

Chapter 6

Plate tectonics

In a number of aspects the Earth's mantle can be regarded as a fluid that shows simple fluid-dynamical behavior. For instance, the mantle of the Earth is probably showing a form of convection. But in some respects it behaves clearly in a different way. As discussed in the former Chapter, the rheology of mantle material is not constant, but strongly temperature dependent, which causes the upper, cold part of the mantle to be very strong. Therefore, the upper and downgoing parts of the convection cell are much more coherent than the rest of the convection cell, and we speak of the lithosphere and slab in these cases. These strong parts move without much internal deformation. The thermal profile of the oceanic lithosphere is discussed before:

$$T(x, z) = T_m \operatorname{erf} \left(\frac{z}{2\sqrt{\kappa x/v}} \right) \quad (6.1)$$

or

$$T(t, z) = T_m \operatorname{erf} \left(\frac{z}{2\sqrt{\kappa t}} \right) \quad (6.2)$$

with $t = x/v$ the age of the lithosphere.

6.1 Slab pull

To calculate the *slab pull* force F_{SP} , i.e. the force which the cold slab exerts on the convective system, we have to integrate the thermal structure of the downgoing slab. Assuming that the slab is very wide reduces the problem to two dimensions:

$$F_{SP} = \alpha \rho_0 g \int_A (T_m - T) dA \quad (6.3)$$

with A the cross-sectional area of the slab.

Because of the relative rigidity of the lithosphere, the shape and thermal distribution of the lithosphere just before entering the subduction zone is basically similar to the descending slab, only rotated (see Figure 6.1). T is given by Equation 6.2 (again: rotated, so that the vertical axis z becomes the axis perpendicular to the slab surface z'). Since outside the slab $T = T_m$, which does not contribute to the integral, we can conveniently extend the integral to $z' \rightarrow \infty$: Furthermore, once the plate enters the mantle, no heat is added or removed anymore, but is only distributed in the z' -direction, and so the integral of T in the z' -direction doesn't change while the slab descends into the mantle. This leads to:

$$F_{SP} = \alpha \rho_0 g b \int_{z'=0}^{\infty} \left(T_m - T_m \operatorname{erf} \left(\frac{z'}{2\sqrt{\kappa t}} \right) \right) dz' \quad (6.4)$$

$$= \alpha \rho_0 g b \int_{z'=0}^{\infty} \left(T_m \operatorname{erfc} \left(\frac{z'}{2\sqrt{\kappa t}} \right) \right) dz' \quad (6.5)$$

$$= 2\alpha \rho_0 g b T_m \sqrt{\kappa t / \pi} \quad (6.6)$$

using $\int_{x=0}^{\infty} \operatorname{erfc}(x) dx = \frac{1}{\sqrt{\pi}}$ and b the length of the slab. Using typical values for the model parameters ($\rho_0 = 3300 \text{ kg/m}^3$, $\alpha = 3 \times 10^{-5} \text{ K}^{-1}$, $T_m = 1200 \text{ K}$, $b = 700 \text{ km}$, $\kappa = 10^{-6} \text{ m}^2/\text{s}$, and $t = 80 \text{ Ma}$ gives a slab pull force $F_{SP} = 4.7 \times 10^{13} \text{ N/m}$ length parallel to the trench [Turcotte and Schubert, 2002].

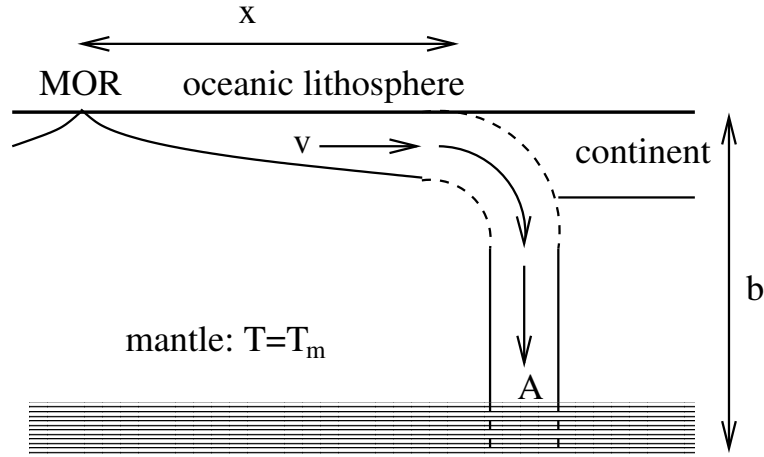


Figure 6.1: Schematic view of the lithosphere-slab: lithosphere just before entering the subduction zone resembles the slab. During its descend the cross-sectional integral of the thermal profile doesn't change, because no heat is added or removed, but only re-distributed.

