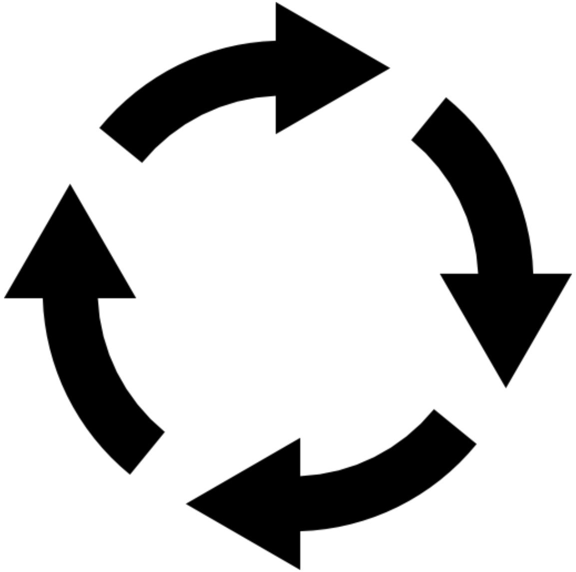
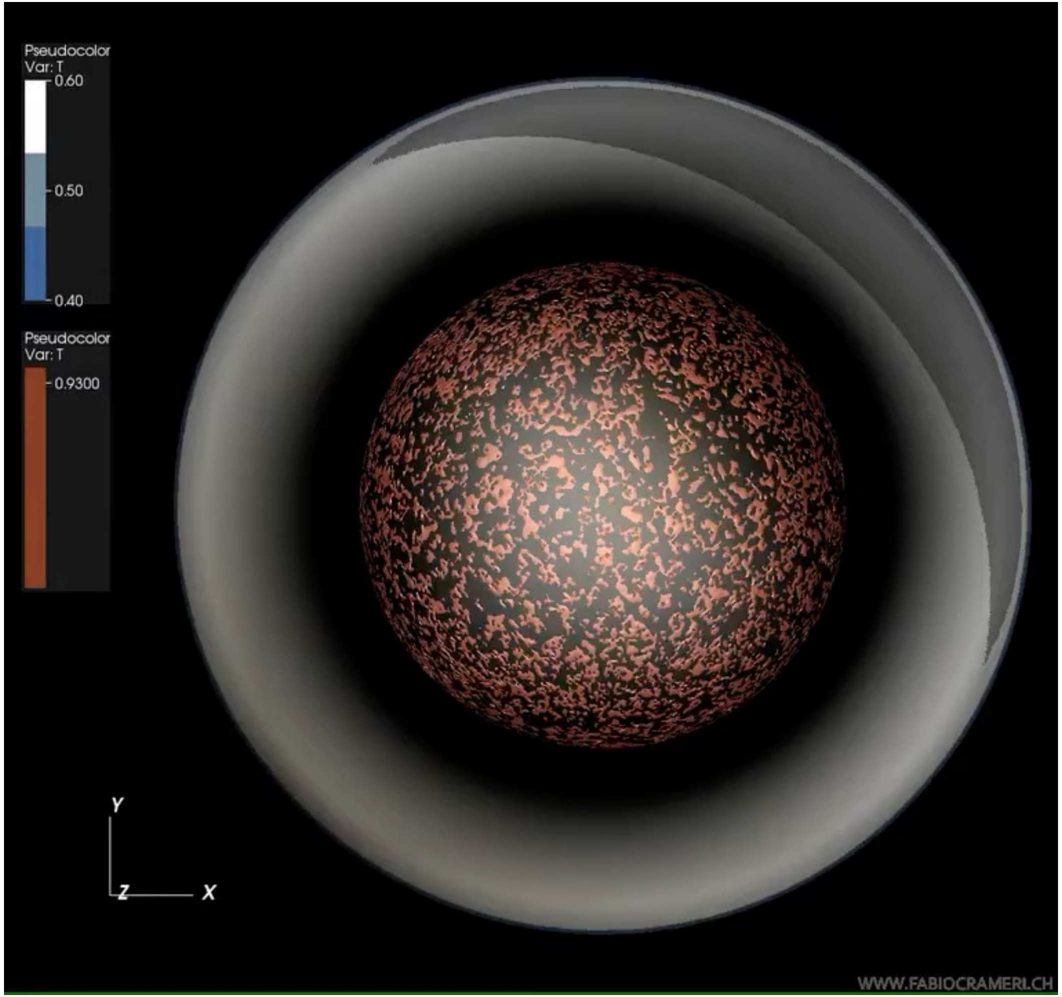
Geodynamics and Plate Driving Forces

Recap:

- Temperature controls density and viscosity
- Density contrasts create (buoyancy) forces
- Forces create stress
- Stress + rheology produce strain rate (deformation)
- Integrated over the planet → plate tectonics

