MODELING THE EFFECTS OF POST-IMBRIUM CRATERS ON THE APOLLO LANDING SITE LOCATIONS.

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Motivation: The cratering chronology for the inner Solar System is anchored in time by the ages of lunar samples that have been correlated to surface features [1]. The lunar chronology curve is well-constrained for ages younger than ~3.8 Gyr, as samples with those ages could be directly correlated with nearby mare basaltic plains. However, samples older than ~3.8 Gyr originate in ejecta deposits from impact craters, which are transported throughout the surface by subsequent impact events and are thus difficult to correlate with their crater of origin [2].

The lunar highlands region consists primarily of impact ejecta, as opposed to the predominantly volcanic mare region. In the early 1970s, Four Apollo missions (Apollo 14-17) landed in ejecta-rich regions, and there has since been much debate over which craters are the sources of the rocks collected at these landing sites. The amount of ejecta produced by a crater increases with increasing crater diameter, so most ejecta in the regions surrounding the Apollo sites have been theorized to come from some of the largest impact craters, known as basins [3]. As the Imbrium basin is the youngest large basin on the nearside, it is theorized to have been the source of many or even all ejecta samples at each of these four sites [4].

Because many Apollo samples have been radiometrically dated to ~3.9 Gyr, this is widely believed to be the age of the Imbrium impact [4,5]. However, the number of basins represented in the Apollo sample collection remains a source of intense debate. The predominance of samples with an age of ~3.9 Gyr led to the concept of a terminal lunar cataclysm [6,7], which states that most lunar basins formed at this time due to an uptick in impact rate. Alternatively, the predominance of samples with this age could also be explained by a declining impact rate with younger basins destroying evidence of older basins in the sampling record [8]. This would result in material sourced from fewer basins being represented in the Apollo sample record.

Impact melt deposits are produced from the heating of the surface upon impact and are widely used to date impact events. This is because melting would completely reset the radiogenic isotopes of the material, and thus the measured age would be the age of the impact [9]. Large craters produce enormous volumes of melt, a portion of which is ejected from the crater; the remaining melt forms a melt sheet inside the crater [10]. The amount of melt that is both produced and ejected increases with increasing crater diameter [11].

Several smaller basins and sub-basin sized craters impacted the Moon after Imbrium. While they produce less melt than larger basins, their deposits should overlay that of older basins. One such basin is Iridum, which is comparable in size to the Chicxulub impact structure on Earth. This basin impacted on the rim of Imbrium, and thus materials from each basin would have similar compositions. Some Iridum ejecta should have reached the Apollo landing sites [12], and it should contain a relatively high portion of melt since melt fraction in ejecta increases with increasing crater diameter [10].

If melt from a crater such as Iridum composes a significant amount of material at the surface of an Apollo landing site, such deposits could be mistaken for melt deposits from larger basins, and the age believed to be the basin could actually be that of a smaller crater. With this in mind, we simulated the impact bombardment of the lunar surface, tracking impact melt from every basin (craters >200 km in diameter), as well as some potentially important smaller craters.

A Global Lunar Bombardment Model: The bombardment history of the Moon from the South Pole-Aitken impact event to the present day was simulated using the Cratered Terrain Evolution Model (CTEM) [13,14]. Basins were emplaced with their location and size [15] on a grid equal to the lunar surface area. Imbrian aged craters [16] whose ejecta may have influenced the Apollo sites have also been emplaced in this way. The rest of the craters have been emplaced randomly using the Monte Carlo method.

Many of the lunar basins have a model age that was previously calculated in the literature from crater-counting statistics [17]. These ages follow the Neukum chronology function [1] and were used for every basin that had such an age. The remaining basins were assigned an age that fits with their stratigraphic grouping relative to the craters with definite model ages [18]. Imbrian aged craters were assigned an age that is younger than Imbrium and older than the closest mare model age [19]. The number of random craters was computed assuming the Neukum chronology [1].

Each crater emplaced by CTEM has a melt zone which is calculated from a scaling law for melt production [20]. The amount of melt emplaced at each surface location was calculated using the Maxwell Z-model [21], which was previously implemented into CTEM [22]. Melt from each manually emplaced crater was tracked for each pixel. Impact gardening was simulated via a mixing algorithm that homogenizes the surface layer to a depth calculated as a function of crater production [22].

Preliminary Indications and Future Work: Post-Imbrium craters are the sole source of ejected melt at the uppermost surface layer of each of the four studied Apollo landing sites (Figs. 1 and 2). This layer represents the upper ~1-2 m of regolith and consists of ~10% ejected melt at each site. Thus, melt deposits ejected from these Imbrian craters have survived long enough to affect the surface to this day. However, melt ejected from the older basins should be buried beneath this regolith layer.

