

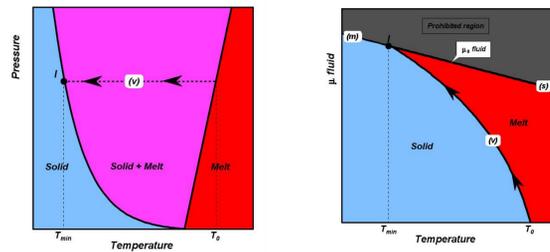
# Some physical aspects of fluid-fluxed melting

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Fluid-fluxed melting is thought to play a crucial role in the origin of many terrestrial magmas. We can visualize the fundamental physics of the process as follows. An infinitesimal amount of fluid infiltrates dry rock at the temperature of its dry solidus. In order to restore equilibrium the temperature must drop, so that enthalpy is released and immediately reabsorbed as enthalpy of melting. The amount of melt produced must be such that the energy conservation and thermodynamic equilibrium conditions are simultaneously satisfied.

## Thermodynamic equilibrium condition



Progressive addition of fluid to dry rock lowers the solid-melt equilibrium temperature from the dry solidus,  $T_0$ , to the fluid-saturated solidus,  $T_{min}$ .

The freezing point depression equation written in terms of the entropy of melting:

$$\gamma_{melt} (1 - X_{fluid}) = \left( \frac{T}{T_0} \right)^{\frac{\Delta_m S}{R}}$$

yields the equation for the vapor-absent curve on the  $\mu - T$  plane (assuming ideal mixing):

$$\mu_{P,T}^{fluid} = \mu_{P,T}^{0,fluid} + RT \ln X_{fluid} = \mu_{P,T}^{0,fluid} + RT \ln \left[ 1 - \left( \frac{T}{T_0} \right)^{\frac{\Delta_m S}{R}} \right]$$

as well as the thermodynamic equilibrium condition for melt composition:

$$T = T_0 \left( 1 - \frac{m_F}{m_F + m_D} \right)^{\frac{R}{\Delta_m S}}$$

where  $m_D$  is the number of moles of molten solid, and  $m_F$  the number of moles of fluid dissolved in the melt. The equation is valid for:

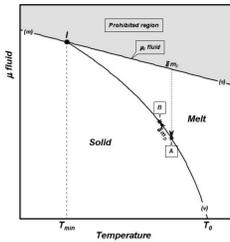
$$\frac{m_F}{m_F + m_D} \leq X_{saturation}$$

where  $X_{saturation}$  is the saturation mole fraction for the fluid at the pressure and temperature of point  $I$ .

We can also define a non-dimensional solid-melt equilibrium temperature,  $\tau = T/T_0$  and write the thermodynamic equilibrium condition in terms of this non-dimensional temperature:

$$\tau = \left( 1 - \frac{m_F}{m_F + m_D} \right)^{\frac{R}{\Delta_m S}}$$

## Energy conservation condition



Consider a system consisting of melt and solid at equilibrium at point A. The system is invaded by a small amount of fluid,  $\delta m_F$ . Because the chemical potential of the pure fluid is higher than that of the fluid component in the melt the added fluid must dissolve in the melt in order to restore equilibrium. But the added fluid also lowers the equilibrium temperature for the solid + melt assemblage, so that enthalpy must be released. The enthalpy is absorbed as enthalpy of melting, causing a small amount of dry solid,  $\delta m_D$ , to melt. Addition of  $\delta m_F$  mols of fluid therefore causes equilibrium to shift from point A to point B. The magnitude of this displacement, or equivalently, the amount of solid that melts,  $\delta m_D$ , is determined by two opposing factors: the melting point depression effect of the added fluid (eq. 1) and the energy balance, which is given by:

$$C_{P,R} m_R \delta T + T \Delta_m S \delta m_D + C_{P,F} (T - T_F) \delta m_F = 0$$

where  $m_R$  is the total number of moles in the system (solid + melt),  $T$  is the temperature after equilibrium is restored ( $T$  of point B in the figure),  $\delta T$  is the temperature change required to supply the enthalpy of melting ( $T_B - T_A$ ),  $\Delta_m S$  is the entropy of melting,  $T_F$  is the initial temperature of the fluid, and  $C_{P,R}$  and  $C_{P,F}$  are the heat capacities of the rock (assumed to be equal to that of the melt) and of the fluid, respectively.

The thermodynamic equilibrium condition and the energy balance condition can be solved for the mass of rock melted,  $m_D$ , and temperature,  $T$  (or  $\tau$ ) as a function of the amount of fluid added,  $m_F$ , for different choices of model parameters such as heat capacities, entropy of melting, and temperature contrast between fluid and rock. An iterative numerical solution makes it possible to study incremental fluid addition, and contrast batch vs. fractional melting behaviors.

