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The impact of carbon on element distribution during core formation

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Abstract—The distribution of Fe, Ni, Co, P, Ge, W, Mo, and O between molten silicate and liquid metal was determined at pressures and temperatures relevant to core formation (50–80 kb, 2000–2300°C) under both carbon-free and graphite-saturated conditions. The effect of carbon is very pronounced in reducing the siderophile tendencies of P and Ge. Germanium showed a significant reduction in metal-silicate partition coefficients ($D^{\text{met/sil}}$) from a value too high to be determined by the electron microprobe in the carbon-free metal/ultrabasic silicate system down to a value of ~ 33 in the carbon-bearing metal/ultrabasic silicate system. Phosphorus becomes lithophile at carbon saturation. Nickel and cobalt show a modest reduction, and W and Mo show a modest increase in siderophility at graphite saturation. These effects are seen both in basic, aluminous, and ultrabasic, magnesian silicate liquids. Carbon-bearing liquids, in combination with their sulfurous cousins, would be less effective at depleting silicate liquids in many siderophile elements than C- and S-free liquids. Limits upon any geochemical role for carbon in the core forming process, however, are provided by P which becomes lithophile at carbon saturation. As P is depleted rather than enriched in the mantle, core formation probably did not occur at carbon saturation. Copyright © 1997 Elsevier Science Ltd

1. INTRODUCTION

Carbon, the fourth most abundant element in the solar system, is an often neglected candidate in the list of plausible light elements in the metallic core of the Earth (e.g., see discussion in Poirier, 1994). In spite of its high cosmochemical abundance, its ability to reduce the melting temperature of iron, and its high solubility in Fe-Ni metal at the pressure-temperature conditions of the outer core, its volatile nature in the cosmochemical condensation scale cast doubt upon its retention in segregating metals. Recently it has been proposed that carbon's volatility is strongly pressure-dependent and that appreciable carbon (up to $\sim 2\text{--}4\text{wt}\%$) can dissolve in molten iron at the pressure and temperature regimes of planetary accretion and differentiation (Wood, 1993). Indeed, the entire inner core has been proposed to be made up of solid iron-carbide (Wood, 1993).

Can carbon have any influence upon element distributions in the core formation event in the Earth? Terrestrial upper mantle abundances of many siderophile (core-loving) elements are 10 to 1000 times higher than those in the other planetary silicates (e.g., lunar basalts; achondritic basalts-ultramafics, probable Martian samples, stony iron meteorites) or the abundances expected from their laboratory-determined, low temperature, atmospheric pressure partition coefficients. A variety of theories like incomplete core segregation (Jones and Drake, 1986), Fe-S-O bearing liquid metal segregation (Brett, 1984), addition of oxidized late chondritic veneer after core segregation (Wanke et al., 1984; Newsom, 1990), equilibrium high temperature-high pressure core segregation (Murthy, 1991; Li and Agee, 1996), etc. have been

proposed to explain this excess abundance. The present study attempts to evaluate any effects carbon may have towards explaining this long-standing excess paradox.

2. EXPERIMENTAL STRATEGY AND ANALYTICAL TECHNIQUES

High temperature-high pressure experiments in a split-cylinder octahedron-in-cube multi-anvil apparatus were performed to investigate this effect (Fig. 1). Both carbon-bearing and carbon-free charges were placed inside identical capsule materials and pressurized with 12 mm truncated-edge-length tungsten carbide cubes around an octahedral pressure medium at a fixed temperature and pressure. In order to maintain similar temperatures, both charges were placed symmetrically on either side of a Type D (W3Re/W25Re) thermocouple, inside a cylindrical lanthanum chromite (LaCrO_3) heater. The thermocouple was inserted through the heater wall in the axio-symmetric position and was electrically insulated from the heater by MgO ceramic sleeves. In order to minimize the effect of estimated temperature gradients ($\sim 40^\circ\text{C}/\text{mm}$) on two sides of the thermocouple, initial lengths of both capsules were kept to a minimum (~ 4 mm). Detailed experimental procedure can be found elsewhere (Walker et al., 1990; Jana and Walker, 1997). Previous experiments with a homogeneous carbon-bearing metal-silicate mixture have created very little quenched area of clean silicate for subsequent analysis by microprobe raster because of strong wetting of dispersed carbon flakes by liquid metal. Metal and silicate components in both charges were, therefore, placed as two separate layers in approximately 1:1 weight ratio. The silicate layers in both charges were placed farther from the thermocouple than the metal layers to reduce thermal migration of the silicate liquid pool towards the central hot zone around the thermocouple. Spectroscopic grade graphite powder (99.9% C) was added as a source of carbon in the metal component of carbon-bearing experiments. In order to obtain statistically detectable peaks in silicate melts, all siderophile elements were added as pure powders at several weight percent levels in the metal layers of each set of experiment.

Quenched run products were sectioned, polished, and analyzed by electron microprobe with the use of a Cameca CAMEBAX instrument and standard wavelength dispersive techniques. Accelerating voltage and beam current used were 20 kV, and 200 nA (for all siderophile elements except iron) and 30 nA (for all lithophile ele-

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