Recent Discoveries in Simulant Behavior and Regolith Handling

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Background

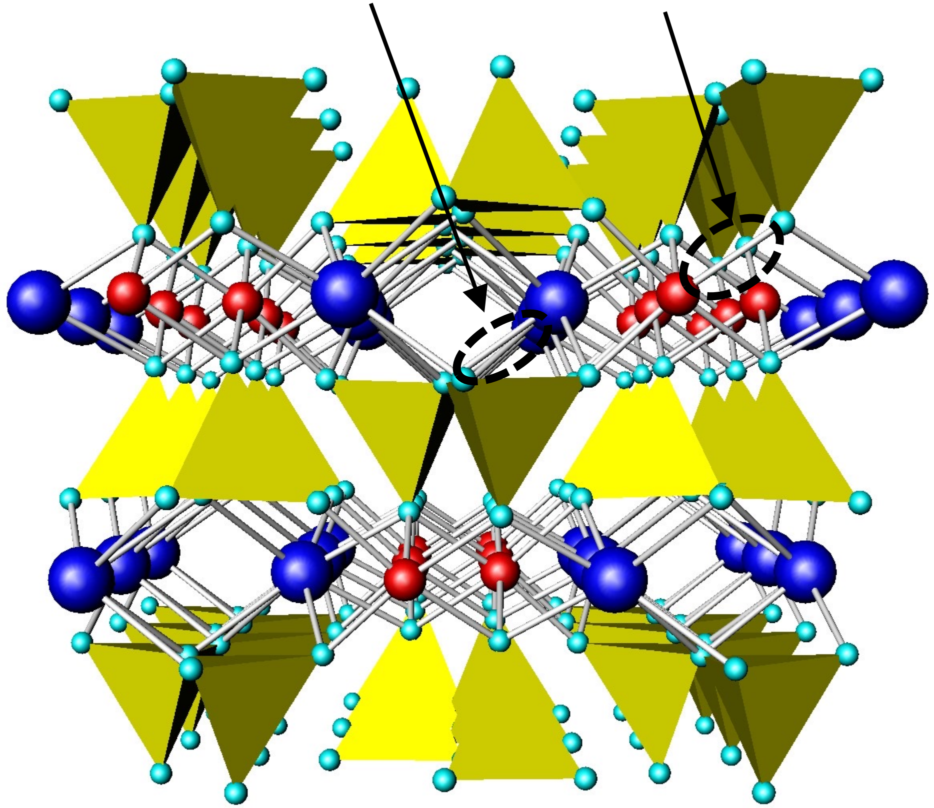
- NASA is taking a 2-prong approach for ISRU production of consumables
  - Water from permanently shadowed regions
  - Oxygen from mineral oxides
- Leading oxygen-from-regolith processes under development
  - Hydrogen reduction
  - Carbothermal reduction
  - Molten regolith electrolysis

Location Matters!

Hydrogen Reduction

- Iron oxides in the mare regions are predominantly contained in ilmenite, which can be reduced by reacting with hydrogen at ~900 °C
- Iron oxides in the highlands regions are predominantly contained in pyroxenes, which cannot be reduced by hydrogen

