The effect of trace elements on the olivine-wadsleyite transformation

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ABSTRACT

Multianvil experiments were conducted at 1400 to 1600 °C on olivine and peridotite starting compositions to determine the partitioning of Ti, Al, Cr, Ni, Ca, and Na between coexisting olivine and wadsleyite. All of these elements occur as minor amounts in mantle olivine. Our experiments indicate that all, except Ca, partition preferentially into wadsleyite relative to olivine. The order of preference for wadsleyite is Ni, Na, Cr, Ti, and Al, with $D_w^\text{avd}$ of about 2 for Ni, 3 for Na, and between 5 and 8 for Cr, Ti, and Al. We observe a strong negative correlation between the Si and Cr (+Al) contents of wadsleyite, indicating a coupled substitution of 2Cr for 1Mg + 1Si. Modeling the influence of the trace elements on the olivine-wadsleyite transformation in the mantle indicates broadening effects on the order of 1–3 km, much smaller than that predicted to arise from mantle concentrations of H₂O. Therefore, effects of these trace elements on the properties of the 410 km seismic discontinuity are considered negligible. The maximum solubility of TiO₂ in wadsleyite (about 0.6%) is consistent with the suggestion that olivines containing about 1 vol% FeTiO₃ could be inverted wadsleyite.

INTRODUCTION

The 410 km seismic discontinuity, which marks the beginning of the mantle transition zone, is generally attributed to the transformation of olivine, the upper mantle’s most abundant mineral, to wadsleyite [β-(Mg,Fe)₂SiO₄]. Seismological observations indicate that the discontinuity is narrow, frequently less than 10 km wide, and locally as narrow as 4 km (Benz and Vidale 1993; Yamazaki and Hirahara 1994). In contrast, phase diagrams for the Mg₂SiO₄-Fe₂SiO₄ system tend to suggest a broader transition interval and that olivine of mantle composition with Mg/(Mg₁Fe) ≈ 0.9 would transform to wadsleyite through a binary loop of 10–20 km width (Katsura and Ito 1989; Akaogi et al. 1989). The width of the two-phase loop is important because it is sensitive to both temperature (Bina and Helffrich 1994) and composition (Wood 1995) and therefore provides the potential for seismological data to constrain the thermal state and composition of the mantle. However, several sources of error exist that need to be addressed. One of these is the effect of garnet and pyroxene in mantle peridotite. These two phases tend to narrow the olivine-wadsleyite loop by buffering the Mg/Fe ratios of the coexisting (Mg,Fe)₂SiO₄ minerals (Stixrude 1997). The phase diagram for the Mg₃SiO₄-Fe₂SiO₄ system is itself subject to uncertainty in pressure and composition and Helffrich and Wood (1996) have shown that, taking account of these uncertainties, the Mg₃SiO₄-Fe₂SiO₄-loop could be as narrow as 4 km for mantle olivine at a reasonable temperature for the 410 km seismic discontinuity of 1773 K. Finally, the chemical complexity of the mantle, relative to experimentally studied compositions may, as discussed below, broaden the transformation interval.

To date, virtually all comparisons of the olivine-wadsleyite transition interval with seismological data have used the simple Mg₂SiO₄-Fe₂SiO₄ system as a model. In the mantle, however, significant concentrations of minor elements, such as Ni, Cr, Al, and H, exist that could alter the stabilities of the two phases relative to the simple system and hence affect the depth and thickness of the 410 km discontinuity (Wood 1995; Wood et al. 1996). Wood (1995) argued that a trace element that is preferentially incorporated into wadsleyite would tend to stabilize this phase to lower pressure and would broaden the olivine-wadsleyite transformation interval. Conversely, if a trace element prefers olivine to wadsleyite, it would tend to expand the stability field of olivine to higher pressure. Water is one component that could have a particularly dramatic effect on the phase transformation. Water dissolves readily into wadsleyite by protonation of the O(1) atom and production of an Mg vacancy, as well as by population of the bridging O and other sites (Smyth 1987; Downs 1989; Young et al. 1983). Furthermore, measured partitioning between wadsleyite and olivine indicates that H₂O prefers the former by a ratio of about 20:1 (Kohlstedt et al. 1996). Assuming disorder of the point defects, as little as 500 ppm by weight of H₂O in the mantle could widen the olivine-wadsleyite transition interval by 15 km (Wood 1995). Other minor components, which are even more abundant than H₂O in the