Manufacturing High-Fidelity Lunar Agglutinate Simulants

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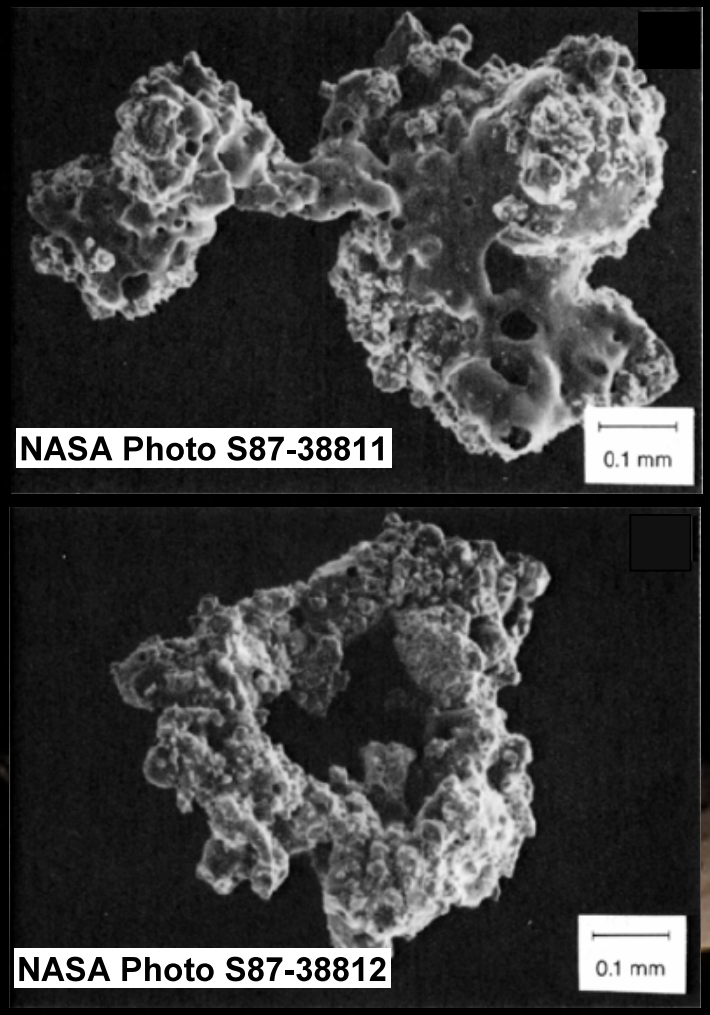
Lunar Regolith Properties

- The lunar regolith is very different than any naturally occurring material on Earth due to the unique, impact-dominated environment on the surface of the Moon
- Lunar regolith is composed of five basic particle types
  - Mineral fragments
  - Crystalline rock fragments
  - Breccia fragments
  - Glasses of various kinds
  - Agglutinates
- Agglutinates are abundant in the lunar regolith, especially in mature regolith where they can constitute up to 65% of the regolith by volume (Heiken at al., 1991)
- Due to the abundance of agglutinates in the lunar regolith and their unique characteristics, several organizations have been attempting to create simulated agglutinate particles

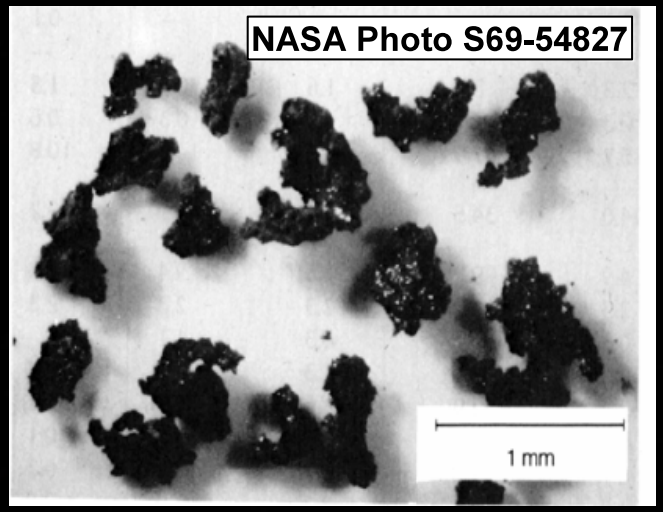
Properties of Lunar Agglutinates

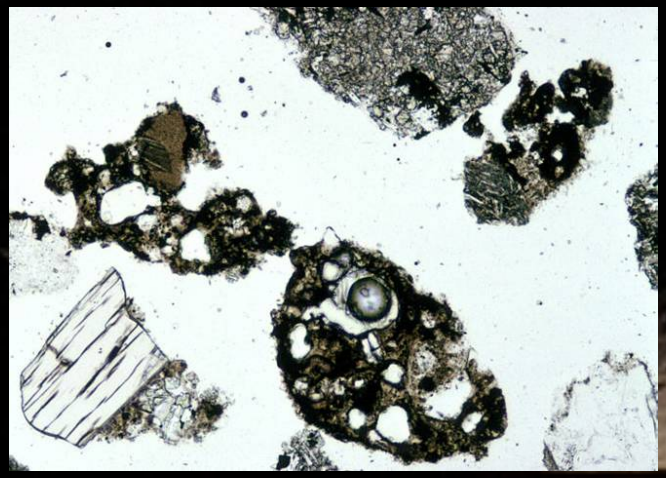


Images of lunar agglutinates

- Agglutinates are individual particles that are aggregates of smaller lunar soil particles (mineral grains, glasses, and even older agglutinates) bonded together by vesicular, flow-banded glass (Heiken at al, 1991)
  - A highly irregular shape (often with branching morphologies)
  - Heterogeneous composition (due to the presence of individual soil particles)
  - Vesicles present in the glass
  - Contains numerous metallic iron (Fe^0) globules ranging from ~3 nm – 1µm
  - Overall size of less than a few mm

Effects of Lunar Agglutinates

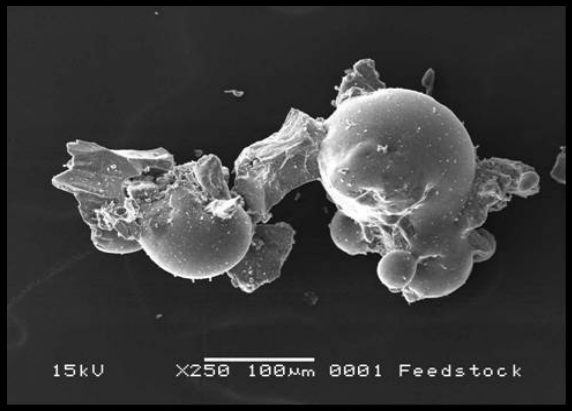


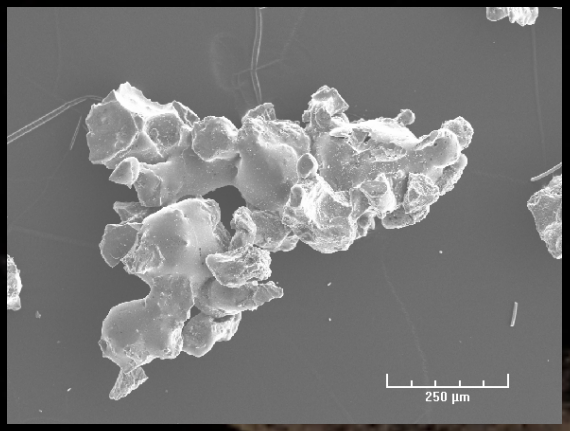


Lunar sample 68501,94 (image courtesy of Kurt Hollocher, Union College)

