Beyond Geotechnics: The Case for Thermochemically-Focused Regolith Simulants

Dr. Kyla P. Edison

Outward Technologies

Expanding our Thinking on Simulants

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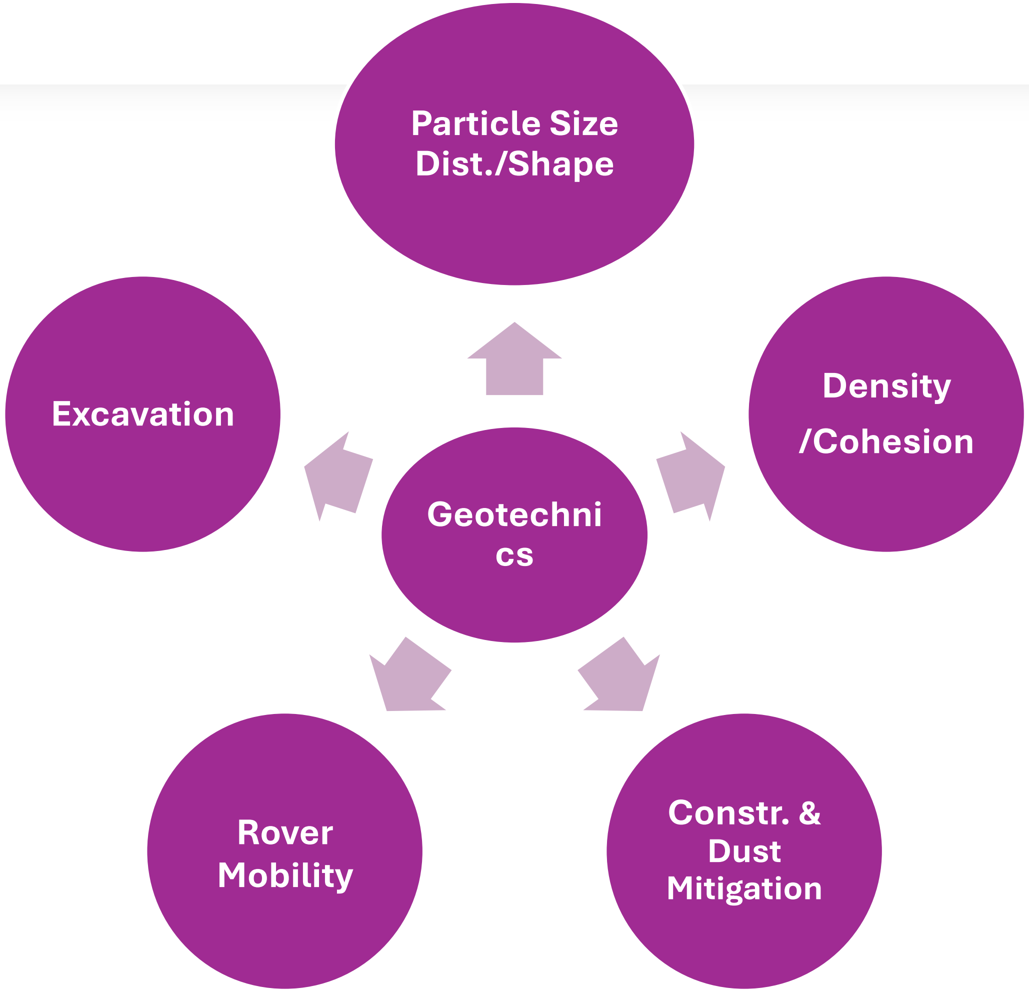
Current Regolith Simulant Design



- Molten Regolith Electrolysis (MRE)
- Pyrolysis/Vaporization
- Additive Manufacturing
  - Sintering
  - Casting
  - 3D printing
- Oxygen/Water Production

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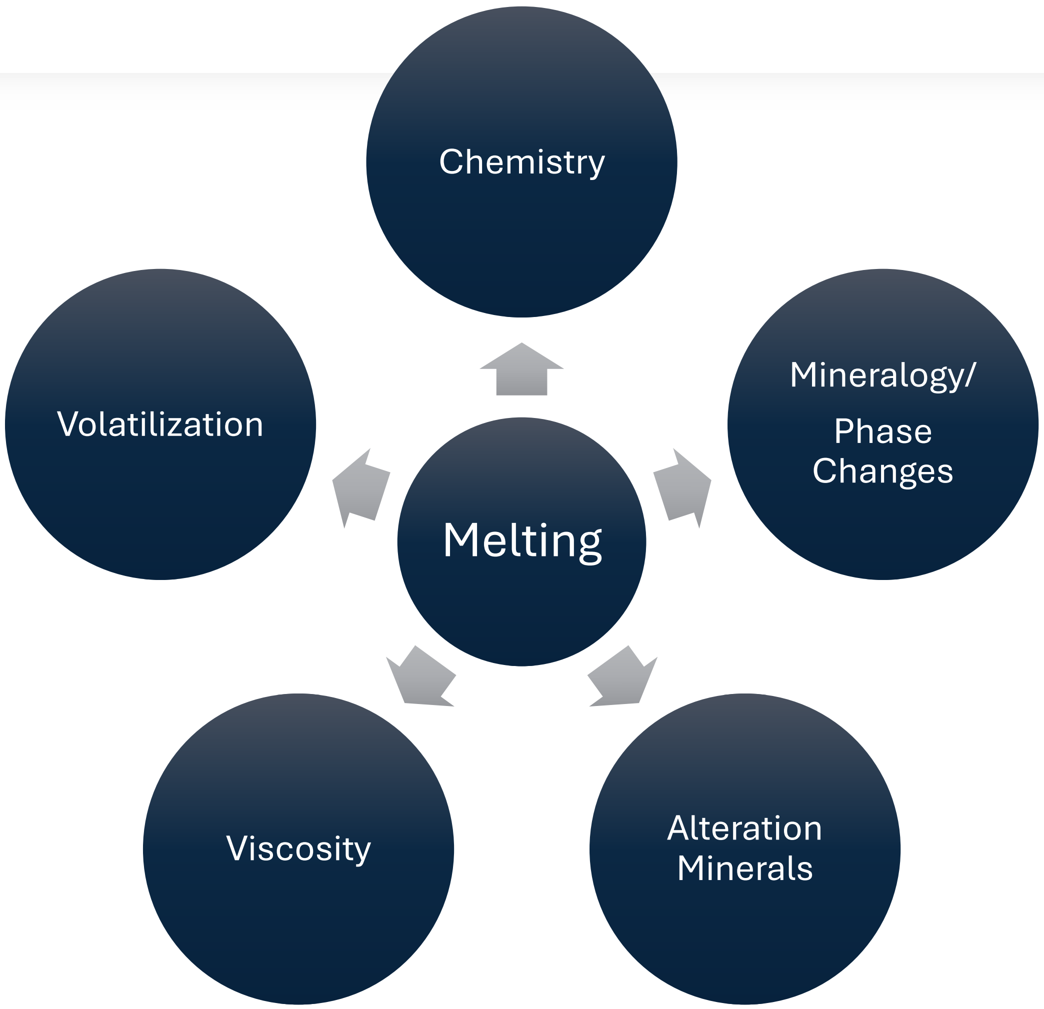
A Melt Fidelity Design Considerations



