**METAL-SULFIDE-CEMENTED AGGLUTINATES: WHAT'S REALLY HAPPENING WITH SULFUR ON ASTEROIDAL SURFACES?** T.J. McCoy[1], M.R.M. Brown[1,2], L.R. Nittler[3] and D. Rost[1] [1]Dept. of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, DC 20560-0119 USA (mccoy.tim@nmnh.si.edu), [2]Dept. of Geological Sciences, Arizona State University, Tempe, AZ 85287-1404 USA [3]Dept. of Terrestrial Magnetism, Carnegie Institution of Washington, Washington, DC 20015 USA.

**Introduction:** The Near Earth Asteroid Rendezvous mission to 433 Eros addressed fundamental issues in asteroid and meteorite science, including the composition (both chemical and mineralogical) and physical state of asteroids. However, NEAR highlighted our still incomplete understanding of the nature of asteroidal regolith and the processes that operate at the asteroid-space boundary. This dearth is in strong contrast to studies of lunar regolith. In particular, lunar agglutinates provide a physical record of the effects of micrometeorite bombardment in lunar regolith, but similar asteroidal agglutinates remain unknown from asteroidal regolith breccias.

Our incomplete knowledge of asteroidal regolith was best highlighted by the unexpected finding of a marked depletion of sulfur on the surface relative to the bulk composition of the most likely meteoritic analog, ordinary chondrites [1]. These authors postulated that S may have been lost by melting and volatilization of troilite during micrometeorite impact or dissociation by charged particle bombardment, with the latter being subsequently supported by several other authors. If these processes are actively altering troilite within the regolith of modern asteroids, we might expect to see some indications of this in the abundance and/or morphology of troilite within ordinary chondrite regolith breccias.

In this study, we report on troilite abundance and morphology in the Dwaleni regolith breccia, including our finding of fine-grained, sulfide-bound silicates that may be the long-missing asteroidal agglutinates.

**Results:** Dwaleni is a classic, ordinary chondrite (H6), light-dark regolith breccia and the section we studied (USNM 5447-2) contains subequal proportions of dark, solar wind-exposed matrix and light clasts. We observed no significant difference in troilite abundance between the light (2.3 vol.% troilite) and dark (2.2 vol.%) areas. These volumetric abundances equate to ~3.1 wt.% FeS, which is well below the value reported by [2] (5.2 wt.%). This probably reflects an undersampling of small grains by our X-ray mapping technique, given that bulk Dwaleni has a S/Si ratio typical of ordinary chondrites [2].

It is among this population of small grains that we found one that proved particularly interesting. The particle is a composite metal-sulfide particle measuring ~65 x 80 microns (Fig. 1) with sulfide comprising ~80% of the particle. It occurs within the dark portion of Dwaleni, that material which was exposed to the solar wind at the surface of the asteroid. The metal is taenite, which is reasonably compositionally homogeneous with ~37 wt.% Ni. Composite metal-sulfide particles are extremely common in meteorites, but this one is unusual in containing a myriad of inclusions ranging in size from 5 μm to «1 μm. An adjacent, more typical troilite grain is devoid of these inclusions.

The small size of the silicate inclusions prevented quantitative chemical analyses, but mineral identifications were possible using a combination of EDS analyses and elemental mapping on the FEG-SEM at the Carnegie Institution and elemental mapping using SEM and TOF-SIMS at the Smithsonian Institution. We have identified mafic silicates (likely both olivine and orthopyroxene based on Mg/Si ratios from EDS), plagioclase and chromite occurring as inclusions within the metal-troilite host.

While the TOF-SIMS offers that highest spatial resolution, it also affords us the opportunity to examine volatile elements, such as those concentrated or depleted by micrometeorite impact. Among these, the halogens (Br, F, Cl) appear enriched in the taenite, although matrix effects complicate this interpretation.

**Discussion:** The small size of this particle could belie its importance in understanding the history of asteroidal regolith. In the 35 years since the return of the first Apollo samples, no agglutinates have been found in asteroidal regolith breccias. Several explanations have been offered, including (1) these breccias are ancient and may not record the processes occurring in modern regolith, (2) the compaction processes that create breccias destroy the delicate agglutinates that are present in the regolith, (3) asteroids may have lacked regolith altogether or at least the mature, fine-grained regolith that forms most agglutinates, or (4) differences in impact velocity might explain the lack of agglutinates [3].

