Chromium-bearing phases in the Earth’s mantle: Evidence from experiments in the Mg$_2$SiO$_4$–MgCr$_2$O$_4$ system at 10–24 GPa and 1600 °C

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ABSTRACT

Phase relations in the system Mg$_2$SiO$_4$–MgCr$_2$O$_4$ were studied at 10–24 GPa and 1600 °C using a high-pressure Kawai-type multi-anvil apparatus. We investigated the full range of starting compositions for the forsterite-magnesiocromite system to derive a P–X phase diagram and synthesize chromium-bearing phases, such as garnet, wadsleyite, ringwoodite, and bridgmanite of a wide compositional range. Samples synthesized at 10 GPa contain olivine with small chromium content and magnesiochromite. Mg$_2$SiO$_4$ wadsleyite is characterized by the pressure-dependent higher chromium solubility (up to 7.4 wt% Cr$_2$O$_3$). The maximal solubility of chromium in ringwoodite in the studied system (~18.5 wt% Cr$_2$O$_3$) was detected at P = 23 GPa, which is close to the upper boundary of the ringwoodite stability. Addition of chromium to the system moves the boundaries of olivine/wadsleyite and wadsleyite/ringwoodite phase transformations to lower pressures. Our experiments simulate Cr-rich phase assemblages found as inclusions in diamonds, mantle xenoliths, and UHP podiform chromitites.

Keywords: Magnesiocromite, forsterite, olivine, wadsleyite, ringwoodite, knooringite, majorite, bridgmanite, mantle, high-P-T experiments, phase relations

INTRODUCTION

The Earth’s upper mantle consists of olivine (~60 vol%), ortho-, clinopyroxenes, spinel, and garnet (Ringwood 1966; Harte 2010; Pushcharovsky and Pushcharovsky 2012). The phases of the transition zone include wadsleyite/ringwoodite and majoritic garnet. At higher pressures (corresponding to the lower mantle), the ringwoodite-bearing assemblage converts into a bridgmanite + ferropericlase association with a minor amount of CaSiO$_3$ perovskite (Liu 1976; Ito and Takahashi 1989). Some of these phases are observed as inclusions in natural diamonds (Harte 2010). Mantle minerals show variable concentrations of minor elements. Although the solubility of minor elements in high-pressure phases is poorly studied, it is known that even small concentrations of these elements may significantly influence the physical properties as well as the crystal-chemical peculiarities of mantle phases and control the physicochemical parameters of the main phase equilibria (Panero et al. 2006; Andrault 2007; Sirotkina et al. 2015).

Chromium one of such elements with the low bulk concentrations in the Earth’s mantle (0.42 wt% Cr$_2$O$_3$) (Ringwood 1966), although some mantle phases (garnet, chrome spinel, etc.) are characterized by significant Cr contents (Stachel and Harris 1997; Harte et al. 1999). The studies of phase equilibria in multicomponent mantle systems (pyrolyte and peridotites) (Hirose 2002; Irifune 1987; Irifune and Ringwood 1987) provide only limited information on interphase partitioning of chromium, which is mostly explained by its very low concentrations in starting compositions.

The highest Cr concentrations have been documented in such mantle phases as chrome spinel (Meyer and Boyd 1972; Sobolev 1974). Magnesiocromite (MgCr$_2$O$_4$) is an important end-member of chrome spinel in mantle peridotites (Fig. 1). Its concentration in chrome spinel from inclusions in diamonds and xenoliths of Grt-peridotite reaches 95 and 85 mol% (63–68 wt% and 57–63 wt% Cr$_2$O$_3$), respectively (Meyer and Boyd 1972; Sobolev 1974). The lowest chromium content (25–38 wt% Cr$_2$O$_3$) is typical of spinel from Sp-peridotite xenoliths in kimberlite and alkali basalt. Chrome spinel from ophiolites occupies an intermediate position between the Grt- and Sp-peridotite xenoliths. There is a clear positive correlation between chromium content in Cr-spinel from peridotites and both the degree of partial melting and pressure (Dick and Bullen 1984).

Although the concentrations of Cr in (Mg,Fe)$_2$SiO$_4$ polymorphs and bridgmanite are low, abundance of these phases in the mantle allows us to consider them as the major hosts for chromium. Mantle olivine in association with chromite contains an exceptionally high content of chromium (up to 1.10 wt% Cr$_2$O$_3$) (Phillips et al. 2004). More Cr-rich phases (1.49 wt% Cr$_2$O$_3$) with the composition of olivine were identified in UHP podiform chromatites of the Luobusa ophiolite, Southern Tibet (Robinson et al. 2004; Liang et al. 2014); such phases could be originally ringwoodite, then transformed to a Mg-Fe silicate with an octahedral shape.

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