NASA Lunar Regolith Simulant Update

National Aeronautics and
Space Administration

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Astromaterials Research and Exploration Science
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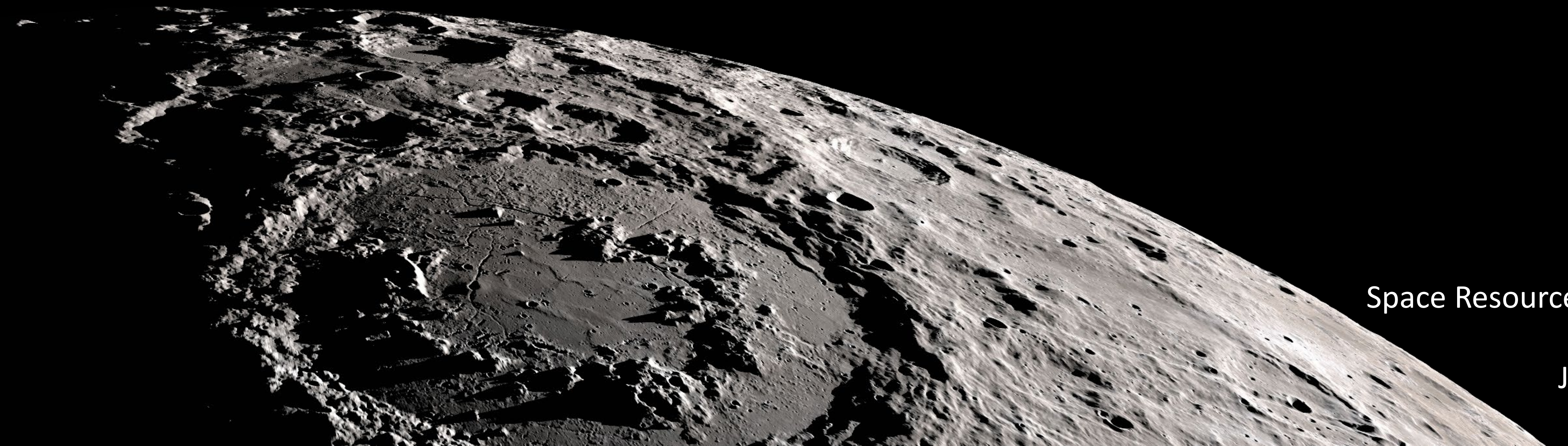


Space Resources Roundtable
Golden, CO
June 4-7, 2024

NASA Simulant Activities

- Simulant Advisory Committee
  - Small group providing NASA centers and projects with simulant SMEs for project interaction (*at SRR)

    JSC: John Gruener*, Ross Kovtun*, Ane Slabic*

    MSFC: Jennifer Edmunson, Doug Rickman

    KSC: Laurent Sibille*

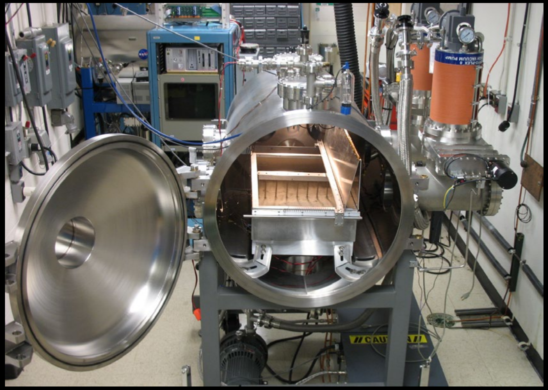
    GRC: Heather Oravec
- Motivation is to improve lunar simulants and the usage of simulants for NASA and the lunar exploration community
- A new lunar highlands simulant has been developed, NUW-LHT-5M
  - Collaboration with Washington Mills of Niagara Falls, NY
  - NASA-provided Stillwater anorthosite and norite; WM-provided synthetic glass and olivine
  - 60% crystalline, 40% glass, < 1mm
  - see Rickman et al., (2022) Design of NU-LHT-5M and -6M,lunar highland simulants. LPSC53, abstract 1146; -5M paper in review

NASA Simulant Activities

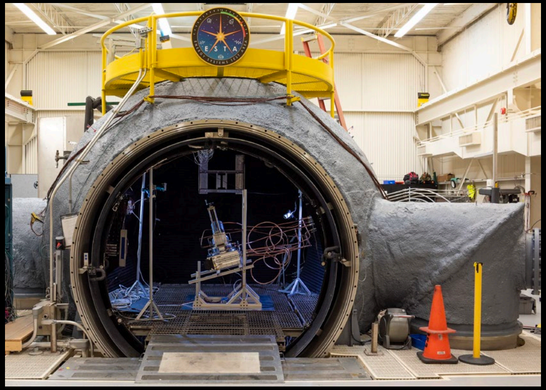
- A subset of NASA testing facilities using lunar simulants (a full listing can be found at https://ares.jsc.nasa.gov/projects/simulants/development-lab.html)


