

SPECTROSCOPIC GROUND TRUTHING OF A CARBONACEOUS ASTEROID: INITIAL REFLECTANCE SPECTRA OF RYUGU SAMPLES AND IMPLICATIONS FOR REMOTE OBSERVATIONS. R.E. Milliken¹, T. Hiroi¹, C. Schultz¹, K. Robertson¹, R. Brunetto², C. Lantz², T. Nakamura³, K. Amano³, M. Matsuoka⁴, M. Matsumoto⁴, Z. Dionnet², A. Aléon-Toppani², K. Kitazato⁵, T. Morita³, M. Kikui³, E. Kagawa³, H. Yurimoto⁶, T. Noguchi⁷, R. Okazaki⁸, H. Yabuta⁹, H. Naraoka⁸, K. Sakamoto¹⁰, S. Tachibana^{10,11}, S. Watanabe¹², Y. Tsuda¹⁰. ¹Brown University, Providence, RI 02912 (ralph_milliken@brown.edu), ²IAS, Univ. Paris-Saclay, France, ³Tohoku Univ., Japan, ⁴LESIA, Obs. De Paris-Meudon, France, ⁵Univ. of Aizu, Japan, ⁶Hokkaido Univ., Japan, ⁷Kyoto Univ., Japan, ⁸Kyushu Univ., Japan, ⁹Hiroshima Univ., Japan, ¹⁰ISAS/JAXA, Japan, ¹¹Univ. of Tokyo, Japan, ¹²Nagoya Univ., Japan.

Introduction: The successful return of samples from Cb-type asteroid (162173) Ryugu [1-3] provides a significant step forward in understanding how to better interpret the composition of primitive asteroids from spectral reflectance data acquired with space and ground-based assets. Decades of telescopic observations have shown that various low-albedo asteroids exhibit absorptions in the $\sim 3 \mu\text{m}$ wavelength region that can be attributed to hydrous (OH and/or H₂O-bearing) phases, and there exists a wide range in the shape and strength of these absorptions [4-5]. Intriguingly, in some cases there are no spectral analogs in existing meteorite collections [5].

The interpretation that these absorption features are indicative of the presence of hydrous minerals such as phyllosilicates is strongly linked to the observation of such phases in aqueously altered (type C1 and C2) carbonaceous chondrites [e.g., 6]. Though swelling (smectite) clays are observed in some C chondrites, interlayer H₂O in these phases should not be stable at the optical surface of asteroids in the vacuum of space. To further complicate matters, diagnostic positions of OH absorptions at $\sim 2.7\text{--}2.8 \mu\text{m}$ for 7, 10 and 14 Å clays are not measurable in ground-based observations due to Earth's atmosphere, and other water-related spectral features at $\sim 3 \mu\text{m}$ may appear similar for many non-phyllosilicate hydrous phases.

This leaves open many questions as to which phases give rise to asteroid 'hydration' features observed at $\sim 3 \mu\text{m}$, the degree to which degree of aqueous alteration can be properly inferred from the strength of such absorptions, and the extent to which terrestrial alteration of C chondrites has biased how we attempt to relate spectra of meteorites to those of primitive asteroids [e.g., 7]. In this work we present initial laboratory spectra of a Ryugu sample that can be compared directly with remote observations by the Hayabusa2 NIRS3 instrument in an effort to begin to address some of these issues. Our results demonstrate that the number of hydrous asteroids and the degree of alteration on low-albedo objects with $3 \mu\text{m}$ features may be severely underestimated by a lack of data in the $2.7\text{--}2.8 \mu\text{m}$ wavelength region.

