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Extant and Extinct Lunar Regolith Simulants: Modal Analyses of NU-LHT-1M and -2m, OB-1, JSC-1, JSC-1A and -1AF, FJS-1, and MLS-1

Christian Schrader [1]*, Doug Rickman [2], Carole Mclemore [2], John Fikes [2], Stephen Wilson [3], Doug Stoeser [3], Alan Butcher [4], Pieter Botha [4]

[1] BAE Systems-MSFC, Huntsville AL; [2] NASA-MSFC, Huntsville AL; [3] USGS, Denver CO; [4] Intellection Ltd., Brisbane, QLD Australia



NASA - Marshall Space Flight Center leads this simulant development and characterization



JSC, GRC, and KSC contribute other work towards the characterization of simulant and lunar materials

The United States Geological Survey in Denver assists in characterization and leads in the manufacturing of NU-LHT series



Intellection, Ltd., in Brisbane and Intellection Corp., USA in Westminster CO



- This work is part of a larger effort to compile an internally consistent database on lunar regolith (Apollo samples) and lunar regolith simulants.
 - Characterize existing lunar regolith and simulants in terms of
 - Particle type
 - Particle size distribution
 - Particle shape distribution
 - Bulk density
 - Other compositional characteristics
 - Evaluate regolith simulants (Figure of Merit) by above properties by comparison to lunar regolith (Apollo sample)

This presentation covers new data on lunar simulants.



The NASA-MSFC simulant group is compiling a simulant user's handbook with a matrix of simulant properties.

This will help guide users choose a simulant for their applications.



- 1) Simulant types and specific simulants
- 2) New work – modal data
 - A. QEMSCAN® instrument and approach
 - B. Preliminary results of modal analysis of simulants
 - i. Plagioclase
 - ii. Pyroxene
 - iii. Olivine
 - iv. Glass
- 3) Phase chemistry (mostly previous work)
 - A. Plagioclase composition
 - B. Glass composition
- 4) Examples of other new results



Lunar simulants -- mare and highlands



JSC-1A lunar mare simulant



NU-LHT-1M lunar highlands simulant



NASA lunar architecture places the first permanent bases near a pole, which is likely dominated by lunar highlands-type terrain.

NASA-MSFC and USGS are focusing on process control. Current prototypes are characteristic of lunar highlands material.

We plan to characterize and prototype mare types in the future.

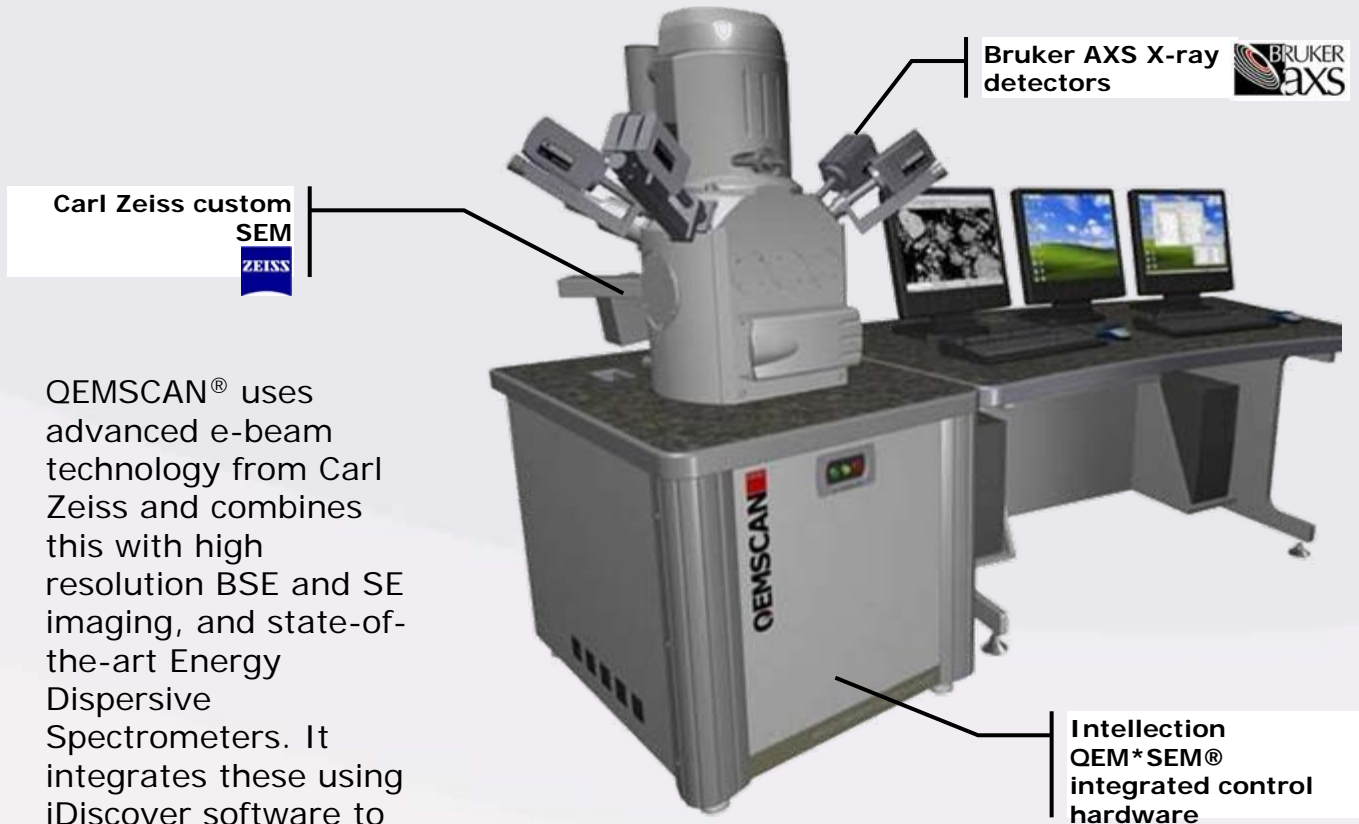


Overview of lunar simulants

Simulant(s)	Type	Primary Reported Use	Manufacturer	feedstock	status
NU-LHT series	Highlands	General	NASA-MSFC and USGS	Stillwater mine (MT), commercial minerals	In production and use
OB-1	Highlands	Geotechnical	Norcat	Shawmere anorthosite, olivine slag glass	In production and use
JSC-1 (-1A, -1AF)	Mare, low-Ti	Geotechnical and lesser chemical	Orbitec, Inc.	Basalt ash, San Francisco volcanic field (AZ)	In production and use
FJS-1	Mare, low-Ti	Geotechnical	Japanese, (JAXA, LETO)	Mt. Fuji area basalt	No longer available
MLS-1	Mare, high-Ti	Chemical	University of Minnesota	Basalt sill, Duluth complex	No longer available