The absence of agglutinates may result from the misconception that asteroidal agglutinates should resemble lunar agglutinates. The term "agglutinate" has been applied in both the lunar sample and volcanology communities. In both cases, the term includes materials welded together by molten material. There is, however, no a priori reason that this molten material should be silicate glass. On the moon, glass dominates this material because silicate dominate the <10 μm fraction of lunar soil – the material most readily melted by micrometeorite impact.

Formation of this particle must have predated its consolidation into Dwaleni, since immediately adjacent troilite grains do not exhibit these fine inclusions. We suggest that the particle observed in Dwaleni is, in fact, an asteroidal agglutinate. It consists of fragments of all of the phases that typically dominate ordinary chondrites, including olivine, pyroxene, plagioclase and chromite. Unlike lunar agglutinates, these materials are bound by metal and sulfide, rather than by a silicate glass. This may be typical for asteroidal surface, which could lack the extremely fine-grained component of the regolith (although the silicate grains within this agglutinate are remarkably fine-grained and would be typical of a mature regolith). Instead, micrometeorite impact may preferentially melt metal and sulfide, which has high shock impedances and are typically the most readily melted phase in heavily shocked chondrites.

The occurrence of these particles is essentially undescribed, probably as a result of only finding what you seek. Metal and sulfide particles with silicate inclusions are often found on chondrule rims in unequilibrated ordinary chondrites, probably as the result of nebular processes. These textures appear to be erased during metamorphism [e.g., 4]. We have examined a number of solar wind-bearing regolith breccias, specifically targeting those with light-dark structure visible in thin section. Among these, we identified similar metal and/or sulfide-cemented silicates in Fayetteville and St. Mesmin. In all cases, these particles were within the dark, solar-wind exposed portion of the meteorite, consistent with their origin as agglutinates.

While several lines of evidence are consistent with the origin of these particles as agglutinates, definitive proof of their origin remains elusive. TOF-SIMS analyses were insufficient to identify depletion of volatile elements (e.g., Se) within the sulfide. The origin of the halogen concentration in the metal remains uncertain, with terrestrial weathering one possible explanation. The large metal grain is Ni-rich taenite, quite unlike the Ni-poor metal we might expect if it were Fe produced by the dissociation of FeS and volatilization of S. Planned future analyses include examination of S isotopes – for an enrichment of the less volatile heavy isotopes – and TEM studies – for minute Ni-free metal blebs produced by volatilization or structures in troilite produced by rapid melting and crystallization.

These particles may hold the key to our understanding the history of sulfur on asteroidal surfaces. If they are agglutinates, they do not exceed the size of average metal and sulfide particles in ordinary chondrites and, thus, would not behave differently (e.g., sink due to a reverse Brazil Nut effect) on the surface of the asteroid. It remains unknown whether S volatilization accompanied formation of these particles, but if this proves to be the case, they suggest that evidence for S volatilization is likely to be found in the finest-size fraction of sulfide within regolith breccias, a situation not altogether dissimilar from the lunar case.

**References:** [1] Nittler L.R. et al. (2001) *MAPS, 36*, 1673-1695. [2] Jarosewich E. (1990) *Meteoritcs, 25*, 323-337. [3] Taylor G.J. and Wilkening L. (1982) *LPI Tech. Rpt.* 82-02. [4] Zanda B. et al. (1997) *LPI Tech. Rpt.* 97-02.

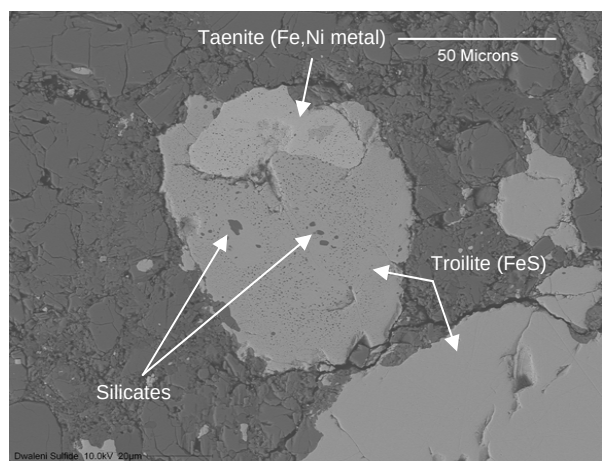


Figure 1 Metal-sulfide particle with included olivine, orthopyroxene, plagioclase, and chromite within the dark portion of the Dwaleni regolith breccia.