COMPREHENSIVE EXAMINATION OF LARGE MINERAL AND ROCK FRAGMENTS IN STARDUST TRACKS: INSIGHTS INTO THE SOURCE REGIONS OF COMET WILD 2 MATERIALS. D. J. Joswiak, D. E. Brownlee and G. Matrajt, University of Washington, Dept. of Astronomy, Seattle, WA 98195 joswiak@astro.washington.edu

Introduction: Knowledge of the constituent minerals in comets is fundamental to improving our understanding of how these bodies may have formed and their relationship to the Solar System. The samples returned from comet 81P/Wild 2 by the Stardust (SD) spacecraft provide an unparalled opportunity toward this end.

Here we summarize our observations from the study of more than 85 large discrete rock and mineral fragments from 16 SD tracks. Based on the large number of observed fragments and multitude of tracks, we believe that these fragments are representative of the range of materials in comet Wild 2. Our goals are to understand the morphologies and mineralogical diversity of impacting grains that produced the tracks, to make direct comparisons of the impactors to other ET materials such as chondritic meteorites and interplanetary dust particles (IDPs) and decipher possible source regions of the materials that formed comet Wild 2.

Methods: The SD tracks were removed in keystones [1] from their aerogel cells. The tracks were then flattened and embedded in acrylic resin. After optical examination, large fragments were cut from the tracks and microtomed for TEM studies. Standard TEM techniques including STEM imaging, bright- and dark-field imaging, electron diffraction and EDX were employed. FESEM imaging and qualitative EDX were performed on many of the potted butts.

Track types and impactor morphology: We studied large (> 2 um) fragments from 10 type A (thin, carrot-shaped) and 6 type B (bulbous) tracks [2]. The number of fragments and types of minerals present in the tracks was highly variable and ranged from single terminal particles (TP) in some of the type A tracks to > 30 fragments dispersed along the bulbs and stylii of some type B tracks. Clearly track shape (A or B) and length provide useful physical and mineralogical constraints on the impactor particles. In our study, type A tracks were produced by competent single mineral or rock fragments which had little propensity to fracture during capture while type B tracks were produced by impactors composed of a greater number and diversity of minerals ranging in size from coarse- to fine-grained that were apparently loosely held together. The type B impactors may have had significant porosity, a characteristic typical of chondritic porous or cluster IDPs and some meteorite matrices.

A summary of some of the mineral and rock fragments that we observed, the number of tracks they were observed in and other ET materials with similar mineralogy is shown in the table below. Possible origins of these materials are also listed.

Mineral fragments: Isolated forsterite (>Fo_{99}) and enstatite (>En_{99}) are relatively common single mineral fragments in the SD tracks (upper portion of table). Surprisingly, LIME (low-iron, manganese-enriched) forsterites (MnO > FeO) were also found in four tracks (all type B). LIME forsterites have been reported in CP IDPs and chondrite matrix [3]. Other significant minerals include Fe-rich olivines (~Fo_{40-70}) and rare crystalline SiO_2 (tridymite and cristobalite) fragments. Fe-rich olivines are commonly reported in IDPs, type II chondrules and as clasts/chondrule fragments in chondrite matrix [4]. Cristobalite and tridymite are relatively uncommon in chondrites but are seen in OC clasts/chondrules in LL3.6 chondrites [5].

Rock Fragments: The terminal particles from at least three type A tracks contain polymineralic fragments (lower portion of table) that are directly analogous to chondrules or clasts from CC and OC meteorites. These TPs are all composed of uncommon mineral assemblages. The TP from track 26 (Ada) contains tridymite nodules rimmed by Mn-rich fayalite and is remarkably similar to chondrules/clasts in type 3 UOC's [6]. The unusual roedderite-bearing TP from track 56 (Key A) [7] is similar to chondrules/clasts that are present in OC's of type 3.5 – 3.7 [8]. And the TP from track 130 (Bidi) which is composed of Fo_{97}+aluminous augite+anorthite may be directly analogous to Al-rich chondrules from carbonaceous and ordinary chondrites [9].

A large 5 µm fragment from track 130 (Coki) is composed of fassaitic pyroxene+anorthite+spinel and closely resembles either a type C CAI or a plagioclase-rich chondrule [10].