- The interaction of agglutinates increases the resistance shear and decreases the flowability of lunar regolith
- The mechanical properties of lunar regolith change with loading due to crushing of agglutinates
- The presence of the small metallic iron globules in the agglutinitic glass is believed by some to affect the absorption of microwave energy, the magnetic susceptibility, and the electrostatic properties of the lunar regolith

Manufacturing Simulated Agglutinates





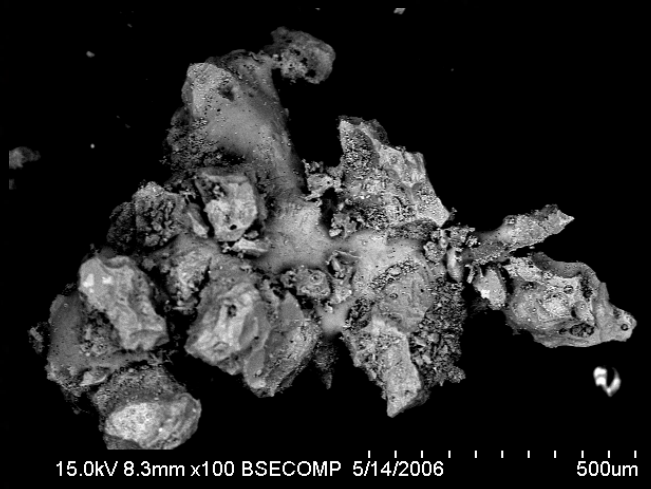
Images of ORBITEC simulated agglutinates

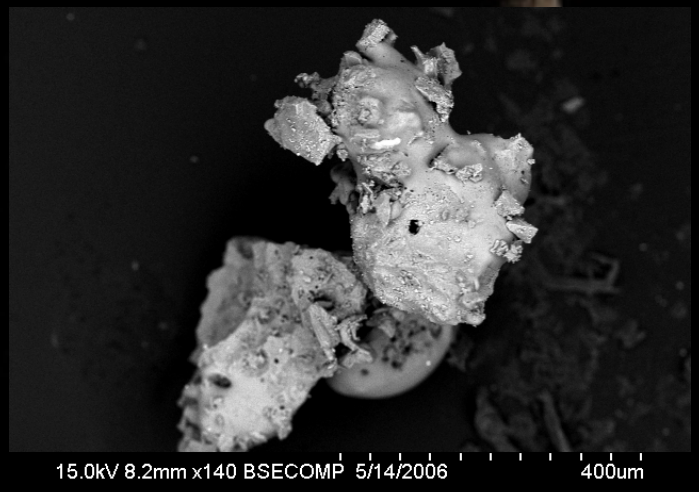
- Over the past 25 years, many organizations have attempted to manufacture particles that match the unique properties of lunar agglutinates
- Several groups have been successful in creating material that matches some properties of the lunar agglutinates, but development of a manufacturing process to create simulated agglutinates that match all of the primary characteristics of lunar agglutinates has been elusive
- ORBITEC, with the support of NASA, has been developing processes to manufacture high-fidelity agglutinate simulants since 2005

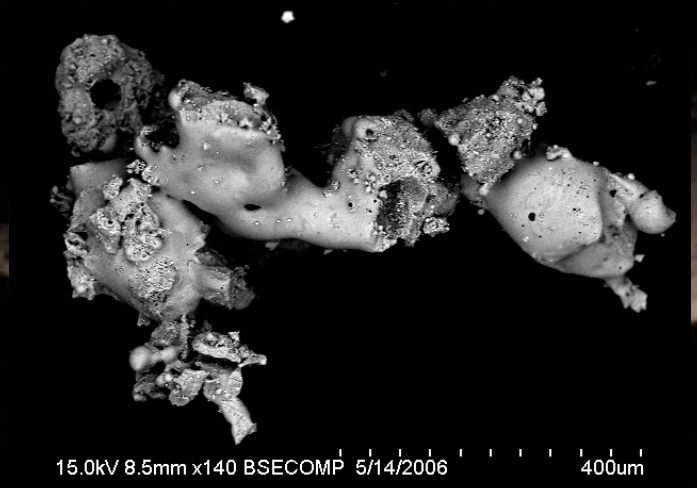
High-Fidelity Simulated Agglutinate Requirements

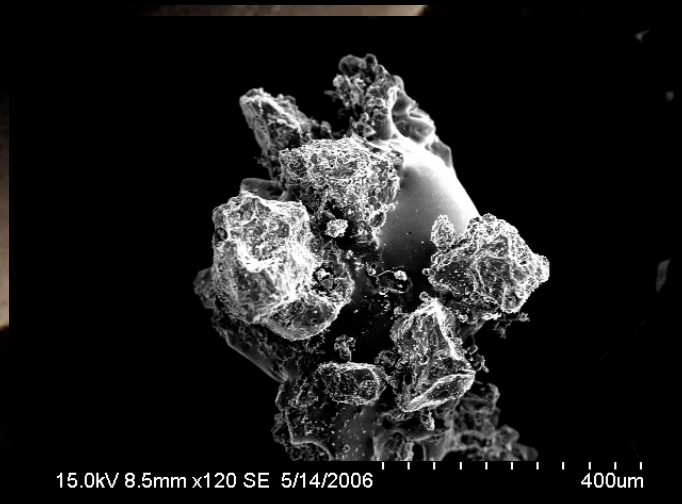
- Heterogeneous composition (mixture of glass and smaller regolith particles)
- A highly irregular shape (often with branching morphologies)
- Overall size of less than a few mm
- Vesicles present in the glass
- Numerous Fe^0 globules ranging from ~3 nm – 1µm both on and within the glass