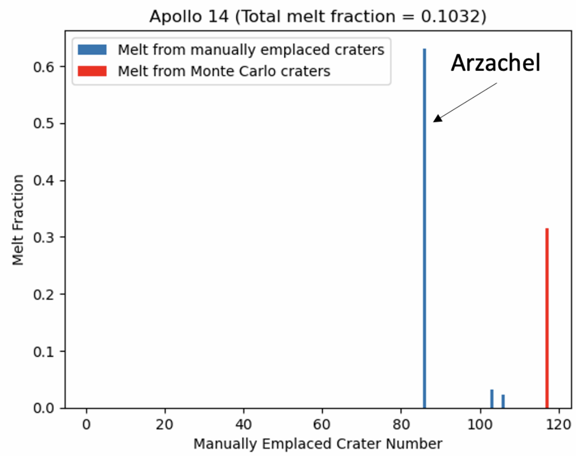

Figure 1: Normalized melt fraction for the top ~1m of regolith at the Apollo 14 landing site. The x-axis is crater number for manually emplaced craters such as basins in order of oldest to youngest (so the oldest basin would be the first number, etc.). Total melt from Monte Carlo craters (such as small, local craters) was added at the right-most column and colored red. The y-axis is the normalized melt fraction (so contribution from every crater should add up to 1). The total melt fraction at this pixel was 0.1032, meaning ~10% of ejecta in the surface layer was ejected melt.

The ejected melt in this topmost layer is dominated by the ~100-km Arzachel crater at the Apollo 14 landing site (Fig. 1). For the remainder of the studied Apollo landing sites, ejected melt is dominated by the Iridum basin and local sources (Fig. 2). The remaining ejecta may include melt from other craters that has been re-transported as ejecta, such as that of impact melt sheets. For example, the Iridum basin likely would have excavated melt from Imbrium that could compose part of the uppermost regolith. This type of melt was not tracked in the preliminary portion of this project, but it will be very important for assessing total melt composition of the regolith. The effect of impacts of this size on age chronometers in pre-existing melt rocks is also important and will be explored. While post-Imbrium craters have a presence at the Apollo 14-17 landing sites, the extent of their influence on the Apollo sample record is yet to be determined.

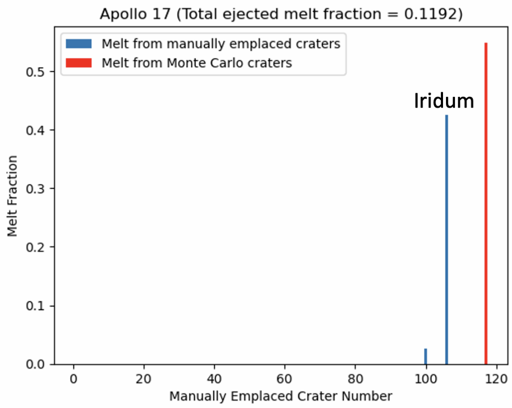

Figure 2: Like Figure 1, but for the top ~1m of regolith at the Apollo 17 landing site.

References: [1] Neukum, G. et al. (2001) *Space Science Reviews 96,* 55–86. [2] Stoffler, D. & Ryder, G. (2001) *Space Science Reviews 96,* 9–54. [3] Liu, T. et al. (2020) *Icarus, 339,* 113609. [4] Haskin, L. A. (1998) *JGR 103 E1,* 1679–1689. [5] Norman, M. D. et al. (2010) *GCA 74,* 763–783. [6] Tera, F. et al. (1974) *EPSL 22,* 1–21. [7] Bottke, W.F. & Norman, M.D. (2017) *Annu. Rev. Earth Planet. Sci. 45,* 619–647. [8] Morbidelli, A. et al. (2018) *Icarus 305,* 262–276. [9] Ryder, G. & Bower, J. F. (1977) *Proc. LSC, 8,* 1895–1923. [10] Liu, T. et al. (2022) *JGR 127,* e2022JE007264. [11] Cintala, M. J. & Grieve, R. F. (1998) *Meteoritics & Planetary Science 33,* 889-912. [12] McGetchin, T. R. et al. (1973) *EPSL 20,* 226–236. [13] Richardson, J. (2009) *Icarus 204,* 697–715. [14] Minton, D. A. et al. (2015) *Icarus 247,* 172–190. [15] Head, J. W. et al. (2010) *Science 329,* 1504–1507. [16] Losiak, A. et al. (2009) *LPS XV,* Abstract #1532. [17] Orgel, C. et al. (2018) *JGR 123,* 748–762. [18] Byrne, C.J. (2016) *Springer, Cham.* [19] Hiesinger, H. et al. (2003), *JGR 108 E7,* 5065. [20] Abramov, O. et al. (2012), *Icarus 218*, 906-916. [21] Maxwell, D. E. & Seifert, K. (1974) *Defense Nuclear Agency, Washington.* [22] Huang, Y. H. et al. (2017), *JGR 122,* 1158–1180.