SCALES OF BRECCIATION IN HYDRATED CARBONACEOUS CHONDRITES: THIN SECTIONS TO ASTEROIDAL BOULDERS. T.J. McCoy[1], H.C. Connolly Jr.[2,3], C.M. Corrigan[1], E.R. Jawin[1], [4]Scott Sandford, [5]Jamie Molaro, [3]D. S. Lauretta, [3]D. DellaGiustina, [3]B. Rizk, [3]M. Nolan and the OSIRIS-REx team, [1]Dept. of Mineral Sciences, National Museum of Natural History, Smithsonian Institution, Washington, DC USA (mccoyt@si.edu), [2]Dept. of Geology, Rowan University, Glassboro, NJ, USA, [3]Lunar and Planetary Laboratory, University of Arizona, Tucson, AZ, USA, [4]NASA Ames Research Center, [5]Planetary Sciences Institute, Tucson, AZ, USA

Introduction: Carbonaceous chondrites that are extensively hydrated include CI, CM and CR groups and record presolar and pre-accretionary components, including ices, which accreted into asteroidal bodies that were subsequently aqueously altered as an early phase of thermal metamorphism. While these events occurred in the first tens of millions of years of Solar System history and dominate the study of these meteorites, impact bombardment has dominated most of the history of these asteroids. Impact produced shock effects within individual components [1], shock melting [2] and brecciation [3]. With the arrival of OSIRIS-REx at asteroid Bennu, scales of brecciation that had extended only to hand samples can be extended to the scale of boulders.

How common is brecciation in hydrated carbonaceous chondrites: Brecciation is commonly observed in chondritic meteorites. Among ordinary chondrites, 10-60%, depending on chemical type, are brecciated [4] and ~10% of all ordinary chondrites are regolith breccias containing solar-wind implanted gases [3]. In sharp contrast, of 30 hydrated carbonaceous chondrites (CI, CM, CR) surveyed, all of them contain solar wind implanted gases and are regolith breccias [3]. Such a high percentage suggests that the surfaces of asteroids are dynamic environments for mixing.

Brecciation at the millimeter to centimenter scale: Petrographic study of CI, CM, and CR chondrites reveals widespread evidence of brecciation at the thin section scale [3 and references therein]. In all cases, these are genomict breccias comprised of material of the same chemical group with different states of aqueous alteration.

CI chondrites. Although few in number, CI chondrites exhibit prominent sub-centimeter clasts that differ in texture and mineralogy, including abundance of carbonates (Fig. 1a). Clasts are angular and boundaries between clast and host are distinct, suggestive of impact mixing after aqueous alteration.

CM chondrites. CM chondrites vary widely in evidence for brecciation. Typically, areas of more extensive aqueous alteration occur adjacent to areas in which chondrules are only modestly aqueously altered (Fig. 1b,c). In Nogoya, these clasts are visible in hand sample at the centimeter-scale [3]. Even within meteorites that exhibit limited petrographic evidence of brecciation, solar wind implanted gases restricted to the clastic matrix [5] confirm the brecciated nature of these CM chondrites.

CR chondrites. Among the hydrated carbonaceous chondrites, CR2 chondrites exhibit the lowest degree of aqueous alteration. Even these meteorites contain clasts that appear to have experienced more extensive aqueous alteration (Fig. 1d) akin to a CR1. Completely aqueously altered CR1 chondrites are known from this group, suggesting an origin for these clasts from the same parent body.

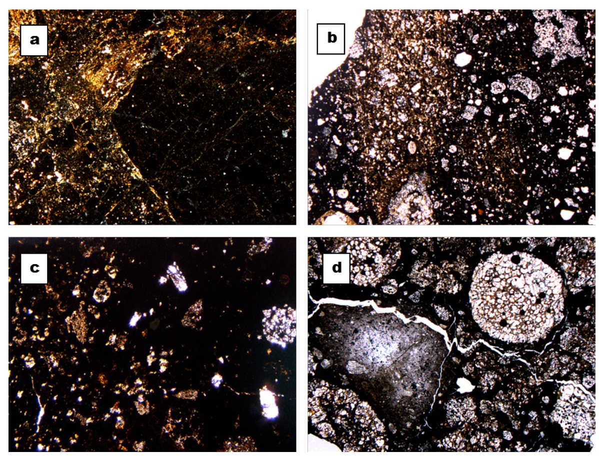

Figure 1. Evidence of brecciation in hydrated carbonaceous chondrites. (a) angular fragment in the Orgueil CI chondrite, (b) difference in aqueous alteration in the CM chondrite Murchison, (c) differences in aqueous alteration in Nagoya CM chondrite, and (d) hydrated clast in the EET 92042 CR2 chondrite. FOV= 1 cm for each image.

