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### EXPLORING THE RESPONSE OF RYUGU-INSPIRED PHYLLOSILICATES TO A PULSED LASER.

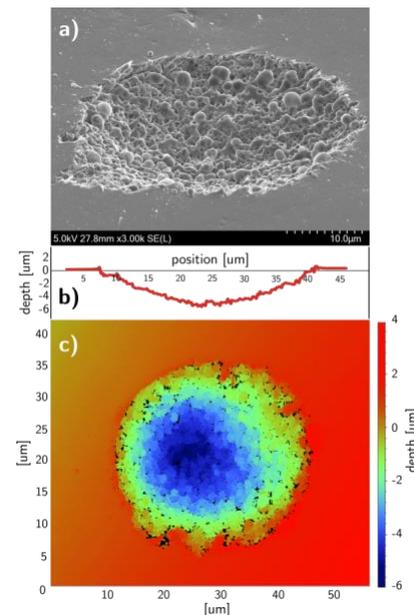
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**Introduction:** Thanks to JAXA's Hayabusa2 mission, samples returned from Ryugu mark a new era of opportunity in extraterrestrial materials science [1]. Along with NASA's ongoing sample return mission to Bennu, returning samples from C-group asteroids promises to offer novel insights into the material history of our Solar System. One material that may draw particular attention in the returned samples is a family of sheet-structured minerals called phyllosilicates. Phyllosilicates are not only believed to occur in widespread abundance on both sampled asteroids (thanks to consistent and recognizable spectral signatures [2, 3]), but, thanks to their alterable mineralogy, may be able to be used as an indicator of the environment that they (and potential parent bodies which they comprised) have experienced. It is from an understanding of their response to the environment of space, coupled with the relative geologically inactivity of primitive asteroidal hosts, such as Ryugu, that the use of phyllosilicates as tracers of extraterrestrial-material processing may make it possible to understand the role of asteroids as messengers of times past.

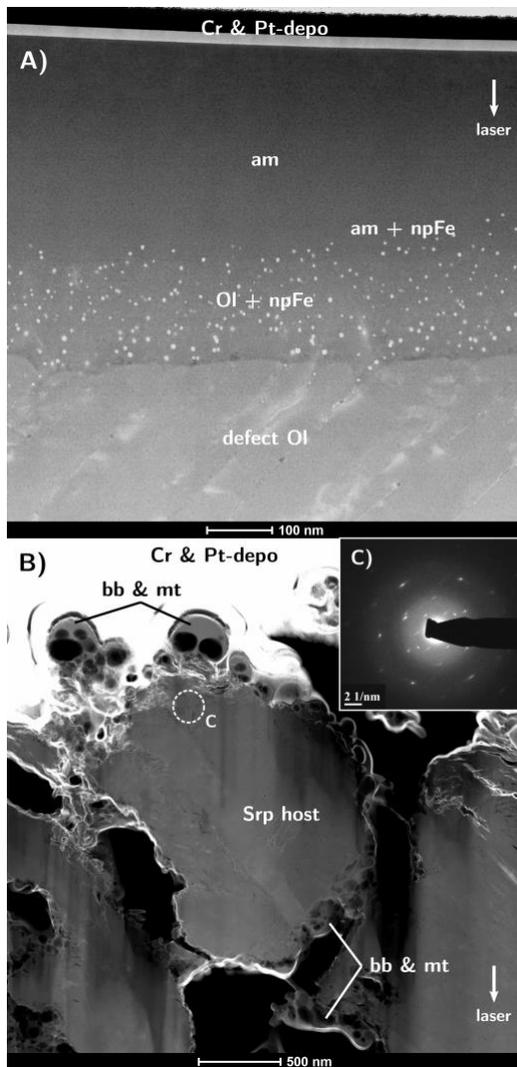
In the context of asteroids, materials are thought to experience a diverse series of phenomena depending on the dynamic history of the body. These may include thermal alteration (radiogenic decay, solar heating, etc.), irradiation (solar-wind, cometic-rays, etc.), aqueous alteration, and impact (micrometeorite bombardment, large scale collisions, etc.). It is with regards to the latter phenomena that we present, as a partial derivation from a broader investigation (a doctoral thesis), work using a pulsed laser to simulate the effect of impact on phyllosilicates. In its full scope, the entirety of the study also includes a bulk look into the behaviour of phyllosilicates under thermal conditions, followed by 2-stage light-gas gun experiments to compare to these laser-simulated impacts.

