SILICATES AND GLASS IN COMET WILD 2 SAMPLES: AN ANALYTICAL TRANSMISSION ELECTRON MICROSCOPE STUDY.

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Introduction: We received a total of nine Wild 2 samples from NASA JSC for our examination during the period of February to June, 2006 (Table 1). In this paper, we present the results of detailed mineralogical investigation of those samples using an analytical transmission electron microscope (TEM). The results reveal that the nine samples can be divided into three groups on the basis of their constituents: (1) crystalline silicate-rich (three samples), (2) Si-O glass-rich (four), and (3) indefinable (two) (Table 1). All three samples in group (1) were found at track termini in the aerogel capture cells, whereas the rest were found along tracks. This paper focuses on the results of the samples in groups (1) and (2). The two samples in group (3) contain a variety of unusual materials, some of which may be contaminants; their results will be shown elsewhere.

Table 1 Wild 2 samples.

(1) Silicate-rich	FC13-0-17-1-3
	C2115-24-22-1-8
	C2027-2-69-1-4
(2) Si-O glass-rich	C2004-1-44-4-4
	C2054-0-35-16-6
	C2054-0-35-44-3
	C2054-0-35-53-3
(3) Indefinable	FC4-0-3-1-1
	FC12-0-16-1-6

The samples used in this study are ultramicrotomed sections (70-100 nm in thickness) mounted on amorphous carbon-supported TEM grids [1]. They were studied with a JEM-2010 TEM, operated at 200 kV and equipped with an energy dispersive X-ray spectrometer (EDS).

Results: Silicate-rich Particles:

FC13-0-17-1-3: Thin sections consist of lath-shaped to anhedral grains (0.3-1.5 µm in size) of low-Ca pyroxene and minor amounts of anhedral grains (0.2-1.0 µm) of Fe-rich olivine and high-Ca pyroxene (augite). Selected-area electron diffraction (SAED) patterns and EDS spectra from low-Ca pyroxene grains indicate that they are orthoenstatite. Olivine ranges in composition from Fa_{30} to Fa_{50}. Minor amounts of anhedral grains (0.1-0.3 µm in diameter) of Ni-bearing Fe sulfide are scattered.

C2115-24-22-1-8: Thin sections consist of lath-shaped to anhedral grains (0.3-2.0 µm in size) of Fe-rich olivine and less abundant high-Ca pyroxene (diopside) and Si-O-Al-rich glass. Olivine has a wide compositional range, from Fa_9 to Fa_{36}. The Si-O-Al-rich glass contains minor variable amounts of Na, Mg and K.

One of olivine grains has a high density of dislocations that have Burgers vector $b = [001]$ (Fig. 1). The density of dislocations is in the order of 10^{10} cm^{-2}. Such a high density of dislocations of this type is known to be diagnostic of deformation at high strain rates and low temperatures [e.g. 2, 3], and they most likely resulted from shock deformation. The micro-texture exactly matches those found in naturally shocked chondrites [2-6] and an experimentally shocked chondrite [7].

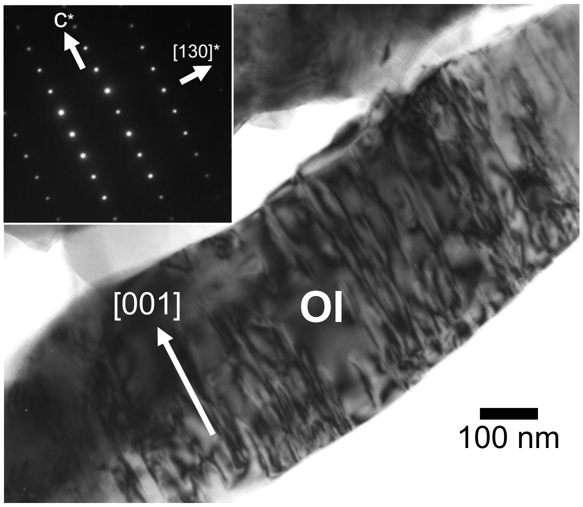

Fig. 1 An olivine grain having a high density of dislocations with straight [001] segments in C2115-24-22-1-8. In the inset is its SAED pattern.

C2027-2-69-1-4: Thin sections partly have smooth, rounded external shapes and exhibit a zone texture consisting of a core surrounded by inner and outer rims.

The core consists of lath-shaped to anhedral grains (0.5-2.0 µm in size) of low-Ca pyroxene, which range in composition from enstatite to pigeonite. SAED patterns from the pyroxene grains indicate that they are clinopyroxene having a disordered stacking of clino- and ortho-pyroxene. Fe-rich olivine (Fa_{19-24}) occurs in minor amounts as small grains (0.2-0.4 µm in size).

