Sintered Icy Regolith Simulants and their Implications for Lunar Subsurface Modification on Geologic Timescales

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Introduction

- Research questions:
  - How do we expect water ice to interact with lunar regolith?
  - How can we best produce icy lunar regolith simulants on Earth to replicate the expected properties?
- Motivation of research: Facilitate exploitation of lunar ice as a resource

Acknowledgements

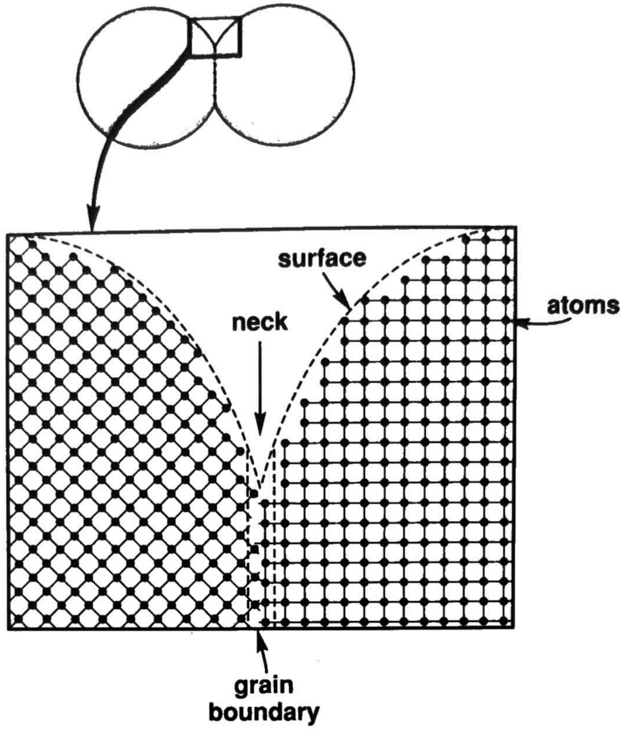
- CRREL (US Army's Cold Regions Research and Engineering Lab)
  - Lab facilities, testing support

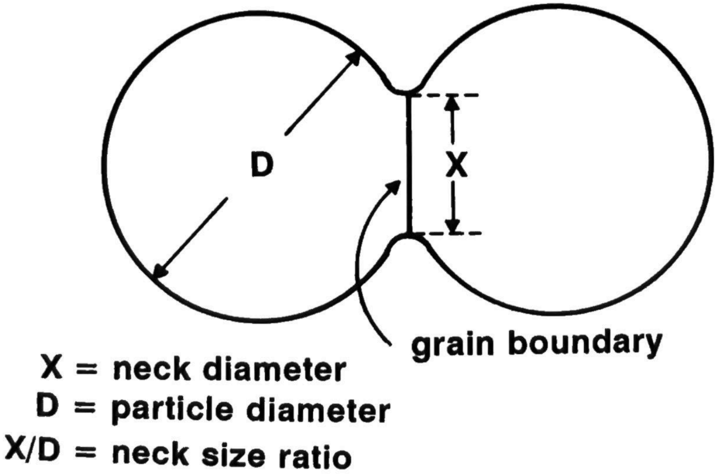
- Colorado School of Mines Space Resources Department
  - Funding

Sintering

Sintering Basics

- Bonding of two or more solid-state particles by mass transport to a neck region
  - Degree of sintering usually defined by neck growth, neck size ratio
- Surface area reduces
- Relevant temperatures: T>50% of melting point, or close to a phase change

