The age of lunar south circumpolar craters Haworth, Shoemaker, Faustini, and Shackleton: Implications for regional geology, surface processes, and volatile sequestration.

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February 22, 2015

Abstract

The interiors of the lunar south circumpolar craters Haworth, Shoemaker, Faustini, and Shackleton contain permanently shadowed regions (PSRs) and have been interpreted to contain sequestered volatiles including water ice. Altimetry data from the Lunar Orbiter Laser Altimeter (LOLA) onboard the Lunar Reconnaissance Orbiter provide a new means of examining the permanently shadowed interiors of these craters in unprecedented detail. In this study, we used extremely high-resolution gridded LOLA data of Haworth, Shoemaker, Faustini, and Shackleton to determine the size-frequency distributions and the spatial density of craters superposing their rims, inner slopes, and floors. Based on their population of superposed $D \geq 2$ km craters, Haworth, Shoemaker, and Faustini have pre-Nectarian formation ages. Shackleton is interpreted as having a Late Imbrian age on the basis of craters with diameter $D \geq 0.5$ km superposed on its rim. The local density of craters with sub-km diameters across our study area is strongly dependent on slope; because of its steep interior slopes, the lifetime of craters on the interior of Shackleton is limited. The slope-dependence of the small crater population implies that the population in this size range is controlled primarily by the rate at which craters are destroyed. This is consistent with the hypothesis that crater removal and resurfacing is a result of slope-dependent processes such as diffusive mass wasting and seismic shaking, linked to micrometeorite and meteorite bombardment. Epithermal neutron flux data and UV albedo data show that these circumpolar PSRs, particularly Shoemaker, may have ~1-2% water ice by mass in their highly porous surface regolith, and that Shoemaker may have ~5% or more water ice by mass in the near subsurface. The ancient formation ages of Shoemaker, Faustini and Haworth, and the Late Imbrian (~3.5 Ga) crater retention ages of their floors suggests that any water ice

that might have been deposited in their permanently shadowed areas was insufficient to modify the superposed crater population since that time.

1. Introduction

Craters Haworth, Shoemaker, Faustini, and Shackleton (diameters 52 km, 52 km, 41 km, and 20 km respectively; Fig. 1) in the lunar south circumpolar region have large parts of their interiors in permanent shadow (Fig. 2). These permanently shadowed regions (PSRs) have long been posited to contain sequestered volatiles (Watson et al., 1961; Arnold, 1979; Nozette et al., 1996; Stacy et al., 1997; Haruyama et al., 2008; Zuber et al., 2012). Altimetry data from the Lunar Orbiter Laser Altimeter (LOLA) onboard the Lunar Reconnaissance Orbiter (LRO) have allowed examination of the topography of the south circumpolar region, including the PSRs, in unprecedented detail (Smith et al., 2010). LOLA data also make it possible to map craters in areas that are permanently shadowed in images, enabling relative and absolute age calculations from the resulting superposed crater size-frequency distributions (CSFDs). In this study, we describe the CSFDs for these four craters and assess their formation age and their relative retention of small craters. We also discuss the implications of the observed ages and superposed crater populations of these craters for regional geology, volatile sequestration, and surface modification processes.

2. Methods

For all measurements in this study, we used the Planetary Data System-released LOLA gridded digital terrain model (DTM) of the south polar region (south of 85°S) with 20 meter per pixel resolution. Using ArcGIS, we created artificially illuminated hillshade maps of this DTM at a range of azimuth angles, as well as slope maps at 20-m and 200-m baselines. Using these products, especially the hillshade maps, a catalogue of craters in the study area was created. We estimate that this catalogue is complete across the study area to $D \geq 250$ m.

We also used the LOLA DTM to map subunits for each crater, subdividing each into a rim subunit, inner slope subunit, and floor subunit. The outer edge of the crater rims are mapped along the topographic boundary between the rim and surrounding material. Where there was no obvious topographic boundary, the width of the rim was mapped to maintain its width approximately equal to areas where the topographic boundary is obvious. Similarly, the floor of each crater was defined to be interior to the inner slopes of each crater, where the slope transitions from being generally greater than, to generally less than, 10° at a 20 m baseline.

