Melting behaviour of mantle peridotites and compositional variations of partial melts at high pressures

I. Kushiro   *Geological Institute, University of Tokyo, Hongo, Tokyo 113, Japan.*

Introduction

Determination of composition of melts formed by partial melting of peridotite at high pressures is important for understanding genesis of magmas in the upper mantle; however, the previous experimental studies had more or less shortcoming in the method and the results were not always satisfactory. Recently, a new method which seems to have less shortcoming than the previous methods was developed independently by two groups. In the new method, aggregates of diamond grains are placed on top of or between peridotite layers. Upon heating partial melts formed in the peridotite layers segregate into pore space between diamond grains, and after quencheing they can be analysed without quench problem (Johnson and Kushiro, 1992; Kushiro and Hirose, 1992, Baker *et al.*, 1992; Hirose and Kushiro, 1993, Baker and Stolper, 1993). In the present studies, this method is applied to (1) equilibrium partial melting of a relatively fertile mantle peridotite, (2) stepwise fractional melting of the peridotite, and (3) melt segregation from the peridotite. The compositional variations of melts formed by these processes are determined.

Experimental methods

The starting material is a garnet-lherzolite (PHN1611) from Thaba Patsoa kimberlite in Lesotho (Nixon and Boyd, 1973), which was ground to <10μm in size. It has a Mg# of 0.87 and contains 0.14 wt.% K_2O. A small chip (200–500μm across) of loosely sintered diamond grains (40–60μm in diameter) is placed in the peridotite powder which is packed in a graphite capsule. It is important to reduce the pore space between diamond grains to get equilibrium melts. The pore space can be significantly reduced with a small chip of loosely sintered diamond grains. In the melt segregation experiments, however, larger amounts of diamond grains (30–40μm) were directly packed on top of peridotite powder. The charges were heated at 1000°C at 10–14 atm f_{O_2} for about 1 hour before they were sealed in Pt capsules. All the experiments were made with a piston-cylinder apparatus. The run durations were 24–48 hours at 1300–1400°C and 30–72 hours at 1200–1300°C. After quenching, the charges were polished with diamond discs with several different grain sizes and finally with 1 μm diamond powder. Analyses of glass and crystalline phases were made with a JEOL scanning electron microscope with Link EDS systems.

Results and discussion

Equilibrium partial melting. The compositions of partial melts were determined in the pressure range between 5 and 30 kbar. The melt fraction (F) was estimated from the K_2O content in quenched melts assuming that K_2O is completely partitioned into melt. Fig. 1 shows the changes of melt fraction as a function of pressure and temperature. At pressures between 5 and 15 kbar, the isobaric melt fraction-temperature curve has an inflection at about 20 wt.% melt fraction, where Ca-rich clinopyroxene disappears. The solidus is less steep at pressures lower than about 10 kbar. Because of these two effects, a relatively flat surface is formed at melt fractions less than 20 % and at pressures lower than about 10 kbar in the P-T-F space. Presence of this flat surface indicates that melt fractions up to about 20 % are formed with a small increase in temperature at pressures lower than about 10 kbar. The compositional changes of partial melts were determined as a function of melt fraction and pressure. MgO, FeO and Cr_2O_3 increase almost linearly with increasing melt fraction, whereas Al_2O_3, Na_2O and TiO_2 decrease also monotonically with increasing melt fraction from 5 to 35 %. The variations of SiO_2 and CaO have a maximum and a minimum, respectively at about 20 % melt fraction. With increasing pressure, SiO_2 and Al_2O_3 decrease, whereas MgO and FeO increase when melts with the same melt fractions are compared. Effect of pressure is insignificant for CaO, TiO_2, Na_2O and Cr_2O_3. The compositions of partial melts are olivine tholeiitic for 10–25 % melt fractions at 10–20 kbar, alkali basaltic for melt fractions <10 % at >15 kbar, and picritic for >25% melt
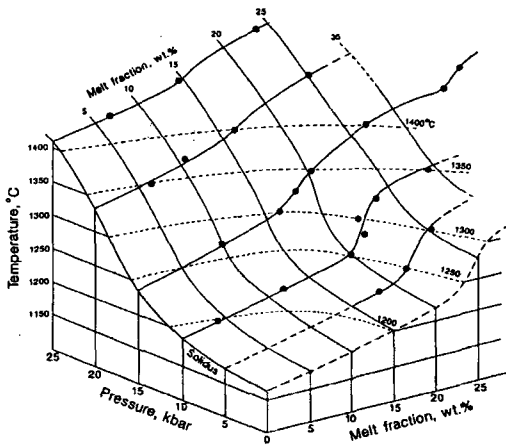
FIG. 1.

