# Development of High-Fidelity Lunar Regolith Simulants with Agglutinates

**Robert Gustafson[1], Brant White[1], Marty Gustafson[2], and Dr. John Fournelle[3]**

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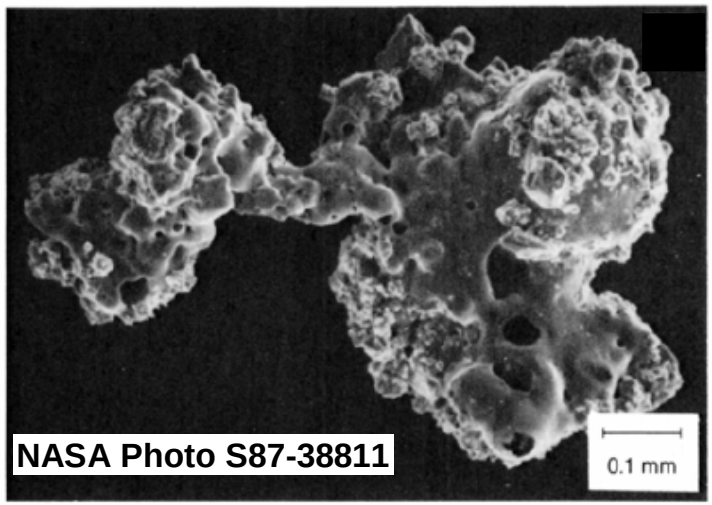
[1]Orbital Technologies Corporation
[2]PLANET LLC
Space Center, 1212 Fourier Drive
Madison, WI 53717
(608) 229-2725, (608) 827-5050 *fax*
http://www.orbitec.com

[3]Department of Geology, University of Wisconsin-Madison

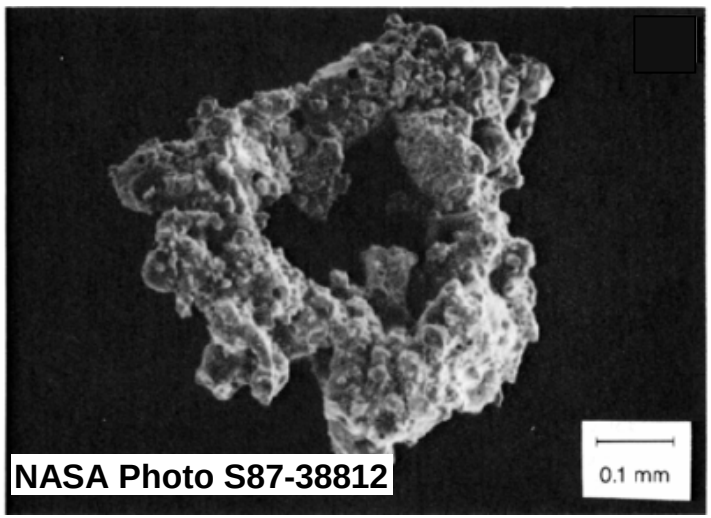
# High-Fidelity Lunar Regolith Simulant

- The lunar regolith is very different than any naturally occurring material on Earth due to the unique formation processes of disaggregation and agglutination
- 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 soil, especially in mature regolith where they constitute up to 65% of the regolith by volume.
- A high-fidelity lunar regolith simulant must contain particles that mimic the unique properties of lunar agglutinates
- ORBITEC has developed a process to create agglutinate-like particles within a variety of materials, including JSC-1A lunar regolith simulant

# Unique Properties of Lunar Agglutinates




NASA Photo S87-38811




NASA Photo S87-38812

(Heiken et al., 1991)

- 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.
- A highly irregular shape (often with branching morphologies)
- Heterogeneous composition (due to the presence of individual soil particles)
- Presence of trapped bubbles of solar wind gases (primarily hydrogen) that are released when the agglutinates are crushed
- The presence of very small iron metal droplets or globules (sometimes referred to as “nanophase” iron) in the agglutinitic glass

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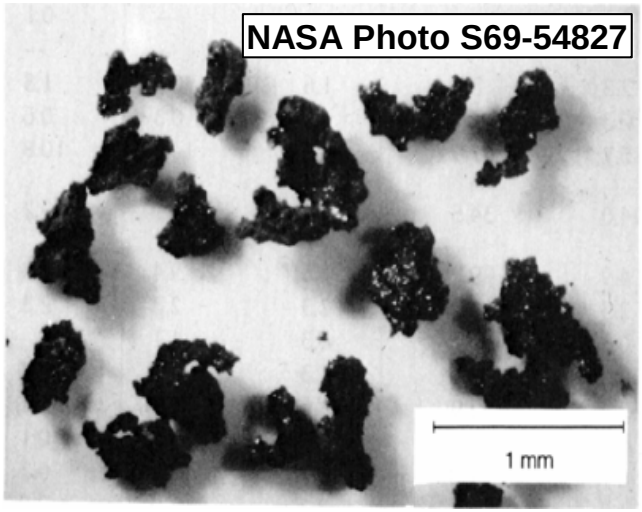
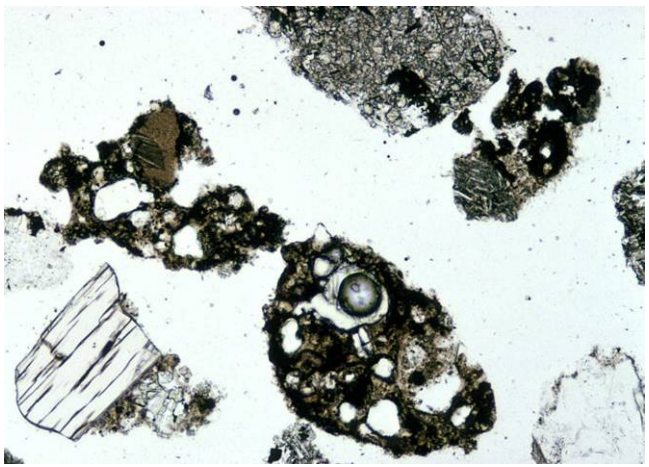
# Need for High-Fidelity Simulants with Agglutinates



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

- The unique properties of lunar agglutinates significantly affects the mechanical behavior and other thermo-physical properties of the simulant
  - The agglutinates tend to interlock and produce unusually high shear strength (Heiken et al., 1991)
  - Lunar soil is more compressible than JSC-1 simulant due to the crushing of agglutinates under load
  - The mechanical properties of lunar soil change with loading due to crushing of agglutinates
  - Presence of the small metallic iron globules in the agglutinitic glass is believed to affect the absorption of microwave energy (Taylor et al., 2005), the magnetic susceptibility, and electrostatic properties of the regolith
- Current lunar regolith simulants do not contain any particles that accurately represent the morphologies or metallic iron globules found in lunar agglutinates

