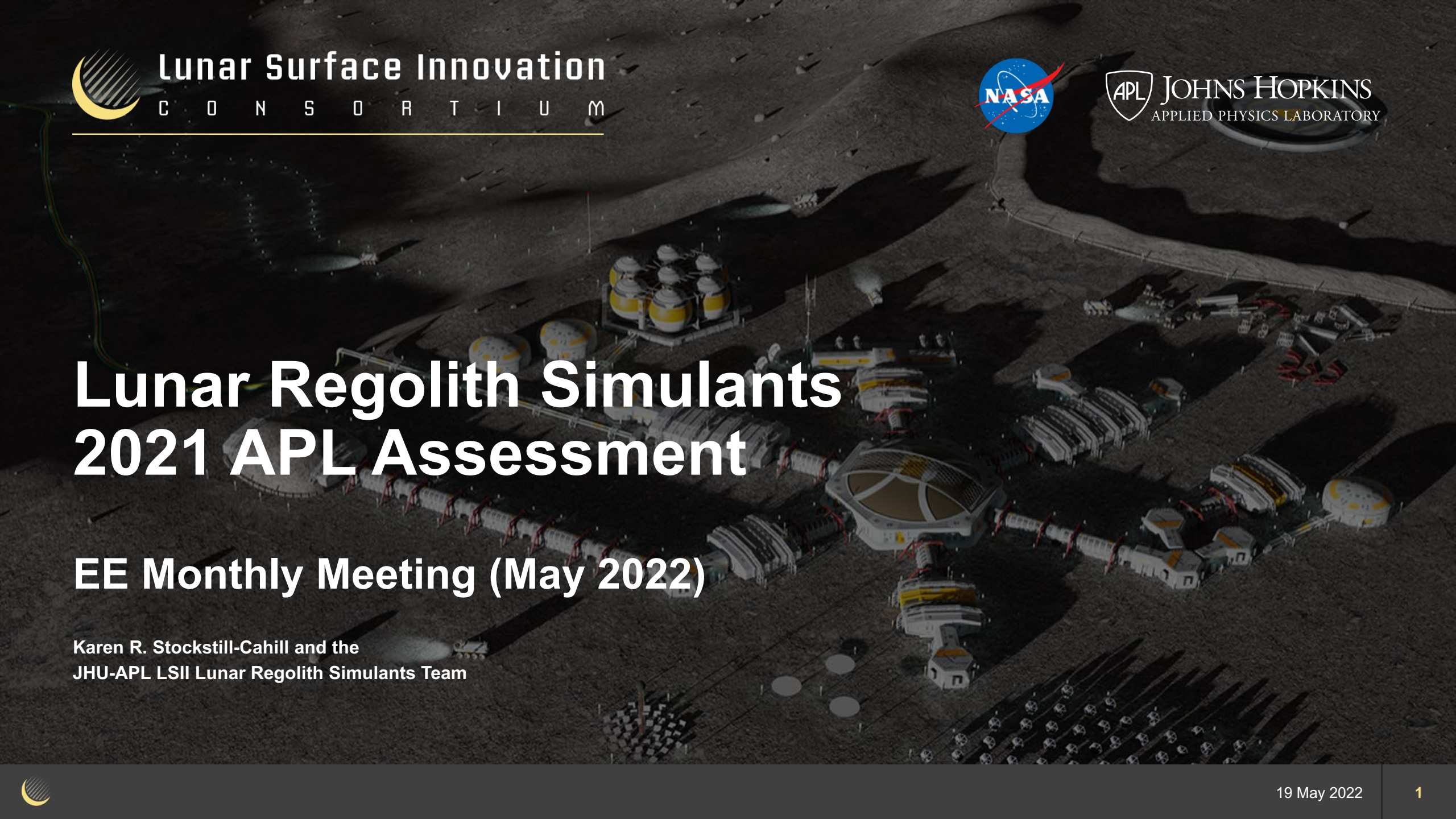


Lunar Surface Innovation Consortium

NASA

APL Johns Hopkins Applied Physics Laboratory

Lunar Regolith Simulants 2021 APL Assessment

EE Monthly Meeting (May 2022)

Karen R. Stockstill-Cahill and the
JHU-APL LSII Lunar Regolith Simulants Team

Lunar Regolith

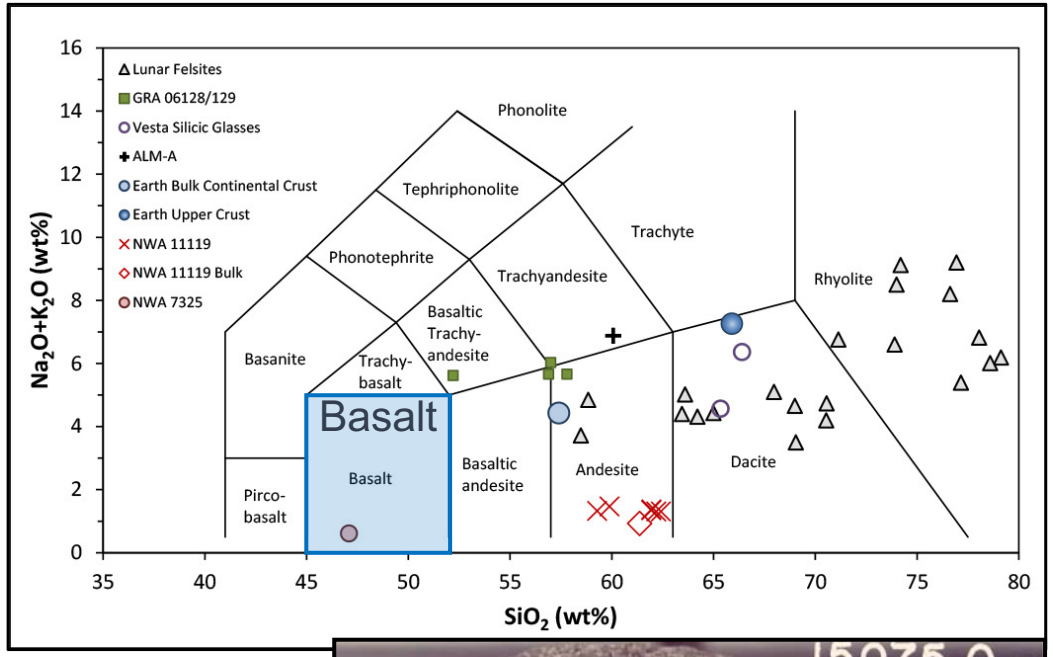
- Unconsolidated material covering the lunar surface
  - Mostly a fine, gray “soil”
  - Breccia and rock fragments
  - Agglutinates
  - Pyroclastic materials (volcanic glass)
- Relevance (It’s EVERYWHERE!)
  - **ISRU** (volatiles, other materials)
  - **Excavation and Construction** (building materials, excavation processes)
  - **Extreme Access** (“bulk transport of lunar regolith”)
  - **Extreme Environments** (“endogenic factor”)

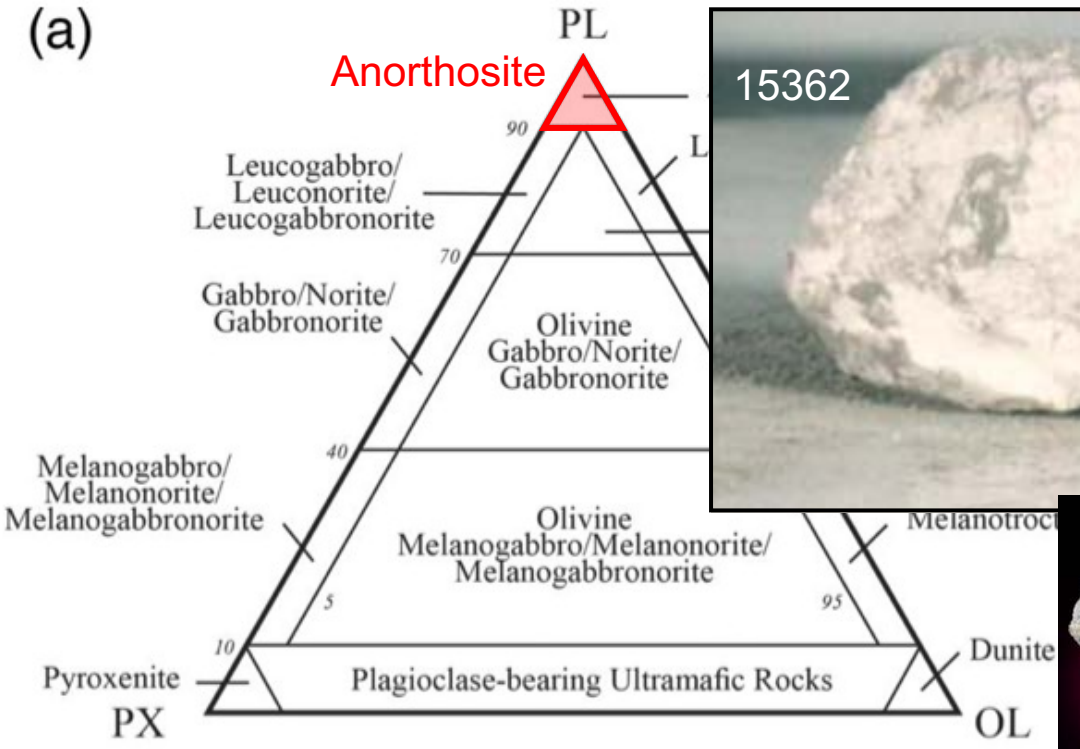
NASA photo AS11-40-5877

From Lunar Sourcebook
Ch. 7, Fig. 7.2

Lunar Regolith Facts

- Regolith Properties (ala Roy Christoffersen)
  - **Composition - Underlying rock**
    - **Basalt (Fe-rich)**
    - **Anorthosite (Ca-rich Anorthite)**

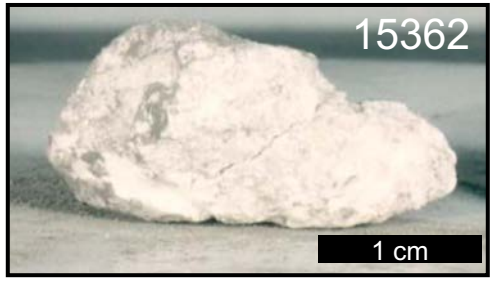


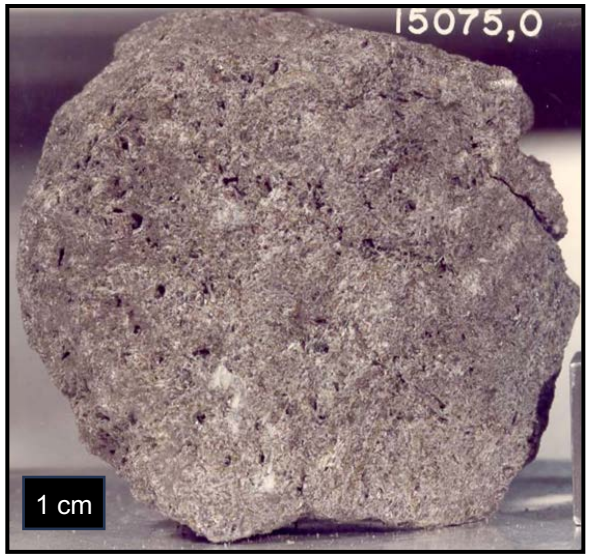


Anorthite (plag)

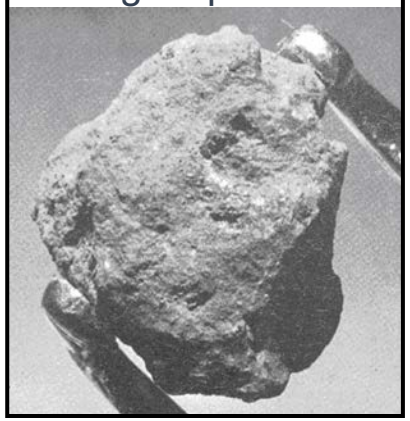
Lunar Regolith Facts

- Regolith Properties (ala Roy Christoffersen)
  - Composition - Underlying rock
    - Basalt
    - Anorthosite
- **Grain size & shape**
  - **~50% <31 um**

