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Formation and thermal evolution of Ceres infered from hydrothermal experiments and mineralogical analyses

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The dwarf planet Ceres is the largest body in the asteroid belt and is frequently referred as one of the few protoplanets remaining in the inner solar system. Ceres' low density and spherical shape indicate that its interior is highly likely differentiated into a rocky core and water-rich ice mantle. Theoretical models of thermal evolution suggest that Ceres possibly underwent significant melting to explain the interior structure. These results further suggest that primitive minerals, such as olivine, would have been hydrothermally altered inside Ceres. The compositions of such secondary minerals may vary according to not only temperature but also the composition of aqueous solution, such as CO_2 abundances. Accordingly, the mineral assemblages on Ceres' surface would provide clues for understanding the timing of formation and chemical compositions of planetesimals that formed Ceres. Recent observations of Ceres suggested the possible presence of brucite, magnesium carbonates, Fe-rich serpentine, and magnetite on the surface. However, it remains unclear the temperature conditions and aqueous compositions that can account for the formation of these minerals.

In this study, we conduct hydrothermal experiments simulating chemical reactions that would have occurred in the interior of Ceres. In particular, we aim at investigating the effects of temperature and the amount of initial CO_2 on mineralogical and chemical compositions of secondary minerals formed from olivine. The experiments were conducted at temperatures of 200, 300, and 400^oC and a pressure of 400 bar. We used powdered San Carlos olivine (Mg/(Mg/Fe)=0.9) as starting materials. Aqueous solution of 0.02% or 0.6% of $NaHCO_3$ (as a source of CO_2) and 1% of NH_3 was also used in the experiments. After the experiments, we collected rock residues and analyzed their mineralogical and chemical compositions using a XRD and SEM-EPMA, respectively.

Our experimental results suggest that temperature dependency of oxidation of Fe(II) to magnetite strongly affects the mineralogical and chemical compositions of secondary minerals. Magnetite formation proceeds efficiently at 300^oC, which diminishes partitioning of Fe(II) into secondary minerals resulting in low Fe/Mg ratios in serpentine. At 200^oC, serpentines with relatively high Fe/Mg ratios and a very small number of magnetite were found in rock residues. These results suggest that oxidation of Fe does not proceed efficiently at 200^oC, leading to partitioning of Fe(II) into secondary minerals during serpentinization. Brucite was found in rock residues formed only at 300^oC. There are few brucite in rock residues formed at 200^oC. Because olivine is thermodynamically stable, any alteration minerals were not formed at 400^oC.

Initial amount of CO_2 also affects the compositions of secondary minerals via carbonate formation. Brucite tends to be abundant under a low CO_2 condition in rock residues, whereas few brucite are formed under a high CO_2 condition. Serpentines with relatively high Fe/Mg ratios were produced under a high CO_2 condition. These results suggest that efficient carbonate formation under a high CO_2 condition prevents from formation of brucite and results in formation of serpentines with relatively high Fe/Mg ratios.

In our experiments, we cannot find a single condition, under which the secondary mineral assemblages found on Ceres' surface are reproduced. Especially, we found that brucite tends to be formed more efficiently under lower CO_2 conditions. In contrast, formation of Fe-rich serpentine prefers lower temperature (~200^oC) and higher CO_2 conditions. These results suggest that Ceres' surface would be compositionally heterogeneous owing to geological activities, such as impact cratering. Our experimental results suggest that formation of brucite requires moderate temperatures, such as 300^oC. To achieve such temperatures, Ceres is required to have been formed at ~200-300 My after the formation of CAIs.

Keywords: hydrothermal reactions, Ceres, early solar system, mineralogical analysis