

Secondary Craters and Ejecta on the Moon:

Estimating the maximum secondary sizes & A scale-dependent trend in ejecta size-velocity distributions

Kelsi Singer – Southwest Research Institute

Brad Jolliff & Bill McKinnon – Washington University in St. Louis

Note: We have a manuscript with these results under review at the Journal of Geophysical Research but I am happy to share a pre-print if you email me ☺ (ksinger@boulder.swri.edu).



Research Motivation

How can we better understand:

Impact fragmentation
&
Ejection of material?

Introduction

- One way is to use empirical data → to validate experiments and modeling
- These data can be compared for craters on the Moon, terrestrial planets, and icy satellites.

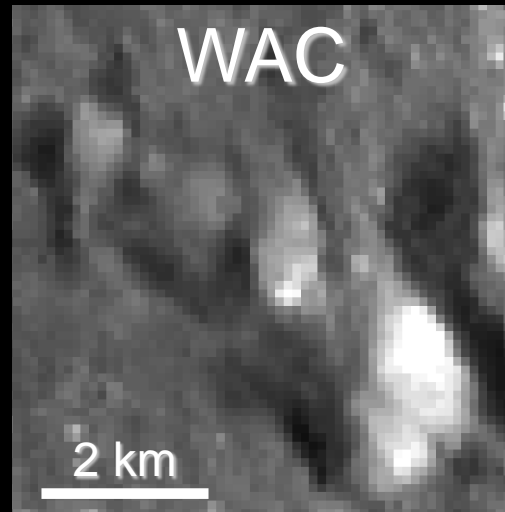


We use the Lunar Reconnaissance Orbiter Narrow and Wide Angle Camera images (NAC and WAC) to collect these data.

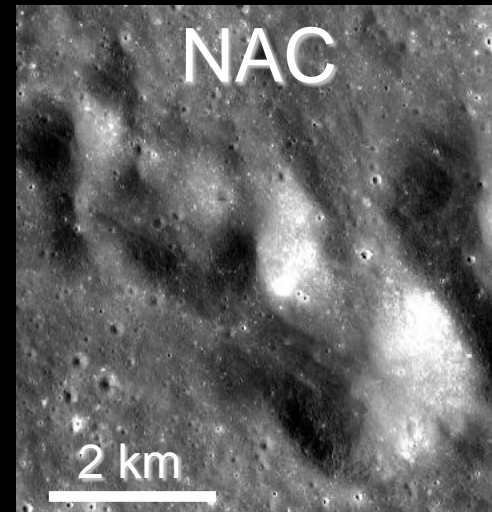


Empirical Observations with LRO WAC and NAC

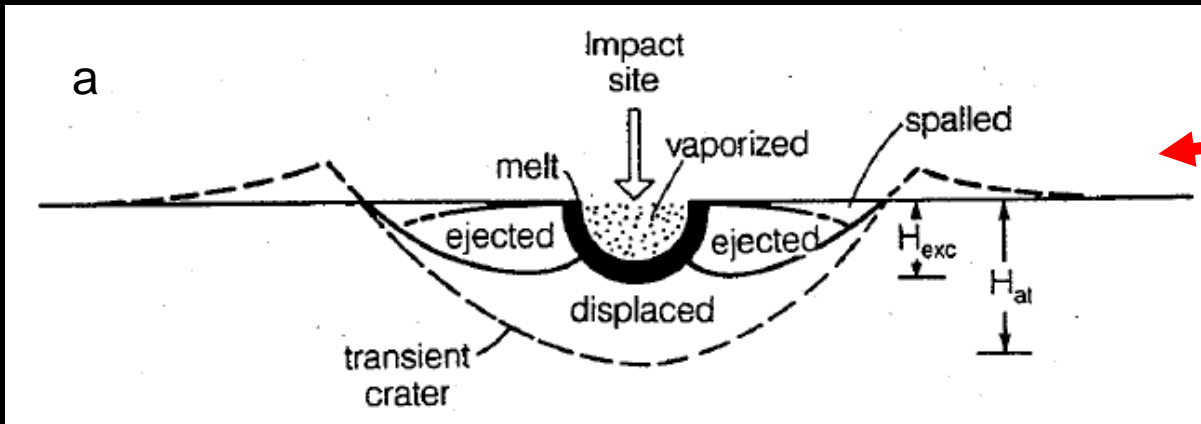
- Can see small secondaries = small ejecta fragments
- Explore a range of primary sizes and target properties
- Low and high sun images useful for ray identification
- Can use NAC to investigate secondary crater morphology



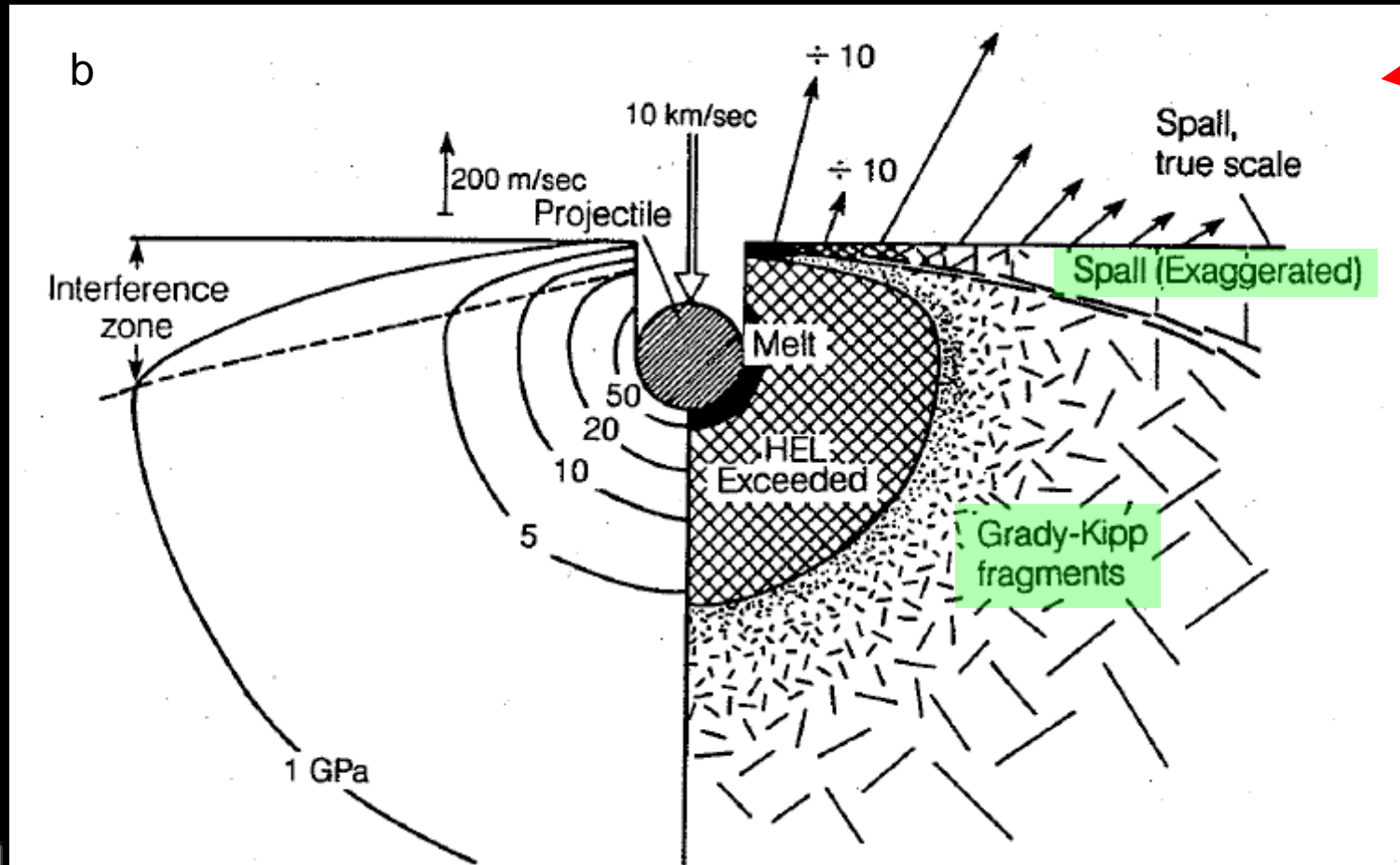
~100 m/px



~2.5 m/px



Shock wave contours and fragmentation of target material, and



Fate of material at different locations inside of the transient crater.