The Lunar Geology

- The lunar surface is composed primarily of two major rock types:
  - Mare basalts – dark, iron- and magnesium-rich volcanic rocks that filled ancient lava plains (the darker regions of the Moon).
  - Highlands anorthosites – light-colored, aluminum- and calcium-rich rocks that make up the older, cratered highlands.
- These two lithologies define the chemical extremes of lunar crustal materials.
- In this study, Merriam Crater basalt was used as a mare analog, and Stillwater anorthosite glass as a highland analog.
- Understanding how these compositions melt, crystallize, and strengthen when cast provides critical insight into how lunar regolith could be transformed into construction materials through ISRU.

Anorthosite

Anorthosite is a light-colored, coarse-grained igneous rock composed primarily of plagioclase feldspar (typically >90%). On the Moon, it represents the ancient highlands crust, formed from early magma ocean crystallization.

Formation:

- Forms when low-density plagioclase crystals float to the top of a magma ocean, creating a feldspathic crust.
- Commonly associated with deep crustal or layered intrusions on Earth (e.g., Stillwater, Nain, and Greenland complexes).

Composition:

- Dominated by Ca-rich plagioclase (anorthite)
- Low in Fe and Mg, with minor pyroxene and oxide phases
- High in Al_2O_3 and CaO, low in SiO_2

Relevance to ISRU:

- Analogous to the lunar highlands, which make up ~80% of the Moon's surface.
- High melting point (~1400 +°C) makes it challenging to process, but potentially ideal for high-temperature ceramics.
- Source of aluminum and oxygen for future lunar manufacturing.

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https://www.geologyforinvestors.com

A fine-grained, mafic volcanic rock formed from rapidly cooled lava rich in iron and magnesium. It makes up most of Earth's oceanic crust and much of the lunar maria.

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Basalt

Formation:

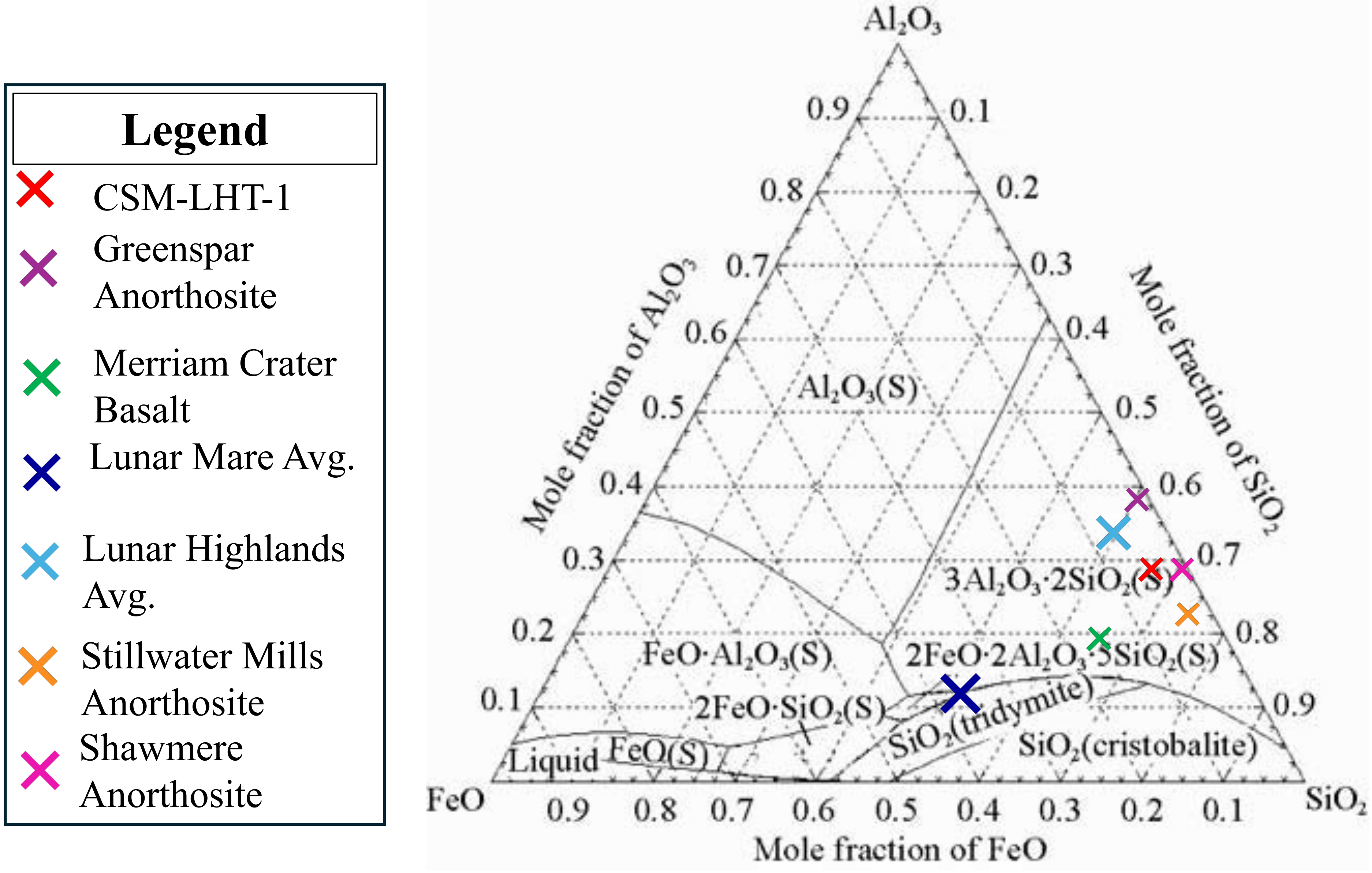
- Produced by the partial melting of the mantle.
- Erupts at ~1,100–1,250 °C as low-viscosity lava that flows easily.

