ANALYSIS OF COMETARY DUST IMPACT RESIDUES IN THE ALUMINUM FOIL CRATERS OF STARDUST. G.A. Graham[1], A.T. Kearsley[2], E.P. Vicenzi[3], N. Teslich[1], Z.R. Dai[1], D. Rost[3], F. Hörz[4], J.P. Bradley[1]. [1]IGPP, LLNL, CA 94551, USA (graham42@llnl.gov), [2]Mineralogy Department, Natural History Museum, SW7 5BD, UK, [3]Department of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington DC 20560, USA, [4]ARES, NASA Johnson Space Center, TX 77058, USA.

Introduction: In January 2006, the sample return capsule from NASA's Stardust spacecraft successfully returned to Earth after its seven year mission to comet Wild-2 [1]. While the principal capture medium for comet dust was low-density graded silica aerogel [2], the 1100 series aluminum foil (approximately 100 μm thick) which wrapped around the T6064 aluminum frame of the sample tray assembly (STA) contains micro-craters that constitute an additional repository for Wild-2 dust. Previous studies of similar craters on spacecraft surfaces, e.g. the Long Duration Exposure Facility (LDEF), have shown that impactor material can be preserved for elemental and mineralogical characterization [3], although the quantity of impact residue in Stardust craters far exceeds previous missions. The degree of shock-induced alteration experienced by the Wild-2 particles impacting on foil will generally be greater than for those captured in the low-density aerogel. However, even some of the residues found in LDEF craters showed not only survival of crystalline silicates but even their solar flare tracks, which are extremely fragile structures and anneal at around 600°C [4]. Laboratory hypervelocity experiments, using analogues of Wild-2 particles accelerated into flight-grade foils under conditions close to those of the actual encounter, showed retention of abundant projectile residues at the Stardust encounter velocity of 6.1 km s^{-1} [5-6]. During the preliminary examination (PE) of the returned foils, using optical and electron microscopy studies, a diverse range in size and morphologies of micro-craters was identified as detailed in [7]. In this abstract we consider the state of residue preservation in a diverse range of craters with respect to their elemental composition and inferred mineralogy of the original projectiles.

Methods: During the Stardust PE period individual strips of the 1100 series aluminum foil were extracted from the STA at NASA Johnson Space Center (JSC). The foils were initially scanned optically at JSC, prior to allocation to the different institutions comprising the Stardust Cratering Sub-team [7]. Foils C2027N, C2054W, C2100N were surveyed at Lawrence Livermore National Laboratory using an FEI Nova 600 Nanolab dualbeam focused ion beam/field emission scanning electron microscope (FIB/FESEM) with an EDAX Genesis energy-dispersive spectrometer (EDS) and both an Omniprobe™ in-situ micromanipulator and an Ascend Instruments Extreme Access™ extraction system. Foil C2125N was surveyed at the Natural History Museum (NHM) using a JEOL 5900LV SEM fitted with an Oxford Inca EDS. The foils were scanned at a magnification sufficient to enable identification of sub-micrometer craters down to approximately 100 nm [7]. Using the methodology discussed in [8], FIB milling enabled cross-sectional profiling and extraction of sections for further characterization. We will analyze the FIB sections using the Ion-TOF ToF-SIMS IV microprobe at the Smithsonian Institution, to investigate the inorganic and organic phases preserved within the impact residues.

In addition to the standardized surveys of foils, seven relatively large craters with lip-to-lip diameters > 50 μm were analyzed at the NHM.

Interpretation of Impact Residues: Of the seven relatively large craters with lip-to-lip diameters > 50 μm, most show a bowl-shaped morphology similar to those observed in LDEF [e.g. 3] and typical of those generated by laboratory impact experiments using projectiles with low internal porosity [5-6]. The bowl-shaped craters contain either single mineral or complex multiple component residues composed of Mg-silicates (probably olivine or pyroxene) and Fe-sulfides, an assemblage broadly similar to that observed in LDEF residues [3]. One crater contained residue composed solely of an Mg-rich silicate with a stoichiometry comparable to that of olivine (Fo ~97.5%), and had a crater form very similar to the olivine impacts of [6] (Fig. 1). Using the density-scaling calibration of [5-6], the top lip diameter of 59 μm yielded an original particle diameter of 11 μm, with an approximate mass of 2 ng.

