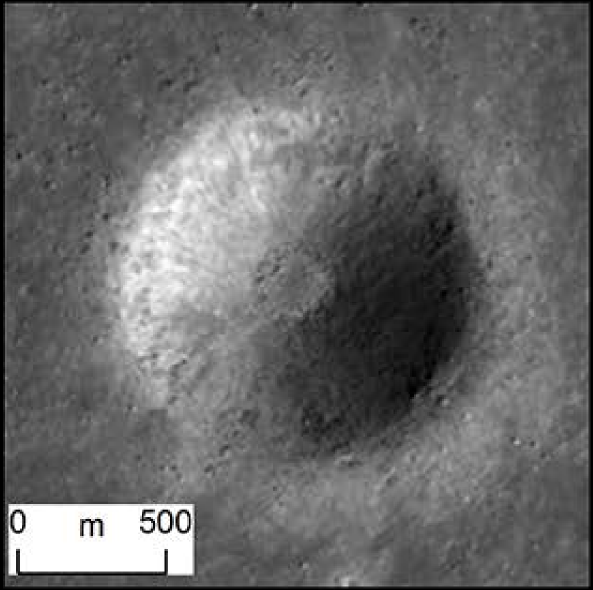
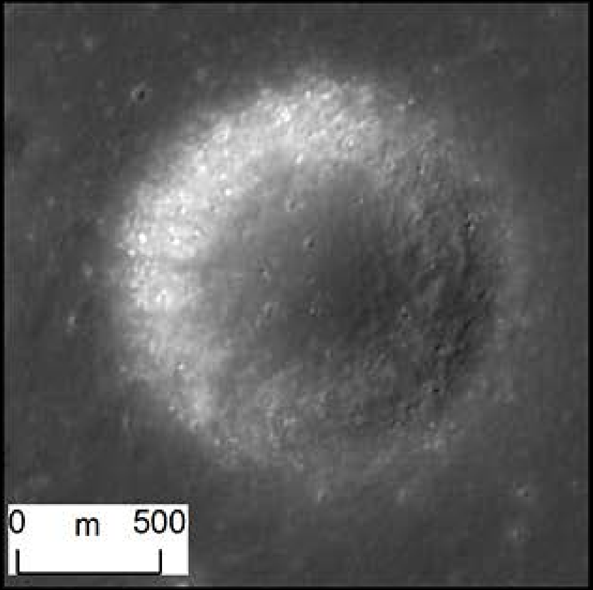
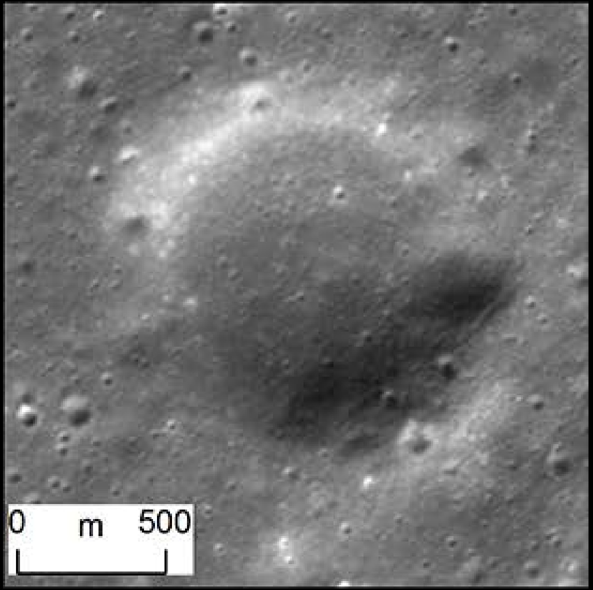
The Rate of Surface Evolution on the Moon (and Why it Matters)



Fresh Crater
T~0.01 Ga



Moderately Degraded
T~3 Ga



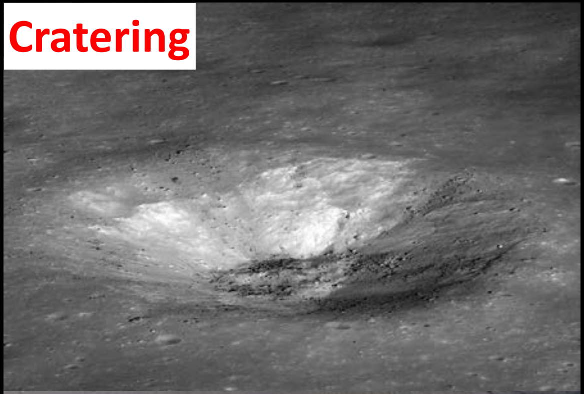
Very Degraded
T~3.7 Ga

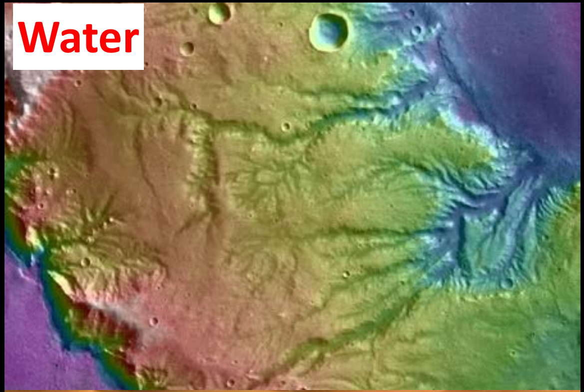
Caleb Fassett
August 23, 2019

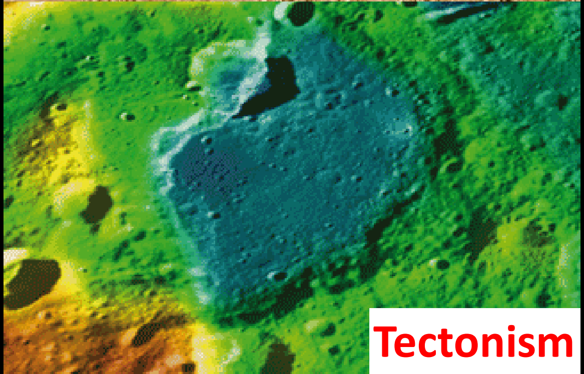
Planetary Geomorphology

- Use observations of topography and geology:
  - To understand the *physical processes* that affect planet surfaces;
  - To infer *geologic history and environment*;
  - To help set boundary conditions for *future exploration*.


Volcanism


Cratering


Water


Tectonism


Ice


Wind

Rates and Ages

- **Remote Sensing: *Orbital Exploration***

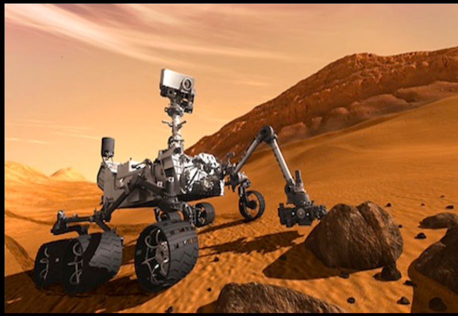
  Geochronology from impact crater density…

  …Relative age interpretations, done carefully, are reliable.

  …Absolute ages on Moon, extrapolated elsewhere.

- **Fieldwork: *In Situ Exploration***

  In situ geochronology in a few places. Future might be bright: many new concepts and instruments

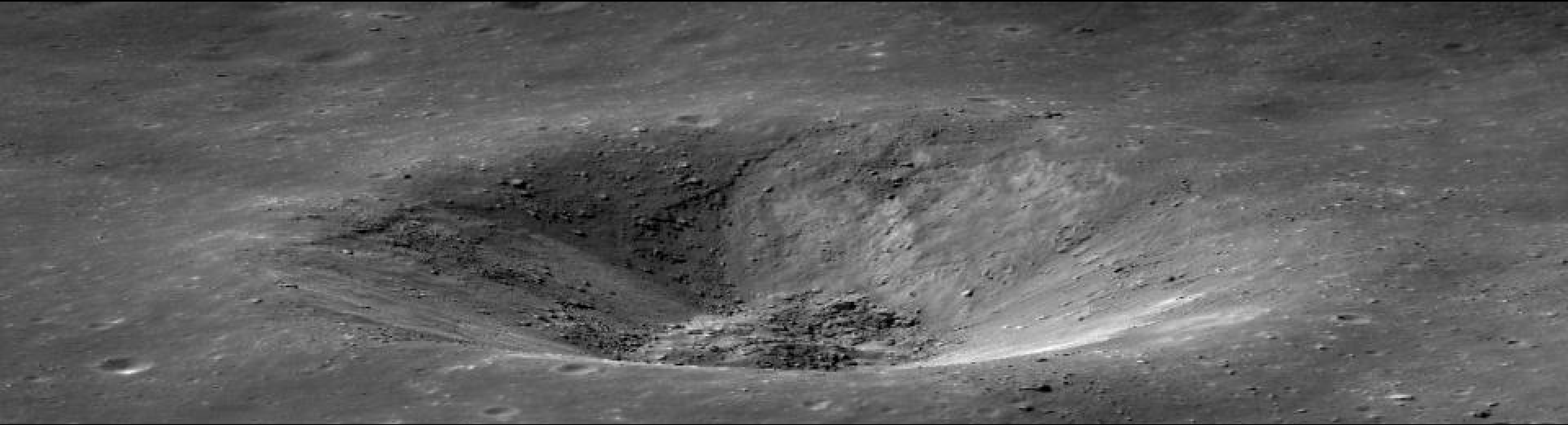


- **Experimental work + Sample Analysis**

  Best example: Dating of lunar sample collection from well-characterized field sites

Motivating science questions

1. How does the topography and regolith of the Moon evolve?
2. Can we constrain the age of features and surface from their topography?
3. Can we understand future landing sites?

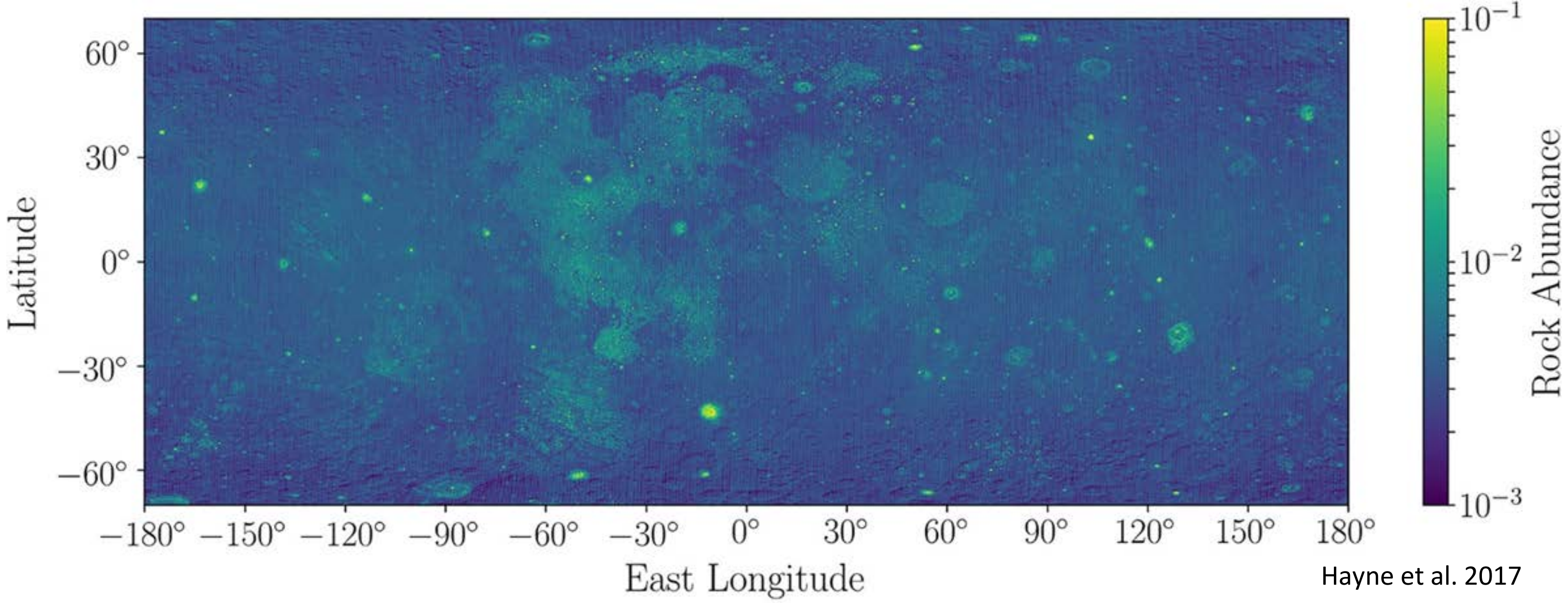


LROC NAC Synthetic Perspective of North Ray Crater (50 My old)

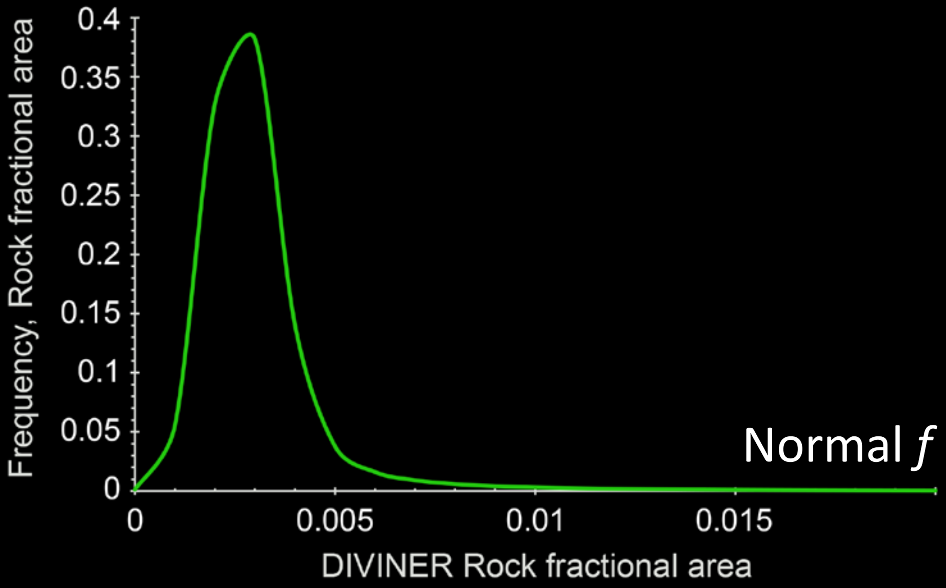
The Moon’s Surface

1. Ubiquitous **regolith**, extremely rare **bedrock.**
2. Sizable rocks on the surface are almost always associated with fresh craters or very steep slopes.