Composition:

- ~45–53 wt. % SiO_2
- High in Fe, Mg, and Ca
- Dominant minerals: *plagioclase*, *pyroxene*, and *olivine*

Relevance to ISRU:

- Basalt is abundant on both Earth and the Moon.
- When melted and cooled, it forms durable, glass-ceramic materials suitable for casting, sintering, or fiber production.
- Its low viscosity and high toughness make it a promising candidate for lunar construction.



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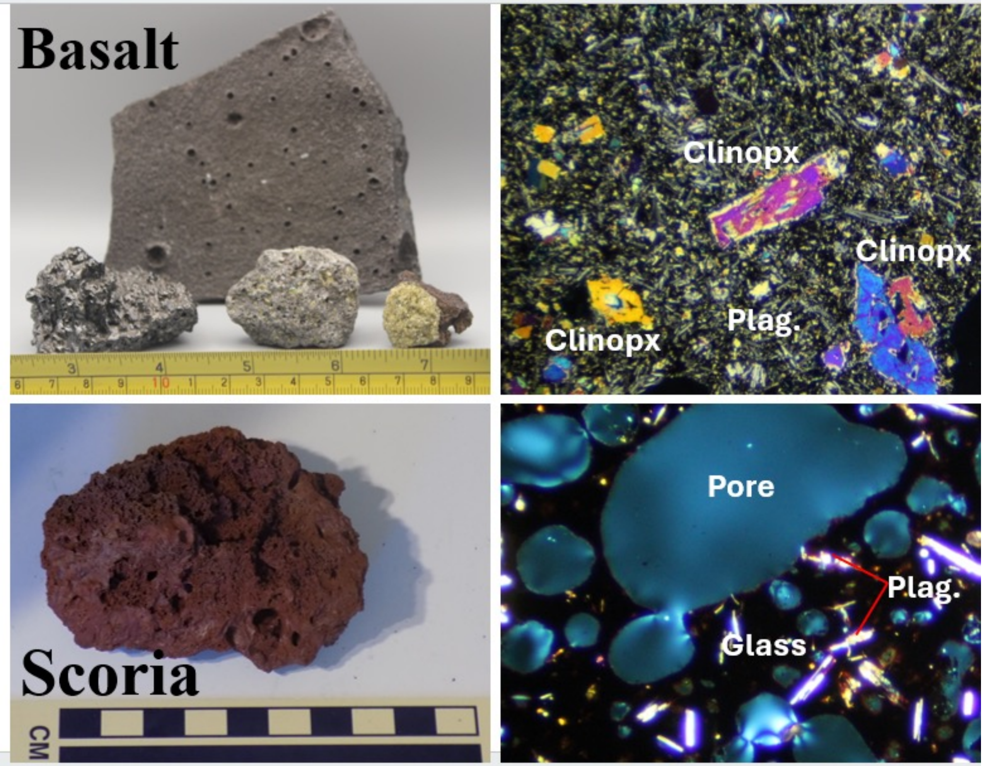

Basalt vs. Scoria

- **Basalt** is a dense, fine-grained volcanic rock composed mainly of plagioclase and pyroxene, with little to no vesicles (gas bubbles).
- **Scoria,** by contrast, is a highly vesicular form of basaltic lava, containing abundant gas cavities formed by the escape of volatiles during eruption. This gives scoria a lower density and a more frothy, porous texture than typical basalt.

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Merriam Crater Basalt Scoria

Feature	Details
Age	*50,000-60,000 years old; enough time for weathering and alteration*
Formation Process	*Explosive eruption; gas-rich magma forms vesicular scoria*
Texture & Structure	*Highly porous, frothy, fragmental; microlitic/glassy with no continuous groundmass*
Trapped Volatiles	*Some gas escapes, but vitrified glass can seal in residual volatiles*
Secondary Hydrated Minerals	*Weathering leads to formation of hydrated phases (e.g., clays, zeolites)*
Melting Behavior	*Foaming and swelling during melting due to trapped gas and dehydration*
Suitability as Lunar Analog	*Unstable melt behavior makes it a poor analog for dense lunar basalt*