Heterogeneous Composition of Simulated Agglutinates









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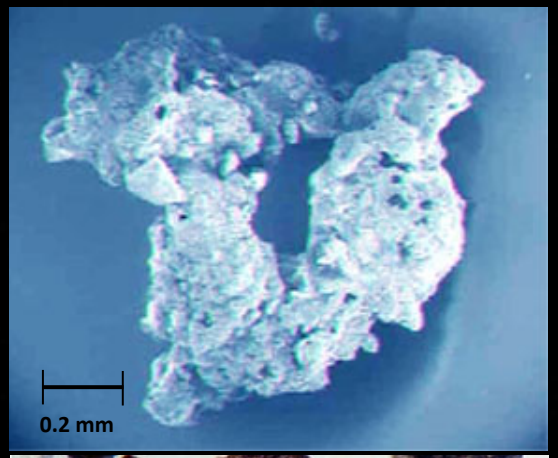
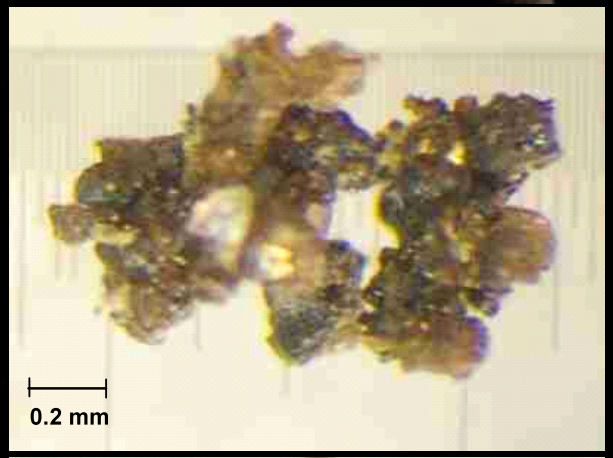
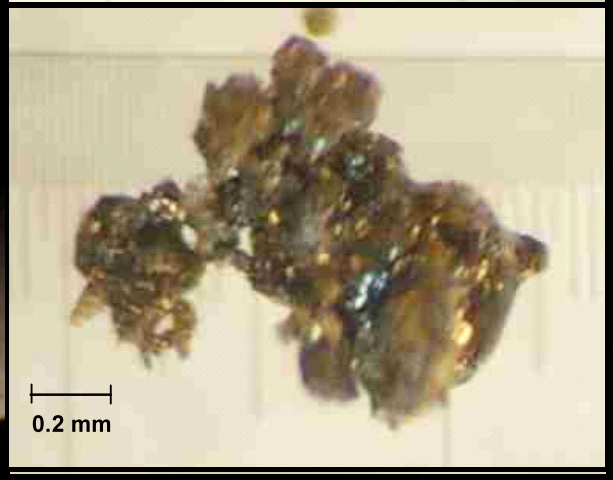
Comparison of the Shape and Size

1-mm Lunar Agglutinate (courtesy of Dave McKay, NASA Johnson Space Center)



Lunar Agglutinates in Highlands Regolith (courtesy of Kurt Hollocher, Union College)





ORBITEC Simulated Agglutinate Particles (produced from JSC-1A simulant)

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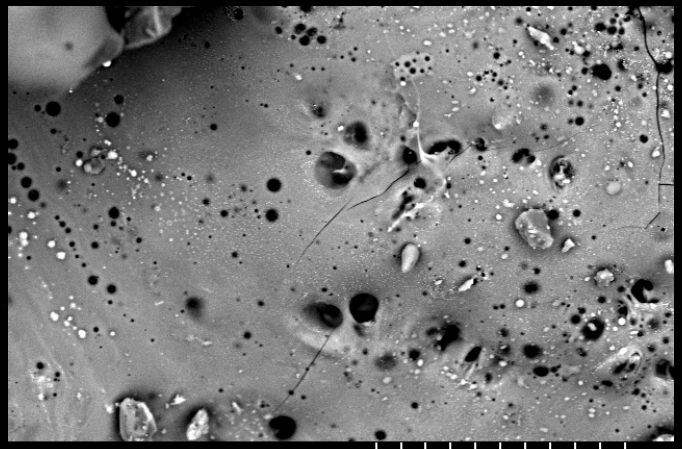
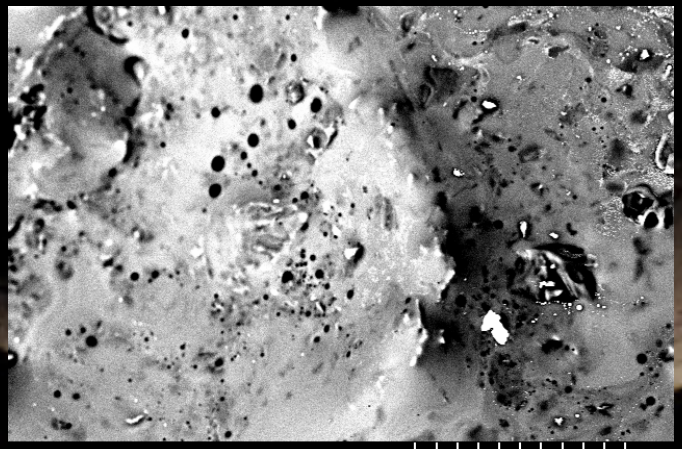
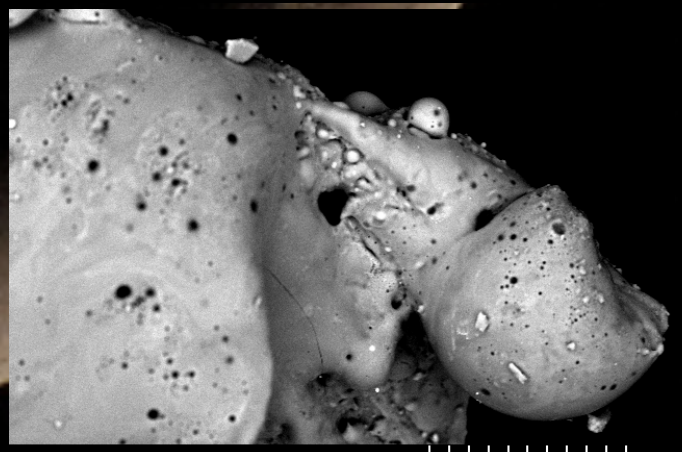
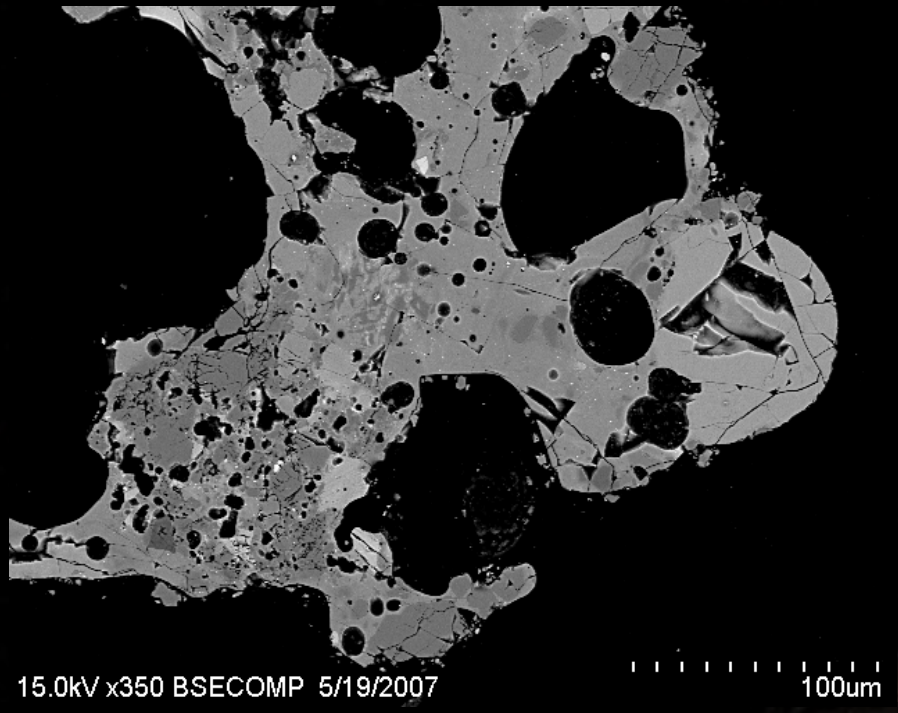
Vesicular Glass in Simulated Agglutinates



