Secondary Craters and Ejecta

1st set of results: Singer et al. 2020 (JGR)

Kelsi Singer – Southwest Research Institute

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

Continued Lunar/Mercury/Mars work:

Julie Stopar, Clark Chapman, Lillian Ostrach

Helle Skjetne, Cristian Udovicic, Mikayla Huffman

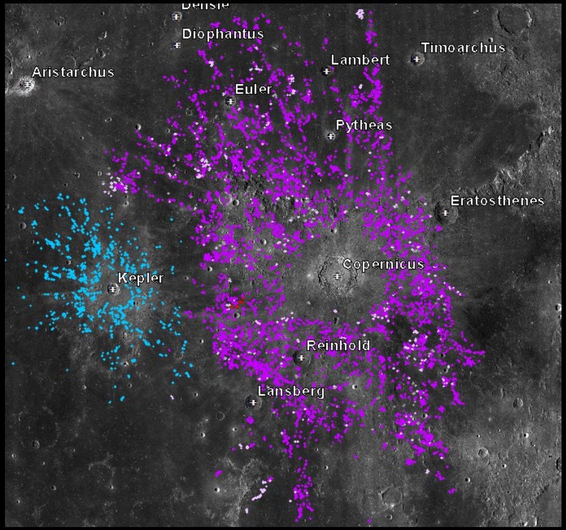
Topics

1. Research Motivation
2. Secondary Craters
3. Ejecta Fragments
4. Future Work

Research Motivation

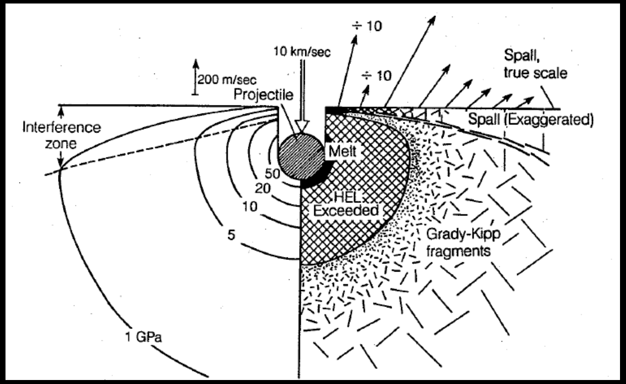
How can we use empirical data to better understand:

The distribution of secondary craters



Impact fragmentation

Ejection of material



Comparative Planetology

Singer et al., 2020

Singer et al., 2013

Material differences

Gravity

Current/future work

Lots of Results!

1. Secondary Craters

Secondary morphologies

Secondary spatial distributions

Maximum size of secondaries as a function of:

- Distance from primary
- Size of the primary

2. Ejecta Fragments

Size-velocity distributions

Largest fragments at escape velocity

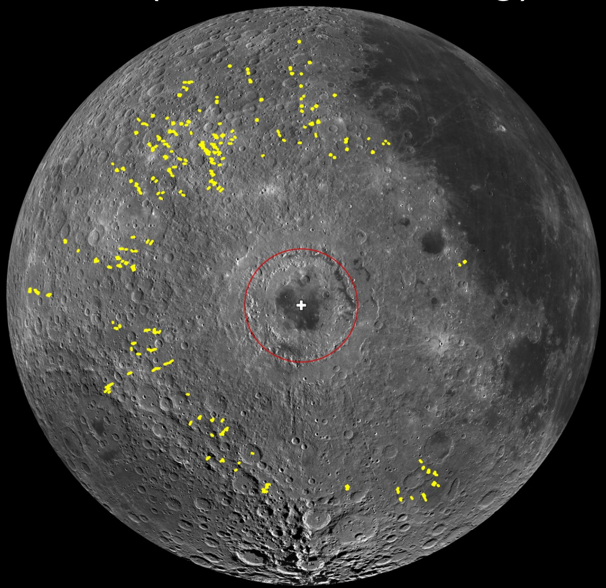
Fragment sizes consistent with forming auto-secondaries?

Part 1 – Secondary Craters

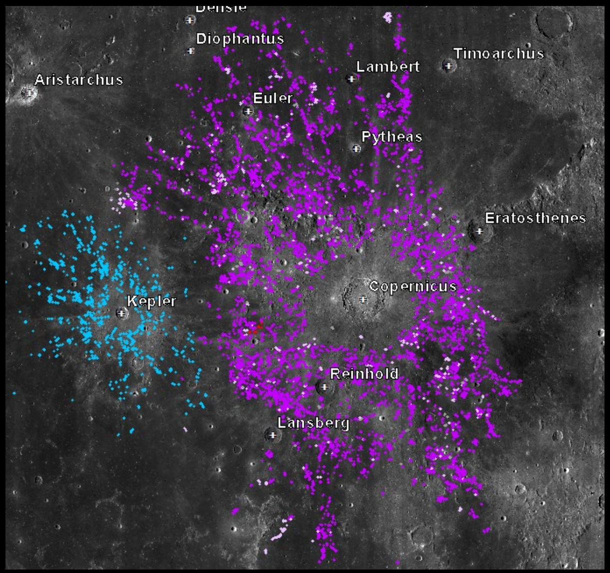
Mapping Methods

Lunar: Six Secondary Crater Fields (first paper)

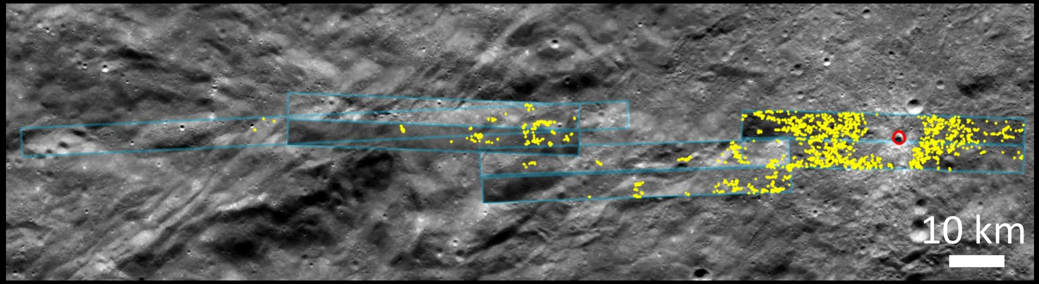
Orientale - 660 km equivalent rim (Outer Rook Ring)



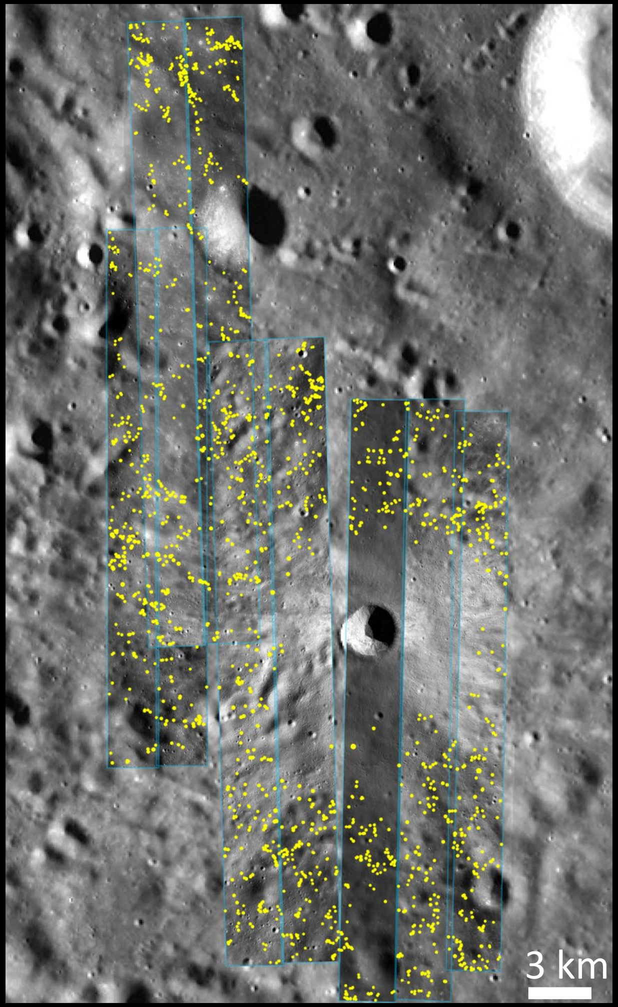
Copernicus (93 km) & Kepler (31 km)

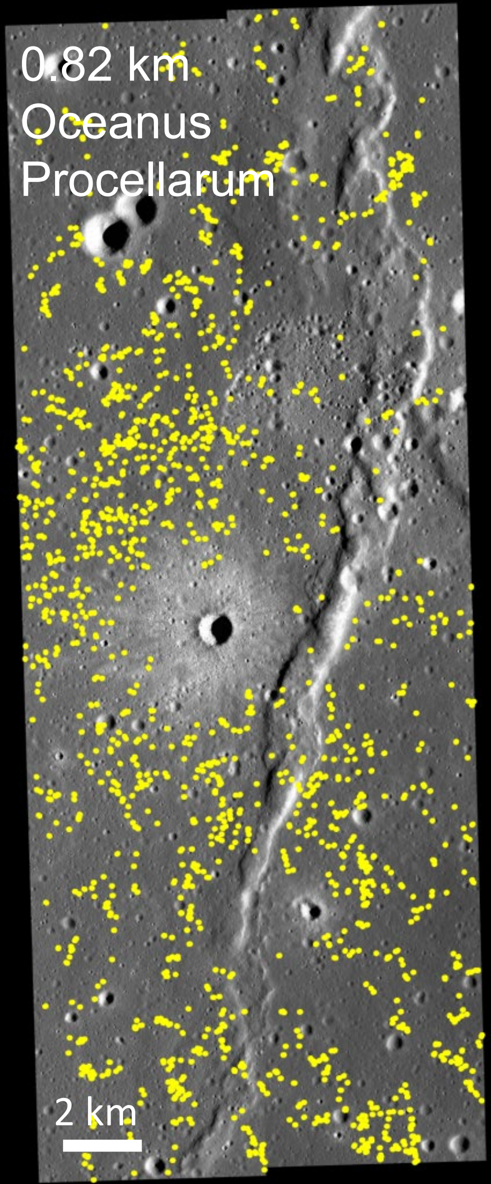


2.2 km in Orientale ejecta



3.0 km in SPA





LROC WAC and NAC

Singer et al., 2020, JGR

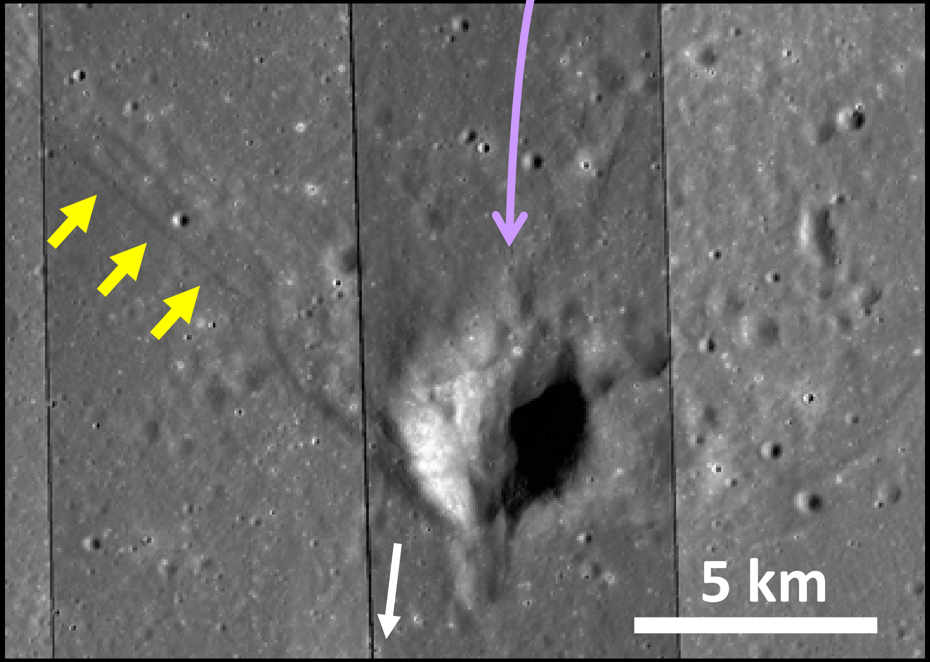
Different than primary crater mapping!

1. Different research questions:
   - Learn about ejecta and fragmentation
   - Maximum secondary size with distance
2. Cannot capture all of them
   - Large sample sizes
   - Statistical and error analysis
   - Examination of data biases