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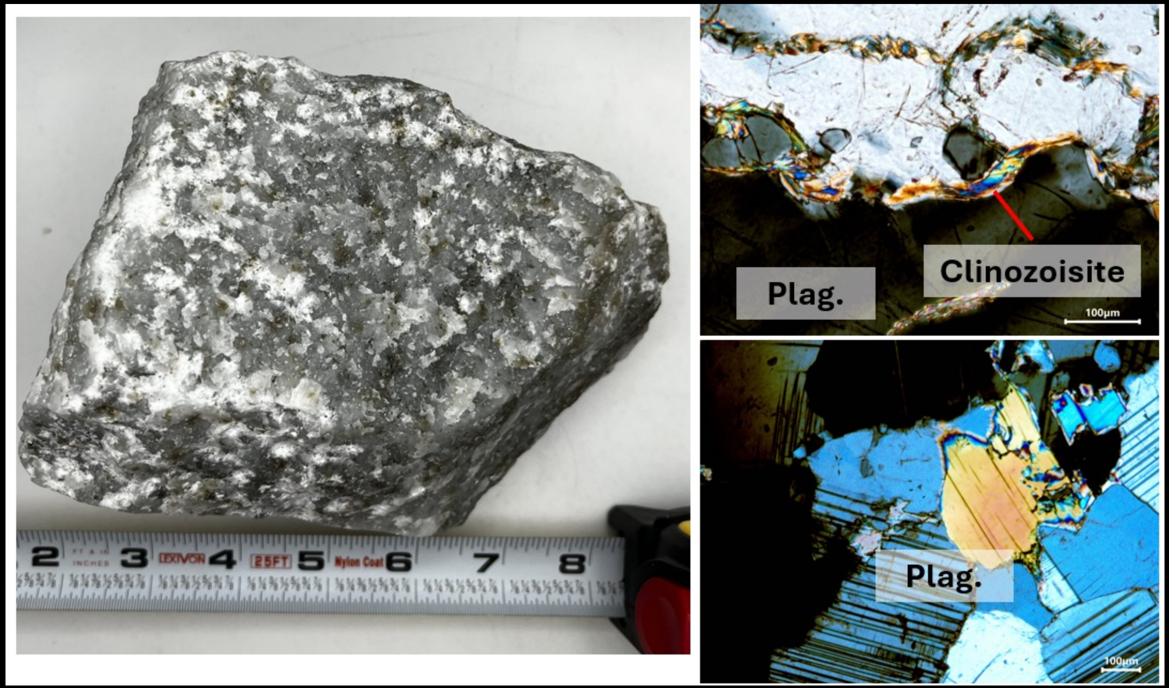
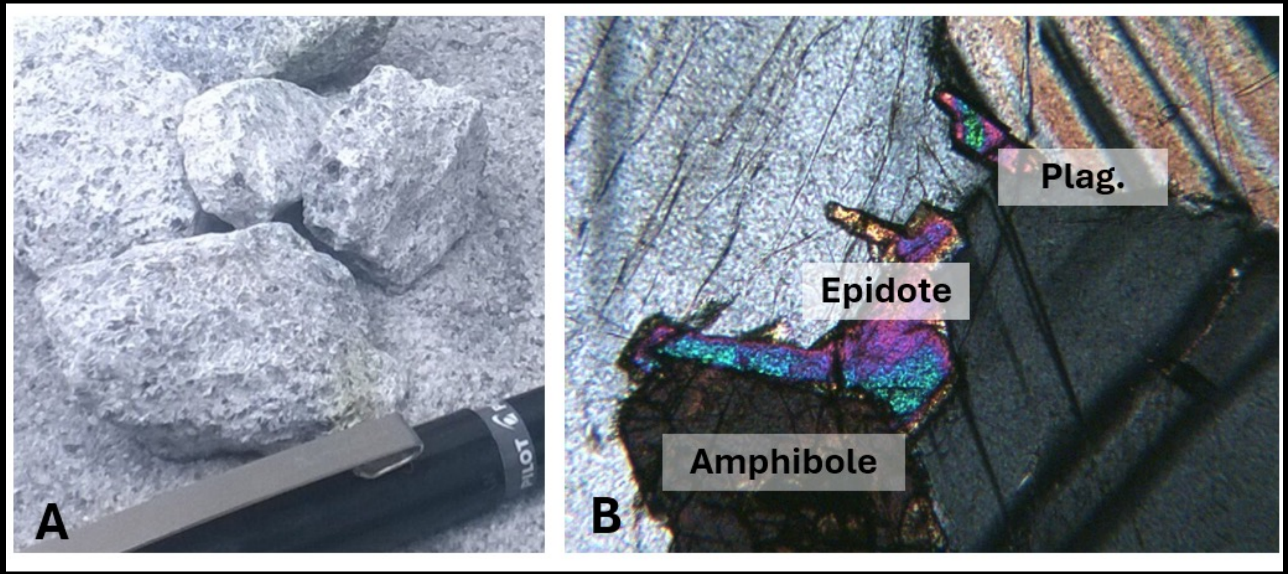
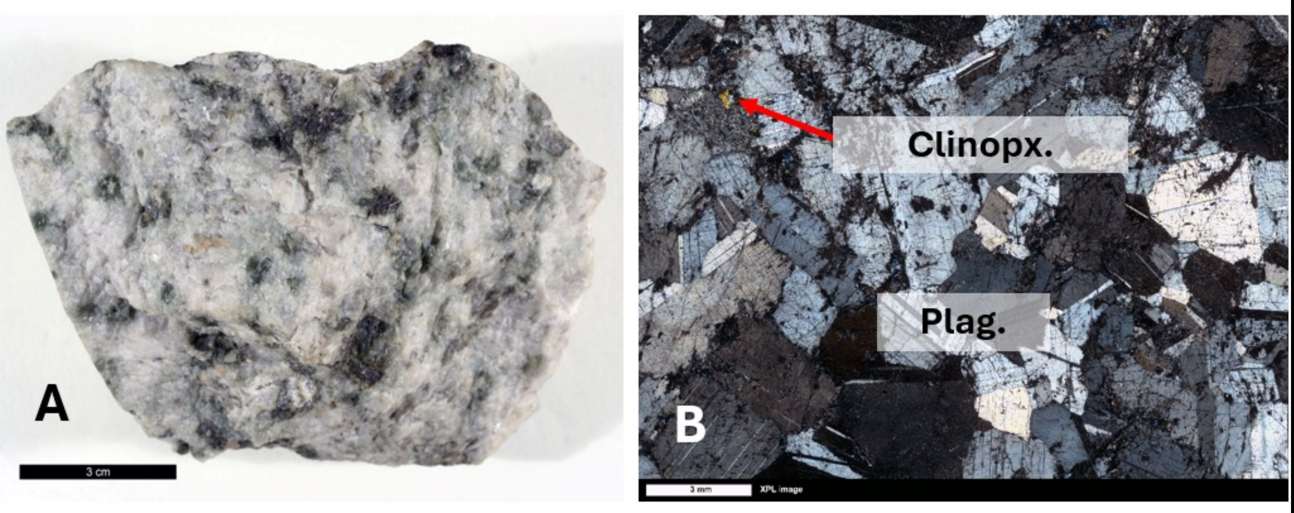
Greenspar Anorthosite,
Greenland



