What is "delamination"?

Form of convective removal

Convection = advection driven by \( \rho \) contrasts

- e.g. buoyancy forces (\( \rho \) is necessary)
- \( \Delta \rho \) can be compositional (chemical convection)
- or thermal, e.g. \( \frac{\Delta \rho}{\rho} = -\alpha \Delta T \) (thermal convection)

Magnitude of buoyancy forces

- compositional
  - eclogite: 3400 kg/m^3
  - peridotite: 3300 kg/m^3
  - \( \frac{\Delta \rho}{\rho} \approx 3\% \)

- Thermal
  - consider a TBL
  - \( \Delta T \approx 500^\circ C \)
  - \( \alpha = 3 \times 10^{-5} / ^\circ C \)
  - \( \frac{\Delta \rho}{\rho} \approx 1.5\% \)

So why are \( \rho \) (high) things negatively buoyant?

Consider a crustal column made of
- basaltic crust \( C \) and eclogite crust \( X \)
- with \( \rho_C < \rho_X \) (mantle)
- but \( \rho_X > \rho_m > \rho_C \)

- note that upper part gravitational collapses
- lower part, \( P \) pushes in which tries to force denser cool off.
This dense root will come off if the downward buoyancy forces exceed viscous resistance.

Let assume that the dense layer is slightly colder than ambient mantle m. Then, the main viscous resistance comes down within the dense layer rather than from the surroundings.

\[ \Delta p = p_x - p_m \]

\[ \Delta p g H \sim \eta \frac{\dot{e}}{\eta} \sim \eta \frac{dT}{dt} \frac{1}{H_0} \]

\[ H = H_0 \exp \left( \frac{\gamma \Delta p g H_0 t}{\eta} \right) \]

\[ t_{e-fold} = \frac{\eta}{\gamma \Delta p g H_0} \]

Rayleigh-Taylor approximation

if \( \Delta p = 0, H_0 = 0 \), \( \eta \) is huge it takes too long to fall \( \Delta f \)
growth \( g \) instability aided if \( H_0 \) large
\( \Delta p \) large
\( \eta \) small

Note: if \( \Delta p \) is thermal, then thermal diffusion competes

\[ \frac{H_0^2}{k} \sim t_{th} \quad \text{if} \quad t_{th} < t_{growth} \quad \text{thermal anomaly} \ \Delta T \quad \text{and} \ \Delta p \ \text{erased} \]

This requires thickening rate to be fast.
$$t_{	ext{half}} \sim \frac{\eta}{\gamma \Delta g \Delta H_0} = \frac{\eta}{\gamma f_{\alpha} \Delta g \Delta T \Delta H_0}$$

Consider thermal contracts

\[ 3 \times 10^3 \text{ kg/m}^2 \]

\[ 3 \times 10^{-5} \text{ C} \]

\[ 10^{-2} \text{ m/s} \]

\[ \sim 10^2 \text{ C} \]

Assume \( H_0 \sim 10 \text{ km} \)

Then if \( \eta = 10^{19} \text{ Pa s} \), \( t = 1 \text{ My} \)

\[ \eta = 10^{20} \]

\( t \sim 10 \text{ My} \)

\[ \eta = 10^{21} \]

\( 100 \text{ My} \)

For \( H_0 = 10^2 \text{ km} \), \( \eta = 10^{21} \text{ Pa s} \), \( t = 10 \text{ My} \)

So viscosity is very important

\[ \eta = \eta_0 \exp\left( + \frac{E_A}{RT} \right) \]

\[ \eta(1400^\circ \text{C}) = \eta_0 \exp\left( + \frac{E_A}{R \times 1673 \text{ K}} \right) \]

\[ \frac{\eta(T)}{\eta(1673 \text{ K})} = \exp\left( + \frac{E_A}{R} \left( \frac{1}{T} - \frac{1}{1673} \right) \right) \]

\[ E_A \sim 300 \text{ to } 500 \text{ kJ/mol} \]

\[ R = 8.314 \times 10^{-3} \text{ kJ/K mol} \]

If \( \eta_{1673} = 10^{18} \text{ Pa s} \)

\[ \begin{array}{c|cc|cc}
\eta_{1200^\circ \text{C}} & \eta_{1473 \text{ K}} & 1.9 \times 10^{19} & 1.3 \times 10^{20} \\
\eta_{1600^\circ \text{C}} & \eta_{1273 \text{ K}} & 8.8 \times 10^{20} & 8 \times 10^{22} \\
\eta_{1800^\circ \text{C}} & \eta_{1073 \text{ K}} & 1.7 \times 10^{23} & 5 \times 10^{26}
\end{array} \]
It can be seen that if the dense layer is too cold, it cannot founder viscously because \( \eta \) is too high. \( T < 1000^\circ C \), no foundering!

