The composition of high-pressure mantle melts: results from diamond aggregate experiments

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Introduction Determining the composition and fraction of melt near the solidus of peridotite as functions of temperature (T), pressure (P), and bulk composition is a difficult problem, but one whose solution is fundamental to understanding the petrogenesis of basaltic magmas. In principle, such experiments are easy to design and carry out – a peridotite sample is loaded into a capsule, melted, allowed to equilibrate at P and T, and then quenched. The difficulty is that low melt fraction liquids crystallize extensively on quenching, and thus recognizing what was liquid under the conditions of the experiment and reconstructing its composition is difficult. Consequently, there are few reliable data on the composition *and* amount of melt coexisting with mantle peridotite over a range of P and T (especially near the peridotite solidus).

Here we present results of mantle melting experiments conducted using a technique developed by us (Baker *et al.*, 1992; Baker and Stolper, 1994), Hirose and Kushiro, 1993, Johnson and Kushiro, 1992, and Kushiro, 1994, that circumvents the quenching problems that have plagued previous peridotite melting studies. We place diamond powder (40–54 μm) adjacent to peridotite in a capsule. At P and T, partial melt from the peridotite layer collects in the pores between the diamonds and equilibrates diffusively with residual peridotite. Isolated from the peridotite residue, the melt quenches to glass that faithfully records the composition of the liquid coexisting with the residual crystalline phases under the conditions of the experiment. We have used this technique to investigate melting of a fertile mantle composition at 10 and 20 kbar, 1250–1500°C.

Bulk composition, experimental technique and attainment of equilibrium The peridotite composition we used was made of minerals from a Kilbourne Hole spinel lherzolite. The composition approximates estimates of 'primitive' upper mantle: SiO_2, Al_2O_3, FeO^*, MgO, CaO and Na_2O concentrations are 45.5, 4.0, 7.2, 38.3, 3.6 and 0.3 wt%. In 'single-stage' experiments, peridotite and a layer of diamond were sealed in a graphite crucible that in turn was sealed in a Pt capsule and run for 1–98 hr at controlled T and P in a piston-cylinder apparatus. In 'two-stage' experiments, a capsule containing only peridotite was run for $\geqslant 120$ hr at controlled T and P; after quenching, the peridotite plug was extracted from the capsule, reloaded with a layer of diamond in a new capsule, and rerun at the same T and P for $\geqslant 24$ hr.

Melt moves into the pores in the diamond layer on a short time scale ($<$ hr), so it is initially out of equilibrium with the residual peridotite. Consequently, it is necessary to demonstrate that the liquid equilibrates with the residual lherzolite assemblage over the course of the experiment. This is especially important for low T, melt-poor experiments near the solidus, where diffusion in the liquid (especially silica) is slow and the liquid paths from the peridotite to the diamond layer are narrow and tortuous. Although 'single-stage' experiments produce nearly time-invariant liquid compositions after ~ 26 hr, this is not sufficient to demonstrate the achievement of equilibrium. We conducted a pair of reversal experiments, where a final T of 1310°C was approached from both higher and lower T; i.e., a sample was initially held at 1290°C (40 hr) or 1330°C (32 hr) and then T was raised or lowered to 1310°C, and both runs were continued for an additional 73 hr. The liquid compositions from these two experiments bracket the liquid compositions generated in 'single-stage' experiments. Although these reversal experiments indicate that liquids in the diamond layers can 're-equilibrate' over a period of 73 hr, slow diffusion could still limit the approach to equilibrium. In contrast, 'two-stage' experiments minimize problems due to diffusion in the melt because during the lengthy first stage all liquid is in intimate contact with the residual peridotite. A 'two-stage' experiment at 1270°C (first stage – 120 hr; second stage – 32 hr) produced melt that overlaps the melt composition from the 1270°C 'single-stage' experiment at the 1σ level for all oxides (except silica, which is only 0.7 wt% lower than the glass produced in the 'single-stage' run). Results of time series, reversal, and 'two-stage' experiments all indicate that for 10 kbar runs at

1270–1330°C, liquid compositions approach equilibrium closely after 72 hr.

