

Thermodynamics of Mantle Melting

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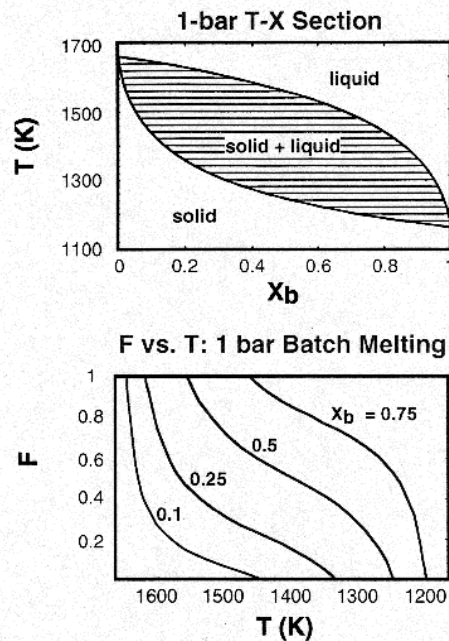
Abstract

The recent increase in available experimental data (see Hirschmann, 2000) on a range of peridotite compositions (e.g. volatile constituent, Mg#, alkali, CaO) allows a more comprehensive evaluation of the role of composition on temperature of the solidus. The effect of compositional variation on the volatile-free peridotite solidus depends in large part on the competing effects of increased abundance of melt-enhancing components (alkalis, lower Mg#) and the effects of increased compatibility of those components (clinopyroxene mode or CaO%).

Based on theoretical, experimental and field studies it seems plausible to infer that a veined peridotite/pyroxenite assemblage is a good candidate to represent the lithologies of the upper mantle. Studies of the thermodynamics of adiabatic decompression melting of veined mantle and the consequences for MORB petrogenesis and geochemistry (Phipps Morgan, 2001; Hirschmann and Stolper, 1996) have been reviewed. Partial melting of pyroxenite during mantle upwelling can be particularly productive in the depth interval where pyroxenite is melting but peridotite is not. This results from a lower solidus for pyroxenite and melt enhancement by conductive heat flow from neighboring non-melting material. The proportion of melt derived from pyroxenite may be therefore greater than the abundance of pyroxenite in a mantle source region. Further investigations in progress (such as melt inclusions studies) should lead to a more comprehensive picture of the scale of mantle heterogeneities, the way they are produced and preserved in the convecting mantle.

1. Introduction

It is well known that the sources of oceanic basalts vary in their isotopic and trace element composition but direct evidence of the extent of lithologic heterogeneity is more controversial. Mantle heterogeneities can be produced by subducting oceanic crust into the mantle and then mixing these heterogeneities by mantle convection producing a marble-cake mantle (Allegre and Turcotte, 1986). Furthermore, enriched mantle reservoirs (e.g. HIMU, EM...) may be carried by normal peridotite, by peridotite enriched in major and minor



$$\left(\frac{\partial F}{\partial T}\right)_P^{Batch} = -\left(\frac{\partial X_b^s}{\partial T}\right)_P \left(\frac{1}{X_b^l - X_b^s}\right) - \frac{(X_b^l - X_b^s) \left(\frac{\partial(X_b^l - X_b^s)}{\partial T}\right)_P}{(X_b^l - X_b^s)^2}$$

Figure 1: Isobaric productivity of melt (F at 1 bar) as a function of temperature (T) and proportion of component b relative to component a (Xb). Model for batch melting.

components or by pyroxenite-rich lithologies. Understanding the lithologic character of geochemically distinct mantle reservoirs and their roles in basalt genesis would place strong constraints on the origin of such reservoirs and the dynamics of the mantle.

Establishing the presence or absence of lithologic heterogeneity in basalt source regions requires the understanding of the thermodynamics of mantle melting. Both old and new theoretical models and experimental evidence of key parameters controlling melt productivity were reviewed during the GERM workshop. Geochemical evidence for lithologic heterogeneity in basalt sources regions as well as the scale-lengths of local mantle heterogeneity have been also discussed.

2. Basics of decompression melting

Beneath oceanic ridges and islands, partial melting is driven primarily by pressure-release of upwelling mantle. Because decompression melting can be approximated as occurring within a thermally isolated domain, the melt production process should take place as an adiabatic (isentropic) process. The temperature-pressure path of the solidus in complex systems can be estimated

from the thermodynamic properties of the constituent phases and information about the solidus liquid and residual mineral compositions. The production of melt during pressure-release, solidus location and isobaric productivity are dependent on several key parameters. For instance, melt production during decompression melting for isentropic systems is highly variable and depends on the different component compositions and, in particular, the difference in composition between the component b in melt (X_b^l) and in source rock (X_b^s). From equation in [Figure 1](#), the isobaric melt production (F) is highest when the factor ($X_b^l - X_b^s$) is minimal. The proportion of component b relative to a (X_b) is also a key parameter affecting the melt production, other parameters being constant ([Figure 1](#)).

