Startling Discoveries from the LROC!

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LROC Experiment

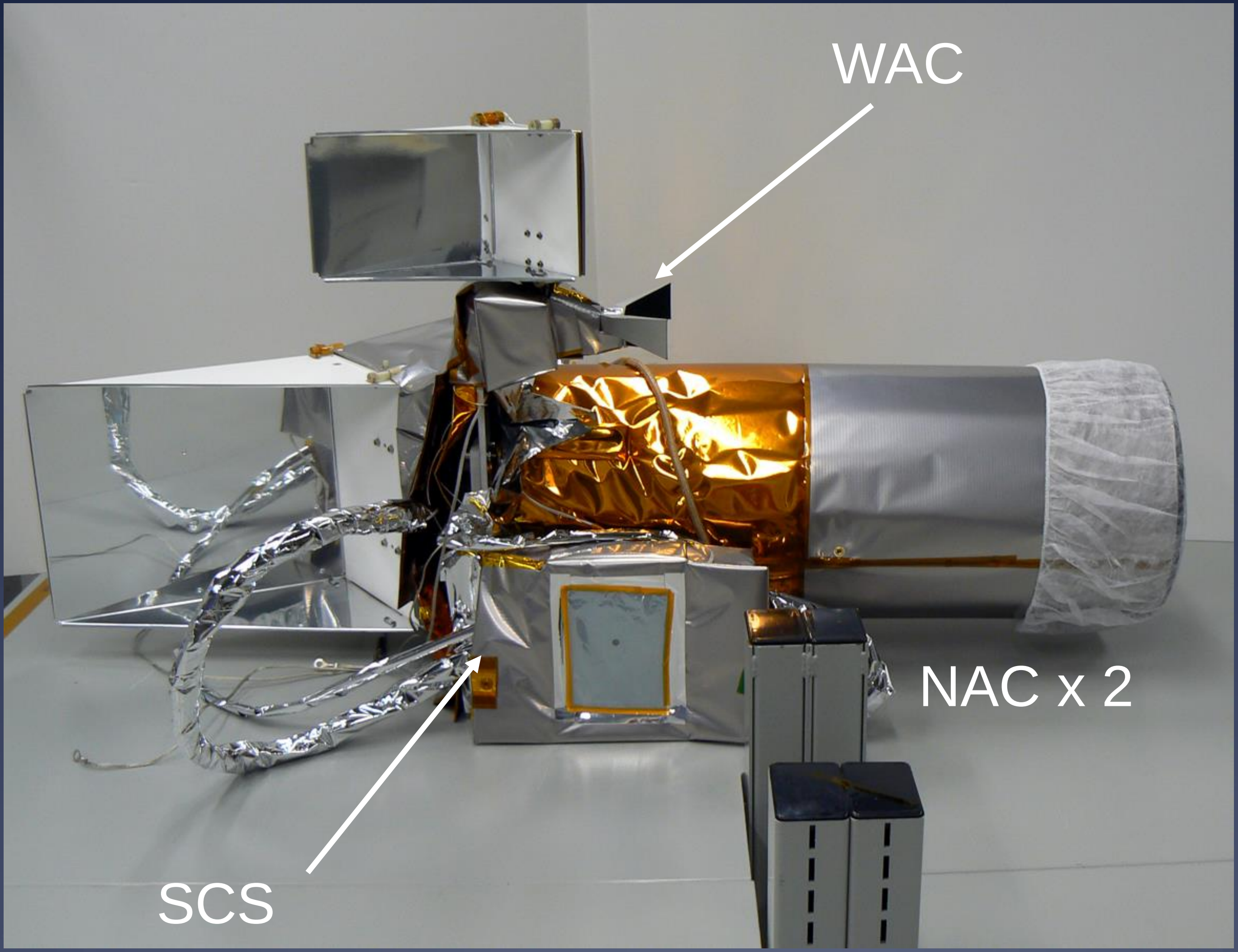
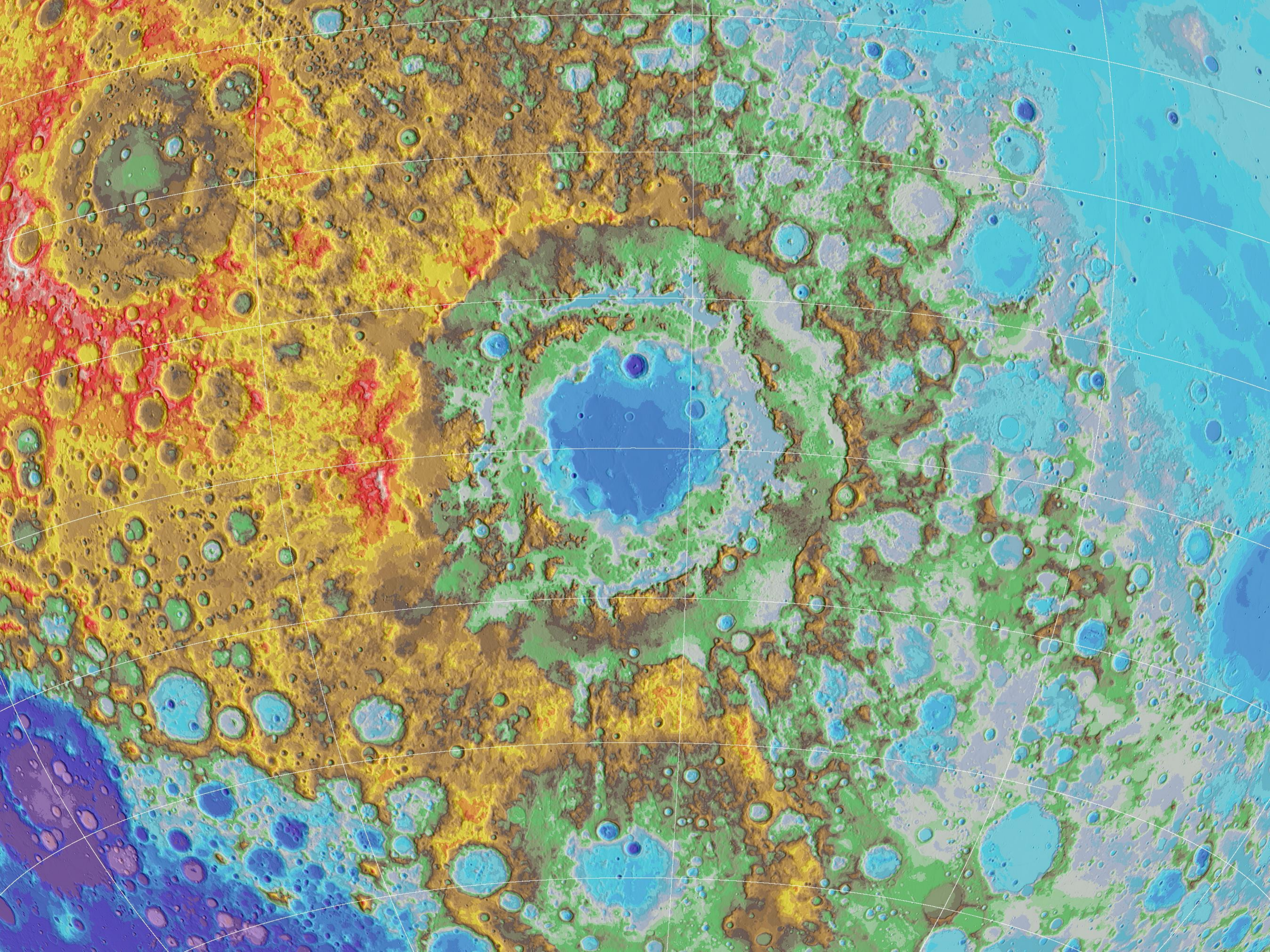