Morphology

Splatty down-range rim

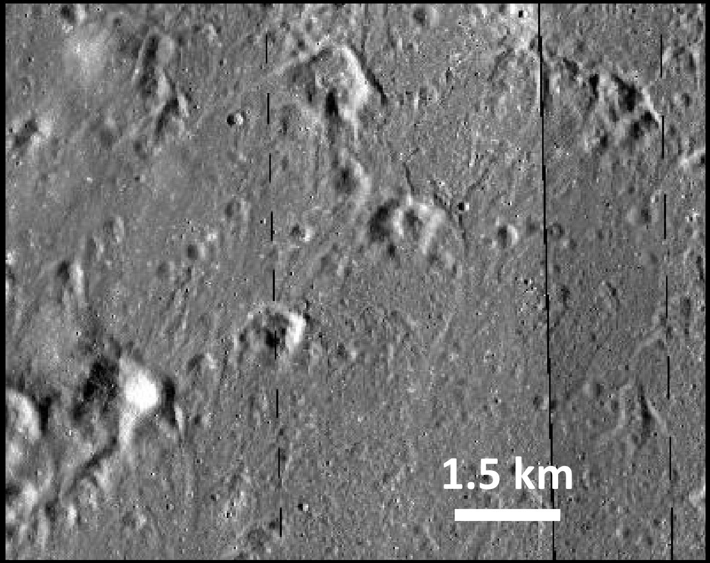
V-shaped ejecta

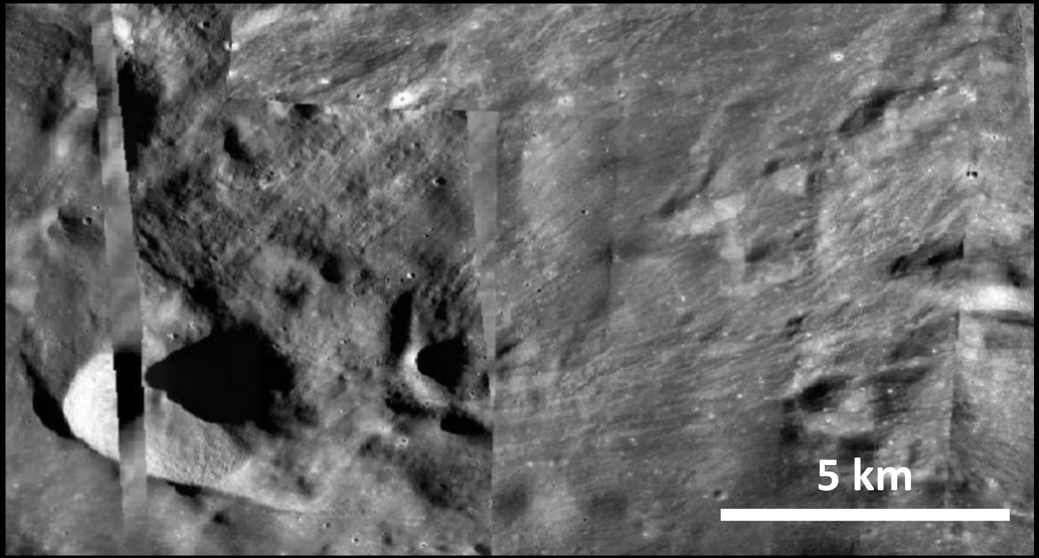


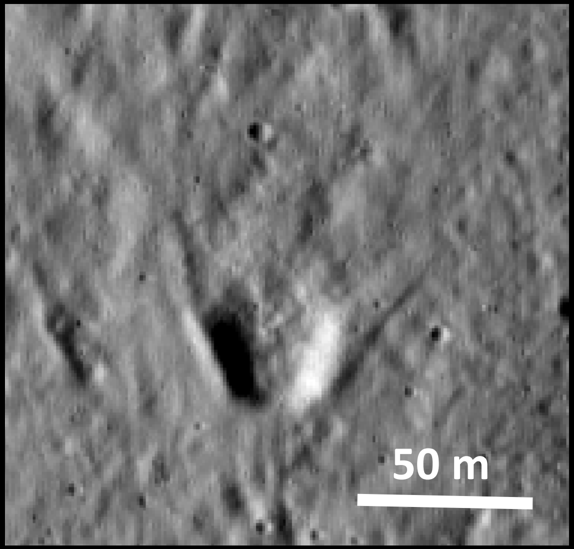
Direction to Copernicus

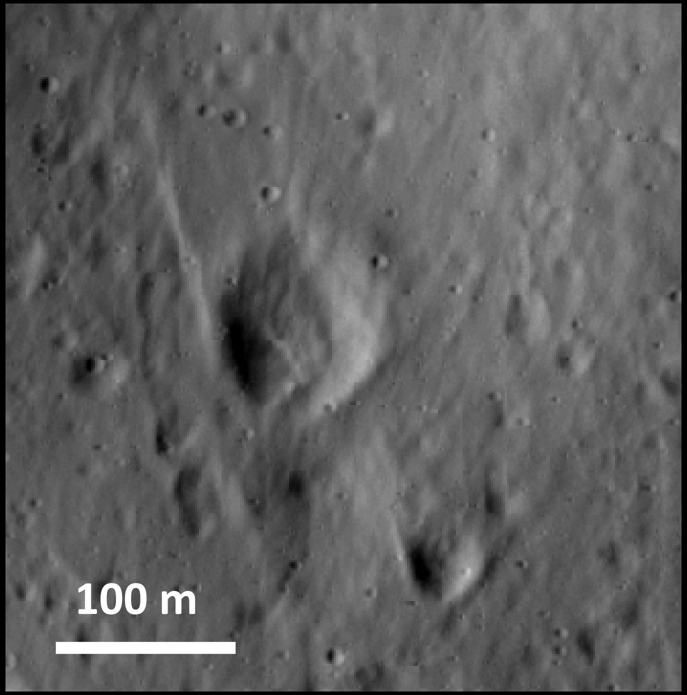
Chains, Clusters, Bright Rays

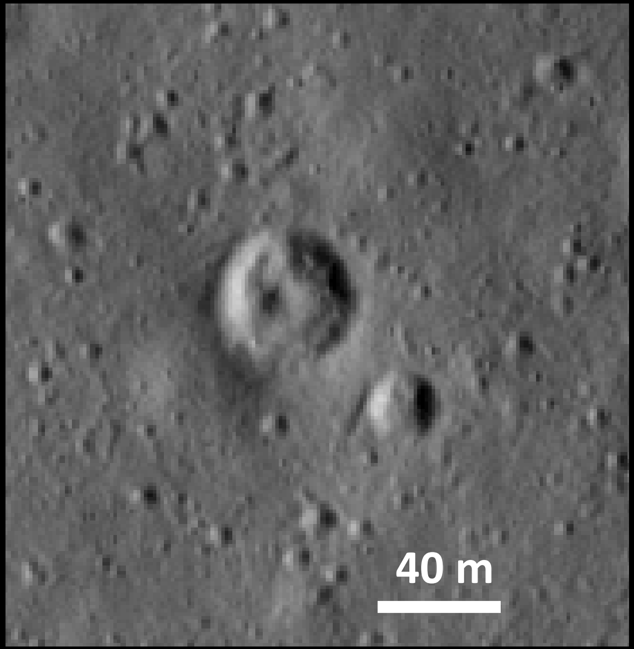
LROC WAC and NAC shown here (we also use some Kayuga)

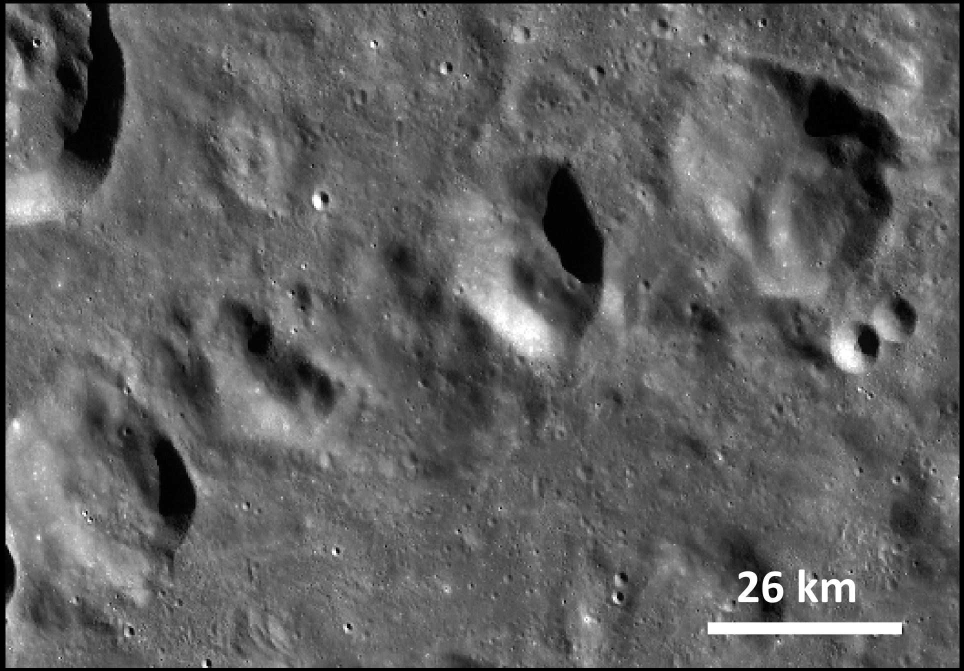












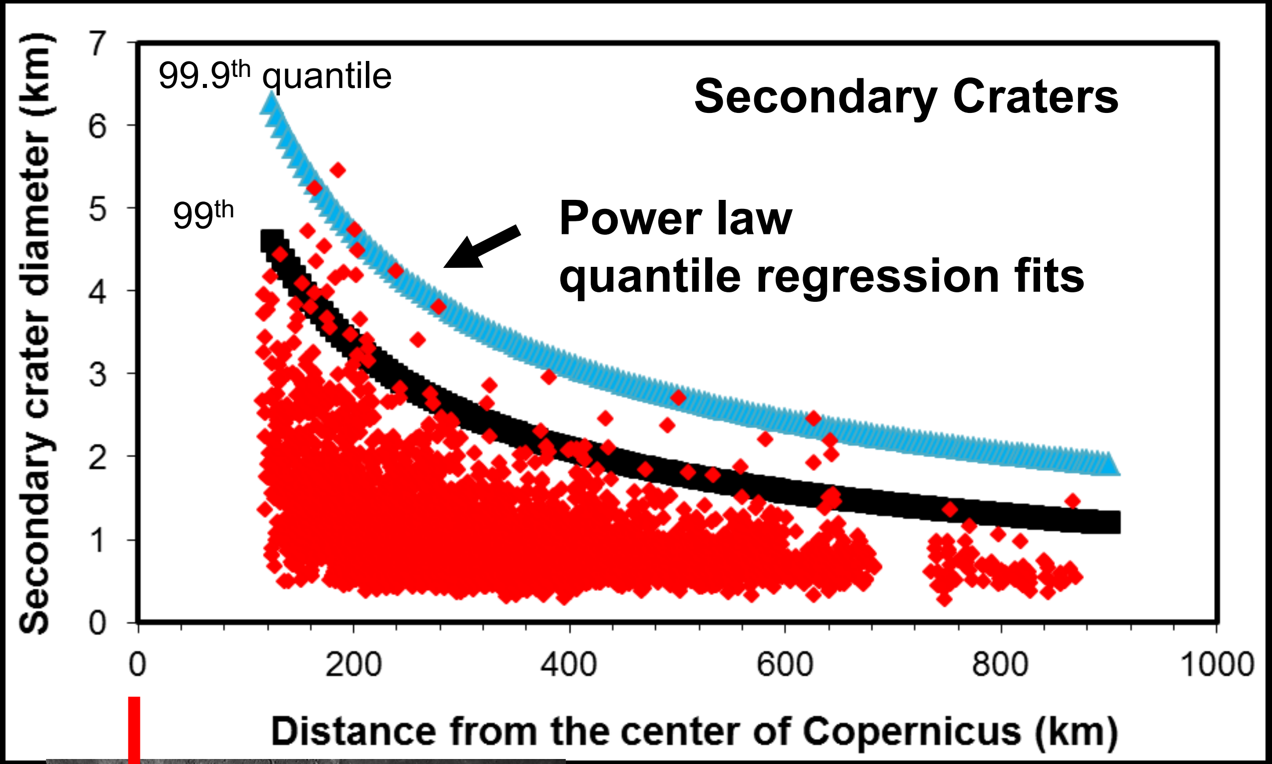
10’s of thousands of potential secondary craters were considered overall…

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

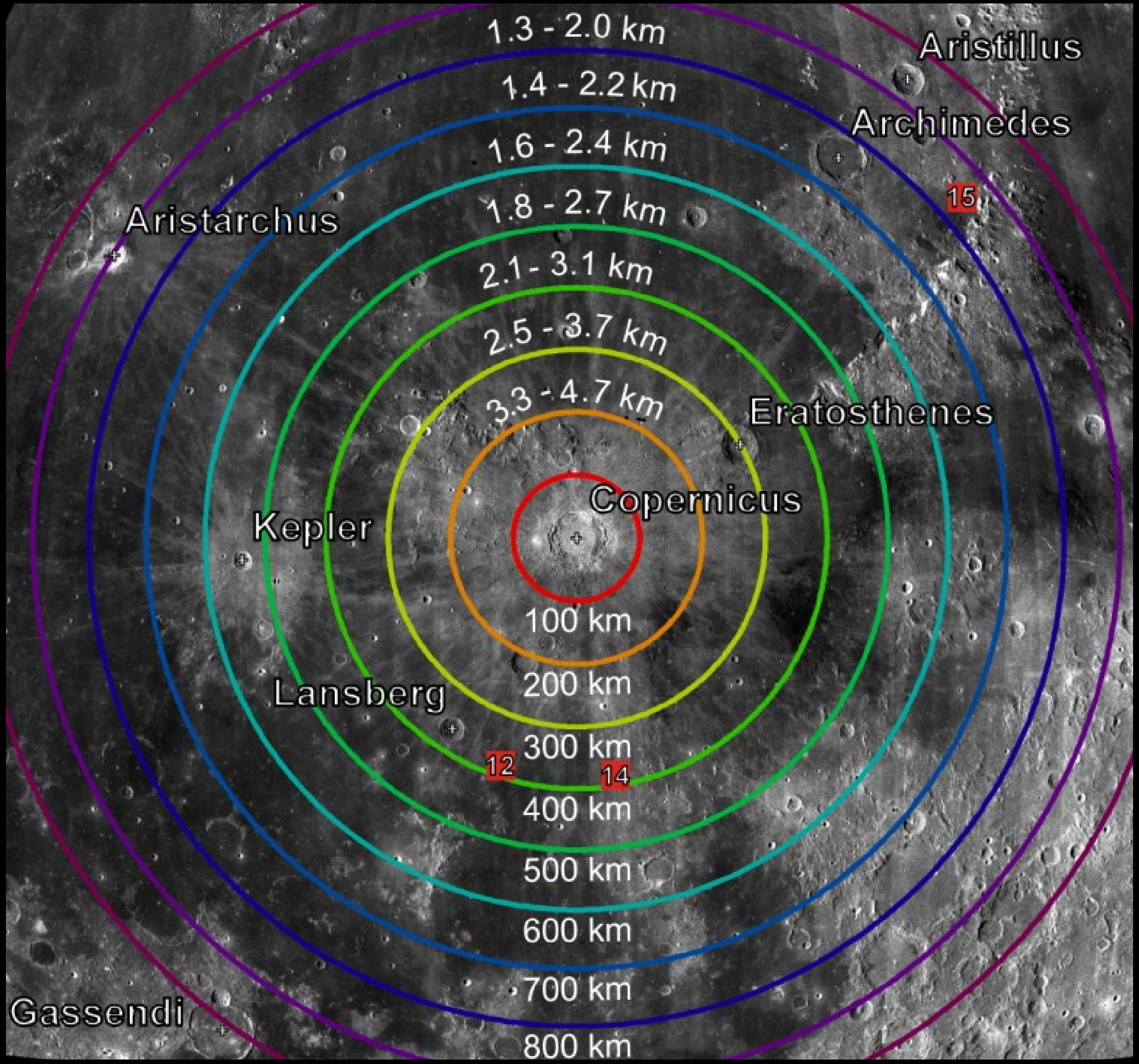
Secondary Crater Results

Please see Singer et al., 2020 for additional results.

