ASCE

Earth & Space Conference

A Virtual Conference | April 19–23, 2021

Engineering for Extreme Environments

An Overview of NASA Lunar Simulants

Short Course

April 19, 2021

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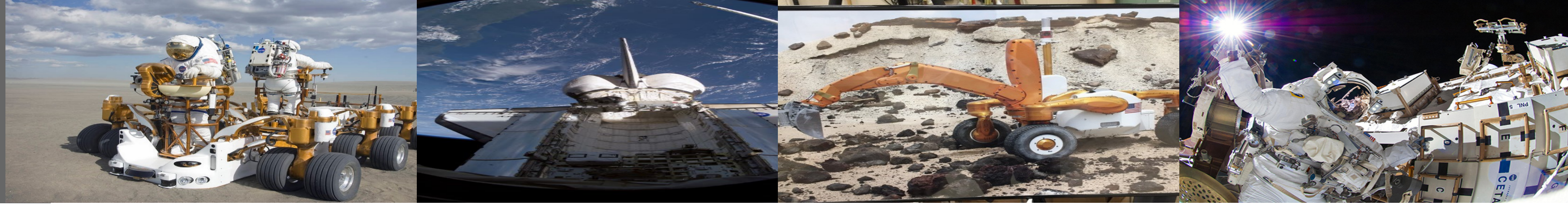
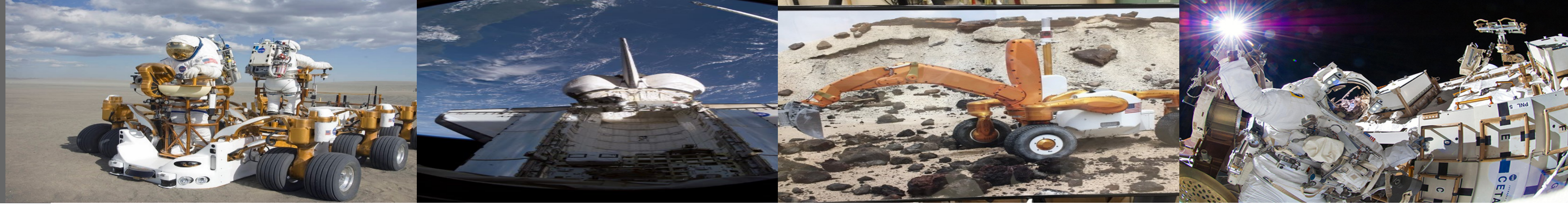
NASA Johnson Space Center

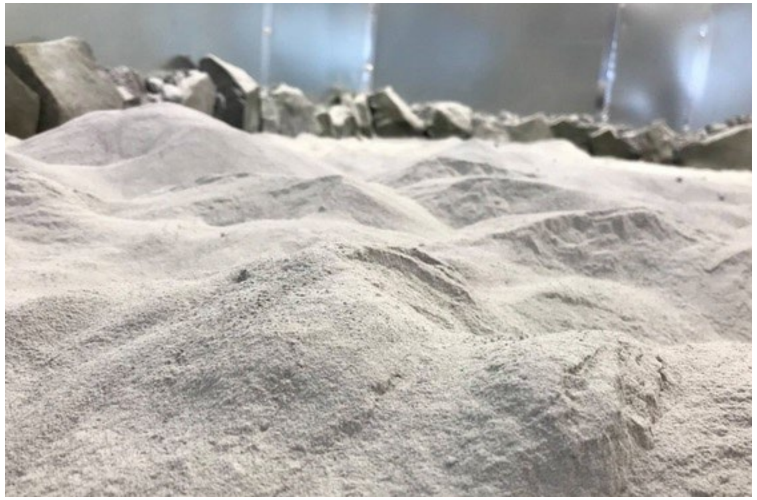


- **NASA Simulant Advisory Team**
  - John Gruener – JSC, planetary scientist, lead
  - Julie Mitchell - JSC, planetary geologist, icy regoliths
  - Jennifer Edmunson - MSFC, geologist, Constellation Program simulants
  - Doug Rickman - MSFC, geologist, Constellation Program simulants
  - Laurent Sibille - KSC, technology development scientist, Constellation Program simulants
  - Elizabeth Carey - JPL, geologist, icy regoliths
  - Julie Kleinhenz - GRC, engineer, testing involving simulants
  - Sarah Dietrick- JSC, geologist, early career
  - Brett Denevi, Karen Stockstill-Cahill – APL Lunar Surface Innovation Consortium (LSIC)

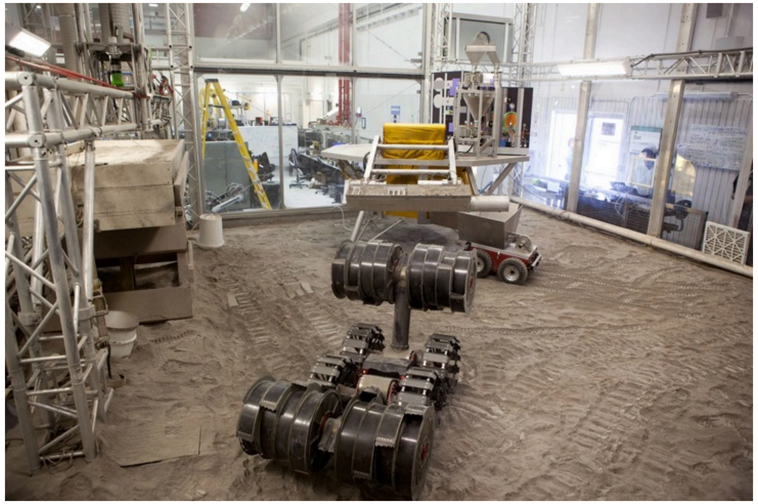
- Team discussions have included: STMD GCD/LSII Projects (i.e., Dust Mitigation, ISRU); APL LSIC simulant work; Commercial simulant providers (Exolith Labs, Off Planet Research, Hudson Resources, Outward Technologies, Deltion)



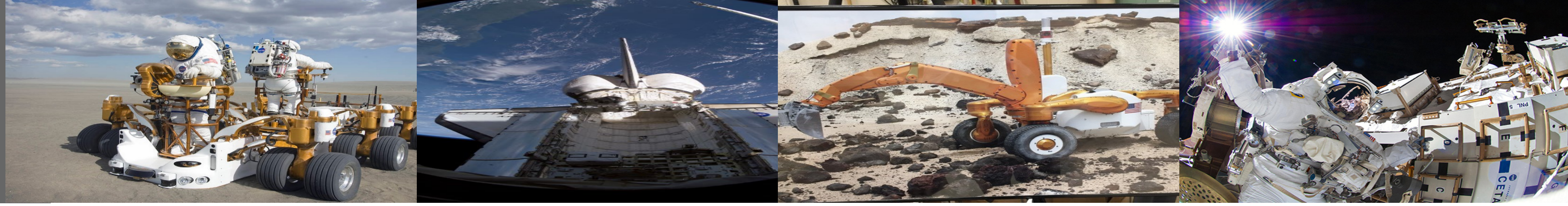
- Project Overview
  - Though lunar simulant is not a “technology” per se, every technology being developed by NASA STMD/GCD for use on the lunar surface needs to be tested with high quality lunar simulants
  - The primary objective of this project is a coordinated approach across NASA for simulant development and to support projects’ simulant needs with a variety of low-, moderate-, and high-fidelity lunar simulants
- Technical Capabilities
  - Correct simulant mineralogy, glass content, particle shape, and particle size distribution will be used to create simulants using appropriate equipment for lunar regions of interest (i.e., polar regions)
  - Technical 'tall poles' - production of lunar agglutinate simulant is difficult, time-consuming, and expensive, there is currently no large-scale production capability; same comment for simulants containing ice, and nano-phase iron
- Exploration & Science Applicability
  - Lunar simulants will be procured in sufficient amounts for earth-based testing of subsystems and systems in a variety of environments (i.e., laboratory, high-bay, thermal-vacuum chambers), required for Artemis missions to the Moon, as well as other missions carrying GCD lunar payloads (i.e., CLPS)



Off Planet Research lunar highlands simulant



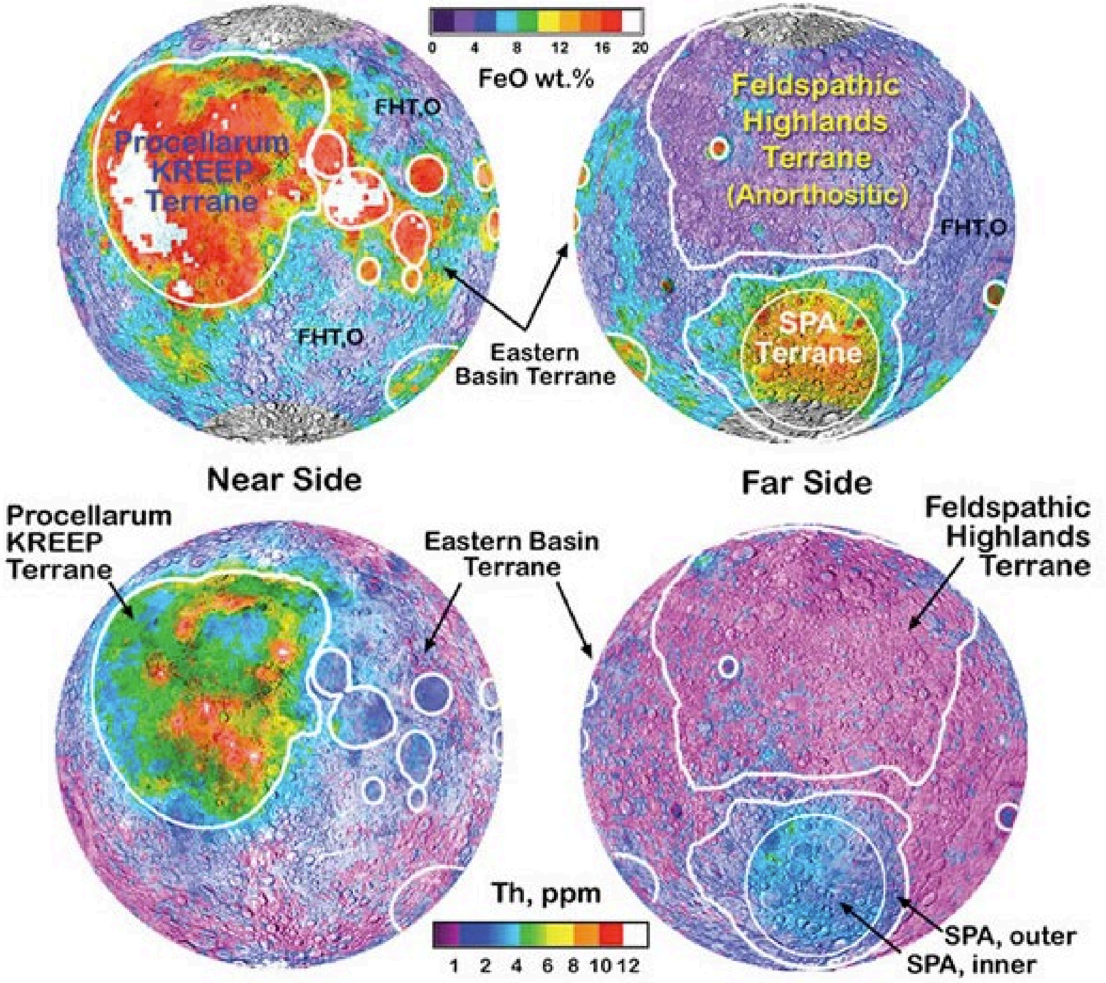
NASA RASSOR excavator testing at KSC in BP-1 lunar simulant