The inner rim consists of an array of plates (0.1-0.3 µm in width, 0.5-2.0 µm in length) that are oriented roughly in the same direction. The plates are Si-O-rich glass containing minor, variable amounts of Mg and Fe. They contain high densities of Fe-Ni sulfide/metal beads (5-150 nm in diameter) and vesicles (10-300 nm).

The outer rim consists of Si-O glass with no other elements, which is probably melted aerogel.

Si-O Glass-rich Particles: The four particles, C2004-1-44-4-4, C2054-0-35-16-6, C2054-0-35-44-3 and C2054-0-35-53-3, show close similarities in mineralogy and texture to each other. Their sections consist of arrays of roughly parallel-oriented plates that are 0.1-0.3 µm in width and 0.5-3.0 µm in length. The plates consist of a Si-O-rich glass containing minor variable amounts of Mg and Fe. The plates contain numerous spherical Fe-Ni metal/sulfide inclusions (5-300 nm in diameter) and vesicles (20-300 nm). SAED patterns from Fe-rich metal inclusions indicate that they are kamacite. Compositions of Fe-Ni-S inclusions show considerable differences between the particles.

Discussion: Mineralogical Characteristics of Silicates: Olivines in the three silicate-rich particles differ in Fa contents between the particles and show a wide range of Fa contents within individual particles. The range of compositions is comparable to those in anhydrous chondritic IDPs [1]. It is remarkable that olivine grains within individual aggregates of C2115-24-22-1-8 have distinct compositions (Fa_{9-36}), exhibiting heterogeneity on a submicron scale. In chondrites, olivines with such fine-scale heterogeneity can be observed in fine-grained matrix of the least equilibrated type 3 chondrites [e.g. 8]. Thus the observations suggest that the degree of thermal metamorphism on comet Wild 2, if any, was extremely low.

The finding of an olivine grain with a high density of dislocations provides evidence that the Wild 2 particle may have experienced hypervelocity impacts before capture. Based on the shock experiments, such a high density of dislocations is known to be formed by deformation induced by shock at peak pressures higher than 27 GPa [e.g. 3, 7]. In the case of impact on aerogel, the shock pressure is significantly lower than on normal rock targets. From the calculations by Kitazawa et al. [9], the shock pressure generated by an impact of an olivine projectile on the aerogel with a density of 0.128 g/cm^3 at a speed of 6.1 km/s is ~1 GPa. Because the density of the Stardust aerogel (<0.05 g/cm^3) is much lower, the pressures generated by impacts on the Stardust aerogel are estimated to be even significantly lower than 1 GPa. This means that the high density of dislocations in the Wild 2 olivine may be ascribed to impact before capture, presumably on the comet.

Pyroxene occurs in all the three silicate-rich particles as a major phase. Their structural types and compositions show striking differences between the particles and within individual particles. Although FC13-0-17-1-3 and C2027-2-69-1-4 contain low-Ca pyroxene, the pyroxene in the former is orthoenstatite, and the pyroxene in the latter are clinoenstatite and pigeonite. Orthoenstatite is known to form through very slow cooling from temperatures above 600 °C, whereas clinoenstatite to form through rapid cooling from above 1000 °C [10]. Therefore, the difference in structural type of enstatite suggests that the Wild 2 particles contain materials that have experienced distinct high-temperature and cooling histories.

Core-to-Rim Texture of C2027-2-69-1-4: The core-to-rim texture of C2027-2-69-1-4 suggests that the Mg-Fe-bearing Si-O glass in the inner rim was formed by mixing of melted low-Ca pyroxene and melted aerogel during capture heating. Fe-Ni sulfide/metal contained in the incident cometary particle would have been preferentially melted and spread as droplets throughout the inner rim. Therefore, the core-to-rim zone texture can be regarded to reflect the temperature gradient from inside to outside of the particle produced during capture heating.

Relationship between Silicate-rich Particles and Si-O Glass-rich Particles: The four Si-O glass-rich particles exhibit a striking similarity in texture and mineralogy to the inner rim of C2027-2-69-1-4. The similarity suggests that the four Si-O glass-rich particles were formed by mixing of melted cometary silicates and melted aerogel during capture. The heterogeneities in Mg and Fe contents in the Si-O glass may be related to the distributions of olivine and pyroxene fragments incorporated before their melting. The Fe-Ni sulfide/metal beads were probably produced by melting of Fe-Ni sulfide/metal carried with the cometary silicates. Therefore, we conclude that the four Si-O glass-rich particles were secondary products formed by interaction between melted cometary particles and melted aerogel during the capture process.

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