GENERATION OF AN ORDINARY-CHONDRITE "REGOLITH" BY REPETITIVE IMPACT. M. J. Cintala,[1] F. Hörz,[1] T. H. See,[2] and R. V. Morris[1], [1]Code SR, NASA JSC, Houston, TX 77058 (Mark.J.Cintala@nasa.gov), [2]C23, Lockheed Martin Space Operations, 2400 NASA Parkway, Houston, TX 77058.

Introduction: Analyses of meteorites[1] and remote-sensing studies[2] for years have suggested the presence of regolith on asteroids, yet detailed observations of asteroid regoliths have been possible only recently with the flybys of 951 Gaspra, 243 Ida, and 253 Mathilde, and with the orbiting of and landing on 433 Eros by the NEAR Shoemaker spacecraft.[3] Virtually all investigations into the generation and evolution of asteroid regoliths to date have been theoretical in nature. These have been guided mainly by observations of the lunar regolith, using what meager experimental data exist for terrestrial materials as substitutes for their asteroidal counterparts.

As part of a program to evaluate the behavior of an ordinary chondrite under impact conditions, about 460 g of the L6 chondrite ALH85017 were subjected to 50 consecutive impacts, sufficient to reduce the target from a mean grain size of 11 mm to 0.5 mm. Some of the details of these experiments are presented here.

Experimental Conditions: The relatively coarse debris generated by the collisional-disruption of the meteorite[4] was used as the initial target for the regolith-evolution series of impacts. The target was housed in a plastic cylinder with a small entrance hole at the top; a plastic "chimney" helped to confine the near-vertical ejecta component. This geometry also permitted the isolation and collection of much of this very fine-grained, near-vertical component of ejecta, which adhered to the inner wall of the cylindrical chimney. In an asteroidal context, this material would assuredly have escaped the target body to become part of the cosmic-dust complex. We hope to present analyses of these fines at a later date.

Impactors were 3.18-mm alumina spheres, used because they are nearly neutral optically and magnetically, thus minimizing contamination for spectral and magnetic studies. Impacts occurred at nominal impact speeds of 2 km s^{-1} in a dry-nitrogen atmosphere at pressures below 1 torr. The target was sieved after every 5 impacts until shot 30, after which it was sieved after every 10 impacts. Small samples (0.2-0.3 g) were removed from all size fractions below 500 µm whenever the target was sieved; some of this mass was used for chemical analyses.

Two additional 25-shot series were conducted for comparison: one with fragments from a basalt (Sheep Canyon, west Texas) target and one from the same Bushveldt gabbro used in our initial, 200-shot regolith-evolution series.[5] Just as the chondrite target was shocked previously in the disruption experiments, so were the basalt and gabbro fragments, having been taken from targets used earlier in 25-shot regolith experiments. Those materials were used to construct targets with size distributions duplicating that of the chondrite to within fractions of a gram in each size bin. Except for the nitrogen atmosphere and sample removal, the conditions for the basalt and gabbro series were identical to those for the chondrite.

Physical Results: The mass comminuted over the duration of the three series is shown in Fig. 1; comminuted mass is defined here as the excess mass in each size bin relative to the mass in that bin in the initial target. After a large initial pulse, the chondrite suffered further comminution at a rather leisurely rate

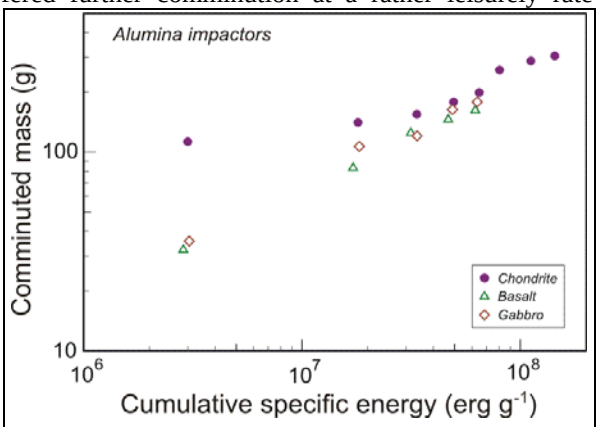

Figure 1. Comminuted mass as a function of total energy delivered to each gram of target material. The first point to the left represents shot 5 for each target; the three almost converge at shot 25.

until a time between shots 25 and 30, during which a large fragment probably was disrupted, resulting in the noticeable jump in the trend. Further comminution then proceeded at basically the same rate as in shots 5 through 25. Given the differences in mineral-grain size, the similarity in the behavior of the basalt and gabbro is surprising. These two trends are more representative of this sort of plot as found in previous regolith-evolution series.[5,6,7] As we have emphasized previously,[6] however, the new surfaces created by the impact process should be more indicative than the comminuted mass of the expenditure of energy into comminution. The surface area can be modeled from the grain-size distribution by assuming a geometry for the fragments; while it can be argued with merit that different materials will break into different shapes, previous models of generated surface areas have proven useful in such comparisons. In any case, the differences that would arise due to most realistic ge-

ometries are typically smaller than the differences due to the inherent behaviors of the target materials. Fig. 2 presents such a surface-area plot, and demonstrates that, while the comminuted masses in Fig. 1 appear to converge, the surface areas tell a considerably different story. Whereas the trends in comminuted mass for the basalt and gabbro were intertwined, the new surface area created in the gabbro is uniformly higher than that in the basalt, and both underwent a gradual but constant increase in the rate at which those surfaces were created. Over the first 25 shots, however, the new surface area in the chondrite target is more than a factor of three greater than in the case of the gabbro and more than four times greater than that of the basalt. This is a consequence of another major difference between the chondrite and the two igneous targets: the chondrite generated twice as much fine material (*i.e.*, <250 µm) as the gabbro and three times as much as the basalt. This seems to be the result of a complex function of the materials' intrinsic strength properties as well as the sizes of individual components, such as minerals or clasts.