Lunar Regolith: the basis for simulants

Mare: mostly basalt lava rock (think Hawaii)

Highlands: mostly feldspathic rock, which is mostly plagioclase feldspar (think, well nothing easily comes to mind)



Jolliff et al. (2006) New Views of the Moon

Lunar Chemistry and Mineralogy – A Quick Primer
(from The Lunar Sourcebook)

Chemical Elements → Minerals → Rocks

Major rock-forming chemical elements

Oxygen (~60% of atoms)
Silicon (~16-17%)
Aluminum (~10%, highlands, ~4.5%, mare)
Calcium (~5%)
Magnesium (~5%)
Iron (~2.5%, highlands, ~6%, mare)
Titanium + Sodium (~1%)

OR

Oxygen (~45 wt%)
Silicon (~21 wt%)
Aluminum (~13 wt%, highlands, ~5 wt%, mare)
Calcium (~10 wt%, highlands, ~8 wt%, mare)
Iron (~6 wt%, highlands, ~15%, mare)
Magnesium (~5.5 wt%)
Titanium (< 1 wt%, highlands, ~1-5 wt%, mare)
Sodium (< 1 wt%)

PLUS

Many, many more minor and trace elements to act as 'irritants' to ISRU systems (i.e, sulfur)

Silicate minerals make up over 90% of the Moon - the Big 3

Pyroxene, $(Ca, Fe, Mg)_2Si_2O_6$
Plagioclase Feldspar, $(Ca, Na)(Al, Si)_4O_8$
Olivine, $(Mg, Fe)_2SiO_4$

Oxide minerals are 'next' most abundant (particularly concentrated in mare)

Ilmenite, $(Fe, Mg)TiO_3$
Spinel
- Chromite, $FeCr_2O_4$
- Ulvöspinel, Fe_2TiO_4
- Hercynite, $FeAl_2O_4$
- Spinel, $MgAl_2O_4$

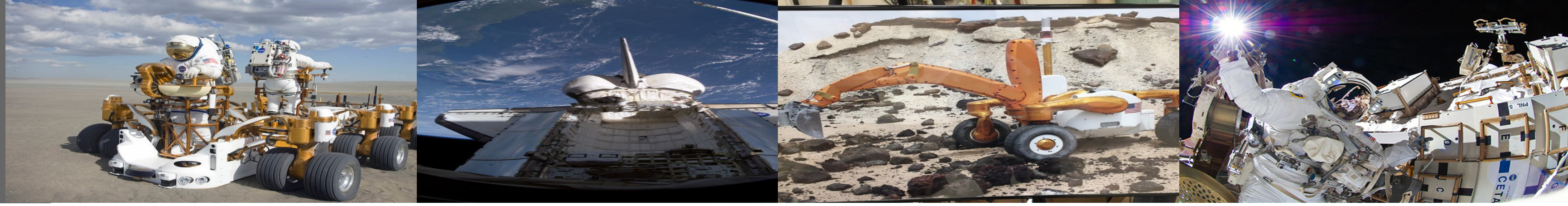
Armalcolite $(Fe, Mg)Ti_2O_5$ (only in Ti-rich mare)

Other minor minerals of note

Native iron, (Fe)
Troilite, FeS (holds most of the sulfur in lunar rocks)

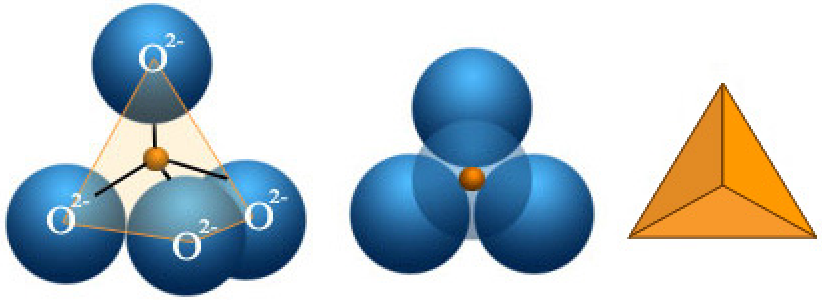
PLUS

Many, many more trace minerals [i.e., apatite, $Ca_5(PO_4)_3(OH, F, Cl)$]



Silicate Minerals

(from Danna Shrewsbury, www.slideplayer.com)



Three ways of drawing the silica tetrahedron:

a) At left, a ball & stick model, showing the silicon cation in orange surrounded by 4 oxygen anions in blue

b) At center, a space filling model

c) At right, a geometric shorthand model. This is the model favoured by geologists because of their simplicity.

Since the common rock forming minerals are all silicates it is worthwhile showing how the silicon tetrahedron is formed. The smaller Si^{4+} cation fits almost perfectly in the middle of a tetrahedron formed of larger O^{2-} anions.

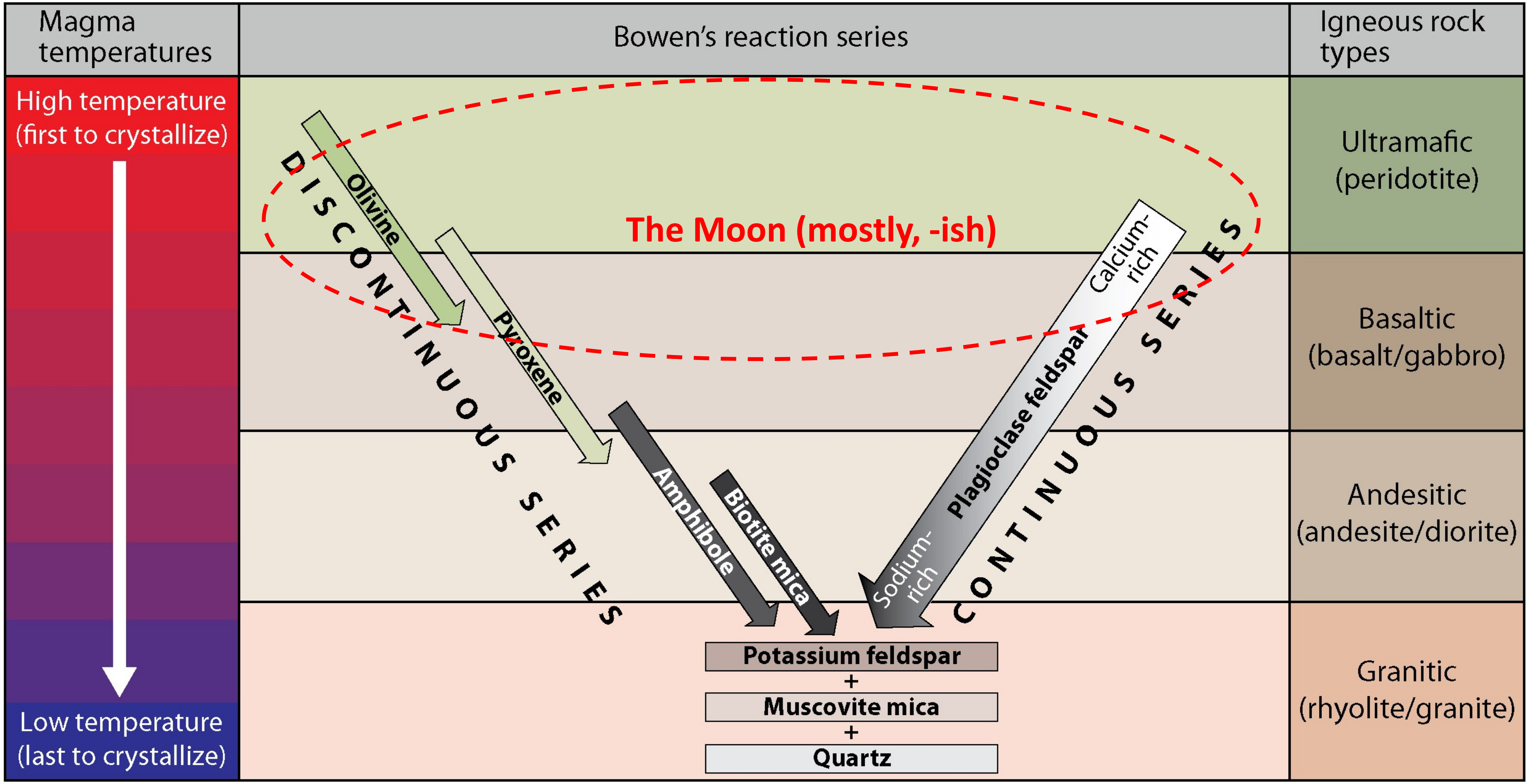
Silicates are network covalent solids that are very stable and have high melting points. Within silicate structures are metal cations – so ionic bonds are also found. The more ionic bonds in the structure, the more easily the mineral is broken down through chemical erosional processes.

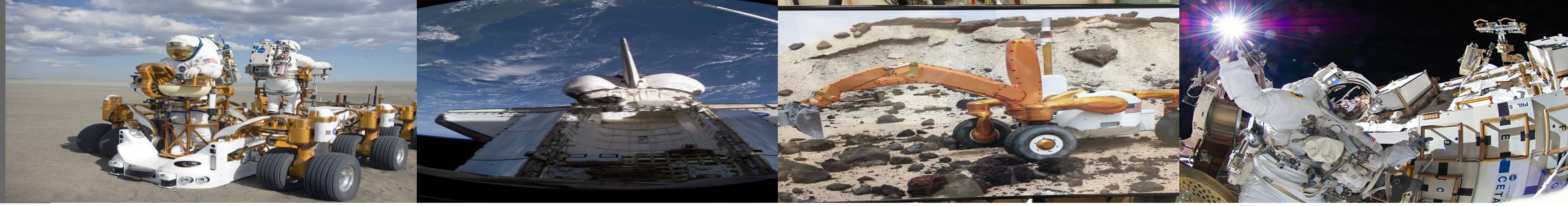
There are 7 classes of silicate minerals
Nesosilicates – isolated single tetrahedra (olivine)
Sorosilictaes – isolated double tetrahedra
Cyclosilictaes – rings of tetrahedra
Inosilicates – single (pyroxene) or double chains of tetrahedra
Phyllosilictates – sheets of tetrahedra
Tectosilicates – framework of tetrahedra (plagioclase)

Bowen's Reaction series

(from www.nps.gov, photo gallery, National Park Service)

Chemical Elements → Minerals → Rocks





Basalt: The most common rock in the inner solar system (the dark areas on the Moon)

(from NASA RELAB Facility at Brown University)

Primary Elements
O, Si, Ca, Al, Mg, Fe, (Ti)

