

Melt segregation and P-T path of mantle melting

H. Iwamori
D. McKenzie

Bullard Laboratories, Department of Earth Sciences, University
of Cambridge, Madingley Road, Cambridge CB3 0EZ, U.K.

Introduction

Chemical composition of the mantle which is undergoing melting can change as melt segregation proceeds, which affects the pressure-temperature path of the melting. The effects can be important when fractional-type melting occurs, because the melt is efficiently isolated from the residue in terms of chemical interaction. In this paper we investigate the critical conditions for chemical and thermal isolation caused by melt segregation and the effects of the isolation on mantle melting.

Model for one-dimensional steady states

Let us consider adiabatic melting in a one-dimensional upwelling column under steady state conditions. The melt produced ascends upward through melt paths such as boundaries of solid grains or fractures, interacting thermally and chemically with the residual solid. Conservation of mass of the melt and solid and conservation of entropy can be expressed by the following equations (McKenzie, 1984):

$$\frac{d}{dz}(\phi\rho_m V_m) = \Gamma = \rho_{s0} V_{s0} \frac{dX}{dz} \quad (1)$$

$$\frac{d}{dz}[(1-\phi)\rho_s V_s] = -\Gamma = -\rho_{s0} V_{s0} \frac{dX}{dz} \quad (2)$$

$$\begin{aligned} \Gamma T \Delta S + \phi \rho_m C_p^m V_m \left(\frac{dT}{dz} - \frac{T \alpha_m}{\rho_m C_p^m} \frac{dP}{dz} \right) \\ + (1-\phi) \rho_s C_p^s V_s \left(\frac{dT}{dz} - \frac{T \alpha_s}{\rho_s C_p^s} \frac{dP}{dz} \right) = 0 \end{aligned} \quad (3)$$

where z is the vertical co-ordinate, ϕ is the volume fraction of melt, ρ_m and ρ_s are the densities of melt and solid, V_m and V_s are the upward velocities of melt and solid, Γ is the melting rate per unit volume, ρ_{s0} is the density of solid before melting starts, V_{s0} is the upward velocity of mantle before melting starts, X is the degree of melting, T is the temperature, ΔS is the entropy change per unit mass associated with melting, α_m and α_s are the coefficients of thermal expansion of melt and solid, C_p^m and C_p^s are the specific heat at constant

pressure of melt and solid, and P is the pressure. (3) assumes no energy dissipation and thermal equilibrium between the melt and solid at a given z . The characteristic distance of the thermal diffusion during mantle upwelling is $d_{thermal} = (\kappa H / V_{s0})^{1/2} \sim 10^3$ m, where the thermal diffusivity $\kappa = 10^{-6}$ m²/s, the height of the melting column $H = 10^4$ m, and $V_{s0} = 10^{-8}$ m/s are assumed. Therefore, if the spacing of melt paths is smaller than 10^3 m, which is likely to be satisfied in the mantle, then thermal equilibrium is achieved. Similar arguments concerning chemical equilibrium (e.g. Iwamori, 1992, 1993; Spiegelman and Kenyon, 1992) suggest that chemical equilibrium may be violated in realistic melting conditions. If the spacing of melt paths is $\gg 0.1$ m, then the melt can be transported without significant chemical interaction with the solid, i.e., the melt can be chemically isolated from the residue.

Integrating (1) and (2) in terms of z , and substituting the results into (3), then we obtain

$$\frac{dX}{dP} = \frac{-\frac{C_p}{T^2} \left(\frac{\partial T}{\partial P} \right)_X + \left[X \frac{\alpha_m}{\rho_m} + (1-X) \frac{\alpha_s}{\rho_s} \right]}{\Delta S + \frac{C_p}{T} \left(\frac{\partial T}{\partial X} \right)_P} \quad (4)$$

where $C_p^s = C_p^m = C_p$ is assumed. The expression for $\frac{dT}{dP}$ is also obtained in a similar procedure. These equations are exactly the same with those describing melting where the melt and solid move together (McKenzie, 1984). Since all the melts produced re-equilibrate thermally with the solid during ascent, the total amount of heat available for melting, which is transported by advection of melt and solid, remains the same whether the relative flow between the two phases occurs or not.

The P - T - X path for adiabatic melting is obtained by integrating (4). However, the accurate values of $\left(\frac{\partial T}{\partial P} \right)_X$, $\left(\frac{\partial T}{\partial X} \right)_P$ and ΔS for fractional melting are unknown. Here we assume that $\left(\frac{\partial T}{\partial P} \right)_X$ and $\left(\frac{\partial T}{\partial X} \right)_P$ for the fractional-type melting are determined simply by stretching the P - T - X relationship of a batch melting system between solidus for the initial composition before melting and liquidus which corresponds to that of the final residual phase (e.g. forsterite for perfect fractional melting of the mantle).

If chemical isolation of melt occurs then the

composition of the residual system and the solidus temperature change, depending on depletion of the residue. Perfect isolation corresponds to the case where the temperature of the system is always on the current solidus. This is important for H₂O-bearing melting, where the initial solidus curve that corresponds to the initial bulk composition before melting has a large negative gradient in a pressure range. Therefore during integration of (4), the current solidus temperature, which is assumed to be calculated from the amount of melt isolated, is monitored. If the temperature is below the current solidus, then the *P-T* path follows dry adiabat.

Results

The *P-T-X* paths for dry peridotite melting and H₂O-undersaturated (0.2 % H₂O) melting have been calculated, with appropriate solidus and liquidus curves (Green, 1973; McKenzie and Bickle, 1988; Presnall and Walter, 1993). In each case, melting paths for both no chemical isolation of melt and perfect chemical isolation are calculated. For dry melting, the *X-T'* (nondimensional temperature normalized to the temperature difference between liquidus and solidus) relationship described by McKenzie and Bickle (1988) is used. For H₂O-undersaturated (0.2 % H₂O) melting, a *X-T'* relationship which is arbitrary chosen to suppress $(\frac{\partial X}{\partial T})_P$ between the dry and H₂O-undersaturated solidi is used. The results show: (i) for dry melting perfect isolation causes 5 to 15 % decrease in degree of melting at a

given potential temperature when compared to the case where no chemical isolation occurs; (ii) for H₂O-undersaturated melting, if no chemical isolation of melt occurs, the convex-up solidus that corresponds to the amphibole stability field can be overridden by a temperature increase due to solidification, whereas if chemical isolation is significant, even at a higher potential temperature, melting of the upwelling mantle can cease in a pressure range corresponding to the convex-up solidus. It should be emphasized that the results obtained here can not be compared quantitatively to the observations because the parameters for fractional melting and wet melting are unknown. However, chemical isolation of melt from the residue, which is controlled by the mode of melt segregation, has probably important effects on melt generation, especially for H₂O-bearing melting in subduction zones.

References

- Green, D.H. (1973) *Earth Planet. Sci. Lett.*, **19**, 37–53.
 Iwamori, H. (1992) *Geophys. Res. Lett.*, **19**, 309–12.
 Iwamori, H. (1993) *Nature*, **366**, 734–7.
 McKenzie, D. (1984) *J. Petrol.*, **25**, 713–65.
 McKenzie, D. and Bickle, M. (1988) *J. Petrol.*, **29**, 625–79.
 Presnall, D.C. and Walter, M.J. (1993) *J. Geophys. Res.*, **98**, 19777–83.
 Spiegelman, M. and Kenyon, P. (1992) *Earth Planet. Sci. Lett.*, **109**, 611–20.