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

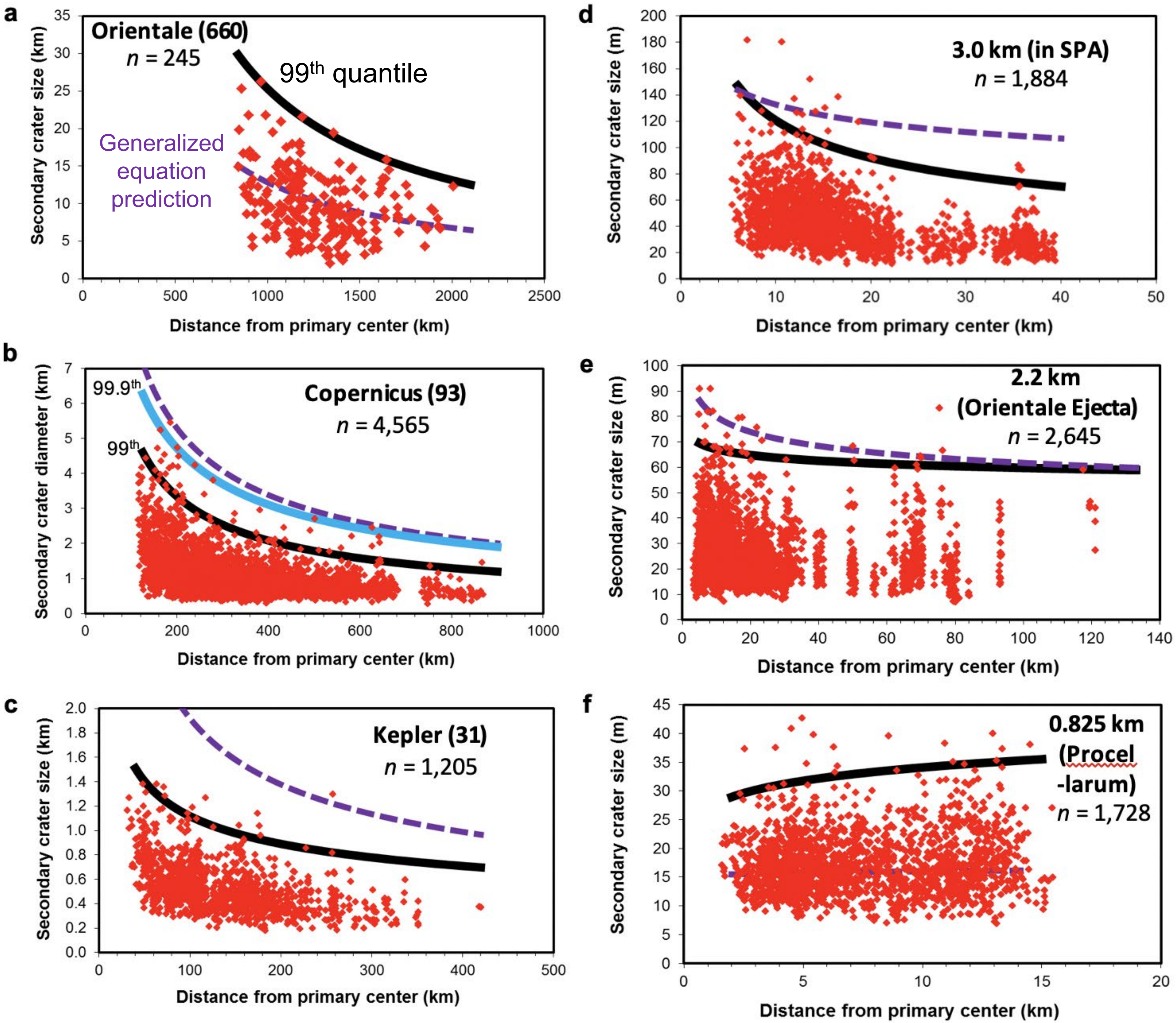


These two values give a range of the maximum secondary sizes expected at a given distance.



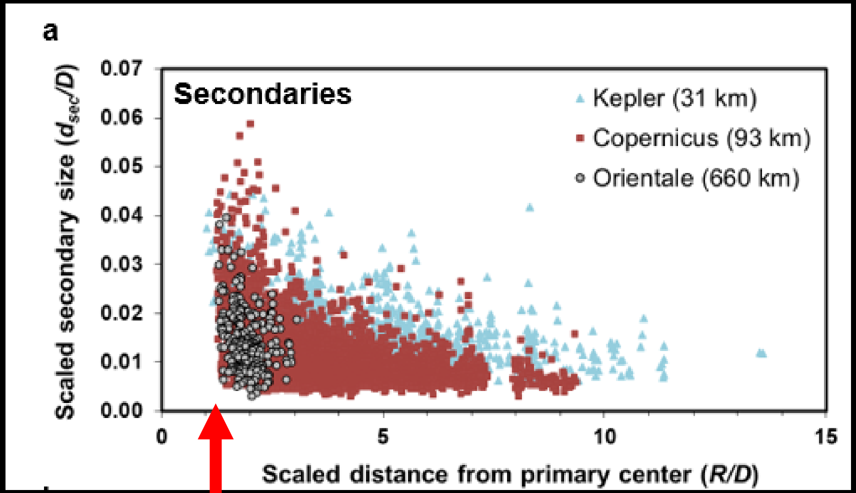
Secondary Craters

Scale Dependence in Size Drop-off



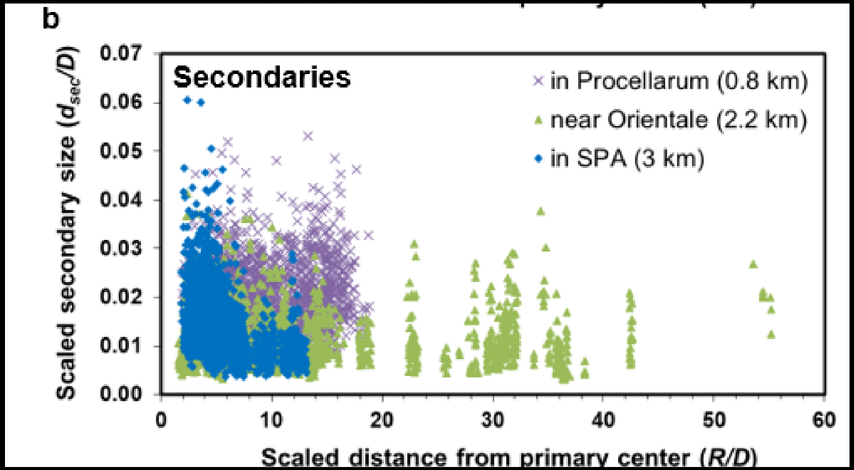
Results 4: Normalized Distributions

Largest 3

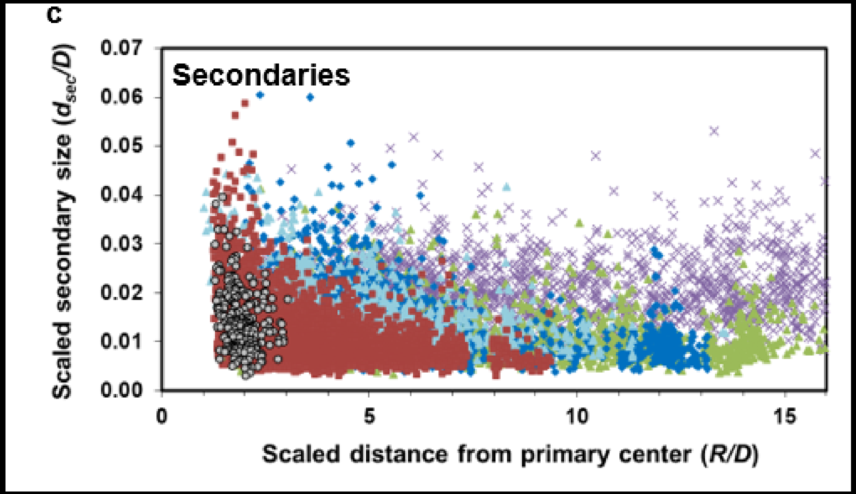


1.3*D

Smallest 3



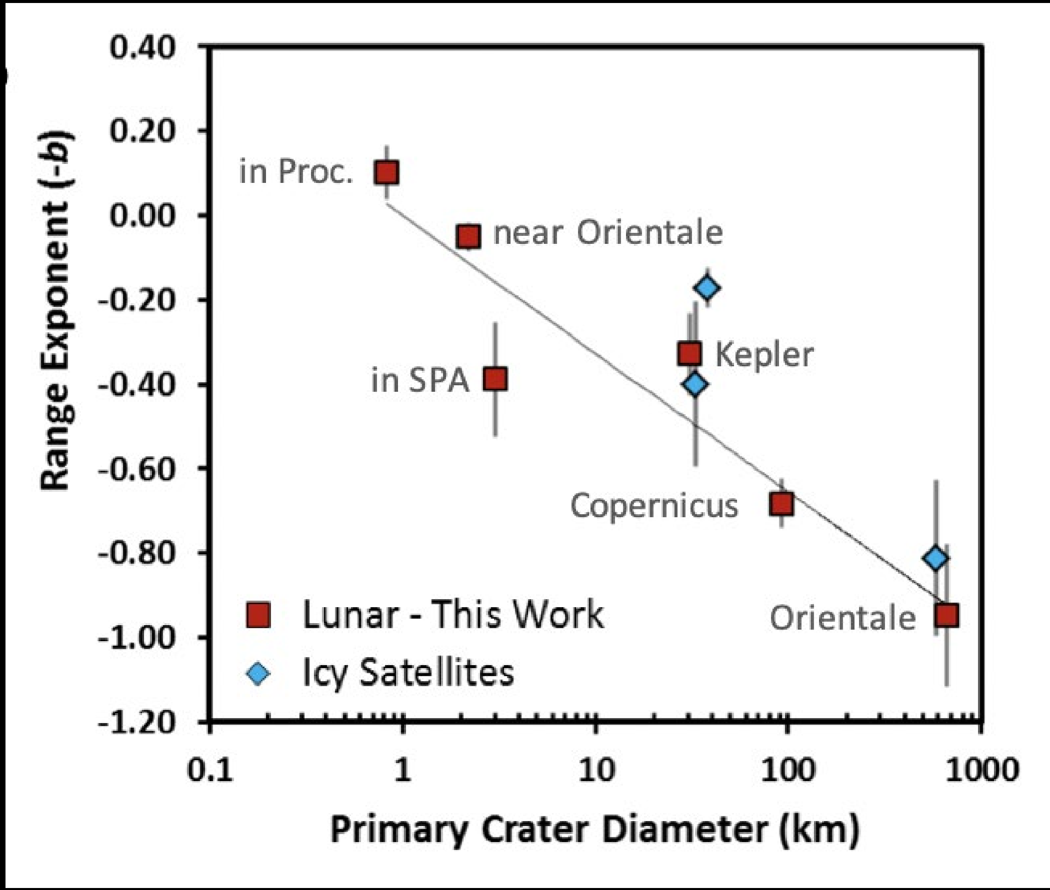
All together!

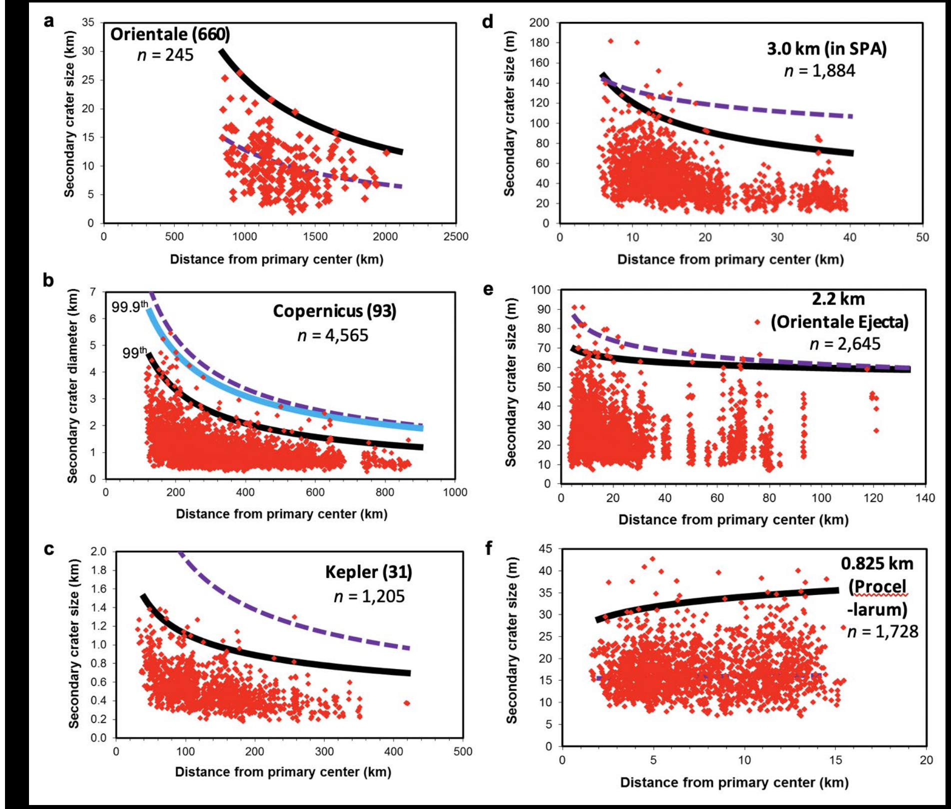


Results 2: Scale-dependence

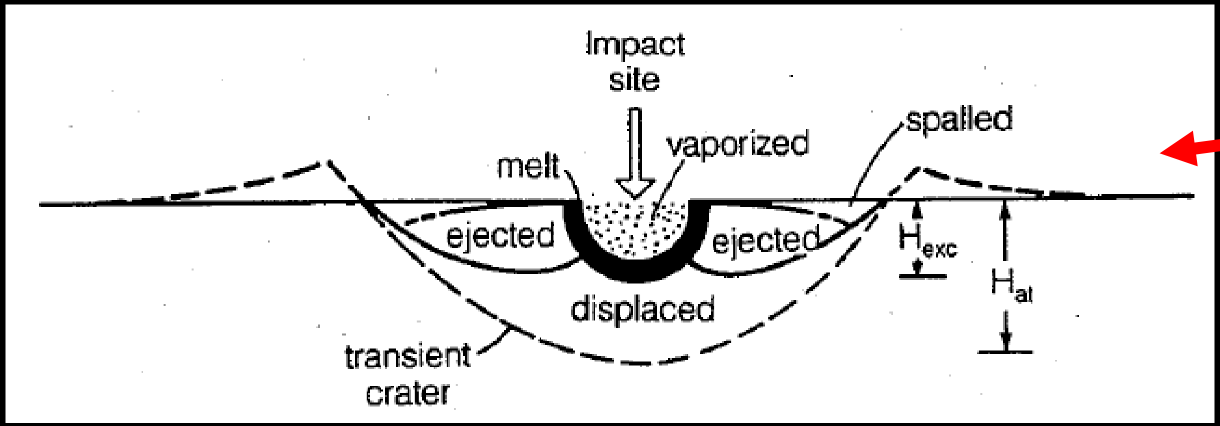
Quantile regression power-law fits to the upper envelope.