QEMSCAN[®] instrumentation

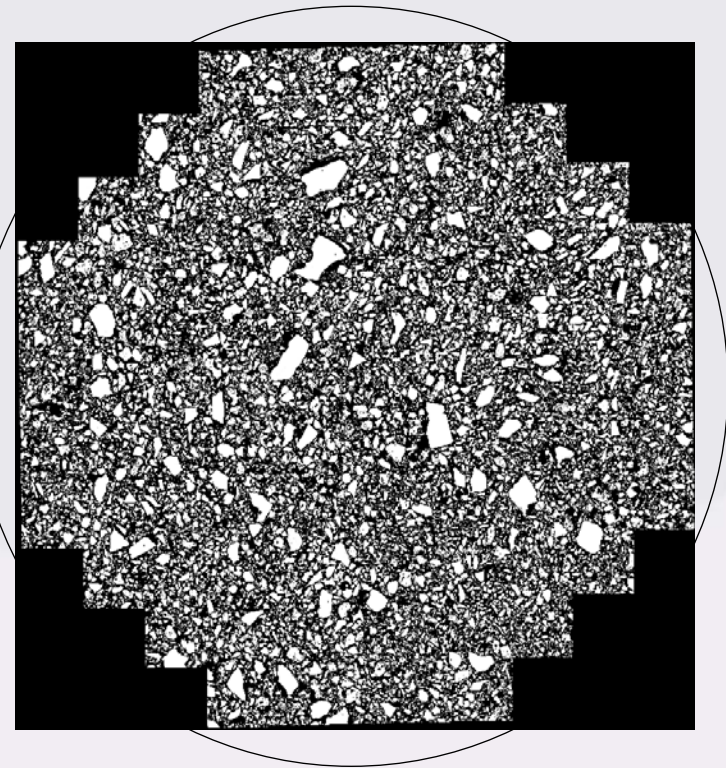


QEMSCAN[®] uses advanced e-beam technology from Carl Zeiss and combines this with high resolution BSE and SE imaging, and state-of-the-art Energy Dispersive Spectrometers. It integrates these using iDiscover software to provide a solution capable of identifying most rock-forming minerals in just milliseconds





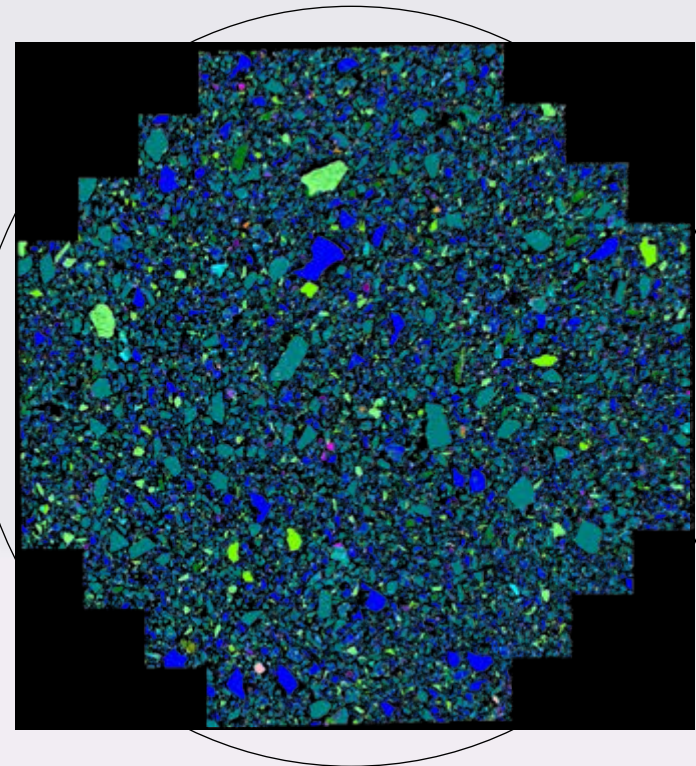
Digital photograph of polished block



QEMSCAN[®] Backscattered Electron photo-micrographic montage of a polished block



Digital photograph of a 30mm diameter polished block



QEMSCAN[®] false-coloured, digital particle mineral map montage of a polished block

