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Experimental constraints on melting temperatures in the MgO–SiO_2 system at lower mantle pressures

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ABSTRACT

Eutectic melting curves in the system MgO–SiO_2 have been experimentally determined at lower mantle pressures using laser-heated diamond anvil cell (LH-DAC) techniques. We investigated eutectic melting of bridgmanite plus periclase in the MgO–$MgSiO_3$ binary, and melting of bridgmanite plus stishovite in the $MgSiO_3$–SiO_2 binary, as analogues for natural peridotite and basalt, respectively. The melting curve of model basalt occurs at lower temperatures, has a shallower dT/dP slope and slightly less curvature than the model peridotitic melting curve. Overall, melting temperatures detected in this study are in good agreement with previous experiments and *ab initio* simulations at ~25 GPa (Liebske and Frost, 2012; de Koker et al., 2013). However, at higher pressures the measured eutectic melting curves are systematically lower in temperature than curves extrapolated on the basis of thermodynamic modelling of low-pressure experimental data, and those calculated from atomistic simulations. We find that our data are inconsistent with previously computed melting temperatures and melt thermodynamic properties of the SiO_2 endmember, and indicate a maximum in short-range ordering in MgO–SiO_2 melts close to Mg_2SiO_4 composition. The curvature of the model peridotite eutectic relative to an $MgSiO_3$ melt adiabat indicates that crystallization in a global magma ocean would begin at ~100 GPa rather than at the bottom of the mantle, allowing for an early basal melt layer. The model peridotite melting curve lies ~500 K above the mantle geotherm at the core–mantle boundary, indicating that it will not be molten unless the addition of other components reduces the solidus sufficiently. The model basalt melting curve intersects the geotherm at the base of the mantle, and partial melting of subducted oceanic crust is expected.

1. Introduction

Seismic velocity and density profiles of Earth's lower mantle as depicted in 1-D radially averaged models (Dziewonski and Anderson, 1981) are generally consistent with a peridotitic bulk composition. However, the exact proportions of the primary mineral phases, bridgmanite, ferropericlase, Ca-perovskite and possibly stishovite, are not yet uniquely constrained, and it is not known if the upper and lower mantle are compositionally similar, or if the lower mantle composition has a higher Si/Mg ratio due to a more chondritic primitive composition (e.g. Murakami et al., 2012) or through accumulation of mafic material via subduction. Seismology also reveals the presence of both small (e.g. Helffrich, 2006) and large-scale velocity anomalies (e.g. Garnero and McNamara, 2008) in the lower mantle. Large-scale features include two antipodal large low shear wave velocity provinces (LLSVP), as well as the more localized ultra-low velocity zones (ULVZ; Garnero and McNamara, 2008; Lay et al., 2008) just above the core–mantle boundary (CMB). Depending on their origin and mineralogical constitution, these structures may exert a strong control on the distribution and magnitude of heat flow at the CMB and, therefore, on the convective dynamics and evolution of the Earth (e.g. Nakagawa and Tackley, 2008; Torsvik et al., 2016).

One possible explanation for large-scale features in the deep lower mantle is mineralogical layering inherited from solidification of a deep global magma ocean during the earliest part of the

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Hadean Eon. Although geochemical arguments strongly preclude large-scale fractionation, segregation of bridgmanite-rich domains constituting up to ~15% of the lower mantle remain plausible (e.g. Walter et al., 2004; Liebske et al., 2005). Another possible mechanism is the continued accretion of subducted oceanic crust at the base of the mantle, and the potential for melting of that material at the CMB (e.g. McNamara and Zhong, 2005). Testing these possibilities requires a detailed knowledge of the melting behaviour of mantle materials at the extreme conditions of the lower mantle.

Recent experiments on natural peridotitic and basaltic compositions (Fiquet et al., 2010; Andrault et al., 2011; Nomura et al., 2014; Andrault et al., 2014; Pradhan et al., 2015) yield a range of solidus and liquidus temperatures at lower mantle pressures, and it is difficult to discriminate between the effects of bulk composition, the presence or absence of volatiles in starting materials, and the different melting criteria and detection techniques used to establish the melting curves. In this study, we focus on eutectic melting in the system MgO–SiO_2 in order to eliminate the complexity inherent in natural multi-component systems. The MgO–SiO_2 system describes ~95% of the mineralogy of peridotite and ~70% of basalt at lower mantle conditions. Importantly, because melting is eutectic, compositions can be chosen that produce large amounts of melt at an invariant melting temperature, facilitating greatly our ability to detect melting in experiments at extreme pressures and temperatures.