→

Primary Minerals
Pyroxene
Plagioclase Feldspar
Olivine

→

Dominant Rock Type
Basalt

Bulk chemistry (oxides wt %)	Low-Ti basalt (15071)-52	Medium-Ti basalt (12030)-14	High-Ti basalt (71501)-35
SiO_2	46.07	46.25	31.87
TiO_2	1.89	3.32	9.52
Al2O$_3$	13.87	11.70	11.83
Cr2O$_3$	0.44	0.43	0.43
MgO	10.88	9.42	9.49
CaO	10.52	9.78	10.36
MnO	0.19	0.20	0.22
FeO	13.87	16.27	16.05
Na_2O	0.40	0.46	0.38
K_2O	0.16	0.29	0.09
P_2O_5	0.15	0.25	0.06
SO_2	0.11	0.12	0.19

Source: RELAB

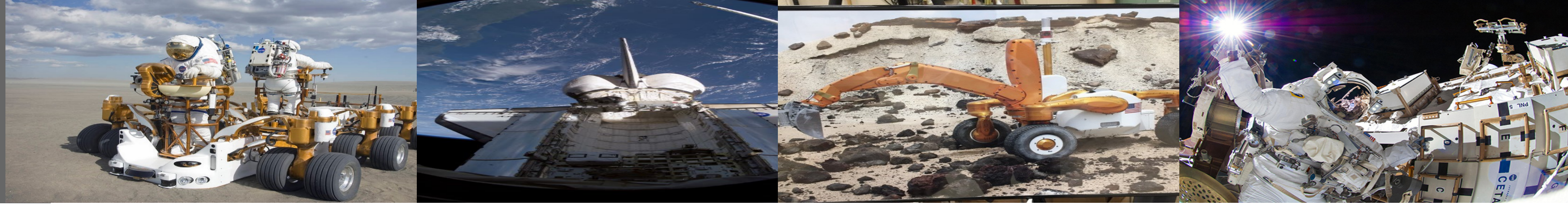
How a geochemist describes basalt

Modal abundance of minerals (wt %)	Low-Ti basalt (15071)-52	Medium-Ti basalt (12030)-14	High-Ti basalt (71501)-35
Ilmenite	1.63	2.93	9.86
Plagioclase	19.10	15.76	18.76
Pyroxene	16.56	23.50	14.60
Olivine	2.86	3.50	3.40
Agglutinitic glass	52.16	48.06	45.40
Volcanic glass	3.90	1.43	6.70
Others	3.76	4.80	1.30

Source: RELAB

How a mineralogist or petrologist describes basalt

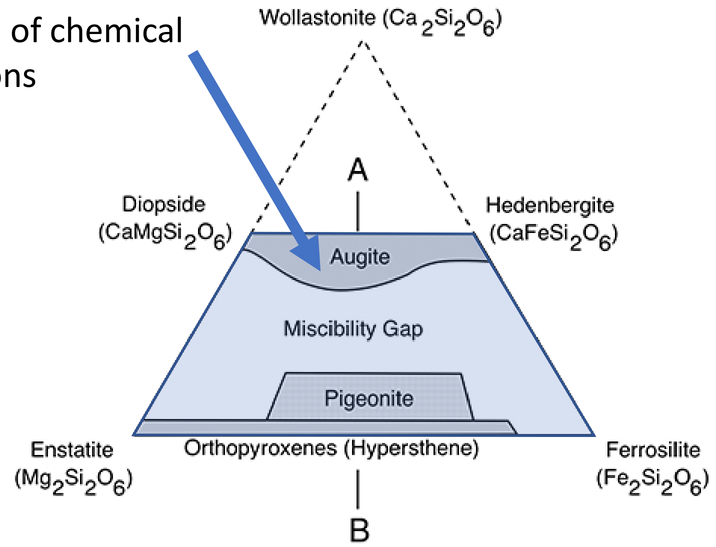
This causes confusion!



Pyroxene: A silicate mineral

Augite $(Ca,Na)(Mg,Fe,Al)(Al,Si)_2O_6$

Note: Augite can have a wide range of chemical compositions



Pyroxene Quadrilateral, from:
http://www.alexstrekeisen.it/english/pluto/pyroxene.php

Even if you break these metal-oxygen bonds, the oxygen is still tightly bound in the silica tetrahedra

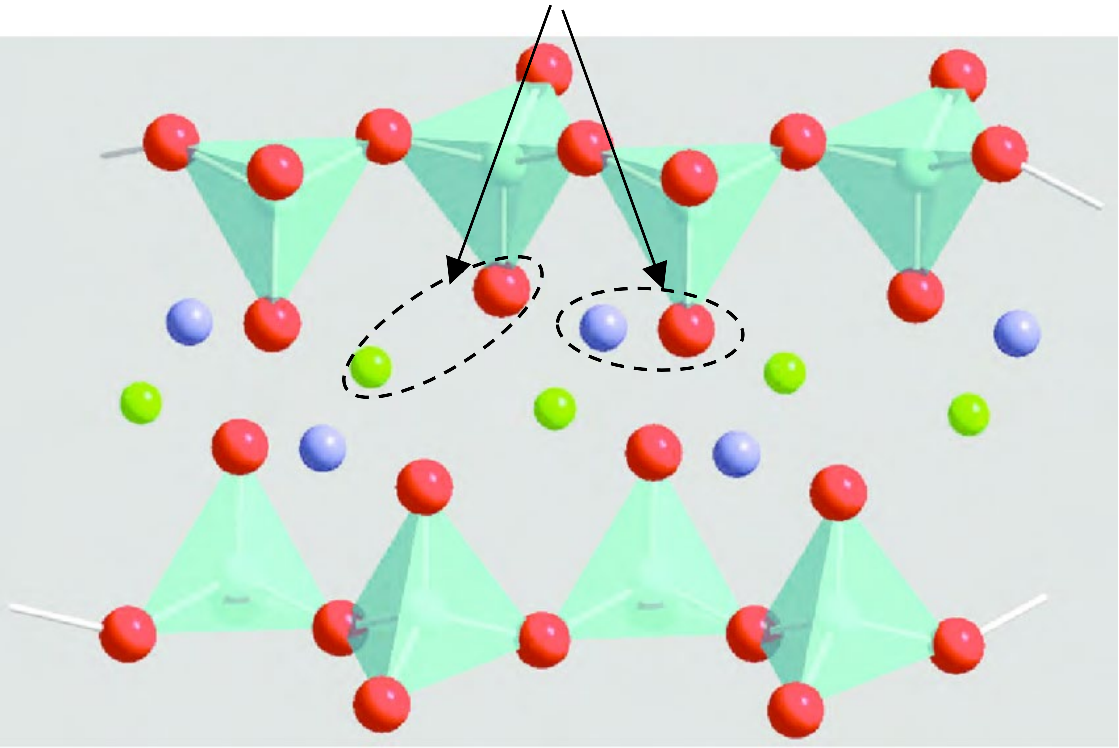
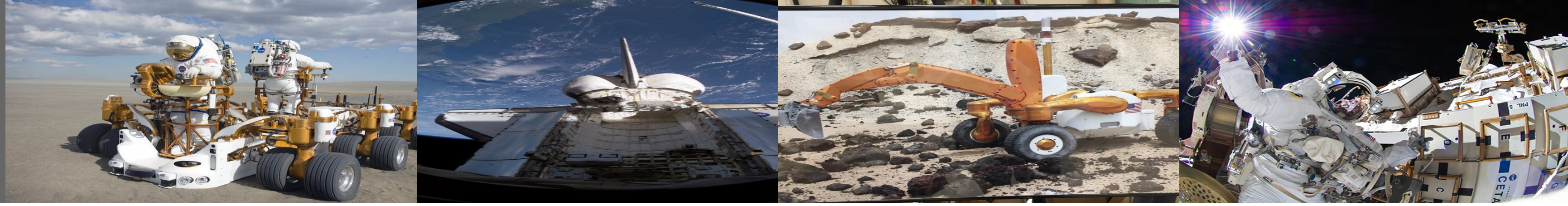
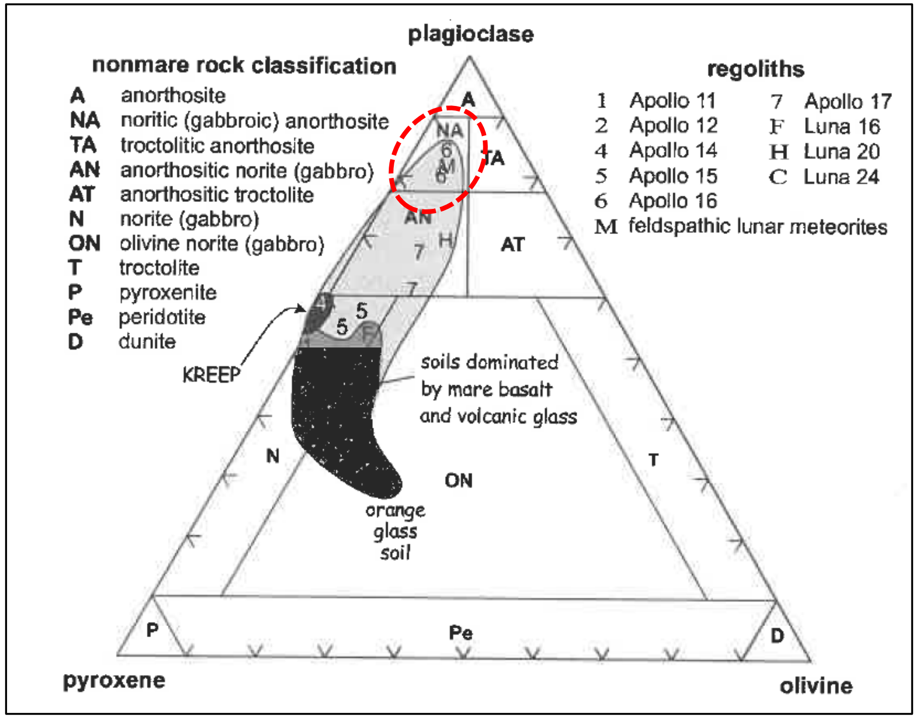


Figure 9. Section of the Augite crystal structure. The gaps within the parallel silicate chains are occupied by the metal ions calcium or iron (blue), magnesium or aluminium (green).