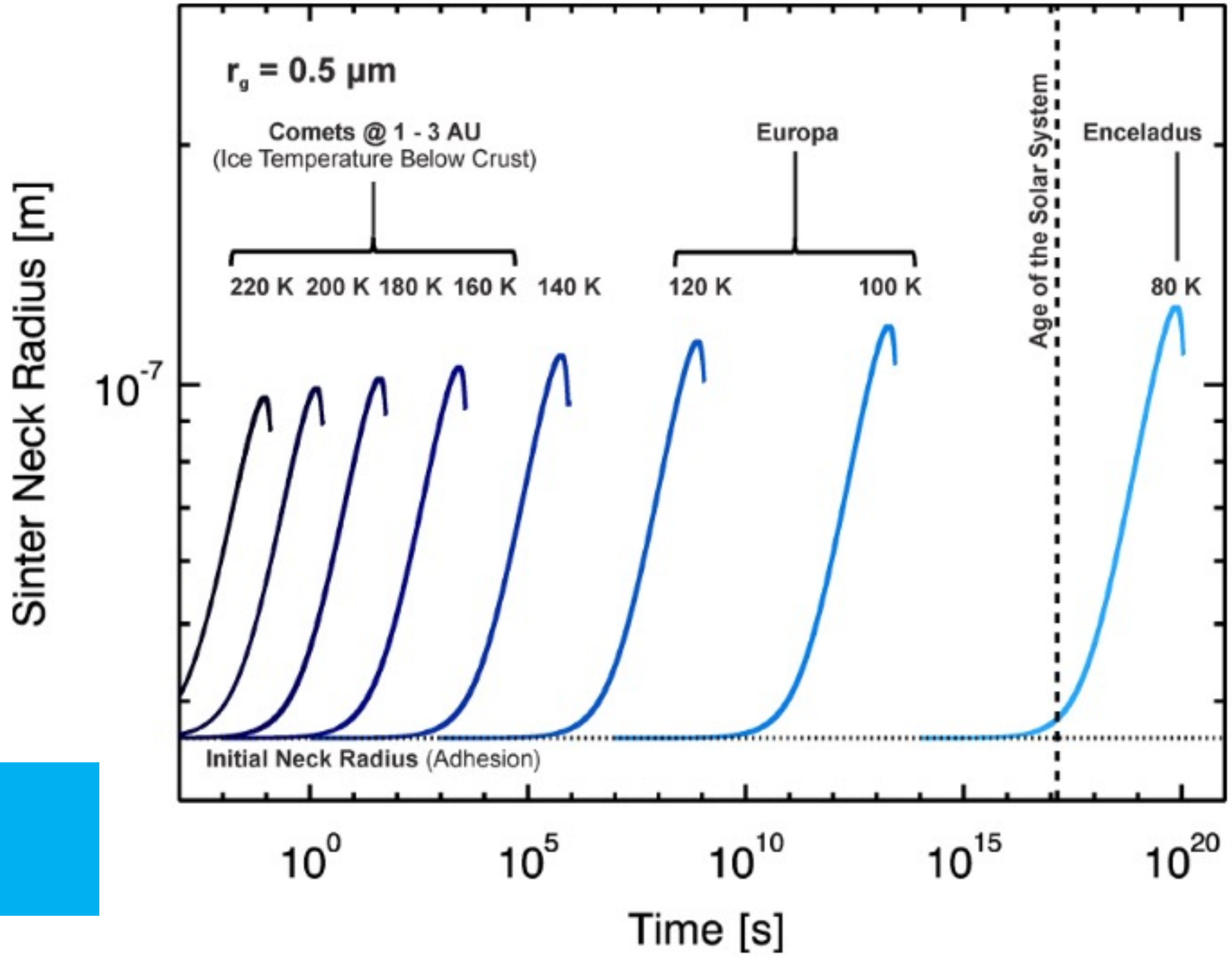




Ice Sintering in Planetary Science

- Cryogenic Ice Vacuum Sintering Experiments
  - 120 K: 32 years
  - 100 K: 320,000 years
  - 80 K: >age of the solar system
- Ice sintering shown to occur at temperatures and pressures relevant to lunar PSRs