Image ~50” wide



LROC Discovery Highlights*

- Ongoing tectoniism?
  - Small, young contractional fault scarps and very small graben
  - Liquid outer core – interior still cooling
- Recent volcanism
  - Shallow magma generation
  - Still hot lunar interior
- Silicic volcanism
  - Complex differentiation in mantle
- Pits
  - Pristine preservation of basalt flows
  - Potential habitats
- Permanent Shadow Regions
  - Complex volatile transport mechanisms
  - Resources for future explorers
- Crater topography
  - New tool for estimating ages
  - Impact event dynamics
- Photometry
  - Fine scale structure of regolith
  - Engine blast zones
- Ages of Copernican Craters
  - Copernicus, Aristarchus, Tycho, Giordano Bruno, and small very young…
- Stratigraphy, Early chronology
  - Sequence of early Solar System events
- Recent impacts
  - Inner Solar System cratering rate
  - Hazard mitigation
- Cartography
  - Global accuracy to ±15 m
  - Global topography 100 m scale
- Swirls
  - Two largest areas now shown to be one mega-area!
  - New small swirls discovered

*short list

Ongoing Tectonism

- Discovery of globally distributed population of 1-10 km scale low angle thrust faults (compression)
- Moon is still contracting (core freezes)
- Orientations of faults not random, evidence that Earth tides effect crustal stress patterns

- Ages <50 my
  - Smaller highland examples (10 m relief) expressed solely in regolith
  - Cross-cut 10 m scale craters
  - Associated back scarp graben (extension) 100 to 200 meters in length few meters deep

Small scale graben (image 692 m wide)

Watters et al, 2012, Nature Geosciences

Scarps Cross-cut Small Craters

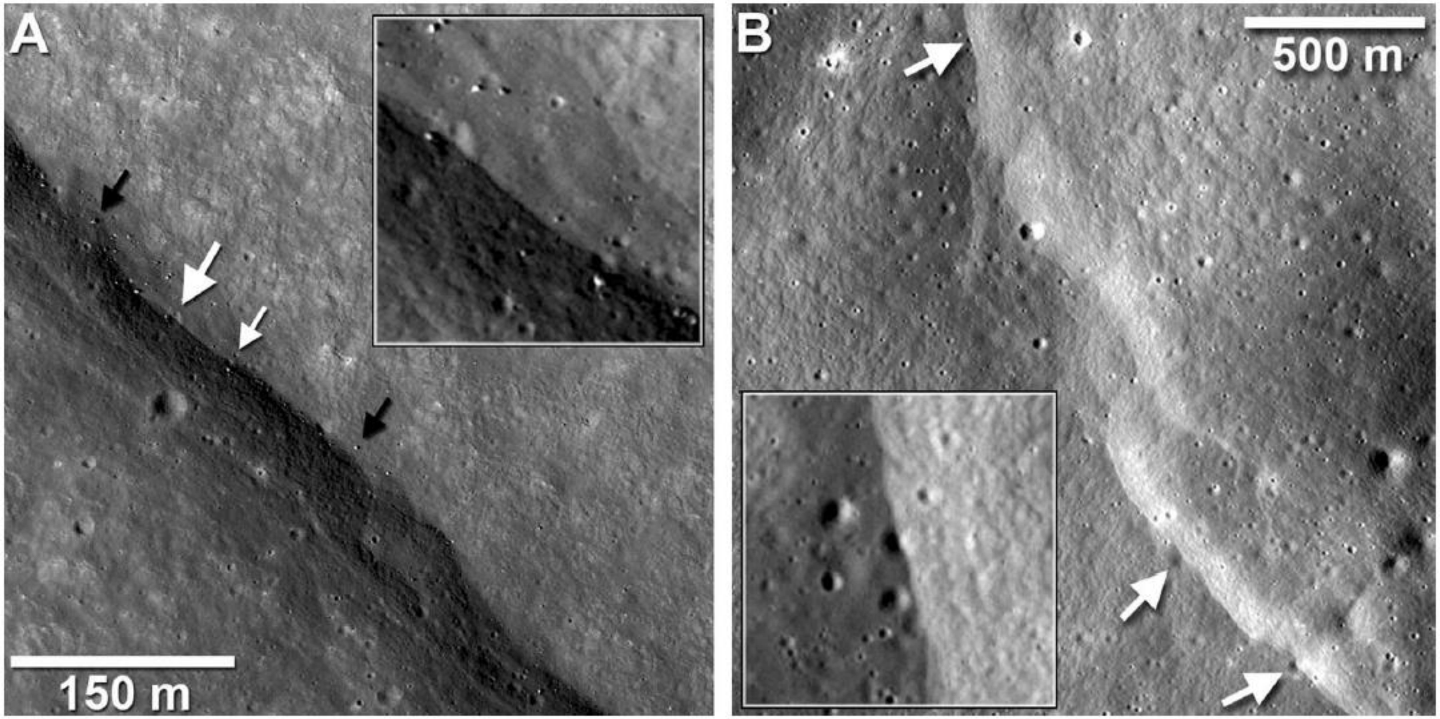
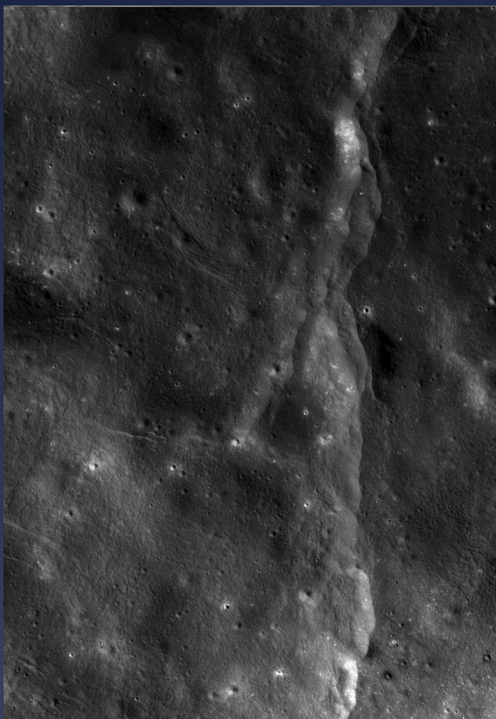


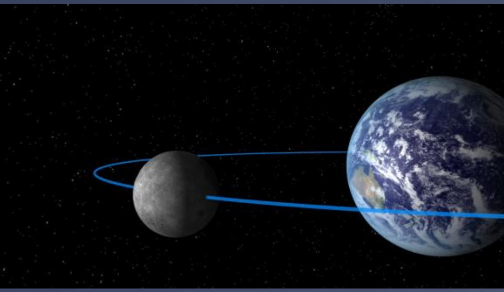
Fig. 4. Crosscutting relations between lobate scarps and impact craters. (**A**) The Lee-Lincoln scarp in North Massif crosscuts an ~12-m-diameter impact crater (large white arrow and inset) and a ~7-m-diameter crater (small white arrow and inset). Boulders are found along the scarp face (black arrows). The figure location is shown in Fig. 1A. (LROC NAC frame M119652859LE.) (**B**) Degraded ~40-m-diameter craters (lower white arrows) and a ~20-m-diameter crater (upper white arrow and inset) are crosscut by the Mandel′shtam scarp. The figure location is shown in Fig. 2A. LROC NAC frames M103460280LE and M103460280RE.

