

# Underplating and Partial Melting: Implications for Melt Generation and Extraction

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The quantitative assessment of underplating and concomitant partial melting of continental crust requires the use of geologically reasonable melt fraction distributions as a function of temperature. Conductive modeling indicates that simple underplating of metapelite by basalt can yield magma bodies with melt fractions above the rheological limit of extraction for almost any reasonable geotherm. Convection and subsequent homogenization are likely in these bodies. Granitic and tonalitic protoliths do not appear to yield substantial amounts of extractable magma. These results indicate that underplating involves repeated intrusion or occurs in deep crust.

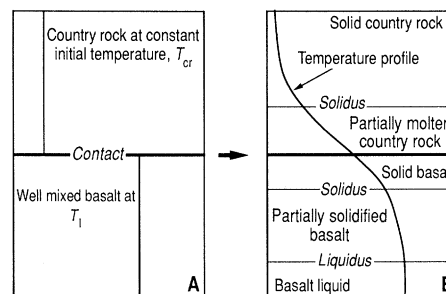
**U**NDERPLATING AND INTRUSION OF continental crust by basaltic magma has repeatedly been invoked as a mechanism to provide the needed heat and mass transfer to initiate and sustain magmatism in a variety of tectonic settings (1-7). An understanding of the time and length scales associated with this coupled solidification and fusion is needed for discrimination of chemical evolutionary paths, the manner in which magma chemistry reflects that of their source regions, and magma transport mechanisms in continental lithosphere (7-9).

The underplating process is thought to proceed in the following way (Fig. 1): basalt at the liquidus temperature  $T_l$  intrudes country rock, which is at an ambient temperature  $T_{cr}$ . In response to cooling at the contact, the basalt will begin to solidify, forming regions of solid and of crystals and liquid (mush). Phase changes may also occur in the country rock; both the sensible and latent heat from the basalt can induce melting. The overall progress of the concomitant solidification and melting and the manner in which the mushy regions are partitioned will depend on the heat transfer systematics between the basalt and country rock. The composition of the country rock will strongly influence the rate of heat transfer and dynamic state of the partially molten regions. This influence is largely due to the manner in which solid fraction, and hence latent heat, varies as a function of temperature for a variety of common rock types. Geologically reasonable solid fraction distributions have not been explicitly invoked in earlier studies of underplating, and although some generic elements of underplating have been demonstrated, available models cannot be used to address issues such as the temporal and spatial distribution of melt in the country rock, the degree of convective mixing, or the schedule and efficiency of melt extraction.

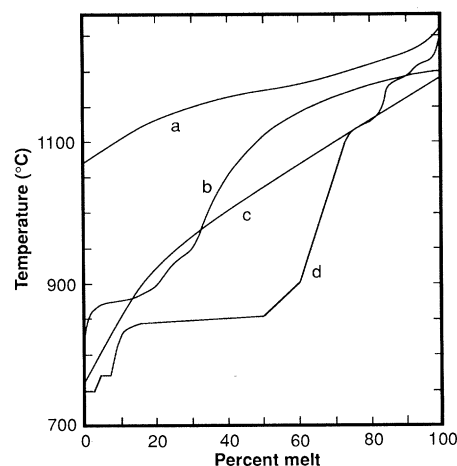
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The latent heats of crystallization and melting for the basalt and country rock are a function of the solid fraction distribution, which is typically reported as a function of temperature for a given pressure, volatile content, composition, and modal mineralogy, as pointed out by Patino-Donce and Johnson (10). A variety of mathematical expressions for the solid fraction distribution have been proposed (11-13), but the multitude of possible melting reactions in geological materials usually precludes the use of these expressions across the entire melting range. Instead, I have used experimentally determined solid fraction distributions during melting (Fig. 2) for crystallizing basalt and for three country rock compositions: tonalite, muscovite granite, and metapelite. The data are all for vapor-absent melts at 1 GPa (10 kbar), where the only source of water was from the breakdown of the hydrous minerals. There is some controversy regarding the amount and distribution of fluids in the deep crust. However, the assumption of dry melting is in keeping with the results of several studies (5, 14-17) showing that liquid compositions obtained during partial melting under saturated conditions did not match commonly observed rock compositions.