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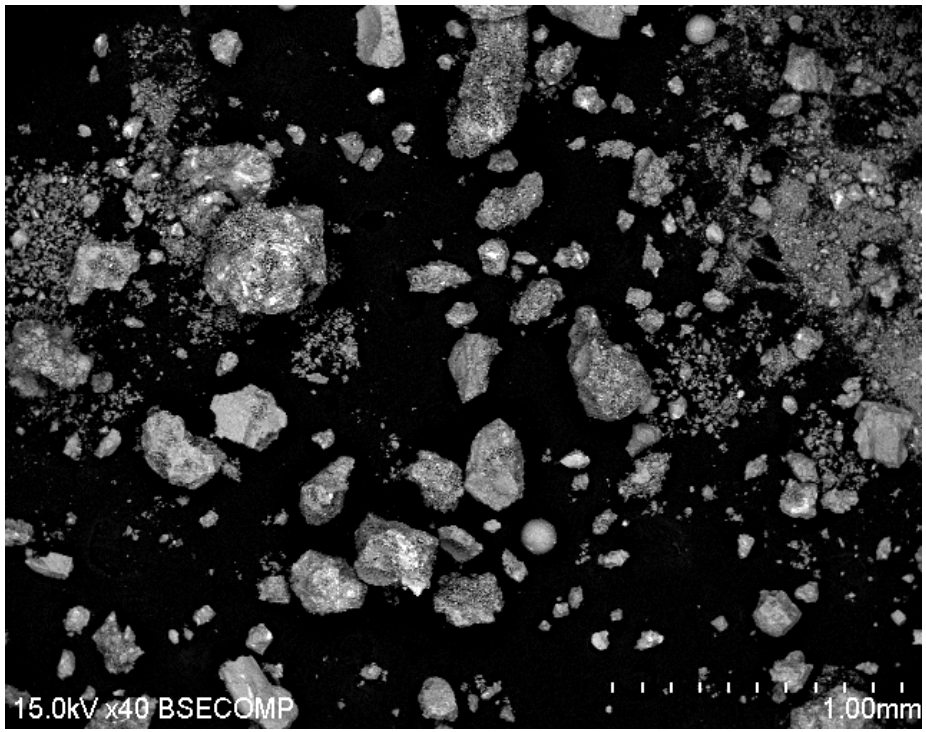
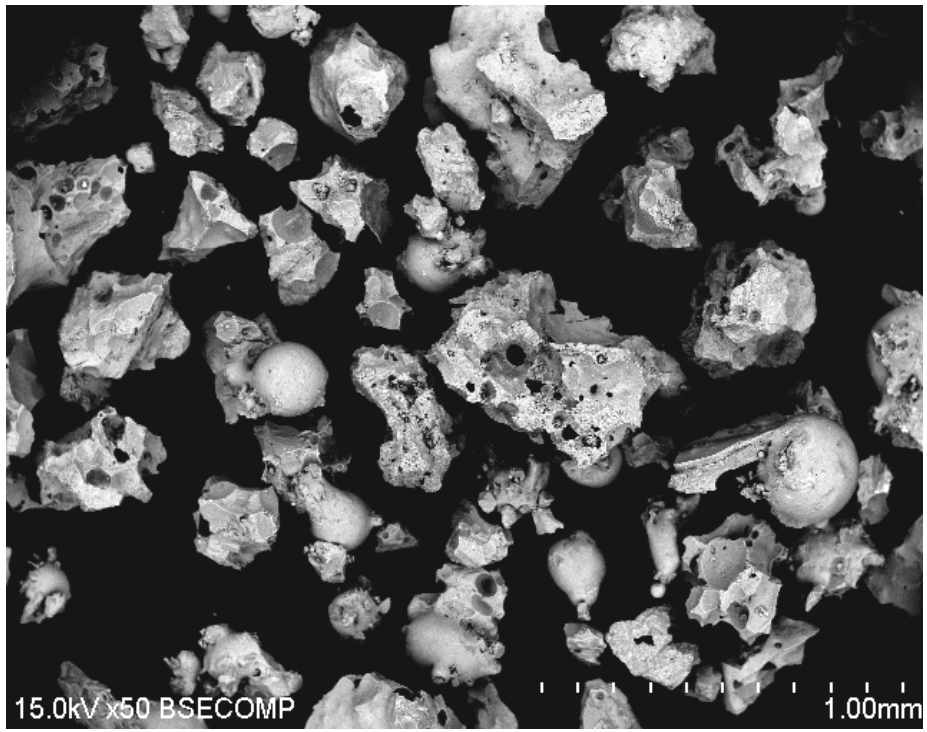
# New High-Fidelity Simulants with Agglutinates

- ORBITEC began work in December 2005 to create an agglutinate additive that could be added to existing and new lunar regolith simulants
- Several problems were encountered in the early attempts to create an agglutinate additive
  - Difficult to create an additive that contained 100% agglutinate-like particles
  - Some of the friable agglutinate-like particles produced were broken when they were isolated and remixed into a lunar regolith simulant
- A new process was developed that creates agglutinate-like particles within the feedstock material
  - Output of the process is a mixture of agglutinate-like particles, glass spherules and the feedstock material

# Comparison of Lunar Soil with an Agglutinate Simulant




**Apollo Sample 10084 Soil**




**Agglutinate Simulant**
**(made from JSC-1A)**

***Note that both images (same scale) were produced by Dr. John Fournelle (University of Wisconsin-Madison) with the same SEM.***

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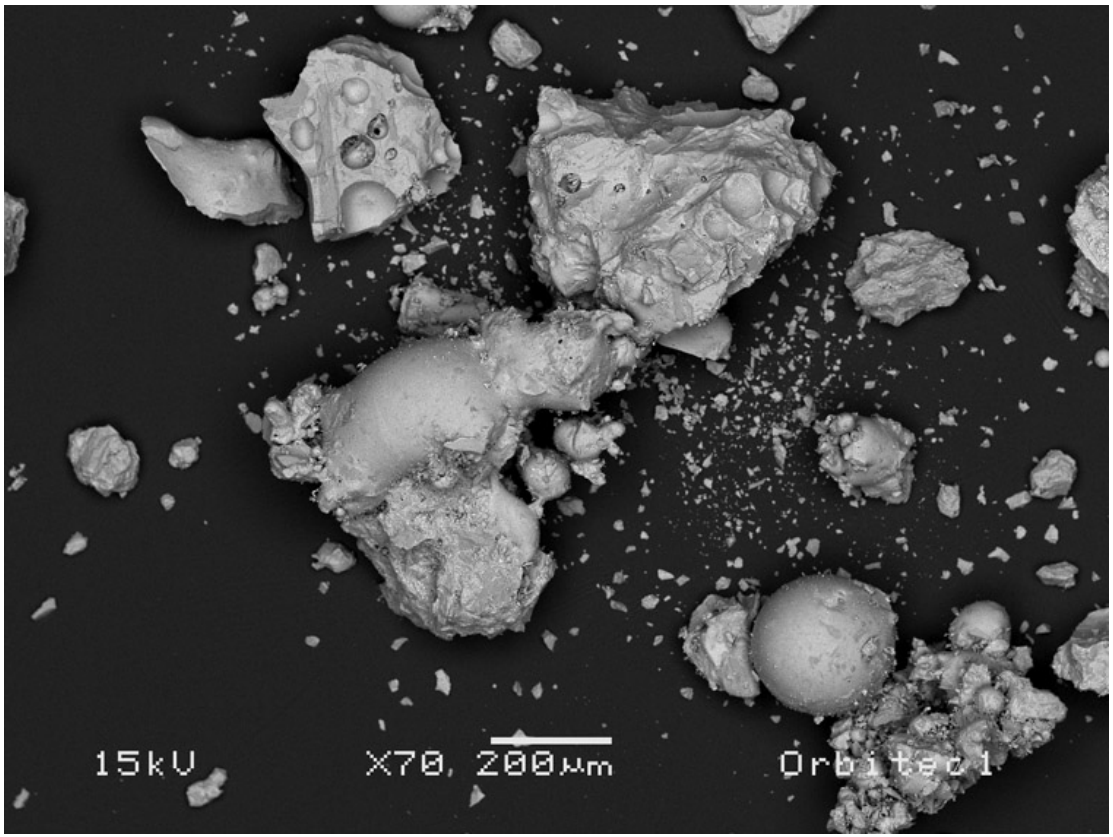
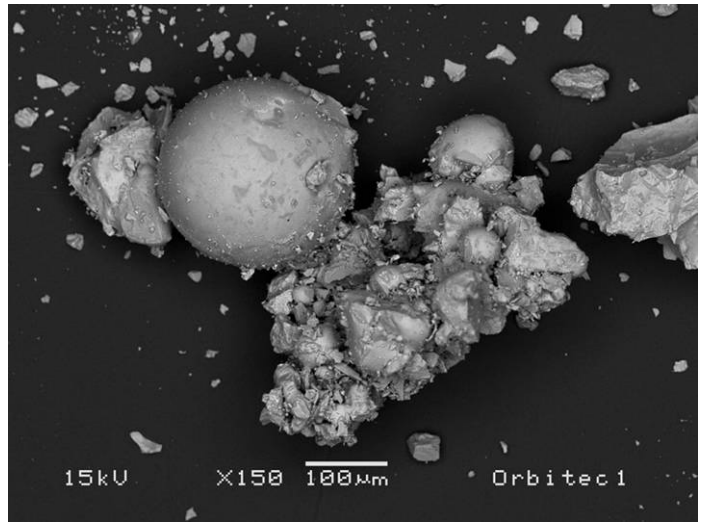
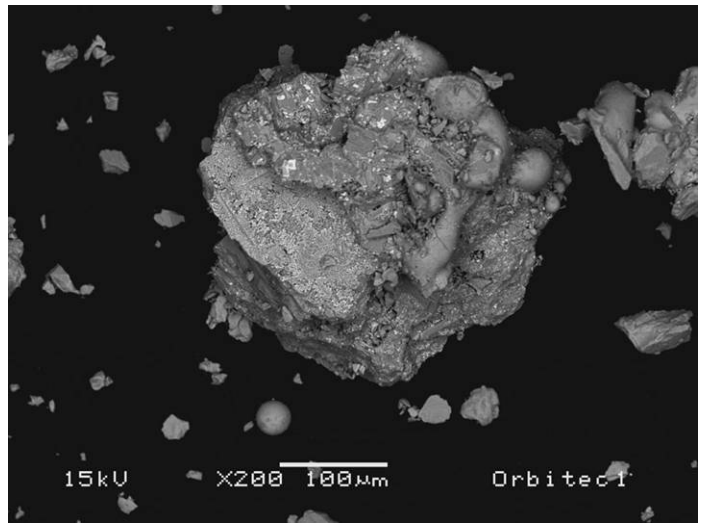
# Agglutinate Simulant Made from JSC-1A



