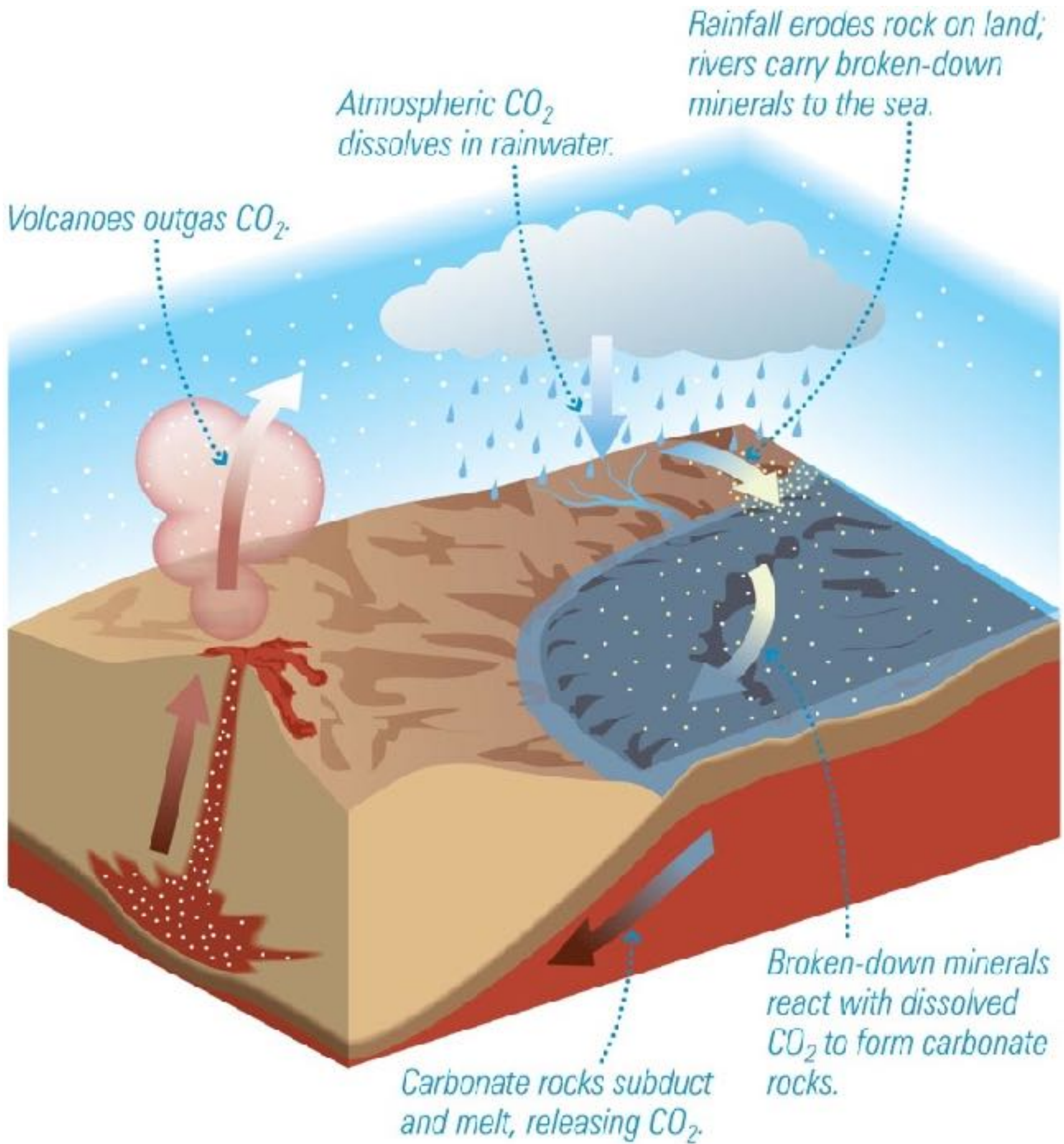
- Earth escapes this fate because most of its carbon and water are in rocks and oceans.

