Frequency-Range Distribution of Boulders around Cone Crater: Relevance to Landing Site Hazard Avoidance

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Background

LROC NAC images enable the determination of boulder distributions around craters of varying sizes and ages to:

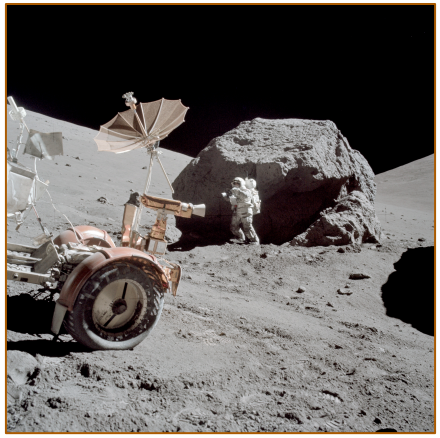
- inform how far craters distribute boulders
- the rate at which rocks become regolith and how rock distributions relate to crater age and degradation state
- to establish criteria for safety hazards for future landings.

<u>Important questions:</u>

1. How far do craters distribute boulders?
2. How does the size distribution of boulders vary as a function of crater size, age, and terrain properties?
3. How do variations in boulder distributions as a function of crater age inform erosion rates and the process of how rocks become regolith?
4. How do LROC boulder distributions compare with other observations of boulders (Diviner and surface photographs)

Scope of This Work

Use NAC images to provide the first complete quantitative analysis of boulder populations at spacecraft landing sites. Counts completed at Apollo 14 (Cone crater) and Apollo 16 (North Ray crater)



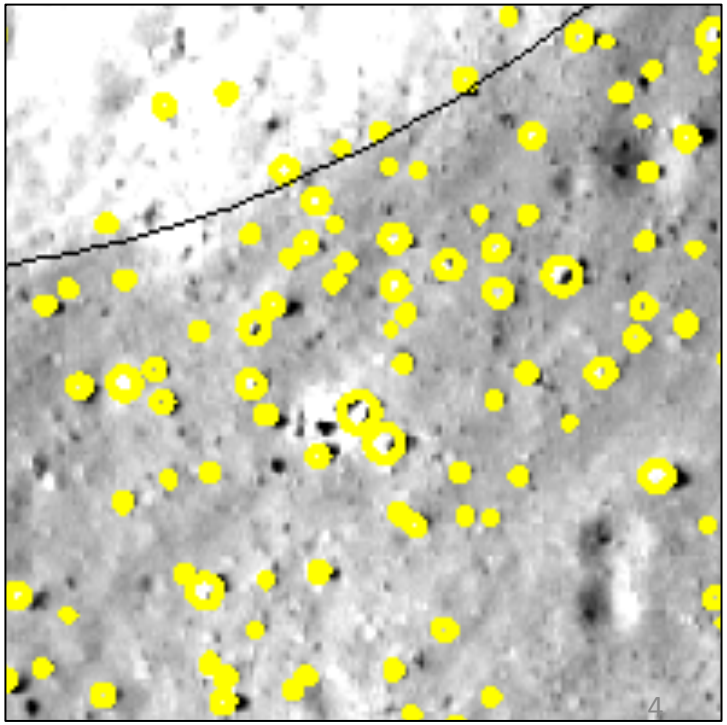
AS17-146-22294

Why landing sites?

- Extensive LRO coverage of these sites
- Surface photography for validation
- Known ages of many craters from returned samples and/or crater counting
- Knowledge of terrain properties
- Determining boulder distributions at locations where landers have safely touched down is important for determining landing hazard criteria for future missions

Methods

- CraterTools (Kneissel et al., 2011) in ArcMap was used to identify, count, and estimate the size of boulders in an ~7 km^2 count area centered on Cone Crater and an ~18.6 km^2 count area at North Ray.
- Boulders estimated in terms of a circular diameter
- Distance of each boulder from center of crater determined using the *haversine formula* (great-circle distance for small distances; uses latitude and longitude coordinates)



example of boulder counts near rim

Important Distributions

Boulder Range-Frequency Distribution

Informs how the frequency of boulders varies as a function of distance from the crater rim.

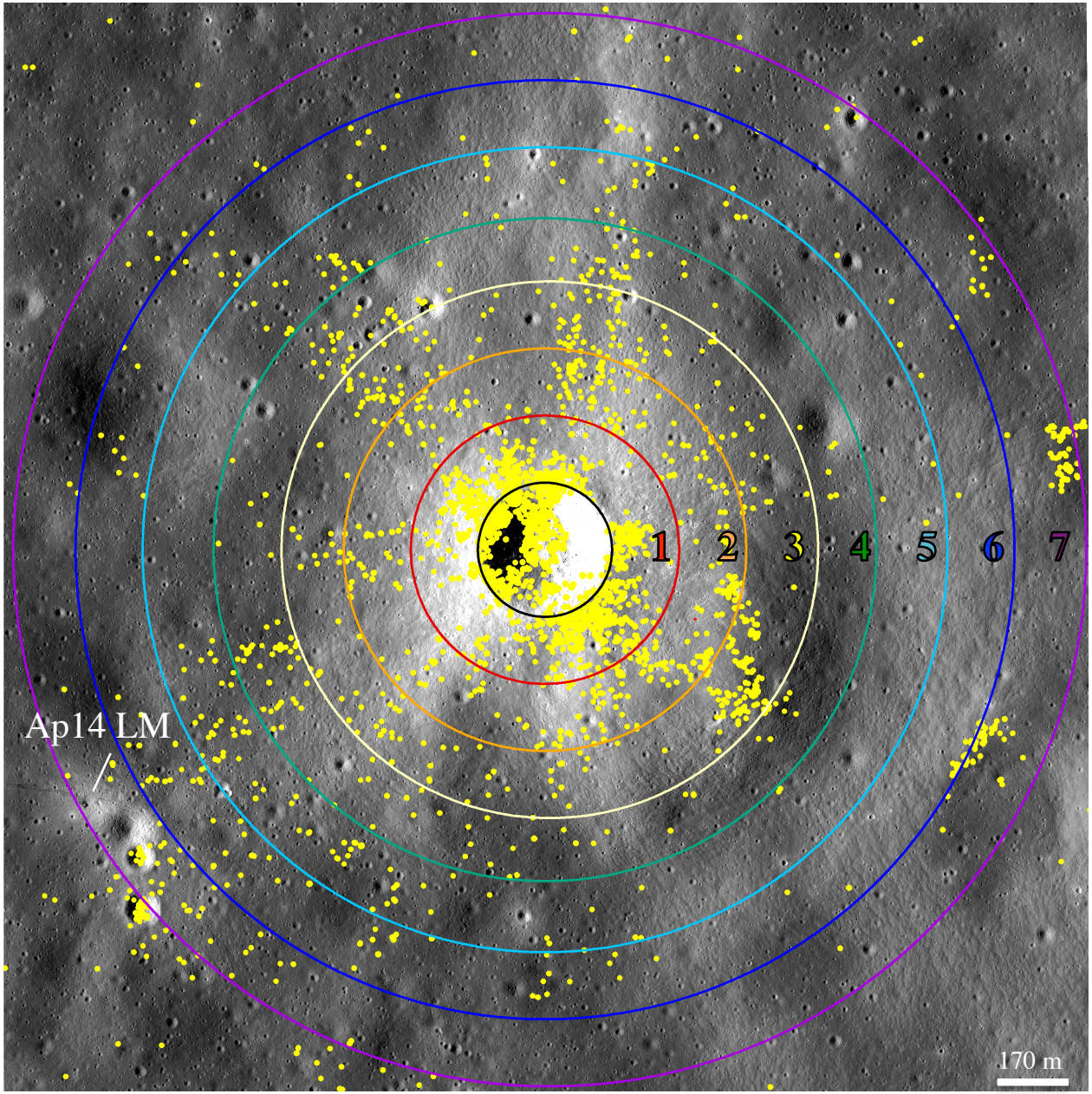
Boulder Size-Frequency Distribution

Informs how many boulders of a particular size are present.

Boulder Size-Range Distribution

Informs how the size distribution changes as a function of distance from crater rim.