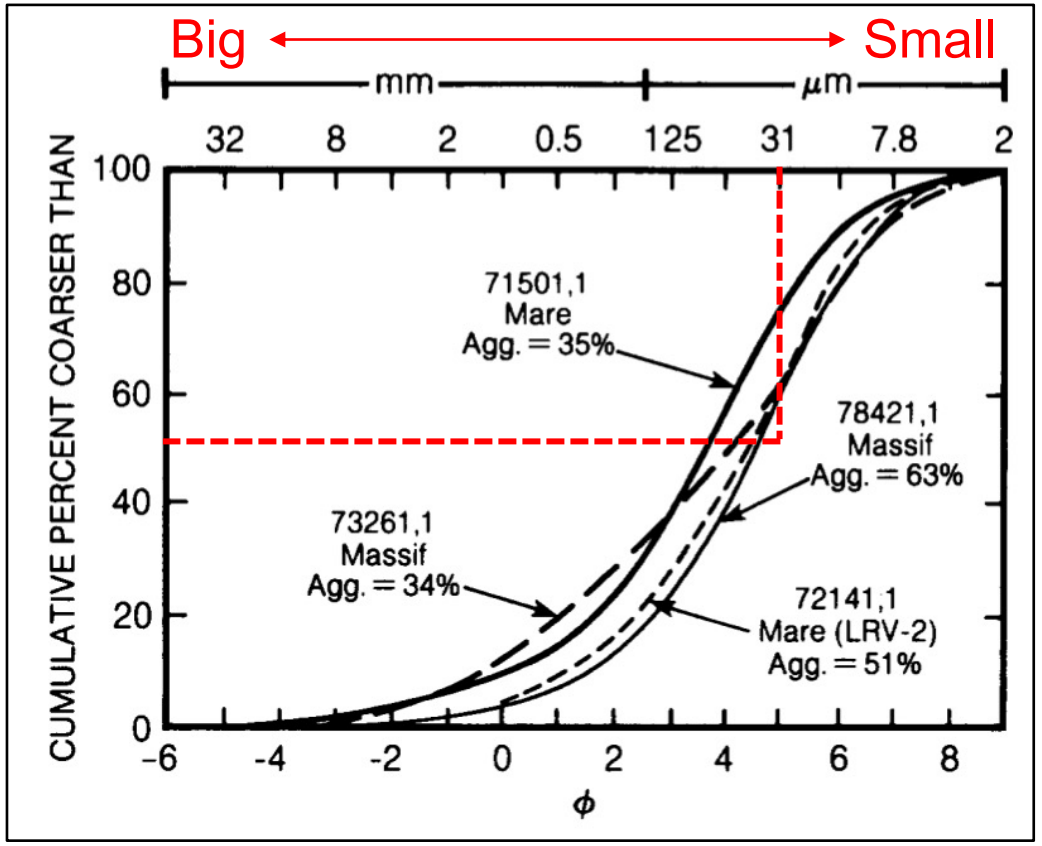


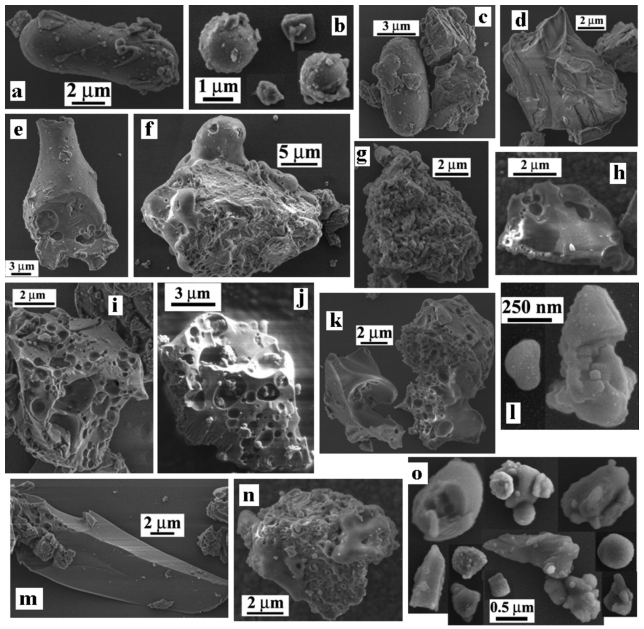


15012,B
largest particle



From Lunar Sourcebook Ch. 7, Fig. 7.9

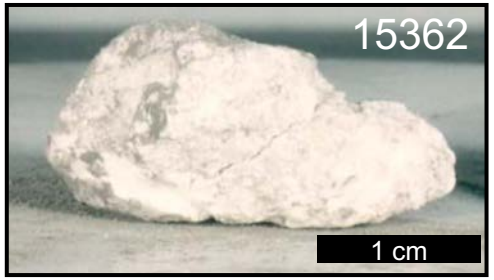


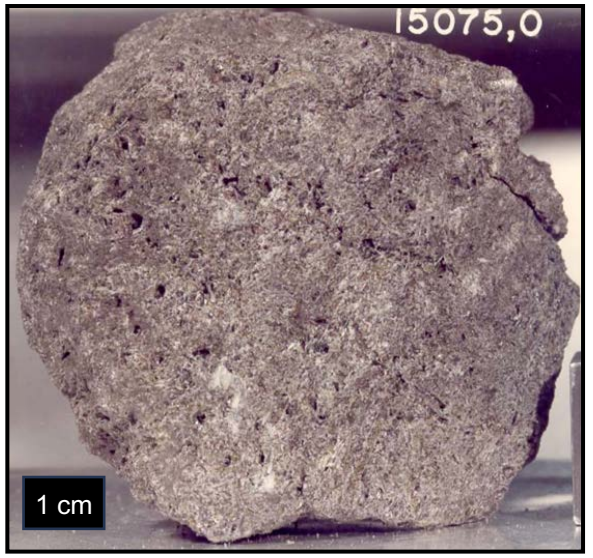


Liu et al. (2008) Fig. 1

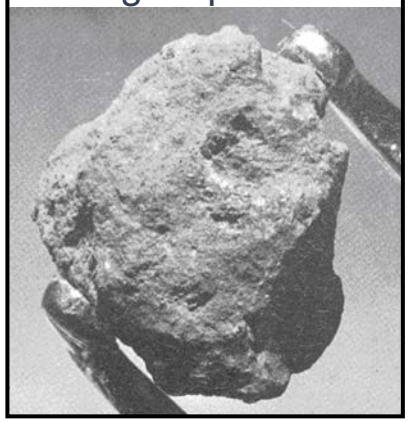
Lunar Regolith Facts

- Regolith Properties (ala Roy Christoffersen)
  - Composition - Underlying rock
    - Basalt
    - Anorthosite
- Grain size & shape
  - ~50% <31 um
- **Unique components**
  - **Agglutinates**
  - **Nanophase Fe metal (npFe^0)**
  - **Amorphous mineral rims (especially Plagioclase)**

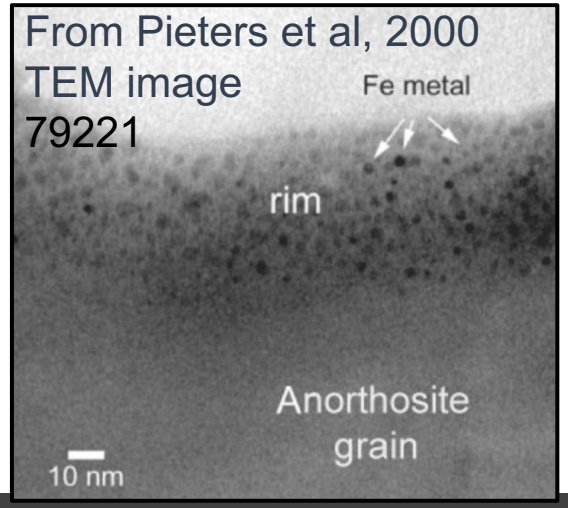




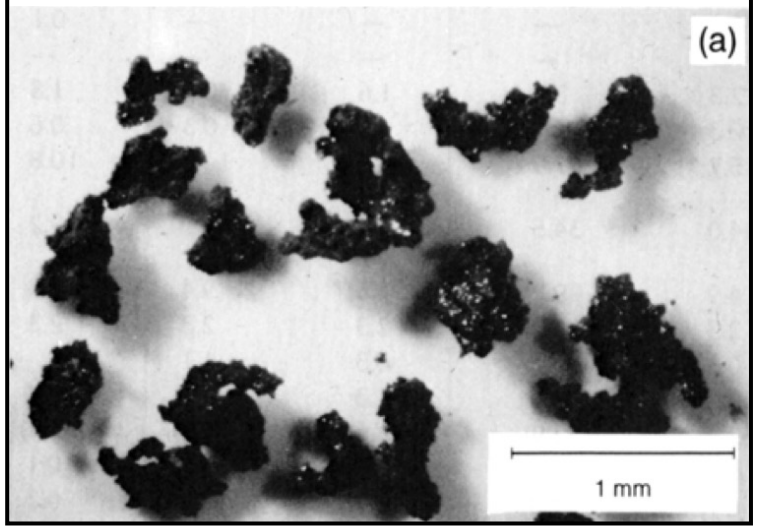
15012,B
largest particle



Liu et al. (2008)
Fig. 1o



Apollo 11 soil sample 10084



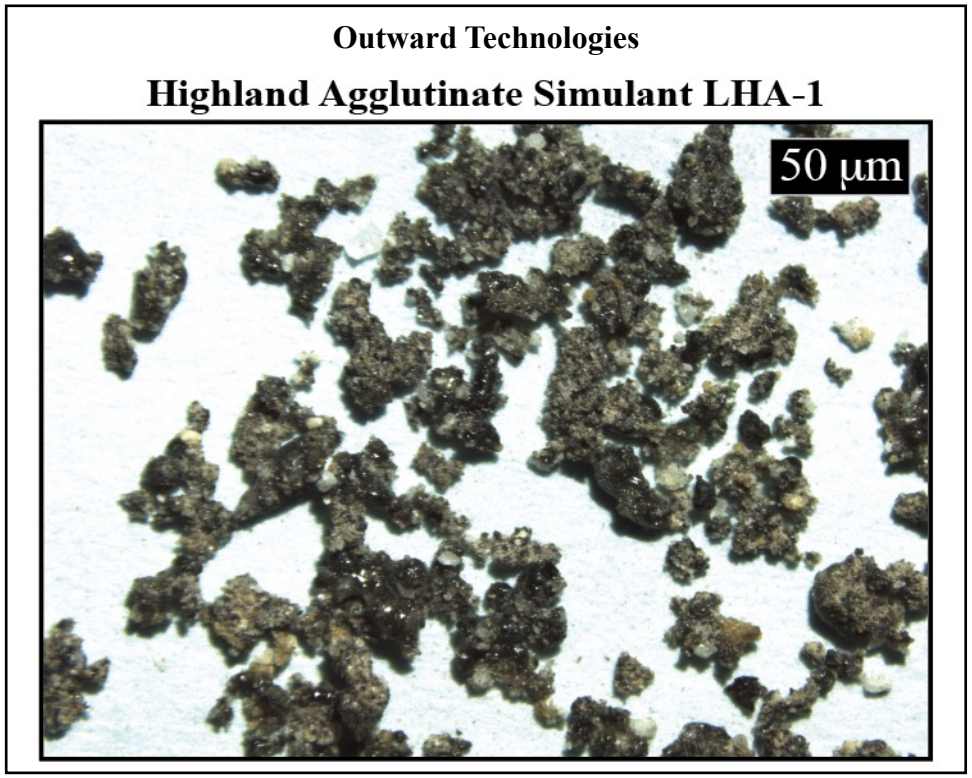
From Lunar Sourcebook
Ch. 7, Fig. 7.2

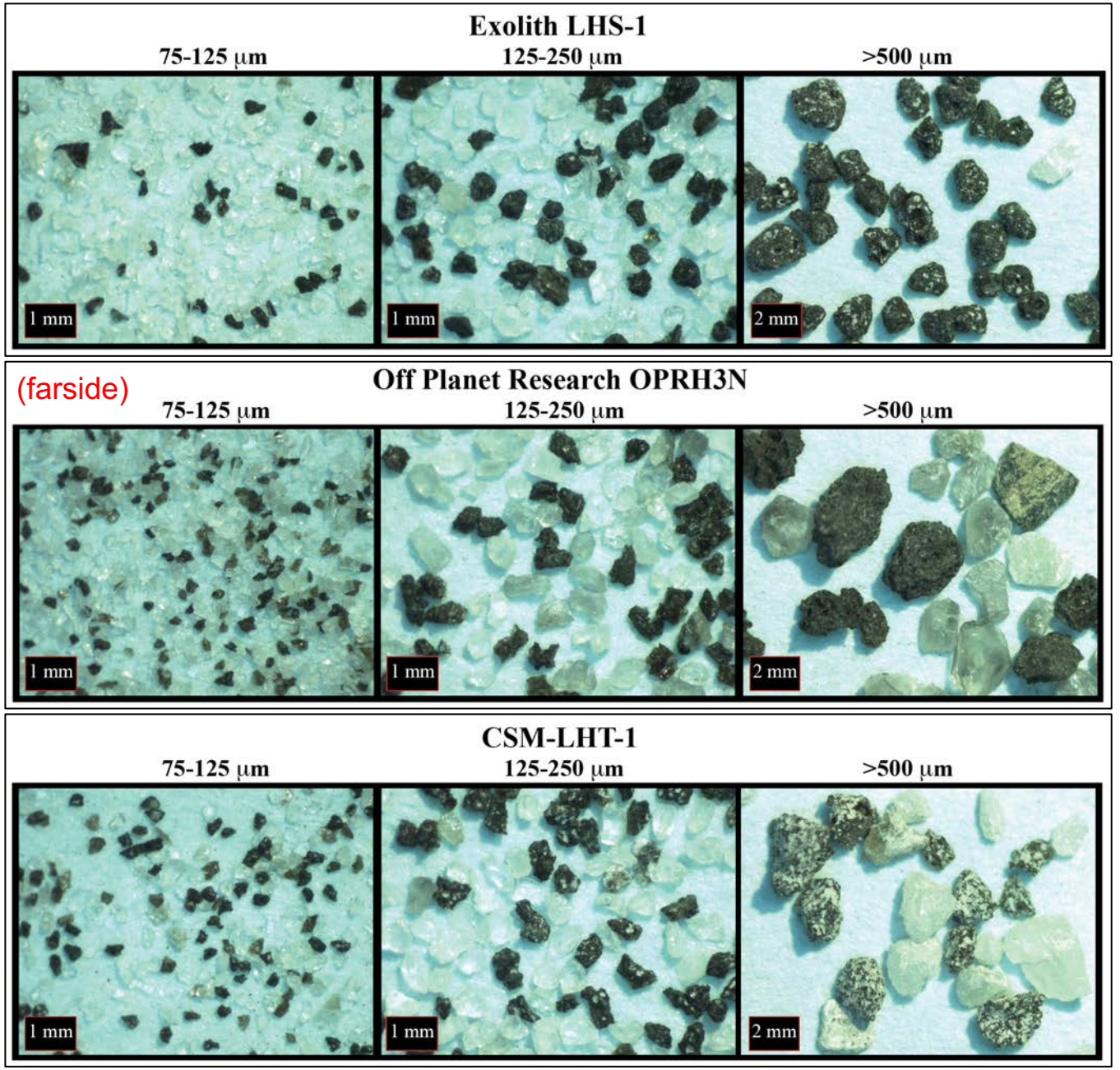
Lunar Regolith Simulants

- An approximation of Lunar Regolith
  - Composed of Terrestrial Rocks
    - Compositional differences
      - Terr. Plag. is more Na-rich
      - Terr. Basalt may not be as Fe-rich
    - Exposed to water at the surface
      - Weathered surfaces, oxidized
  - Missing unique components
    - No Agglutinates
    - No nanophase Fe^0 metal
    - Mineral rims tend to be crystalline
  - We do have similar rock types
    - Breccia and rock fragments
    - Pyroclastic materials (volcanic glass)