3. Effect of composition of peridotite melting

The effect of peridotite composition on the location of the peridotite solidus can be inferred using both theoretical models and experimental investigations. The recent increase in available experimental data (see Hirschmann, 2000) on a range of peridotite compositions (e.g. volatile constituent, Mg#, alkali, CaO) allows a more comprehensive evaluation of the role of composition on the solidus.

The effect of compositional variation on the peridotite solidus depends in large part on the competing effects of increased abundance of melt-enhancing components (alkalis, lower Mg#) and the effects of increased compatibility of these components (clinopyroxene mode or CaO%). For instance, at 3GPa, volatile-free peridotite solidus temperatures correlate with decreasing Mg# and increasing bulk alkalis. Increased clinopyroxene mode has the effect of making Na more compatible in residual solids and so diminishes the solidus-lowering tendencies of alkalis. As a consequence, experiments performed on a range of peridotite compositions with inappropriate correlation between alkali content and clinopyroxene will tend to exaggerate the effect of composition.

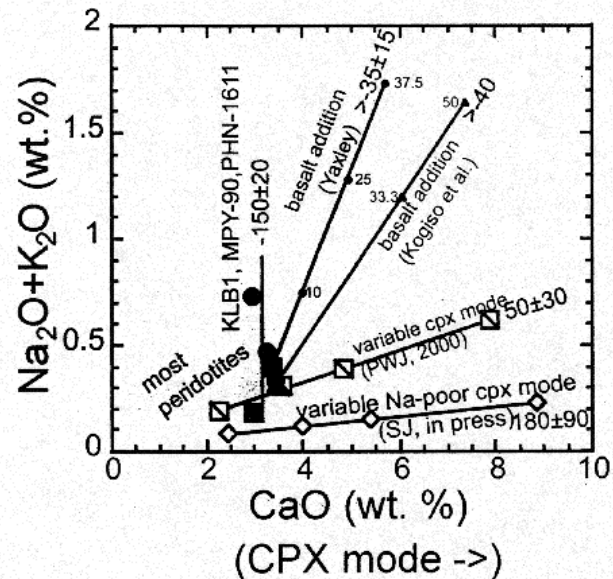


Figure 2: Effects of various enrichment processes on peridotite composition and, by inference on solidus temperature (Hirschmann G-cubed 2000).

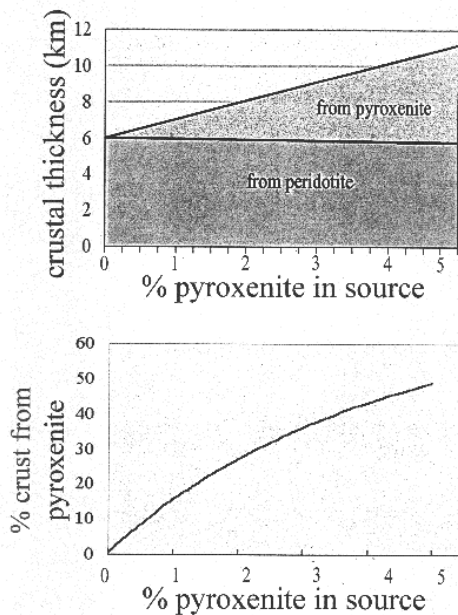


Figure 3: pyroxene-rich rocks have a greater melt productivity than peridotite during pressure release melting of upwelling mantle.

melt productivity than peridotite during upwelling (Figure 3). An interesting consequence of the interlayering of pyroxenite and peridotite in the mantle is the diffuse heating of pyroxenite due to thermal equilibration (but not chemical) between peridotite and pyroxenite along the P-T path (Figure 4). This results of an enhancement of melting of the pyroxenite. Furthermore, the heat consumed by deep pyroxenite melting may cool the ascending mantle mixture enough so that peridotite melting begins several km shallower than it would in the absence of precursor pyroxenite melting (Phipps Morgan, 2001).

3. Implication for MORB geochemistry

The presence of pyroxenite-rich lithologies in the mantle can be tested further using their potential effects on MORB geochemistry. In particular, Os isotope signatures of oceanic basalt could be a sensitive indicator of participation of pyroxenite in MORB petrogenesis. Because pyroxenite has highly radiogenic $^{187}\text{Os}/^{188}\text{Os}$ (and low Os content) whereas peridotite has low $^{187}\text{Os}/^{188}\text{Os}$ (and higher Os content), high $^{187}\text{Os}/^{188}\text{Os}$ in values in MORB, if not of secondary origin, may imply the presence of pyroxenite-rich lithology in MORB source. Simple Os isotopic mass balance suggest that Os isotope signature of MORB is best explained if the melt of each components (*i.e.* peridotite and pyroxenite) is extracted first and then mixed (Figure 5). This model requires less than 10% of pyroxenite in the source (Figure 5). Furthermore, to preserve the pyroxenite-like Os signature in mantle derived rocks, it is important that melt equilibrates with only a small fraction of the

Figure 2 permits the examination of the effects of various enrichment processes on peridotite composition and, by inference on solidus temperature. In contrast to the small effect of basalt addition on peridotite solidus temperature, just a few percent of metasomatism by alkalis-rich liquid could lower the peridotite solidus by 100°C or more.