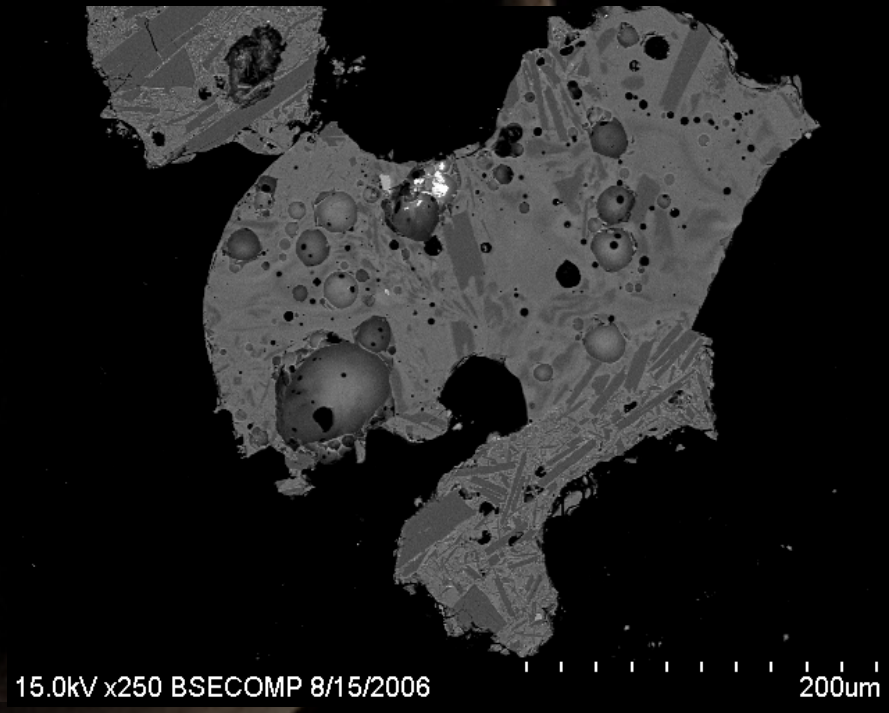




Comparison of the Internal Structure

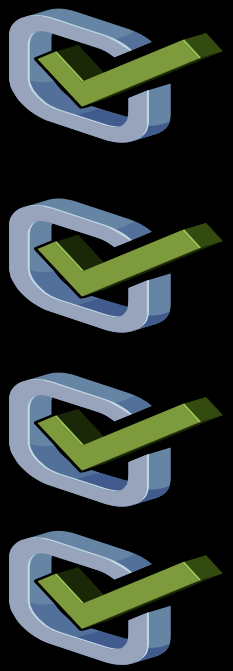


Lunar Agglutinate Thin Section
(Apollo Sample 15103)