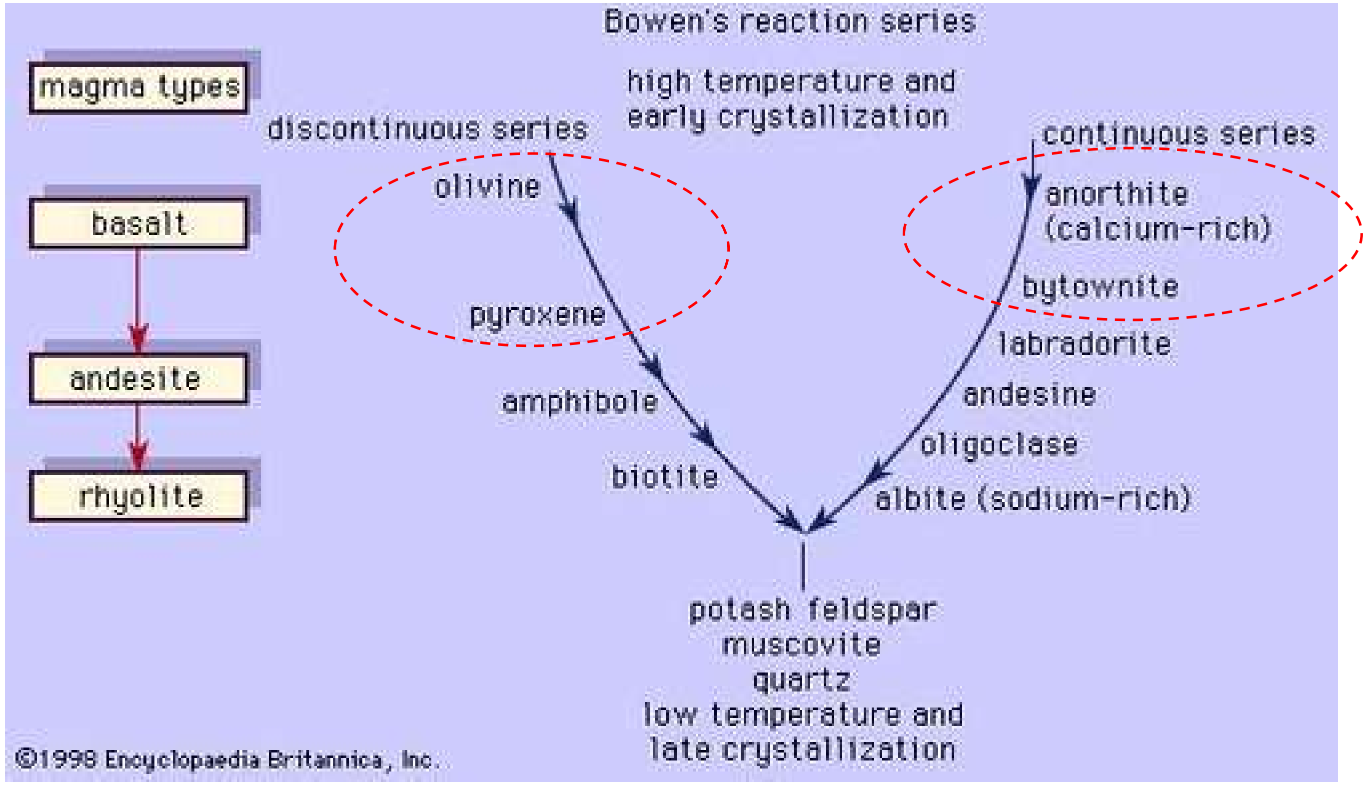
From: https://www.researchgate.net/figure/Abbildung-9-Ausschnitt-der-Kristallstruktur-des-Augits-In-die-Zwischenraeume-der_fig3_275580379



So, what can we expect at the Lunar Poles?



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



<u>Primary Elements</u>

O, Si, Ca, Al, Mg, Fe

<u>Primary Minerals</u>

Anorthite (Ca-rich plag)
Pyroxene
Olivine

<u>Dominant Rock Types</u>

Anorthosite (plag)
Norite (plag + pyx)
Troctolite (plag + ol)

NOTE: ISRU oxygen from regolith processes used at the lunar poles will have to be able to break apart the Si-O tetrahedra

Classic basis for lunar polar simulants

From The Lunar Sourcebook (1992, Cambridge University Press)

Apollo 16 highlands soil (closest to polar soil)

<u>By volume</u>

~17-64%	highlands lithics (i.e., anorthosite)
~21-45%	fused soil (agglutinates + breccias)
~12-33%	plagioclase
~1-3%	glass (i.e., impact)
~1-2%	mare lithics (i.e., basalt)
~1-2%	mafic (i.e., pyroxene, olivine)

<u>Dominant rock and rock fragments</u>

Anorthosite (i.e., plagioclase>>>>pyroxene>>olivine>others)

<u>Dominant mineral and mineral fragments</u>

Plagioclase feldspar

<u>Lesser minerals</u>

Pyroxene, Olivine, others

Agglutinate = rock fragments + mineral fragments + impact glass

Breccia = complex rock composed of fragments of older rocks, created by heat and shock associated with impacts

Highland lithics + plagioclase = 50-76 vol %

Agglutinates + glass + breccia = 22-48 vol %

Mare lithics + mafic minerals < 5 vol %

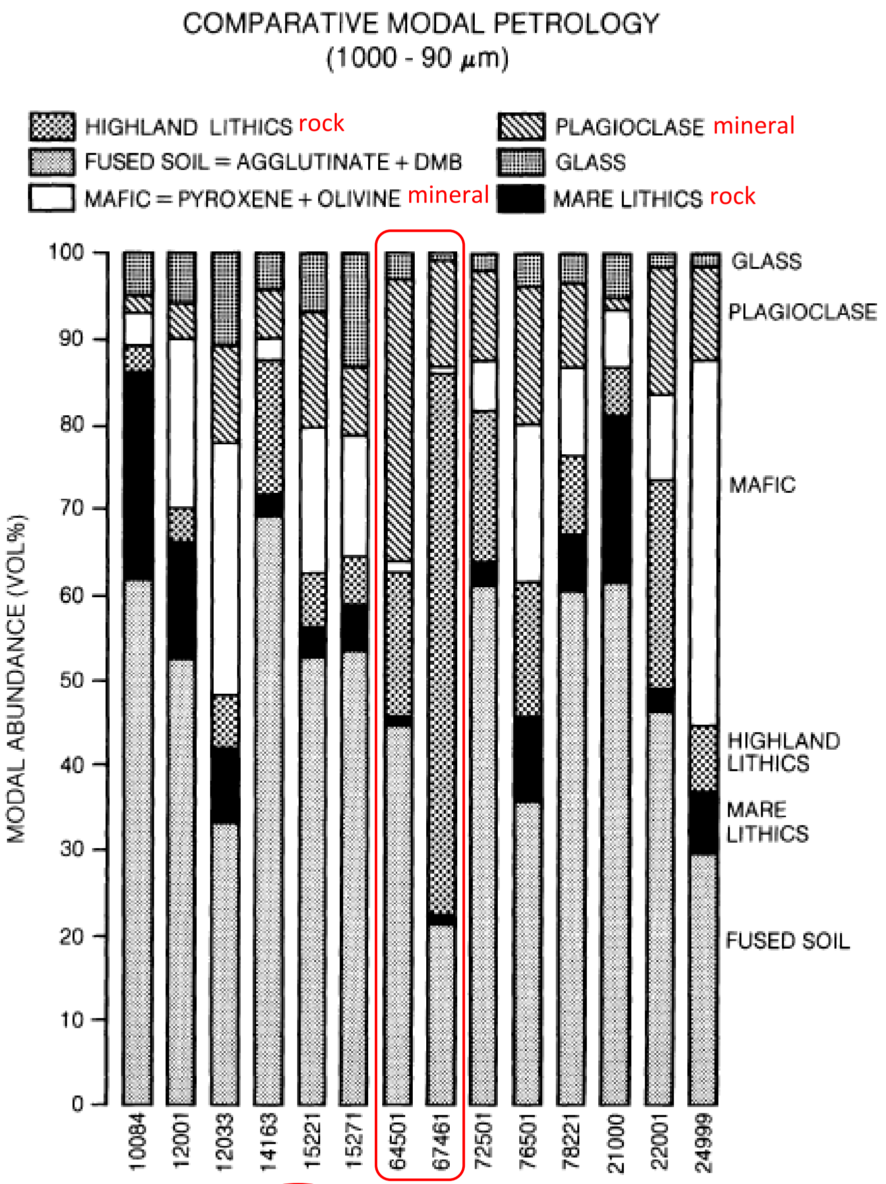
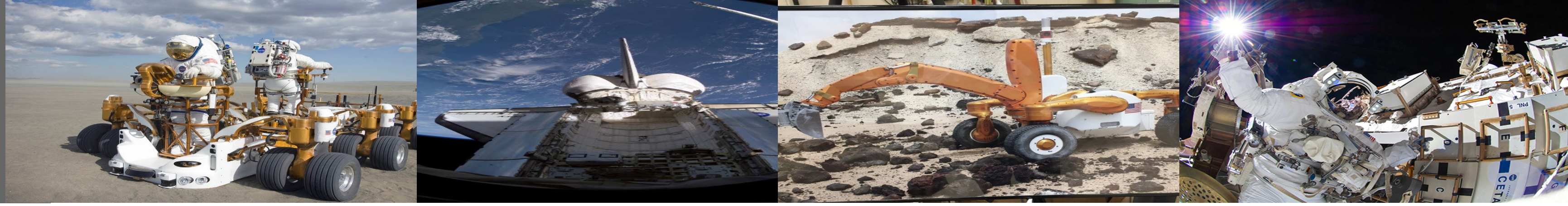
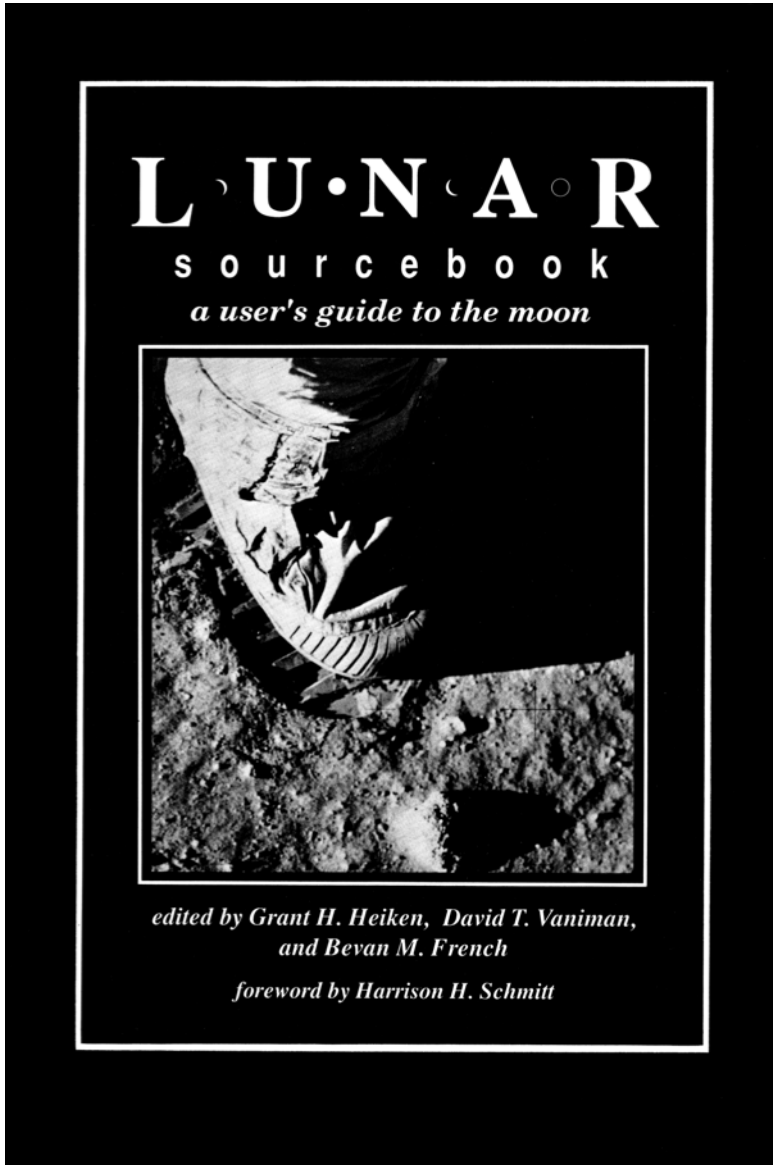