Secondary craters as a function of distance: $d_{sec,max} = aR^{-b}$

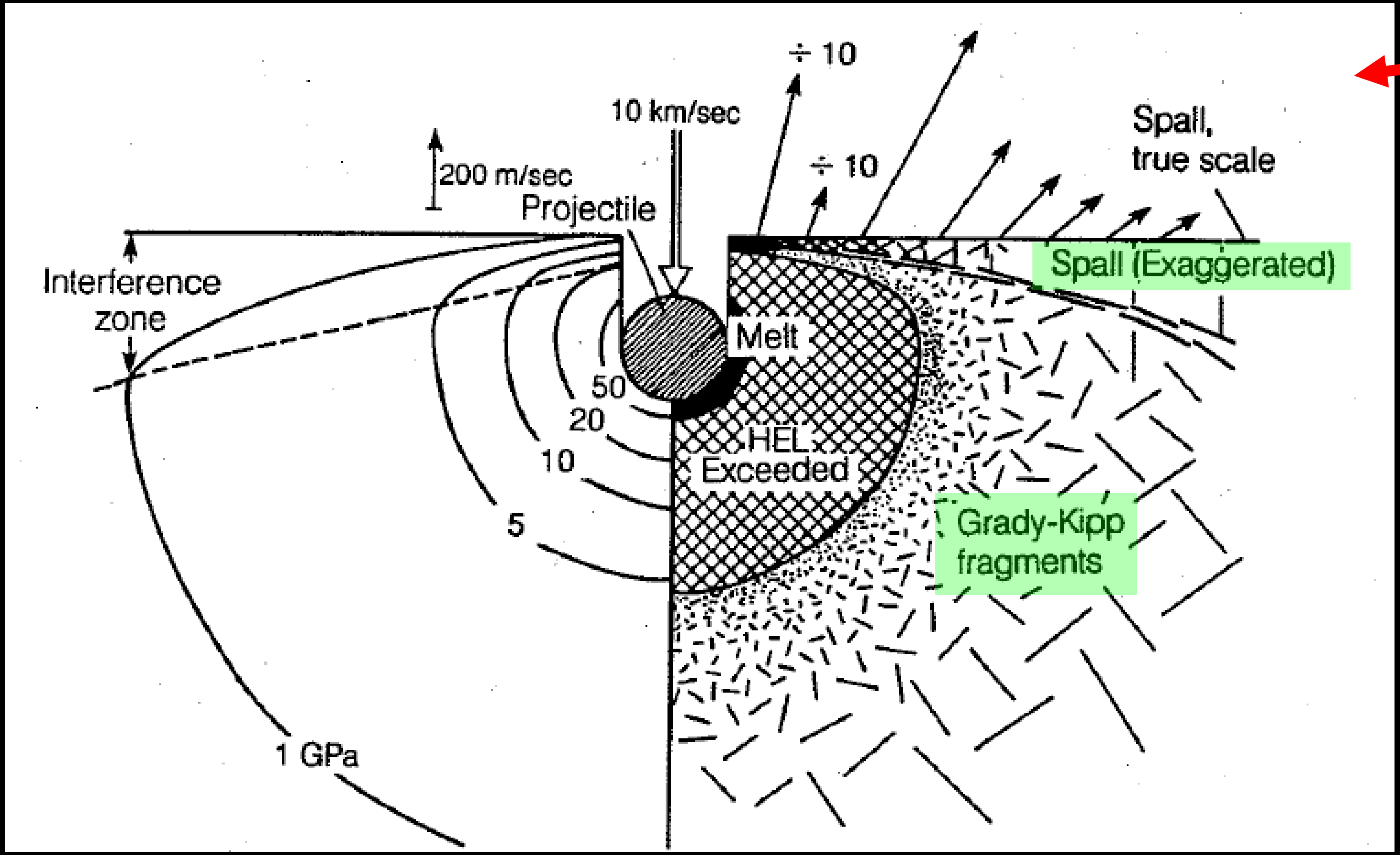




Part 2 - Ejecta Fragments



Shock wave contours and fragmentation of target material, and

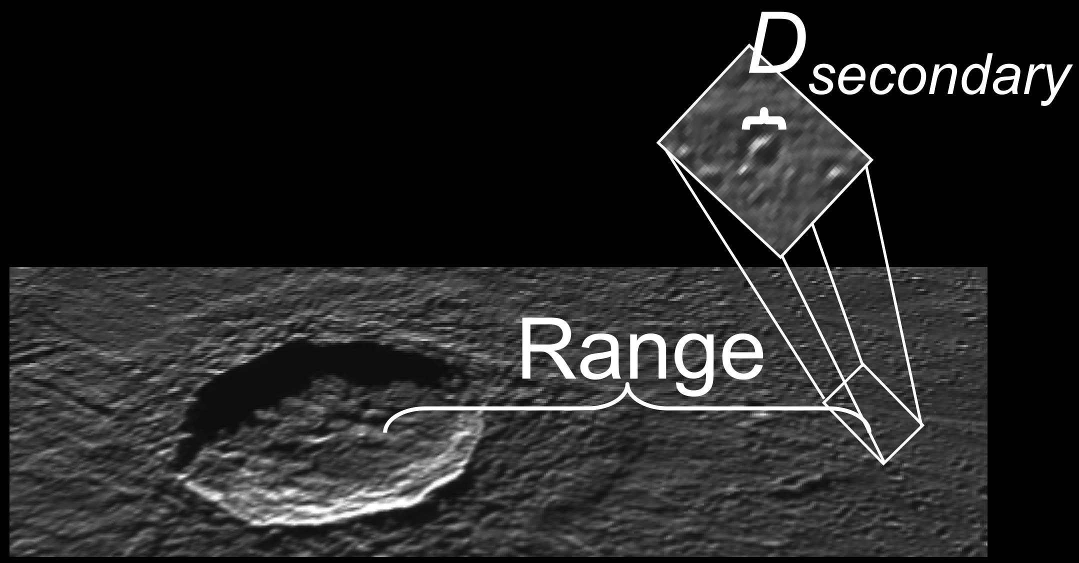


Fate of material at different locations inside of the transient crater.

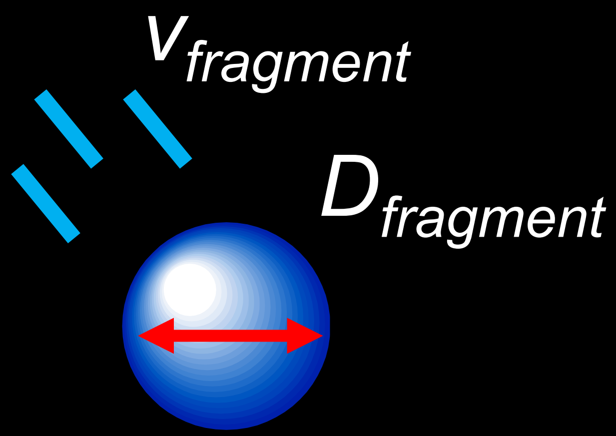
We are studying both the spalled and ejected portions (Grady-Kipp fragments).

Diagrams from Melosh, 1989

Measured Quantities



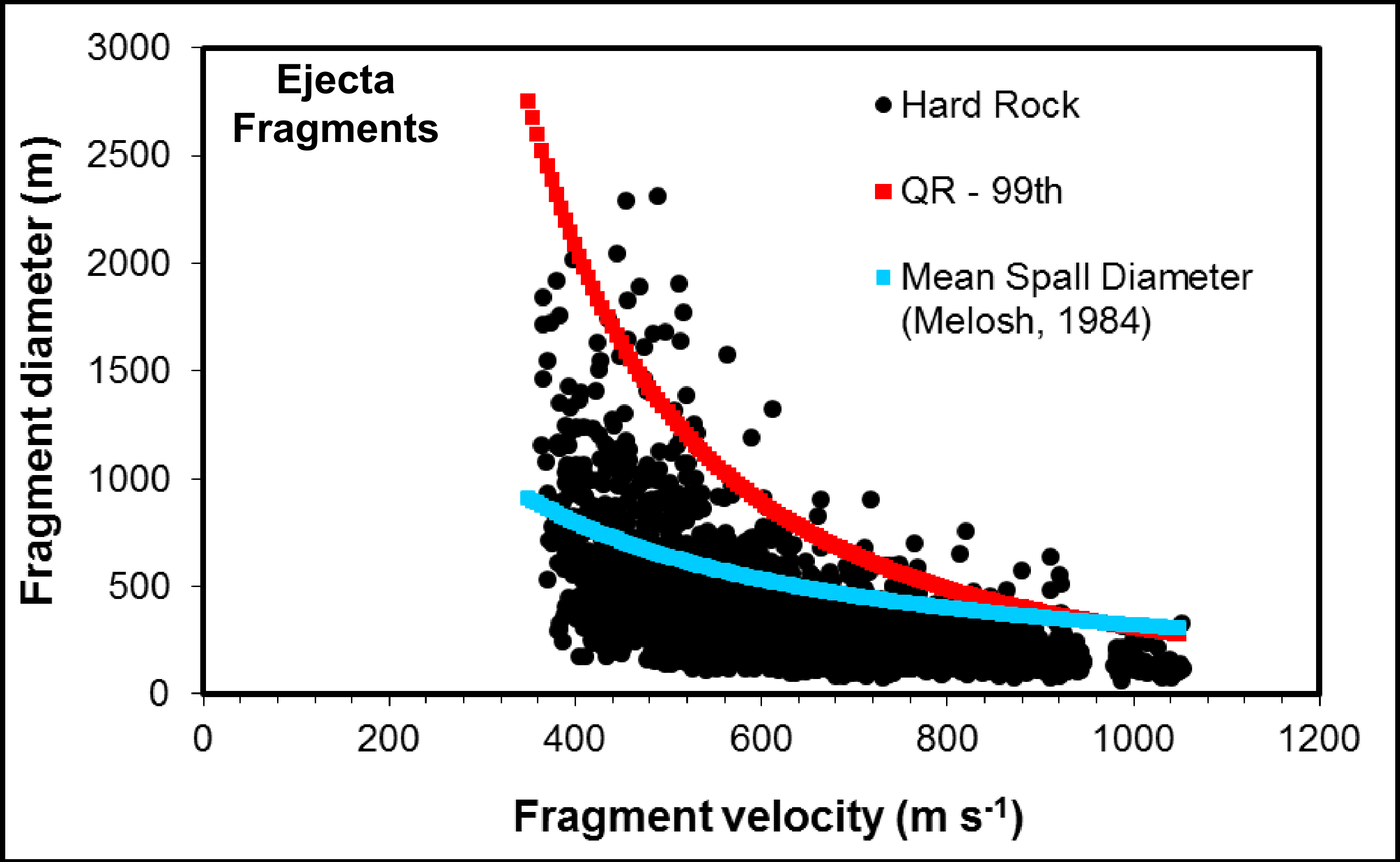
Derived Quantities



- Secondary Range $\xrightarrow{\text{Ballistic range equation}}$ 1. Fragment Velocity
- Secondary Size $\xrightarrow{\text{Scaling equations}}$ 2. Fragment Size

Ejecta Fragment Results

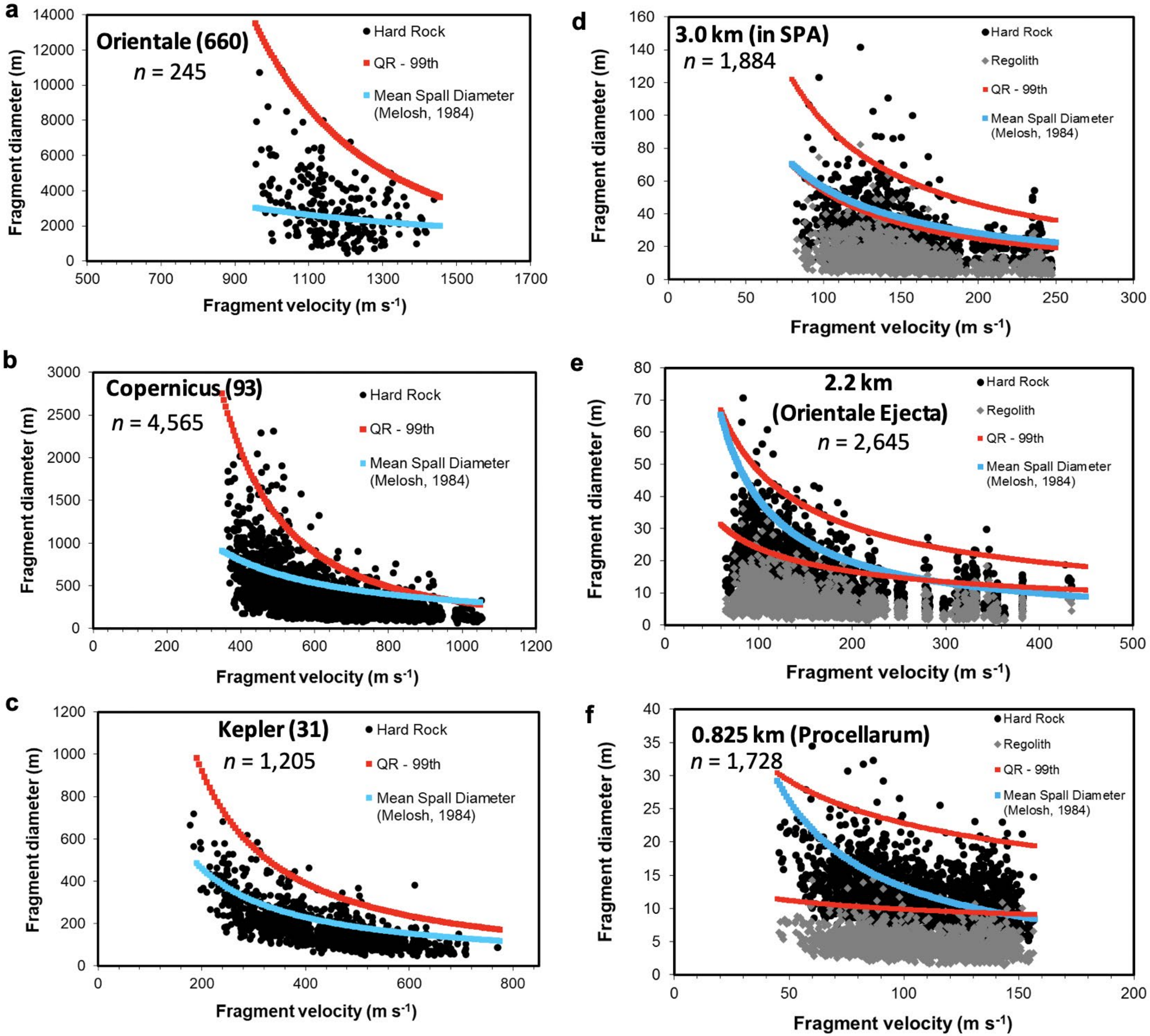
Results 5: Ejecta fragment size fall-off with ejection velocity



