THE NATURE OF C ASTEROID REGOLITH FROM METEORITE OBSERVATIONS. M. Zolensky[1], T. Mikouchi[2], K. Hagiya[3], K. Ohsumi[4], M. Komatsu[5], P. Jenniskens[6], L. Le[1], Q.-Z. Yin[7], Y. Kebukawa[8], M. Fries[9].

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Introduction: Regolith from C (and related) asteroid bodies are a focus of the current missions Dawn at Ceres, Hayabusa 2 and OSIRIS REx. An asteroid as large as Ceres is expected to be covered by a mature regolith, and as Hayabusa demonstrated, flat and therefore engineeringly-safe ponded deposits will probably be the sampling sites for both Hayabusa 2 and OSIRIS REx. Here we examine what we have learned about the mineralogy of fine-grained asteroid regolith from recent meteorite studies and the examination of the samples harvested from asteroid Itokawa by Hayabusa.

Asteroid Ponds: From imaging of Itokawa from Hayabusa and Eros from the NEAR Mission we know that even sub-km sized asteroids have fine-grained (cm-sized or small grain size) ponds [1], and as the Hayabusa Mission illustrated, the relative safety of these ponds make them probable sampling targets of all foreseeable missions. Since the processes that form ponds include electrostatic grain levitation [2], it is likely that ponds provide a global sampling of lithologies on an asteroid (to a certain degree, see below), and also include a representative sampling of xenolithic objects. However, seismic shaking causes the ponds to differentiate vertically, such that smaller and denser grains settle to the pond bottoms, and larger and lower density grains remain near the surface, which introduces a bias in spectroscopic and XRD analyses of pond surfaces from spacecraft, and in collected samples from the tops of ponds. There is some insight into the mineralogy and composition of the Eros ponds' surfaces from NEAR spacecraft spectroscopy and XRF [1,3,4,5,6,7]. Compared to the bulk asteroid, ponds are distinctly bluer (high 550/760 nm ratio). This blueness is consistent with loss of metal from the pond surfaces compared to bulk Eros regolith, as seismic shaking causes the heavy metal grains to percolate downwards. The samples returned from Itokawa (an LL chondrite object) by the Hayabusa spacecraft revealed the same phenomenon – metal was much less abundant in the returned samples than in the LL chondrites [8]. Similarly, we have interpreted clasts in Vigarano and Allende to be indurated pond deposit fragments, where metal is absent from top layers, and concentrated in bottom layers [9].

Pond Deposit Clasts in Meteorites: We have studied the pond deposit clasts present in Vigarano sections AMNH 2227-6 (previously described by Tomeoka and Kojima [10]) and BMNH 1911 and a new Allende section. As revealed by SEM, microprobe and TEM, the clasts consist nearly entirely of 5μm- to submicron-sized grains of olivine: Fa22-57, with a pronounced peak at Fa50. This is also the distribution of matrix olivine compositions in host meteorite matrix, and since most CVs have distinctive matrix olivine distributions [11&12] this observation suggests that these particular clasts are indigenous to the Vigarano and Allende host asteroid, making them genomict clasts. TEM imaging reveals that the majority of the clast olivine grains have irregular faces, and rounded edges and corners. Even the lath-shaped olivines which, in most CV chondrites have fairly euhedral crystal faces and sharp corners [11&12], are substantially rounded. This sort of rounding is similar to that observed in space-weathered Itokawa grains [8&13]. The most distinctive feature of these genomic clasts are numerous, closely-spaced, frequently cross-bedded, arcuate bands, previously noted by [10] and [14]. We define each layer as a "bed", each of which contains within it a "band" with a high concentration of iron-rich olivine. The entire clast consists of a porous aggregate of (predominantly) olivine grains. Within the bands, the pores are almost entirely filled with very fine-grained, iron-rich olivine, and other minor fine-grained minerals. One side of each iron-rich band is a transitional boundary, and the opposite side is very abrupt. Within each clast the same side of every band is transitional, and the same (opposite) sides are always very sharp. The bands exhibit cross-bedding, which reveals the original orientation of the layers in the parent C asteroid. The relatively fine-grained bands are located at the *bottom* of each bed. Element maps reveal a gradual increase in metal population downwards towards the band, which then increases dramatically within the band, and finally sharply drops at the lower boundary (bottom) of the band. Sulfides are absent from the clasts. Sulfides were also depleted in the Eros pond surfaces [1,3,4,5,6,7]; it has been proposed that this depletion is due to preferential volatilization of sulfide minerals during micrometeorite impacts. In addition, Eros' surface Fe/Si ratio is apparently sub-chondritic, probably due to downward percolation of iron-rich olivine (which have higher relative densities than Mg-rich olivine) and Fe-Ni metal grains by seismic shaking, as observed in the CV chondrite genomic clasts.