Alternative is to delaminate
- here, dense layer is strong and detaches wholesale
- facilitated by a weak zone

Delamination can initiate along weak zone.
- weak zone in crust is enhanced when crust is thick.

Model

Assume lubrication theory

\[
\frac{\Delta \rho g L xy}{\eta L} - \frac{dH}{dt} = \frac{\eta V}{H} \cdot Ly
\]

Buoyance force from dense slab

Conservation of mass

\[
V \cdot H = \frac{dH}{dt} \cdot L
\]

\[
V = \frac{dH}{W} \cdot L
\]

Plug in

\[
\frac{\Delta \rho g L^2 H}{\eta L} - \frac{dH}{dt} \Rightarrow H = \frac{\eta L H_0}{\eta L - \Delta \rho g x t H_0}
\]

\[
t_{H_0} = \frac{\eta L}{\Delta \rho g x H_0}
\]
rate of delamination scales with gap thickness to $H^2$ inversely to $\eta$

$$t_{delm} = t_{Hoo} = \frac{\eta L}{\Delta \rho g \times H_o} = \frac{\eta}{\Delta \rho g} \times \frac{L}{H_o}$$

- if gap is long and thin ($L \gg 1, H_o << 1$) then $t$ is long
- note also that $t_{Hoo} \sim \frac{1}{x}$ which is thickness of dense layer. If dense layer grows by magnetic underplating at rate $\frac{dx}{dt}$ then initially not unstable

$$x_0 = \sqrt{\frac{\eta}{\Delta \rho g \times H_o}} \frac{dx}{dt}$$

$x > x_0$ to delaminate, $x < x_0$ no delamination
Now, once the dense layer detaches, isostatic rebound will give rise to high elevations.

\[ h + d + m = c + x \]

\[ p_c c + p_x x = p_c d + p_m m \]

\[ h = \left( \frac{p_m - p_c}{p_m} \right) c + \left( \frac{p_m - p_x}{p_m} \right) x + \left( p_c - p_m \right) d \]

2nd term on RHS controls elevation \( h \) if everything else held constant.

\[ \frac{dh}{dx} = \left( \frac{p_m - p_x}{p_m} \right) \text{ change in elevation due to change in } x \text{ thickness} \]

- If \( p_m - p_x < 0 \)
  - Decrease \( x \), increase elevation

- If \( p_m - p_x > 0 \)
  - Decrease \( x \) \rightarrow decrease elev. \( h \)

Detamination of dense lower crust, if previously in isostatic balance, leads to uplift.

Note: the mantle \( m \) doesn't have to be anomalously fast.
What happens after delamination in terms of melting?

- delamination is fast (once it initiates)
  too fast for thermal re-equilibration
  (by diffusion)
- asthenosphere upwells in response

pre-delamination

after delamination
What is response in terms of melting?

From Langmuir (1992)

\[(P_f - P_0) \left( \frac{dT}{dP_a} - \frac{dT}{dP_s} \right) = F \left[ \frac{H_f}{C_p} + \frac{dT}{dF} \right] \]

\[
\frac{dF}{dP} = \frac{(dT/dP)_a - (dT/dP)_s}{H_f/C_p + dT/dF} 
\]

\[
\frac{dT}{dF} = 3.5^\circ/\% \text{ for } F < 0.22 
\]

\[
\frac{dT}{dP_a} = 1^\circ/ \text{kbar} 
\]

\[
\frac{dT}{dP_s} = 12^\circ/ \text{kbar} 
\]

\[
H_f = 100 \text{ cal/g} 
\]

\[
C_p = 0.3 \text{ cal/g }^\circ \text{K} 
\]

Extent of melting depends on \( T_p \) and \( P_f \)

\( P_f \) limited by point of delamination.