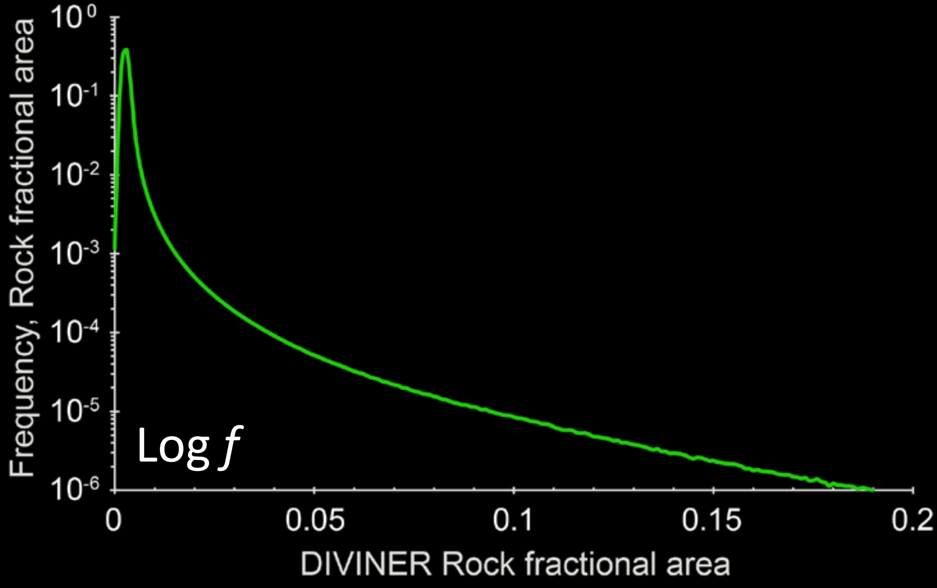
The Moon's Surface



Hayne et al. 2017



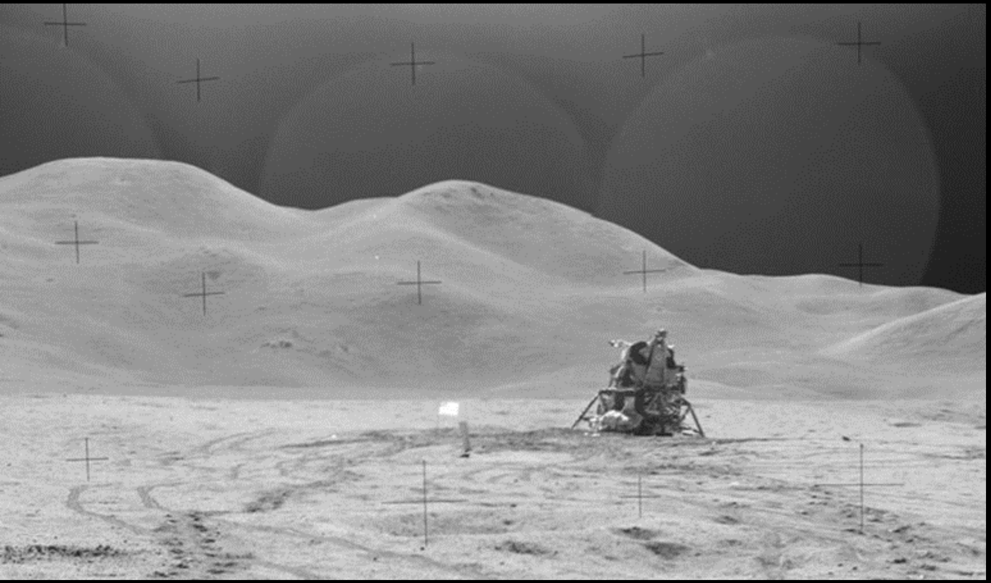
Normal *f*



Log *f*

The Moon’s Surface

3. Hillslopes (and craters) are rounded unless they are very fresh.



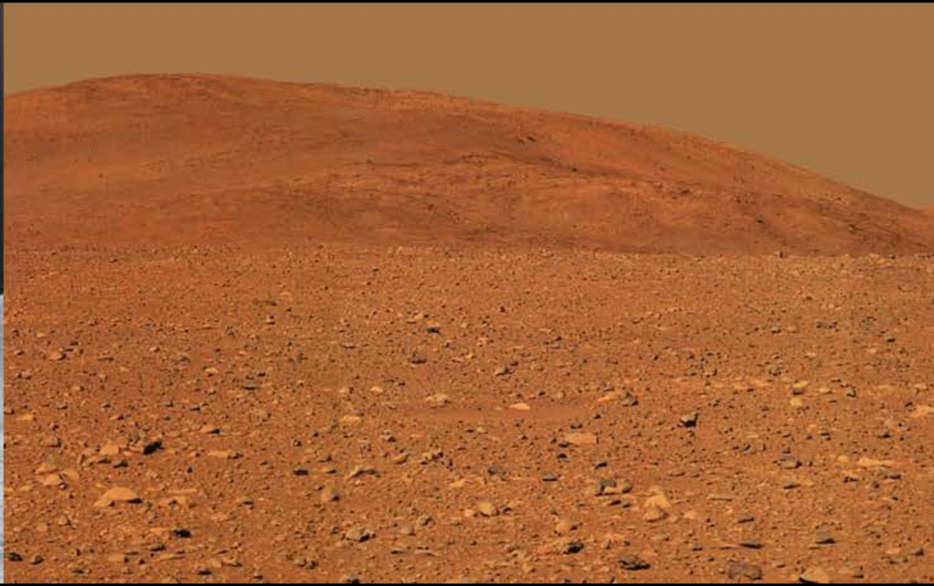
Swann Ridge, Apollo 15, the Moon

North Massif, Apollo 17

Rounded Hillslopes

Dietrich and
Perron, 2006

Atacama Desert

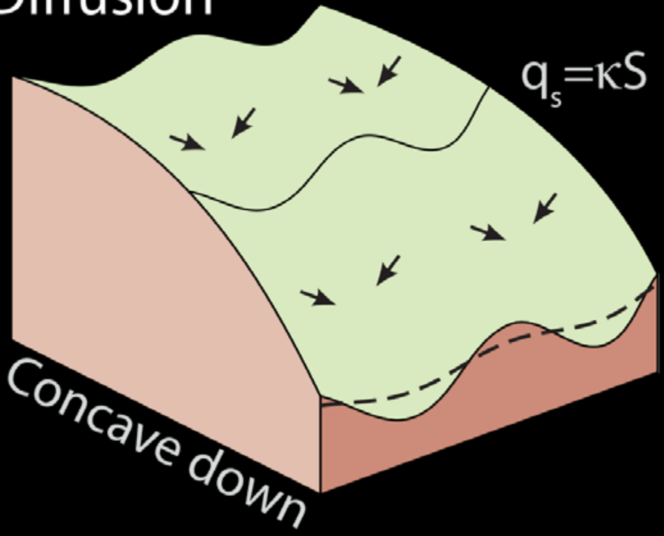


Swann Ridge, Apollo 15, the Moon

Columbia Hills, MER Spirit, Mars

Landform Evolution

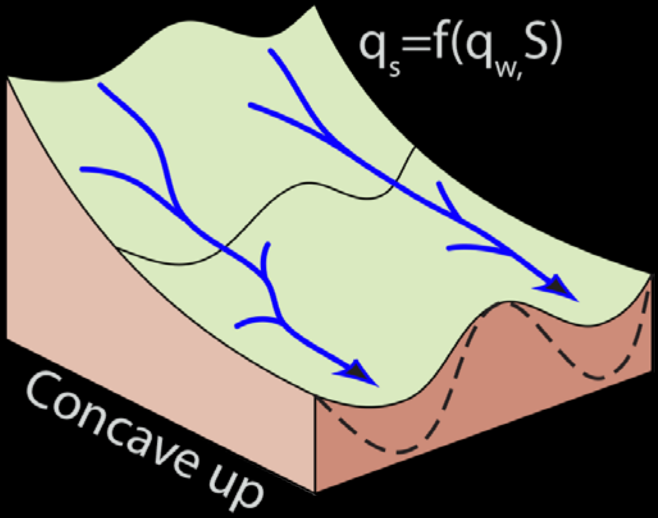
Diffusion



Pertubations damped

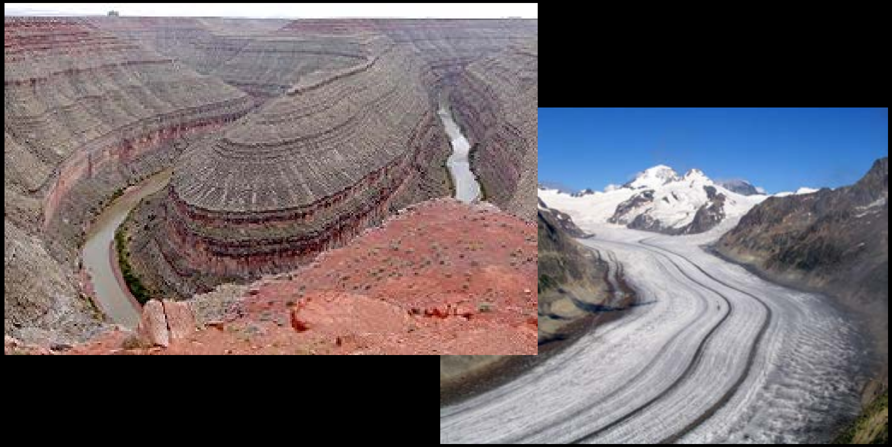
Rainsplash, freeze-thaw, gophers

Advection



Pertubations grow

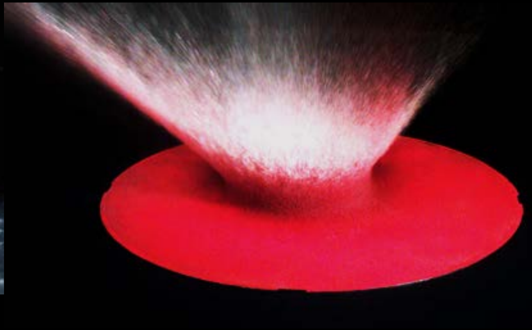
Rivers, glaciers, landslides



Diffusion and Cratering

"…[impact cratering] is analogous, but generally at a larger scale, to the effect of a raindrop …"

Alan Howard, 2007 (Geomorphology)



Soderblom (1970)

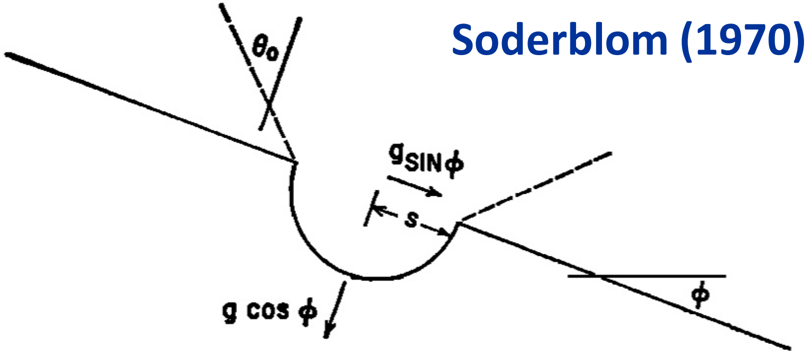
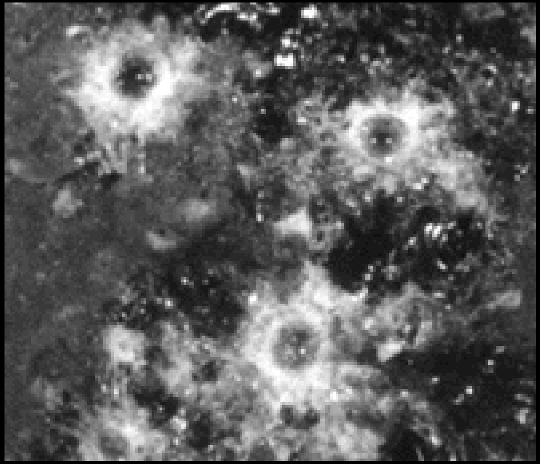


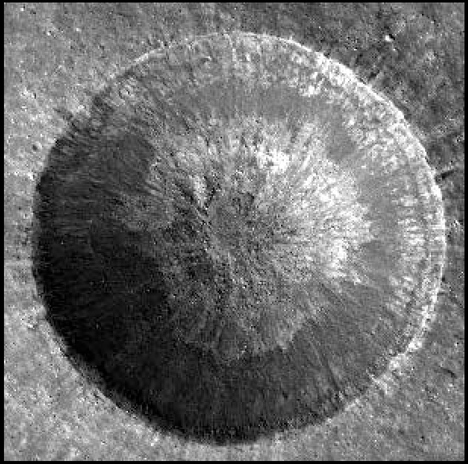
Fig. 2. The geometry of the ejecta trajectories of a crater eroding a surface with slope Φ.

North Massif, Apollo 17

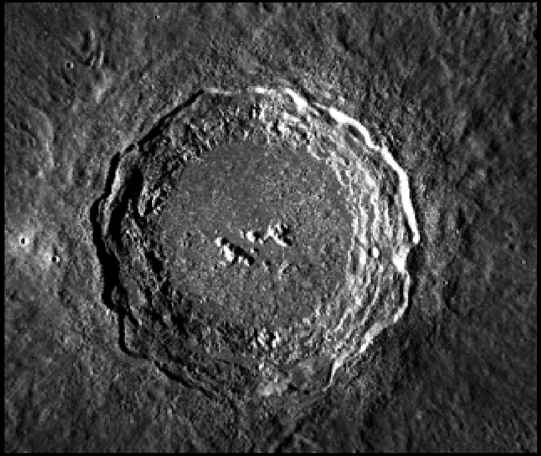
Lunar Craters



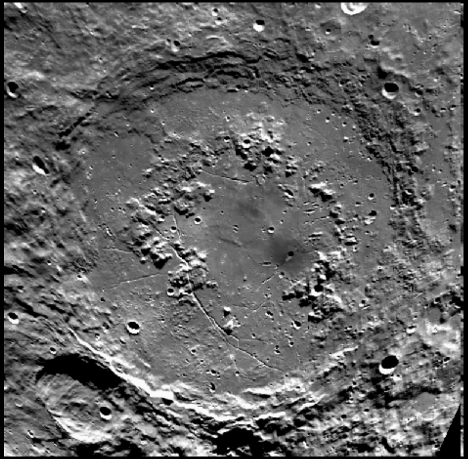
'Zap pits' D~1 mm
(Apollo sample 64455)



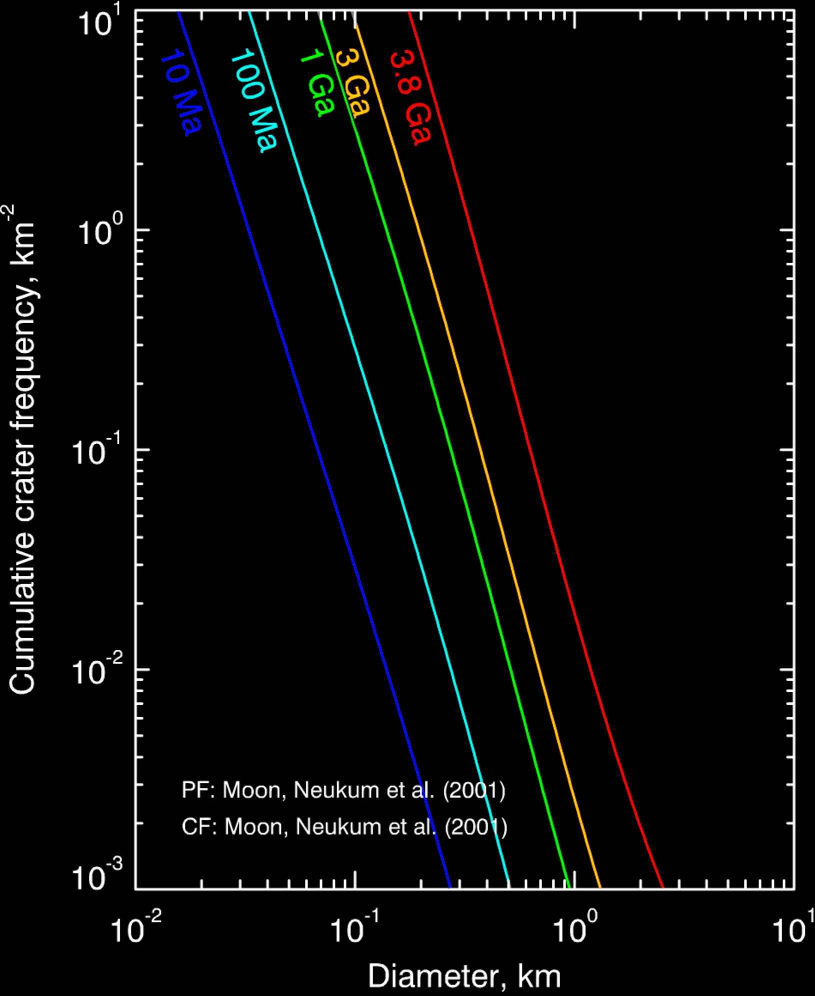
Linné Crater D=2.2 km
(LROC NAC)



Tycho Crater D=90 km
(Kaguya Terrain Camera)



Schrodinger Basin D=310 km (Clementine)



Craters at all scales, but small craters form much more often.

Simple Craters:
Known, self-similar initial forms

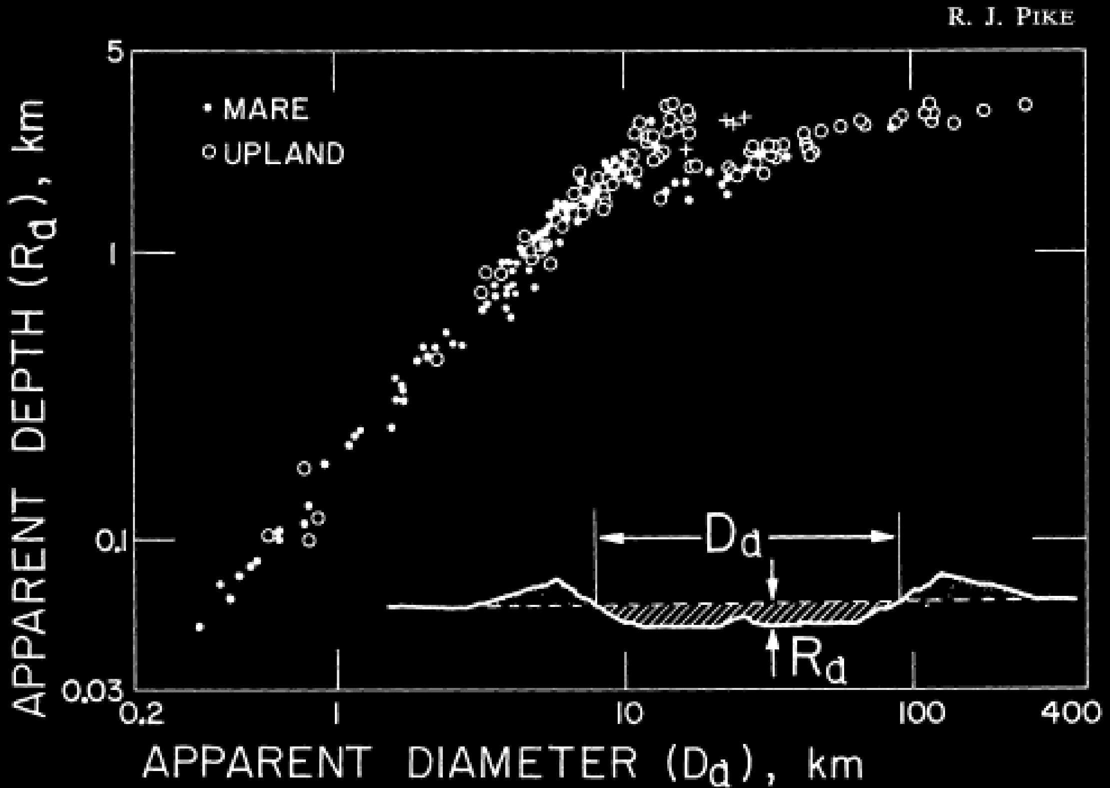
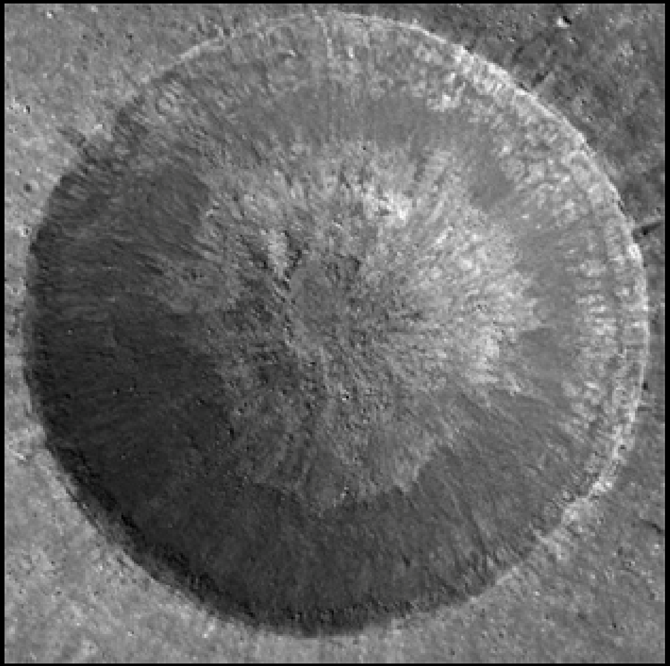
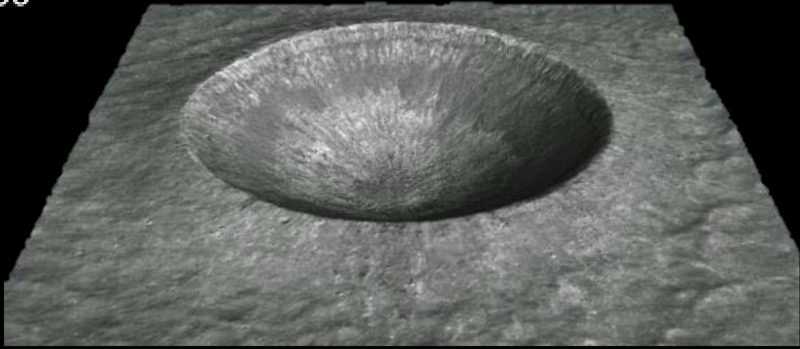


Fig. 1. Apparent depth (R_a)/apparent diameter (D_a) relation for 170 fresh lunar craters. See text for explicit descriptions of variables and their mensuration. All data from maps and profiles compiled photogrammetrically from Apollo 15, 16, and 17 pictures. Distribution separates into two major fields at an apparent diameter of roughly 15 km (equivalent to a rim-crest diameter of about 18 km). Crosses are four upland craters with transitional morphology, discussed in text. Craters below 900 m D_a may be a third field. Data available from the author upon request.