Experimental results at 10 kbar Olivine, orthopyroxene and spinel coexist with melt over the entire investigated T interval (1250–1390°C), while clinopyroxene disappears in the residual peridotite at 1330–1350°C. From 1270 to 1390°C, liquid composition varies from roughly basaltic (~ 10 wt% MgO; melt fraction, F = 0.08) to picritic (~ 16 wt% MgO; F = 0.27). Over this same T interval, TiO_2, Al_2O_3 and Na_2O contents decrease monotonically, while Cr_2O_3, FeO* and MgO contents increase steadily. Overall variation in silica content with T is small (50–51 wt%). CaO shows more complex behavior, first increasing and then decreasing, with the crest in the T–CaO trend approximately coincident with the disappearance of clinopyroxene from the residue. At T below the cpx-out curve, melt generation occurs via the reaction: 0.38 opx + 0.71 cpx + 0.13 sp → 0.22 oliv + 1.0 liq, and the proportions of minerals that enter the melt appear to be nearly independent of T. At T above cpx-out, the less well constrained melting reaction is: 1.06 opx + 0.04 sp → 0.1 oliv + 1 liq. The slope of the T–F curve is not constant, but decreases as T increases from 1270 to 1330°C. Extrapolating the curve back to zero melt suggests that the anhydrous solidus for our peridotite composition is ~ 1240°C.

A 'two-stage' experiment (total duration: 171 hr) at 1250°C produced an unusual glass (estimated F ~ 0.02): SiO_2, TiO_2, Al_2O_3, FeO*, MgO, CaO and Na_2O contents are 56.4, 0.6, 19.8, 4.2, 5.4, 6.6 and 6.0 wt%. More work is needed to confirm that this is an equilibrium near-solidus partial melt. However, if it is, it is the lowest melt fraction yet achieved experimentally and provides important insights into melt compositions in this important near-solidus region. The high SiO_2 value is consistent with the effect of Na_2O on the activity of silica in silicate melt. The low oliv–liq Fe*–Mg exchange coefficient (0.24 ± 0.02; the mean for the higher T experiments is 0.33 ± 0.01) is also consistent with the known effect of alkalis on Fe*–Mg partitioning. Between 1340 and 1270°C, the cpx/liq partition coefficient for TiO_2 is 0.28–0.33; at 1250°C this partition coefficient is 0.5 ± 0.1. This increase in the partition coefficient for Ti between clinopyroxene and liquid has a significant influence on the behaviour of Ti during partial melting in that the TiO_2 content of the liquid remains nearly constant as F decreases from 0.08 (1270°C) to ~ 0.02 (1250°C). Other highly charged elements (e.g. Hf, Zr, Th and U) may exhibit similar behaviour. Thus compared to results of calculations using currently accepted partition coefficients, these trace elements may be less depleted in the MORB source region during initial stages of fractional polybaric fusion.

Preliminary results at 20 kbar Olivine and orthopyroxene coexist with melt over the entire investigated T interval (1400–1500°C); spinel and clinopyroxene disappear in the residual peridotite at 1420–1440°C and 1440–1480°C, respectively. The 1400–1500°C partial melts are enriched in normative olivine relative to the 10 kbar experimental liquids and display systematic oxide trends with increasing T: SiO_2, Cr_2O_3, MgO increase in the liquid while TiO_2, Al_2O_3 and Na_2O decrease. Compared to the 10 kbar trends, SiO_2 and Al_2O_3 are lower in the 20 kbar glasses, while FeO* and MgO contents are higher; the CaO trend is only slightly concave-downward, probably reflecting a drop in the CaO content of the residual clinopyroxenes.

Conclusions The diamond technique is well-suited for characterizing the melting of peridotite. Experiments within ~ 10°C of the 10 kbar peridotite solidus produce Si-, Al- and Na-rich liquids; these unusual liquid compositions may strongly affect mineral/melt partition coefficients for some trace elements. Hirschmann *et al.* (1994) predicted similar liquid compositions from independent thermodynamic calculations. Finally, the compositions of our 10 kbar partial melts and those of Hirose and Kushiro (1993) show that when the bulk Mg/(Mg + Fe*) of the experimental system is limited to ratios $\geqslant 0.89$ (the generally accepted lower limit for primitive mantle), the liquids have FeO* contents that are lower than those measured in primitive MORB glasses. This observation is further evidence that primitive MORBs are not simple low-pressure partial melts, but involve a component of higher pressure partial melting.

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