

**DERIVING LIFETIMES OF LUNAR EJECTA
CONSTITUENTS: A MODEL FOR LUNAR EROSION
AND REGOLITH OVERTURN**

A Thesis Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

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December 2019

Abstract

Young ejecta deposits on the lunar maria are visible in radar and thermal infrared images as bright rings around impact craters. As a result of space weathering processes, the rocks present in ejecta deposits erode into fine-grained regolith, and the corresponding, remotely sensed signatures fade. The goal of this thesis is to determine rates at which lunar ejecta deposits erode, with a hypothesis that surface rocks erode more quickly than subsurface rocks. To accomplish this goal, I assess impact crater ejecta deposits by measuring the radar-derived circular polarization ratio (CPR) and thermal infrared-derived rock abundance (RA) of small ($\sim 1.5\text{--}2.0$ km) craters on the lunar maria. Ejecta deposits are characterized by extracting radial medians from the associated CPR and RA data. A curve is then fit to the radial median of each crater and the parameters of that curve are compared with a modelled crater age to assess changes in roughness with time. Results show decreasing trends in CPR and RA data, indicating that ejecta are eroding over time, but these signatures of observed ejecta deposits vary considerably. Linear regression models fit to the CPR and RA data suggest that CPR values of ejecta deposits may decrease more quickly than RA values. Goodness-of-fit statistics for each model indicate that the respective linear fits are poor representations of the variance in the data. These results weakly refute my hypothesis that surface rocks erode more quickly than subsurface rocks. In attempts to understand the cause of the observed scatter, separate analyses of crater ejecta and rims suggest that RA values of crater rims may remain elevated for the first ~ 2.2 Ga of a crater's lifetime. One speculative interpretation of this suggestive decoupled evolution is that the crater rims are composed of in-situ material that is continually uncovered by mass wasting of the overlying regolith. This mechanism implies that the rate of mass wasting at crater rims outpaces that in the

more distal ejecta. Moreover, this interpretation suggests that one rate of erosion may be insufficient to characterize the evolution of lunar ejecta rock concentration.

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Section 1: Introduction

Impact craters on the Moon provide the standard reference for age-dating other planetary surfaces as the ages of surfaces throughout the Solar System are tied to the lunar impact crater production rate (e.g., Neukum et al., 2001; Fassett, 2016). When viewed in synthetic aperture radar backscatter and thermal infrared images, some of these lunar impact craters appear bright relative to the surrounding terrain. This observation suggests that the crater ejecta has elevated roughness at the centimeter-to-meter scale at the surface and near subsurface (e.g., Thompson et al., 1974; Bandfield et al., 2011; Neisch, et al., 2013; Ghent et al., 2016). Most craters, however, appear to lack this brightness. This transition from a bright radar signature to a darker signature has been inferred to represent the erosion of lunar surface rocks with time due to macroscopic space weathering processes (e.g., Bandfield et al., 2011; Bell et al., 2012; Neisch et al., 2013; Ghent et al., 2014; Fassett et al., 2018). Previous work on crater degradation has inferred individual crater ages based on topographic degradation state (Fassett and Thomson, 2014), rock abundance (Ghent et al., 2014, 2016), and the radar parameter of circular polarization ratio (CPR) (Bell et al., 2012; Neish et al., 2013; King et al., 2017). Moreover, Fassett et al. (2018) showed that an evolution of ejecta roughness and corresponding CPR is decipherable. Despite previous studies, a robust correlation between CPR and RA fading rates for lunar craters has remained elusive due to a lack of definitive age dates for large sample sizes of lunar craters and the noise that is inherent in the CPR dataset.

The work presented in this thesis is focused on improving lunar surface age controls and constraining lunar surface evolution by measuring rates at which lunar rocks break down and surface roughness associated with craters across the lunar maria is diminished (**Fig. 1; all figures are located in Appendix A**). In this thesis, I seek to quantify the rate at which impact crater

ejecta evolves with time. I utilize a combination of radar and thermal infrared-derived data to characterize the roughness of simple lunar impact crater ejecta deposits (**Fig. 2**) and assess the rate at which those ejecta blankets erode. This approach builds on prior work (Fassett and Thomson, 2014; Ghent et al., 2016; King et al., 2017; Fassett et al., 2018), and in particular uses modelled crater ages previously derived from topography by Fassett and Thomson (2014). By establishing these rates, this work will improve our understanding of lunar regolith and will help provide a method for obtaining model ages for individual lunar impact craters based on their CPR or RA signatures. An improved understanding of the nature of ejecta erosion will improve our understanding of the dynamism of the lunar surface and the time frame over which lunar rocks break down. Moreover, a robust rate of ejecta erosion has the potential to redefine our understanding of the time required for overturn of the upper layers of lunar regolith. Recent work using sub-meter-resolution images of recent craters indicates that overturn rate of the uppermost 2 cm of regolith may be more than two orders of magnitude greater than previously estimated (Speyerer et al., 2016). Lastly, the work presented in this thesis will contribute to establishing a local and regional assessment of lunar surface roughness, which will be crucial to the safety and success of future landed missions on the Moon.

Section 2: Background

2.1 The impact cratering process

Impact craters form as the result of asteroid or cometary impactors and are common features on the Moon and other planetary bodies. Impact craters that are formed at impact angles greater than 10 to 15° appear as circular rimmed depressions that vary in size from <0.1 μm to >2000 km in diameter (e.g., Melosh, 2011). Simple impact craters are bowl-shaped depressions with smoothly sloped crater walls, a flat crater floor, and a parabolic profile. On the lunar maria, the rim-to-floor depth of a fresh simple crater is roughly 1/5 of its rim-to-rim diameter (Pike, 1977; Stopar et al., 2017). Ejecta blankets associated with simple craters are described as hummocky, with mounds and shallow depressions alternating in no discernible pattern (Melosh 1996, 2011; Osinski et al., 2011; Osinski and Pierazzo, 2012).

The crater formation sequence can be broadly broken down into three stages: contact and compression, excavation, and modification (e.g., Melosh, 1996, 2011). The contact and compression stage is characterized by the projectile coming into contact with a planetary surface. This stage results in most of the impactor's kinetic energy being transferred into the impacted body. Following the contact and compression stage, the excavation stage involves the propagation of a primary shock wave and rarefaction waves propagating back through the target. In this stage, a majority of the impactor vaporizes and the parent body material through which the primary shock wave propagates is vaporized, melted, or shattered and ejected from the crater cavity at high velocities. The initially ejected material travels at high velocities forming distal ejecta (e.g., Melosh, 1996, 2011). The ejection of this high-speed material that becomes distal ejecta is followed by ejection of material at lower velocities. This slower material, which becomes the proximal or continuous ejecta, is deposited between the crater rim and a distance of

~2.5 crater radii (e.g., Melosh, 1996, 2011; Koeberl, 2013). When deposited, the proximal ejecta blanket typically represents an inverted stratigraphic section of the underlying rock; that is, the layers of country rock into which the crater formed are represented in reverse stratigraphic order within the ejecta blanket (e.g., Shoemaker, 1963; Melosh, 1996; O'Keefe and Ahrens, 1999).

Lunar ejecta deposits are emplaced ballistically with no drag resistance due to the lack of an atmosphere. Additionally, the rocks and boulders in ejecta deposits are variable in size. Observational studies have shown that larger boulders are deposited closer to the crater rim and rock sizes gradually fine with distance from the crater (e.g., Bart and Melosh, 2010; Pajola et al., 2018). The size of the largest ejecta blocks associated with a given crater also have been shown to be loosely dependent on crater diameter (Bart and Melosh, 2007).

2.2 Lunar weathering

The last stage of the impact cratering process, modification, is the focus of the work presented in my thesis. The modification stage of impact crater formation involves the infilling, topographic degradation, and weathering of an impact crater structure that can remain for billions of years on the lunar surface. Weathering or degradational processes occur on all rocky bodies within the Solar System. On Earth, weathering processes are predominantly tied to the presence of liquid water. On Mars, the past dominant mechanism responsible for the breakdown of rocks at the surface was water (e.g., Craddock and Howard, 2002), and the current dominant erosional mechanism is wind (Sagan and Bagnold, 1975; Greeley 2002; Kok et al., 2012). On Earth's Moon, an airless body with no evidence for liquid water, the dominant weathering mechanism is micrometeoroid bombardment (Ross, 1968; Soderblom, 1970; Hörz et al., 1971; Langevin and Arnold 1977; Fassett and Thomson, 2014). Other mechanisms, such as internal seismic events or surficial thermal expansion and contraction have also been shown to contribute to the breakdown

of solid rock on the lunar surface (Schultz and Gault, 1976; Molaro and Byrne, 2012; Molaro et al., 2017). Over geologic time, numerous μm - to cm-sized objects known as micrometeoroids have continuously impacted rocks at the lunar surface. This micro-bombardment has continually chipped and shattered surface rocks, a process which reduces rocks at the lunar surface to fine dust over timescales of 10^6 to 10^9 years (Ross, 1968; Soderblom, 1970; Basilevsky et al., 2013, 2019). The process of boulder breakdown has been studied extensively using high-resolution optical images to manually count boulders >2 m in diameter present on the ejecta blankets and rims of craters with varying ages (Basilevsky et al., 2013, 2019; Li et al., 2018). Based on counts of boulders >2 m in diameter on ejecta blankets and rims of craters, these studies suggested that boulders associated with lunar impact ejecta should be completely destroyed in 150–300 Ma. The fine-grained regolith produced by this process of boulder breakdown then moves from higher to lower elevations via incremental creep and splashing by micro-impacts (Lindsay, 1976; Fassett and Thomson, 2014; Fassett et al., 2018). This combination of micrometeoroid impact and downslope movement of regolith has been shown to degrade a lunar impact crater from a fresh, recently formed crater with a distinct bowl-like shape and a rocky ejecta blanket to a shallower, more muted depression that lacks an abundance of ejecta rocks (e.g., Ghent et al., 2005; Kreslavsky et al., 2013; Fassett and Thomson, 2014).

Impact craters in the diameter range examined here (1.5–2.0 km) have accumulated continuously throughout the entirety of geologic time. Therefore, these features span the full range of degradation states on the surface of the Moon from fresh to heavily eroded. Recent work has shown that the roughness of simple lunar crater ejecta evolves separately from crater interiors (Fassett et al., 2018; Fa and Eke, 2018). Specifically, Fassett et al. (2018) used radar data to show that the interiors of simple lunar craters increase in roughness for the first ~ 0.5 Ga of

their lifetimes due to a constant boulder influx into the crater interiors from the crater walls and rim.

2.3 The Mini-RF instrument

The source of the backscatter radar data for this study is the Mini-RF instrument, a hybrid-polarized synthetic aperture radar (SAR) instrument onboard the Lunar Reconnaissance Orbiter (LRO) (Nozette et al., 2010; Raney et al., 2011) (**Fig. 3**). The instrument was originally designed to operate in a monostatic configuration in which a single, left-circular polarized signal was emitted from the spacecraft. After reflecting off the surface, the horizontal and vertical counterparts of the returned signal would then be received by the instrument antenna. The initial Mini-RF monostatic campaign acquired ~97% radar coverage of the polar regions and 67% of the non-polar regions of the Moon. In 2012, however, a malfunction left the instrument unable to transmit radar signals and, therefore, collect data in the monostatic mode of operation (Patterson et al., 2017). The instrument was reconfigured for a bistatic mode of operations. In this configuration, S-band and X-band signals are transmitted from the Earth-based Arecibo observatory or the Goldstone Deep Space Communications Complex, reflected off of the lunar surface, and measured by the still-operable Mini-RF receiver (Patterson et al., 2017) (**Fig. 4**). In this bistatic configuration, the Mini-RF instrument collected 28 S-band (~12.6 cm) radar images and 30 X-band (~3 cm) images between 2012 and 2015 and is still operating today with a combined total of 61 bistatic images collected as of 2018.

The collection of bistatic data requires complex geometries and a varying phase angle between the emitted and received radar signals. The effects of this phase angle on true bistatic data values remain a subject of active research (e.g., Patterson et al., 2017). The images used in this work are from the more spatially complete Mini-RF S-band monostatic campaign. Because

the monostatic data are collected by emitting a signal from the spacecraft and collecting the return signal on the same spacecraft, the phase angle of the emitted signal is consistently zero across all data. However, a known timing error exists between the LRO spacecraft clock and Mini-RF instrument clock (Patterson, 2019, personal communication). The results of this systematic timing error are slightly offset pixels in images where local topography is substantial. This timing offset primarily affects the spatial control of the monostatic data but can be corrected manually using a series of ISIS3 processing scripts.

2.4 Radar properties and circular polarization ratio (CPR)

The radar properties of ejecta blankets examined in this work are measured in terms of their circular polarization ratio values or CPR. CPR is defined as the ratio of backscatter power reflected in the same sense of circular (SC) polarization as that transmitted over the echo in the opposite sense of circular (OC) polarization (e.g., Campbell, 2012). In other words, CPR represents the change in radar signal polarization caused by surface and volume (subsurface) reflectance. The radar signal emitted from the Mini-RF instrument travels to the lunar surface in a left-circular polarization state. When that signal is reflected off the lunar surface, the signal changes polarization state and the signal travels back to the spacecraft in a right-circular polarization state. CPR measures the amount of returned radar signal that has been “flipped” from left-circular to right-circular polarization as a result of contact with a surface or subsurface scatterer (**Fig. 5**). This change in polarization state for a given electromagnetic signal is the result of a 180° phase shift in the vertical and horizontal components of the signal that occurs as the signal meets the surface of a lunar ejecta boulder.

Previous work has shown that CPR values associated with rough surfaces on the Moon can reach values up to 3.0 (e.g., Jawin et al., 2014). CPR varies widely across the lunar surface,

however. The background CPR value for the lunar highlands radar-dark terrane is 0.49 with intermittent radar-bright terranes reaching CPR values as high as 0.60. The CPR background values of the lunar maria are somewhat variable and are typically averaged based on respective mare surface. For example, Humorum, Imbrium, and Nubium exhibit background CPR values of 0.52, 0.45, and 0.49, respectively, and Serenitatus, Crisium, and Fecunditatus exhibit CPR background values of 0.46, 0.52, and 0.45, respectively. Previous studies using CPR to assess lunar impact structures have shown that CPR fades with time from an initially high CPR value (~ 1.0 – 2.0) to a lower CPR value (< 0.5) (e.g., Bell et al., 2012; Neish et al., 2013; King et al., 2017; Fassett et al., 2018). A high CPR value (> 1.0) is typically inferred to be a result of double bounce reflectance, in which SC power is enhanced due to contact with multiple reflecting surfaces (Campbell et al. 2009; Campbell, 2012; Jawin et al. 2014). This reflectance is typically caused by the presence of multiple dihedral blocks in the case of lunar ejecta. In contrast to double bounce reflectance, single bounce reflectance is defined as a specular reflection from a planar surface which is oriented at a right angle to the incoming electromagnetic energy (Raney et al., 2012).

As impact crater ejecta degrades over time and these once-rough surfaces erode, a transition from primarily double bounce to primarily single bounce radar reflectance occurs, and corresponding radar signatures becomes noticeably less bright (e.g., Thompson et al., 1974; Bell et al., 2012; Ghent et al., 2016; King et al., 2017). This transition provides an evolutionary sequence from radar bright to radar dark that is discernable using the Mini-RF radar dataset. The angular nature of fresh ejecta deposits typically causes more signal reflections and phase offsets of the vertical component of the EM signal, therefore giving a higher CPR value (e.g., Bell et al., 2012; Jawin et al., 2014; Fassett et al., 2018), visually represented as a ring of radar brightness

(referred to hereafter as a “halo”) around impact craters. As the angularity of fresh ejecta deposits is gradually subdued by macroscopic space weathering processes, the subsequent CPR halo associated with the ejecta fades to background noise (**Fig. 6**).

The Stokes parameters capture all information embedded in dual-polarized backscattered fields and are the basis for radar property quantification and CPR calculation (Raney, 2006; Raney et al., 2011, 2012; Cahill et al., 2014). Use of the horizontal and vertical components of the radar signal allows for calculation of the Stokes parameters. Stokes parameter theory states that an electromagnetic field is represented by the ellipse swept out by the electric potential vector, E (Raney, 2006). The associated backscatter field may be represented by four real, dimensionless values (the Stokes parameters) that are derived from the sum of the vertical and horizontal power vectors of the emitted electromagnetic (EM) signal (S_1), the difference of the vertical and horizontal power vectors of the emitted EM signal (S_2), and the real and imaginary components of the two received signals (S_3 and S_4), respectively (Raney, 2006; Raney et al., 2012). The four Stokes parameters are represented by the following four equations (Raney, 2006; Raney et al., 2011, 2012):

$$S_1 = (|E_H|^2 + |E_v|^2) \quad (1)$$

$$S_2 = (|E_H|^2 - |E_v|^2) \quad (2)$$

$$S_3 = 2Re(E_H E_v) \quad (3)$$

$$S_4 = 2Im(E_H E_v) \quad (4)$$

where E_H and E_V represent the voltage (power) of horizontal polarization and vertical polarization, respectively, and Re and Im refer to the real and imaginary parts of the complex cross-product of these two linear polarizations, respectively. The Stokes parameters (S_1 – S_4) can be rearranged to represent CPR (μ_c) and to create CPR images through the following equation:

$$\mu_c = (S_1 - S_4) / (S_1 + S_4) \quad (5)$$

In the work presented here, CPR is useful as it represents the amount of diffuse surface and volume (subsurface) scattering caused by features at the scale of the radar wavelength (e.g., Campbell et al. 2009; Campbell, 2012; Jawin et al., 2014). Radar data are sensitive to roughness elements on the scale of the radar wavelength and to substrate elements to a depth of ~10x the radar wavelength (Campbell and Campbell, 2006). Given the wavelength of the Mini-RF instrument (12.6 cm), CPR derived from Mini-RF S-band are sensitive to lunar rocks greater than the diameter of the S-band wavelength (~0.1 m) at the lunar surface and down to a depth of 10x the S-band wavelength (~1.0 m) in the lunar subsurface.

LRO Mini-RF data are available from the University of Washington St. Louis Planetary data system (<http://pds-geosciences.wustl.edu/missions/lro/mrf.htm>). These data are organized in five data acquisition bins (LROMRF_0001-LROMRF_0005) and further subdivided by orbit number within each bin. Within each data bin, Mini-RF images are organized by level 1, level 2, or raw data. The level 2 Mini-RF data exhibits the highest processing level available and includes CPR images, all four stokes parameters for each image, and label files which contain all embedded metadata for each image. The level 1 unprocessed data are also available and can be manually processed to level 2 quality with a higher spatial resolution than the pre-processed level 2 data already available from the PDS.

2.5 The Diviner Lunar Radiometer Experiment

Thermal infrared data used in this work were obtained by Diviner Lunar Radiometer Experiment aboard LRO (**Fig. 3**). The Diviner instrument is an infrared and solar radiometer that has mapped and characterized the global thermal state of the lunar surface (Paige et al., 2009). The instrument collects data in nine spectral channels with passbands ranging from 13–400 μm and was designed to characterize the lunar thermal environment using two instrument telescopes (Paige et al., 2010a). The purpose of this instrument was to further the understanding of the extreme lunar thermal environment. At the subsolar point, lunar surface temperatures can exceed 400 K, while polar temperatures can concurrently lie below 40 K (Paige et al., 2010a). Early goals of the Diviner Radiometer Experiment included: (1) characterization of the Moon’s surficial thermal environments, (2) mapping of lunar surface properties, and (3) characterization of the lunar polar cold traps. Diviner’s nine-channel configuration is designed to characterize the extreme lunar environment by utilizing two solar channels (0.35–2.8 μm), three 8- μm Christiansen feature channels (7.55–8.68 μm), and four thermal channels (13–400 μm) (Paige et al., 2010; Hayne et al., 2017). The Diviner instrument began collecting data in 2010 and has been successful in achieving all three of the initial science goals of the mission. To date, the Diviner instrument science team has produced global temperature maps and derived non-polar maps of surface structure variability (Paige et al., 2010b; Bandfield et al., 2011; Hayne et al., 2017).

2.6 Diviner radiometer data and rock abundance

The thermal infrared (TIR) measurements acquired by Diviner are responsive to the thermal inertia of the lunar regolith. Thermal inertia is the resistance of a surface to changes in temperature and is defined as the square root of the product of density, thermal conductivity, and specific heat capacity (Price, 1977). The TIR measurements from three of the seven spectral

channels (6, 7, and 8), which are dependent on the aforementioned lunar surface properties, are used to derive rock abundance (RA) data. Derived RA values represent areal rock fraction, which is the percentage of rocks >1 m that are exposed at the surface (Bandfield et al., 2011). Rock abundance values are derived by modeling the temperatures of lunar regolith with various surface rock percentages. Assumed parameters in this model include a rock density, thermal conductivity, and heat capacity for vesicular basalt (Horai and Simmons, 1972) that are used to define a rock thermal inertia of $1570 \text{ J m}^{-2} \text{ K}^{-1} \text{ s}^{-1/2}$ at 200 K. Using this rock thermal inertia, an assumed albedo of 0.15, and an emissivity of 0.95, a rock temperature lookup table was constructed at 5-degree latitude and 15 min local time intervals over the course of the lunar day. For each latitude and local time, the lookup table is linearly interpolated to estimate the rock temperature for each Diviner observation. As the real lunar surface exhibits a variable anisothermality due to the presence of both rocks and fine-grained regolith within a given field of view (FOV), the observed radiance is modeled as a combination of regolith radiance and rock radiance, with the latter weighted by the rock areal fraction. For each latitude/longitude/local time bin, the root mean squared (RMS) difference between modeled and measured radiance is calculated. In this manner, the RMS difference is minimized using the optimal combination of regolith temperature and rock areal fraction (Bandfield et al., 2011). The rock areal fraction derived from this model can theoretically reach a maximum value of 1.0, where 100% of the surface is composed of rocks >1 m in diameter. A RA value of 1.0 is not observed for the Moon, however, where rock abundance values average 0.4% globally and span a range from 0.5–1.0% on the lunar maria (Bandfield et al., 2011). The result of this algorithm is an estimated areal fraction of the rocks >1 m in diameter which are present at the very surface of the lunar regolith. These RA data are readily available on the University of Washington St. Louis Planetary Data

System as a global mosaic (http://pds-geosciences.wustl.edu/lro/lro-l-dlre-4-rdr-v1/rodr_1001/data/gdr_13/cylindrical/img/dgdr_ra_avg_cyl_128_img.img) with an accompanying label file that contains all associated metadata and projection information. The global RA mosaic is also available as a projectable layer on the LROC Quickmap interactive data website (<https://quickmap.lroc.asu.edu/>).

Previous work has shown that ejecta deposits of large craters (18–100 km in diameter) exhibit a range of rock abundance signatures (Ghent et al., 2011). This variation was attributed to age, and it was shown that RA values for the nine craters sampled decreased with age where age was inferred from superposed crater populations on the ejecta blankets of the craters in question. Further work has compared RA values with CPR for 24 craters >18 km in diameter that have varying age values modelled from crater counts (Ghent et al., 2016). This latter study concluded that the rate at which CPR signatures fade is unclear due to an abundance of noise in the data whereas RA diminishes to background over approximately 1 Ga.

2.7 Topographic degradation modelling

Crater ages used in my study result from a previous topographic degradation model for small (0.8–5 km) impact craters on the lunar maria. Fassett and Thomson (2014) modelled the degradation states of approximately 13,000 craters on the lunar maria and showed that these craters have topographically degraded over the past 3.0 Ga. This degradation was then extrapolated to sort craters based on degradation state and age. In the Fassett and Thomson (2014) topographic degradation model, each crater was assigned a degradation state. This degradation state is referred to as the κt value where κ (kappa) represents the diffusivity, a rate of downslope creep measured in m^2/Myr , and t represents time in Myr. The κt value is a proxy for the degree of degradation that a crater has undergone in a given amount of time. In this model, a

higher κt value corresponds to an increased age value for a given crater. The erosional processes responsible for modifying the topography are assumed to be the same processes responsible for the smoothing of rough ejecta deposits and the muting of radar halos.

2.8 Hypothesis

For this work, my hypothesis is that rocks that are exposed at the lunar surface erode at a more rapid rate than the rocks in the shallow lunar subsurface. I will test this hypothesis by comparing ejecta deposits in two remotely sensed datasets with different depth sensitivities. Rock abundance estimates from TIR data are most sensitive to rocks at the lunar surface, whereas S-band CPR data are sensitive to both rocks exposed at the surface and buried rocks in the shallow subsurface (i.e., within $\sim$ ten radar wavelengths) (**Fig. 1**). Hence, my hypothesis would be supported if rock abundance values for lunar ejecta are shown to fade to background values at a rate that is more rapid than radar signatures of lunar ejecta. The results will provide a better understanding of how the lunar surface evolves with time as a function of depth and can provide better age control for impact craters.

Section 3: Methods

3.1 Impact crater selection

The craters analyzed in this work were selected from the 13,657 craters within the Fassett and Thomson (2014) crater database. The resulting sample set contained 6,209 craters with Mini-RF monostatic data coverage. This sample set was same as that studied in Fassett et al. (2018). To ensure that the craters could be definitively characterized in the coarser resolution (237 m/px) RA data, a lower diameter limit of 1.5 km was established, resulting in a sample set of 399 craters with a diameter range of 1.5–2.0 km. Each crater includes a degradation state and corresponding modelled age. Of these 399 craters, some 10 to 15% were excluded from consideration due to obstruction by other, smaller craters within a diameter range of 6 crater radii. Finally, we selected 112 craters for analysis in both RA and CPR data by sorting them by increasing LRO orbit number, which is a pseudo-random sampling that yielded a spatial unbiased sample of craters across the lunar maria. The methods described in this section are used to associate modelled ages for these craters with CPR and RA values and determine the relationship between modelled age value, RA, and CPR.

3.2 Radar data processing

The Level 1 Mini-RF data for this study were downloaded from the Planetary Data System (PDS) Geosciences node (<http://pds-geosciences.wustl.edu/missions/lro/mrf.htm>) and processed using the United States Geologic Survey (USGS) Integrated System for Imagers and Spectrometers version 3 (ISIS3). Once downloaded, the radar images used in this study required several processing steps (given in **Fig. 7**) in order to be converted into a high-resolution, geospatially accurate product. The radar images that correspond to each crater are listed in the

supplementary information (Appendix B). The respective ISIS3 utilities used to process the Mini-RF radar data include: *mrf2isis*, which converts the PDS image file to an ISIS3-compatible cub file; *spiceinit*, which discerns and attaches the necessary spacecraft, planet, instrument, c-matrix, and events (SPICE) information kernels to the processed image metadata; *maptemplate*, which assigns the desired map projection to each Mini-RF image; and *cam2map*, which converts the spice-tagged camera image to a map-projected file (**Fig. 7**).

This ISIS3 processing pipeline converts a Mini-RF level 1 radar image to a map-projected level-2 image. The final CPR images used to characterize craters in this study were created from the level-2 data files using the ISIS3 *algebra* utility and **Eqns. 1, 4, and 5**, sequentially. The images that result from this processing pipeline are orthorectified CPR images that are not down-sampled and retain their original resolution of 15 and 30 meters in azimuth and range, respectively (Raney et al., 2011). The products have a higher spatial resolution than the level 2 pre-processed Mini-RF CPR images on the PDS, which are archived at a resolution of 30 m/px. The image products created via this pipeline for my study are 32-bit images in raster format with a set number of lines and samples and a consistent incidence angle.

For the images used in my work, the map projection varied based on the latitude of the crater in question. For any crater poleward of $\pm 40^\circ$ latitude, a Mercator projection was used to reduce distortion of the crater and maintain the approximate geospatial geometry of each crater. Below that bound, a simple cylindrical projection was used. This projection bound is somewhat conservative, as no craters were visually distorted below or above 45° N and S latitudes, respectively.

3.3 Characterization of crater ejecta using CPR

The 112 craters downselected from the Fassett and Thomson (2014) database were located on the appropriate CPR images using the geographic coordinates of the craters. I visually identified and recorded the center point of each crater in Mini-RF total power (S_1) images for extracting the radial median CPR values. In some cases, the center points listed in the Fassett and Thomson (2014) database did not line up geospatially with crater center points in the Mini-RF S_1 images (e.g., **Fig. 8**). This error is due to an offset between the Mini-RF images and the Lunar Laser Orbital Altimeter (LOLA) terrain digital elevation model (DEM) used in Fassett and Thomson (2014) to identify craters and extract topographic profiles. The offset between these two datasets is due to a known timing error between the LRO spacecraft clock and the Mini-RF instrument clock that remains undocumented in the literature and results in a slight misalignment of the Mini-RF dataset. In any case, the offset between the Fassett and Thomson (2014) crater center points and the Mini-RF S_1 image center points never exceeded 2 km. In cases where the offset resulted in any uncertainty in crater identification, that crater was omitted from my dataset.

CPR images were processed in MATLAB to extract 360° radial median profiles of CPR values given the input values of crater radius, approximate crater center point, and maximum distance to which the radial median would extend. The maximum distance input parameter is defined as the edge of the continuous impact crater ejecta which typically falls between 2.5 and 4 crater radii (Melosh, 1989). A radial median of CPR is used rather than a mean to represent the characteristic values in the radial profiles because the distribution of CPR data values is non-Gaussian. Median values are also less sensitive to statistical outliers in the data than mean values. Beginning at the center point of a given crater, the MATLAB script records a median of all pixels that cross a circular boundary line starting at a distance of one pixel diameter (237 m)

from the center of the crater. The annulus is repeatedly advanced outward from the crater center in one-pixel-length increments and successive medians are collected at those distances until a distance of four crater radii is reached. Once this maximum distance is reached, all collected medians are recorded as a binary set of values (distance, CPR or RA median) and plotted as a function of distance from the crater center normalized by the crater radius (**Fig. 9**).

After these CPR radial median profiles were produced, a power law curve was fit to the profile for each crater using the MATLAB curve-fit toolbox (*cftool*). This MATLAB utility uses a non-linear least square fitting method. This method minimizes the summed square of residuals in order to provide coefficient estimates that relate real data to the predicted fit. Also provided by this method of fitting is a 95% confidence bound on the coefficients of each predicted fit that gives an estimate of the uncertainty of each fit. This information, along with a complete description of the Mathworks MATLAB curve fitting method, can be found at the Mathworks data fitting help website (<https://www.mathworks.com/help/curvefit/least-squares-fitting.html>). The curve fitting was applied to exterior crater data only. Data from the crater interior indicate that the interior region evolves independently from the crater exterior region (Fassett et al., 2018; Fa and Eke, 2018). Excluding the interior region isolated the consistent fall-off of CPR data associated with crater ejecta. A power law fit was chosen as it provided reasonably accurate fits with relatively high goodness-of-fit parameters for each radial median. The equation produced from the power fit of each crater is in the form:

$$f(x) = ax^b \quad (7)$$

The fit parameters for each radial median profile were then collected. The acquisition of a CPR signature for every crater is essential for the comparison of CPR and κt . In order to draw a direct comparison between age and CPR, the multiplicative term (a) of each CPR fit curve was

plotted against κt value. In most cases throughout this thesis, the fit terms are directly compared to κt values, but in instances where a more direct correlation between κt and age is made, the polynomial fit from figure 11 in Fassett and Thomson 2014 was manually used to connect κt and age. The multiplicative term (a) was chosen as a primary comparison parameter; several attempts were made to correlate the κt values and the exponent (b) values for each crater, but those data did not yield a clear trend. The coefficients associated with of each fit are influenced by how the CPR and RA data values associated with of the ejecta deposits change over time. Hence, any changes in these two values over time should effectively represent some level of change in ejecta roughness. The multiplicative term (a) is a constant that represents the y-intercept of the curve that is fit to the CPR and RA data. This value is governed by all data points to which the curve is fit and acts as an amplitude which records the amount of stretching that the curve has undergone in the y dimension. The exponential term (b) of each curve is dictated by how sharply the data values fall off with distance from the rim. A larger b suggests a sharp decrease in data values, and small b represents a more gradual decrease.

3.4 Characterization of crater ejecta using RA

Rock abundance (RA) data are available from the PDS as a global mosaic with spatially consistent resolution (237 m/px) and projection (**Fig. 10**). Hence, the task of selecting and processing multiple image swaths, as is done with CPR data, is unnecessary for the use of RA. As for high-latitude CPR data, a Mercator projection was used for the RA mosaic to reduce any distortion associated with high-latitude craters. For RA characterization, the same radial median MATLAB code used for CPR characterization was modified and employed to collect RA radial median profiles. This code produces a radial median profile of RA pixel values for each crater given the input parameters of crater center point and radius of the crater in kilometers (**Fig. 11**).

Using MATLAB *cftool*, I then fit power law curves to the RA radial median exterior data and the terms of these power law fits (**Eq. 7**) were collected for comparison with topographically modelled age to assess how RA values associated with crater ejecta evolve with time. As with CPR, data points under 1 crater radii were excluded from the fit.

For consistency, this process was implemented for the same craters analyzed using CPR data. The lower resolution of the RA data (~ 237 m/px) as compared to CPR data (~ 15 m/px) limit the number of data points on the RA radial median plot. Error propagation for the RA data was conducted in the same manner as with the CPR data.

3.5 Uncertainty propagation

In order to propagate the uncertainties with these data, the standard deviation of CPR values associated with each annuli sample in every radial median was determined. Once curves were fit to the median profiles, the 95% confidence bound provided by the *cftool* utility was used to assess the uncertainty associated with each fit coefficient. These confidence bounds were also used to determine the statistical significance of any overall trends and to determine how those trends differed between the CPR and RA data.

Section 4: Results

4.1 Ejecta evolution as shown in CPR data

When plotted as a function of κt (a proxy for time), CPR multiplicative terms and exponent values exhibit a considerable amount of unexplained variance (**Figs. 12, 13**). A linear fit to the CPR fit multiplicative terms has a R^2 value of 0.236 (**Fig. 12**), indicating that ~24% of the variance in the CPR multiplicative term data can be accounted for using this fit. Additionally, the linear trendline corresponding to these data has a slope of $-5.8 \times 10^{-6} \pm 9.8 \times 10^{-7}$ CPR/ κt . This slope denotes a weak and gradual decreasing trend with time and suggests that CPR halos associated with small craters on the lunar maria fade with time but may remain elevated out to extended timescales of ~3.8–3.9 Ga.