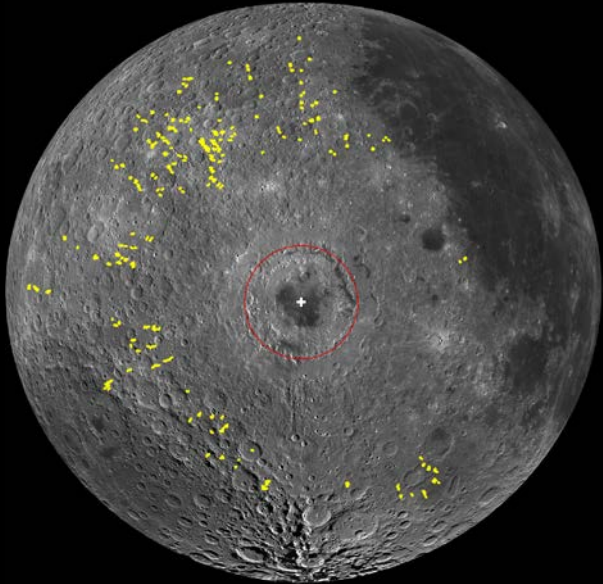
We are studying both the spalled and ejected portions (Grady-Kipp fragments).

Diagrams from Melosh, 1989

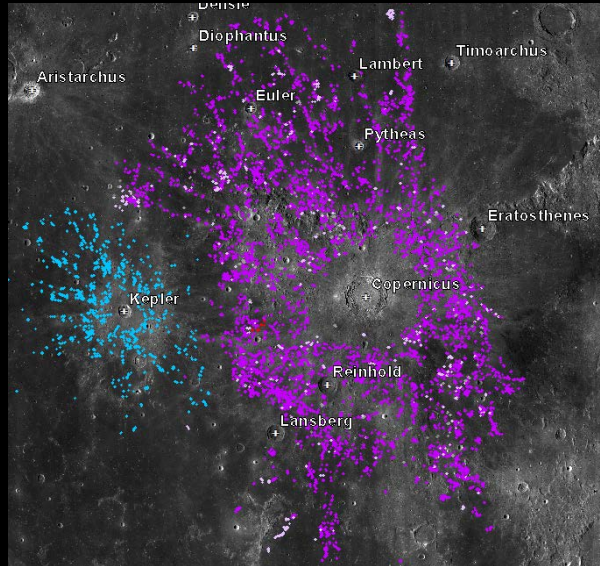
Mapping Methods

Six Secondary Crater Fields (so far!)

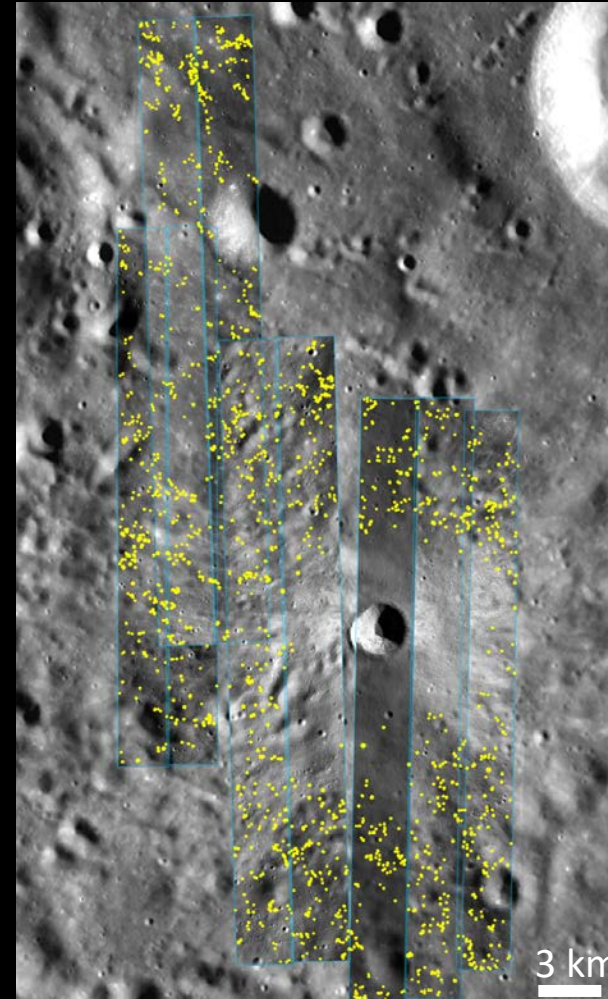
Oriente - 660 km equivalent rim (Outer Rook Ring)



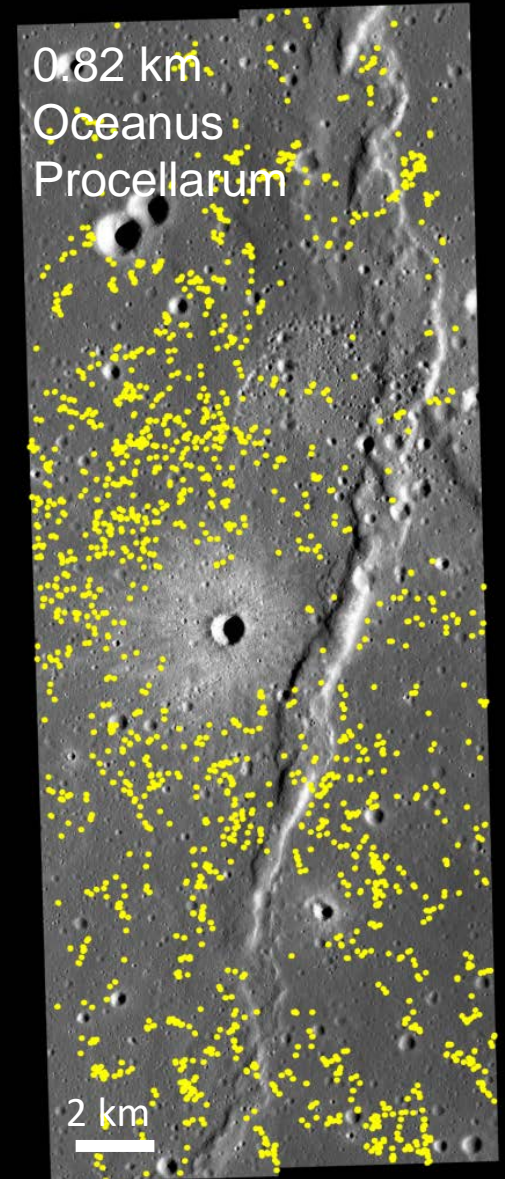
Copernicus (93 km)
& Kepler (31 km)



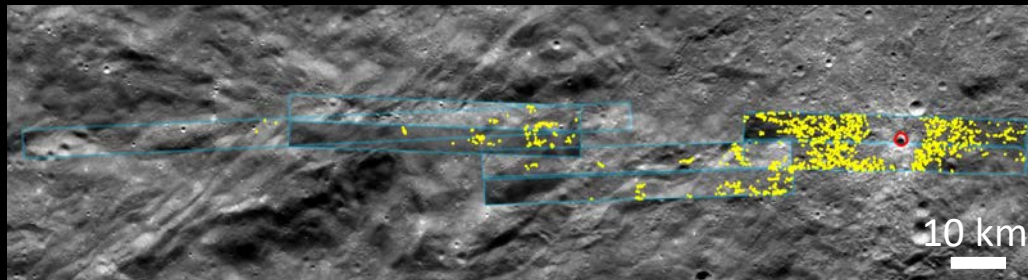
3.0 km in SPA



0.82 km
Oceanus
Procellarum



2.2 km in Orientale ejecta



Mapping Methods

- **For the 3 larger craters:** The WAC 100 m px⁻¹ global mosaic served as the base for all mapping. We also examined NAC images (~1–2 m px⁻¹) for confirmation of secondary crater morphologies.
- **For the 3 smaller craters:** NAC images with sufficient incidence angles for viewing topography were used.

Mapping Methods

Only the craters with:

- the highest likelihood of being secondaries (*see next slide)
- whose diameters were fairly clear
- and had radial indicators pointing back to the primary crater

are used in the results shown below.