3. Results

Overall, we catalogued 19,478 craters in the study area (Fig. 3), including those from a previous study of Shackleton (Zuber et al., 2012), while systematically excluding obvious secondary craters (crater chains, tight clusters, and misshapen craters). From these data, we derived size-frequency distributions (Fig. 4) and estimated the model ages (Table 1) for each of the four major craters we examined. We also map the crater densities spatially in a range of sizes (Fig. 5). When estimating formation ages, each CSFD is fit using the Neukum et al. (2001) model production function (MPF) in CraterStats (Michael and Neukum, 2010). All error bars are 1-sigma from counting statistics alone, and exclude systematic errors in the chronology function. Note that the absolute age estimates for Pre-Nectarian model ages are particularly uncertain because the chronology function lacks confident sample calibration beyond ~3.9 Ga.

	Model Formation Age	Period	Minimum Crater Size Used for Fits	Number of Craters in Fit	Area (km^2)	Equivalent Model N(1) # $D \geq 1$km / km^2
Faustini	4.10 Ga, +0.03, -0.03 (all subunits)	Pre-Nect.	2 km	27	2.09×10^3	1.18×10^{-1}
Haworth	4.18 Ga, +0.02, -0.02 (all subunits)	Pre-Nect.	2 km	46	3.23×10^3	2.10×10^{-1}
Shackleton	3.51 Ga, +0.05, -0.08 (rim)	Late Imb.	500 m	26	4.56×10^2	4.99×10^{-3}
Shoemaker	4.15 Ga, +0.02, -0.02 (all subunits)	Pre-Nect.	2 km	60	4.27×10^3	1.69×10^{-1}

Table 1. Interpreted formation ages for the four craters in this study.

The CSFDs for Faustini, Haworth, and Shoemaker all have densities of $D \geq 2$ km craters that imply they are Pre-Nectarian (see Wilhelms, 1987; Stöffler et al., 2006). They are also not statistically distinguishable from one another, so the relative sequence of these craters from CSFD data is uncertain. Both the CSFDs (Fig. 4) and the lower crater density in its spatial neighborhood (Fig. 5) clearly demonstrate that Shackleton is much younger than Faustini, Haworth, or Shoemaker. Measurements of its rim suggest that Shackleton is Late Imbrian. Shackleton’s floor (Table 2) and inner slopes are highly depleted in craters relative to its rim, which we interpret to be primarily controlled by surface erosion and deposition, modulated by local slopes, rather than a function of the age of Shackleton itself. (Fig. 5).

Indeed, across our study area, the crater density for craters less than 1 km in diameter is highly dependent on surface slope (Figs. 3, 5, 6). Areas with slopes of even a few degrees become depleted in sub-km craters relative to a flat surface (Fig. 5, 6). Figure 6 shows crater densities as a function of slope for three different subsets of crater size. As expected, the magnitude of the crater density depletion is a function of both slope and crater size; craters larger than 1 km appear comparatively unaffected by slope-related modification.

These trends suggest that slope-dependent erosion processes plays a major role in crater retention measurements (see Basilevsky, 1976), especially on the steeply sloped inner walls of Haworth, Shoemaker, Faustini, and Shackleton (Fig. 3). The specific processes that control this retention are likely to be related to diffusive mass wasting and seismicity from micrometeorite and meteorite bombardment (e.g., Soderblom, 1970; Gault et al., 1972; Craddock and Howard, 2000; Fassett and Thomson, 2014), which control the resurfacing rate and crater retention.

It is important to note that, although the rate of these are much enhanced on slopes, even on surfaces with low or zero slopes, the lifetime of craters, particularly for craters less than $D \leq \sim 500$ m, is much less than the age of the Moon. Table 2 shows the crater retention ages on the floor subunit of each of the four craters we examine. In all four craters we measured, the crater retention age implied by 250-500 m craters on the floor is Late Imbrian (or possibly younger, in the case of Shackleton). These data are consistent with the idea that craters in this size range are generally retained for only ~3.5 Ga even on crater plains with modest slopes (consistent with estimates on the basis of topographic diffusivity measurements, see Fassett and Thomson, 2014). The measurements in this size range on Faustini, Haworth, and Shoemaker's floor are similar, suggesting that this is a measurement of the equilibrium density on highlands plains, and is not particularly dependent on local conditions.

