SULFIDE-METAL TEXTURAL RELATIONS IN A GLASSY STARDUST PARTICLE.

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Introduction: The majority of captured Stardust grains examined during the Stardust Preliminary Examination (PE) stage are aggregates of crystalline phases (predominantly the silicate minerals olivine and/or pyroxene, with less abundant but ubiquitous Fe-Ni sulfides [1,2]) and amorphous silica-rich material [1]. Heating effects during particle capture in aerogel varied widely, from preservation of crystalline phases in multiphase aggregates to complete melting [1].

Sulfides are the only mineral group common to all primitive solar-system materials [1]. Capture-melted sulfide-metal grains may preserve compositional information that illuminates the pre-capture chemical (aqueous alteration?) history of the parent [1]. PE results suggest strong similarity (compositional overlap) of Stardust sulfides with the sulfides of anhydrous interplanetary dust particles (IDPs) and much less compositional overlap with the sulfides of hydrous IDPs [1]. Because they are ubiquitous in Stardust samples, Fe-Ni-S minerals are also useful indicators of impact-collection heating [1].

This paper describes the (TEM-scale) petrography of sulfides and metals in one large and almost completely melted Stardust fragment. The sample described here represents an opportunity to examine in detail petrographic relationships of minerals in the Fe-Ni-S system that coexist in a single fragment, but that are in many ways representative of the same minerals in a broad range of Stardust grains examined to date.

Methods: Fragment C2054.0.35.16 was prepared at NASA JSC as part of the Stardust PE effort. TEM (bright-field) imaging, EDS data acquired in TEM and STEM modes, and SAED data are reported here.

Results: Most of this extracted grain consists of vesicular glassy material with dark inclusions, identical to that previously described from multiple Stardust samples [1]. EDS analyses indicate broadly chondritic compositions of elements indigenous to the cometary particles. Iron is the most abundant element (except for contaminant-enhanced Si); ratios of most elements to Fe are within a factor of four of chondritic (CI) abundance ratios.

Angular and rounded objects darker (in bright-field TEM) than the vesicular glass are ubiquitous in this sample. Shapes range from angular to rounded, with rounded objects dominant. Angular objects appear to consist most commonly of single crystals, and are referred to here as angular minerals. Rounded objects are here termed "beads", without genetic connotation.

Sulfides and metal both occur as both angular minerals and beads. Beads commonly contain both metal and sulfide (details below). The rounded inclusions (beads) are identical to those previously described from multiple Stardust samples [1].

Angular crystals: Angular minerals are not abundant, and appear to occur in clusters rather than being uniformly distributed throughout the sample. They are commonly subequant, and range from a few tens of nanometers to slightly more than 100 nm in longest dimension. SAED patterns from several angular/subhedral minerals indicate FeS (troilite) and pentlandite; EDS maps indicate appreciable Ni in all grains in the cluster.

Beads: Rounded objects (beads) are very common and widely distributed in this sample as in many other samples [1], ranging in diameter from tens of nanometers or smaller to slightly more than 100 nm. TEM images show both concentrically layered (two-phase) spherical beads and hollow spherical shells strongly resembling the outer shells of the concentrically layered beads. EDS mapping reveals that the cores of concentrically layered spherical objects are dominated by Fe, whereas S appears to be preferentially concentrated in the outer layers of layered spherical beads. SAED patterns indicate FeS (troilite) in some, Fe,Ni metal (taenite) in others. Hollow shells appear identical to shells around cores; cores may have been separated from some shells during ultramicrotomy.

Individual spherically symmetric beads are by far the most common in this sample as in others [1]. However, other morphologies also occur. Deviations from circular-spherical symmetry include cross-sections of elongate (e.g., oblate) forms, beads with irregular shells, beads with cores that are not spherically symmetric, and compound beads in which two distinct cores are enveloped by continuous shell material. Fe-Ni-S abundances from EDS analyses of pairs of cores in compound beads, their adjacent outer-layer material, the "bridging" material connecting the two layered objects, and the host glass, indicate that outer-layer material, bridging material, and host glass have Fe-S abundances consistent with Ni-free and largely stoichiometric FeS. Only the core objects contain detectable Ni, and their (Fe+Ni)/S ratios are far too low to be consistent with pure Fe-Ni sulfide.