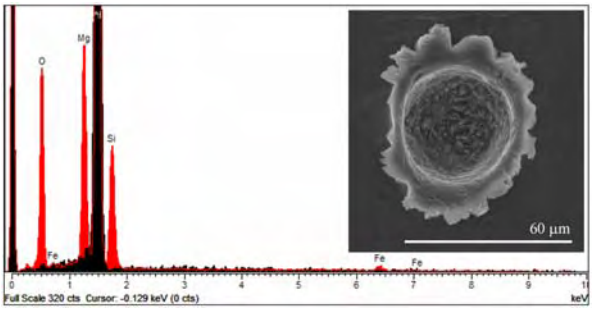

Fig. 1. Secondary electron image of the bowl-shaped crater preserved in foil C2086N and the 20 kV EDS spectra for the dominant Mg-silicate residue phase.

Another of the seven impact features, on foil C2029W, has a significantly different morphology, being broad and shallow with clearly distinguishable

bases of superimposed crater bowls. The crater morphology suggests that the impacting particle was an aggregate of smaller dense grains each of a few micrometers diameter. SEM-EDS also revealed patches of residue from different phases within different parts of this compound feature, including Mg-silicates, Ca-rich silicates (probably pyroxenes), Fe- and Ni-sulfides and carbon-rich material.

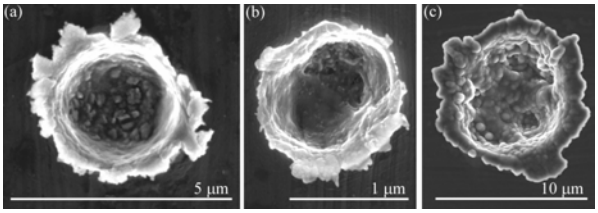

Fig. 2. Secondary electron images of the typical morphologies seen in impact craters preserved on the foil surfaces.

The survey of foils C2027, C2054W, C2100N and C2125N yielded a diverse range of smaller craters, from 8 μm to approximately 100 nm in diameter. Crater morphologies are equally diverse, with both bowl-shaped and complex shapes observed (Fig. 2). SEM-EDS analysis of the bowl-shaped crater (Fig 2a) showed an elemental assemblage that suggests the original cometary projectile was a single Mg-Fe silicate mineral grain. Further detailed TEM study of a FIB cross-section of residue confirmed the elemental composition of the dominant amorphous residue to be indistinguishable from that of olivine. However, the amorphous residue also contained nano-meter scale crystalline olivine grains of similar composition. At the Stardust impact capture velocity, the peak pressure experienced by an impacting silicate particle is likely to be ca. 70 GPa, at the lower limit of "whole rock" melting. The survival of crystalline grains suggests that during hypervelocity capture, even within small projectiles (original particle diameter is less than 1 μm), strain is not evenly distributed. Perhaps the most highly shocked "front-face" of the projectile becomes "molten" upon contact with the target, whereas the "rear-end" is less altered.

SEM-EDS of the complex-shaped crater (Fig. 2b) revealed elemental assemblages of at least two components within the residue, enriched in Mg-Fe-Si and Fe-S, implying that the cometary precursor particle was a mixture of silicate and sulfide. The inferred mineralogy of these two examples is consistent with the grains captured in the aerogel [9].

For the craters generated by aggregate particles, the question arises as to how the different components were held together. Did these grains, like anhydrous IDPs, contain carbonaceous material that essentially cements the silicates and sulfides together? Several craters with a distinctive irregular morphology (e.g. Fig 2c) show a very high carbon peak within their elemental assemblages, substantially above both the background level of the foil and the level of potential contamination deposited during SEM studies. We suspect this may indicate the presence of volatile organic material. As SEM-EDS does not allow more extensive characterization of carbon-rich material, we propose to FIB extract the residue for analysis using ToF-SIMS.

From analysis of this limited data-set, the crater residues have not yet revealed any additional "exotic" mineral phases, such as the CAI-like materials observed in the aerogel tracks [1, 9], and we have found no convincing evidence of layer-silicates and carbonates, minerals inferred to be present in the Deep Impact ejecta of comet 9P/Tempel 1 on the basis of Spitzer Space Telescope spectral data [10]. We have not yet identified a crater residue that is analogous to the stratospheric-collected anhydrous IDPs, which are fluffy aggregates composed of silicates, sulfides and carbonaceous material, previously attributed to a cometary origin [11]. Finally there is also no sign of material that might have been derived as secondary impact ejecta from other parts of the spacecraft itself.

Conclusions: The analysis of cometary residues preserved within the craters indicate a similar compositional diversity throughout the micrometer to nanometer scale particle size range of dust released by Comet Wild-2, with no obvious relationship between chemical composition and size of the impacting particle. Further detailed studies of the residues using multiple techniques are required to assist in the interpretation of these unique sample return materials.

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