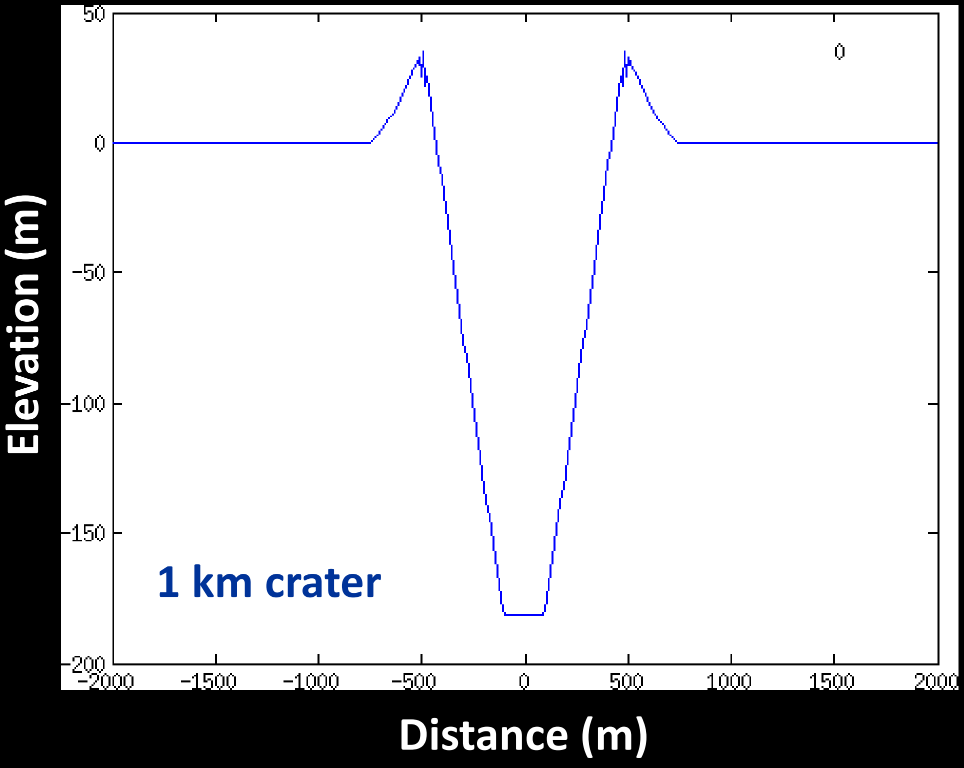
Pike 1977

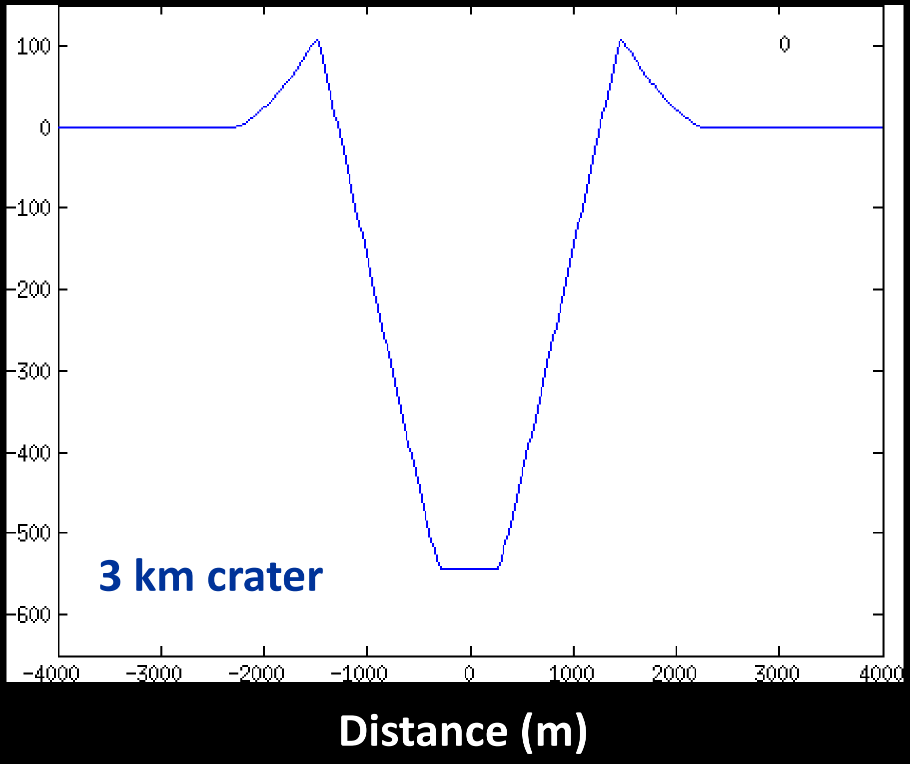




Linné Crater, 2.2 km diameter
(LROC; Garvin et al., 2011)

Topographic Diffusion & Crater Degradation



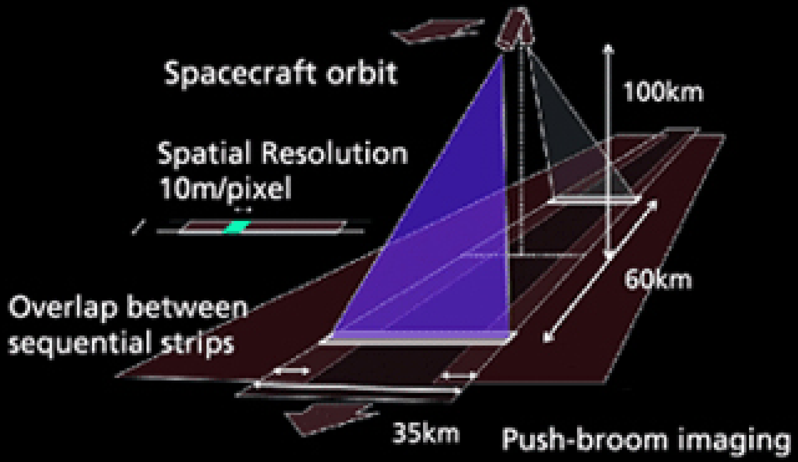


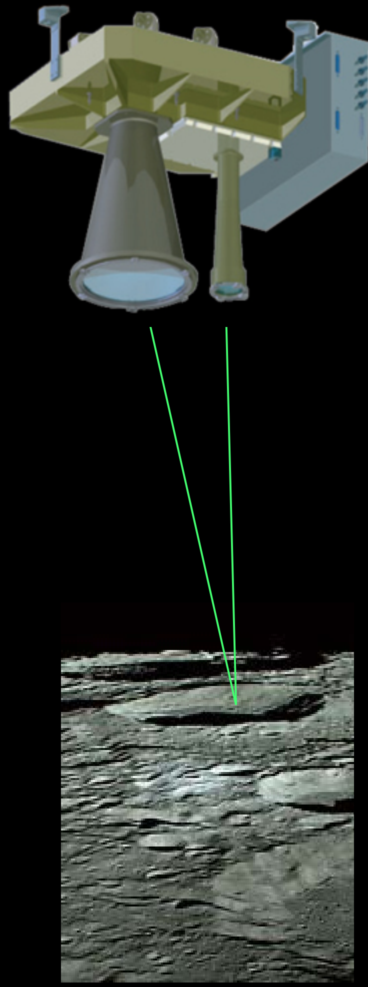
Topographic evolution
of elevation field *h*,
with diffusivity *κ*:

$$\frac{\partial h}{\partial t} = \kappa \nabla^2 h$$

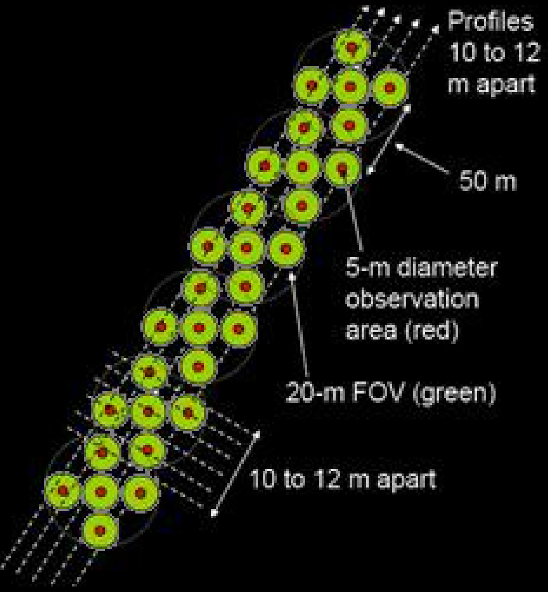
Two Sources of Topography Data: LOLA Laser Altimetry and Kaguya TC Stereo Imaging

Kaguya (Selene) Terrain Camera

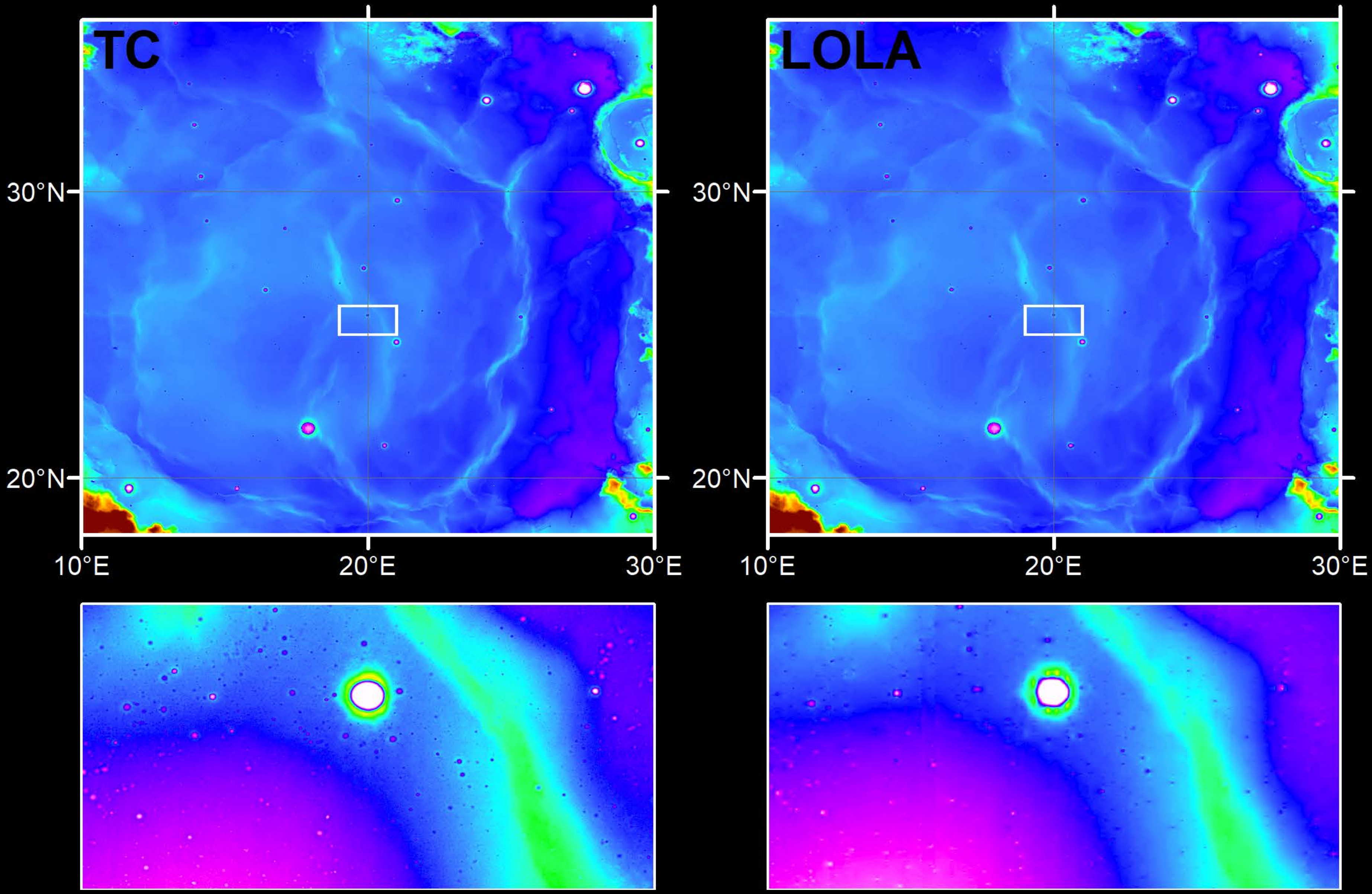




Lunar Orbiter Laser Altimeter (LOLA)

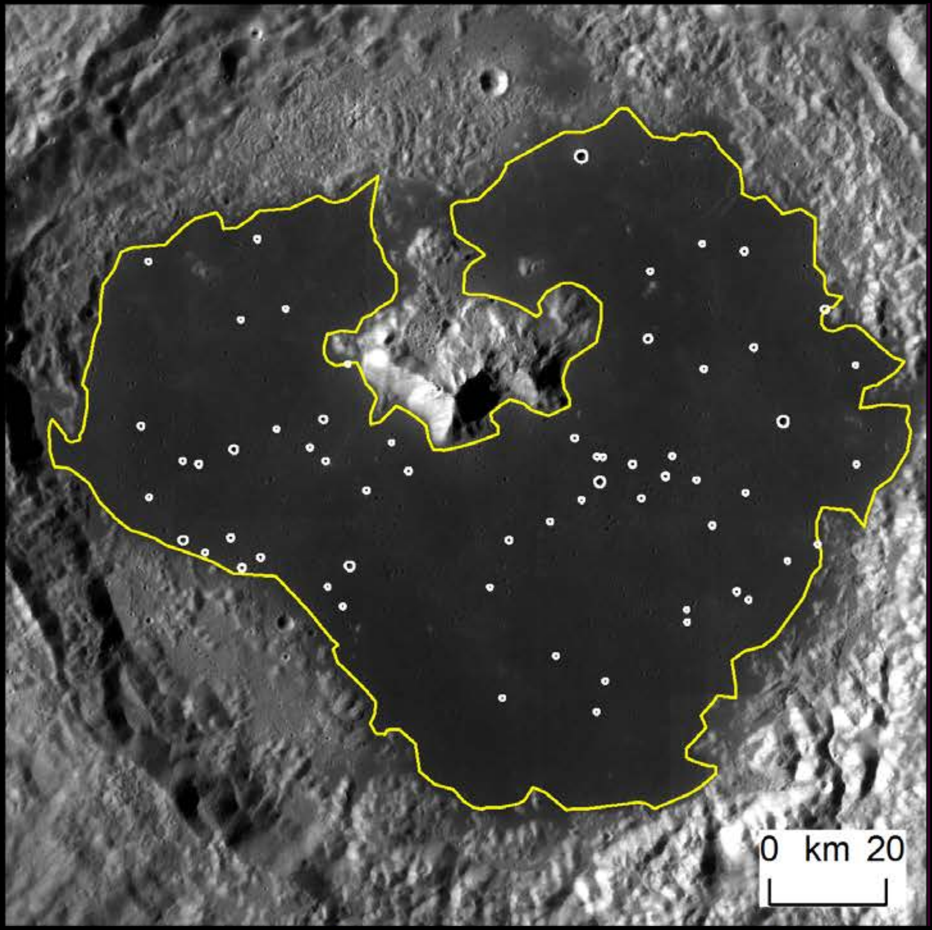


LOLA 512ppd (~59m/px) versus Kaguya Terrain Camera Stereo Data (7-20 m/px)