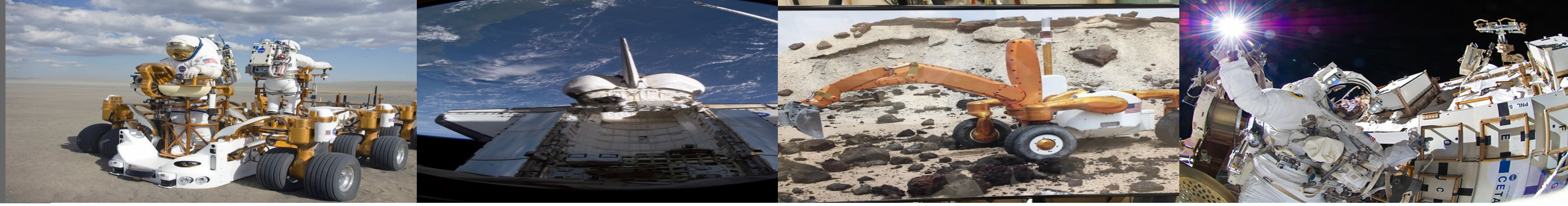
Fig. 7.1. Bar graphs showing modal (volume) abundances of principal particle types in 14 lunar soil samples (*Simon et al.*, 1981). This diagram distinguishes between rock fragments (mare lithics, highland lithics), single mineral and glass fragments (pyroxene and olivine, plagioclase, glass), and fused soil (agglutinates and dmb—Dark Matrix Breccia). Soil samples are from Apollo 11 (10084), Apollo 12 (12xxx), Apollo 14 (14163), Apollo 15 (15xxx), Apollo 16 (6xxxx), Apollo 17 (7xxxx), Luna 16 (21000 and 22001), and Luna 24 (24999).





The Lunar Sourcebook is free to download

https://www.lpi.usra.edu/publications/books/lunar_sourcebook/



Cross Program Design Specifications for Natural Environments (DSNE)

- SLS-SPEC-159 Revision H, Effective Date August 12, 2020
- https://ntrs.nasa.gov/api/citations/20205007447/downloads/SLS-SPEC-159%20Cross-Program%20Design%20Specification%20for%20Natural%20Environments%20(DSNE)%20REVISION%20H.pdf

National Aeronautics and Space Administration

SLS-SPEC-159
REVISION H
EFFECTIVE DATE: AUGUST 12 , 2020

CROSS-PROGRAM
DESIGN SPECIFICATION FOR
NATURAL ENVIRONMENTS (DSNE)

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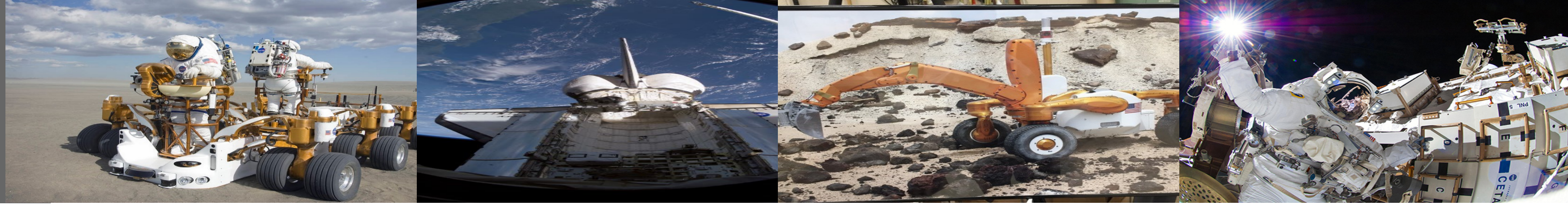


Particle Size Distribution (Section 3.4.2.2.1)

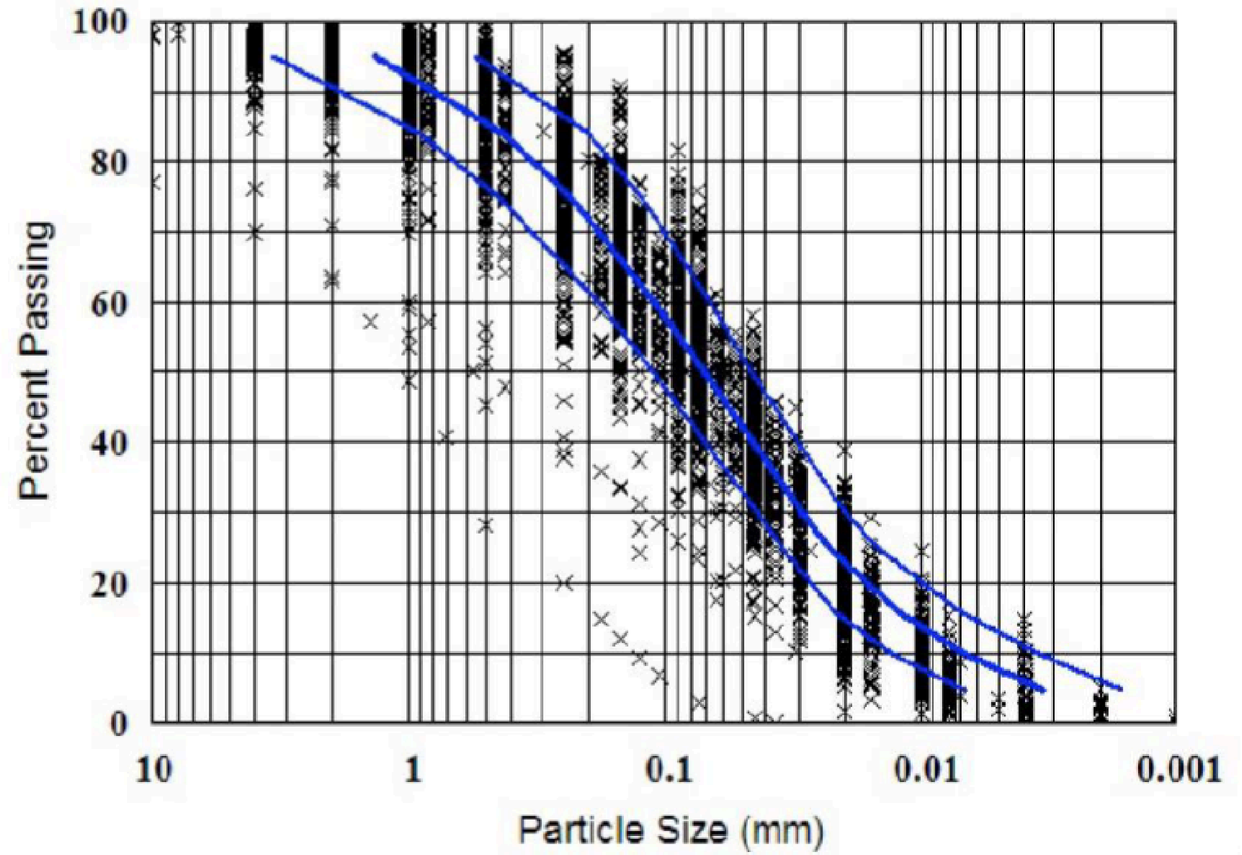
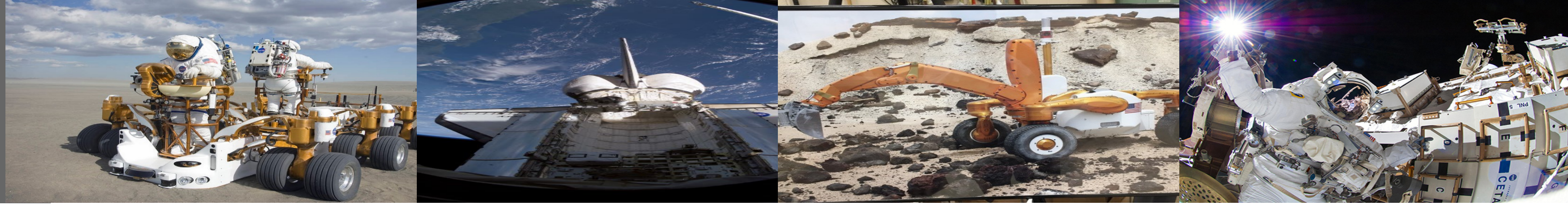


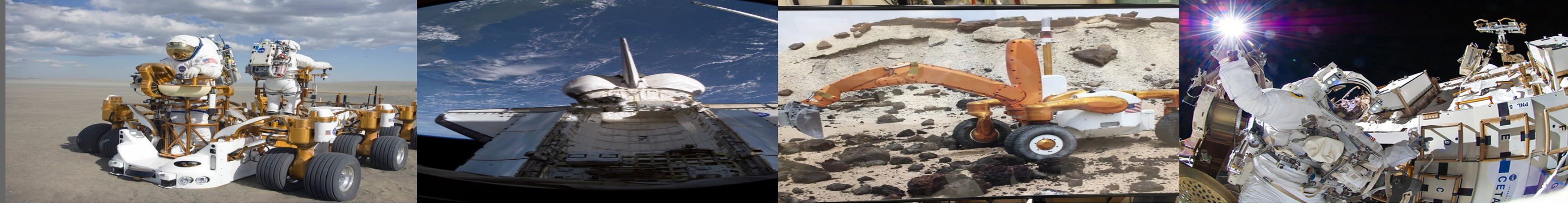
Figure 3.4.2.2.1-1 Geotechnical particle size distribution: middle curve showing the average distribution; left-hand and right-hand curves showing ± 1 standard deviation (from Carrier 2003).