Results: QEMSCAN[®] modal analysis

Average of two replicate runs

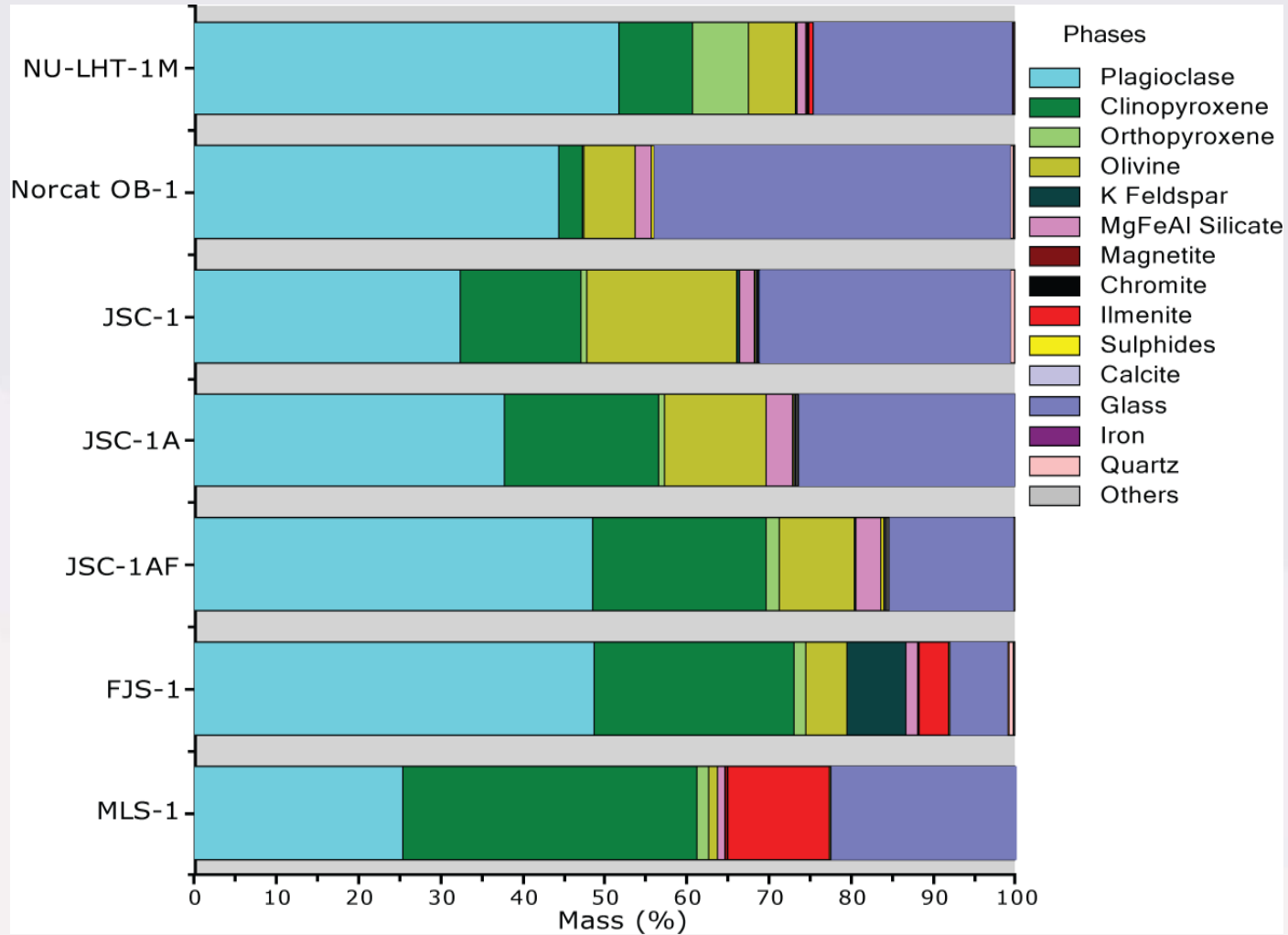
These modal data are total % of phase proportion regardless of occurrence, e.g., as free minerals, in a lithic fragment or agglutinate...

Minerals	NU-LHT-						
	1M	OB-1	JSC-1	JSC-1A	JSC-1AF	FJS-1	MLS-1
Plagioclase	51.87	44.35	32.47	37.83	48.47	48.78	25.45
Clinopyroxene	8.95	2.95	14.67	18.77	21.15	24.39	35.86
Orthopyroxene	6.76	0.19	0.65	0.66	1.62	1.37	1.37
Olivine	5.79	6.27	18.29	12.44	9.22	4.94	1.06
Glass	24.07	43.22	30.86	26.67	15.68	7.15	22.29
Magnetite	0.15	0.07	0.02	0.01	0.00	0.04	0.45
Chromite	0.11	0.01	0.01	0.00	0.00	0.01	0.00
Ilmenite	0.53	0.00	0.07	0.11	0.08	3.65	12.38
Sulphides	0.02	0.35	0.19	0.17	0.31	0.16	0.10
Iron	0.20	0.01	0.00	0.00	0.00	0.00	0.06
MgFeAl Silicate	1.13	1.83	1.76	3.06	3.09	1.53	0.82
K Feldspar	0.13	0.08	0.39	0.07	0.11	7.24	0.07
Quartz	0.21	0.48	0.50	0.01	0.04	0.47	0.00
Calcite	0.06	0.08	0.07	0.11	0.14	0.00	0.02
Others	0.04	0.12	0.07	0.07	0.08	0.27	0.08
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00