	Floor, Crater Retention Age 250 to 500 m craters only	Period 250 to 500 m craters only	Number of Craters in Fit	Area (km^2)	Equivalent Model N(1) # $D \geq 1$km / km^2
Faustini	3.50 Ga, +0.03, -0.03	Late Imbrian	155	2.17×10^{2}	4.73×10^{-3}
Haworth	3.55 Ga, +0.01, -0.02	Late Imbrian	367	4.47×10^{2}	5.43×10^{-3}
Shackleton	2.63 Ga, +0.54, -0.76	Late Imb/Era.	12	3.69×10^{1}	2.15×10^{-3}
Shoemaker	3.46 Ga, +0.02, -0.02	Late Imbrian	359	5.63×10^{2}	4.22×10^{-3}

Table 2. Crater retention of 250 m to 500 m craters, examining only the floor subunits for each crater.

The crater retention age on the floor of Shackleton is younger than for the other three craters, but it is also more uncertain because of its much smaller spatial extent. It is plausible, however, that it is truly younger, for two reasons: its surrounding slopes are much steeper (Fig. 3), enhancing the transport of material to its floor, and the floor unit itself is rougher, with local 20-m baseline slopes locally exceeding 15°. Both of these factors could contribute to less retention of small craters in Shackleton than is observed in the other three nearby craters.

4. Discussion

Crater Ages compared to past studies, and implications for regional geology

The Shackleton floor and inner slope are here found to have ages modestly different from those reported in Zuber et al. (2012), which utilized the same superposed crater populations but chose slightly different units and crater sizes to examine. The Shackleton floor in that study was reported to have an age of 3.29 Ga on the basis of 500 m craters, which is slightly greater than, but statistically indistinguishable, from what we find here, which is a $D \geq 300$ m crater retention age of 3.22 Ga +0.20/-0.85. The age estimates of Zuber et al. (2012), which implied Late Imbrian ages of 3.60 Ga and 3.69 Ga, respectively, were based on measurements on only the flattest portions of Shackleton's floor and ejecta, which is likely to explain the modestly younger (though still Late Imbrian) age we find here (3.51 Ga, see Table 1). Our findings are thus consistent with Zuber et al. (2012).

The age of units in the study area was also previously assessed during lunar mapping based on stratigraphy and morphology (Wilhelms et al., 1979) (Fig. 7; note that limited photo coverage caused the mapping to be incomplete). Our results differ from their stratigraphic estimates on the ages of Shackleton and Faustini, and LOLA has provided much greater coverage of the area so that a more complete picture can be obtained. Wilhelms et al. (1979) suggest that Faustini is of both Nectarian age and pre-Nectarian age in different areas (Fig. 7) due to deposition of Amundsen ejecta on part of it, but we find its formation age is pre-Nectarian. Wilhelms et al. (1979) mapped Shackleton as Eratosthenian; our data show that the formation age of Shackleton is Late Imbrian, and our crater ages for the Shackleton floor and rim are consistent with a Late Imbrian crater retention age for its ≥300 m crater population as well.

Our results share differences and similarities with geologic interpretations from radar imagery from Small Missions for Advanced Research in Technology (SMART-1) Advanced Moon micro-Imager Experiment (AMIE) and Arecibo (Spudis et al., 2008). Spudis et al. (2008) found that the floors of Haworth, Shoemaker, and Faustini are Imbrian plains, in agreement with our estimates on the basis of small craters. The map of Spudis et al. (2008; their Fig. 3) shows that the inner slopes and rim of Haworth are pre-Nectarian, and the inner slopes and rim of Shoemaker and Faustini are Nectarian. Our crater ages show these three craters all have Imbrian or younger crater retention ages for small craters (<500 m) (on both their plains, slopes, and rims), but our data suggest that the formation age of Haworth, Shoemaker and Faustini are all pre-Nectarian. Shackleton's formation age was interpreted by Spudis et al. (2008) to be Imbrian, which is consistent with our age estimates and those of Zuber et al. (2012).