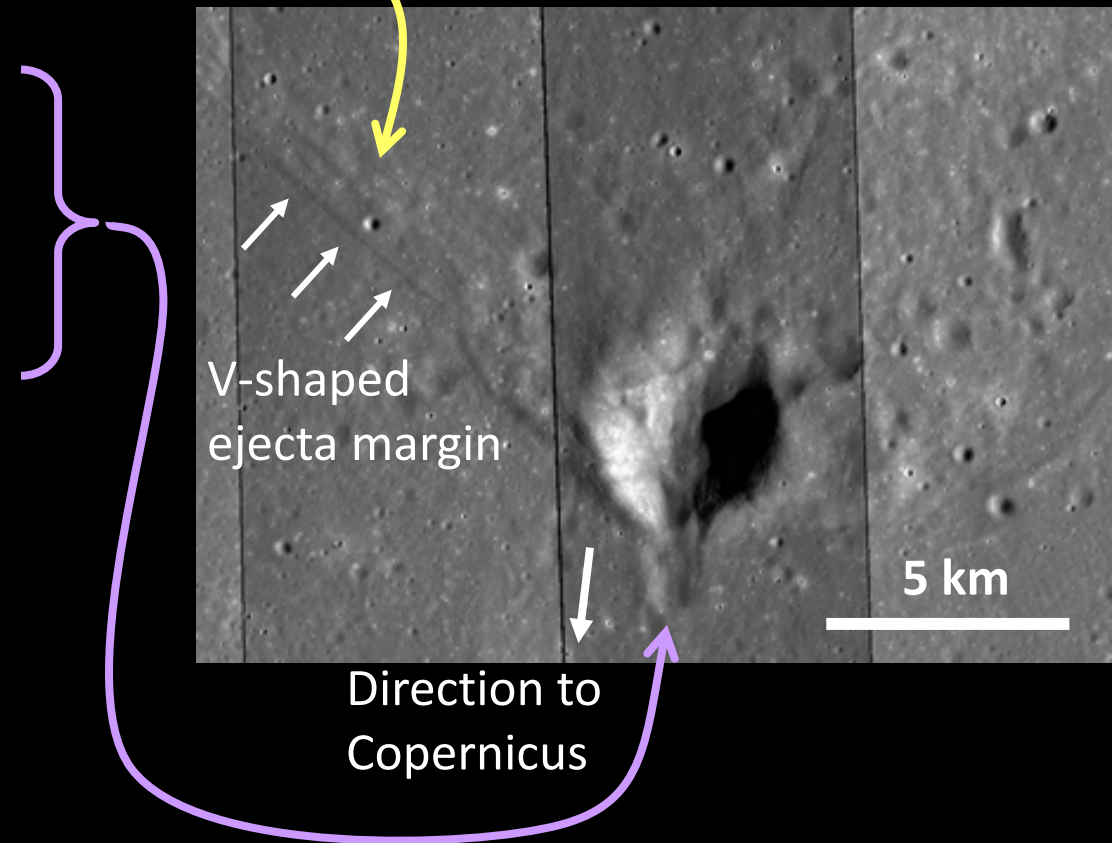
Mapping Methods

*We gave each crater a general rating as to how many morphological indicators were present, which could include:

- v-shaped or chevron-like ejecta
- elongation in the radial direction,
- asymmetrical rim heights (most often with a less well-defined rim in the downrange direction)

And:

- occurrence in a chain, cluster, or ray of craters that share these morphologies
- similar degradation state to other secondaries in the field

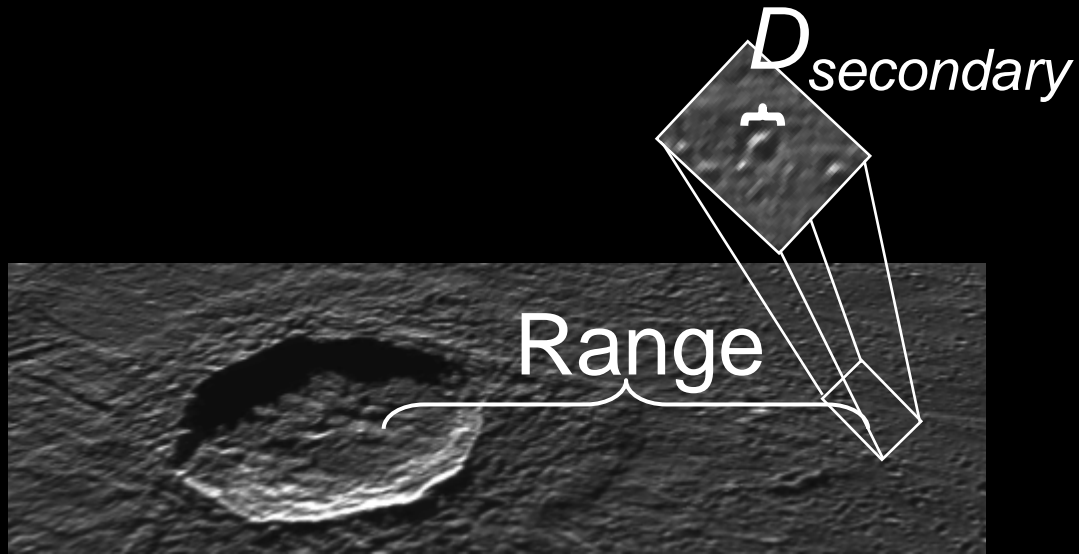


10's of thousands of potential secondary craters
were considered overall...

→ and only a fraction of those - the highest
confidence features - were retained for analysis.