A linear regression fit to the CPR exponent fit values has a slope of $5.3 \times 10^{-6} \pm 1.4 \times 10^{-6}$ CPR/ κt (**Fig. 13**). This positive slope suggests that the CPR exponent values also change systematically with time, but the R^2 value of 0.1102 associated with these data indicates that only ~11% of the variance within CPR coefficient data can be accounted for using this term. Based on the R^2 values of these two terms and the large uncertainty measured for the exponential linear fit slope, the CPR multiplicative term data appear to be a slightly more sensitive indicator of the rate at which CPR values change.

4.2 Ejecta evolution as shown in RA data

Using the RA global mosaic (Bandfield et al., 2011), I fit power law curves to 112 simple impact craters on the lunar maria and the multiplicative term and exponent values of those fits were plotted against corresponding degradation states from the Fassett and Thomson (2014) crater database (**Fig. 14, 15**). The fit to the RA multiplicative terms has a R^2 value of 0.2571

which is similar to but slightly higher than that of the CPR multiplicative term data (**Fig. 14**).

The linear regression has a slope of $-2.6 \times 10^{-6} \text{ RA}/\kappa t \pm 4.2 \times 10^{-7} \text{ RA}/\kappa t$. This slightly shallower slope than the CPR multiplicative data suggesting that RA multiplicative data values of lunar impact ejecta fade at a slightly slower rate than that of the CPR values.

A linear regression associated with the RA exponent fit values has a R^2 value of 0.3159, indicating that ~31% of the variance in these data are represented by this model with an increasing slope of $5.6 \times 10^{-5} \text{ RA}/\kappa t \pm 7.9 \times 10^{-6}$ (**Fig. 15**). This slightly higher R^2 value suggests that the RA exponential data may be a better approach to measure the behavior of RA ejecta data over time; although, the linear regressions associated with both sets of coefficient data show only modest correlations with degradation state. This slope of the RA data trend is slightly steeper than that of the CPR exponential data, suggesting that the RA exponentials change at a rate that is slightly more rapid than the rate at which the CPR exponential data change. This difference in slope is contrary to the slope results of the multiplicative term analyses for both CPR and RA.

4.3 Decoupled behavior of crater rims and ejecta in RA data

These CPR and RA fit data presented in the previous sections (**Figs. 12–15**) show the behavior of proximal crater ejecta blankets from 1.0–4.0 crater radii. Motivated by the findings of Fassett et al. (2018) and Fa and Eke (2018) that simple crater interiors evolve separately from crater exteriors in CPR data, I re-collected fit terms over distances of 1.5–4.0 crater radii and compared with those terms presented in the previous section (**Figs. 16, 17**). In all radial medians, the RA and CPR data associated with the region from 1.0–1.5 crater radii can be used to infer roughness at and just outside the crater rim. By measuring CPR and RA data at 1.5–4.0 radii and comparing them with data from 1.0–4.0 radii, it becomes possible to isolate the behavior of the

region between 1.0 and 1.5 radii. This test allowed me to separately assess the behavior of the RA and CPR data with time in these two regions.

The variability amongst the CPR multiplicative fit term that include the near-rim ($R^2 = 0.1959$) is similar to, albeit slightly lower than that of the CPR pre- multiplicative fit terms that exclude this region ($R^2 = 0.236$) (**Fig. 16**). However, the confidence bounds on these two linear regressions are largely coincident and fall within the uncertainty of the other. Any slight differences in these model slopes are not separable, and the exclusion of crater rims from CPR median fits has minimal influence on the change in crater exterior CPR multiplicative data. A similar comparison using RA data reveals that the slope of a linear regression fit to RA multiplicative data from 1.0–4.0 crater radii ($-2.6 \times 10^{-6} \text{ RA}/\kappa t \pm 4.2 \times 10^{-7}$) is more steep than the slope of a linear fit to multiplicative data from 1.5–4.0 crater radii ($-5.6 \times 10^{-7} \text{ RA}/\kappa t \pm 1.8 \times 10^{-7}$). The linear regression models fit to each of the RA multiplicative datasets (**Fig. 17**) are less consistent than those for CPR (**Fig. 16**), particularly for the range of 0 to 15,000 κt where the linear trend associated with the RA multiplicative terms representing fits from 1.0–4.0 radii lies above the upper confidence bound of the 1.5–4.0 multiplicative linear regression. This relationship suggests that there may be a statistically significant difference between these two data sets in the first ~ 2.2 Ga. of a crater's lifetime.

Building on the findings of a distance-based comparison of RA median fit terms (**Fig. 17**), I measured the decoupled behavior of crater rims and ejecta blankets in RA data by averaging binned median fit data. This method allowed me to further investigate this relationship of decoupled evolution outside of the curve-fitting method. The data obtained using this median averaging method (**Fig. 18**) represent mean ejecta and rim RA values for binned radial medians of all crater bins on the y-axis. The data points associated with the crater rim (1.0–1.5 crater

radii) in each binned radial median were averaged. The data for the ejecta at 1.5–4.0 crater radii were also collected and averaged. The linear regressions fit to both of these data sets exhibit visually separable trends. The trends associated with the crater rim and ejecta data only fall within the confidence bounds of one another after ~ 2.2 Ga and the slope of the linear fit to the crater rim data ($-0.0027 \pm 2.4 \times 10^{-18}$ RA/0.25 Ga) is separable from the slope of the ejecta data ($-0.00032 \pm 3.2 \times 10^{-20}$ RA/0.25 Ga) in this region. Hence, results of this averaging method show separable variation in the behavior of RA data associated with crater rims and ejecta from the beginning of a craters lifetime until ~ 2.2 Ga.

Section 5: Discussion

From the data presented in section 4 and from the differing sensitivities of the RA and CPR data, it appears that both surface and subsurface rocks associated with lunar ejecta blankets erode over time. The slopes of the linear regression fits to the CPR and RA fit data are small for both the multiplicative and exponential terms. These regressions suggest that the CPR and RA data values decrease, and the ejecta rock concentrations represented in both of these datasets diminishes. Over time, the small R^2 values of all the regressions call into question whether the model of a linear dependence of power-law coefficients on degradation state is an appropriate model for the variability in these data (**Figs. 12–15**). The slope of the CPR multiplicative term regression ($-5.8 \times 10^{-6} \pm 9.8 \times 10^{-7}$ CPR/ κt) is steeper than that for the RA data ($-2.6 \times 10^{-6} \pm 4.2 \times 10^{-7}$ RA/ κt). Taken at face value, this difference in slope suggests that rocks in the lunar subsurface erode slightly faster than surface rocks. Thus, the primary test we performed appears to refute our initial hypothesis. However, based on the low R^2 values (CPR=0.236, RA=0.257) and large confidence bounds of the individual linear fits to the multiplicative data, we conclude that the test was not as robust as we had expected, and the variance that can be reliably be accounted for in the linear regression models for each dataset is low. In this section, I investigate several mechanisms that may be causing the observed variance among the CPR and RA exponential and multiplicative term data presented in section 4. Variability in the presented data may be attributable to real variations in these data due to some combination of variation in mare titanium content (section 5.1), regional regolith thickness (section 5.2), size differences between craters (section 5.3), uncertainties associated with the ages derived in Fassett and Thomson (2014) (section 5.4), fitting errors of crater radial medians in the MATLAB curve fit toolbox

(section 5.5), intra-ejecta variations in roughness (section 5.7), or some combination of these factors.

5.1 TiO₂ variations as a potential scatter-causing mechanism

Campbell et al. (2010) and Carter et al. (2009) have shown that titanium dioxide (TiO₂) contained in the lunar regolith has the potential to alter associated dielectric coefficients and, therefore, CPR values. These prior studies have shown that high levels of TiO₂ in mare regolith directly correlate to lower CPR values. Moreover, TiO₂ content varies widely across the lunar maria, ranging from close to 0 to >10 wt% (Sato et al., 2017). The finding of heterogeneity in TiO₂ content across mare surfaces, coupled with the finding that the radar return of geologic targets containing TiO₂ is diminished, leads to the possibility that the CPR of ejecta blankets may vary based on the TiO₂ content of mare surface onto which they are emplaced.

In order to test for any correlation of RA and CPR with TiO₂, I utilized the Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) TiO₂ mosaic (**Fig. 19**). The LROC TiO₂ mosaic was created by using 62 LROC WAC near-global observations and laboratory spectra of Apollo samples to characterize and map an increase in reflectance at wavelengths shorter than 450 nm that is distinct to the mineral ilmenite (FeTiO₃) (Sato et al., 2017). This new mosaic provides higher resolution and more accurate TiO₂ wt.% estimates than were previously available from orbital data. For the test presented here, the mosaic was imported into ArcGIS 10.6 and study craters were overlain onto the mosaic as a shapefile. A 3 km circular polygon was then created around each crater and the ArcMap zonal statistics tool was used to extract a mean pixel value of TiO₂ wt.% covered by each buffer polygon. The CPR and RA curve fit terms of each crater were then compared directly to the TiO₂ wt.%. Linear regression

fits to these two datasets exhibit R^2 values of 0.0003 for the RA data and 0.1083 for the CPR data (**Fig. 20**). There appears to be no strong correlation between the fit coefficients of study craters and the TiO_2 content of ejecta material that surrounds each crater. Hence, these models do not adequately account for the variance in both the CPR and RA data correlated with TiO_2 wt%. In light of these results, I conclude that TiO_2 content is not a likely cause of the variance amongst the CPR and RA median fit coefficients (**Figs. 12–15**).

5.2 Regolith thickness variations across the lunar maria

In addition to TiO_2 , regolith thickness has been shown to vary across the lunar surface; ranging from ~1 to 30 m in depth on the lunar maria (e.g., Quaide and Oberbeck, 1968; Oberbeck et al., 1973; Bart et al., 2011; Vijayan et al., 2015). Given average depth-to-diameter ratios of 0.2 (Pike, 1977; Stopar et al., 2017), even the smallest craters in this study, having diameters of ~1.5 kilometers, should reach bedrock (Melosh, 1989; Yue et al., 2013). However, regolith thickness has the potential to influence the amount of rock produced by an impact in the size range considered here by creating a barrier between lunar bedrock and the surface. This barrier inhibits impact-generated boulder mobility and thus reduces the number of boulders that can reach the surface during the ejecta formation process (Wilcox et al., 2005; Bart, 2014). Mare surfaces that are made up of dominantly older lava flows, such as Mare Tranquilitatus and Nubium, have had more time to accumulate thicker surface regolith deposits (Quaide and Oberbeck, 1968, Wilcox et al., 2005; Vijayan et al., 2015). Hence, an older mare surface with a thicker layer of surface regolith may exhibit superposed young craters that have fewer than the typical amount of rocks in their ejecta for craters of similar age (Wilcox et al., 2005; Bart and Melosh, 2010; Bart, 2014). In the reverse case, an impact into a younger mare surface with a thinner layer of regolith may result in an excess of rocks present in their ejecta. The

overabundance of rocks produced in this thin regolith situation could produce a CPR or RA signature that persists for an extended period of time. The result would be an older impact crater with [?] the appearance of a younger, fresh crater in the roughness datasets used here.

With the potential effects of regolith thickness on CPR and RA data in mind, I conducted an analysis of CPR and RA multiplicative terms to test if the observed variation in the data presented in section 4 is a result of variations in regolith thickness across various mare surfaces. This test utilized median regolith depths estimated by Bart et al. (2011). That study produced median regolith thickness values for 30 regions across the lunar surface based on impact crater morphologies in those regions. I compared the median regolith thickness values with the CPR and RA multiplicative fit values for craters of similar age. The sample set of craters used for this comparison was limited to the number of craters with topographically modelled ages that fell within each region described in Bart et al. (2011). Of the 30 regions described in Bart et al. (2011), only four of these regions contained craters with topographically modelled ages from Fassett and Thomson (2014). My sample size of craters was then further limited by craters that had both CPR and RA data coverage in each of those regions. One of those four regions, Mare Imbrium, contained no craters with complete coverage of either data type and was excluded from this test. I then chose craters from each of the remaining three regions that were most similar in age for the final comparison of regolith thickness and CPR and RA values. The final sample set of craters include one crater each from the Tranquillitatus, Humorum, and Letronne regions with topographically modelled ages of ~ 2 Ga. If regolith thickness plays a significant role in influencing CPR or RA, the impact crater ejecta on the Mare Tranquillitatus region (4.4 m regolith thickness) should exhibit a lower CPR and RA multiplicative term than the craters

located on Mare Humorum and Letronne with regolith thickness values of 2.5 and 2.9 m, respectively.

Results of this test show that the impact crater located on Mare Tranquilitatus exhibits a lower multiplicative term in both datasets, whereas the crater situated on Mare Humorum exhibits the highest multiplicative term (**Fig. 21**). This apparent trend suggests that there may be a relationship between regolith thickness and CPR and RA data associated for craters on the lunar maria. The sample size of craters used in this test is small, however, and the uncertainties on the coefficients are large. A larger sample size of craters across more of the regions modelled for regolith thickness in Bart et al. (2011) would be necessary to determine if the relationship observed here is statistically significant.

5.3 Crater diameter dependencies of RA and CPR

As was shown in Fassett and Thomson (2014), the time required for a fresh crater to become degraded is strongly dependent upon the diameter of the crater. Under space weathering conditions, larger craters physically degrade more slowly, by the measure used in Fassett and Thomson (2014), attributed to their increased depth and internal surface area. Smaller craters exhibit less internal surface area which requires less time to fill in with mass-wasted lunar regolith. In this section, I investigate whether crater diameter has any influence on CPR intensity for craters of similar age. The craters examined in this work were binned in 100-m-size increments for the size range of 1.5–2.0 km. The fit coefficients in each of the resulting five bins were then averaged. Those averages were compared to assess the rate of fit coefficient change in 5000 κt increments for the time span of 0.0–3.8 Ga (**Fig. 22**). Results of this binning show no obvious, systematic trend of CPR fit coefficient with size as a function of degradation state and age.

As an additional test of size dependency in my dataset of CPR fit coefficients, the CPR multiplicative terms for eight craters of increasing age in the size range of 1.8–2.0 km are compared to the coefficients of eight craters with similar ages in the size range of 0.8–1.0 km diameter (**Fig. 23**). Results of this test show no consistent relationship among size and CPR fit multiplicative term. The goodness of fit value for the small (0.8–0.85 km) crater evolution ($R^2=0.681$) is ~60% higher than the goodness-of-fit for the evolution of larger (>1.8 km) craters ($R^2=0.425$). This difference in R^2 values indicates that the linear regression and the downward, decreasing slope of 6.0×10^{-6} associated with the smaller craters is a somewhat better representation of the variance in those data than those of the larger craters. This difference in model predictability may also be a result of a scant sample size. Further analysis of more craters in this manner is necessary to determine if this observed relationship is statistically significant.

5.4 Uncertainty in Fassett and Thomson (2014) κt values

The modelled degradation (κt) values used in this work have inherent error and may be an additional source of variance in the primary data. The error associated with an estimated degradation state and model age from Fassett and Thomson (2014) is stated to be $\pm 30\%$ of the κt value. This error is a result of the inherent relationship between the derivation of a κt value and the Neukum production function (Neukum et al., 2001). A necessary step in the derivation of κt values is the connection between a crater with a given degradation state and the size frequency distribution of other craters that are local to that crater being measured. This step in the derivation of a κt value necessitates crater counting, a method of deriving planetary surface ages that has the potential for human error and variability between individuals (e.g., Robbins et al., 2014). The error that is inherent in the process of counting craters is also inherent in the topographic degradation ages derived in Fassett and Thomson (2014). The error within the κt

degradation model is derived using the error bars on the crater bins from Fassett and Thomson (2014), which increase in size with crater density (**Fig. 24**).

5.5 Radial median goodness-of-fit metrics

The method of fitting power curves to the CPR and RA medians in this work is a simplified characterization for a series of complex geologic processes and attributes. Hence, the power curves used here are not always perfect characterizations of the radial medians to which they were fit, and some curves fit their corresponding radial medians better than others. The MATLAB curve-fit toolbox provides several goodness-of-fit metrics for a given curve fit to assess how well a curve represents a given radial median profile in RA and CPR data. In my curve fitting methods presented here, root mean squared error (RMSE) (**Fig. 25b, c**), sum of squares due to error (SSE) (**Fig. 25a, d**), and R-squared values (R^2 ; **Fig. 26**) were recorded for the analyzed craters. These error parameters represent the total deviation of the data from the fit to the data, the standard error of regression, and the square of the correlation between the data points and the predicted data trend, respectively.

The goodness-of-fit values of the power law to the radial median data exhibit considerable variability (**Fig. 25-26**). This variability suggests that the power law model is a good method of characterization for some radial medians (e.g. $R^2 > 0.7$) whereas some other radial medians may not be as well represented (e.g. $R^2 < 0.2$). Goodness-of-fit values associated with RA fits are much lower than those associated with CPR fits, attributable to the coarser resolution of the RA data. The coarse resolution of the RA data leads to fewer data points, and the variance of the median data points from the median fit curves is minimized. For example, whereas the CPR median fit curve (**Fig. 9**) and the RA median fit curve (**Fig. 11**) appear to visually match the consistent decrease of ejecta CPR and RA data that I seek to characterize in both instances, the

R^2 value of the coarse resolution RA median data is higher than that of the high-resolution CPR median data.

Both RA and CPR median fit coefficients show variable R^2 values (**Fig. 26b**). R-squared values associated with RA median fits are consistently higher (**Fig. 26b**), whereas R^2 values associated with CPR median fits are widely varying for craters of all κt values and ages. Similar to the lower SSE and RMSE values associated with RA median fits (**Fig. 25a,b**), the R^2 values associated with the RA median fits are consistently higher than those associated with the CPR median fits. These goodness-of-fit metrics, specifically the R^2 values, suggest that the results of the CPR radial median fits may be less reliable than the results of the RA fits. This lack of reliability in the presented rate of CPR fading is further evidence that the interpretation of subsurface rocks eroding more quickly than surface rocks is weak.

5.6. Comparison with the methods and results of Ghent et al., 2016

The work presented here has a strong parallel with the work of Ghent et al. (2016). Briefly mentioned in section 2.6, the Ghent et al. (2016) study also investigated the relationship of CPR and RA, and how the two change with time for crater ejecta, though that study focused on larger craters ($D > 18$ km) using different methods. Results from Ghent et al. indicate that the RA of large crater ejecta deposits fades in a systematic manner and reaches background values in ~ 1.0 Ga, but a similar trend in CPR could not be determined due to significant variability in their observed data. Their result differs from my findings in that observed trends in my results suggest that CPR and RA coefficient data may be decreasing similarly over time, but the observed CPR and RA values remain elevated above background values of these data for the unaltered lunar mare for 2–3 Ga. In Ghent et al., a 95th percentile pixel value of the area around each crater out to the visual boundary of the proximal ejecta was used to characterize each crater in CPR and

RA data. This method provided a single value representing the CPR and RA of a given lunar impact ejecta deposit that could be used to compare the CPR and RA data of ejecta with different modelled ages. The 95th percentile method is useful in that it records anomalously high RA pixel values in a pixel value distribution that is strongly skewed towards higher values for fresh, rocky craters. A radial median differs from this method in that radial medians effectively measure intra-crater variability in CPR or RA data if present. Hypothetically, if there were a zone of increased rock concentration in a proximal ejecta deposit that existed from 1 to 2 crater radii from the rim in all directions, this zone may be distinguishable as a series of high CPR or RA values in a radial signature whereas the signature of that increased roughness may be lost in a 95th percentile pixel value, which is a modified average of the entire proximal ejecta deposit. Although unlikely, I acknowledge this situation is possible. Intra-crater sensitivity was key to the results of Fassett et al., (2018) where, using radial medians to characterized craters in CPR only, those authors found that simple crater interiors evolved separately from crater ejecta. Those authors concluded that interiors of simple craters became rockier for the first ~500 Ma of their lifetime.

Other notable differences between this work and that of Ghent et al. (2016) include the size range of craters analyzed and the sample size of craters. Ghent et al. (2016) studied 24 lunar impact craters in the diameter range of 18.6 to 99.6 km. Despite our finding (section 5.3) that the CPR multiplicative terms do not depend on crater size in the narrow size range of 0.8–2.0 km, future comparisons of km-scale craters and the larger craters studied by Ghent et al. (2016) may have the potential to show crater size influences CPR or RA characteristics. The test results discussed in section 5.3 (**Fig. 22**) were limited in size range (0.8–2.0 km in diameter) and did not show any correlation between crater size variations and RA or CPR behavior. A similar, but

more extensive, test with a wider size range of craters may yield results necessary to decipher if any diameter-related differences exist between CPR and RA data for lunar craters.

Lastly, the method of obtaining model age values for craters is a fundamental difference between this work and that of Ghent et al. (2016). As discussed in sections 2.7 and 5.4, my work uses model crater ages based on topographic degradation state whereas Ghent et al. (2016) uses model crater ages derived directly from crater counts on ejecta deposits of the 24 craters in their work. This difference in age determination should be seen as a minor difference, however, as the error for ages derived in both manners is comparable. The error for the crater ages in Ghent et al. ($\pm 20\%$) was derived from the crater counting methods used and varies based on the size of the crater counting surface and the crater size frequency distribution (see Ghent et al, 2016, their Table 1). Furthermore, Fassett and Thomson (2014) conducted a thorough, lunar maria-wide comparison of ages derived from crater counting methods and ages derived from topographic degradation states and found only minor differences of $\sim 0.03\text{--}0.10$ Ga between the two.

5.7 Synthesis of findings

Taken at face value, the finding that RA data may be fading faster than CPR data associated with lunar ejecta deposits potentially indicates that subsurface rocks in the uppermost meter of lunar ejecta deposits may be eroding slightly faster than rocks at the surface, which is a physically counterintuitive result. However, the large confidence bounds and low R^2 values associated with the CPR ($R^2 = 0.236$) and RA ($R^2 = 0.3159$) multiplicative term trends indicate that other factors exert a controlling influence on the results. Results of my initial tests to identify the cause of the variability in these data suggest that variation amongst CPR and RA ejecta signatures due to differences in regolith thickness is a contributing complication.

My analysis also revealed a possible dichotomy between the linear trends of curves that were fit to radial medians of RA data from 1.0–4.0 crater radii and from 1.5–4.0 crater radii in the range of 0–15000 κt ($\sim$ 0–2.2 Ga) (**Figs. 17, 18**). One physical explanation for this observation may be the preferential emplacement or retention of larger boulders closer to the rims of simple impact craters. Prior work has revealed that larger ejecta boulders are emplaced closer to the rim during the impact crater formation process, and the mean diameter of ejecta boulders gradually fines with distance from the crater rim (e.g., Bart and Melosh, 2010). These larger boulders require more time to break down than smaller boulders farther out in the ejecta blanket, and the CPR and RA values which correspond to the regions where these larger boulders exist should remain elevated for longer periods of time. The prospect of these larger rim boulders remaining present on crater rims for 2–3 Ga. seems unlikely, however. Prior work has showed that even the largest boulders (10–20 m diameter) on crater rims and ejecta should be eroded into fine grained regolith on time scales of 150–300 Ma (Basilevsky et al., 2013). Another possible explanation for the observation of elevated crater rim rock concentration is that rocks and boulders are being continually uncovered on and near to the crater rim due to the disruption and downslope creep of the fine-grained regolith that surrounds and covers the once-concealed boulders. To provide a visual assessment of this possibility, I examined a high-resolution image of one of the older ($\sim$ 3.7 Ga), more degraded impact craters in my dataset (**Fig. 27**). This examination revealed the presence of boulders near the rim of this heavily degraded crater. To account for this observation, I separately considered the averaged median data associated with the crater rim and proximal ejecta (**Fig. 18**). The separate linear regression fits associated with the crater rim and ejecta RA data remain outside of the confidence bounds of one another until $\sim$ 2.2 Ga. This relationship suggests that rocks present at the surface of the crater rim region remain uneroded

for the first ~ 2.2 Ga of a crater's lifetime. However, this mechanism would require mass wasting rates to be faster than breakdown of buried rocks, which is ostensibly not consistent with my finding that subsurface rocks may be eroding slightly faster than surface rocks. A more physically reasonable interpretation of this observation is that in-situ, fragmented bedrock is present at or very near the surface of the crater rims and the continual downslope motion of the overlying regolith acts to continually expose fresh bedrock fragments, leading to elevated rock abundance values at the crater rim. This interpretation remains speculative and requires a mass wasting rate at the crater rim that outpaces the mass wasting rate in the more distal ejecta and a rate of rock breakdown in the ejecta that exceeds the rate of breakdown at the crater rim. The former requirement – that mass wasting is faster at the crater rim than the distal ejects – is consistent with the findings of Fassett et al. (2018). That study showed that mass wasting operates at crater rims in the form a constant influx of regolith of rock into the crater interior over time. This mass wasting process is not present to the same degree in the more distal crater ejecta as that ejecta lacks the steep slopes necessary for the rapid downslope movement of rocks and regolith.

My results differ from prior work on the topic of ejecta erosion by Ghent et al. (2014, 2016). Whereas Ghent et al. found that rocks associated with lunar ejecta deposits are destroyed in ~ 1.0 Ga, my results seem to suggest that rocks may be replenished on ejecta deposits for extended periods of time (2.5–3.0 Ga). A cause for this difference is not currently known to me.

An additional, potential scatter-causing mechanism that remains untested for my data is the noise and the theoretical interpretation of the Mini-RF CPR dataset. Although the surface roughness levels represented by circular polarization ratio are well-defined in theory, CPR analyses of other bodies have yielded variable and unreliable results in some cases. One such

case utilized CPR to characterize and compare the surface roughness of the asteroid Bennu with other asteroids such as Itokawa and Eros (Nolan et al., 2013). The results of Nolan et al. indicated that the surface roughness of Bennu was less than that of the other asteroids in question. This conclusion played a role in the design and planning of the sample return mission, OSIRIS-REx. This spacecraft was designed to make contact with the relatively smooth surface of Bennu, collect a regolith sample, and return that sample back to Earth. Upon the spacecraft rendezvous with the asteroid, high-resolution images and measurements of Bennu's surface were obtained, revealing that the surface of Bennu was, in fact, exceedingly rough and rocky (Lauretta et al., 2019). This finding continues to complicate the sample-return objective of the OSIRIS-REx mission, which was designed for operations on a much less-rough surface based on early CPR measurements.

This case study serves as a caution for any analysis of surface roughness using CPR alone. The speckle noise in the Mini-RF CPR dataset is substantial and should be taken into consideration when using these data to interpret the physical attributes of the lunar surface. Moreover, the physical interpretation of the surface roughness that is represented in the CPR dataset is theoretical and subject to variation based on planetary body. Scattering models and laboratory experiments on the interactions between radar signals and surface roughness are one possible solution to variable CPR interpretations, but these analyses are in their infancy. Any analysis of lunar surface roughness would be considerably strengthened by the use of multiple remotely sensed datasets.

Section 6: Conclusions

The goal of this thesis was to compare the rates at which surface and subsurface rocks associated with lunar ejecta deposits erode with time. My working hypothesis was that rocks at the surface of lunar ejecta erode more quickly than those in the subsurface. To accomplish this goal and assess the initial hypothesis, I attempted to establish the long-term erosion rates of ejecta constituents by characterizing the ejecta blankets of small lunar impact craters in CPR and RA data and then correlating these data with modelled age values. Overall observed trends in CPR and RA coefficient behavior indicate that surface rocks may break down more slowly than subsurface rocks. This result may indicate that there is a period of time after all subsurface rocks have been eroded when remnant surface rocks have yet to be eroded. However, the confidence bounds and goodness-of-fit statistics associated with these data indicate that the linear regression models used to establish the quoted rates are poor representations of the variation in the data as a whole. Therefore, the data weakly refute my hypothesis. Several tests were implemented in an attempt to understand the variability in these data and the physical processes at the lunar surface that could be causing this scatter. Results of those tests suggested that inter-mare variation amongst CPR and RA ejecta signatures may be due to differences in regolith thickness.

An analysis of roughness evolution in different radial regions of ejecta deposits suggests that material present on crater rims – whether boulders or in-situ fragmented bedrock – is continually being uncovered for a minimum of ~2.2 Ga. That result, coupled with the findings of Fassett et al. (2018) that simple impact crater interiors evolve separately from exteriors, builds a credible case that small lunar impact craters are geologically dynamic features with mass wasting rates at crater rims that may exceed those in the more distal ejecta. For a more complete assessment of ejecta erosion at a given crater that would account for roughness at the crater rim and in the

proximal ejecta, multiple rates of regolith breakdown corresponding to different regions in the ejecta deposit may be necessary.

Section 7: Future work

In future work on this topic, an analysis of crater ejecta evolution with smaller (down to ~800 meters in diameter) craters included could be used to determine if the evolution of smaller craters is more self-consistent (i.e., is less variable) than that of larger (>2.0 km) craters. A direct comparison of craters in these size ranges would provide a quantitative measurement of any size-based discrepancies amongst the remote sensing signatures of ejecta deposits associated with simple lunar impact craters. This analysis would be challenging, however, due to the low resolution of the RA dataset and the difficulty of identifying craters <1.0 km diameter craters which are sampled by only ~3–4 RA pixels in some cases. In addition, a comparison of small and larger craters in the diameter range of ~10–100 km using both radial medians and 95th percentile values would provide a better understanding the differences between the results presented here and those of Ghent et al. (2016). This analysis has the potential to identify discrepancies in simple and complex crater evolution using remote sensing data. For example, this comparison could reveal whether boulder exhumation or bedrock exposure is active at the rims of much larger, complex craters. The assessment of any correlation between remote sensing signatures of mare thickness variations and ilmenite content would also be useful in assessing the degree to which those variables affect the intensity of CPR and RA haloes.

Lastly, laboratory studies of radar remote sensing techniques could greatly improve our interpretation of variable radar backscattering and intensity. The current understanding of what is represented in a typical radar backscatter field is primarily theoretical (Campbell et al., 1997, 2012). Although progress is being made on backscatter models, these tools are in their infancy and require laboratory measurements of radar parameters in order to provide accurate representations of how a given geologic target would behave as a backscatter field (Prem and

Patterson, 2018; Prem, personal communication 2019). Laboratory measurements would provide a wealth of information to the radar remote sensing and broader scientific community regarding how geologic targets are interpreted in radar and how useful radar can be as a scientific tool.

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Appendices

Appendix A: Figures

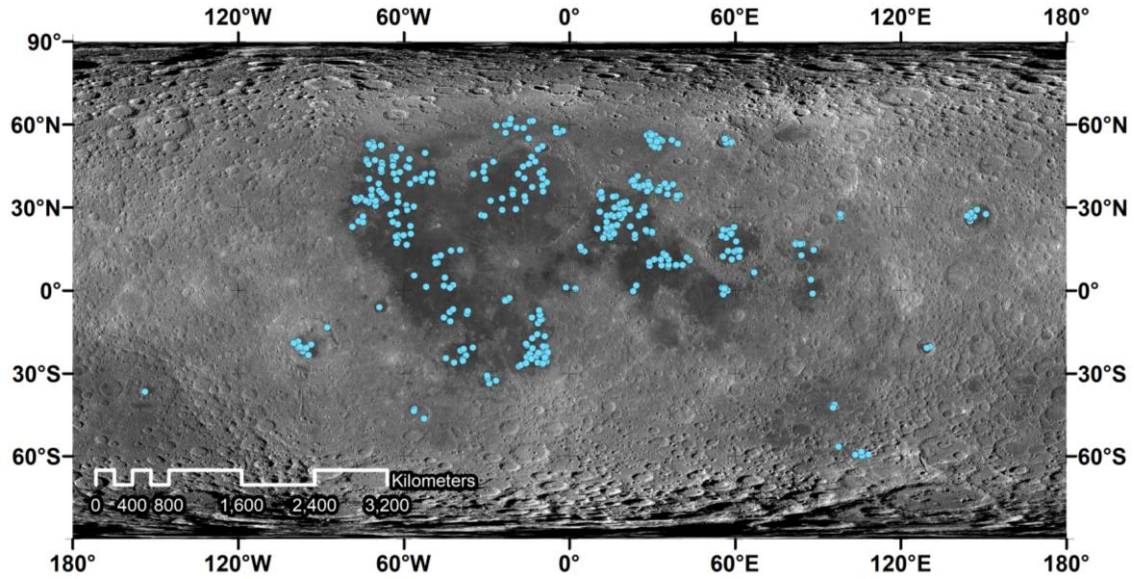


Figure 1. Global map of study craters: LOLA topographic image of the lunar surface with blue dots depicting study craters. Craters in this work are located exclusively on mare units at latitudes no greater than $\pm 55^\circ$. The sample set of craters in this study is limited to those craters studied in Fassett and Thomson (2014) as that work is the source for our modelled crater ages.

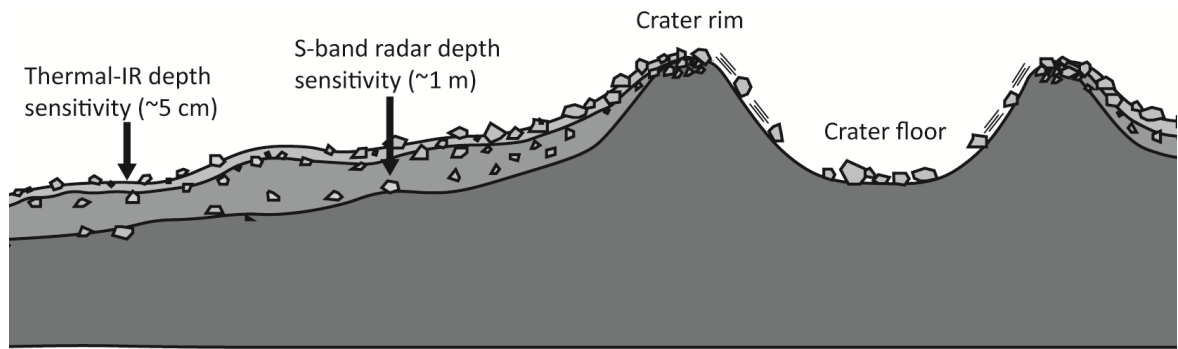


Figure 2. Schematic simple crater cross section: Illustrated cross-section of a simple impact crater showing the depth sensitivities of the data used in this study. Thermal infrared data are sensitive to rocks at a depth of ~5 cm in lunar ejecta deposits whereas S-band radar data are sensitive to rocks buried by up to a meter of regolith. The difference in sensitivities between these two datasets is used in this investigation of lunar ejecta erosion to assess the hypothesis that surface rocks erode more quickly than subsurface rocks. See sections 2.4 and 2.6 for additional details on penetration depths.

