Revised Lunar Cratering Chronology for Planetary Geological Histories

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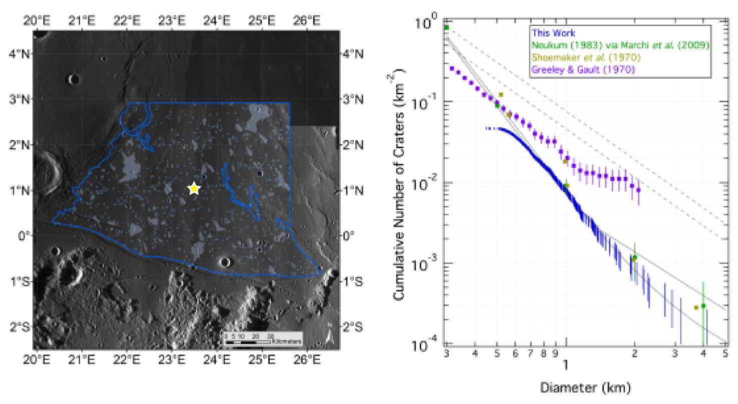
Abstract Crater age-modeling is the primary method of estimating surface ages across the solar system, and all age estimates are tied to the Moon based on *Apollo* and *Luna* sample returns. The basic method is that radiometric ages were determined for all landing sites with sample returns. Craters on each sampled unit were identified and then correlated with the radiometric ages; this crater chronology is often expressed as the sum of all craters $D \geq 1$ km on a given unit, written as $N(1)$, and that density corresponds to the radiometric age of that unit. That basic work was completed in the 1970s by various researchers with little reanalysis in the subsequent years. The work I present is the first uniform, comprehensive reexamination of all *Apollo* and *Luna* calibration points' crater densities in several decades, making use of modern imagery . These revised $N(1)$ crater densities are plotted against the sites' radiometric ages [1] and a new chronology function is fit. This revised chronology indicates that surfaces with ages based on the old chronology [2] are up to 1.1 billion years younger under this new one.

Apollo 11

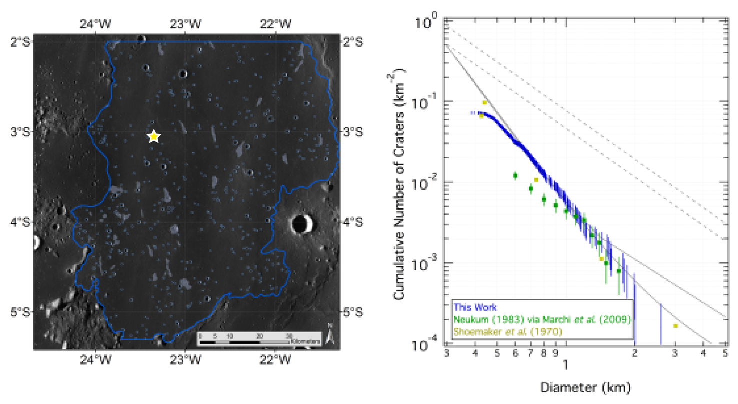


Landing: Mare Tranquilitatis.

$N(1)$: Good PF fits, density is close to historic "old" values.

Notes: Previous work [8] identified "old" and "young" densities that have been used since, but two ages were not seen here.

Apollo 12

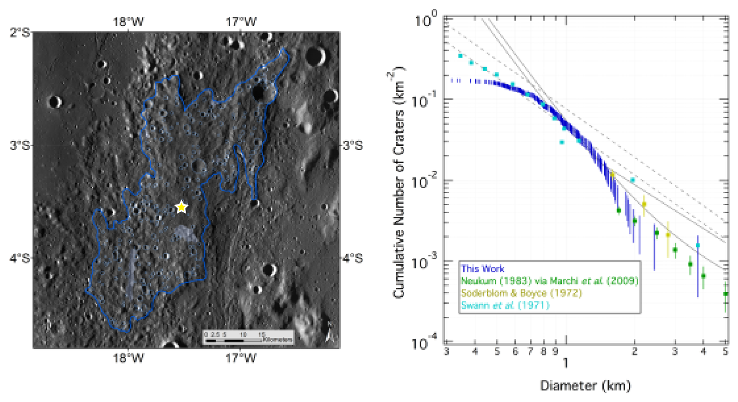


Landing: Oceanus Procellarum.