Glenn Research Center
SLOPE facility and Excavation Lab

Kennedy Space Center
Swamp Works and
new IPEx Facility



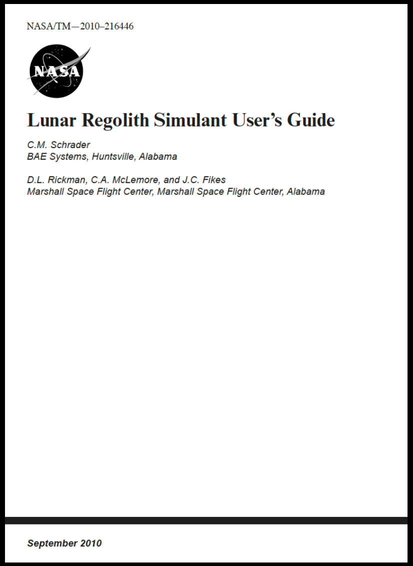
Marshall Space Flight Center
V20 Thermal Vacuum Chamber
Lunar Environment Test System

Johnson Space Center
Simulant Development Lab and
15' Dirty Thermal Vacuum Chamber

NASA Simulant Activities

- Large outdoor and indoor testing/training facilities in development at NASA centers
  - 10,000s mt of surface materials needed
  - Material and logistical challenge
- Figure of merit calculations for a number of lunar simulants (see Kovtun poster this evening)
  - the heterogeneity of geologic units and blended simulants makes it a challenge when using very small samples for analytical analyses
  - variability of analytical measurements from different labs for the same simulant
- UTEP geotechnical measurements on 16 simulants
- New NASA simulant data base in work
- The new Lunar Regolith Simulant User's Guide, Revision A is in progress
  - Updates the first guide from 2010
  - Patterned after Cross-Program Natural Environments (DSNE) document
  - Will be online at NASA Technical Reports Server (NTRS)



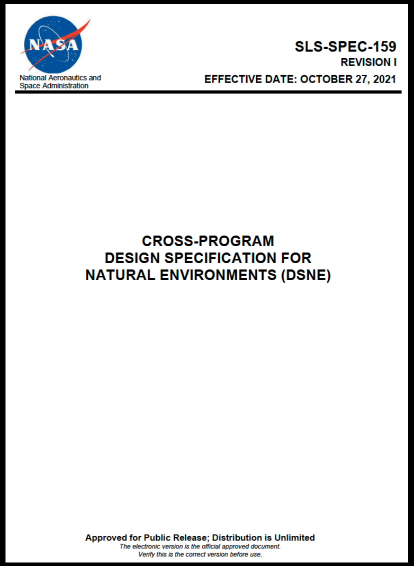
NASA/TM—2010–216446

Lunar Regolith Simulant User's Guide

C.M. Schrader
BAE Systems, Huntsville, Alabama

D.L. Rickman, C.A. McLemore, and J.C. Fikes
Marshall Space Flight Center, Marshall Space Flight Center, Alabama

September 2010



National Aeronautics and Space Administration

SLS-SPEC-159
REVISION I
EFFECTIVE DATE: OCTOBER 27, 2021

CROSS-PROGRAM DESIGN SPECIFICATION FOR NATURAL ENVIRONMENTS (DSNE)

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NASA Lunar Regolith Simulant User's Guide

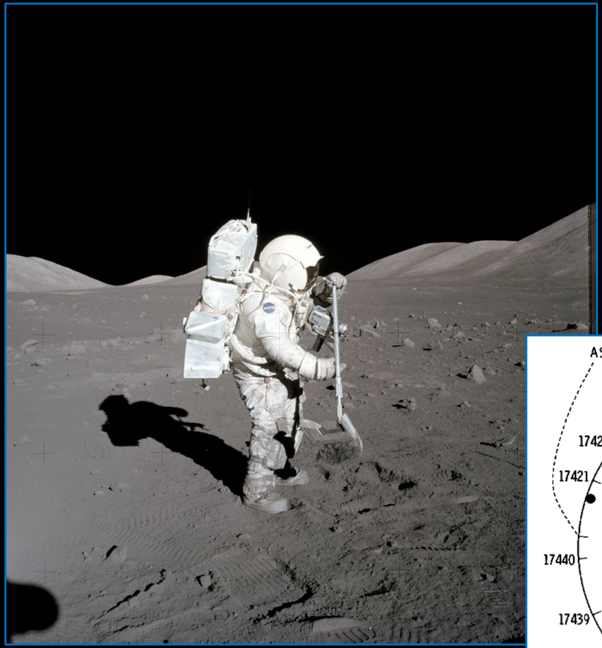
(Working Table of Contents)