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

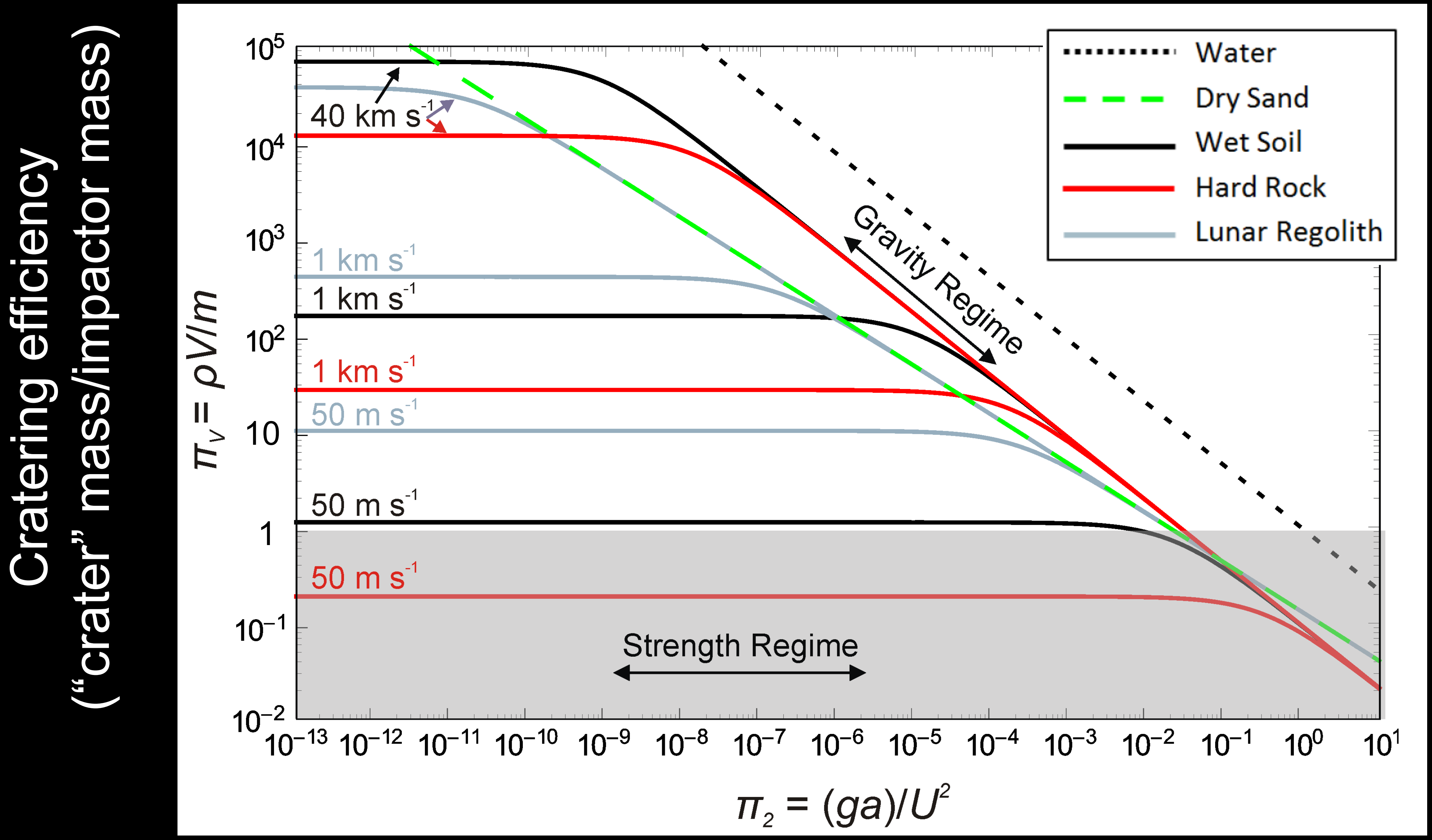
- Compare to analytical predictions.
- No scale dependence in current analytical results. (spallation or Grady-Kipp fragment sizes)

Ejecta Fragments



Scaling

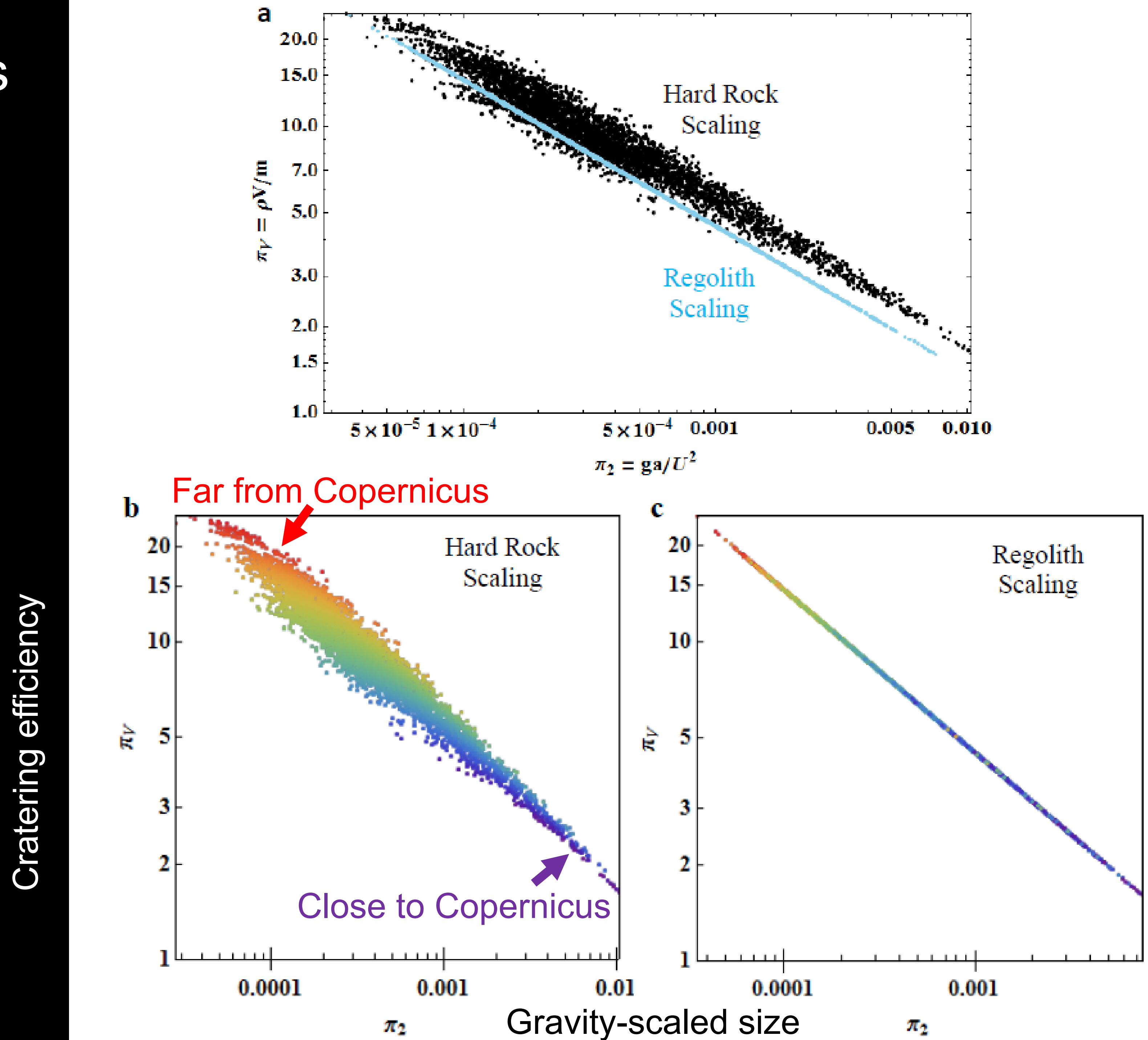
- Explored a wide range of parameters
- Used “hard rock” and “lunar regolith” (sand with a bit of strength) as endmember materials
- Used full equation that spans both strength and gravity regimes



Gravity-scaled size

Copernicus

Velocity Range:
365-1055 m/s



Main Points

- Secondaries are… everywhere!

- We provide a formula for calculating the largest size of secondaries at a given location

- We find a scale dependence to the dynamic fragmentation that occurs during an impact event that is not included in most analytical models of fragmentation (e.g., Spallation, Grady-Kipp).

Future Work

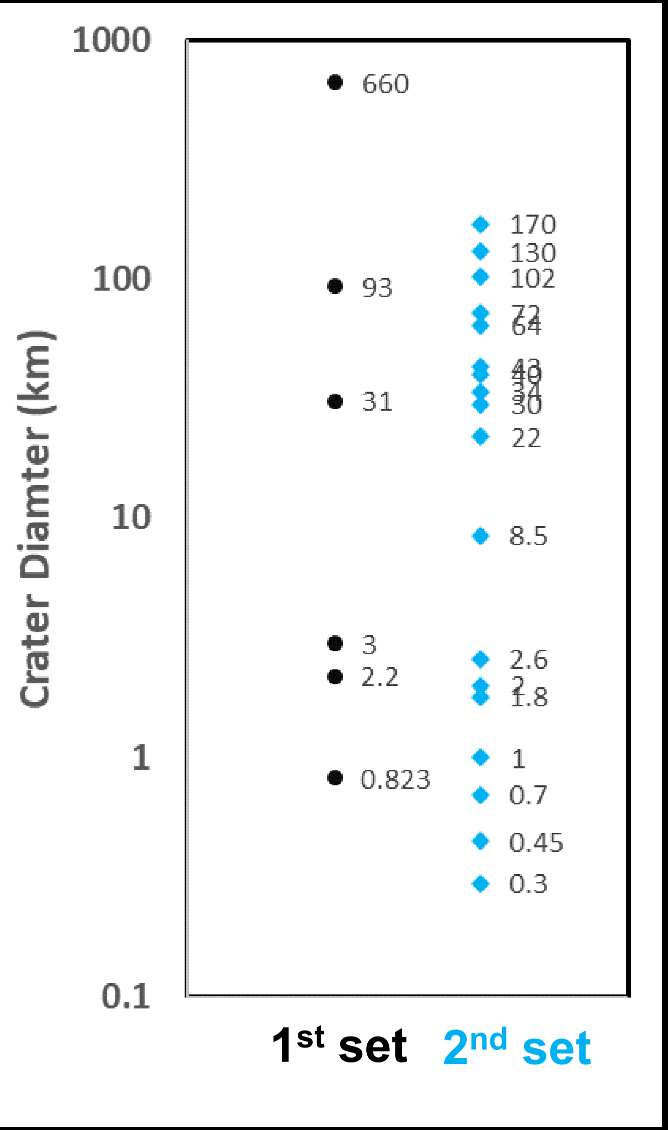
Current and Future Work 1/3

Continued secondary crater mapping on the Moon and Mercury (and soon Mars!)

Lunar:

- Fill in size range
- See variation in the same size primary
- Possibly look at material differences

Moon

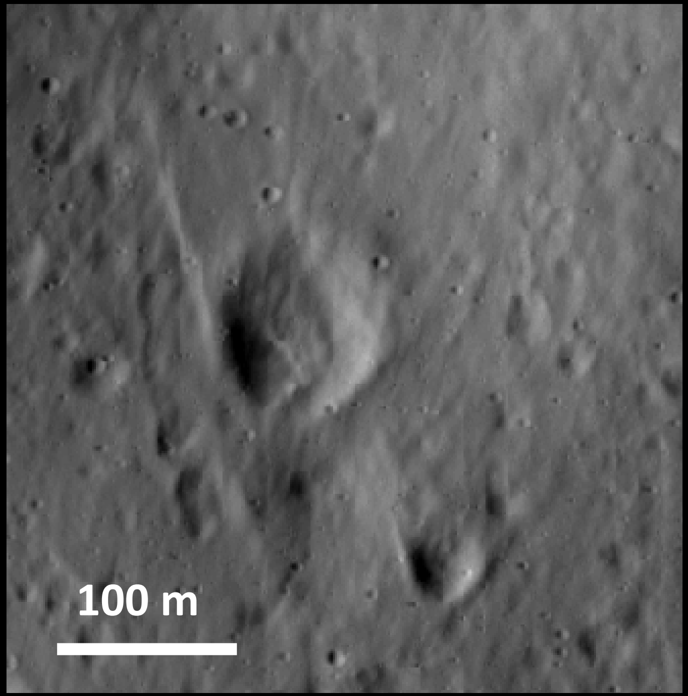


Current and Future Work 2/3

- "Anatomy of a secondary crater"

- Secondary Morphology
  - Secondary d/D, ellipticity
  - V-shaped ejecta
  - Floor morphologies