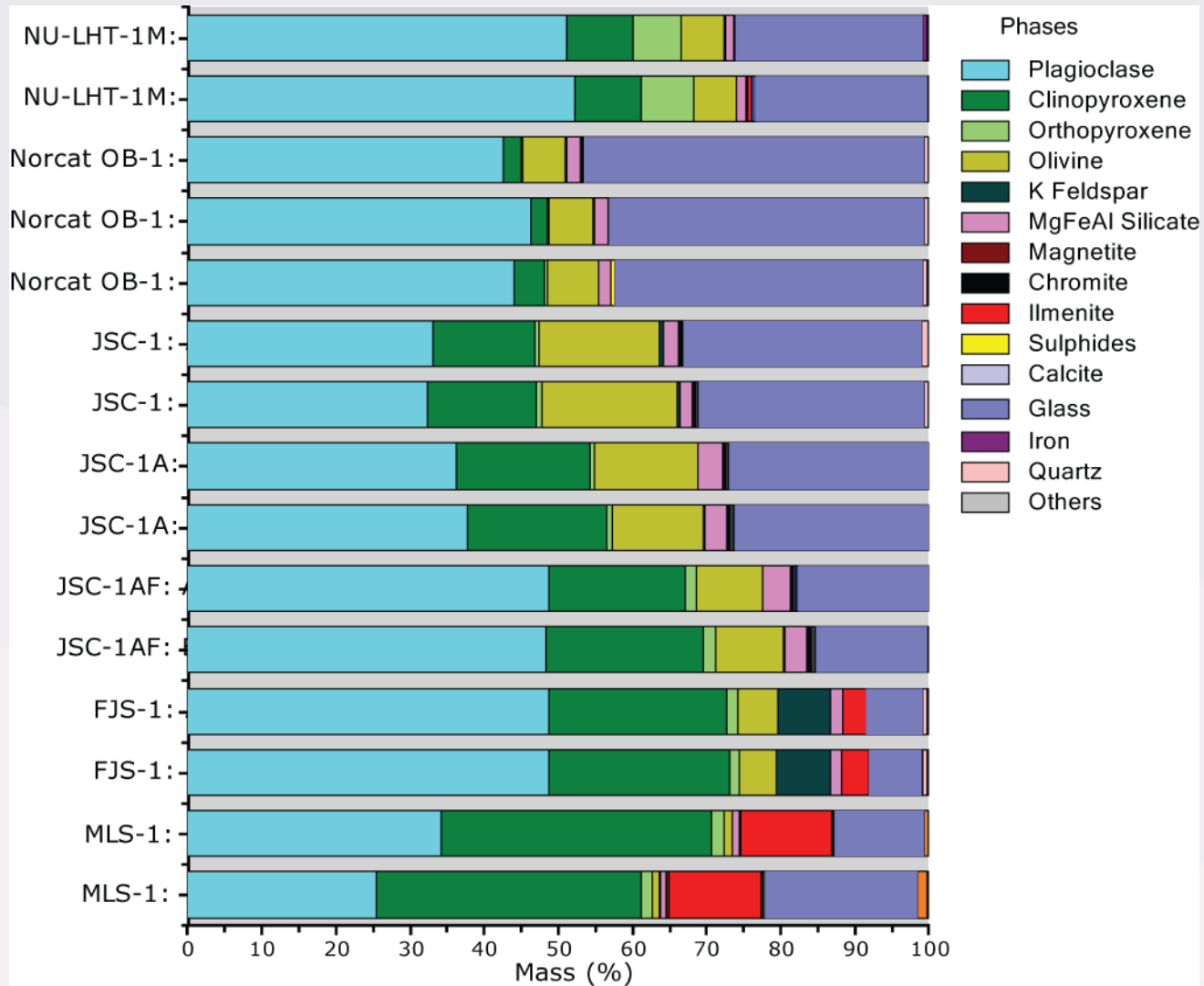
Results: QEMSCAN[®] modal analysis

Average of two replicate runs



Results: QEMSCAN[®] modal analysis

Replicate runs



Modal analysis measures the proportion by area% of a phase (mineral or glass) in a material. Area% is the same as volume% in a randomly oriented material and mass% can be computed if composition is known.

Physical characteristics such as hardness, fracture and cleavage behavior (which control abrasiveness, e.g.) are intrinsic characteristics of minerals and glass.

Geo-mechanical behavior of a material is controlled largely by the proportions of these constituent parts, as well as by the size and shape distributions of particles.

Modal proportions of phases are also the first piece of information necessary in understanding physiochemical behavior important to melting, oxygen extraction, etc.



Results: QEMSCAN[®] modal analysis

Average of two replicate runs

Minerals	Apollo 16: 64001/2	NU-LHT- 1M	OB-1	Apollo 11 &12	JSC-1	JSC-1A	JSC-1AF	FJS-1	MLS-1
Plagioclase	43-44	51.87	44.35	11-15	32.47	37.83	48.47	48.78	25.45
Clinopyroxene	0.6-0.7	8.95	2.95		14.67	18.77	21.15	24.39	35.86
Orthopyroxene	~2.5	6.76	0.19		0.65	0.66	1.62	1.37	1.37
<i>Total Pyroxene</i>	~3	15.71	3.14	25-37	15.32	19.43	22.77	25.76	37.23
Olivine	0.8-0.9	5.79	6.27	2-10	18.29	12.44	9.22	4.94	1.06
Glass	44-46	24.07	43.22	31-45	30.86	26.67	15.68	7.15	22.29

Highlands data are from QEMSCAN[®] analysis of thin sections from 64001,6031 and 64002,6019 Apollo 16 drive core.

Mare data are from Taylor et al. (1996) from 10084,1618, 12030,122, and 12001,7 Apollo 11 and 12 samples of low-Ti mare samples of varying maturity. Values determined by SEM EDS



Other crucial phases

Minerals that occur in much less abundance such than those mentioned can be very important to ISRU processes.

Ilmenite (FeTiO_3) is an important lunar mineral for oxygen extraction by H_2 -reduction.

Halogen (F, Cl)-bearing phases like apatite can have significant adverse effects on many ISRU processes. Sulfur, phosphorus, bromine and iodine bearing phases are also almost certain to be important.

Data on these minerals is still being refined.



Chemical composition of minerals and glass

In addition to modal proportions, the chemical make-up of phases exerts a huge control over physiochemical processes such as melting and those processes necessary to oxygen extraction.

Plagioclase feldspar, a major constituent of lunar regolith, is a good example.



Plagioclase chemistry

Another consideration is the chemical composition of the plagioclase mineral grains.

Plagioclase feldspar is a solid solution mineral that varies between two end-member compositions:



and



⇒ The Ca/Na and Al/Si ratios vary simultaneously.



Plagioclase composition

Lunar Highlands: An >90%

NU-LHT-1M range: An 75-85%

OB-1: Shawmere, approx. An 75%?