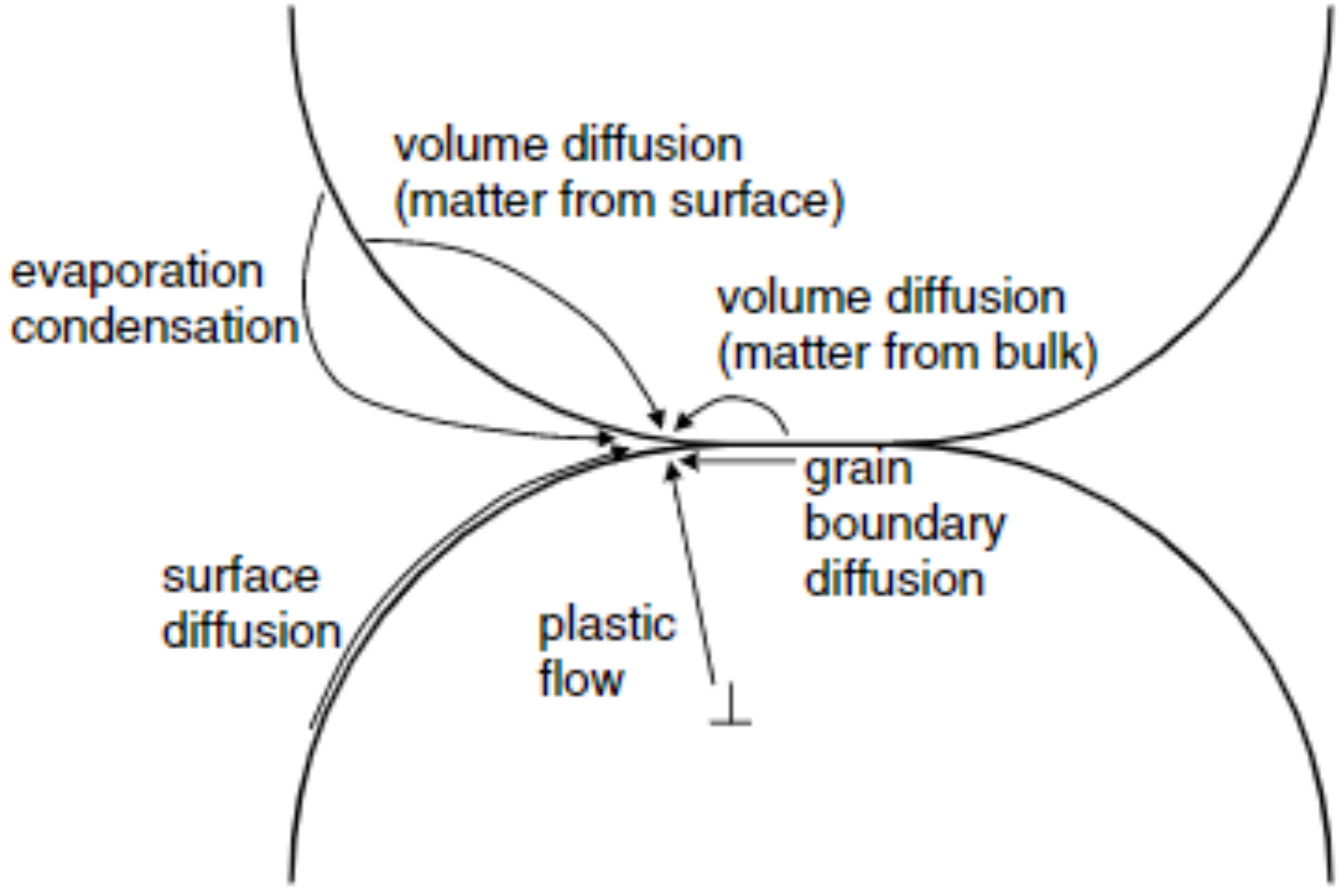
Ice is Hot!