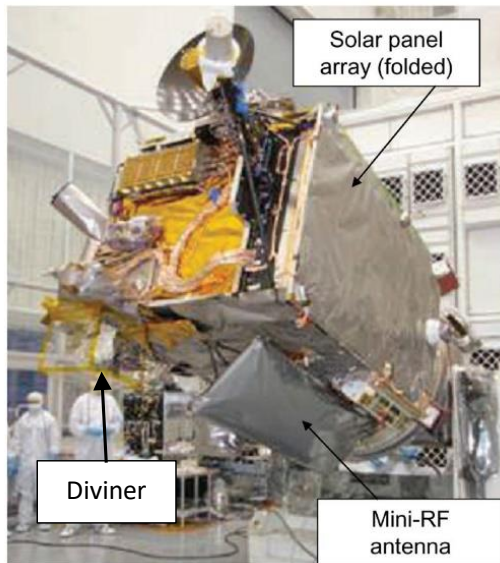


Figure 3. LRO in assembly: The Lunar Reconnaissance Orbiter during final assembly. The Mini-RF antenna is visible on the underside of LRO, and the Diviner Radiometer is located on the front-left corner of LRO in this image. From Raney et al., (2010).

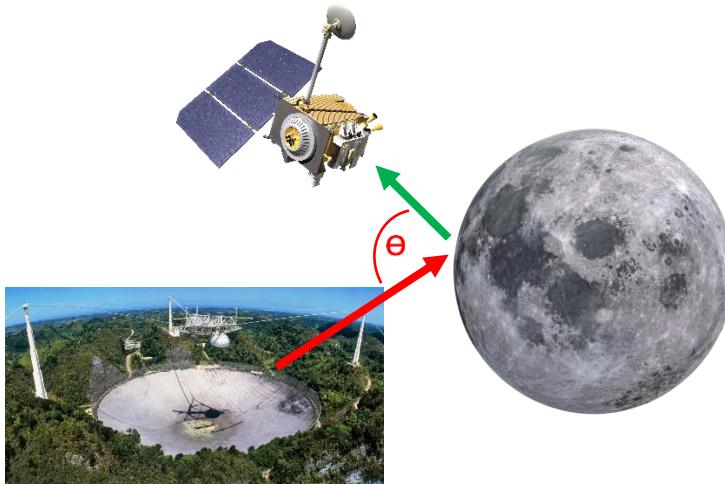


Figure 4. Mini-RF bistatic configuration: Mini-RF bistatic configuration showing signal emitted from the Earth-based Arecibo Observatory (red) and signal collected by the Mini-RF instrument (green) with varying phase angle (θ) between the signals.

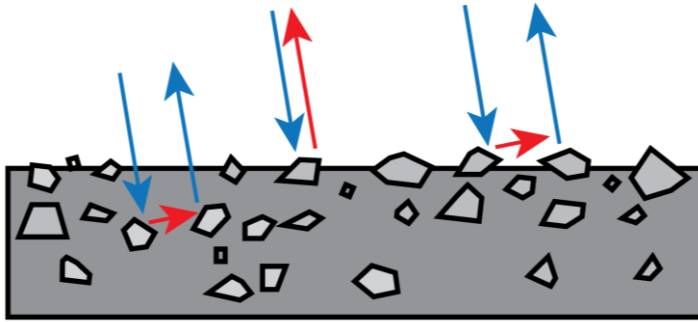


Figure 5. Radar reflection schematic: Schematic cross section of the lunar regolith with same-sense emitted signals which travel to the lunar surface in a left-circular manner of polarization (blue arrows), are reflected off of subsurface scatterers, and flip to an opposite sense right-circular polarization state (red arrows). The center reflection represents a single-bounce reflection whereas the left and right instances represent double-bounce reflection.

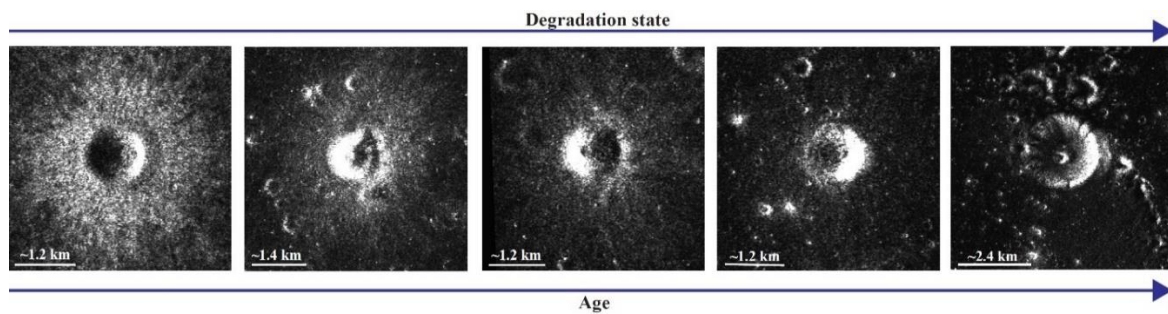


Figure 6. Impact crater evolutionary sequence: Evolutionary sequence of lunar craters from radar-bright to-radar dark. Prior work has inferred the evolution of crater halos from bright to dark to represent progressing surface erosion and surface rock breakdown. The craters in this diagram decrease in age, degradation state, and radar brightness from left to right.

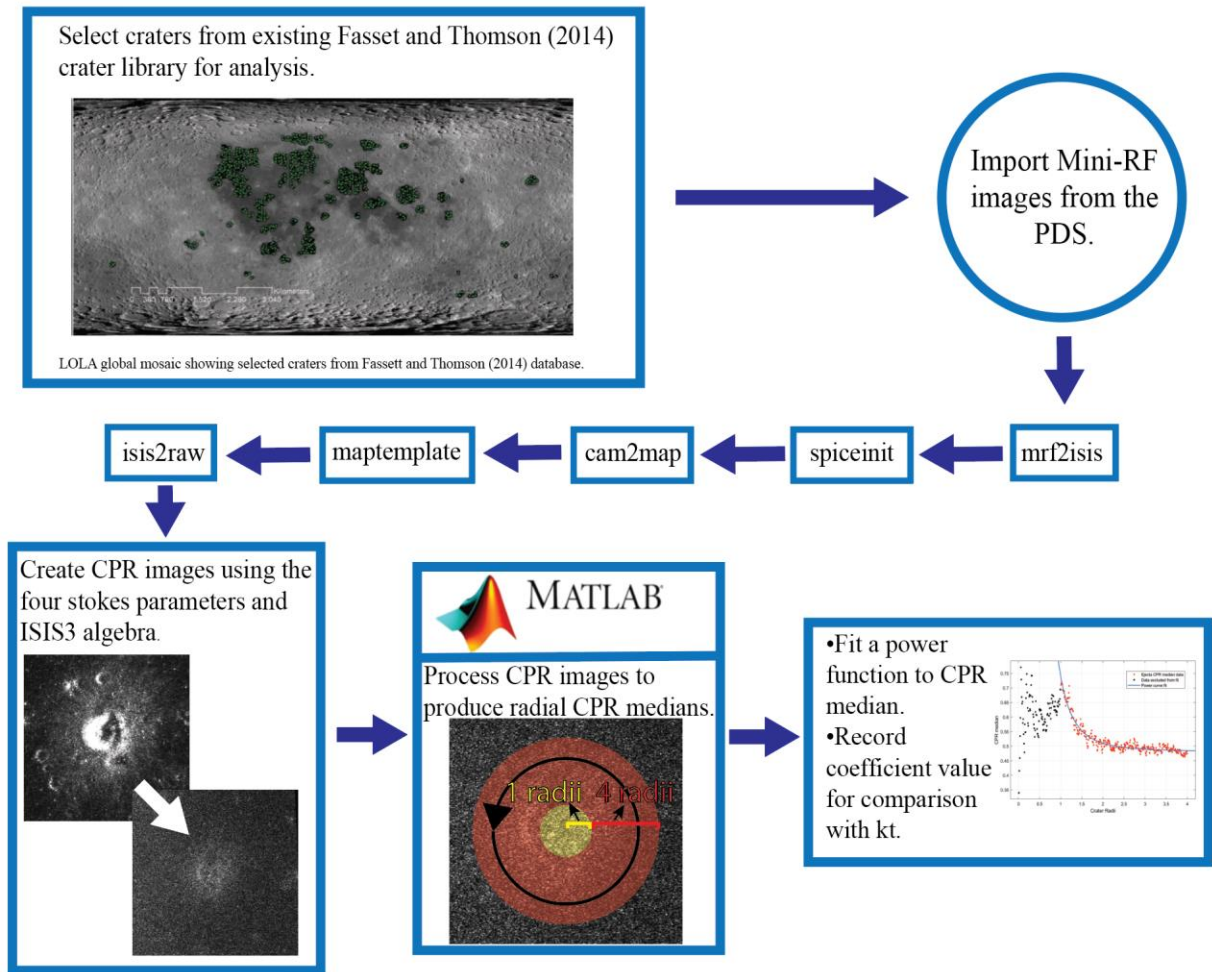


Figure 7. CPR processing flow chart: Flow chart depicting the methods of radar data processing and characterization. Steps in this process include downsampling of craters from Fassett and Thomson (2014), the use of ISIS3 utilities mrf2isis, spiceinit, cam2map, maptemplate, and isis2raw sequentially, calculating CPR data from the Mini-RF stokes parameters using ISIS3 algebra, extraction of a radial median from 1.0-4.0 crater radii in MATLAB, and curve fitting in the MATLAB Curvefit toolbox.

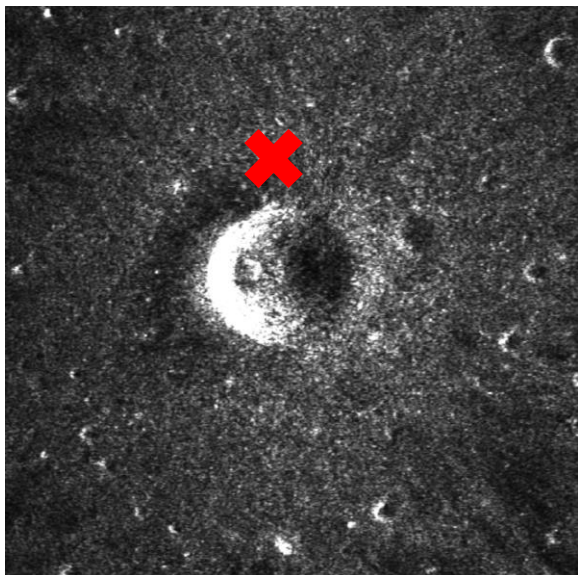


Figure 8. Offset center point diagram: Small (1.85 km diameter), fresh crater in Mini-RF S₁ image lsz_01843_1cd_xku_22s263_v1. Red “x”, located at 38.712 N, -69.021 W, depicts the crater center point as is listed in the Fassett and Thomson (2014) crater database (UniqCratID: 4546). The shifted crater center point is ~1.44 km to the south of the false center point at 38.663 N, -69.017 W.

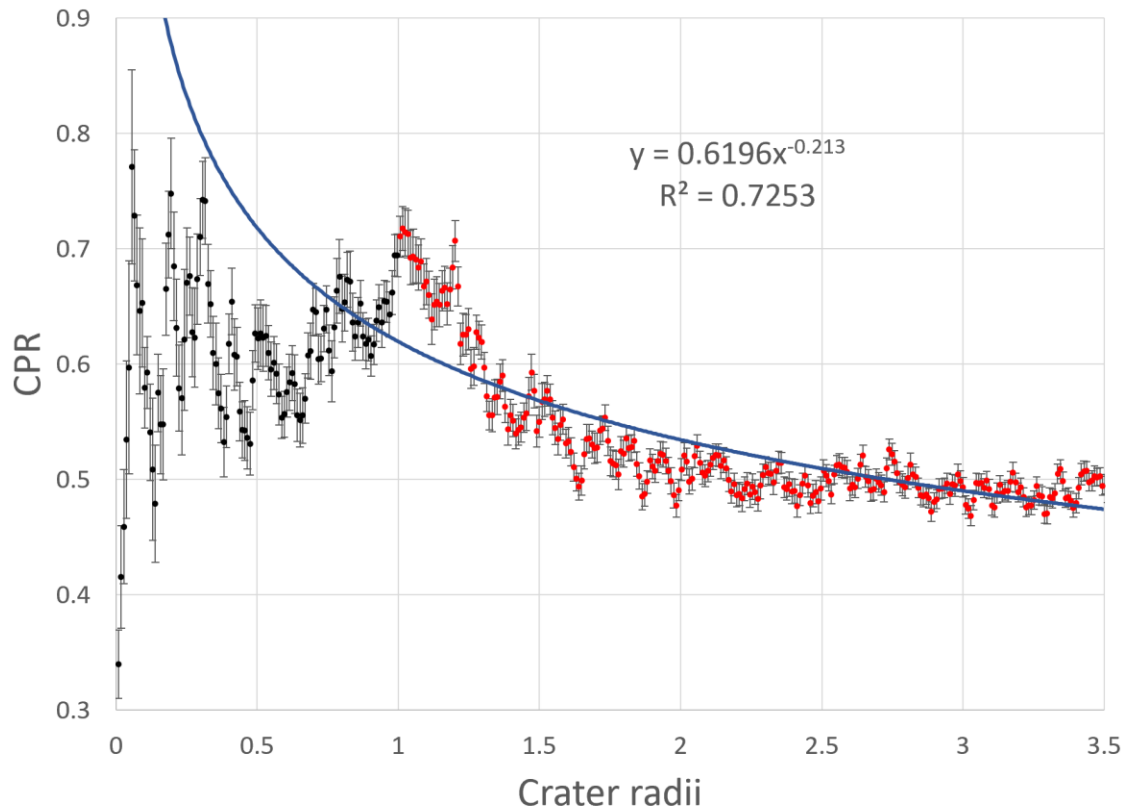


Figure 9. CPR radial median profile: Radial median plot of median CPR values vs. normalized distance for a young (<100 Ma) crater from the Fassett and Thomson (2014) crater database (UniqCratID: 8694) located at 36.08° N -20.33° W. CPR values are given on the Y-axis and normalized distance is given on the X-axis. Interior, excluded data are given in black, while data associated with the crater ejecta are given in red. The blue power curve is fit to the ejecta CPR data.

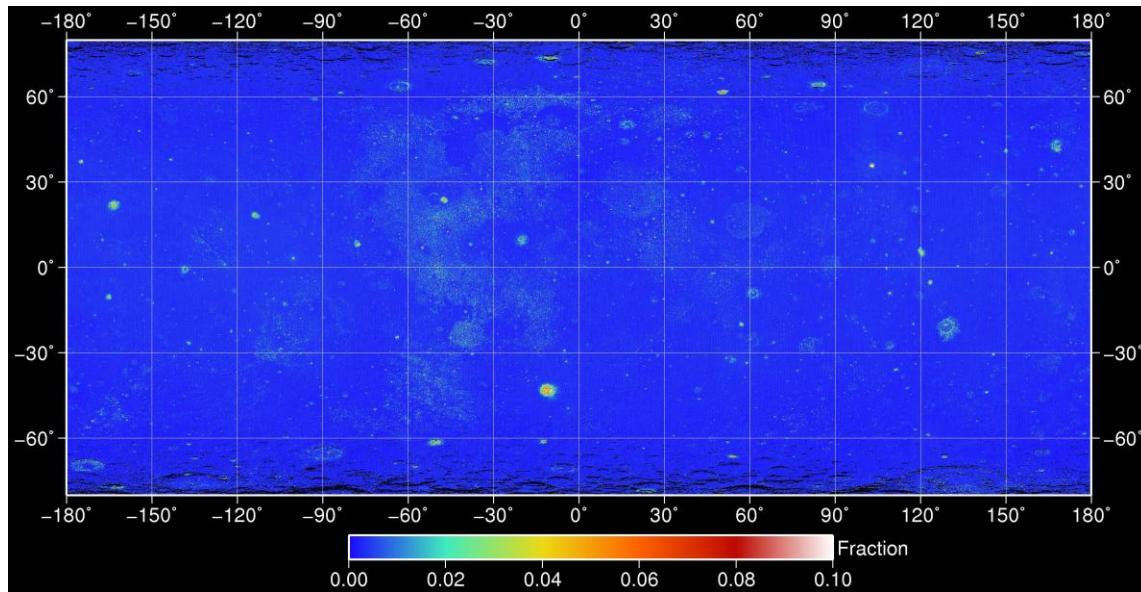


Figure 10. RA global mosaic: Rock abundance mosaic extending from 180°E to -180°W and 70°N to -70°S. Cooler colors represent smoother areas of the lunar surface whereas warmer colors represent rockier areas of the lunar surface. In this dataset, features such as the lunar maria and impact craters stand out as rockier areas of the lunar surface. Image resolution is ~237m/px.

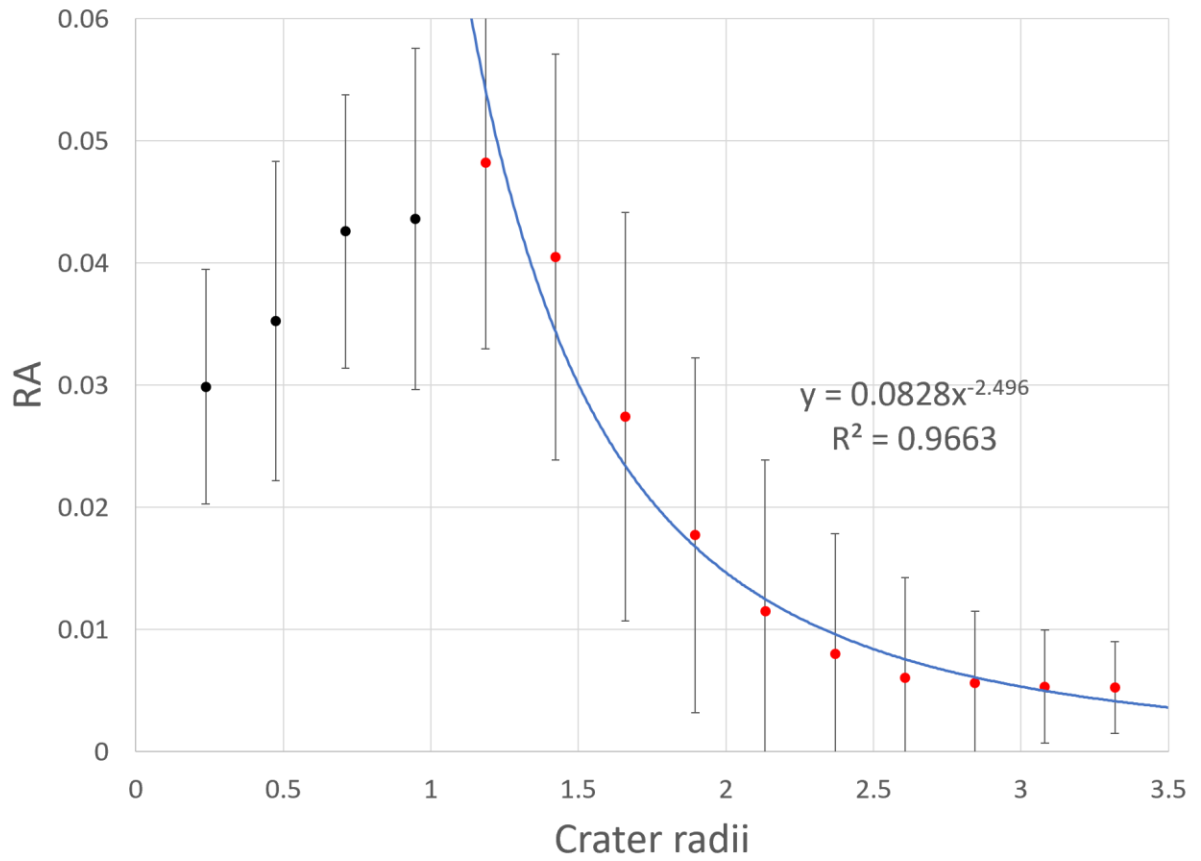


Figure 11. RA radial median profile: Radial median plot of RA data for a young, fresh crater with RA value given on the Y-axis and normalized distance given on the X-axis. This crater is documented in the Fassett and Thomson (2014) crater database as UniqcradID: 2697 located at 49.82N, -52.18W. Interior, excluded data are given in black, and data associated with the crater ejecta are given in red. The blue power law curve is fit to the ejecta RA data (red dots). Error bars represent the standard deviation for each annuli sample.

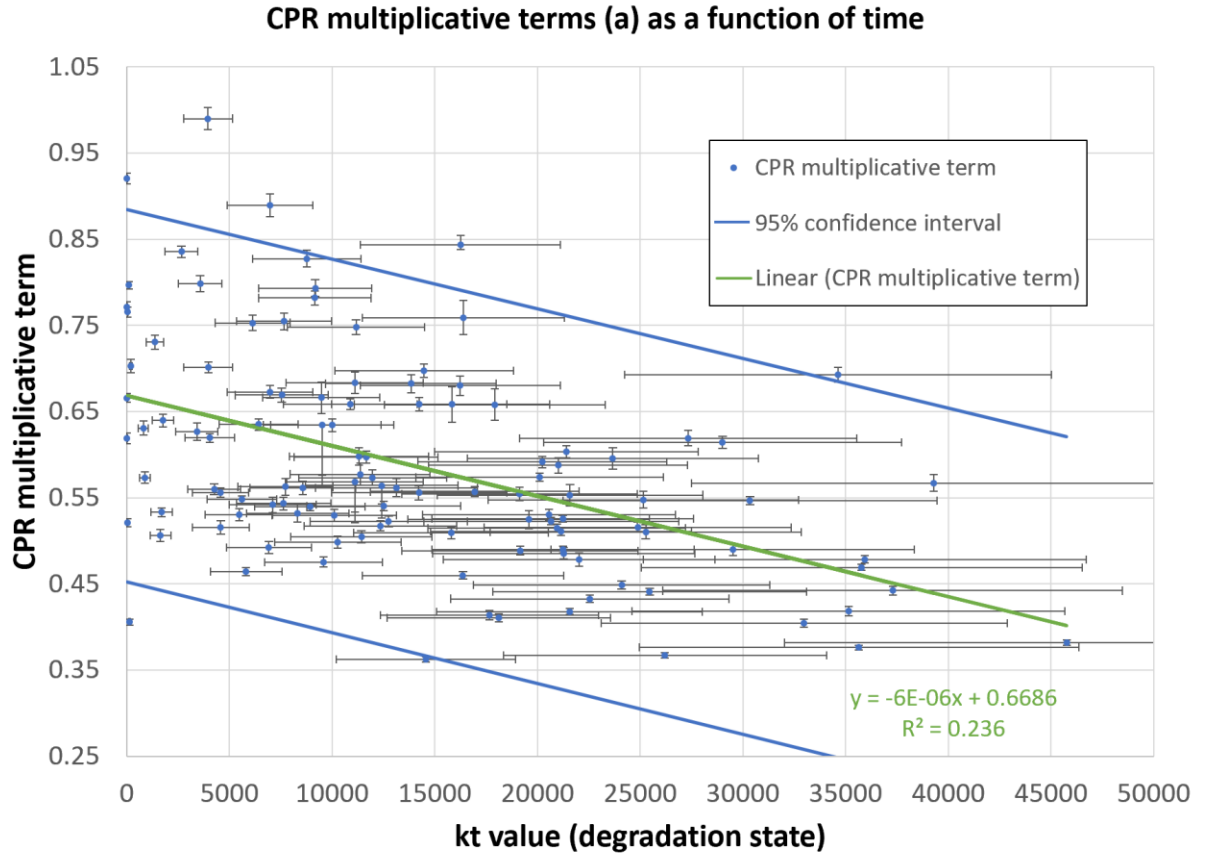


Figure 12. CPR multiplicative term evolution: CPR multiplicative terms (Y-axis) for 112 simple impact craters (orange points) characterized in high-resolution CPR images and plotted as a function of modelled age (lower X-axis) and corresponding κt value from Fassett and Thomson (2014) (upper X-axis). Error bars on these data represent the 95% confidence interval of the least squares method of curve fitting for each radial median in the y-direction and the standard error of $\pm 30\%$ given in Fassett and Thomson (2014) in the x-direction. Confidence bounds on these data are represented by the solid blue lines above and below the linear regression represented by a thicker, solid green line. All primary data is located in appendix B and individual radial median profiles are located in appendix C.

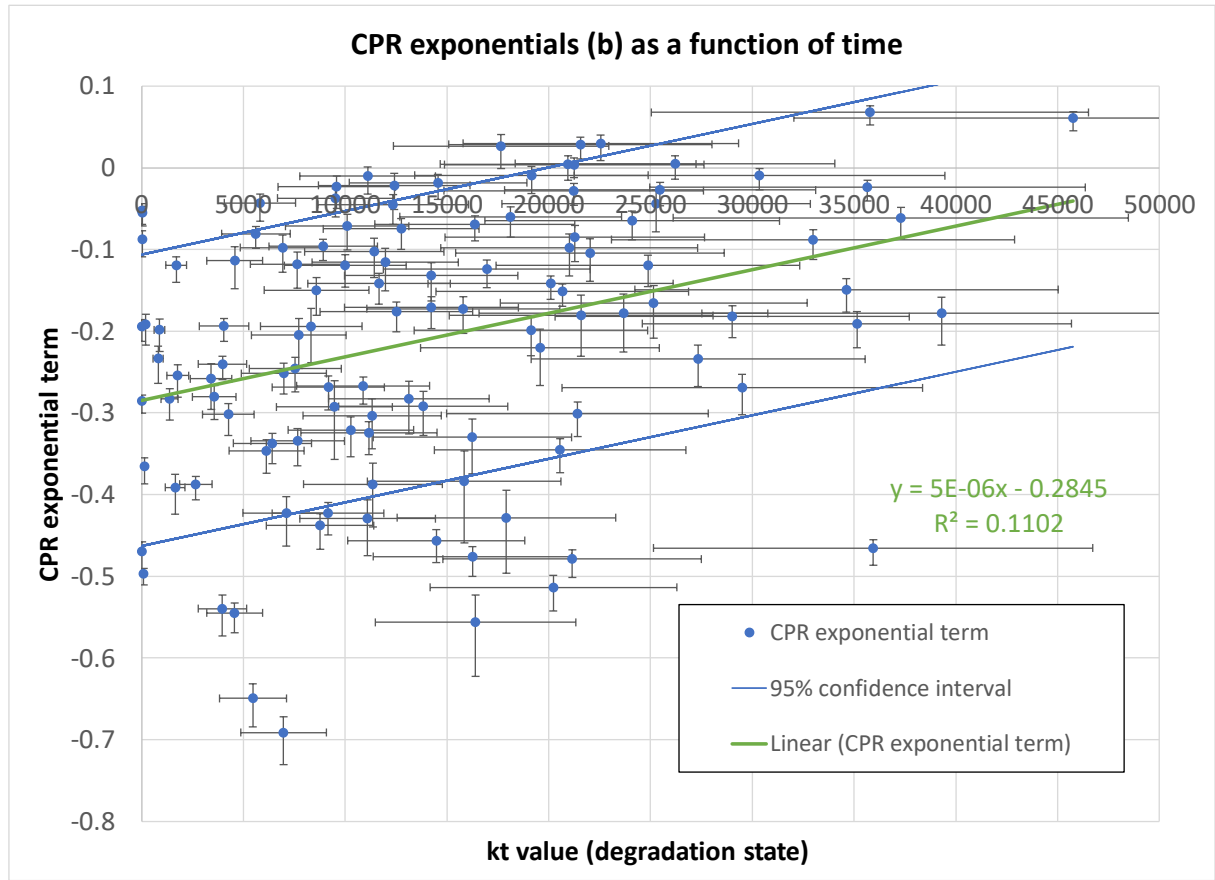


Figure 13. CPR exponential term evolution: CPR exponential fit terms (Y-axis) for 112 simple impact craters (blue points) characterized in high-resolution CPR images and plotted as a function of modelled age (lower X-axis) and corresponding kt value from Fassett and Thomson (2014) (upper X-axis). Error bars on these data represent the 95% confidence interval of the least squares method of curve fitting for each radial medial in the y-direction and the standard error of $\pm 30\%$ given in Fassett and Thomson (2014) in the x-direction. Confidence bounds on these data are represented by the solid blue lines above and below the linear regression represented by a thicker, solid green line.

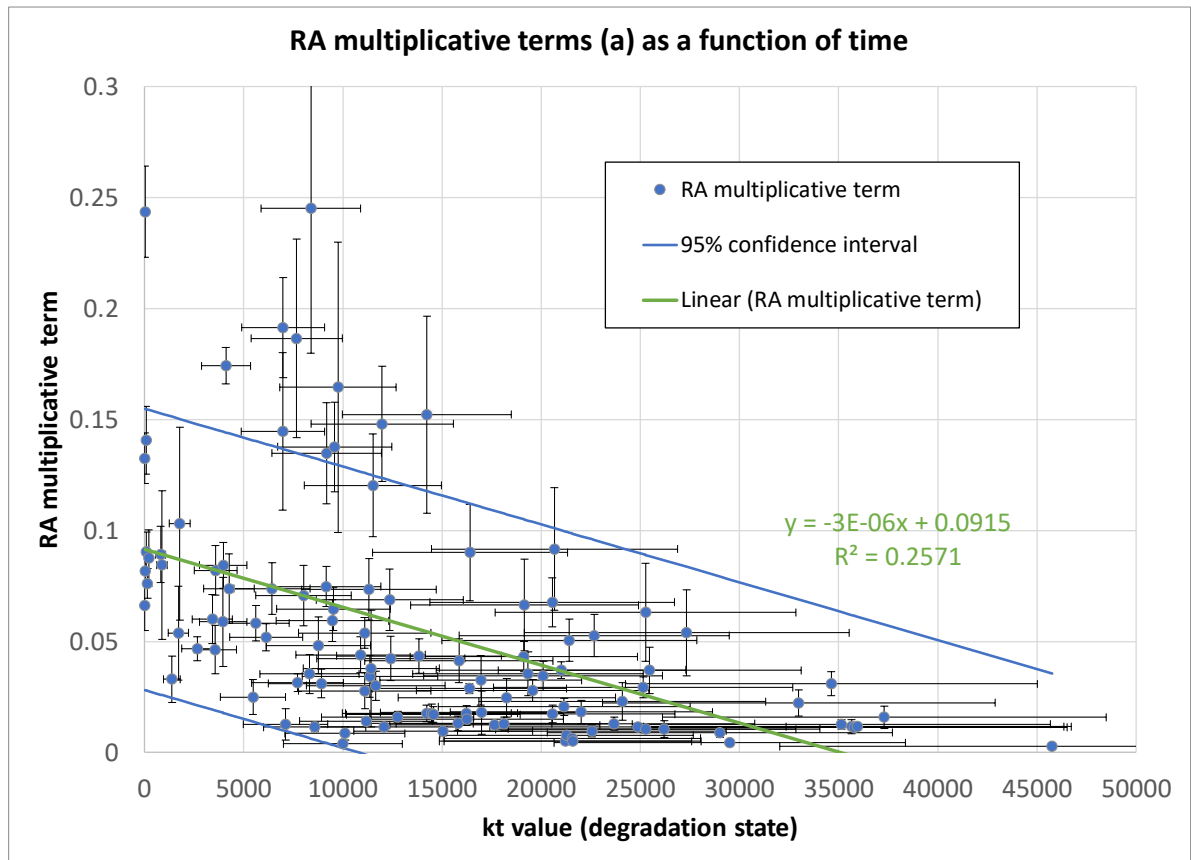


Figure 14. RA multiplicative term evolution: RA multiplicative terms (Y-axis) for 112 simple impact craters (yellow points) measured in the RA global mosaic and plotted as a function of modelled age (lower X-axis) and corresponding κt value from Fassett and Thomson (2014)(upper X-axis). Error bars on these data represent 95% confidence interval of the least squares method of curve fitting for each radial medial in the y-direction and the standard error of $\pm 30\%$ given in Fassett and Thomson (2014) in the x-direction. Confidence bounds on these data are represented by the solid blue lines above and below the linear regression represented by a thicker, solid green line.

