Using constraints from experimental petrology studies to model mantle melting processes under anhydrous and hydrous conditions

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Introduction

The information obtained from mantle peridotite and mantle-analog melting studies provides fundamentally important constraints for the development of mantle melting models which integrate the thermal, mechanical and chemical interactions between melt and mantle. The goal of the models is to use the information preserved in the chemistry of basaltic magmas to infer melting processes. In the case of anhydrous melting beneath mid-ocean spreading centers, the general characteristics of melting process are understood. In this environment melting occurs during adiabatic ascent and mantle melting begins when the temperature exceeds that of the solidus. Magmatic output is determined by mantle temperature, melt production rate, the geometry of melt production and melt migration, mantle flow in response to melting-induced buoyancy and thermal structure effects and by mantle bulk composition. Chemical information from mantle-derived melts can be used to deduce geometric and physical aspects of melting during adiabatic ascent. In the case of hydrous mantle melting that occurs above the subducted slab in convergent margin and island arc environments, the fundamental controls on melt generation are less firmly established and chemical compositional information preserved in magmas can provide insight into the depth range over which melt is generated, the thermal structure of the melting regime and the physical aspects of the melting processes.

Parameterization of experimental data

Our method for the parameterization of mantle melting employs a thermodynamically-guided, empirical approach that is relatively accessible to non-specialists and that retains sufficient quantitative rigor so that is has predictive value (Kinzler and Grove, 1992a,b; 1993). We have also developed a model that is consistent with all the available experimental data on mantle melting and that includes experiments on natural basalt and natural mantle compositions and the experimental data on mantle analog compositions (e.g. the system $CaO-MgO-Al_2O_3-SiO_2$ or CMAS which comprises about 90 % of the chemistry of the mantle and CMAS + Na_2O). The inclusion of CMAS data facilitates the application of thermodynamic constraints on mantle melting. In the case of analog CMAS peridotite, melting involves 5 phases (phi): melt - olivine - orthopyroxene - high-Ca pyroxene - aluminous phase (spinel, garnet or plagioclase) and 4 chemical components (C) so that the thermodynamic variance (F) as given by the Gibbs phase rule is F = C + 2 - phi = 1. In this analog case one needs to specify only one variable (pressure) and the temperature and compositional characteristics of melting are fixed. The effects of other important, though less abundant, chemical constituents (Na_2O, FeO, TiO_2, Cr_2O_3, H_2O) introduce additional degrees of freedom to the mantle melting equilibrium, and thus potential changes in the temperatures of melting and the compositions of melts produced. The parameterization describes the regular effects that these other components have on mantle melting. For example, the effect of adding FeO, Na_2O, TiO_2 and K_2O to the bulk mantle composition is to lower the solidus at any given pressure, relative to the solidus in CMAS and a linear equation involving these components describes this effect. This equation can also be implemented to estimate the quantity of melt produced from a given spinel peridotite at a specified pressure and temperature. Additional equations describe the effects of the non-CMAS

components on melt composition. To implement these equations in models of mantle melting, the abundance levels of the non-CMAS components must be tracked. This is accomplished through the use of mineral - melt exchange KDs and partition coefficients. Methodology is described in Kinzler and Grove (1992a, b; 1993). The other information provided in our description of the mantle melting process is the stoichiometry of the melting reaction, which is required to track the mantle residue mineralogy. The addition of non-CMAS components also changes the pressures and temperatures at which solid phase transition boundaries intersect the solidus. The addition of Na_2O expands the plagioclase peridotite stability field to higher pressures relative to that for spinel and expands the spinel stability field to higher pressures relative to that for garnet (Walter and Presnall, 1994). The addition of either FeO or H_2O stabilizes garnet to lower pressures while addition of Cr_2O_3 stabilizes spinel relative to garnet to higher pressures.

Application to anhydrous melting processes

The constraints provided by our experimental parameterization of the mantle melting process allow the development of fully self-consistent physical models of mantle melting. These models incorporate conservation of mass expressions in terms of equations that constrain the melt production rate, melt compositions and mineral and bulk chemical composition of residual mantle. Using best estimates of latent heat of melting, assumptions of the connectivity and permeability of the melt-containing network, the effects of melt-extraction-induced density variations and thermal advection by melt transport have been explored (Cordery and Phipps Morgan, 1992). An important advance in the parameterization of anhydrous peridotite melting will be the description of melt compositions and melting reactions in the vicinity of the spinel to garnet phase transition. Recent progress in this area is presented by Kinzler (this volume).

Application to hydrous mantle melting processes

When H_2O is present the melt still forms an interconnected network at low melt fractions, but the wetting angle is higher (Watson, 1991) and this effect could change the porosity and the amount of melt retained in the partially molten aggregate, thereby influencing the compositions of both melt and mantle residue. The mechanisms for melt generation are also not well established. A possibility is that a water-rich contribution from the subducted slab induces a small degree of partial melting in the lower part of the mantle wedge. This partial melt ascends through an inverted geotherm and finds itself constantly superheated. The melt will impose an H_2O activity on the surrounding mantle as it ascends ,thereby inducing further melting. The amount and composition of melt produced by such a process will be greatly influenced by regional variations in fluid flux from the subducted slab as well as by other subduction parameters such as slab dip, crustal thickness, etc. Furthermore, transport mechanisms in the lower part of the mantle wedge may eliminate significant interaction of a deep, small degree, partial melt with its surrounding mantle (Davies and Stevenson, 1992). This melt may be transported to shallow depths and its arrival in the shallow part of the mantle wedge may influence the melting process. Knowledge of the influence of H_2O on mantle melt compositional variation is becoming available (Gaetani, this volume) and should contribute toward an understanding of the depth ranges and physics of the melting process.

References

Cordery, M. J. and Phipps Morgan, J. (1992) *Earth Planet. Sci. Lett.*, 111, 493–516.
Davies, J. H. and Stevenson, D. J. (1992) *J. Geophys. Res.*, 97, 2037–70.
Kinzler, R. J. and Grove, T. L. (1992a) *J. Geophys. Res.*, 97, 6885–906.
Kinzler, R. J. and Grove, T. L. (1992b) *J. Geophys. Res.*, 97, 6907–26.
Kinzler, R. J. and Grove, T. L. (1993) *J. Geophys. Res.*, 98, 22339–47.
Walter, M. and Presnall, D. (1994) *J. Pet.* (in press).
Watson, E. B. (1991) *Contrib. Mineral. Petrol.*, 107, 417–34.