Melting of mantle peridotite at pressures approaching the spinel to garnet transition

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Introduction

Melting of the Earth's upper mantle beneath mid-ocean ridge spreading centers is likely to be a dynamic, near-fractional process during which pressure (P), temperature (T), and source composition change as melting proceeds (Cooper and Kohlstedt, 1986; Johnson et al., 1990; Kinzler and Grove, 1992a,b; Langmuir et al., 1992). Well constrained melting models are required in order to use the compositions of mid-ocean ridge basalts to infer characteristics of the melting processes that lead to ocean ridge volcanism. These include the pressure range over which melting occurs, the extent to which the melting process approaches fractional melting; the geometry of the melting region, the role played by garnet in the source region, and the extent to which melts react with their surroundings as they migrate to the surface, etc. Current models for the generation of portions of the oceanic crust generally predict initial pressures of melting of 25–30 kbar (Klein and Langmuir, 1987, 1989; Kinzler and Grove, 1992b, Langmuir et al., 1992), however, the experimental data base available upon which to build full major element peridotite melting models has been limited by a lack of data at pressures greater than ~ 15 kbar. This abstract presents new experimental data relevant for melting of spinel lherzolite obtained over the pressure range of 15–25 kbar. A modified version of the method of Kinzler and Grove (1992a) is used to provide a preliminary parameterization of these data, combined with data from the literature.

Data and parameterization description

The new data set consists of roughly 30 synthesis experiments carried out in a piston cylinder that contain melt coexisting with olivine (oliv), orthopyroxene (opx), high-calcium clinopyroxene (cpx), and spinel (spin) ($\pm$ garnet) between 15 and 25 kbar. The bulk compositions of the experiments are synthetic mixes calculated to be intermediate between basalt and peridotite and thus result in experimental assemblages that contain melts present in fairly high melt fractions (0.2–0.6) that coexist with mantle minerals of compositions appropriate for the Earth's mantle. Bulk compositions contained the CMAS (CaO-MgO-Al_2O_3-SiO_2) components plus FeO, Na_2O, Cr_2O_3, TiO_2 and K_2O. Experimental durations were generally 72+ hours.

We have chosen the 9 molar components SiO_2, TiO_2, $AlO_{1.5}$, Cr_2O_3, MgO, CaO, $KO_{0.5}$, $NaO_{0.5}$ and Mg# ($[Mg/[Mg+Fe^{2+}]]$) to describe our system. For a system at chemical equilibrium the number of degrees of freedom (F) is specified by the Gibbs phase rule to be equal to the number of chemical components (C) plus 2 minus the number of phases ($F = C + 2 - phi$). The number of phases present is at least 5 (melt + oliv + opx + cpx + spin), and thus $F = 6$. Therefore, the spinel lherzolite melting equilibrium in P–T–composition space can be described by 6 independent variables. We have chosen P and the compositional parameters that distinguish our experimental system from the mantle analog system CMAS as our independent variables, and used a least squares multiple regression technique to obtain the simplest preliminary parameterization of the 60 experimental determinations of melt compositions saturated with oliv, opx, cpx, and spin ($\pm$ garnet) at known P and T (see Table 1 for details of the model as well as additional data sources).

Stoichiometric coefficients of peridotite melting reactions

The pressure dependence of the stoichiometric coefficients of the reaction that governs melting of spinel peridotite has been investigated using the data described here and the method described in Kinzler and Grove (1992a). Over the pressure range from 10 to 23 kbar spinel peridotite melts according to a reaction relationship. For moderately depleted spinel peridotite, at pressures between 10 and ~ 16 kbar, oliv is produced in addition to melt (cpx + opx + spi = oliv + melt); with further increase in P (17–19 kbar) opx joins oliv on the product side of the reaction (cpx + spi = oliv + opx + melt); and at higher P (21–23 kbar), oliv moves to the reactant side (cpx + oliv + spi = opx + melt). Preliminary garnet peridotite melting data indicate that opx is also on the product side in the garnet peridotite melting

TABLE 1. Preliminary parameterization of spinel lherzolite melting equilibrium

General Form: $Y = A_0 + A_1 P + A_2 P_{0.33} + A_3 TiO_2 + A_4 Cr_2O_3 + A_5 NaO_{0.5} + A_6 KO_{0.5} + A_7 (1-Mg\#)$

Y	A_o	A_1	A_2	A_3	A_4	A_5	A_6	A_7	R^2	SE[a]
T	427	−7.424	446	-b	21,940	−583	−6640	−44	0.96	15
SiO_2	0.772	0.003	−0.174	1.87	7.33	0.173	1.58	−0.081	0.75	0.009
$AlO_{1.5}$	0.322	–	−0.050	–	−34.0	0.199	2.87	−0.095	0.77	0.009
CaO	0.150	−0.0009	–	–	–	−0.475	−0.936	−0.027	0.93	0.004
MgO	−0.029	–	0.105	−1.64	12.7	−0.756	−2.74	−0.057	0.94	0.012

No. of observations[c]: 60

[a]Standard Error of Estimate on Y, thus T is estimated with a SE of $\pm 15°$, and SiO_2 with a SE of ± 0.009 molar units.
[b]Unable to discern between (1) insufficient data to resolve dependence or (2) no dependence.
[c]Data sources: This study, Kinzler and Grove (1992a); Walter and Presnall (1994); Elthon and Scarfe (1984); Hirose and Kushiro (1993).

reaction. The occurrence of this tie line switch that stabilizes opx relative to oliv on the product side of the reaction at pressures approaching the spinel to garnet transition has also been observed in the system CMAS + Na$_2$O (Walter and Presnall, 1994) and appears to result primarily from P induced changes in the pyroxene compositions. Peridotite composition is also anticipated to exert control on the nature of the melting reaction. Preliminary analysis indicates that greater abundances of Na$_2$O and K$_2$O in the peridotite stabilize opx on the product side, even at lower pressures. Thus, melting at higher P of a more enriched source composition creates residues that are enriched in opx relative to oliv. As P decreases and the source becomes more depleted in Na$_2$O and K$_2$O (as is anticipated for polybaric, near-fractional melting) the residues become enriched in oliv relative to opx.

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