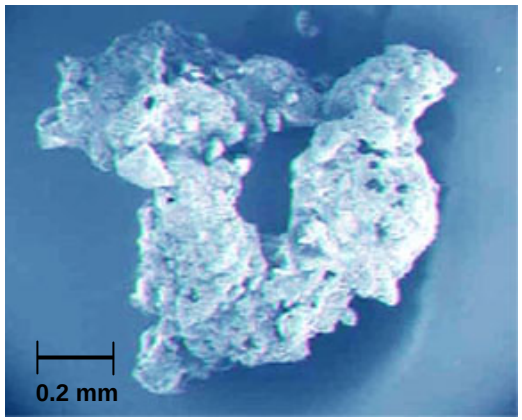



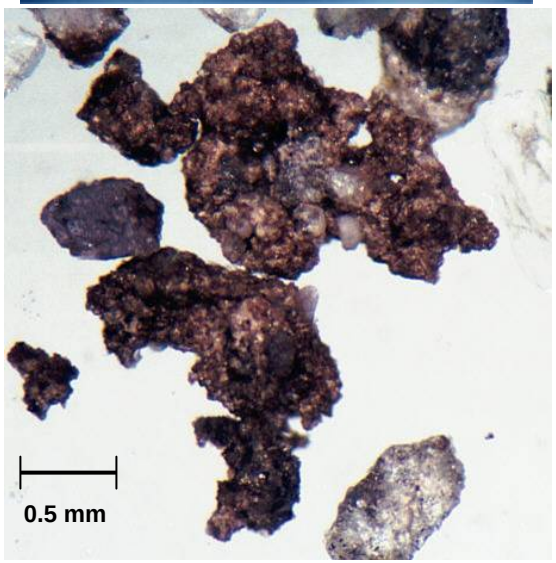

***Images produced by Sarah Noble at the NASA Johnson Space Center.***

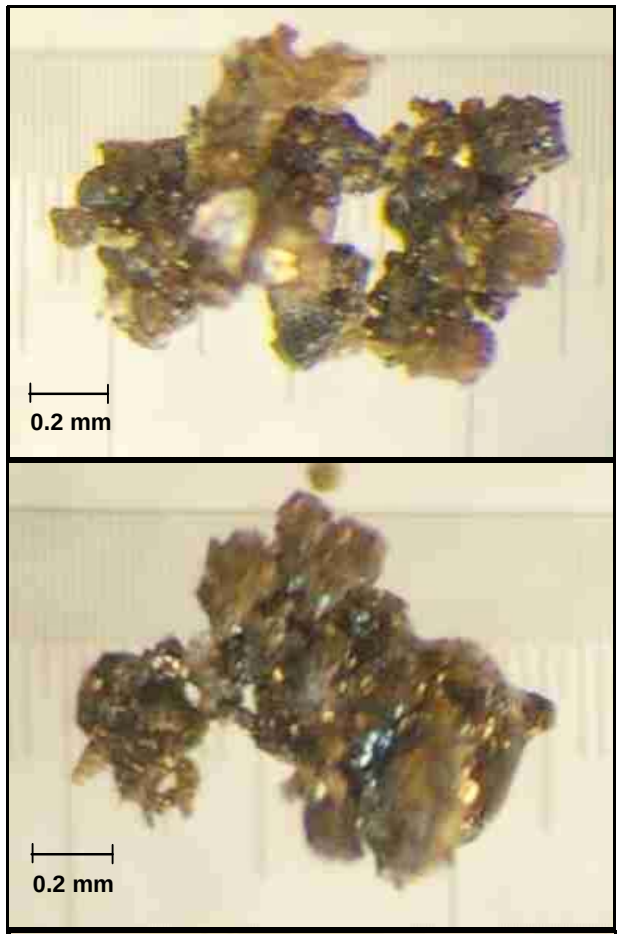
# Comparison to Typical Lunar Agglutinate Shapes

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




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




**Agglutinate Simulant Particles Produced from JSC-1A Lunar Regolith Simulant**

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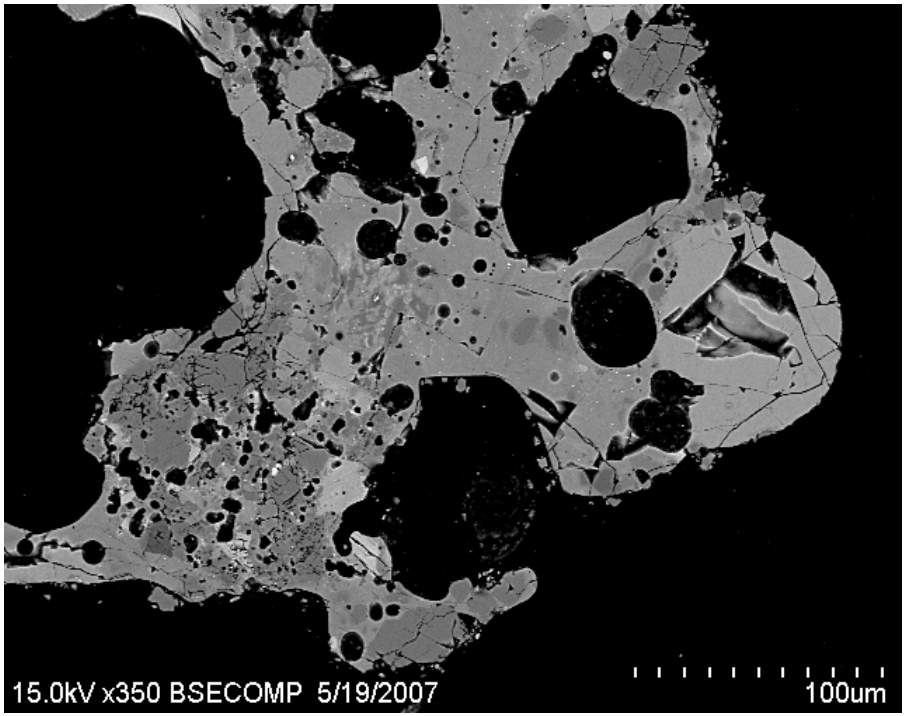
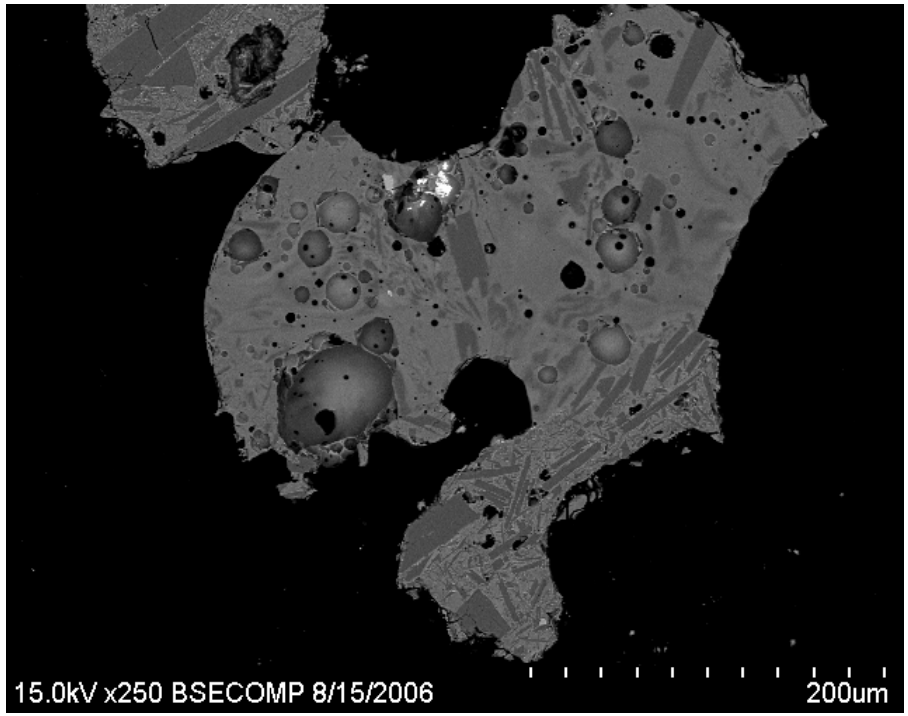
# Presence of Vesicles (Bubbles) in the Glass