fractions at < 20 kbar and for > 14% melt fractions at > 25 kbar. Primary MORB-like melts are formed at 10 kbar in the temperature range between 1225 and 1275°C and for melt fractions between 10 and 20 % (within the flat surface in the P-T-F space in Fig. 1), although the melt compositions are not exactly the same as those of primitive MORB. It should be noted that the extent of melting to produce MORB magmas was suggested to be up to about 20 % (e.g., Klein and Langmuir, 1987). The compositions of partial melts formed from two different spinel lherzolites (Mg# 0.90 and 0.95) at 10 kbar are very close in major element compositions to those formed from the PHN1611 except for the Fe/Mg ratios (Kushiro, 1993, 1994).

Stepwise fractional melting (incremental batch melting) Four-step fractional melting was performed at 15 kbar (Hirose, 1994). The first step is an equilibrium partial melting at 1275°C on the PHN1611 peridotite described above, which produced 9.8 wt.% melt. The second step melting was made at 1350°C on the composition of crystalline residue after complete removal of melt formed in the first step melting. It produced 3.9 % melt. The starting material was a gel of this composition with addition of 0.1 wt.% K_2O, which was crystallized just below the solidus before the run. The third and fourth steps were made at 1400 and 1425°C on the compositions of the residues after removal of melts in the second and third steps, respectively. The total degree of melting (accumulated melt fractions) up to temperature T_i by the stepwise fractional melting is significantly lower than that formed by equilibrium partial melting at T_i (e.g., 13.3% and 20.3%, respectively when T_i = 1350°C). The compositions of fractional melts, determined with

the diamond aggregate method, change more rapidly with increasing temperature than those of equilibrium partial melts. For example, Al_2O_3 decreases from 17.7 to 7.8 % (wt.) and MgO increases from 8.9 to 15.7 % in fractional melts compared to 17.7 to 14.3 % and 8.9 to 12.0 % respectively in equilibrium partial melt, when the total degree of melting is 20 wt.%. The accumulated compositions of fractional melts are, however, similar to those of equilibrium partial melts formed by the same total degree of melting. Although only four steps of fractional melting were examined in this study, the results are qualitatively applicable to fractional melting of mantle perido-tites in general. The facrtional melting produces smaller amounts of melt than the equilibrium batch partial melting in the upper mantle so far as the thermal structures are the same.

Melt segregation. Melt segregation experiments were made at pressures between 5 and 15 kbar using larger amounts of diamond aggregates. The ratio of diamond to peridotite ranges from 2:1 to 3:1. In the runs longer than 5 hours complete separation of melt from peridoite and recrystalli-zation of olivine and pyroxene was observed. Because of the existence of a pressure gradient druing the runs, melts formed are higher in SiO_2 and MgO than the equilibrium melts. The crystalline residues show slight compositional variations; MgO increases whereas SiO_2 decreases (both by about 1 wt.%) or olivine/pyroxene ratio increases from the bottom of the peridotite layer toward the diamond layer. The experiments suggest that complete melt withdrawal from partially molten peridotite is possible and that the compositional changes of residues would occur during the segregation and migration of melts in the upper mantle.

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