Brecciation at the decimeter scale?: More than 100 ordinary chondrites have total masses in excess of 100 kg, making assessment of brecciation at the decimeter scale relatively straightforward. In contrast, among hydrated carbonaceous chondrites, only Murchison has a total recovered mass of 100 kg and only Murchison, Murray and Orgueil have recovered masses above 10 kg. A recovered mass of 100 kg requires a preatmospheric diameter for Murchison of at least 40 cm and, likely, in the range of a meter. Interestingly, these meteorites do not exhibit evidence of brecciation at the decimeter scale. Published descriptions of Murchison stones, as well as our examination of several dozen stones, do not suggest gross differences in degree of alteration between stones. This despite the apparent sub-cm petrographic evidence for brecciation in the same meteorite.

Brecciation at the meter scale: Examination of thousands of boulders on the surface of Bennu at a pixel scale of ~30 cm/pixel reveals a range of textures, including exfoliation and complex planar and irregular fracturing. Collectively, these processes undoubtedly play significant roles in production of regolith by breakdown of larger boulders. Rarely, boulders of the scale of tens of meters exhibit differences in albedo suggestive of brecciation and mixture of materials of different origin (Fig. 2). The nature of those differences (e.g., extent of aqueous alteration, mineralogy) will require further data to discern.

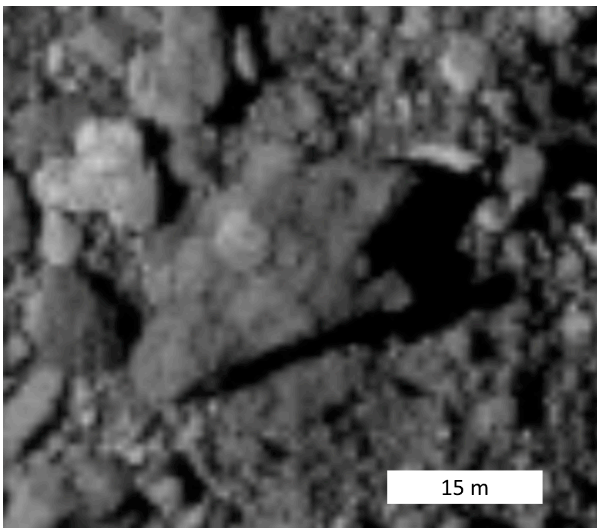

Figure 2. Boulder on the surface of Bennu suggestive of a brecciated structure..

Why are breccias rare at the meter scale? While breccias are ubiquitous in hydrated carbonaceous chondrites at the millimeter to centimeter scale [3], they are rare at the dm- to m-scale. While the paucity of large CI, CM and CR chondrites previously explained part of this difference, breccias appear rare even among the abundant boulders on Bennu at the current pixel scale of ~30 cm/pixel. Possible explanation for these differences may stem from the three processes responsible for formation of breccias: fragmentation, mixing, and reconsolidation.

Fragmentation. Production of a genomict breccia begins with fragmentation. In hydrated carbonaceous chondrites, impact and thermal cycling may have both played a role. Impacts should produce particles of a range of sizes, although smaller particles are likely orders of magnitude more abundant than larger particles. In contrast, thermal cycling particularly in materials with hydrated phases may be inefficient at particle sizes in excess of the thermal depth, while producing numerous smaller particles through processes such as exfoliation.

Mixing. Whereas fragmental breccias are akin to cataclastic rocks, regolith breccias of the type that dominate hydrated carbonaceous chondrites require mixing in the surface regolith. Further, genomict breccias require mixing of materials that may have formed in distinct regions on the parent asteroid. Whether movement of particles occurs via impact mixing or migration of particles on the surface or in the interior of asteroids, smaller particles may be easier to move and mix than meter sized blocks.

Reconsolidation: While fragmentation and mixing are expected to produce more millimeter to centimeter size fragments, they cannot explain the rarity of breccias with decimeter to meter sized fragments. In contrast, the processes that reconsolidate breccias may be more effective at the mm- to cm-scale. Shock melting along clast boundaries is commonly invoked for ordinary chondrites. While exceptionally rare, impact and shock melts of hydrated carbonaceous chondrites are known both in situ [3] and as clastic material in howardites [6]. To invoke such a process at the meter scale would require shock melt veining of a scale not previously observed. Alternatively, such breccias could form prior to the cessation of aqueous alteration and be cemented by subsequent alteration. These would be akin to granulitic breccias in ordinary chondrites, which formed prior to the cessation of thermal metamorphism. In either case a large impact forming shock melt veins or formation during the period of active aqueous alteration – those processes likely occurred prior to the formation of Bennu as a rubble pile, suggesting that the meter-scale breccia on Bennu predates the formation of the current asteroid and may provide clues to a previous generation of Bennu's parent body(ies) in the asteroid belt.

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