Shawmere Anorthosite,
Ontario Canada



Stillwater Mills,
Montana USA

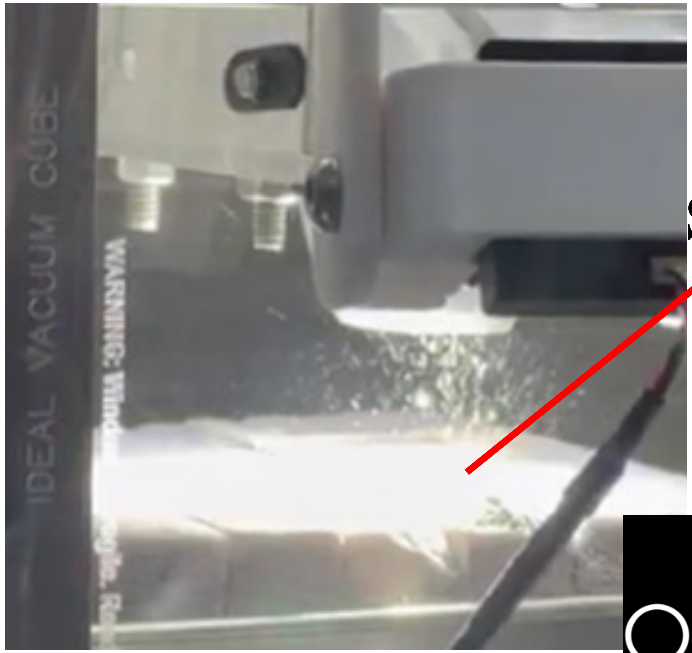


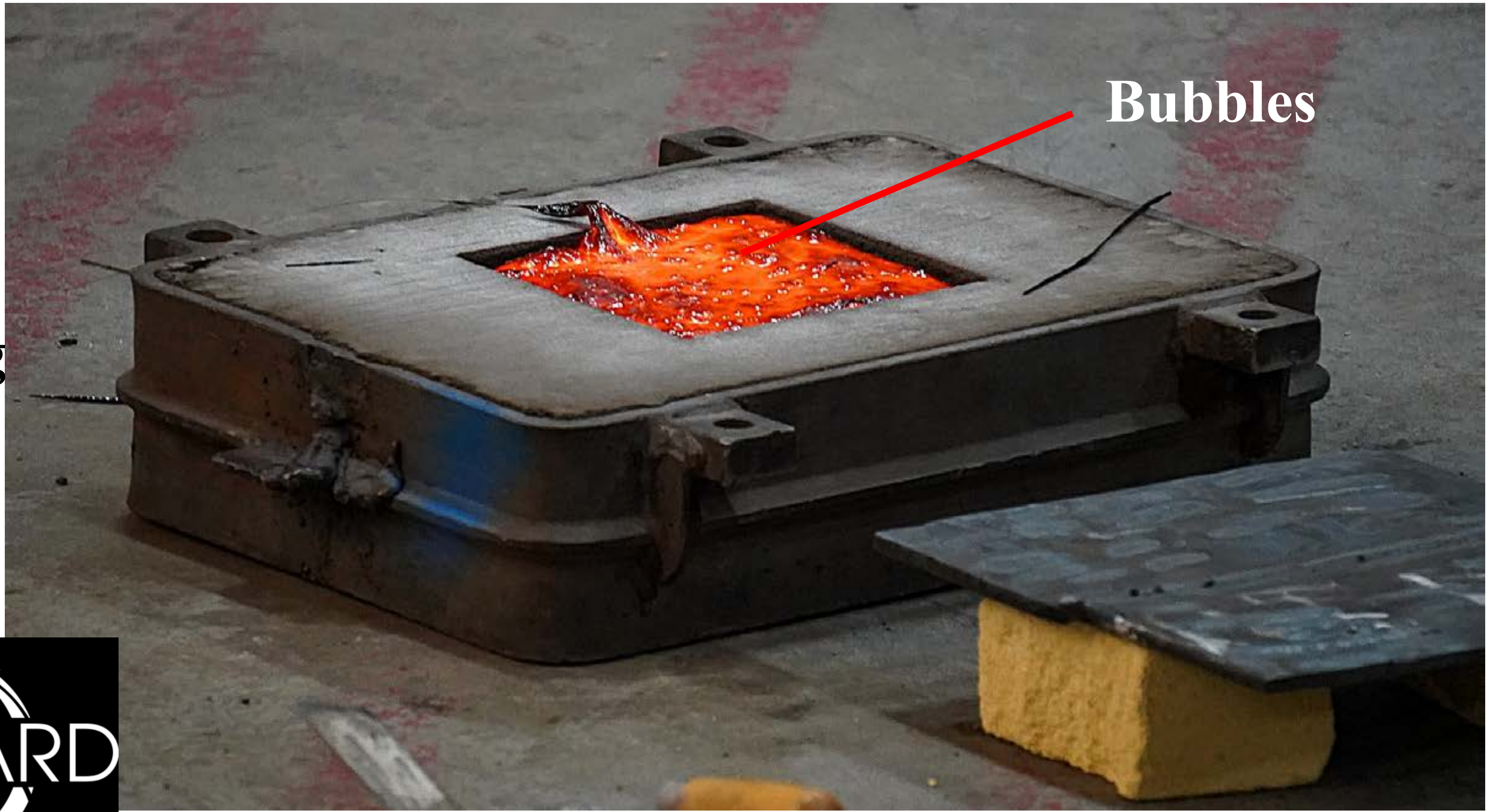
Although from different locations, these anorthosites all exhibit similar characteristics such as:

