

## Driving Forces of Plate Motion

‘Ridge Push’ and ‘Slab Pull’ are thought to be the major forces driving the motion of oceanic plates. Ridge push is caused by the potential energy gradient from the high topography of the ridges. Slab pull is caused by the negative buoyancy of the subducting plate. Both forces act on one part of the volume of the plate, and are translated across the rest of the plate (as long as the assumption of rigid plates is valid).

Slab pull force ( $F_{SP}$ ):

$$F_{SB} = (\rho_s - \rho_m)Vg \quad (1)$$

Ridge push force ( $F_{RP}$ ):

$$F_{RP} = (\rho_s - \rho_w)Vg \quad (2)$$

A similar approach is appropriate for calculating the ridge pull force, since these two forces have essentially the same cause: buoyancy. Since the models are very sensitive to the density structure of the plate, assume that the subducting slab consists of 1 km of sediment, 6 km of basaltic crust and 90 km of cold mantle. Since the thickness changes away from the ridge crest, we can use an approximation based on the cooling as the plate ages, calculating the force per unit meter of ridge length (from Parsons 1980, eq. 17):

$$F_{RP} = g\alpha\rho_l\kappa(\text{age} * 1600K) \quad (3)$$

where 1600K is the thermal boundary between lithosphere and asthenosphere.

The forces acting against the motion of the plates are more difficult to calculate, because they are driven by activity in the mantle and are not directly observed. In this exercise, assume that ridge push and slab pull are the forces motivating subduction and solve for the net force acting (in equal and opposite magnitude and direction) to maintain constant rates of plate motion.

Schellart (2004) performed an experiment to explore the magnitude of forces resisting the motion of a subducting plate. In this simplified analog model, the forces resisting subduction include:

1. the force required to drive mantle flow (out of the way of the slab;  $F_{MF}$ )
2. the bending resistance of the plate (where it must bend to subduct at the trench;  $F_B$ )
3. viscous shear resistance along the base of the plate ( $F_{SH}$ )

The first one cannot be directly measured, but can be constrained by the other forces by the observation that if a plate has a constant rate of motion (is not accelerating), then the forces are balanced, so that:

$$F_{SB} + F_{RP} + F_{SH} + F_B + F_{MF} = 0 \quad (4)$$

Bending resistance ( $F_B$ ):

$$F_B = \eta_s \dot{\epsilon}_b WT \quad (5)$$

Viscous shear resistance ( $F_{SH}$ ):

$$F_{SH} = \eta_m A_s v_x v_z + \eta_m A_h v_x v_z \quad (6)$$

Variable	Definition
$\rho_s$	density of the slab
$\rho_m$	density of the asthenosphere
$\rho_w$	density of seawater
$\alpha$	coefficient of thermal expansion
$\kappa$	thermal diffusivity
V	volume of the slab contributing to slab pull
g	gravitational acceleration (9.81 m/s)
$\eta_s$	Viscosity of the slab
$\eta_m$	Viscosity of the asthenosphere
$\dot{\epsilon}_b$	strain rate in bending slab (assume $10^{-15}/s$ ; Billen et al. (2003))
x, z	horizontal and vertical distance (reference frame)
v	velocity of the subducting plate
W	length of the trench
T	thickness of the slab
t	time
$A_s$	Total area of contact of the base of the slab
$A_h$	Area of contact of slab on asthenosphere where it is flat on the surface

Using the assumption that the forces described by Schellart (2004) are the same as those acting in the earth. Values for some of these factors are in Schellart (2004) - for other numbers you need, find appropriate literature. Answer the following questions, submitting all calculations with your answers. Be careful to set up your reference frame (including sign conventions) to make the calculations simple:

1. van der Hilst et al. (1991) display tomographic models for slabs at 4 different subduction zones (Izu Bonin, central Japan, Mariana and Kuril. Pick one of these and calculate the mantle resistance force.
2. In recent models, slab break off occurs when tensile stress in the slab exceeds 250 MPa for more than 4 MY (simplified from van Hunen and Allen, 2011). The tensile stress can be approximated as the difference between the forces promoting subduction (slab pull and ridge push) and the forces opposing subduction (viscous shear resistance, bending resistance, and mantle flow stress) resolved in the direction parallel to the slab motion between 0-600 km depth. Slabs may change dip with time (don't worry about why for this question). At what dip, if any, would the slab you chose for #1 be at risk for breaking off?
3. In the Archean, the mantle viscosity might have been 2 orders of magnitude lower (due to higher temperature, which is supported by some models; van Hunen and Moyen, 2012). If the mantle resistance force scales linearly with viscosity, how would this difference affect the motion of Archean plates? How could this difference affect the other parameters assuming equation (3) still holds for the Archean?

Billen, Gurnis and Simons (2003) Multiscale dynamics of the Tonga–Kermadec subduction zone. *Geophysical Journal International* v. 153, 359–388.

Schellart (2004) Quantifying the net slab pull force as a driving mechanism for plate tectonics. *Geophysical Research Letters* v. 31 L07611

van der Hilst, Engdahl, Spakman and Nolet (1991) Tomographic imaging of subducted lithosphere below northwest Pacific island arc. *Nature* v. 353 37–43

van Hunen and Allen (2011) Continental collision and slab break-off: A comparison of 3-D numerical models with observations. *Earth and Planetary Science Letters*, v. 302 27–37.

van Hunen and Moyen (2012) Archean subduction: Fact or friction? *Annual Reviews Earth and Planetary Sciences* v. 40, 195–219.