Watters et al. (2010) Science

Global thrust faulting on the Moon and the influence of tidal stresses



Lobate thrust fault scarp in the Vitello cluster



Radial contraction from interior cooling

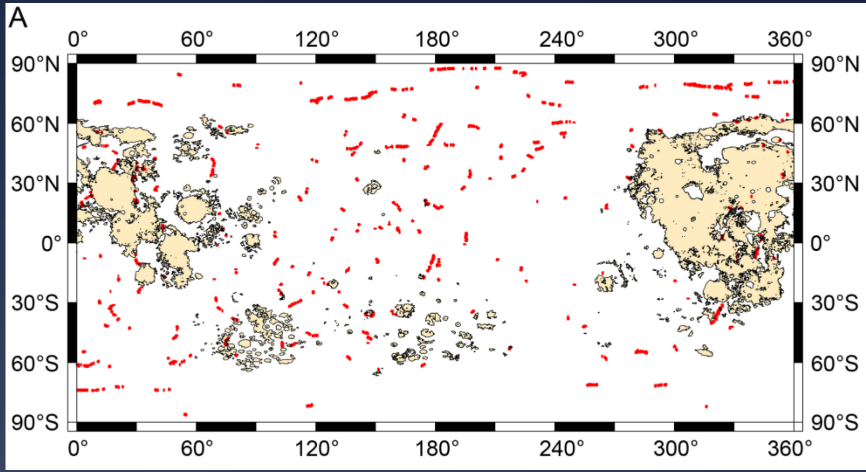
- Produces a isotropic compressional stress field
- Random distribution of orientations predicted

Non-random orientations of faults indicate other influences

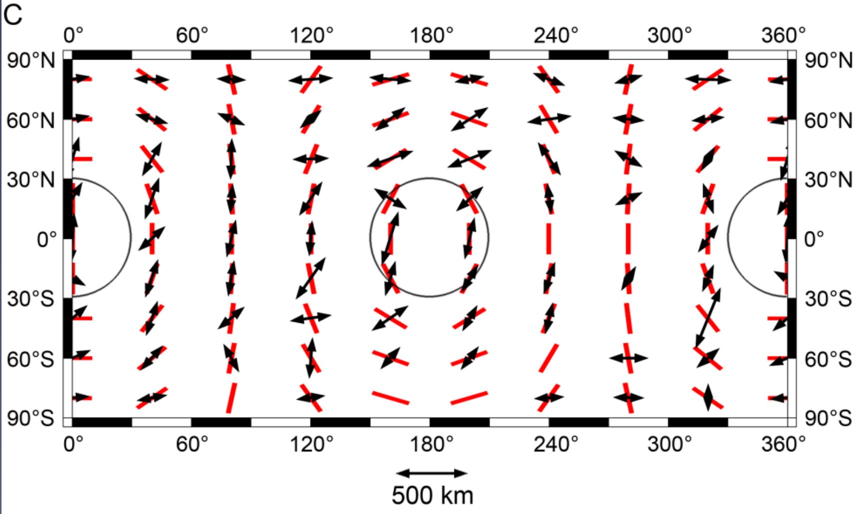
Two sources of tidal stress acting on the Moon today are

- Orbital recession (σ_r)
- Earth-raised diurnal tidal stress (σ_t)

Superimposed tidal stresses on global contraction (σ_c) result in a net non-isotropic compressional stress field ($\sigma_c >> \sigma_r > \sigma_t$) and faults with preferred orientations



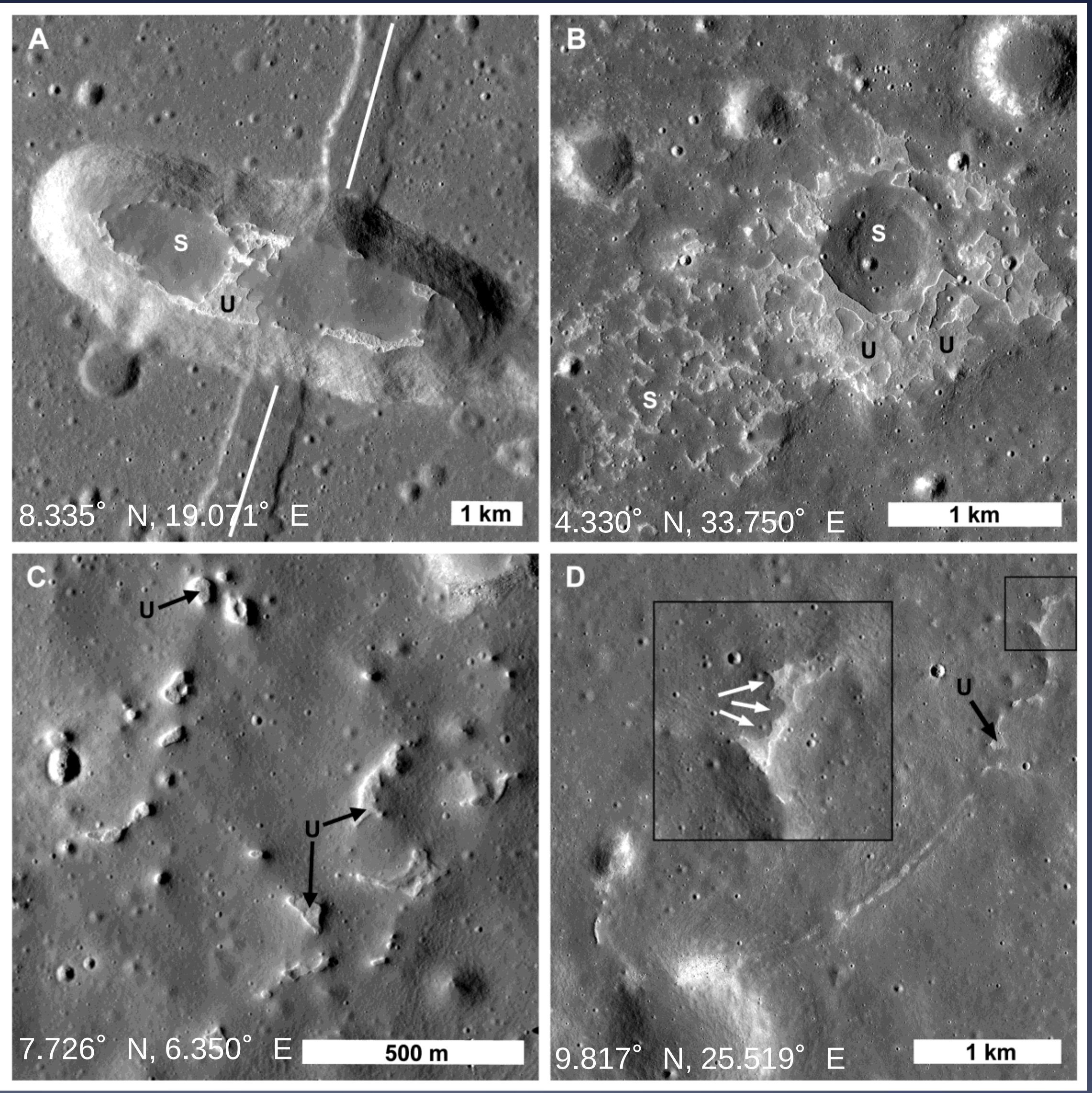
Digitized locations of over 3, 200 young lobate thrust fault scarps on the Moon.



