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

F.E. Brenker[1,*], B. Bazi[2], E. DePauw[2], M. Di Michiel[3], G. Falkenberg[4], J. Garrevoet[4], M. Lindner[1], T. Nakamura[5], P. Tack[2], B. Tkalcec[1], B. Vekemans[2], M. Uesugi[6], M. Matsumoto[5], D. Nakashima[5], Y. Fujioka[5], T. Morita[5], M. Kikuiri[5], K. Amano[5], E. Kagawa[5], H. Yurimoto[7], T. Noguchi[8], R. Okazaki[9], H. Yabuta[10], H. Naraoka[9], K. Sakamoto[11], S. Tachibana[12,11], S.-il. Watanabe[13], Y. Tsuda[11], and L. Vincze[2], [1]Goethe University, Dept. of Geoscience, Altenhoeferallee 1, 60438 Frankfurt, Germany, [2]Ghent University, XMI, Belgium, [3]ESRF, Grenoble, France, [4]DESY, Hamburg, Germany, [5]Tohoku University, Sendai 980-8578, Japan, [6]JASRI/SPring-8, Sayo 679-5198, Japan, [7]Hokkaido University, Sapporo 060-0810, Japan, [8]Kyoto University, Kyoto 606-8502, Japan, [9]Kyushu University, Fukuoka 812-8581, Japan, [10]Hiroshima University, Higashi-Hiroshima 739-8526, Japan, [11]ISAS/JAXA, Sagamihara 252-5210, Japan, [12]The University of Tokyo, Tokyo 113-0033, Japan, [13]Nagoya University, Nagoya 464-8601, Japan, *f.brenker@em.uni-frankfurt.de

**Introduction:** The successful probing, return and curation of asteroid Ryugu provides pristine sample material from the surface and subsurface of this C-class 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 20.5keV and 90 keV respectively, using Si(111) monochromator optics. The Kirkpatrick-Baez (KB) mirror-based X-ray beam focusing provided a 0.2×0.24 µm² beam spot size at sample position during the P06 experiments, and a 0.5×1 µm² beam spot at sample position for the ID15A experiments. High-energy X-ray photon detection at the ID15A beamline was performed using a Canberra Mirion Cryo-pulse 5 plus Ge detector. At the P06 beamline a Vortex 4-element Si-based detector was used, in combination with a single element Si-based Vortex detector equipped with a polycapillary X-ray optic for confocal detection. XRF data were normalised for primary beam intensity fluctuations, detector dead time and processed using PyMca v5.6.2 [4] fitting routines.

**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 (Fig. 1). In case of sample C0033 an Fe-rich vein in the upper part of the sample was identified during the high energy (90 keV) measurements at ESRF beamline ID15A.

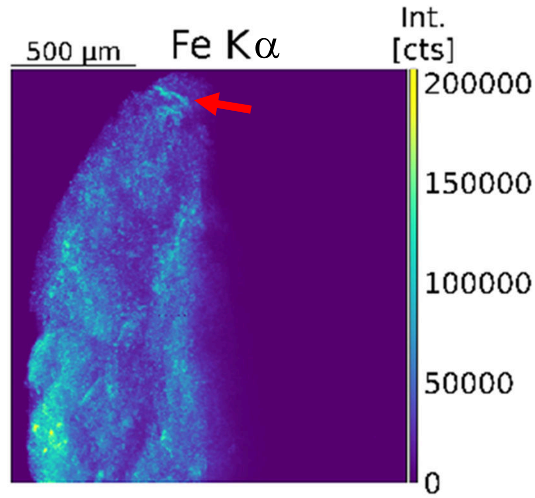


**Fig. 1:** High-energy SXRF projection of grain C0033. The Fe Kα signal indicates an Fe-rich vein crossing the uppermost part of the rock fragment (red arrow).

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. Due to careful positioning a precise redirection to the vein was provided which helped to cut and polish exactly to the desired region of interest (Fig. 2).