Admixture of Foreign Materials: It is a curious fact that although C chondrite and related clasts are rather

common as xenoliths in other meteorites, xenolithic clasts are relatively uncommon in carbonaceous (C) chondrites. We have examined xenolithic clasts in 60 meteorites, and only 6 of these meteorites are C chondrites. The vast majority of what appear to be foreign clasts in C chondrites turn out to be host materials that have been more extensively aqueously altered (most clasts in CRs and CMs, for example Al Rais, Renazzo, Cold Bokkeveld, LON 94101), or are thermally metamorphosed (clasts in CVs, for example NWA 2086, NWA 2900, NWA 3118, NWA 1232, Allende [11] and Camel Donga 040 [15]). Exceptions are an R chondrite clast in Murchison that we have been examining, and the abundant clasts in CH/CB chondrites such as QUE 94411, HaH 237, PAT 91546, ALH 85085 [16] and Isheyevo [17], Bencubbin, and the unique C chondrite Ningqiang [18]. Sutter's Mill is a newly fallen CM regolith breccia, consisting predominantly of CM clasts of differing degrees of aqueous alteration and thermal metamorphism [19]. The fine-grained matrix consists mainly of fine-grained olivine, but also contains comminuted xenolithic materials including very abundant enstatite, Fe-Ni-Cr phosphides, and old-hamite (Figure 1). There are no carbonates (unlike the bulk of Sutter's Mill) or sulfates in this matrix, and rare metal, but there are 10-μm diamonds, and a significant amount of organics [20]. The striking abundance of oldhamite, phosphides and enstatite suggests a physical mixing of C and E asteroid materials. The scarcity of metal could be due to seismically-driven gravitational settling, and perhaps carbonates were destroyed by shock. The presence of the diamonds hints at an ureilitic component. Halite has been found in two H chondrite regolith breccias [21&22], a C chondrite [23], ureilites [24], and tentatively among the Itokawa regolith samples. Our recent work has show that the halite in Monahans and Zag H chondrites is xenolithic, and contain fluid and solid inclusions derived from a cryovolvanically-active, early solar system body, perhaps Ceres [25].

Summary and Predictions: When Dawn arrives at Ceres, and when Hayabusa and OSIRIS-REx scoop up and return their samples to Earth they will find that the materials in the fine-grained pools of dust will be global samples, but will not be completely representative of the host asteroid. The topmost surface samples will likely lack much of the most Fe-rich olivine and pyroxene. Metal and sulfides will be lacking. Brittle minerals such as carbonates may be lacking. It is likely that thermally metamorphosed materials will lie adjacent to unmetamorphosed clasts. Xenolithic materials will be present, most probably E chondrite or aubrites materials. Although brittle materials may be lacking, late arriving halides may be present, containing aqueous fluid inclusions and trapped solid inclusions from earlier-formed worlds.

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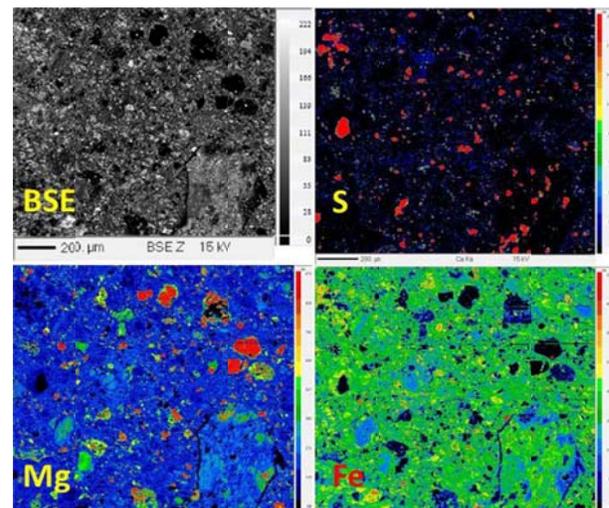

Figure 1. Sutter's Mill regolith breccia matrix lithology. Shown are a BSE image (scale bars in all images are 200 um), a S map, Mg map and Fe map. In the S map red phases are oldhamite. In the Mg map most red phases are enstatite. In the Fe map most green phases are olivine. In the lower right there is a clast with essentially the same mineralogy as the matrix, indicating the occurrence of multiple impact and lithification episodes. This particular sample was recovered before it rained.