I assumed that heat transfer in the basalt and from the basalt to the country rock is by conduction. The applicability of a conduction equation in describing the heat transfer in the basalt near the liquidus is based on the work of Brandies and Marsh (18) and Smith (19), who have shown that there is little convection ahead of a crystallization front in a variable viscosity liquid at or below the liquidus. Convection is inhibited because of the strong rheological contrast that inevitably occurs near the crystallization front of a magma (18, 20, 21) from the presence of crystals. Solidification produces a strong viscosity gradient that inhibits convection and causes the hot, basaltic reservoir to recede away from the intrusion-wall rock contact. Crystals falling away from the mush layer,



**Fig. 1.** (A) The initial condition at the time of underplating. Well-mixed basalt forms a planar contact against country rock at some ambient temperature  $T_{cr}$ . The temperature profile is initially a step function. (B) After some time has passed, the basalt will have crystallized and formed a region of solid and mush. Melting in the overlying country rock also produces a region of mixed phase where the solid fraction is a function of temperature.



**Fig. 2.** Melt fraction as a function of temperature for four rock types at 1 GPa, dry. a, Basalt (11); b, tonalite (5); c, muscovite granite (4); d, metapelite (14); the large increase in melt fraction at  $\sim 835^\circ\text{C}$  is the reaction: biotite + aluminumsilicate + quartz + plagioclase  $\rightleftharpoons$  garnet + potassium feldspar + liquid.

either as single crystals or plumes, cannot yield sustained convection of the magma chamber, as they will be replaced as the system cools and resorbed as they interact with hotter magma; convection of a superheated magma would cause the mush layer to stop growing. The center of the basalt may be largely stagnant, much like that documented at the Hawaiian lava lakes (22). The assumption of conductive heat transfer yields a minimum estimate of the degree of partial melting in the country rock. An alternative picture of heat transfer during underplating has been given by Huppert and Sparks (23), who suggested that the basalt would turbulently convect and, as a result, melting of the country rock and cooling of the basalt would be rapid. These conditions are appropriate for underplating by strongly superheated magmas where con-

vection is initially turbulent and strongly time-dependent: rapid convection increases the rate of heat loss from an intrusion. This superheated condition precludes the development of a solidification front at the contact.

The physical modeling of the crystallization of underplated basalt and the simultaneous melting of the overlying country rock requires solving the coupled heat equations for both regions. A solution can be obtained by partitioning the regions of basaltic magma and country rock into subdomains that are delimited by isotherms. This method yields a set of equations

$$\frac{\partial T_i}{\partial t} = \kappa_i \frac{\partial^2 T_i}{\partial x_i^2} + \frac{L_i}{C_{p_i}} \frac{df_i}{dt} \quad (1)$$

where  $x_i$  and  $t$  are the independent variables distance and time and  $T_i$  is the temperature,  $\kappa_i$  the thermal diffusivity,  $L_i$  the specific latent heat,  $C_{p_i}$  the specific heat capacity, and  $f_i$  the solid fraction distribution, all in the  $i$ th subdivision.

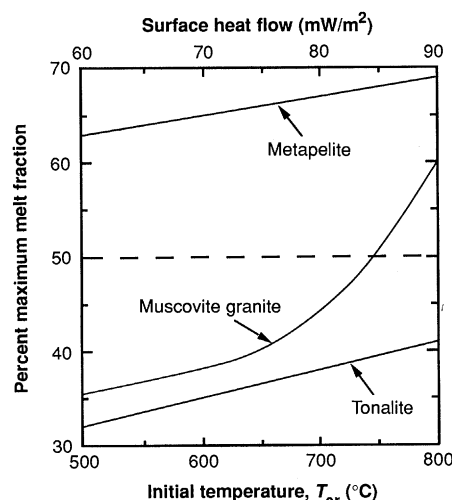
The set of equations can be further simplified by introducing the usual similarity variables

$$\xi_i = \frac{x_i}{2\sqrt{\kappa_i t}} \quad (2)$$

$$\delta_i = 2\lambda_i \sqrt{\kappa_i t} \quad (3)$$

where  $\xi_i$  is the new independent variable across a domain of  $\delta_i$  thickness. This substitution reduces the system of equations to a sequence of ordinary differential equations where  $\lambda_i$  is a constant to be determined. This transformation is possible for constant-temperature boundary conditions regardless of the form of the solid fraction distribution. If the solid fraction distribution is nonlinear by virtue of a dependence on temperature, the resulting set of ordinary differential equations is also nonlinear. I have used two approaches in solving these equations: (i) I fit third-order polynomials to the solid fraction distribution curves across any  $i$ th region, as a function of  $T_i$ , and then solved the resulting system using the method of Adomian (24); and (ii) (a much more direct method) I assumed that the solid fraction varied linearly in  $x_i$  across any  $i$ th region. Examination of the residuals between the two methods suggests that the assumption that the solid fraction has a linear stretching in  $x_i$  is nearly equivalent to assuming a third-order dependence in  $T_i$ .