Runaway Greenhouse Effect

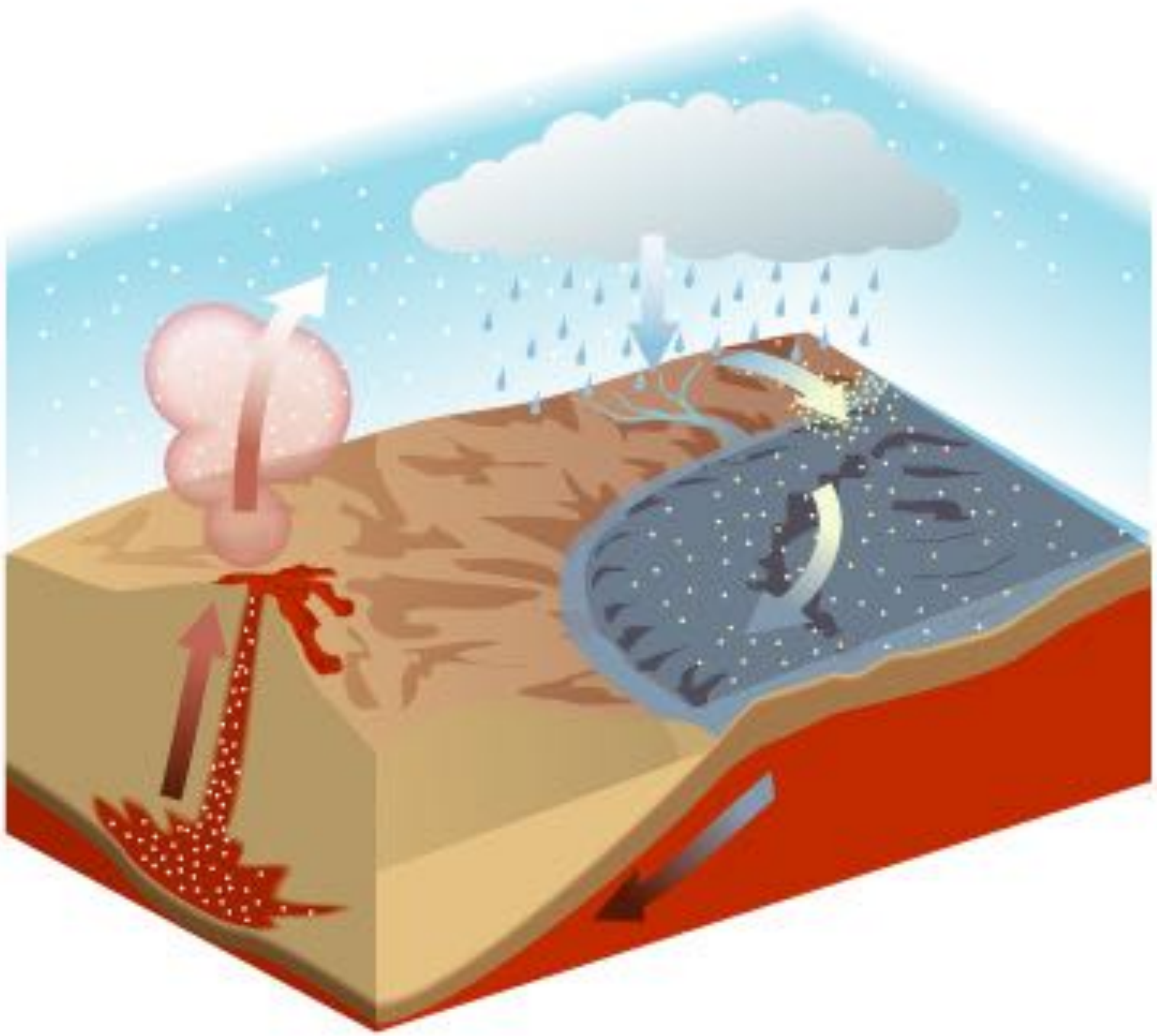


- Oceans evaporate; no longer absorb CO_2.
  - CO_2 builds up in atmosphere unchecked
  - "runaway greenhouse"