Implications for Surface Processes

Surface slope has a negative correlation with crater density across our study area (Figs. 3, 5, 6). The relationship between crater retention and slope was systematically explored by

Basilevsky (1976), who suggests that there is an inverse exponential relationship between crater density and slope across slopes from ~5° – 25° (see his Fig. 5). Because of this functional form, the difference in crater retention is more pronounced between a flat slope and a 5° slope than between a 10° slope and a 15° slope. Our measurements of crater removal as a function of slope (Fig. 6) of sub-km craters support this result, and are also fit well by inverse exponential functions. A key result here, consistent with earlier work, is that even slopes of a few degrees can have an appreciable effect on the crater population. It would be valuable to use new topographic data to assess how slope and surface roughness correlate with crater retention in other areas of the highlands, since this is a sensitive indicator of lunar topographic evolution.

Implications for Volatile Deposition/Bulk Resurfacing

In Shackleton, pristine parts of the floor and the ejecta deposit have very similar crater ages (Zuber et al., 2012), evidence against the deposition of thick blankets of volatiles. This argument works less well in the case of Haworth, Shoemaker, or Faustini, all of which have floors that retain only an Imbrian population of small craters, as noted in the past (Spudis et al., 2008). However, the retention ages of these plains on the basis of small craters is not likely to be unusual for the Moon, but reflects mainly the lifetime of craters in these size ranges.

Epithermal neutron flux suppression data from the LRO Lunar Epithermal Neutron Detector (LEND) (Litvak et al., 2012) have revealed the presence of hydrogen-enhanced regolith in some of the PSRs in our study area, particularly in the interior of Shoemaker (Mitrofanov et al., 2010). Based on epithermal neutron flux suppression of −5.5% to −6.3%, Sanin et al. (2012) interpret a hydrogen concentration in Shoemaker regolith of 220-245 ppm if the hydrogen is homogeneously distributed. Spectral and UV albedo data are consistent with highly porous regolith and ~1-2% surface water ice in lunar PSRs (Gladstone et al., 2012; Retherford et al., 2012). Data from the LRO Lyman Alpha Mapping Project (LAMP) show that Shoemaker in particular has a high UV water band depth more consistently across its interior than Haworth, Faustini, Shackleton, or nearby crater Cabeus (see Fig. 1), where the Lunar Crater Observation and Sensing Satellite (LCROSS) experiment excavated material with up to ~5% water ice by mass (Colaprete et al., 2010; Hayne et al., 2014). Thus, Shoemaker may have ~5% or more water ice by mass below the surface. We observe no significant differences in the crater population of the floor of Shoemaker from Haworth or Faustini, so the water ice in the regolith does not seem to be substantially affecting crater retention in the PSRs.

5. Conclusions

1) The inner slopes and rims of Haworth, Shoemaker, and Faustini have crater-ages derived from populations of large, km-scale superposed craters that are in close agreement with each other and indicate that these three craters were likely to have formed in pre-Nectarian time, ~4.1 to 4.2 Ga. In the case of Shoemaker and Faustini, this is older than previously interpreted (Wilhelms et al., 1979; Spudis et al., 2008).
2) Our age results for Shackleton are consistent with Zuber et al. (2012), who suggest that it is of Late Imbrian age, and whose analysis was based on the same superposed crater populations as this study but slightly different outlines of map units.
3) The floors of craters Haworth, Shoemaker, and Faustini have retained their population of sub-km craters only since the Late Imbrian, with implied 250 m-500 m crater retention of ~3.5 Ga. Correlation between crater frequency and surface slope for sub-km craters suggests that observed crater populations are controlled primarily by slope-related crater

retention, rather than deposition of a particular unit or emplacement of volatiles within these craters. Though not inconsistent with the concentrations of regolith water ice suggested by epithermal neutron flux and spectral and UV albedo data, our data show that volatiles have had minimal influence on superposed crater populations in Haworth, Shoemaker, Faustini, and Shackleton.