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

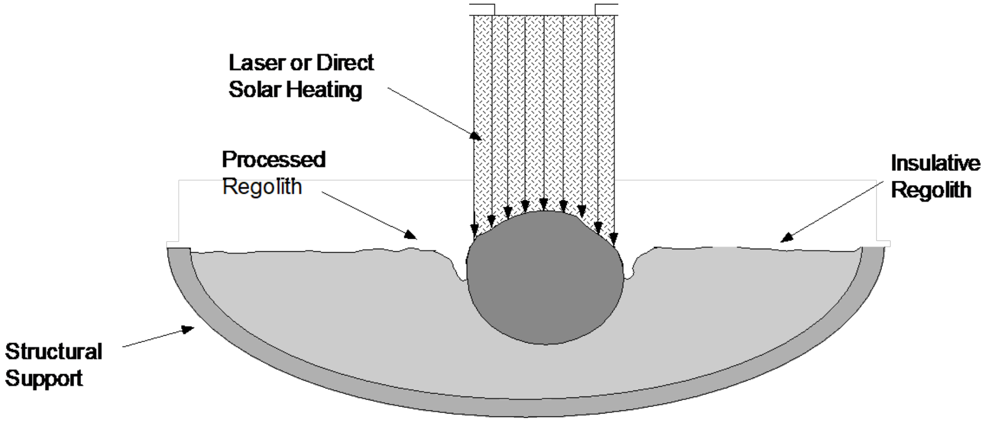


Crystalline structure of a typical pyroxene. Yellow SiO_4 tetrahedra, with light blue spheres representing oxygen atoms. Dark blue and red spheres represent metal cations such as calcium, magnesium, and iron

From Perkins, D., Introduction to Mineralogy, 2020, fig 6.69, https:/opengeology.org/

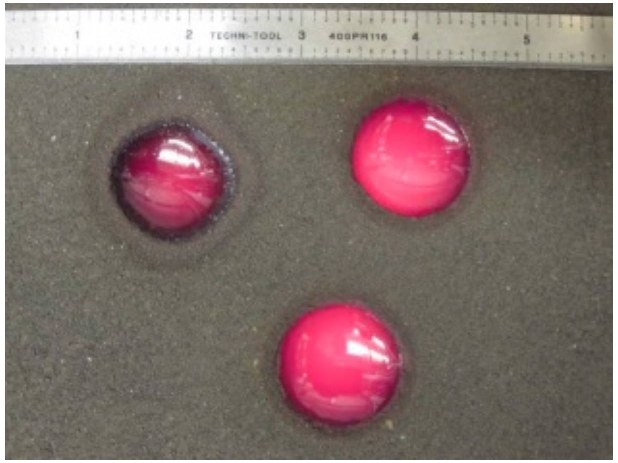
Next up: Carbothermal Reduction

- Regolith is melted to ~1800 °C and reacted with carbon to break the silicate bonds and extract oxygen in the form of carbon monoxide
- Process developed by Orbital Technologies (now owned by Sierra Nevada Corp (SNC)) in the 00's created individual reaction zones in a bed of regolith
    - Carbon is added by cracking methane gas above the melts and allowing the carbon to mix into the molten region.
- Until recently, all of SNC's testing was done with JSC-1A, a mare simulant



Direct heat process – the regolith becomes its own insulative 'container'

Ref: Gustafson, R.J., White, B.C., Rice, E.E., and Gramer, D.J., "Carbothermal Lunar Regolith Processing System (CLRPS) Final Report, NASA Contract NAS9-03021, OTC-GS-131-FR-03-1, July 2003



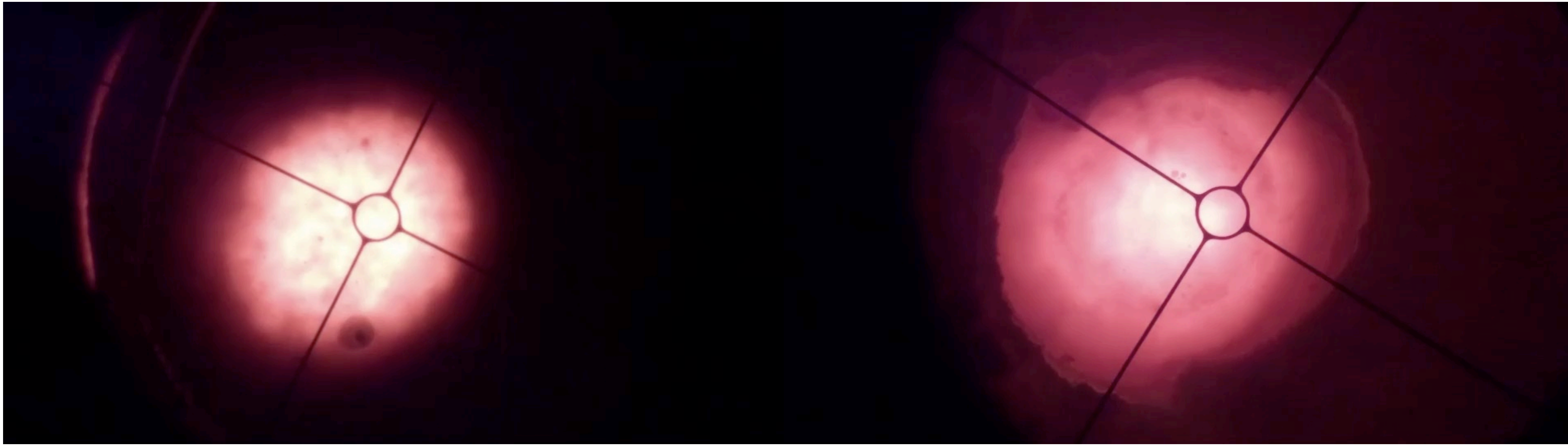
Regions of molten JSC-1A lunar regolith simulant