Highland Simulants: 3 Grain Sizes

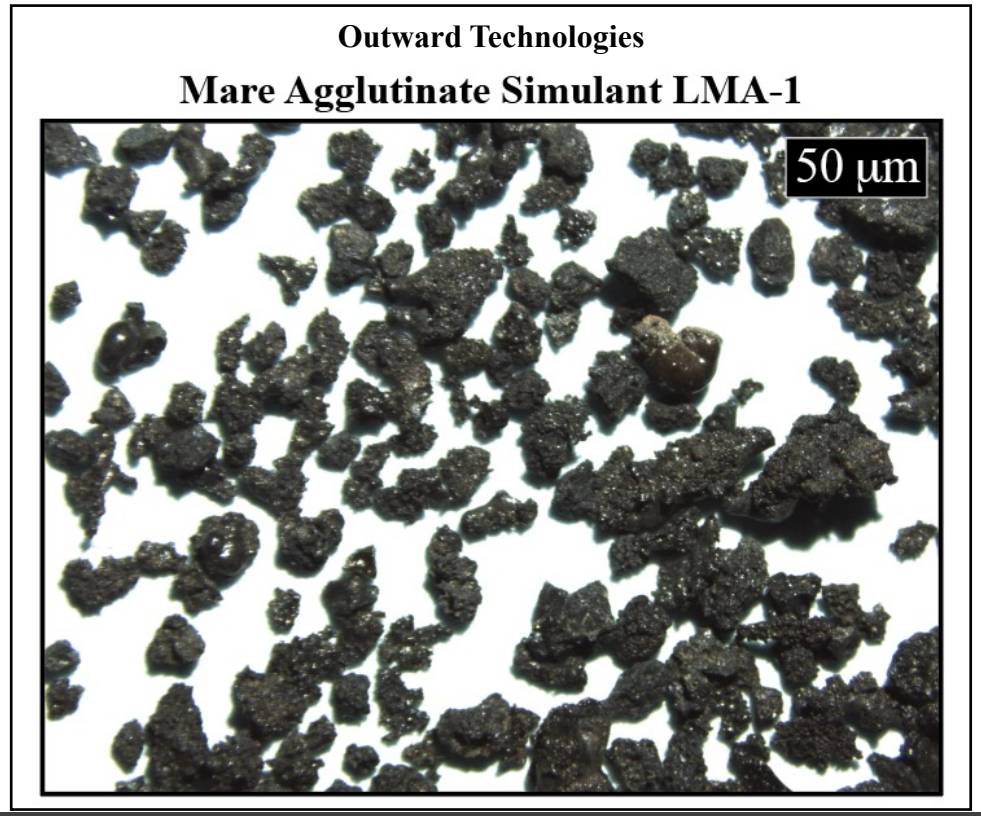
Highland Pseudo-agglutinate

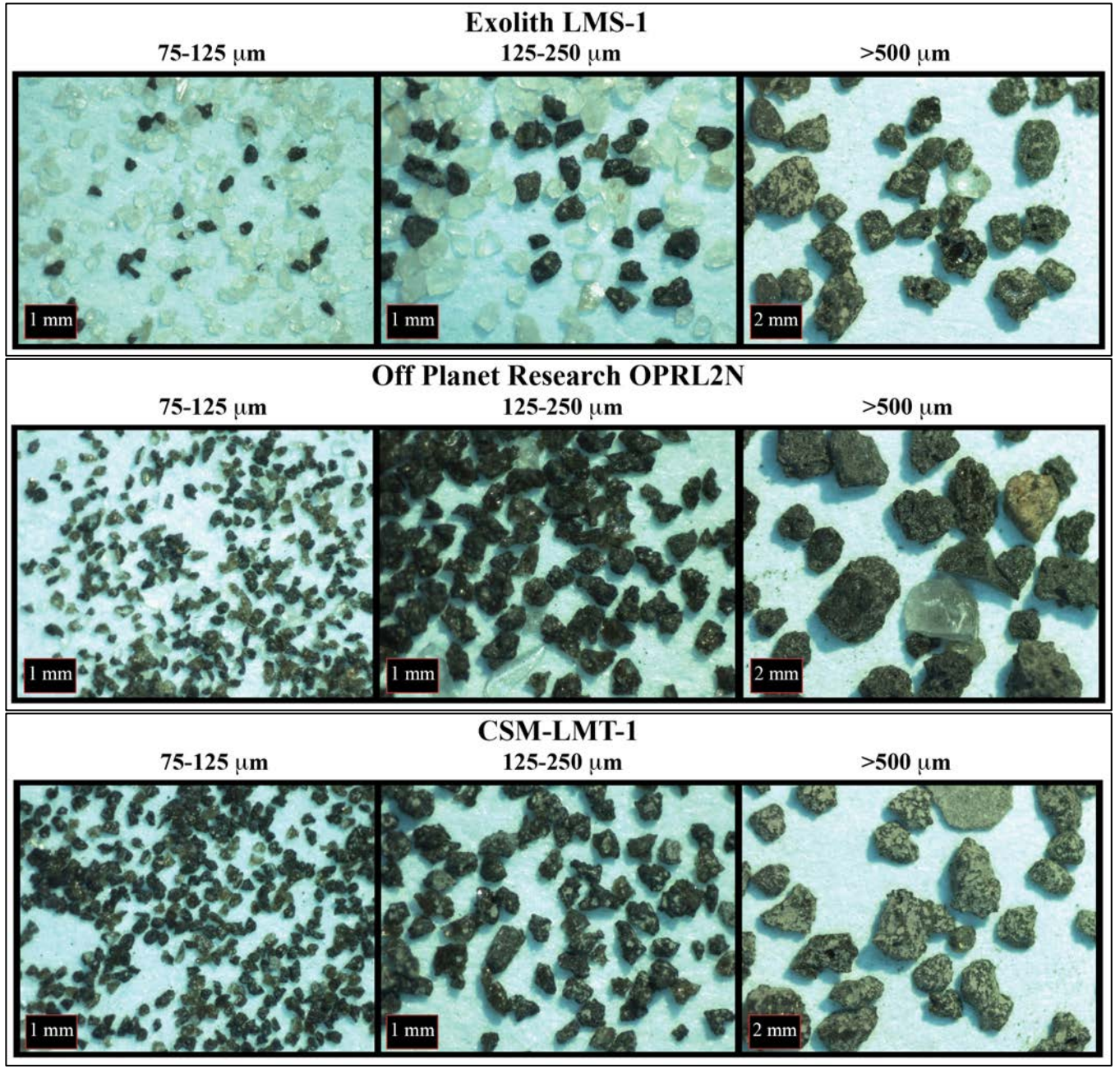




Mare Simulants: 3 Grain Sizes

Mare Pseudo-agglutinate





Particle Size and Shape

- Particle size bins of 3 µm for all samples (i.e., 0-3 µm, 3-6 µm, etc.)

- Particle size distribution (PSD) results are D(10), D(50), and D(90)
  - e.g., D(50) = 75 µm indicates that 50% of the particles are <75 µm in diameter
  - Should be equivalent to weight percent derived from sieve analysis

- Camsizer system also reports several shape parameters for each bin size, including
  - Aspect ratio (i.e., AR = b/a; perfect sphere = 1)
  - Sphericity (i.e., perfect sphere = 1; aka complexity)

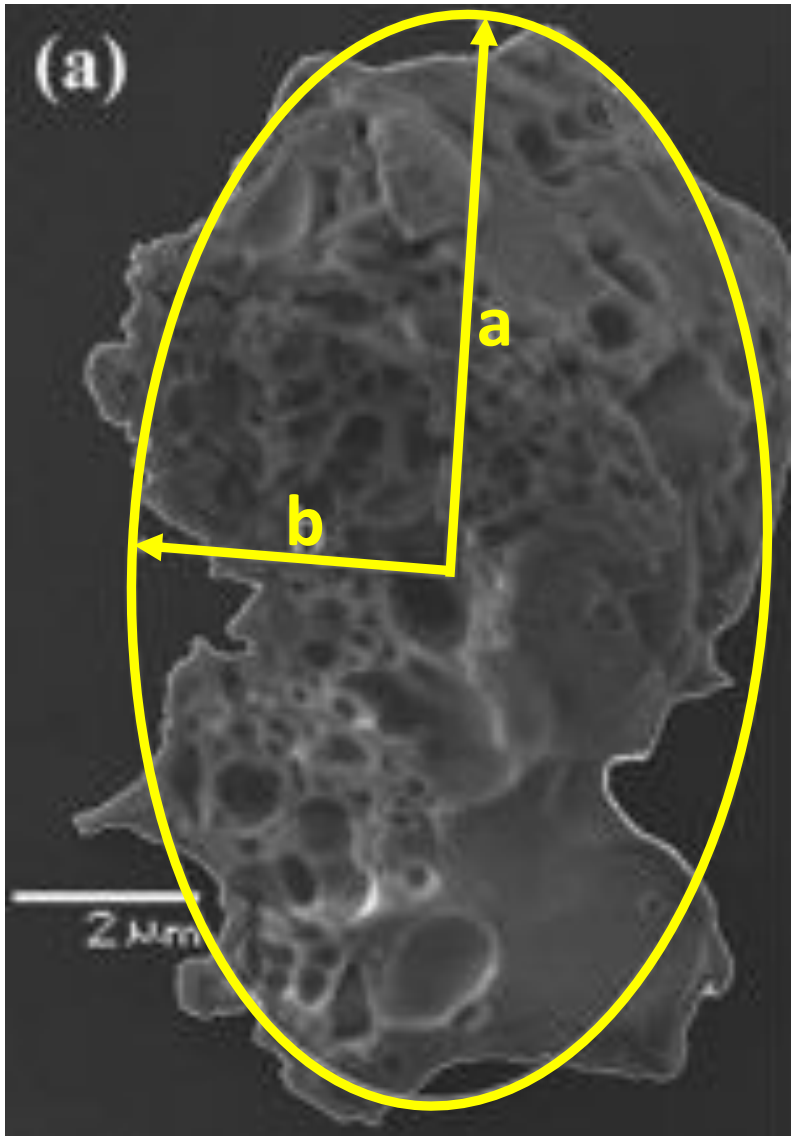
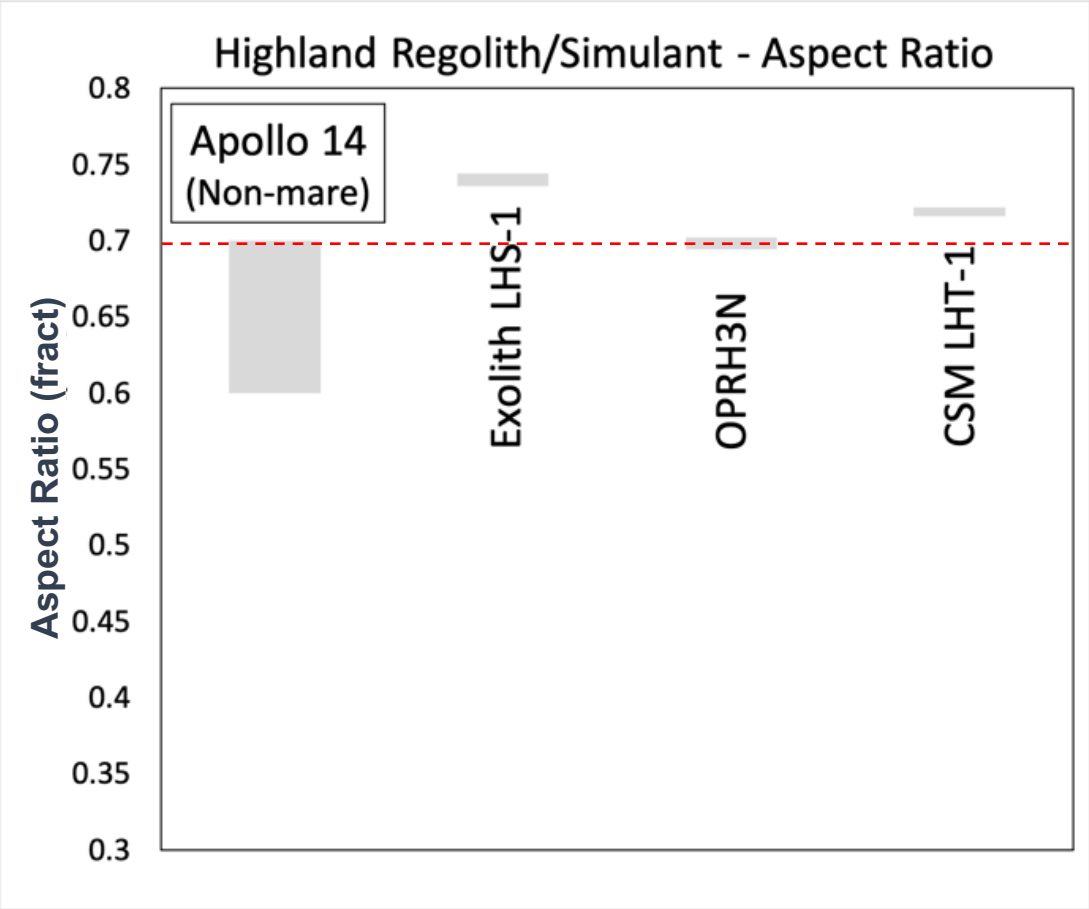
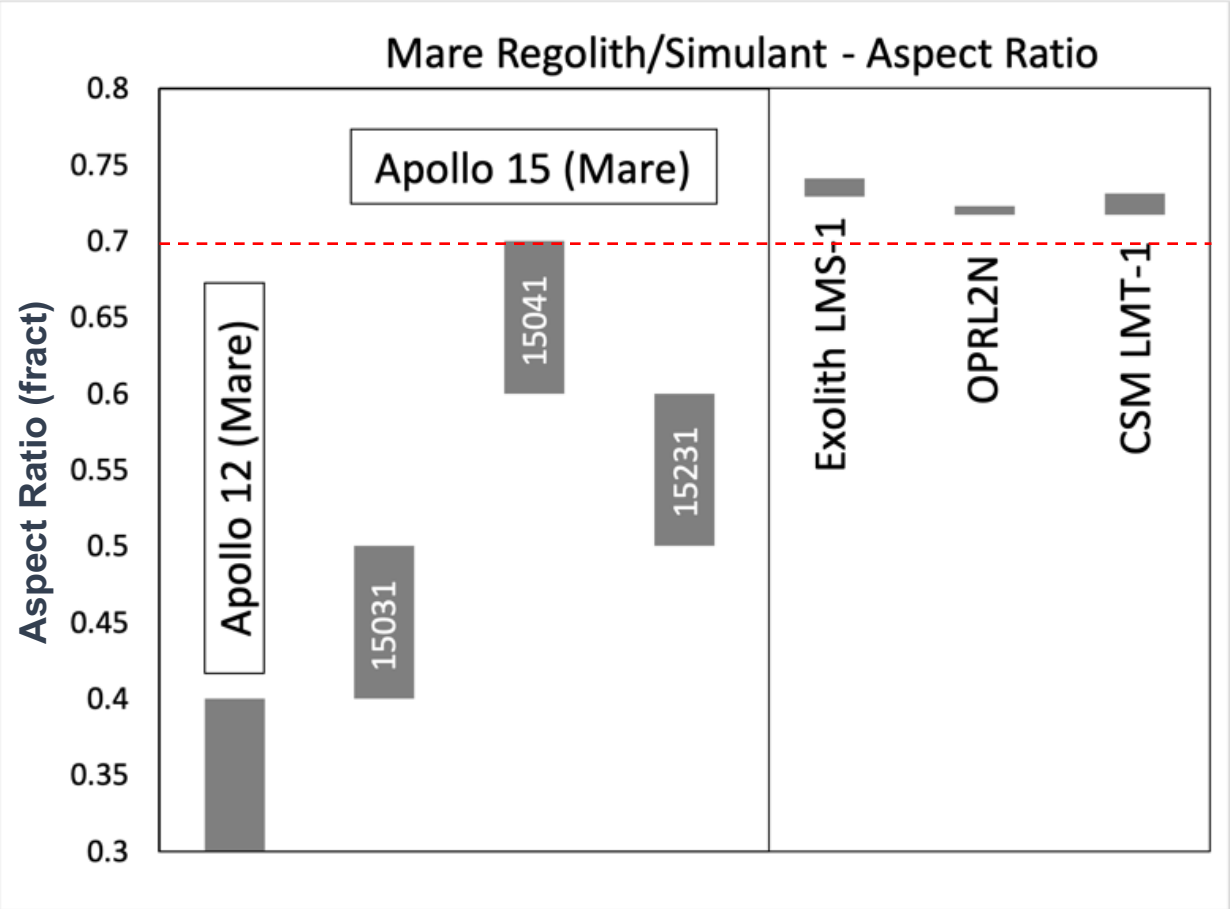