1. *Extreme old age.*
2. *Partial metamorphism*
3. *Hydrated minerals*

Regolith Simulant Characteristics

- Water is released upon heating.
- Foaming/spalling
- Poor mixing in the melt





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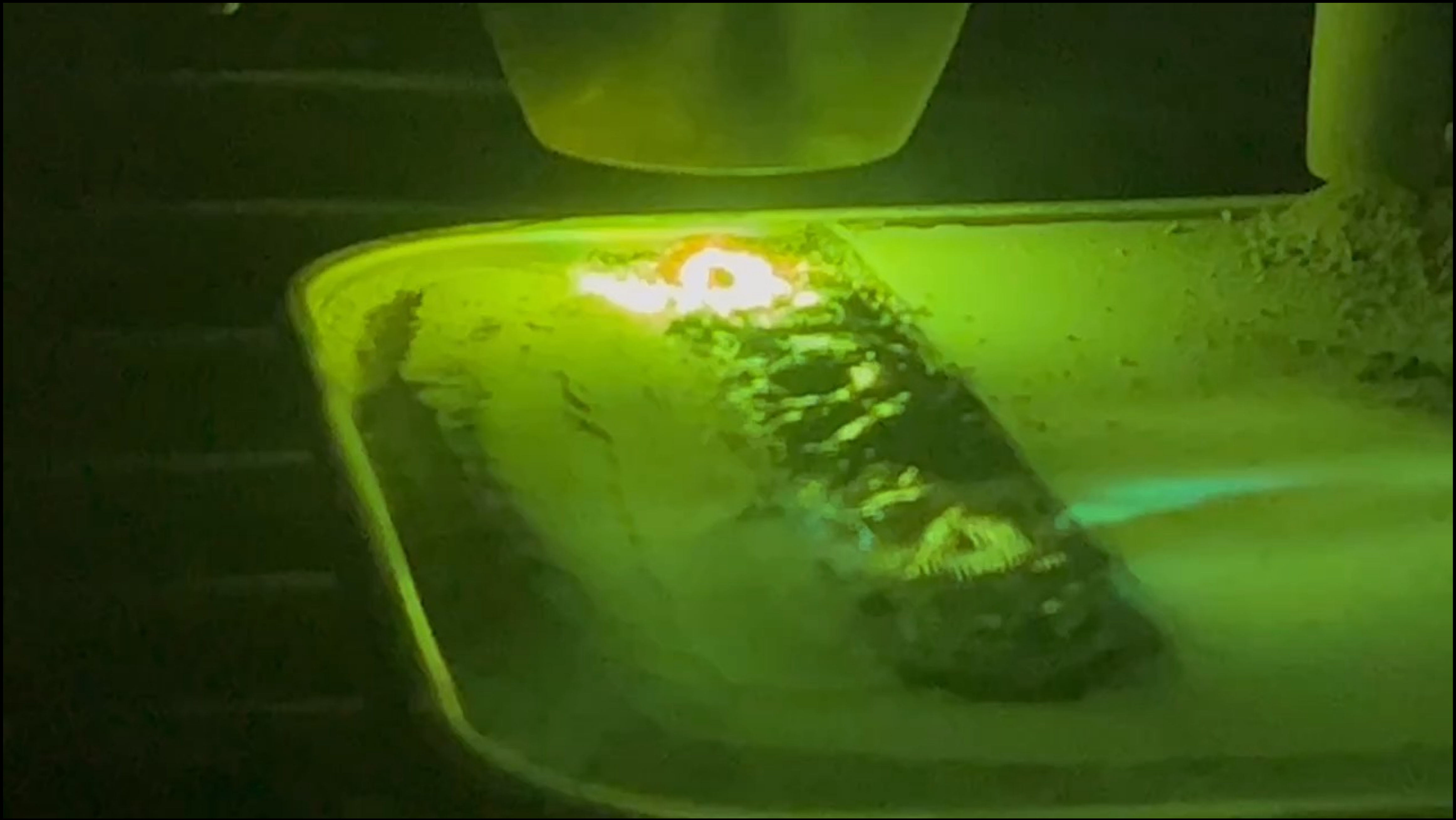
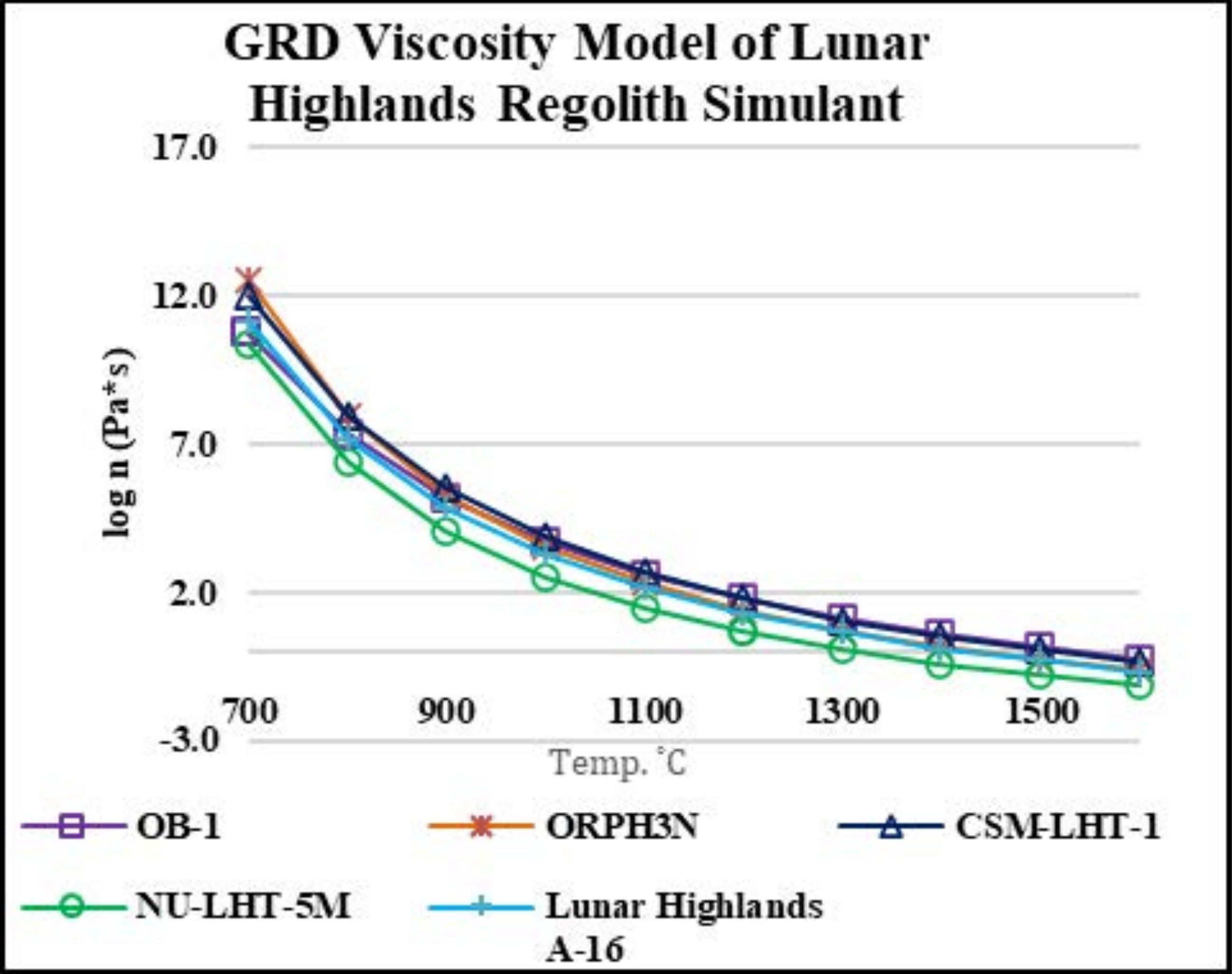
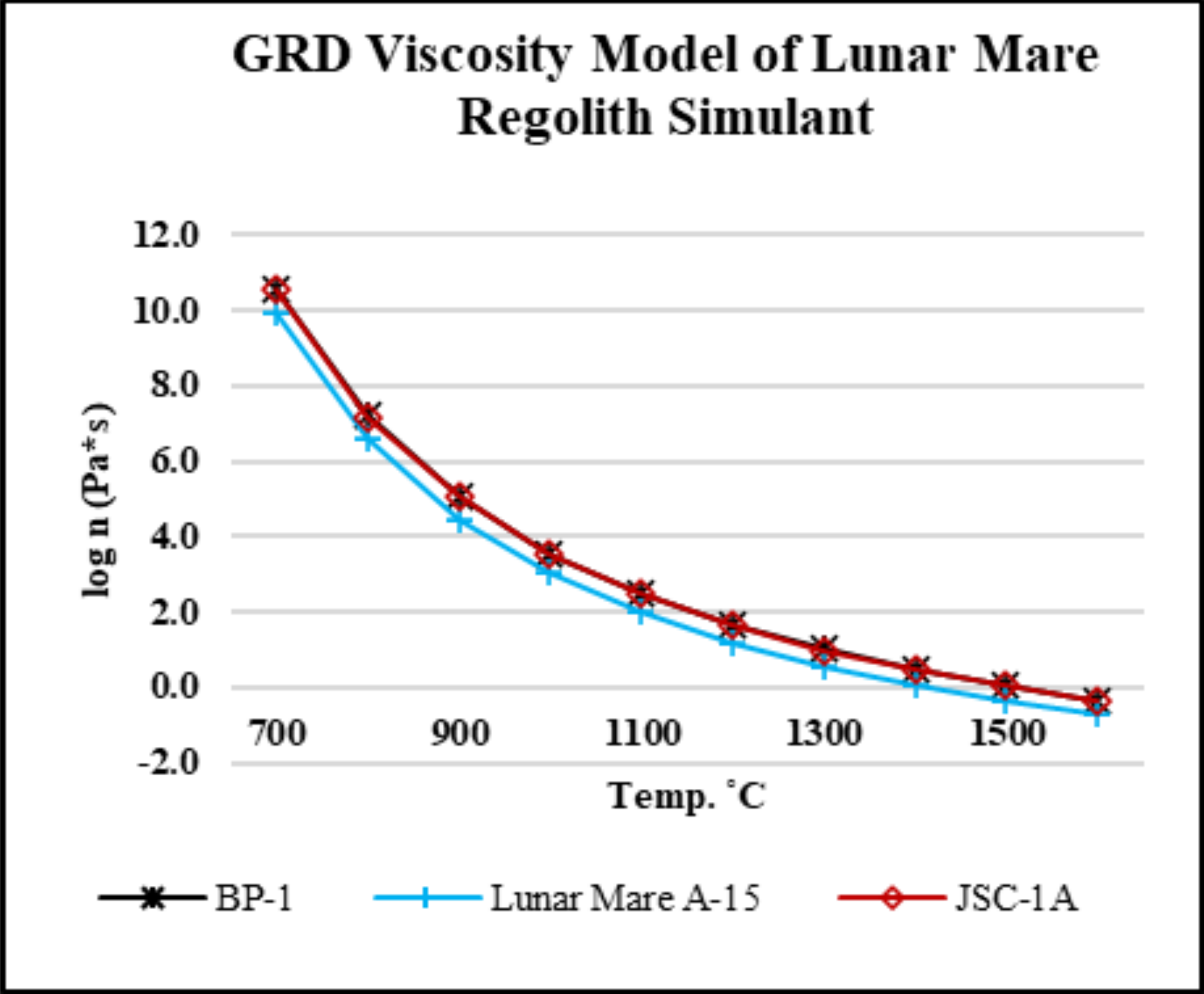
Water Release Upon Heating