Ref: Gustafson, R.J., White, B.C., and Fidler, M.J., "2010 Field Demonstration of the Solar Carbothermal Regolith Reduction Process to Produce Oxygen," AIAA 2011-434, Jan 2011

Location Matters!

Carbothermal

- Recent tests performed at Sierra Nevada Corporation (SNC) with JSC-1A and GreenSpar simulants observed significantly different melt behaviors
  - Higher viscosity of GreenSpar affects amount of carbon that can dissolve into melt, as visually observed by formation of carbon cap growing around edges



JSC-1A in methane environment

Greenspar in methane environment

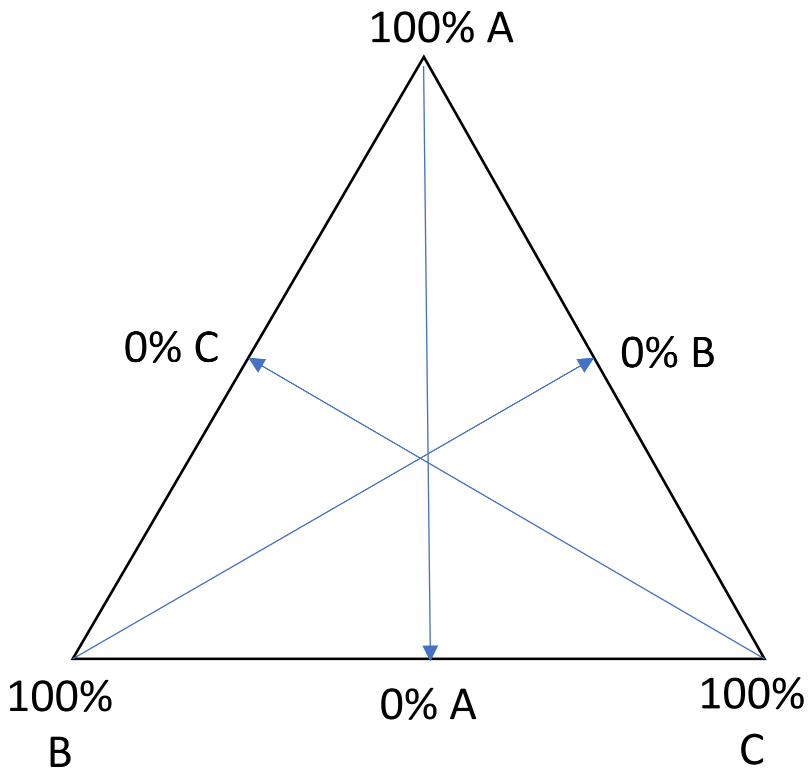
(Video used with permission from Sierra Nevada Corp)

