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Redox environment estimation of Ryugu's parent body by analyzing valence of multiple redox-sensitive elements

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Inside Ryugu's parent body, water ice melting driven by radioactive decay has likely produced an alkaline and reducing aqueous environment through reactions with metallic iron and anhydrous silicates. Because organic matter formed under such conditions may have contributed to the precursors of the building blocks of life on Earth, constraining the redox state (Eh) and pH of the environment is essential for understanding how chemical evolution occurred in an extraterrestrial environment.

To constrain these conditions, powdered, resin-embedded, polished, and bulk samples of Ryugu asteroid returned by the Hayabusa2 mission and the CI chondrite Orgueil were analyzed. All preparation and analyses of resin-embedded Ryugu samples were performed under air-tight conditions to prevent terrestrial oxidation. X-ray Absorption Near Edge Structure (XANES) spectra of Sulfur (S), Chromium (Cr), Vanadium (V) and Iron (Fe) were measured at several synchrotron facilities, from bulk scale to 1 μm spatial resolution. Elemental valences were compared with thermodynamically calculated Eh–pH diagrams. Results from CI chondrite were used to assess terrestrial oxidation effects.

A Cr-enriched region was identified in moderately altered Ryugu sample, where Cr occurred as divalent. SEM-EDS and μ-XRD analyses indicated that Cr(II) is hosted by phyllosilicates formed through aqueous alteration under extremely reducing conditions. Such Cr(II) can be stabilized at relatively low pH (~6) when sufficient H_2 is produced by the dissolution of metallic iron into water. This picture is consistent with previous thermodynamic models of hydrothermal reactions. Vanadium is uniformly distributed as V(III) throughout the Ryugu samples, based on the pre-edge peak analysis of V K-edge XANES. This valence state is more reduced than the V(IV) observed in Orgueil and Bennu samples, providing constraints on the Eh–pH range of Ryugu's aqueous environment in the past.

These results might reflect the evolving aqueous environment during alteration. In the early stage, relatively low pH conditions allowed formation of Cr(II)-rich serpentine with magnetite. As pH increased, V(III)-bearing saponite precipitated. This evolutionary scenario is consistent with numerical hydrothermal models and with mineral formation sequences inferred from Ryugu sample textures.