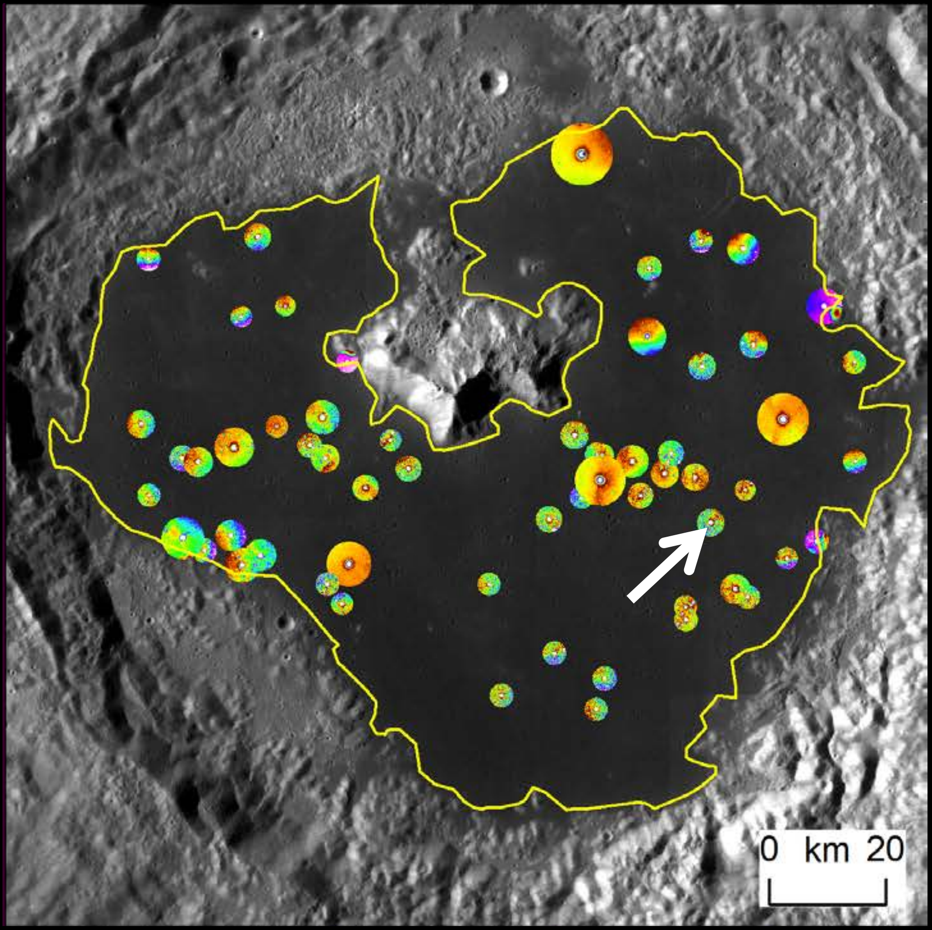


Methodology and Data Analysis

Map all craters *D*=800m to 5 km

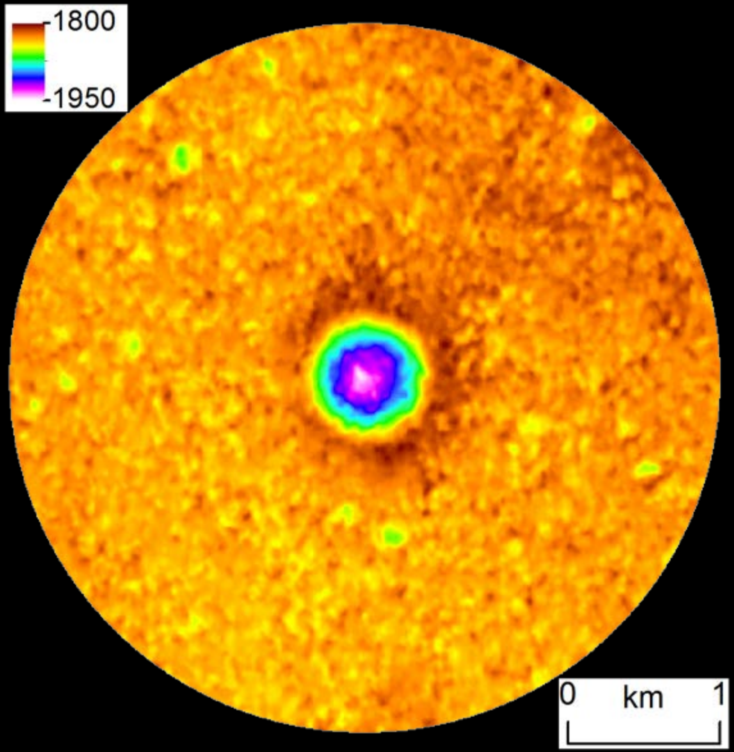


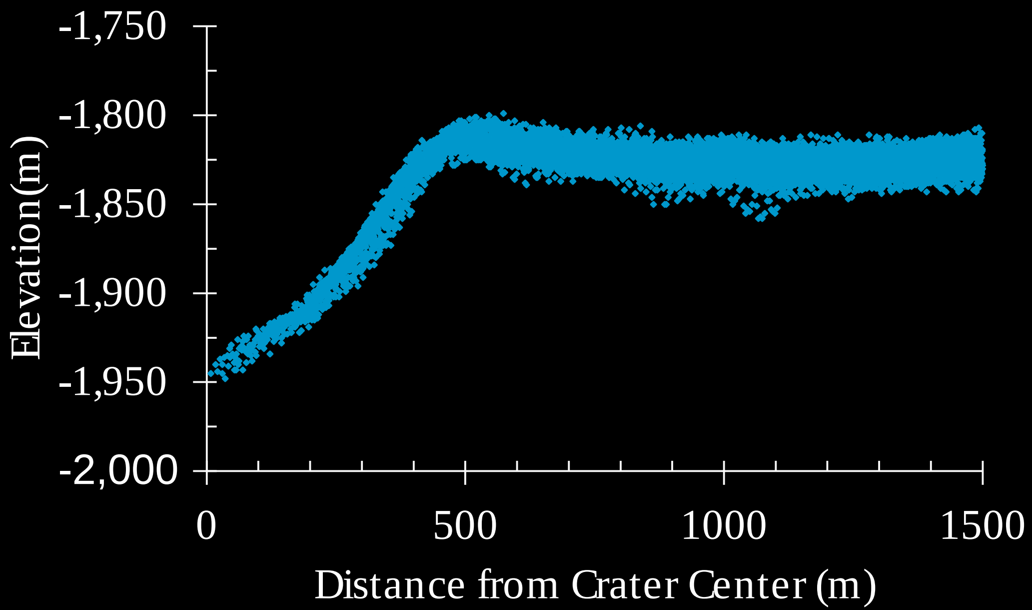
Extract topography for each crater



Mare inside Tsiolkovsky Crater

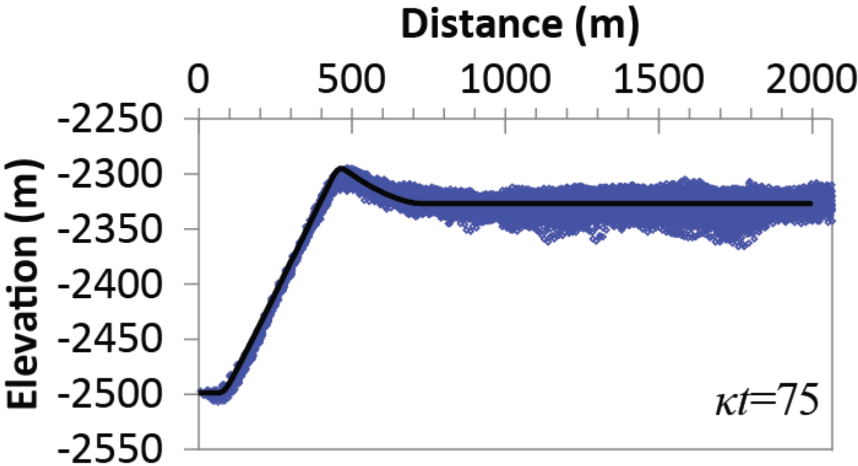
Methodology and Data Analysis

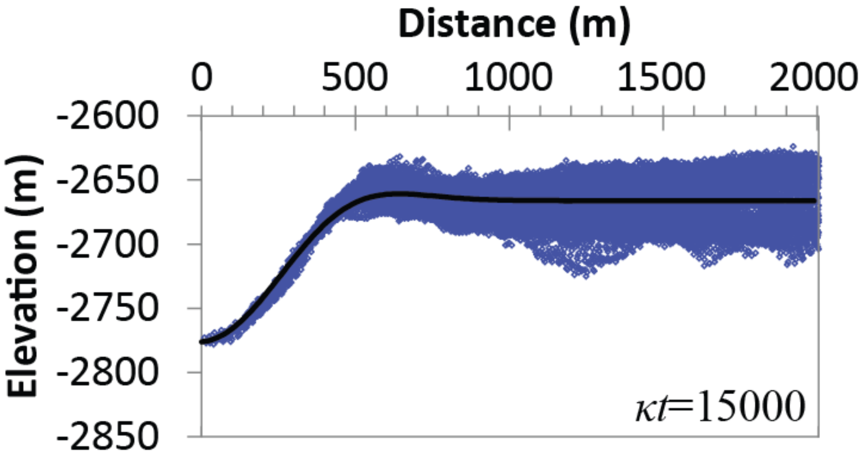


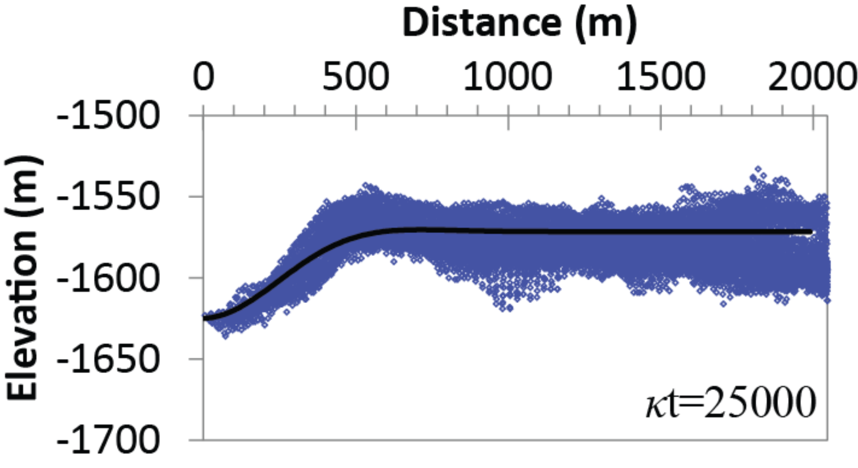


Fitting Diffusion Profiles

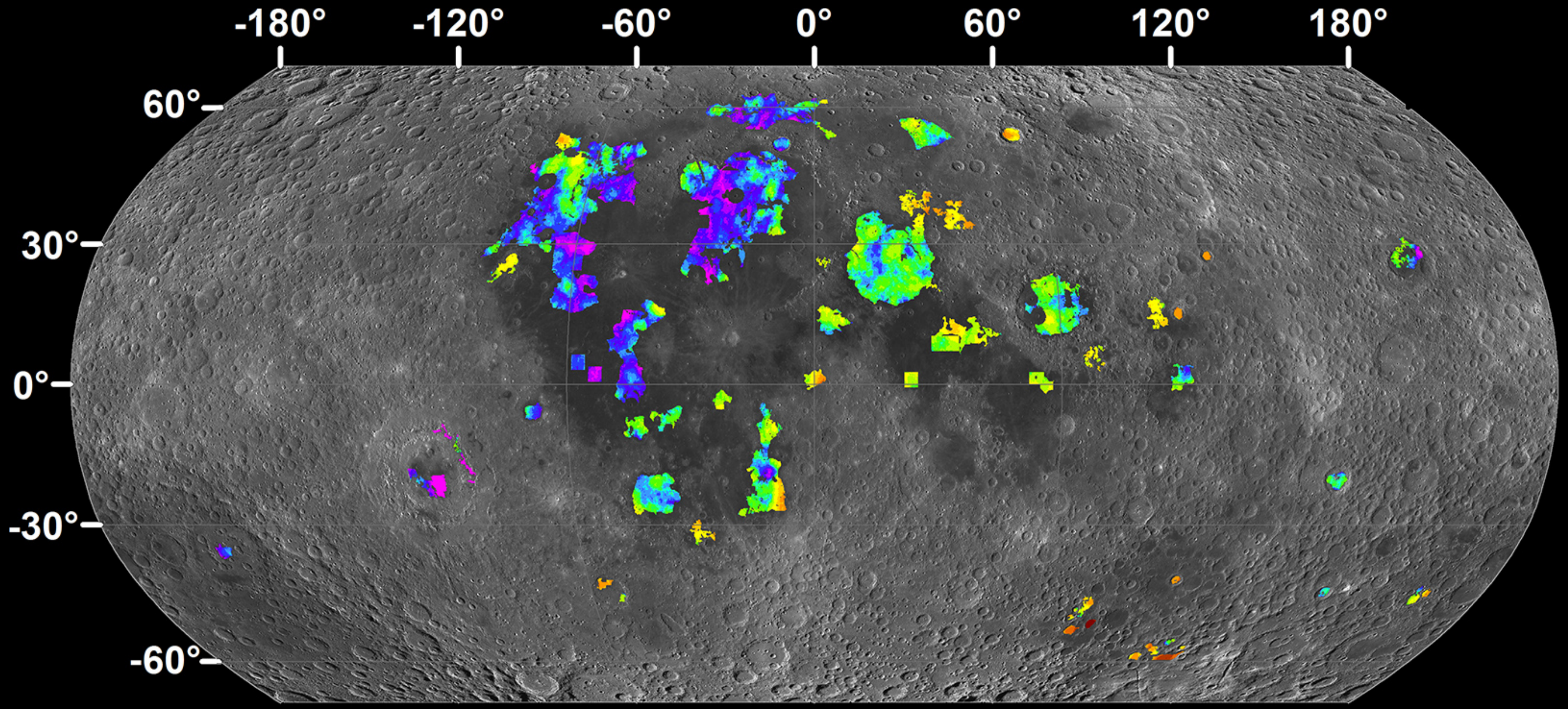
- Mapped, extracted topography, and fit diffusion profiles (in 2D) for 13000+ craters.
- Solve for three parameters:
  - H_0: "zero value" for surrounding elevation
  - D_0: initial diameter
  - κt: Degradation state
- Typical fitting uncertainties:
  - κt is ~2.5%
  - D_0 is ~0.5%
    (larger and more degraded craters have worse fits)







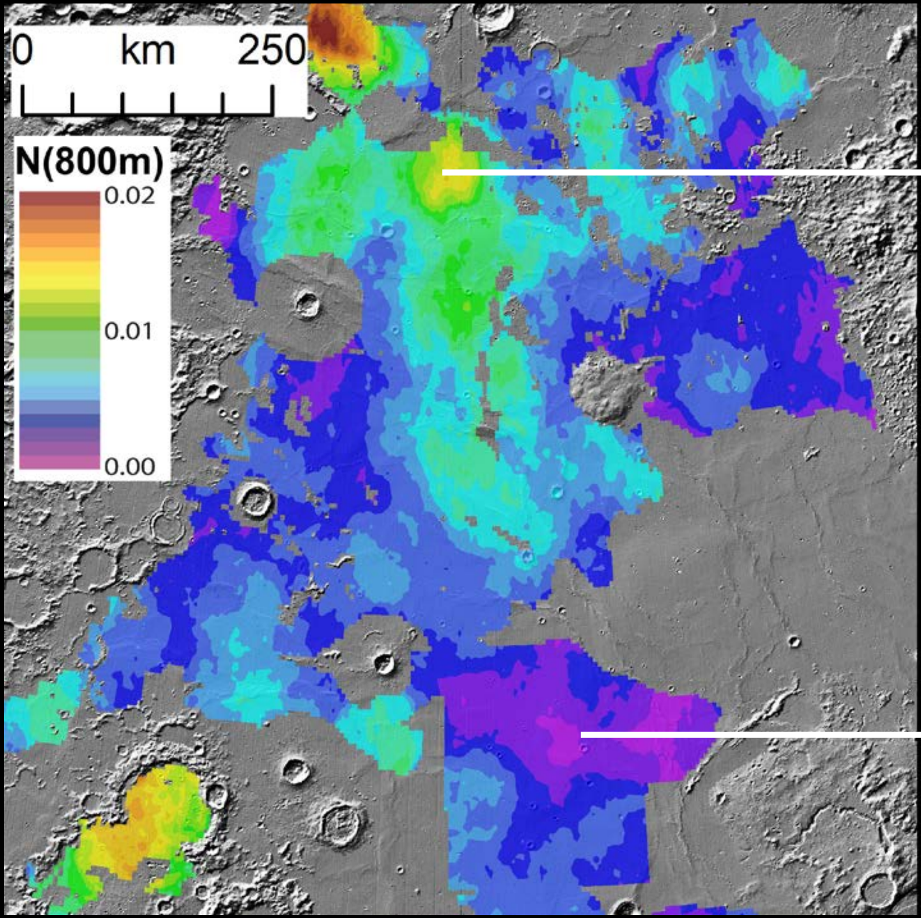
Crater Density on the Lunar Maria



N(800m): Crater density number of
$D \geq 800$ m craters per 10^3 km^2

Neukum Model Age (Ga) from Crater Density

Crater Density (Detail)