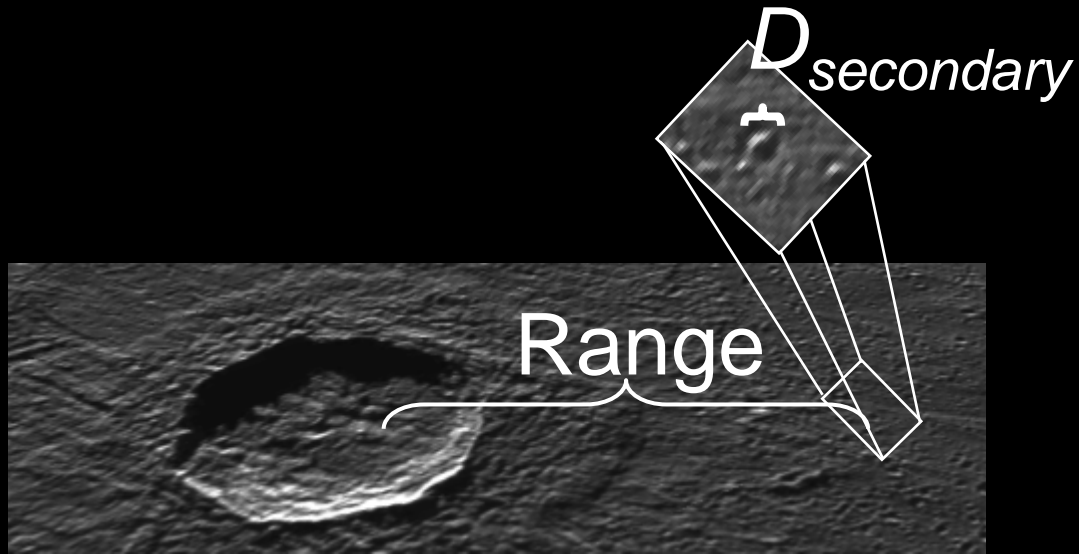
Estimating Ejecta Fragment Sizes

Measured Quantities

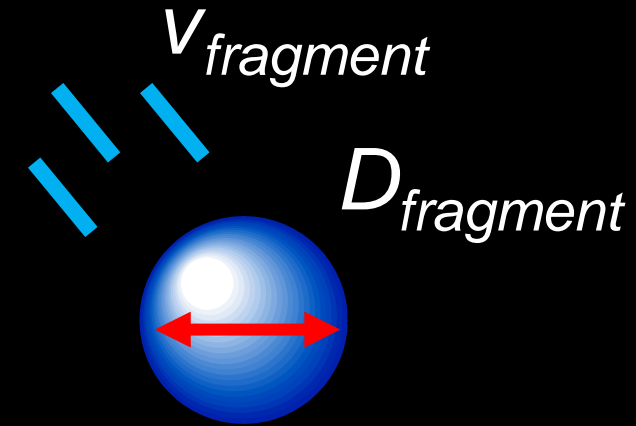


- Secondary Range
- Secondary Size

Measured Quantities



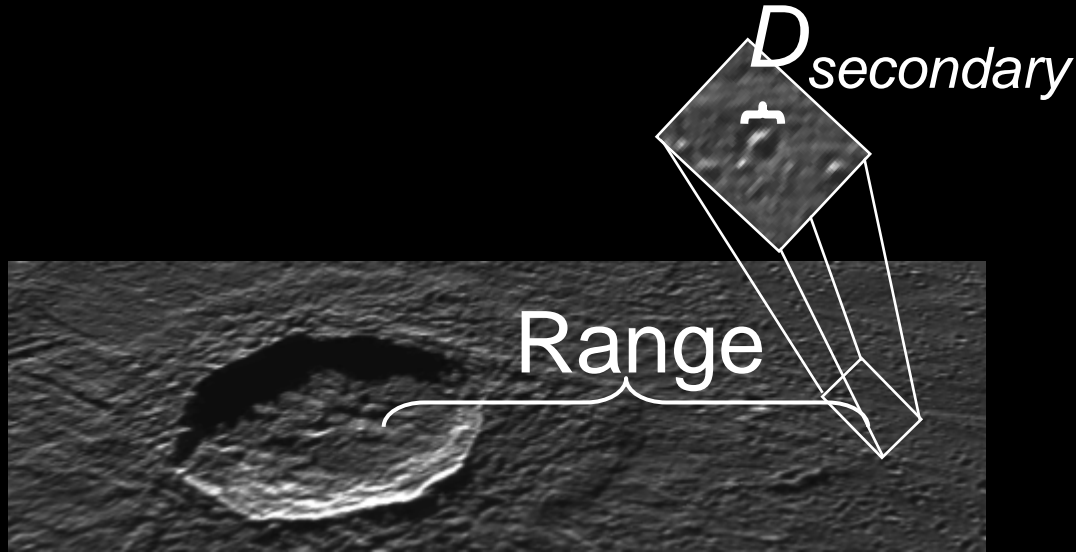
Derived Quantities



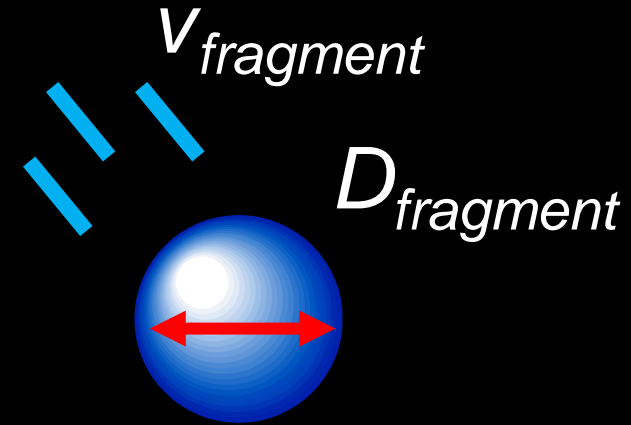
Ballistic range equation

- Secondary Range \longrightarrow 1. Fragment Velocity
- Secondary Size

Measured Quantities



Derived Quantities



Ballistic range equation

- Secondary Range \longrightarrow 1. Fragment Velocity

Scaling equations

- Secondary Size \longrightarrow 2. Fragment Size

1. Fragment Velocity

Ballistic trajectory on a sphere

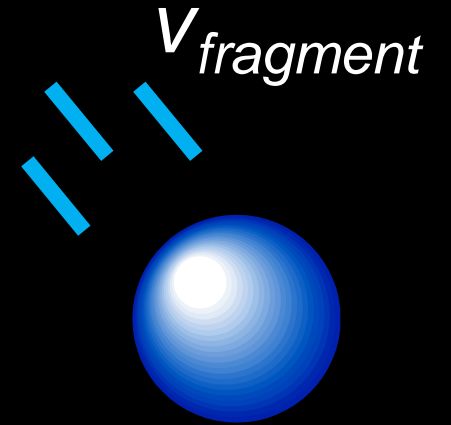
$$Range = 2R_p \tan^{-1} \left(\frac{v_{frag}^2 \sin \theta \cos \theta}{R_p g - v_{frag}^2 \cos^2 \theta} \right)$$

R_p – Radius of planet or moon

v_{frag} – velocity of ejected fragment

Assumptions:

- Launched at $\frac{1}{2}$ transient crater radius (transient estimate from McKinnon et al., 2003)
- $\theta = 45^\circ$ (see Singer et al., 2013 for discussion)
- $v_{frag, eject} = v_{frag, impact}$



2. Fragment Diameter

Schmidt-Holsapple scaling equations

$$d_{frag} = D_{sec}^{1.275} \left(g / v_{frag}^2 \right)^{0.275}$$

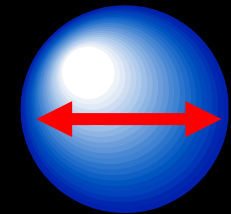
d_{frag} – Diameter of ejecta fragment

D_{sec} – Diameter of secondary crater

Details:

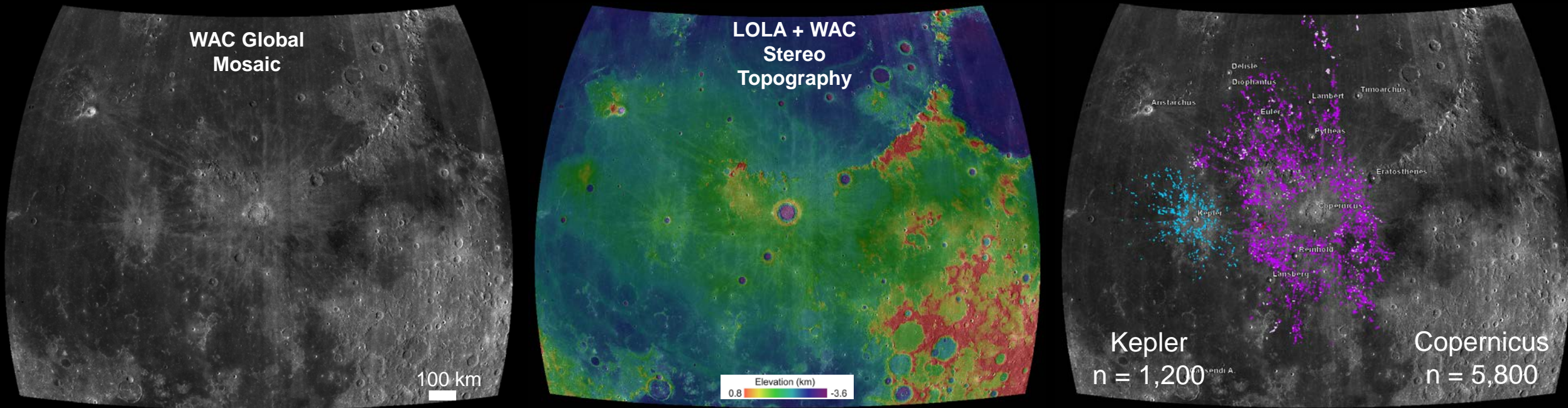
- Depth/Diameter = 0.125 for secondaries
- Material parameters for non-porous rock (e.g., Holsapple, 1993, Holsapple, 2007) – see appendix slides for a bit more info
- π_2 values consistent with gravity regime for the most part