- Introduction
- Lunar regolith (this talk)
  - Formation of the Moon, major rocks and minerals, creation of the lunar regolith, radiation, plasma, and space weather effects on the lunar regolith, particle size distribution, particle shape
- Lunar regolith simulants (this talk)
  - Apollo era, first lunar simulants, Constellation era, Artemis era, limitations of simulants, simulant classification, simulant best practices
- Picking a simulant: Figures of merit (Kovtun poster)
  - FOM background, mineralogy, chemistry, particle size distribution, particle geometry, density, shear strength, cohesion, angle of internal friction, magnetic susceptibility
- Working safely with lunar simulants (Slabic poster)
  - Silica background, silicate minerals, silica (SiO_2) minerals, crystalline silica exposure pathways and health effects, hazards vs risks, hazard warning labeling requirements, content in simulants, hazard control
- Preparing lunar simulants for testing (Sibille poster)
  - ambient testing conditions, particle size distribution and cohesion, bed layering and compaction, vacuum conditions dry regolith vs ice-bearing regolith tests, extractive processing, drying, impurity removal, freezing
- References

- The draft version of the User's Guide is going thru the NASA STRIVES process and will posted for review once it is available at https://ares.jsc.nasa.gov/projects/simulants/development-lab.html

Particle Size Distribution

- Most lunar regolith samples would correspond to pebble- or cobble-bearing silty sands [NVM 1, LSB,]
- The lunar regolith is not < 1mm, so why are lunar regolith simulants?
  - Curation processing artifact (see Graf, 1993)
  - Historical interest in <1mm (i.e., research focus)
  - MLS-1 (based on 10084) and JSC-1 focus on O_2 production
- Apollo rake samples
  - A17, 113 rake samples with the longest dimension of the small rocks ranging from 1.2 cm to 11.0 cm
  - A16, 109 rake samples with the longest dimension of the small rocks ranging from 0.75 cm to 7.0 cm
- Kovtun, et al., LPSC 2024
  - 25 Apollo 16 soil samples → simulant SDL-16M
  - Suggested PSD with particles ≤ 3 cm



Apollo 17 rake sample

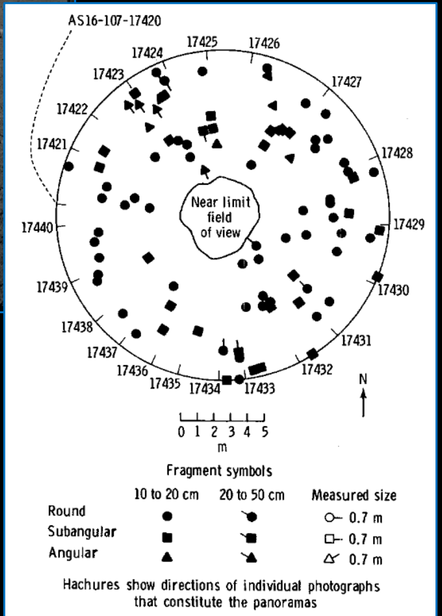


FIGURE 6-14.–Rock distribution within 10 m of the panorama north of the LM.

From Apollo 16 Preliminary Science Report

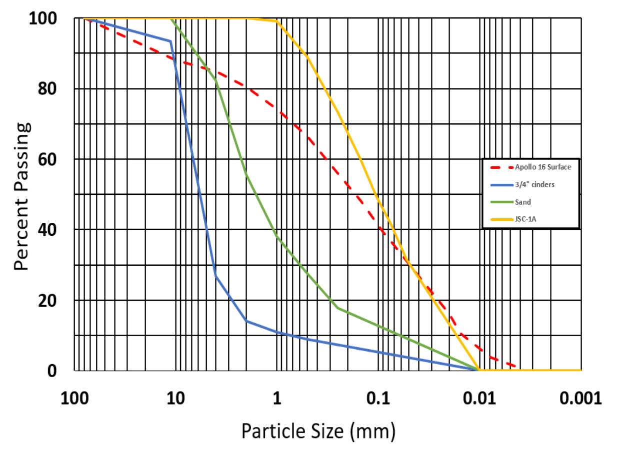
PARTICLE SIZE DISTRIBUTION
(SDL-16M)

SDL-16M Components:
JSC-1A
Flagstaff Landscape Products, Basaltic Sand
Flagstaff Landscape products, ¾" Basaltic Cinders