Discussion: *Textures:* Fe,Ni metal, FeS (troilite, possibly with some Ni in solid solution), and (Fe,Ni)S

(pentlandite) occur as angular crystal fragments. The same minerals (taenite, troilite, and pentlandite) occur in beads; the combined evidence suggests the shells are sulfides. Rounded and angular/subhedral Fe-Ni-S grains span the same range of grain sizes (tens of nanometers to slightly more than 100 nm), suggesting that the two forms might be genetically related.

Deviations from simple spherical geometry, although relatively uncommon as a fraction of all occurrences, might be especially informative. In some beads with cores and distinct shells of largely uniform thickness, the cores are not spherical. This geometry is difficult to explain as a surface-tension controlled form taken on by a fully molten core. This suggests the possibility of incomplete melting of a precursor mineral still preserved as the core. Equant but initially angular grains become rounded (beginning with rounding of edges and corners) if mass- or heat-transfer is rate-determining during dissolution or melting [3]. This core morphology suggests that some bead/droplet precursors were not completely melted during particle capture. Compound beads consist of pairs of Fe-Ni-rich cores connected to one another by bridging material consisting of Fe-S-rich material. One particularly informative larger core suggest that the core material separated in a not-fully-molten, and that this compound droplet was still in translational (and possibly rotational) motion while the shell material was in a liquid state (still fully molten).

Multiple origins of phases in the system Fe-Ni-S: Texture-composition-mineralogy relations imply a range of degrees of melting of metal/sulfide crystals and beads in this Stardust grain. Angular/subhedral minerals may be either unmelted cometary minerals unmodified by capture, or fragments of partially or completely capture-melted droplets. Compositionally layered beads with non-spherical cores may in some instances represent incomplete melting of precursor material; in other instances, non-spherical cores may represent plastic deformation of partially solidified core material after complete melting.

Crystalline sulfides (troilite, pentlandite) occur both as parts of bead (molten, droplet) assemblages in beads of ~100 nm diameter, and as isolated angular/subhedral crystals of similar size. Some, possibly most, troilite (the shell material of the abundant beads/droplets) is certainly a product of heating during aerogel capture followed by cooling from a molten state. SAED patterns of shells (especially hollow shells separated from their cores) indicate crystalline FeS, consistent with numerous EDS analyses of S-rich shells close to stoichiometric (Ni-poor) FeS. However, it is unlikely that all the troilite in this sample was modified by melting during

capture. While in principle the angular minerals might be fragments of similarly capture-processed melt assemblages, it is noteworthy that droplets large enough that their mechanical disruption might have liberated such sulfides are not observed. It appears more likely that the angular/subhedral sulfides are precapture minerals that escaped heating in the extremely heterogeneous thermal regime of aerogel capture [1], rather than pieces of disrupted capture-melted metal/sulfide assemblages like the beads/droplets. Thus, it appears that the inventory of crystalline FeS (troilite) in this sample contains contributions of both pristine cometary (precapture) and capture-modified melt-produced origins. As pentlandite occurs in both angular grains and droplets, pentlandite, too, may represent both cometary and capture-modified populations. Further work is required to establish more precisely (1) important differences between the two populations, (2) the cometary significance of the inferred precapture population, (3) the details of the capture-heating process, and (4) any precapture compositional information retrievable from the compositions of partially and complete melted beads.

Summary and Conclusions: FeS in this Stardust sample is polygenetic. Much FeS in this sample occurs as the outer shells of beads (solidified sulfide/metal droplets), indicating that much stoichiometric FeS in this Stardust particle is thoroughly melted and extensively modified. FeS occurs both as unmelted angular-subhedral grains (primary cometary FeS; [1]) and as shells/envelopes around rounded Ni-bearing (completely melted) metal and/or (residual primary?) pentlandite cores (secondary, capture-produced FeS). Pentlandite similarly occurs as both a primary preserved precapture mineral (occurring as isolated angular crystals), and as part of partially or completely melted (rounded) grains. The presence of primary Ni-bearing sulfides (pentlandite) and the widespread occurrence of Fe,Ni metal (taenite) cores in most Fe-Ni-S beads suggests that Stardust projectile particles contained Ni-bearing sulfides.

References: [1] Zolensky M. E. et al. (2006) *Science*, *314*, 1735. [2] Hörz F. et al. (2006) *Science*, *314*, 1716. [3] Velbel M. A. (2004) *J. Geosci. Educ., 52,* 52.