  Function of
  - distance from primary
  - Different target materials

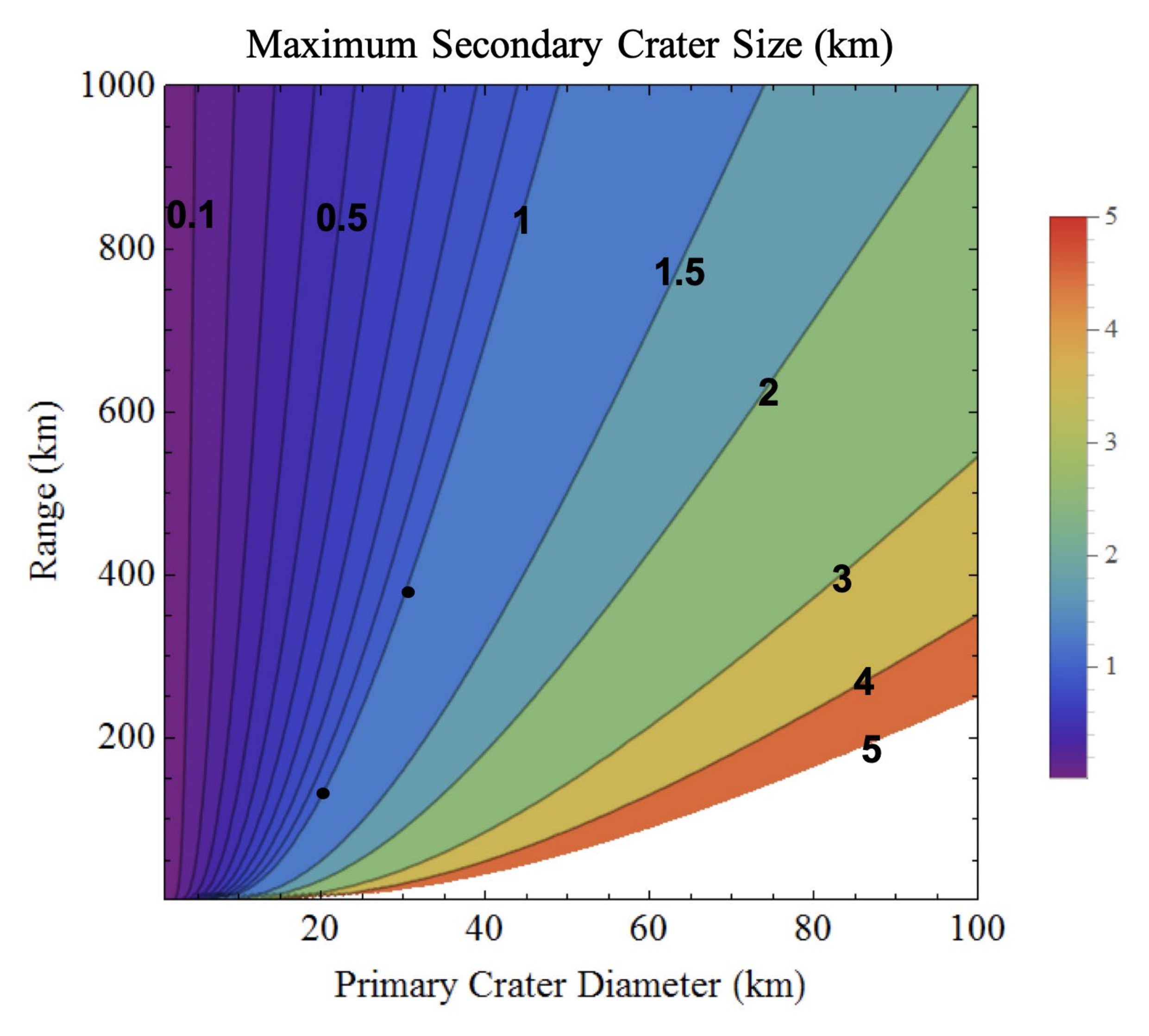


Appendix Slides

Results 3: Predictions of secondary crater size from any primary

- The ~*maximum* size of secondary craters as a function of two parameters:

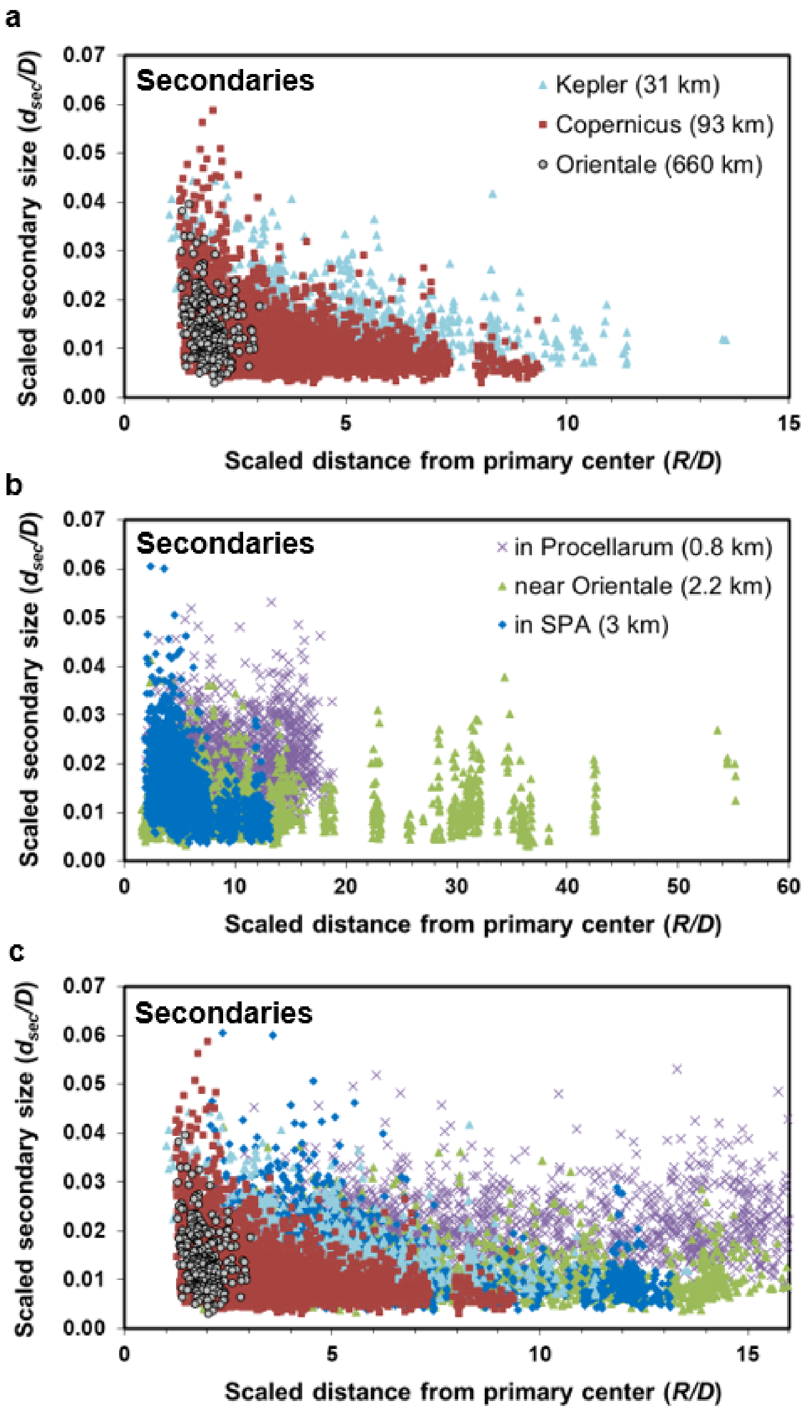
1. Distance/range
2. Primary crater diameter



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

Normalized Distributions

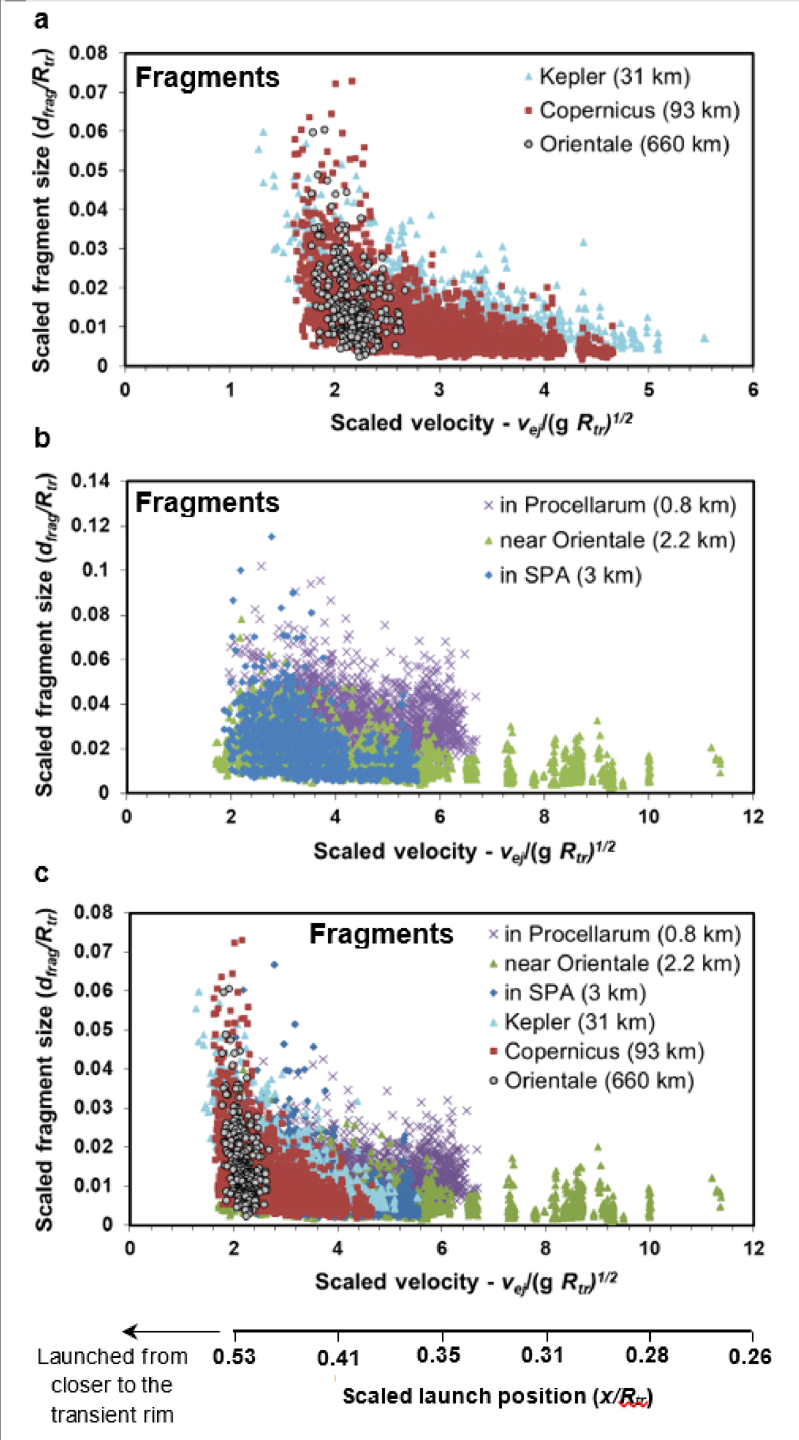
For more information on the normalizations see Singer et al. 2013.



Normalized Distributions

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

Scaled launch positions from Housen and Holsapple, 2011.