Simulated Agglutinate Cross Section

High-Fidelity Simulated Agglutinate Requirements



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- Vesicles present in the glass
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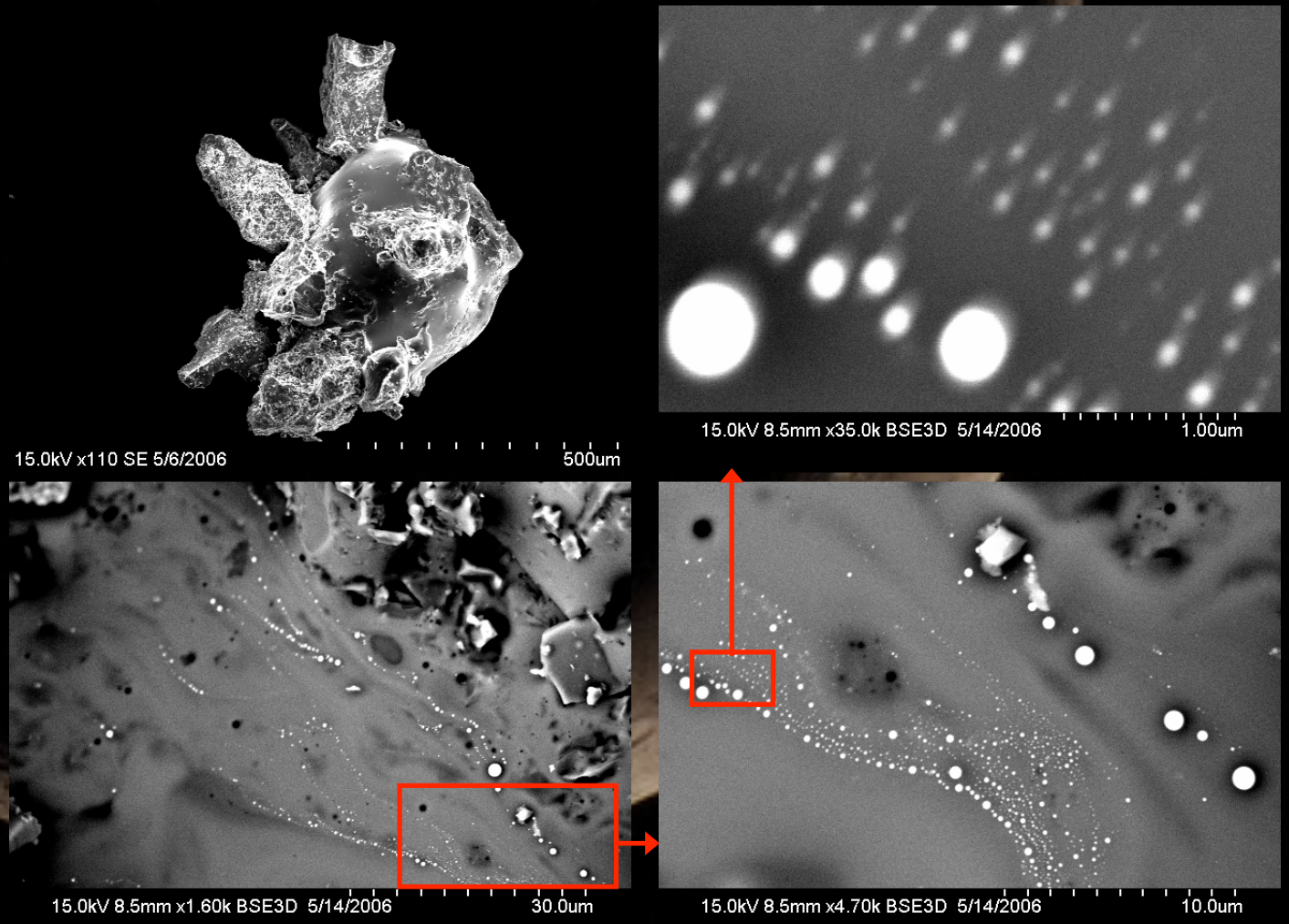
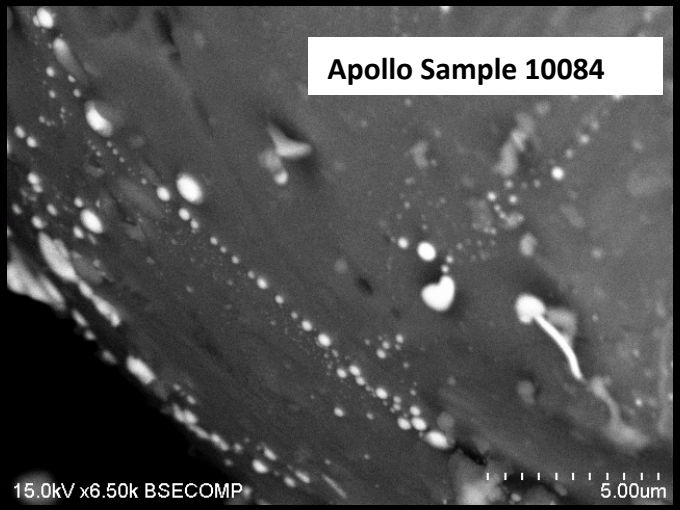
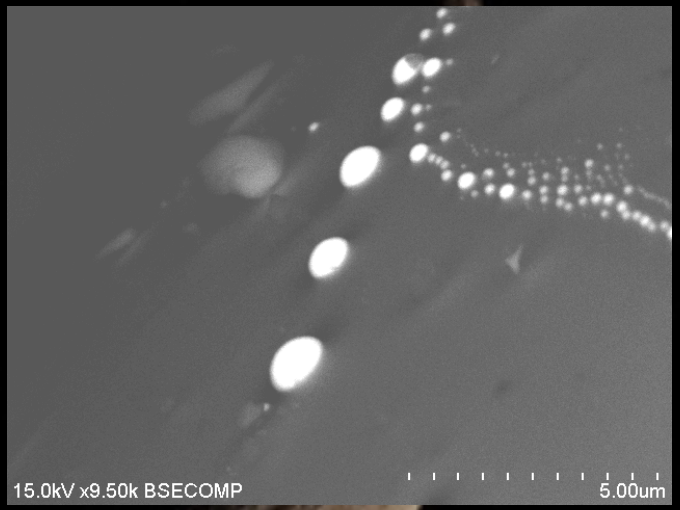
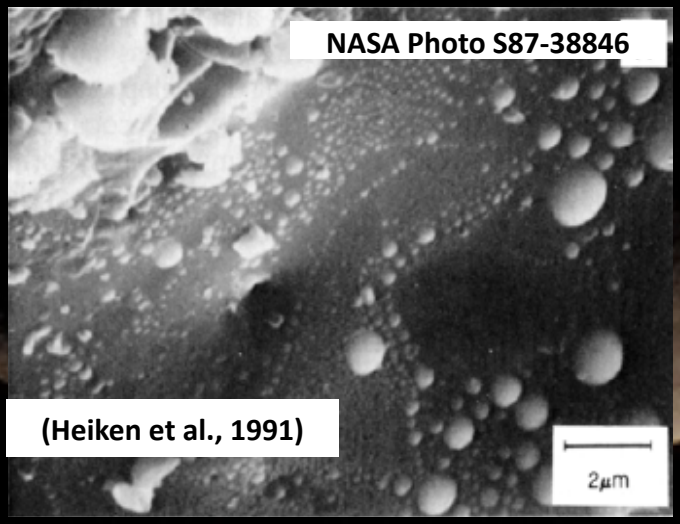
Iron Globules on a Simulated Agglutinate