Particle Shape (Section 3.4.2.2.2)

Table 3.4.2.2.2-1 Summary of grain-specific properties (<1mm size-fraction)

Property	Value	Units	Notes	Section	Sources
Sorting	1.99 - 3.73: range	ϕ	Very poorly sorted	3.4.2.2.2.1	Heiken et al. 1991
Elongation	1.32 - 1.3835: range; 1.35: avg	-	Somewhat elongated	3.4.2.2.2.2	
Aspect ratio	0.3 - 0.9: range; 0.55: avg	-	Slightly to medium elongation	3.4.2.2.2.3	
Roundness	0.19 - 0.29: range; 0.21: avg	-	Subangular to angular	3.4.2.2.2.4	
Volume Coefficient	0.32 - 0.35: range; 0.3: avg	-	-	3.4.2.2.2.5	
Specific Surface Area	0.4 - 0.78: range; 0.5: avg	$m^2\ g^{-1}$		3.4.2.2.2.6	



Particle Shape (Section 3.4.2.2.2)

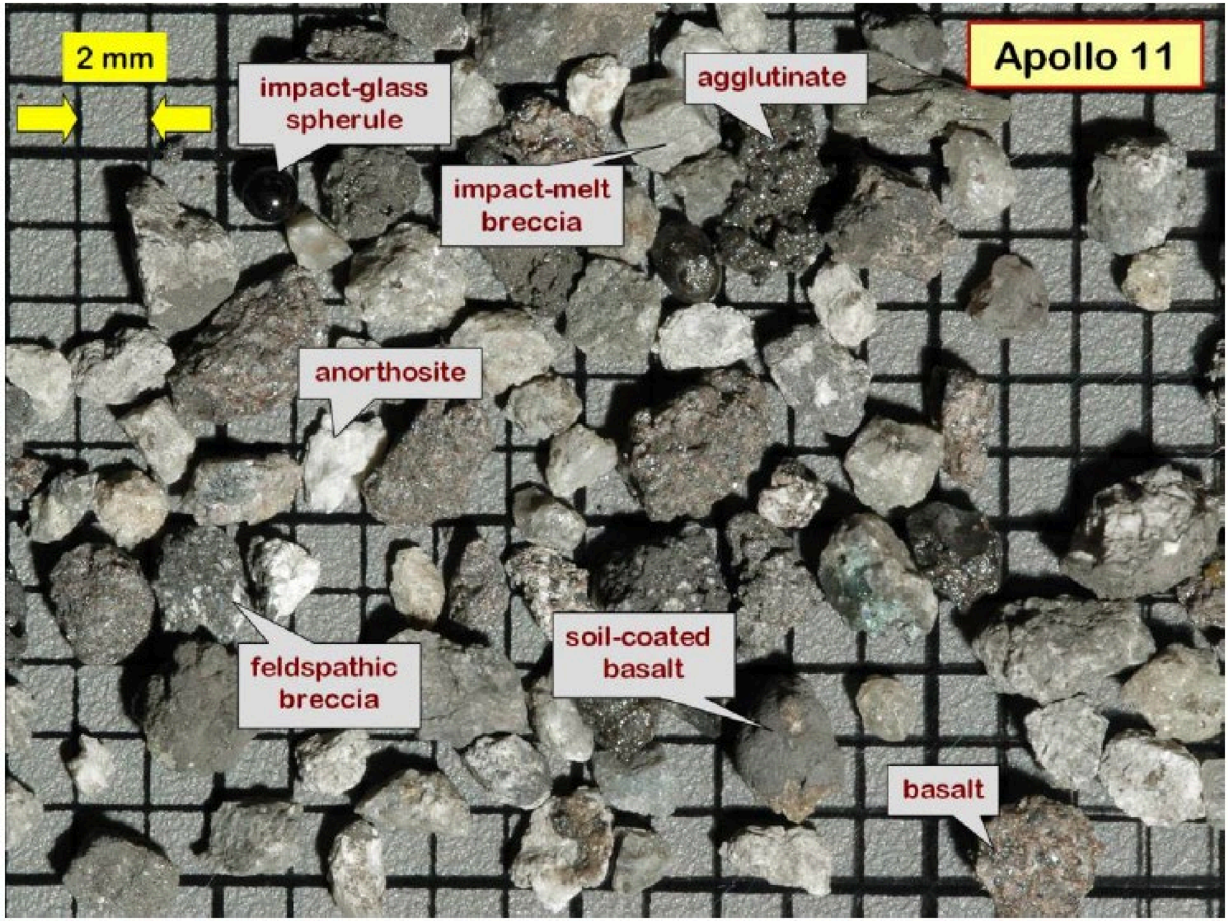


Figure 3.4.2.2.2-2 Apollo 11 regolith fragments from the 2-4 mm grain-size fraction. Note the diversity in shapes and angularity, including two impact-glass spherules. (Photo Credit: Randy Korotev, http://meteorites.wustl.edu/lunar/regolith_breccia.htm).

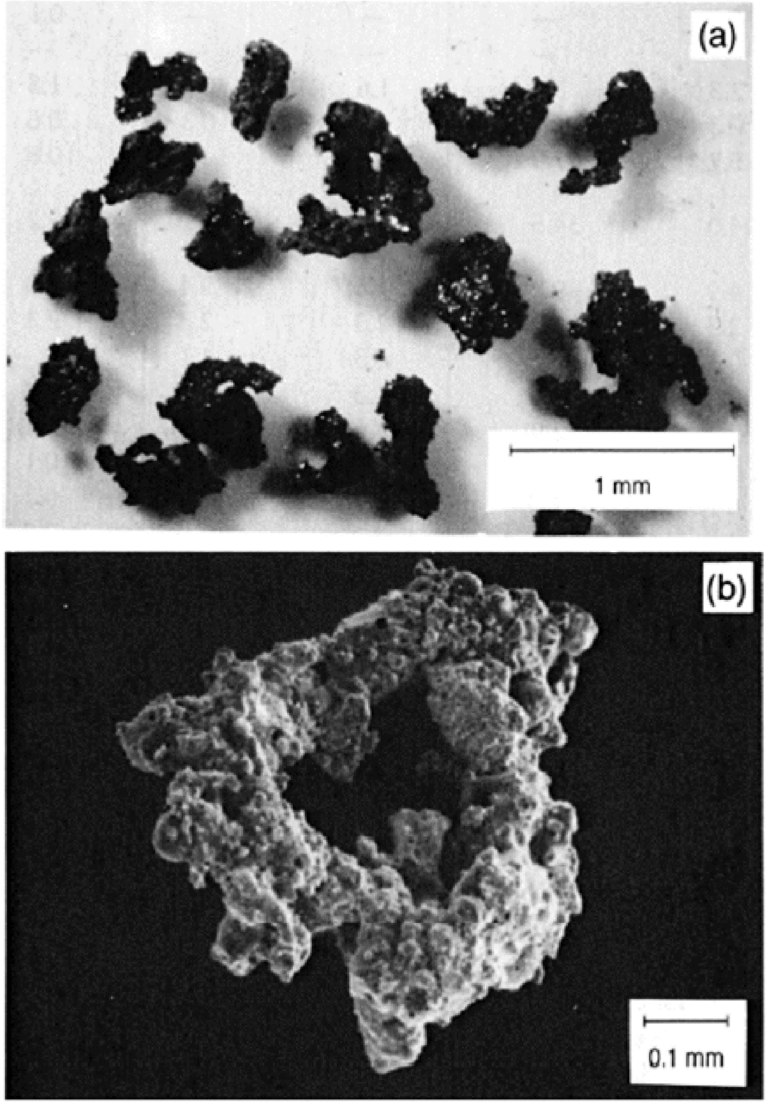
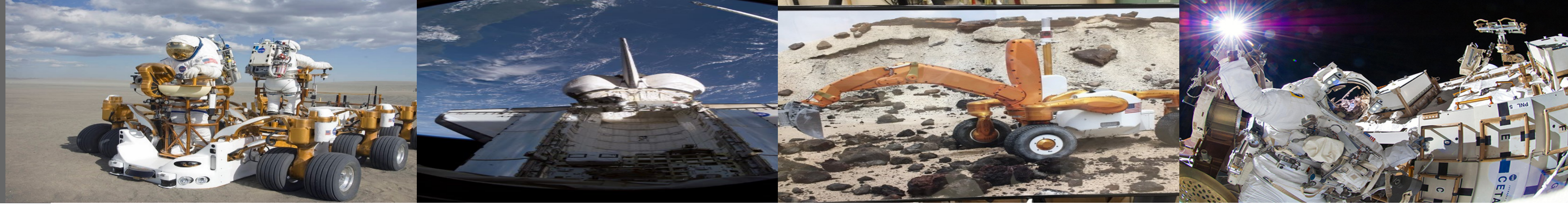


Figure 3.4.2.2.2-1 Typical lunar soil agglutinates.



Limitations with Terrestrial Feedstock

- We live on a water world
  - Many hydrated minerals typically found with the targeted lunar-like minerals (plagioclase, pyroxene, olivine)
    - Amphiboles - e.g., hornblende $(Ca, Na)_{2\text{-}3}(Mg, Fe, Al)_5Si_6(Si, Al)_2O_{22}(OH)_2$
    - Micas – e.g., muscovite $KAl_2(AlSi_3O_{10})(OH)_2$
    - Apatite $Ca_5(PO_4)_3(F, Cl, OH)$
  - Minerals associated with chemical weathering are also present
    - Clays – e.g., kaolinite $Al_2Si_2O_5(OH)_4$
    - Quartz SiO_2

- We live on a world teaming with life
  - Many carbon-bearing minerals typically found with the targeted lunar-like minerals
    - Calcite $CaCO_3$
    - Dolomite $CaMg(CO_3)$
  - Volcanic ash and mineral sands may have plant material (e.g., roots)
  - Lunar regolith has very little carbon content, typically ≤ 100 μg/g implanted by the solar-wind

- The 'rock-loving' lithophile elements Na and K are depleted on Moon compared to Earth
  - This affects the melting and melt viscosity of lunar minerals vs simulants, particularly plagioclase