Gundlach et al. 2018

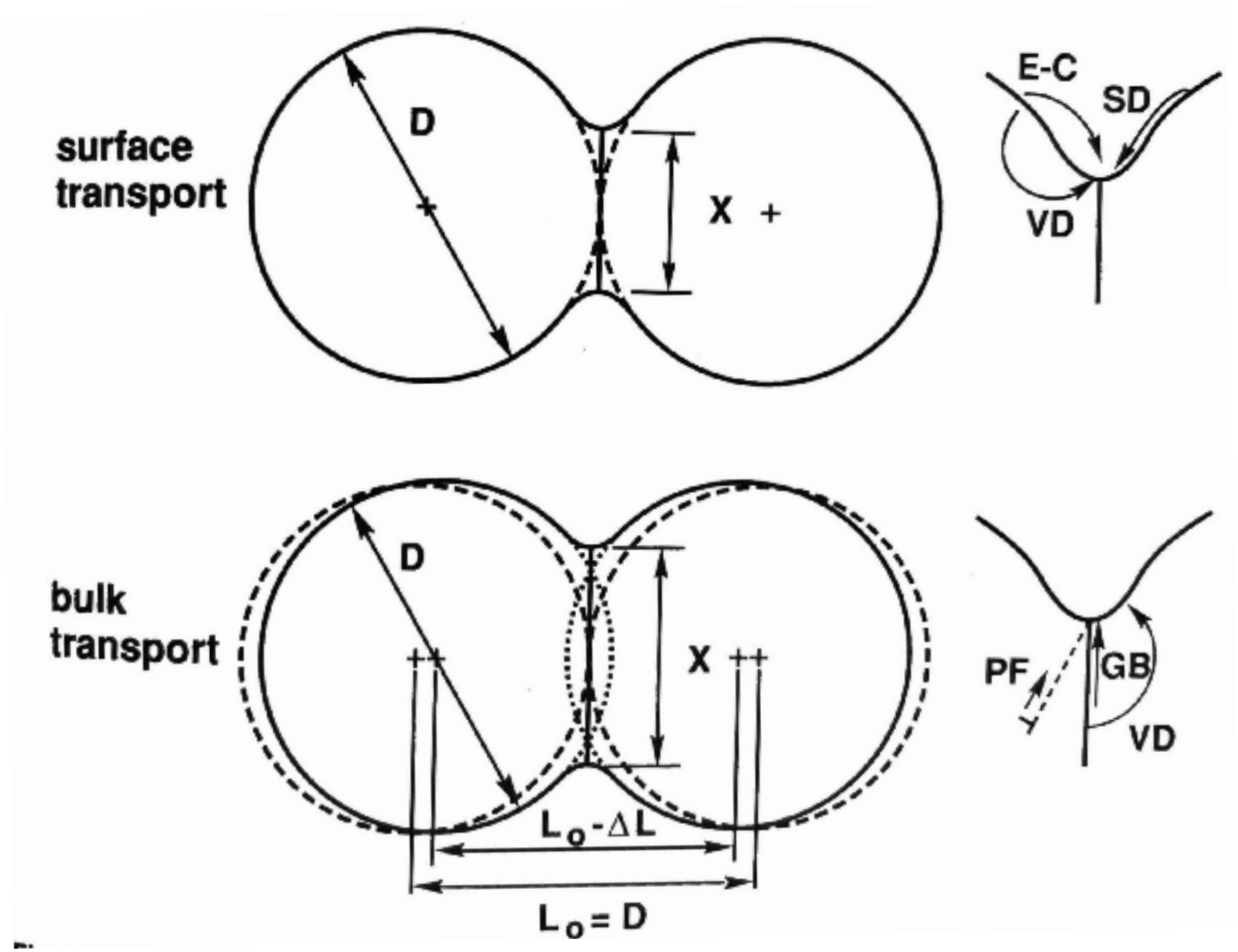
Sintering Mass Transport Mechanisms

- Two categories of mass transport: surface and bulk transport
- Surface Transport:
  - sublimation-deposition
  - surface diffusion
  - volume diffusion
- Bulk Transport:
  - plastic flow
  - volume diffusion
  - creep



Surface vs. Bulk Transport

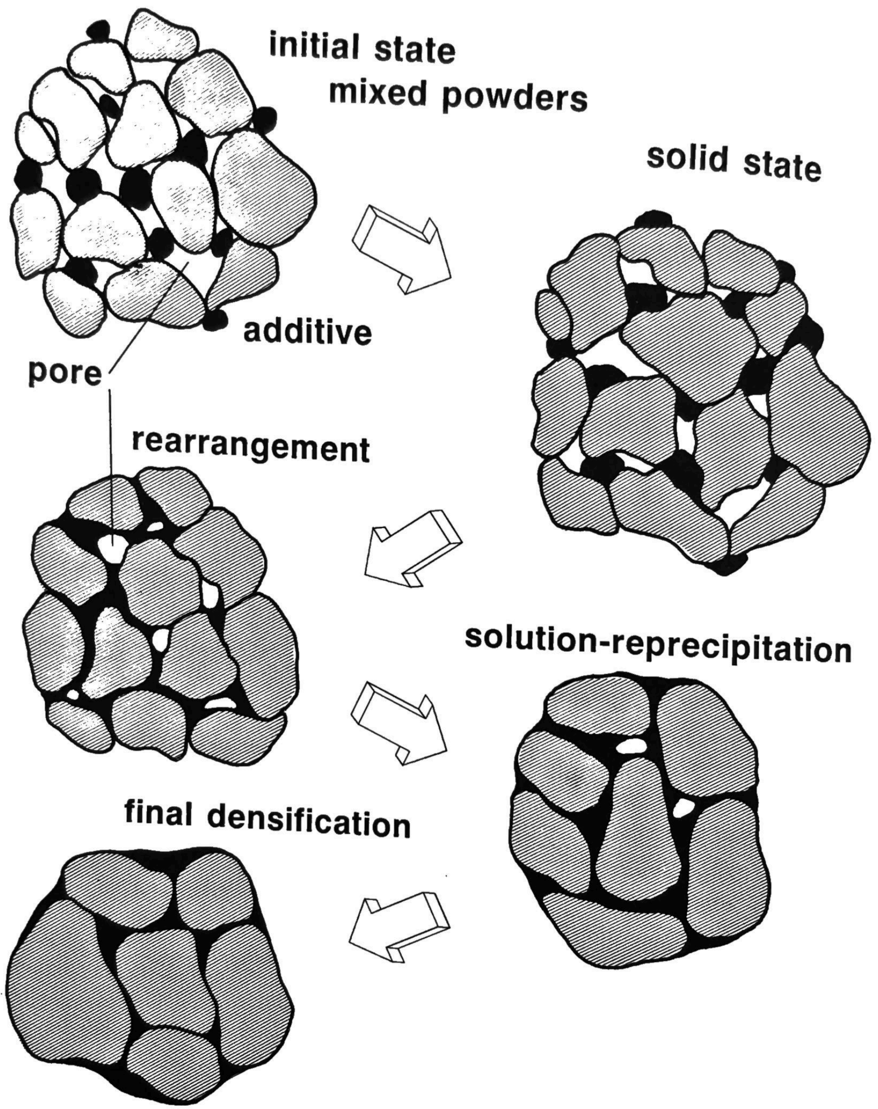
- Surface Transport: no densification
  - Reduction in total surface area, no change in bulk density
- Bulk Transport: Significant densification
  - Pressure-assisted sintering often used to drive bulk transport and densification in industrial processes



