リュウグウ母天体の水-岩石反応
Water-rock reactions in the parent body of Ryugu

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The recent remote-sensing observation by Hayabusa2 is providing a large amount of data to unravel the origin of Ryugu. The Near Infrared Spectrometer (NIRS3) onboard Haybusa2 revealed that the IR reflectance of the global surface of Ryugu is extremely low (~0.02) and the spectra include small but clear absorption at 2.72 μm. These findings indicate the great abundance of dark materials and the subordinate amount of hydrous minerals in the surface, respectively. These materials on Ryugu are important clues to constrain the conditions of aqueous alteration such as the temperature experienced by the parent body and the original volatile compositions during accretion stage. In this work, we conducted thermodynamic modeling of chondrite-water reactions under various conditions to establish a model explaining the aqueous alteration of the parent body. In the thermodynamic calculations, a mean composition of CV chondrites was assumed for the initial bulk rock (minor amount of carbon, nitrogen and chlorine are also included) (Pearson et al., 2006; Clay et al., 2017). For the initial fluid, four cases were assumed; CO_2 concentration is 0, 1, 3 and 10 mol% (Cases 1–4, respectively) relative to water while the latter three cases also include NH_3 (0.5%) and H_2S (0.5%) additionally (Mumma and Charnley, 2011). The equilibrium temperature and pressure were assumed to be 0, 100, 200, 300 and 350 ˚C, and vapor pressure of water. In the calculations, pyrene was considered as a representative of polycyclic aromatic hydrocarbon while C1 compounds except CH_4 were included as soluble species (Zolotov, 2012).
The calculations showed that stabilities of hydrous/anhydrous minerals, carbonate, pyrene change with temperature and W/R value. In Case 1 (CO_2-free), the altered chondrite consists of serpentine, troilite and subordinate amount of hydrous/anhydrous minerals (e.g., magnetite, saponite, gibbsite and chlorite) at 0–300 ˚C. However, with increasing temperature above 300 ˚C, olivine and clinopyroxene become major phases as the amounts of serpentine, chlorite and magnetite decrease. At 350 ˚C, olivine becomes the most abundant minerals in conjunction with disappearance of serpentine. Similar temperature dependencies of hydrous mineral stabilities were also shown at low W/R in Cases 2–4 (CO_2 =1–10%) whereas carbonate is predominant at high W/R. Although the total amount of hydrous minerals in the surface of Ryugu is still unconfirmed, the calculation results suggest that the temperature of hydrothermal reactions experienced by Ryugu is lower than approximately 300 ˚C if a certain amount of hydrous minerals are present in the surface rocks. In contrast, if the amount of hydrous minerals is relatively small, higher temperatures (>350 ˚C) may account for the observed IR spectra. In this case, the parent body may have undergone high-temperature hydrothermal reactions that could occur in relatively large body. Otherwise, it is also possible that the parent body underwent instantaneous high-temperature events such as impacts after the aqueous alteration.Regarding the discriminating darkness of Ryugu, pyrene and/or magnetite are considered as the abundant dark materials on the surface of Ryugu in the predicted alteration minerals (pyrene is not dark by itself but can be altered to dark organic matter through geologic time). Especially, pyrene can be consolidated through reduction of CO_2in Cases 2–4 because of water-chondrite reactions generate abundant H_2. These solid phases are minor or absent at high W/R where carbonate is predominant but the sum of them exceeds several % at low W/R because

water-chondrite reactions at low W/R generate abundant hydrogen. Therefore, the results indicate that the altered chondrites broadly become darker with decreasing W/R. However, if the water-chondrite reactions start under H_2-rich condition, the CO_2 in the fluid would be effectively reduced to form organic materials (Cases 2–4) even at high W/R, which also potentially contribute the low reflectance of Ryugu.