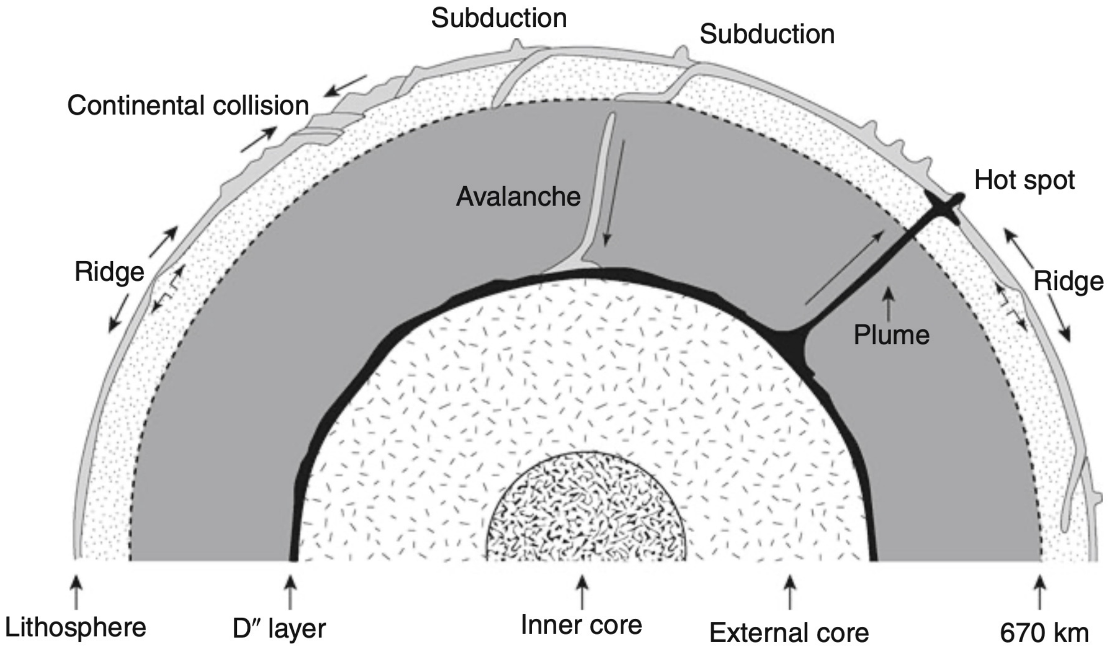


What do you see?



Driving Forces:

- Slab Pull
- Ridge push or gravitational sliding
- Basal Tractions
- Slab Resistance
- Collisional Resistance
- Slab Suction
- Transform resistance



Schematic cross section of the Earth showing cold subducting plates down to D” layer and upwelling mantle plumes from D” layer

Plate boundaries: where forces are applied

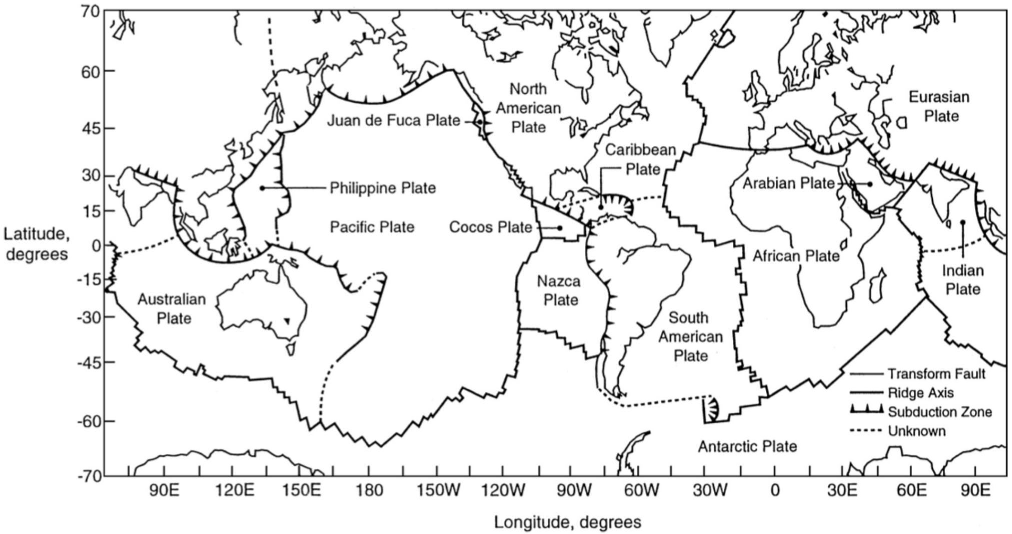
Earth's lithosphere is divided into rigid plates that move relative to each other. Motion is concentrated along three types of boundaries:

Mid-ocean ridges, plates are created and move apart.

Subduction zones, plates are consumed and sink into the mantle.

Transform faults, plates slide laterally past each other.

These boundaries are not just geometric features, they are where forces are generated and transmitted.



The force balance acting on a plate

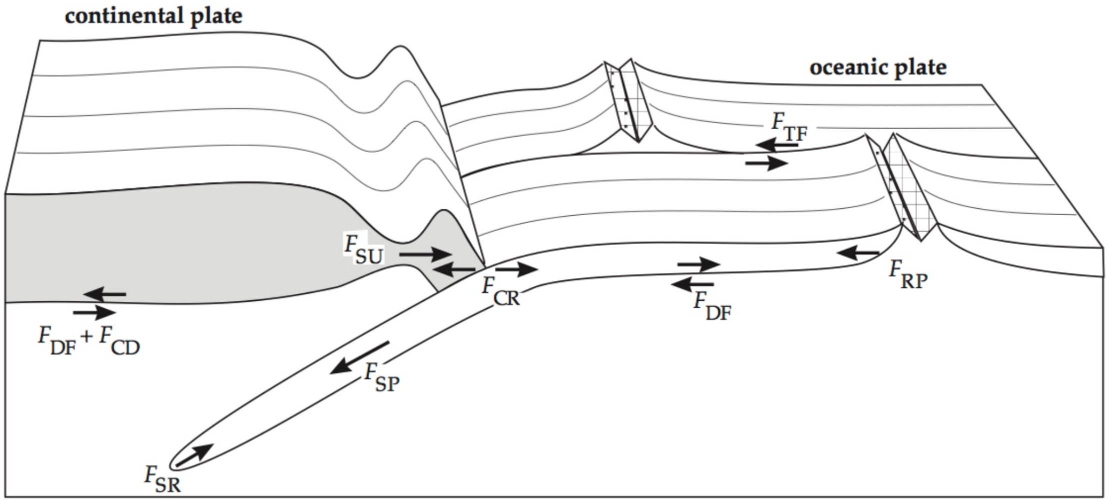
A tectonic plate is not pushed by a single force. It is the result of a force balance between:

Driving forces:

- Slab pull
- Ridge push (gravitational sliding)
- Basal traction

Resisting forces:

- Slab resistance
- Collisional resistance
- Transform resistance
- Mantle drag



Concept #1: buoyancy

Buoyancy is the upward "push" you get in a fluid because pressure increases with depth: the bottom of the object is pushed up more than the top is pushed down, so the net force upward equals the weight of the displaced fluid.