Lunar Mare: An 75-95%

JSC-1: An 64-71% (Carpenter 2005)

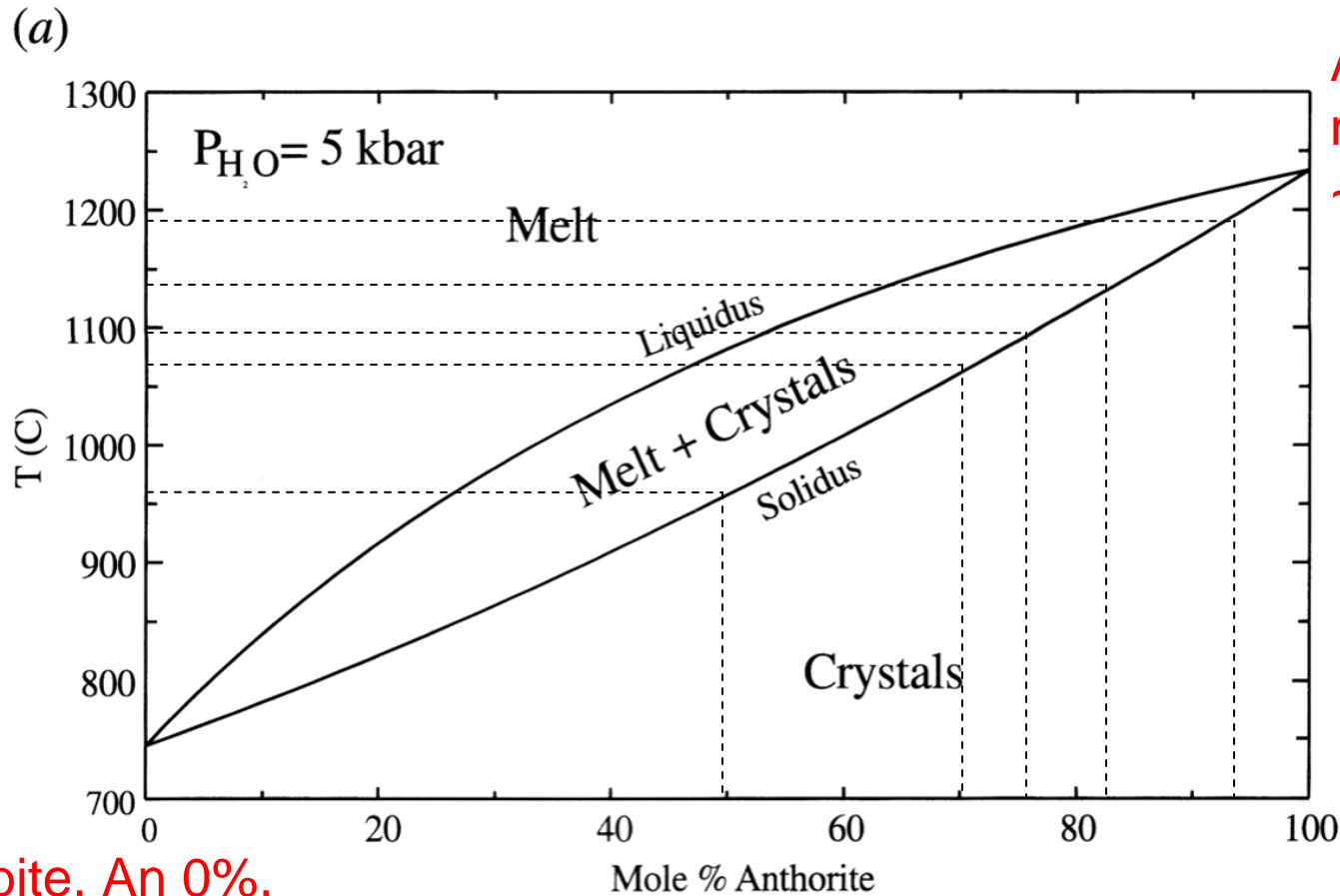
JSC-1A: An 70% (average -- Hill et al., 2007)

JSC-1AF: An 70% (Carpenter, 2006)

MLS-1: An 44-50% (Carpenter, 2005; Hill et al., 2007)



Example - Why mineral chemistry matters



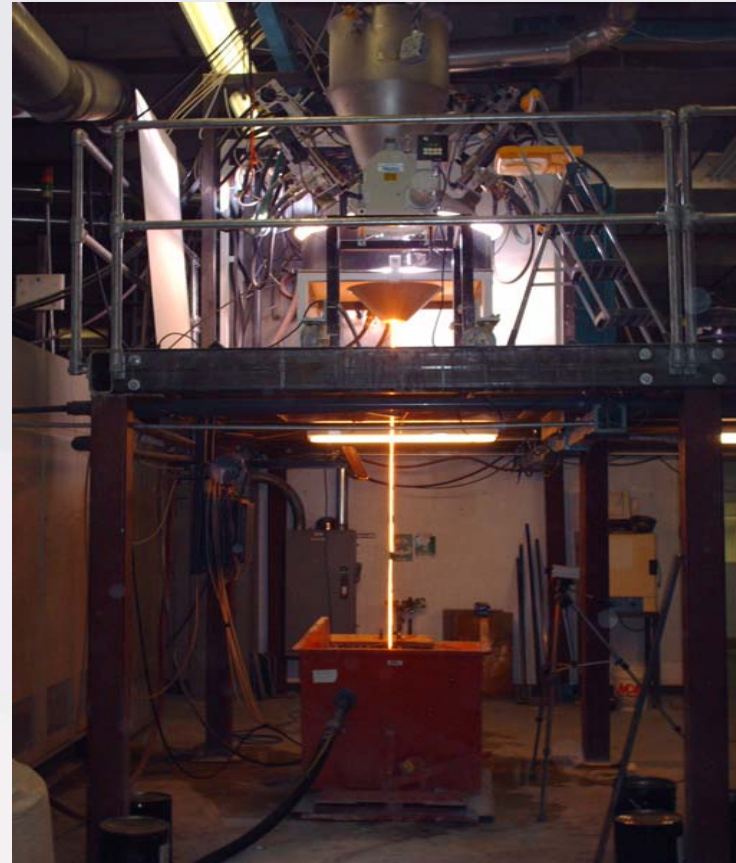
An 100%
melts at
~1230° C

Albite, An 0%,
melts at ~750° C



NU-LHT series glass: plasma melting

NU-LHT-1M and -2M: glass is derived from melting fine-grained material (mill sand) from the Stillwater mill.