Once the solid fraction distribution is given, such as those in Fig. 2, the system of equations can be solved. The manner in which the solid and mush in both the country rock and solidifying magma distribute themselves allows determination of whether



**Fig. 3.** Maximum melt fraction as a function of the ambient temperature in the country rock. This maximum will occur near the contact and is not the average melt fraction of the partially molten region. Surface heat flow is plotted along the upper axis, values taken from (28). Basalt temperature at time of underplating is 1250°C.

convection or ascent of the magma in the partially molten zone is possible. Figure 3 is a plot of the maximum melt fraction that will be achieved in the mush zone, and this occurs at the contact; all the magma down the thermal gradient from the contact will have smaller melt fractions as specified by the solutions to Eq. 1 and percent melt curves. The dashed horizontal line at 50% melt fraction represents the approximate rheological limit of eruptability or extraction (11); a more conservative limit of 30% has been suggested by Clemens and Vielzeuf (16). I used 50% on the basis of the work of Miller *et al.* (8), who identified this limit with the contiguity limit. Contiguity is a measure of grain contact, and the contiguity limit separates that portion of the mush which has a continuous framework of solids from the portion that can be rheologically considered as a suspension. Country rock lithologies that yield maximum melt fractions that are in excess of the contiguity limit could be considered reasonable magmatic protoliths, as the region of crystals and liquid could conceivably be extracted or undergo crystal-liquid separation. The maximum melt fraction is achieved almost immediately following underplating and is independent of the volume of underplated basalt. However, the total amount of melt at any time depends on the volume of basalt; I assumed that the basaltic chamber is so large that conditions at the bottom can be ignored.

The maximum melt fraction in the metapelite following underplating is significantly greater than the contiguity limit for any reasonable geotherm and indicates that ba-

saltic underplating of metapelites at 1 GPa could yield substantial amounts of melt. This large melt fraction suggests that convection in the mixed phase region with melt fractions greater than the contiguity limit may occur. For an ambient country rock temperature of 650°C and the critical Rayleigh number for a growing melt layer (25), the time to the onset of convection in this portion of the partially melted country rock is about 4500 years. At this time the distance between the contact and the region of contiguity is a little over 200 m, and the distance between the region of contiguity and the solidus is ~288 m. The upper 80 m of basalt will have solidified, below which will be ~375 m of mush. Thus, the underplated basalt would have to be a sill at least 455 m thick for convection in the overlying partial melt pile to be initiated. Convection in the region where the melt fraction is less than the contiguity limit is best approximated by porous-media flow as suggested by Lowell (26). For a permeability of  $10^{-8} \text{ m}^2$  in the crystal matrix and a melt viscosity of  $1 \text{ m}^2/\text{s}$ , the region with a melt fraction less than the contiguity limit would have to be on the order of  $10^5 \text{ m}$  for convection to begin, which represents a time of about  $10^8$  years after underplating. This analysis suggests that very little convection will occur in the region of contiguity, which is in keeping with the results of Wickham (27).

The muscovite-granite protolith can also yield a substantial melt fraction but only under higher ambient thermal conditions typical of regions of extension (28). Underplating of tonalite appears unlikely to yield much extractable magma unless the crust is under sustained thermal attack such as in a hotspot environment. The generation of tonalitic liquids by vapor-absent melting of amphibolite appears to be a promising source for magmas (29).

The efficiency of the underplating process can be estimated by calculation of the ratio of the total melt generated in the country rock to the total amount of basalt crystallized. This estimate requires integrating the melt and solid fraction distributions as a function of temperature across all the subdivisions. At an ambient country rock temperature of 700°C, underplating of basalt yields ratios of 0.4 for the tonalite to 0.6 for the metapelite. These differences are a direct result of the functional form of the solid fraction distribution and the difference in sensible heat contents of the magma and country rock as expressed by the difference in their initial temperatures. Thus, generation of 500 km<sup>3</sup> of peraluminous (S-type) magma from a metapelite by underplating takes at least 833 km<sup>3</sup> of basalt, and if only 25% of the melted region was above the

contiguity limit, over 3333 km<sup>3</sup> of underplated basalt would be required to yield 500 km<sup>3</sup> of extractable magma.

