**A Roedderite-Bearing Terminal Particle from Stardust Track 56: Comparison with Rare Peralkaline Chondrules in Ordinary Chondrites.** D. J. Joswiak[1], G. Matrajt[1], D. E. Brownlee[1], A. J. Westphal[2] and C. J. Snead[2], [1]Dept of Astronomy, University of Washington, Seattle, WA 98195, [2]Space Sciences Laboratory, University of California, Berkley, CA 94720. email: joswiak@astro.washington.edu

**Introduction:** Comet samples returned by the Stardust (SD) spacecraft provide important insights into the physical conditions and dynamic behavior of the early Solar System. High temperature CAI-like minerals from a SD grain, for instance, have shown that large-scale transport of grains likely occurred from the hot inner region of the solar nebula to the cold outer portion where comets formed [1].

Here we examine the mineralogy of a Mg-bearing alkali-rich silicate terminal particle removed from the Stardust collector and note its similarity to the mineralogy of a small group of rare alkali-rich silicate chondrules present in ordinary chondrites (OC's). Our goal is to assess whether these two ET materials could be related to one another and thus potentially have a common origin. The presence of chondrules or chondrule fragments in comet Wild 2 would show material transfer from the chondrule-forming regions in the proto-solar nebula to the comet-forming Kuiper Belt region in the outer Solar System. Further, if chondrule fragments from comet Wild 2 can be identified in SD, they could potentially provide important insights into early chondrule-forming processes.

**Sample Preparation and Analysis:** In this work, the terminal particle (TP) that we studied was removed from an aerogel tile on the Stardust collector grid at JSC and keystoned at the University of California, Berkeley [2]. The TP was extracted from the 650 um long Track 56 in April 2006 with a glass needle and sent to the University of Washington where it was embedded in acrylic and microtomed with a 45° diamond knife. Sub-100 nm thick sections were placed on carbon film substrates on Cu or Au TEM grids and examined with a 200 kV Tecnai F20 FEG TEM/STEM. A combination of techniques were used to study this grain including bright- and dark-field imaging, electron diffraction and energy dispersive X-ray analysis in STEM mode. Compositional analyses were typically obtained on grains using electron beam rastering rather than spots to minimize sample degradation and element loss.

**Mineralogy:** The following phases were all observed in the TP from Track 56: roedderite, low-Ca pyroxene, troilite, a crystalline Na+Cr-bearing Fe+Mg+Ca silicate believed to be the mineral richterite and feldspathic glass. See Table 1 for compositions. Accessory silica and chromite were also observed. Since silicate grains are brittle and tend to shatter and fall somewhat randomly on TEM grids during microtoming, grain-to-grain textural relationships are often obscured thus is was often difficult to establish petrographic relationships between phases except locally where phases were in direct contact.

Table 1: Compositions of terminal particle minerals and glass observed in Stardust Track 56.

| | ***Roed*** | ***Enst*** | ***Fld Gl*** | ***Troil*** | ***Richt(?)*** |
|---|---|---|---|---|---|
| O | 66.039 | 61.427 | 66.287 | 4.743 | 62.193 |
| Na | 5.475 | | 1.025 | ----- | 2.890 |
| Mg | 5.685 | 18.494 | 5.358 | ----- | 6.645 |
| Al | 0.195 | 0.072 | 0.637 | ----- | 0.205 |
| Si | 21.228 | 19.931 | 26.171 | 0.559 | 16.534 |
| S | ----- | ----- | ----- | 46.660 | ----- |
| K | 0.898 | ----- | 0.333 | ----- | 0.365 |
| Ca | ----- | ----- | ----- | ----- | 2.229 |
| Ti | ----- | ----- | ----- | ----- | ----- |
| Cr | ----- | 0.059 | ----- | 0.259 | 1.978 |
| Mn | 0.087 | ----- | 0.017 | ----- | 0.402 |
| Fe | 0.388 | 0.014 | 0.170 | 47.662 | 3.528 |
| Ni | ----- | ----- | ----- | 0.114 | ----- |

Roed=roedderite, Enst=enstatite, fld gl=feldspathic glass, Troil=troilite, Richt=richterite. Normalized atom %.

The most prevalent phase, roedderite- $(Na,K)_2(Mg,Fe)_5Si_{12}O_{30}$ – is observed as broken shards and fragments up to 1 um long. Roedderite is part of a solid solution series with the minerals eifelite $(Na,K)_2(Mg,Fe)_5Si_{12}O_{30}$ and merrihueite. Merrhueite is structurally similar to roedderite but has higher Fe/(Fe+Mg) and lower Na/(Na+K) ratios. In the microtomed sections that we examined roedderite exhibits a fairly narrow range in composition with Na/(Na+K) = 0.83 – 0.87 and Fe/(Fe+Mg) < 0.1. High resolution lattice fringe imaging along with electron diffraction confirm the atomic structure of this mineral as roedderite (Figure 2).

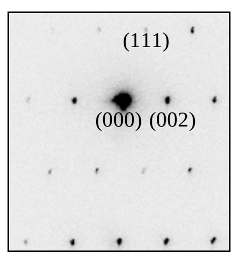


Figure 2: [1-10] electron diffraction pattern consistent with roedderite JCPDS pattern 23-76.

In places roedderite was found to occur with alkali-bearing silicate glass and in at least one location very pure SiO2 glass was observed in sharp contact with the roedderite. Silica is apparently a minor phase as we did not find it in high abundance; we cannot be certain that it is not aerogel melt that was injected between grains from impact heating during particle collection. Likewise, we cannot be certain that roedderite and alkali silicate glass that we observed were not modified, compositionally or structurally during capture.