Additionally, we observed two mineralogically unusual lithologies in the SD tracks that have only been found in CP IDPs. The first is a mixture of Fe-rich olivine and kosmochloric high-Ca pyroxene +/- albite +/- alkali silicate glass +/- spinel and has been given the name 'Kool' grain (Ko=<u>ko</u>smochloric pyroxene, ol=Fe-rich <u>ol</u>ivine) [11]. This assemblage is present in approximately half of the SD tracks and in at least 4 chondritic IDPs. The second lithology is composed of pyrrhotite+pentlandite+Fe-rich sphalerite and has been observed in two type B tracks. We have observed this sulfide assemblage in at least two IDPs but we found no reports of this lithology in chondritic meteorites in the literature.

Noteworthy are the lack of phyllosilicates and associated phases (carbonates, sulfates and carbonaceous materials) that are commonly found in chondrite matrices and in many IDPs.

Discussion: Detailed TEM characterization of a large number of fragments from 16 tracks has shown that the SD fragments are chemically and mineralogically similar to a range of other well-known ET materials including CP IDPs, cluster IDPs, large mineral IDPs, chondrules/clasts, chondrite matrices and refractory inclusions (RI). The chondrule/clast-like materials and RIs support previous studies that suggest inner Solar System materials were thermally processed prior to their transport to comet Wild 2 [12, 13]. However, if the commonly observed minerals forsterite, enstatite and LIME forsterite are hot gas condensates, then a significant portion of the comet may be composed of early-formed primary materials. The unusual Kool grain lithologies and the three-sulfide assemblages (pyrrhotite+pentlandite+Fe-rich sphalerite) which are only found in SD tracks and in IDPs may indicate a source region that selectively fed the Kuiper belt but not regions of the inner Solar System.

The inferred lower densities of the impactors that formed type B tracks are consistent with either IDP aggregates or porous chondrite matrix containing chondrules/clasts and refractory inclusions. In general, the smaller sizes of the SD fragments compared to their meteoritic counterparts suggests that size sorting of some finer-grained materials (particularly chondrules and refractory inclusions) to the Kuiper belt occurred.

The lack of phyllosilicates and associated phases indicates that water-rich minerals, at least on a micron or greater scale, are absent suggesting that these phases may form only on parent bodies rather than in the nebula as advocated by some authors.

Conclusions: Large mineral and rock fragments studied from 16 tracks represent a wide range of materials that formed in the solar nebula. These include single mineral grains that are likely to be nebular condensates, chondrules and refractory inclusions that formed in hot environments in the inner portion of the disk and unequilibrated loosely bound mineral and rock assemblages (type B impactors) that are analogous to CP IDPs or porous chondrite matrix. These materials suggest that comet Wild 2 was a collector of Solar System debris over large time and space scales. The lack of phyllosilicates shows that comet Wild 2 is a mineralogically dry comet and provides direct evidence that hydration of minerals, at least on a large (> 1 μm) scale, did not occur in the nebula.

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Stardust Fragment	# Tracks	Other ET Sources	Possible origin
Mineral Fragments			
Forsterite (>Fo_{99})	3	CP IDPs, chondrite matrix	Condensate
Enstatite (>En_{99})	7	CP IDPs, chondrite matrix	Condensate
LIME Fo [3]	4	CP IDPs, chondrite matrix	Condensate
High-Fe olivine (~Fo_{40-60})	2	IDPs, chondrules, chond matrix	Chondrule
Cyrystalline SiO_2	1	OC chond/clasts (LL3.6) [5]	Fractional Condensate, annealing
Rock Fragments			
Fayalite+Tridymite	1	Type 3 UOC [6]	Chondrule/clast
Roedd+En+Ko-aug+Alk gls	1	L/LL3.5 and LL3.7 OC [8]	Chondrule/clast
Fo_{97}+Augite+Anorthite	1	CC, OC	Al-chondrule
Kool Grain [11]	4	CP IDPs	High T nebular region
Pyrr+Pent+Sphalerite	2	CP IDPs	
Al-Diop+Aug+En_{99}	1	OC matrix lump (H3.7) [14]	Chondrule/clast
Fassaite+Anorthite+Spinel	1	Refractory Inclusions	Refractory inclusion

Roedd=roedderite, En=enstatite, Ko-augite=kosmochloric augite, alk gls=alkali glass, pyrr=pyrrhotite, pent=pentlandite.