STRUCTURE AND COMPOSITION OF COMET WILD 2 RESIDUES IN SUB-MICRON TO MICRON-SIZED CRATERS.
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Introduction: The analysis of residues in craters produced by the impact of comet Wild 2 dust grains on Al foils provides complementary information to the study of the grains collected in aerogel. Although in general the grains that impacted the Al foil experienced much higher levels of shock-induced alteration than did the grains captured in low density aerogel, the crater residues are localized in a readily analyzable volume, and do not suffer from contamination with melted aerogel, or aerogel contaminants, such as hydrocarbons. Craters produced by impacting grains ≤ 1 um in diameter can be readily identified by SEM mapping of the foils, and analyses of nearly 300 of these craters were reported as part of the preliminary examination [1, 2]. Some information about the mineralogy of the impacting grains can be inferred directly from SEM-based energy dispersive spectroscopy (EDS) measurements, including whether the individual impacting grains were Fe(Ni) sulfides, Mg, Fe silicates, aggregates of both sulfides and silicates, or of a more rare type, such as an oxide or carbonaceous phase. Transmission electron microscopy (TEM) studies of crater cross-sections can provide more detailed mineralogical information, but due to the time-consuming nature of these measurements, only 8 such analyses were performed during preliminary examination [3]. Here we report on 89 additional micrometer-sized and smaller craters that we identified by automated SEM mapping, and TEM analysis of cross-sections from 6 of these craters.

Experimental methods: Automated SEM mapping of foil C2043 N, 1 was performed at the Carnegie Institution with a JEOL 6500 FE-SEM, equipped with an EDAX energy dispersive spectrometer and particle analysis system. Crater candidates were identified by visual examination of individual SE images, and subsequently re-imaged at higher resolution. The nominal elemental compositions of the residues were determined by EDS. The crater diameters were measured at the inner and outer edges of the rim; reported diameters are from the midpoint of the rim.

Transmission electron microscopy (TEM) studies of six craters were performed at the Naval Research Laboratory. We used a FEI Nova 600 to prepare focused ion beam (FIB) lift-out cross-sections of the craters for the TEM analyses. The TEM studies were carried out on a JEOL 2200FS field-emission microscope, equipped with a Noran System Six EDS system. Scanning TEM (STEM) high-angle annular dark-field images and EDS spectrum images, conventional high resolution and bright field images were obtained for each sample and diffraction patterns where possible. Additional point EDS measurements were obtained in STEM mode using a fixed probe with a nominal 1-nm diameter.

Results: We identified a total of 89 craters, ranging in diameter from 110 nm to 1070 nm. The shape of the craters varied significantly from round and symmetric, to oval and asymmetric. Two of the craters were shallow enough to indicate a low density impacting grain. Three of the craters showed double bowls, indicative of complex aggregate impacting grain. SEM-EDS spectra indicated that: 21 craters contained only sulfide; 24 contained only Mg, Fe silicate; 26 contained both sulfide and silicate; 4 contained carbon and in 13 cases the composition of the residue could not be determined. Of the carbon-bearing craters, only one was shallower than average.

More detailed elemental analysis was obtained from STEM-EDS measurements of the FIB lift-out sections. All 6 crater cross-sections contained sulfide residue, although in one case (crater 154), no S was detected in the corresponding SEM-EDS spectrum. The composition of the sulfides (Fig. 1) varied from S-poor to Fe-poor, with Ni contents ranging from 3 to 12 at%, with no statistically significant correlation between S and Ni content. The grain size of the sulfides was typically significantly smaller than the nominal 100-nm thickness of the lift-out section, prohibiting quantitative measurements of individual grains in most cases. It is possible that these residues actually contain Fe, Ni metal in addition to sulfides, and we use the convention Fe-Ni-S to refer to these mixtures.

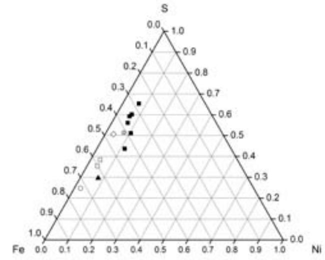

Figure 1. Elemental Composition of the Fe-Ni-S Component of Wild 2 Residues in Al Foil Craters. Filled symbols correspond to individual point dwell measurements (▲ C174; ■ 113) and open symbols to averages calculated from spectrum images (□ d71; ○ b4; ☆154; ◇ 369).

In addition to Fe-Ni-S, 5 of the 6 crater sections show at least one additional phase. In three cases, (d71, 369, and 113) the additional phase was an Mg, Fe silicate with minor amounts of Ca, Cr, and Mn (Fig. 2A). The other two craters contained unusual residues: Crater b4 (Fig. 2B) showed a 50-nm chromite ($FeCr_2O_4$) grain and 154 (Fig. 2C) showed carbon and Mg-free silica phases, in addition to sulfides.