4. Effect of minor lithology in mantle.

Pressure-release melting within a lithologically veined mantle composed of peridotite/pyroxenite assemblage has been investigated by recent studies (See Hirschmann and Stolper, 1996 and Phipps Morgan, 2001) Since pyroxenite and peridotite lithologies have different mineral compositions, the pressure-release melting occurs at different P-T conditions. The difference between pyroxenite and peridotite solidi means that pyroxenite layers in an adiabatically upwelling mantle will begin to melt deeper (or earlier) than the enclosing peridotite. An important result of this different melting interval is that pyroxene-rich rocks have a greater

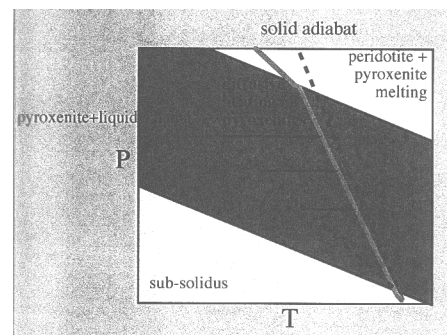


Figure 4: Effect of thermal equilibration between peridotite and enclosed pyroxenite. Solid lines indicate temperature-pressure paths of veined upwelling mantle. Partial melting of pyroxenite in the region where peridotite is solid leads to extra (super-adiabatic) melting of residual pyroxenite. (modified from Hirschmann and Stolper, 1996)

peridotitic Os. This equilibration can be a function of the size of the pyroxenite bodies for different melting/diffusion time (Figure 6) providing information about the scale of mantle heterogeneity. As suggested by Becker (2000), another way to preserve pyroxenite Os signature could be achieved by the shielding of Os-rich phases in peridotite by silicate. This likely precludes reaction with partial melts of pyroxenite.

References

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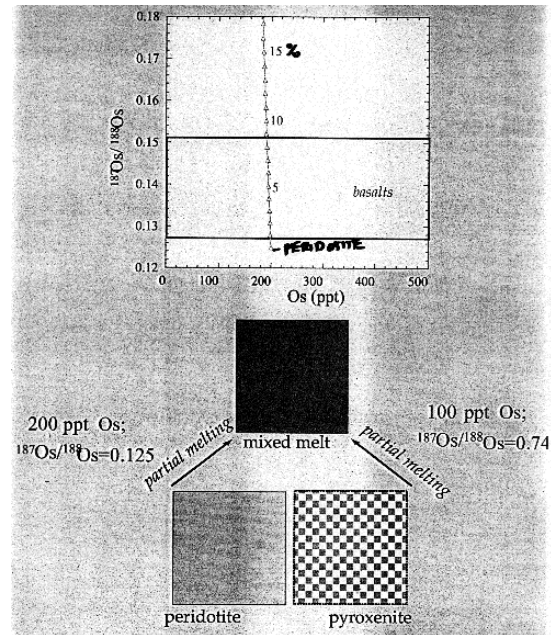


Figure 5: More radiogenic Os isotope signature of MORB may be explained by the partial melting and mixing of pyroxenite-rich lithology enclosed in peridotite.

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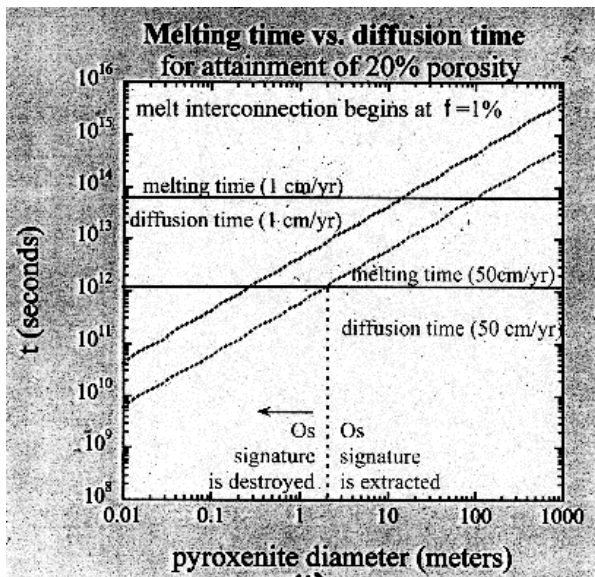


Figure 6: Effect of the scale of mantle heterogeneity (pyroxenite veined mantle) on melting time vs diffusion time. Os isotope signature of the mixt pyroxenite/peridotite lithologies can be preserved if large bodies of pyroxenite are involved (i.e. chemical equilibrium between pyroxenite-derived melt and solid peridotite is limited).