Mineralogical Characterization of Cast Lunar Regolith Simulants

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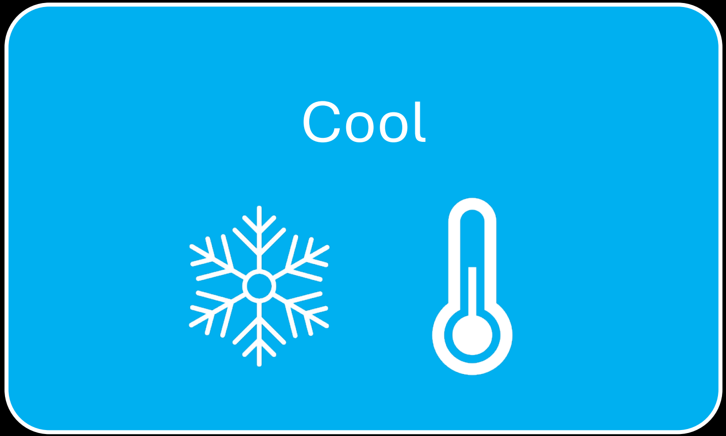
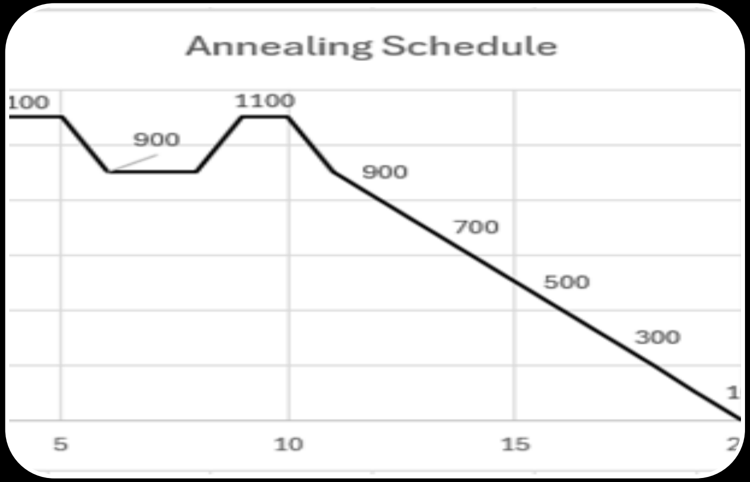
Scope

This work develops a systematic framework for casting lunar regolith and simulants by identifying key process variables, melt behaviors, and material outputs—providing critical data to inform the design of future in-situ melting and casting systems for lunar infrastructure.