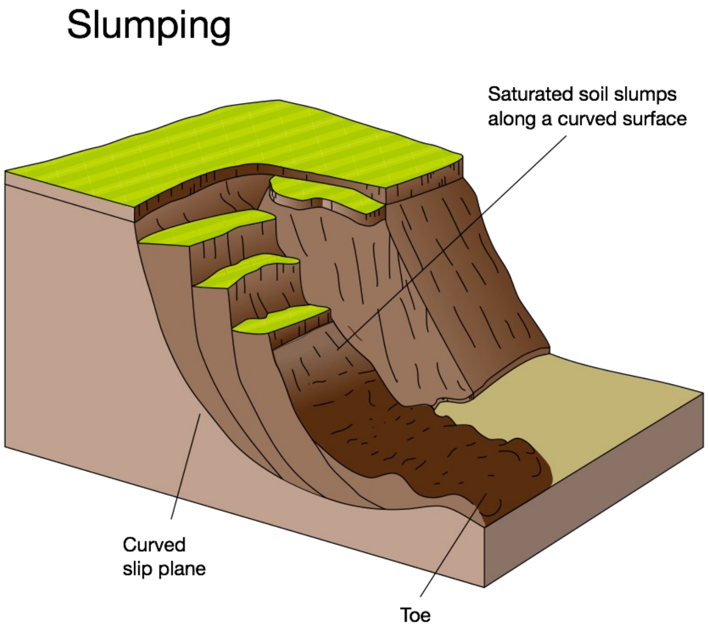
If the object (for example, the iceberg) is less dense than the fluid, that buoyant force wins and it floats. If it's denser, it sinks.

Concept #2: Gravitational sliding

The soil at the top sits on a slope. When it becomes weak (often because it is wet and saturated), gravity pulls it downward. But instead of sliding straight down, it moves along a curved slip surface. The mass rotates slightly as it moves, forming a steep head scarp at the top and a bulging “toe” at the bottom.

The key idea is simple:

gravity pulls material downslope, and if the slope is unstable, the mass moves along a curved surface under its own weight.

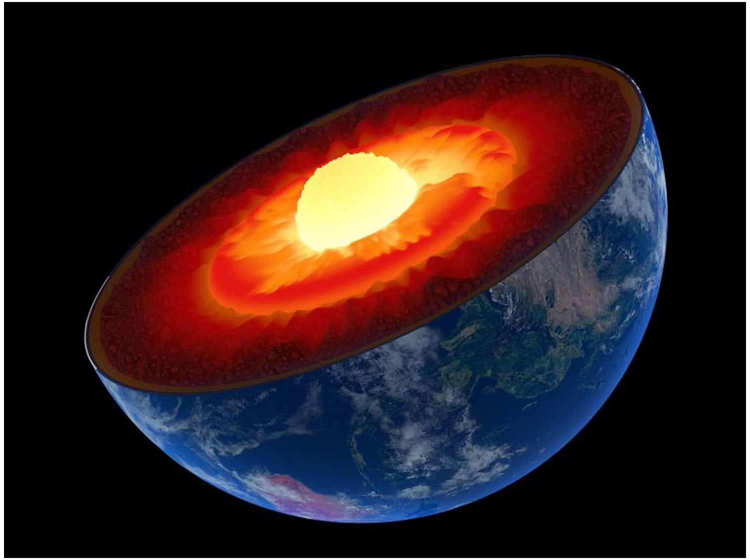


Geodynamics: why plates move

(and why the Earth works the way It does)

Geodynamics & plate driving forces: From temperature → rheology → buoyancy → plate motion

The Earth is a cooling planet. Why is the Earth hot?



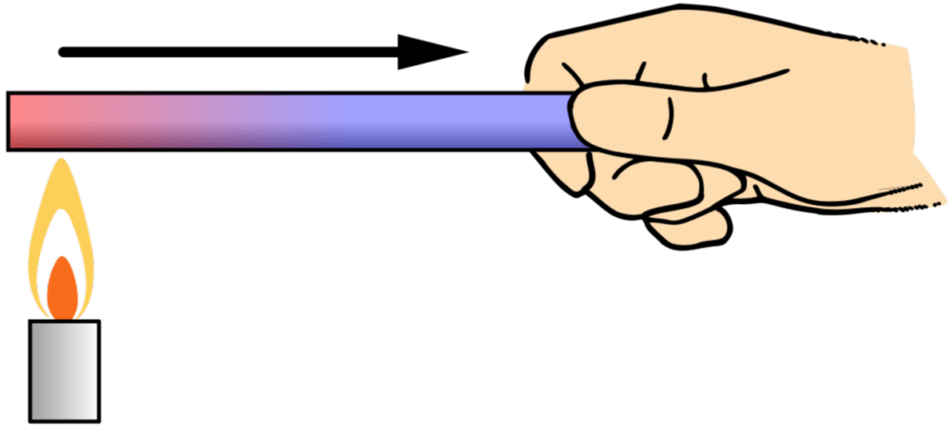
The deep Earth is hot because it formed hot, and it has not finished cooling. There are three main heat sources, such as primordial heat, and radiogenic heat.

The Earth is out of thermal equilibrium. The mantle is hotter than the surface. That temperature difference must be reduced over time. The planet continuously dissipates heat.

Two ways to transport heat: conduction vs convection

How does heat move?