**Lunar Agglutinate Thin Section (Apollo Sample 15103)**




**Agglutinate Simulant Cross Section**

***Note that both images were produced by Dr. John Fournelle (University of Wisconsin-Madison) with the same SEM.***

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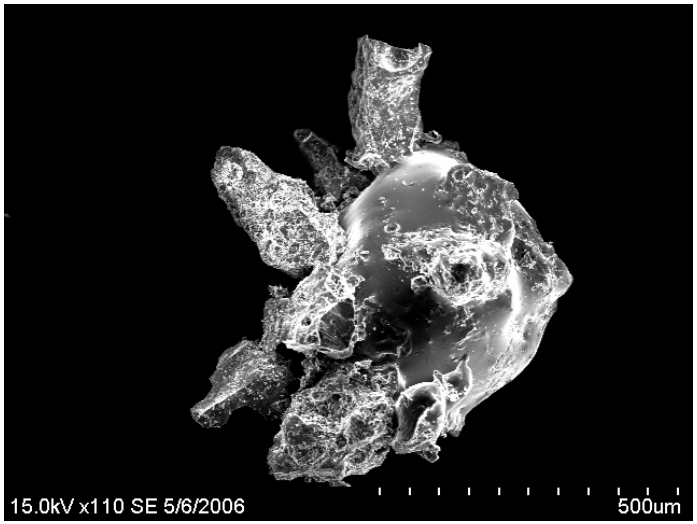
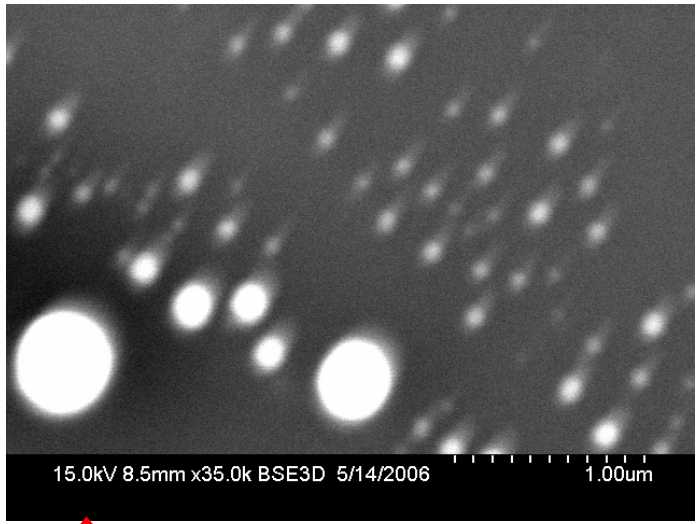
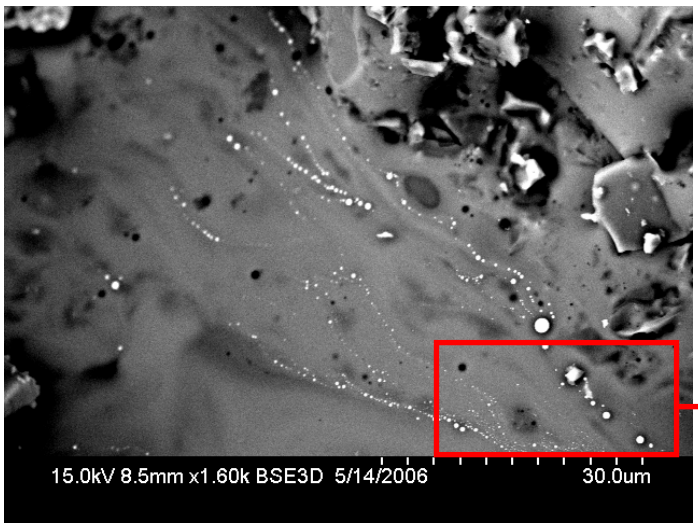
# Importance of Iron Globules in Lunar Agglutinates

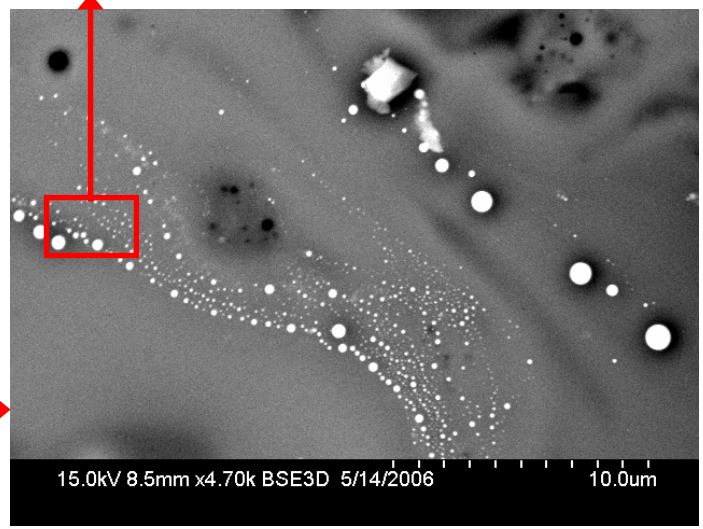
- Coarse and fine-grained metallic iron globules exist in the glassy portions of lunar agglutinates
- Fine-grained iron globules have diameters less than 30 nm
  - Often referred to as “nanophase iron”
  - This single domain iron is super-paramagnetic, so it is attracted to magnetic fields but does not retain any magnetization
  - Believed to significantly increases the absorption of microwave energy (Taylor et al., 2005)
  - Necessary for toxicology studies of lunar dust
- The coarse-grained iron globules have diameters greater than 30 nm up to ~1 µm
  - Multi-domain iron is highly magnetic, so it is strongly attracted to magnetic fields and will retain a magnetic moment

