A Landscape Evolution Perspective on How Young is Young on the Lunar Surface

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1. Introduction and Summary

High-resolution topography and image data have renewed interest in the possibility that localized volcanism and tectonism occurred on the Moon in the last tens-to-hundreds of million years. In a recent study, we used impact crater degradation to constrain how fast the lunar surface changes. This methodology can also be applied directly to landforms besides craters to provide a new source of information about their age. An important caveat is that, unlike for craters where the initial topography is well known, for other landforms we do not generally know their initial form. Because diffusion cannot be run backwards, we are thus mostly limited to constraining the maximum age of landforms.

Nonetheless, our results are consistent with the interpretation that lunar features that have been hypothesized to be young - small lobate scars, graben, and irregular mare patches - are, in fact, young (less than 100 Myr), but in some cases much younger than that. In fact, in the case of Ina Caldera, its small-scale topography suggests it is actively evolving today.

We also looked at Hadley Rille and the well-preserved Eratosthenian lava flows in Imbrium. Hadley Rille has infilled and widened since its formation. Our estimates for the rille’s maximum age are consistent with ages from Apollo 15 samples, although a wide range of scenarios can reasonably match the rille's current topography. The margins of the young lava flows in Imbrium are less degraded than expected from either crater statistics or from the degradation of craters on their surface. The most straightforward explanation is that the margins of these flows are more resistant to lateral erosion and degradation than expected.

2. Lunar Crater Degradation, Diffusivity, and Erosion Rates

If lunar surface topography evolves diffusively, as expected from both theory and observations, the downslope material flux \(q\) is a function of the diffusivity, \(\kappa\) and gradient of the topography \(\partial h/\partial t\):

\[ q = \kappa \partial h/\partial t \]

Combining this with a statement of material conservation:

\[ \partial h/\partial t = -q/\kappa \]

results in topographic evolution following the classic diffusion equation:

\[ \partial h/\partial t = \kappa \partial^2 h/\partial x^2 \]

By measuring how fast craters evolve (Fig. 1, Fig. 2), we have estimated \(\kappa\) (Fig. 2). Our crater degradation measurements suggest an average \(\kappa\) of 5.5 ± 0.5 m²/Myr over the last ~3 Gyr; the crater degradation rate increases with age.

From this we can estimate the material flux at a crater:

\[ \rho \kappa \partial h/\partial t = \rho \kappa \kappa \partial^2 h/\partial x^2 \leq \rho \kappa \kappa \partial^2 h/\partial x^2 \]

These values illustrate why small-scale, sharp features, which are, in general, rare on the Moon, are likely young, because otherwise they would be degraded beyond recognition.

3. Ina Caldera

A maximum age of 10-32 Myr has been suggested for Ina. Based on its topography, we find maximum ages of 50-140 Myr for profiles Aa, Bb, Cc and 5 to 40 Myr for Dd, Ee, and Ff. However, more stringent limits exist on the most recent activity. Both profiles Ee and Ff have ~15-180 cm deep troughs at the base of scars with the local topographic curvature of 0.1-0.2 m⁻¹. With these curvatures, these troughs should exist at ~0.5-3 m/Myr, or within 1-2 Myr, yet they remain topographic lows. This implies they formed at the base of these scarps recently, or are forming currently (in a geologic sense).

4. Small Scarps, Wrinkle ridges, and Graben: Lee-Lincoln and Virtanen

Many fresh tectonic features on the Moon are potentially young. Lee-Lincoln scarp, which was examined closely during Apollo 17, has an extension onto the steep slopes (15-18°) of North Massif. Because of these steep slopes, the scarp would be efficiently erased if the most recent tectonic activity was ancient. Our best-fit maximum age for the scarp is 75 Myr. Small graben northeast of Virtanen crater are consistent with more recent activity, with best-fit ages of 1-2 Myr.

5. Hadley Rille

Apollo 15 samples suggest Hadley rille is ~3.3 Gyr old (t~18600). The rille’s rim and inner slopes are smoothed and appear to have undergone topographic diffusion. Maximum best-fit \(E_t\) values of ~22000-25000 (t~3.5-3.7 Gyr) are found assuming initially vertical walls. The walls were initially ~32-35°, the best-fit \(E_t\) values are decreased, and can match, or fall below, the expected \(E_t\). Results are thus non-unique and a wide range of models can approximate the rille’s current topography. However, such models generally imply that the rille has widened and infilled by tens-of-hundreds of meters.

6. Imbrium Lava Flows

Some of the most prominent lava flows on the Moon are observed in west Imbrium. These flows are Eratosthenian in age, 2.1±0.3 Gyr in the Neukum chronology. Crater degradation measurements give a consistent age, ~1.7±0.5 Gy (median at ~8050, st. dev. ~12400). However, topographic profiles of the flow’s margins have best-fit diffusion profiles of ~10000-60000, a factor of 2-4 less degraded than expected given the degradation of craters on the flow’s surface and the flow’s inferred age. We hypothesize that the margin of these lava flows are more resistant to erosion than expected.

Figure 3. (top) Ina topography from LROC stereo.

(bottom) Profiles of Ina with best-fit diffusion models (assuming initially vertical scarps). Extraneous material on smooth unit A-A’, B-B’. From smooth hillocks to troughs: D-d, E-e, F-f. Note the rounded forms of most profiles.

(left) LROC oblique view of Ina (ML1010231501L12)

Figure 4. (top two) LROC stereo topography of Virtanen graben with resulting profiles and fits. (bottom row) LROC stereo of Lee-Lincoln scarp, with profiles and fits. (left) Composite mosaic of the Lee-Lincoln scarp extension onto North Massif from Apollo 17 during the traverse from Station 24 to 3.

Figure 5. (top) Topography of Hadley Rille from the Kaguya Terrain Camera. (below) Fits to profiles, assuming initially vertical walls (left panel) or a triangular profile (right panel) with walls slopes of ~32-35°. (left) Mosaic of Hadley rille from the Apollo 15 Station 1 pan.

Figure 6. (top) LROC stereo topography of Imbrium flows. (bottom) Profiles of flows with best-fit diffusion models (assuming initially vertical scarp). (left) Composite of Apollo 15 view of young lava flows.