Cone Crater Counts



Age: 26 Ma (Arvidson et al., 1975)
Diameter: 340 m

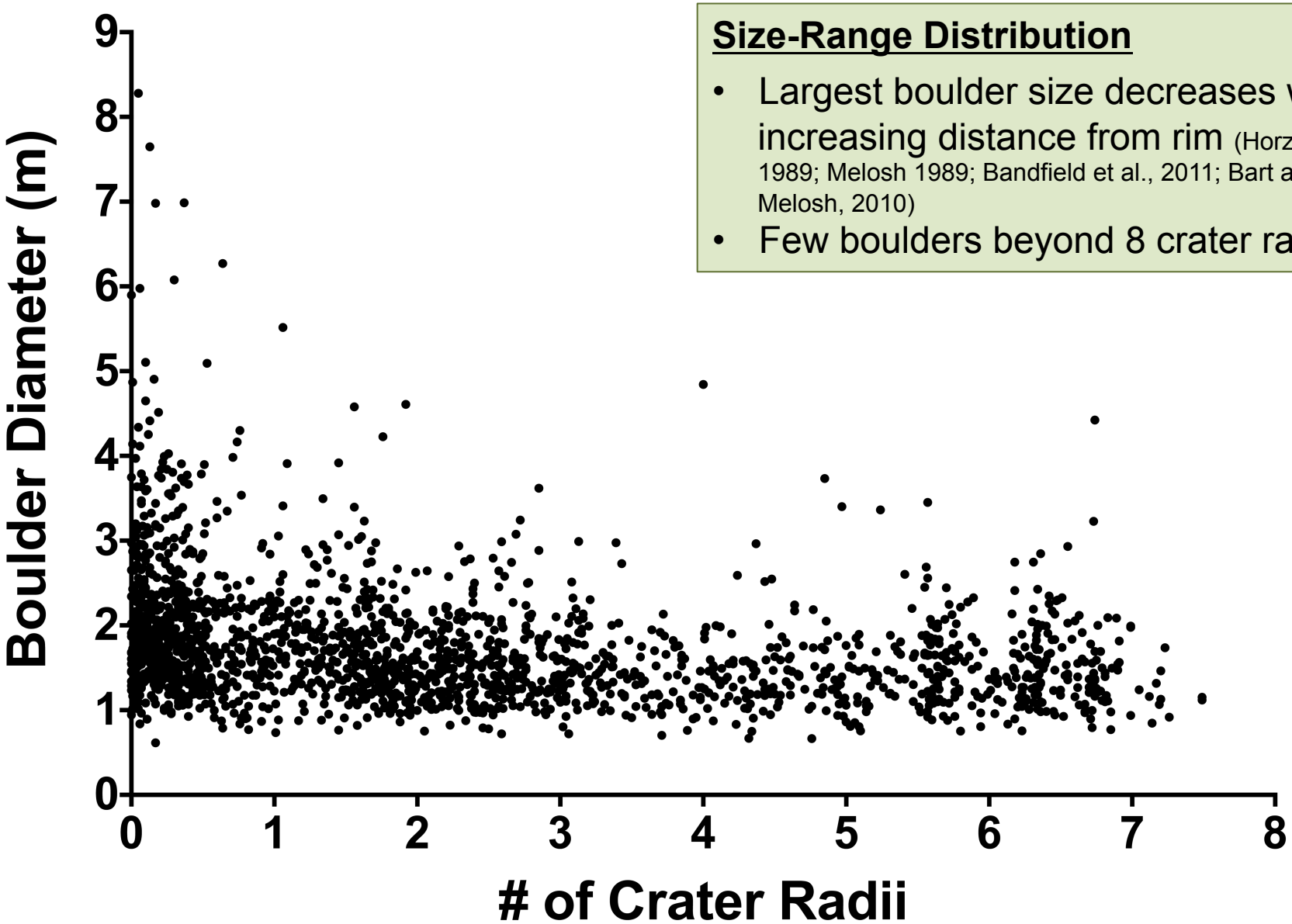
Total Boulders (outside crater): 2011

Largest boulder: 8.3 m

Some prominent clusters present at 6 and 7 crater radii

NAC M150633128
i = 60°

Distribution of Measured Boulders

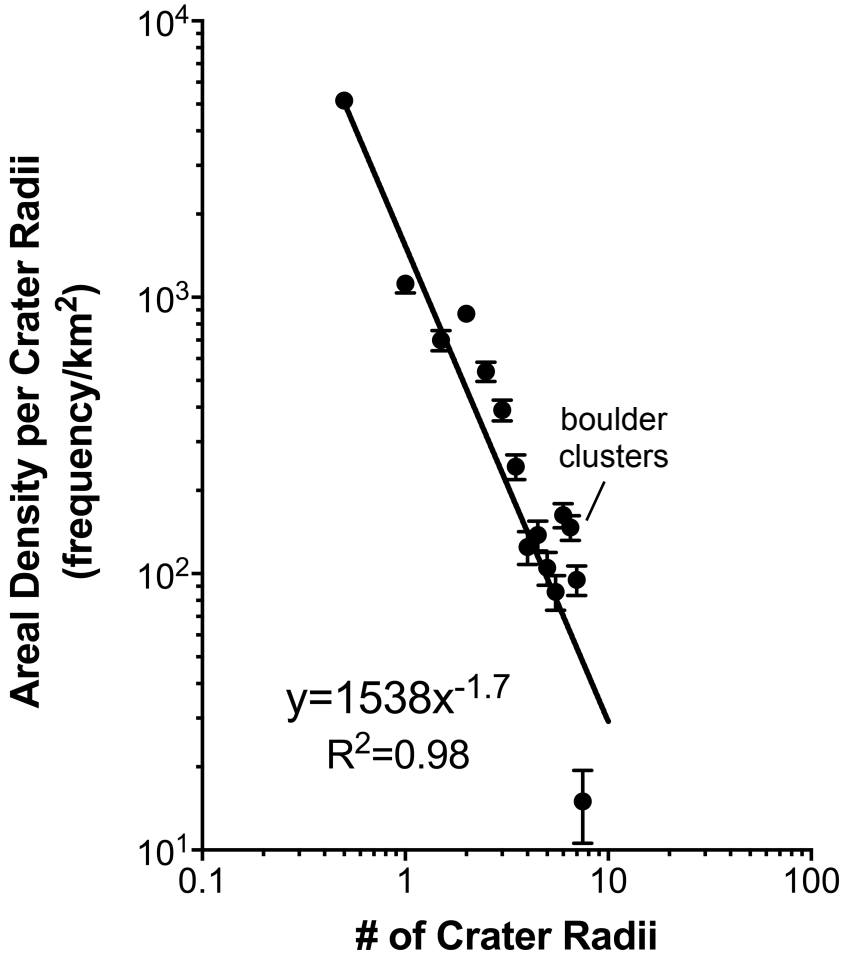


Size-Range Distribution

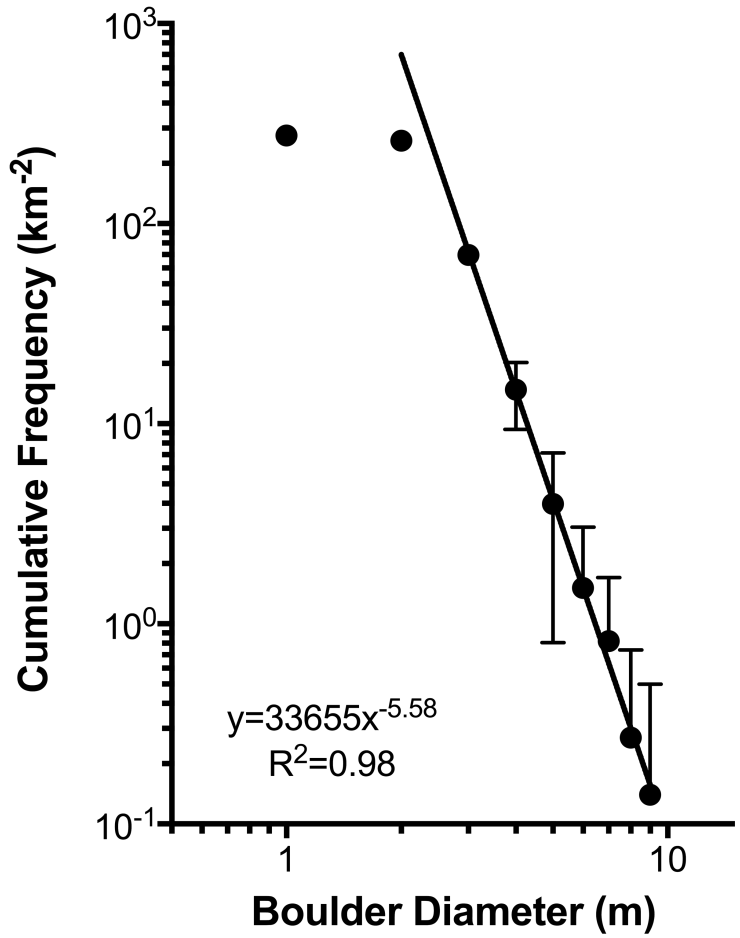
- Largest boulder size decreases with increasing distance from rim (Horz et al., 1989; Melosh 1989; Bandfield et al., 2011; Bart and Melosh, 2010)
- Few boulders beyond 8 crater radii