Effects of Higher Viscosity on Carbothermal Process

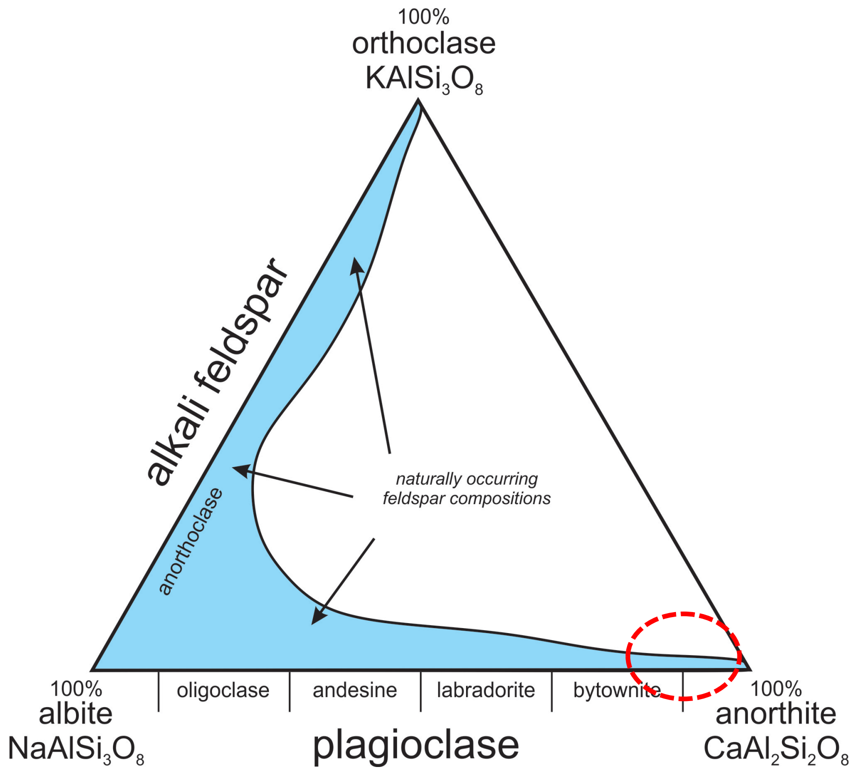
- Performance effects observed two ways
  - Oxygen Rate: reduced more than an order of magnitude due to inability to introduce enough carbon into full melt volume
  - Carbon Cap: inability of carbon to dissolve/mix into melt volume leaves too much at melt surface, forming cap which essentially halts the reaction
- Operating condition variations failed to recover performance (compared to JSC-1A)
  - Higher total power / heat flux into melt
  - Higher melt temperature
  - Methane concentration, absolute pressure in reactor chamber
  - Test duration
  - Mechanical vibration
  - Variable rate of methane introduction throughout test

The Explanation

- Mare regolith is predominantly basalts, which is the basis for the JSC-1A simulant
- Highland regolith (including the poles) is predominantly plagioclase, which is the basis for the NU-LHT-series and GreenSpar simulants
  - Plagioclase consists of sodium (Na) and calcium (Ca) components, but in varying ratios



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.