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Glass in lunar simulants

NU-LHT-1M: Glass is derived by plasma-melting of noritic feedstock
Ca-Al-Si with moderate Fe and Mg

OB-1: Glass is an olivine slag
Fe and Mg-rich with Si

JSC-1 series: Natural basalt glass
Fe-Mg-Ca-Al-Si with lesser Na

FJS-1: Natural basalt glass
no analyses available

MLS-1: Glass is derived by plasma-melting of basaltic feedstock
Fe-Mg-Ca-Al-Si with lesser Na



Some simulant glass chemistry

oxide	NU-LHT	JSC-1A	JSC-1AF
SiO ₂	46.6	46.8	46.11
TiO ₂	0.115	2.44	2.8
Al ₂ O ₃	21.55	13.9	14.92
FeO**	5.08	12.1	12.66
MnO	0.09	0.21	0.22
MgO	9.5	5.6	5.07
CaO	12.6	10.5	9.98
Na ₂ O	0.965	3.89	3.96
K ₂ O	0.12	1.17	1.43
P ₂ O ₅	0.07	1.04	1.02
Cr ₂ O ₃	0.12	b.d.l.	0.01
LOI	2.74	n.d.	n.d.
Total	99.55	97.65	98.18

NU-LHT values are from an analysis of the feedstock Stillwater “mill sand” melted to form glass.

JSC-1A and -1AF analyses from Hill et al. (2007) and Paul Carpenter (2005, 2006) reports and presentations.

**total Fe as FeO



We are compiling huge numbers of data points on lunar regolith and simulants. Analysis and refinement is continuing.

Modal composition is one important parameter to both geotechnical and to physiochemical behavior.

For physiochemical behavior important to many ISRU purposes, phase chemistry is also very important, perhaps particularly with regards to glass chemistry.





References:

Heiken, G., Vaniman, D., and French, B.M., 1991, Lunar Sourcebook: A User's Guide to the Moon. Cambridge University Press, Cambridge [England], New York.

Hill, E., Mellin, M.J., Deane, B., Liu, Y., and Taylor, L.A., 2007, Apollo sample 70051 and high and low-Ti soil simulants MLS-1A and JSC-1A: Implications for future lunar exploration, *Journal of Geophysical Research*, v. 112, E02006.

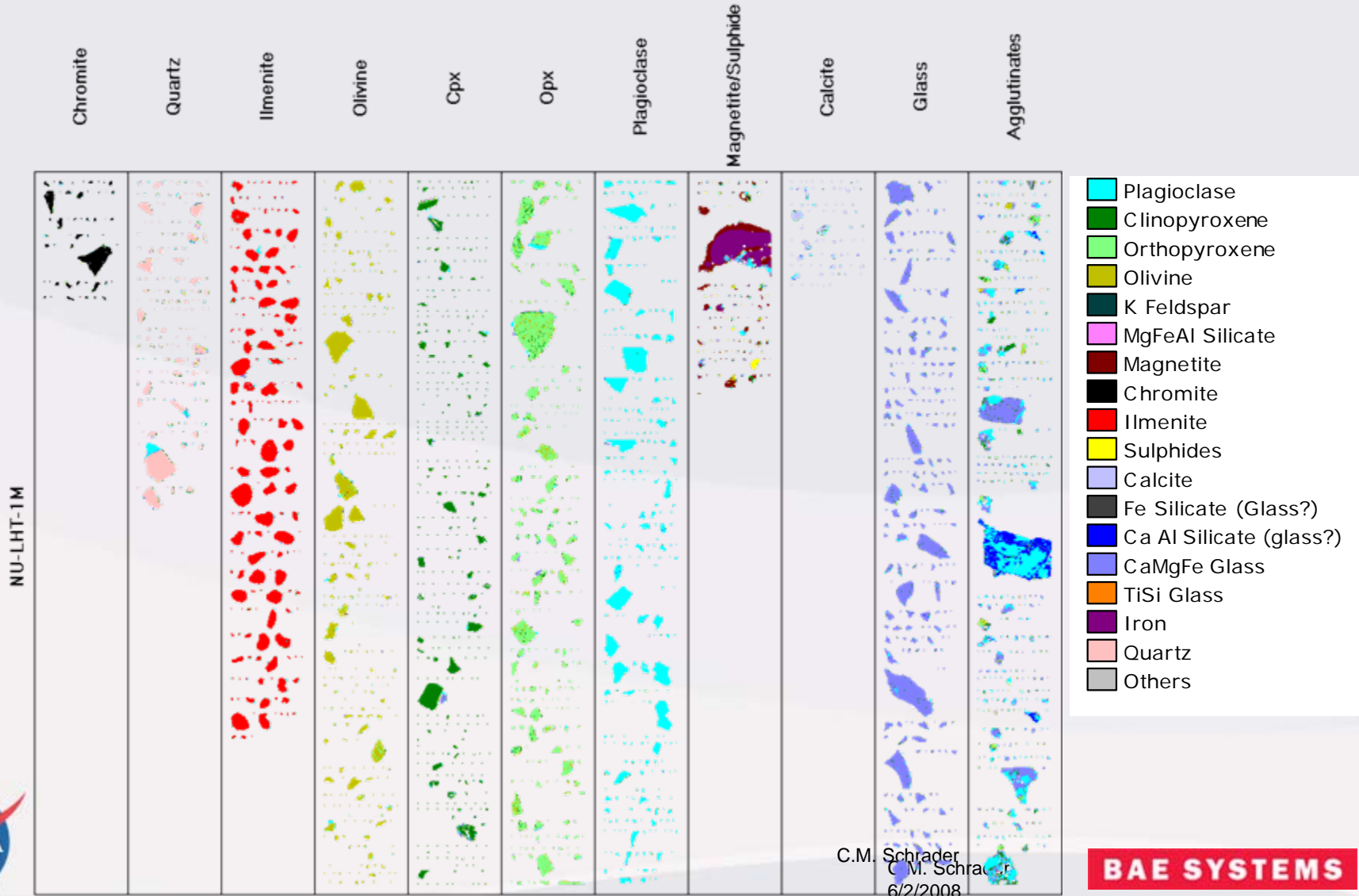
Richard, J., Sigurdson, L., and Battle, M.M., 2007, OB-1 Lunar highlands physical simulant: Evolution and roduction, abstract and presentation at Lunar and Dust Regolith Simulant Workshop, Huntsville, AL.

