

SYNCHROTRON BASED TRACE ELEMENT ANALYSES OF A MAGNETITE VEIN CROSS CUTTING A MM-SIZED RYUGU ROCK FRAGMENT

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Introduction: The successful probing, return and curation of asteroid Ryugu provides pristine sample material from the surface and subsurface of this C-type asteroid. The sampled material of the Hayabusa2 mission includes many coarse-grained fragments [1, 2]. In order to obtain the highest level of scientific output the initial study included several non-invasive and non-destructive analytical techniques. Synchrotron X-ray fluorescence computed tomography (SXRF-CT) [e.g. 3] is an ideal non-invasive analytical technique to achieve detailed in depth structural and chemical information and was applied to several mm-sized rock fragments of the asteroid Ryugu from both, surface and sub-surface samples. Here we present the first dataset on coarse grain C0033, collected at the second touchdown site.

Methods: X-ray fluorescence spectroscopy experiments were performed at the P06 beamline of PETRA III (DESY, Hamburg, Germany) and at the ID15A beamline of the ESRF (Grenoble, France). The excitation energy E_0 was 20.5 keV and 90 keV respectively, using Si(111) monochromator optics. The Kirkpatrick-Baez (KB) mirror-based X-ray beam focusing provided a $0.2 \times 0.24 \mu\text{m}^2$ beam spot size at sample position during the P06 experiments, and a $0.5 \times 0.5 \mu\text{m}^2$ beam spot at sample position for the ID15A experiments.

High-Energy SXRF: Every detailed SXRF analysis was started with a chemical 2D overview projection of the full volume of the mm-sized rock fragment. In case of sample C0033 an Fe-rich vein was identified. Several cross-section CT scans were performed during our subsequent study, one exactly at the height where the Fe-rich vein was observed. The cross section indicates the presence of REE-rich phases throughout the vein and confirms the vein-like nature of the Fe-enriched area.

Lower-Energy SXRF: For further studies a polished section ($\sim 100 \mu\text{m}$ thick) of grain C0033 was prepared exactly at the height of the magnetite vein and was then further analysed at lower X-ray energy (20.5 keV) at PETRA III beamline P06. The Fe distribution found confirms the existence of a magnetite-rich vein. Ca and Y element maps indicate the presence of multiple apatite grains closely related to the vein.

Quantification: The SXRF measurements not only provide element distribution maps but can also be quantified. In order to get better statistics small area maps and point analyses were performed. The resulting CI normalized trace element concentrations of magnetite and apatite grains located within the magnetite vein observed in C0033 show values close to CI bulk composition. All quantified measurements were acquired at PETRA III P06 beamline applying a primary beam energy of 20.5 keV.

Discussion and Conclusion: The detailed SXRF study of mm-sized Ryugu rock fragments enabled the identification and localization of unique sample characteristics like the magnetite-apatite vein found in grain C0033. Veins crosscutting the sample material are compelling evidence for intense hydrous alteration on the parent body. The widespread occurrence of sulphate veins found in most CI chondrites was first interpreted as evidence for late stage low-temperature alteration on the asteroid [e.g. 5], but later clear proof was found for the terrestrial formation of these features in almost all samples [6]. The study of rock samples sampled on the sub-surface of asteroid Ryugu now for the first time enables to study hydrous alteration processes without any terrestrial alteration. Our study shows compelling evidence for the existence of low temperature hydrous alteration veins on asteroid Ryugu. Surprisingly, the vein consists of a mixture of mostly magnetite with apatite, which is in contrast to the observation of carbonate veins found on the surface of asteroid Bennu [7].

References: [1] Yada et al. (2021) *Nature Astr.*, doi.org/10.1038/s41550-021-01550-6. [2] Nakamura et al. (2022) *Science* submitted. [3] De Pauw et. al. (2021) *Spectrochim. Acta B: Atomic Spectr.* 188, 106346. [4] Solé et al. (2007) *Spectrochim. Acta B: Atomic Spectr.* 62, 63-68. [5] Bischoff et al. (1998) *Meteorit. Planet. Sci.* 33, 1113-1122. [6] Gounelle and Zolensky (2001) *Meteorit. Planet. Sci.* 36, 1321-1329. [7] Kaplan et al. (2020) *Science* 10.1126/science.abc3557.