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Physics of the Earth and Planetary Interiors 156 (2006) 89–107

PHYSICS
OF THE EARTH
AND PLANETARY
INTERIORS

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Internally consistent thermodynamic data set for dense hydrous magnesium silicates up to 35 GPa, 1600 °C: Implications for water circulation in the Earth's deep mantle

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Received 8 August 2005; received in revised form 20 November 2005; accepted 3 February 2006

Abstract

Fluid-undersaturated high-pressure experiments were carried out in the system MgO–SiO_2–H_2O in a multi-anvil apparatus from 15.5 to 21.5 GPa and from 1000 to 1200 °C in order to constrain fluid-absent solid–solid reactions. From the experimentally determined fluid-absent phase equilibria, thermodynamic parameters for high-pressure hydrous phases were retrieved by a linear programming method. Together with dry mantle minerals from the existing data set and high-pressure hydrous phases from our previous study, an internally consistent set of thermochemical and thermophysical parameters for dense hydrous magnesium silicates (DHMSs) was evaluated up to 35 GPa and 1600 °C. High-pressure hydrous phases involved in the data set are, phase A, phase E, clinohumite, phase D, superhydrous phase B, hydrous wadsleyite, and hydrous ringwoodite. In addition, by calculating water-bearing reactions, we evaluated water activities in the fluid phase coexisting with mantle minerals. The water activity decreases with increasing pressure or temperature, suggesting that the amount of silicate component dissolved in the fluid phase increases with pressure or temperature. The calculated petrogenetic grid consisting of 89 univariant reactions can be used for the discussion of water circulations in the mantle. In a subducting slab peridotite, water in phase A as the post-serpentine phase is transferred to other DHMSs via solid–solid reactions down to the bottom of the transition zone. At around 660-km depth, in the stagnant slab heated from the surrounding mantle, a free fluid will be released by the dehydration of superhydrous phase B or phase D. The released fluid will be trapped by wadsleyite or ringwoodite in the surrounding mantle. In a cold subducting slab without stagnation at 660-km depth, DHMSs will survive into the lower mantle. In an upwelling plume through the water-bearing transition zone, a free fluid will be produced when the plume passes 410-km depth. Finally, water will be released to the Earth's surface by magmatism. The fluid generated in the deep mantle dissolves significant amounts of a silicate component. Therefore, at 410- and 660-km depths, some chemical differentiation will be processed.

Keywords: High pressure; Hydrous phase; Thermodynamic data; Water circulation

1. Introduction

Phase relations in the mantle systems are one of the fundamental data sets for understanding the Earth's dynamics. The phase relations in the system MgO–SiO_2–H_2O (MSH) have been studied for over 40 years, because this system can be a first-order approximation of a hydrous peridotite, which is one of the most fundamental, and therefore, important systems in the mantle. In the hydrous peridotite system, at lower temperatures below 1400 °C, dense hydrous magnesium silicates (DHMSs) and hydrous polymorphs of olivine,

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0031-9201/$ – see front matter
doi:10.1016/j.pepi.2006.02.002

which are hydrous wadsleyite and hydrous ringwoodite, occur at pressures beyond serpentine or chlorite stability (e.g., Liu, 1987; Gasparik, 1993; Irifune et al., 1998a; Shieh et al., 1998; Frost, 1999; Ohtani et al., 2000; Stalder and Ulmer, 2001; Bromiley and Pawley, 2002; Iwamori, 2004; Komabayashi et al., 2004, 2005a,b). Thus, the phase relations at lower temperatures in the system have been discussed in relation to the water transport process in subduction zones.

The phase relations in the dry peridotite system (e.g., the system MgO–SiO_2) have been studied by both high-pressure experiments and thermodynamics. In the past decade, they have been well described by the internally consistent thermodynamic data base up to 30 GPa which is sometimes updated (e.g., Saxena et al., 1993; Fabrichnaya et al., 2004).