**Methods:** The Ryugu-relevant phyllosilicates reported here include a pressed pellet of powdered serpentine, and polished chips of cut serpentine and saponite. To validate our experimental conditions, polished chips of San Carlos olivine were subject to identical laser conditions as the phyllosilicate targets, to be exploited as a reference to the more mature literature on lasered olivine. Each sample was irradiated with a femtosecond pulsed laser source (Tangerine from

Amplitude Systèmes), embedded within an Oxford Lasers machining. The 1030 nm laser had a unit pulse duration and energy of  $\sim 300$  fs and  $50 \mu\text{J}$  respectively. The Gaussian laser beam was circularly polarized, and, once focused onto each sample surface through a flat-field telecentric lens (Still optics), achieved a beam waist of  $\sim 15 \mu\text{m}$  at the focal point. For each target, a specific matrix of laser spots ( $10 \times 10$  with  $100 \mu\text{m}$  spacing) was applied such that the effect of both the number of successive pulses and power could be studied afterwards with confidence (5 repeats of each #pulse/power combination). The general, post-laser sequence of analysis of each crater was as follows: a) optical microscopy (Keyence VHX-7000), b) White Light Interferometry (WLI, Bruker Contour GT), c) hyperspectral imaging (not reported on here), d) Scanning Electron Microscopy (SEM, Hitachi SU 5000 at 5 keV), and e) Transmission Electron Microscopy (TEM, TECNAI G2-30 Twin and FEI TITAN Themis 300). All of the experimental and characterization tools used here are located at the Université de Lille, France.



**Figure 1.** An example of the techniques used to characterize the topography and morphology of a crater (serpentine chip): a) an SE-SEM (tilted) image, b) a WLI-generated line-scan profile, and c) a WLI-generated topography colour-map.



**Figure 2.** An example of part of the approach to study crater cross-sections with TEM: a) a bright-field micrograph at the crater surface in San Carlos olivine (am = amorphous, npFe = nano-phase iron, Ol = olivine), b) a bright-field micrograph of a grain of serpentine powder at the crater surface (bb = bubble, mt = melt, Srp = serpentine), and c) an SAED pattern near the crater surface of the serpentine grain in b).

**Results and discussion:** Using topographic data from WLI, the first implementation of an ad-hoc code (called *TopoCrater*) was used to generate crater topography profiles (Fig. 1b), calculate crater size metrics such as diameter:depth, and to estimate crater volume (related to quantity of ejected material). These analyses were then used to construct trends in both the number of laser pulses and laser power on each sample. 3D visual-reconstructions and topographical colour-maps (Fig. 1c) were also reproduced from WLI data, giving insight into the radial and angular morphology of each crater, and affording ‘ground-truth’ to morphology

quantifications. As shown in Fig. 1a/c, WLI was able to resolve the complex surface structure of craters on serpentine, and identify them against other craters like those produced in olivine (which are smoother).

The SEM of laser craters also helped identify morphological trends with changing laser parameters. To probe topography inside a crater, the use of sample tilting in secondary electron (SE) mode has been particularly helpful (Fig. 1a). With SE-SEM, trends in the radial distribution of complex surface features such as melt, vesicles, bubbles, and ejecta have been studied.

By employing TEM, we have been able to spatially resolve material features and traits of interest across particular craters on each sample. This includes EDS to quantify the chemical state (not reported on here), Selective Area Electron Diffraction (SAED) to understand the crystallinity throughout a grain (Fig. 2c), and bright- and dark-field imaging to record features such as potential dislocations, fractures, or the complicated structures mentioned above (Fig. 2b). For example, after laser-cratering the olivine, Fig. 2a shows the reproduction of commonly reported laser-induced and natural Space Weathering (SpWe) features, such as an amorphous surface layer and potential nano-phase iron (shown in Fig. 2a offset from the surface, but whose spatial distribution varies radially) [4, 5].

Concerning the returned samples from Ryugu, our empirical results may help interpret apparent SpWe features that have been recently discovered on the surface of some Ryugu grains [6]. In fact, surface features of our serpentine samples (Fig. 2b) seem to resemble the bubble and melt continuum structure reported in the Ryugu samples [6]. One particular note, shown in Fig. 2b, is the presence of this melt/bubble layer on presumably laser-shaded grain surfaces, despite the centre of the grain appearing unaltered. We propose this might result from the inter-granular porosity of the pressed serpentine powder target, as this is not observed in our continuous phyllosilicate chips. Understanding the crystallinity of such targets spatially, with prudent SAED (Fig. 2c), may help elucidate this phenomena.

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