Melting in the mantle

Lecture by Timothy L. Grove

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Notes Prepared by Clint Conrad, Mary Agner and Thorsten Becker

Introduction

Melting in the mantle is a complex process which produces variable amounts of melted material of different mineral composition depending on the conditions during the formation. Important points are:

- The melting process itself. Three melting styles are usually considered: Batch, fractional, and assimilative melting. Since melts react with solids as they ascend, the time scale of melting becomes important.
- The temperature needed to melt mantle rock increases with pressure and hence depth.
- Volatiles (such as the best studied one, water) decrease the melting temperature.

Melting is an inverse problem

One assumption involved in the interpretation of melt processes is that the melt samples the conditions in which it was created directly prior to segregation.
Petrologists determine the temperature when a rock is totally liquid for a given pressure in order to create a liquidus curve for that material. Basalts are liquids resulting from such melting processes. The temperature at which basalts coexist with many crystals on the liquidus curve equals the temperature of melt extraction. (This concept is more complex then noted by Herzberg and Zhang, 1996). Also, petrologists melt peridotites to determine the first melt composition.
Melts of the mantle have different composition than the parent body. Peridotites are found in stable cratons, extensional environments, and mid ocean ridges.
The problems in determining what exactly happens in the mantle when material melts are:

- melts are not "batches" from mantle resulting from one temperature and depth
- melt freezes as it rises and will crystallize out other minerals, altering the composition of the melt
- melt assimilates the mantle around it: It is not in equilibrium with the neighboring rock, since the melt temperature is above the solidus
- melt composition does not equal basalt composition

Why does the mantle melt?

Because there are different pressure-temperature slopes for adiabatically ascending bodies and melting curves. We assume that the convection taking place in the mantle implies adiabatic rise. The change in temperature with depth for silicate is around 0.3 degrees Celsius per kilometer. The slope for the melting curve, however, ranges from 1.3 degrees Celsius per kilometer to 5 degrees Celsius per kilometer. A decompression of 1 GPa will give 90 degrees Celsius of superheat. This implies an output of work about 30 calories per gram. Using a change in enthalpy of fusion of 150 calories per gram, this implies about 20% melt. Another assumption is that the time-scales in mid ocean ridges are approximately equal to spending rates.

Melting Models

The two end-member cases are:

- Equilibrium Batch Melting: Melt remains in contact with residual crystals at all times, so the bulk composition remains constant.
- Fractional Melting: Melt leaves the system as soon as it is formed, so the bulk composition of the residual solid changes continuously. Fractional melting requires that the melt pockets get completely interconnected as soon as they are formed. In addition, the density of most melts is lighter than the residual only at pressures less than about 8 GPa (250 km), with a large degree of possible variation in this number. Thus, if melt occurs below this depth in a high permeability rock, the melt will sink and not rise to the surface. Melt connectivity is a function of the dihedral angle at edges of melt regions.

Based on melt connectivity and permeability, and observations by Johnson et. al., 1990, fractional melting seems more likely to occur at ridges than batch melting. Most experimental observations, however, assume batch melting, so it can be unclear how to relate them to the earth.

Equilibrium in Fe and Mg bearing systems

Melt formation kinetics (and the final concentration of FeO and MgO in melts) can be described by equilibriums constants as a function of activity parameters. They depend on the temperature but to first order not on the pressure. Hence, deep melts from regions with high temperatures are high in MgO and FeO as a temperature effect.

Effects of Water

- Additional water lowers the melting temperature - adding only a little bit of water can lower the melting temperature significantly
- Water also allows melt to occur over a wider temperature range. The effects of water depend critically on how much water you add and how you do it.
- Adding water to the system almost completely erases the effect of pressure on melt.
- Adding water decreases the amount of FeO and MgO which goes into the melt.

- Computing the composition of the residual and the melt for fractional melting with water begins to get very complicated. Back-computing the composition of an original rock from a residuum and a melt is even more complicated.

References to papers

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- Johnson, K. T. M., Dick, H. J. B. and Shimizu, N.(1990): *Melting in the oceanic upper mantle: an ion microprobe study of diopsides in abyssal peridotites*. JGR, 95, B3, 2661-2678