$D_{fragment}$



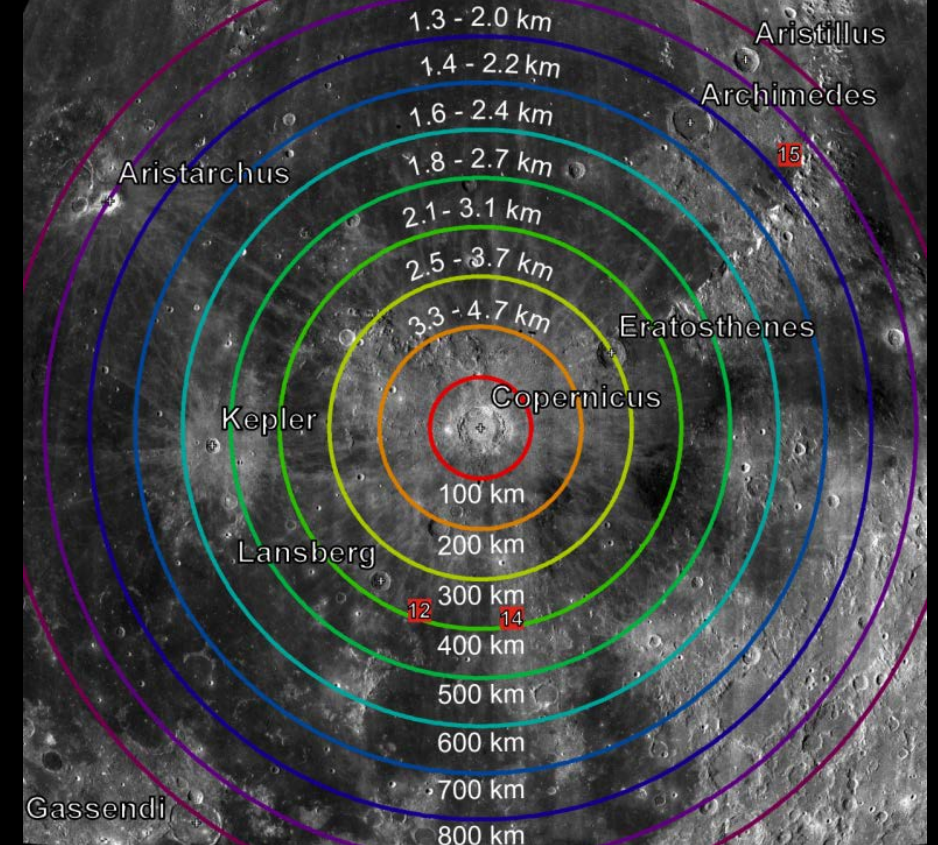
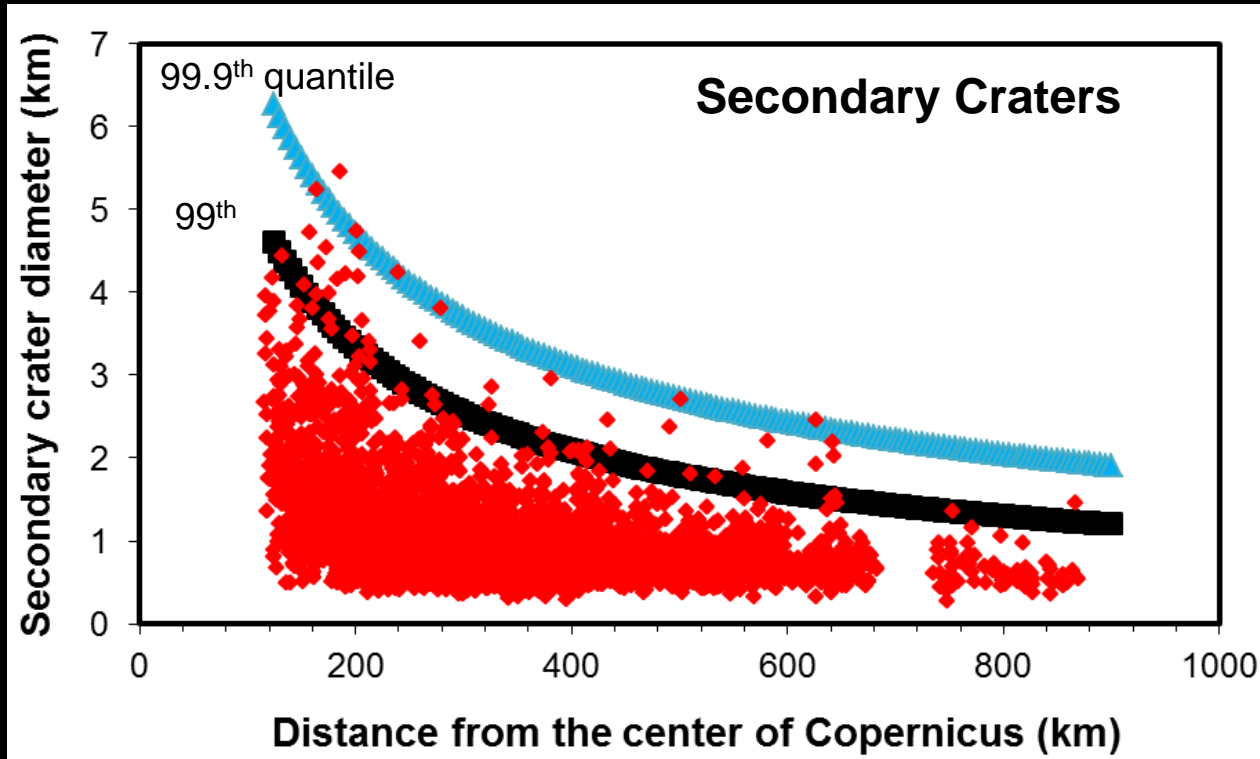
Results

Copernicus (93 km in diameter) and Kepler (31 km)



- We use Copernicus as an example in this presentation. The same results are derived for all 6 secondary crater fields.
- Copernicus has the most mapped secondaries because of its location on mare, relative youth, and large size 😊.

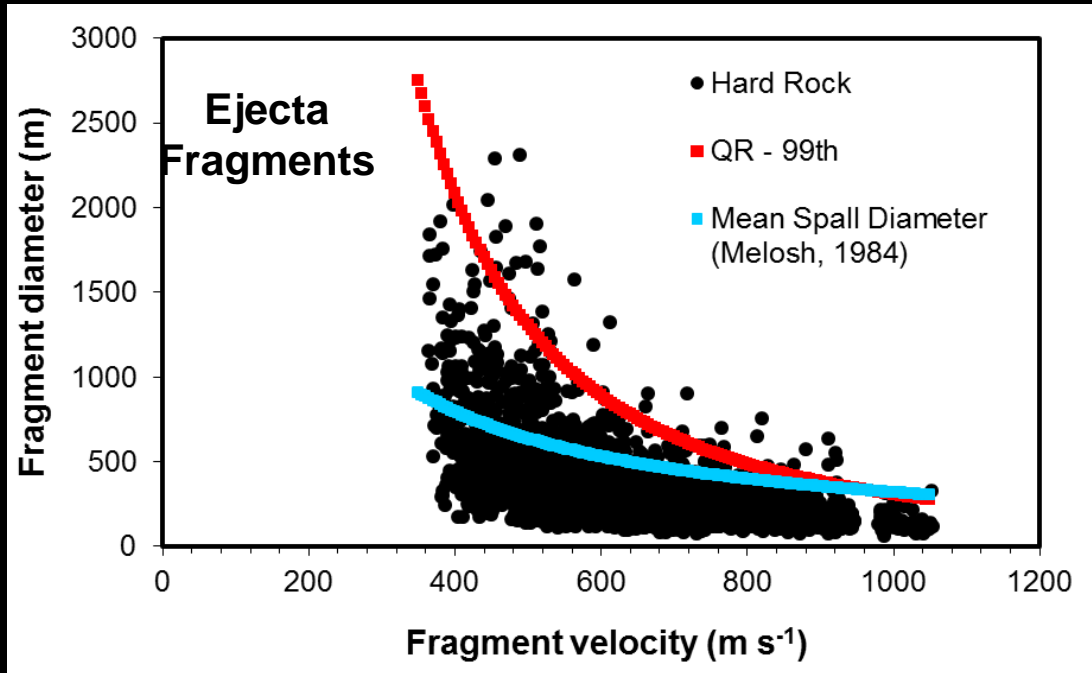
Results 1: Secondary crater size fall-off with distance (range)



- We characterize the upper envelope of the distribution using quantile regression.
- The 99th quantile represents a typical maximum crater size.
- The 99.9th quantile represents more of an absolute maximum size.

These two values give a range of the **maximum secondary sizes expected at a given distance.**

Results 2: Ejecta fragment size fall-off with ejection velocity



- We also fit the upper envelope of the estimated ejecta fragment sizes as a function of velocity (red curve).
- For reference, the estimated spall sizes from Melosh 1984 are shown (blue line).