Casting Method



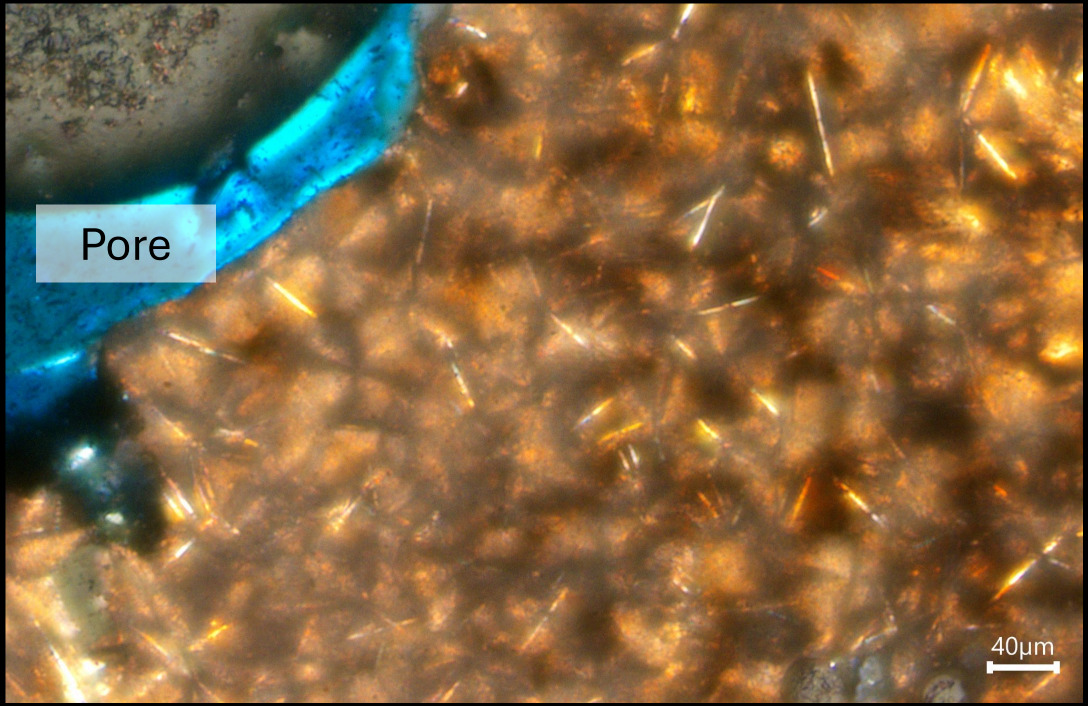


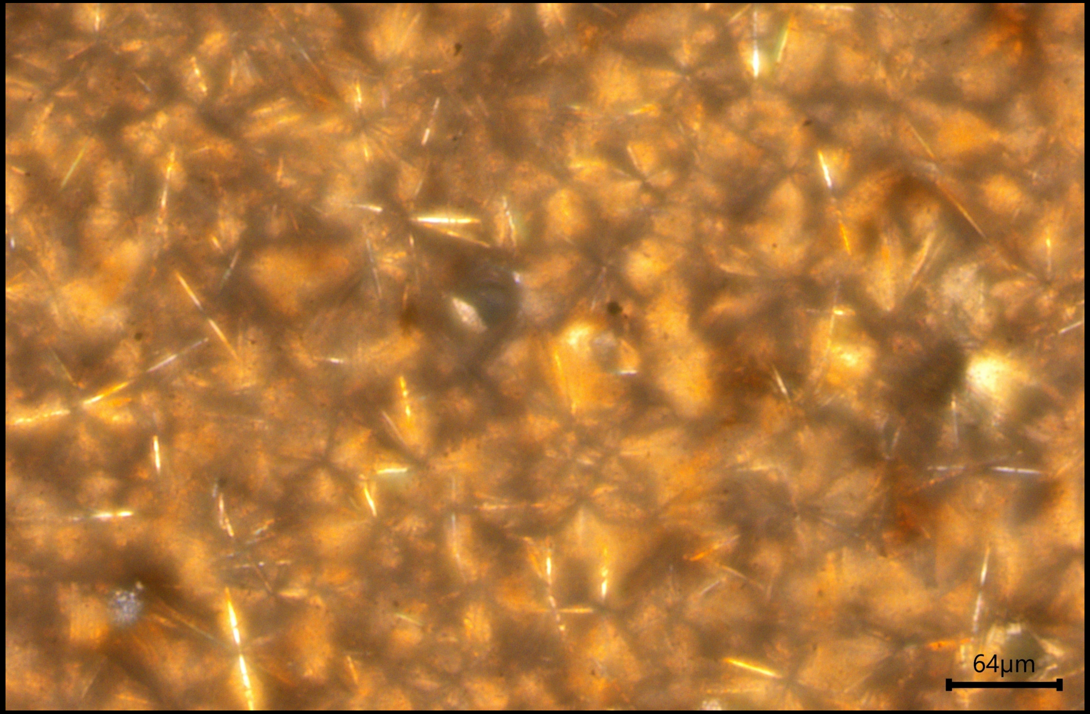
Cast Merriam Crater Basalt

- Cast basalt specimens showed a dense, glassy matrix with minor porosity and light gray splotches—likely localized devitrification or melt instability zones. Microcracking was minimal, and glass boundaries were well-defined. Figure 4 shows cut bars before flexural testing, highlighting these features.