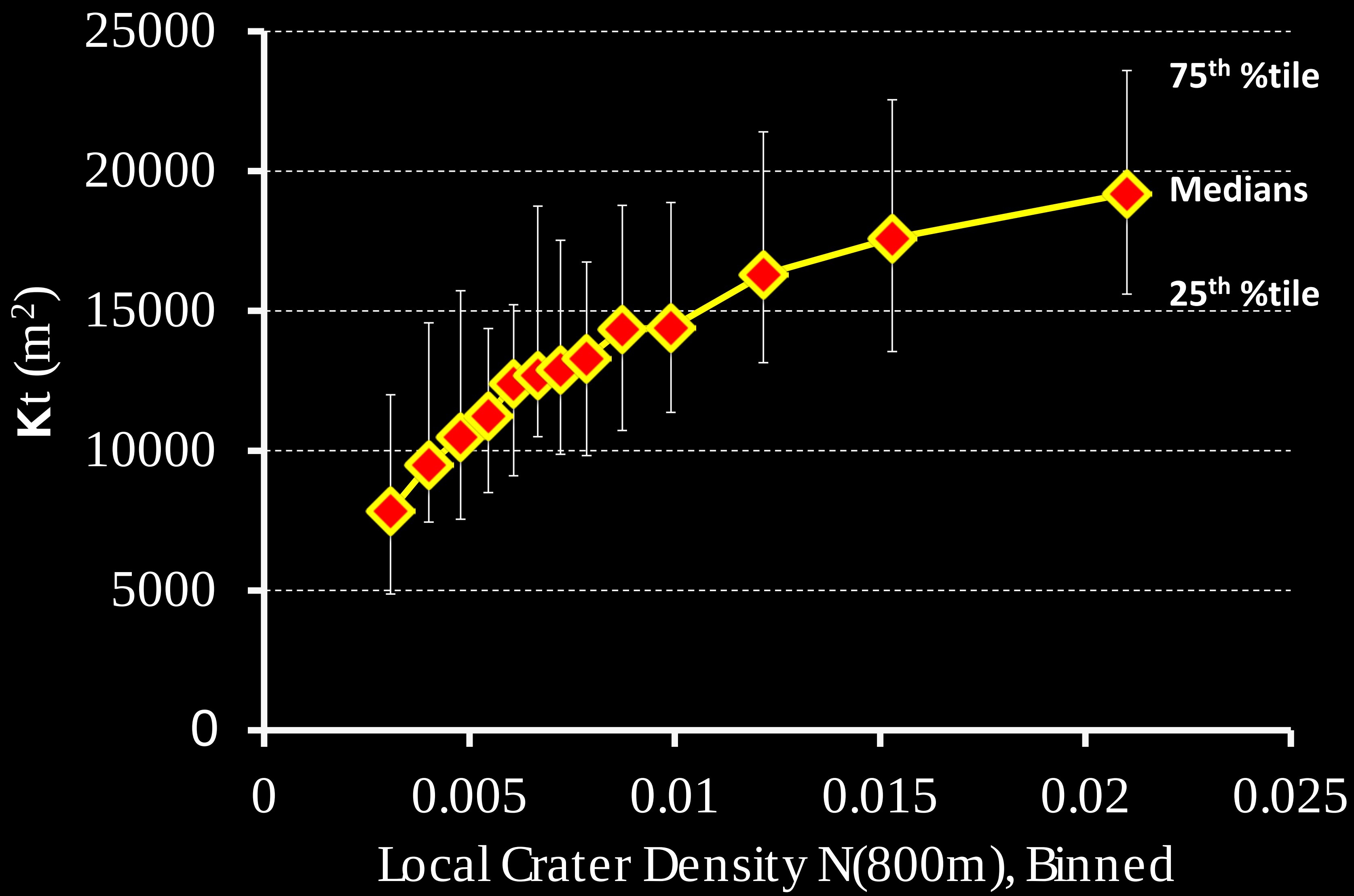


N(800m): Crater density number of
D≥800 m craters per 10^3 km^2

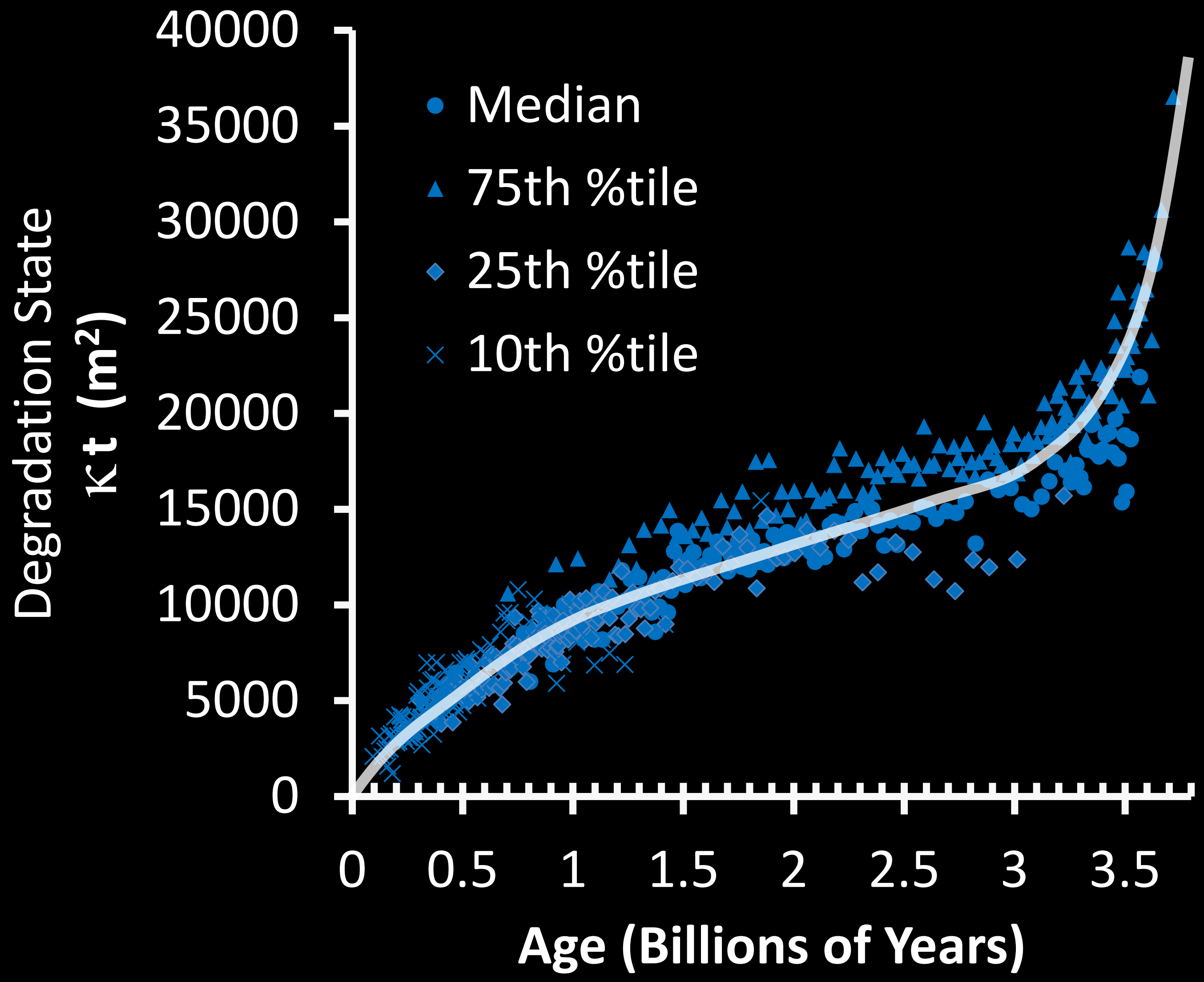
Computed in 50 km radius moving neighborhoods

Factor of 10 × difference in crater density

Degradation State versus Crater Density

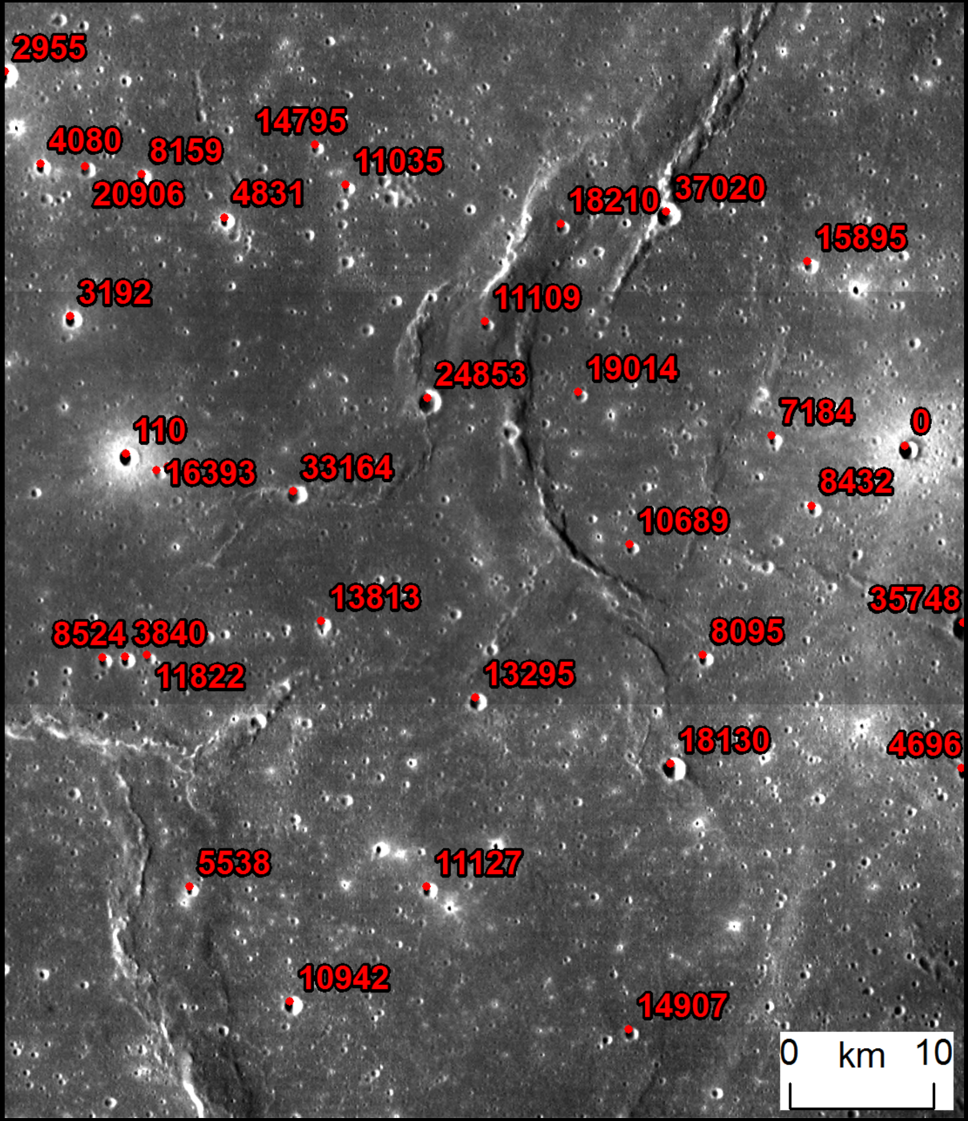


Degradation State versus Age



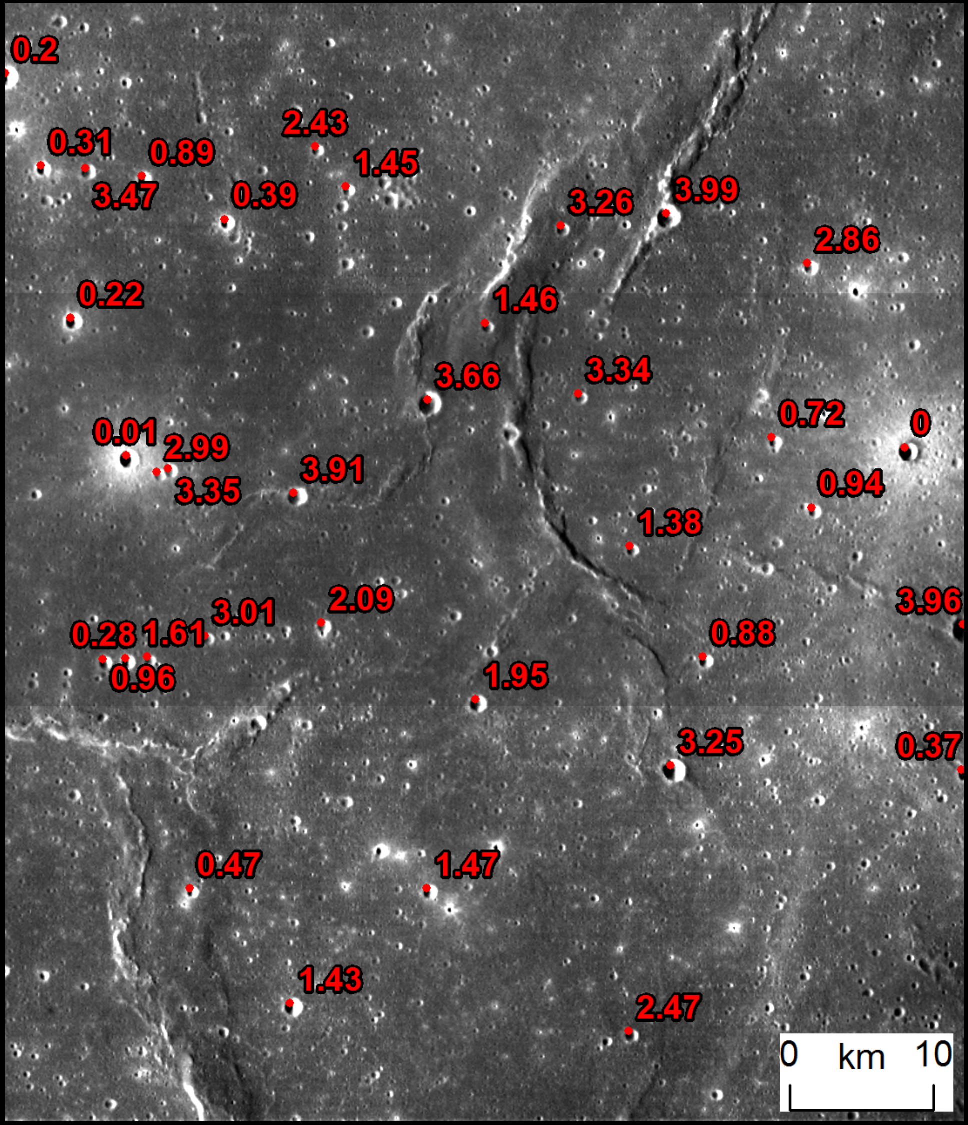
Fassett and Thomson, 2014

Tagging craters with an age



Degradation State, κt

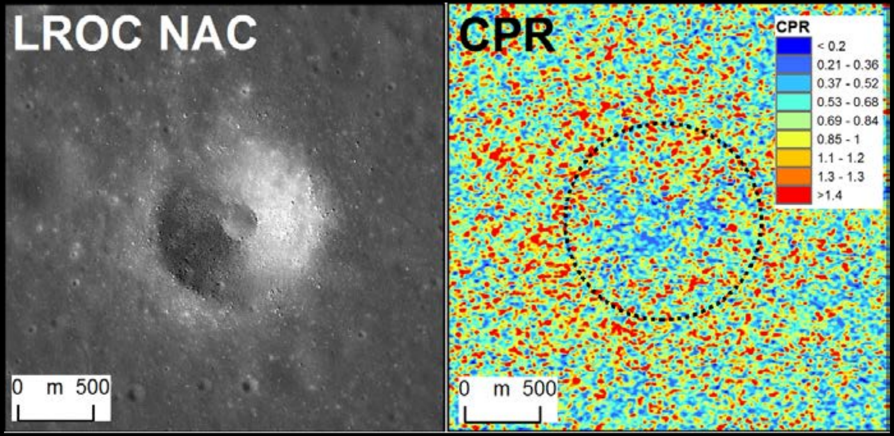
Tagging craters with an age

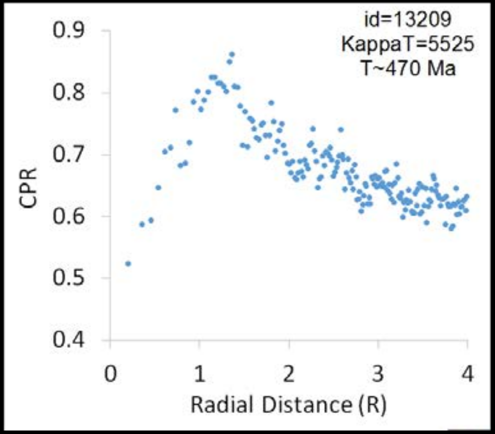


Age (billions of years)

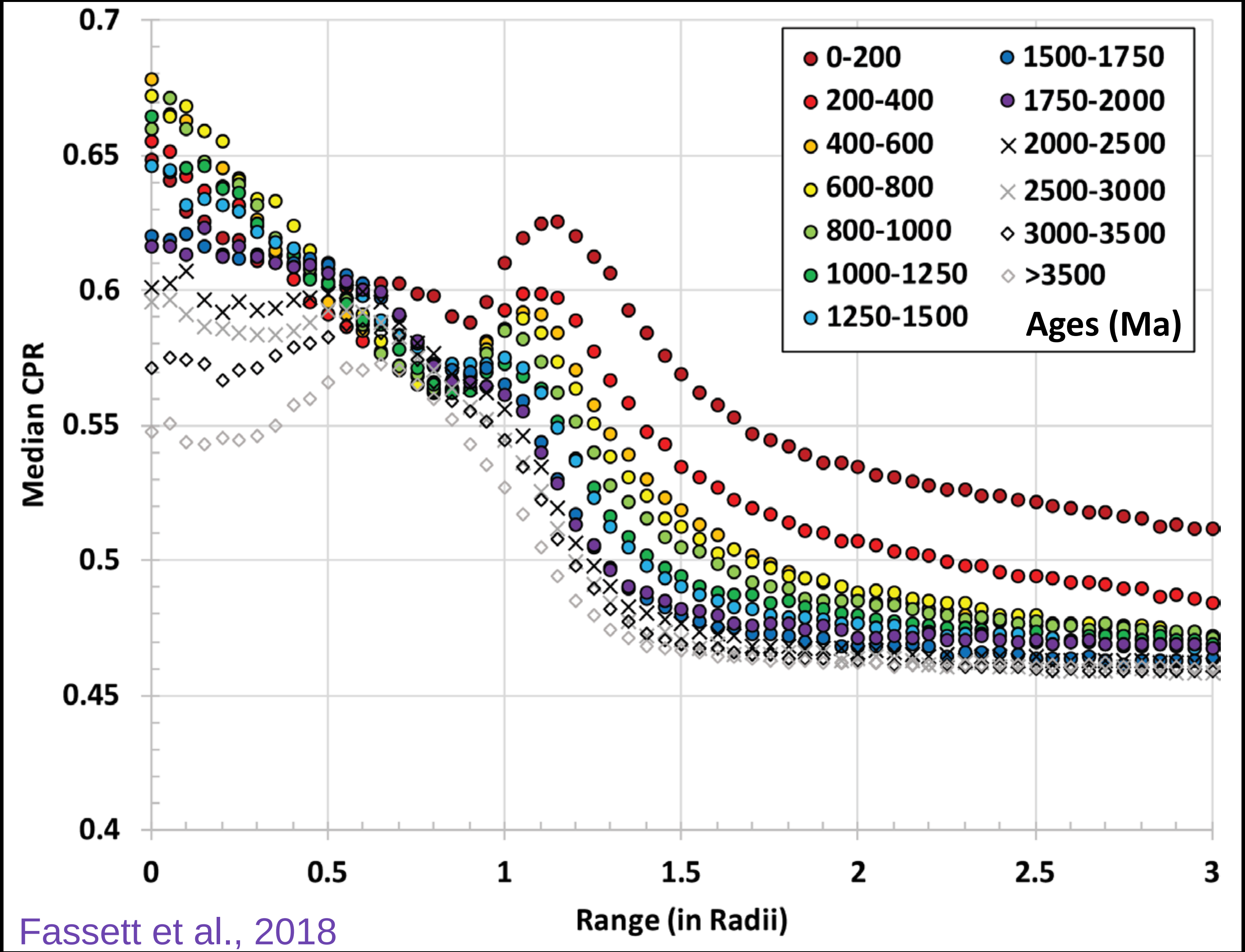
Application: Evolution of the Regolith

- S-band (12.6 cm) radar measurements is sensitive to rocks + roughness ~1 m depth.
- Circular Polarization Ratio, CPR = SC/OC
- Strategy:
    - Look at craters of estimated age, see how their surface materials evolve.