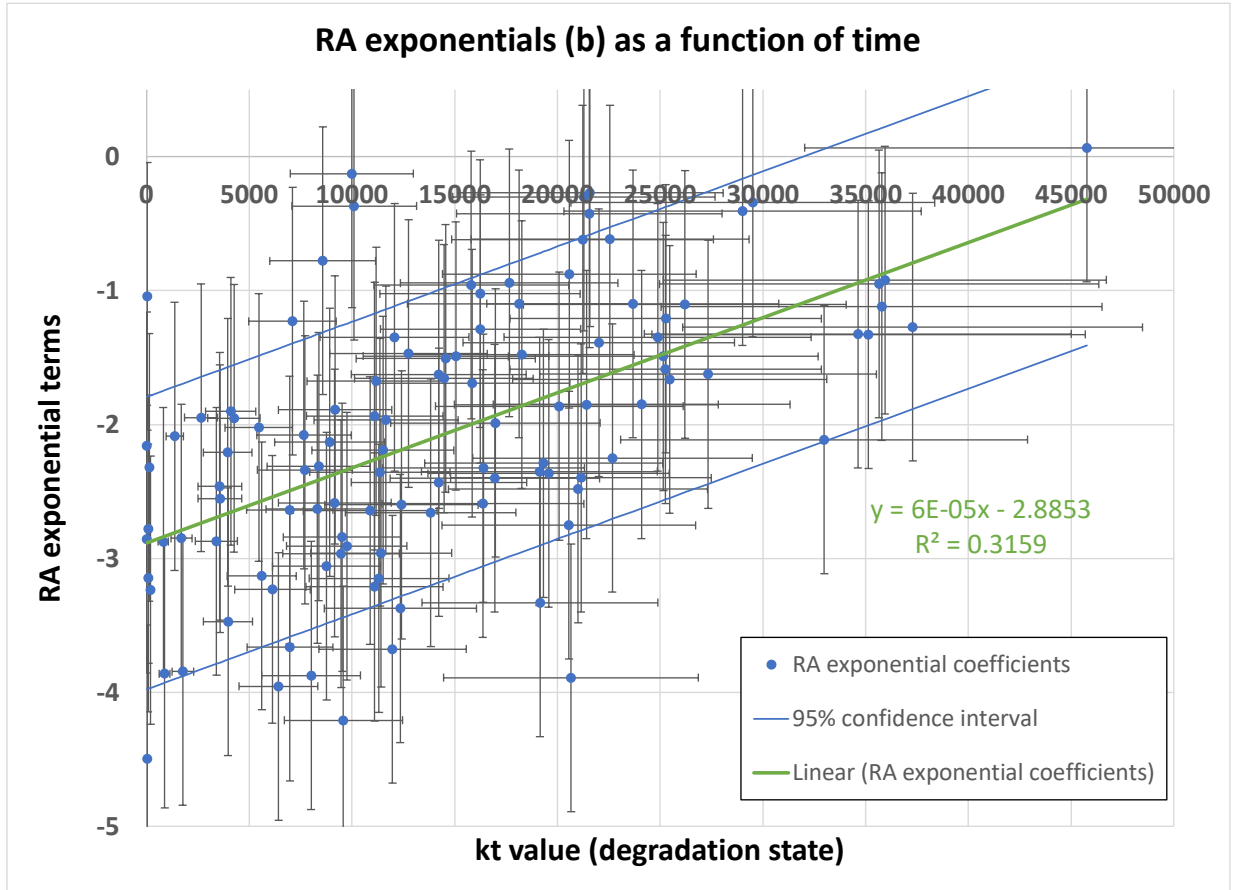


Figure 15. RA exponential term evolution: RA exponential fit terms (Y-axis) for 112 simple impact craters (yellow points) measured in the RA global mosaic and plotted as a function of modelled age (lower X-axis) and corresponding kt value from Fassett and Thomson (2014) (upper X-axis). Error bars on these data represent the 95% confidence interval of the least squares method of curve fitting for each radial medial in the y-direction and the standard error of $\pm 30\%$ given in Fassett and Thomson (2014) in the x-direction. Confidence bounds on these data are represented by the solid blue lines above and below the linear regression represented by a thicker, solid green line.

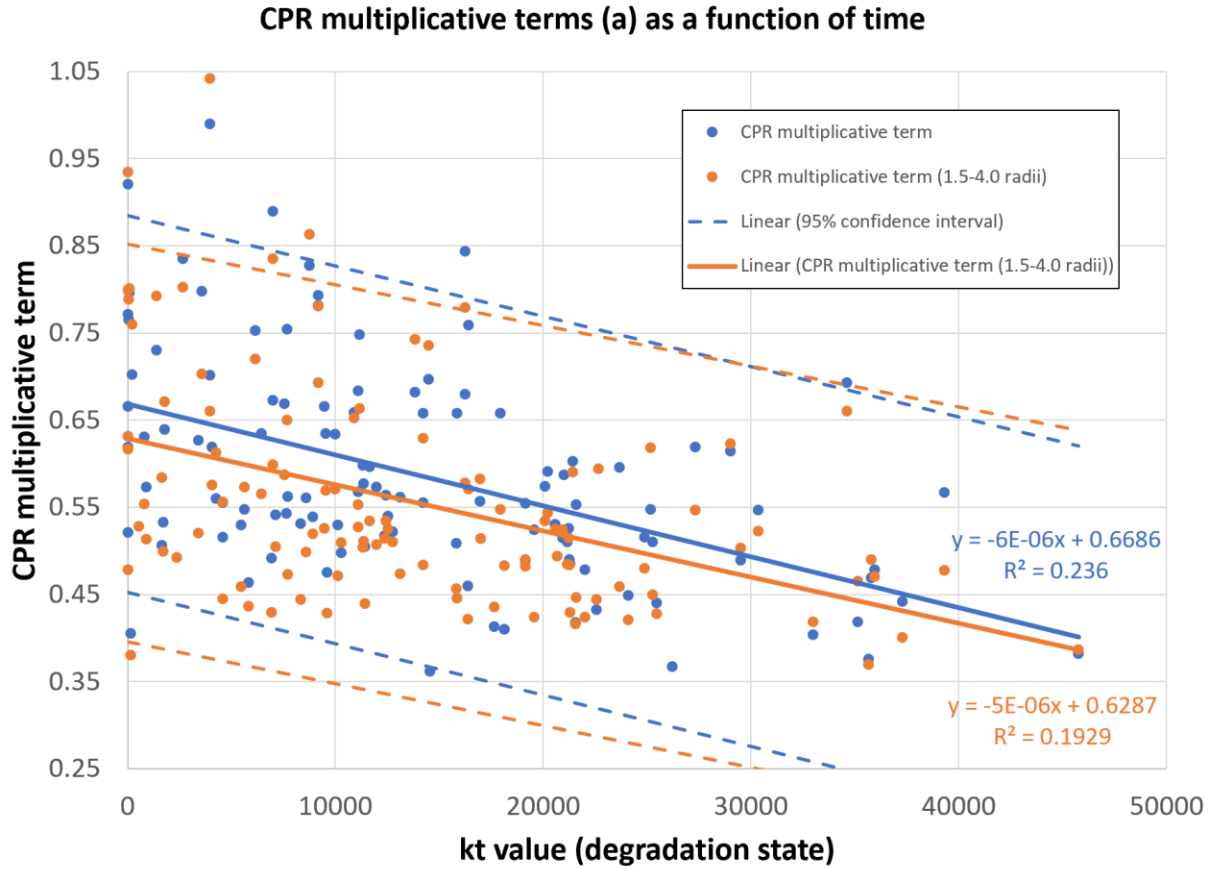


Figure 16. CPR multiplicative term evolution for variable fit ranges: Plot showing multiplicative terms for power law curves which were fit to CPR radial medians from 1.0–4.0 crater radii (blue data points) and from 1.5–4.0 crater radii (orange data points). The overall decreasing trend of these two datasets is similar, albeit the trend associated with fits from 1.5-4.0 crater radii is slightly lower in intensity than that of the trend for fits from 1.0-4.0 crater radii. These slight differences are within the confidence bounds of each dataset (represented by the thinner, solid lines above and below each respective regression), however, and are statistically insignificant. Error bars have been removed from **Figs. 16-17** to show trends but are equivalent to those in **Figs. 12 and 14**.

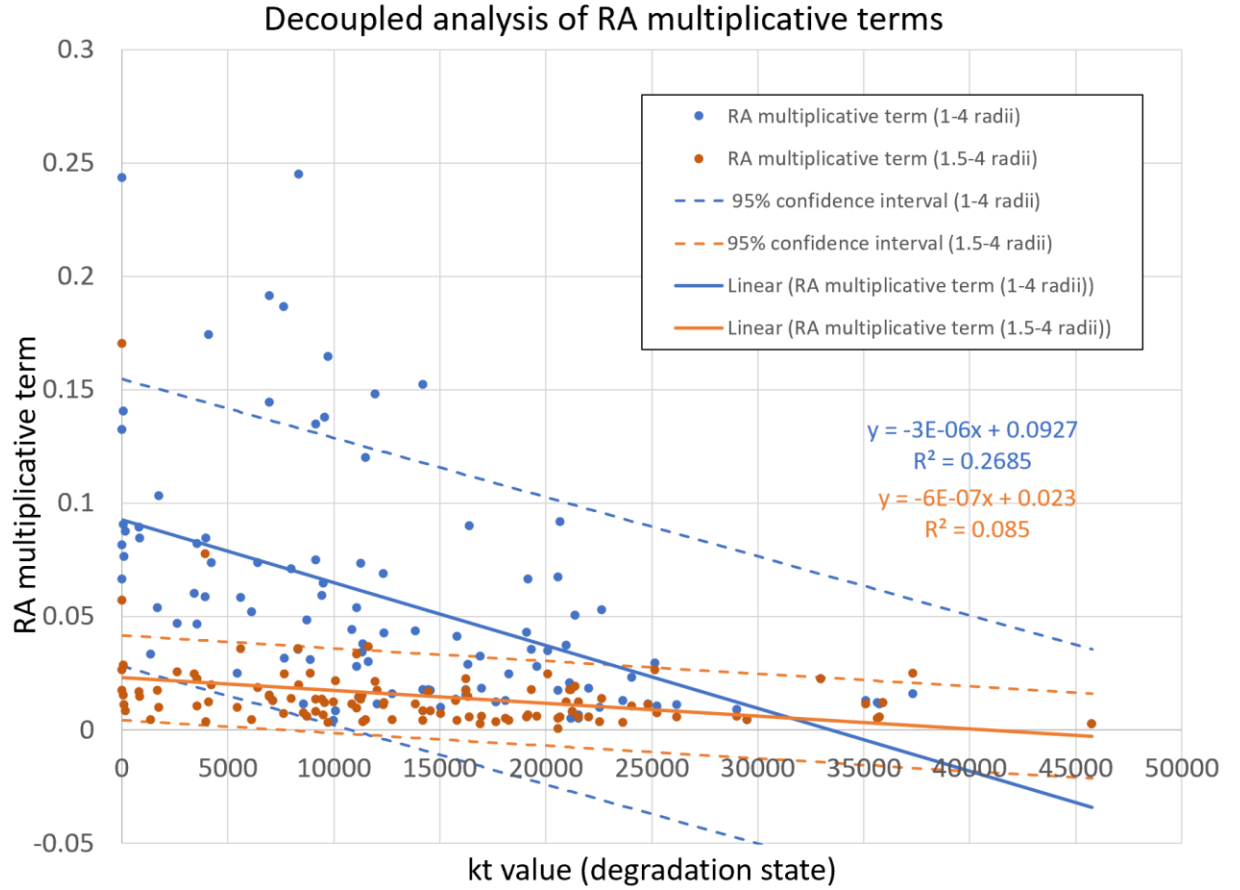


Figure 17. RA multiplicative term evolution for variable fit ranges: Evolution of RA multiplicative terms accounting for data from 1.0–4.0 crater radii (blue data points) and from 1.5–4.0 crater radii (yellow data points). visually, it appears that the inclusion of radial median data from 1.0–1.5 crater radii alters the resulting fit curve coefficients and corresponding linear regressions. This relationship appears to only be statistically significant at the region of 0–15000 κt , however, with the regressions falling within error beyond that point. Regardless, this indicates that the CPR and RA values at the crater rim may dominate the behavior of these data for the first ~2 Ga of a craters lifetime.

Decoupled analysis of crater rim and ejecta RA data

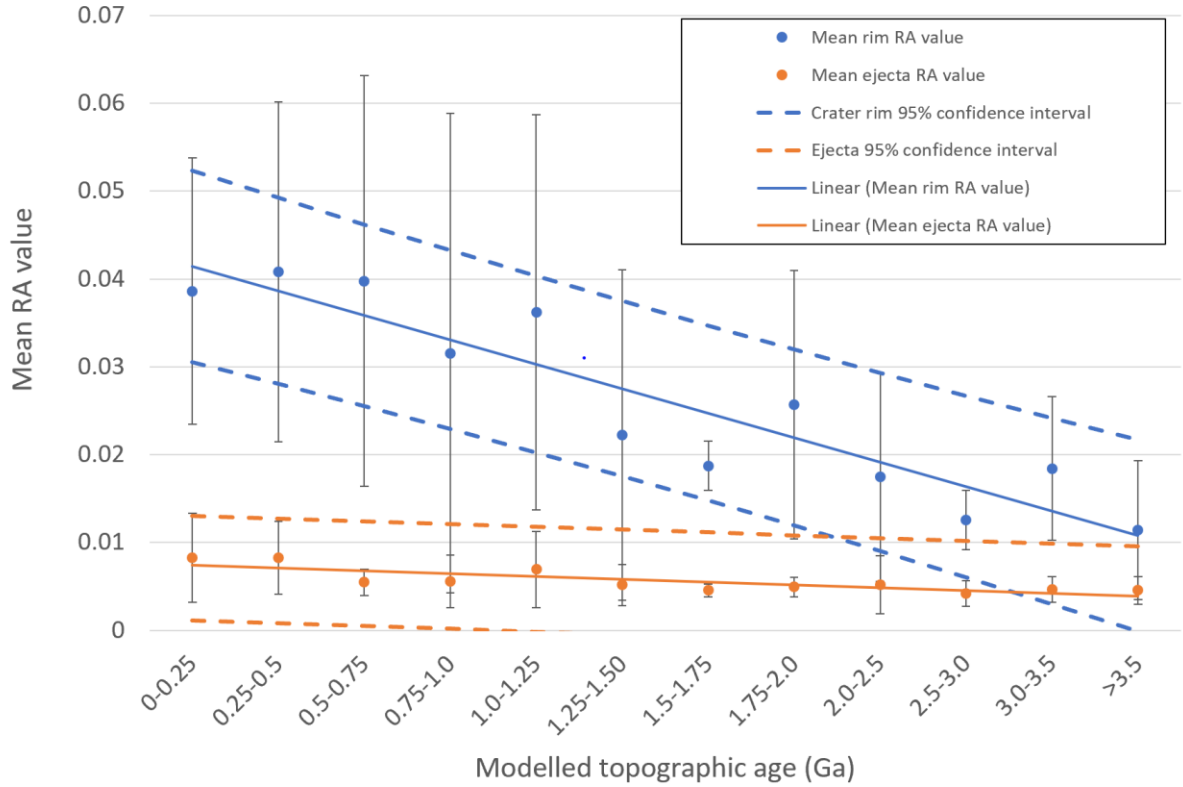


Figure 18. Decoupled evolution of crater rims and ejecta in RA: Plot showing the decoupled evolution of RA values associated with crater rims (blue data points) and crater ejecta (orange data points). These data points represent average RA values associated with the crater rim and ejecta, respectively, in each radial median bin. Similar to the distance-based multiplicative data presented in **Fig. 17**, there appears to be a visual difference between the linear regressions fit to both of these data sets and the behavior of crater rim and ejecta RA data over time. However, these regressions fall within the confidence bounds of the other in both cases, indicating that any visual differences are statistically insignificant. Error bars on all data points represent the standard deviation of RA values from the mean in each bin. The ages on this x-axis are manually converted from κt using the polynomial fit in Fassett and Thomson (2014).

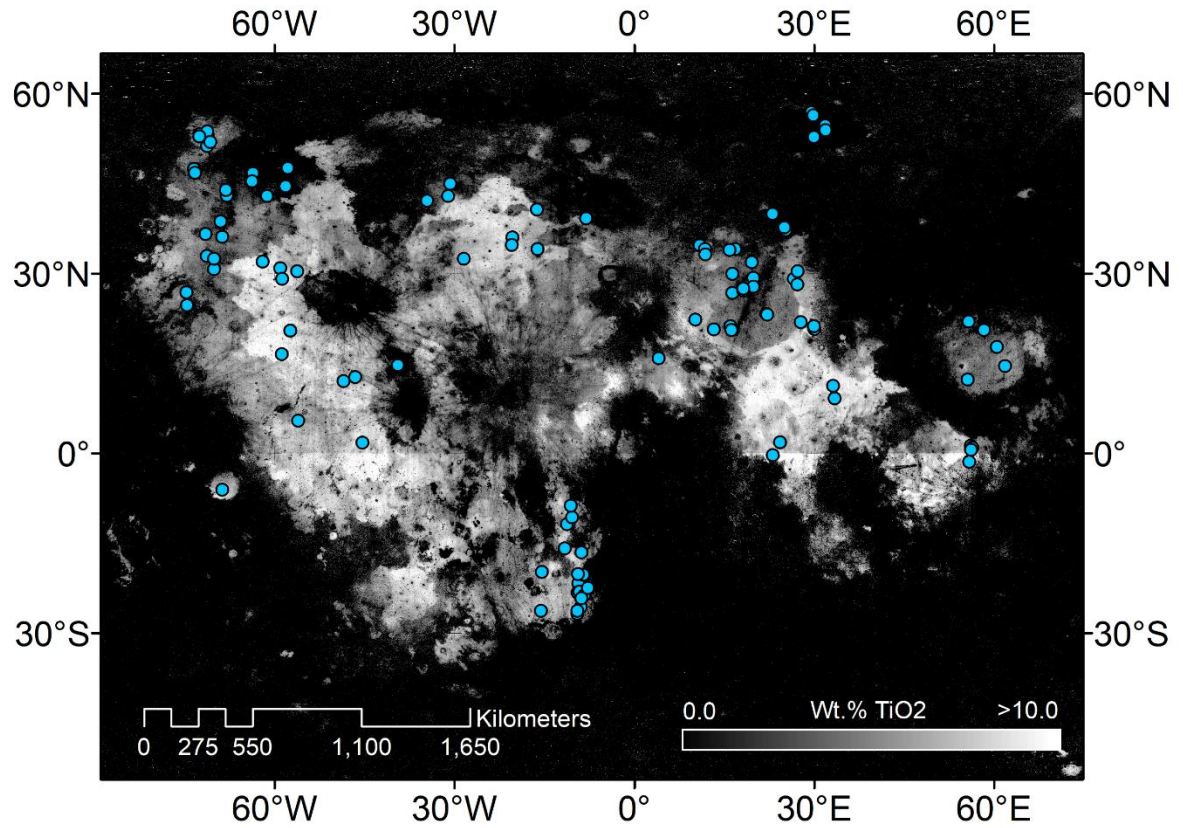


Figure 19. LROC WAC TiO₂ mosaic: Subset image of the LROC WAC TiO₂ mosaic described in Sato et al., (2017) showing the lunar maria only. In this spectrally-derived image, lighter areas can represent as much as 11-12 wt.% TiO₂ whereas darker areas represent as little as 0 wt.% TiO₂. In this image, the lunar maria stands out as very high in TiO₂ content and the surrounding highlands show relatively low TiO₂ content. Within the lunar maria, differences in TiO₂ content are present as well with distinct boundaries apparent in some of the mare units.

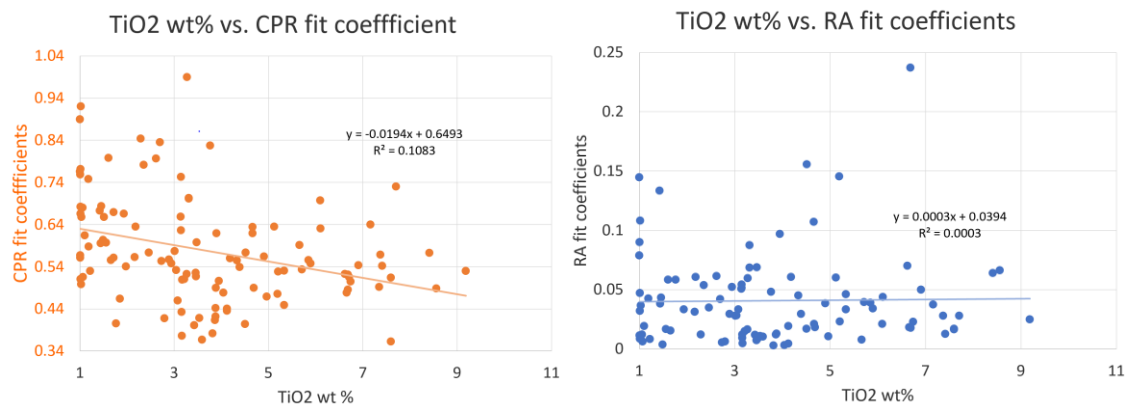


Figure 20. Correlations between CPR, RA, and TiO₂: Comparison plots of (A) TiO₂ content vs. CPR fit terms and (B) TiO₂ content vs. RA multiplicative coefficients. The variability in these plots is substantial and general trends are difficult to decipher. From the data plotted in these graphs, no strong correlation between CPR, RA, and TiO₂ are apparent.

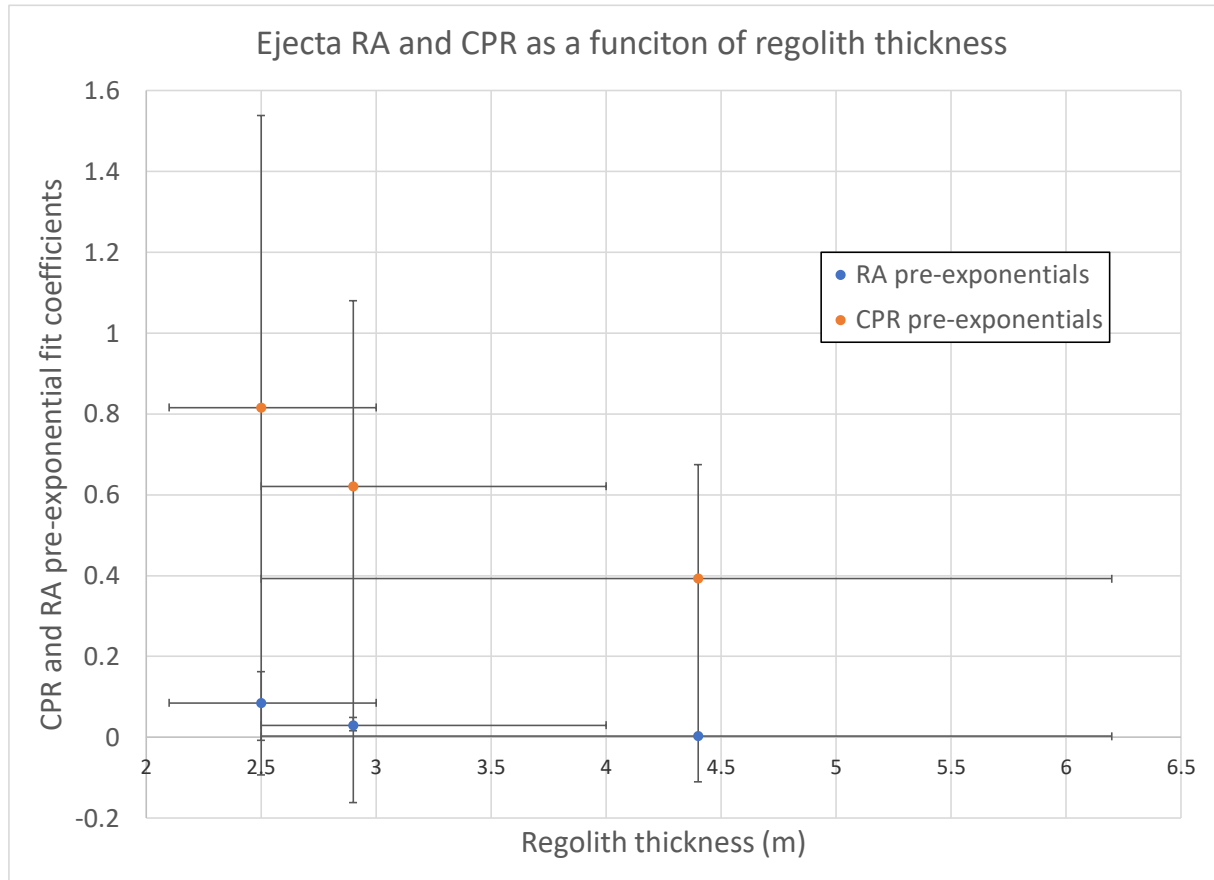


Figure 21. Regolith thickness comparison: A comparison of three impact craters (UniqID: 766, 8870, 175) with similar ages (~ 2.0 Ga) with mare regolith thickness estimated by Bart et al., 2011 from crater morphology. The comparison of multiplicative terms for these three craters in both CPR and RA data reveals a potential correlation between surface roughness and the lunar regolith thickness indicating that variations in regolith thickness may be a scatter causing mechanism in our CPR/RA multiplicative and exponential data.

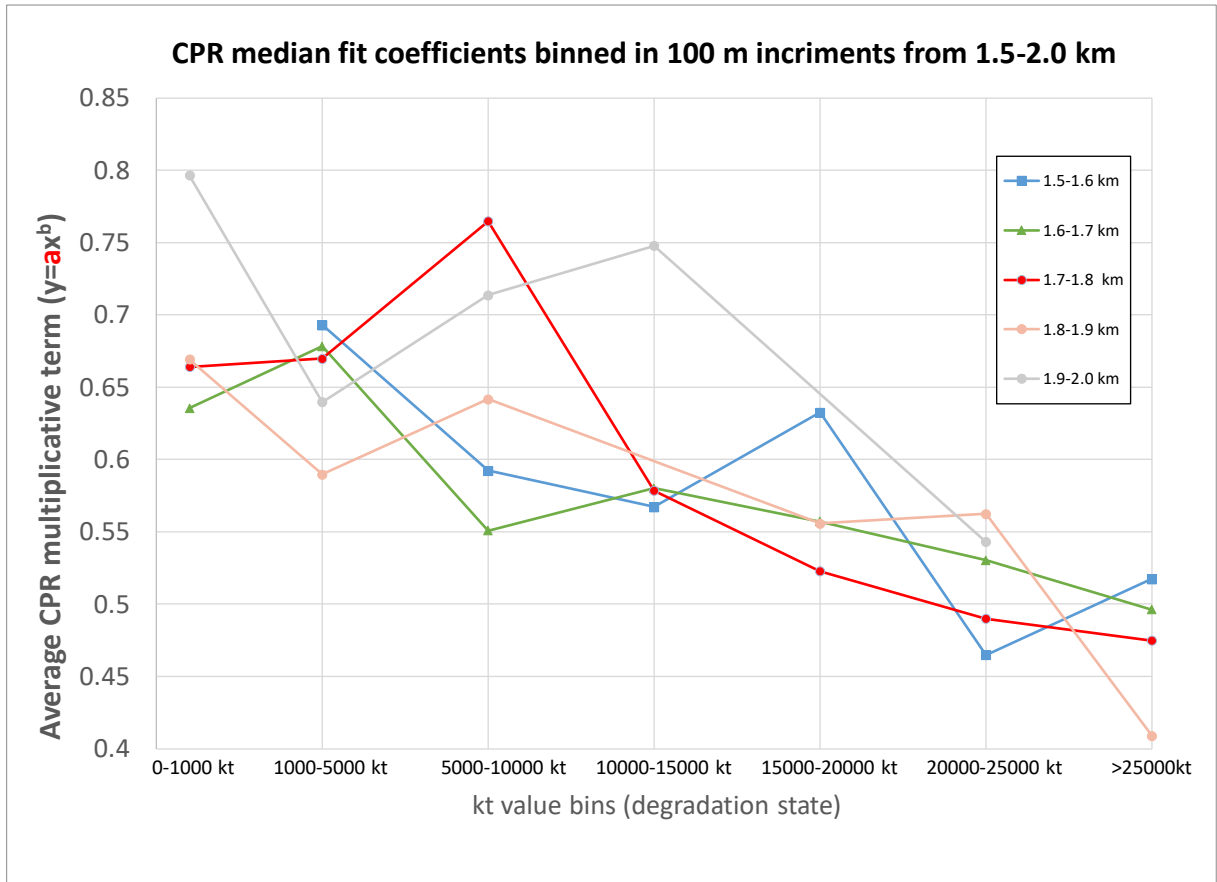


Figure 22. Diameter-based CPR multiplicative term evolution: CPR radial median fit coefficients binned by degradation state and plotted as a function of increasing κt value bin and modelled age. Note that some of the bins are missing data points on their respective trend lines. For example, no craters existed in the size range of 1.5–1.6 km for the κt bin of 0–1000 κt .

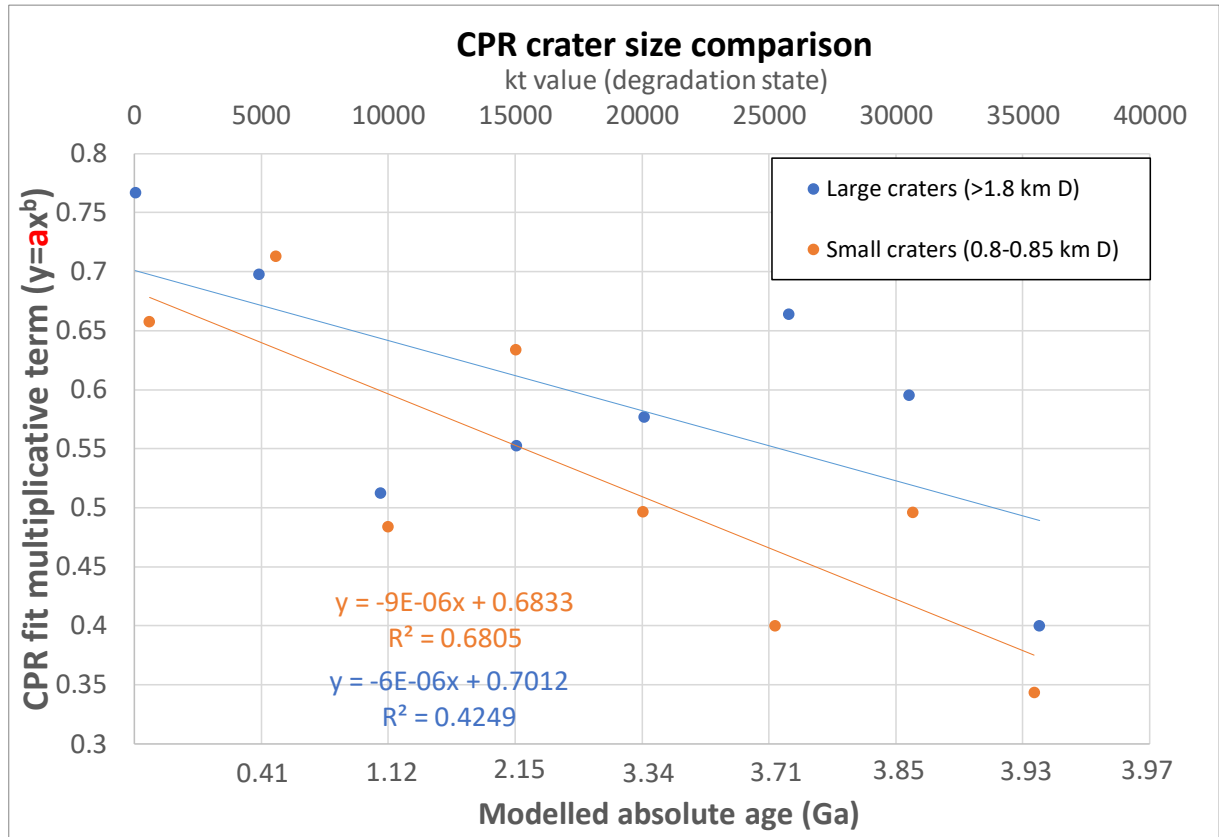


Figure 23. Size-endmember multiplicative term evolution in CPR: Eight fit terms in RA and CPR data plotted as a function of increasing age and κt value. Consistent with the data presented in section 4, the craters plotted here show an overall trend of decreasing CPR and RA halo brightness with time. While no clear dichotomy in fading is apparent between the large and small craters, there is less scatter in the small crater data ($r^2 = 0.6805$) than in the large crater data ($r^2 = 0.4249$). The ages on this x-axis are manually converted from κt using the polynomial fit in Fassett and Thomson (2014).

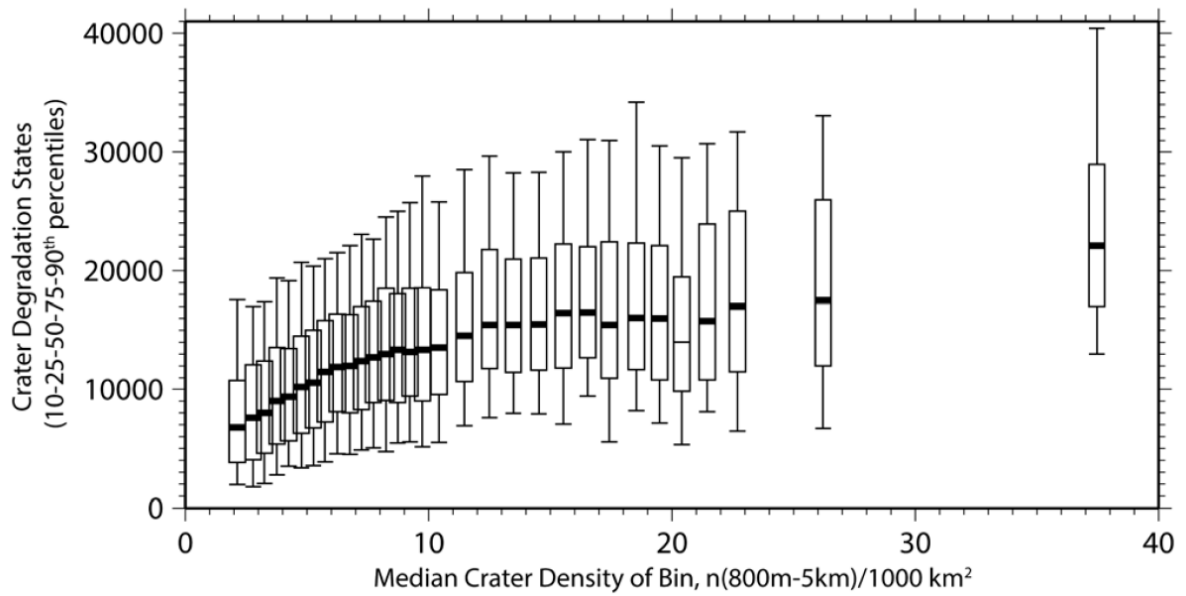


Figure 24. Crater bins and error in Fassett and Thomson (2014) ages: Crater bins from Fassett and Thomson (2014) showing larger error bars on crater bins with higher mean degradation states. The error bars on this plot represent the populations of craters in each bin with degradation states that are higher or lower than the median. The thin black line at the center of each box represents the 50th percentile degradation states (the median degradation state) where 50% of the craters in each bin are more degraded and 50% are less degraded. The edges of the white boxes represent the 25th and 75th percentile degradation states in each bin, and the edges of the error bars represent the 10th and 90th percentile degradation states in each bin.