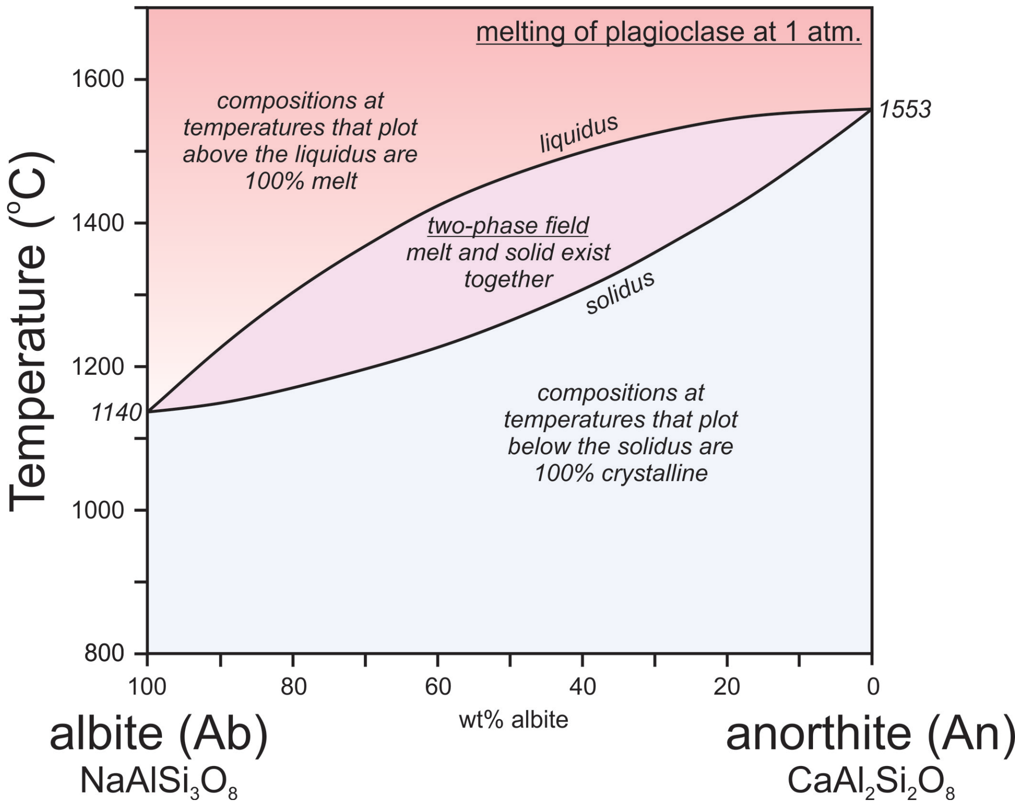


Feldspar mineral classification based on chemical make-up. Bottom base goes from high-sodium albite to high-calcium anorthite. Red dashed circle represents what we expect at the lunar south pole.

From Perkins, D., Introduction to Mineralogy, 2020, fig 6.34, https:/opengeology.org/

The Explanation (cont.)

- More Na will decrease the viscosity (i.e., make the melt more fluidic)
- More Ca will increase the viscosity (i.e., make the melt ‘thicker’)
- The An (Anorthite) number is the ratio of Ca / (Ca + Na)
  - Melt viscosity increases with increasing An number
- Increasing the An number will also increase the melting point temperature of the simulant
- Lunar plagioclase at the south pole is expected to have an An in the upper 80s to mid 90s



Plagioclase crystallization at 1 atm pressure. Full liquidus temperature increases from 1140 °C for albite (high-Na) to 1553 °C for anorthite (high-Ca)

From Perkins, D., Introduction to Mineralogy, 2020, fig 6.54, https:/opengeology.org/