Figure after Liu et al. (2008)

Particle Shape: Aspect Ratio

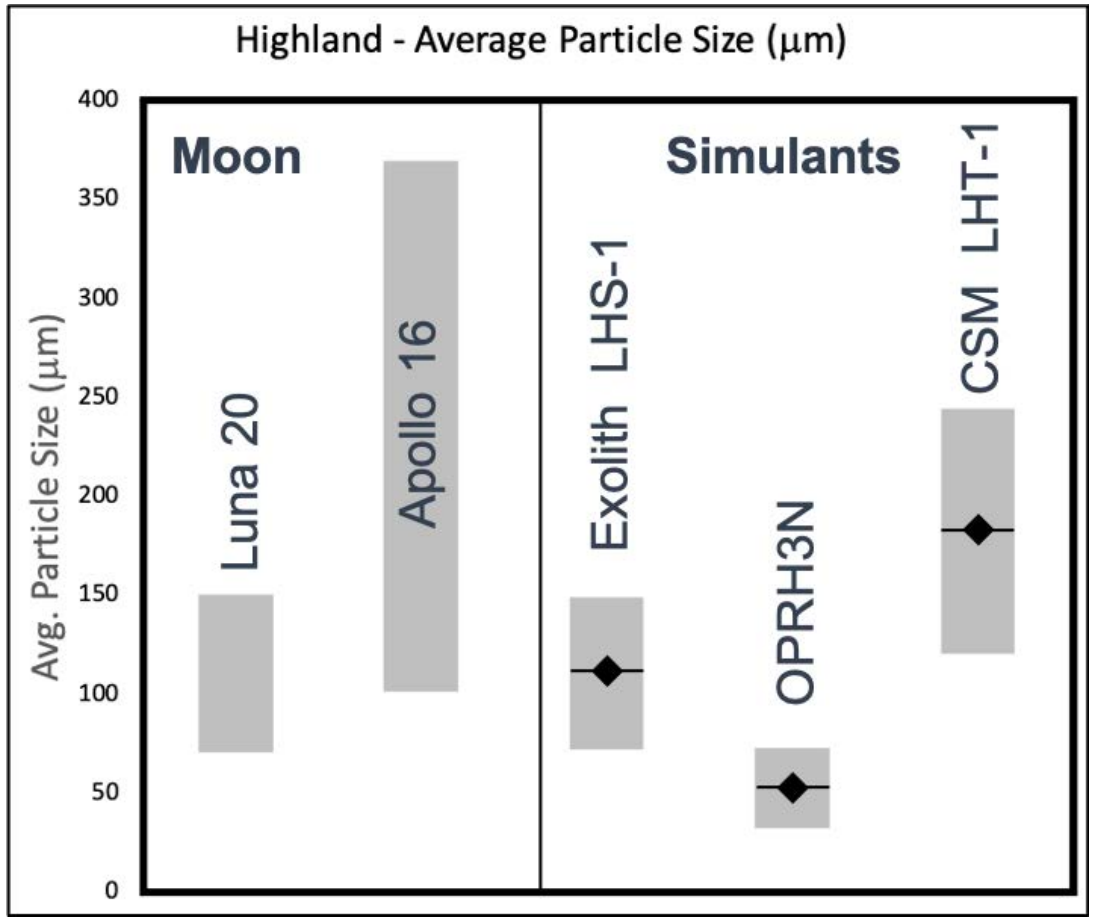
- Simulant aspect ratios are higher (more rounded) than Apollo regolith

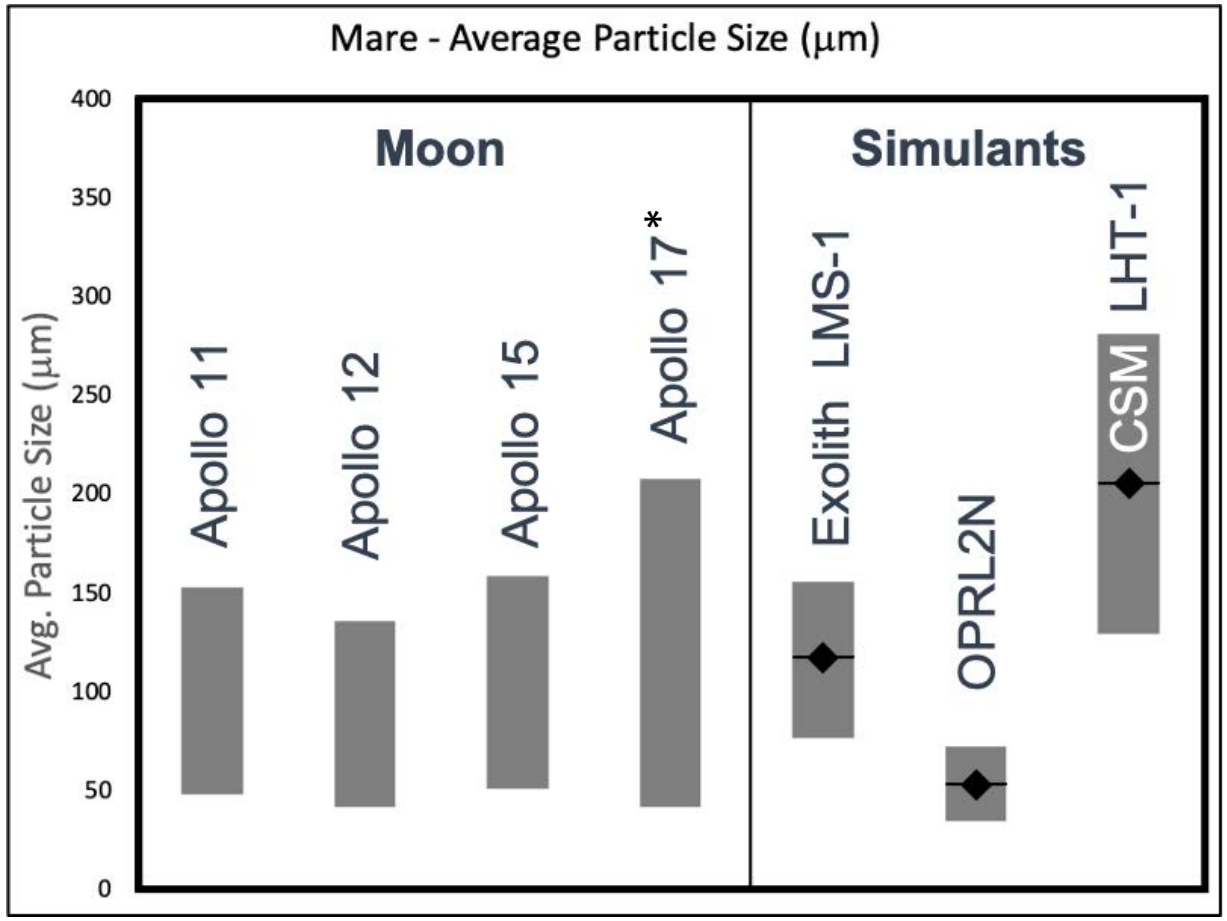




Particle Size: Median vs. Mode

- Simulant D(50) values overlap with lunar regolith median particle size

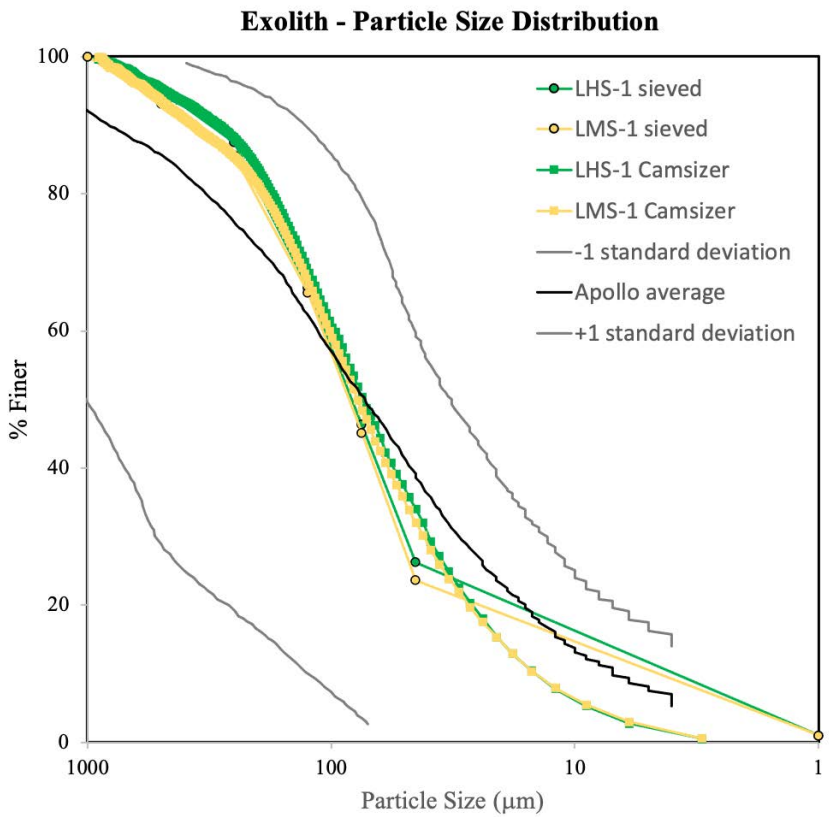


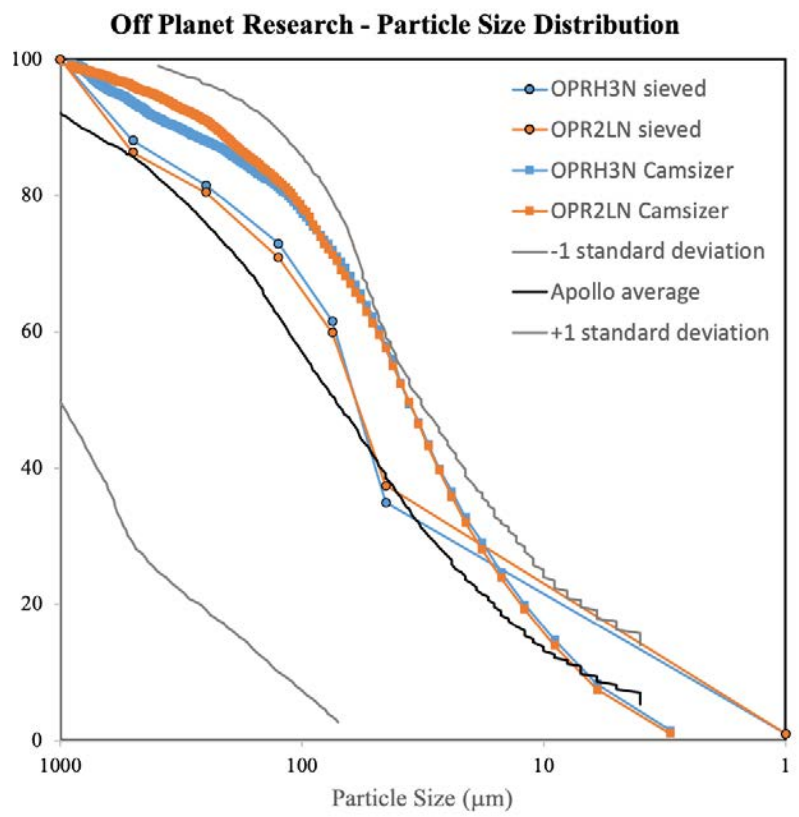


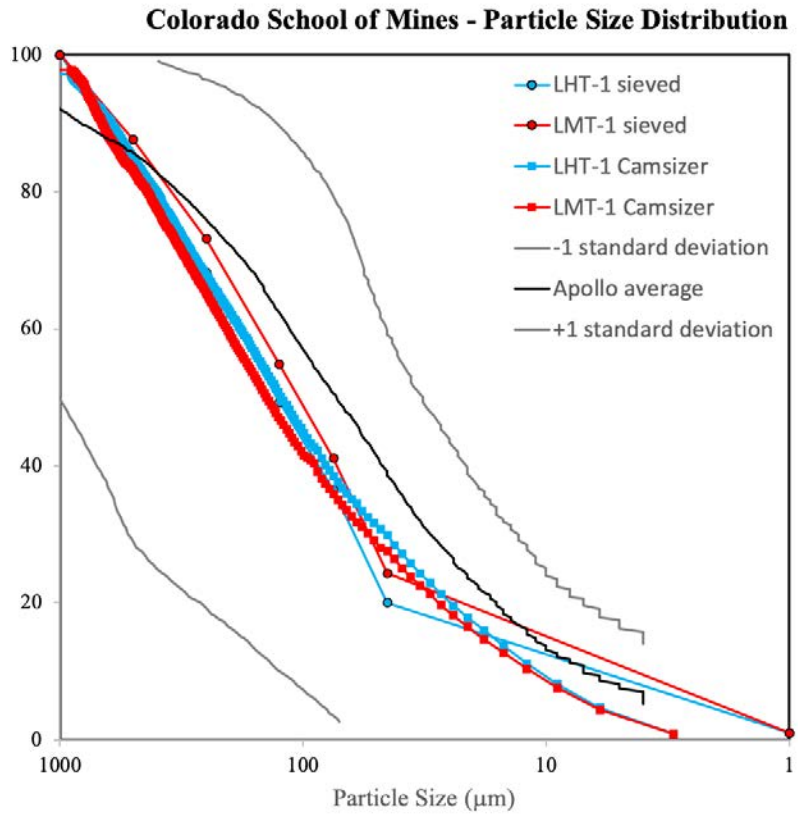
*Mean value, no medians reported for Apollo 16 or 17