German, 1996

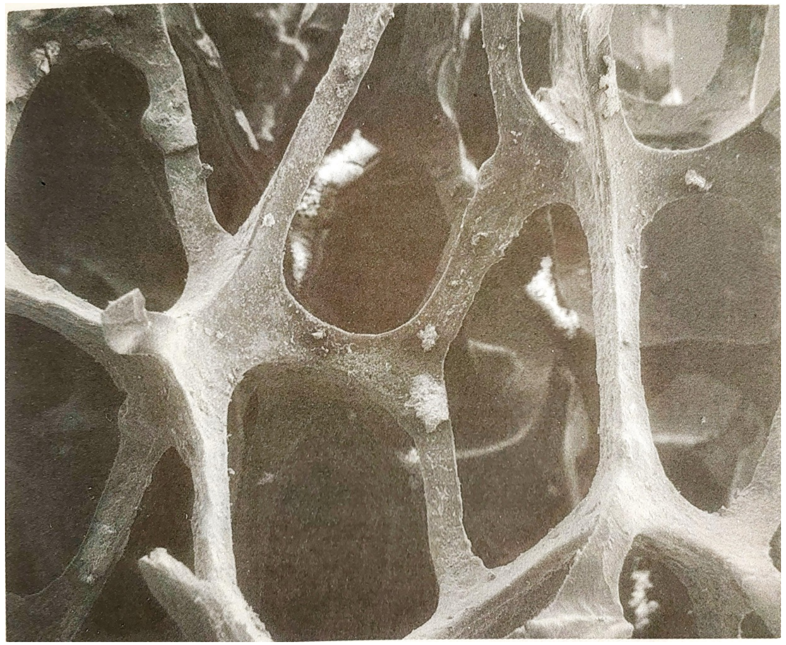
Liquid Sintering

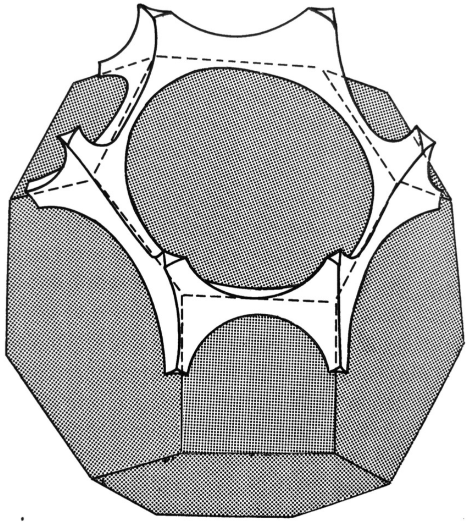
- At least one phase is liquid
  - Characteristic of very high sintering rates
- Liquid phase lubricates particles, allows rearrangement and advanced densification



Liquid Sintering Contd.