Carbon cycle on Earth

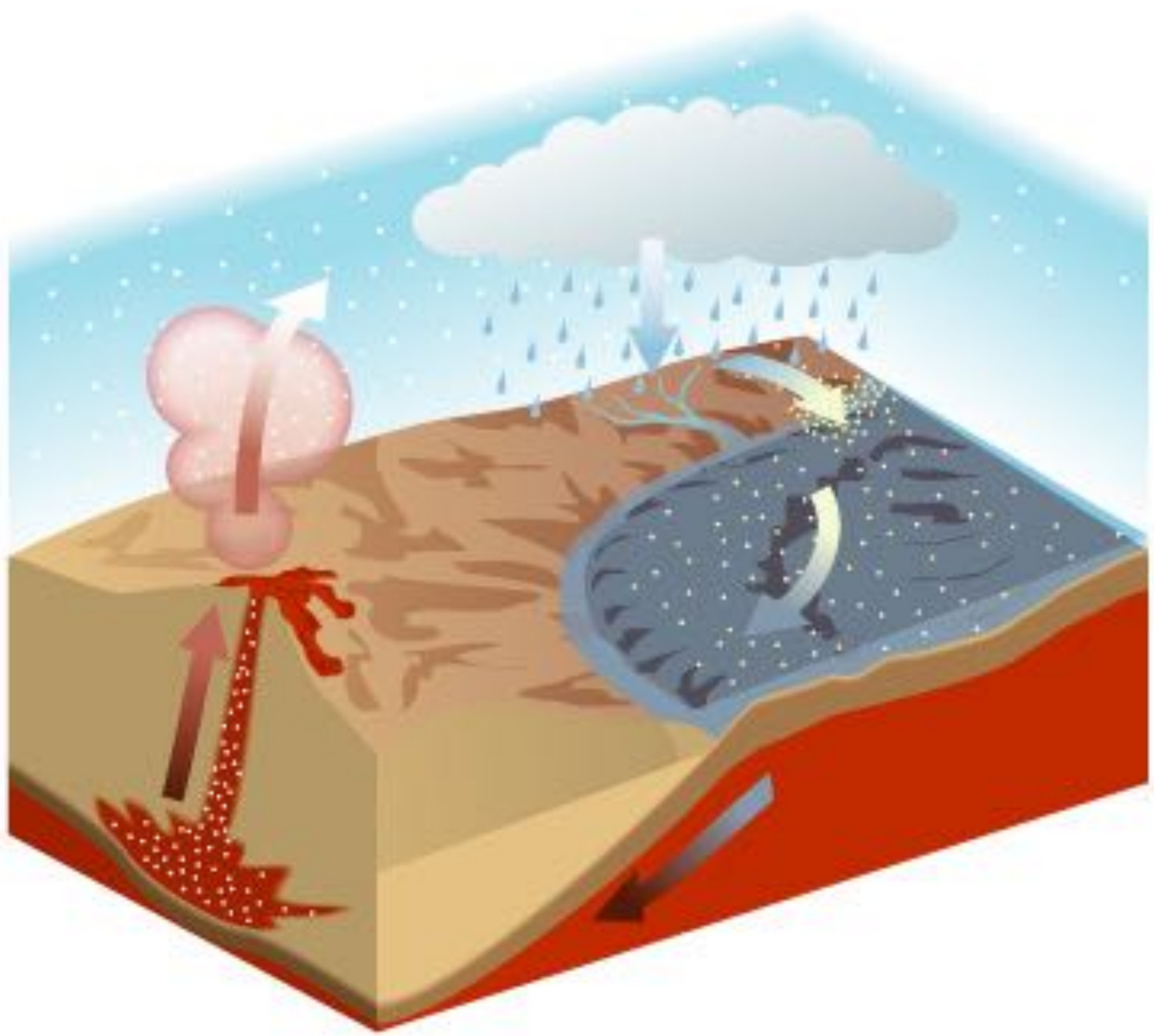


Carbon Dioxide Cycle



1. Atmospheric CO_2 dissolves in rainwater.
2. Rain erodes minerals that flow into the ocean.
3. Minerals combine with carbon to make rocks on ocean floor.

Carbon Dioxide Cycle



4. Subduction carries carbonate rocks down into the mantle.

5. Rock melts in mantle and outgases CO_2 back into atmosphere through volcanoes.