Taylor, L.A., Patchen, A., Taylor, Chambers, J.G., and McKay, D.S., 1996, X-ray digital imaging petrography of lunar mare soils: Modal analyses of minerals and glasses, *Icarus*, v. 124, pp. 500-512.



NU-LHT-1: QEMSCAN® particle analysis

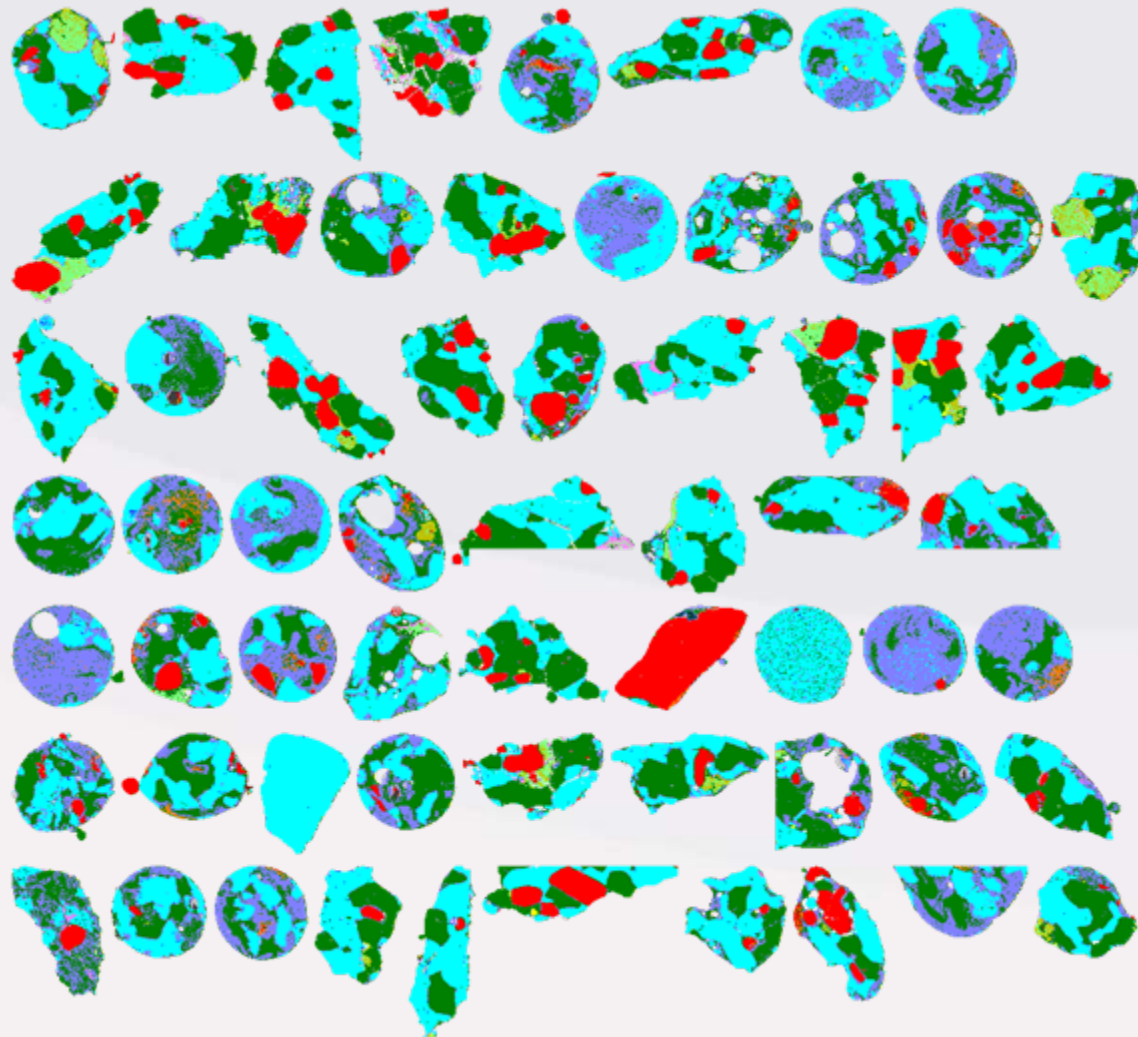
NU-LHT-1M Lunar Simulants Categorization