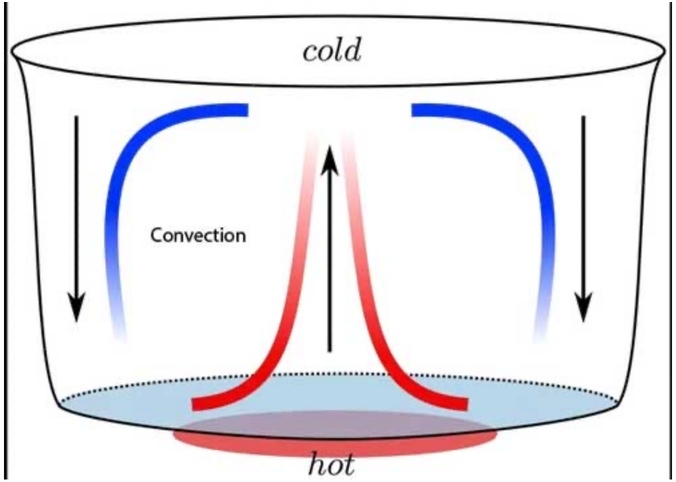
1. Conduction: Heat moves by molecular vibration and diffusion. Material does not move. Energy diffuses. Conduction is slow over large distances.



Two ways to transport heat: conduction vs convection

How does heat move?

2. Convection: Heat moves because material itself moves. Hot material rises. Cold material sinks. Energy transport occurs through bulk motion.



Conduction + convection

When you start heating a pot of water, heat initially moves by conduction. But as heating continues, the water at the bottom becomes warmer, and when a fluid warms, it expands slightly. Expansion means lower density. Lower density means buoyancy.

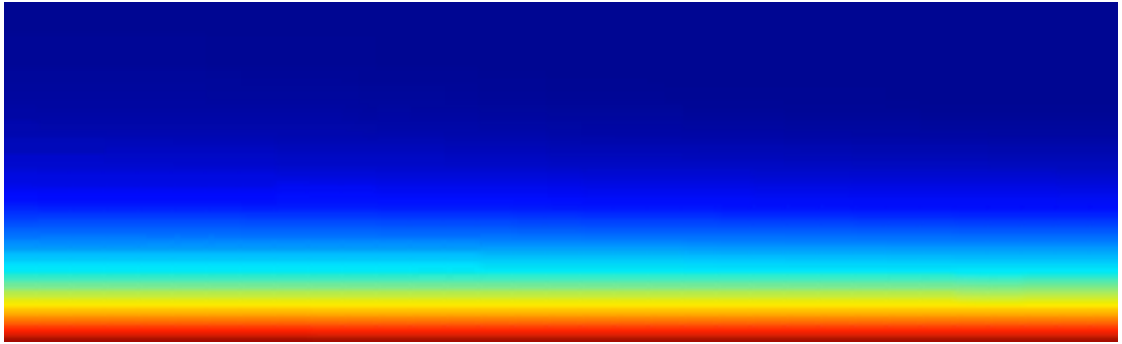
And buoyancy means that parcel of water wants to rise. At that moment, the system becomes gravitationally unstable: warm, light fluid is underneath colder, heavier fluid. That is the onset of convection.

**Convection happens before boiling.*

When does convection start?

Convection does not happen automatically. A layer heated from below can either conduct heat quietly or become unstable and start “overturning”. What determines which one? Competition between:

- Thermal buoyancy (drives motion)
- Viscous resistance (resists motion)
- Thermal diffusion (removes temperature contrast)



When does convection start?

This competition is captured by one dimensionless number:

$\rho =$ density

$g =$ gravity

$\alpha =$ thermal expansion coefficient

$\Delta T =$ temperature difference

$H =$ layer thickness

$\kappa =$ thermal diffusivity

$\eta =$ viscosity

$$Ra = \frac{\rho g \alpha \Delta T H^3}{\kappa \eta}$$

This is the Rayleigh number (dimensionless)

Convection begins when the Rayleigh number exceeds a critical value, typically around ~1708 for infinite horizontal plates, marking the shift from conductive to buoyancy-driven flow.

What controls convection in the mantle?

First observation:

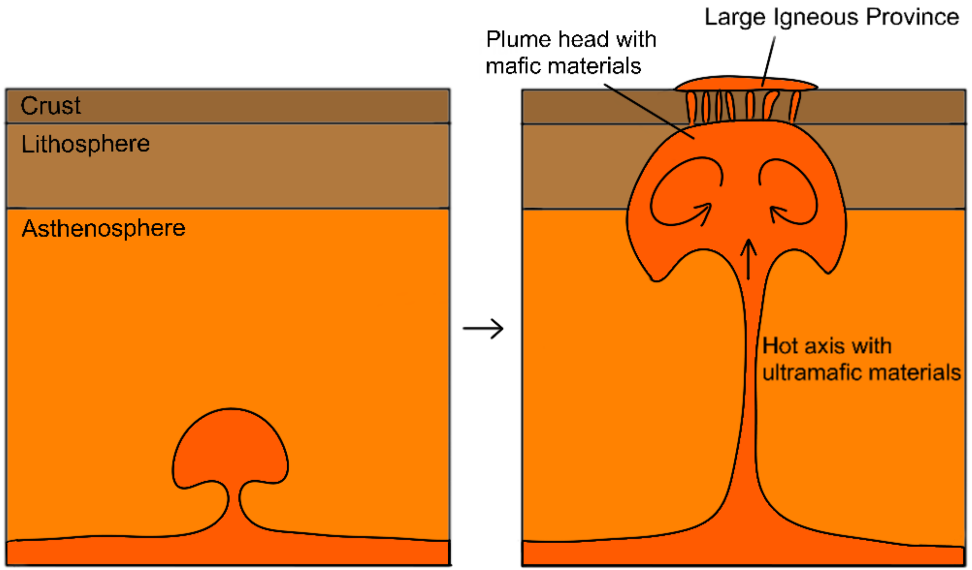
$$Ra = \frac{\rho g \alpha \Delta T H^3}{\kappa \eta} \implies Ra \propto H^3$$

Thickness matters enormously. A layer twice as thick increases Rayleigh number by 8.

