EXPERIMENTAL ANALOG FOR HIGH-SPEED PARTICLE CAPTURE FROM IO VOLCANIC PLUME.

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Introduction: The inner-most Jovian moon Io is subjected to intense tidal heating via the Laplace resonance between it, Europa, and Ganymede. As a result, Io is the most volcanically active body in the solar system, with hundreds of active volcanoes observed erupting on its surface by the two *Voyager* spacecraft, the Hubble Space Telescope, *Galileo*, *New Horizons*, and most recently, *Juno* [1]. Remote sensing observations suggest that the erupting lava is basaltic to ultramafic, with eruption temperatures as high as ~1600 °C [2]. However, the composition of the lava can only be roughly modelled with data gathered from remote sensing observations.

Several volcanic ash plumes have been observed erupting simultaneously from the surface of Io, with the larger Pele-class plumes reaching ~350 km in height [3]. To constrain the composition of material erupting from Io, a spacecraft will need to fly through a volcanic plume, collect a sample, and return the material to Earth for analysis [4]. Sample return will allow us to measure both micrometer-scale and bulk chemical and isotopic compositions of volcanic particles and associated volcanic gases erupted from Io. Sample collection will likely proceed at high speed (~6 km/s), such that plume sampling of solid particles will be analogous to the *Stardust* comet sampling mission. While in situ analyses of particles captured at hypervelocity has been conducted successfully for >15 years with the Stardust samples from Comet Wild 2 [5], bulk geochemical analysis will require the development of new methods that maximize the science return of collected material. To that end, we conducted a study using laser irradiation of analog materials into Si wafers.

Methods: For the purpose of simulating hypervelocity impacts, a Continuum Surelite I-20 Nd:YAG laser was used to deposit energy onto a 5 × 5 mm silicon wafer coated with fine (<10 μm) San Carlos olivine dust. The olivine dust was sandwiched between the silicon chip and a glass cover slide. This method kept the dust from being dispersed by the shock of the laser.

The laser wavelength was 1064 nm. Its pulse duration was 6–8 ns, which is comparable to a micrometeorite bombardment timescale. We operated the laser in single shot mode. The diameter of the focused beam was about 1 mm on the Si wafer. The position of each laser hit was controlled by an X- Y-actuated mirror. The wafer was shot approximately 50-60 individual times. Each shot was with 30 mJ of energy or 121 W/mm^2 of power. All experiments were performed under vacuum (1x10^{-6} torr).

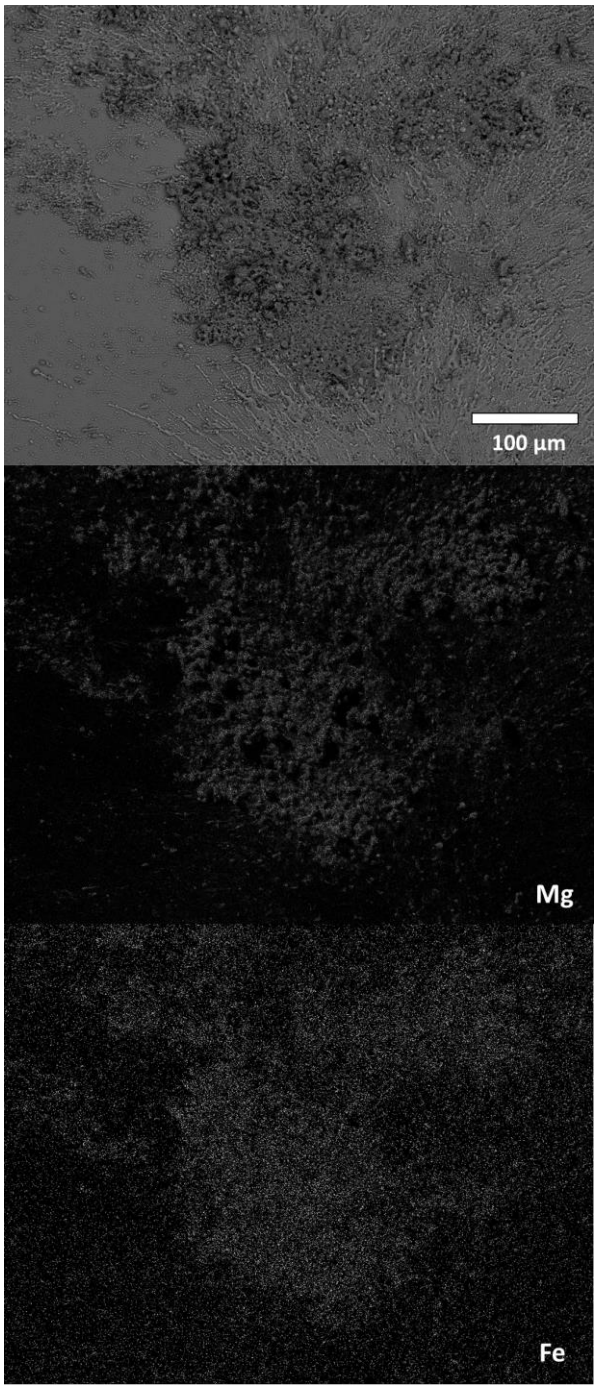

Figure 1. BSE (top) and X-ray (middle and bottom) images of a lased area in an Si wafer.