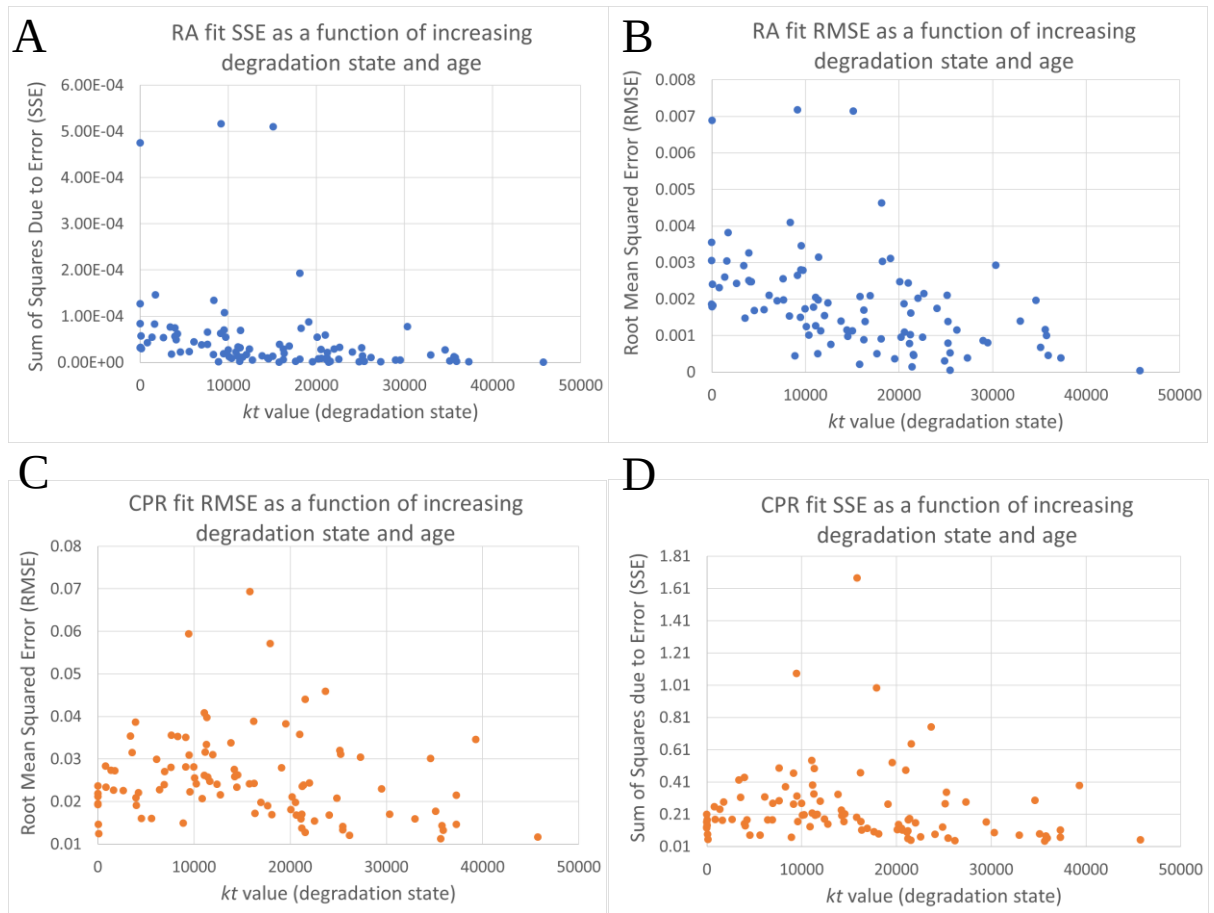


Figure 25. Goodness-of-fit metrics for CPR and RA median fits: Goodness-of-fit metrics, including SSE and RMSE, for RA median fits (A, B) and CPR median fits (C, D). In each of the plots, the goodness-of-fit metric is plotted on the y-axis with kt value plotted on the x-axis as an increasing metric from left to right. The SSE and RMSE metrics for RA fits are a near-inverse of those associated with CPR fits. With increased kt value and age, the variability in SSE and RMSE for RA fits appears to decrease, while the variability in those parameters appear to increase with kt value and age for the same fits in CPR data.

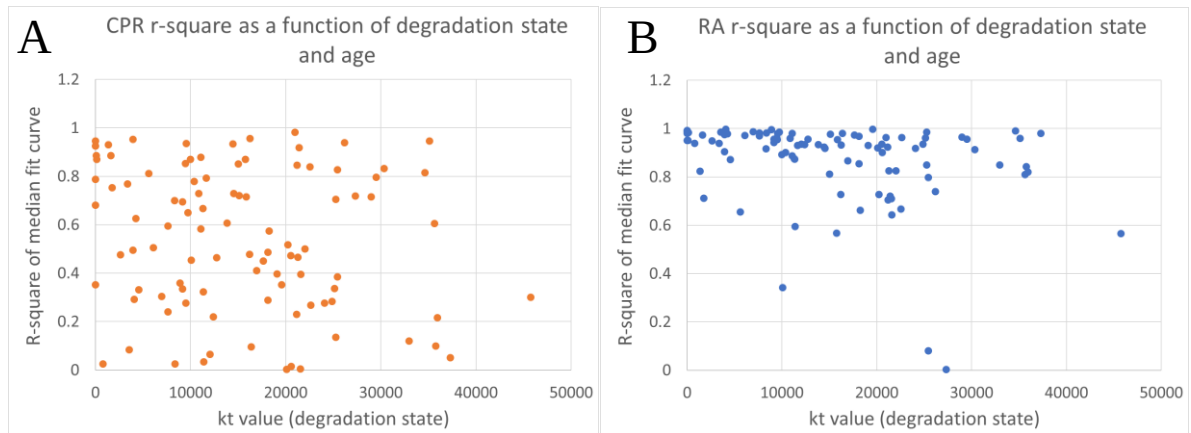


Figure 26. R-squared values for CPR and RA median fits: R-squared values for CPR median fit curves (A) and RA median fit curves (B). The comparison of these plots reveals generally higher RA median R-squared values with minimal variability, and CPR R-squared values which show considerable scatter throughout all of the data.

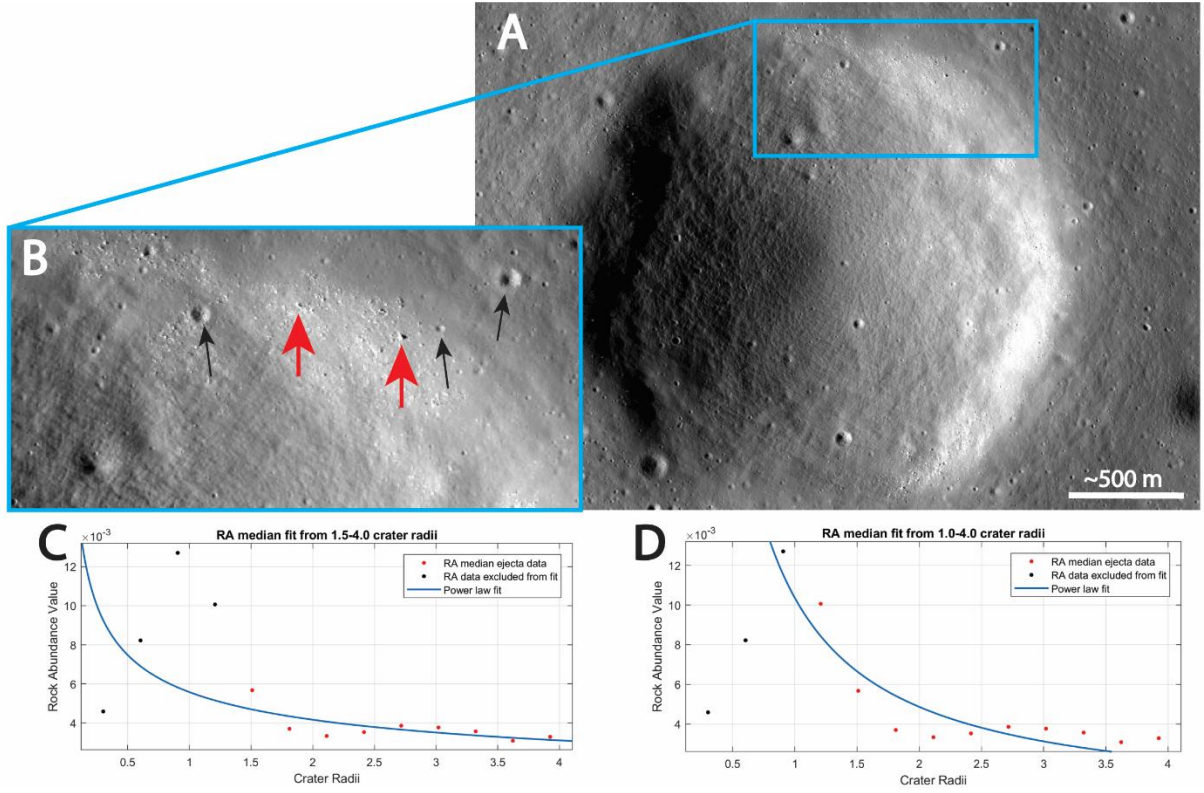


Figure 27. Enlarged NAC image of a ~3.7 Ga crater rim: (A) LROC NAC image of a degraded simple crater (UniqID: 5157) on Mare Nubium (-20.206° S, -9.031° W) with a topographically modelled age value of ~3.7 Ga (kt: 26203). Boulders are clearly present on the crater rim while they are absent on the ejecta and crater interior material. (B) Enhanced image of the NE portion of the crater showing an abundance of large (>2.0 m) boulders on the crater rim. Red arrows in (B) indicate large boulders and white arrows indicate other features such as small craters that are not of interest in this study. Given prior estimates of lunar boulder lifetimes, boulders of this size are expected to be completely destroyed on timescales of 0.2-0.7 Ga. Also shown are the RA radial medians of this crater fit from 1.5-4.0 crater radii (excluding rim data) (C) and from 1.0-4.0 crater radii (including rim data) (D). Fit coefficients for the power law curves in these plots are 0.0058 (r^2 : 0.5199) for (C) and 0.0104 (r^2 : 0.7377) for (D).

Appendix B: Individual crater parameters

Pre-exponential	Pre-exp. uncertainty (negative)	Pre-exp. uncertainty (positive)	Exponential	Exp. Uncertainty (negative)	Exp. uncertainty (positive)	UniqCratID	Diameter (km)	Longitude	Latitude	Source file	kt_cor_1km
0.57	0.56	0.58	-0.18	-0.20	-0.16	198.00	1.72	-63.72	47.06	lsz_6681_2cp_eku_58n296	39304.86
0.68	0.67	0.69	-0.33	-0.35	-0.31	207.00	1.88	-63.63	46.76	lsz_6681_2cp_eku_58n296	16239.66
0.66	0.64	0.68	-0.38	-0.42	-0.35	335.00	1.74	-63.79	45.41	lsz_6681_2cp_eku_34n296	15848.25
0.73	0.72	0.74	-0.28	-0.30	-0.27	530.00	1.62	-59.09	30.93	lsz_3029_2cp_eku_32n301	1376.56
0.64	0.63	0.65	-0.25	-0.27	-0.24	537.00	1.93	-58.76	29.11	lsz_3029_2cp_eku_32n301	1767.80
0.62	0.61	0.63	-0.47	-0.48	-0.46	871.00	1.81	-56.09	5.46	lsz_1806_2cp_eku_01n304	15.76
0.67	0.66	0.67	-0.19	-0.20	-0.19	936.00	1.76	16.38	26.78	lsz_2609_2cp_eku_32n017	15.51
0.58	0.56	0.59	-0.39	-0.41	-0.36	985.00	1.57	16.37	29.98	lsz_2609_2cp_eku_32n017	11360.95
0.57	0.57	0.58	-0.14	-0.15	-0.13	1013.00	1.81	55.90	-1.42	lsz_1697_2cp_eku_06s056	20093.58
0.48	0.47	0.49	-0.10	-0.12	-0.09	1027.00	1.51	56.20	1.28	lsz_3609_2cp_eku_05n056	22023.49
0.55	0.54	0.56	-0.17	-0.19	-0.14	1028.00	1.68	56.46	0.92	lsz_3609_2cp_eku_05n056	25153.70
0.49	0.48	0.49	-0.09	-0.10	-0.07	1071.00	1.67	56.22	0.58	lsz_3609_2cp_eku_05n056	21278.70
0.49	0.49	0.49	0.00	0.00	0.01	1123.00	1.72	-46.55	12.74	lsz_1449_2cp_eku_14n314	21245.76
0.52	0.52	0.53	-0.09	-0.10	-0.08	1156.00	1.86	-48.51	12.03	lsz_1451_2cp_eku_14n311	28.47
0.57	0.52	0.53	-0.01	-0.02	0.00	1287.00	1.66	-45.34	1.77	lsz_1448_2cp_eku_01s315	11106.60
0.63	0.56	0.58	-0.04	-0.05	-0.03	1632.00	1.70	-11.57	-15.86	lsz_2635_2cp_eku_16s348	9521.48
0.70	0.70	0.71	-0.24	-0.25	-0.23	1655.00	1.73	-11.21	-11.82	lsz_3674_2cp_eku_13s349	3968.92
0.63	0.63	0.64	-0.12	-0.13	-0.11	1771.00	1.75	-10.39	-10.67	lsz_2634_2cp_eku_16s349	10001.47
0.52	0.52	0.53	-0.07	-0.09	-0.06	1793.00	1.53	-10.58	-8.75	lsz_2634_2cp_eku_16s349	12757.61
0.50	0.50	0.51	-0.10	-0.12	-0.09	1916.00	1.54	-28.48	32.49	lsz_1779_2cp_eku_30n332	11424.34

0.50	0.49	0.51	-0.32	-0.34	-0.30	2016.00	1.77	-39.43	14.75	lsz_1790_2cp_eku_17n320	10273.56
0.38	0.38	0.38	0.06	0.05	0.07	2213.00	1.85	-74.73	26.88	lsz_3044_2cp_eku_32n285	45764.46
0.55	0.54	0.57	-0.18	-0.21	-0.16	2298.00	1.67	-74.64	24.73	lsz_3044_2cp_eku_32n285	21584.28
0.49	0.49	0.50	-0.10	-0.11	-0.08	2455.00	1.54	-61.99	32.03	lsz_3032_2cp_eku_32n298	6925.18
0.56	0.55	0.56	-0.54	-0.56	-0.53	2483.00	1.54	-56.25	30.39	lsz_1806_2cp_eku_33n303	4566.79
0.56	0.53	0.54	-0.02	-0.04	-0.01	2740.00	1.61	-26.62	29.15	lsz_1725_2cp_eku_33n026	12414.98
0.62	0.61	0.62	-0.19	-0.20	-0.18	2742.00	1.86	27.26	30.38	lsz_4333_2cp_eku_33n027	4042.04
0.52	0.51	0.54	-0.22	-0.24	-0.20	2763.00	1.89	27.23	28.16	lsz_4333_2cp_eku_33n027	19571.69
0.52	0.52	0.53	-0.15	-0.16	-0.14	2780.00	1.99	27.78	21.89	lsz_3293_2cp_eku_22n028	20665.41
0.55	0.54	0.55	-0.08	-0.09	-0.07	3039.00	1.54	-16.12	34.09	lsz_4374_2cp_eku_34n344	5611.59
0.59	0.58	0.60	-0.10	-0.12	-0.08	3282.00	1.89	16.84	34.09	lsz_2609_2cp_eku_32n017	21007.18
0.56	0.55	0.57	-0.20	-0.23	-0.18	3291.00	1.61	15.89	33.96	lsz_2083_2cp_eku_26n016	7718.04
0.49	0.48	0.49	-0.01	-0.02	0.00	3360.00	1.56	33.18	11.29	lsz_2067_2cp_eku_09n033	19150.23
0.51	0.50	0.52	-0.04	-0.06	-0.03	3787.00	1.78	25.28	37.25	lsz_1726_2cp_eku_35n025	25270.03
0.68	0.67	0.69	-0.29	-0.31	-0.27	3855.00	1.54	25.05	37.69	lsz_1726_2cp_eku_35n025	13839.37
0.52	0.51	0.52	-0.12	-0.13	-0.11	4011.00	1.64	23.09	39.98	lsz_1728_2cp_eku_33n023	24878.60
0.84	0.83	0.84	-0.39	-0.40	-0.38	4114.00	1.76	-70.15	30.77	lsz_2692_2cp_eku_30n290	2660.43
0.75	0.74	0.76	-0.35	-0.36	-0.33	4208.00	1.78	-71.36	32.96	lsz_3041_2cp_eku_32n289	6129.98
0.77	0.76	0.77	-0.05	-0.06	-0.05	4211.00	1.83	-70.13	32.50	lsz_2692_2cp_eku_30n290	43.54
0.41	0.40	0.41	-0.37	-0.38	-0.35	4318.00	1.71	-71.56	36.63	lsz_3041_2cp_eku_32n289	138.10
0.78	0.77	0.79	-0.42	-0.44	-0.41	4327.00	1.73	-68.76	36.17	lsz_1818_2cp_eku_36n291	9159.04
0.77	0.77	0.78	-0.05	-0.06	-0.04	4546.00	1.86	-69.02	38.71	lsz_1818_2cp_eku_36n291	14.30
0.66	0.64	0.68	-0.43	-0.46	-0.39	4692.00	1.59	-61.28	42.92	lsz_1463_2cp_eku_44n298	17919.28
0.92	0.91	0.93	-0.29	-0.29	-0.28	4698.00	1.79	-68.02	43.01	lsz_1817_2cp_eku_39n292	14.73
0.75	0.74	0.76	-0.32	-0.34	-0.31	4705.00	1.97	-68.11	43.94	lsz_1817_2cp_eku_39n292	11163.29
0.60	0.60	0.61	-0.30	-0.31	-0.29	4726.00	1.60	-73.49	47.44	lsz_4956_2cp_eku_50n287	21415.22
0.60	0.58	0.61	-0.18	-0.20	-0.15	4751.00	1.91	-73.31	46.86	lsz_4956_2cp_eku_50n287	23671.23
0.89	0.88	0.90	-0.69	-0.71	-0.67	4928.00	1.71	-58.18	44.57	lsz_1807_2cp_eku_47n302	6972.39
0.76	0.74	0.78	-0.56	-0.59	-0.52	5024.00	1.59	-57.81	47.58	lsz_1807_2cp_eku_47n302	16403.70
0.41	0.41	0.42	-0.06	-0.07	-0.05	5114.00	1.72	-8.81	-16.57	lsz_6627_2cp_eku_23s351	18128.22
0.37	0.36	0.37	0.01	0.00	0.01	5157.00	1.69	-9.03	-20.36	lsz_6627_2cp_eku_23s351	26203.48
0.43	0.43	0.44	0.03	0.02	0.04	5158.00	1.53	-8.44	-20.53	lsz_2632_2cp_eku_20s352	22553.04
0.53	0.52	0.53	-0.03	-0.04	-0.02	5170.00	1.84	-9.35	-21.67	lsz_2633_2cp_eku_16s351	21228.60
0.54	0.54	0.54	-0.10	-0.10	-0.09	5176.00	1.52	-9.42	-23.25	lsz_2633_2cp_eku_16s351	8918.34
0.51	0.51	0.52	-0.48	-0.49	-0.47	5177.00	1.97	-9.14	-23.07	lsz_6627_2cp_eku_23s351	21151.73
0.42	0.41	0.42	0.03	0.02	0.04	5215.00	1.51	-8.47	-20.26	lsz_2632_2cp_eku_20s352	21556.56
0.47	0.47	0.47	0.07	0.06	0.08	5217.00	1.80	-9.40	-20.13	lsz_2633_2cp_eku_16s351	35778.51
0.48	0.47	0.48	-0.02	-0.04	-0.01	5297.00	1.68	-15.39	-19.82	lsz_1766_2cp_eku_15s345	9585.13
0.57	0.56	0.58	-0.12	-0.13	-0.10	5321.00	1.53	-15.53	-26.29	lsz_1766_2cp_eku_31s344	11971.16
0.46	0.46	0.46	-0.07	-0.08	-0.06	5444.00	1.88	-8.35	-23.70	lsz_2632_2cp_eku_20s352	16374.04
0.46	0.46	0.47	-0.04	-0.05	-0.03	5538.00	759.00	-7.72	-22.44	lsz_2106_2cp_eku_25s352	5815.47
0.38	0.37	0.38	-0.02	-0.03	-0.02	5555.00	1.88	-8.92	-25.63	lsz_6627_2cp_eku_23s351	35653.99
0.42	0.41	0.42	-0.19	-0.21	-0.18	5606.00	1.61	-9.50	-26.76	lsz_2633_2cp_eku_32s351	35145.00
0.40	0.40	0.41	-0.09	-0.10	-0.08	5616.00	1.61	-9.47	-26.29	lsz_2633_2cp_eku_32s351	32983.41
0.41	0.41	0.42	0.03	0.01	0.04	5629.00	1.55	-8.83	-24.18	lsz_6627_2cp_eku_23s351	17658.36
0.67	0.67	0.68	-0.25	-0.26	-0.24	5715.00	1.90	-16.26	40.72	lsz_4374_2cp_eku_34n344	6982.00
0.67	0.65	0.68	-0.29	-0.32	-0.26	5915.00	1.55	-8.02	39.25	lsz_1411_2cp_eku_38n352	9470.61
0.70	0.69	0.70	-0.46	-0.47	-0.44	6093.00	1.51	10.18	22.30	lsz_1741_2cp_eku_20n010	14475.14
0.80	0.79	0.81	-0.28	-0.29	-0.27	6255.00	1.60	10.91	34.75	lsz_1740_2cp_eku_36n011	3573.90
0.53	0.52	0.54	-0.19	-0.22	-0.17	6261.00	1.54	11.79	34.08	lsz_4348_2cp_eku_40n011	8320.27
0.55	0.55	0.56	-0.20	-0.21	-0.18	6262.00	1.89	11.87	33.21	lsz_4348_2cp_eku_40n011	19126.67
0.52	0.51	0.52	-0.05	-0.06	-0.03	7216.00	1.78	4.10	15.85	lsz_2095_2cp_eku_17n004	12352.65
0.44	0.44	0.45	-0.06	-0.07	-0.05	7560.00	1.56	-71.18	53.11	lsz_4426_2cp_eku_50n289	37297.90
0.49	0.48	0.50	-0.27	-0.29	-0.25	7572.00	1.58	-72.54	53.27	lsz_4956_2cp_eku_50n287	29507.17
0.44	0.44	0.44	-0.03	-0.04	-0.02	7591.00	1.72	-71.28	53.72	lsz_4426_2cp_eku_50n289	25462.12
0.53	0.52	0.54	-0.35	-0.36	-0.33	7617.00	1.55	-72.62	52.87	lsz_4956_2cp_eku_50n287	20558.97
0.56	0.55	0.57	-0.30	-0.31	-0.29	7660.00	1.82	-71.31	51.31	lsz_4426_2cp_eku_50n289	4256.89
0.48	0.47	0.48	-0.47	-0.48	-0.46	7677.00	1.72	-70.77	51.97	lsz_4426_2cp_eku_50n289	35937.78
0.61	0.61	0.62	-0.18	-0.19	-0.17	7916.00	1.52	55.80	22.01	lsz_1698_2cp_eku_26n055	29011.99
0.56	0.55	0.56	-0.12	-0.14	-0.11	8009.00	1.70	55.66	12.33	lsz_1698_2cp_eku_10n056	16955.41
0.63	0.63	0.64	-0.26	-0.28	-0.24	8242.00	1.74	61.88	14.57	lsz_6560_2cp_eku_17n062	3411.60
0.56	0.55	0.57	-0.15	-0.17	-0.13	8318.00	1.84	58.39	20.58	lsz_2043_2cp_eku_19n058	8584.95
0.80	0.79	0.80	-0.50	-0.50	-0.49	8599.00	1.97	-31.07	42.97	lsz_4388_2cp_eku_50n329	94.63
0.63	0.62	0.64	-0.23	-0.25	-0.22	8694.00	1.61	-20.33	36.04	lsz_2992_2cp_eku_32n340	814.27
0.60	0.59	0.60	-0.14	-0.15	-0.13	9520.00	1.72	-30.72	44.97	lsz_4388_2cp_eku_50n329	11662.13
0.56	0.55	0.56	-0.13	-0.15	-0.12	9531.00	1.55	-34.60	42.17	lsz_1437_2cp_eku_42n325	14224.45
0.53	0.53	0.54	-0.12	-0.13	-0.11	9730.00	1.52	-57.42	20.51	lsz_1807_2cp_eku_15n303	1704.97
0.57	0.57	0.58	-0.20	-0.21	-0.19	9799.00	1.63	-58.81	16.57	lsz_1461_2cp_eku_16n301	880.93
0.51	0.50	0.51	-0.39	-0.41	-0.38	10018.00	1.70	13.27	20.66	lsz_3307_2cp_eku_22n014	1645.70
0.83	0.82	0.84	-0.44	-0.45	-0.42	10099.00	1.56	16.07	21.21	lsz_2083_2cp_eku_26n016	8763.57
0.70	0.69	0.71	-0.19	-0.20	-0.18	10117.00	1.66	16.24	20.58	lsz_2083_2cp_eku_26n016	204.85
0.84	0.84	0.85	-0.48	-0.49	-0.46	10200.00	1.54	19.64	31.93	lsz_5904_2cp_eku_37n020	16252.02
0.60	0.59	0.61	-0.30	-0.32	-0.28	10393.00	1.53	22.03	23.23	lsz_2951_2cp_eku_16n022	11316.33
0.66	0.65	0.66	-0.27	-0.28	-0.26	10394.00	1.61	22.21	23.16	lsz_2951_2cp_eku_16n022	10881.94
0.51	0.50	0.52	-0.17	-0.19	-0.16	11111.00	1.71	88.53	14.64	lsz_6534_2cp_eku_10n088	15802.15
0.53	0.52	0.54	-0.07	-0.09	-0.06	11288.00	1.61	83.76	16.80	lsz_1671_2cp_eku_16n084	10102.88
0.52	0.51	0.52	0.00	-0.01	0.01	12263.00	1.65	-96.85	-20.81	lsz_1843_2cp_eku_22s263	20939.78
0.99	0.98	1.00	-0.54	-0.56	-0.52	12342.00	1.50	88.17	-1.19	lsz_6534_2cp_eku_10n088	3959.15
0.67	0.66	0.68	-0.25	-0.26	-0.23	12447.00	1.83	60.53	17.76	lsz_2041_2cp_eku_20n060	7546.36
0.53	0.52	0.54	-0.65	-0.67	-0.63	12706.00	1.67	30.11	20.75	lsz_2070_2cp_eku_19n030	5465.91
0.36	0.36	0.37	-0.02	-0.03	-0.01	12707.00	1.54	30.00	21.22	lsz_2070_2cp_eku_19n030	14559.79
0.45	0.44	0.45	-0.06	-0.08	-0.05	12872.00	1.63	24.32	1.84	lsz_1728_2cp_eku_01n024	24096.36
0.59	0.58	0.60	-0.51	-0.53	-0.50	12902.00	1.63	23.16	-0.30	lsz_1729_2cp_eku_02n023	20229.44
0.75	0.75	0.76	-0.33	-0.35	-0.32	13000.00	1.97	29.57	56.93	lsz_6589_2cp_eku_58n029	7659.46
0.52	0.51	0.52	-0.11	-0.13	-0.10	13036.00	1.72	-68.76	-6.06	lsz_1817_2cp_eku_13s291	4579.52
0.56	0.55	0.57	-0.28	-0.30	-0.26	13092.00	1.54	18.18	27.15	lsz_2081_2cp_eku_22n018	13128.30
0.54	0.53	0.55	-0.18	-0.19	-0.16	13111.00	1.74	18.19	27.48	lsz_2081_2cp_eku_22n018	12516.12
0.64	0.63	0.64	-0.34	-0.35	-0.32	13173.00	1.71	19.86	29.27	lsz_5904_2cp_eku_37n020	6423.02
0.68	0.67	0.70	-0.43	-0.45	-0.41	13190.00	1.74	19.87	27.80	lsz_5904_2cp_eku_37n020	11099.76
0.54	0.53	0.55	-0.42	-0.44	-0.40	13349.00	1.53	33.43	9.16	lsz_2067_2cp_eku_09n033	7105.27
0.54	0.54	0.55	-0.12	-0.13	-0.10	13496.00					

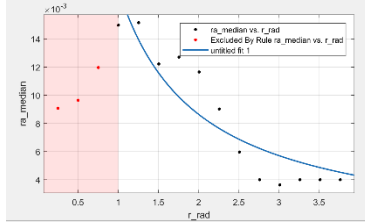
0.02	0.01	0.02	-1.02	-1.37	-0.68	207.00	1.88	-63.63	46.76	16239.66
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0.03	0.02	0.04	-2.09	-2.82	-1.35	530.00	1.62	-59.09	30.93	1376.56
0.10	0.06	0.15	-3.84	-5.20	-2.49	537.00	1.93	-58.76	29.11	1767.80
0.03	0.02	0.04	-2.36	-3.01	-1.70	985.00	1.57	16.37	29.98	11360.95
0.17	0.17	0.18	-1.90	-2.01	-1.80	1010.00	1.74	55.79	-1.30	4100.35
0.03	0.03	0.04	-1.86	-2.32	-1.41	1013.00	1.81	55.90	-1.42	20093.58
0.02	0.01	0.02	-1.39	-1.95	-0.83	1027.00	1.51	56.20	1.28	22023.49
0.03	0.02	0.03	-1.49	-1.85	-1.13	1028.00	1.68	56.46	0.92	25153.70
0.01	0.01	0.01	-0.30	-0.48	-0.12	1071.00	1.67	56.22	0.58	21278.70
0.24	0.22	0.26	-4.50	-5.21	-3.78	1156.00	1.86	-48.51	12.03	28.47
0.03	0.02	0.04	-1.94	-2.57	-1.31	1287.00	1.66	-45.34	1.77	11106.60
0.06	0.06	0.07	-2.84	-3.35	-2.33	1632.00	1.70	-11.57	-15.86	9521.48
0.08	0.07	0.09	-3.47	-4.02	-2.92	1655.00	1.73	-11.21	-11.82	3968.92
0.00	0.00	0.00	-0.13	-0.33	0.08	1771.00	1.75	-10.39	-10.67	10001.47
0.02	0.01	0.02	-1.47	-1.75	-1.19	1793.00	1.53	-10.58	-8.75	12757.61
0.04	0.01	0.06	-2.96	-4.90	-1.02	1916.00	1.54	-28.48	32.49	11424.34
0.00	0.00	0.00	0.07	0.02	0.11	2213.00	1.85	-74.73	26.88	45764.46
0.01	0.00	0.01	-0.27	-0.37	-0.17	2298.00	1.67	-74.64	24.73	21584.28
0.04	0.03	0.05	-2.60	-3.21	-1.99	2740.00	1.61	26.62	29.15	12414.98
0.03	0.02	0.03	-2.37	-2.93	-1.80	2763.00	1.89	27.23	28.16	19571.69
0.09	0.06	0.12	-3.89	-4.97	-2.81	2780.00	1.99	27.78	21.89	20665.41
0.06	0.05	0.07	-3.13	-3.53	-2.73	3039.00	1.54	-16.12	34.09	5611.59
0.14	0.13	0.16	-3.15	-3.48	-2.81	3125.00	1.57	-9.40	35.86	83.29
0.04	0.03	0.04	-2.48	-2.85	-2.11	3282.00	1.89	16.84	34.09	21007.18
0.03	0.03	0.04	-2.34	-2.64	-2.04	3291.00	1.61	15.89	33.96	7718.04
0.07	0.05	0.09	-3.33	-4.31	-2.35	3360.00	1.56	33.18	11.29	19150.23
0.01	0.01	0.01	-1.21	-1.51	-0.91	3787.00	1.78	25.28	37.25	25270.03
0.04	0.03	0.05	-2.29	-2.91	-1.66	3813.00	1.97	29.56	37.17	19332.39
0.04	0.04	0.05	-2.66	-3.08	-2.24	3855.00	1.54	25.05	37.69	13839.37
0.01	0.01	0.01	-1.35	-1.57	-1.12	4011.00	1.64	23.09	39.98	24878.60
0.05	0.04	0.05	-1.95	-2.24	-1.66	4114.00	1.76	-70.15	30.77	2660.43
0.05	0.05	0.06	-3.23	-3.76	-2.70	4208.00	1.78	-71.36	32.96	6129.98
0.08	0.08	0.09	-1.04	-1.13	-0.96	4211.00	1.83	-70.13	32.50	43.54
0.08	0.07	0.08	-2.32	-2.57	-2.07	4318.00	1.71	-71.56	36.63	138.10
0.07	0.07	0.08	-2.59	-2.98	-2.20	4327.00	1.73	-68.76	36.17	9159.04
0.13	0.12	0.14	-2.16	-2.42	-1.90	4546.00	1.86	-69.02	38.71	14.30
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0.01	0.01	0.02	-1.10	-1.44	-0.76	4751.00	1.91	-73.31	46.86	23671.23
0.14	0.11	0.18	-2.64	-3.43	-1.85	4928.00	1.71	-58.18	44.57	6972.39
0.09	0.07	0.11	-2.33	-2.92	-1.74	5024.00	1.59	-57.81	47.58	16403.70
0.01	0.01	0.02	-1.10	-1.44	-0.76	5114.00	1.72	-8.81	-16.57	18128.22
0.01	0.01	0.01	-1.10	-1.64	-0.57	5157.00	1.69	-9.03	-20.36	26203.48
0.01	0.01	0.01	-0.62	-0.95	-0.29	5158.00	1.53	-8.44	-20.53	22553.04
0.01	0.00	0.01	-0.62	-0.88	-0.35	5170.00	1.84	-9.35	-21.67	21228.60
0.03	0.02	0.04	-2.13	-2.58	-1.69	5176.00	1.52	-9.42	-23.25	8918.34
0.02	0.02	0.02	-2.40	-2.83	-1.97	5177.00	1.97	-9.14	-23.07	21151.73
0.01	0.01	0.01	-0.43	-0.62	-0.23	5215.00	1.51	-8.47	-20.26	21556.56
0.01	0.01	0.01	-1.12	-1.42	-0.82	5217.00	1.80	-9.40	-20.13	35778.51
0.14	0.12	0.16	-4.21	-4.89	-3.52	5297.00	1.68	-15.39	-19.82	9585.13
0.15	0.12	0.17	-3.68	-4.23	-3.13	5321.00	1.53	-15.53	-26.29	11971.16
0.03	0.03	0.03	-2.59	-2.90	-2.28	5444.00	1.88	-8.35	-23.70	16374.04
0.01	0.01	0.01	-0.95	-1.35	-0.55	5555.00	1.88	-8.92	-25.63	35653.99
0.01	0.01	0.01	-1.33	-1.67	-0.99	5606.00	1.61	-9.50	-26.76	35145.00
0.02	0.02	0.03	-2.11	-2.70	-1.53	5616.00	1.61	-9.47	-26.29	32983.41
0.01	0.01	0.01	-0.94	-1.08	-0.81	5629.00	1.55	-8.83	-24.18	17658.36
0.19	0.17	0.21	-3.66	-4.02	-3.31	5715.00	1.90	-16.26	40.72	6982.00
0.06	0.05	0.07	-2.96	-3.41	-2.52	5915.00	1.55	-8.02	39.25	9470.61
0.07	0.06	0.08	-3.87	-4.48	-3.26	6047.00	1.90	-9.71	40.71	8015.34
0.01	0.01	0.02	-1.68	-1.85	-1.50	6064.00	1.56	-10.62	42.68	11177.71
0.02	0.01	0.02	-1.66	-2.08	-1.23	6093.00	1.51	10.18	22.30	14475.14
0.08	0.07	0.09	-2.55	-2.91	-2.19	6255.00	1.60	10.91	34.75	3573.90
0.04	0.03	0.04	-2.63	-3.27	-2.00	6261.00	1.54	11.79	34.08	8320.27
0.04	0.04	0.05	-2.35	-2.83	-1.88	6262.00	1.89	11.87	33.21	19126.67
0.07	0.05	0.08	-3.37	-4.23	-2.51	7216.00	1.78	4.10	15.85	12352.65
0.02	0.01	0.02	-1.27	-1.78	-0.77	7560.00	1.56	-71.18	53.11	37297.90
0.00	0.00	0.00	-0.34	-0.43	-0.25	7572.00	1.58	-72.54	53.27	29507.17
0.04	0.03	0.05	-1.66	-2.26	-1.07	7591.00	1.72	-71.28	53.72	25462.12
0.07	0.06	0.08	-2.75	-3.19	-2.32	7617.00	1.55	-72.62	52.87	20558.97
0.07	0.06	0.09	-1.95	-2.50	-1.41	7660.00	1.82	-71.31	51.31	4256.89
0.01	0.01	0.01	-0.92	-1.13	-0.71	7677.00	1.72	-70.77	51.97	35937.78
0.01	0.01	0.01	-0.41	-0.70	-0.12	7916.00	1.52	55.80	22.01	29011.99
0.03	0.02	0.04	-2.40	-3.24	-1.57	8009.00	1.70	55.66	12.33	16955.41
0.06	0.05	0.07	-2.87	-3.51	-2.24	8242.00	1.74	61.88	14.57	3411.60
0.01	0.01	0.01	-0.78	-1.01	-0.54	8318.00	1.84	58.39	20.58	8584.95
0.09	0.08	0.10	-2.78	-3.05	-2.52	8599.00	1.97	-31.07	42.97	94.63
0.09	0.08	0.10	-2.87	-3.30	-2.45	8694.00	1.61	-20.33	36.04	814.27
0.16	0.10	0.23	-2.91	-3.96	-1.86	8954.00	1.52	35.75	37.35	9747.86
0.03	0.02	0.04	-1.97	-2.49	-1.44	9520.00	1.72	-30.72	44.97	11662.13
0.02	0.01	0.02	-1.63	-2.02	-1.23	9531.00	1.55	-34.60	42.17	14224.45
0.05	0.03	0.07	-2.85	-3.90	-1.80	9730.00	1.52	-57.42	20.51	1704.97
0.08	0.05	0.12	-3.86	-5.50	-2.22	9799.00	1.63	-58.81	16.57	880.93
0.05	0.04	0.06	-2.46	-3.02	-1.90	9859.00	1.94	-57.54	23.38	3563.54
0.01	0.01	0.01	-1.49	-1.96	-1.02	10048.00	1.89	13.53	22.74	15055.52
0.05	0.04	0.06	-3.06	-3.06	-2.31	10099.00	1.56	16.07	21.21	8763.57
0.09	0.07	0.10	-3.24	-3.78	-2.69	10117.00	1.66	16.24	20.58	204.85
0.02	0.01	0.02	-1.29	-1.67	-0.91	10200.00	1.54	19.64	31.93	16252.02
0.02	0.02	0.03	-1.48	-2.11	-0.84	10249.00	1.61	28.04	21.26	18262.25