Thin Section Analysis of MC Basalt Cast's

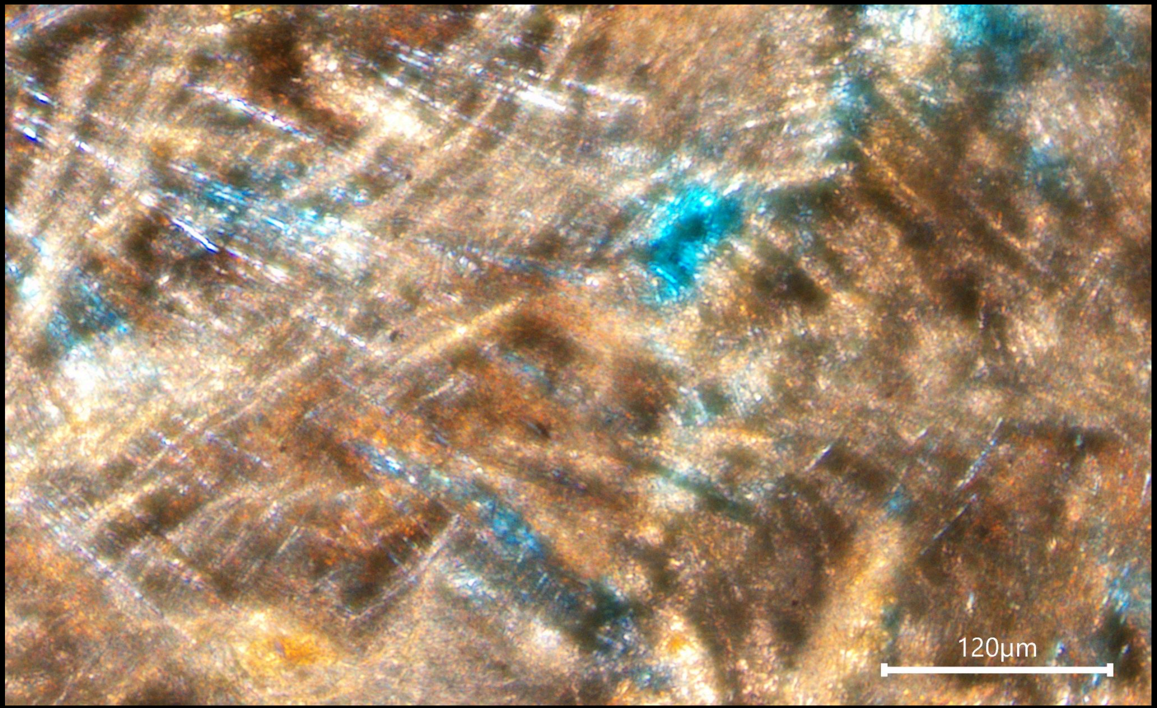
- Sample has undergone controlled partial devitrification, resulting in a matrix filled with fine microlites—likely possibilities include feldspar, pyroxene, and mullite.
    - XRD pending
- The even distribution and lack of large silica spherulites indicate *beneficial devitrification*, potentially enhancing strength and toughness.
    - Mechanical testing pending





Viscous MC Basalt Melt

- Possible combination of flow alignment and pouring shear acting on a viscous melt with early-stage microlite crystallization. The glass wasn’t fully set yet—just viscous enough to let the crystals drag into line.