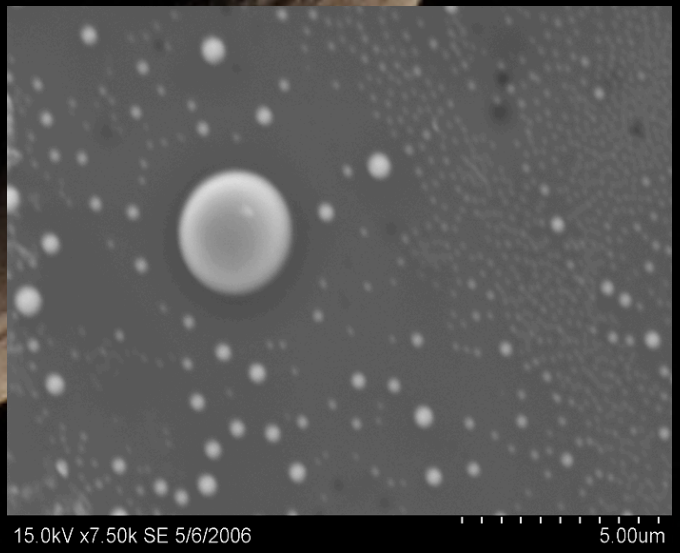


Comparison of the Surface Iron Globules





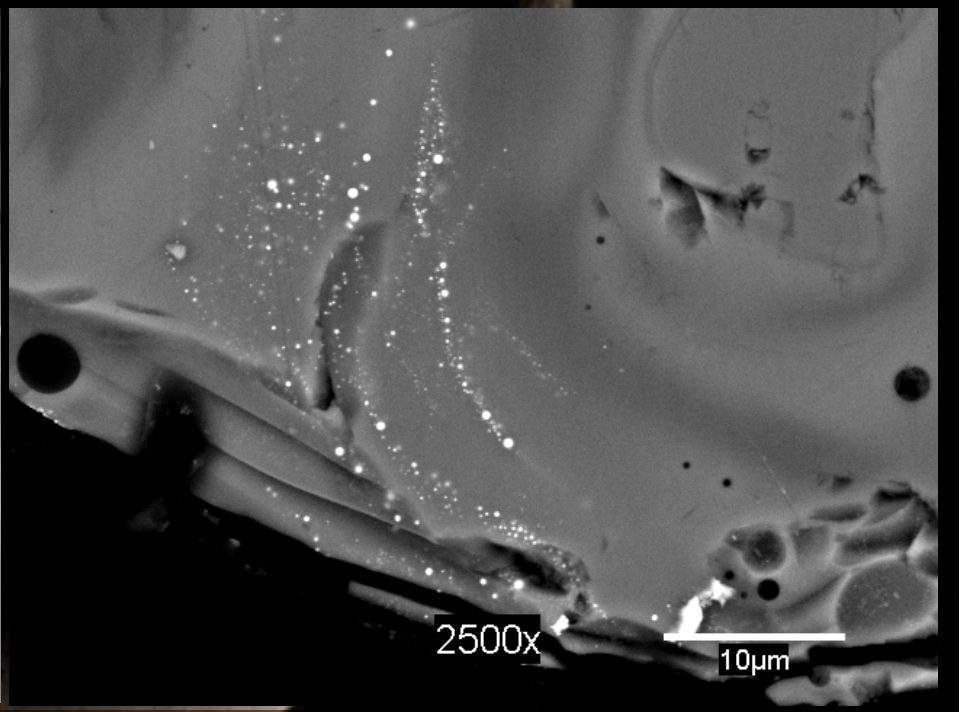




Lunar Agglutinates

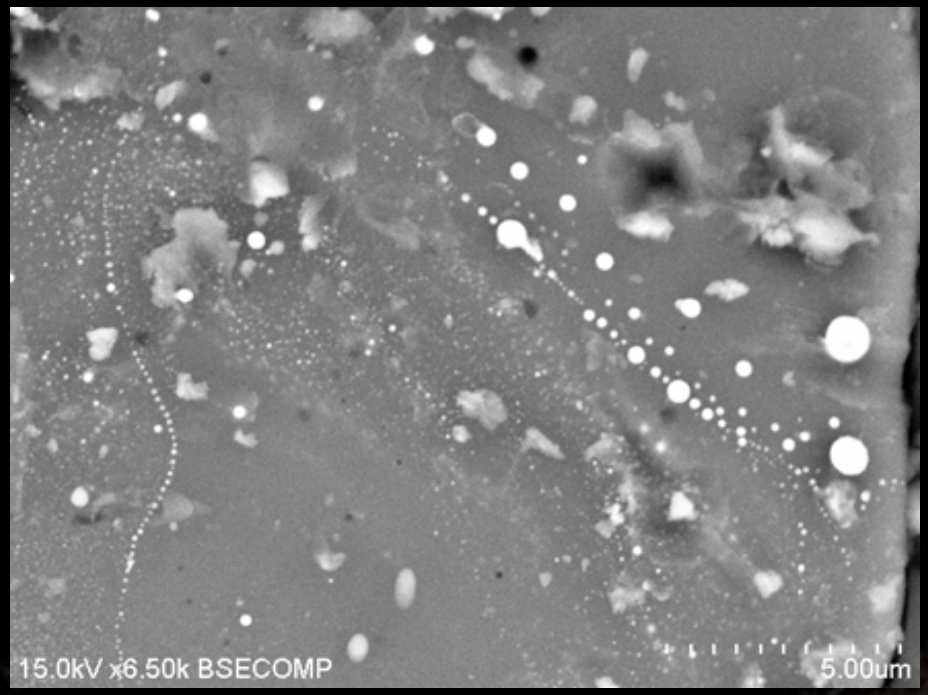
Simulated Agglutinates

Iron Globules Within Simulated Agglutinates

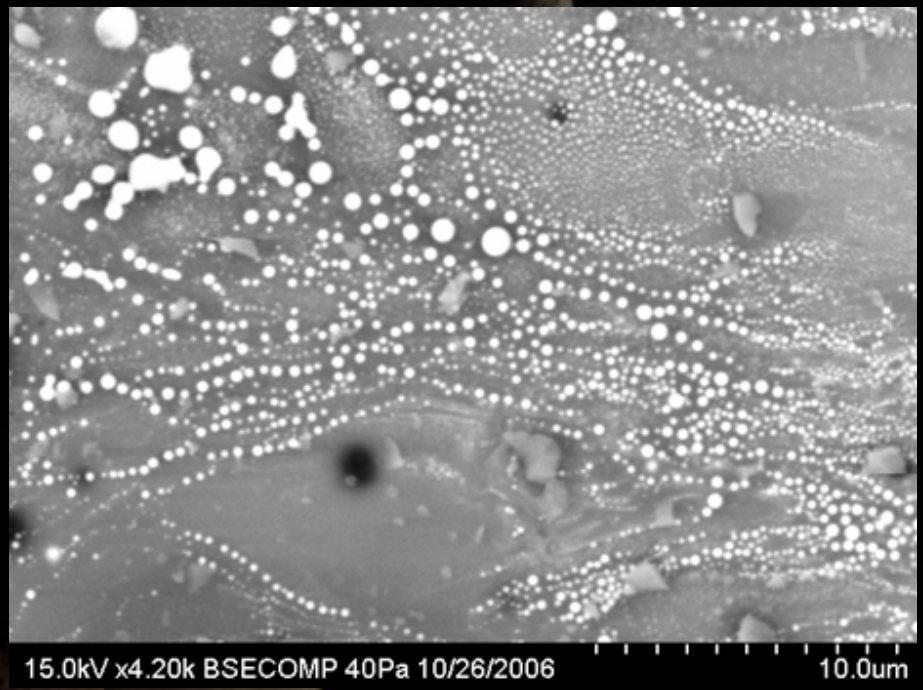


Cross Sections of ORBITEC Simulated Agglutinates

Comparison of Iron Globule Size Distribution