Particle Size: Distribution (PSD)

- PSD for simulants plot within one standard deviation of Apollo regolith PSD average, although simulant PSD have steeper slope







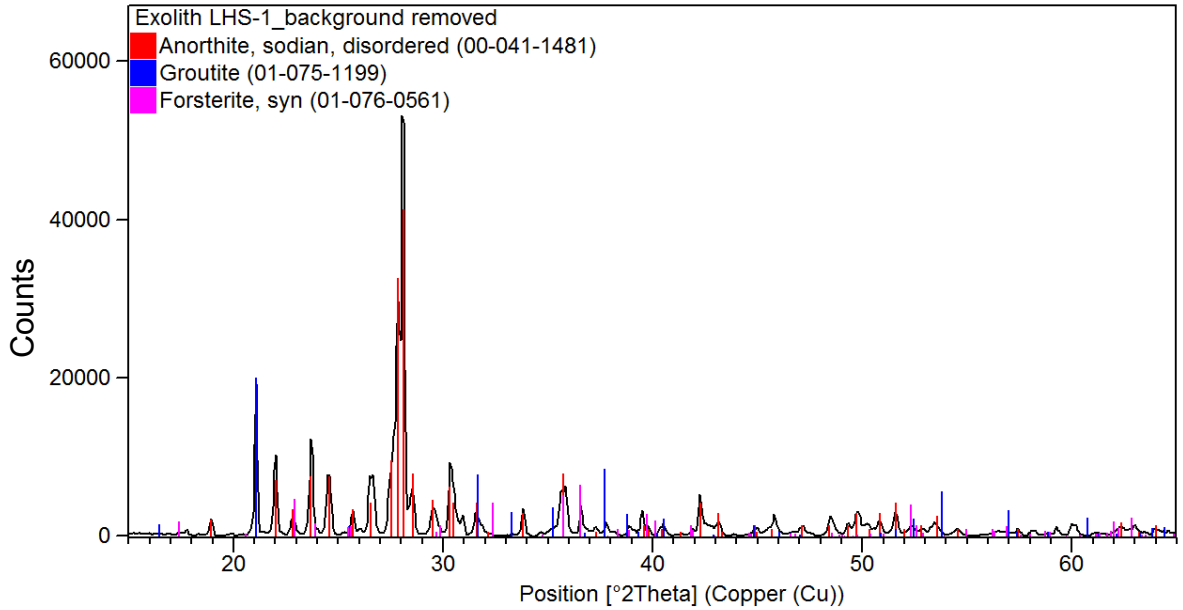
Composition

Bulk Chemistry (XRF)

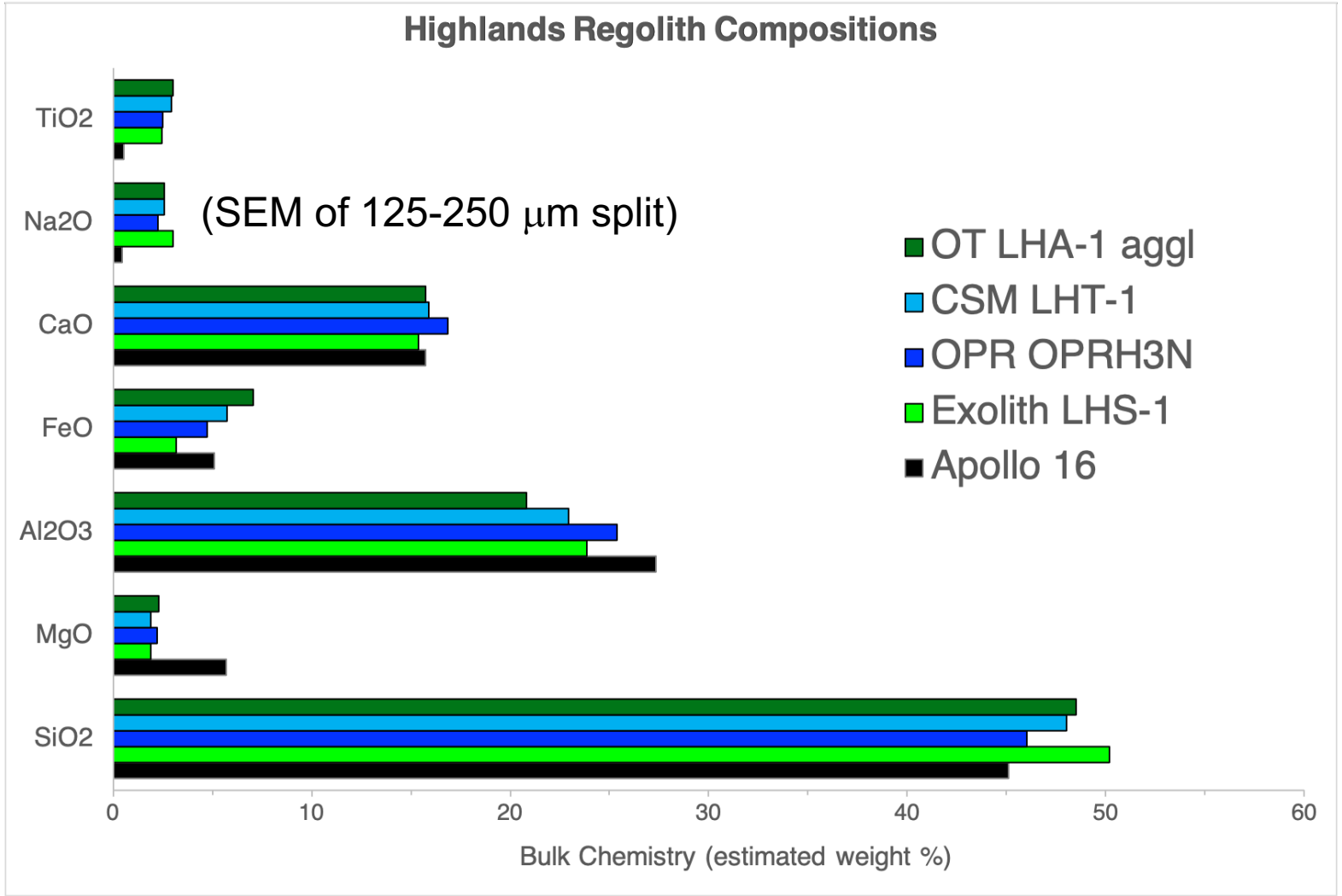
- Portable Thermo Scientific Niton XL3t 980 analyzer
  - Repeated analyses on 5 splits of bulk material
  - Detection limits (Mg, Na)

Minerology (XRD)

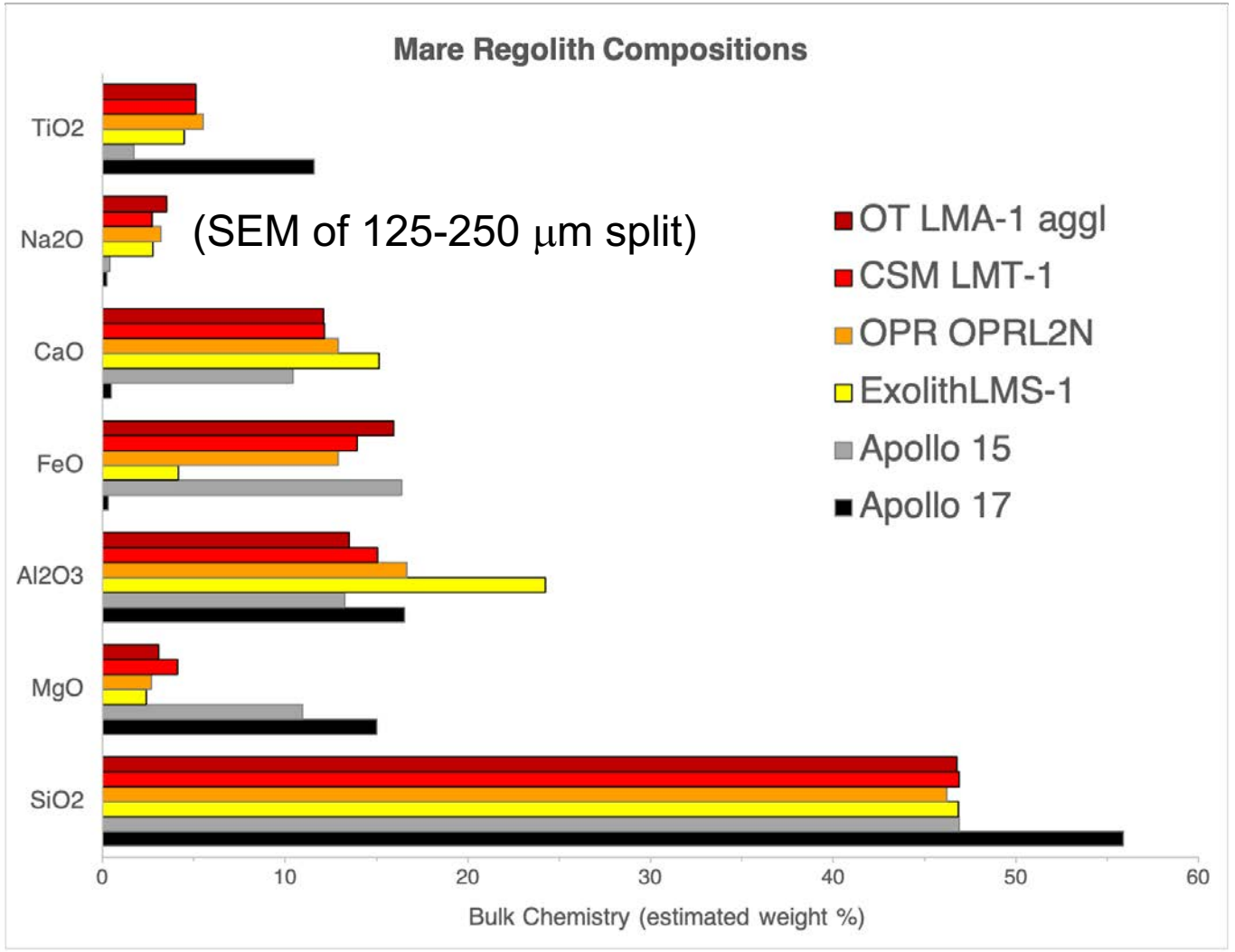
- Panalytical Empyrean diffraction cabinet using Reference Intensity Ratio method
  - Incident x-rays are diffracted by *crystalline material*
  - For samples with multiple phases present, provides semi-quantitative abundances



Composition: Bulk Chemistry (Highland) - XRF



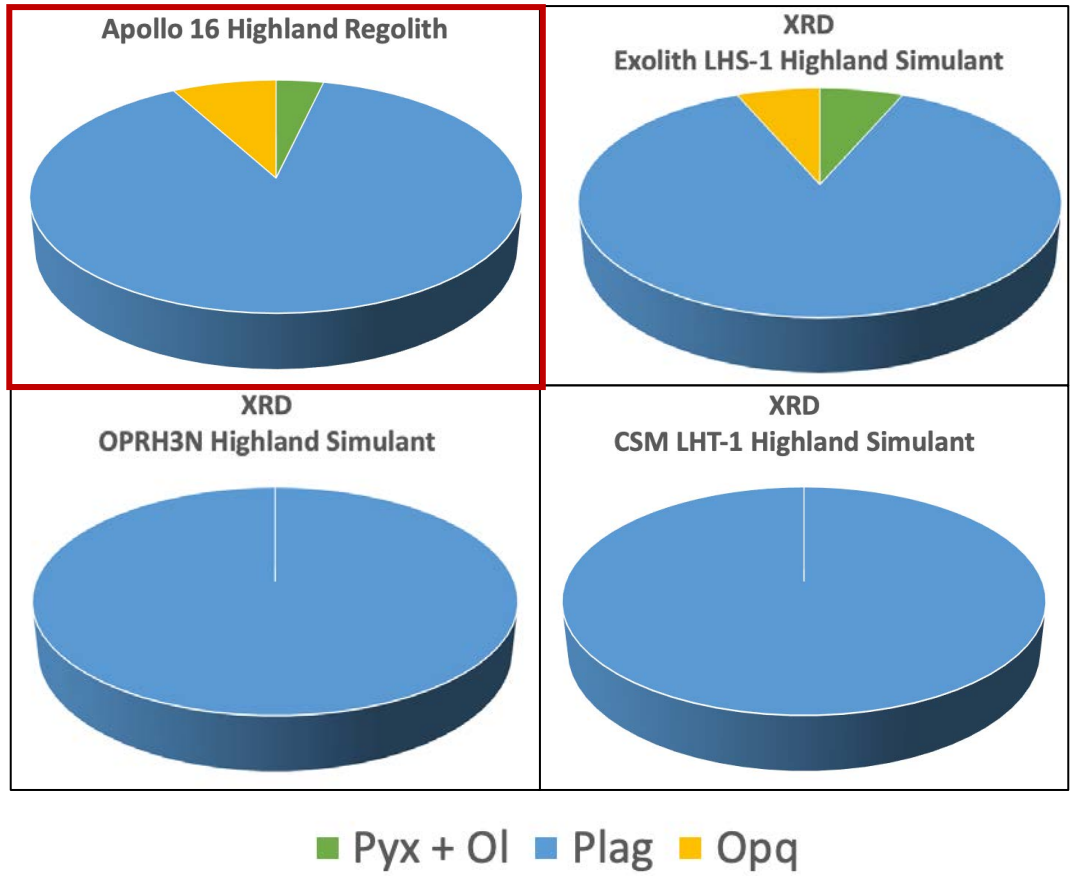
Composition: Bulk Chemistry (Mare) - XRF