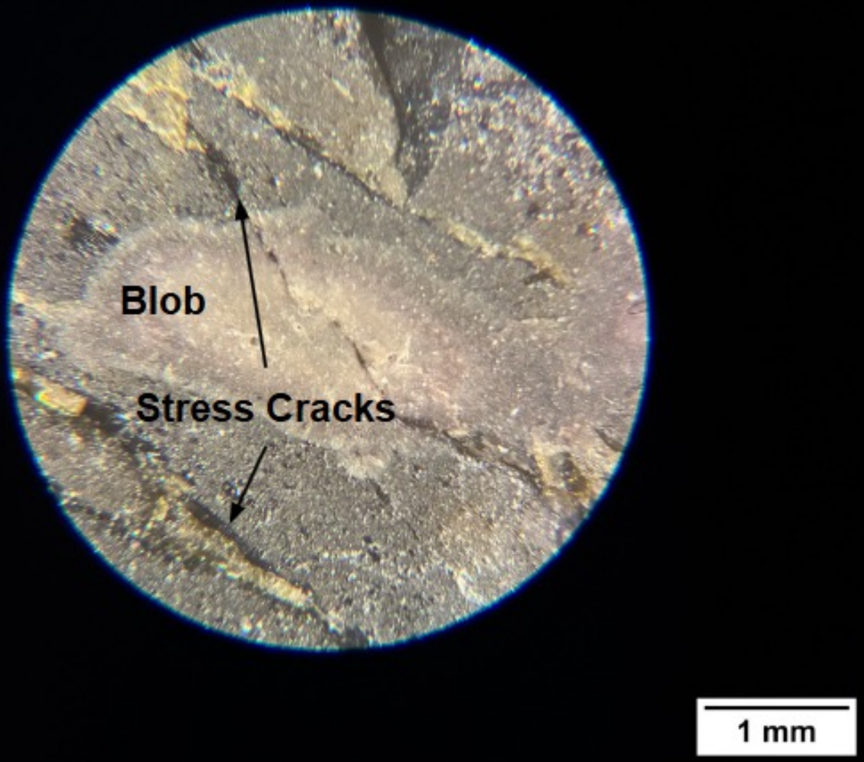


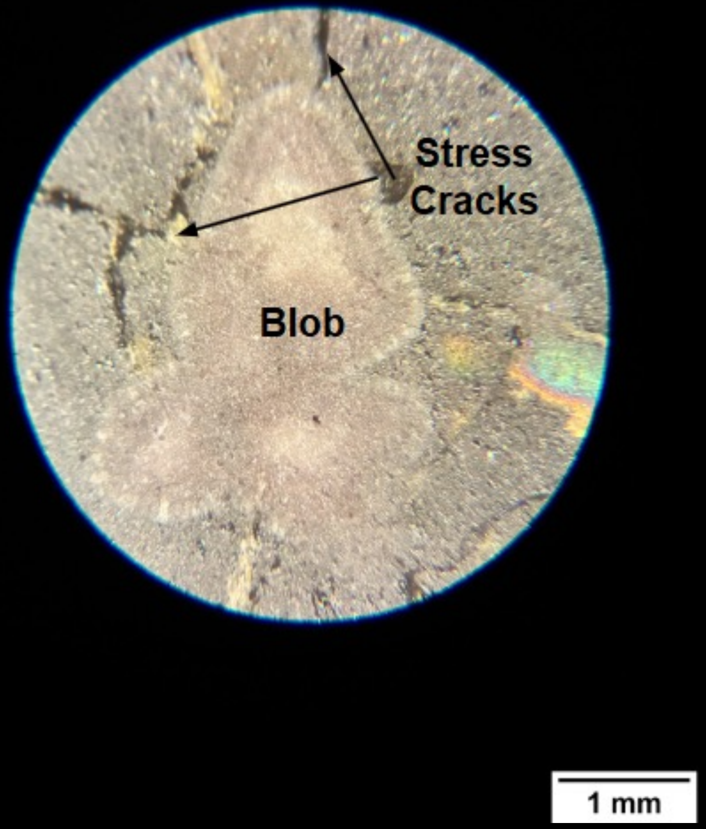
Basalt/Anorthosite Mix

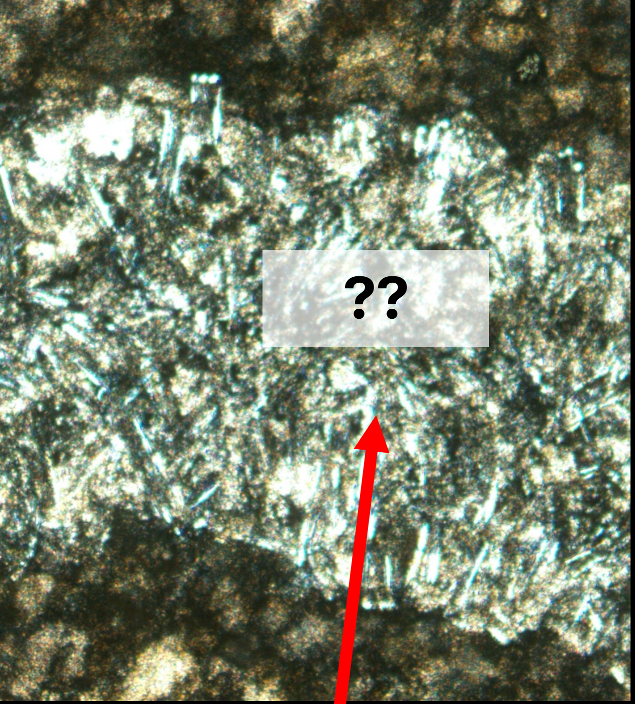
- Although the material feels, and looks well formed and annealed, upon cutting, cross-section revealed an abundance of cracks that ran through the material.
- Another observation was the presence of mineral "blobs", that the cracks seemed to propagate from.