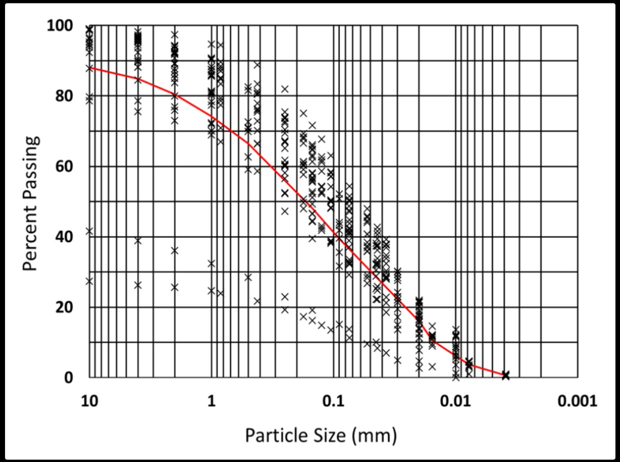
SDL-16M

Sieve No.	Size (µm)	% Passing	Retained (g)	1kg Recipe (g)
7/16 in	11200	94.18	5.82	58.20
5	4000	84.87	9.31	93.10
10	2000	80.52	4.35	43.48
18	1000	74.17	6.36	63.57
35	500	66.54	7.63	76.25
60	250	56.02	10.52	105.21
100	150	48.12	7.90	78.97
140	106	42.21	5.91	59.12
200	75	36.65	5.56	55.62
270	53	31.23	5.42	54.18
Pan	<53	0.00	31.23	312.30

SDL-16M recipe



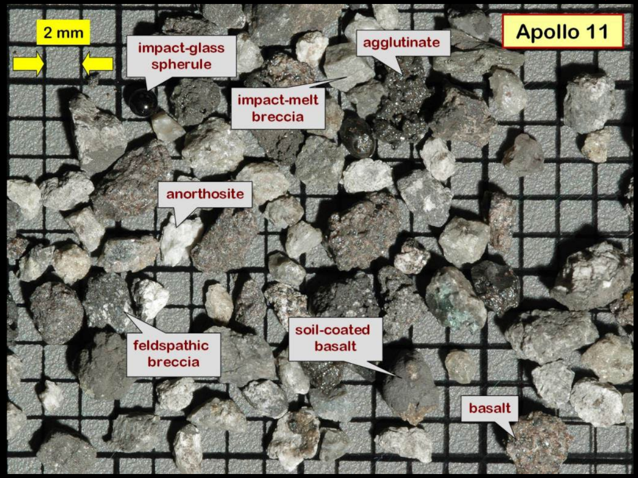
SDL-16M compared to components



SDL-16M compared to Carrier (2003)

Particle Geometry

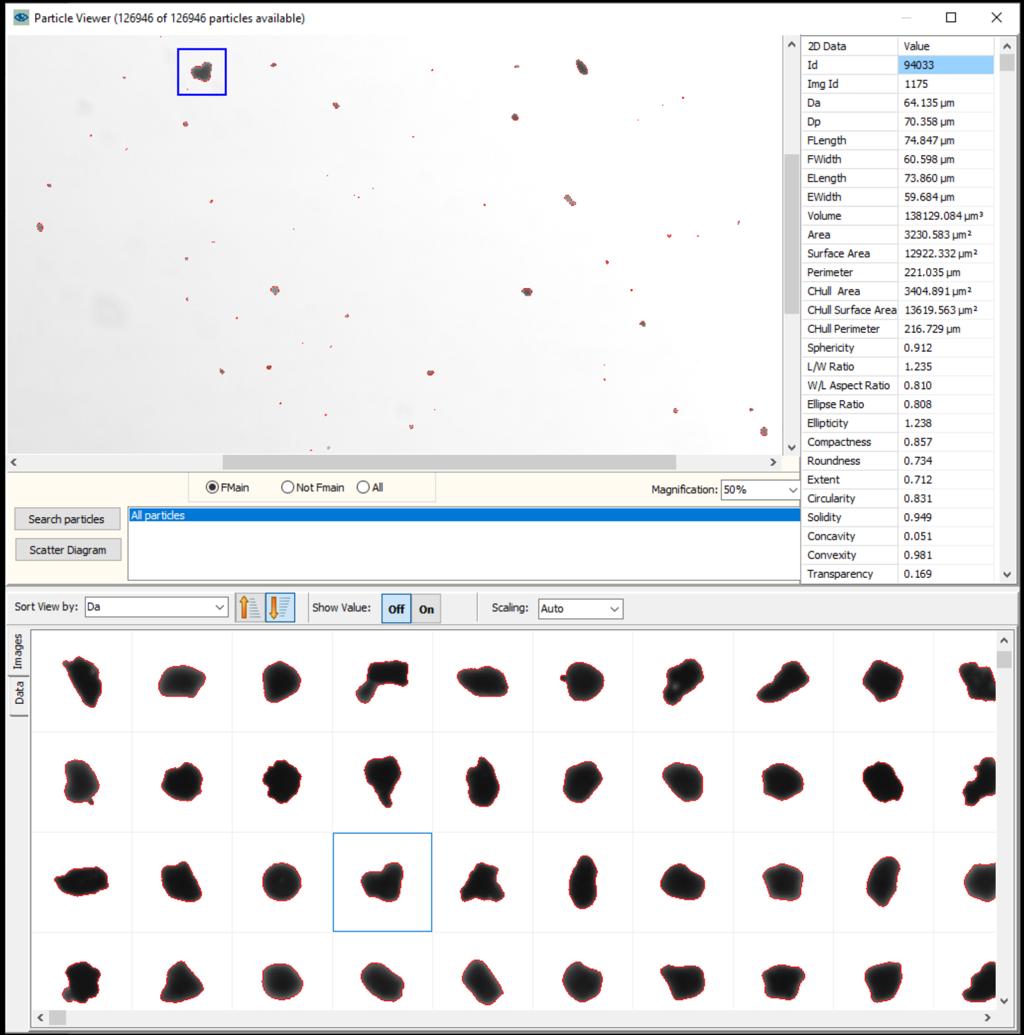
- Initial particle geometry measurements were done manually using a variety of microscopes
  - time consuming → few 10s to few 1000s of particles
  - wide range of geometries, glass component 'book ends'
- Generally, these early studies described the individual particles as being somewhat "sub-angular to angular" [Lunar Sourcebook, Chapter 9]
- Recent studies are suggesting a modification in thought
  - Dynamic Imaging Analysis (DIA) Systems
  - 100s of thousands to a few million particles in a short period of time
- Wilkerson et al. (2024)
  - On the measurement of shape: With applications to lunar regolith. Icarus **412** (https://www.sciencedirect.com/science/article/pii/S0019103524000216
  - Lunar regolith particles are in general less complex, suggesting an average shape of sub-round to sub-angular