In other words, just making the layer twice as thick increases the tendency for convection by a factor of eight!

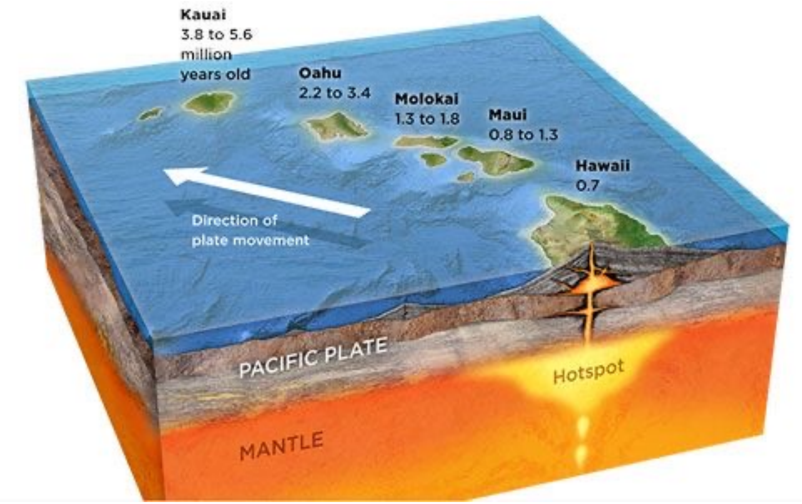
Mantle Plumes: a consequence of thermal instability

If a portion of the lower mantle becomes slightly hotter than its surroundings, its density decreases. This hot region becomes positively buoyant. If the Rayleigh number is large (which it is in Earth's mantle), that thermal anomaly can grow and rise upward as a narrow column of hot material. That rising column is what we call a mantle plume.



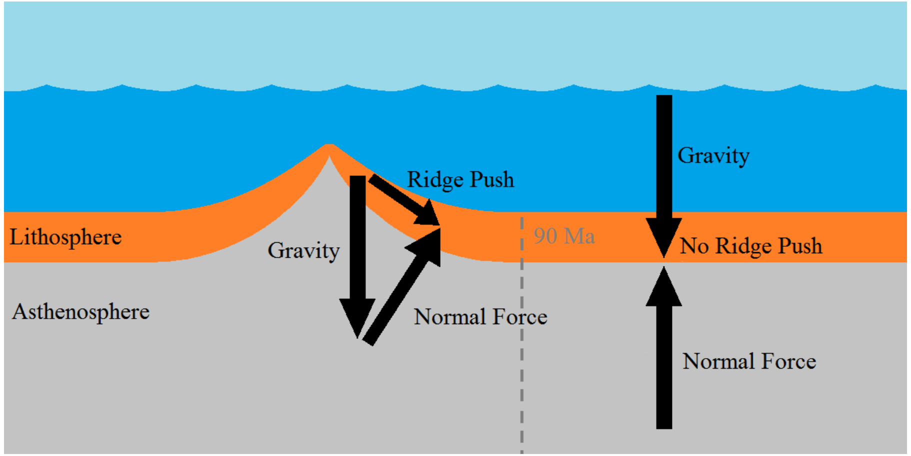
Hot spot: a “permanent” mantle plume

A hotspot is the surface expression of a mantle plume. It is a location where unusually hot mantle material rises from depth and partially melts beneath a tectonic plate, producing sustained volcanism.



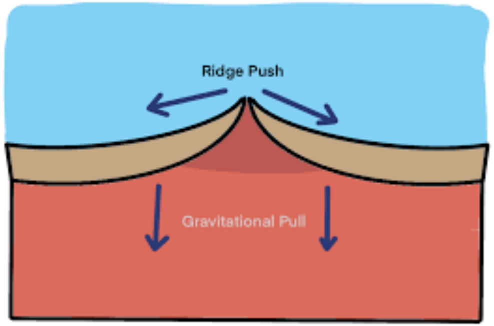
Gravitational sliding ~ ridge push

A mid-ocean ridge is like the "high bump." The seafloor near the ridge is hot and buoyant, so it sits higher. As the plate moves away, it cools and becomes denser, so it sits lower. So the top of the oceanic plate forms a very broad, gentle slope away from the ridge. Gravity acting on that slope creates a sideways push that tends to drive the plate away from the ridge. That sideways gravitational "slide" is the intuition behind ridge push.



Ridge push *(gravitational sliding from a high ridge)*

Mid-ocean ridges sit high because the lithosphere there is hot, thin, and buoyant. As the plate moves away, it cools, thickens, and subsides. This creates a gentle but persistent downslope pressure gradient in the lithosphere that tends to push plates away from ridges, often called gravitational sliding.



Ridge: hot → low density → topographic high.

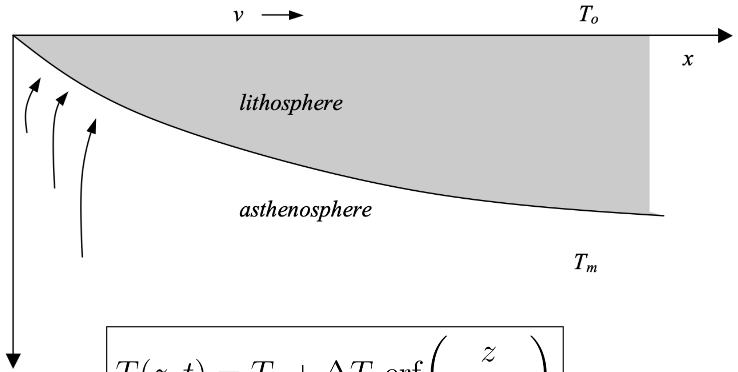
Plate cools with age → thermal contraction → high density → subsidence.