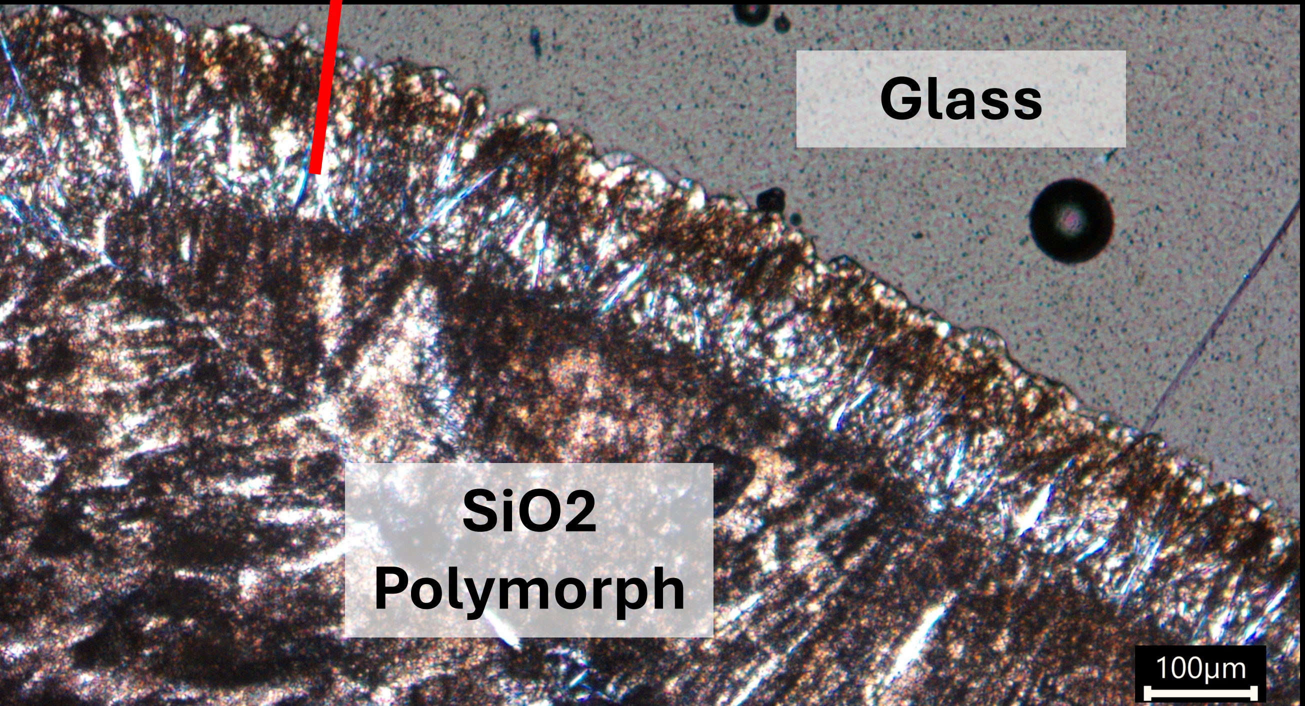
Crystalline Masses:
Blobs

Large crystalline masses that can be seen clearly in the materials cross section seems to have cracks propagating from them.