Distribution of Measured Boulders

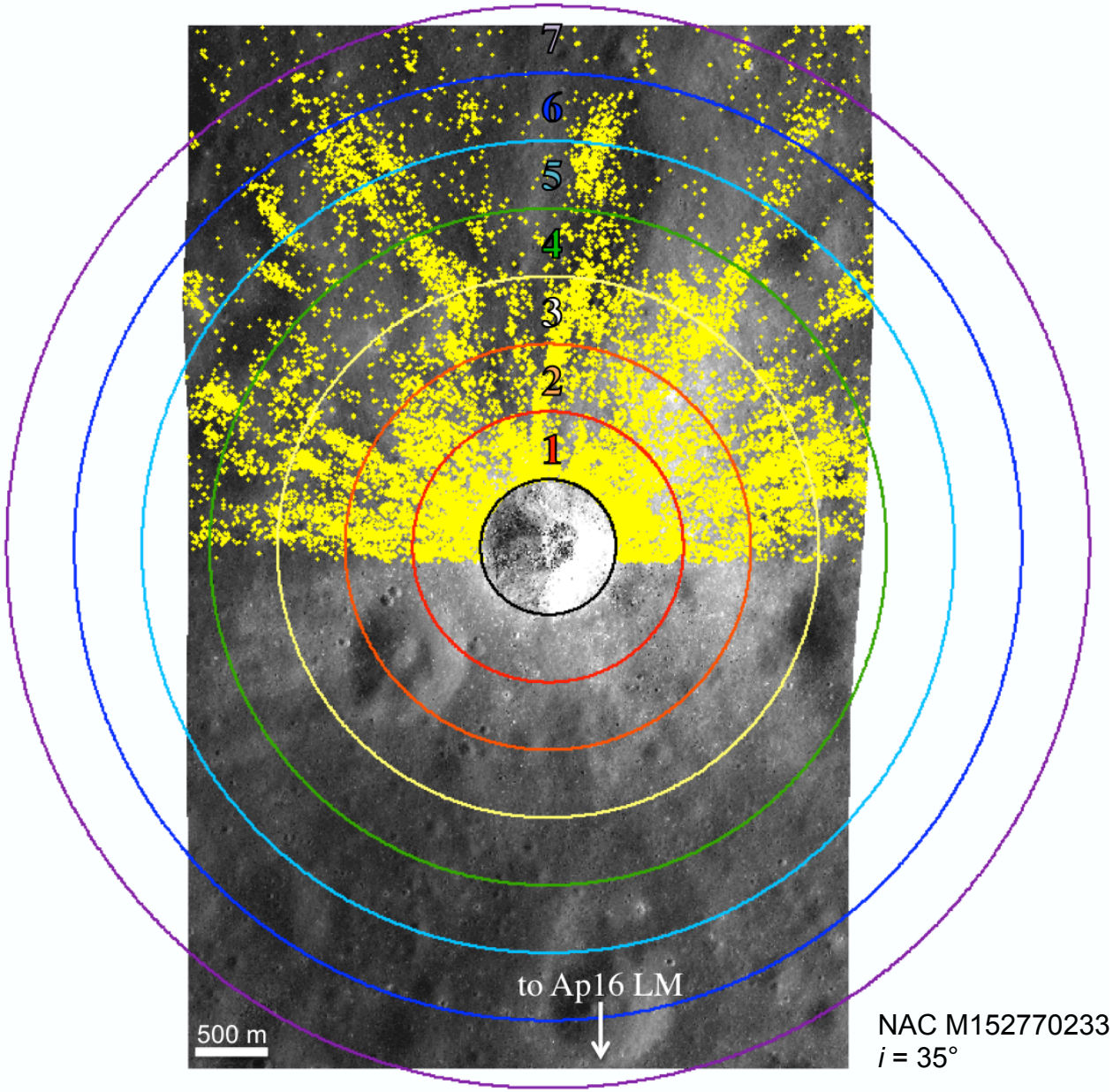
range-frequency distribution
(for annular areas)



size-frequency distribution
(entire count area)



North Ray Counts



NAC M152770233
i = 35°

Age: ~50 Ma (Arvidson et al., 1975)
Diameter: 950 m

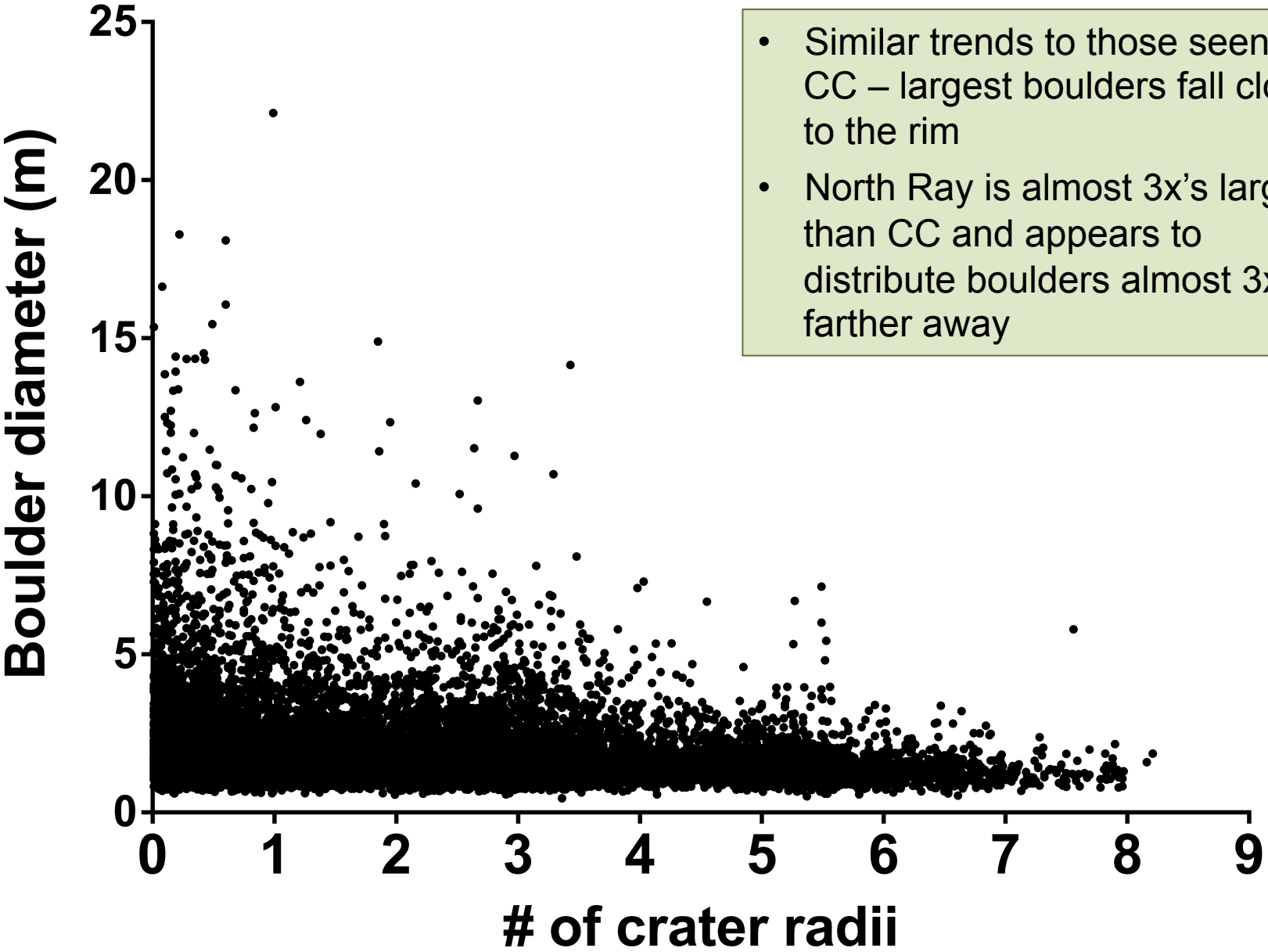
Total Boulders:
18230

Count area
(northern half):
18.6 km^2

Largest boulder:
22 m

Distribution analyses assume the counts for the southern portion, which may be contaminated with South Ray boulders, would show the same trends