The lithosphere has higher gravitational potential energy near the ridge.

Gravity drives “sliding” from high to low → ridge push force.

(Half-space) cooling of the oceanic lithosphere

Idealised model of how newly formed oceanic lithosphere cools as it moves away from a mid-ocean ridge.



$$T(z,t) = T_0 + \Delta T \ \mathrm{erf}\left(\frac{z}{2\sqrt{\kappa t}}\right)$$

What it tells us

- As time (plate age) increases, the cold thermal boundary layer thickens like
- Cooling and contraction make the lithosphere denser and thicker, so the seafloor subsides with age.
- The vertical temperature gradient at the surface decreases, so heat flow drops with age.

Temperature  Density

How to estimate ridge push *(first-order)*

A clean way to express ridge push is: force per unit ridge length equals the horizontal integral of the lithostatic pressure difference caused by the cooling plate.

A very common “back-of-envelope” scaling is:

$$\frac{F_{\mathrm{rp}}}{\ell} \sim \rho_m g\, H\, \Delta z$$

where *H* is a characteristic thickness scale of the lithosphere/asthenosphere density contrast, ρm is the density of the mantle, and Δz ridge height difference.

Interpretation: horizontal push comes from the fact that the plate column near the ridge “stands higher” (higher potential energy).

How to estimate ridge push *(first-order)*

$$\frac{F_{\mathrm{rp}}}{\ell} \sim \rho_m g\, H\, \Delta z$$

Force per unit ridge length (units: N/m). Think of it like this: imagine cutting a 1-meter-wide slice of lithosphere perpendicular to the ridge. You calculate the downslope gravitational force acting on that 1-meter strip. That is “F/l”. So l is simply the ridge length you divide by conceptually “1 meter of ridge”.

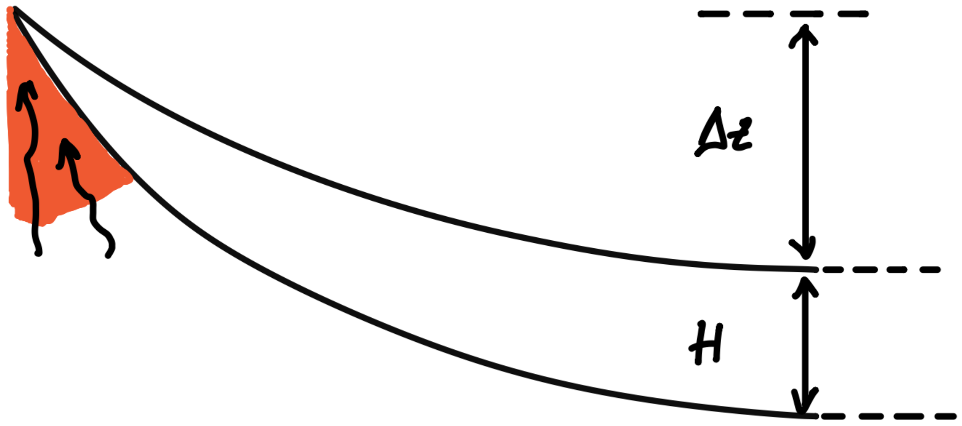
Mini-exercise: estimate ridge push per unit ridge length

$\rho_m = 3300 \text{ kg/m}^3$

$g = 9.81 \text{ m/s}^2$

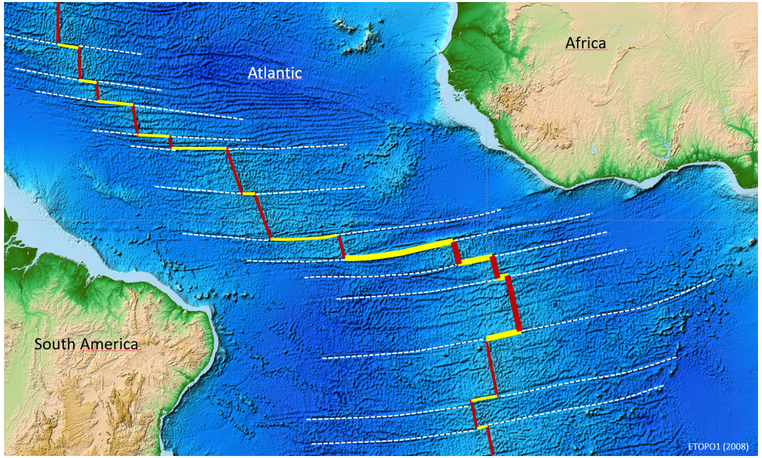
$H = 100$ km (characteristic lithosphere thickness)

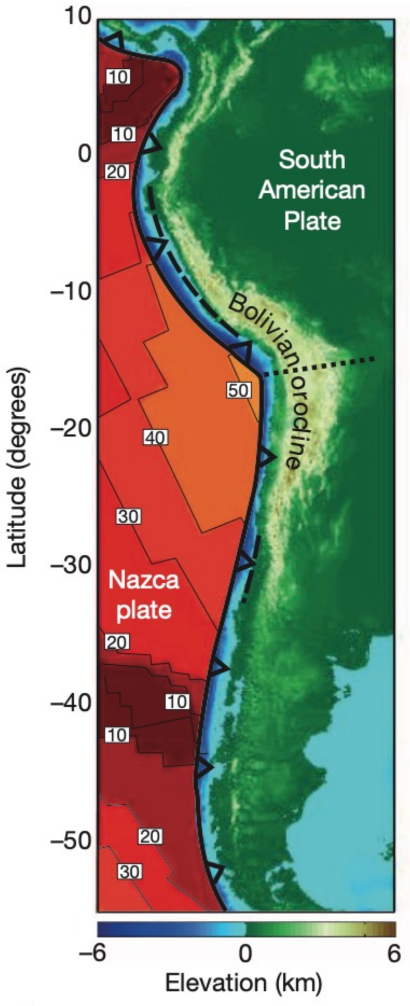
$\Delta z = 2.5$ km (ridge to plain elevation drop)



Complexities in nature

In the simple ridge-push model, we assumed something very clean: a symmetric ridge, plates cooling uniformly away from the ridge axis, and therefore a smooth increase in lithospheric thickness and density with distance. Mid-ocean ridges are segmented by transform faults. These offsets break the ridge into separate spreading segments. Because of that geometry, the age of the oceanic plate is stepped, offset, and spatially variable.