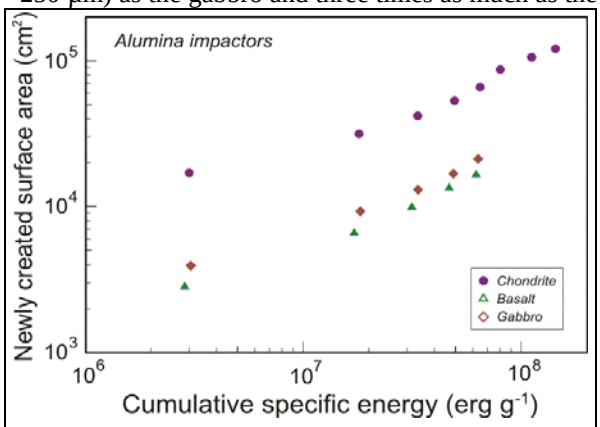

Figure 2. Surface areas newly generated during the impact process for the three targets.

Chemical Results: Our desire to minimize perturbations of the "regolith's" evolution demanded that the samples taken after every five shots be relatively small. While those samples are sufficient for point counting and analyses of specific grains, they would not provide enough material for many bulk-sample investigations. Enough material was available in each size bin after shot 50, however, to examine possible fraction trends as a function of grain size. Because the presence of native Fe-Ni in the meteorite precluded crushing and homogenization of the samples in preparation for glass-bead analyses via microprobe,[8] the compositions of grain-size fractions from 2 mm to <10 µm were obtained through XRF analyses.[9] Acid solution and associated titration methods were used to determine FeO separately, as all of the Fe present was oxidized to Fe_2O_3 for the XRF analyses. The native-Fe content was determined by assuming that all Ni present was in the metallic state and associated with the metallic Fe in approximately chondritic proportions. An excess of Ni occurs in the finest fraction (<10 µm) relative to Fe^0, indicating that a small portion (0.3%) of Ni resided in the silicates or troilite.

Fig. 3 presents the abundances of major-element oxides as a function of grain size, shown relative to the abundances in the 1-2-mm fraction, which, consisting predominantly of lithic fragments, is the least modified and therefore taken to represent that of the bulk rock. While Al_2O_3 is strongly enriched in the finest fractions, it will not be discussed further here, as the potential for some contamination from the projectiles exists. Metallic Fe, however, becomes increasingly depleted with decreasing grain size, showing its expected resistance to comminution. This is supported by the behavior of metallic Ni. Ca, most abundant in the clinopyroxenes ($En_{47}Fs_7Wo_{46}$), is also enriched in the fines, indicating that those minerals tended to comminute very finely. The moderate, simultaneous enrichment of FeO and MgO implies olivine enhancement in the midrange grain sizes. Unlike lunar-regolith processes, in which readily comminuted feldspar enriches the fines, ordinary-chondritic regoliths would fractionate because native metal is highly resistant to comminution.

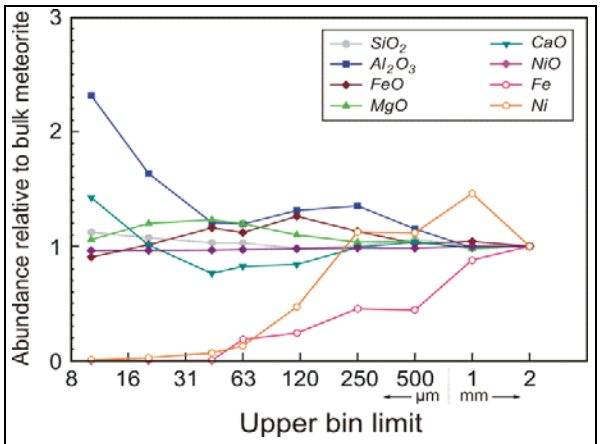

Figure 3. Abundances of major-element oxides and native metals as a function of grain size after shot 50.

References: [1] Kerridge, J.F. and Matthews, J.F. (1988), *Meteorites in the Early Solar System*, Univ. of Arizona Press, Tucson. [2] Dollfus A. (1971) *Physical Studies of Minor Planets*, NASA SP-267, 95. [3] Veverka J. *et al.* (2001) *Science* **292**, 484. [4] Cintala M.J. (2003) to be submitted to *MAPS*. [5] Hörz F. *et al.* (1984) *JGR* **89**, C183. [6] Cintala M.J. and Hörz F. (1988) *PLPSC 18th*, 409. [7] Cintala M.J. and Hörz F. (1992) *Meteoritics* **27**, 395. [8] Brown R. and Mullins O. (1975) *Proc. 10th Nat. Conf. Electron Probe Analysis*, pap. 32 A-D. [9] Boyd F.R. and Mertzmann S.A. (1987) *GSA Spec. Pub. 1*, 13.