Results 3: Scale-dependence

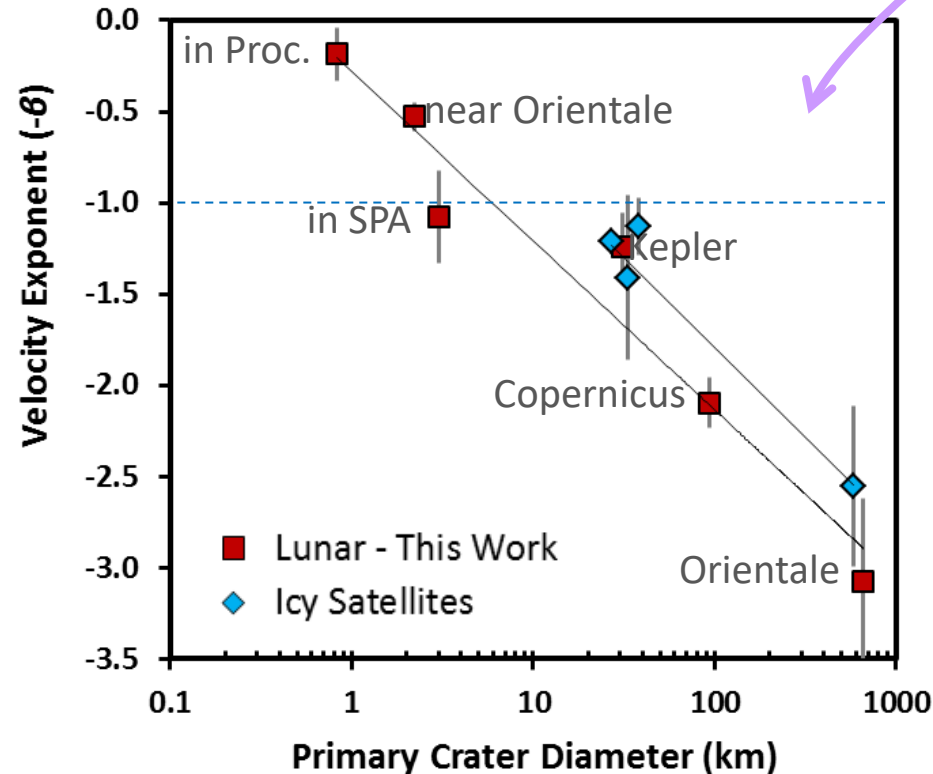
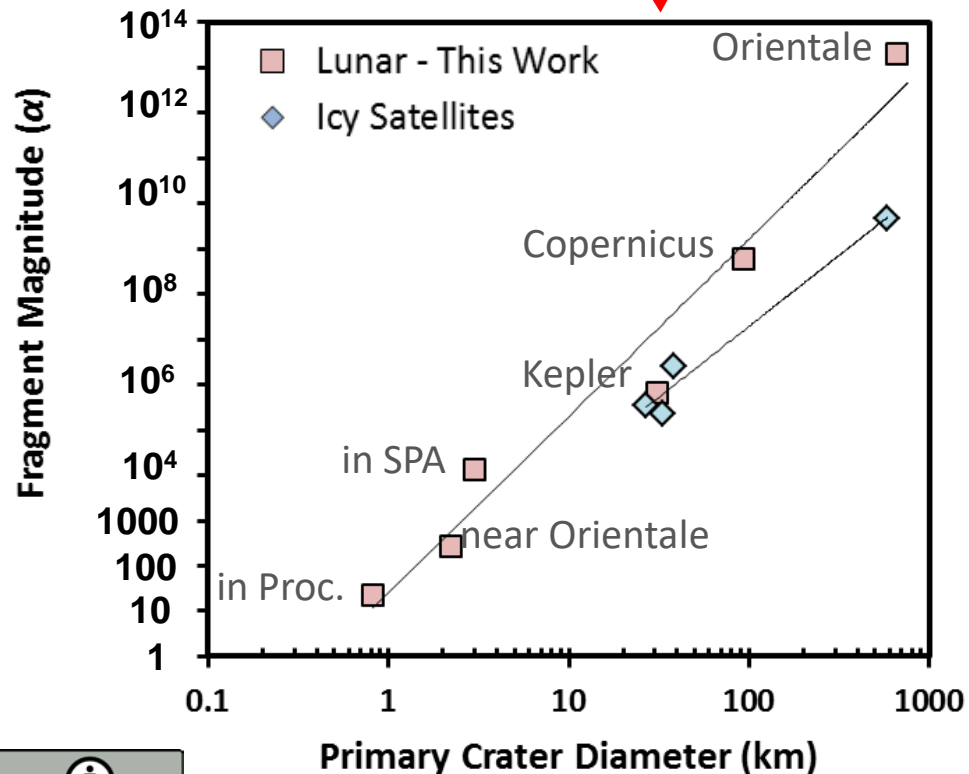
We use quantile regression to find a power-law fit to the upper envelope of:

(1) Secondary craters as a function of distance

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

(2) Estimated fragment sizes and velocities.

$$d_{frag,max} = \alpha v_{ej}^{-\beta}$$



We find there is a trend based on the size of the primary crater.

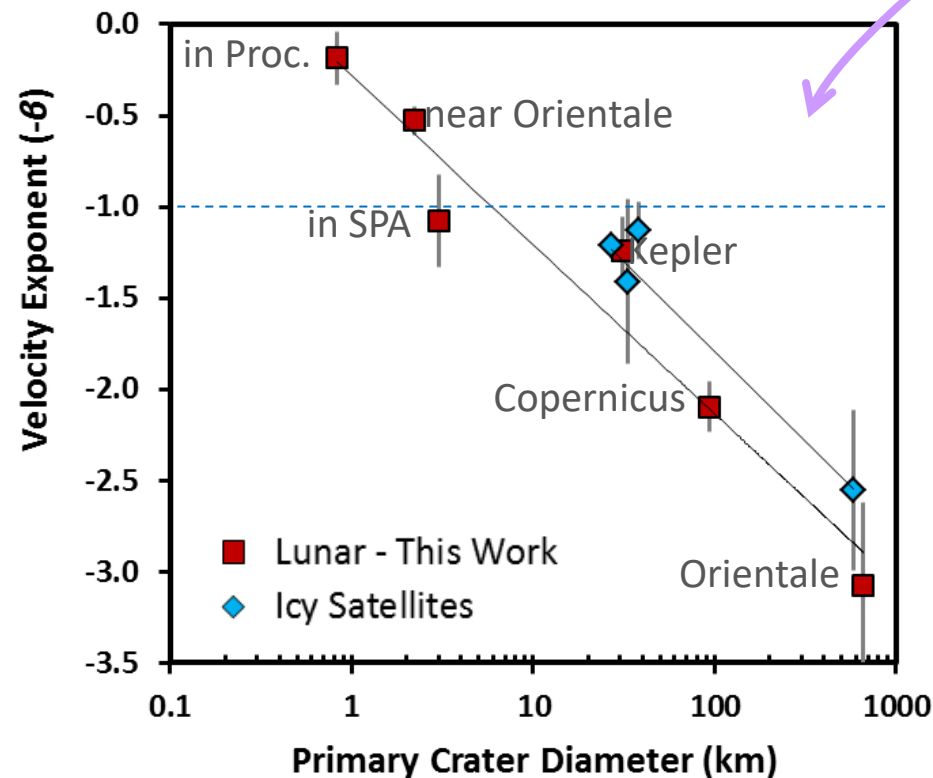
Results 3: Scale-dependence

Finding: Larger primary craters have a steeper drop-off in the ejecta fragment size with velocity.