In addition to roedderite, a second crystalline and compositionally uncommon silicate phase containing Na, Mg, +/- K, Ca, Cr and Fe was observed in euhedral grains up 0.3 um in size. This phase is unusual in its association of Na (up to 3 wt%) with Cr (up to ~5 wt%). Assuming particular cation site distributions (i.e. Cr partitioned between C and T sites) this mineral has stoichiometry similar to the amphibole richterite (Table 1). At least one electron diffraction pattern taken from grains of this mineral is consistent with monoclinic amphibole; some diffraction pattens, however, did not match amphibole diffraction data. Interestingly, richterite has been observed coexisting with roedderite in the iron meteorite, Wichita County [3].

We also observed low-Ca pyroxene (enstatite) in the Stardust TP often occurring as equant crystals up to 0.3 um in size. Other, more Fe-rich pyroxenes may also be present, but most grains studied by EDX were essentially Fe-free enstatite (Table 1).

Subhedral Fe-sulfide up to 0.5 um in size was observed in only a single microtomed slice indicating that this phase is heterogeneously distributed; the measured Fe/(Fe+S) = 1.02 ratio suggests the mineral troilite (Table 1). Additionally a 300 nm rounded grain of chromite was found. Small amounts of Mg, Si and S present in the EDX spectrum imply that silicate and sulfide minerals may have also been present in the analysis.

We note that, unlike the roedderite-bearing chondrules in OC's, fayalitic olivine appears to be absent from the SD grain [4]. This may be significant in that the SD grain may have been removed from its environment before Fe-rich olivine could have formed. Considering that we have observed less than 5 – 10 volume % of the TP, however, this lack of Fe-rich olivine may reflect a heterogeous distribution rather than its absence.

**Comparison to Alkali-rich Chondrules in OC's:** Table 2 shows a comparison between the phases observed in the TP from Stardust Track 56 and those described in the few rare OC's that contain roedderite (or merrihueite) [4,5].

**Table 2: Mineral Comparison between TP from SD Track 56 and alkali-rich chondrules/clasts in OC's**

| Stardust Track 56 | | Chondrules: OC's |
|---|---|---|
| Roedderite | ⇔ | Roedderite |
| Low-Ca Pyroxene | ⇔ | Low-Ca Pyroxene |
| Feldspathic glass | ⇔ | Feldspathic glass |
| Silica (accessory) | ⇔ | Silica |
| Troilite | ⇔ | Troilite |
| ---------- | | Fayalitic Olivine |
| Richterite(?) | | ---------- |
| Chromite | | ---------- |

Grain sizes and modal proportions may differ somewhat but a clear correlation between between the minerals present in the SD grain and the chondrules in the OC's is evident. Thus, it is natural to wonder whether this SD grain may be linked to chondrules in these types of OC meteorites.

**Discussion and Conclusions**: Roedderite is a rare mineral and in ET environments has only been observed in chondrules and clasts from a few ordinary chondrites and in silicate inclusions in two IAB iron meteorites, Wichita County [6] and Canyon Diablo [7].

Two processes have been invoked to explain roedderite/merrihueite formation in these chondrules. In one process, a complex path of fractional crystallization and melting of grains in the solar nebula which ultimately accreted into parent bodies produced roedderite in the PB itself by reaction of alkali-rich gases with siliceous chondrules during mild metamorphic impact events. Late-stage Fe-rich olivine in the chondrules formed by reaction of silica with FeO.

A second model, suggests that merrihueite (akin to roedderite) was formed from condensation and evaporation processes after fractionation of refractory-rich and volatile-rich vapors in the nebula [5]. Alkali-rich vapor reacted with silica-rich chondrules to form merrihueite (roedderite). Fayalitic olivine rims formed on the chondulres later by reaction with FeO-rich vapors.

The rare occurrence of roedderite along with a similar distribution of other minerals and glasses which are present in both the SD Track 56 and a small subset of alkali-rich silicate OC's seems to link these two ET materials and suggest they have a common origin. We cannot uniquely establish a nebular vs PB origin for the Track 56 SD grain, however, as materials in comets could have accreted from both nebular-produced grains and grains dislodged from PB's by collisional events which were presumably common. We indicated that fayalitic olivine has not been observed in the SD particle suggesting that, unlike the alkali-rich silicate chondrules, the SD grain was not altered by FeO-rich vapors. This absence of olivine cannot uniquely establish a nebular vs PB origin for the SD grain. It does indicate, however, that this grain may have been removed from its local environment prior to interaction with FeO. In summary, we believe that the roedderite-bearing TP extracted from SD Track 56 is related to roedderite-bearing chondrules in OC's and may be representative of a small subset of chondrules or proto-chondrules.

**References:** [1] Zolensky et al., *Science*, Vol. 314, no 5806, 1735-1739 (2006). [2] Westphal et al. [2004], *MAPS*, Vol 39, no. 8, 1375-1386. [3] Olsen E. O. (1967) *Science*, Vol. 156, 61-62. [4] Krot, A. N. and Wasso, J. T. (1994) *Meteoritics* 707-718. [5] Wood, J. A. and Holmberg, B. B. (1994) *Icarus* 108, 309-324. [6] Olsen, E. O. (1967) *American Mineralogist* 52, 1519-1523. [7] Seifert, F and Schreyer, W. (1969), *CMP*, Vol 22, 190-207.