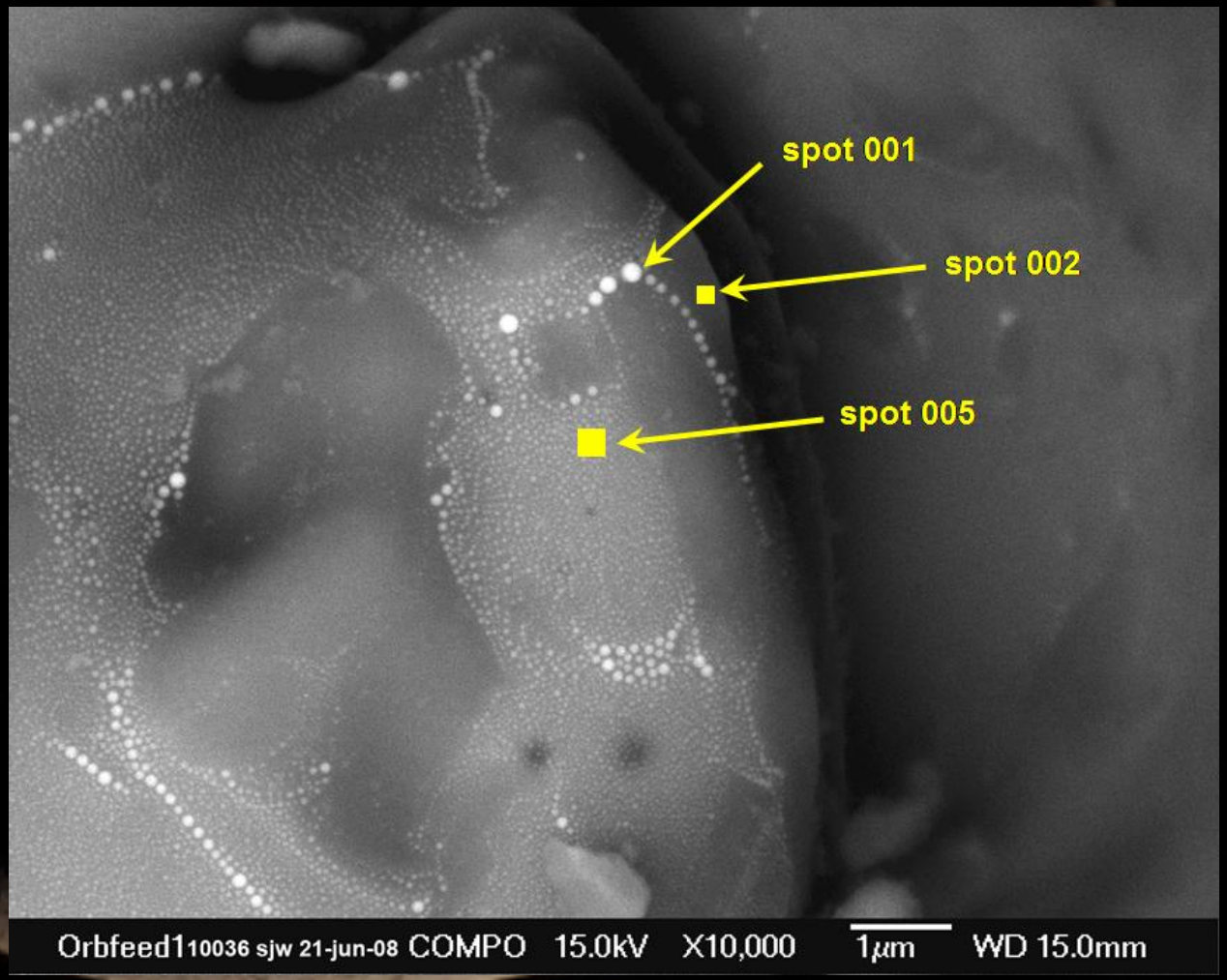


Lunar Agglutinate Particle
(Apollo Sample 10084)



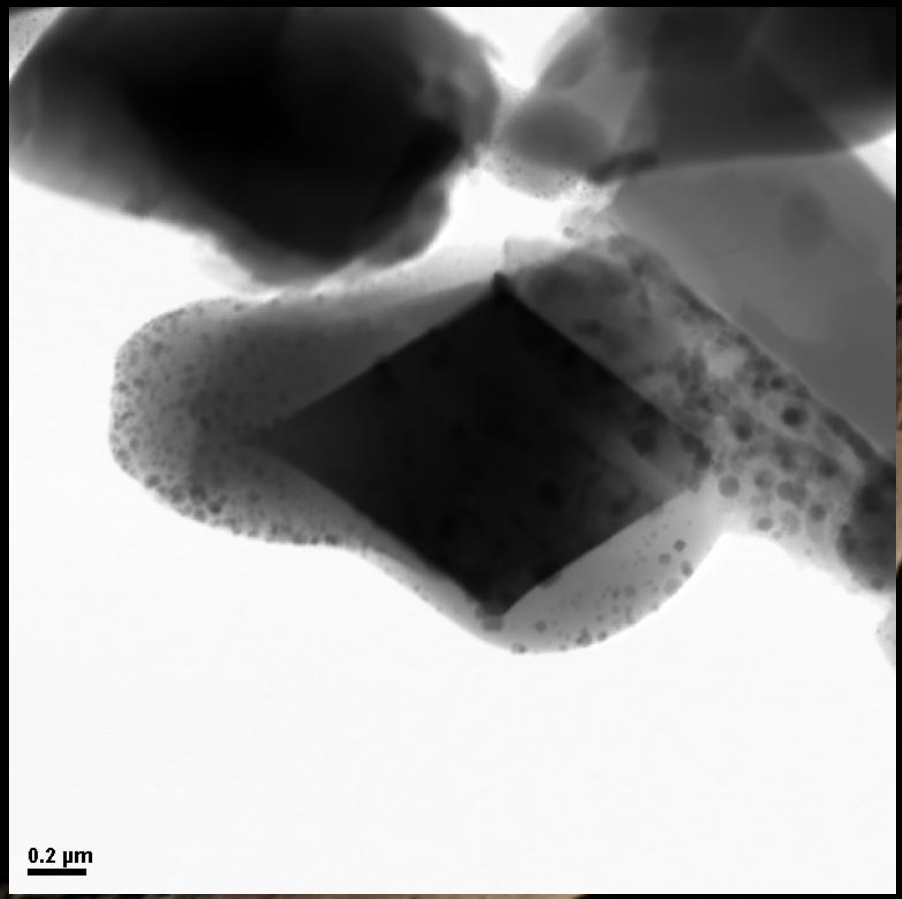
Simulated Agglutinate Particle

Iron Globules on a Simulated Agglutinate



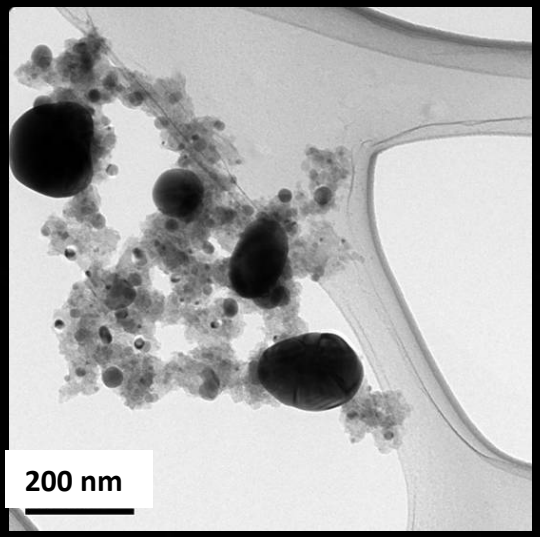
Fe-SEM Image of the Numerous Iron Globules on a Simulated Agglutinate
[Image courtesy of the NASA Johnson Space Center]
(iron globules from ~20 nm – 200 nm visible)