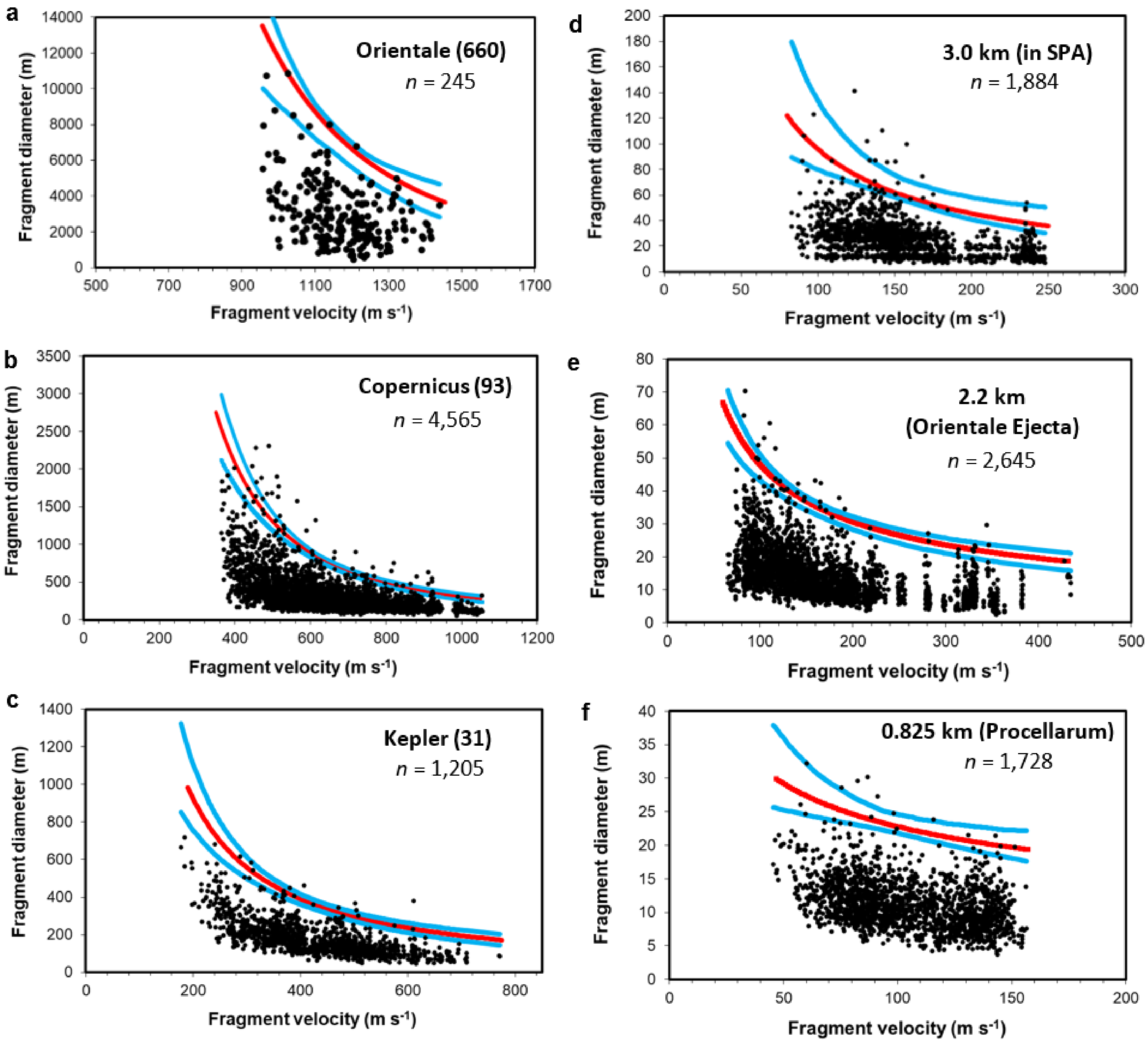


Ejecta
Fragments

99th quantile

95% Confidence Interval

Bootstrap random sampling of residuals with replacement



Notes on Scaling

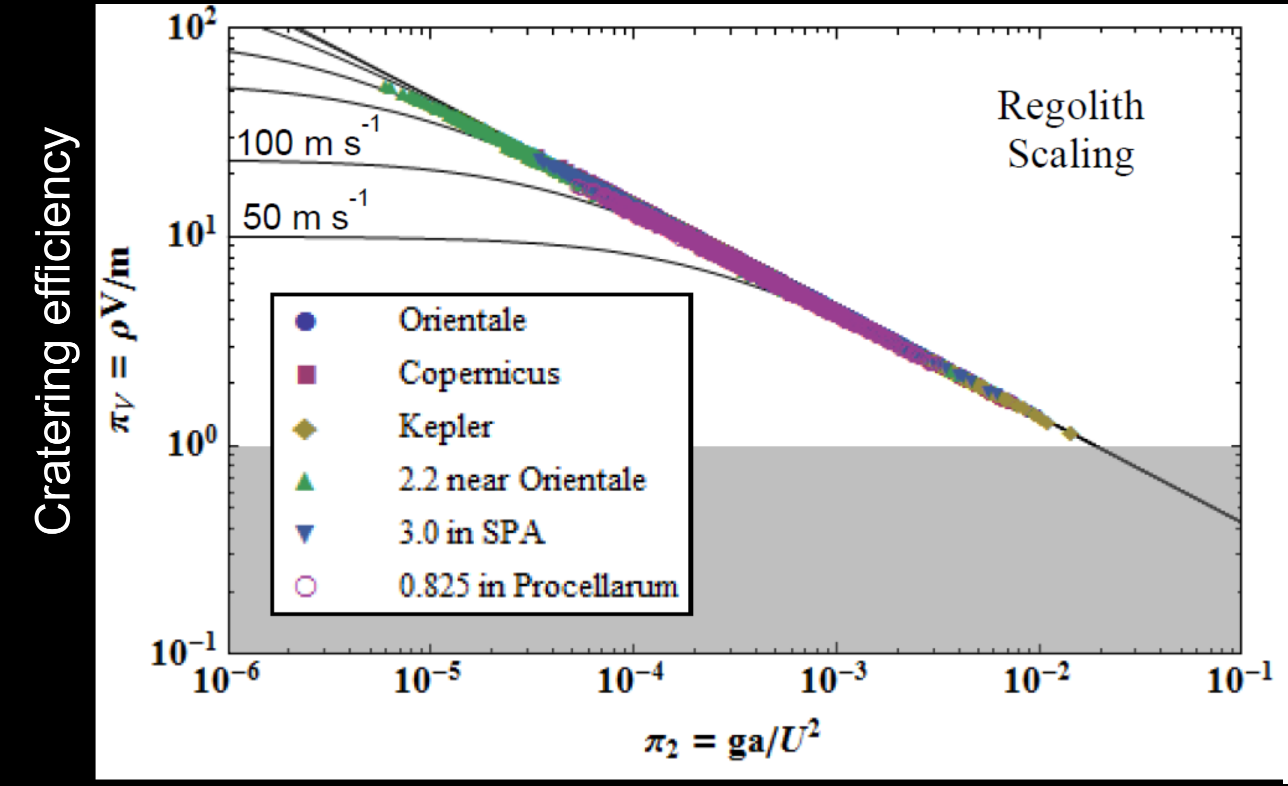
- We used several different material parameters for scaling from the secondary crater diameters to ejecta fragment diameters (e.g., Holsapple, 1993, Housen and Holsapple, 2011).

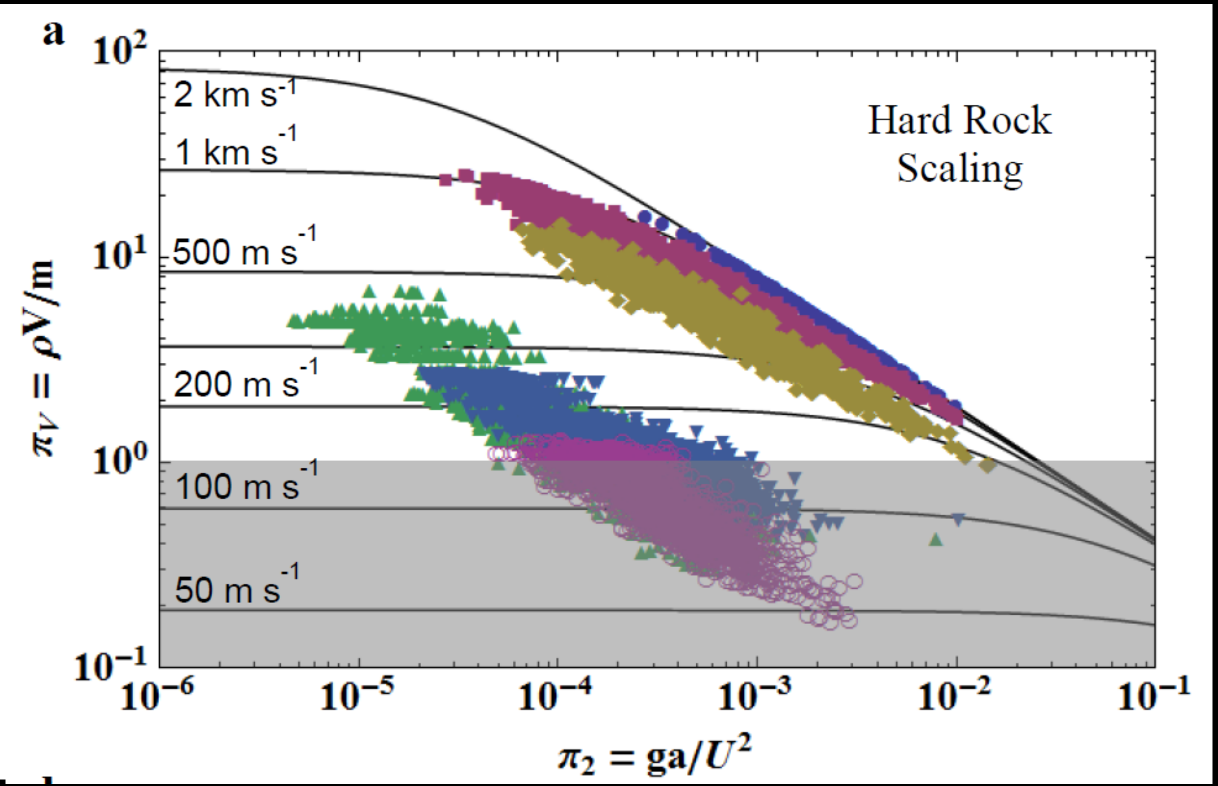
- “Hard rock” material parameters, representing a non-porous surface, are shown above as an example.

- 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.



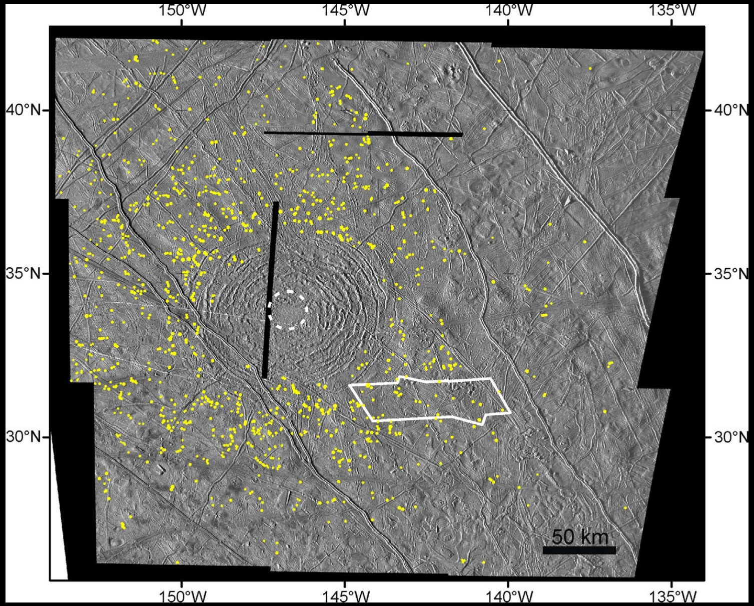


References

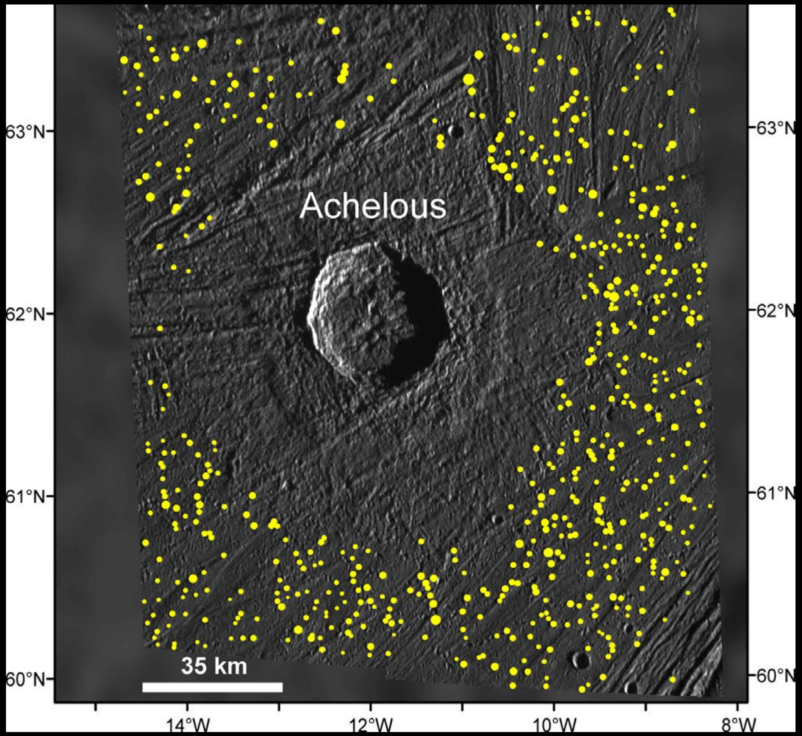
- Holsapple, K. A., 1993. The scaling of impact processes in planetary sciences. Annu. Rev. Earth Planet Sci. 21, 333-373.
- Housen, K. R., Holsapple, K. A., 2011. Ejecta from impact craters. Icarus 211, 856-875. doi:10.1016/j.icarus.2010.09.017
- Melosh, H. J., 1984. Impact ejection, spallation, and 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.

Icy Sats: Three Secondary Crater Fields

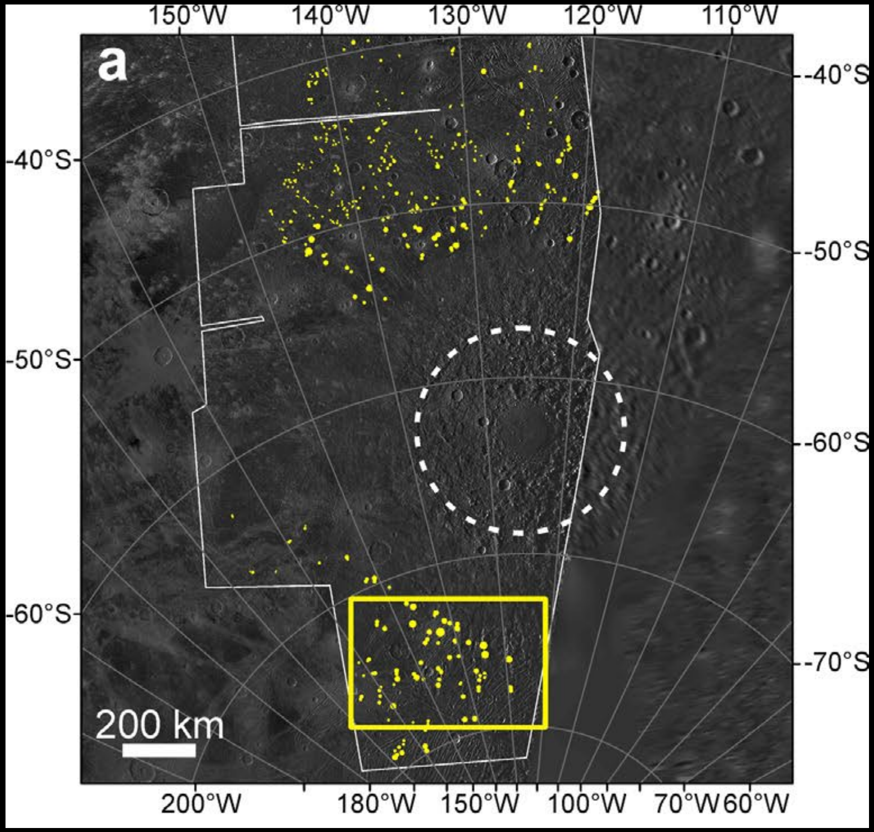
Tyre (38 km equivalent rim diameter)



Achelous (35 km)

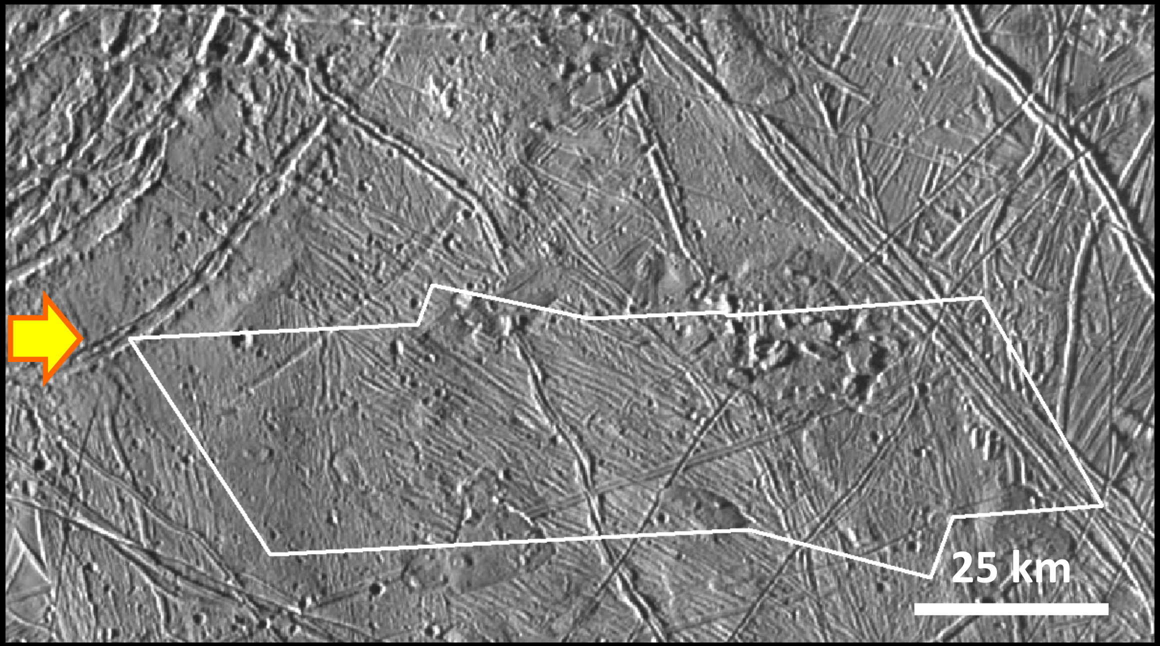


Gilgamesh
(585 km equivalent rim diameter)