1.1. Previous work in the system MgO–SiO_2 at lower mantle pressures

Eutectic melting in the MgO–$MgSiO_3$ binary has been studied experimentally using the multi-anvil apparatus up to pressures of 26 GPa (Gasparik, 1990; Presnall et al., 1998; Liebske and Frost, 2012). There is good agreement between these studies that the bridgmanite + periclase = melt eutectic is located at ~2775 K at 25 GPa, and that the eutectic liquid becomes progressively enriched in MgO with increasing pressure. Liebske and Frost (2012) presented a thermodynamic model for eutectic melting in this system, and based on extrapolation predicted that the eutectic liquid composition becomes richer in MgO up to about 80 GPa (from ~57 mol% at 24 GPa to ~60 mol% at 80 GPa), at which point it maintains a nearly constant Mg/Si ratio that is close to model bulk silicate earth (BSE). Atomistic simulations in the MgO–SiO_2 system by de Koker et al. (2013) show a similar increase in MgO content from 58 to 60 mol% for the bridgmanite + periclase eutectic liquid throughout the lower mantle pressure range (25–135 GPa). These authors also simulated melting in the $MgSiO_3$–SiO_2 binary, and found a reduction in the MgO content of the bridgmanite + stishovite eutectic liquid from 37 to 33 mol% over the same pressure range; the silica phase is either stishovite or modified stishovite in the $CaCl_2$ crystal structure (referred to as stishovite from here onwards).

No previous experimental studies have investigated eutectic melting in the MgO–SiO_2 system throughout the lower mantle pressure range. The melting curves of the unary compounds MgO, $MgSiO_3$ and SiO_2 have been investigated in the laser-heated diamond anvil cell (LH-DAC) at pressures between ~30 and 60 GPa (e.g. Shen and Lazor, 1995), and results from these studies are in broad agreement with corresponding melting curves calculated from atomistic simulations (Stixrude and Karki, 2005; de Koker and Stixrude, 2009; de Koker et al., 2013). The experimentally derived melting curve of bridgmanite (Zerr and Boehler, 1993 and Shen and Lazor, 1995), however, maintains a considerably higher dT/dP slope and less curvature than the computationally derived curve (de Koker and Stixrude, 2009 and Di Paola and Brodholt, 2016) through the 24–60 GPa pressure range.

In this study we performed double-sided laser-heated diamond-anvil cell experiments to constrain eutectic melting temperatures in the MgO–SiO_2 binary system up to 110 GPa. The two eutectics in the MgO–SiO_2 system are considered model analogues for the melting of the natural lower mantle candidate lithologies, peridotite and basalt, respectively.

Table 1
Experimental starting compositions (in mol%).

Starting mixtures	SiO_2	MgO	Components[a]
$M_{58}S_{42}$	42	58	En + Fo
$M_{40}S_{60}$	60	40	En + SiO_2
$M_{35}S_{65}$	65	35	En + SiO_2

[a] En: enstatite glass ($MgSiO_3$), Fo: crystalline forsterite (Mg_2SiO_4), SiO_2: silica glass.

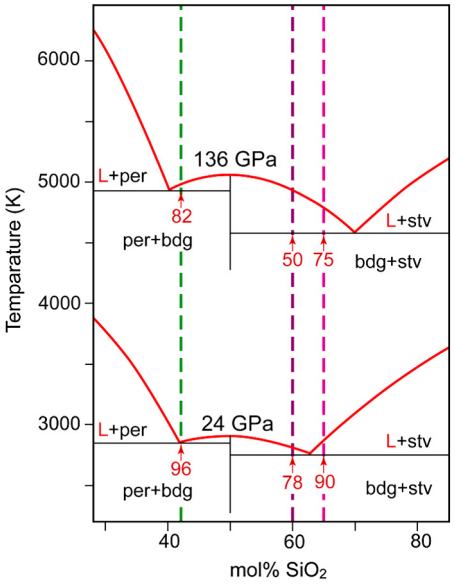

Fig. 1. Liquidus phase relations in the MgO–SiO_2 system at 24 and 136 GPa, adopted from de Koker et al. (2013). The initial fractions of eutectic melt (in percent) for the bulk starting compositions at 42, 60 and 65 mol% silica are calculated by the lever rule and shown beneath the red arrows representing the three starting compositions. bdg = bridgmanite, per = periclase, stv = stishovite and L = liquid. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

2. Experimental and analytical methods

2.1. Starting compositions

The compositions of the starting materials used in this study are listed in Table 1. In selecting starting compositions we aimed to be close to the eutectic melt composition in both the MgO–$MgSiO_3$ and $MgSiO_3$–SiO_2 binary systems, as predicted in the studies of Liebske and Frost (2012) and de Koker et al. (2013). In the MgO–$MgSiO_3$ system we chose a composition with 58 mol% MgO, whereas in the $MgSiO_3$–SiO_2 system we chose two mixes, one with 40 mol% MgO and the other with 35 mol% MgO.

Fig. 1 shows our starting compositions relative to the predicted eutectic compositions derived from the atomistic computations of de Koker et al. (2013), and by applying the lever rule we calculate that our near-eutectic starting materials should yield from ~50% to 95% melt at lower mantle pressures. Producing such a large liquid fraction upon melting aids considerably in melt detection during laser heating and therefore enables higher precision on eutectic temperature assessment.

The MgO–$MgSiO_3$ binary composition was made by mixing enstatite glass with crystalline forsterite in the desired proportions, followed by grinding in an agate mortar under ethanol to a powder with a grain size of ~1 μm. Enstatite glass was made from a