C.M. Schrader
C.M. Schrader
6/2/2008



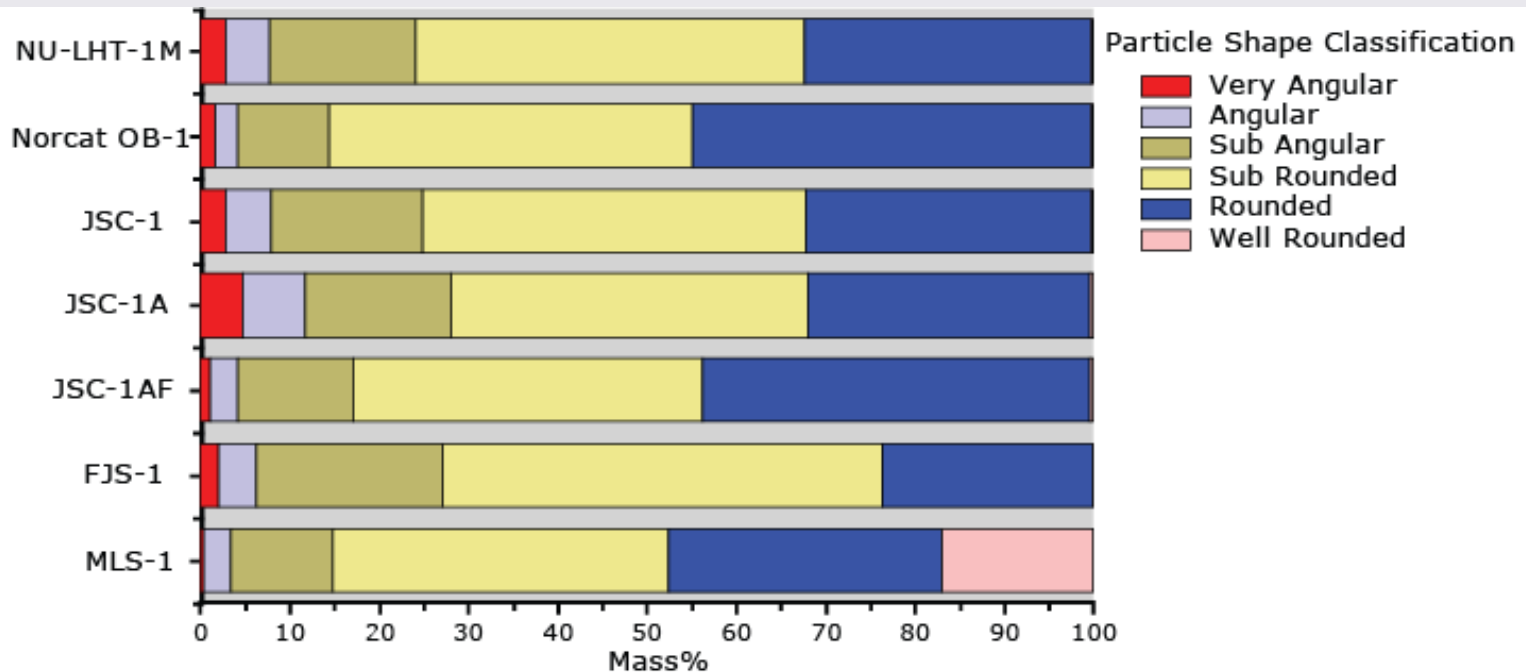
MLS-1: QEMSCAN[®] particle analysis



- Plagioclase
- Clinopyroxene
- Orthopyroxene
- Olivine
- K Feldspar
- MgFeAl Silicate
- Magnetite
- Chromite
- Ilmenite
- Sulphides
- Calcite
- Fe Silicate (Glass?)
- Ca Al Silicate (glass?)
- CaMgFe Glass
- TiSi Glass
- Iron
- Quartz
- Others



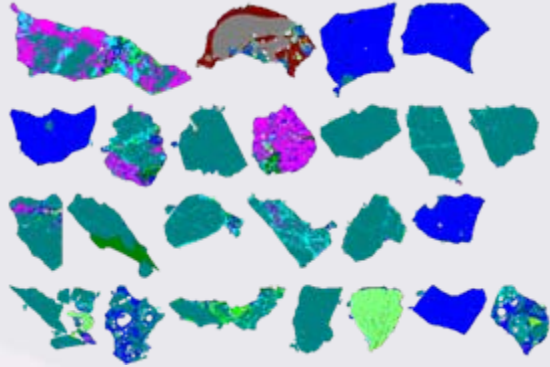
Results: QEMSCAN[®] determined particle shape














Particle Shape Classification	NU-LHT-1M	Norcat OB1	JSC-1	JSC-1A	JSC-1AF	FJS-1	MLS1
Very Angular	2.85	1.74	2.86	4.72	1.11	1.99	0.37
Angular	4.90	2.35	5.13	7.02	3.06	4.19	3.04
Sub Angular	16.33	10.35	16.98	16.34	12.97	20.92	11.47
Sub Rounded	43.67	40.74	42.94	40.02	39.15	49.21	37.49
Rounded	32.05	44.55	31.95	31.59	43.42	23.61	30.77
Well Rounded	0.20	0.27	0.14	0.31	0.30	0.07	16.86
Total	100.00	100.00	100.00	100.00	100.00	100.00	100.00



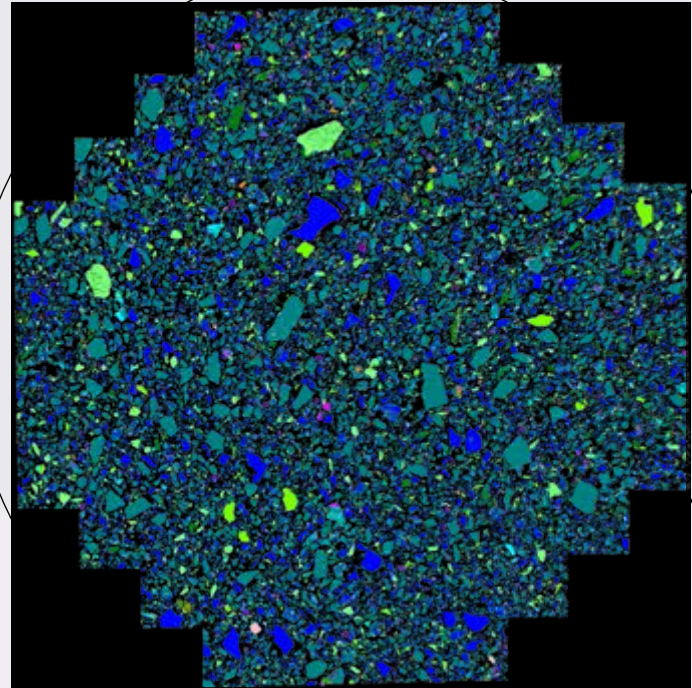
QEMSCAN® analysis



Example of particles delineated by image analysis.

-  Quartz
-  Plagioclase (Ab-An60)
-  Plagioclase (An60-An100)
-  K Feldspar
-  Clinopyroxene
-  Orthopyroxene
-  Olivine
-  Mg Silicates
-  Ca Al Silicate Glass
-  MgFeAl Silicate
-  CaMgFe Glass
-  Iron
-  Magnetite
-  Chromite
-  Ilmenite

Example of a mineral and phase list.



Mosaic images are particulated using off-line image analysis software, so that each measured particle can be examined and quantified for parameters such as modal composition, texture and shape.



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POINT OF CONTACT (If different from author)	E-MAIL	ADDRESS	
Joan R. Presson	Joan.R.Presson@nasa.gov	NSSTC, VP51 320 Sparkman Drive, Huntsville, AL 35805	
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