For example:

- Orientale and Copernicus secondaries, and the therefore the estimate ejecta fragment sizes, fall off very quickly.
- For the smaller craters, the secondary sizes don't change very much with distance from the crater.
- We also looked at the secondary sizes and fragment velocities scaled by relevant factors (see appendix slides) and see the same trend.

$$d_{frag,max} = \alpha v_{ej}^{-\beta}$$

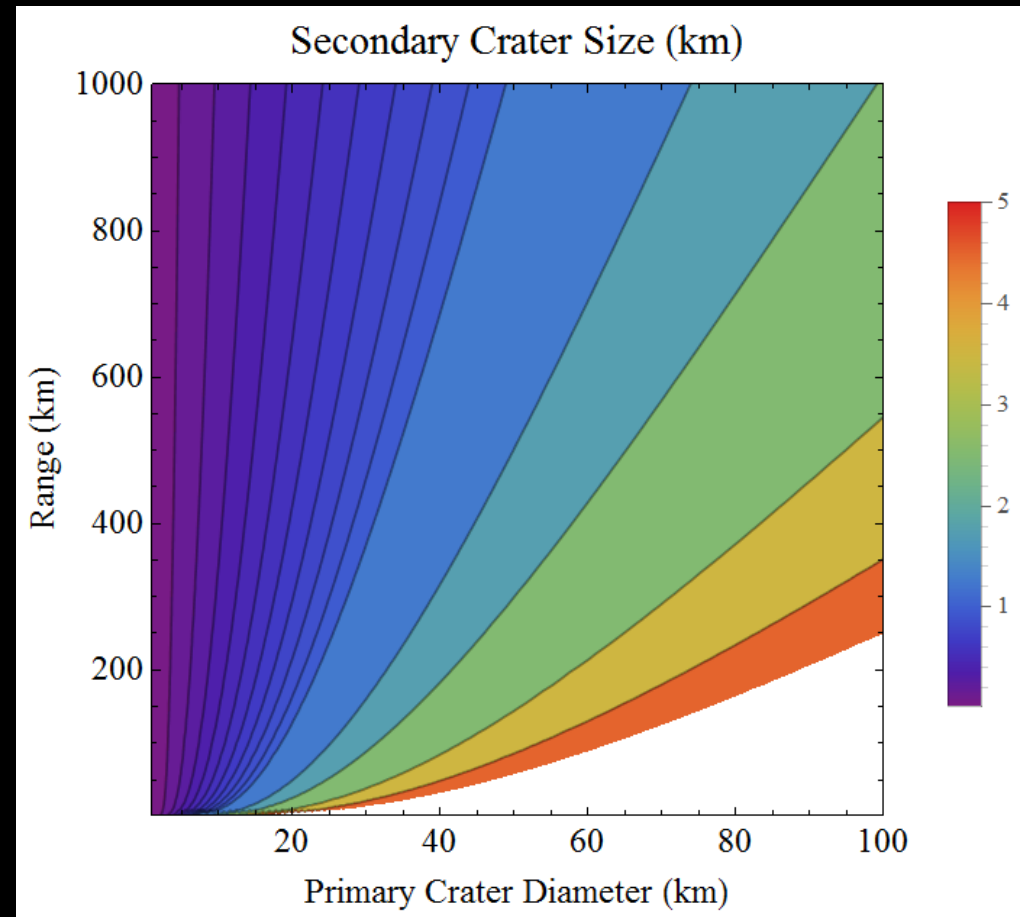


We find there is a trend based on the size of the primary crater.

Please see Singer et al., 2013 for icy satellite data.

Implications 1: Secondary Craters

- The ~*maximum* size of secondary craters at a given distance from a given diameter primary crater can be estimated with our results.



- We will continue to refine these estimates as we collect more results.

Implications 2: Ejecta fragments

- The ~*maximum* size of ejecta fragments at a given velocity ejected from a given diameter primary crater can be estimated with our results.

Implications 2: Ejecta fragments

- The ~*maximum* size of ejecta fragments at a given velocity ejected from a given diameter primary crater can be estimated with our results.
- The max size of fragments ejected at escape velocity can be estimated.

Primary Crater	Primary diameter (km) ^a	Number of secondaries used in the analysis	Largest observed secondary (km) ^b	Average of largest 5 secondaries (km) ^b	Estimated <u>maximum</u> fragment size at escape velocity (m) ^c
Orientale	660	245	26 (4%)	23 (4%)	860
Copernicus	93	4,565	5.5 (6%)	4.9 (5%)	50
Kepler	31	1,205	1.4 (5%)	1.3 (4%)	40
Unnamed in SPA	3.0	1,884	0.18 (5%)	0.16 (5%)	3
Unnamed near Orientale	2.2	2,645	0.10 (5%)	0.08 (4%)	5
Unnamed in Procellarum	0.83	1,728	0.04 (5%)	0.04 (5%)	5

^aFinal diameter for Orientale is estimated at the Outer Rook Mountains.

^bPercentage of the primary diameter given in parentheses.

^cFragment sizes are estimated with quantile regression fit parameters (all details in the paper under review).

Conclusions

- We find a scale dependence to the dynamic fragmentation that occurs during an impact event that is not considered in most analytical models of fragmentation (e.g., Grady-Kipp).
- We provide an equation for estimation of the maximum size of secondary craters with distance from a given primary crater. This can be used to estimate the maximum size of secondary craters across the Moon.