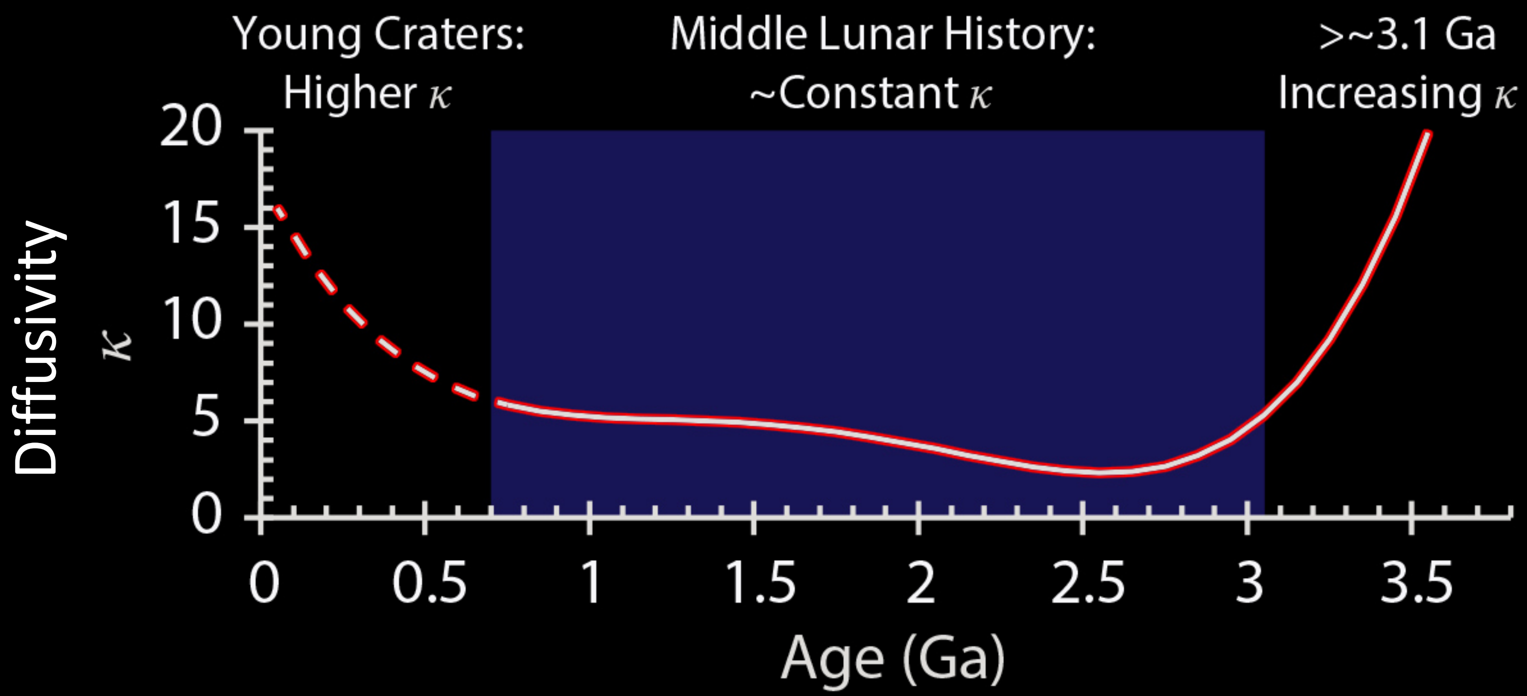


Application: Evolution of the Regolith



Fassett et al., 2018

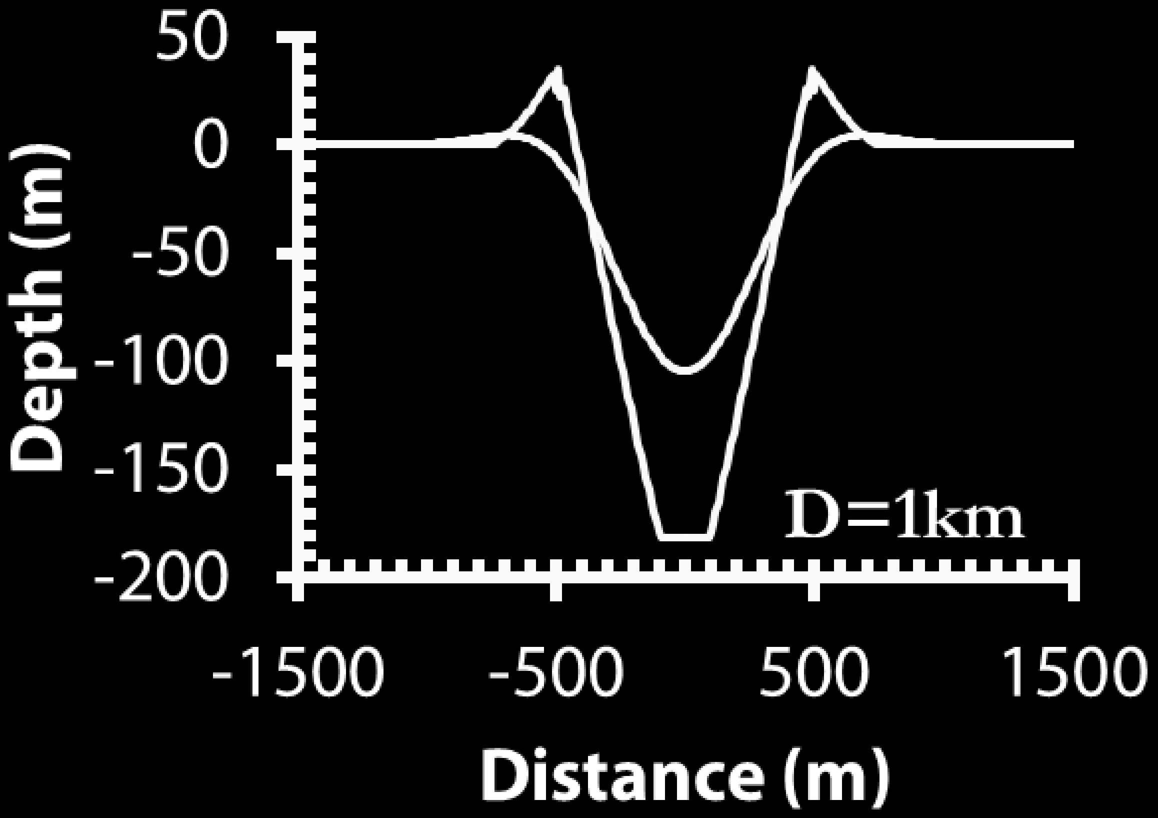
Diffusivity and Erosion History



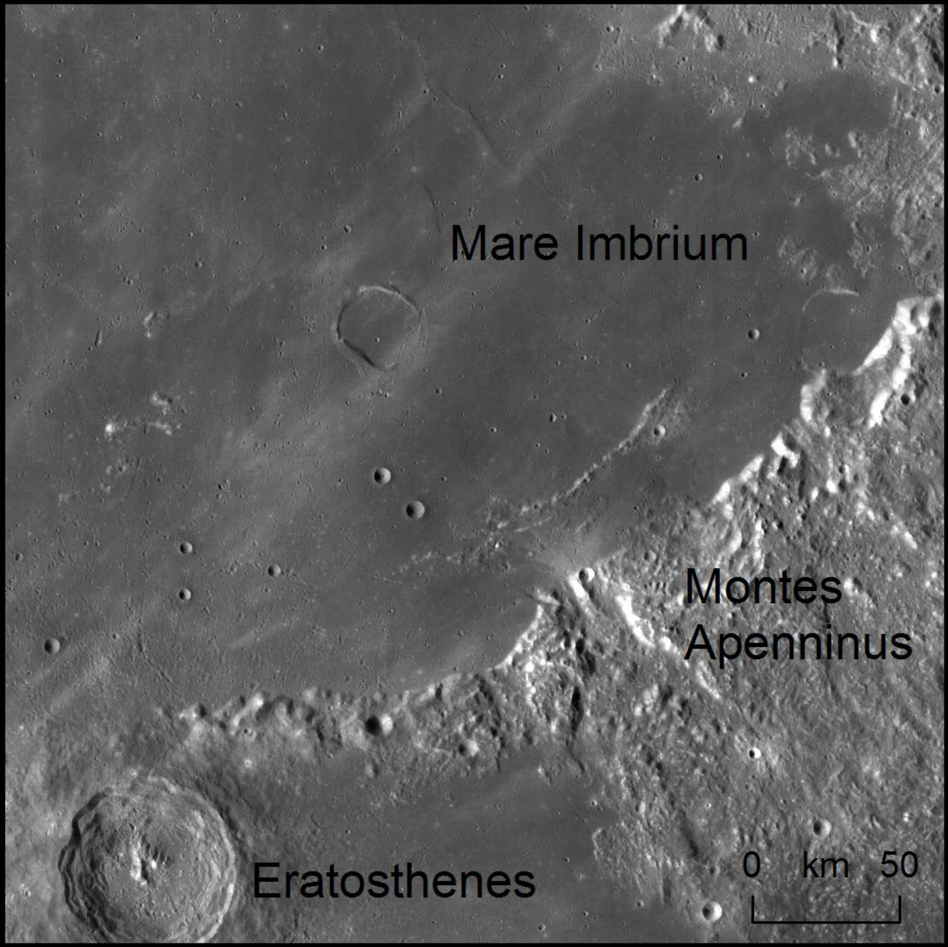
- Typical diffusivity (at km-scale) over last ~3 Gyr is κ~5 m^2/Myr. Diffusivity is ~200 × less than what is measured in the western US (e.g. κ~1000 m^2/Myr; *Colman and Watson* 1983).
- <u>Reminder:</u> Erosion Rate, $dh/dt = \kappa\nabla^2 h$. Median rate of change of topography driven by km-scales: 0.3 mm/Myr.

Application: Crater Erosion

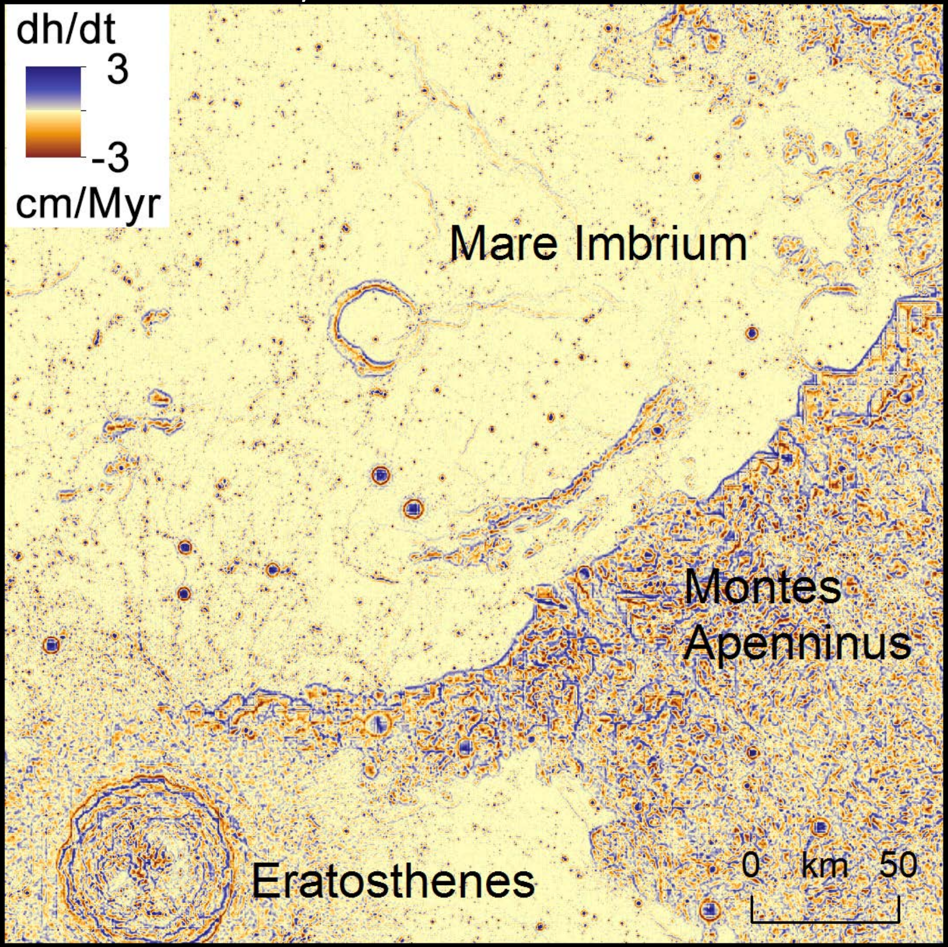
After 3 Gy, a D=1 km crater is reduced to 50% of its original depth.



Application: Erosion Rate



Maximum local dh/dt estimated at 100-m baseline

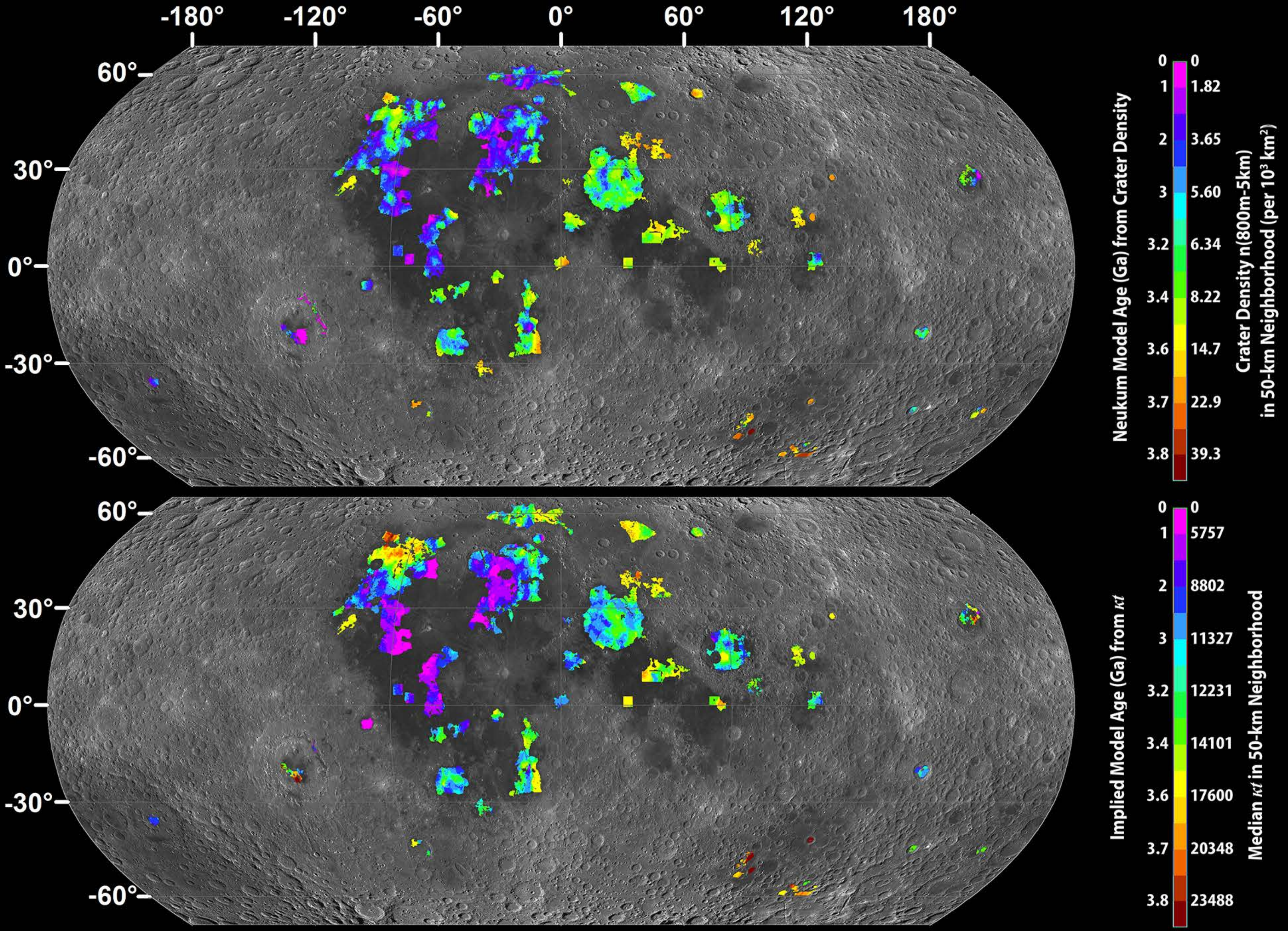


Erosion & deposition at rates ~2-3 cm/Myr in areas with greatest topographic relief.