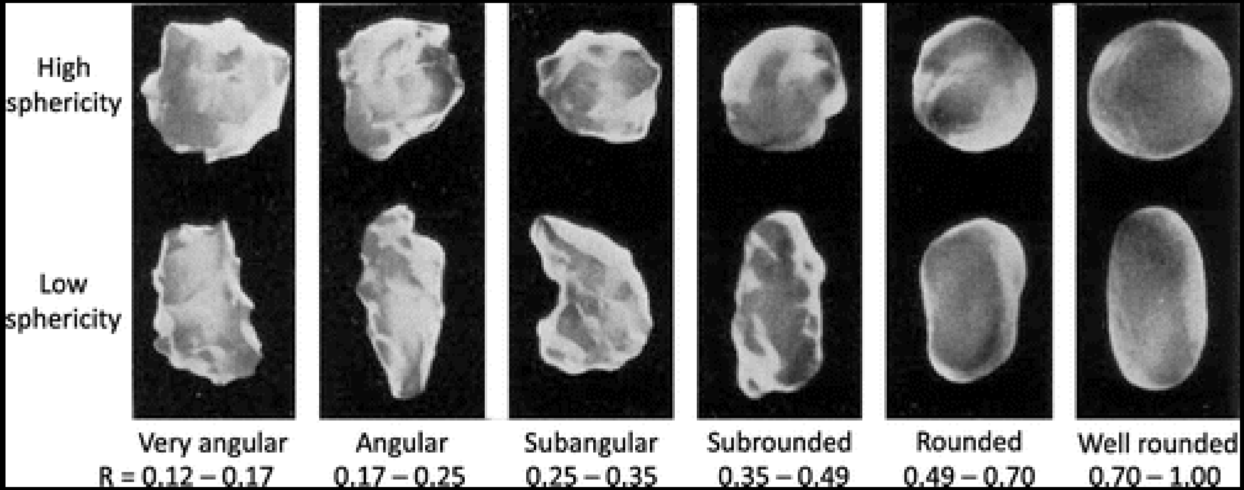
NASA DSNE Fig 3.4.2.2.2-2 (Credit: Randy Korotev)