Orientations of predicted faults (red lines) due to the combination of stresses from orbital recession, diurnal tidal stresses at apogee, and global contraction plotted with the orientation vectors of the lobate scarps.

Irregular Mare Patches (IMPs)

Sharp, meter-scale morphology, stratigraphy and crater size frequency distributions suggest young ages for volcanic activity

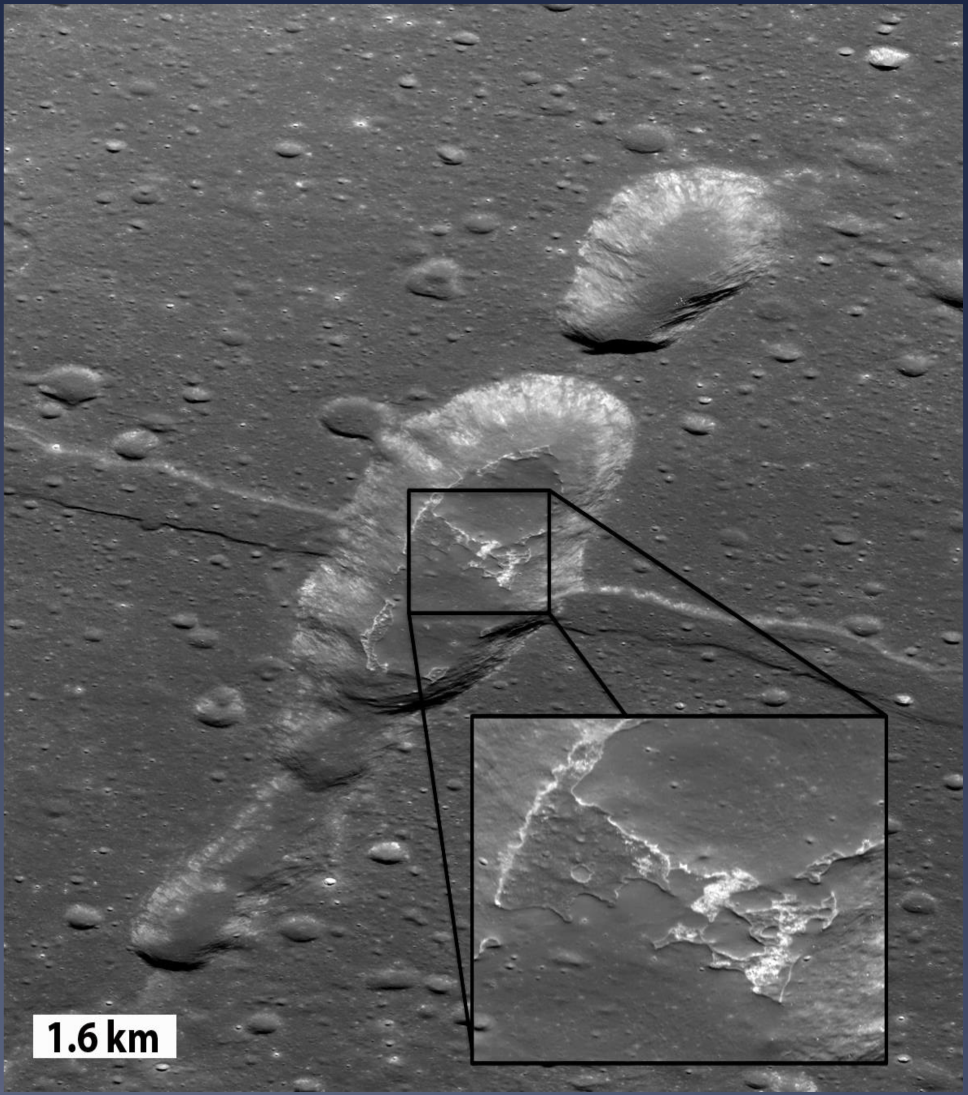


A) Depression containing an IMP crosscuts a smaller northeast-trending graben
B) Maskelyene F, no significant topographic confinement
C) IMPs floor of Hyginus crater
D) IMPs with narrow, discontinuous sections following a curved path

Braden et al. 2014 Nature Geoscience

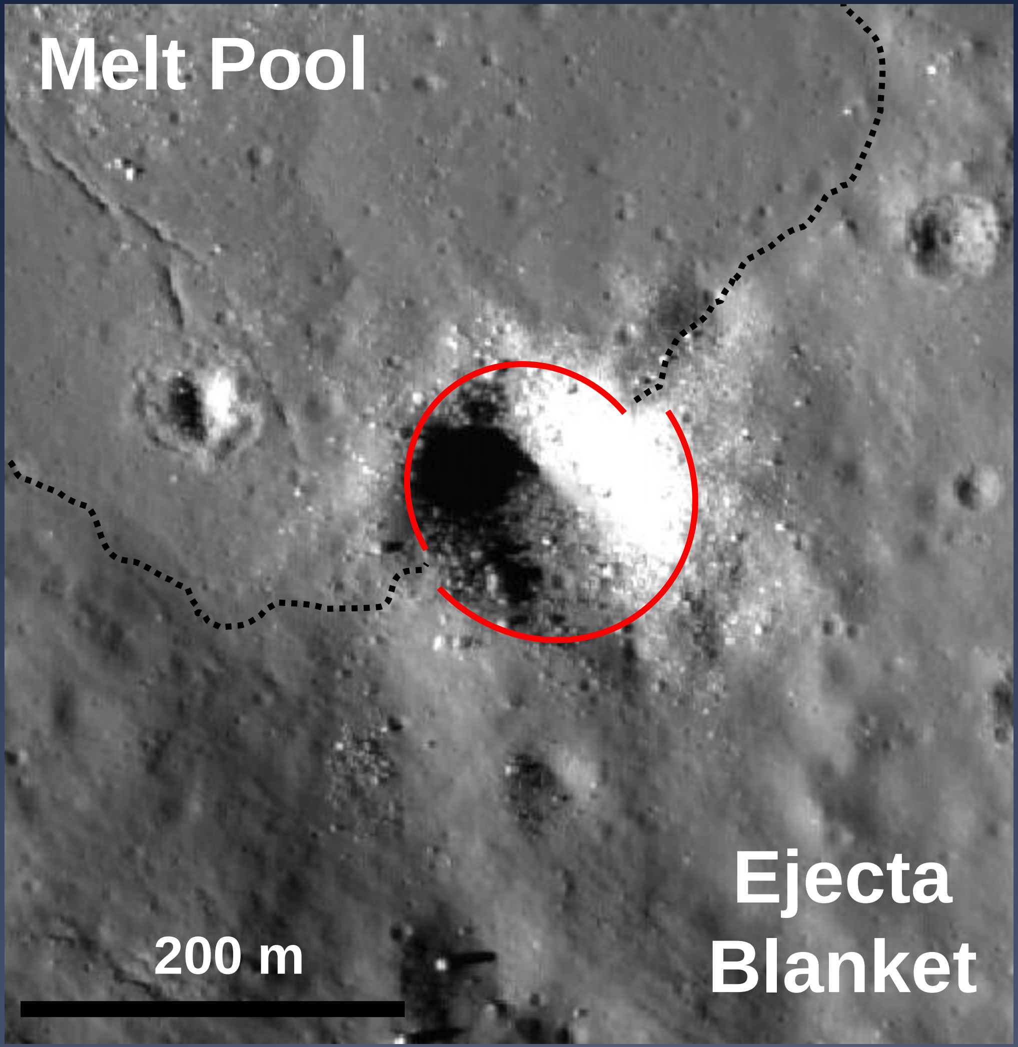
Late Copernican Volcanism

- CSFDs <100 my age
- No equilibrium diameter
- 75 occurrences spread across nearside
- Basaltic
  - Albedo
  - Color
  - Meter scale landforms
- Thermal implications
  - More radioactive materials
  - More efficient magma transport