The lased wafers were cleaned of loose dust with compressed N_2 gas and imaged using a Tescan Mira3 FEG-SEM operating in backscattered electron (BSE) mode. X-ray maps were collected using an EDAX EDX system and processed with EDAX Teams software. Samples were weighed and digested in a 2:1 mixture of concentrated HF and HNO_3 and fluxed in 6N HCl and concentrated HNO_3 to remove any fluorides. They were then dissolved in 2% HNO_3 and diluted for major and trace element measurement using a Thermo iCAP Q quadrupole mass spectrometer.

	S.C. Olivine	Exp. Shots	Si Wafer Blank
Na_2O	0.023	0.002	0.0004
MgO	47.07	0.02	0.0002
Al_2O_3	0.093	0.005	0.0002
P_2O_5	0.014	0.001	0.0005
K_2O	0.006	0.001	0.0001
CaO	0.150	0.003	0.002
TiO_2	0.004	0.0002	0.00006
Cr_2O_3	0.031	0.00002	0.00002
MnO	0.121	0.00005	0.00002
FeO	8.71	0.003	0.0002
SiO_2	43.778	n/a	n/a
Mg#	90.60	90.66	63.05

Table 1. Major and minor element analyses of the olivine, experimental shots, and the blank Si wafer, in wt.%. SiO_2 was determined by subtraction. Mg# = mol. Mg/(Mg+Fe); n/a = not applicable.

Results: BSE and X-ray images of the laser-etched craters show that the Si wafer was partially melted and ablated, while olivine grains were partially melted and incorporated into the crater material (Fig. 1). X-ray maps show resolvable quantities of Mg and Fe incorporated into the craters. Results of major and minor element analysis (Table 1) indicate that the composition of the olivine was not significantly altered by the lasing process. While the minor elements are present in concentrations too low to be measured accurately and have likely been affected by contributions from the Si wafer and fractionation due to ablation, Mg, Fe, and Mn were stoichiometrically conserved. The Mg# of the experimental result is identical within error to the Mg# of the olivine.

The trace elements present in the olivine are also present in the experimental shot analyses, although many are likely subject to similar effects as the minor elements. Many trace elements were either below the detection limit of the iCAP Q mass spectrometer or too low to quantify accurately. Importantly, several rare earth elements (REE) were quantifiable (Fig. 2). The light REE La, Ce, Pr, and Nd show a pattern in the experimental results similar to that of the olivine, in higher concentrations than in the Si wafer. The rest are either below detection limit or overlap with the background measurements obtained by analyzing the blank Si wafer. Eu is in a much higher concentration than the other REE, potentially due to a redox effect.

The calculated total mass of olivine implanted into the 0.000025 m^2 Si wafer is 0.010 mg, or 407 mg/m^2. This is within the expected Io sampling range of 10-100 mg per 0.1 m^2 of collector area.

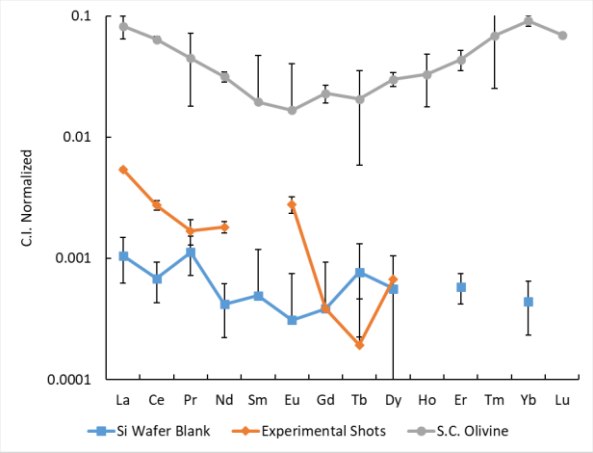

Figure 2. Chondrite normalized REE diagram showing experimental results, S.C. olivine, and Si wafer blank.

Discussion: While remote sensing of Io allows for the determination of geophysical constraints such as tidal Love numbers and libration amplitude, parameters such as silicate melt percentage and extent of fractionation can only be measured geochemically in a returned sample. Our results suggest that high speed capture of small particles can produce quantifiable results via bulk analysis. While this pilot study shows that the laser and acid dissolution ICP-MS methods are feasible, many variables remain to be constrained. Future work using higher purity Si will vary the composition of material lased to include various igneous minerals such as pyroxenes, feldspars, oxides, and volcanic glasses. Quantities of material and laser shot intensity will be varied to produce fractionation curves for minor and trace elements. Additional experiments using different substrates, such as BaF_2 for oxygen isotopic analysis, will also be conducted. Results will be verified by performing light gas gun shots at hypervelocity into solid and porous substrates.

References: [1] Mura A. et al. (2020) *Icarus*, 341, 113607. [2] Keszthelyi L. et al. (2007) *Icarus*, 192, 491-502. [3] Spencer J. R. et al. (2007) *Science*, 318 (5848), 240-243. [4] Ogliore R. C. et al. (2023) *LPS LIV* (this conference). [5] Postberg F. et al. (2014) *MaPS*, 49:9, 1666-1679.