The numerical solution is based on substituting the thermodynamic equilibrium condition in the energy conservation equation, rewriting the resulting equation in terms of discrete increments of fluid, and converting to non-dimensional variables by dividing throughout by the initial rock temperature,  $T_0$ , the heat capacity of the rock,  $C_{P,R}$  and the mass of rock,  $m_R$ . The resulting equation is:

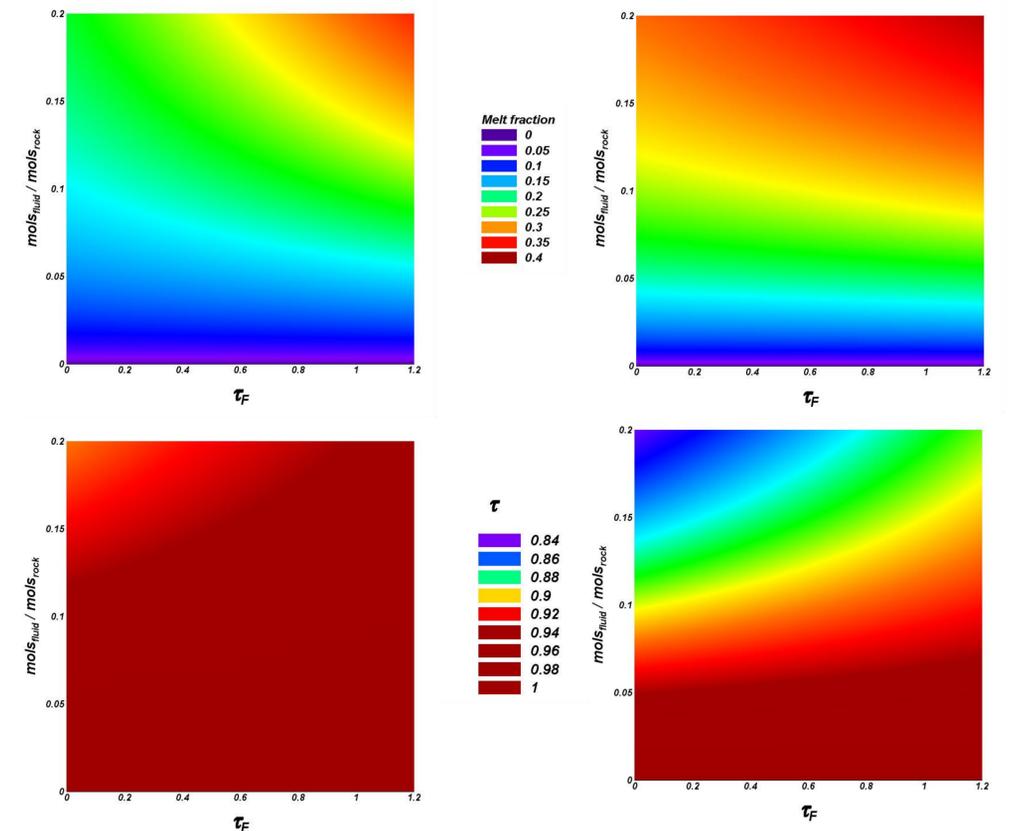
$$\left[ 1 + \frac{\Delta_m S}{C_{P,R}} \frac{\delta m_D}{m_R} + \frac{C_{P,F}}{C_{P,R}} \frac{\delta m_F}{m_R} \right] \left( \frac{m_D}{m_F + m_D} \right)^{\frac{R}{\Delta_m S}} - \tau_{i-1} - \frac{C_{P,F}}{C_{P,R}} \frac{\delta m_F}{m_R} \tau_F = 0$$

Where  $\tau_F$  is the non-dimensional fluid temperature,  $\tau_{i-1}$  is the system's non-dimensional temperature at the end of the previous melting step, and the new temperature  $\tau$  is calculated with the equation to the left.

The colored contours show fraction of solid melted (top) and non-dimensional equilibrium temperature (bottom) for batch (left) and fractional (right) volatile-fluxed melting, as a function of non-dimensional fluid temperature and relative amount of fluid added.

The calculations reveal the somewhat surprising result that fluid infiltration produces more melt by fractional melting than by batch melting. This behavior, which is opposite to that of decompression melting of a dry solid, arises because the melting point depression effect of the added fluid is greater during fractional melting than during batch melting, which results in a greater release of enthalpy and, therefore, greater melt production for fractional melting than for batch melting, for the same total amount of fluid added. The temperature of the fluid has a negligible initial effect on melt production, but becomes important as melting progresses, especially during batch melting.

## Batch vs. fractional fluid-fluxed melting



## Effect of thermal properties

The plots below illustrate the sensitivity of the results to some of the model parameters. The curves show melt production and non-dimensional equilibrium temperature for batch melting, as a function of added fluid. Fluid temperature is assumed to be equal to rock temperature, i.e.,  $\tau_F = 1$ , and entropy of melting is taken at  $\Delta_m S = 56 \text{ J K}^{-1} \text{ mol}^{-1}$ , which is a characteristic value for silicates. Varying the ratio of heat capacity of fluid to heat capacity of rock over a one order of magnitude range has a barely perceptible effect on melt production. This reflects the fact that, if a fluid is soluble in silicate melt, then a small amount of fluid can cause a large melting point depression. In contrast, the ratio of entropy of melting to heat capacity of rock has a huge effect on melt production and system temperature, as one should expect from the fact that during fluid fluxed melting sensible heat is converted to latent heat, i.e., enthalpy of melting is obtained from the melting point depression caused by fluid influx.