Methods: A single Ryugu sample (A0026-pFIB) was measured using a Bruker LUMOS microscope FTIR (μFTIR) at Brown University. The received sample was produced by cutting grain A0026 by xenon-FIB to produce a $\sim 1\text{mm} \times \sim 1 \text{mm}$ flat, 'clean' surface on the

resulting chip, similar to what is discussed in [8]. Point measurements were acquired in raster format to produce spectral image cubes (maps) at spatial scales of $50\text{--}150 \mu\text{m/spot}$ over a wavelength range of $\sim 1.6\text{--}16 \mu\text{m}$ (Figure 1). The sample was enclosed in an environment with weak positive pressure and air with a dewpoint of -70°C to minimize adsorption of terrestrial H₂O. The extremely dark nature of the sample required averaging 100-300 scans per spot to achieve decent signal for resolving weak spectral features. All reflectance spectra were measured relative to either a diffuse or specular (mirror) gold standard.

Results: The near-IR spectral data reported here and by other labs [2,8,9] are consistent with the remote observations by NIRS3: the primary feature in the $\sim 3 \mu\text{m}$ region is a narrow OH feature at $\sim 2.7 \mu\text{m}$ that is consistent with Mg-OH bonds and there is little to no spectral evidence for H₂O. This is consistent with the identified mineralogy of various Ryugu particles that show Mg-phyllosilicates (e.g., saponite and serpentine) to be dominant hydrous phases [2,3], and H₂O from the terrestrial environment is unlikely to be present in smectite (e.g., saponite) interlayers under the dry conditions of our measurements. Minor ($<10 \text{ nm}$) variations in position of the OH feature are observed for our μFTIR spot sizes.

Additional absorption features attributable to carbonate, organics, and possibly N-bearing compounds are also apparent in the μFTIR data of sample A0026 [2,8,9]. The carbonate is heterogeneously distributed in the matrix, is fine-grained [2], and when present (spectrally) it is in portions of the matrix that are slightly less dark than carbonate-poor regions. However, not all 'brighter' portions of the matrix exhibit spectral evidence for carbonate at the scale of our μFTIR measurements. Bright grains/clasts in Figure 1 are spectrally bland in the $\sim 3 \mu\text{m}$ region and are consistent with the presence of sulfide as reported by [2].

Implications: Previous studies of Hayabusa2 NIRS3 reflectance data revealed a weak, narrow Mg-OH feature whose properties were relatively homogeneous across the surface of Ryugu [10]. This is in contrast to the stronger and broader (and also rather homogeneous) $\sim 3 \mu\text{m}$ feature observed at asteroid Bennu [11]. The latter is 'in family' with lab spectra of various phyllosilicate-rich C chondrites [11], whereas the former is rarer and

most similar to spectra of thermally metamorphosed C2 chondrites or artificially heated samples of C1 Ivuna [10].

At face value, the spectral differences between these two asteroids could reasonably be interpreted to suggest that Bennu is currently more water-rich than Ryugu. Sample return allows for this to be tested, and numerous and detailed analyses of the returned Ryugu samples reveal they are most similar to extremely aqueously altered CI chondrites with no clear evidence that Ryugu's materials experienced significant thermal metamorphism [2]. When considering the spectra reported here, their similarity to NIRS3 spectra of Ryugu as a whole, and the overwhelming evidence for pervasive water-rock interaction in Ryugu materials, it stands to reason that despite the weak, narrow nature of the 'hydration' feature observed in remote and lab spectra of Ryugu, this is in fact an accurate spectral representation of a volatile/water-rich asteroid whose parent body experienced extensive aqueous alteration.

Previous studies have shown clear links between the strength of 3 μm features of lab spectra of C chondrites and their H/Si values [12], which in theory could be applied to remotely acquired spectra as a proxy for assessing degree of aqueous alteration on asteroids [13]. In this context, the integrated Ryugu results present somewhat of a contradiction: effectively all of the spectral evidence of Ryugu being a hydrated asteroid is present in a spectral region (2.7-2.8 μm) that is not accessible from Earth and, even when measured from space, the narrow/weak OH feature that is observed is not typically thought of as evidence for an extensively aqueously altered CI-like object. However, increasing degree of alteration may result in Mg-serpentine and saponite as the dominant hydrous phases, and when kept pristine and absent from terrestrial contamination this could be expected to result in spectral signatures of Mg-OH with little or no spectral contribution of H₂O.

