IMPACT OF SECONDARY SURFACE CHANGES ON REGOLITH GARDENING. E.J. Speyerer[1], R.Z. Povilaitis[1], M.S. Robinson[1], P.C. Thomas[2], and R.V. Wagner[1], [1]School of Earth and Space Exploration, Arizona State University, Tempe, AZ, [2]Cornell Center for Astrophysics and Planetary Science, Cornell University, Ithaca, NY.

Introduction: Random bombardment by cometary and asteroidal materials shape and alter the surface of the Moon as well as other planetary surfaces. These impacts form craters and cause surface disturbances many crater diameters away from the primary impact point [1]. Observations from the Lunar Reconnaissance Orbiter Camera (LROC) provide our first detailed look at secondary disturbances from small impactors (resulting craters <50 m diameter).

Temporal Dataset: LROC has acquired over a million Narrow Angle Camera (NAC) images of illuminated terrain. From this collection, 14,092 are observations of regions of the Moon where previous NAC observations with similar lighting geometry exist (i.e. incidence angle difference <3°, incidence angle < 50°, and nadir pointing). These before and after image pairs, called temporal pairs, enable the search for a range of surface changes, including new impact craters, secondary disturbances, and mass wasting events that formed between the time the first and second images are acquired.

Primary and Secondary Impacts: NAC temporal pair observations revealed 222 new impact craters ranging in size from 1.5 to 43 m [1]. In addition, impact flashes observed using Earth-based telescopes also helped locate two new craters that formed on 17 March 2013 and 11 September 2013 [2-4]. Robinson et al. [2], documented the 17 March impact site and found 248 splotches, which refers to a surface reflectance change (either an increase or decrease) that lacks a visible rim. These splotches ranged in size from 2 to 22 m, extended away from the impact site to at least 30 km, and were not present in images acquired in the region just prior to the impact event [2]. Additionally, some of the splotches were asymmetric in shape and pointed back to the 18 m primary crater. This indicates that the splotches most likely formed by ejecta traveling from the main impact site and not from a stream of associated fragments traveling with the bolide that formed the main crater [2].

Using the 14,092 NAC temporal pairs, we discovered over 47,000 new splotches on the Moon. As with the 17 March impact site, we observe clusters of splotches near all of the new impact craters that are 10 m in diameter and larger. This suggests that many of the splotches from as a result of ejecta from larger, nearby impact events. The remaining splotch population is most likely the result of lone secondaries from unidentified parent craters as well as small primary impacts that create unresolved craters (<~3 NAC pixels).

Reflectance and Morphologic Properties: Of the over 47,000 splotches discovered, a majority (90.7%) of the splotches exhibit a lower reflectance (-4%) than the same region in the before images, while 7.4% show an increase in surface reflectance (+10%) (**Fig. 1**). The remaining 1.9% of splotches have mixed reflectance patterns.

While some splotches may contain small primary impact craters that are not resolvable in NAC images, we interpret most to be the result of secondary ejecta modifying the surface. For the latter case, laboratory experiments by Schultz and Gault [5] show that secondary impacts of loose clusters of regolith create a hummocky and pitted surface. These rough surfaces surrounded by a subdued rim with a depth:D ratio of 1:30. At the NAC scale, these clustered impacts sites might be seen as areas with increased surface roughness and lacking a resolvable rim. This morphology is consistent with the observations of splotches, which are characterized by only a subtle reflectance change.

Given such shallow excavation, many of the splotches would only churn the upper few cm of regolith (mature zone), which would have similar maturity and thus optical maturity properties to the regolith at the surface. Immature regolith would only be exposed in the cases where there was only a thin (few cm) mature layer. This is consistent with our observations, which indicate that high reflectance splotches are typically present in areas where a thin layer of mature regolith might be expected, such as along steep slopes (>15°) and near young craters that have resurfaced the surrounding terrain (**Fig. 1**).

For low-albedo surfaces, such as the Moon, the slope of the phase-function is dependent on the composition, porosity and roughness of the surface [6]. Using images acquired at various phase angles of the same area, we examined phase-ratio images covering a series of new splotches. From the phase-ratio images, we find the slope of the phase function for the splotches is steeper than the surrounding terrain and is consistent with an increased surface roughness (i.e. such as one created from a hummocky and pitted surface).

Formation Rate: To date, the NAC has reimaged 2.93×10^6 km^2 (6.6%) of the Moon with a period of 176 to 1241 days between each of the 14,082 temporal observations. To compute a normalized area that can be used to derive a formation rate, we scaled the area covered by each temporal pair by its temporal gap (Surface area × Time between observations). We then normalize it by a year period and computed the sum from all the temporal pairs resulting in an annual search area that can be used to evaluate the formation rate (A_{norm}=3.3×10^6 km^2).