The chromite grain identified in crater b4 has a compact, blocky appearance, and penetrated to a greater depth in the Al than did the associated Fe-Ni-S material. High resolution imaging of the grain shows lattice fringes with spacings of 0.292, 0.251, and 0.164 nm corresponding to the (220), (311), and (333) spacings of chromite respectively. The lattice spacings and planes angles are consistent with the chromite [1,-1,4] zone axis. The lattice fringes are only visible in the bottom half of the chromite grain, where there is no sulfide. The top of the grain is coated in 2 to 20 nm Fe-Ni-sulfides. STEM-based EDS spectra obtained in point dwell mode show Cr, Fe, O and S that quantify to the expected 1:2 ratio for Fe:Cr in chromite. Aluminum is also present in the spectra, and could alloy with Cr spinel. However the lattice spacings indicate pure chromite, thus we attribute the Al signal to the foil substrate.

Crater 154 (Fig. 2C) shows a carbonaceous residue along with Mg-free amorphous silica. The carbonaceous residue shows show some weak lattice fringes suggestive of poorly crystalline graphite.

Discussion: Our studies of craters from the Stardust mission cometary collection are in agreement with prior studies that indicated: (1) even for small craters (< 3 um), the most common impacting cometary grain was polymminerallic, including at least Mg silicate and Fe sulfide components; (2) the observed sulfide compositions are consistent with troilite and pyrrhrotite, and pentlandite is very rare if present; (3) the shape of the crater is highly variable and depends in part on the mineral content, and grain size distribution of the impacting dust aggregates. The crystallographic orientation of the Al substrate may also affect the crater shape, due to the directional dependence of the yield strength, and we plan additional TEM studies of the foil sections to determine the Al grain orientations. The occurrence of chromite, or carbon accompanied by Mg-free silica have not been reported in prior crater studies. Chromite is however a common phase in meteorites [4], and may form by several different processes, including as presolar or solar condensates, solid state reaction or exsolution. The lack of associated phases other than sulfides indicates that this Stardust chromite grain is most likely a primary condensate. The carbonaceous grain associated with silica is possibly the residue of a carbonaceous mantle on an amorphous silicate or GEMS grain. The weak graphitization of the carbon likely occurred on impact.

In these small craters from the cometary tray, the sulfide components appear to have entirely melted on impact. However, more refractory components, such as the chromite observed in the 240-nm diameter crater b4, can survive with less severe impact alteration. This suggests the possibility that refractory oxide components of interstellar grains may be preserved in craters in the interstellar foil collection, which are now under preliminary investigation.

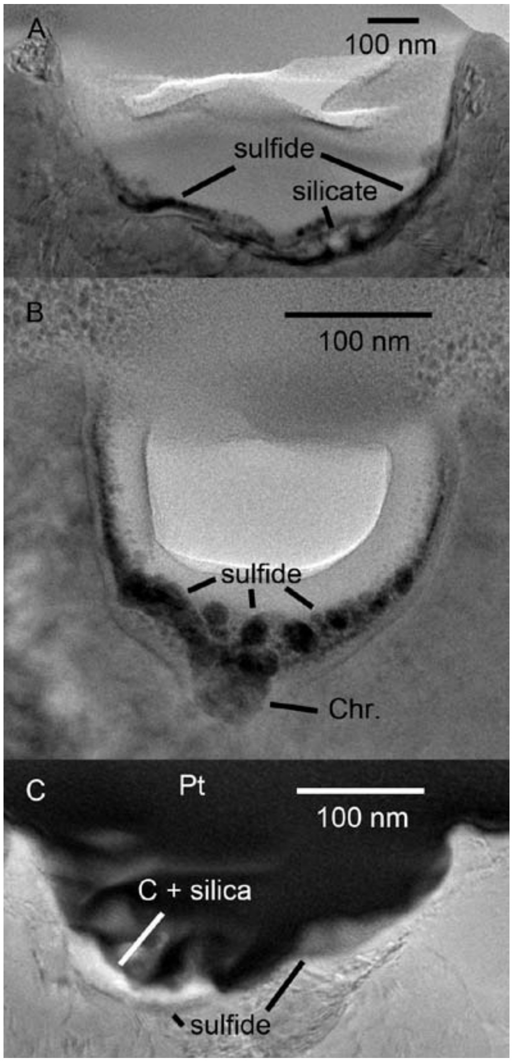

Figure 2. Transmission electron microscope images of Comet Wild 2 Grain Residues in Foil Craters. (A) Crater 369. (B) Crater b4. The label Chr. indicates a chromite grain. (C) Crater 154.

References: [1] Hörz F. et al. (2006) *Science* 314, 1716-1719. [2] Kearsley A.T. et al. (2008) *MAPS* 43, 41-74. [3] Leroux H. et al. (2008) *MAPS* 43, 143-160. [4] Ramdohr P. (1963) *JGR* 68, 2011-2036.