EFFECTS OF SEISMIC SHAKING ON GRAIN SIZE AND DENSITY SORTING WITH IMPLICATIONS FOR CONSTRAINING LUNAR REGOLITH BULK COMPOSITION. L. R. Ostrach and M. S. Robinson, School of Earth and Space Exploration, Arizona State University, Tempe, AZ, 85287 (Lillian.Ostrach@asu.edu).

Introduction: The regolith of an airless body is defined as fragmental debris overlying largely coherent rock [e.g., 1, 2] and is formed by successive impact cratering events. Detailed knowledge of the lunar regolith (including grain size distributions, thickness variations, compositional variations with depth) is important because the regolith is globally distributed, and most remote sensing observations are of the regolith. Since remote sensing techniques sample different depths within the regolith, small-scale compositional variations with depth may bias estimates of the regolith's bulk composition.

The goal of this investigation is to determine whether the lunar regolith exhibits compositional sorting at the few 100 µm to 10 cm depth scale. For example, ilmenite ($FeTiO_3$) is a high-density oxide that is sometimes abundant in returned lunar samples [3]. Compositional information derived from Clementine UVVIS spectral reflectance measures absorptions due to ilmenite as a proxy for titanium (TiO_2). The Lunar Prospector measured neutron absorption to ascertain titanium abundance [e.g., 4-6]. The Lunar Prospector titanium estimates do not match well with those from the Clementine UVVIS work [e.g., 4]. The UVVIS reflectance samples the top few microns while the neutron spectrometer senses to a depth greater than 10 cm [7]. One question we are exploring is how ilmenite content varies in the top centimeters of the lunar regolith versus the top-most portion of the regolith (sub-cm) and whether the differences in TiO_2 reported by Lunar Prospector and Clementine represent true compositional vertical stratification or are simply measures of the imprecision of one or both methods.

We report on preliminary experiments modeling a bimodal granular mixture of materials with strong density contrasts and varying grain sizes. Our first results show that materials with higher densities sink into our "regolith" when the denser material has a significantly larger grain size.

Background: Measurements of the surface may not accurately represent the regolith mixture beneath the surface, even at a few centimeters depth. We know from the Apollo sample collection that the mean grain size of the minerals in the lunar regolith is ~40 – 800 µm and different minerals are comminuted at different rates [e.g., 8]. Regolith samples reveal that concentrations of ferromagnesian minerals, such as ilmenite, decrease with decreasing grain size [e.g., 9], suggesting that ilmenite may persist in larger grain size fractions than other regolith components. Comminution and continuous micrometeorite bombardment of the regolith should promote mechanical sorting of the topmost layer and denser particles may preferentially sink.

The "Brazil-Nut Effect" is a colloquial expression for the size segregation of particles during vertical shaking such that large grains rise to the top regardless of density [10]. Other workers [11, 12] invoked the Brazil Nut Effect to explain grain-size sorting of an asteroidal regolith, with applications to other airless bodies (e.g., the Moon). Examining the behavior of granular systems, [12] experimented with an analog regolith composed of varying grain sizes and densities. While these experiments were shaken laterally and the results are consistent with [10], these results may not completely represent an asteroidal or planetary surface exposed to impact gardening because regolith mixing involves "in situ reworking" that requires a vertical component of movement between particles [13].

Method: To examine physical mixtures of particles representing a regolith and promote size-sorting, we created an experimental procedure to mimic the process of seismic shaking [e.g., 14]. Our first experiment used a metal pan (23.5 cm x 13.3 cm x 6.99 cm) filled with 100 – 170 mesh (~80 – 149 µm) glass beads; an abrasive blasting media manufactured by the McMaster-Carr Company. The pan was placed on the shaking table (17.8 cm x 25.4 cm), a Syntron Jogger model J-I-B designed for jogging and packing of material, surrounded by a foam buffer to prohibit movement off the table. The shaker was positioned on a copy-stand with adjustable lights and a digital camera. A white reference image was captured and then the test materials were placed on the surface of the glass beads. An anti-static pistol was discharged above the container to minimize electrostatic effects. The shaker rheostat was set to the lowest vibration, and the shaker was turned on for increments of two minutes for a total of 10 minutes. An image was shuttered every two minutes during the run. We followed this procedure for mixtures of glass beads and ilmenite chips and glass beads and basalt chips; densities for these materials and other common minerals are provided in **Table 1**. The chips ranged in size from ~2 mm to ~8 mm.