Composition: Mineralogy (Highland Simulants) - XRD

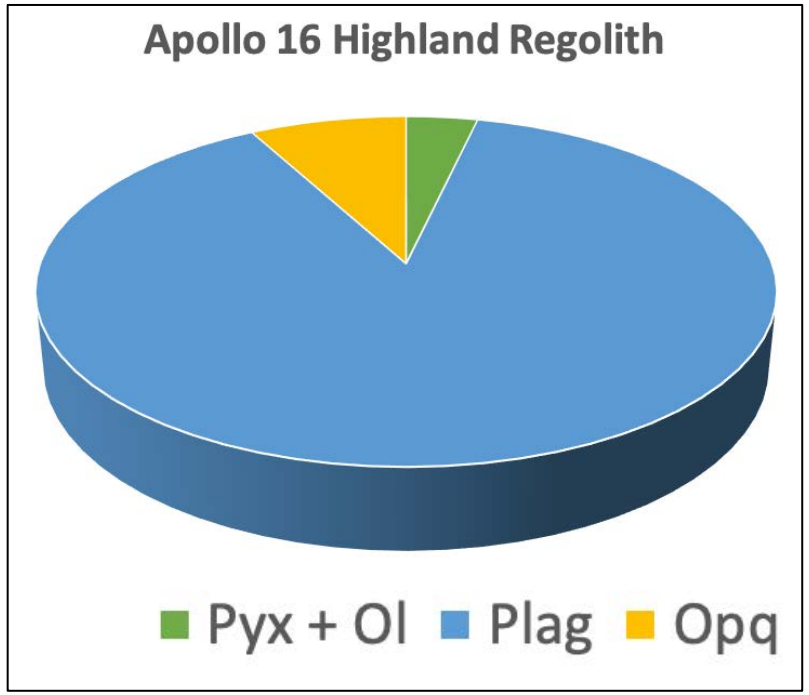
XRD semi-quantitative abundances of crystalline phases (vol %)				
Company	**Exolith**	**Off Planet Research**	**CO School of Mines**	**Outward Technology**
Simulant	**LHS-1**	**OPRH3N**	**LHT-1**	**LHA-1**
Type	Highland	Highland	Highland	HL aggl
Plagioclase	87	100[1]	100	100
Olivine	6.5	-	-	-
Pyroxene	-	-	-	-
Groutite	6.5	-	-	-

[1]Phase ID = Labradorite, (all other identified as anorthite).



Glassy mafic rocks/minerals are not identified by XRD

Composition: Mineralogy (Highland Simulants) - XRD

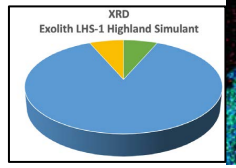


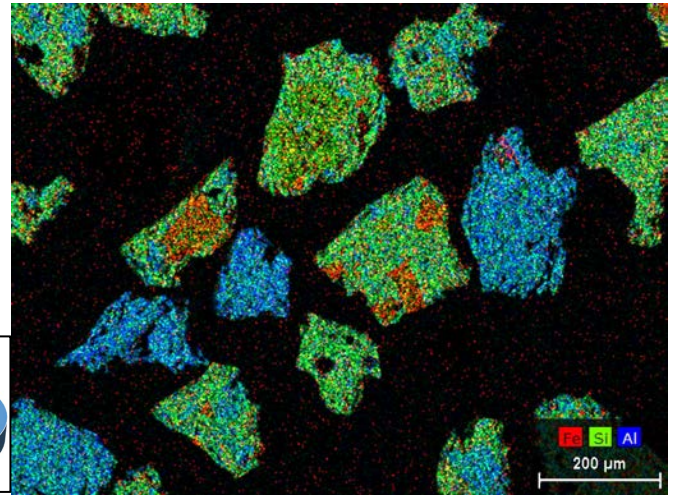
SEM Maps of
125-250 µm split*

R = Fe G = Si B = Al

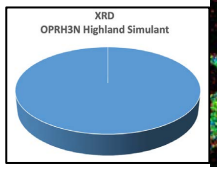
- Plagioclase = blues
- Ol/Pyx = green/orange

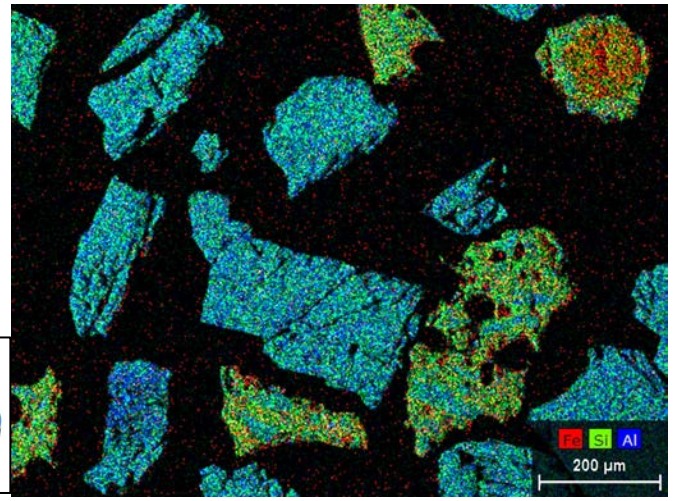
Exolith LHS-1



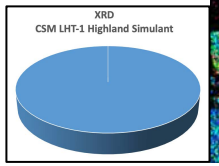


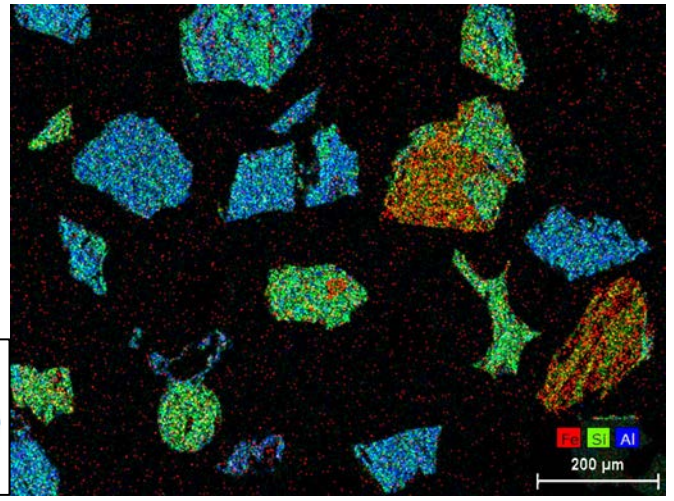
Off Planet Research OPRH3N





CSM LHT-1

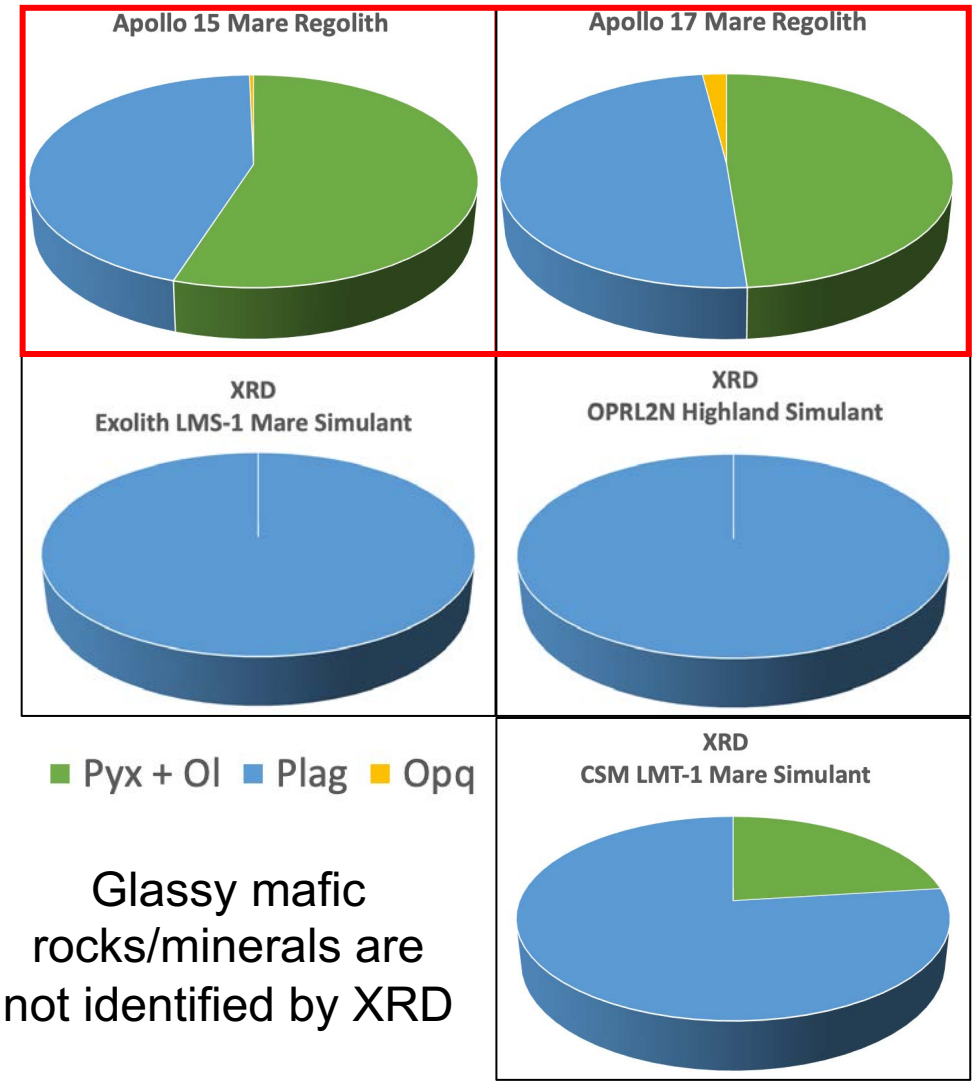




Composition: Mineralogy (Mare Simulants) - XRD

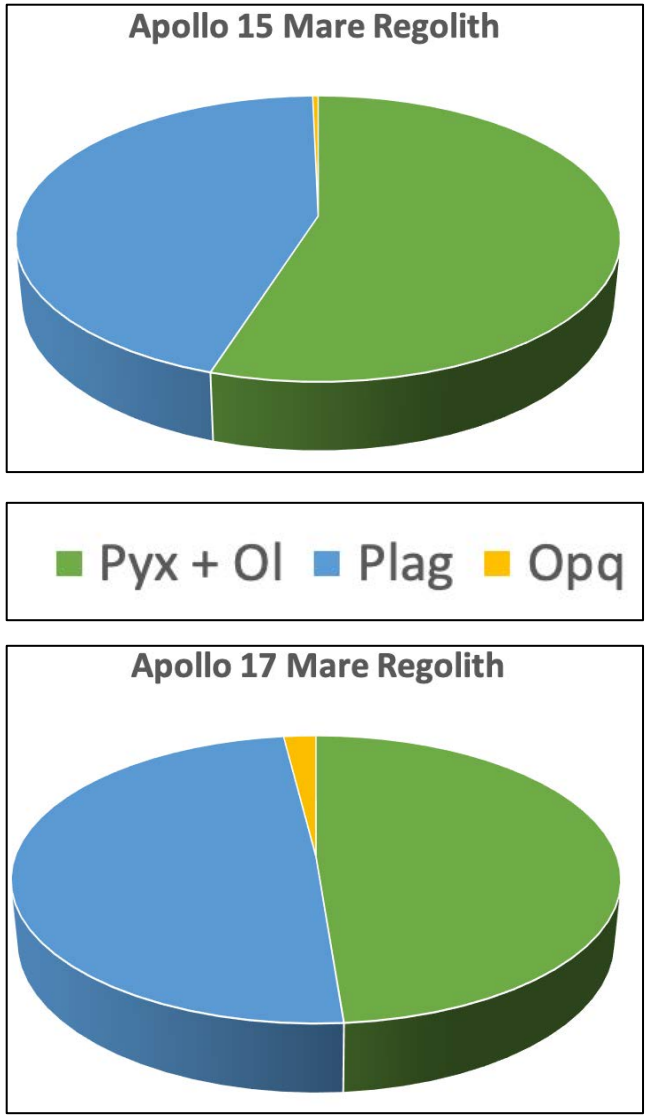
XRD semi-quantitative abundances of crystalline phases (vol %)				
Company	**Exolith**	**Off Planet Research**	**CO School of Mines**	**Outward Technology**
Simulant	**LMS-1**	**OPRL2N**	**LMT-1**	**LMA-1**
Type	Mare	Mare	Mare	Mare aggl
Plagioclase	100	100	77[1]	76[1]
Olivine	-	-	-	-
Pyroxene	-	-	23	24
Groutite	-	-	-	-

[1]Phase ID = Labradorite, (all other identified as anorthite).