4) There is a very strong correlation between average surface slope and crater frequencies in our study area. Further examination of this relationship in other areas of the highlands will lead to a greater understanding of the effect of surface morphology on crater retention and the evolution of lunar topography.

5) The ancient formation ages of Shoemaker, Faustini and Haworth, and the Late Imbrian (~3.5 Ga) crater retention ages of their floors suggests that any water ice that might have been deposited in their permanently shadowed areas was insufficient to modify the superposed crater population since that time.

Acknowledgments: We gratefully acknowledge financial support from the NASA Lunar Reconnaissance Orbiter (LRO) Mission, Lunar Orbiter Laser Altimeter (LOLA) Experiment Team (Grants NNX11AK29G and NNX13AO77G), and the NASA Solar System Exploration Research Virtual Institute (SSERVI) grant for Evolution and Environment of Exploration Destinations under cooperative agreement number NNA14AB01A at Brown University.

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Figure Captions

Figure 1. LOLA topography for the study area, the lunar south circumpolar region. LOLA Digital Elevation Model (LDEM) elevation data shown in color, overlying LOLA hillshade data. Large craters in the region are labeled by name.

Figure 2. Locations of permanently shadowed regions (PSRs) shown in black, overlying LOLA hillshade data. Map units used in this study are outlined in orange, including the floor, inner slope, and rim for Haworth, Shoemaker, Faustini, and Shackleton, and the interior and ejecta deposit of Malinkin.

Figure 3. The four main craters examined in this study: H – Haworth, Sho – Shoemaker, F – Faustini, Sha – Shackleton. Each panel shows craters used to determine crater ages in black outline. Boundaries of map units (floor, inner slopes, rim) shown in orange outline. Mean slopes and standard deviations for crater floors, wall slopes, and ejecta deposits respectively are as follows: Haworth – 5.1° ± 3.7°, 15.1° ± 5.4°, 9.7° ± 5.3°, Shoemaker – 5.0° ± 4.0°, 15.5° ± 4.9°, 8.6° ± 5.7°, Faustini – 4.7° ± 4.3°, 15.4° ± 4.6°, 7.2° ± 4.1°, Shackleton – 9.4° ± 5.8°, 28.6° ± 6.1°, 12.3° ± 5.7°. The backdrop is a slope map (20 m baseline) from LOLA altimetry data, with an emphasis on the 15° - 30° slope range. Malinkin appears on the same panel as Faustini. Its interior and ejecta deposit are also outlined in orange. Below each panel is a W-E elevation cross section. The section is taken along a line shown in black in each panel. All cross sections share the same scaling, with vertical exaggeration of 2x.

Figure 4. Cumulative CSFDs of craters superposed on all subunits of the four craters in our study fit and plotted using CraterStats with pseudo-log binning. The best fit is defined using the Neukum et al. (2001) production and chronology functions. (Note the different diameter range for Shackleton).

Figure 5. Crater densities in different size bins, in moving neighborhoods of radius 10 km. The color stretch is different in each panel, depending on crater density maximums and minimums. Note that as crater size decreases, the crater population becomes more and more depleted on steeply sloped surfaces (Fig. 3) relative to flat-lying terrain. Craters larger than 1 km in diameter show less evidence for slope dependence; instead, the most prominent signature is how the population in this size range was reset by the formation of Shackleton.

Figure 6. Plots of crater density versus slope for craters with diameter 250 m – 500 m, 500 m – 1000 m, and ≥1000 m. This was created by dividing the study area into subareas defined by 200 m-baseline slope (binned from 0-2°, 2-4°, 4-6°, 6-8°, 8-10°, 10-15°, 15-20°, and 20-35°). In our dataset, the measured frequency of sub-km craters is strongly affected by slope, whereas craters larger than 1 km appear generally unaffected.

Figure 7. Geologic map of the study area (Wilhelms et al., 1979) plotted over hillshade of LOLA topography. Map units (floor, inner slope, rim) outlined in orange for each crater.