Application: Terrain Age

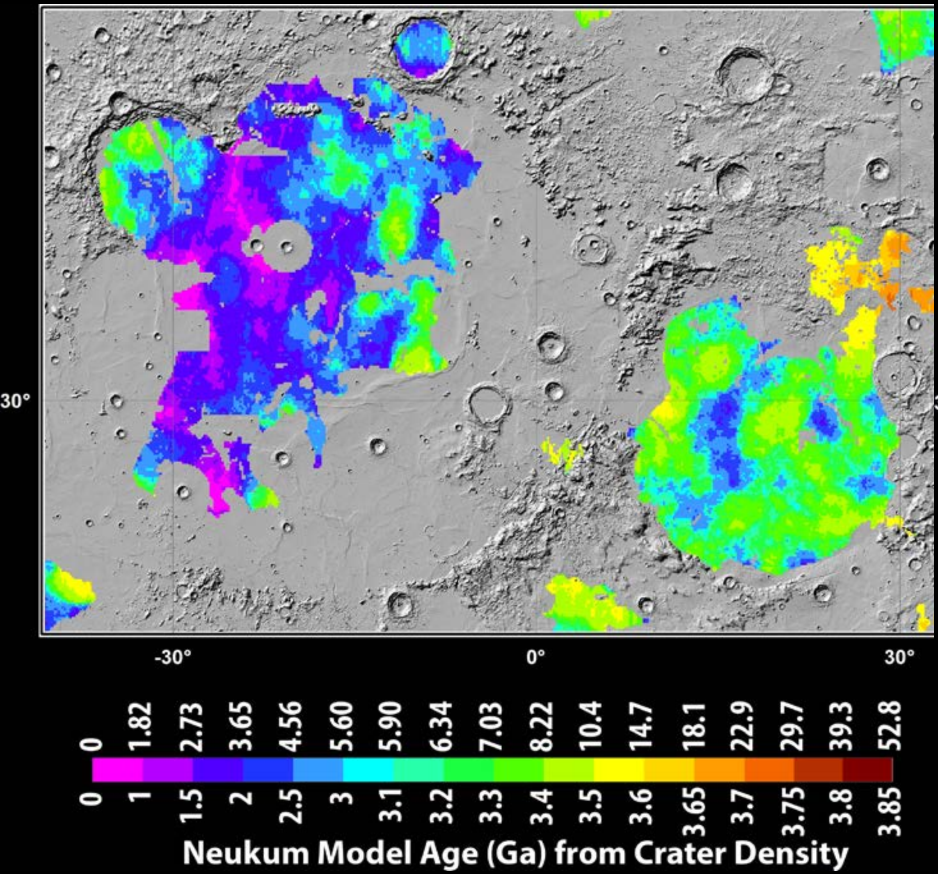
Terrain Age:
Crater Density

Terrain Age:
Crater Degradation

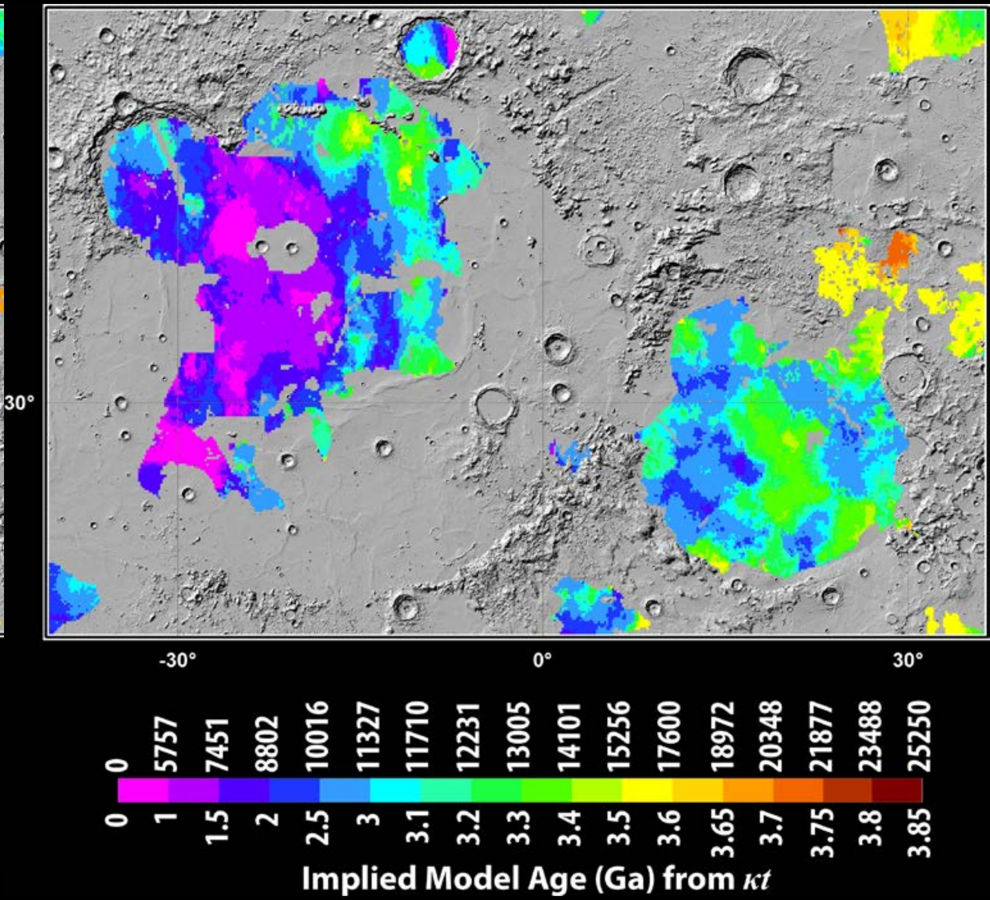


Fassett and Thomson, 2014

Application: Terrain Age
(Detail: Imbrium + Serenitatis)



Crater Statistics

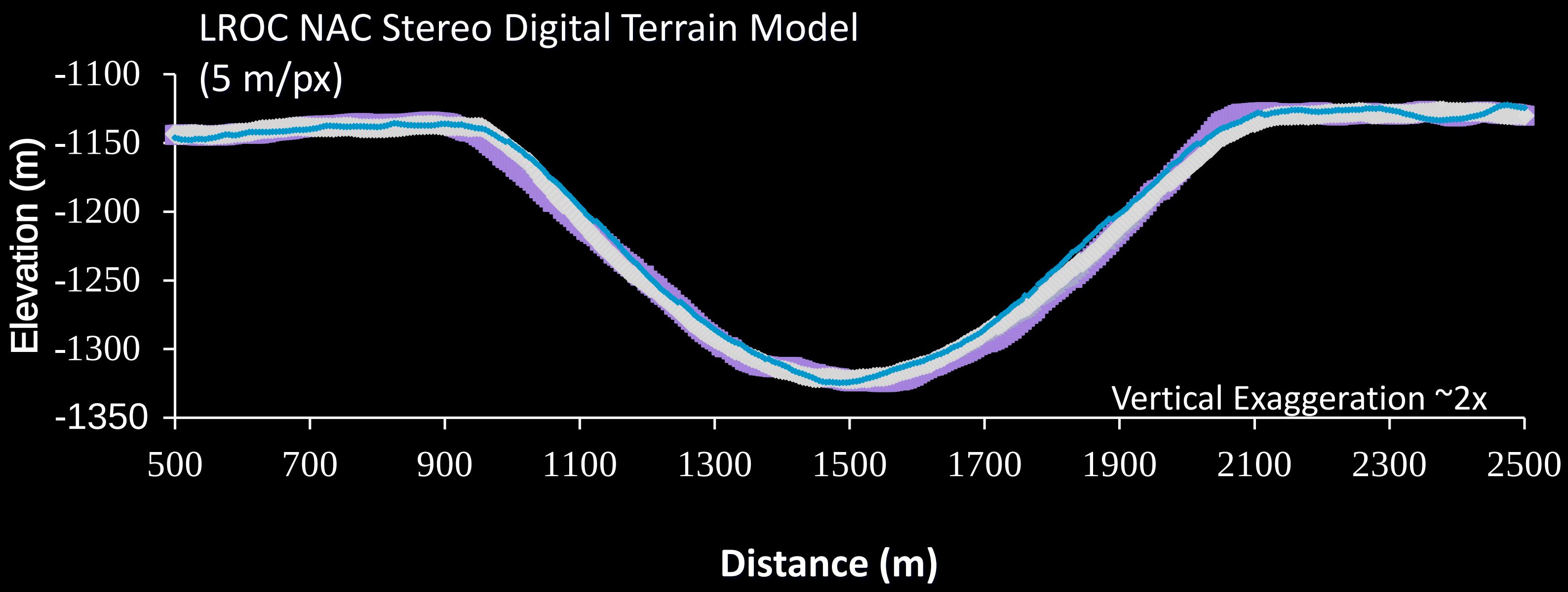


Crater Degradation

Application: Lunar Rilles

AS15-85-11398/AS15-85-11399
Photo Credit: Jim Irwin

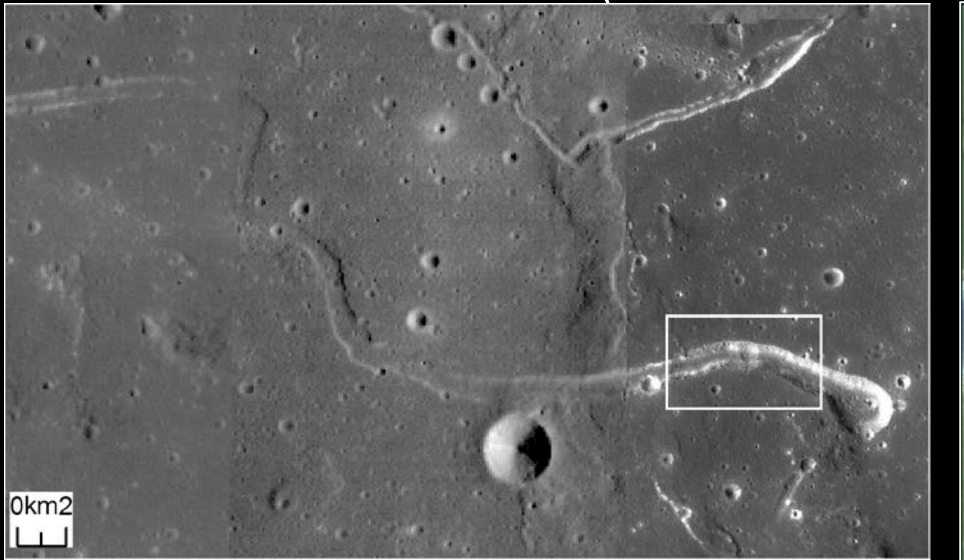
Application: Lunar Rilles

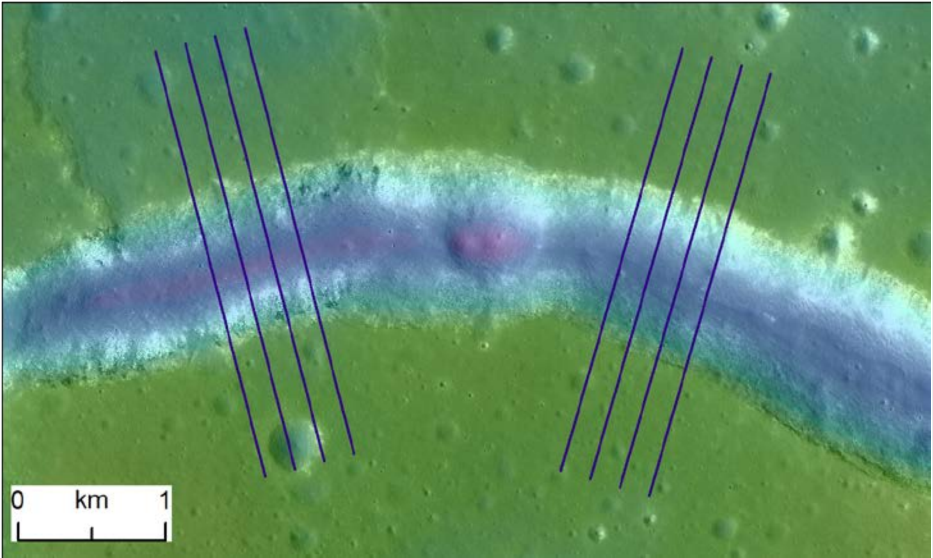


Issue: Unlike with craters, lack good constraint on initial topography

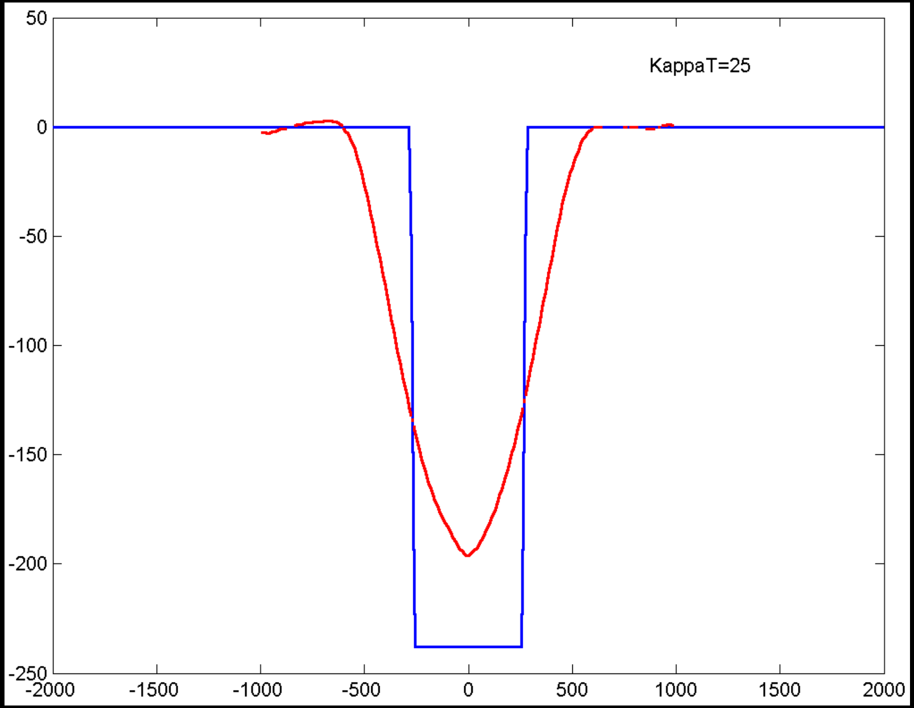
Unnamed Rille in Marius Hills (Hurwitz et al. 2013, #40)

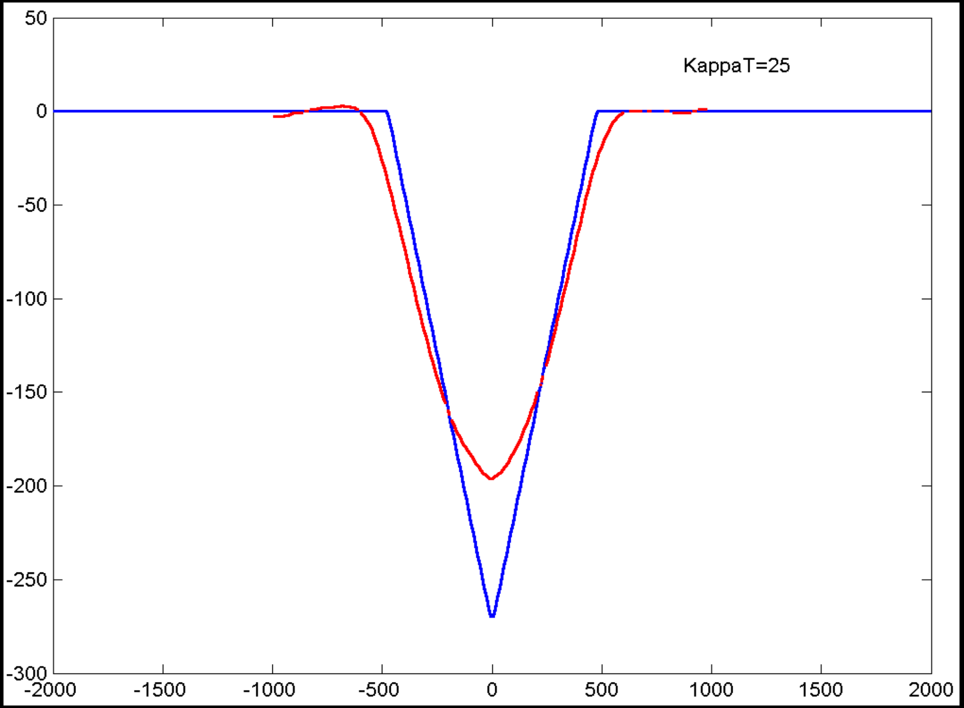
-56E, 13.7N





Application: Lunar Rilles





Rectangular initial profile:
90^o interior slopes…

Final κt ~18300. t~3.5 Gyr
Infill ~ 40 m

Triangular initial profile:
30^o interior slopes…

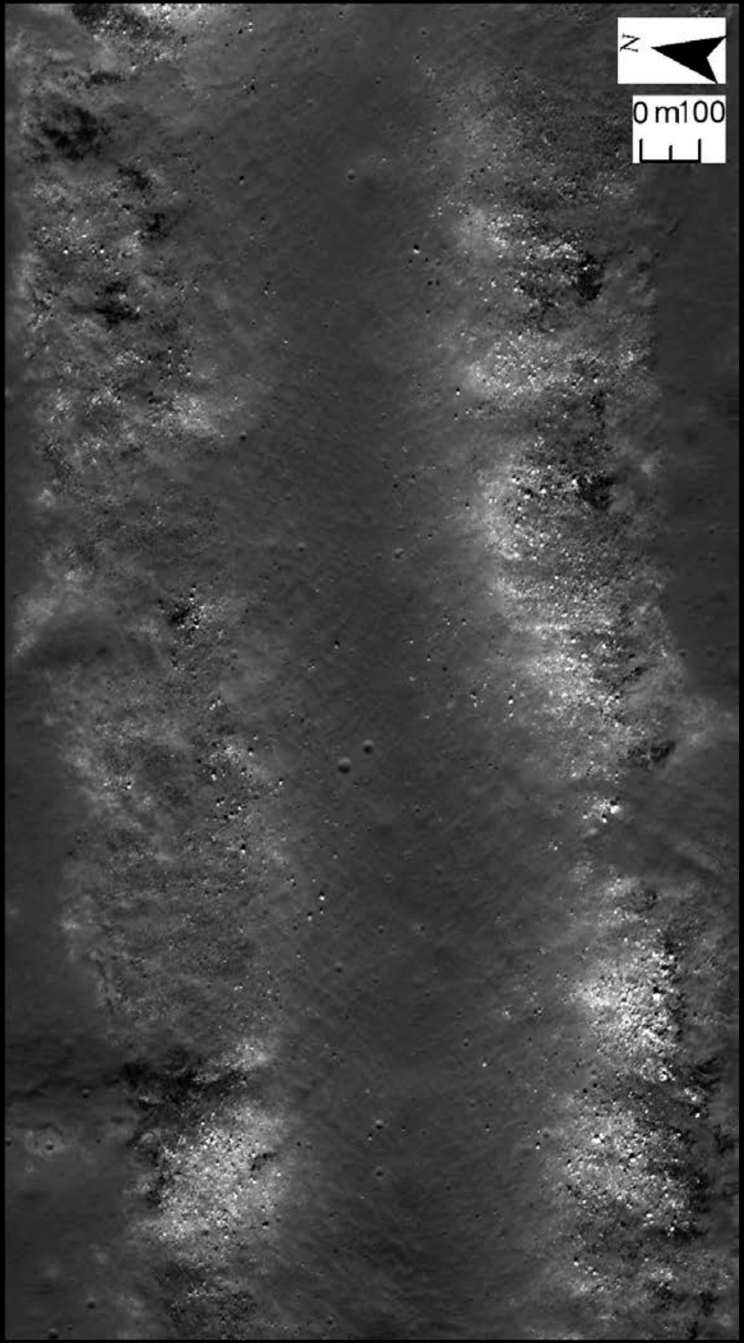
Final κt ~14500. t~2.5 Gyr
Infill ~ 60 m

Application: Lunar Rilles

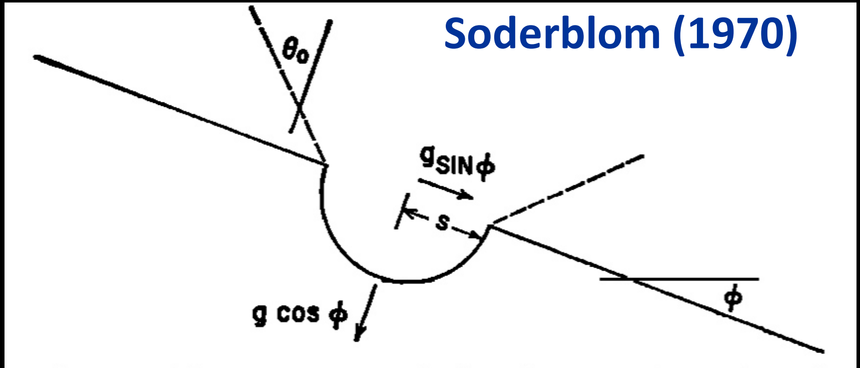
- Many tens of meters of fill over age of exposure;
- Even after ~3 Gy of erosion, wall still is eroding back at ~3 cm/Myr.
- Consistent with exposures of numerous new rocks.