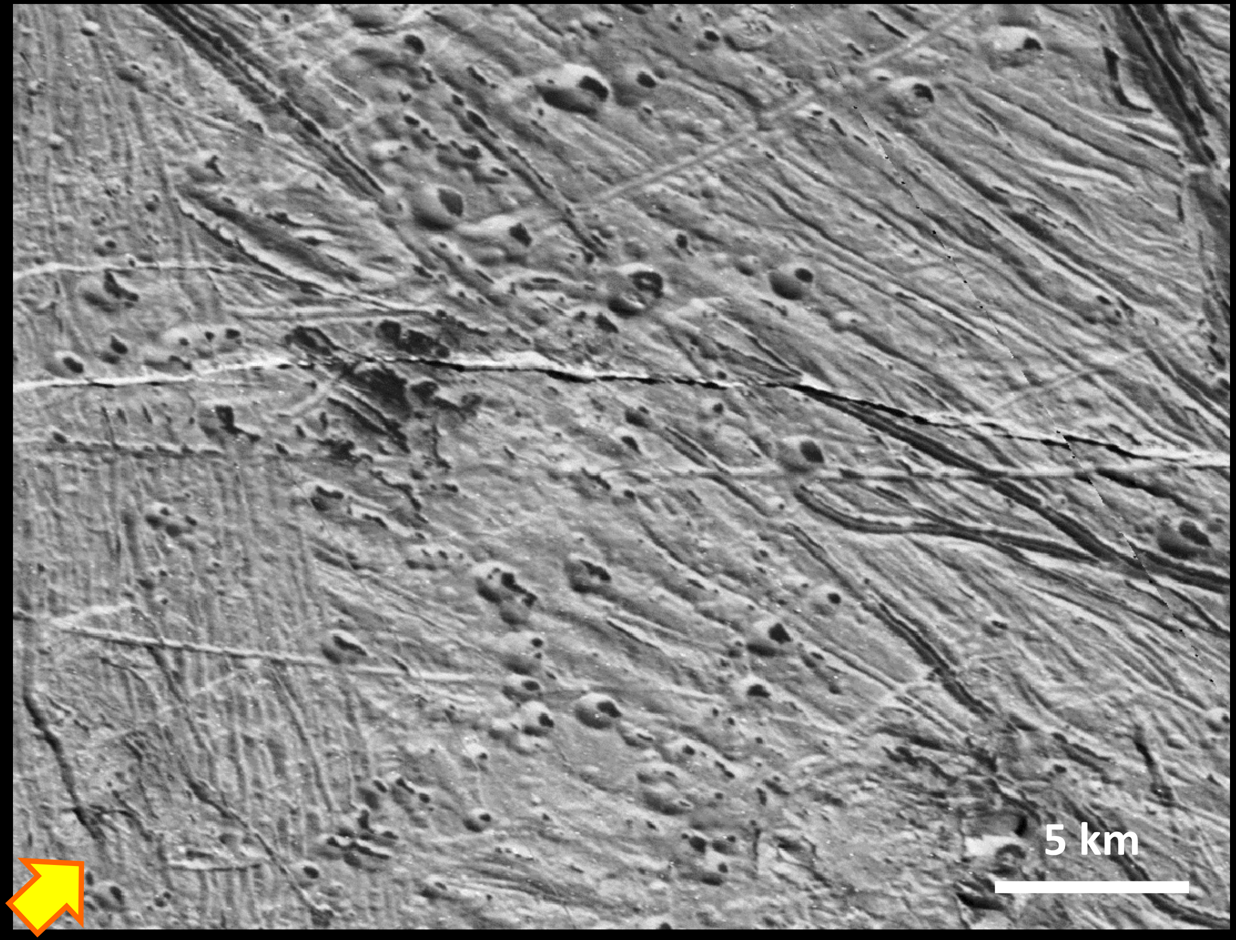


Singer et al., 2013, Icarus

Tyre

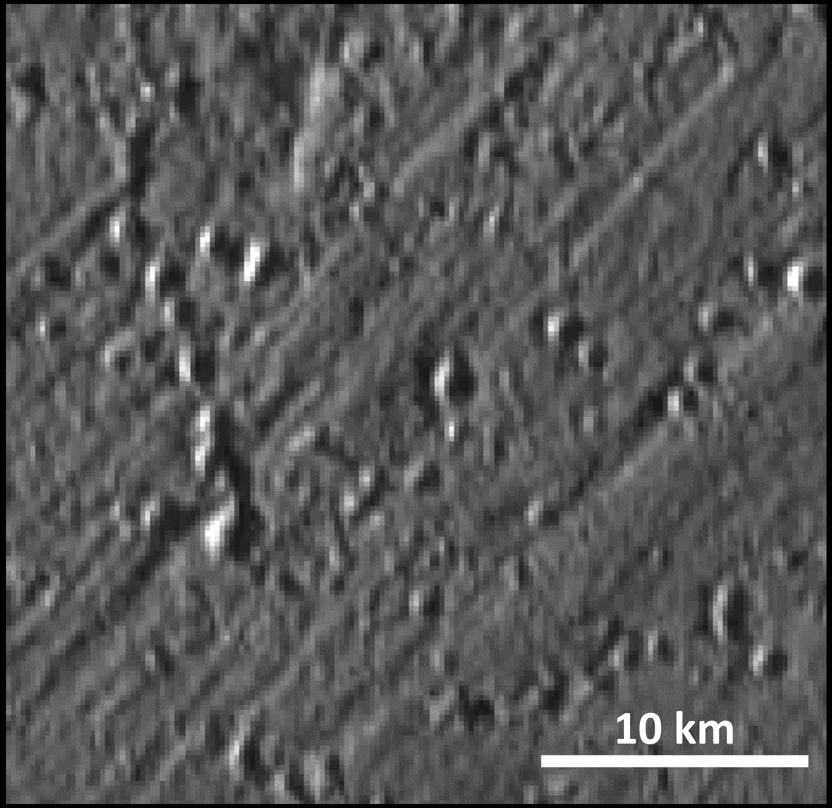


~200 m/px

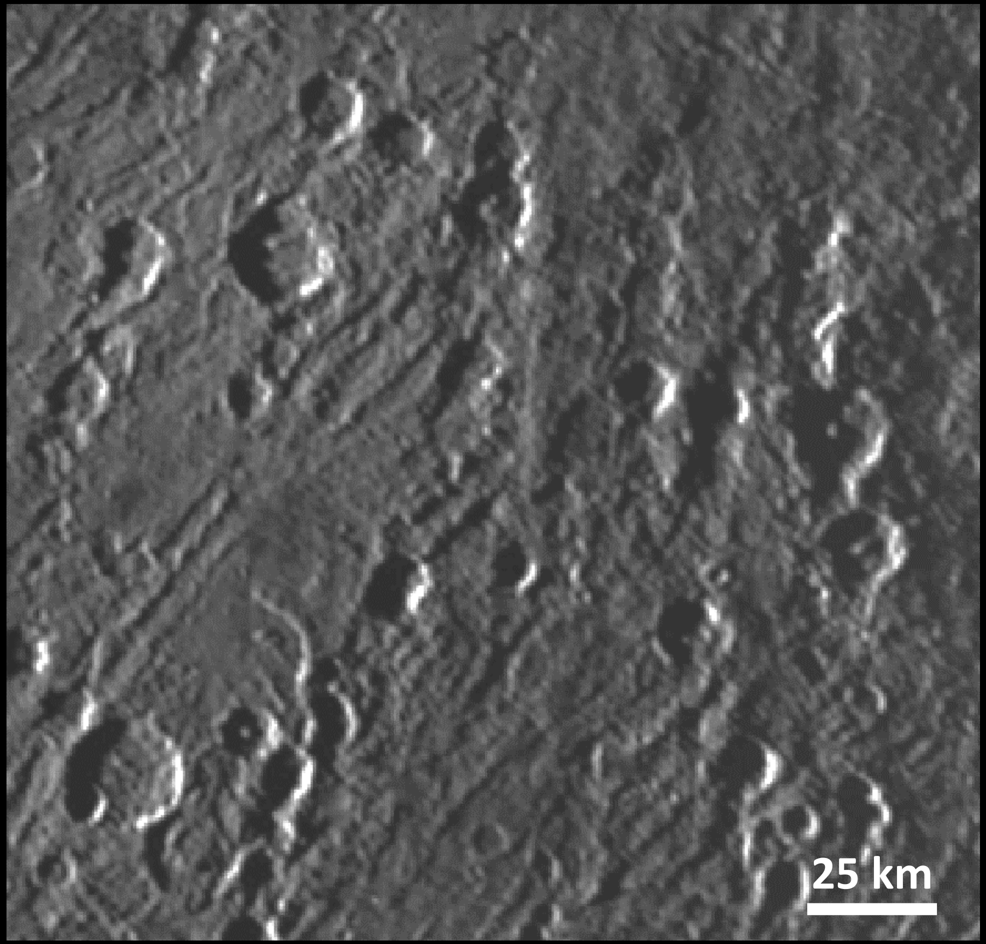


~30 m/px

Achelous & Gilgamesh



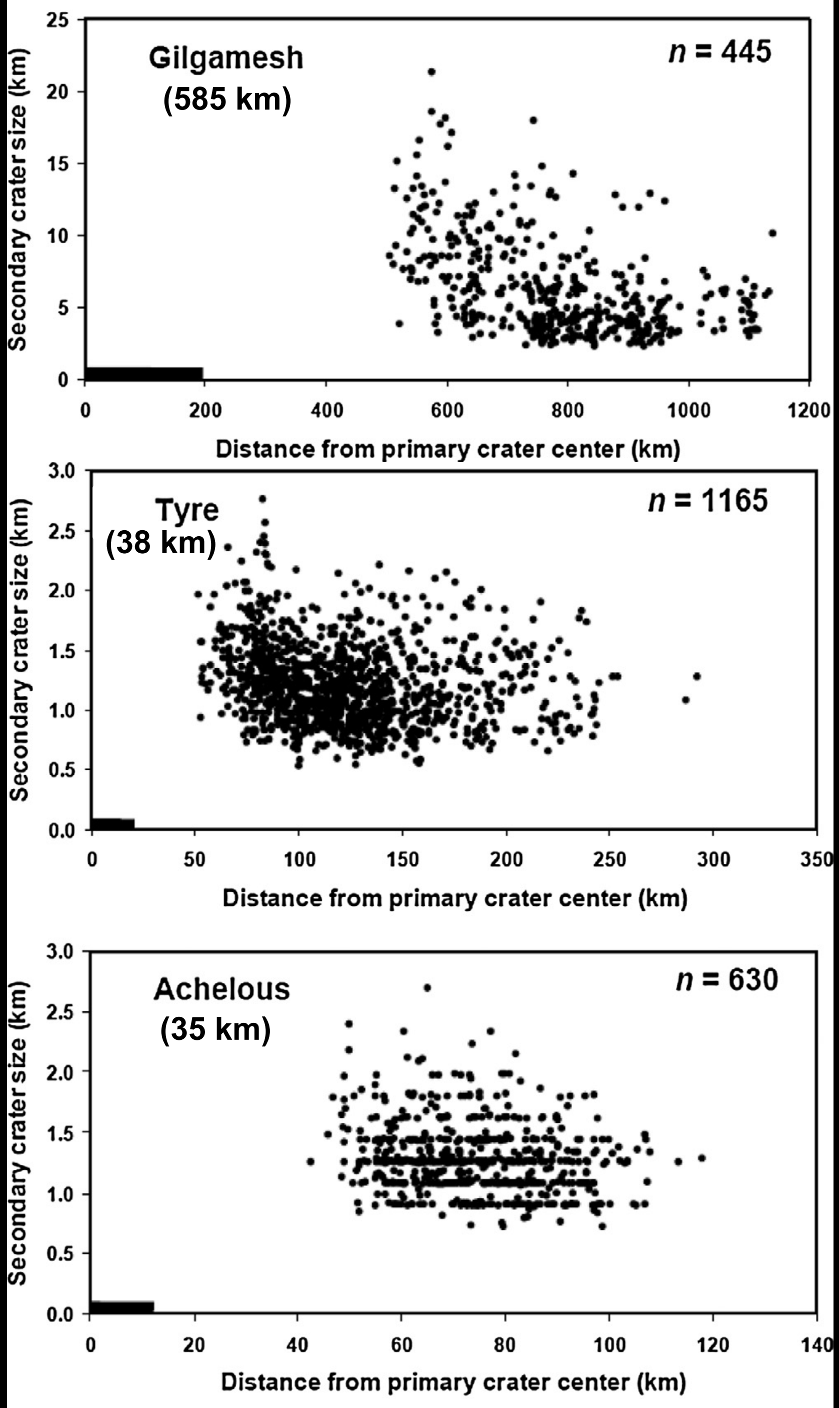
~180 m/px



~550 m/px

Icy Satellite

Secondary Craters



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.

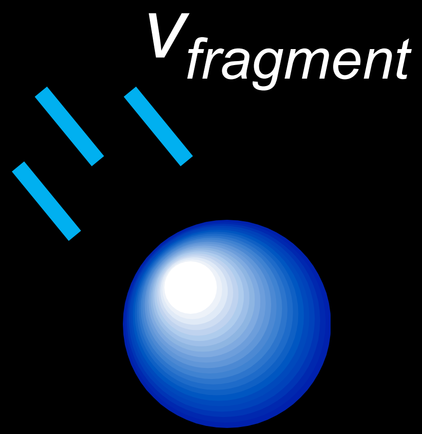
Primary Crater	Primary diameter (km)[a]	Number of secondaries used in the analysis	Largest observed secondary (km)[b]	Average of largest 5 secondaries (km)[b]	Estimated maximum fragment size at escape velocity (m)[c]
Orientale	660	245	26 (4%)	23 (4%)	**860**
Copernicus	93	4,565	5.5 (6%)	4.9 (5%)	**50**
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**

[a]Final diameter for Orientale is estimated at the Outer Rook Mountains.
[b]Percentage of the primary diameter given in parentheses.
[c]Fragment sizes are estimated with quantile regression fit parameters (all details in the paper under review).

1. Fragment Velocity

Ballistic trajectory on a sphere

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



R_p – Radius of planet or moon
v_{frag} – velocity of ejected fragment

<u>Assumptions:</u>

- Launched at ½ transient crater radius (transient estimate from McKinnon et al., 2003)
- θ = 45° (see Singer et al., 2013 for discussion)
- $\upsilon_{frag,\,eject} = \upsilon_{frag,\,impact}$

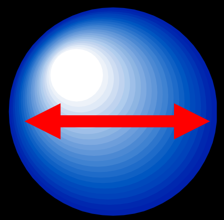
2. Fragment Diameter

Schmidt-Holsapple scaling equations

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

d_{frag} – Diameter of ejecta fragment
D_{sec} – Diameter of secondary crater

$D_{fragment}$



<u>Details:</u>

- 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