The observation that lab spectra of most C1 and C2 chondrites exhibit broader and/or stronger 3 μm features

than Ryugu is perhaps more indicative of how quickly these meteorites are affected by our wet terrestrial environment and how difficult it is to remove terrestrial water, even under vacuum (e.g., [7]), than it is an indicator of parent-body processes. Indeed, resolved μFTIR maps of other C chondrites show that hydrated terrestrial Mg-sulfates in CM2 samples can dominate the 3 μm region even when present in small abundances [14]. In addition, the complex fine-grained nature of C chondrite matrix and strongly nonlinear absorption (darkening) processes are known to weaken hydration features, and this is clearly true for Ryugu.

Several important conclusions can be drawn from these results. 1) asteroids that lack evidence for a 3 μm hydration feature in ground-based spectra may in fact be as aqueously altered as CI chondrites, 2) a full and accurate assessment of the distribution and nature of hydrated asteroids cannot be determined solely from ground-based observations, 3) the strength of features in the 3 μm region cannot always be directly and uniquely linked to degree of aqueous alteration. Left yet to explore is which phases and processes are responsible for the broader, deeper 3 μm absorptions that *are* observed on many asteroids, including Bennu, and how these compare with the ground truthing of Ryugu as revealed by the Hayabusa2 mission.

Acknowledgments & References: Special thanks to Y. Kodama, T. Okawa, N. Suzuki, Y. Deguchi, and T. Nishida at TOYO Corporation for their assistance with Xe FIB sample processing.

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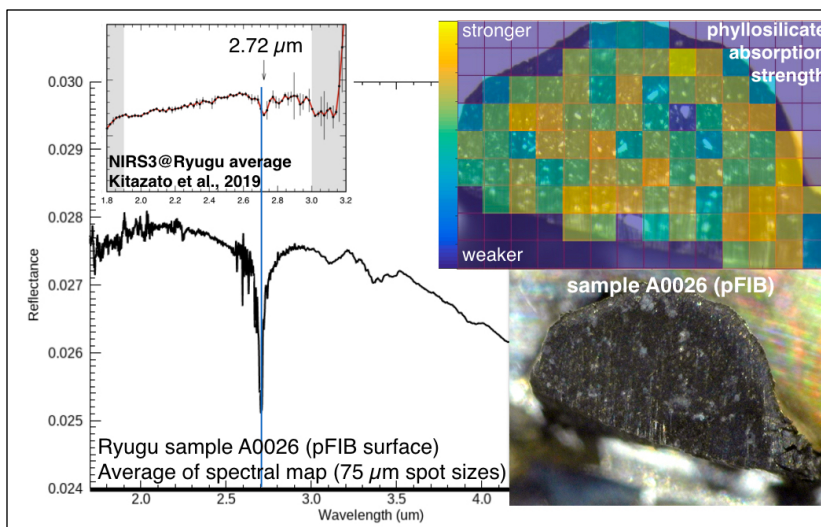


Figure 1. Example μFTIR spectra of returned sample A0026 and comparison with NIRS3 spectral average of Ryugu (upper left inset). Background plot is an average from a spectral map (upper right inset) showing Mg-OH phyllosilicate feature at $\sim 2.7 \mu\text{m}$ and weaker features at ~ 3.05 , ~ 3.4 and $\sim 4 \mu\text{m}$ due to N-bearing phases, organics, and/or carbonates. Difference in OH position between A0026-pFIB and NIRS3 is confirmed by other labs [8] but is not observed in other Ryugu samples, which show OH bands closer to NIRS3 data; this may be due to pFIB processing of A0026. Visible image under polarized light shown in lower right inset for reference.