Alternate Hypotheses

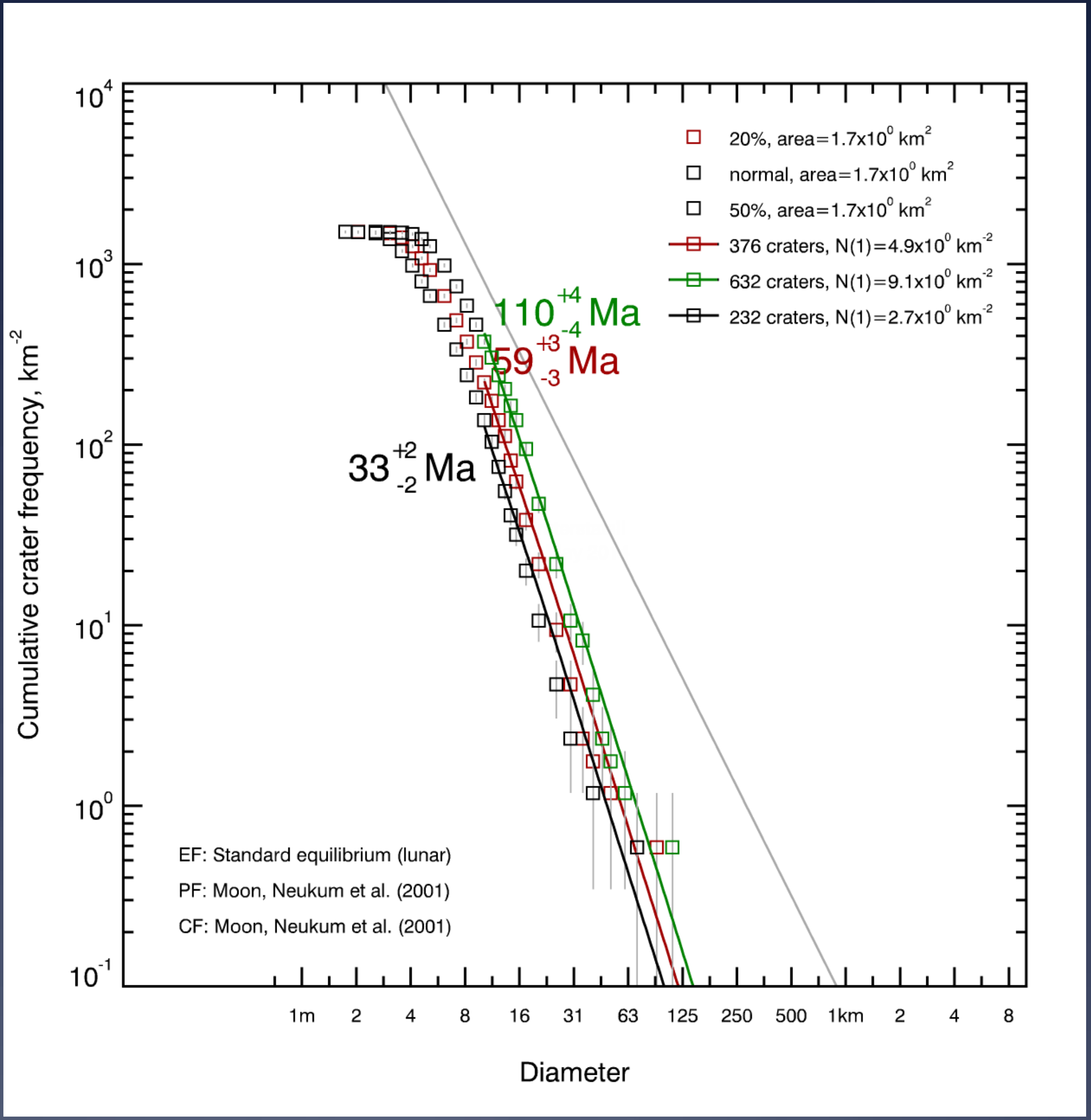
- Impact melt – no nearby Copernican craters, all IMPS in mare, generally associated with other volcanic constructs or contacts, negative and positive relief
- Statistical cratering anomalies – untestable hypothesis, IMPs would be randomly distributed on Moon (mare and highlands, nearside and farside)
- Target strength – craters are "small" due to material strength (solid rock vs. granular material), increasing diameters by reasonable amounts still returns late Copernican ages (requires unobtanium)



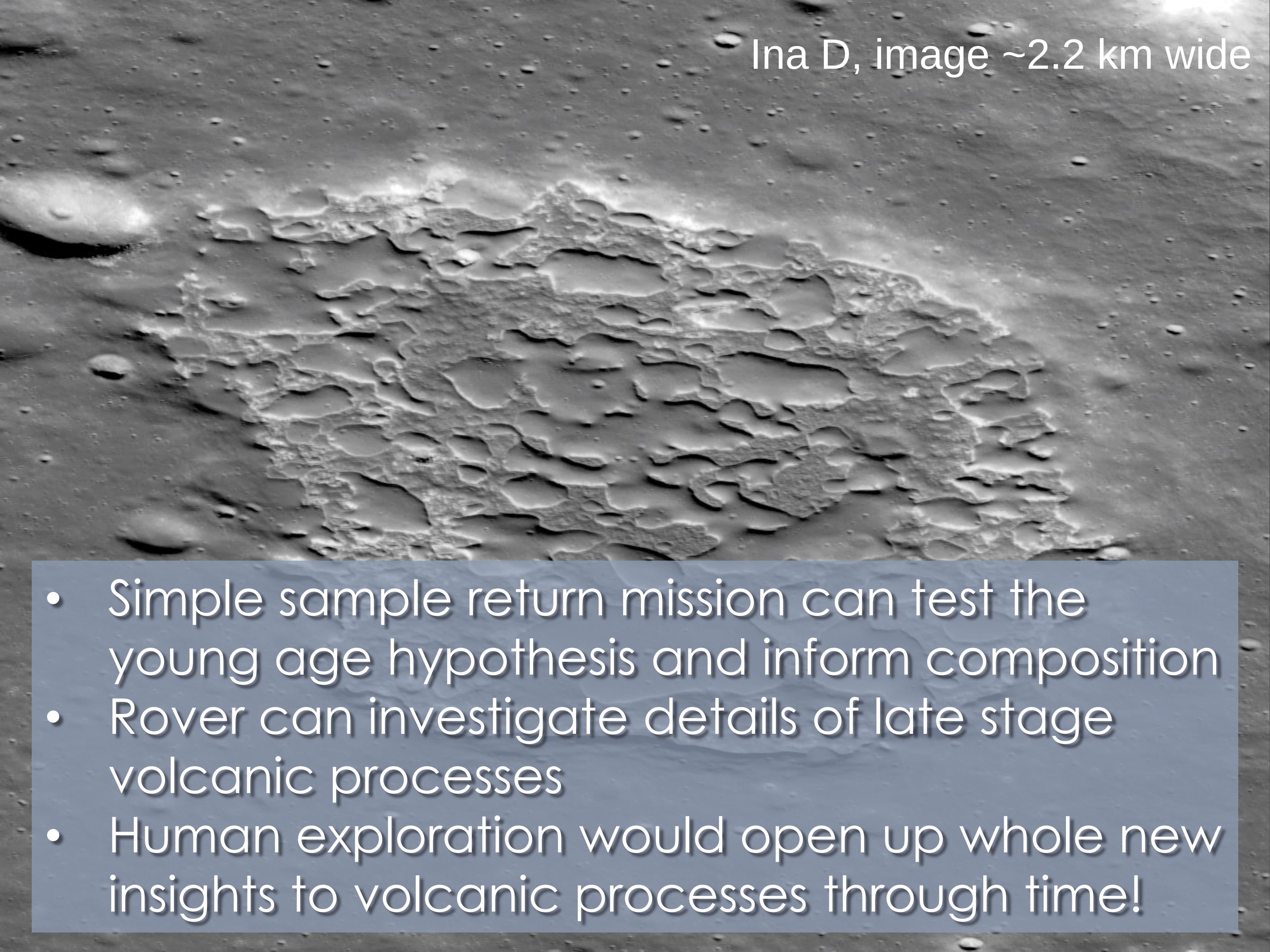
Crater diameter 20% larger in ejecta vs. melt rock