0.02	0.01	0.02	-0.88	-1.19	-0.56	10250.00	1.50	28.08	21.31	20575.76
0.07	0.06	0.09	-3.15	-3.67	-2.63	10393.00	1.53	22.03	23.23	11316.33
0.04	0.04	0.05	-2.64	-3.12	-2.17	10394.00	1.61	22.21	23.16	10881.94
0.01	0.01	0.01	-1.35	-1.57	-1.12	10488.00	1.63	23.86	18.98	12076.99
0.05	0.04	0.06	-2.25	-2.65	-1.85	10492.00	1.64	23.83	20.25	22673.17
0.01	0.01	0.02	-0.96	-1.33	-0.58	11111.00	1.71	88.53	14.64	15802.15
0.01	0.01	0.01	-0.37	-0.77	0.03	11288.00	1.61	83.76	16.80	10102.88
0.25	0.18	0.31	-2.31	-2.94	-1.68	12075.00	1.56	31.46	53.25	8383.11
0.12	0.10	0.14	-2.19	-2.74	-1.65	12295.00	1.78	-11.19	51.21	11516.03
0.06	0.04	0.08	-2.21	-2.91	-1.50	12342.00	1.50	88.17	-1.19	3959.15
0.02	0.02	0.03	-2.02	-2.71	-1.34	12706.00	1.67	30.11	20.75	5465.91
0.02	0.01	0.02	-1.51	-1.86	-1.16	12707.00	1.54	30.00	21.22	14559.79
0.02	0.01	0.03	-1.85	-2.54	-1.17	12872.00	1.63	24.32	1.84	24096.36
0.19	0.14	0.23	-2.08	-2.59	-1.57	13000.00	1.97	29.57	56.93	7659.46
0.02	0.01	0.03	-1.99	-3.08	-0.90	13164.00	1.63	18.17	29.98	16991.85
0.07	0.06	0.09	-3.96	-4.70	-3.21	13173.00	1.71	19.86	29.27	6423.02
0.05	0.05	0.06	-3.21	-3.66	-2.76	13190.00	1.74	19.87	27.80	11099.76
0.01	0.01	0.02	-1.23	-2.05	-0.41	13349.00	1.53	33.43	9.16	7105.27
0.13	0.11	0.16	-1.89	-2.35	-1.43	16275.00	1.90	29.78	56.52	9177.10
0.15	0.11	0.20	-2.43	-3.10	-1.76	20500.00	1.50	29.99	52.78	14232.19
0.06	0.04	0.09	-1.59	-2.22	-0.96	33975.00	1.53	29.82	55.91	25260.74
0.05	0.03	0.07	-1.62	-2.27	-0.98	36525.00	1.55	31.94	53.92	27333.74
0.03	0.03	0.04	-1.32	-1.62	-1.02	50175.00	1.63	29.83	56.38	34626.46

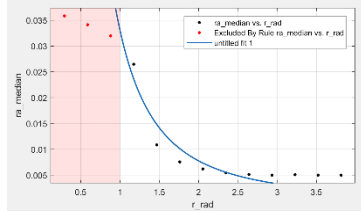
Appendix C: Individual radial median plots

All RA medians created in this thesis are listed below in order of increasing UniqCratID. The UniqCratID value at the top left corner of each plot can be references to **Table 2** in appendix b in order to find the fit coefficients and properties of each crater.

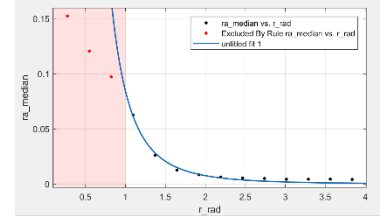
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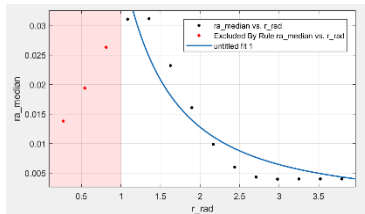
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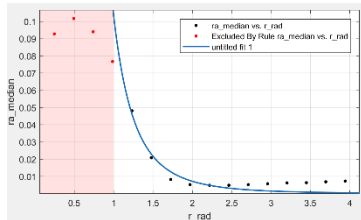
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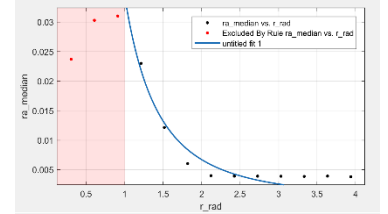
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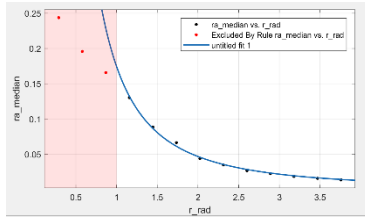
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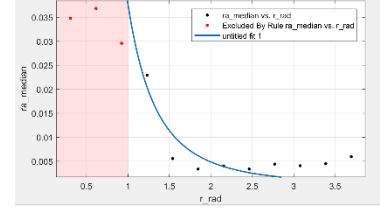
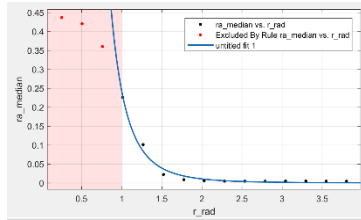
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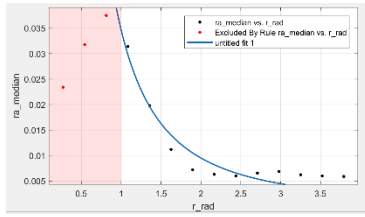


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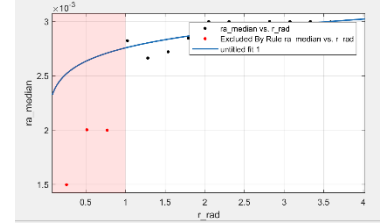
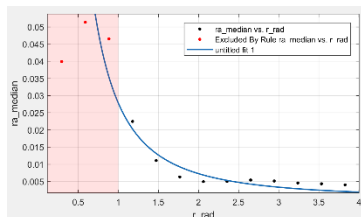


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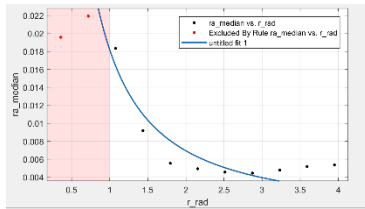


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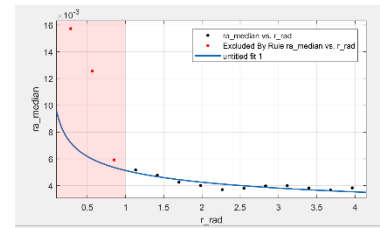
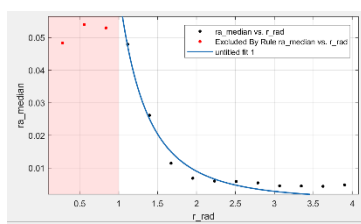


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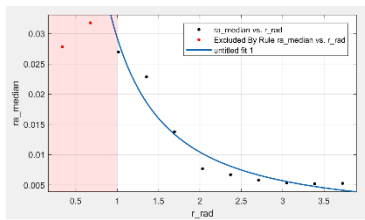


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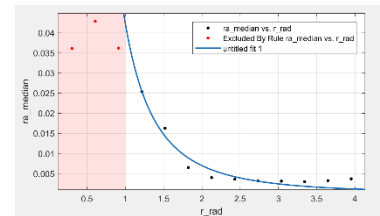
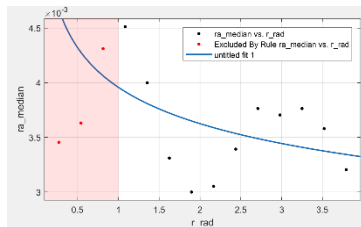


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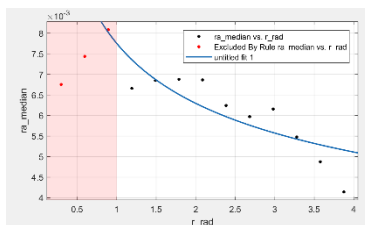


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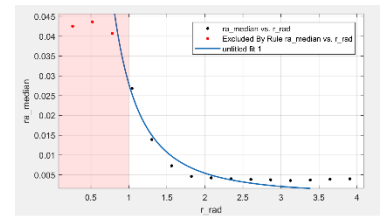
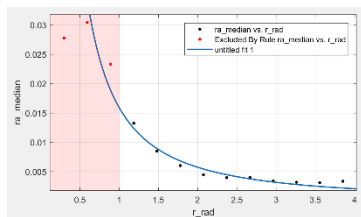


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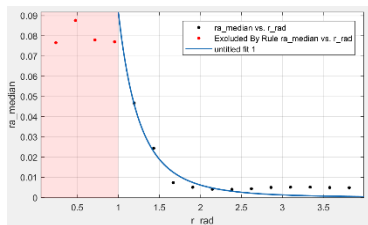


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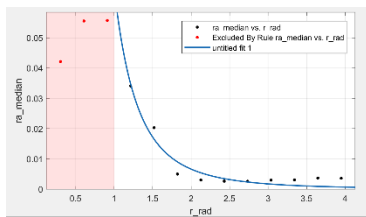


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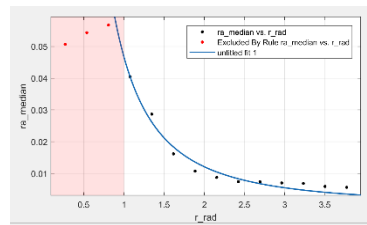
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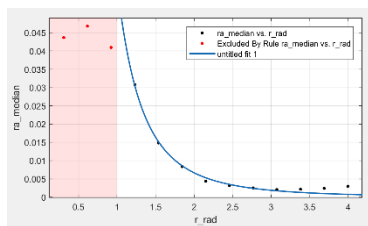
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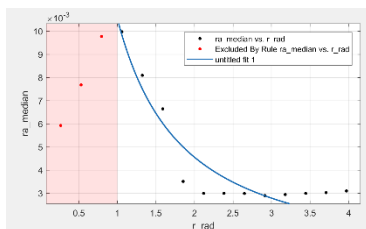
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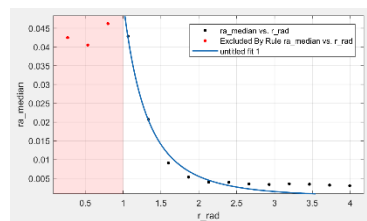
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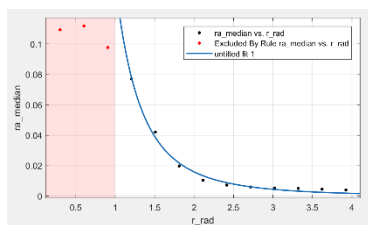
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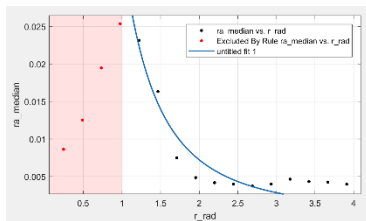
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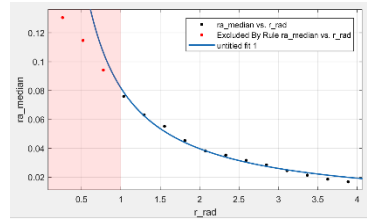
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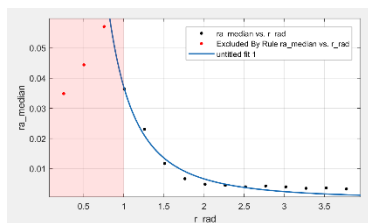
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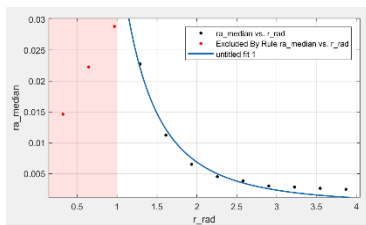
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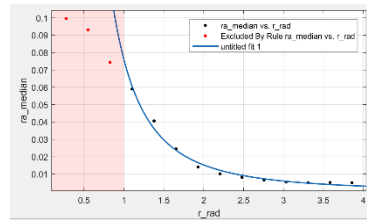
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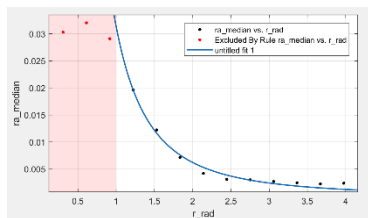
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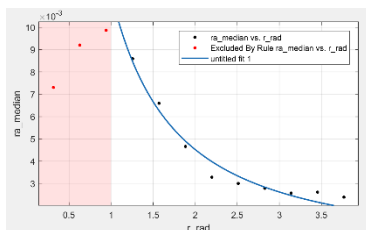
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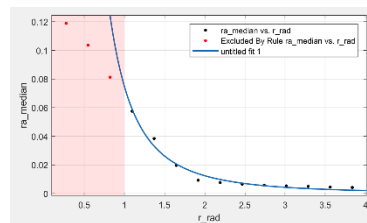
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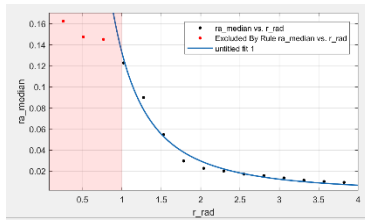
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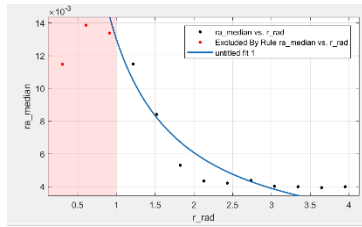
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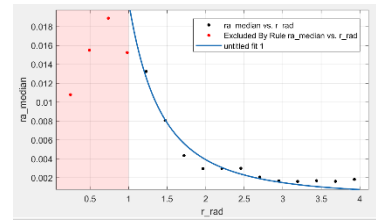
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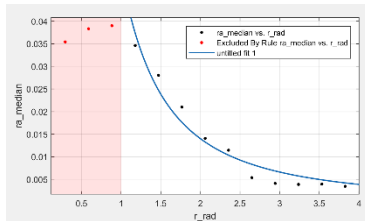
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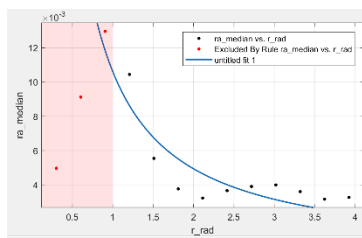
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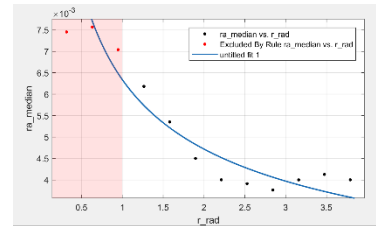
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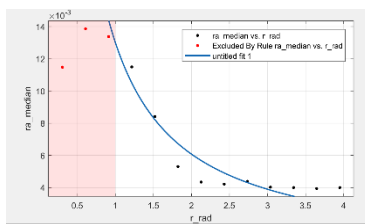
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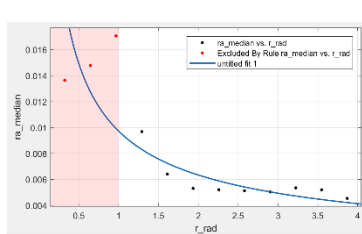
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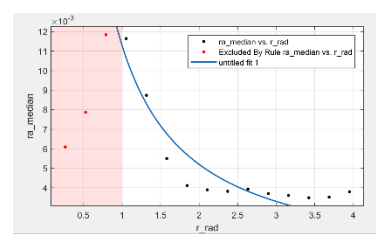
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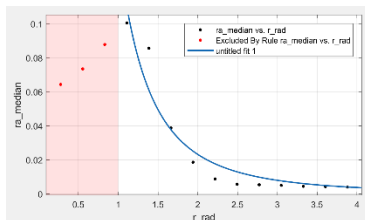
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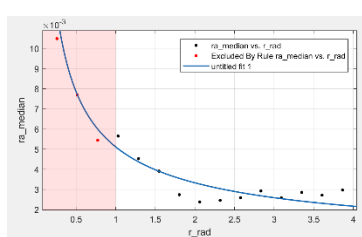
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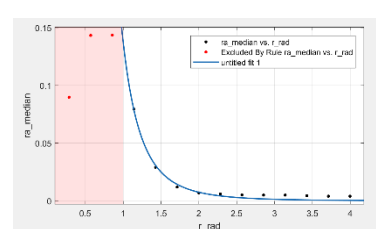
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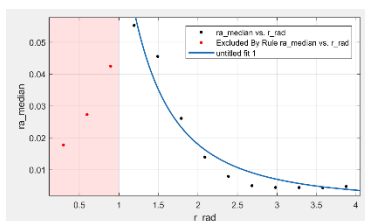
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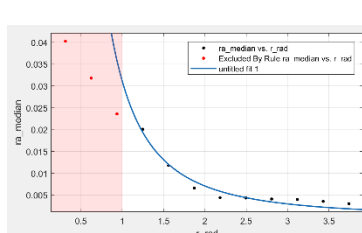
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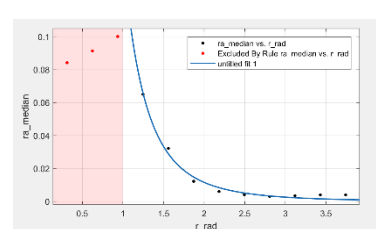
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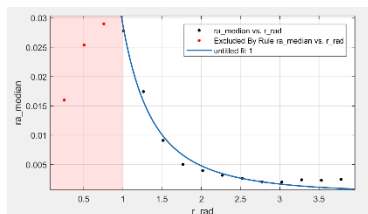
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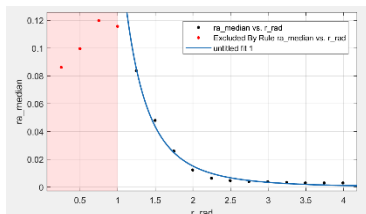
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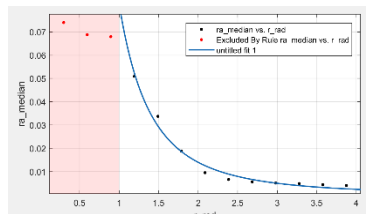
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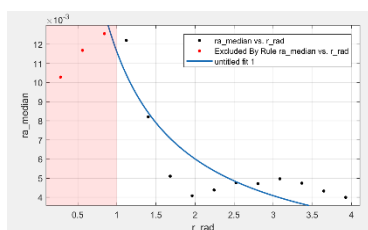
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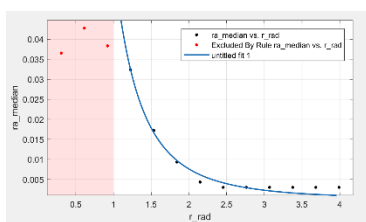
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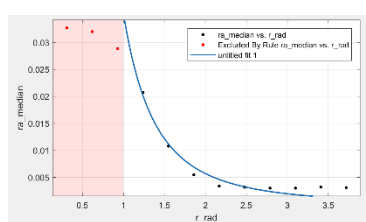
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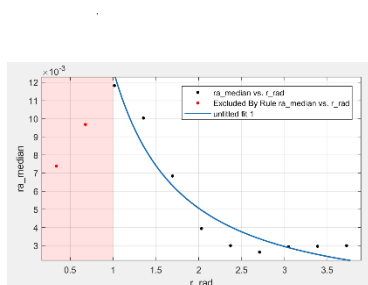
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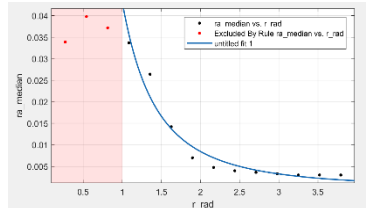
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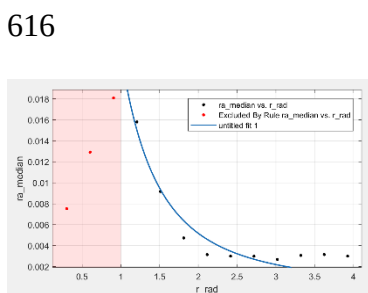
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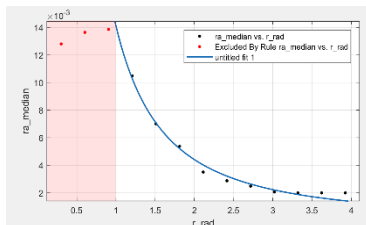
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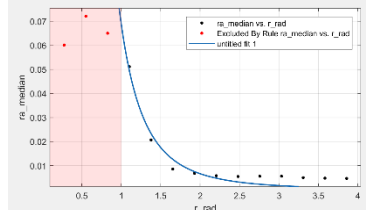
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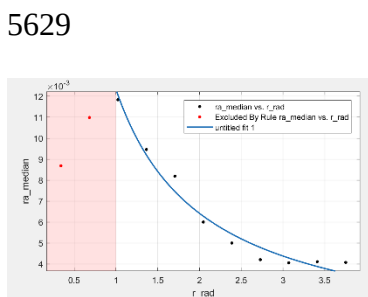
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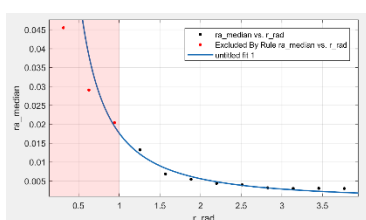
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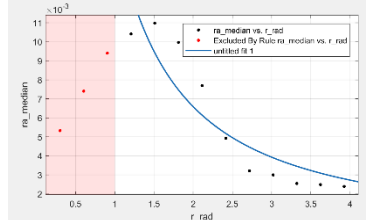
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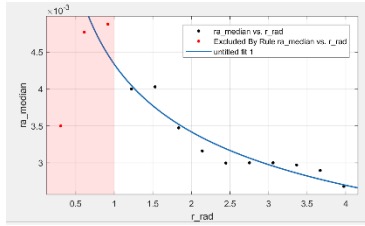


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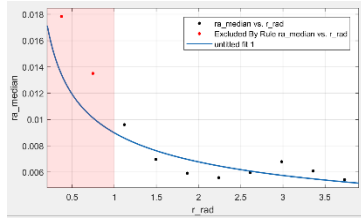


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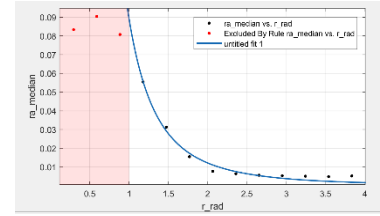
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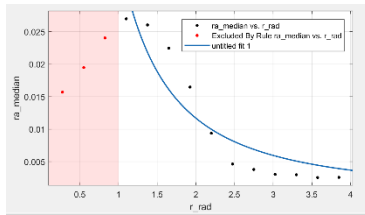
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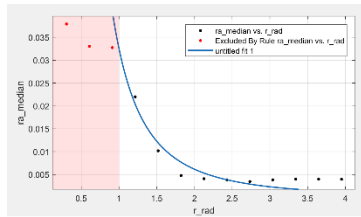
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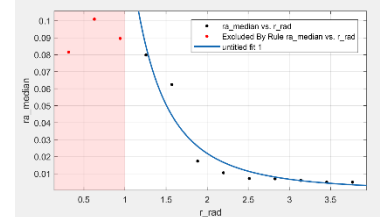
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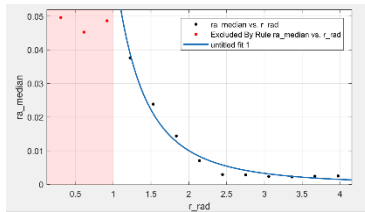
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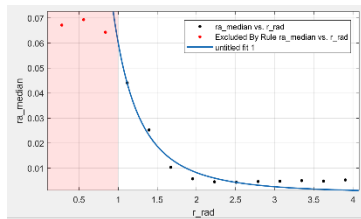
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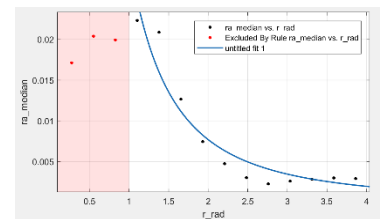
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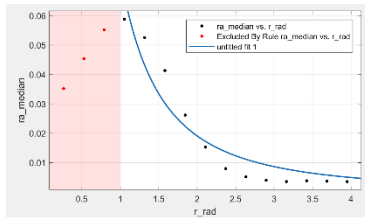
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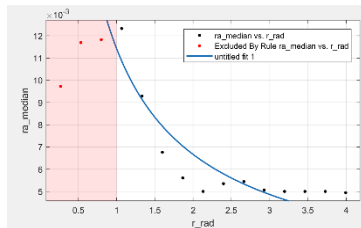
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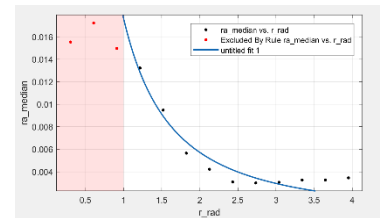
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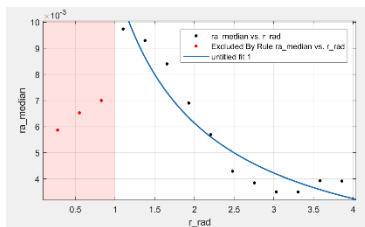
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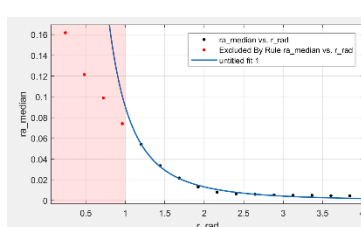
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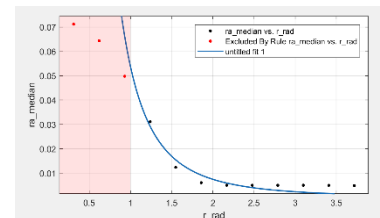
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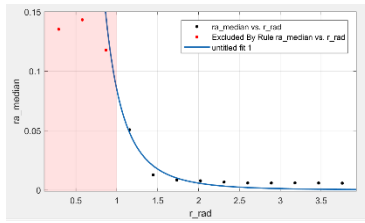
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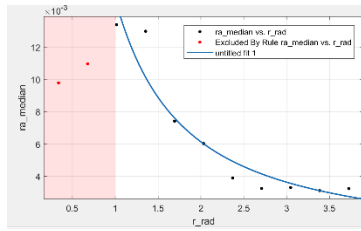
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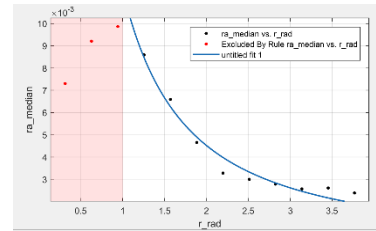
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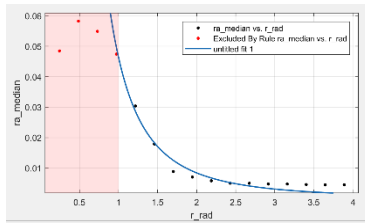
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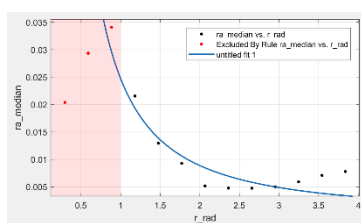
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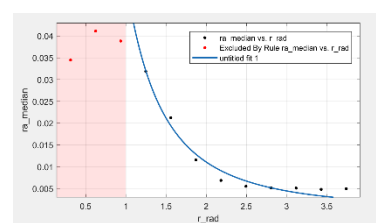
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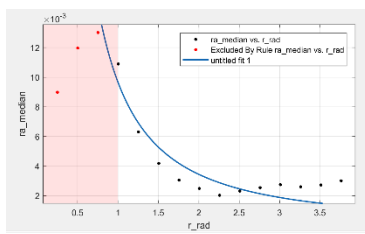
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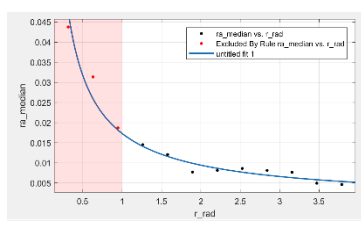
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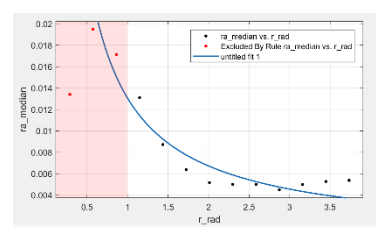
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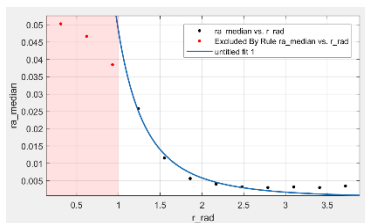
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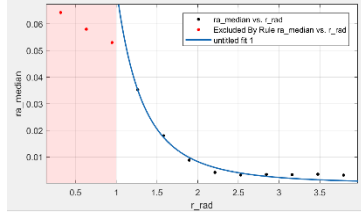
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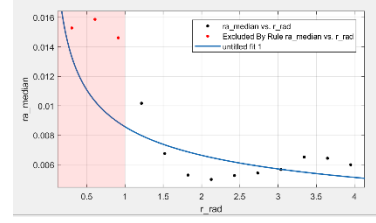
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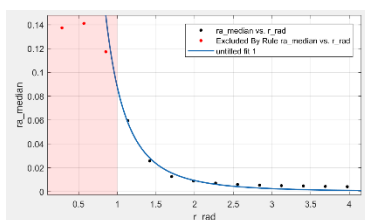
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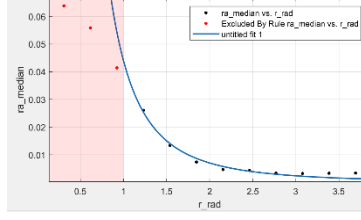
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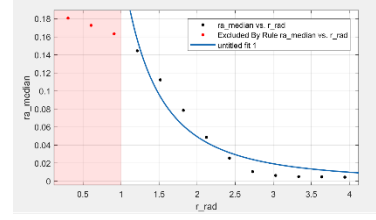
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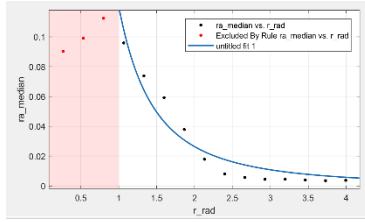
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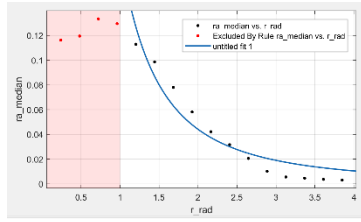
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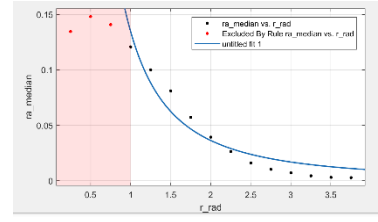
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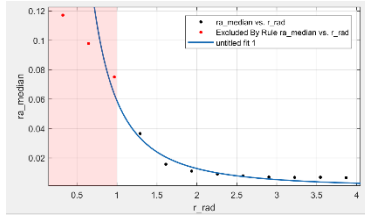
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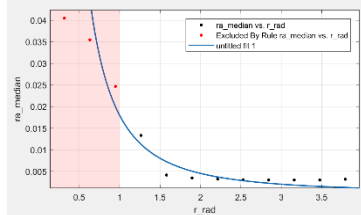
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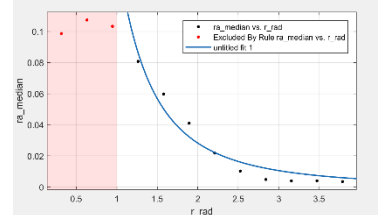
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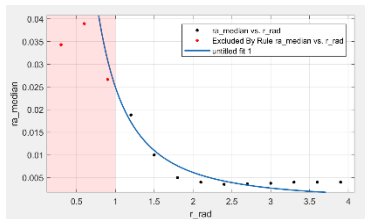
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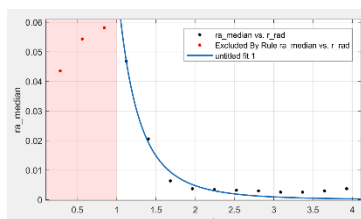
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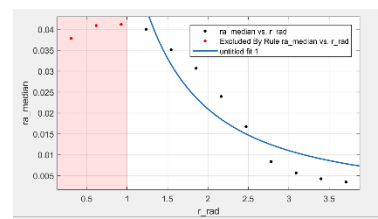
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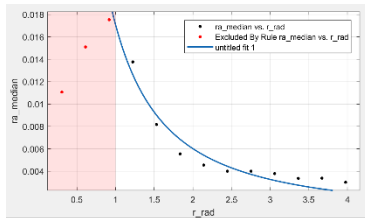
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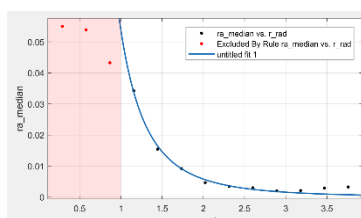
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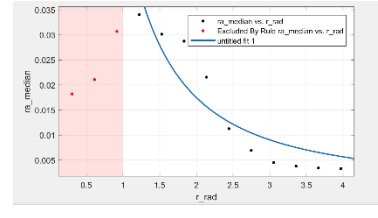
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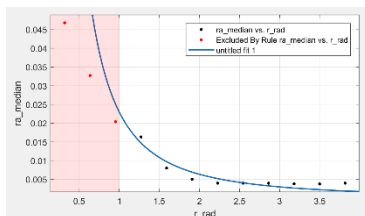
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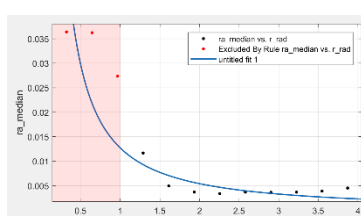
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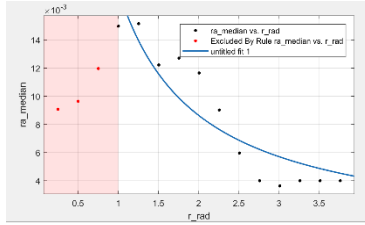
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All CPR medians created in this thesis are listed below in order of increasing UniqCratID.