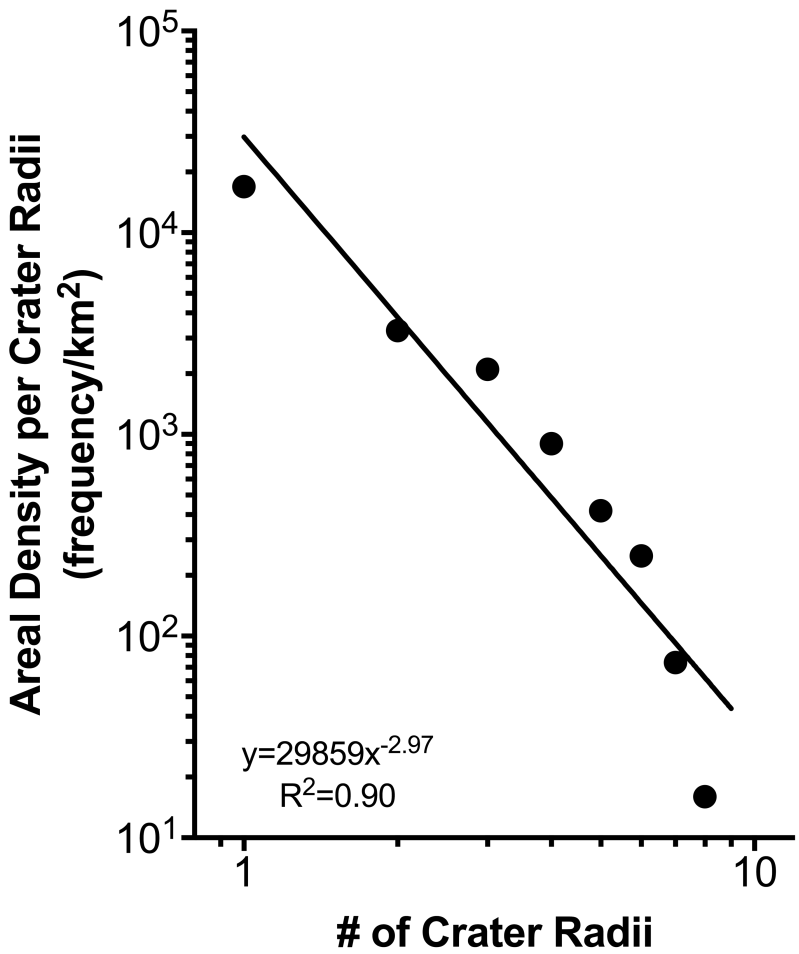
North Ray Size-Range Distribution



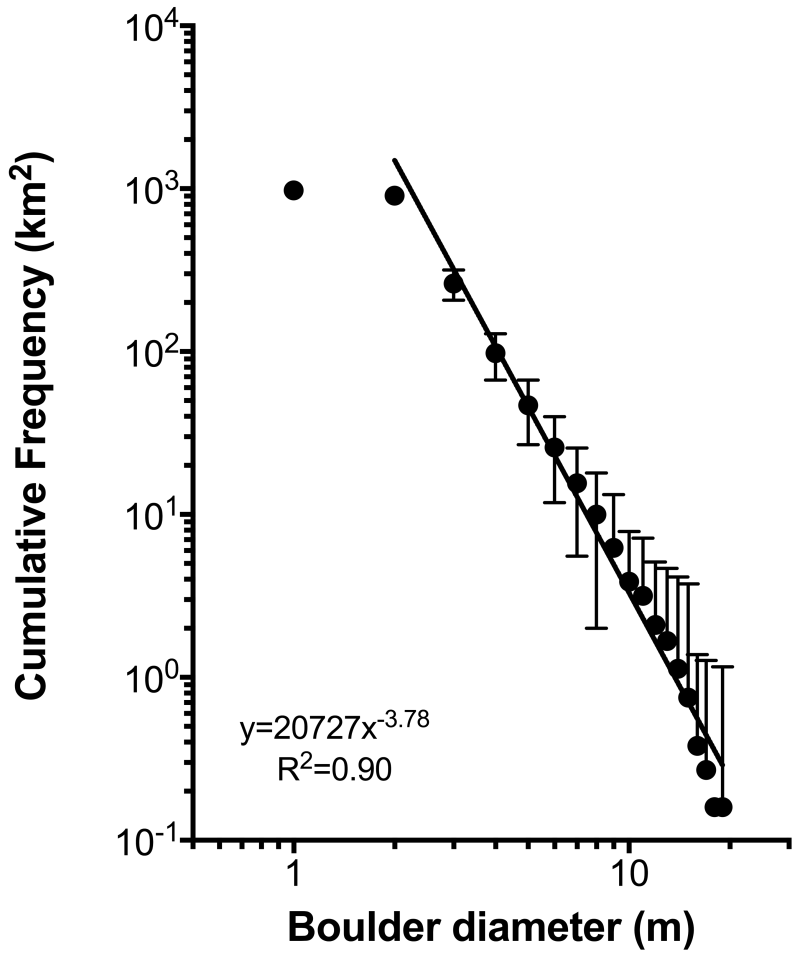
- Similar trends to those seen at CC – largest boulders fall closer to the rim
- North Ray is almost 3x's larger than CC and appears to distribute boulders almost 3x's farther away

North Ray Boulder Distributions

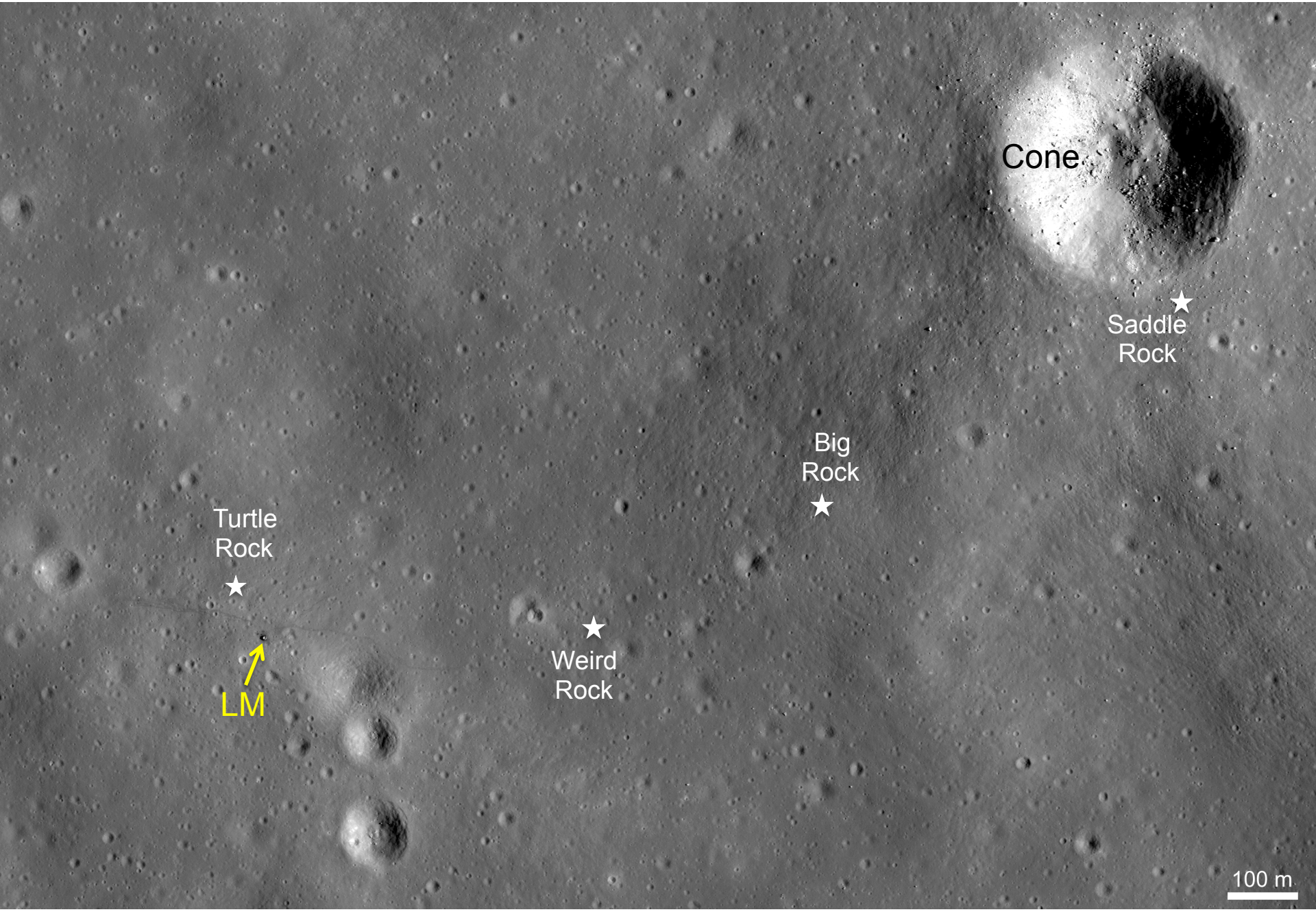
range-frequency distribution
(for annular areas)