Using this area as well as size statistics derived from measuring over 2.5×10^4 splotches, we computed an annual cumulative size frequency distribution (**Fig. 2**). Since the spatial resolution varies in the temporal data set, a roll off occurs in the cumulative frequency plot for splotches < 10 m. However, we can resolve all splotches 10 m and larger at all pixel scales (50 cm to 175 cm). Fitting a power law function to the distribution, enables us to estimate rates for splotches ≥ 10 m and extrapolate rates at finer scales. From this analysis we estimate that 1.09×10^5 splotches ≥ 10 m form across the entire Moon annually. Extrapolating the function down to smaller scales yields a annual rate of 40.2±1.6 per km^2 or 1.52×10^9 globally for splotches ≥ 1.0 m.

Gardening: Using a Monte Carlo model and the formation rate derived in the previous section, we can estimate the time span required to churn and rework the upper layer of regolith. If we assume a conservative depth:D ratio of 1:50 for these splotches [5], we estimate that 99% of the lunar surface would be effectively churned at a depth of 20 cm with 10 m and larger splotches after 1.0×10^7 yrs. Extrapolating the rate down to churning caused by meter size splotches yields a rate of 8.1×10^4 yrs for the upper 2 cm of regolith. This is ~120× faster than the previous models that predicated reworking of the upper cm over a period of 10^7 yrs from meteoritic impacts [7].

Future Observations: Throughout the remaining second extended science mission as well as future extended missions (if funded), the LROC team will continue to acquire and scan high resolution temporal pairs. From lower altitude observations (<100 cm, southern hemisphere), we will identify more small scale splotches (5-10 m in diameter), which will help refine the formation rate at this smaller scale. In addition, we will refine the contemporary cratering rate and the flux of small (>0.5 m) bolides in the inner solar system and study the distribution of splotches around new impact sites. These observations are not only an important scientific finding, but also a key engineering design concern for future long duration surface assets.

References: [1] Speyerer et al. (2015) LEAG, Absract #2052. [2] Robinson et al. (2015) *Icarus*, 252, 229–235. [3] Madiedo et al. (2014) *Mon. Not. R. Astron. Soc.* 439, 2364-2369. [4] Suggs et al. (2014) *Icarus*, 238, 23-36. [5] Schultz and Gault (1985) *JGR*, 90, 3701. [6] Hapke (2012) *Theory of Reflectance and Emittance Spectroscopy*, 513pp. [7] Gault et al. (1973) Lunar Sci. Conf., 2365-2386.

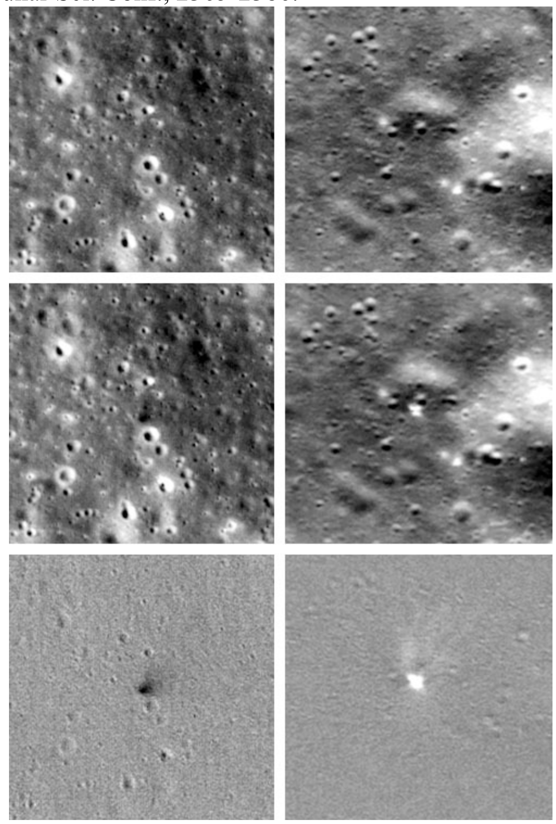

Fig. 1- Example of low (left column) and high (right column) reflectance splotch identified with NAC temporal pairs. The top row consists of a pair of before images, the middle row is a pair of after images, and the bottom row is a ratio of the after/before observation. Each image is 250 m across.

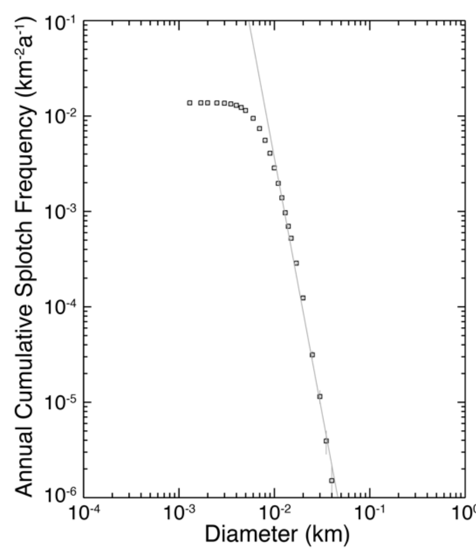

Fig. 2- Annual cumulative size frequency distribution of new splotches derived with temporal pairs with a power law fit overlaid.