- Liquid penetrates pore space and solidifies in a continuous matrix
- Images of the solidified liquid phase shown on the right



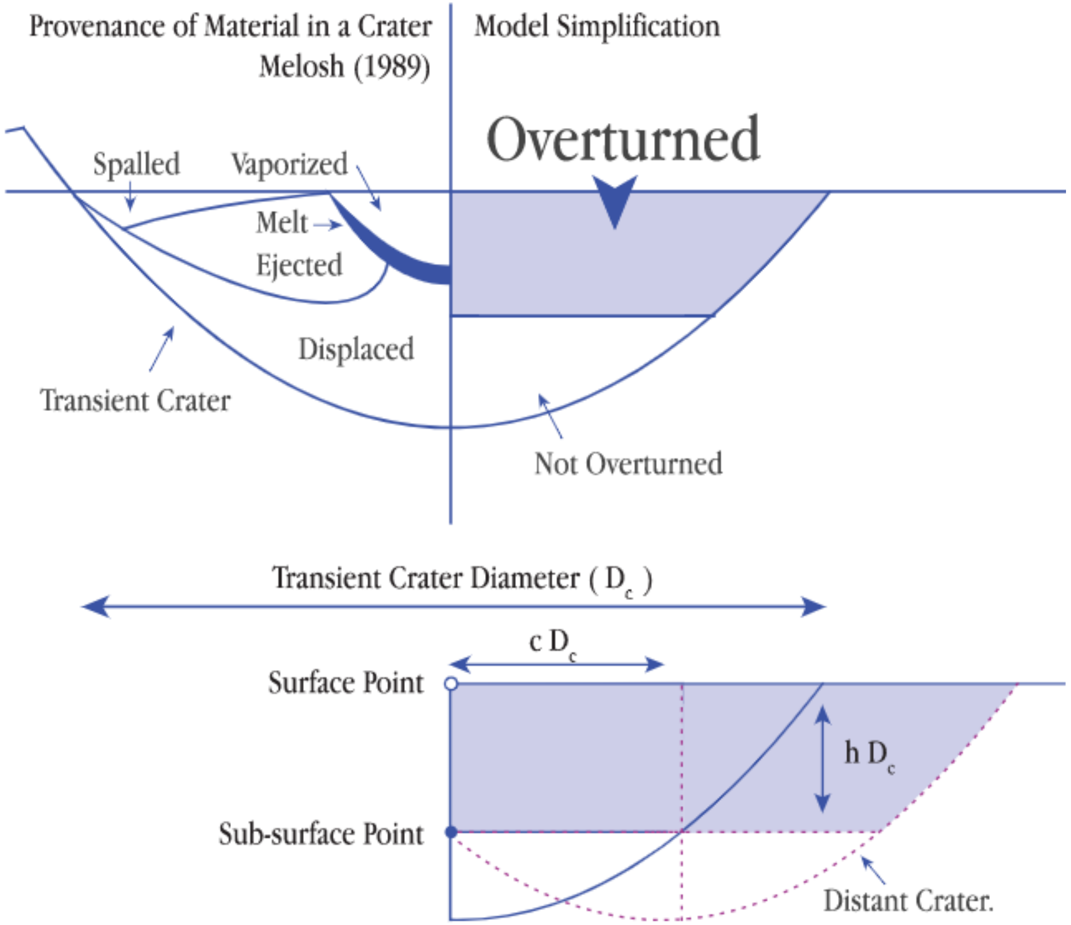


German, 1996

Lunar Water Emplacement and Modification

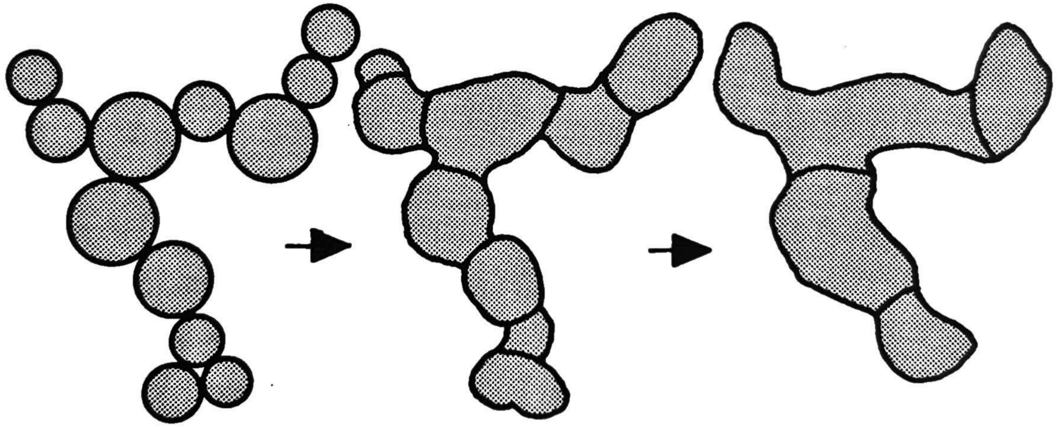
Water Emplacement and Modification Overview