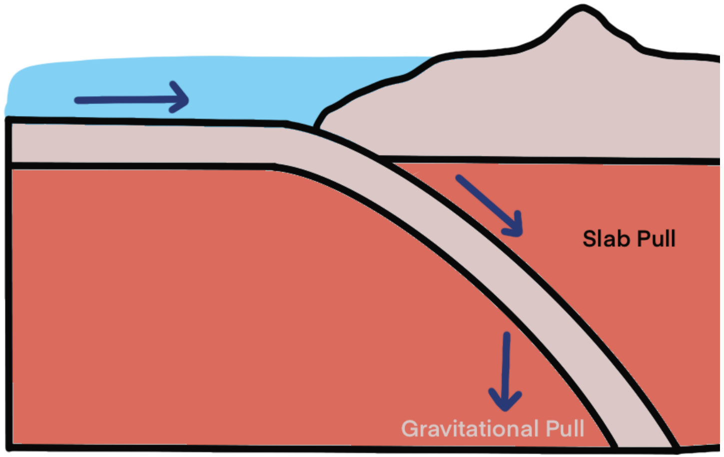




Slab pull

(negative buoyancy of a cold sinking plate)

When an oceanic plate cools, it becomes denser than the surrounding mantle. At a trench, that dense lithosphere starts to sink. Gravity pulls it downward, and that sinking exerts a tensional force along the plate that "pulls" the rest of the plate toward the trench.



Slab pull

(negative buoyancy of a cold sinking plate)

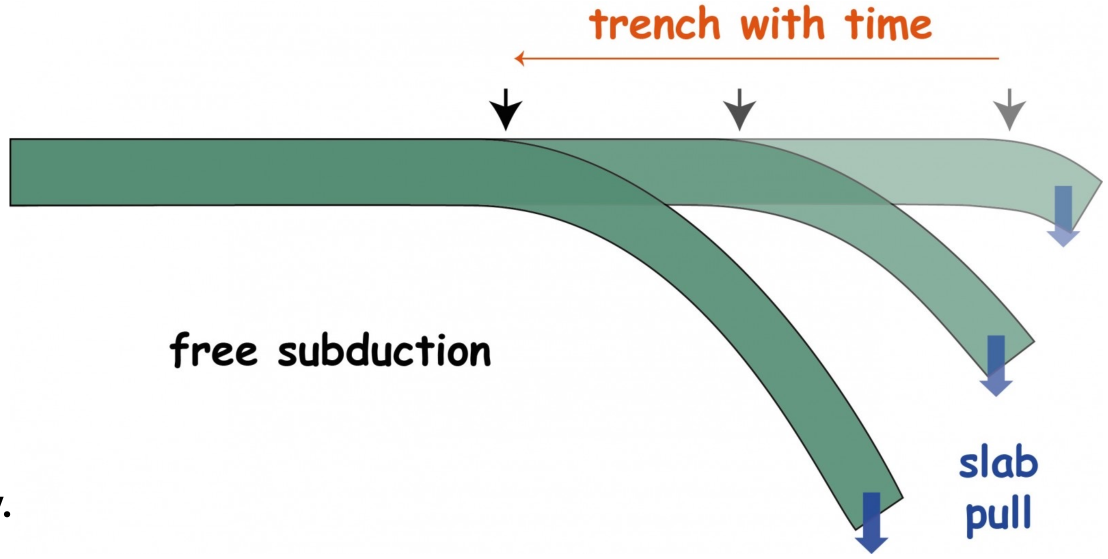


Plate forms hot at ridge → low density.

Plate cools with age → density increases.

At subduction zone, cold lithosphere becomes negatively buoyant.

The sinking slab generates a force that is transmitted as plate-parallel tension.

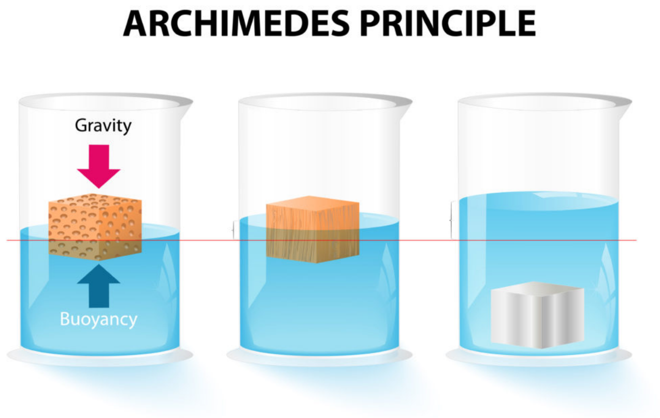
How to estimate slab pull *(first-order)*

Start from Archimedes (buoyancy):

$$F_{\mathrm{sp}} \approx \Delta\rho \, g \, V$$

$$\Delta\rho = \rho_{\mathrm{slab}} - \rho_{\mathrm{mantle}}$$

V is the volume of the slab



How to estimate slab pull *(first-order)*

For tectonics we usually want force per unit trench length (N/m): Take a 2D slab with thickness h and downdip length L: area A = h L.

$$\boxed{\frac{F_{\mathrm{sp}}}{\ell} \approx \Delta\rho \, g \, h \, L}$$

Where the density difference comes from cooling:

$$\Delta\rho \approx \rho_m \, \alpha \, \Delta T$$

Coefficient of thermal expansion (α)