Glassy mafic rocks/minerals are not identified by XRD

Composition: Mineralogy (Mare Simulants) - XRD

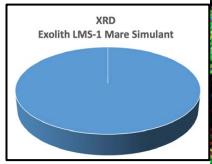


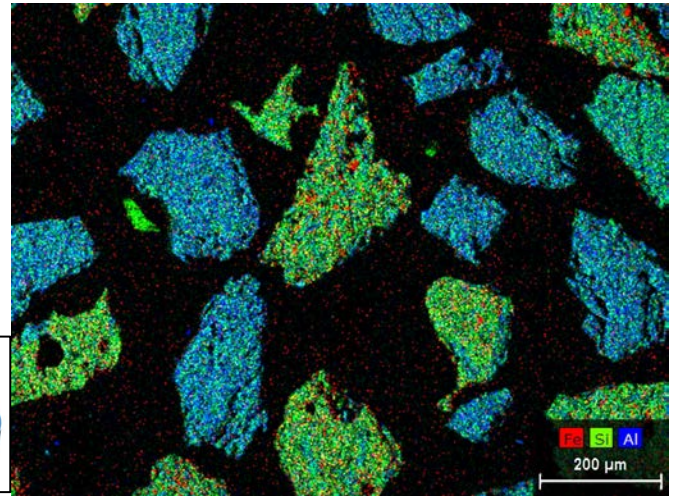
SEM Maps of
<u>125-250 μm split*</u>

R = Fe **G = Si** **B = Al**

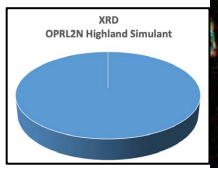
- Plagioclase = blues
- Ol/Pyx = green/orange