$N(1)$: Good PF fits, good data overlap at D=1 km, but density is ~1.5x greater than [10].

Notes: Copernicus crater rays paint the site but they should not affect crater counts at the ~1 km level.

Apollo 14

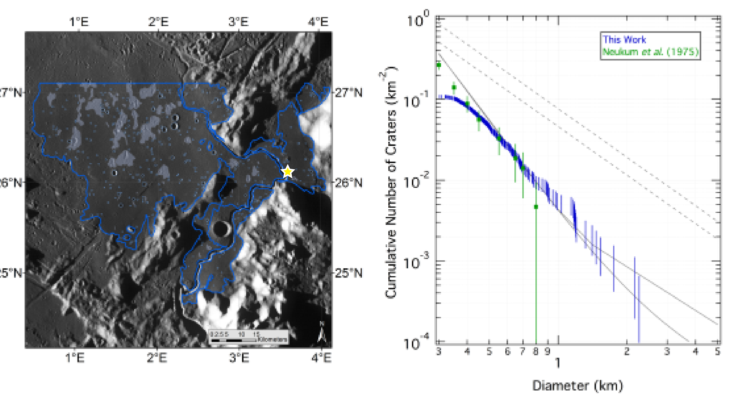


Landing: Fra Mauro highlands.

$N(1)$: Saturated for D<1.5 km, PF fits used to estimate density. Large error bars due to range of estimates, but raw data overlaps previous work well.

Notes: Site is empirically saturated at $N(1)$.

Apollo 15

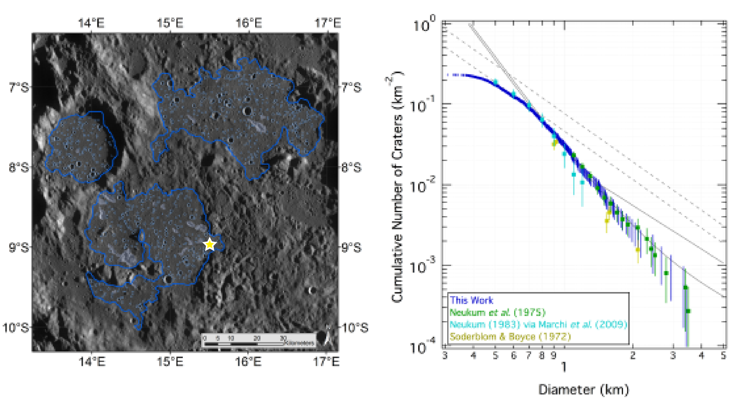


Landing: Mare Imbrium.

$N(1)$: Raw data overlaps well with previous work and PFs fit well. Density is ~2x most previous work.

Notes: ~150 km from Autolycus crater with numerous secondary crater fields.

Apollo 16

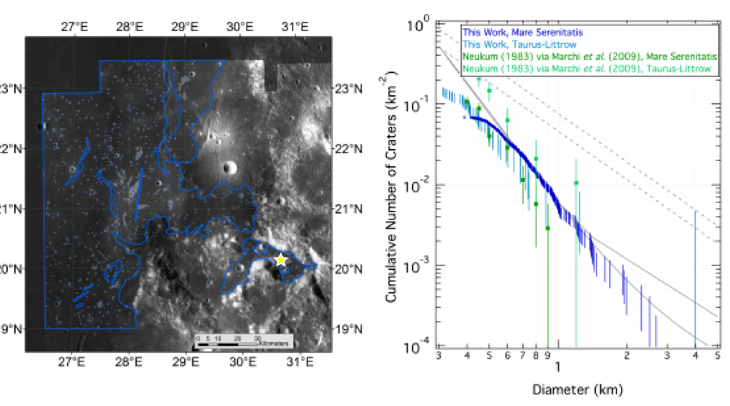


Landing: Cayley formation in Descartes.

$N(1)$: Very good PF fits and overlap with previous work. This datum controls the lunar chronology's exponential region.