  99% of >2m rocks destroyed in 150 to 300 Myr *(Basilevsky et al., 2013).*

- Deviation from diffusive shape near rim may be due to weathering limitation imposed by breakdown of boulders and bedrock.



2015-2019: Insights into diffusive forcing



Soderblom (1970)

Fig. 2. The geometry of the ejecta trajectories of a crater eroding a surface with slope Φ.

- Local proximal crater ejecta alone is totally insufficient. Enhanced micrometeorite flux also insufficient.
- Indirect motions of material triggered by distal ejecta/secondaries matters more than local ejecta.

NASA/GSFC/ASU/LROC team

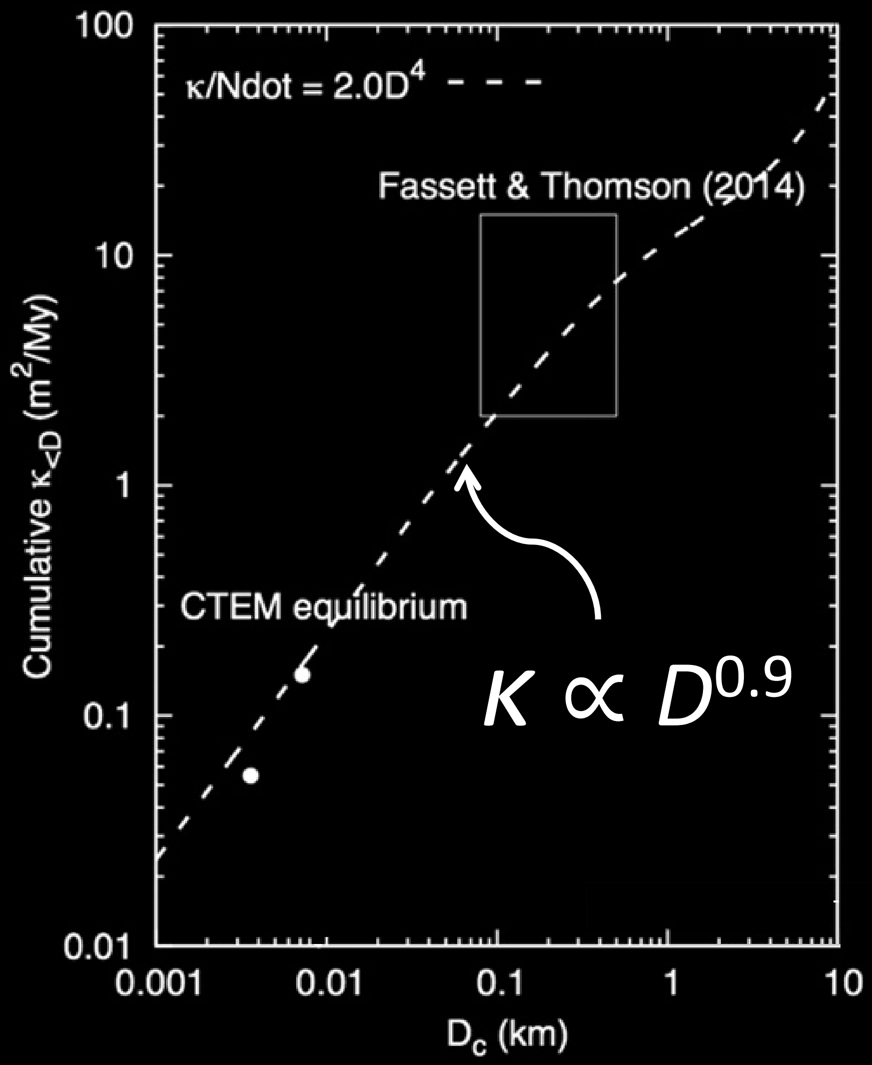
March 17, 2013 impact crater
Before and After

See Speyerer et al., 2016
Minton et al., 2019

2015-2019: Diffusion is Anomalous, or, what I missed in 2014

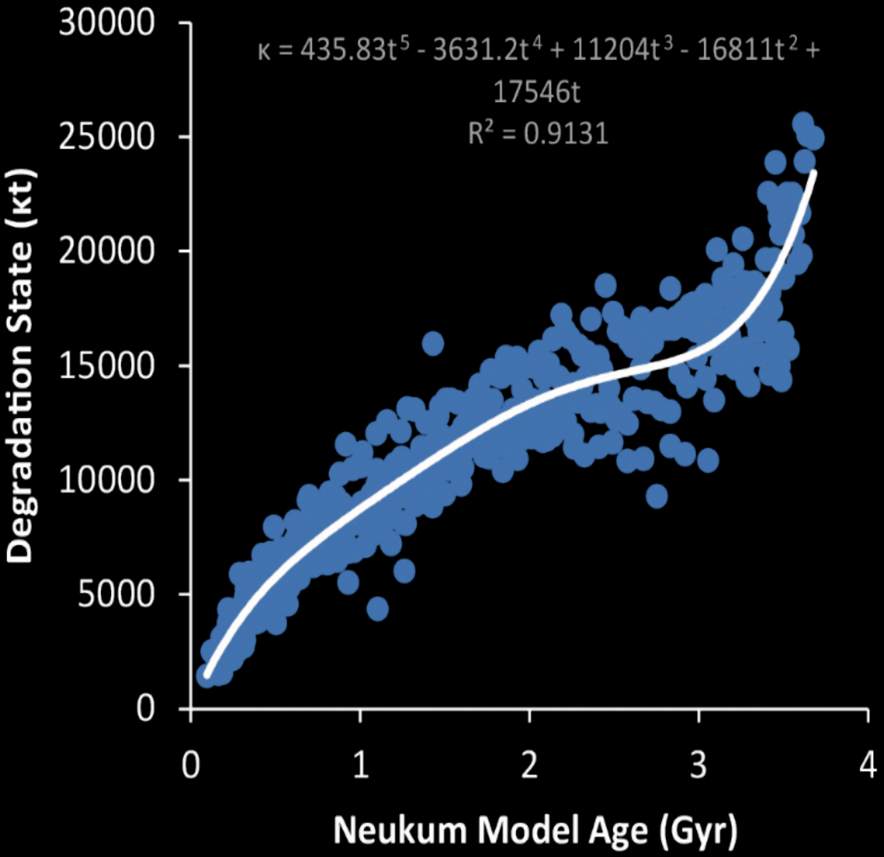
- Effective *κ* experienced by **smaller** craters is **less** than larger ones.
- $\kappa_{\text{eff}} \sim \kappa_{ref} D^{4+\eta}$ where η is the slope of the CSFD and η~−3.1 for craters <~100m.
- Crater lifetime:

$$\tau \sim \frac{D^{2-(4+\eta)}}{\kappa_{ref}} \; \alpha \; D^{1.1}$$

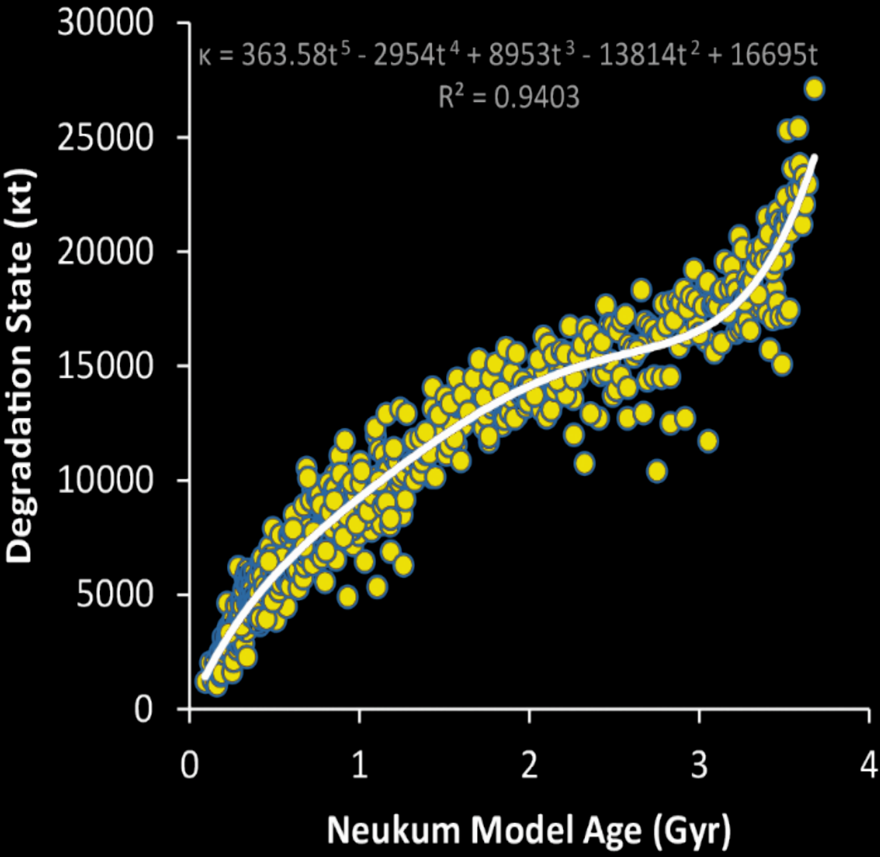


From Minton and Fassett, LPSC 2016

2015-2019: Diffusion is Anomalous, or, what I missed in 2014



Fassett and Thomson (2014)



Re-analysis w/ scale-dependent κ_{eff}
(uses 0.9 power law dependence)

Summary so far

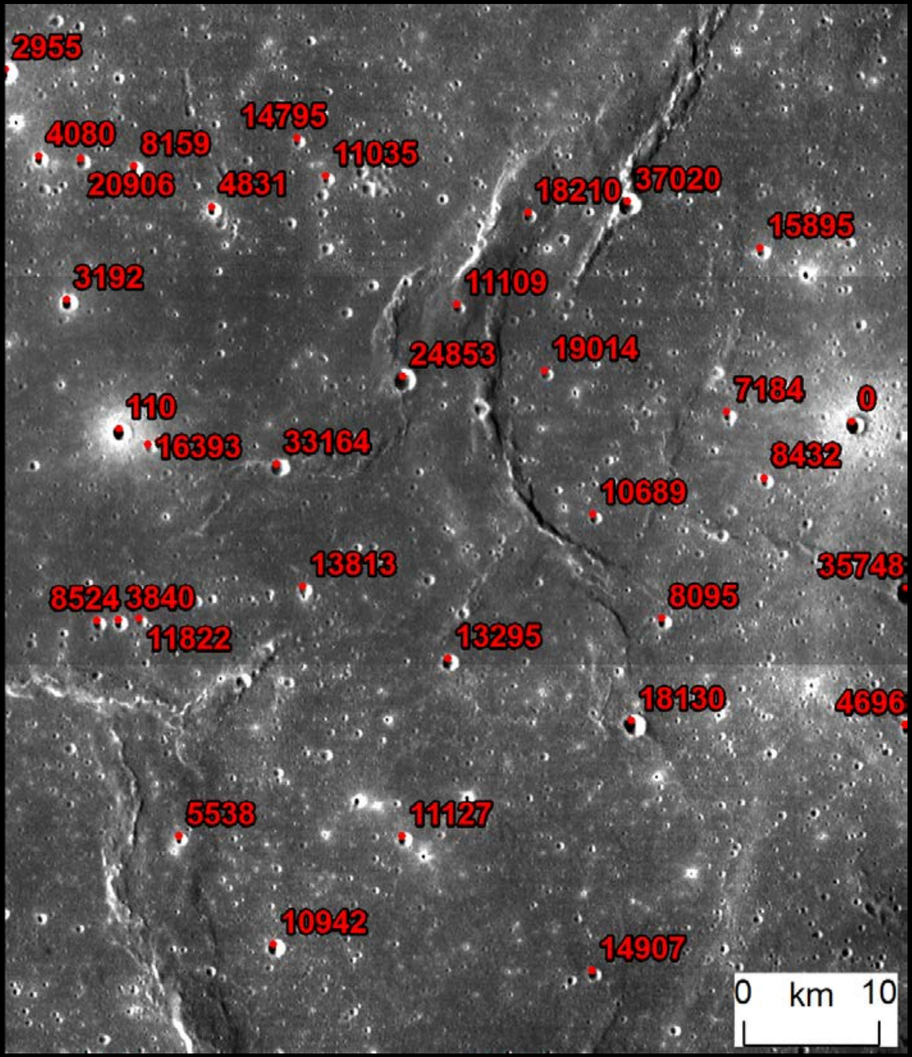
- Topographic evolution of craters and other landforms can be modeled as a diffusive process.

  New calibration for the rate at which the Moon's surface topography changes.

- It's complicated, but with topography of craters, we can:

  → Estimate the age of individual craters & landforms;

  → Estimate the age of surfaces in a manner complementary to crater statistics.



Degradation State, κt

Summary so far

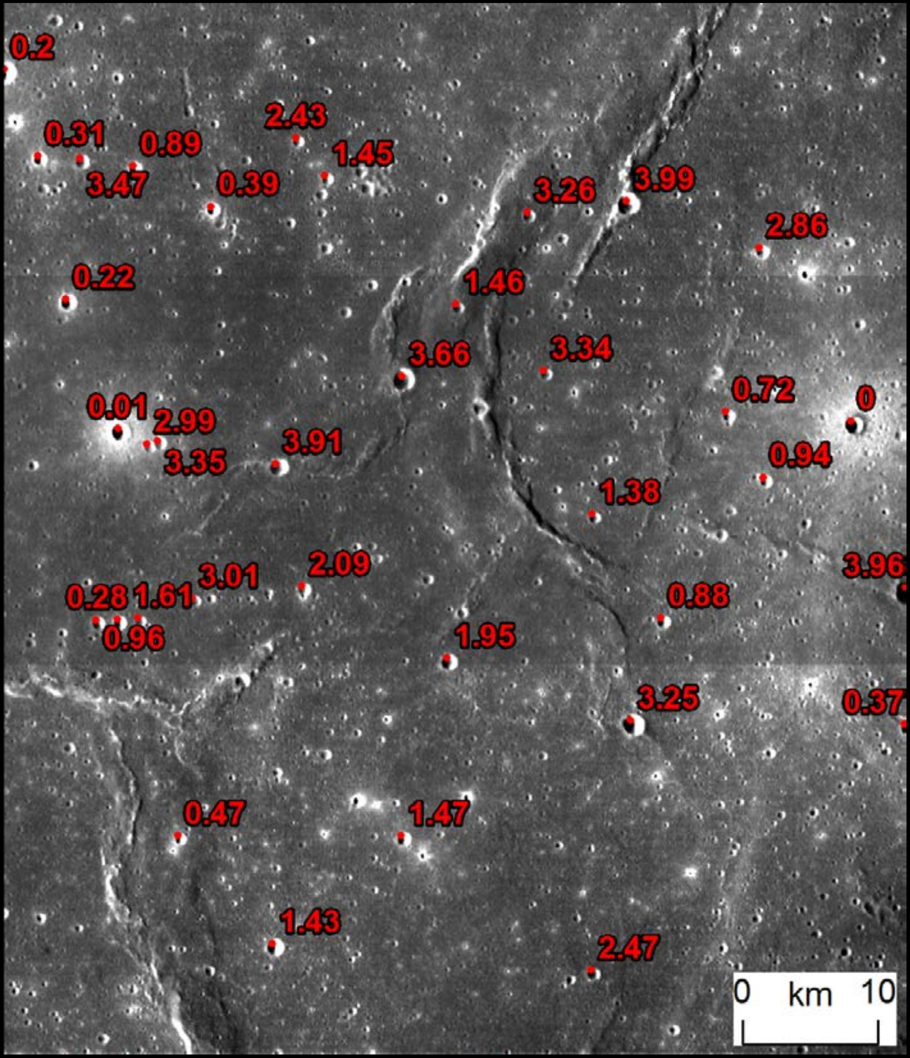
- Topographic evolution of craters and other landforms can be modeled as a diffusive process.

  New calibration for the rate at which the Moon’s surface topography changes.

- It’s complicated, but with topography of craters, we can:

  → Estimate the age of individual craters & landforms;

  → Estimate the age of surfaces in a manner complementary to crater statistics.



Age (billions of years)

Why do we care?

On March 26, NASA was directed to land American astronauts on the Moon by 2024.

"We, the people of NASA, accept this challenge. We will go to the Moon in a way we have never gone before…. This time, when we go to the Moon, we will stay."

"And then we will use what we learn on the Moon to take the next giant leap - sending astronauts to Mars."

Jim Bridenstine, NASA Administrator

Where to?

Image from JAXA Kaguya

Conclusions

- We are converging on a model for how the topography and regolith of the Moon evolves, including *process* and *rate.*
- This understanding provides a framework for constraining the *age of individual craters, features, and surfaces.*