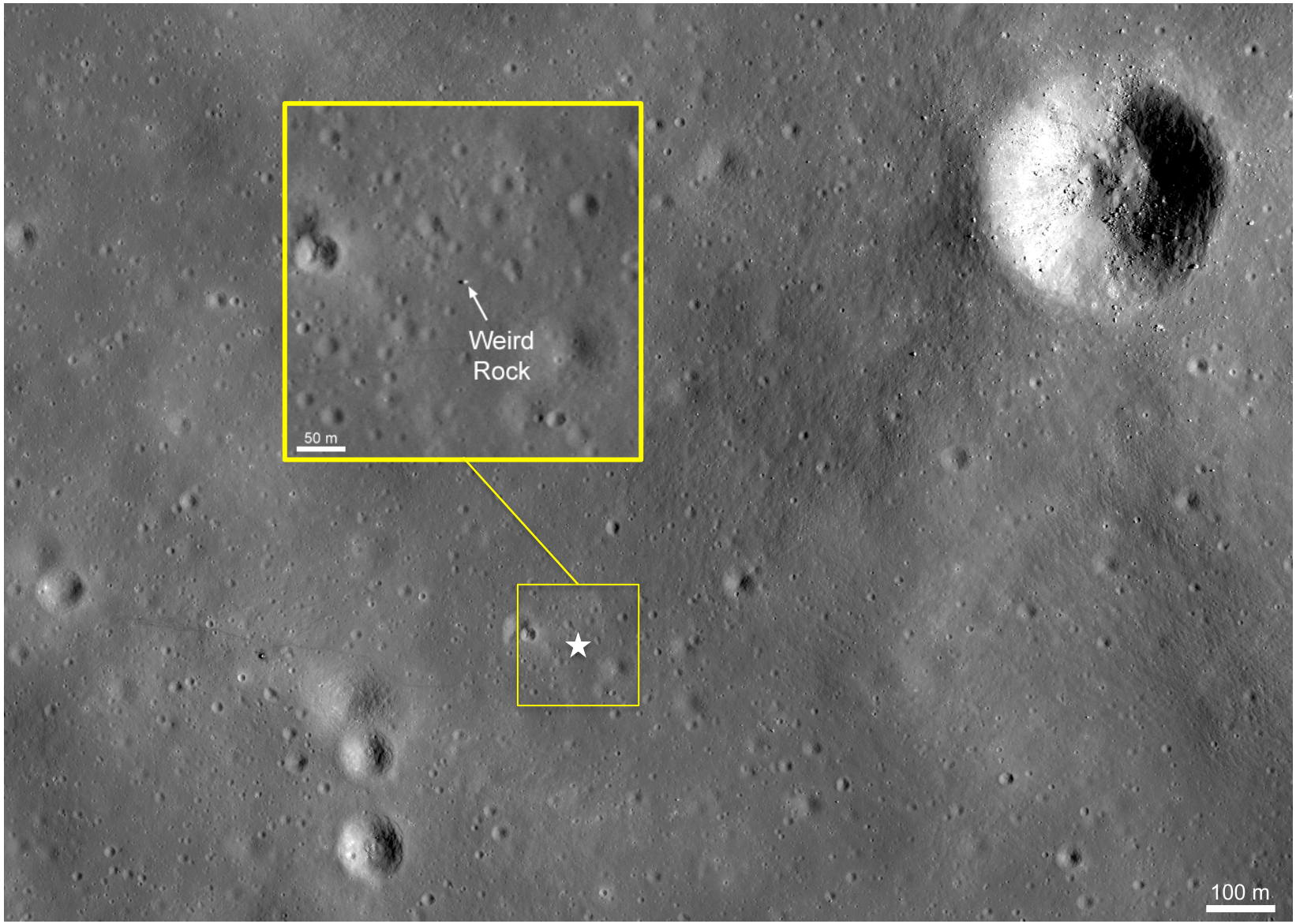
size-frequency distribution
(entire count area)