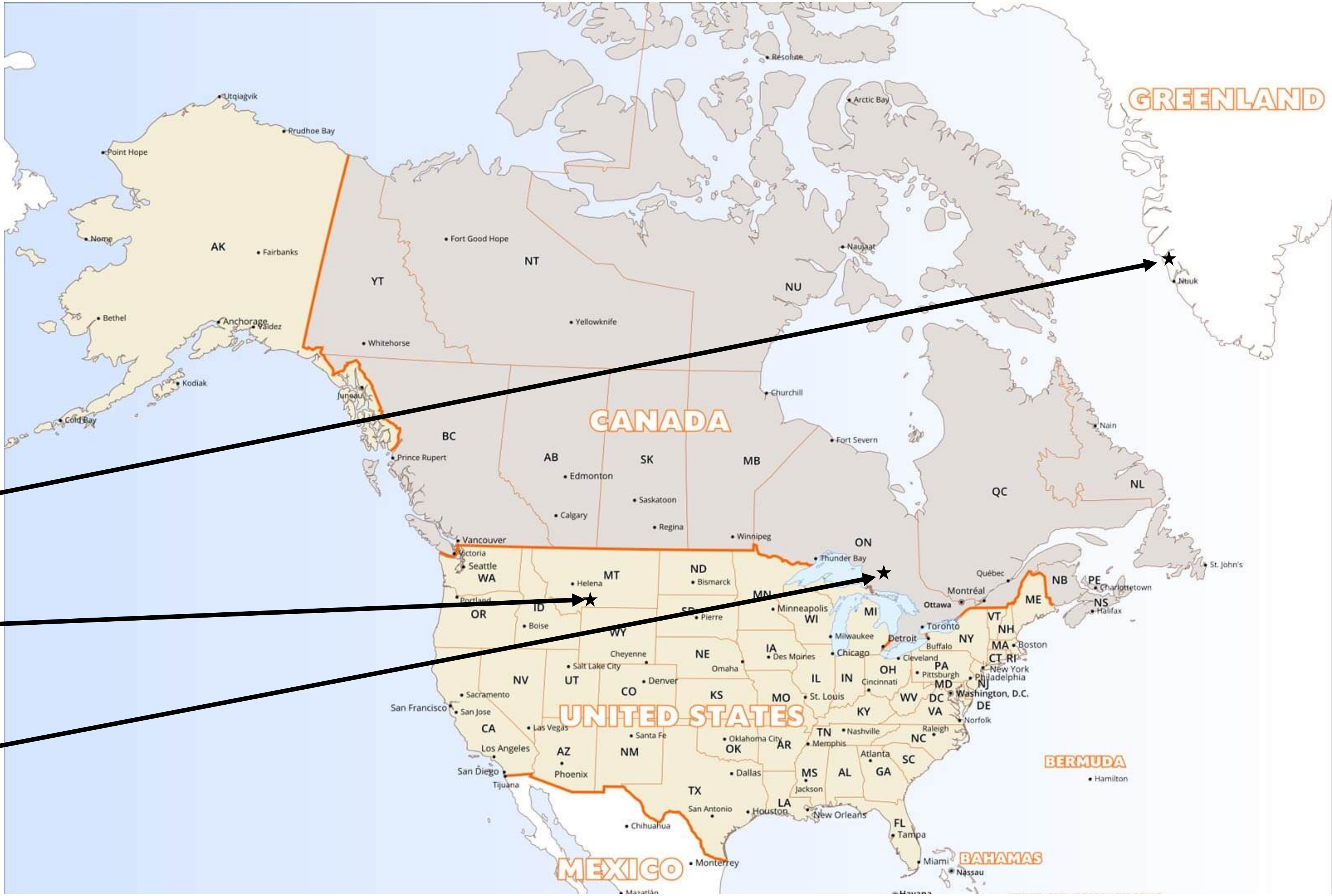
Sources for Simulant Feedstock

North American locations for large quantities of high-Ca Anorthosite

White Mountain

Stillwater

Shawmere



Map graphic from https://www.freeworldmaps.net/download/maps/northamerica/northamerica-map.jpg

Anorthosite Assessment

Deposit	Shawmere (OB-1, Chenobi)	Stillwater (NU-LHT-series)	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), Hudson Resources Inc. presentation 6-16-20

Viscosity Summary

- Continue with the GreenSpar simulant
  - The high An number (ratio of Ca / (Ca+Na)) of lunar highland regolith will result in a highly viscous melt
  - Highlands simulants such as NU-LHT-series and GreenSpar all have high An numbers, although not as high as the lunar highland regolith
    - Should mimic melted viscosity as best as possible with current available simulants
    - Would be of interest to run a few baseline tests with multiple highland simulants and a synthetic plagioclase with matching An number (i.e., synthetic Anorthite)
  - Greenspar has the highest average An number of the available highland simulants, and is the most readily available for larger scale, destructive testing
- Molten Regolith Electrolysis developers should also evaluate whether the high melt viscosity will affect their performance or concept of operations

Note: Recent challenges regarding imperfect simulants further emphasizes the need for a demonstration on the lunar surface with real lunar highland regolith

Acknowledgements

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