JSC-SDL Microtrac SYNC particle analyzer

Particle Geometry



JSC-SDL Microtrac SYNC screen capture of Apollo 11 sample 10084



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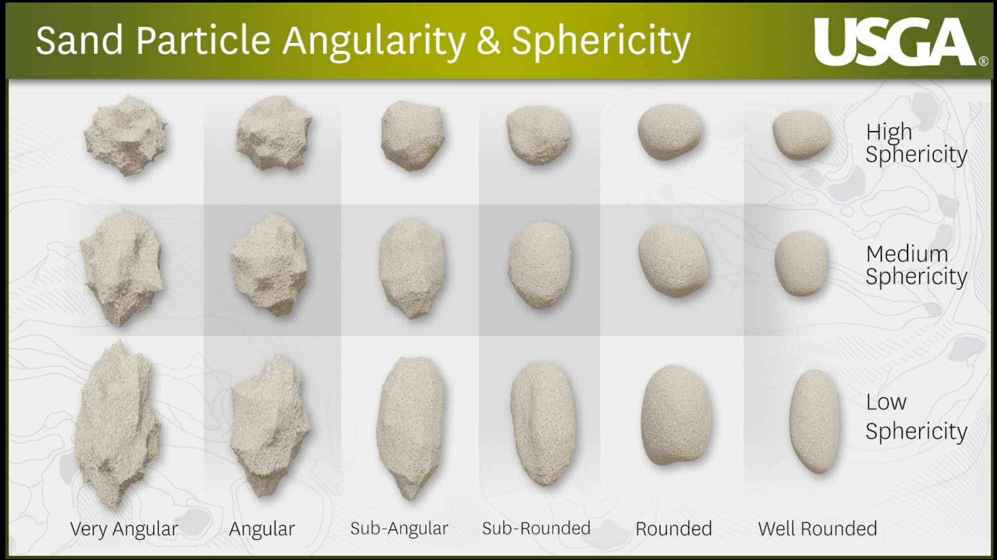
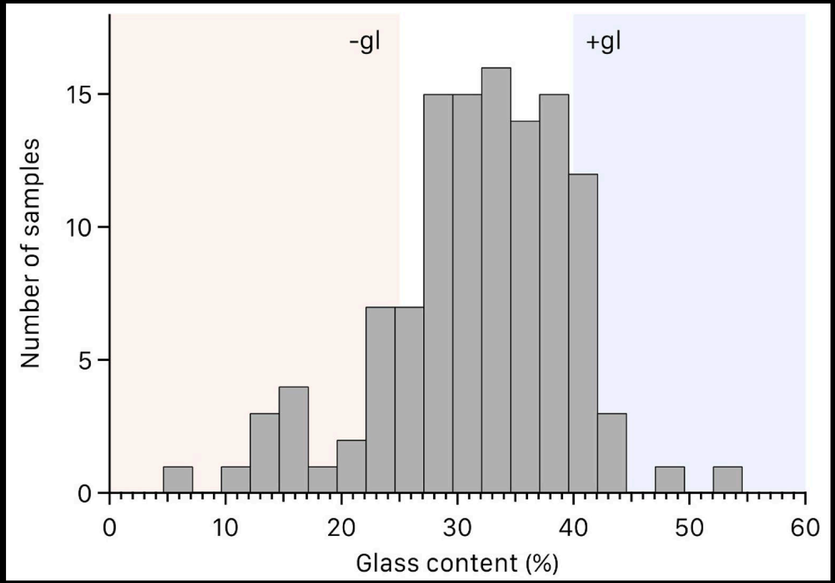


