Introduction: For decades, the composition of cometary dust has been investigated by astronomical observations in the infrared [e.g. 1,2,3]. The ~10 μm and ~16-35 μm silicate features are commonly fit by amorphous and crystalline silicates, and the possible inclusion of phyllosilicates has remained controversial. However, fitting of recent Spitzer space telescope spectra obtained after the Deep Impact event identified phyllosilicates (8% by surface area of all silicates) in comet 9P/Tempel 1 [4]. If correct this identification is intriguing: If phyllosilicates are a common component of cometary nuclei, there are major implications for our understanding of the formation and evolution of these small solar system bodies. Most authors believe that phyllosilicates are formed through aqueous alteration which requires the prolonged presence of liquid water [5], and their abundance within cometary nuclei would challenge the common conception of these bodies as objects frozen since their accretion. It would also require reassessment of the distinction between presumed asteroidal and cometary origins of meteoritic materials which have previously been heavily based on the presence or absence of hydrated minerals (e.g. CS vs. CP IDPs [6]).

The return of Stardust samples from comet 81P/Wild 2 provides an unequalled opportunity for unambiguous laboratory analyses of ‘fresh’ cometary dust and comparisons against spectral data, IDPs and meteorites already in our collections. To date, analysis of Wild 2 dust has revealed a wide range of anhydrous minerals, but no phyllosilicates have been unambiguously identified [7,8]. Although this could be explained by different formation regions or parent body processes from comet to comet, it is possible that the high pressures and temperatures generated during impact collection [9] have resulted in the destruction of these volatile-bearing minerals. To be confident in our interpretations of this unique sample set, it is vital that we understand how phyllosilicates may be modified by collection. Laboratory light gas gun (LGG) experiments simulating Stardust encounter conditions have previously demonstrated that some portion of large (150 μm) phyllosilicate grains survive impact into the collector’s aerogel cells with intact layered structure and compositions [10,11]. We have undertaken a study to explore the survivability of smaller phyllosilicate particles impacting aerogel and phyllosilicates impacting the Al foil. Here we present the results of an investigation into the alteration of phyllosilicates impacting the Al foils.

Figure 1: BF TEM images of lizardite (top) and cronstedtite (bottom) residue FIB sections. In the accompanying colour-coded maps, red is the protective Pt strap, yellow is epoxy, blue is the Al foil substrate and green is the impact residue.

Experimental Methods: Powdered phyllosilicates, lizardite and cronstedtite, were prepared from grains extracted from terrestrial rocks. The powders were fired as single component buckshots [12] at Stardust flight spare Al foils in LGG shots at the U. of Kent.

Focused ion beam microscopy (FIB) was used to prepare sections from remaining projectile grains and crater residues for analysis by transmission electron microscopy (TEM). The FIB process for creating these sections is greatly complicated by non-flat sample geometry (e.g. deep craters). Indeed, the deepest regions of the craters, where the majority of residue resides, remain inaccessible to FIB lift-out. For this reason a section of foil was mounted vertically within a
resin block. This block was then polished down until the cross section of a >50μm diameter crater was exposed. Scanning electron microscopy with energy dispersive X-ray analysis (SEM EDX) was then used to determine the major elements in the outcropping residue and identify a suitable crater. Projectile material was prepared for FIB in similar resin blocks.

FIB sections were produced using FEI Nova600 NanoLab and Strata dual-beam FIB microscopes. They were then analyzed using the LLNL 300kV FEI Titan scanning transmission electron microscope (STEM). TEM EDX data was obtained for bulk chemistry, and STEM EDX maps provided detailed chemical data for the highly complex residues. High-resolution TEM imaging and diffraction patterns were used to identify crystalline and amorphous components.

Results & Discussion: TEM analyses confirm that the projectiles are pure, crystalline samples of lizardite and cronstedtite. Bright field (BF) TEM images of each residue (Fig. 1) show complex effects of impact.

Lizardite. The lizardite residue is highly vesiculated, a texture indicative of the release of volatiles (i.e. water) during intense impact-generated heating. Dark field TEM imaging combined with diffraction patterns show the residue to be completely amorphous, however, it retains an Mg to Si ratio close to that of the original impactor, although slightly depleted in Mg: 100Mg/(Mg+Si) = 54.8±2.5 (1σ error) from 59.9±1.1 originally (Fig. 2). The section thickness is non-uniform due to complexities of FIB-milling heterogeneous residues and, as such, lower Mg counts may be due to X-ray absorption in thicker regions. Minor loss of Mg cannot be completely excluded although previous work suggests Si would be preferentially lost [13,14,15]. EDX maps show some sub-micron segregation of Mg and Si but no evidence for Al incorporation into the silicate.

Cronstedtite. The cronstedtite residue is also vesiculated, although to a lesser degree than the lizardite. While the bulk of the residue is amorphous, a large number of sub-micron crystalline Fe metal spheres are present throughout. The Al foil contains inherent Fe rich inclusions [16] which, if impacted, might spread Fe melt droplets throughout a residue, however, TEM EDX data indicate the bulk Fe to Si ratio has remained close to that of the original projectile (Fig. 2, 100Fe/(Fe+Si) = 79.5±3.6 (1σ error) from 77.2±0.7 originally) and therefore suggests these spheres are the result of segregation of Fe from Si in the cronstedtite.

Conclusions: The layered structure of lizardite and cronstedtite has been completely destroyed by impact and altered to a moderately-to-highly vesiculated amorphous residue. Such vesiculated textures may be signatures of phyllosilicate impacts (cf. [17]) since to date, they have not been observed in LGG anhydrous silicate residues [18]. Previous TEM analyses of 8 Stardust craters did not identify such vesiculated residues [19] providing no clear evidence of phyllosilicates in Wild 2 so far. While bulk chemical data indicates retention of near-original Mg to Si and Fe to Si ratios, closer inspection reveals segregation of these elements on a sub-micron scale indicating rapid diffusion and, in the case of cronstedtite, crystallization of new phases even in the short timescales applicable to such impacts.


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