Validating LROC counts with Surface Photography

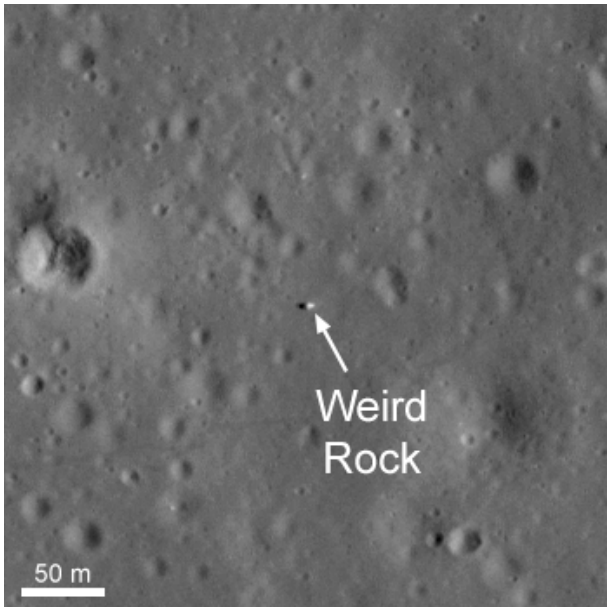

Cone
Saddle Rock
Big Rock
Turtle Rock
Weird Rock
LM
100 m

Weird Rock

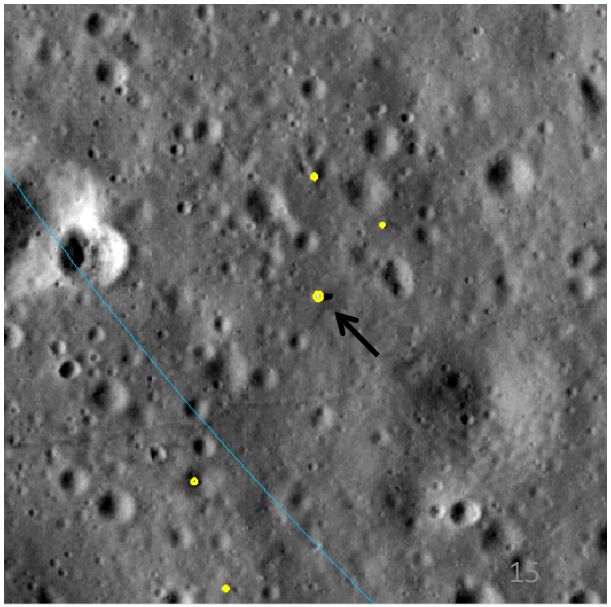


Weird Rock

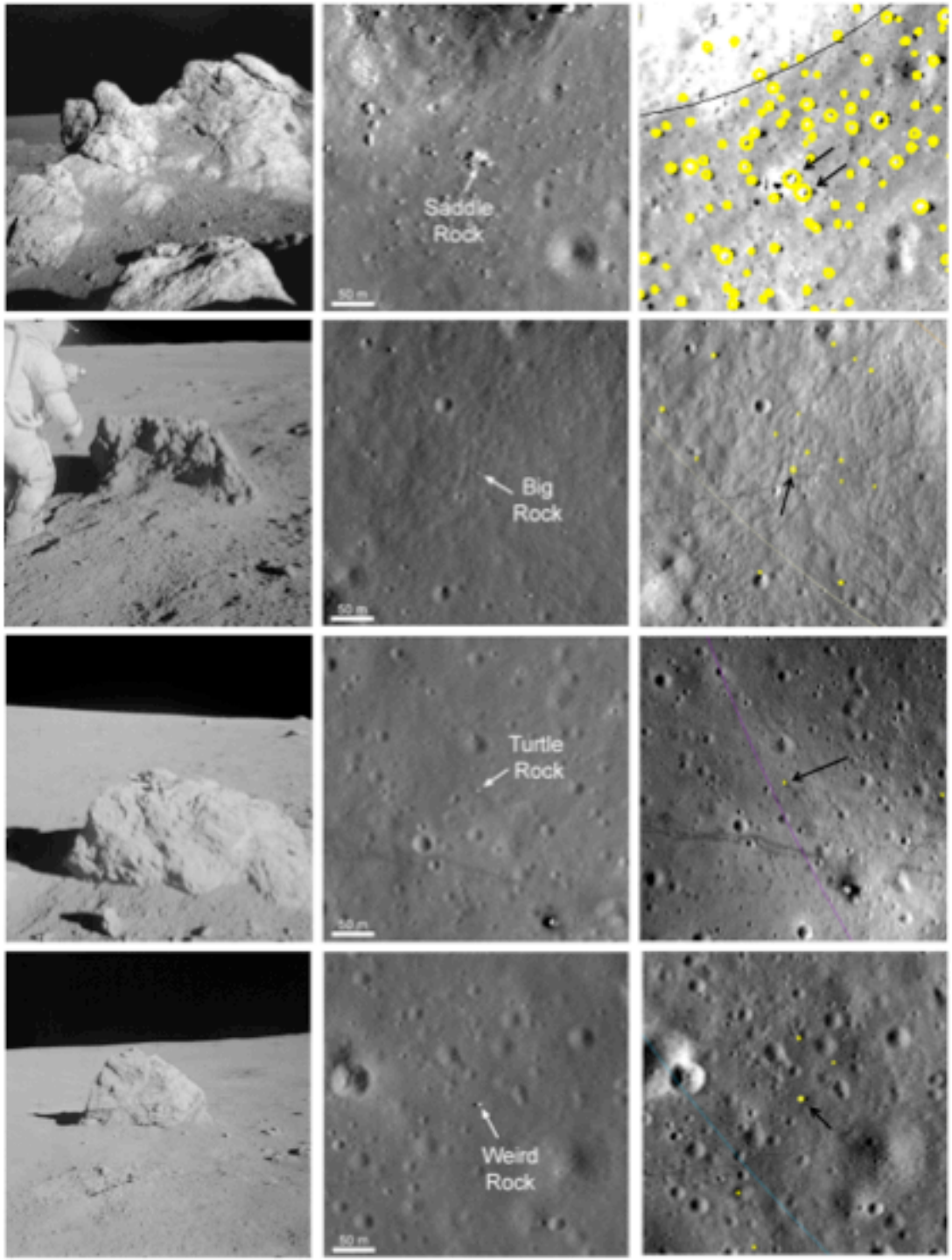
NAC



Boulder Count



Actual size: 2.5 m
Measured size: 2.5 m



Saddle Rock*

measured: 9.4 m
actual: 4.5 m

*measured as 2 boulders

Big Rock

measured: 3.0 m
actual: 1.5 m

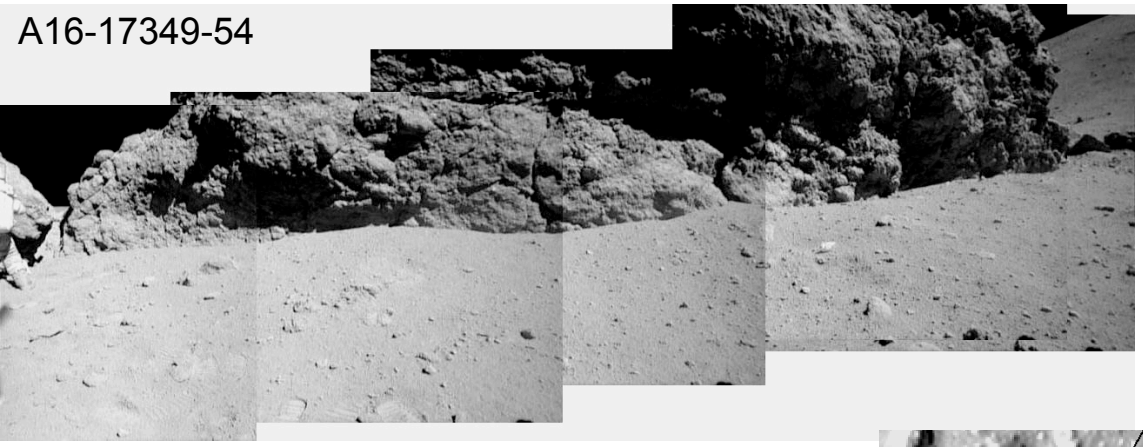
Turtle Rock

measured: 1.3 m
actual: 1.5 m

Weird Rock

Measured: 1.5 m
actual: 1.5 m

Apollo 16 Surface Photography



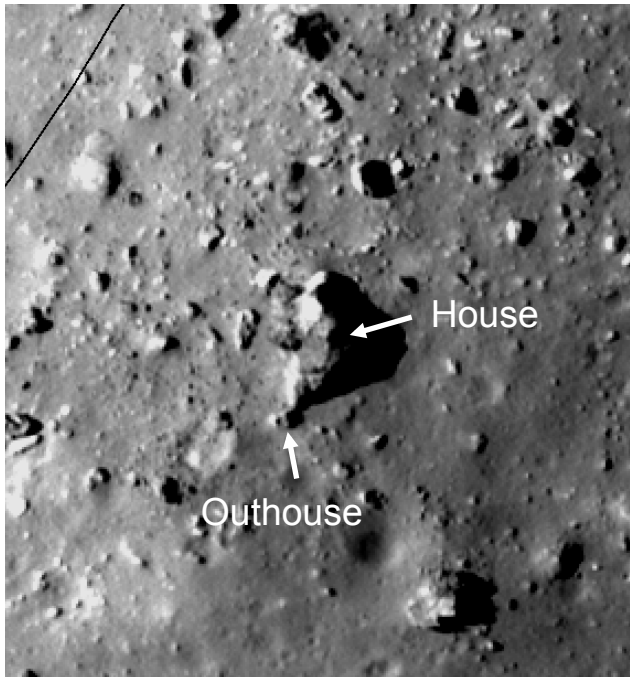
House Rock

measured: 26 m
actual*: 25 m

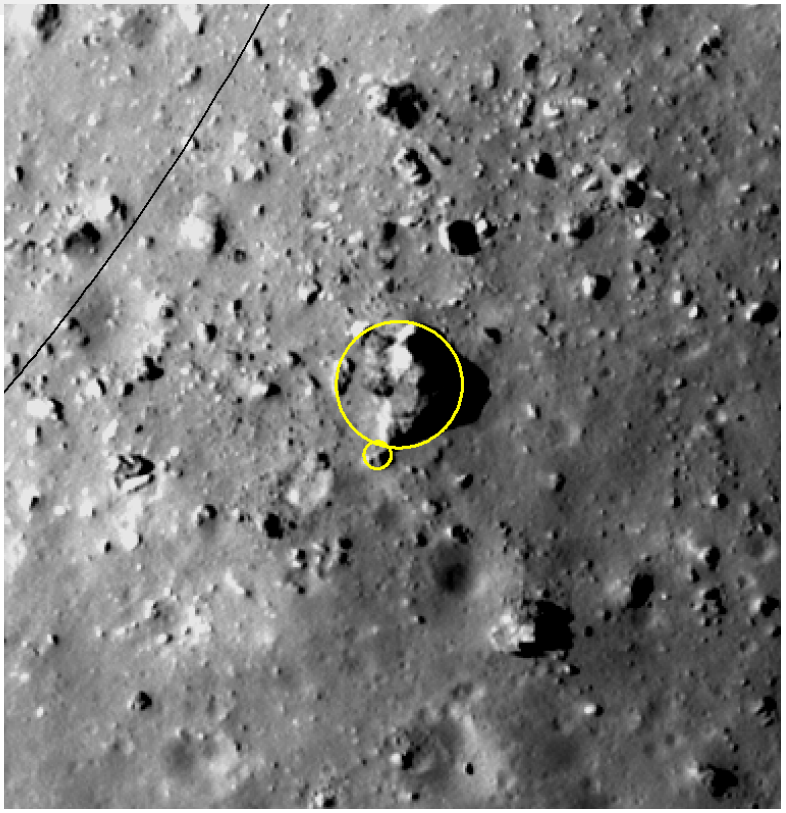
Outhouse Rock

measured: 5.6 m
actual*: 5 m

*(Ulrich et al., 1981)