# Example of Iron Globules on the Surface of an Agglutinate Simulant Particle

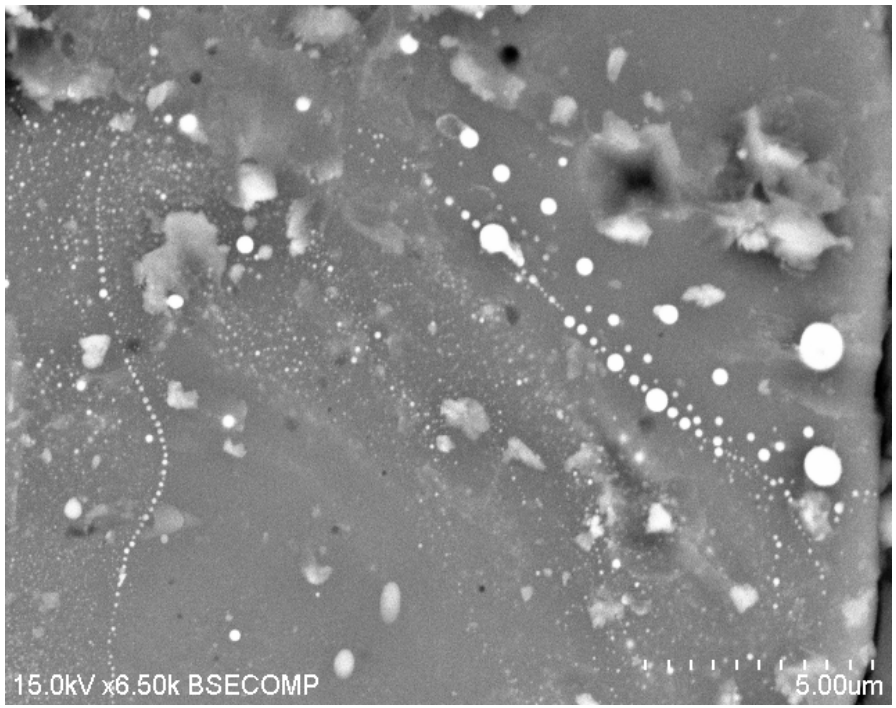


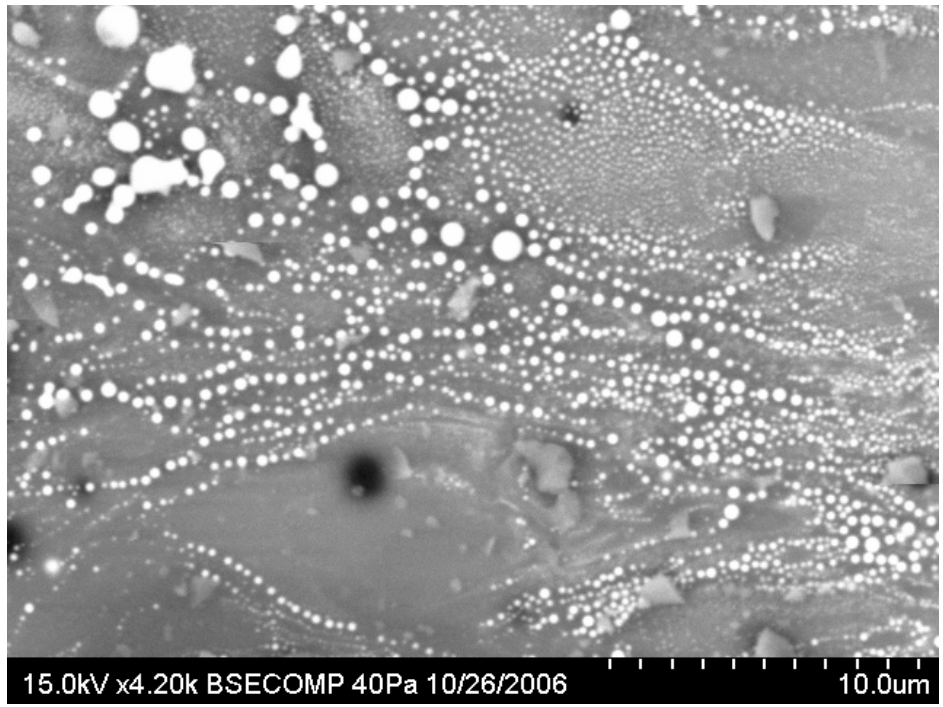



# Comparison of Iron Globules on Agglutinitic Glass



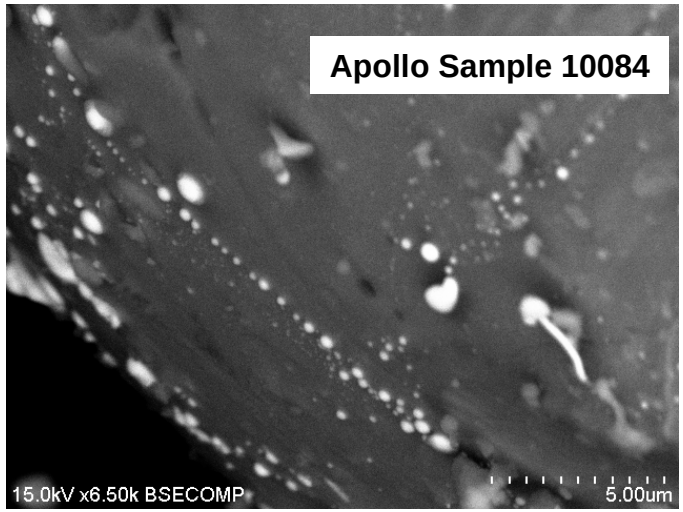

**Lunar Agglutinate Particle (Apollo Sample 10084)**

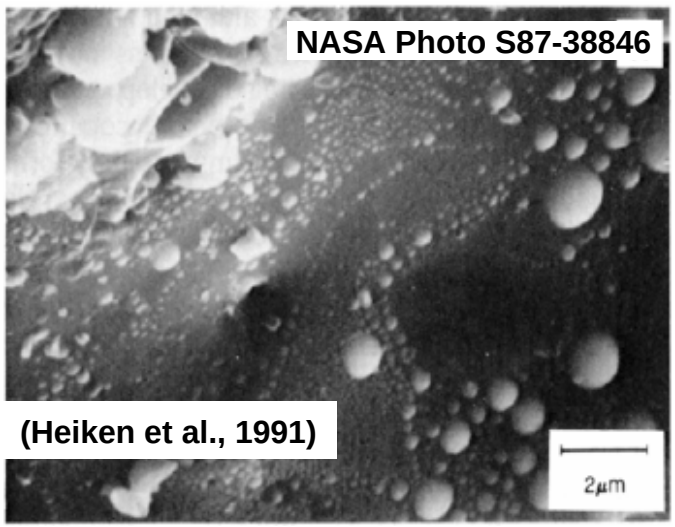



**Agglutinate Simulant Particle**

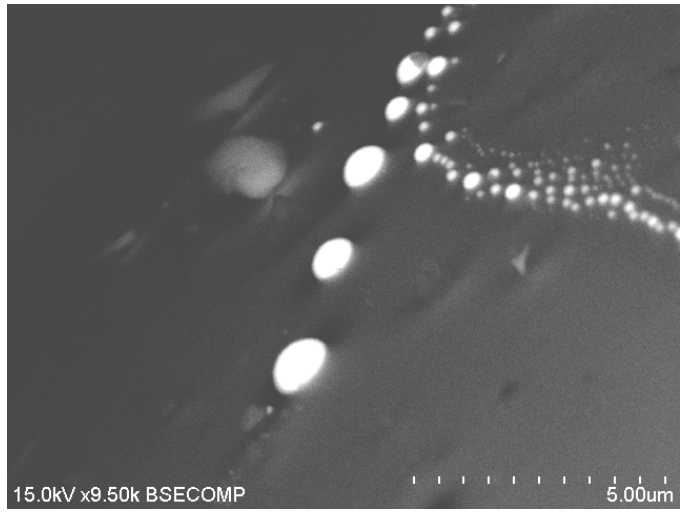
***Note that both images were produced by Dr. John Fournelle (University of Wisconsin-Madison) with the same SEM.***