Material Strength

- Craters formed half-way in impact melt rock and granular material show 20% diameter increase in the granular material
- Crater sizes artificially increased by 20% and 50% shift ages to 59 and 110 my (still late Copernican)



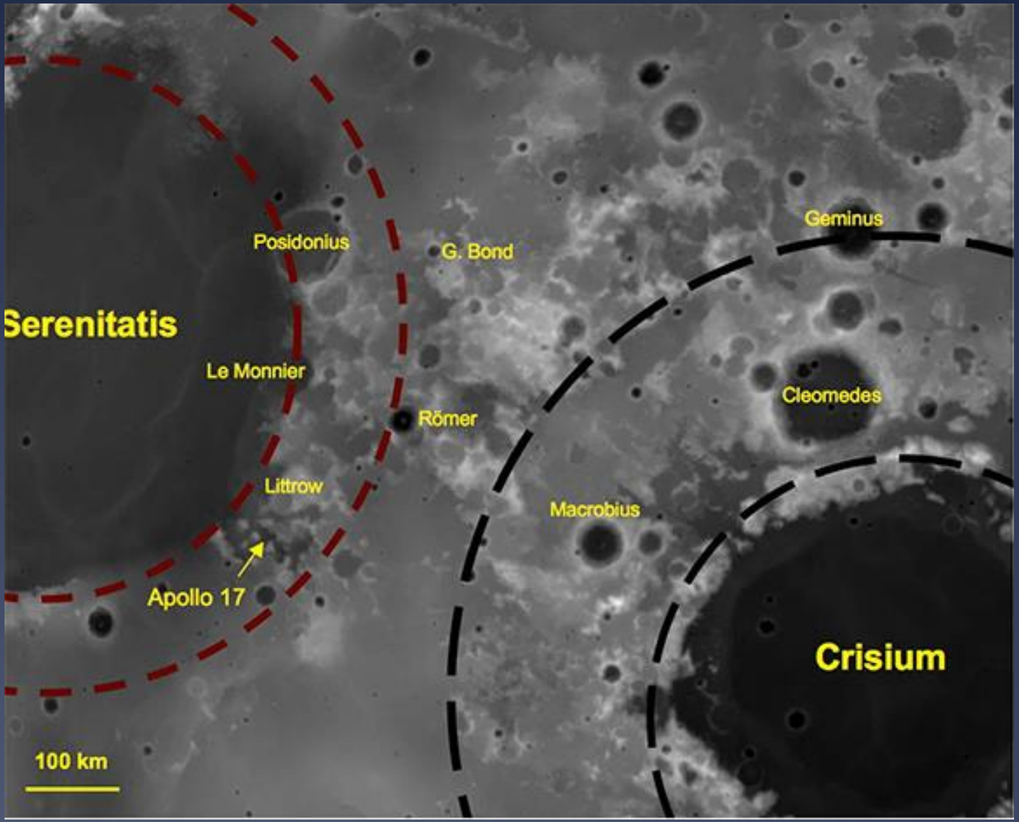
Ina CSFD



- Simple sample return mission can test the young age hypothesis and inform composition
- Rover can investigate details of late stage volcanic processes
- Human exploration would open up whole new insights to volcanic processes through time!

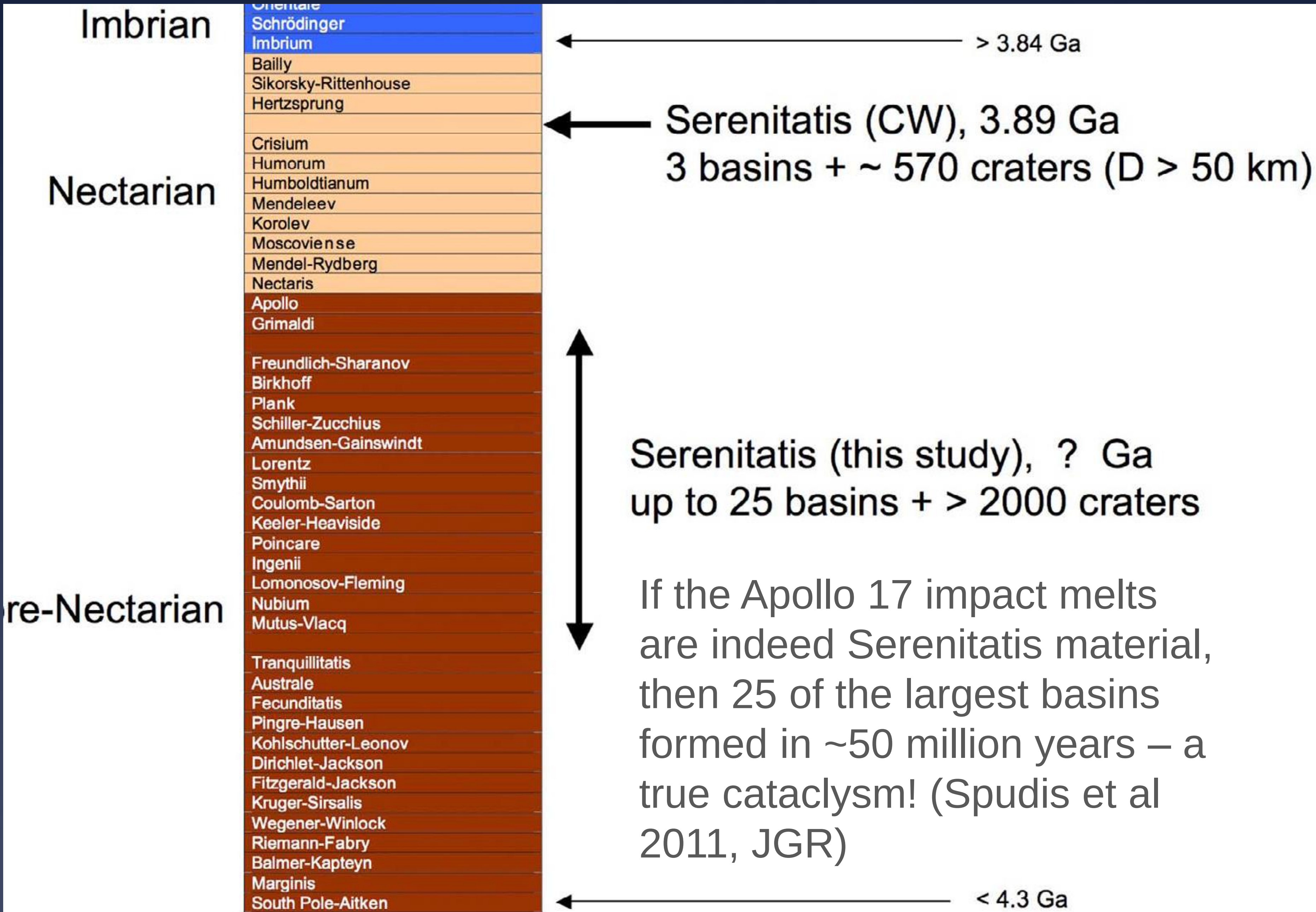
Age of Serentatis Basin?