NAC

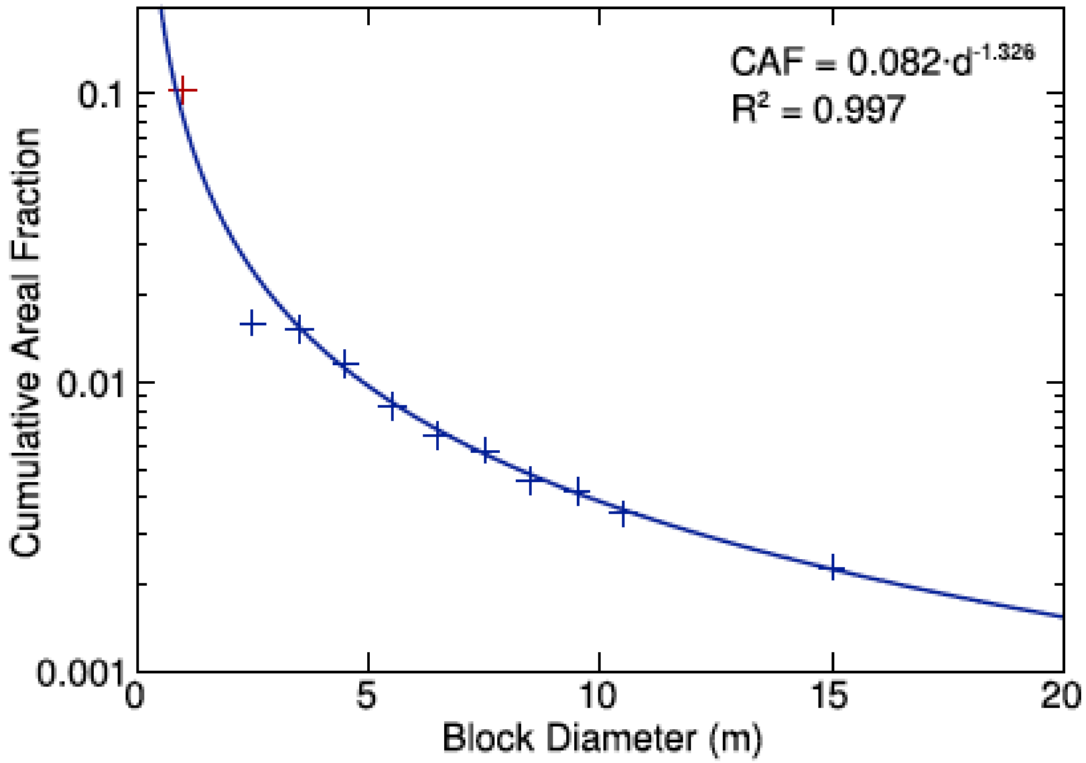


Comparing with Diviner

- DRA measures the areal density of the surface covered in boulders (sensitive to rocks ~1 m in size).

- Following the method of Bandfield et al. (2011), we calculate the cumulative areal fraction of the surface covered in boulders for each diameter bin.

(Bandfield et al., 2011)



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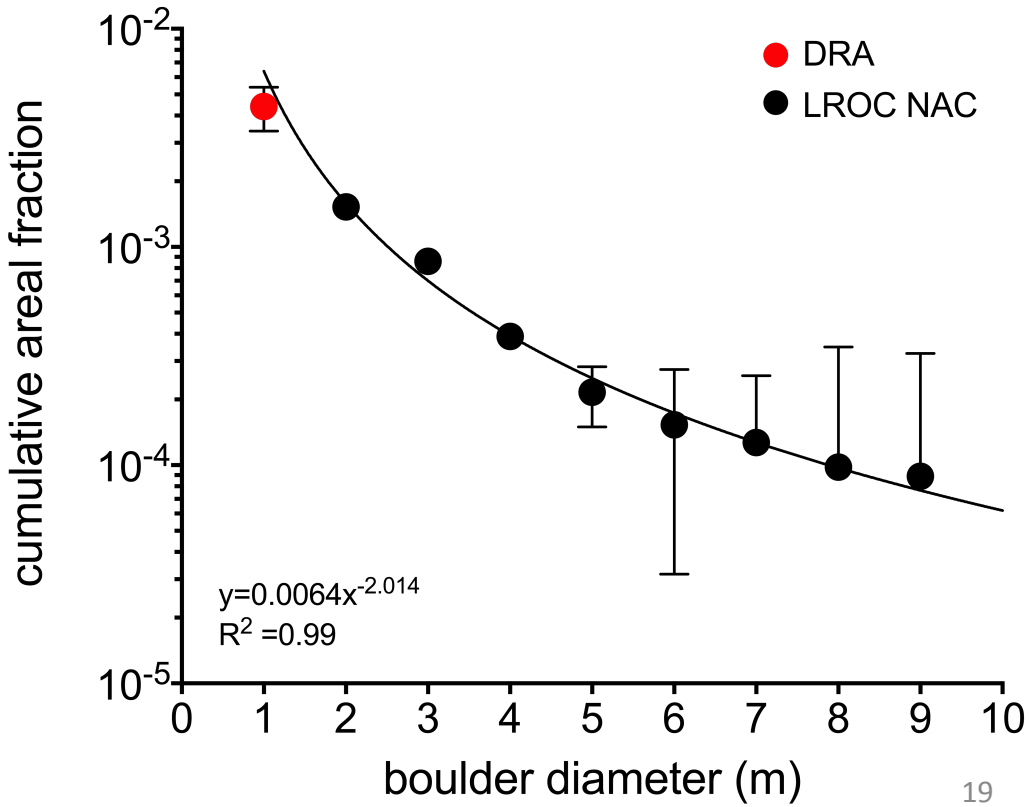
- LROC distribution is well-fit with a power law.
- LROC counts closely match DRA values



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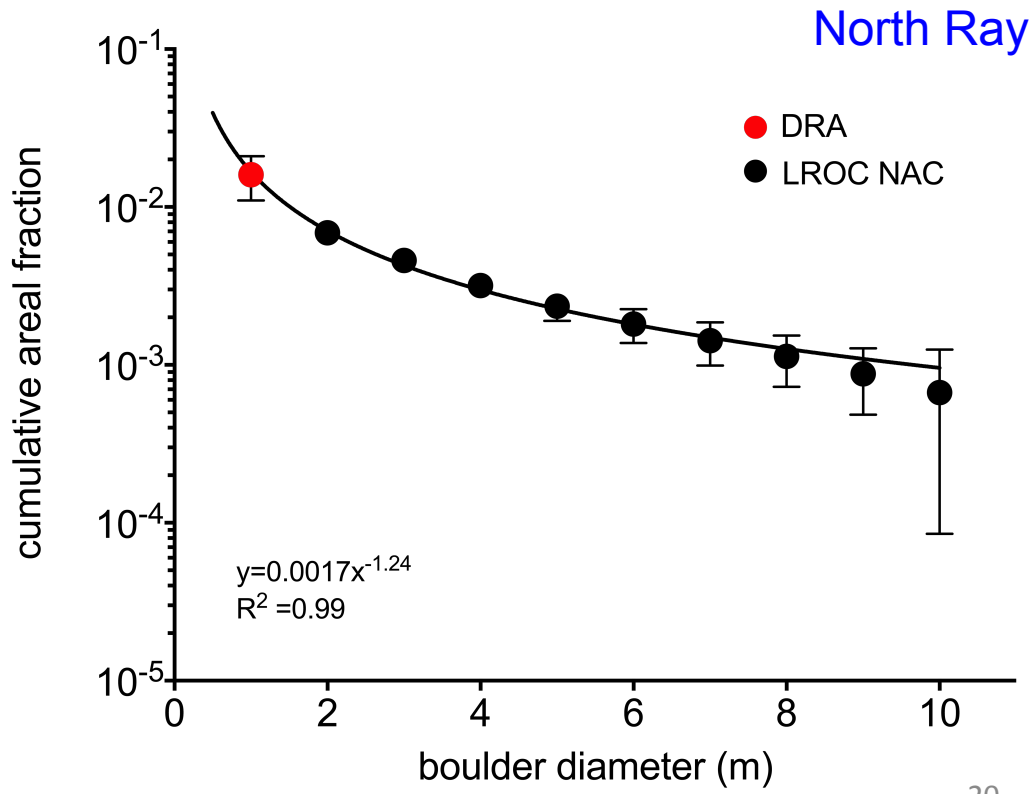
- LROC distribution is well-fit with a power law.
- LROC counts closely match DRA values
- North Ray counts also validate DRA, thus DRA values can be used to extend NAC boulder count trends to smaller boulder sizes

