Thermal Evolution of Hydrous Minerals on Small Bodies: To Understand Thermal Histories of Ryugu and Bennu

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Asteroid sample return missions JAXA’s Hayabusa2 and NASA’s OSIRIS-REx are currently exploring asteroids Ryugu and Bennu, respectively. Infrared spectroscopic observation done by the near-infrared spectrometer on board Hayabusa2 (NIRS3) suggests that Ryugu has a weak absorption feature of hydrous minerals, while the visible and infrared spectrometer on board OSIRIS-REx (OVIRS) have detected a clear absorption feature of hydrous minerals on the surface of Bennu. These findings indicate that two asteroids experienced different thermal histories, and dehydration of hydrous phases could have occurred more effectively on Ryugu. It is thus important to understand thermal transformation processes of hydrous minerals, but there has been limited kinetic data that can be extrapolated to the processes occurring in the geologic timescale. Therefore, with the aim of understanding thermal metamorphism on Ryugu/Bennu, we conducted heating experiments of serpentine in vacuum.

The starting material of serpentine was ground into powder using an agate mortar and pestle to a particle size of ~1 μm. Samples were heated at 500 - 800°C, for durations of 2 –88 hours in vacuum (10^{-4}–10^{-5} Pa). The analyses were done with XRD (X-ray powder diffraction) at the University of Tokyo and FTIR (Fourier transform infrared spectroscopy) at Hokkaido University. The weight changes of the samples were obtained by weighing them before and after the experiments using an electric balance.

The serpentine samples heated at 500°C were dehydrated with heating, but crystalline serpentine was still dominant in the run products. The samples heated at 600°C decomposed to become amorphous. The XRD spectra of the samples heated at 650℃ show the presence of small and broad peaks of olivine that recrystallized from the amorphous and also a slight halo representing remaining amorphous. The samples heated at 700°C also have small and broad XRD peaks of olivine without the halo feature of amorphous silicate. The XRD spectra of the samples heated at 800°C show the strongest peak of enstatite in addition to the peaks of olivine. FTIR spectra also confirm the above observations.

The FTIR spectra of the samples heated at 650°C and 700°C were analyzed further to obtain the kinetics of crystallization of olivine from dehydrated serpentine. The absorbance ratio of the peaks at 10.4 and 11.4 mm, both of which are characteristic of olivine, was converted into the degree of olivine crystallization based on the results by [1]. The time evolution of crystallization degree at 650 and 700°C were fitted by the Johnson-Mehl-Avrami-Kolmogorov equation with the Avrami exponent of 1.5 [1], and the crystallization rate constant k [$h^{-1.5}$] of 0.032 and 0.34 were obtained at 650 and 700°C, respectively. The estimated activation energy for the crystallization is 356 kJ mol^{-1}.

The TTT (time-temperature-transformation) diagrams for dehydration and recrystallization of serpentine were obtained. The dehydration timescale was adopted from [2]. Considering that the decay of ^{26}Al with a half-life of 0.72 My is a possible heat source within parent bodies of Ryugu and Bennu in the early Solar System, the heating time scale should be shorter than 10 Myr. The diagram indicates that Bennu, with a clear infrared feature of hydrous minerals should not have experienced heating at >350 K on its parent body. Ryugu, with a subtle feature of hydrous minerals may have been heated at >450 K on its parent body. Fujiya et al. (2012) [3] estimated that within a 60-km sized asteroid accreted 3.5 Myr after the Solar System formation, the highest temperature is about 400 –450 K that lasts for 2 –3 Myr at 3 km distance from the center. If this is the case, most part of the asteroid was kept below 350 K, which could be similar to Bennu. In order to dehydrate Ryugu, its parent body may have been larger than 60 km in diameter or may have accreted earlier than 3.5 Myr after the Solar System formation with a more available heat source (^{26}Al).

References: [1] Yamamoto D. and Tachibana S. (2018) ACS Earth Space Chem. 2, 778–786. [2] Yamamoto D. (2016) Master thesis. [3] Fujiya W. et al. (2012) Nat. Commun. 3, 627(6 pp).

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