**Lower-Energy SXRF:** For further studies a polished section (~100 µm thick) of grain C0033 was prepared exactly at the height of the magnetite vein (Fig. 2A) identified during the high-energy studies of C0033 and was then further analysed at lower X-ray energy (20.5 keV) at PETRA III beamline P06. The red rectangle on the BSE image (Fig 2A) marks the range of the detailed 2D-scans performed (e.g. Fig, 2B). The distribution of several of the main phases is visible within the RGB map (Fig. 2B). The Fe distribution (red) confirms the existence of a magnetite rich vein. Numerous pyrrhotite laths (green) and grains are spread throughout the matrix and some are in close contact to the vein. Ca (blue) and Y element maps indicate the presence of multiple apatite grains closely related to the vein. A large apatite was found within the matrix in contact with a pyrrhotite lath (red arrow in Fig. 2).

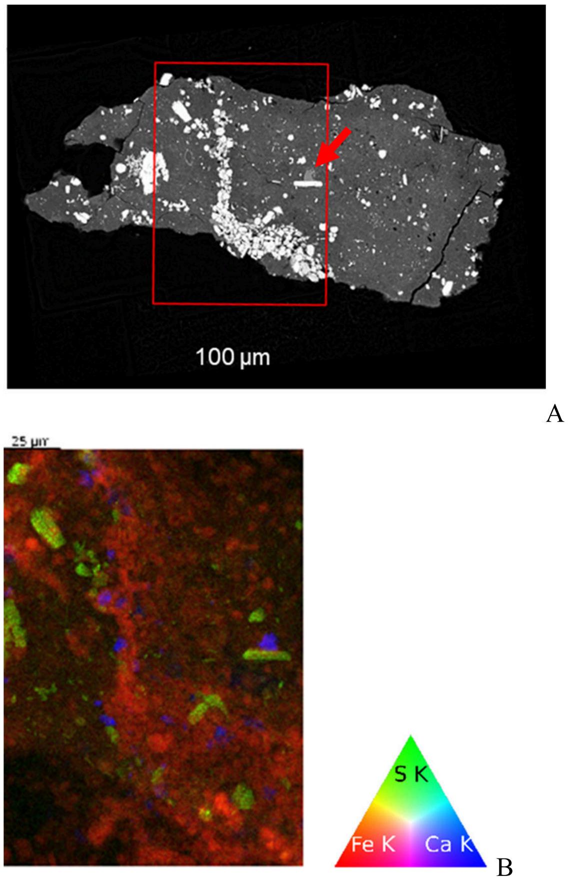


**Fig. 2:** A) BSE image of grain C0033 cut and polished exactly to the magnetite vein identified and located during the high-energy SXRF measurements. B) RGB (Fe, S, Ca) map of the area indicated with the red rectangle showing the distribution of magnetite (red), pyrrhotite (green) and apatite/dolomite (blue).

**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. A matrix measurement of the surrounding area in rock fragment C0033 is shown for comparison (Fig. 3). All quantified measurements shown here were acquired at PETRA III P06 beamline applying a primary beam energy of 20.5 keV.

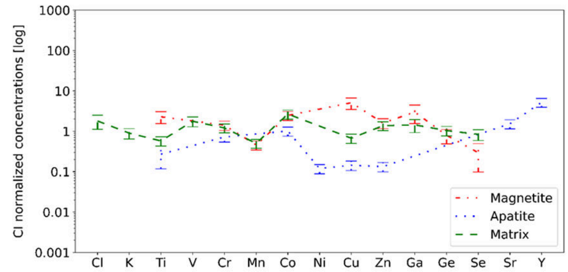


**Fig. 3:** CI normalised trace element concentrations in magnetite and apatite grains located within the magnetite vein observed in C0033. A matrix value from C0033 is added for comparison.

**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].

**Acknowledgments:** We thank the German Research Foundation DFG grant BR2015/38-1, Dr. Rolf M. Schwiete Stiftung, Ghent University Special Research Fund Grants BOF20/PDO/037, BOF17-GOA-015, Research Foundation Flanders grants G0D5221N,1205322N for funding. Also, special thanks to J. Wyatt (aeroconcept) for successfully delivering Ryugu rock fragments from Japan.

**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 E. 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.