- Collisional water atmosphere formed primarily by asteroid impacts
  - Water deposits in cold traps at the poles
- Impact gardening over billions of years causes mixing
  - Possible desiccation in top layers

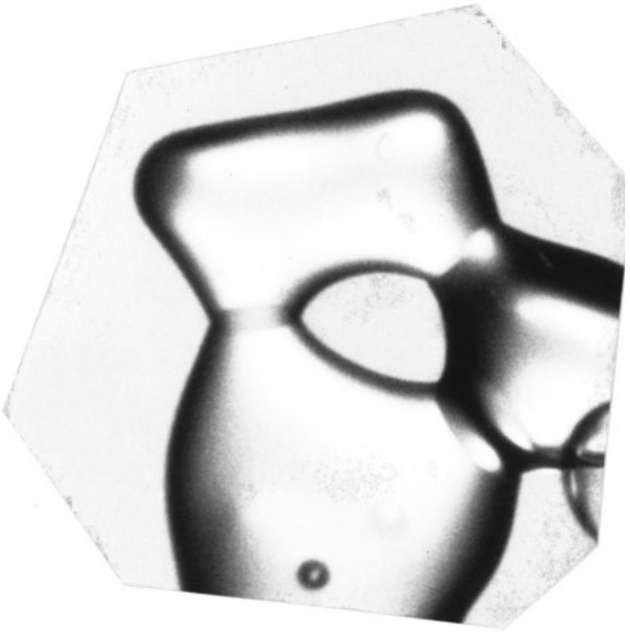


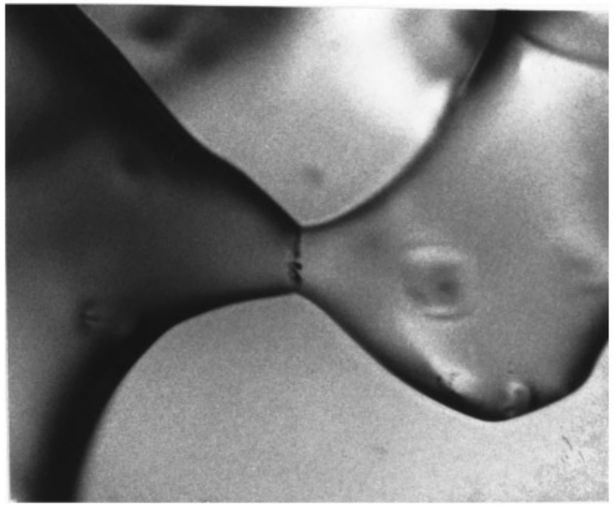
Ice Sintering

- Extensive literature exists on the sintering of dry snow
  - Water has a high vapor pressure and is generally found in nature near its triple point, so surface-transport is the primary driver
  - Maintains bulk density through sintering, but particles combine and coarsen
- Bulk transport occurs with application of pressure