Temperature difference between the slab (cold) and the mantle (hot) (ΔT)

Mini-exercise: estimate slab pull per unit trench length

$\rho_m = 3300\ \mathrm{kg/m^3}$

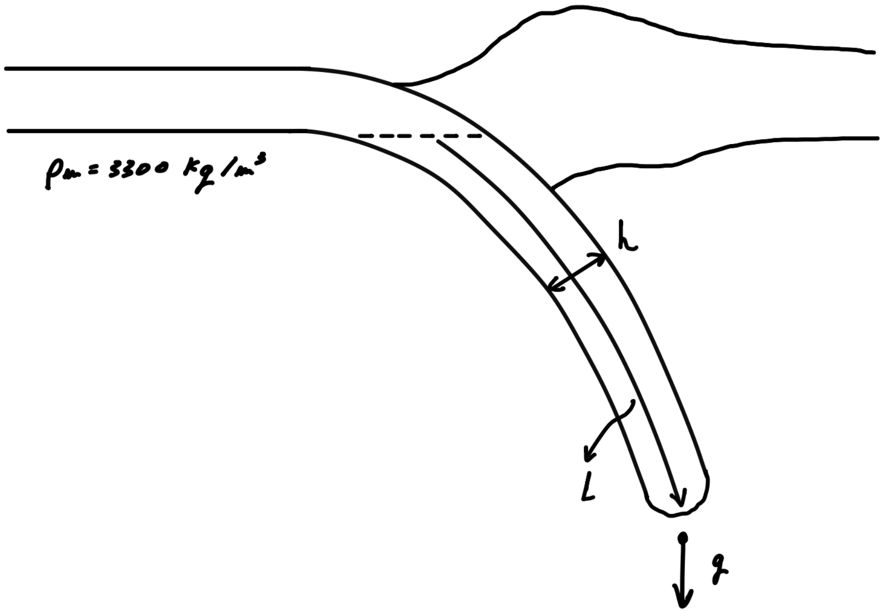
$\alpha = 3 \times 10^{-5}\ \mathrm{K^{-1}}$

slab is colder by $\Delta T = 500\ \mathrm{K}$

$h = 80$ km (effective dense lithosphere thickness)

$L = 600$ km (length of slab contributing)

$g = 9.81\ \mathrm{m/s^2}$



Tasks :

1. Compute $\Delta\rho \approx \rho_m \alpha \Delta T$.

2. Compute slab pull per unit trench length :

$$\frac{F_{\mathrm{sp}}}{\ell} \approx \Delta\rho\, g\, h\, L$$

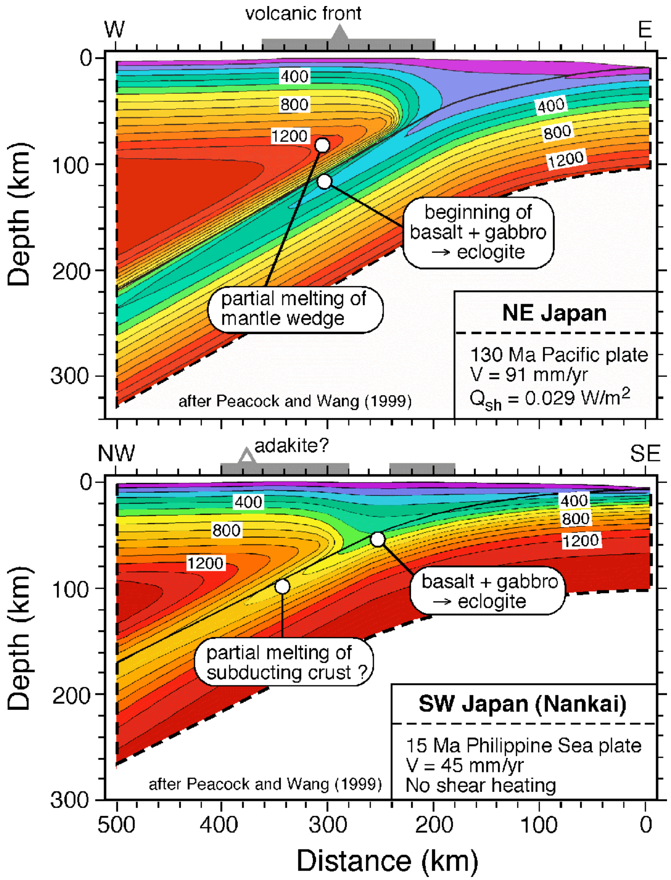
$$\boxed{\Delta\rho \approx 3300 \cdot 3 \cdot 10^{-5} \cdot 500 \approx 49.5\ \mathrm{kg/m^3}}$$

$$\boxed{F/\ell \approx 49.5 \cdot 9.81 \cdot (8 \times 10^4)(6 \times 10^5) \approx 2.3 \times 10^{13}\ \mathrm{N/m}}$$

Complexities in nature

In the mini-exercise, we treated the slab as a simple, uniform block: one temperature difference, one density contrast, one thickness, one length. That gives us a clean first-order estimate of slab pull. <u>But nature is not uniform.</u>

If you look at these thermal models of real subduction zones, temperature is not constant inside the slab. The slab interior is very cold, but the slab–mantle interface is warmer. The mantle wedge above is much hotter. Temperature varies with both depth and horizontal position. Since density contrast depends on temperature, and temperature varies in space, the density contrast also varies in space. That means the buoyancy force is not uniform along the slab.



Slab pull vs ridge push: what's the real difference?

- Slab pull = body force from negative buoyancy of a sinking slab
- Ridge push = lateral force from gravitational potential energy gradients
- Both ultimately come from: cooling + gravity
- Slab pull often dominates because slabs are the strongest cold anomaly on Earth