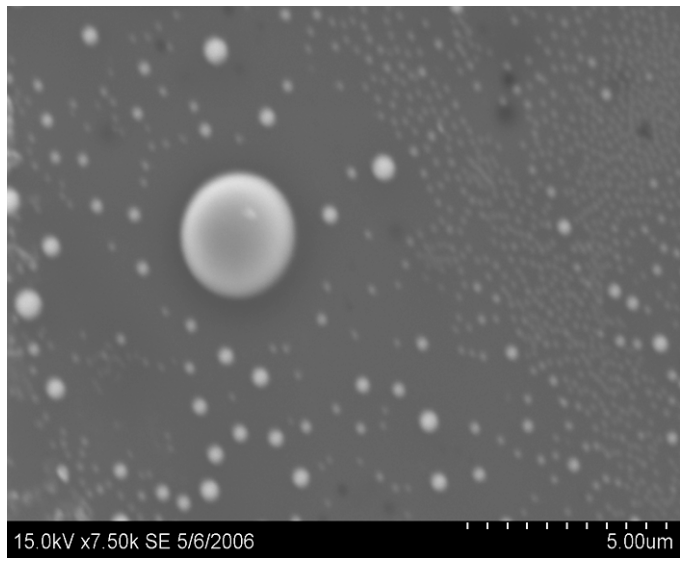
# Comparison to Iron Globules on Lunar Agglutinates



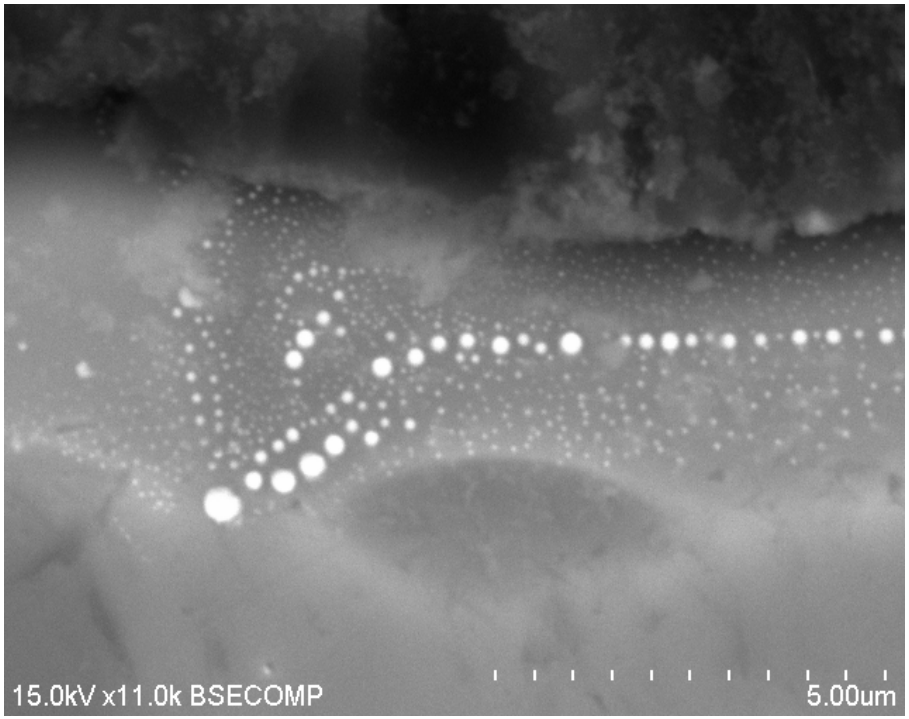

Lunar Agglutinates

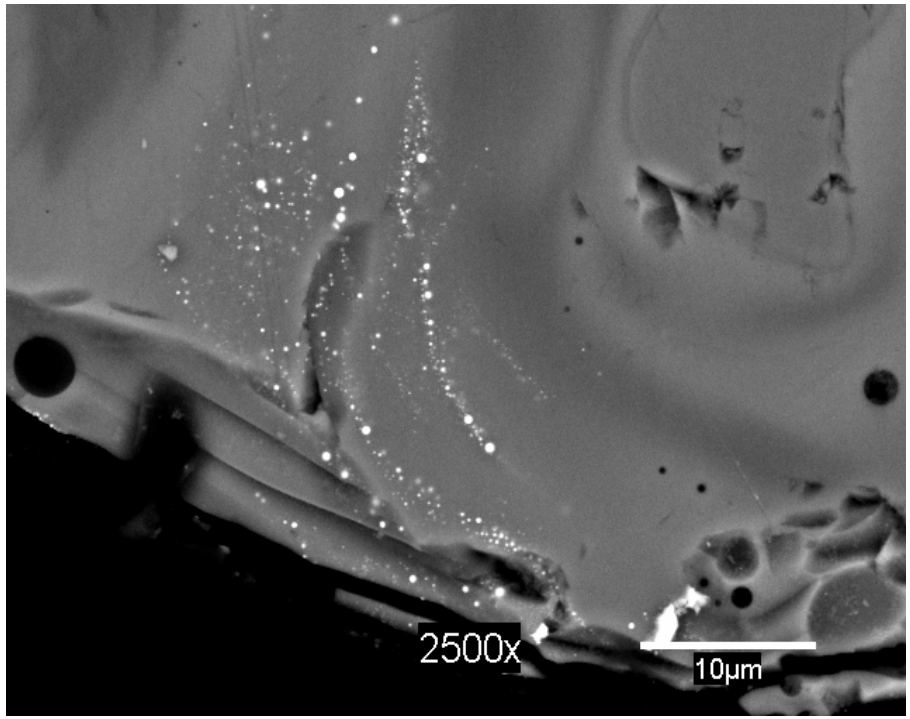



Agglutinate Simulant Particles

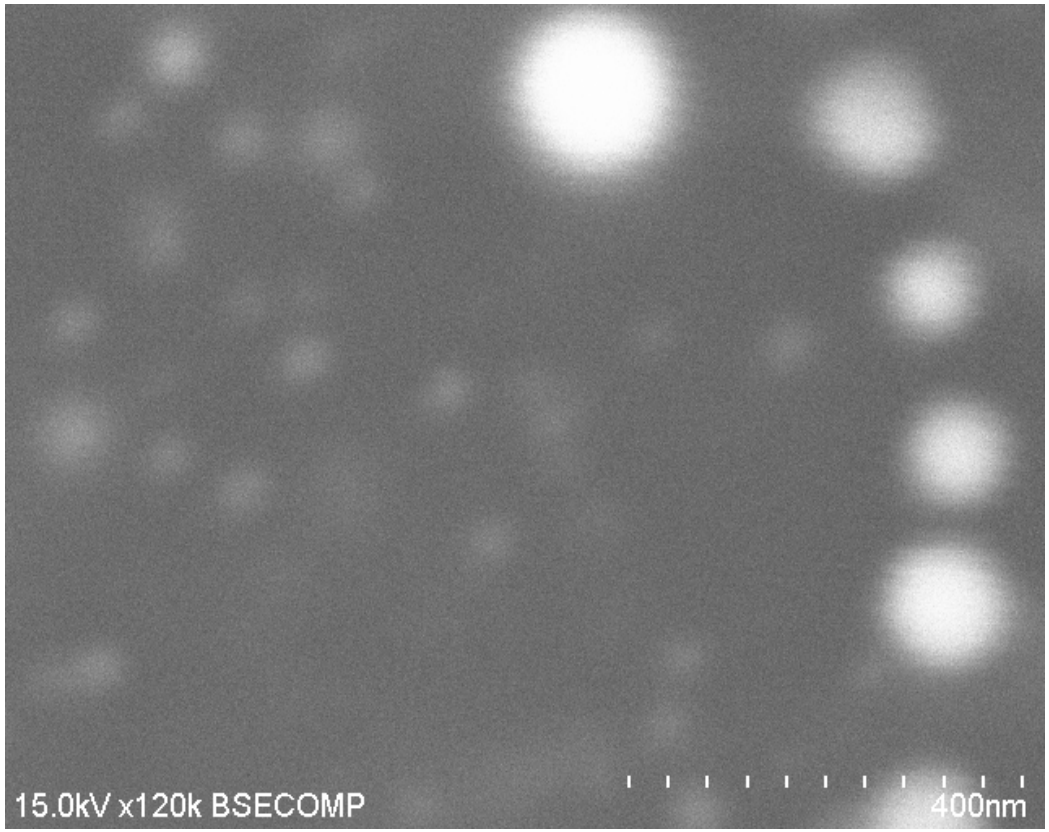
# Iron Globules Inside an Agglutinate Simulant Particle