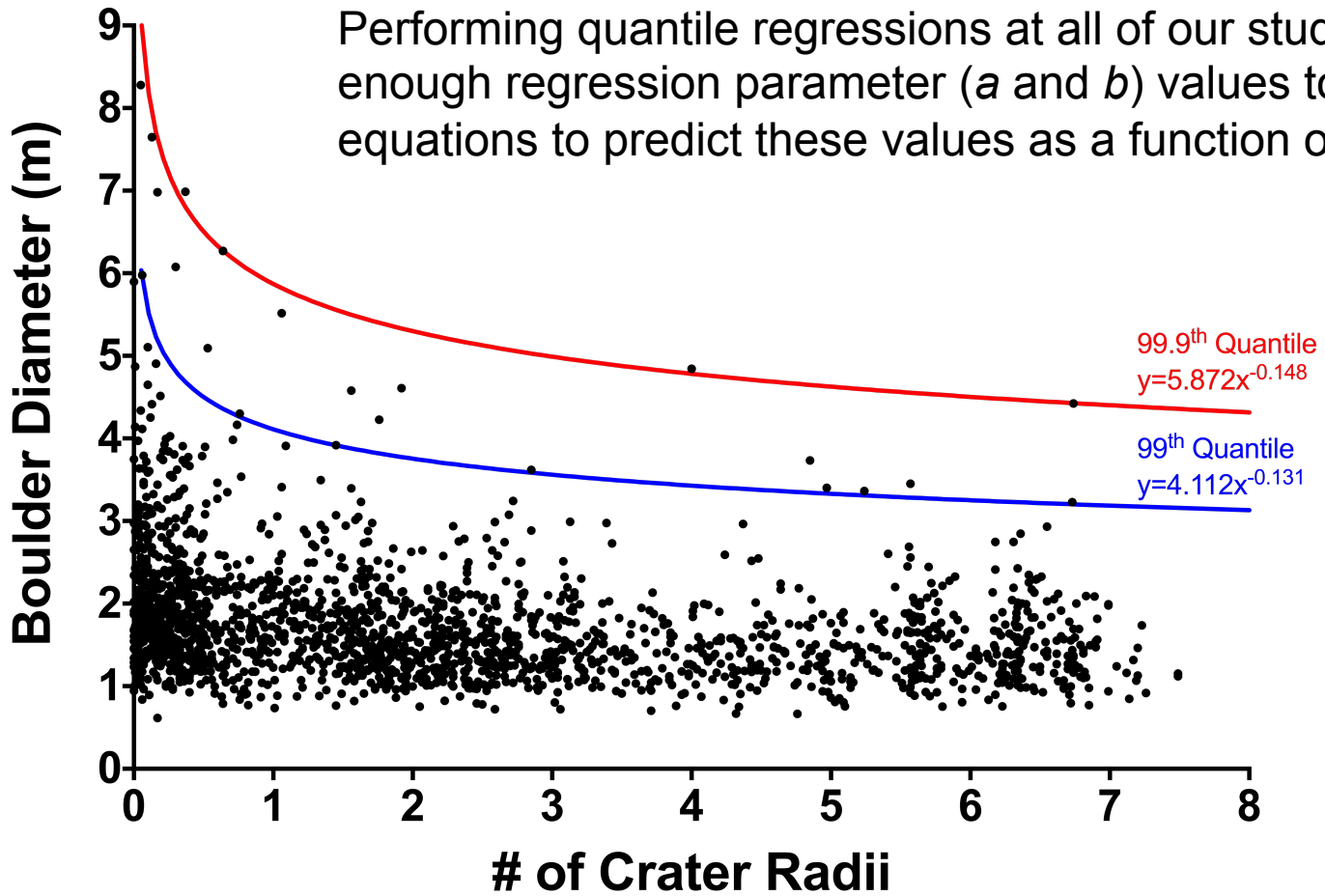


Predicting Landing Site Safety Hazards

Quantile regression curves predict the maximum boulder size at any radial distance from the crater

$$d_{max} = aR^{-b}$$

Performing quantile regressions at all of our study areas will provide enough regression parameter (*a* and *b*) values to allow us to derive equations to predict these values as a function of crater size.



Conclusions and Future Work

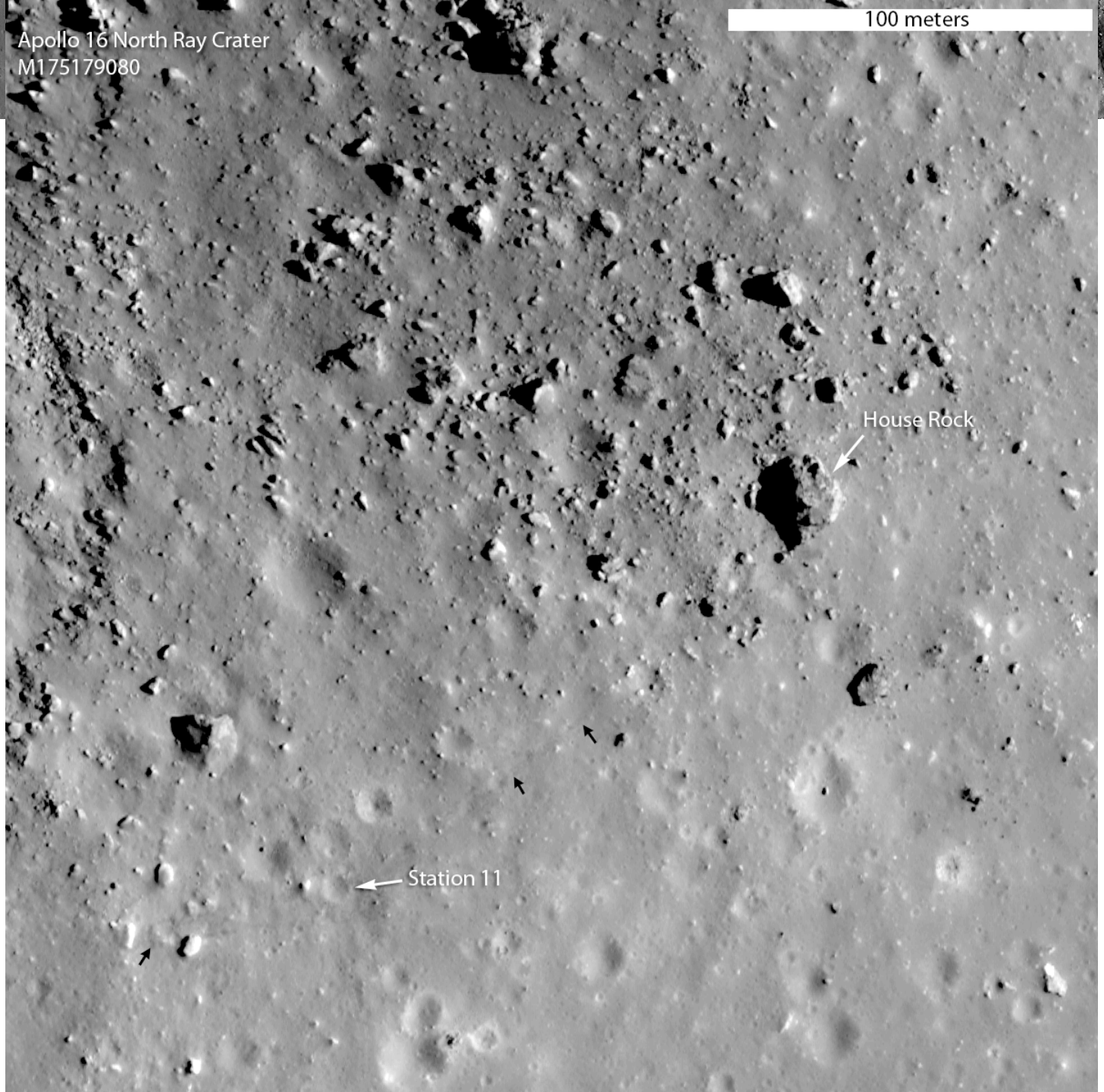
- Boulder distributions can be used to inform how far craters distribute boulders and how this distribution changes as a function of crater size, age, and target properties.
  - No boulders are seen beyond 8 crater radii from the rim of Cone crater, providing a constraint on how far craters of this size distribute boulders.
  - Similar distribution trends are seen for both Cone and North Ray craters.
- NAC boulder distributions at Cone crater and North Ray crater are consistent with DRA data
  - More counts at other study areas are needed to comprehensively verify DRA.
- Surface photography of boulders at spacecraft landing sites can be used to verify LROC counts.
  - These counts can then be used to determine landing site hazard criteria for future missions.

Future Work:

Immediate future – Compare North Ray counts with Ulrich et al. (1972) surface photography derived distributions.

Long-term - counts at craters at all/most spacecraft landing sites and comparison with age, size, and target properties

BACK-UP SLIDES


Apollo 16 North Ray Crater
M175179080
100 meters
House Rock
Station 11