Notes: Three different regions were mapped, but SFDs all overlap well.

Apollo 17



Landing: Taurus-Littrow valley (TLV) on edge of Mare Serenitatis.

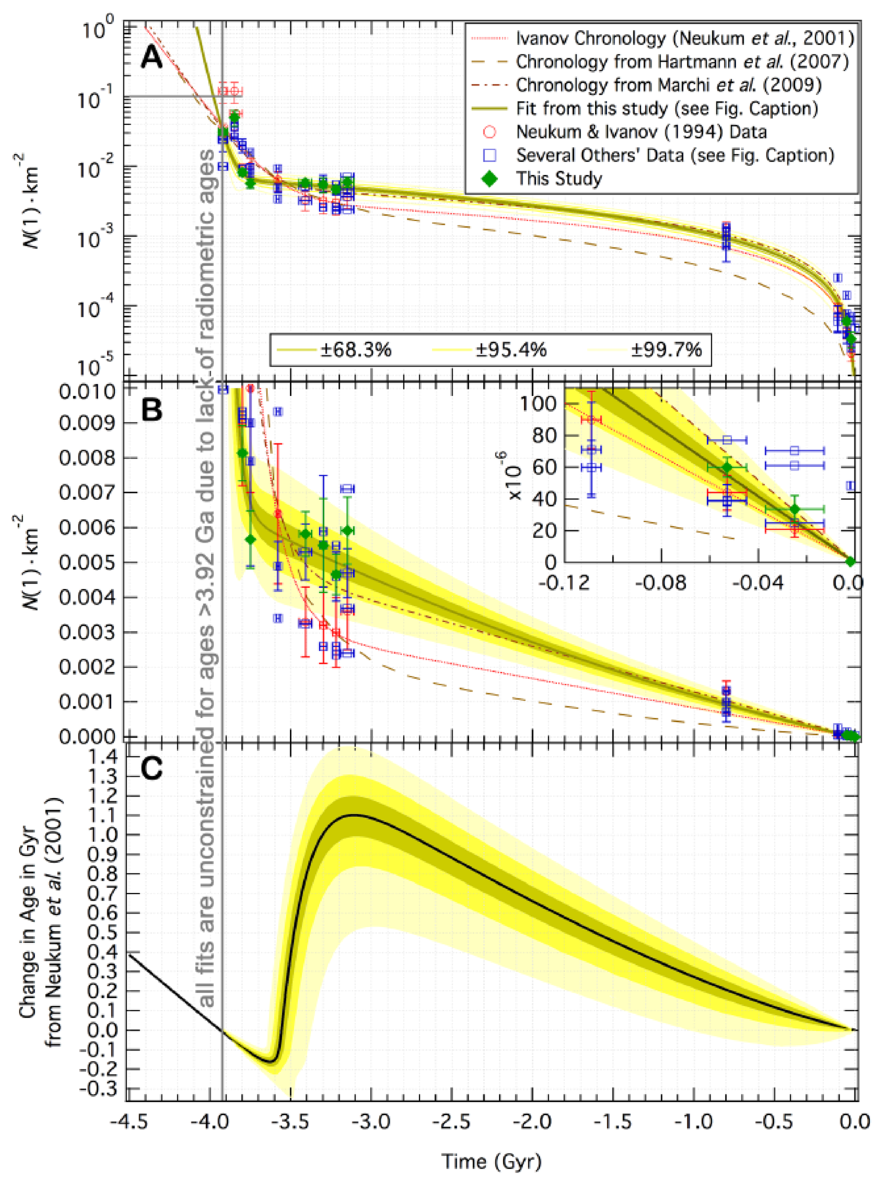
$N(1)$: TLV is too small for $N(1)$ and are low density, and while broader region counts are larger $N(1)$, they are still less than [5]

Notes: Uncertain what unit was sampled.