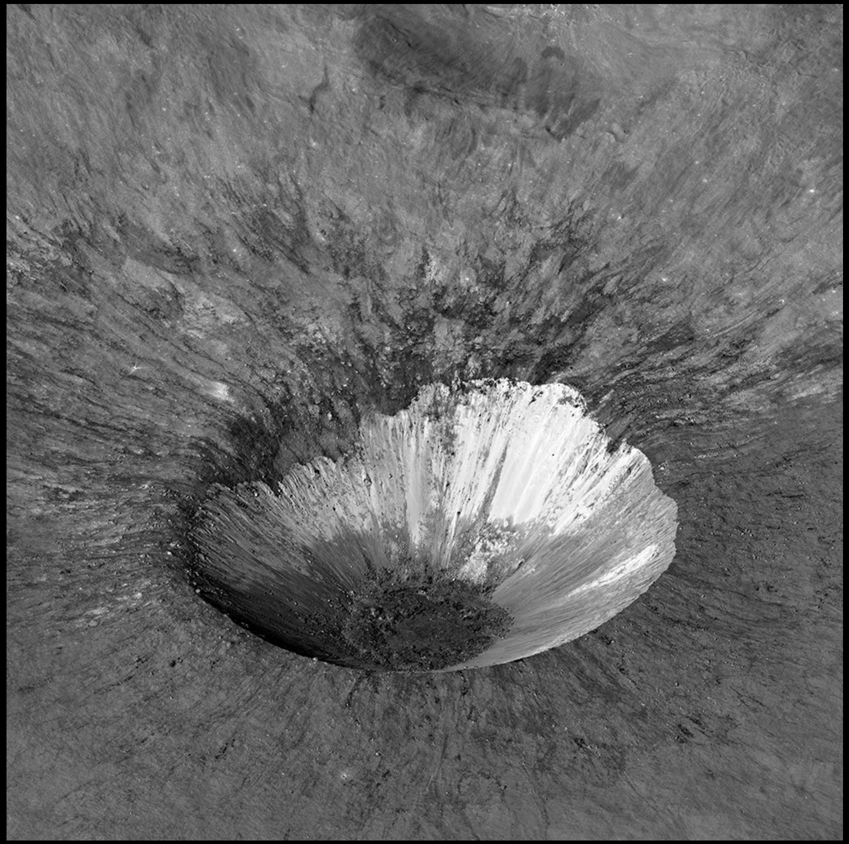
THE GLASS COMPONENT

- Most lunar regolith samples have a glass content percentage that ranges from the low 20s to low 40s
  - Some locations could be as high as 60%
- Agglutinates are the major source of glass in the lunar regolith (Taylor et al., 2019)
- Lunar mare simulants using Merriam Crater volcanic cinders have ~ 50% glass (McKay et al., 1994)
- Typical current lunar highland simulants utilize Merriam Crater cinders for glass and mafic components
  - A 30% basaltic cinder content only results in ~15% glass
  - NUW-LHT-5M glass (40 wt%) based on the average composition of Apollo 16 soil samples
- Production of accurate agglutinitic-like particles for simulant is difficult and expensive for bulk production
  - Gillis-Davis, J.J. et al. (2023) LPSC54, abstract 1001
- NASA looks for simulants with highest glass content as possible, preferring ≥ 30%

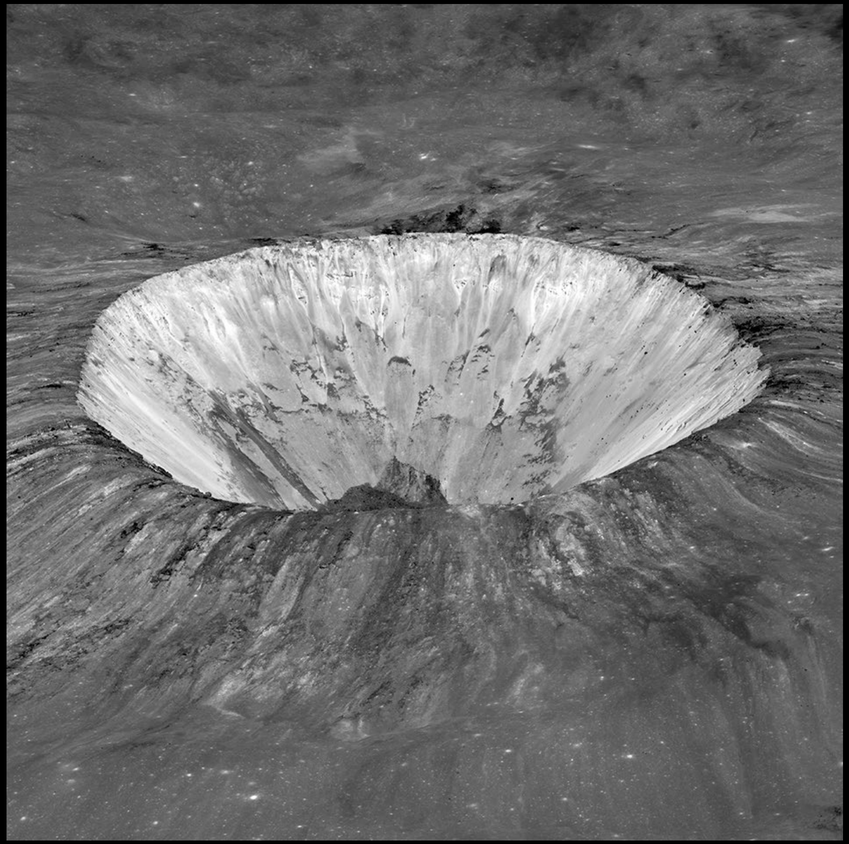


Amorphous content (assumed to be glass) from 188 soils measured by Taylor et al. (2019). Graph from Cannon, K.M. (2023) A lunar soil classification system for space resource utilization

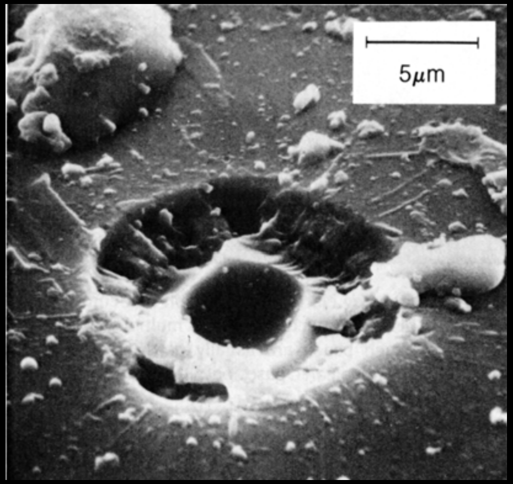
THE GLASS COMPONENT



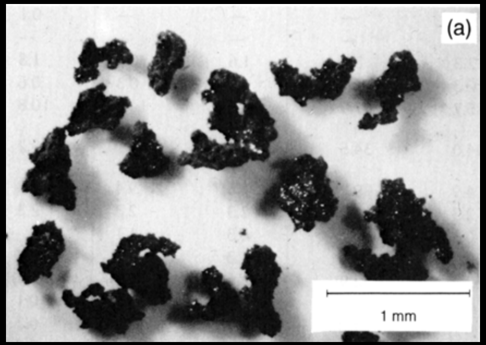
Hell Q crater
LROC NAC image M1221369684LR