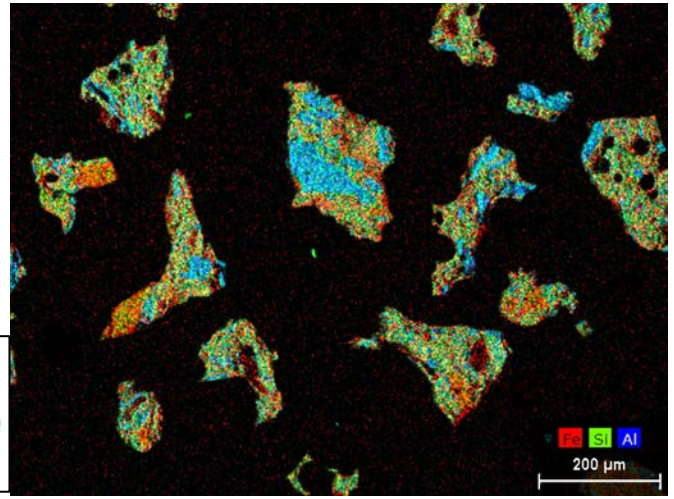
Exolith LMS-1



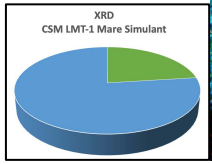


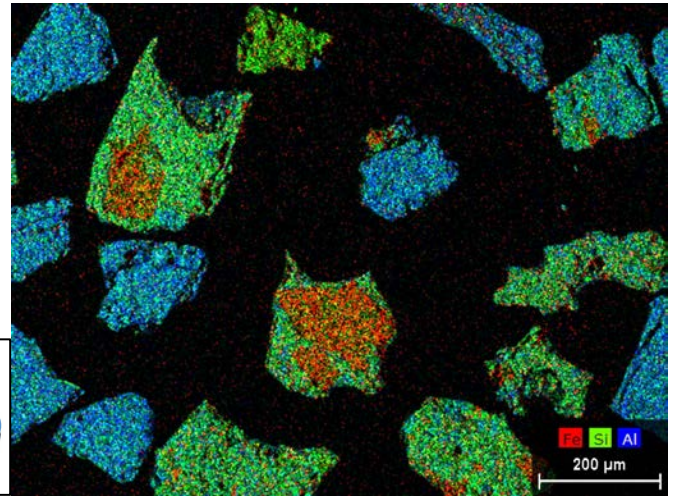
Off Planet Research OPRL2N





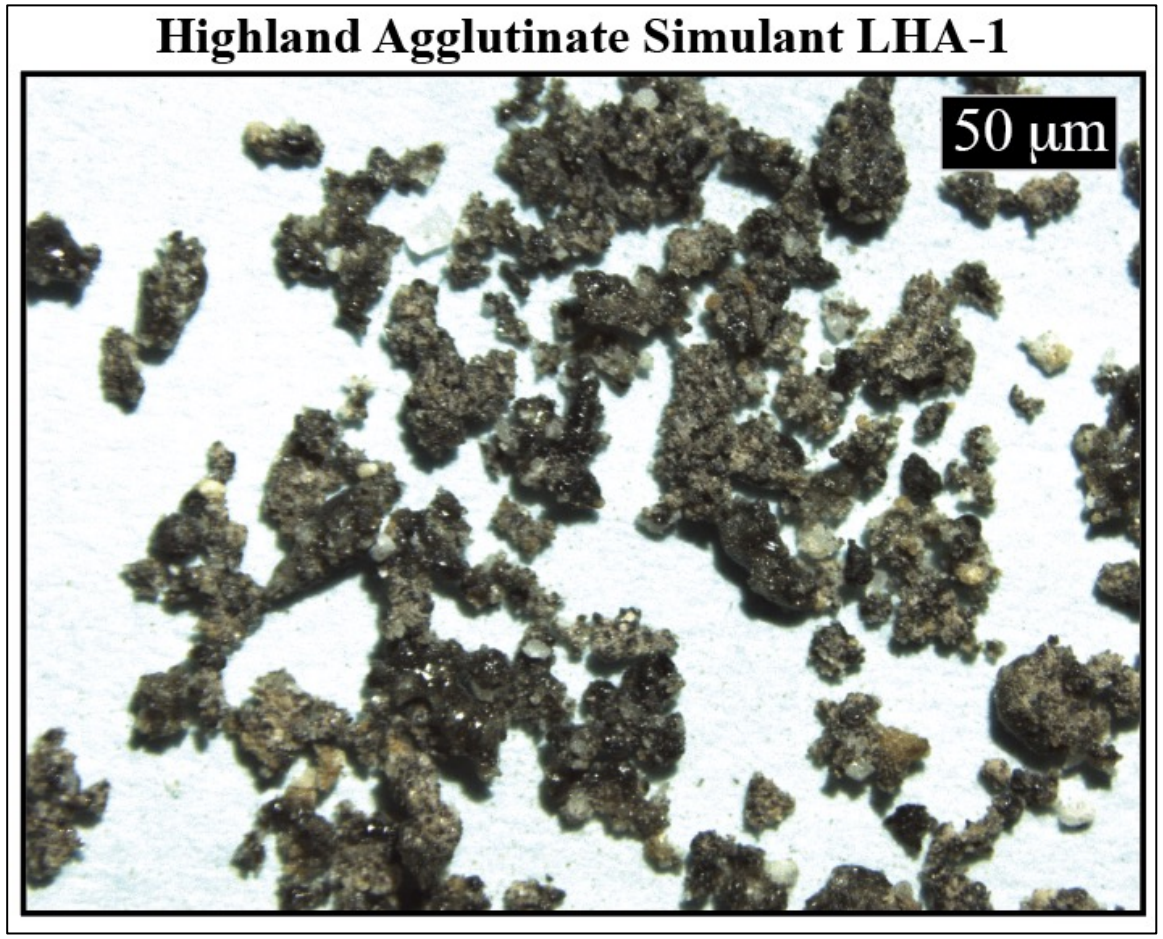
CSM LMT-1

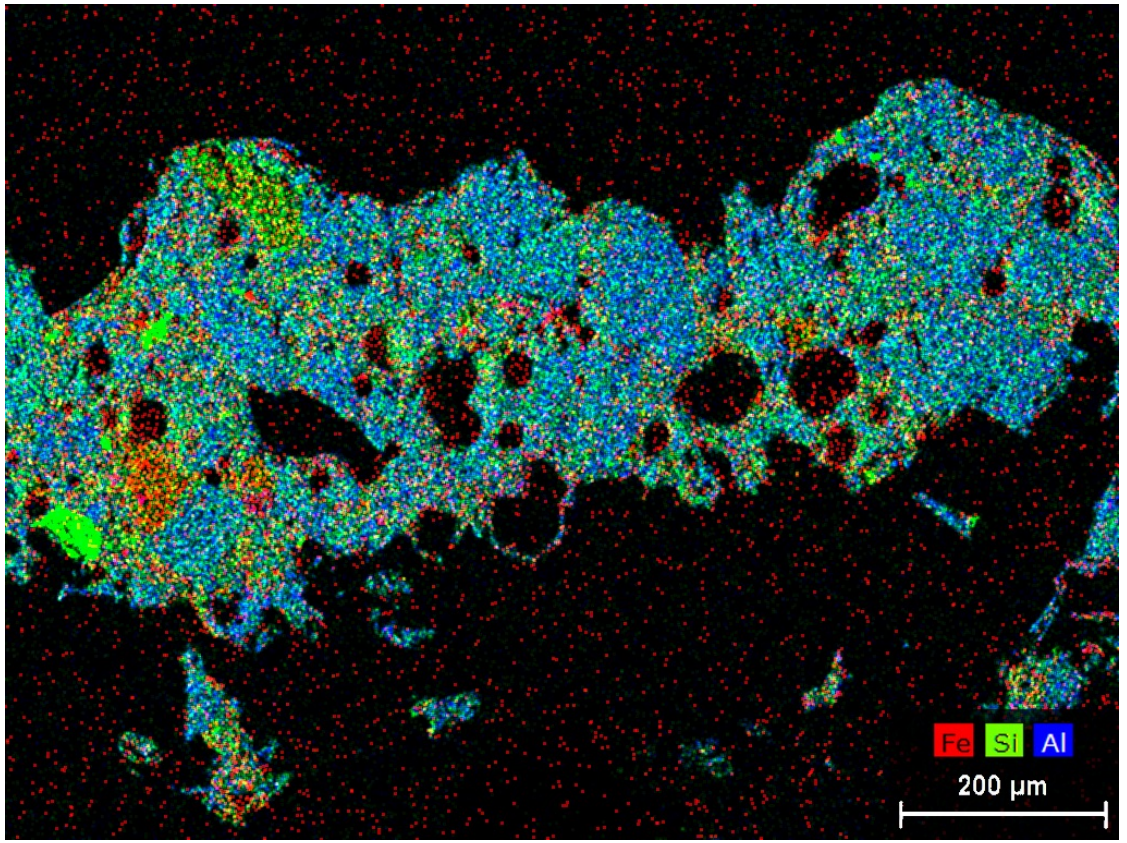




Pseudo-Agglutinates by Outward Technologies

- ***2021*** OT Highland Pseudo-Agglutinate Simulant

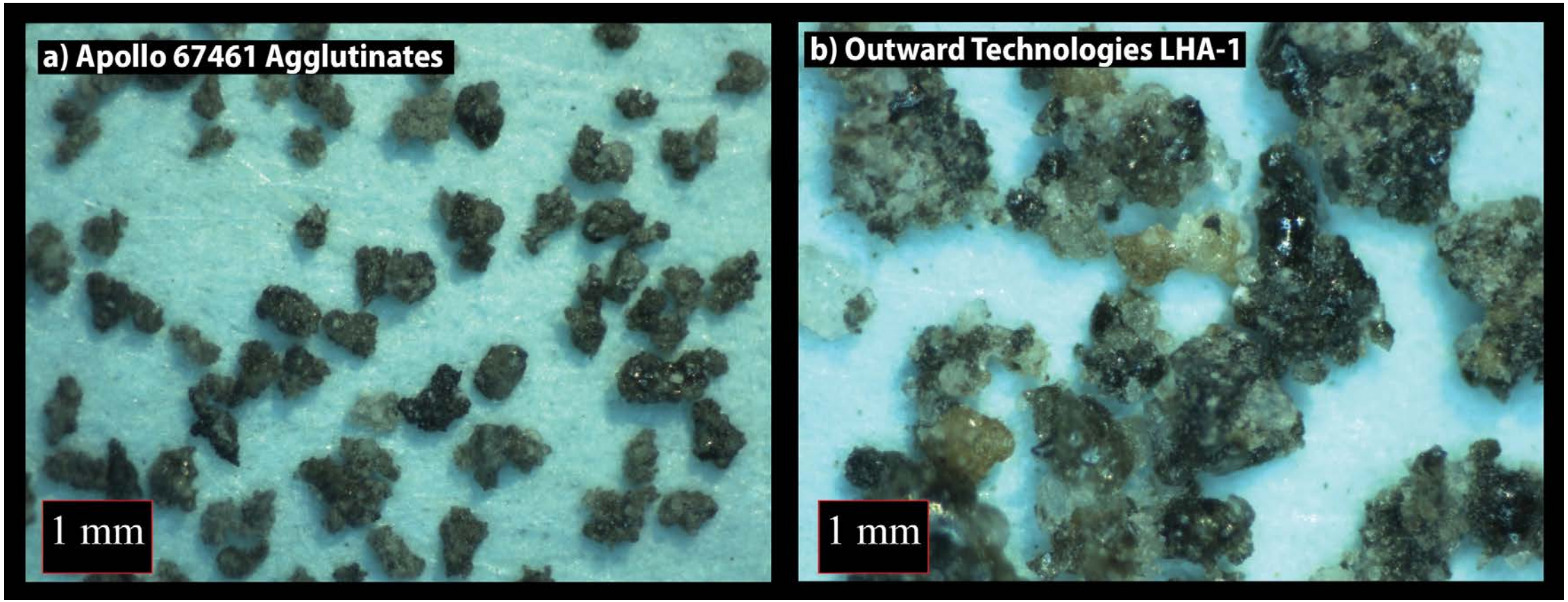




Comparison: Lunar Highland Pseudo-Agglutinate

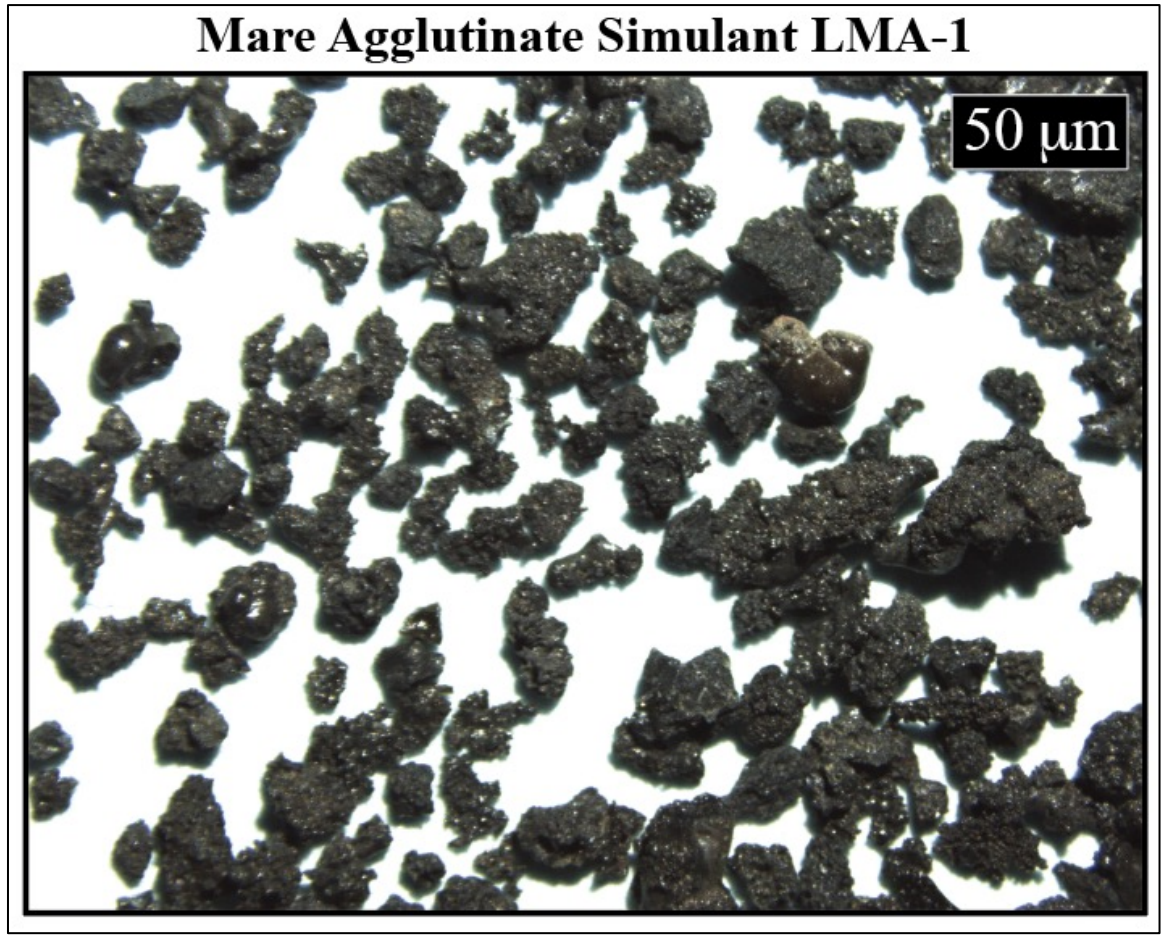
Apollo Regolith

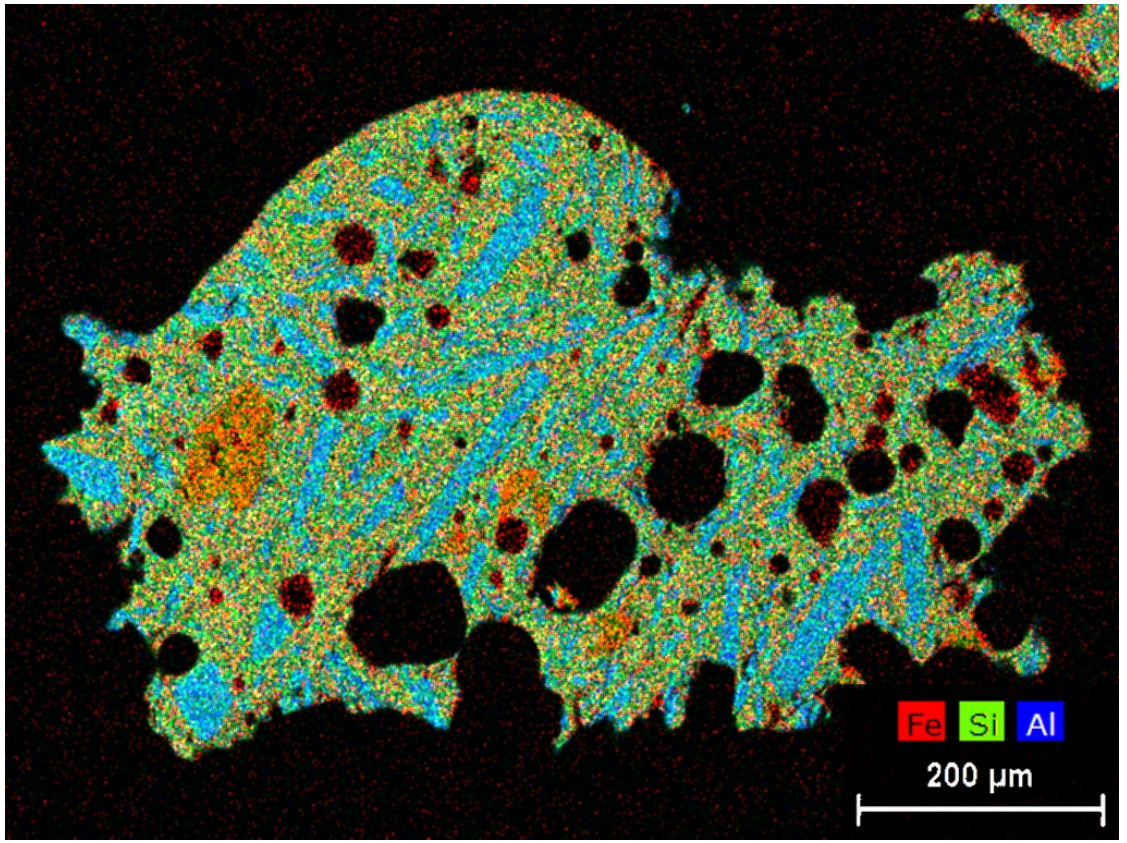
Outward Technologies Pseudo-Agglutinate



Pseudo-Agglutinates by Outward Technologies

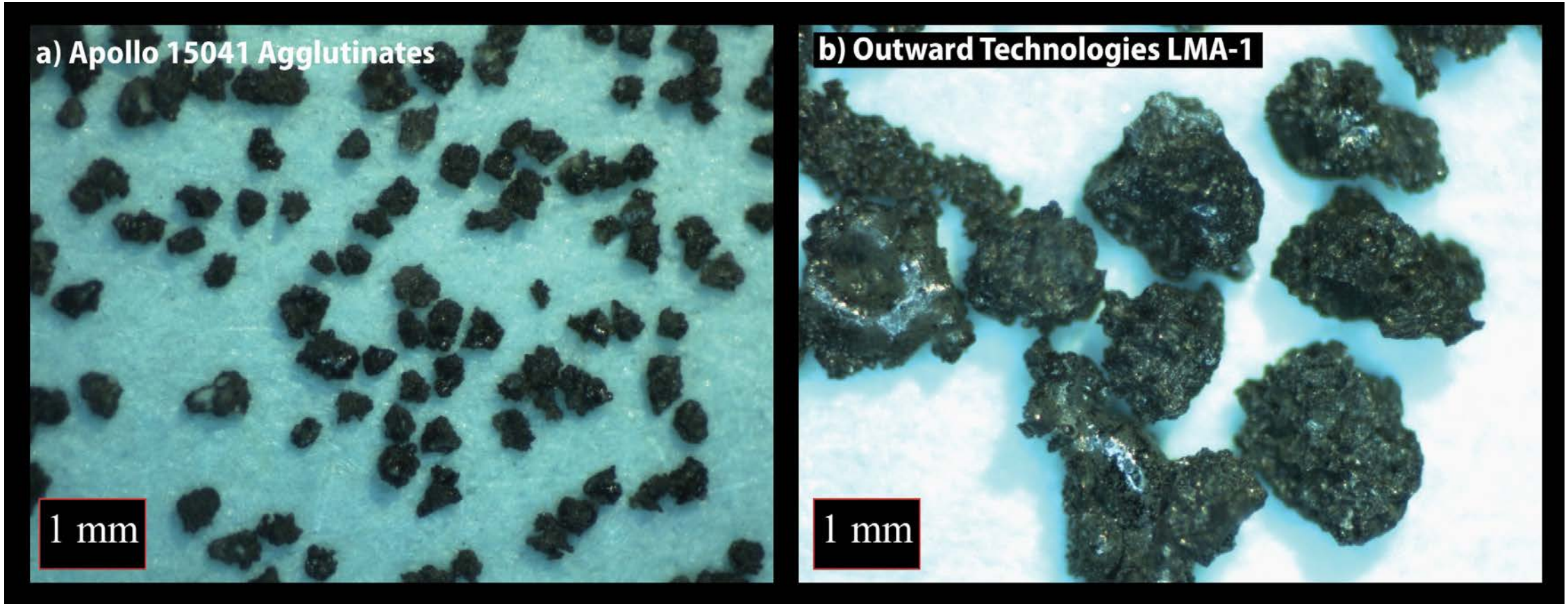
- ***2021*** OT Mare Pseudo-Agglutinate Simulant





Comparison: Lunar Mare Pseudo-Agglutinate

Apollo Regolith | **Outward Technologies Pseudo-Agglutinate**



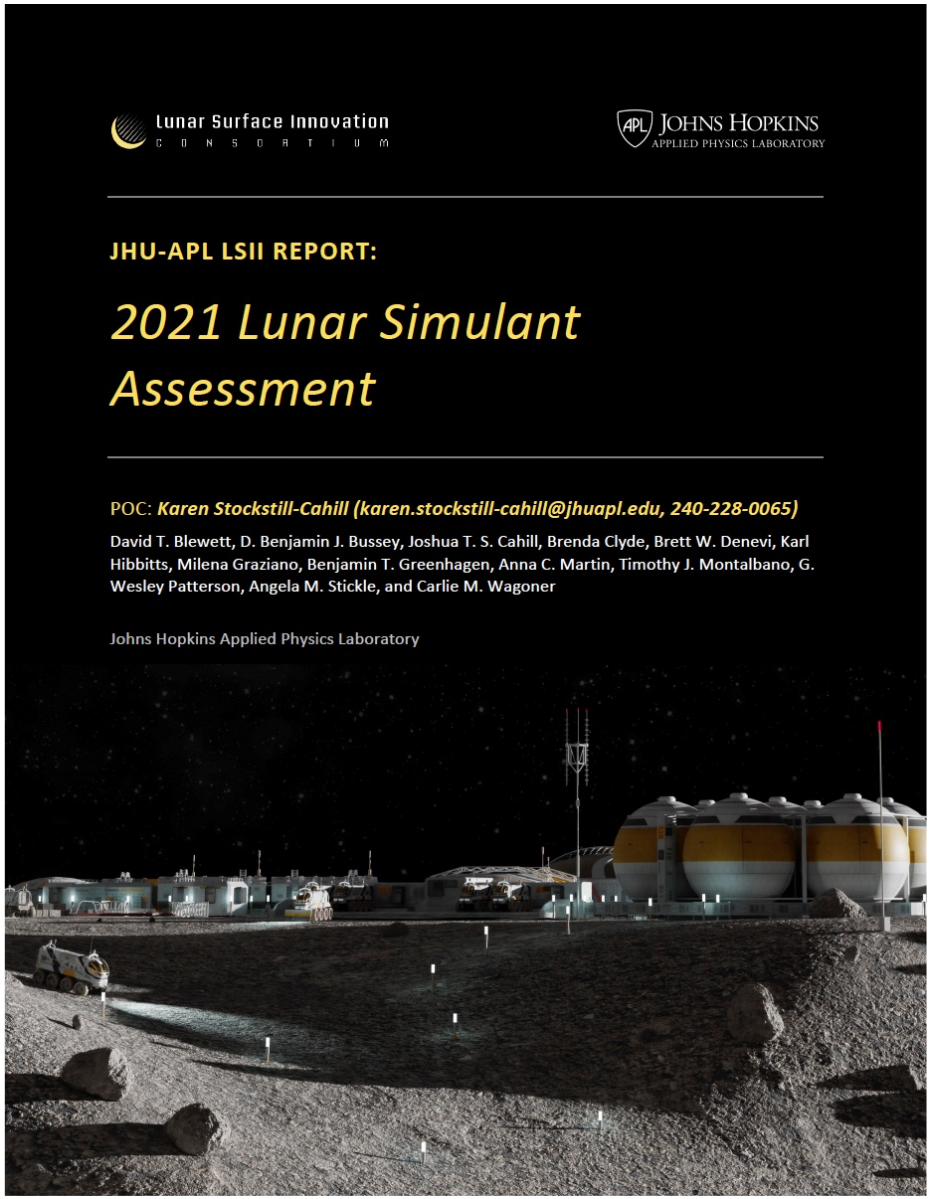
2021 Assessment Conclusions

- The evaluation and utility of a simulant is specific to its application
  - e.g., Melting/microwaving regolith requires high compositional fidelity
  - e.g., Material durability studies would require high fidelity in particle shape & size
- Regolith simulants and even lunar regolith do not necessarily behave in the same way on Earth as they would on the Moon
  - Solar wind implants volatiles on lunar surface (reactivity, cohesive forces, etc.)
  - Nanophase Fe^0 results in magnetic properties in lunar regolith
  - Lower confining stresses at lunar surface
- Lunar regolith simulants from current simulant providers could meet the needs of most users
  - You can add components – including synthetic materials – to increase fidelity in appropriate areas
- For advanced (high TRL) testing related to ISRU needs, it may be wise to compare results using a simulant with and without pseudo-agglutinates, and potentially even a lunar soil (in the lab or on the lunar surface).

Downloadable Assessment doc

- Confluence: https://lsic-wiki.jhuapl.edu
  - **Lunar Simulants Working Group**
  - LSWG Resource Library -> Recent Simulant Assessments
    - Scroll to the bottom of the Page

- Public webpage: https://lsic.jhuapl.edu
  - **Resources -> Lunar Simulants**
  - Click on Assessments and Databases tab
    - Click on the 2021 Lunar Simulant Assessment




Lunar Surface Innovation
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