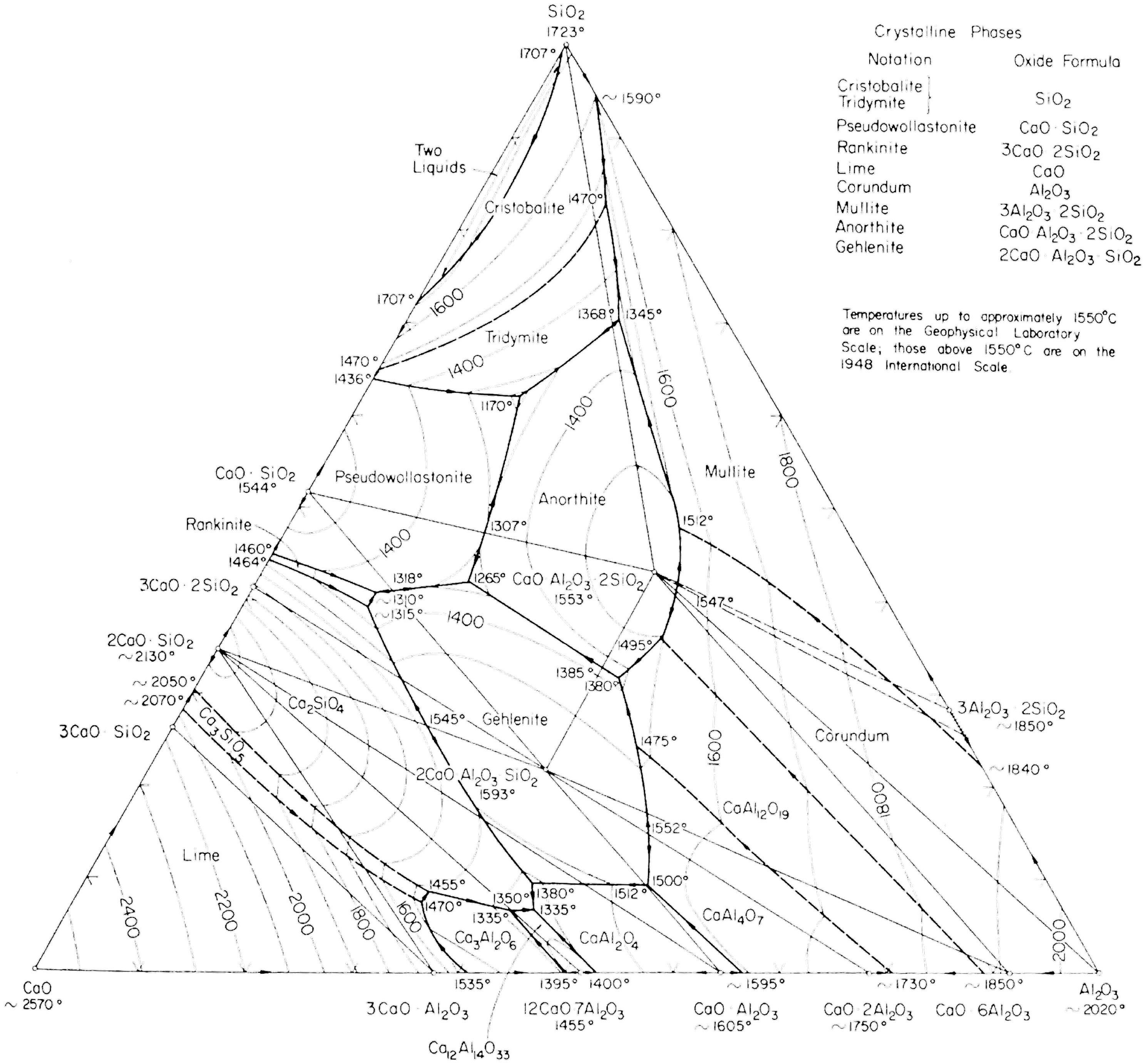






Thin Section Analysis of Basalt/Anorthosite Mix

- **SiO_2 Polymorph Growth**
    - Large radiating crystal formations are evident in multiple regions, identified as high-temperature silica polymorphs, likely **cristobalite** or **tridymite**. These phases formed during **slow annealing** below the glass transition temperature, consistent with silica-rich glass devitrification behavior.
- **Glass Matrix**
- **Unidentified Phase (??)**
    - Possibly more SiO2 polymorph or mullite.
- **Interpretation:** The coexistence of glass and crystalline SiO_2 polymorphs, along with a possible third phase, suggests **heterogeneous nucleation driven by local chemistry**, possibly influenced by sodium migration or water vapor. The appearance of these silica phases correlates with mechanical brittleness in the final product and may need to be suppressed in future processing.
- **XRD Pending**