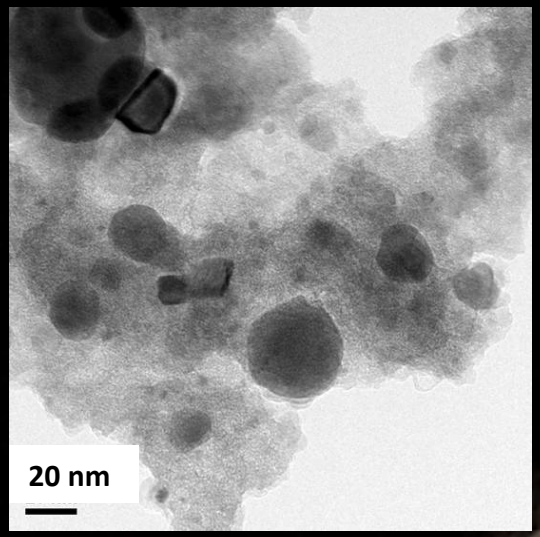
Evidence of Nanophase Fe^0

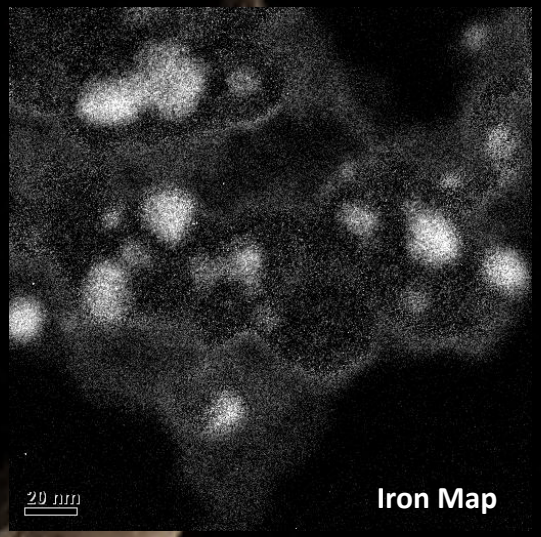


STEM bright-field image of an euhedral Fe-oxide crystal (residual from the JSC-1A simulant) enclosed in silicate glass with nanophase globules created by the ORBITEC process. EDS analyses indicate nanophase globules are primarily Fe^0.
[Image courtesy of the NASA Johnson Space Center]

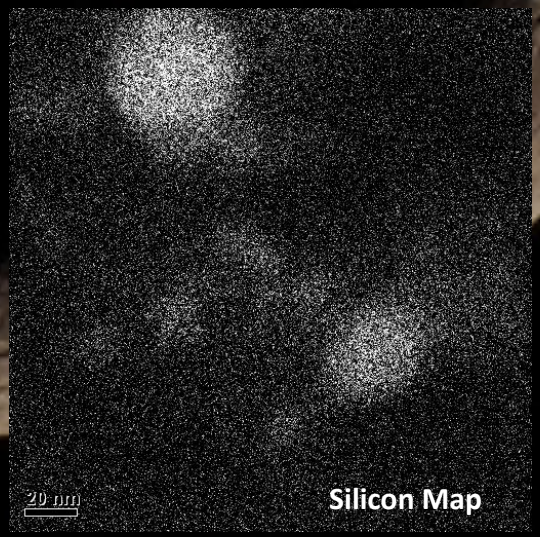
TEM Analysis of a Simulated Agglutinate

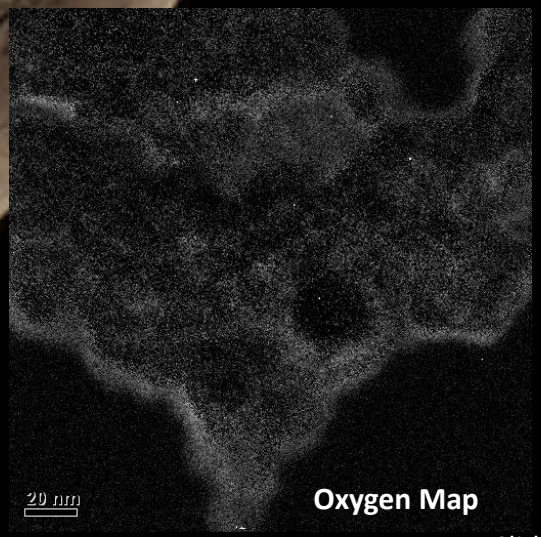






Gatan image filter (GIF) maps using electron energy loss spectroscopy.





(Images courtesy of the NASA Glenn Research Center)

Verification of the Iron Globule Composition

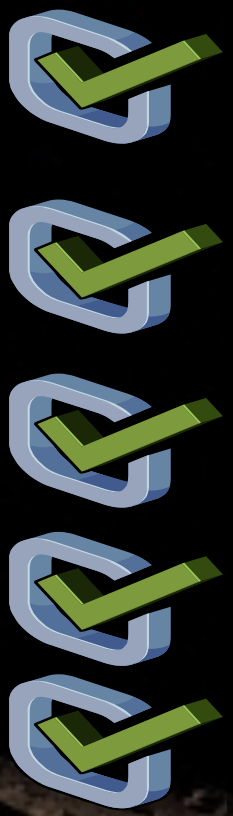
- Energy dispersive spectrometry (EDS) and wavelength dispersive spectrometry (WDS) performed at the University of Wisconsin-Madison indicate the larger iron globules (~1 μm) in both lunar agglutinates and the ORBITEC simulated agglutinates are Fe^0, not iron oxide
- Electron energy loss spectroscopy (EELS) performed by the NASA Glenn Research Center indicates that iron globules <20 nm do not contain any significant amounts of oxygen
- SEM and STEM analyses by the NASA Johnson Space Center indicate iron globules as small as 5 nm exist and contain primarily Fe^0
- Plasma Processes Inc. recently reported an analogous process created nanophase-sized globules of Fe^0 within a glass matrix as verified by EDS and electron diffraction analyses (Sen et al., 2010)

Immiscibility of Fe^0 in Molten Regolith

- Metallic iron that exists in molten regolith is immiscible, so some of the globules of coalesce and form larger globules
- This mechanism allows ORBITEC to produce a wide range in the sizes of iron globules like those observed in lunar agglutinates
- This mechanism also explains why all of the iron globules present in the simulated agglutinates must have the same composition (Fe^0)
- ORBITEC has visually recorded the coalescence of Fe^0 globules in molten regolith simulant during recent carbothermal reduction experiments
- Although this is a very different process than the one used to create the simulated agglutinates, it does illustrate the behavior of Fe^0 in molten regolith

Immiscibility of Fe^0 in Molten Regolith

High-Fidelity Simulated Agglutinate Requirements



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Conclusions

- ORBITEC, with the support of NASA, has developed a process to manufacture simulated agglutinates that match the key features of lunar agglutinates
  - Vesicular glass bonding unmelted grains
  - Size and shape typical of lunar agglutinates
  - Numerous globules of Fe^0 ranging in size from ~3 nm – 1µm
- Since the finest fraction of the lunar regolith is 70-90% broken pieces of agglutinates, the ability to manufacture simulated agglutinates also allows high-fidelity lunar dust simulants to be developed

Acknowledgements

- The work reported here was supported by NASA under the SBIR program through the Marshall Space Flight Center and the NASA Glenn Research Center
- Unless otherwise credited, the SEM images of the ORBITEC simulated agglutinates were courtesy of Dr. John Fournelle, University of Wisconsin-Madison

References

Heiken, G., D. Vaniman, and B. French (eds). (1991) *Lunar Sourcebook- A User's Guide to the Moon.* Cambridge: Cambridge University Press.

S. Sen, D. Butts, J. O'Dell, and C. Ray. (2010) "Plasma Processing of Lunar Regolith Simulant for Oxygen and Glass Production." Earth & Space 2010, American Society of Civil Engineers, March 14-17, Honolulu, HI.