However, the phase relations in the system MSH, in particular, the stability relations of high-pressure hydrous phases above 10 GPa, have been mostly studied by empirical experimental studies (Irifune et al., 1998a; Ohtani et al., 2000, 2001). This might be because quite complicated phase relations are encountered even in the simple ternary system MSH. Komabayashi et al. (2004) made an attempt to elucidate the phase relations in the system MSH by performing Schreinemakers analysis on the existing experimental data up to 30 GPa, 1600 °C. They showed one possible sequence of phase changes by constructing a petrogenetic grid with chemographic consistency. According to Komabayashi et al. (2004, 2005b), high-pressure hydrous phases which occur in the peridotite system (i.e., Mg/Si ratio of ∼1.4), are phase A (phA), clinohumite (cHu), phase E (phE), phase D (phD), superhydrous phase B (shB), hydrous wadsleyite (hy-Wad), and hydrous ringwoodite (hy-Rin). In our recent study we tried to make an internally consistent thermodynamic data set including phA, cHu, phE, and hy-Wad, compatible with dry mantle minerals under deep upper mantle conditions (∼15 GPa) (Komabayashi et al., 2005b).

In the present study, we have included the remainder hydrous phases that appear at higher pressures: superhydrous phase B, hydrous ringwoodite, and phase D. Calculating phase relations for these phases, we will demonstrate a quantitative petrogenetic grid in the system MSH up to 35 GPa, 1600 °C, corresponding to the middle part of the lower mantle. In addition, we have estimated the water activity of a fluid phase under deep mantle conditions. On the basis of the calculated phase equilibria, water circulation in the mantle will be discussed. In addition to the above hydrous phases, the following mantle phases were encountered in this study; forsterite (Fo), dry wadsleyite (dry-Wad), dry ringwoodite (dry-Rin), high-pressure clinoenstatite (En), akimotoite (Aki), magnesium-perovskite (Pv), periclase (Pc), stishovite (St), brucite (Br), and fluid (Fl). Note that enstatite in this study is high-pressure clinoenstatite that is stable above 5 GPa and unquenchable at ambient conditions (Fabrichnaya et al., 2004). The compositions of these phases are illustrated in Fig. 1.

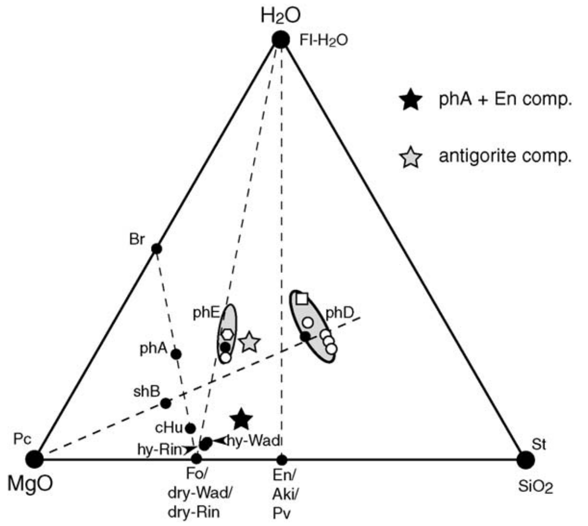

Fig. 1. Chemography of the system MgO–SiO_2–H_2O. Bulk compositions in the present experiments are shown by stars. A solid circle denotes the composition of the phase listed in Table 3 and used for the thermodynamic calculations. A white circle denotes the composition of the phase in the present experiments listed in Table 2. The hexagonal for phase E is from Shieh et al. (2000), and the square for phase D is from Ohtani et al. (2003). Grey shows the compositional range reported by Frost (1999). Phases are: phA, phase A; phE, phase E; phD, phase D; shB, superhydrous phase B; cHu, clinohumite; Br, brucite; hy-Wad, hydrous wadsleyite; hy-Rin, hydrous ringwoodite; Pc, periclase; Fo, forsterite; dry-Wad, dry wadsleyite; dry-Rin, dry ringwoodite; En, high-pressure clinoenstatite; Aki, akimotoite; Pv, magnesium-perovskite; St, stishovite; Fl-H_2O, fluid-H_2O. Note that the composition of the fluid phase at higher P–T conditions is not pure H_2O. See text for details.

2. Method

For retrieving thermodynamic parameters for the high-pressure hydrous phases, the basic strategy taken in this study is same as that in Komabayashi et al. (2005b), briefly described as follows. First we make high-pressure experiments under fluid-undersaturated conditions in order to constrain fluid-absent phase relations. Next, we retrieve thermodynamic parameters of standard enthalpy of formation and standard entropy of the phases by using a linear programming method on the fluid-absent phase relations constrained by the experiments. In the construction of a thermodynamic model, we accepted