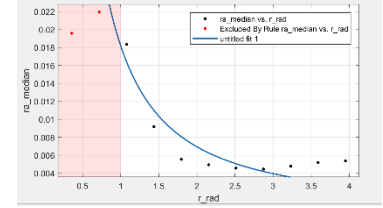
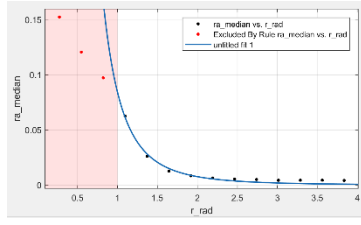
The UniqCratID value at the top left corner of each plot can be references to **Table 2** in appendix

b in order to find the fit coefficients and properties of each crater

207

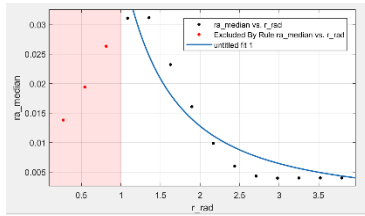


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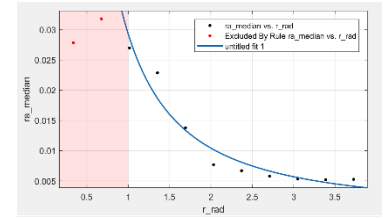
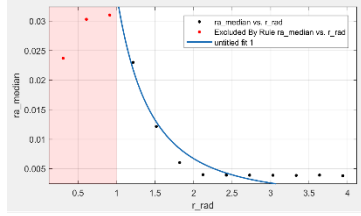


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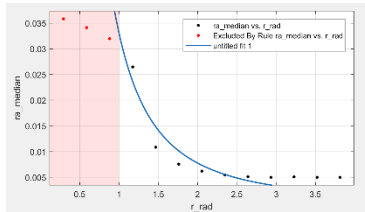


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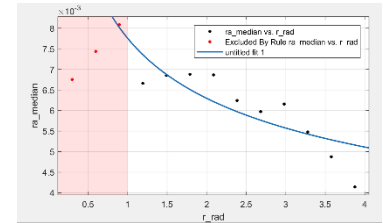
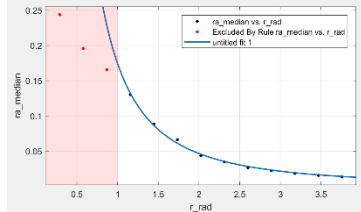


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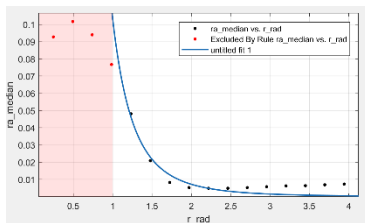


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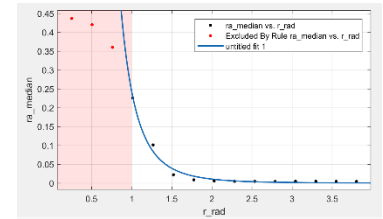
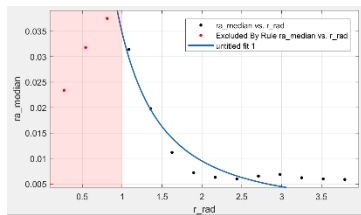


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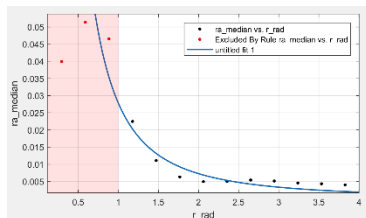


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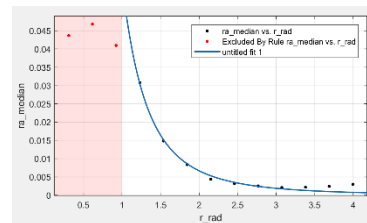
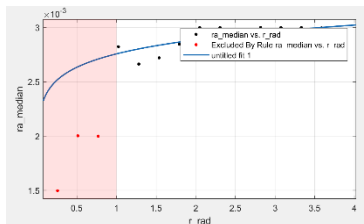


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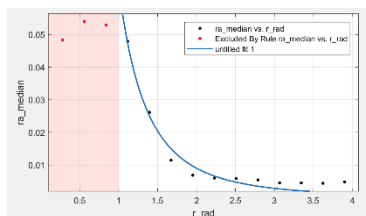


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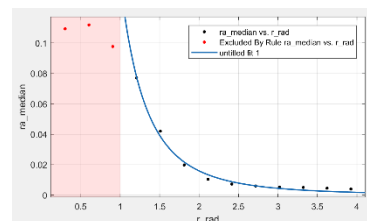
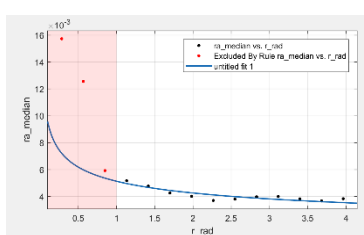


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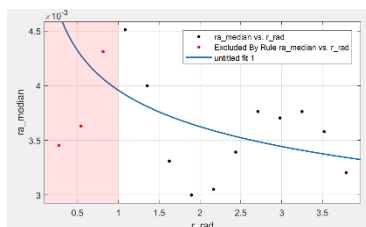


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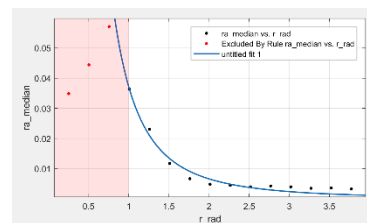
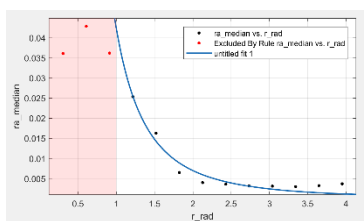


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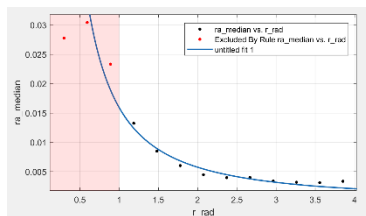


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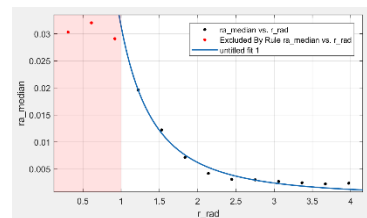
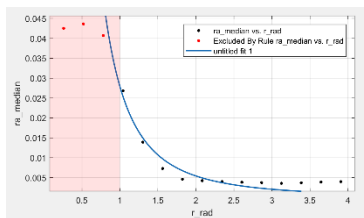


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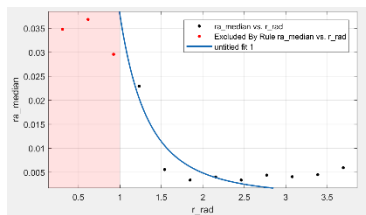


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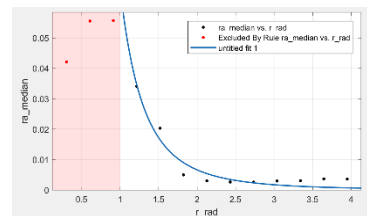
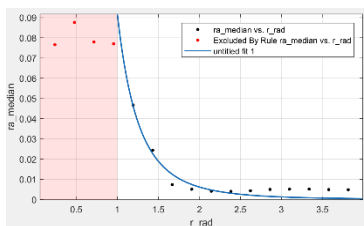


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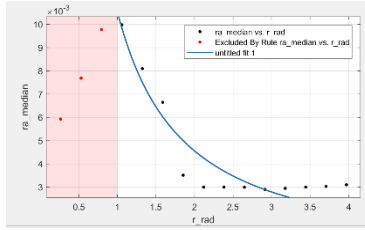


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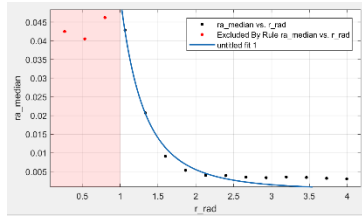


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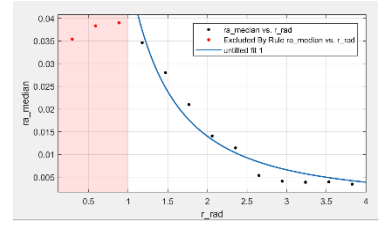
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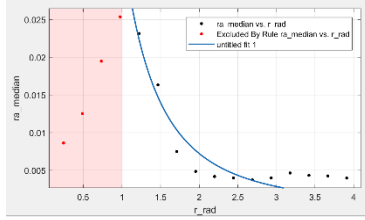
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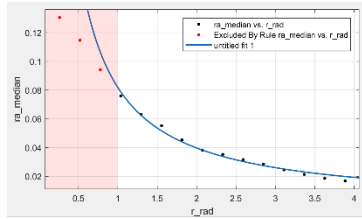
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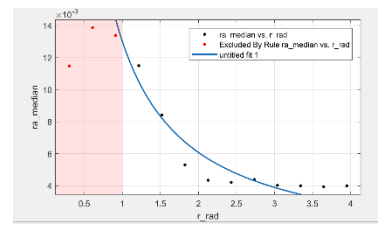
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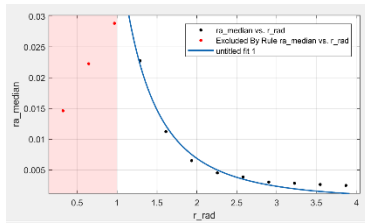
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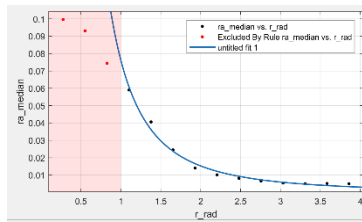
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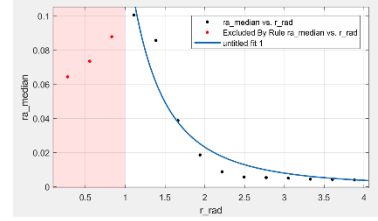
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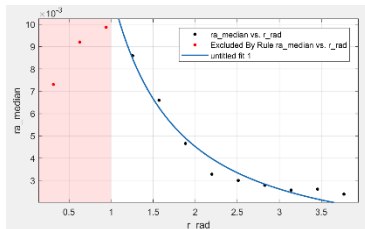
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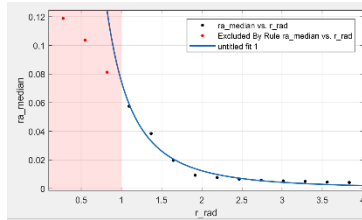
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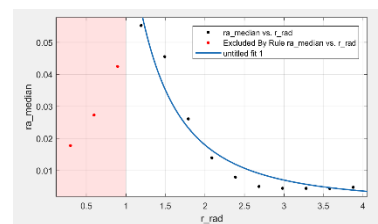
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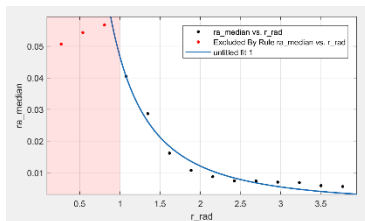
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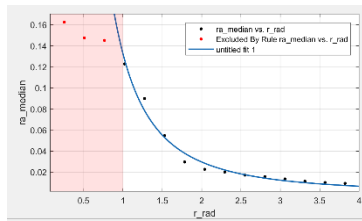
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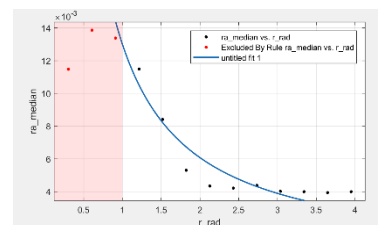
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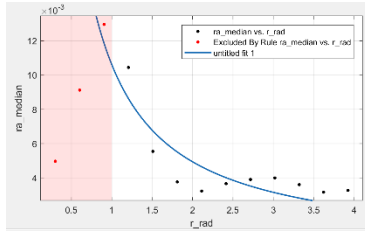
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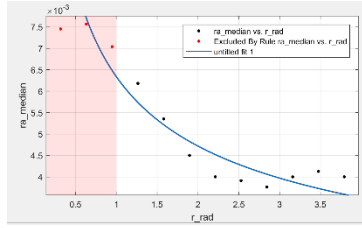
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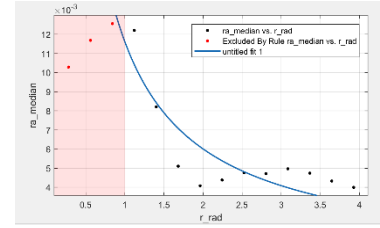
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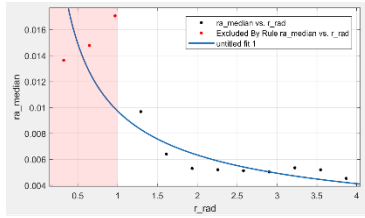
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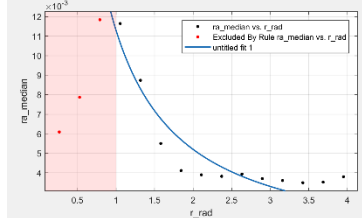
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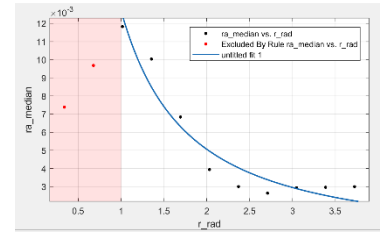
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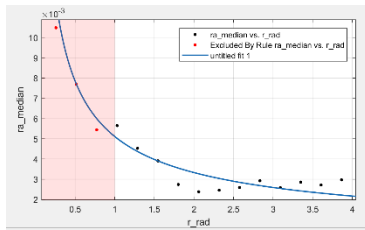
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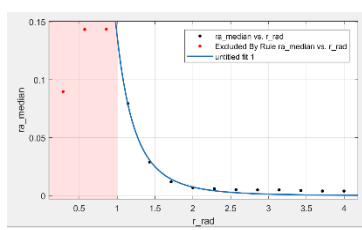
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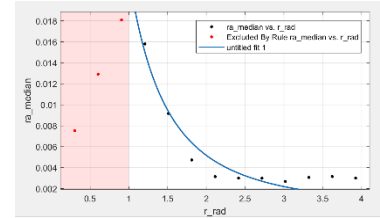
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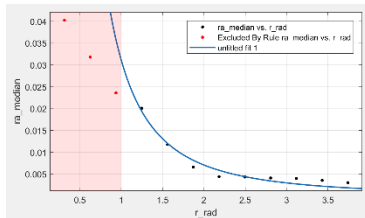
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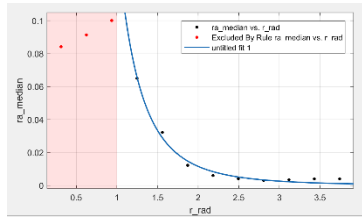
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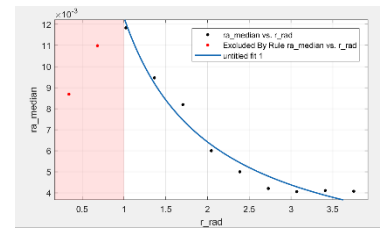
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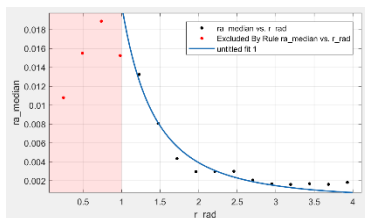
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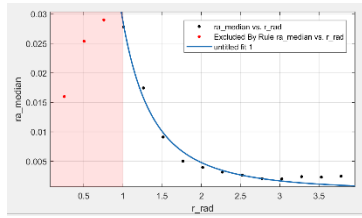
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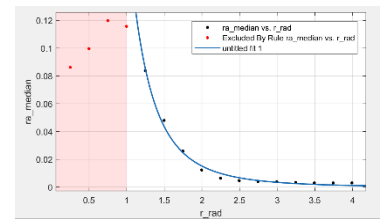
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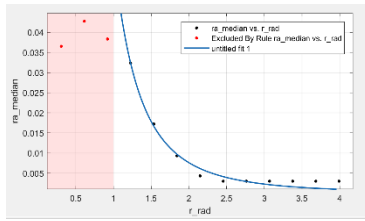
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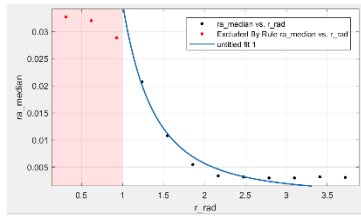
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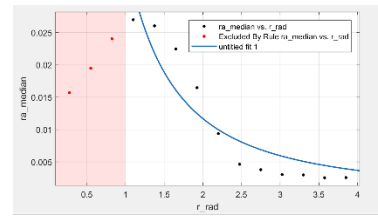
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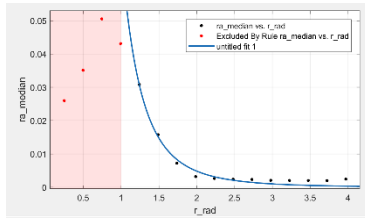
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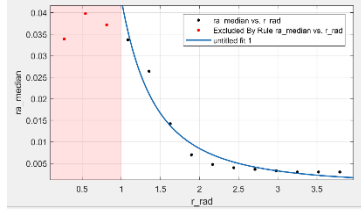
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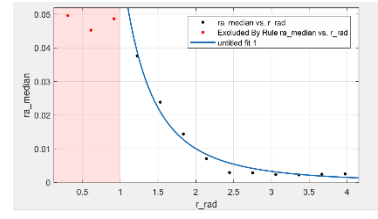
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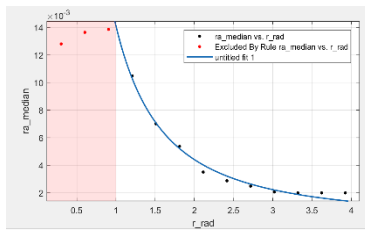
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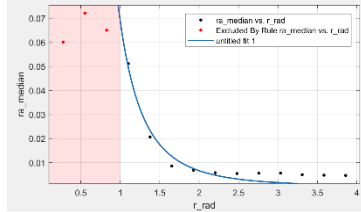
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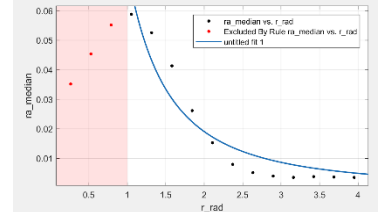
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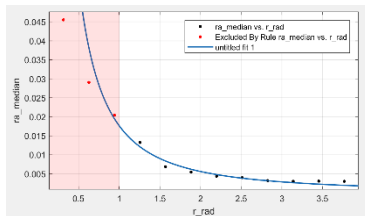
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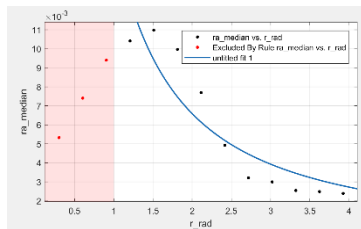
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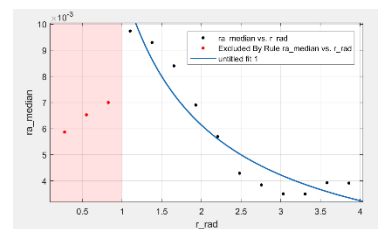
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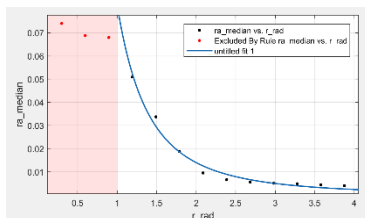
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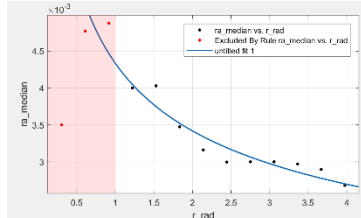
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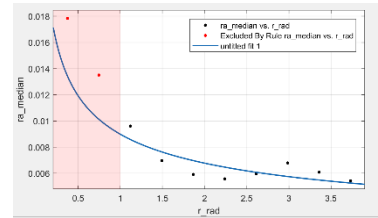
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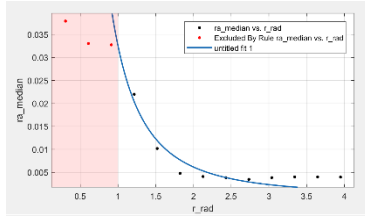
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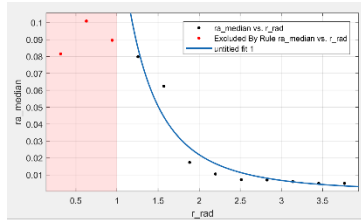
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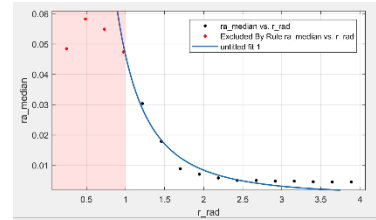
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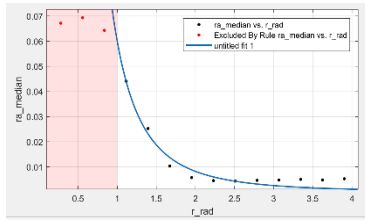
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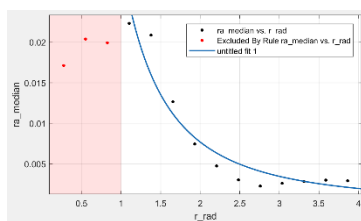
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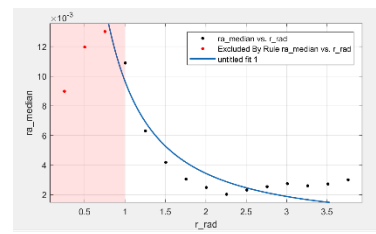
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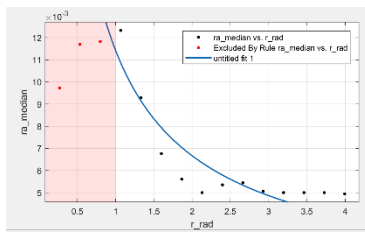
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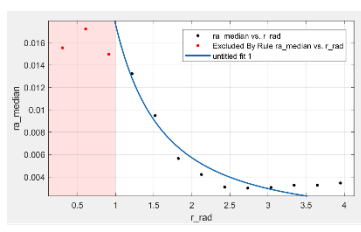
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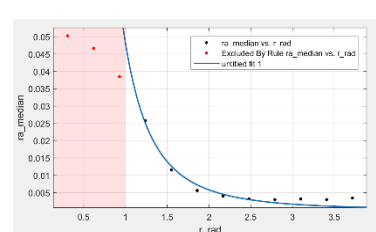
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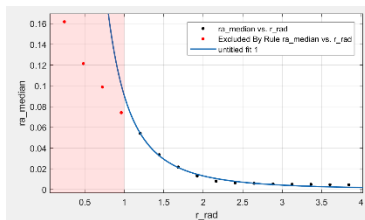
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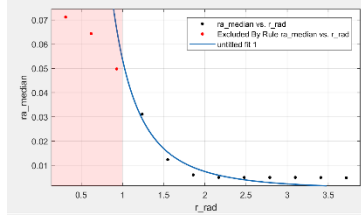
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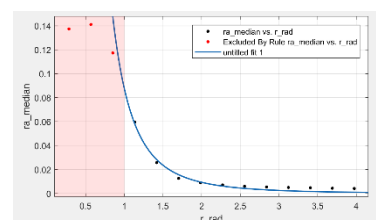
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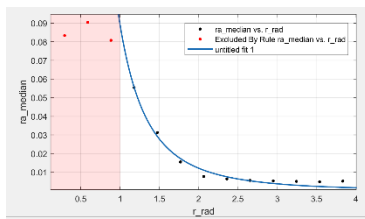
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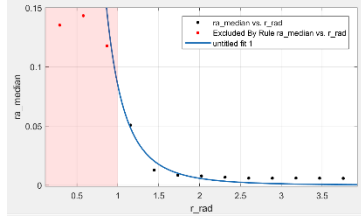
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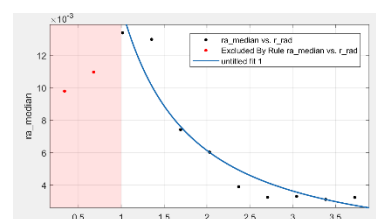
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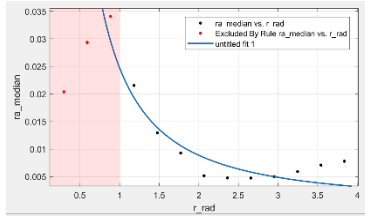
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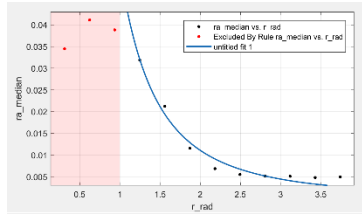
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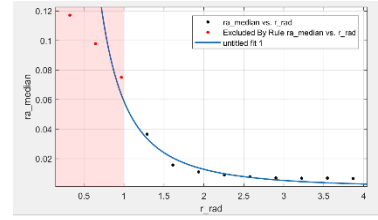
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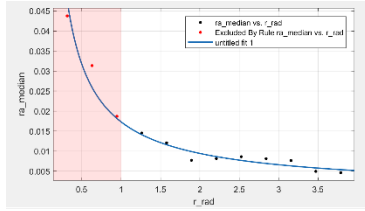
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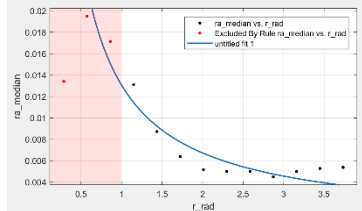
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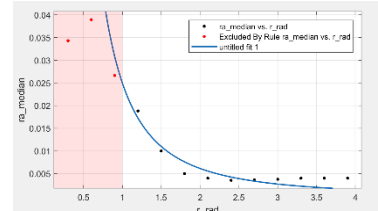
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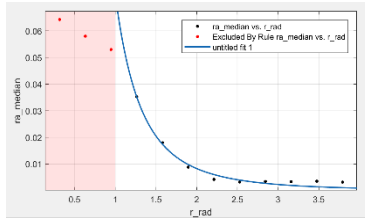
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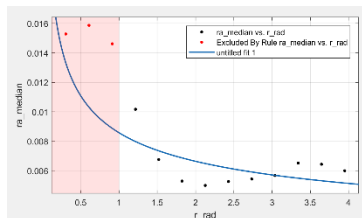
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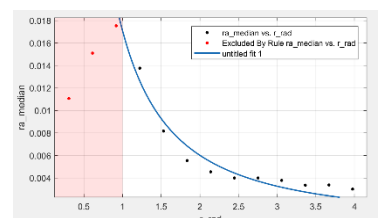
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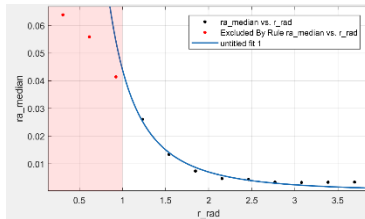
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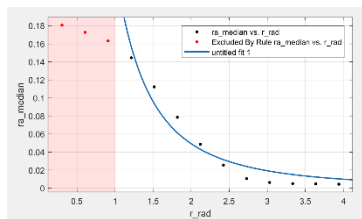
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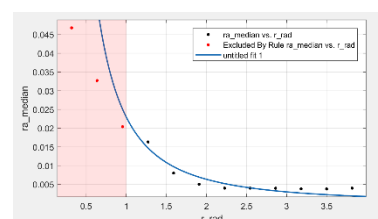
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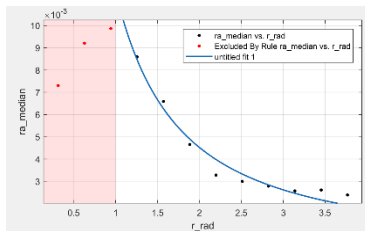
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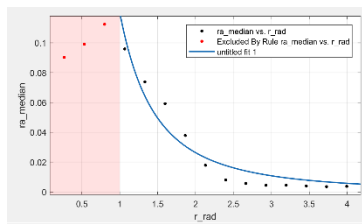
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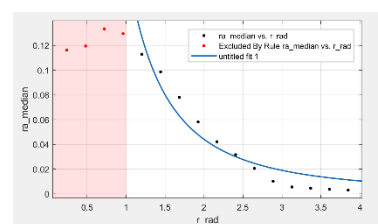
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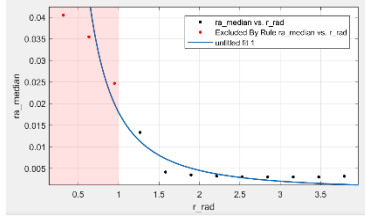
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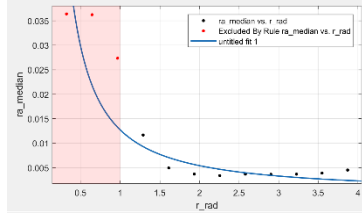
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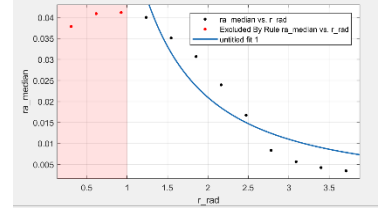
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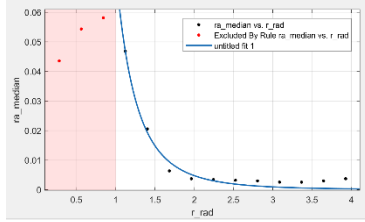
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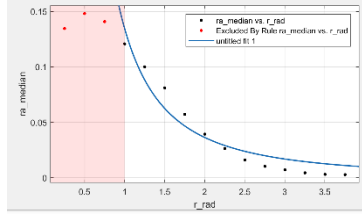
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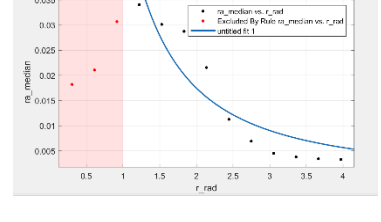
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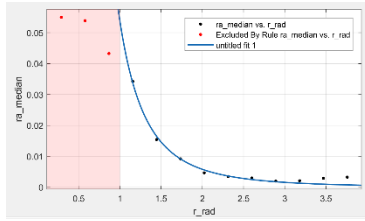
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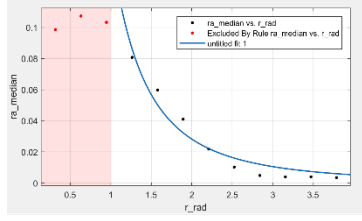
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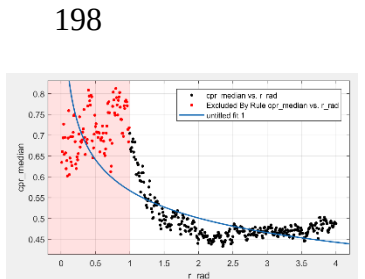
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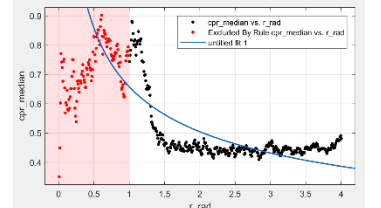
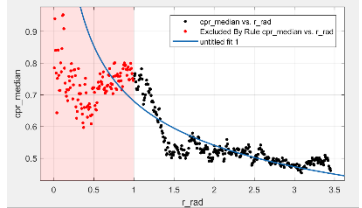
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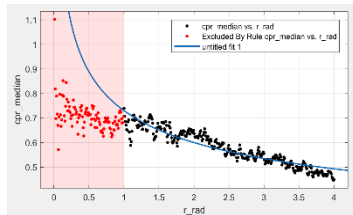
All CPR medians created in this thesis are listed below in order of increasing UniqCratID.