Also the exothermic phase transition of olivine to spinel exerts a driving force on the downgoing slab, because in the cold slab this phase transition will shift to shallower depth. The material between this elevated and normal depth of the phase transition will have an excess density (spinel is denser than olivine) pulling the slab down. Following the description in [Turcotte and Schubert, 2002], the total downward gravitational force of the uplifted phase transition is written as:

$$F_{PhTr} = \int_{x'=0}^{x'=x'_s} \Delta\rho_{PhTr} g h_{PhTr} dx' \quad (6.7)$$

where

$$h_{PhTr} = \frac{\gamma(T_m - T)}{\rho_0 g} \quad (6.8)$$

with $\gamma = \frac{dp}{dT}$ is the *Clapeyron slope*. Just like in calculating F_{SP} , the integral of the temperature perturbation throughout the slab does not change when the slab descends into the mantle over time: heat is only re-distributed. Therefore, we can again use Equation 6.2 to describe the temperature T in Equation 6.8. Elaborating the integral like done for the F_{SP} calculation gives:

$$F_{PhTr} = \frac{2T_m \gamma \Delta\rho_{PhTr}}{\rho_0} \sqrt{\kappa t / \pi} \quad (6.9)$$

For $\Delta\rho_{PhTr} = 270 \text{ kg/m}^3$ and $\gamma = 4 \text{ MPa/K}$ and parameters used as above gives $F_{PhTr} = 1.6 \times 10^{13} \text{ N/m}$ [Turcotte and Schubert, 2002], about half of F_{SP} , and the total driving force of the slab acting on the convecting system is about $6 \times 10^{13} \text{ N/m}$.

6.2 Ridge push

Another driving force for plate tectonics is called *ridge push*. Unlike the name suggests, the plate is not 'pushed away' from the ridge, but the horizontal pressure difference between columns of material at the mid-ocean ridge (MOR) and away from the MOR drives the plates (Figure 6.2). At the MOR, the total pressure force acting on the system F_1 is written given by

$$F_1 = \int_{z=0}^{z=W+L} \rho_m g z dz \quad (6.10)$$

The column of water exerts a pressure F_2 :

$$F_2 = \int_{z=0}^{z=W} \rho_w g z dz \quad (6.11)$$

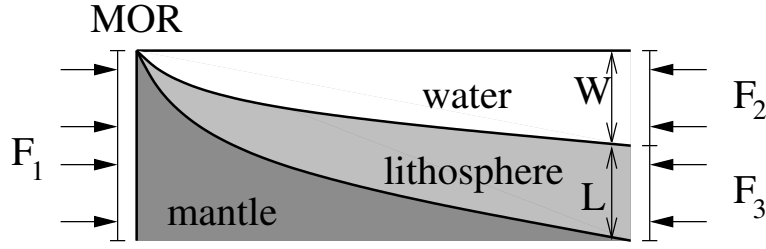


Figure 6.2: Schematic representation of competing pressure forces for acting on a spreading oceanic plate. The sum of the forces is called *ridge push* force F_{RP} .

and the lithosphere buried under the load of the water column) acts on the system with the pressure force F_3 :

$$F_3 = \int_{z=W}^{z=W+L} (\rho_w g W + \int_{z=W}^{z=W+L} \rho_l(z) g dz) dz \quad (6.12)$$

in which the lithospheric density $\rho_l(z) = \rho_l(z' + W) = \alpha \rho_0 T(z')$ where $z' = z - W$ is the depth measured from the top of the lithosphere, and we use once more Equation 6.2 for the thermal structure of the lithosphere. Adding all terms with the right signs gives the ridge push force

$$F_{RP} = F_1 - F_2 - F_3 \quad (6.13)$$

Elaborating this equation (see [Turcotte and Schubert, 2002] for a more detailed description) finally gives:

$$F_{RP} = \alpha \rho_m g T_m \kappa \left(1 + \frac{2 \rho_m \alpha T_m}{\pi (\rho_m - \rho_w)} \right) t \quad (6.14)$$

So the ridge push force is linearly proportional to the age t of the lithosphere. For the 80 Ma example lithosphere used above, this gives a ridge push force $F_{RP} = 3.1 \times 10^{12}$ N/m. This shows that the ridge push force is roughly an order of magnitude smaller than the ridge push force. These driving forces must be counterbalanced by resisting forces to obtain a zero acceleration of the plate. The most likely resisting force is drag by the mantle below the lithosphere and around the slab, and frictional resistance at the contact between the subducting and overriding plate. Although these forces are difficult to estimate, they are probably roughly proportional to the plate velocity (i.e. the faster the plate, the larger the resistance).

Since slab pull is the dominant driving force of plate tectonics one expects the plates that have one or more subduction zones attached to it would move faster in an absolute sense (relative to the deep mantle) than the ones without a subduction zone. This correlation is indeed clearly present, as shown by [Forsyth, 1975]. Also does slab pull increase with the age of the plate at subduction, and so old plates with a subduction zone attached are expected to move faster than young ones. Indeed, the Pacific plate is the oldest plate with a subduction zone, and is also almost the fastest moving plate.

Bibliography

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