Methods

Lunar Reconnaissance Orbiter Wide-Angle Camera images were mosaicked to produce 60 m/px basemaps of each landing site. Narrow-Angle Camera images were used for the three most recent chronology points (Cone, North Ray, South Ray craters). Each site was mapped to exclude units not sampled and remove as many secondary crater fields as possible. Craters were identified and a cumulative histogram (size-frequency distribution, "SFD") created. The $N(1)$ density was read off each SFD; for the three recent sites, $N(1)$ could not be measured and Hartmann and Neukum [2-3] production functions ("PFs") were fit to estimate $N(1)$. Maps and SFDs are onthe left and right with production functions and 3% and 5% saturation curves overlaid.

A New Lunar Chronology



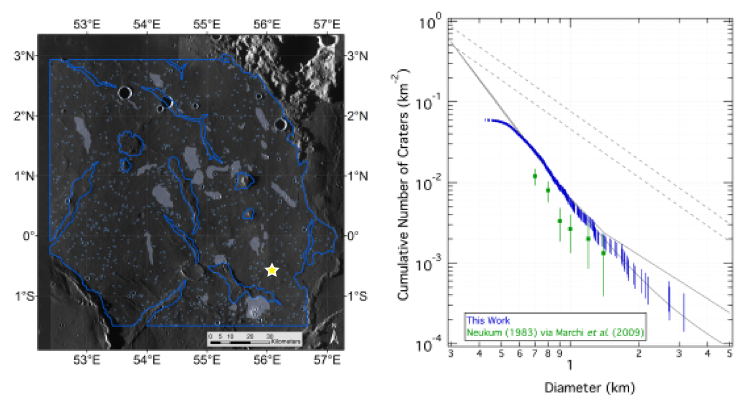
$$N(1) = 1.79 \cdot 10^{-40}\left(\exp(-22.47T) - 1\right) + 1.62 \cdot 10^{-4}T^2 + 1.04 \cdot 10^{-3}T$$

Panels A & B: The classic chronology [2], revisions [3-4], and this work versus radiometric ages from [1]. Data originally used by [5] are displayed along with those from this study and several comparison works [4-14].

Panel C: Difference between the new chronology and [2] as a function of age in the old chronology.

All: Line at 3.92 Ga and $N(1) = 10^{-1}$ indicate values greater than which the function should not be used.

Luna 16

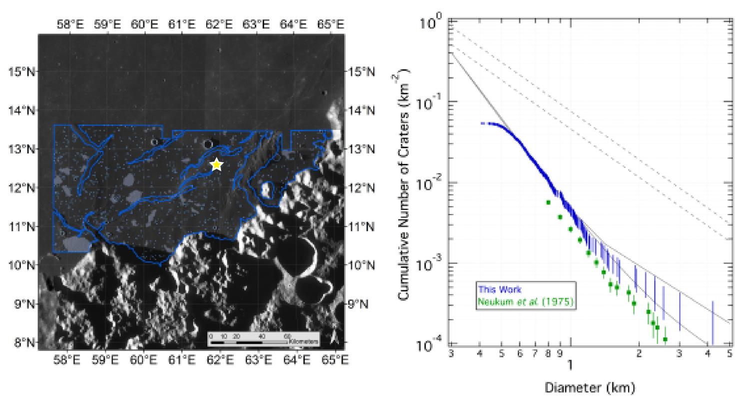


Landing: Mare Fecunditatis.

$N(1)$: Good PF fits, though the crater density is ~2x that found in previous work.

Notes: Numerous wrinkle ridges, massifs, and secondary crater fields were excluded.

Luna 24

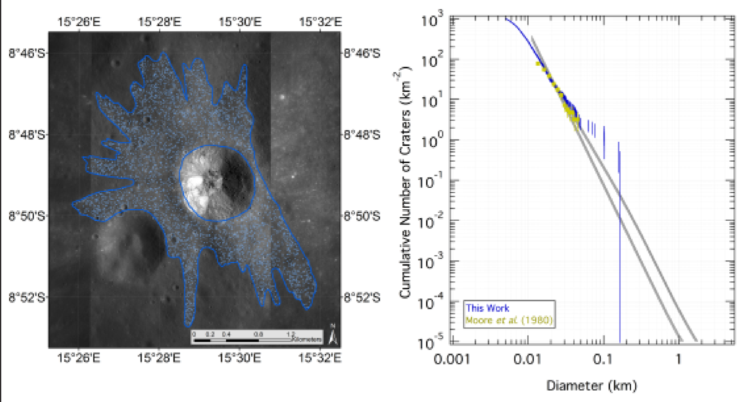


Landing: Mare Crisium.