Results: Over the ten minute test period, the coarse fragments of basalt and ilmenite sank into the glass beads (**Fig. 1**). The higher-density ilmenite sank more completely than the basalt. This simple experiment shows that denser and larger particles may sink into the top of a fine grained regolith due to seismic disturbance.

Implications: Grain-size sorting is influenced by density. Our results suggest that a bimodal mixture of coarse-grained relatively dense and fine-grained particles experiences density-driven size-sorting where the larger, denser particles sink. Furthermore, the density contrast between the coarse-grained and fine-grained particles affects the depth of descent of the dense grains. Ilmenite has a higher density than basalt, and over the same test period with similar sized grains, the ilmenite sank deeper than the basalt. In both cases, most of the sorting occurred in the first four minutes, suggesting rapid particle response to perturbation. Interesting facets not yet explored with this end-member experiment are calculating the rate of descent, the depth of descent of the coarse-grained particles, and the compaction of the fine-grained component. These properties may constrain mechanical mixing of regolith by limiting the amount of mixing over a period of time as well as by determining whether a surficial layer of mixed material exists and over what depths.

Initial tests showed that edge effects dominate in small containers. Initial tests with different sized containers suggests that a large container with a depth greater than ~7.6 cm is ideal. Increasing the size of the container and ensuring that the container base is flat with sides angled at ~45° will help decrease particle convection. However, we are limited to a ten pound load limit on the shaker table. This limit constrains the size of the container as a fine-grained glass bead depth of greater than 5.1 cm is desired to diminish perturbations from the container base. We are developing an optimal container to mitigate edge effects and provide a large sample volume to test size-fractions more closely matched (e.g., 100 mesh ilmenite powder and the glass beads).

Applications: The results of our preliminary experiments have significant applications for interpreting remotely sensed data, especially for the Moon. Comminution rates vary for different minerals based on crystal structure; the presence of good cleavage planes promotes fracturing [e.g., 17]. Moreover, the different densities of minerals should promote density-driven sorting in the regolith, perhaps regardless of size. Constraining the mechanical mixing properties including grain-size sorting, density sorting, and depth of sorting of a regolith is essential to more accurately interpret remotely sensed measurements.

Conclusions: Our two-component physical mixtures contain particles of different size fractions and different densities. The denser materials sink into the glass bead medium, even when there are small density differences. These results suggest that the Brazil Nut Effect is not applicable to geologic applications except when the materials have the same density.

Future experiments will tests a range of grain size and density contrasts. With the results of future experiments, we aim to understand the inconsistencies between compositional remote sensing datasets. For example, are both the Lunar Prospector and Clementine titanium estimates accurate and do the data only seem inconsistent because previous workers have assumed that titanium abundances are uniform at all scales in the top 10 cm of the regolith?

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Table 1: Density of common minerals, test materials

Material	Density (g/cm^3)
Anorthite	2.76
Enstatite	3.21 – 3.96
Diopside	3.44 – 3.55
Olivine	3.22 – 4.39
Ilmenite	4.70 – 4.78
Glass Beads	~2.46 – 2.49
Flood Basalt	2.40 – 3.10

The mineral densities were obtained from [15], glass bead density from the MSDS provided by McMaster-Carr Co., and flood basalt from [16].

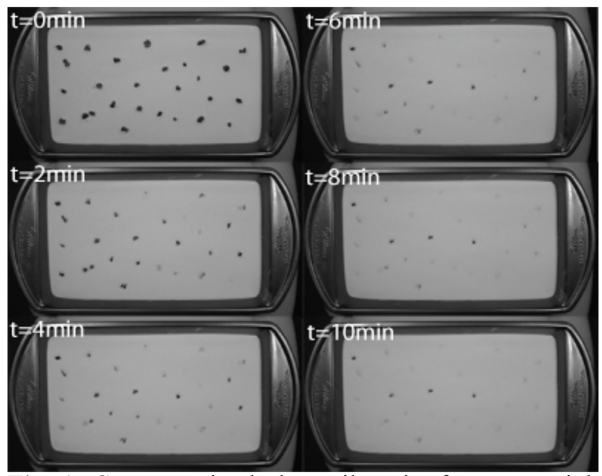

Fig. 1: Coarse-grained, dense ilmenite fragments sink quickly in the metal container filled with fine-grained, less-dense glass beads. The ten minute time-series of photographs taken every two minutes illustrates the effects of seismic disturbance on an analog regolith surface. Furthermore, our first experiment demonstrates the need for a larger container to mitigate edge effects during vibration.