Major North American Anorthosite Sources

White Mountain

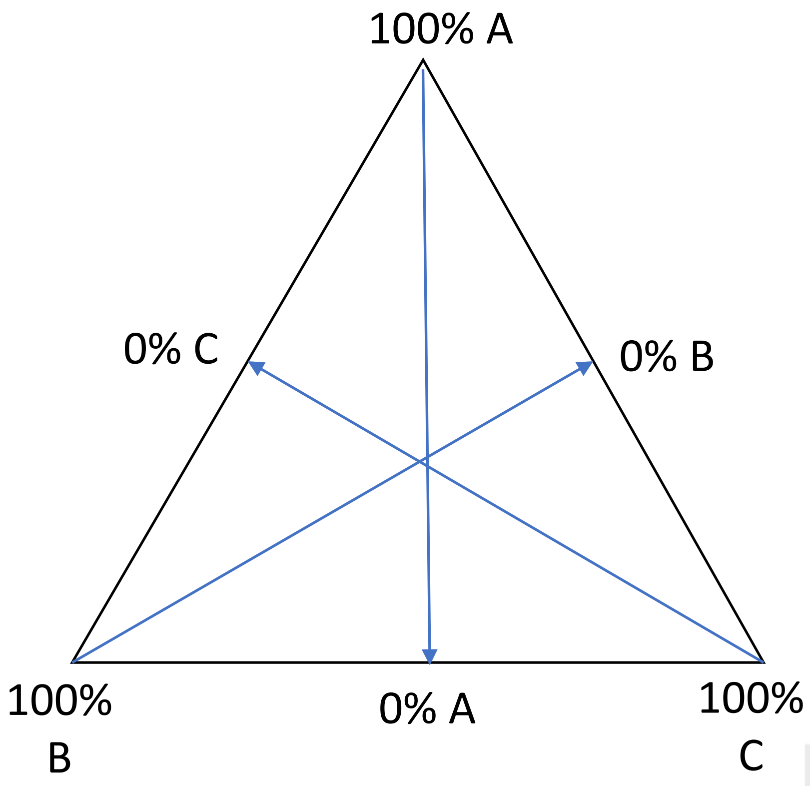
Stillwater

Shawmere

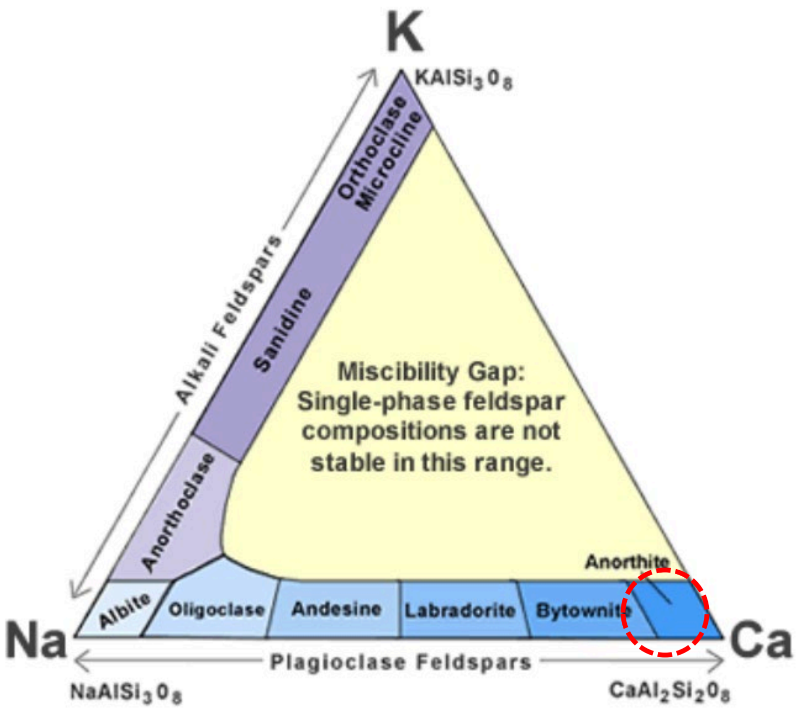
Deposit	Shawmere (OB-1, Chenobi)	Stillwater (NU-LHT)	White Mountain (GreenSpar)
Location	Near Foleyet, Ontario, Canada	Near Nye, MT, USA	Near Itivdleq, Greenland
Mining Co.	Various	Stillwater Mining Co.	Hudson Resources, Inc.
Mined for	Filler, plastics and paper production, cement and glass manufacture	Platinum	E-glass, paint, coating fillers, alumina, white cement
An content of plagioclase*	Average 78 (68-95, with areas of higher An content in rocks with lower plagioclase percentage)	75-88 (depends on the layer, An 70-80 are more common in Stillwater deposits)	78-86 (calculated as 87 based on analysis presented in Hudson Resources' presentation)
Trace phases (depends on proximity to alteration zones)	Apatite, zircon, hornblende, garnet, biotite, muscovite, calcite, epidote/clinozoisite, and chlorite	Biotite, olivine, pyroxene, chromite, augite, quartz, albite, zoisite, epidote, chlorite, amphibole, and calcite	Quartz, epidote/clinozoisite solid solution phases, muscovite, trace carbonate
Comments	The Shawmere Complex is not uniform – plagioclase content varies from 25-85% of the rock, various areas of metamorphism and alteration are present.	Note that Stillwater does not mine the anorthosite deposit. Geologists must pick rocks by hand for simulant feedstock.	Areas of metamorphism and alteration are present.

*An resources: Shawmere, Battler and Spray (2009) and Simmons et al. (1980); Stillwater, Page et al (1985), Meurer and Boudreau (1996); White Mountain, Polat et al. (2018)

Lunar South Pole Ternary Plots

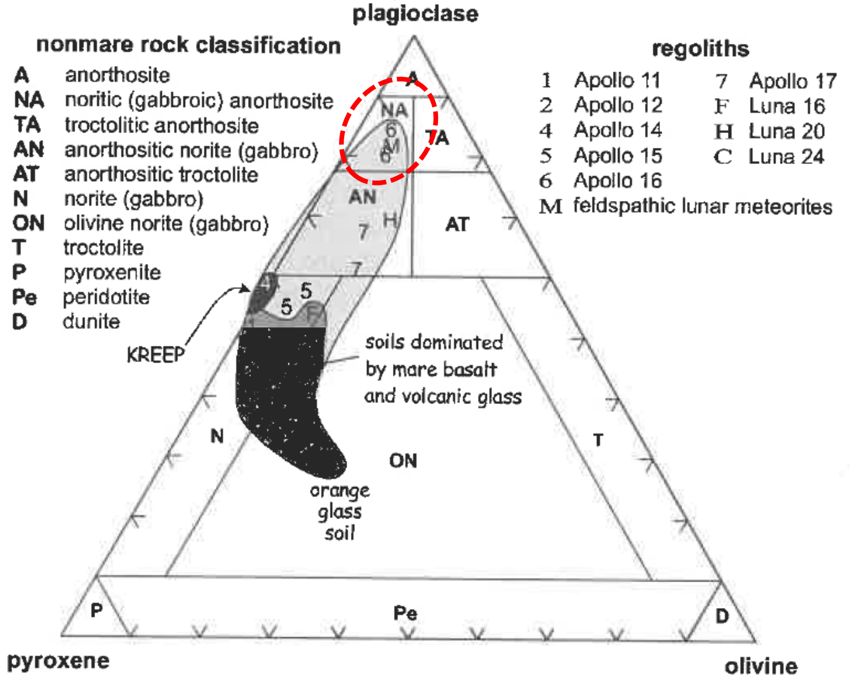


Basic three-variable ternary plot, where any vertex represents a composition of 100% of that variable. The side of that triangle opposite of that vertex represents 0% of that variable.

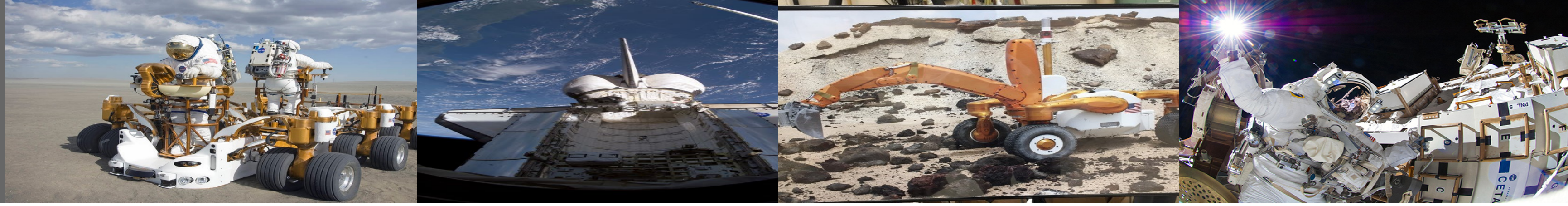


Feldspar classification: This diagram shows how feldspar minerals are classified on the basis of their chemical composition. The sequence of minerals along the base of the triangle represents the solid solution series of plagioclase between albite and anorthite.

[Red dashed circle represents what we expect at the lunar south pole. From https://geology.com/minerals/plagioclase.html]



Nonmare Rock Classification: Red dashed circle represents what we expect at the lunar south pole. Not pure plagioclase, but close. [From New Views of the Moon (Jolliff, et al., 2006), p. 91]



Example: A Plagioclase Challenge

- Lunar highland regolith (including the poles) is predominantly plagioclase, which is the basis for the many highland simulants (e.g., NU-LHT series, LHS-1, OPRH series, GreenSpar)

  Plagioclase consists of sodium (Na) and calcium (Ca) components, but in varying ratios

  More Na will decrease viscosity (i.e., make a melt more fluid)

  More Ca will increase viscosity (i.e., make the melt ‘thicker’ and less fluid)

- Lunar plagioclase has higher Ca content than the vast majority of terrestrial plagioclase, which form the basis of lunar simulants

  The An (Anorthite) number is the ratio of Ca / (Ca + Na)

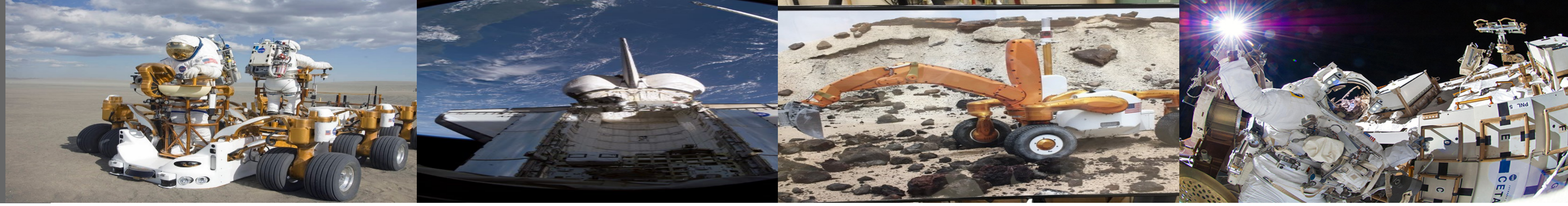
  Anorthite is the Ca-rich endmember plagioclase solid solution series (see previous chart)

  Melt viscosity increases with increasing An number

  Lunar plagioclase An number ~ 95

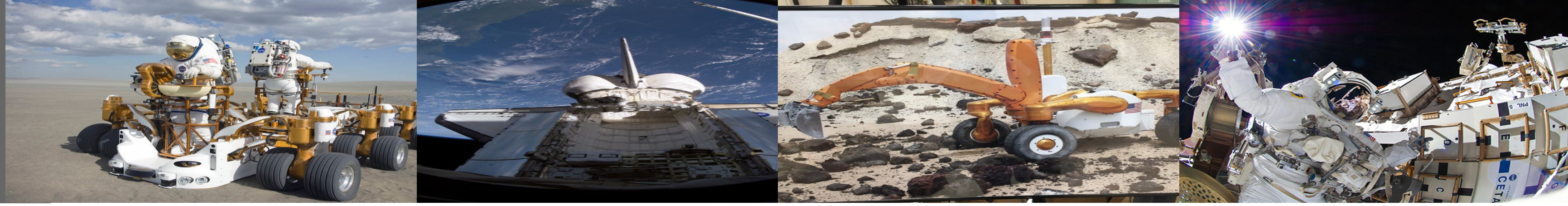
  Best simulant An number in high 80’s

- Increasing the An number will also increase the melting point temperature of the simulant