$N(1)$: Good PF fits, though the crater density is ~2x that found in previous work.

Notes: Mare is non-uniformly cratered and previous work [10] measured craters in the mare's center, where the density is less.

North Ray Crater

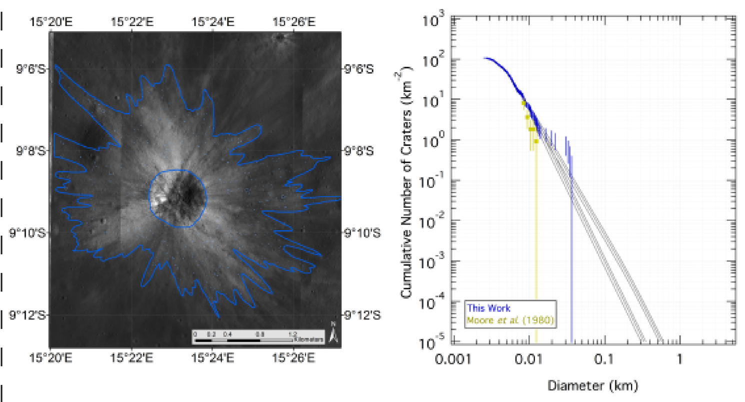


Landing: Cayley (*Apollo 16*).

$N(1)$: Good PF fit to smaller craters, in general agreement with previous work [11].

Notes: $N(1)$ density must be extrapolated over 10x in diameter, and PFs disagree by ~5x in the final density.

South Ray Crater

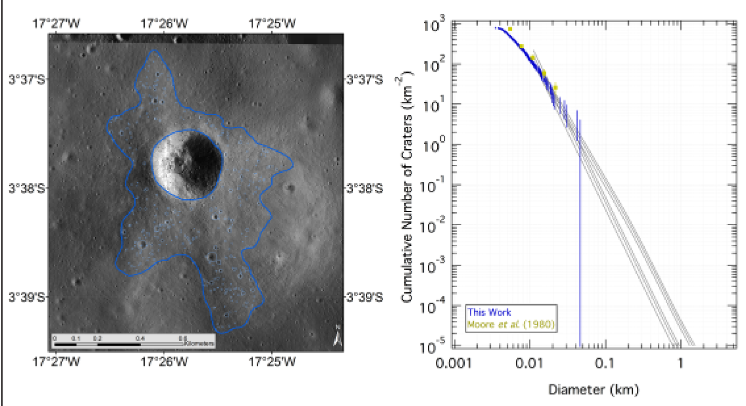


Landing: Cayley (*Apollo 16*).

$N(1)$: Good PF fit to smaller craters, in general agreement with previous work [11].

Notes: $N(1)$ density must be extrapolated over 10x in diameter, and PFs disagree by ~5x in the final density.

Cone Crater



Landing: Descartes (*Apollo 14*).

$N(1)$: Good PF fit to smaller craters, in general agreement with previous work [11].

Notes: $N(1)$ density must be extrapolated over 10x in diameter, and PFs disagree by ~5x in the final density.

Conclusions

The literature-standard crater densities used to establish the lunar crater flux are not as definite as previously thought, and at a minimum, my work shows that this problem deserves and requires further study. From this work, almost all sites' $N(1)$ crater densities are different from historic work, and that difference means that a greater crater density is required to have a surface of a given age. The likely reasons are that previous work did not always (a) directly measure the $N(1)$ calibration point, but instead extrapolated from larger/smaller craters; (b) identify craters on the same geologic unit as the sampling sites; (c) accurately measure crater-counting surface areas, and/or exclude areas covered by secondary craters; and (d) use quality images to generate a crater census. This new chronology fit means ages previously dated via craters to ≲3.5 Gyr are up to 1.1 billion years younger. This has implications for ages of numerous inner solar system processes such as lava flooding on Mercury, resurfacing of Venus, and aqueous activity on Mars.

References & Acknowledgements

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