Future Work

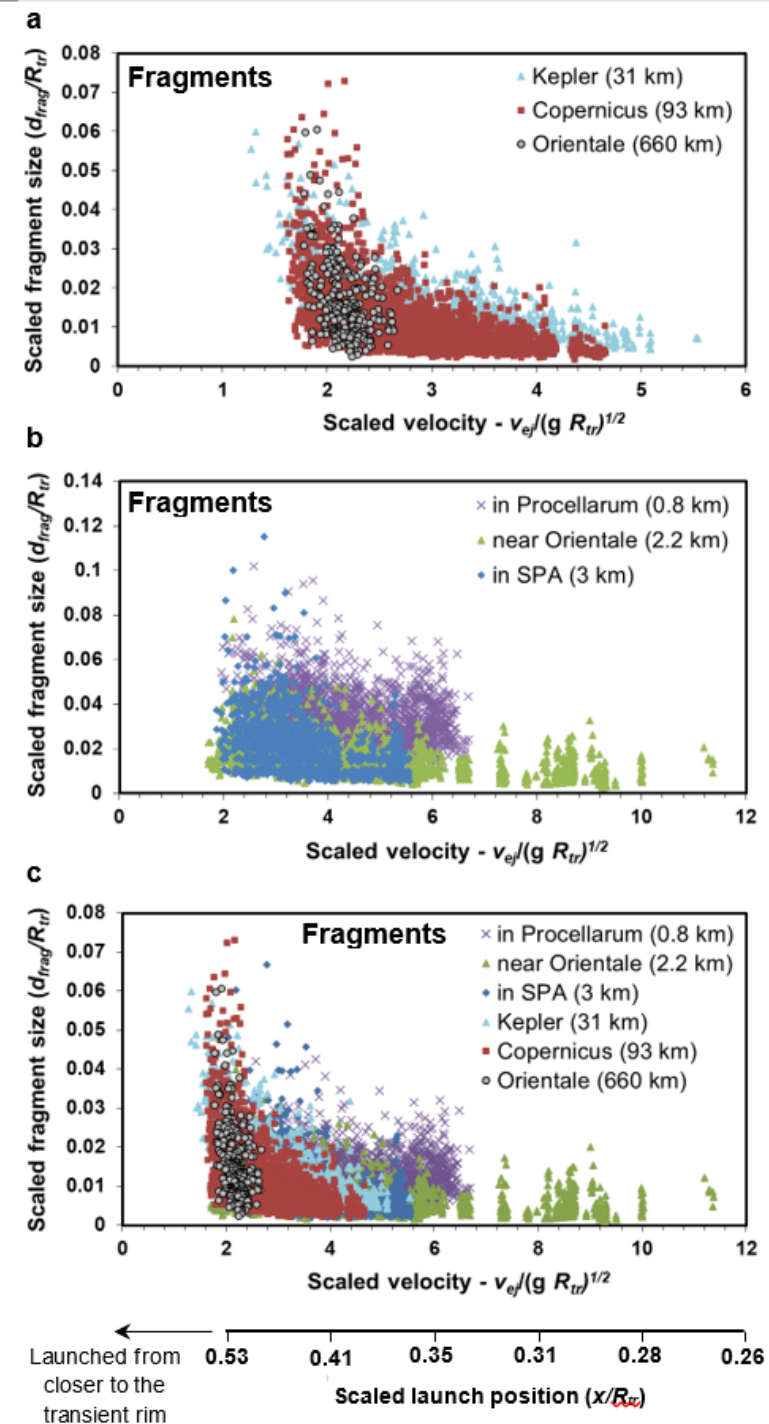
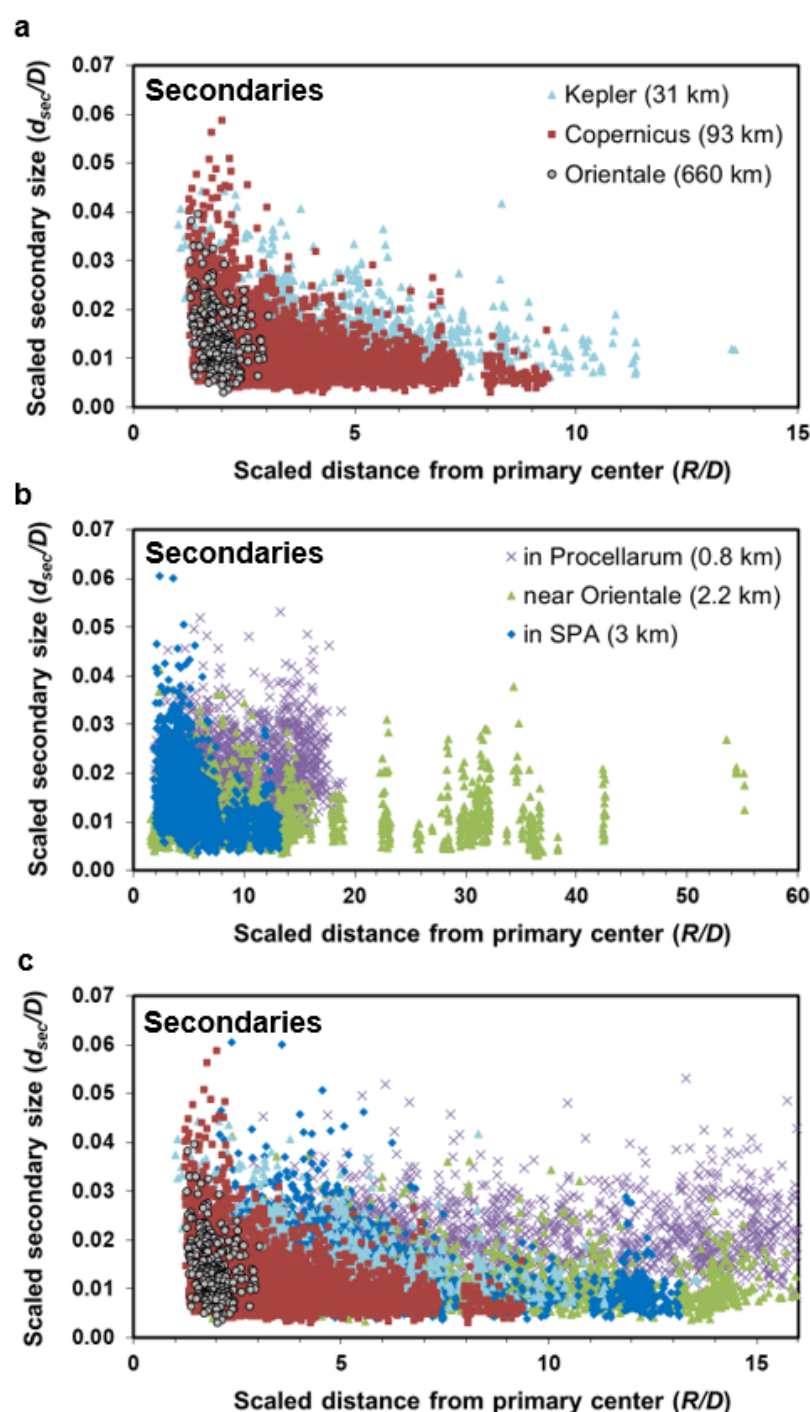
- More mapping!
- Comparison to icy satellites and other rocky bodies.
- Work is currently in progress to compare to Mercury, where the influence of gravity can be considered in comparison to the lunar results.

Appendix Slides

Normalized Distributions

For more information on the normalizations see Singer et al. 2013.

Scaled launch positions from Housen and Holsapple, 2011.



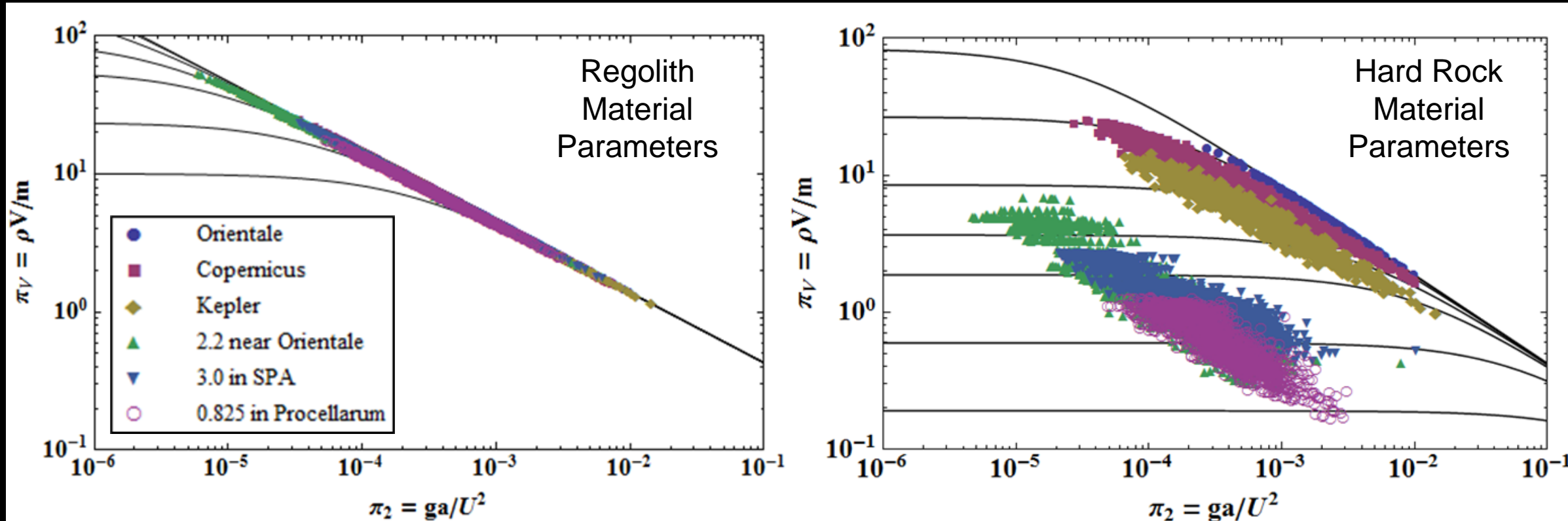
Notes on Scaling

- We used several different material parameters for scaling from the secondary crater diameters to ejecta fragment diameters (e.g., Holsapple, 1993, Housen and Holsapple, 2011).
- “Hard rock” material parameters, representing a non-porous surface, are shown above as an example.
- We also used “regolith” material parameters representing a porous surface as an alternative endmember in the paper.

Notes on Scaling

And for those of you who like to look at the π -values ☺, here they are for the secondary craters mapped in this project.

Cratering efficiency



Gravity-scaled size

Gravity-scaled size

References

- Holsapple, K. A., 1993. The scaling of impact processes in planetary sciences. *Annu. Rev. Earth Planet Sci.* 21, 333-373.
- Housen, K. R., Holsapple, K. A., 2011. Ejecta from impact craters. *Icarus* 211, 856-875.
doi:10.1016/j.icarus.2010.09.017
- Melosh, H. J., 1984. Impact ejection, spallation, and the origin of meteorites. *Icarus* 59, 234-260.
- Melosh, H. J., 1989. *Impact Cratering: A Geologic Perspective*. Oxford Univ. Press, New York.
- Singer, K. N., Jolliff, B. L., McKinnon, W. B., 202X. Lunar Secondary Craters and Scaling to Ejected Blocks Reveals Scale-dependent Fragmentation Trend. *J. Geophys. Res.* Under Review.
- Singer, K. N., McKinnon, W. B., Nowicki, L. T., 2013. Secondary craters from large impacts on Europa and Ganymede: Ejecta size–velocity distributions on icy worlds, and the scaling of ejected blocks. *Icarus* 226, 865-884.