The apparently significant volumes of basalt required to mobilize large quantities of crustal melt suggest that underplating is not a one-stage process; repeated intrusion is required for underplating to be effective; a similar conclusion was reached by Younker and Vogel (7). The calculations also suggest that magma generation following underplating requires elevated geotherms or greater depths (2, 7). If successive parcels of basalt can intrude and breach the solidified portion of the early underplated material, further melting will be enhanced, as will magma mixing and mingling. This process could produce a complex where assimilation and magma mixing would give rise to homogenization at a variety of length scales, as proposed by Hildreth and Moorbath (2) and observed in the southern Sierra Nevada batholith (30).

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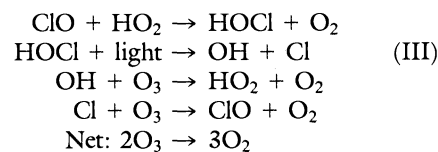
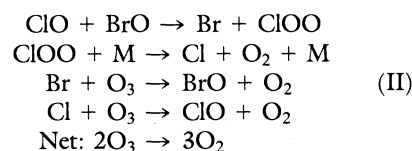
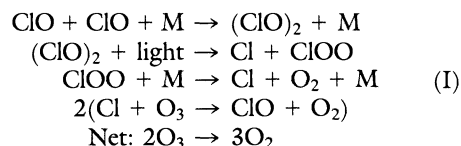
## Rate of Formation of the ClO Dimer in the Polar Stratosphere: Implications for Ozone Loss

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The gas-phase recombination of chlorine monoxide (ClO) has been investigated under the conditions of pressure and temperature that prevail in the Antarctic stratosphere during the period of maximum ozone (O<sub>3</sub>) disappearance. Measured rate constants are less than one-half as great as the previously accepted values. One-dimensional model calculations based on the new rate data indicate that currently accepted chemical mechanisms can quantitatively account for the observed O<sub>3</sub> losses in late spring (17 September to 7 October). A qualitative assessment indicates that the existing mechanisms can only account for at most one-half of the measured O<sub>3</sub> depletion in the early spring (28 August to 17 September), indicating that there may be additional catalytic cycles, besides those currently recognized, that destroy O<sub>3</sub>.

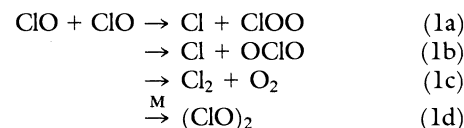
THE LARGE DECREASES IN O<sub>3</sub> concentrations in the Antarctic stratosphere during early spring (1) are accompanied by unusually high concentrations of ClO, OClO, and HOCl and low concentrations of HCl and of species containing odd nitrogen (NO, NO<sub>2</sub>, and HNO<sub>3</sub>) relative to their observed values at lower latitudes (2). Current thinking regarding the chemical mechanisms of O<sub>3</sub> destruction suggests that the perturbation of polar stratospheric chemistry occurs in two phases (3).

In the first phase, which occurs primarily during the polar night, the inactive chlorine reservoir species HCl and ClONO<sub>2</sub> are converted to photochemically labile Cl<sub>2</sub> and HOCl by heterogeneous reactions on ice crystals and on nitric acid trihydrate aerosols. Denitrification of the stratosphere occurs as a result of particle sedimentation. In the second phase, atomic chlorine is released by photolysis of Cl<sub>2</sub> and HOCl after sunrise. The resulting free chlorine participates in efficient catalytic O<sub>3</sub> destruction cycles, of which the following cycles are believed to be important (3, 4) (M is a third-body molecule):



The relative importance of these and other catalytic cycles in polar O<sub>3</sub> destruction is uncertain. Because the first reaction in each of the above cycles is the rate-limiting step, the rate coefficients and product distributions for these processes must be determined under polar stratospheric conditions. To date, only the BrO + ClO reaction (cycle II) has been adequately described at low temperatures (5, 6). Both the ClO + HO<sub>2</sub> (cycle III) and the ClO + ClO (cycle I) reactions are poorly characterized under these conditions, the latter despite almost 40 years of laboratory study (7).

The kinetic analysis of reaction 1 has been greatly complicated by the existence of at least four product channels:



We studied the ClO + ClO reaction under conditions relevant to the polar stratosphere and have concluded both that the reaction proceeds at rates significantly lower than previously believed and that the only reac-

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