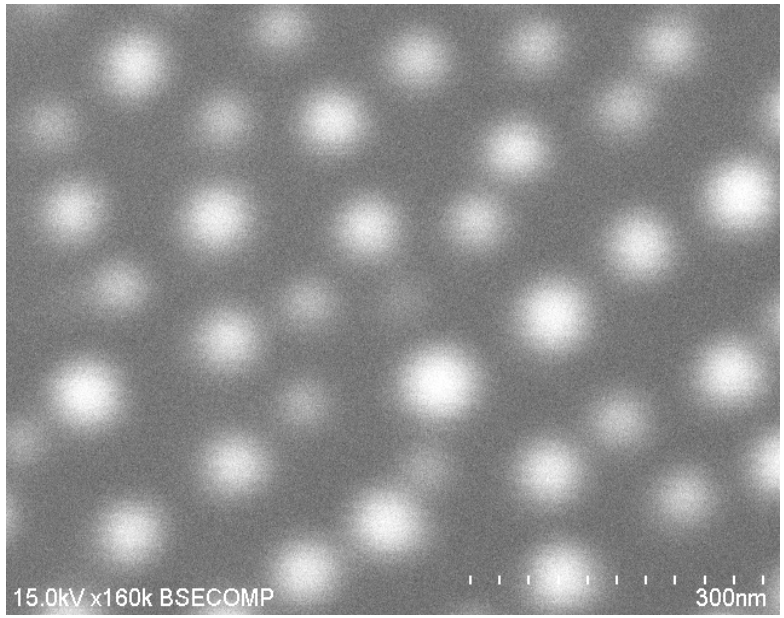




- The iron globules are also found within the glassy regions of the agglutinate-like particle (similar to lunar agglutinates)
- The iron globules tend to form “trains” like the ones observed on the surface

# Comparison of Fine-Grained Iron Globules



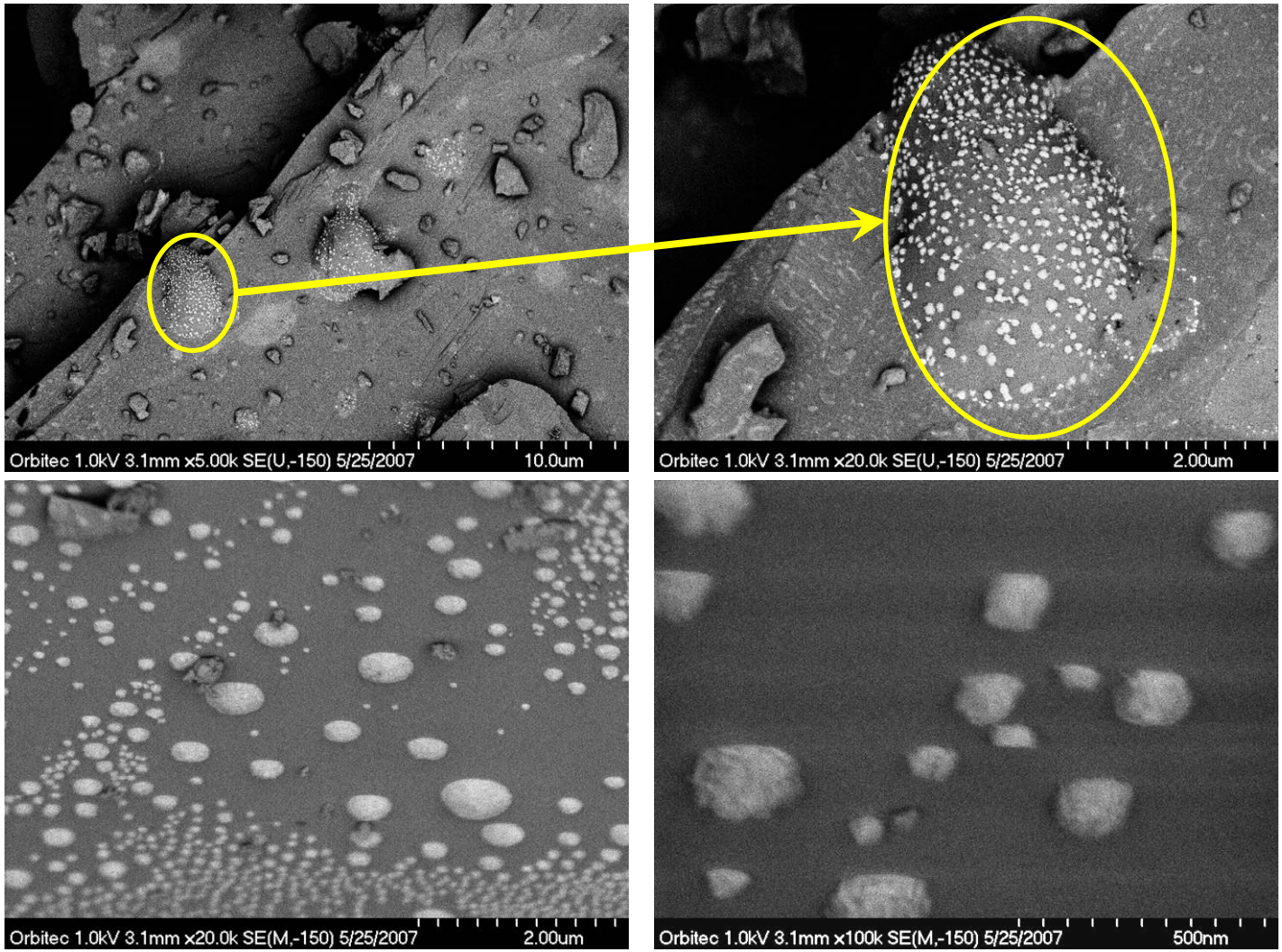

**Lunar Agglutinate Particle (Apollo Sample 10084)**




**Agglutinate Simulant Particle**

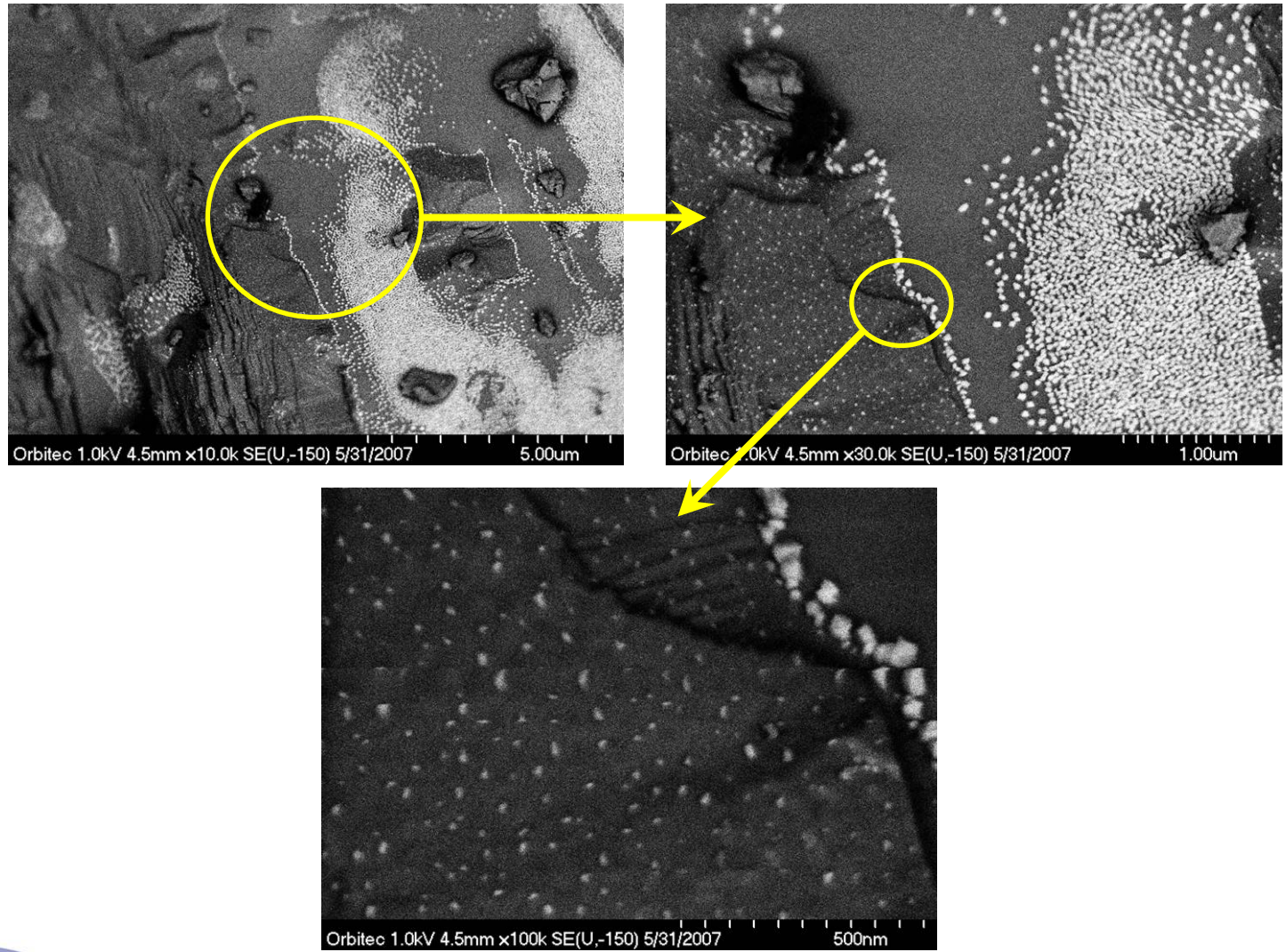
***Note that both images (scaled to same size) were produced by Dr. John Fournelle (University of Wisconsin-Madison) with the same SEM.***

