AGE ESTIMATES FOR PERMANENTLY SHADOWED CRATERS IN THE VIPER MISSION AREA BASED ON THEIR TOPOGRAPHY.

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Introduction: A primary objective of the VIPER [1] mission is to characterize the distribution and physical state of volatiles at the lunar poles, including within permanently shadowed regions (PSRs) where water ice has been inferred to be stable [e.g.. 2,3]. A mission area for VIPER has been defined that enables this scientific objective near Nobile crater (Fig. 1) [4]. This location enables a traverse that can both meet VIPER's engineering constraints (Earth-direct communication, adequate power, etc.) as well as accomplish the planned scientific exploration.

In this abstract, we describe observations of crater topography that provide insight into the age of several craters that host PSRs within the planned VIPER mission area. The role that the age of PSRs plays in controlling the presence or absence of polar volatiles is of substantial interest for discerning volatile history [e.g., 5-7]. The physical state, depth distribution, and spatial distribution of volatile deposits may also vary as a function of PSR age due to gardening and/or differing emplacement mechanisms [8]. Understanding the age of PSRs that VIPER may explore is thus a useful goal.

Method: The main agent of landscape evolution on the Moon is impact cratering, which over long-enough time periods effectively modifies the entire lunar surface. The cumulative effect of impacts and their ejecta is sufficient to cause older craters to have less distinct rims, less relief, and lower depth-diameter ratios [e.g., 9, 10].

This process can be modeled as a diffusive one [11-14] that mutes relief over time so that surface topography h changes as $\frac{dh}{dt} = \kappa_{eff} \nabla^2 h$ *(eq. 1)*. A complication is that the effective diffusivity (κ_{eff}) that landforms experience is scale-dependent (anomalous diffusion) [14-16] and varies depending on the size of crater under consideration. The effective diffusivity may also vary as a function of time: at km-scales, measurements of numerous craters provide a calibration of the diffusivity history since the emplacement of the maria and averaged over the last 3 Gyr, κ_{1km} ~5.5 m^2/Myr [13].

From constraints related to equilibrium as well as measurements at a range of scales, we estimate that $\kappa_{eff}=\kappa_{1km}D^{0.9}$ (*eq. 2*) [15, 16]. The uncertainty in κ_{eff} increases far from the km-scale measurements on which the diffusivity was calibrated. O'Brien and Byrne [17] report an effective diffusivity based on median roughness at 8-m scale of ~0.1 m^2/Myr, within a factor of ~1.5-2 of our estimate. With the different spatial and temporal scale that led to these estimates, this is reasonably good agreement.

By fitting model diffused cratered profiles to individual craters' topography, we can estimate the age of degraded craters. The uncertainties in derived degradation ages are dominated by systematic uncertainties rather than model fits. Some factors driving uncertainty include: (1) the underlying crater chronology that degradation ages are tied to, (2) possible variability in the degradation process in space and time, and (2) possible variability in initial crater morphometry. We estimated typical uncertainties in degradation age ±30% for individual craters on the mare [13], excluding systematic uncertainties in the underlying crater chronology. Relative interpretations based on the measured crater degradation are likely to be more robust than the absolute age estimates.

Here, we have applied this method to a subset of large craters in the mission area that host PSRs (Fig. 1).

Data: The Ames Stereo Pipeline (ASP) [18] has been used to produce a shape-from-shading [19] digital terrain model (DTM) of the VIPER mission area using >100 LROC NAC images with different illumination geometries, infilled with LOLA topography where the surface was unilluminated. Figure 2 shows median crater profiles extracted from this DTM, along with model degradation fits for craters hosting the three largest PSRs in the VIPER mission area (Fig. 1).

Results: The craters hosting the largest PSRs on the Nobile plateau are all highly degraded, with estimated ages >3.5 Ga. Given that remote sensing and modeling [5-7] generally are consistent with the largest ice deposits being >3 Ga, these PSRs are an exciting target that VIPER should be able to characterize during its mission. Our measurements suggest that smaller PSRs in the Nobile mission area are generally younger (<1 Ga) based on their observed degradation states.

Because of gardening [8] and short equilibrium lifetimes for small craters on the Moon, micro-PSRs [20] that are <10 m are all likely <100 Ma. Thus, any volatiles found in micro-PSRs may have distinct sources and/or evolution from volatiles in larger PSRs. One possibility is that any volatiles in smaller PSRs could be redistributed from longer-lasting reservoirs.

References: [1] https://www.nasa.gov/viper. [2] Watson, K. et al. (1961), *JGR*, *66*, 3033-3045. [3] Vasavada, A.R. et al. (1999), *Icarus*, *141*, 179-193. [4] https://go.usa.gov/xtCA7. [5] Deutsch, A.N. et al. (2020), *Icarus*, *336*, 113455 [6] Cannon, K.M, et al. (2020), *GRL*, *46*, e2020GL088920. [7] Siegler, M.A. et al. (2016), *Science*, *531*, 480-484. [8] Costello, E.S. et al. (2020), *JGR*, *125*, e2019JE006172. [9] Trask, N.J. (1967), *Icarus*, *6*, 270-276. [10] Basilevsky, A.T. (1976), *Proc. LPSC 7th*, 1005-1020. [11] Soderblom, L.A. (1970), *JGR*, *75*, 2655-2661. [12] Craddock, R., Howard, A. (2000), *JGR*, *105*, 20387-20401. [13] Fassett, C.I., Thomson, B.J. (2014), *JGR*, *119*, 2255–2271. [14] Xie, M. et al. (2017), *GRL*, *44*, 10171-10179. [15] Fassett, C.I. et al. (2018), *LPSC 49*, 1502. [16] Minton, D.A. et al. (2019), *Icarus*, *326*, 63-87. [17] O'Brien, P.O., Byrne, S. (2020), *JGR*, 126, e2020JE006634. [18] Beyer, R.A. et al. (2018), *ESS*, *5*, 537–548. [19] Alexandrov, O., Beyer R.A. (2018) *ESS*, *5*, 652-666. [20] Hayne, P.O. et al. (2020), *Nature Astro.*, *5*, 169-175.

