How do Ryugu-Inspired Phyllosilicates Respond to Micro-Mechanical Impact?

Daniel Hallatt, Penny J. Wozniakiewicz, Mark Burchell, Hugues Leroux

HOW DO RYUGU-INSPIRED PHYLLOSILICATES RESPOND TO MICRO-MECHANICAL IMPACT?

D. Hallatt[1,2], P. J. Wozniakiewicz[2], M. J. Burchell[2], H. Leroux[1], Univ. Lille., CNRS, INRAE, Centrale Lille, UMR 8207 - UMET - Unité Matériaux et Transformations, F-59000 Lille, France. [2]Dept. of Physics and Astronomy, University of Kent, Canterbury, Kent, CT2 7NH, UK. (email: daniel.hallatt@univ-lille.fr)

Introduction: Samples delivered from Ryugu, as part of JAXA's Hayabusa2 mission, have offered us a new perspective of the Solar System [1]. In particular, a well-known family of sheet-structured minerals called phyllosilicates have been found making up the majority of Ryugu's surface; in the extraterrestrial context, these have mainly only been available from the meteorite collection up until now [2]. As hydrated and relatively susceptible phases, their alteration promises to testify not only to the aqueous alteration of the environment that they, and their parent bodies, likely experienced, but also the conditions interacting with them since then [2]. From an asteroidal perspective, a unique catalogue of phenomena are likely experienced by materials as they are exposed to space. These may include thermal alteration (radiogenic decay, solar heating, etc.), irradiation (solar-wind, comic-rays, etc.), and hyper-velocity impact (micrometeoroid bombardment and large scale collisions). It is from an understanding of their response to these phenomena, coupled with the relative geologic inactivity of primitive asteroidal hosts, that, as delicate tracers of extraterrestrial-material processing, phyllosilicates may make it possible to use carbonaceous asteroids as messengers of times past.

The possibility for signatures of micrometeoroid bombardment on returned asteroidal samples is uniquely interesting because the phenomenon imparts physical alteration on a scale that is now more readily available and quantifiable than ever. To understand the nature of this effect, prior work has attempted to study the injection of impact-scale energy by the application of pulsed lasers [2]. Natural craters have also been reported on materials from the Moon, meteorites, and asteroid Itokawa. However, until Hayabusa2's return from Ryugu, most literature has not had the opportunity or practical motivation to study phyllosilicates [1].

Here we present results from a subset of a larger study: micron-scale mechanical impacts on phyllosilicates performed using a Light-Gas Gun (LGG, Fig. 1A). In its full scope, our study is focused on characterizing the impact signature on phyllosilicates, and attempting to deconvolve their thermal behaviour from their response to impact. This will be done by complementing the work presented here with our previous work on the same phyllosilicate's thermal decomposition and their response to a pulsed laser [3, 4].

Methods: The majority of the returned sample from Ryugu has been found consisting of two intimately mixed phyllosilicates: Mg-rich serpentine and saponite [1]. In each of our LGG targets, we included one type of saponite and two types of serpentine, all of terrestrial origin. Both serpentines were similarly Mg-rich, however, one was likely antigorite and the other likely lizardite, according to Raman spectroscopy. We also included Mg-dominated San Carlos olivine in each target, which we used as a reference thanks to the well-developed literature on its hypervelocity impact. A target for the LGG was made by wet-cutting ~1 mm thick slices from each natural rock sample, followed by embedding and polishing those samples in a single puck of epoxy (Fig. 1C). By using a multi-sample target, we were able to compare each sample under equivalent conditions. In addition, craters found in the epoxy of each target afforded us a baseline between each shot. Shots were performed under ~ 0.4 mbar.

Here we report on five LGG shots, each with unique combinations of the speed (~ 2 - 5 $km \cdot s^{-1}$), density (1.18 - 3.95 $g \cdot cm^{-3}$), size (1 - 30 μm), and shape of powder projectiles. Four shots used Al_2O_3 or Poly(Methyl MethAcrylate) (PMMA) projectiles, primarily due to their availability as highly spherical, Fe-, Si- and Mg-free, micron-scale particles. The fifth shot was an attempt at simulating a more realistic micrometeoroid: non-spherical agglomerates of 1 - 50 μm grains of serpentine (*UB-N,* a well characterized French standard and also mostly Mg-rich lizardite). The ion irradiation response of the serpentine projectiles and the lizardite target (therein *Rawhide*) has already been studied, affording us a relatively complete picture of these samples when coupled with our work [5].

Each sample was shot using the LGG of the Center for Astrophysics and Planetary Science at the University of Kent [7]. After a shot, each sample was imaged with Secondary-Electron Scanning Electron Microscopy (SE-SEM). We report here the surface morphology of craters, helping us to not only resolve the parameter-space of mechanical impact in each sample, but to also compare our microcraters to natural ones reported in literature [1, 6]. Future work will include studying crater topography via white-light interferometry, recording infrared hyper-spectral imaging and Raman spectroscopy on their surface, and studying their cross-sections via transmission electron microscopy.

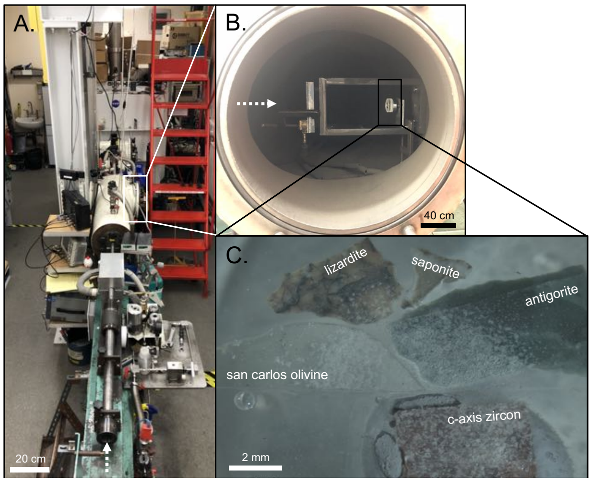

Figure 1. A) The LGG at the University of Kent. A quantity of powder was accelerated horizontally towards the sample, in the direction of the dotted white arrow. B) A side-facing view of where a target (at the right) was housed in the LGG. C) The front face of a typical multi-sample target, covered in adhering projectile particles (white Al_2O_3). Note: results for zircon are not reported on here.