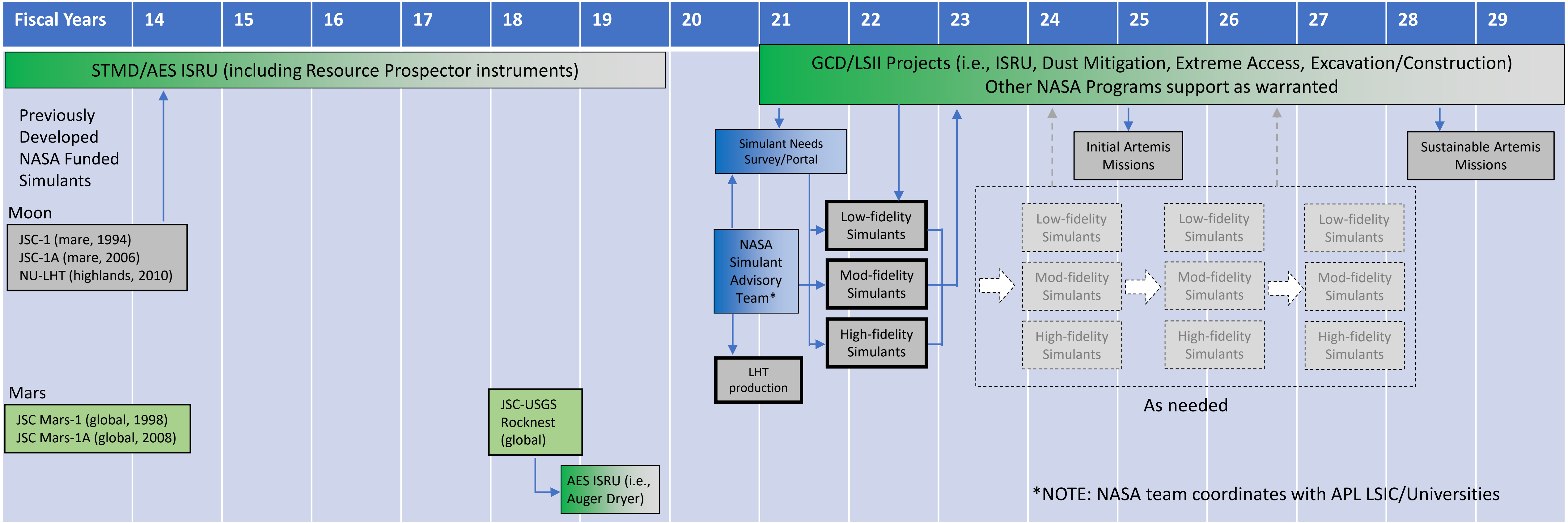
NASA's approach to lunar simulants

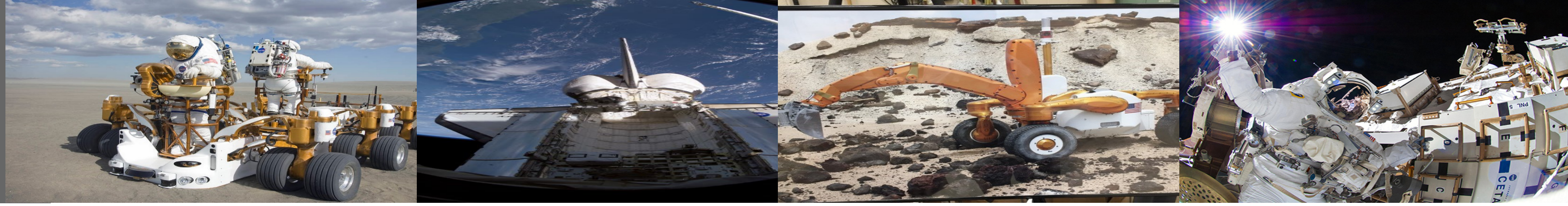
- Lunar simulants will be procured in sufficient amounts for earth-based testing of subsystems and systems in a variety of environments (i.e., laboratory, high-bay, thermal-vacuum chambers), required for Artemis missions to the Moon, as well as other missions carrying GCD lunar payloads (i.e., CLPS)
- Overall Concept
  - The primary objective of this project is a coordinated approach across NASA for simulant development and to support projects' simulant needs with a variety of low-, moderate-, and high-fidelity lunar simulants
  - The project includes a small team of NASA personnel (civil servants and contractors)
  - Purchase simulants from existing vendors when possible; government development and production when warranted
  - Coordinate with JHU/APL Lunar Surface Innovation Consortium
- Technologies to Enable the Concept
  - Correct simulant mineralogy, glass content, particle shape, and particle size distribution will be used to create simulants using appropriate equipment for lunar regions of interest (i.e., currently polar regions)
- Interface Needs/Requirements
  - NASA's simulant needs, requests and recommendations are coordinated and tracked on a NASA Simulant Portal
  - A similar service is in development with JHU/APL Lunar Surface Innovation Consortium for non-NASA needs



NASA's approach to lunar simulants and timeline

Though lunar simulant is not a “technology” per se, every technology being developed by GCD for use on the lunar surface needs to be tested with high quality lunar simulants



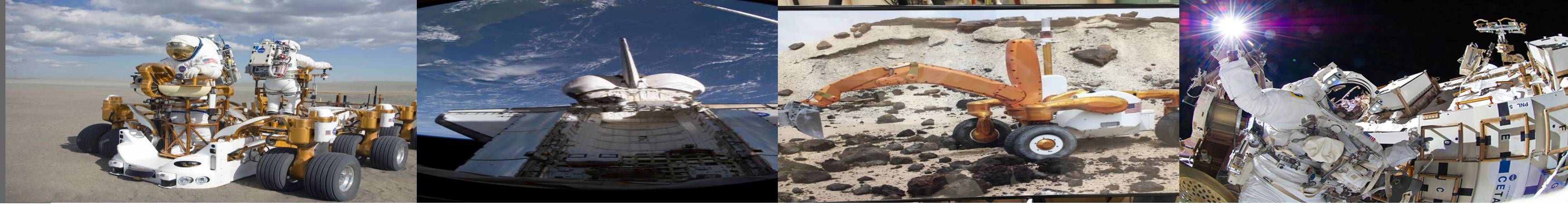


Key Performance Parameters

Increasing complexity, lead-time, and cost

Parameter	State of the Art	Threshold Value	Project Goal
KPP 1: Basic simulants (i.e., low fidelity; partial mineralogy and particle size distribution(PSD) match)	commercial availability	N/A	N/A
KPP 2: Standard simulants (i.e., moderate fidelity; correct mineralogy for major minerals, decent match to PSD, and particle shape)	commercial availability	N/A	N/A
KPP 3: Enhanced simulants (i.e., high fidelity; mostly correct mineralogy, PSD, and particle shape + agglutinates)	partial commercial availability	N/A	N/A
KPP 4: Specialty simulants (i.e., above + ice-bearing, nano-phase iron, etc.)	possible commercial availability[1]	N/A	N/A

Notes:
(1) Off Planet Research advertises a lunar ice simulant, but the operational plausibility of this is unknown. Creating and using ice-bearing simulants is currently under development at NASA Johnson Space Center, and Jet Propulsion Laboratory has created some ice simulants (outer solar system investigations) in the past.



Commercial Simulant Suppliers that NASA has talked with

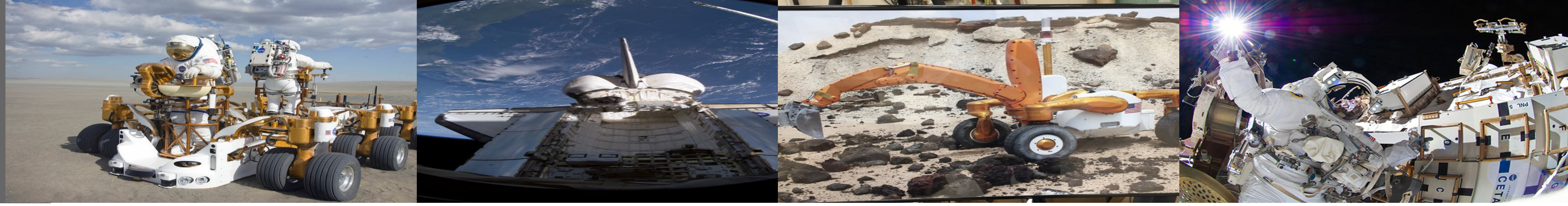
Deltion Innovations Ltd
Ontario Canada
https://deltion.ca/

Exolith Lab, University of Central Florida
NASA SSERVI CLASS (Center for Lunar & Asteroid Surface Science) Node
https://sciences.ucf.edu/class/exolithlab/

Hudson Resources Inc
Vancouver Canada
https://hudsonresourcesinc.com/

Off Planet Research
Lacey, Washington
https://www.offplanetresearch.com/

Outward Technologies
Broomfield, Colorado
https://outward.tech/

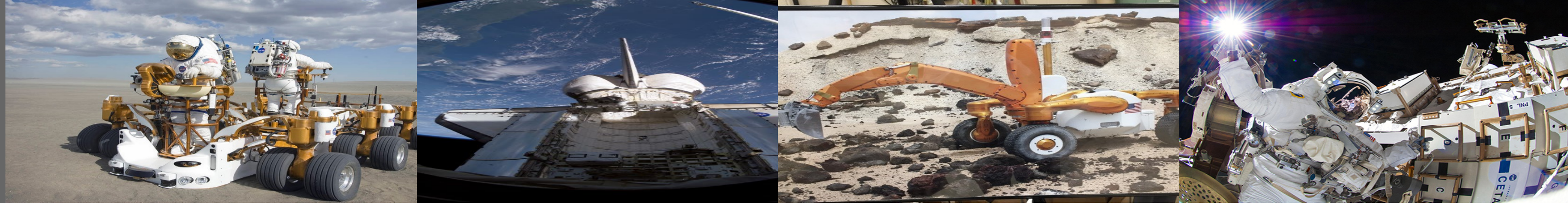


JHU APL Lunar Surface Innovation Consortium

http://lsic.jhuapl.edu/

- **Commercial Lunar Simulant Assessment**
    - Initial review of lunar simulants from Exolith Lab, Off Planet Research, Outward Technologies
    - http://lsic.jhuapl.edu/Resources/files/simulant_eval_2020.pdf
    - "Simulants from the CLASS Exolith Lab or from Off Planet Research could meet the needs of most users"
    - "These providers have worked to develop simulants that provide fidelity to lunar soils in terms of composition, particle size and particle morphology, and have the flexibility to adapt to user needs for a site-dependent composition"
    - "Where the Exolith and Off Planet simulants are lacking, there is no easy remedy"
    - "Including agglutinates in a simulant is likely to benefit only certain uses or testing for advanced TRL"

- **Lunar Simulant Needs Survey**
    - Became available September 11, 2020 at APL LSIC website
    - https://docs.google.com/forms/d/e/1FAIpQLSeHoq6_XvUPfY4jV5ZzBGzcYOA06ojWlC-uohynKtu3RWzlVg/viewform
    - survey assessment is initial stages



Other Useful Resources

Kevin Cannon's Simulant Database
https://simulantdb.com/

Lunar Regolith Simulant User's Guide (to be updated in 2021, contingent on Covid-19 lab restrictions)
NASA/TM-2010-216446
https://www.nasa.gov/sites/default/files/atoms/files/nasa_tm_2010_216446_simuserg.pdf

Lunar Regolith Simulant Materials: Recommendations for Standardization, production, and Usage
NASA/TP-2006-214605
https://ntrs.nasa.gov/api/citations/20060051776/downloads/20060051776.pdf

NASA MSFC Simulant Archive
https://www.nasa.gov/oem/simulants

Lunar and Planetary Institute (LPI) lunar simulant references
https://www.lpi.usra.edu/lunar/samples/#simulants