- New WAC maps allowed detailed mapping of basin unit contacts – compelling case that sculptured hills (Apollo 17 impact melt samples) were result of Imbrium ejecta, not Serenitatis massifs
- Did we only sample Imbrium basin material at all Apollo sites? If so there is no evidence supporting a terminal cataclysm – important for all inner Solar System solid bodies
- Are we correctly interpreting the provenance of and thus ages of returned samples?



Serenitatis crater counts now place it as older than Crisium and even Nectaris!

Ancient Serenitatis is a Real Problem



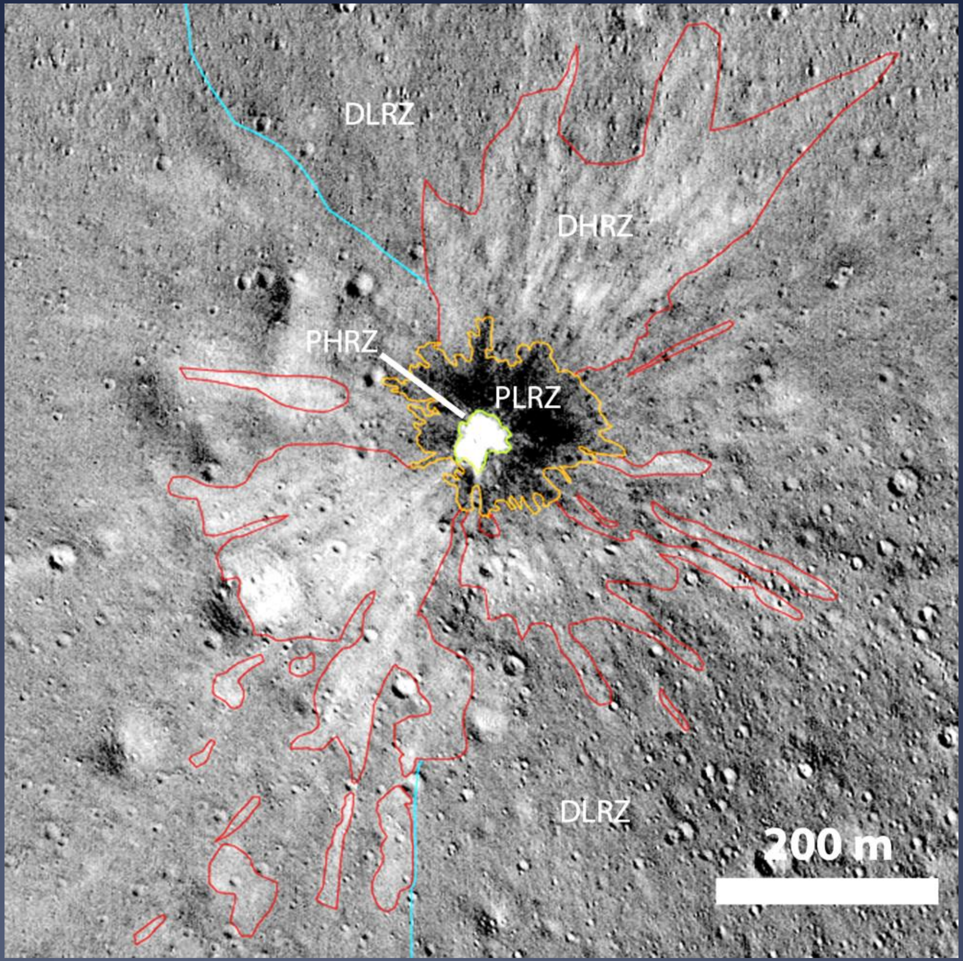
LROC Temporal Imaging

- Discovered hundreds of impact related changes since start of mission (NAC Before/After pairs)
- Twenty resolved craters!
- Significance
  - Refine flux of >0.5 m bolides inner Solar System
  - Seeing new complex ejecta patterns
  - Secondaries from small craters are extensive
  - Engineering constraints for future long lived assets

17 March 2013 impact, 18 m crater, secondaries found >30 km distant

17 March Crater: Ejecta

- Four Distinct Zones
  - Proximal high reflectance (+25 to +50%)
  - Proximal low reflectance (-5% to -10%)
  - Distal high reflectance (+3% to +5%)
  - Distal low reflectance (-3%)
- Abundant splotches out to 30 km distant



Robinson et al, 2015, Icarus

Why Low Reflectance?

- Ejecta
  - PLRZ – outer portion of continuous ejecta composed of upper layer of regolith (mature)
  - DLRZ – small amounts of granular material impact at 100 m/s velocities roughening surface (GRAIL, astronaut trails)
- Splotches
  - Same as DLRZ
  - Perhaps no central impact crater?

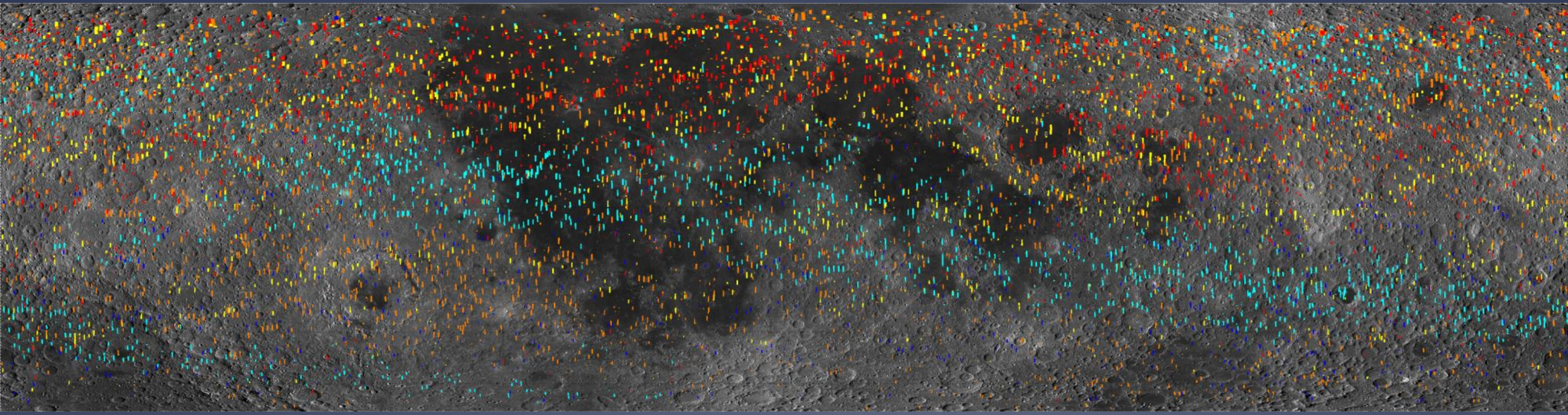
Increased mm to cm scale roughness

Status: NAC Temporal Pairs

As part of the LRO ESM2, the LROC Science Team is collecting a series of before and after NAC observations (temporal pairs) to quantify the:

- Current impact rate
- Secondary surface changes
- Ejecta and regolith disturbances
- Recent mass wasting events

Map of 10,400 NAC Temporal Pairs Searched and Cataloged

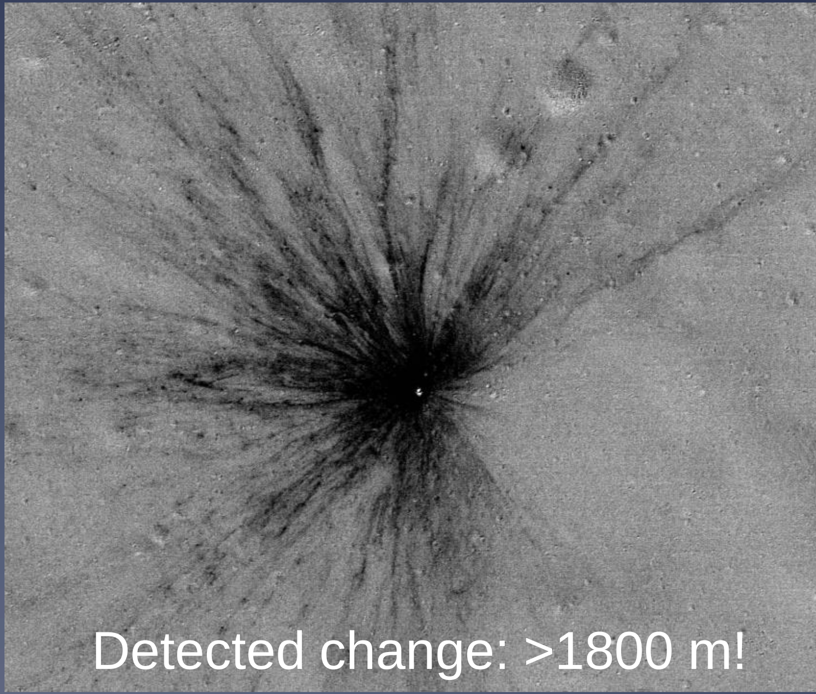


177 days | 354 days | 531 days | 709 days | >886 days

New Impact Craters!

Identified 139 resolved impact craters that formed since orbit insertion (1.5 m to 43 m diam)

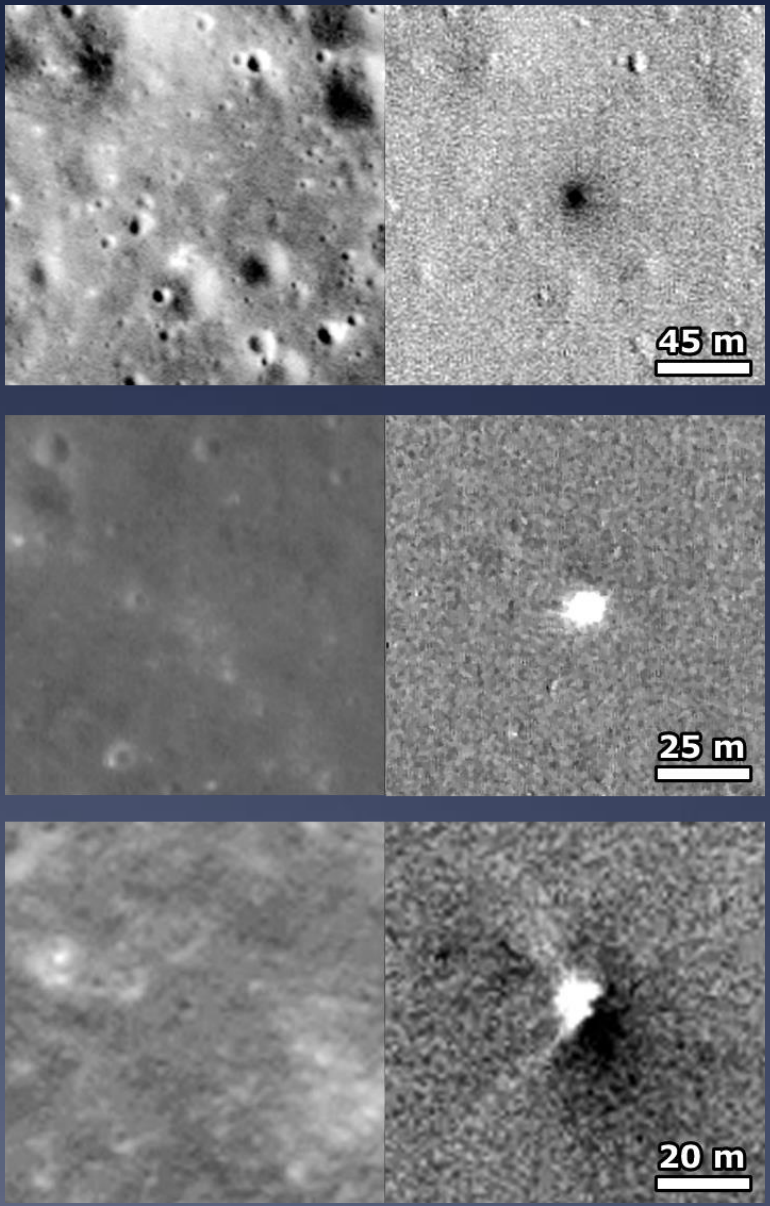
- Total excludes craters located with recorded flashes (n=2)
- 11 of these craters have a diameter greater than 10 m (>30% more than the Neukum production function estimates).
- Witnessed complex ejecta patterns and regolith disturbances that extend well beyond 1.5 crater diameters



Other Surface Changes

Identified over 35,000 other surface changes!

- Mixture of small primary and secondary surface changes that lack a measurable rim
  - 31,663 low reflectance changes (90%)
  - 2,868 high reflectance changes (8%)
  - 702 mixed reflectance changes (2%)
- Clusters of the "splotches" are present near new craters



LROC (LRO) Discoveries Enable a Coherent and Sustainable Human Exploration Strategy

- Series of logically progressing missions: $10M, $100M, $500M, $1000M - address set of strategic goals to check off key goals every year! Then we will get to Mars!
- Address key Solar System science questions on the Moon
- Prove key technologies on the Moon
- Moon is most accessible science and exploration target in the Solar System
  - Technology demonstration
  - Discover new resources ⟷ Assay resources
  - Tie remote sensing data to ground (LP, LRO, Chandrayaan, Selene, GRAIL)
  - Engineering observations enabling future technology development
- Engage public in NASA exploration in a sustained collaboration!
- Workforce development!
- Get us on track to humans on Mars!