Results and Discussion: According to SE-SEM micrographs, a clear dependency on the impact-regime was found in some samples. In one shot with PMMA for example (5 km · s^1, ~7.9 μJ, and 33 GPa planar-impact approximated P_{peak} in olivine), microcraters in olivine appeared as circular, crack-filled depressions, similar in diameter to the silhouette of the projectile. These were reminiscent of the *dent* morphology reported in literature [8]. When shot with 5 km · s^{-1} Al_2O_3 (~22 μJ and 81 GPa), a significant amount of material was found removed beyond a central, glassy pit of the olivine craters (Fig. 2C). This morphology aligns with the *pit-plus-spall* (or even *stylus*) crater of literature [9], and bears a striking resemblance to a natural microcrater reportedly found in lunar olivine (Fig. 2F) [6]. A spalled morphology is also similar to the laser-spots we generated in olivine (Fig. 2E) [4]. Serpentines exhibited extra-crater material removal even in the former shot. Here, the central depression of a crater in antigorite was found surrounded by what appeared to be vertically torn out sheets of material, while those in lizardite were encircled by a shallower lift-out of material, appearing more finely textured and circularly edged. Craters in antigorite from the latter shot seemed to lose all recognition of a central feature, with the vertical tear-out encompassing its entirety (Fig. 2A). After laser-cratering, this morphology was found only outside the edge of the central pit or most-obviously when approaching antigorite's apparent ablation threshold (10 - 16 J · cm^{-2}, Fig. 2D). Such Al_2O_3 craters in lizardite were distinguishable as a deep central pit surrounded by large segments of removed material (Fig. 2B).

There are a number of impact characteristics to consider in our interpretation: energy, fluence, power, peak pressure, and particle velocity for instance. Through crater morphology, we will organize insights into μm-scale impacts in phyllosilicates, where we hope to improve our interpretation of impact events on phyllosilicate-bearing asteroids such as Ryugu.

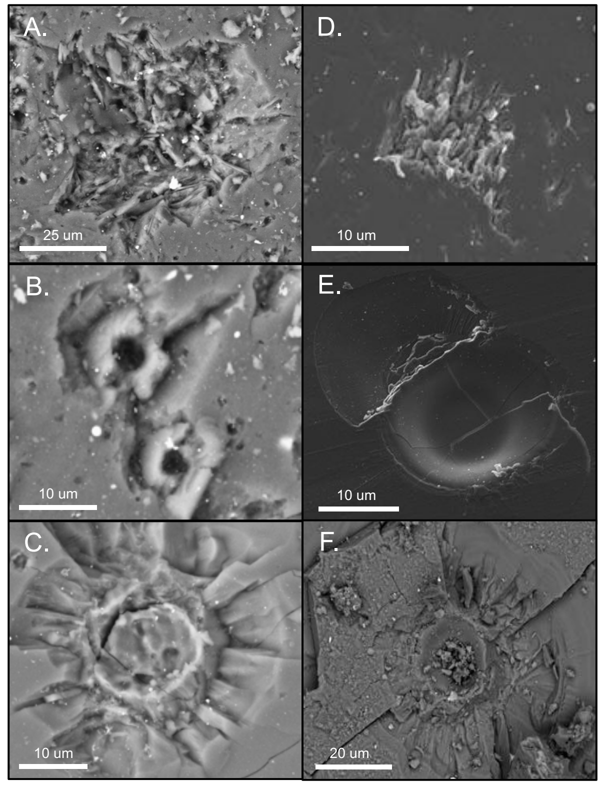

Figure 2. SE-SEM micrographs of microcraters. A-C) LGG-produced microcraters from 5 km · s^{-1} Al_2O_3 in our antigorite, lizardite, and olivine respectively. D) The response of our antigorite to a single laser pulse (~21 μJ over 300 fs) and E) that of olivine after 9 pulses (~52 μJ · pulse^{-1} over 300fs · pulse^{-1}) [3]. F) A microcrater found in an olivine phenocryst from lunar rock 12075 [6].

Acknowledgments: The authors thank the I-SITE Université de Lille Nord Europe, the Métropole Européenne de Lille, and the National Research Agency for funding. Special thanks are owed to L. Alesbrook and V. Spathis for help operating the LGG and Raman training respectively (Kent), and to S. Rubino and R. Brunetto (Univ. Paris-Saclay, Fr) for the lizardite chip.

References: [1] Noguchi et al. (2022) *Nat. Astron.*, 6, 1-12. [2] Thompson et al. (2019) *Icarus,* 319, 499-511. [3] Hallatt et al. (2021) *LPSC LII*, #2518. [4] Hallatt et al. (2022) *LPSC LIII*, #2568. [5] Rubino et al. (2020) *Planet. Sci*., 1. [6] Noble et al. (2015) *SpWe of Airless Bodies Workshop*, #2034. [7] Hibbert et al. (2017) *Procedia Eng.*, 204, 208-214. [8] Mandeville et al. (1971) *Earth Planet Sci. Lett.*, 11, 297-306. [9] Horz et al. (1971) *J. Geophys. Res*., 76, 5770-5798.