# Iron SEM Images of a Simulated Agglutinate




***Note that the bright regions are iron globules.***

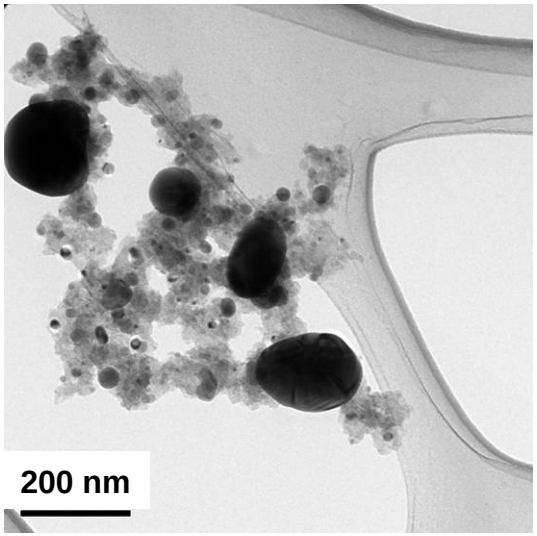
# Iron SEM Images of a Simulated Agglutinate

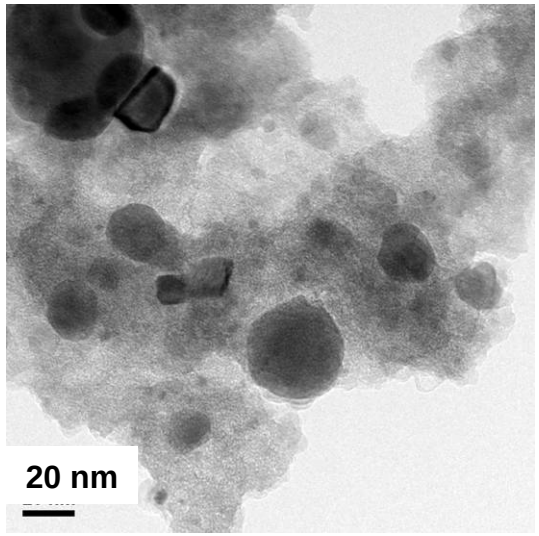


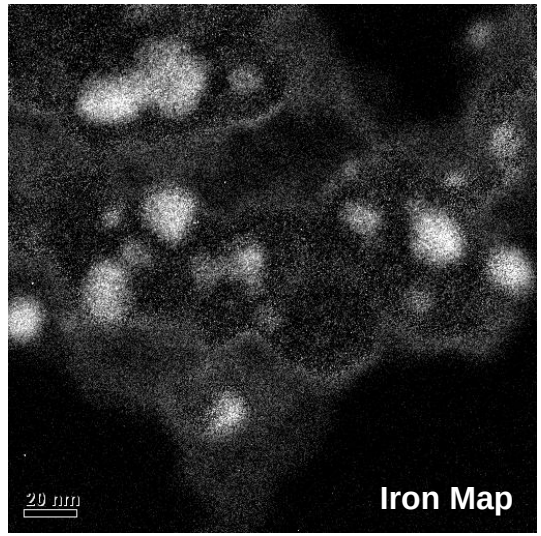


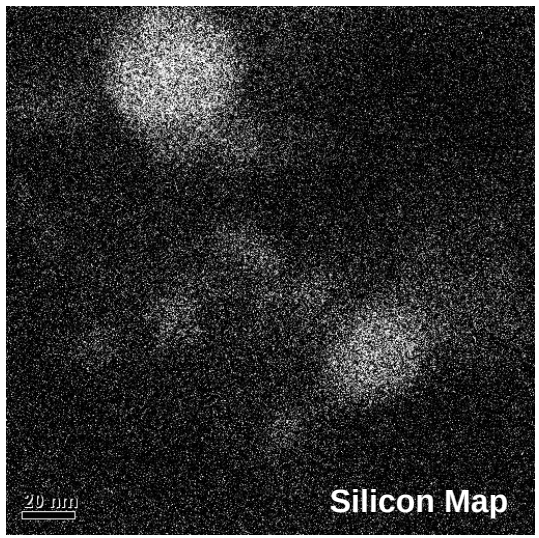

***Note that the bright regions are iron globules.***

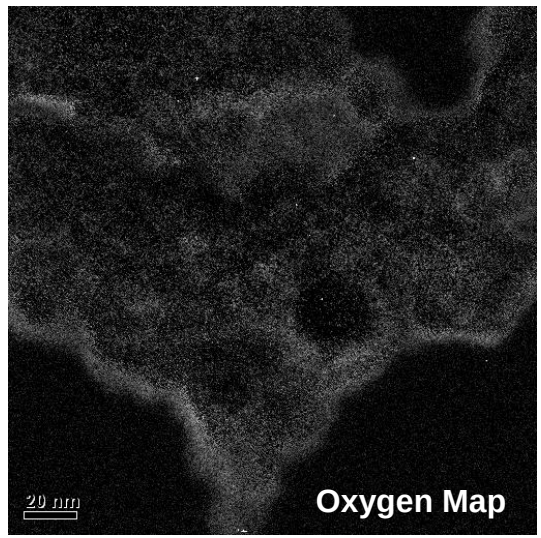
# TEM Images of a Simulated Agglutinate




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

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# Availability of Agglutinate Simulant

- Production hardware is currently being built and assembled
- Samples of an agglutinate simulant made from JSC-1A lunar regolith simulant will be available for evaluation by researchers in December 2007
- Agglutinate simulant samples can be requested at http://www.lunarmarssimulants.com
- The process used to create the agglutinate simulant has been successfully used with other feedstock materials, so ORBITEC is interested in applying this process to the new simulant materials being developed
- Please contact Bob Gustafson at (608) 229-2725 or gustafsonr@orbitec.com with any technical questions

# Acknowledgements


- The work reported is being supported by the NASA Marshall Space Flight Center through Small Business Innovative Research (SBIR) Phase II contract in addition to internal research and development funding by ORBITEC
- Most of the SEM images of the agglutinate simulant particles are courtesy of Dr. John Fournelle at the University of Wisconsin-Madison
- A few of the SEM images of the agglutinate simulant were provided courtesy of NASA Johnson Space Center
- The iron SEM and TEM images of the agglutinate simulant particles are courtesy of NASA Glenn Research Center

# References


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