Pierazzo crater
LROC NAC image M1265532953LR



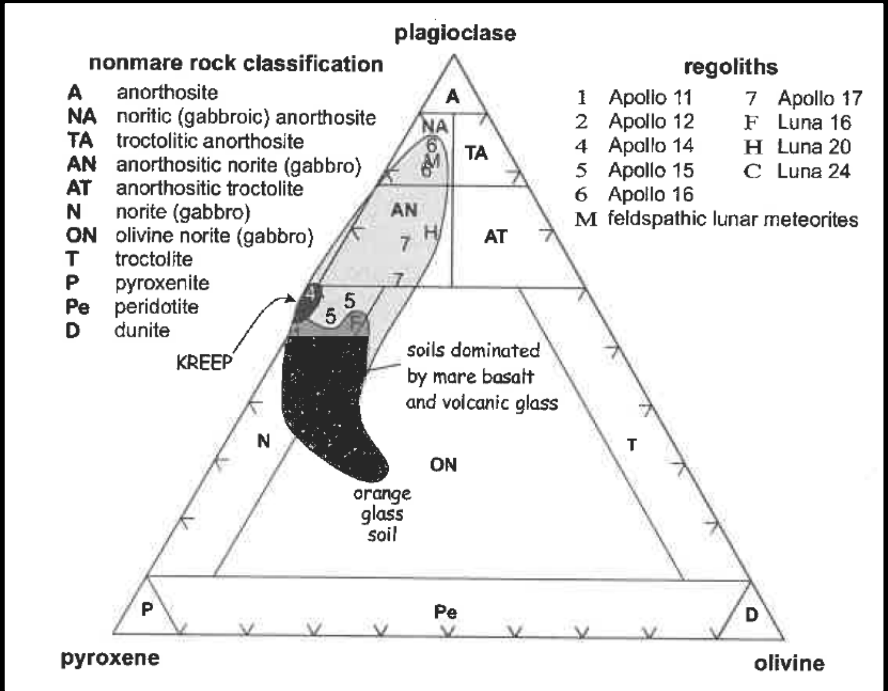
Micrometeoroid impact crater
Lunar Sourcebook, Fig. 7.8



Lunar agglutinates
NASA photo S69-54827

The Crystalline Component

- Simulant producers for decades have done a nice job on getting the right petrology and mineralogy into simulants
- Lunar mare simulants are more straight forward
  - Merriam Crater basaltic cinders mostly works
  - It would be beneficial to get basaltic rock (i.e., from flows) into use for simulants with expanded PSD
- For lunar highlands simulants, two different anorthosites are still accessible in bulk (Canada, Greenland)
  - Norite would be a welcomed addition (plag + pyx)



From New Views of the Moon (Jolliff, et al., 2006), Fig. 2.3, p. 91

Thoughts on Simulant Classification

- At NASA we tend to avoid the word "fidelity" in describing simulants to our projects
  - Fidelity is a somewhat subjective term, and Figures of Merit lead the way (possibly principal component analysis in the future, see Katzer et al., *Aerospace* **2024**, 11, 348)
  - Project dependent (i.e., dust mitigation vs excavation)
  - Instead, broad categories are used to describe simulants in project interactions
- BASIC
  - Typically: one rock type, major minerals present, PSD partial match, no glass (i.e., BP-1, Greenspar, Bunker Sand)
- GENERAL PURPOSE
  - Typically: mixed rock types; mostly correct major minerals, PSD and particle shape, glass is present (i.e., most commercial simulants)
  - Lunar highlands example: 70% anorthosite, 30% basaltic cinders
- ENHANCED
  - Typically: correct major minerals, PSD, particle shape, glass component in the range of ≥30% and chemically correct, agglutinate-like particles, minor minerals present (i.e., NU-LHT-2M, -4M, NUW-LHT-5M)
- SPECIALTY
  - Typically: general purpose or enhanced simulants with addition of frozen volatiles, agglutinates with nano-phase Fe, or emphasized minerals (i.e., ilmenite)

increased difficulty and expense

Conclusion

- The lunar regolith is dusty, gritty, rocky, and glassy
- NASA needs bulk lunar simulants that are dusty, gritty, rocky, and glassy
- NASA is continuously working with simulant providers to improve the state-of-the-art of lunar simulants
- New information on the shape of lunar regolith grains is emerging
- The glass component in lunar simulants could use more emphasis
  - the 'ever-elusive' practical agglutinate bulk production
  - lunar highlands glass component mass % and composition
- Lunar mare simulants are the most straight-forward and practical to make
  - also applicable for south pole-bound systems for physical/mechanical interaction with the regolith
- NASA is open to comments on the User's Guide and ideas for surface materials for future large (outdoors and indoors) testing and training facilities