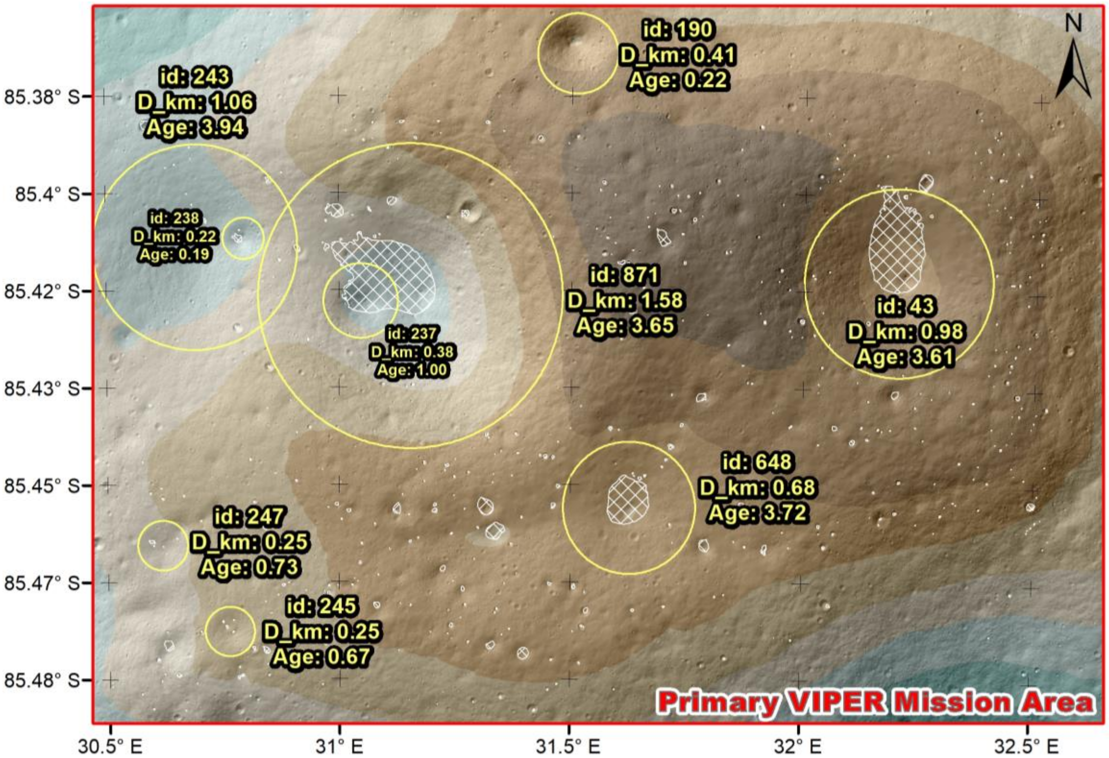

Figure 1. Nine of the largest craters in the currently mission area with degradation-derived age estimates in billions of years. Hashed regions are PSRs (note there is a PSR in the crater with id 190 as well). The three craters (Fig. 2) with the largest PSRs on the Nobile plateau are all interpreted as Imbrian based on their degradation state. The largest crater, id 871, has a younger crater, id 237, that formed on its interior floor and subsequently altered the shape of its PSR. All smaller PSRs (<500 m) are younger (<~1 Ga), as expected.

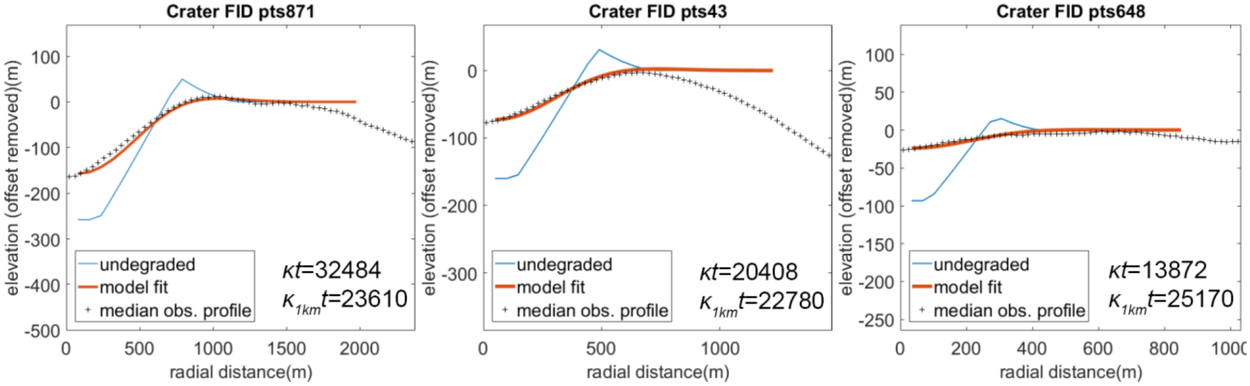

Figure 2. Diffusive fits to the craters with the three largest PSRs in the VIPER mission area. The κt values are model fits, with $\kappa_{1km}t$ values reporting the equivalent degradation state renormalizing to a constant 1-km scale (see eq. 2). (Blue: model fresh crater profile; Orange: model diffused crater profile; Crosses: Median observed crater topography.)