- Hydrated Mineral
- Dehydration
- Water Release
- Fluxing/Lowering Melting Temperature
- Volatile Migration
- Secondary Mineral Formation




GRD Viscosity Model of Lunar Highlands Regolith Simulant
17.0
12.0
7.0
2.0
-3.0
log n (Pa*s)
700
900
1100
1300
1500
Temp. ˚C
OB-1
ORPH3N
CSM-LHT-1
NU-LHT-5M
Lunar Highlands A-16


GRD Viscosity Model of Lunar Mare Regolith Simulant
12.0
10.0
8.0
6.0
4.0
2.0
0.0
-2.0
log n (Pa*s)
700
900
1100
1300
1500
Temp. ˚C
BP-1
Lunar Mare A-15
JSC-1A

Engineering Consequences

- Power requirements underestimated
- Reactor Sizing Underestimated
- Thermal Management Underestimated
- Containment Materials May Fail

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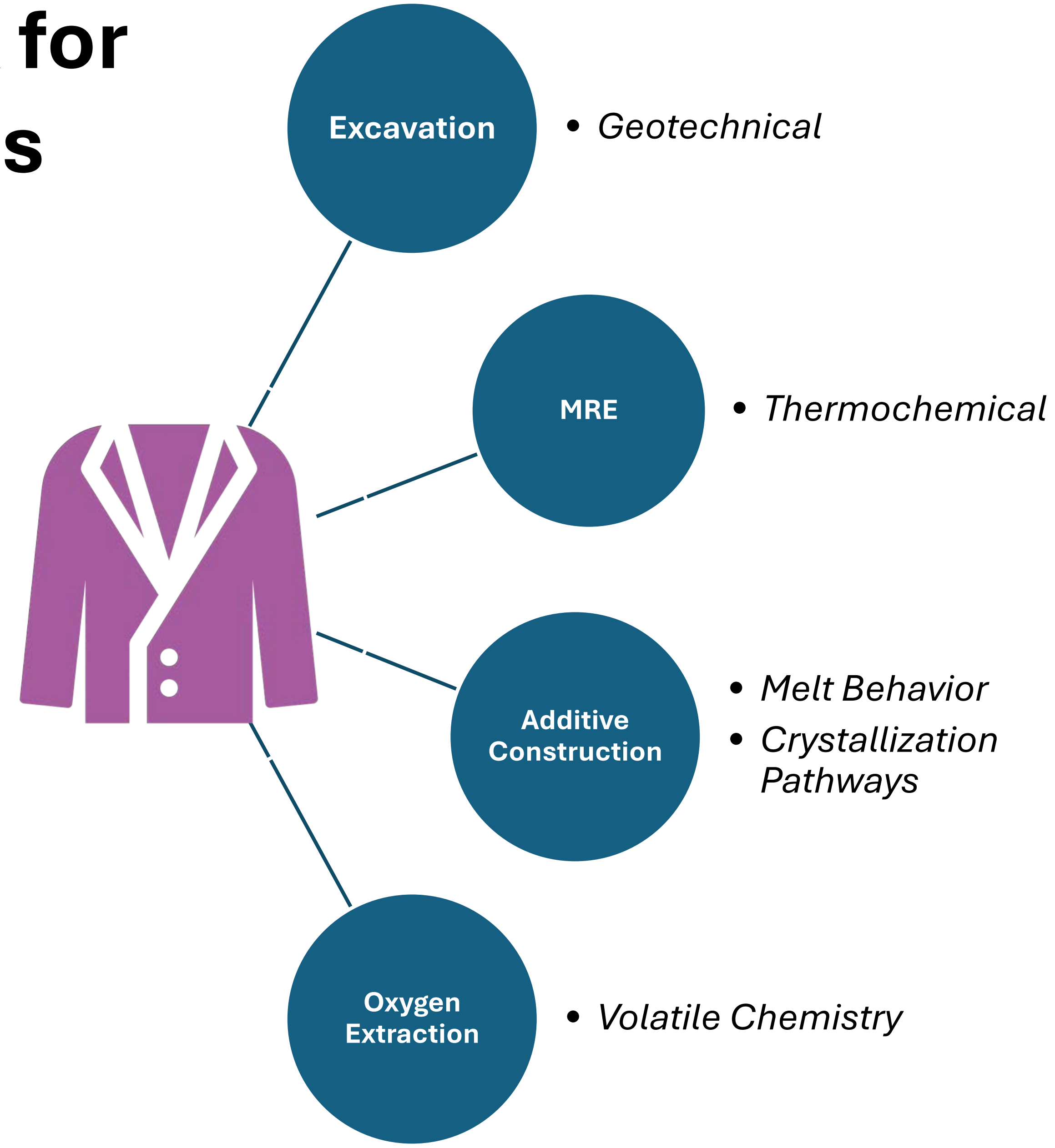
Proposed Framework for Tailor-Made Simulants

❌ **Universal Simulant**

✅ ***Simulants Optimized for Specific Applications***



Key Aspects of Lunar Regolith

- **Chemical Oxide Species**
- **Mineralogy**
- **Agglutinates**
- **Nanophase Iron**
- **Anhydrous**

Major Challenges

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Beneficiation Can Alter More Than Water Content

- Dehydration Of Hydrated Phases
- Volatile mobilization (ex: Na)
- Chemical Redistribution
- Secondary Mineral Formation

Result:

The final simulant may differ significantly from the original feedstock.

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Geologic Processes Govern Simulant Curation

- Thermal dehydration releases volatile species.
- Volatiles may migrate through the system.
- Condensation and secondary phase formation can occur.
- Simulant properties may evolve during processing.

Therefore: Simulant curation should consider not only composition but also the ***GEOLOGIC PROCESSES*** induced during preparation.

Key Takeaways

- Many simulants were designed for geotechnics.
- High-temperature ISRU introduces different requirements.
- Hydrated phases and fluxing agents (Na) can distort results.
- Purpose-driven simulants improve experimental reliability.
- Thermochemical fidelity should become a major design criterion.

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