Crystalline Phases
Notation
Oxide Formula
Cristobalite
Tridymite
SiO2
Pseudowollastonite
CaO · SiO2
Rankinite
3CaO 2SiO2
Lime
CaO
Corundum
Al2O3
Mullite
3Al2O3 2SiO2
Anorthite
CaO Al2O3 2SiO2
Gehlenite
2CaO Al2O3 SiO2
Temperatures up to approximately 1550°C are on the Geophysical Laboratory Scale; those above 1550°C are on the 1948 International Scale
SiO2
1723°
1707°
~1590°
Two Liquids
Cristobalite
1470°
1707°
1600
1368°
1345°
Tridymite
1470°
1436°
1400
1170°
1400
1600
Mullite
1800
CaO · SiO2
1544°
Pseudowollastonite
Anorthite
1512°
Rankinite
1307°
1400
1460°
1464°
1318°
1265°
CaO Al2O3 2SiO2
1553°
1547°
3CaO · 2SiO2
~1310°
~1315°
1400
1495°
2CaO · SiO2
~2130°
1385°
1380°
~2050°
~2070°
Ca2SiO4
Ca3SiO5
3CaO · SiO2
1545°
Gehlenite
1475°
1600
Corundum
3Al2O3 2SiO2
~1850°
~1840°
2CaO Al2O3 SiO2
1593°
CaAl12O19
1800
1552°
Lime
1500°
1455°
1380°
1512°
1470°
1350°
1335°
1335°
CaAl4O7
Ca3Al2O6
CaAl2O4
2400
2200
2000
1800
1600
2000
CaO
~2570°
1535°
1395°
1400°
~1595°
~1730°
~1850°
Al2O3
~2020°
3CaO · Al2O3
12CaO 7Al2O3
1455°
CaO · Al2O3
~1605°
CaO · 2Al2O3
~1750°
CaO 6Al2O3
Ca12Al14O33

Regolith Grain-Size Mismatch

Crucible

$SiC + O_2 \rightarrow SiO_2 + CO\uparrow$
(gas release)

SiO_2 would form either:

- A thin protective layer
- breakdown and re-dissolve into the melt
- That extra SiO_2 dissolving into the melt could tip local regions toward extreme silica enrichment.

CO gas:

- Create tiny bubbles (foaming)
- Further destabilize local chemistry

Glass Chunks	Basalt Grains	Result
Fast melting	*Slow melting*	*Thermal mismatch*
Smaller size	*Larger size*	*Surface area imbalance*
Already amorphous	*Crystalline*	*Uneven energy absorption*
Flow early	*Sit solid*	*Viscosity mismatch*
Local Si/Al flooding	*Slow Ca/Fe release*	*Poor mixing leading to composition mismatch*
Blobs grows here	*Microcracks start here*	*Structurally weak material*

Category	Factor	Effect
Starting Material	1–2 cm coarse scoria grains	Slow, uneven melting → local compositional gradients
	Anorthosite glass chunks (not mineral)	Rapid softening → early melt pockets → chemical imbalance
Processing Environment	SiC crucible	SiO_2 leaching into melt → silica enrichment
	Greensand mold (water mixed in)	Possible vapor interaction at mold-melt boundary, thermal shock
Thermal History	Remelt cycles	Further chemical inhomogeneity, growing phase separation
Observed Outcome	Formation of blobs	Silica-rich phase separation due to kinetic and chemical mismatch
	Cracking, brittle failure	Local strain around cristobalite, thermal expansion mismatch

Grain size uniformity is critical to achieving consistent melt behavior.

Feedstock vesicularity and crystalline/amorphous character must be considered to avoid kinetic melting mismatches.

Simple sieving and mild milling of regolith could provide sufficient uniformity without requiring full powderization, preserving energy efficiency.

Repeated remelting without full re-homogenization risks amplifying phase separation and degrading mechanical properties.

Conclusion

1. *Commonly used simulants may misrepresent lunar melt behavior due to vesicularity, alkali retention, and uneven crystallization.*
2. *Uneven melting caused by a mismatch in grain-size.*
3. *Crucible material and shape drive how the simulant melts and contributes to chemical leaching into the material.*
4. *Thermal gradients caused undesirable phase separations that ultimately affect material quality.*

Moving Forward

- Mechanical Testing of cast materials
- XRD mineral analysis of cast materials.
- Melting powdered CSM-LHT-1 rather than clasts, in a smaller furnace—to check for differences between pouring techniques and phase changes.
- Cast a fully anorthosite material and compare to other materials.

Thank You