The UniqCratID value at the top left corner of each plot can be referenced to **Table 2** in appendix b in order to find the fit coefficients and properties of each crater

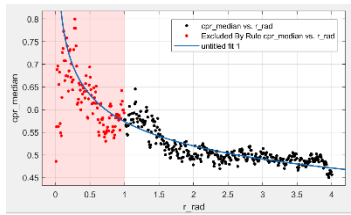


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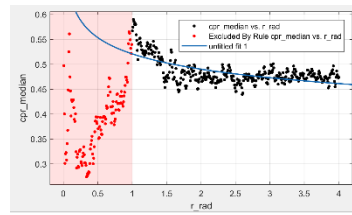




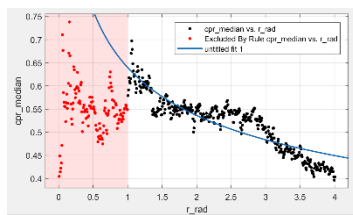
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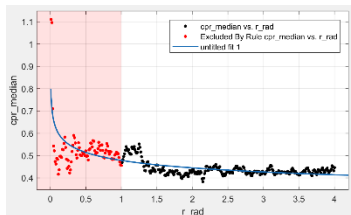
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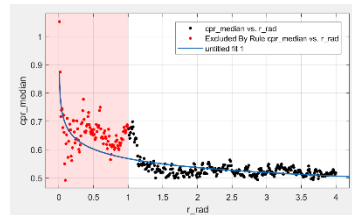
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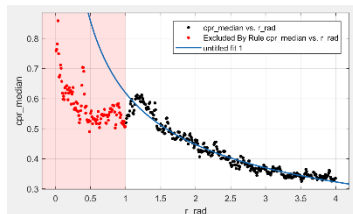
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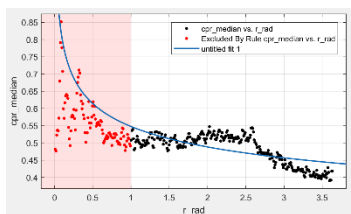
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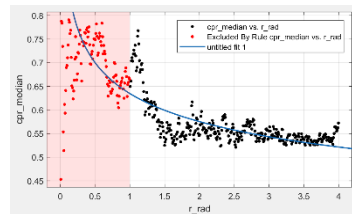
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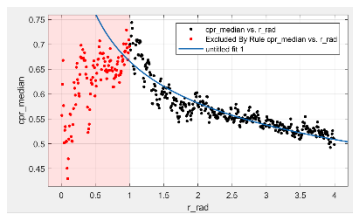
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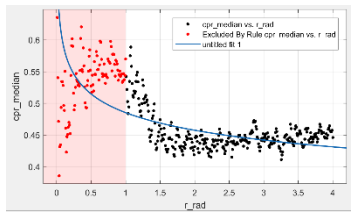
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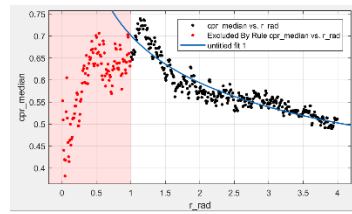
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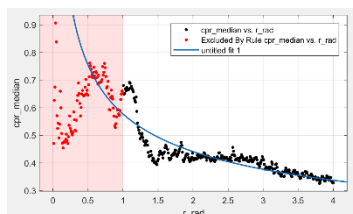
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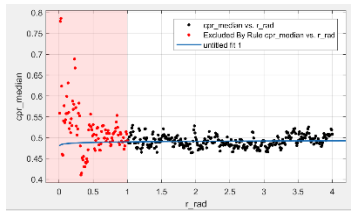
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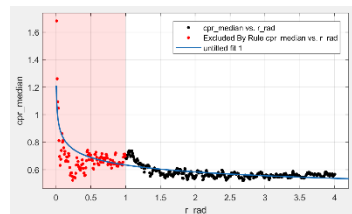
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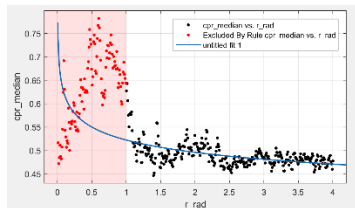
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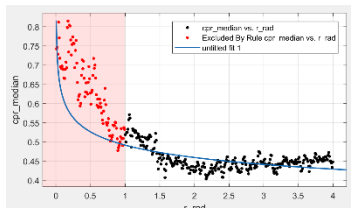
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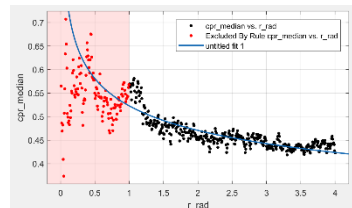
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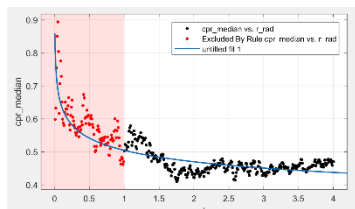
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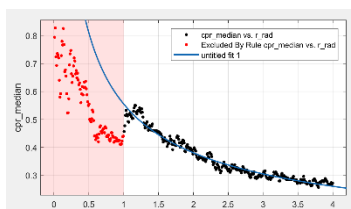
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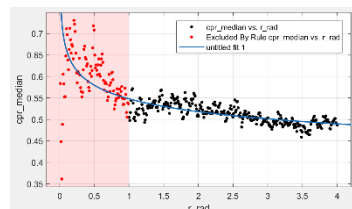
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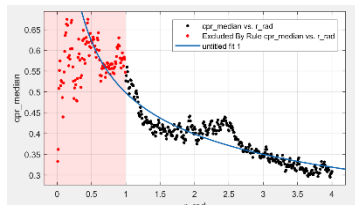
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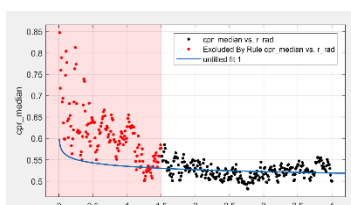
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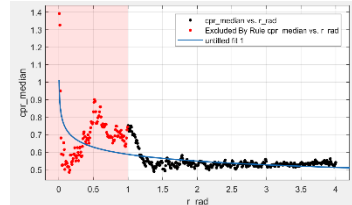
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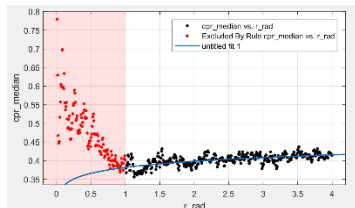
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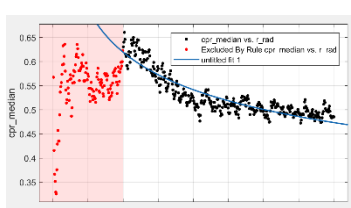
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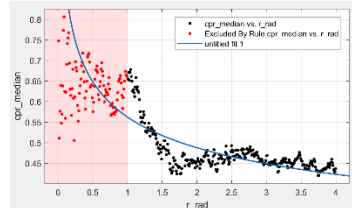
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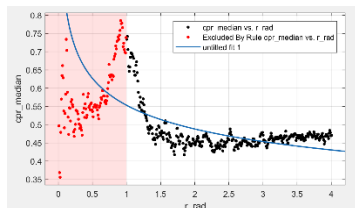
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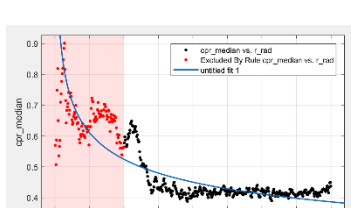
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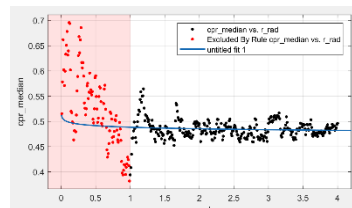
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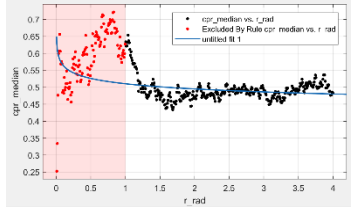
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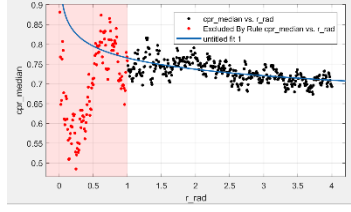
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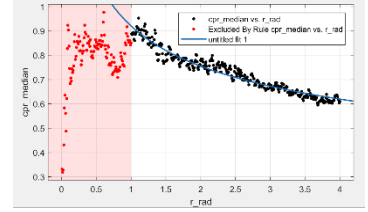
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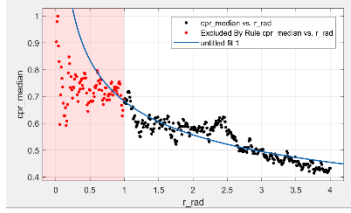
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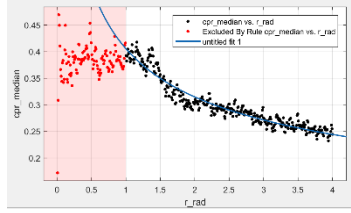
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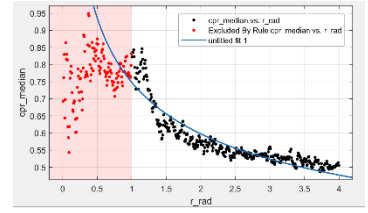
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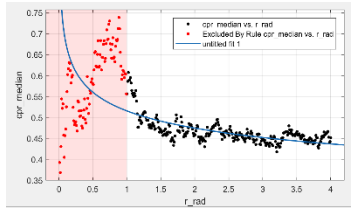
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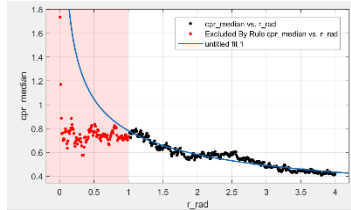
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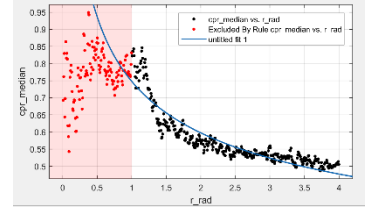
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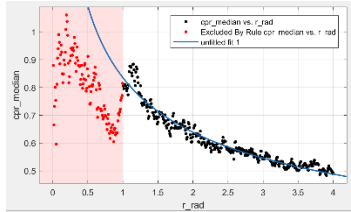
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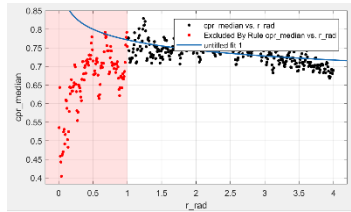
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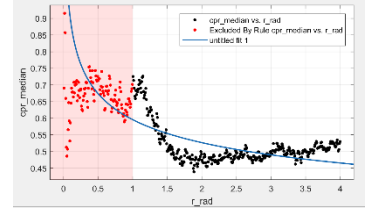
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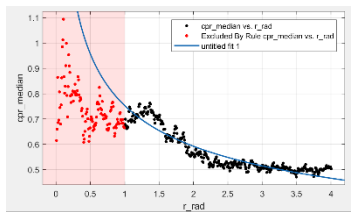
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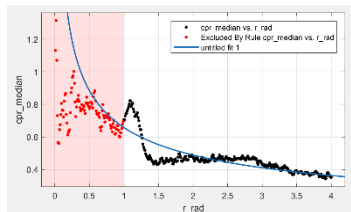
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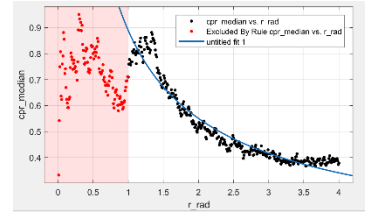
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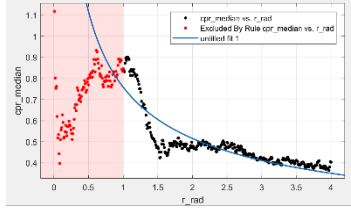
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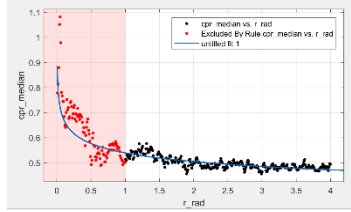
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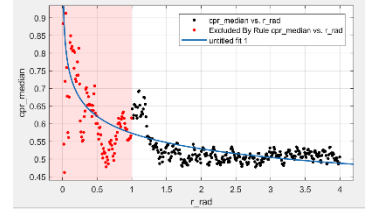
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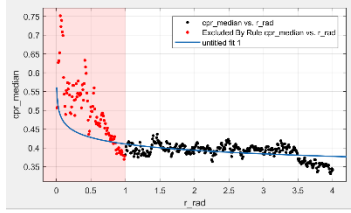
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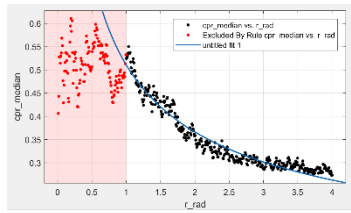
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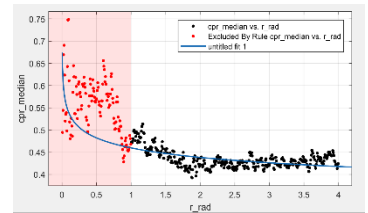
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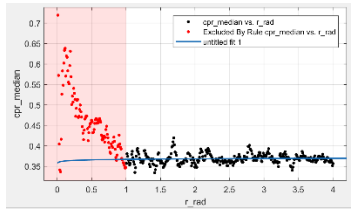
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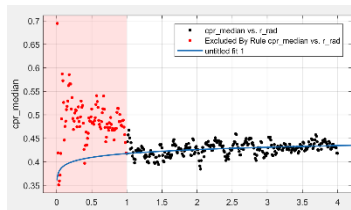
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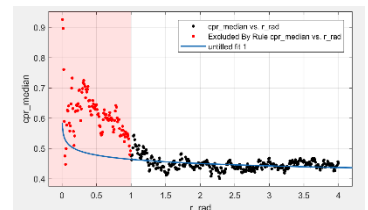
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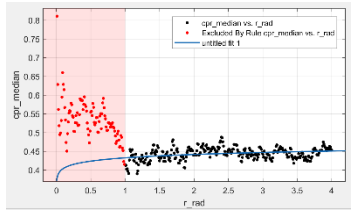
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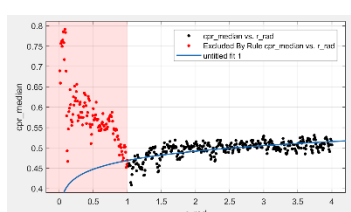
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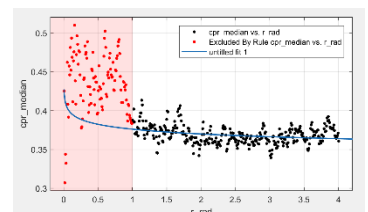
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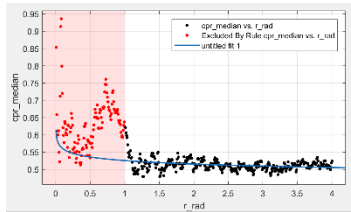
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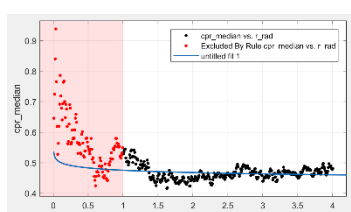
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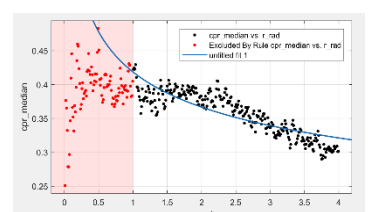
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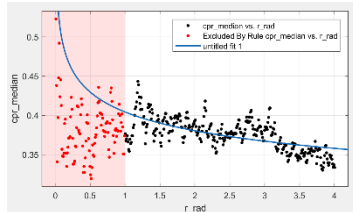
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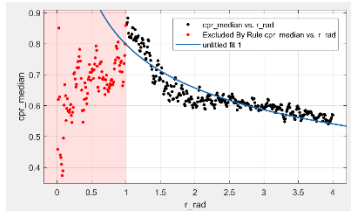
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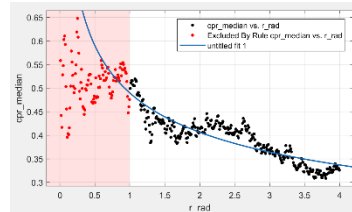
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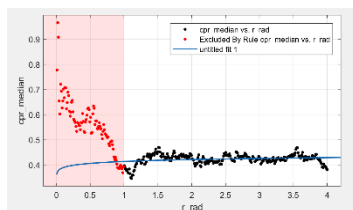
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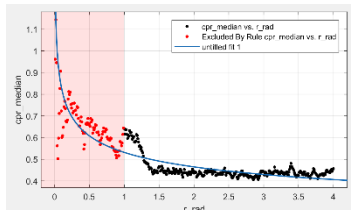
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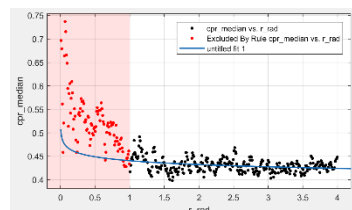
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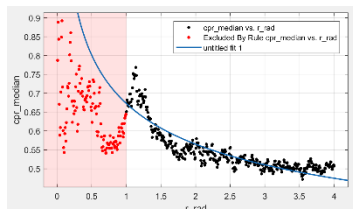
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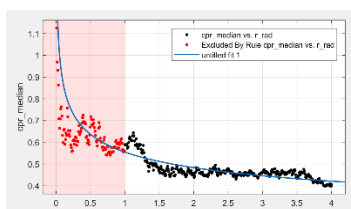
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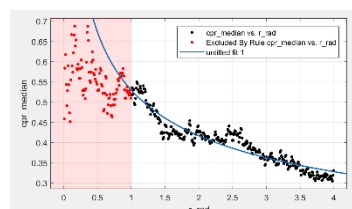
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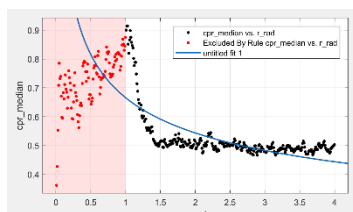
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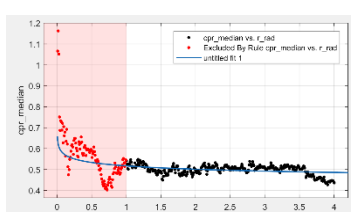
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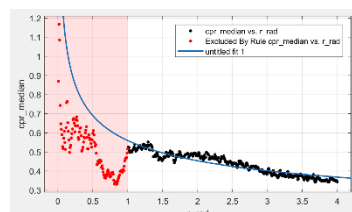
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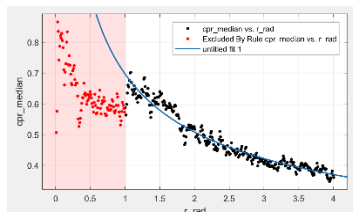
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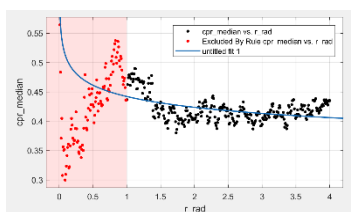
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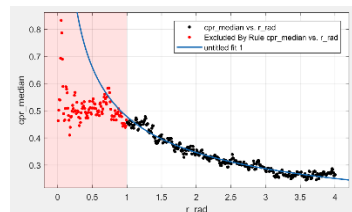
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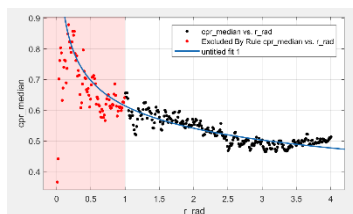
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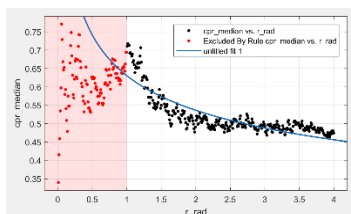
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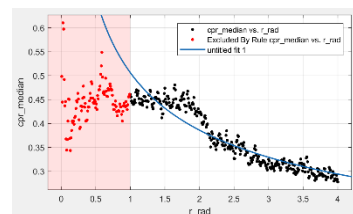
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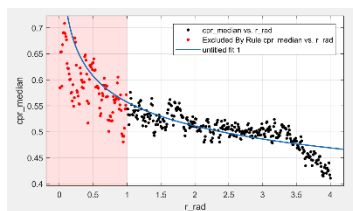
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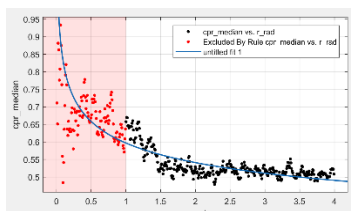
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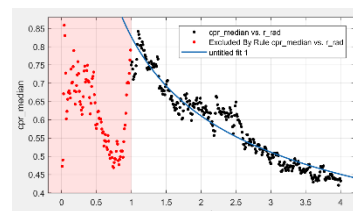
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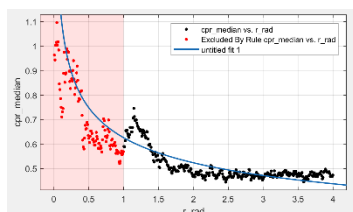
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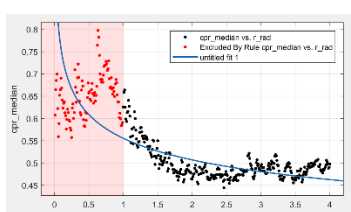
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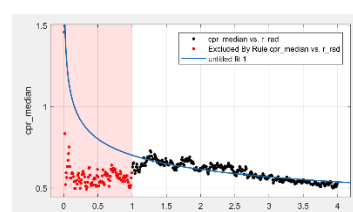
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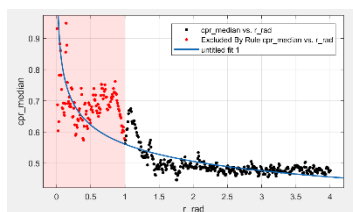
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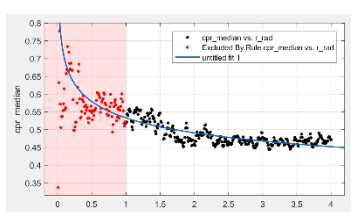
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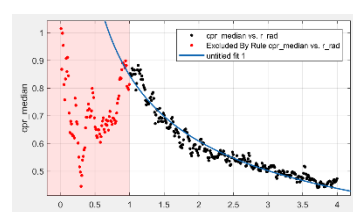
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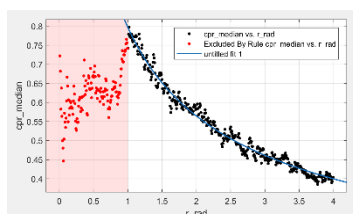
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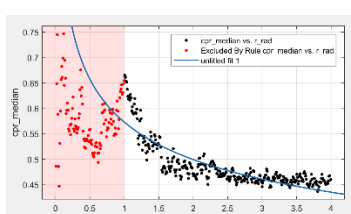
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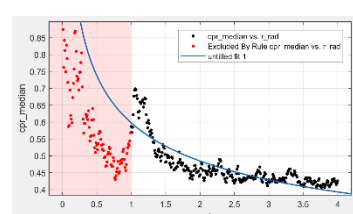
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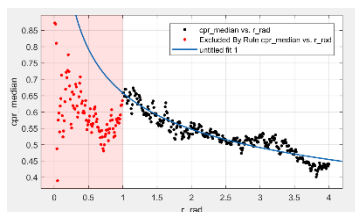
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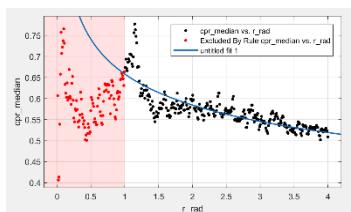
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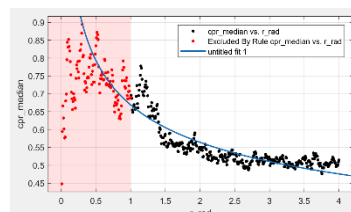
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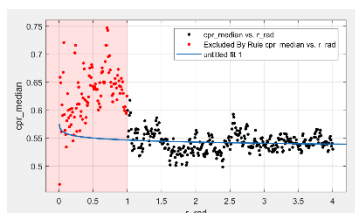
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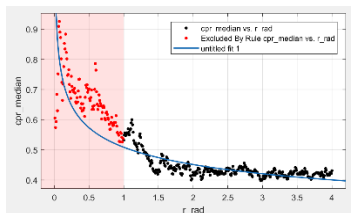
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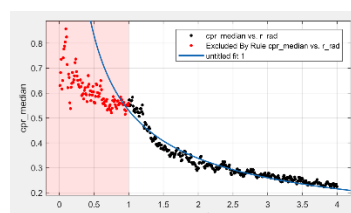
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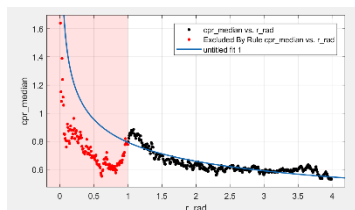
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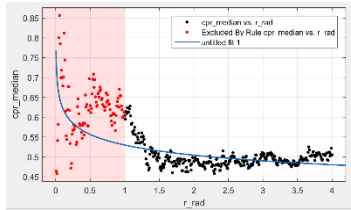
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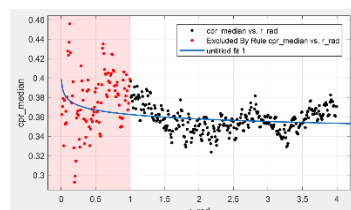
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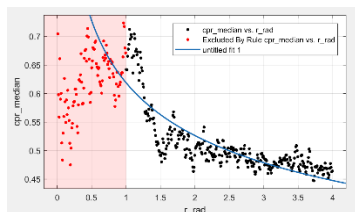
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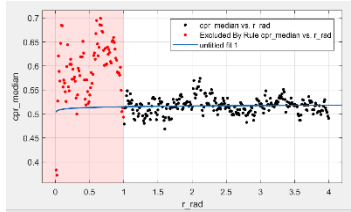
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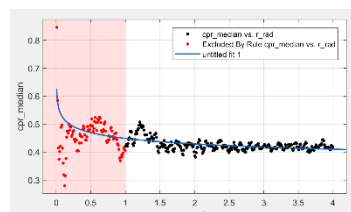
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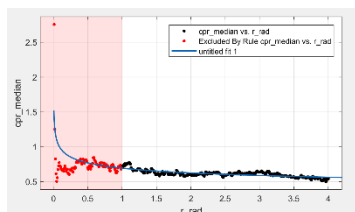
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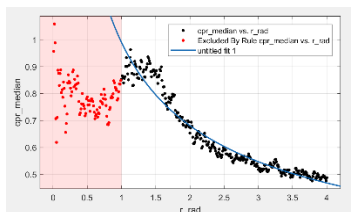
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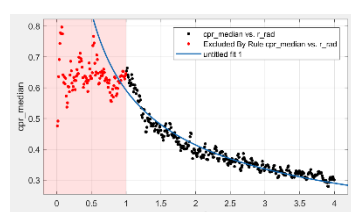
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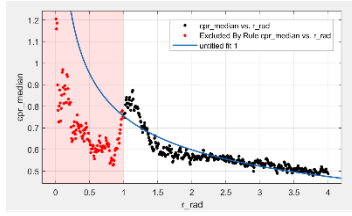
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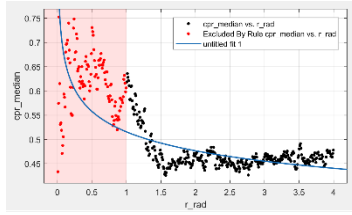
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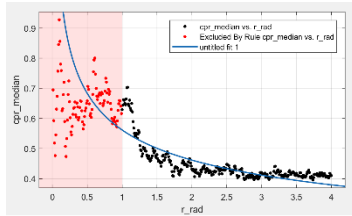
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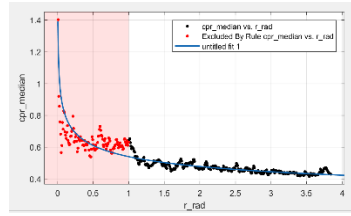
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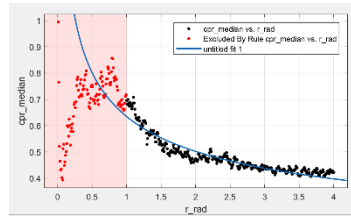
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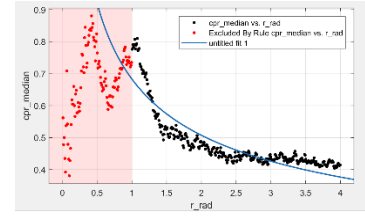
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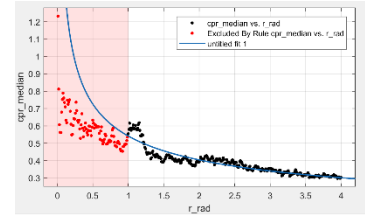
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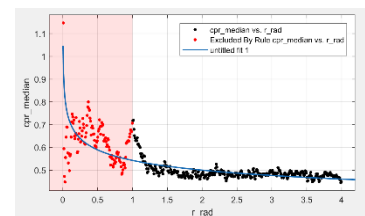
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13349



13496



Vita

Cole Nypaver graduated cum laude from Mercyhurst University with a Bachelor of Science degree in Geology on May 14th, 2017. Mr. Nypaver went on to pursue his Master of Science degree at the University of Tennessee Department of Earth and Planetary Sciences where he studied long-term evolution of impact craters on Earth's Moon. During his first academic year at the University of Tennessee, he saw his undergraduate thesis through to publication as a first author, and a second manuscript pertaining to his MS research through to publication as a co-author. While pursuing the Master of Science degree at the University of Tennessee, Mr. Nypaver was the recipient of several departmental and college-wide awards including the UTK Graduate Student Senate Excellence in Service award, the UTK EPS Bibee Colloquium Presentation award, the UTK EPS Rock Solid Award, the McClung Museum of Natural History and Culture Most Volunteer Spirit Award, and the Tennessee Space Grant Consortium Award for Excellence in Outreach and Service. Mr. Nypaver is also the recipient of the 2018 UTK Graduate School Student/Faculty award which allotted Mr. Nypaver and his co-advisor, Dr. Bradley Thomson, \$4796 for travel and research assistance in the 2018-2019 academic year. Mr. Nypaver also participates actively in the larger scientific community as an active science team affiliate for the Lunar Reconnaissance Orbiter Miniature Radio Frequency (Mini-RF) instrument which is currently acquiring lunar data and playing a major role in advancing our understanding of Earth's Moon.