microstructure coarsening



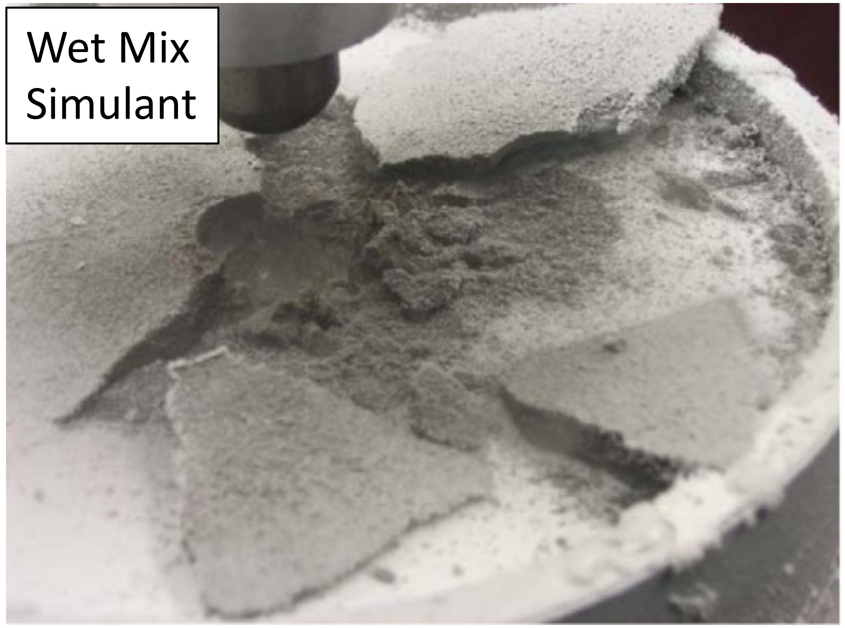


German, 1996; Colbeck et al., 1998

Icy Simulants

Wet Mix Icy Regolith Simulant

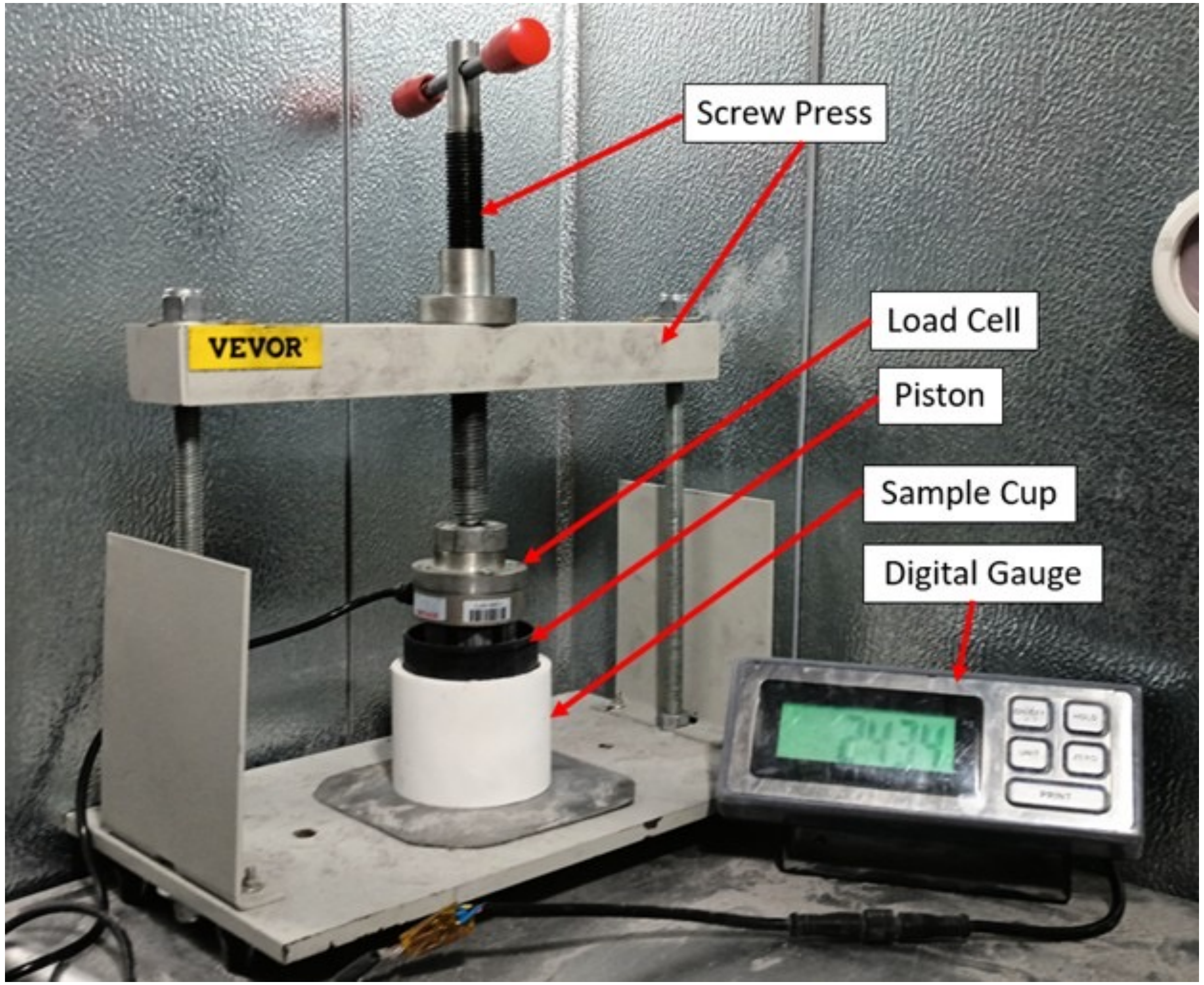
- Oldest, most common method in literature
- Mix liquid water with regolith simulant
  - Sometimes compact
- Freeze mixture
- Characteristics: Very high strength, limestone or concrete
- Requires aggressive excavation methods
  - Jackhammers, impact drills, etc.



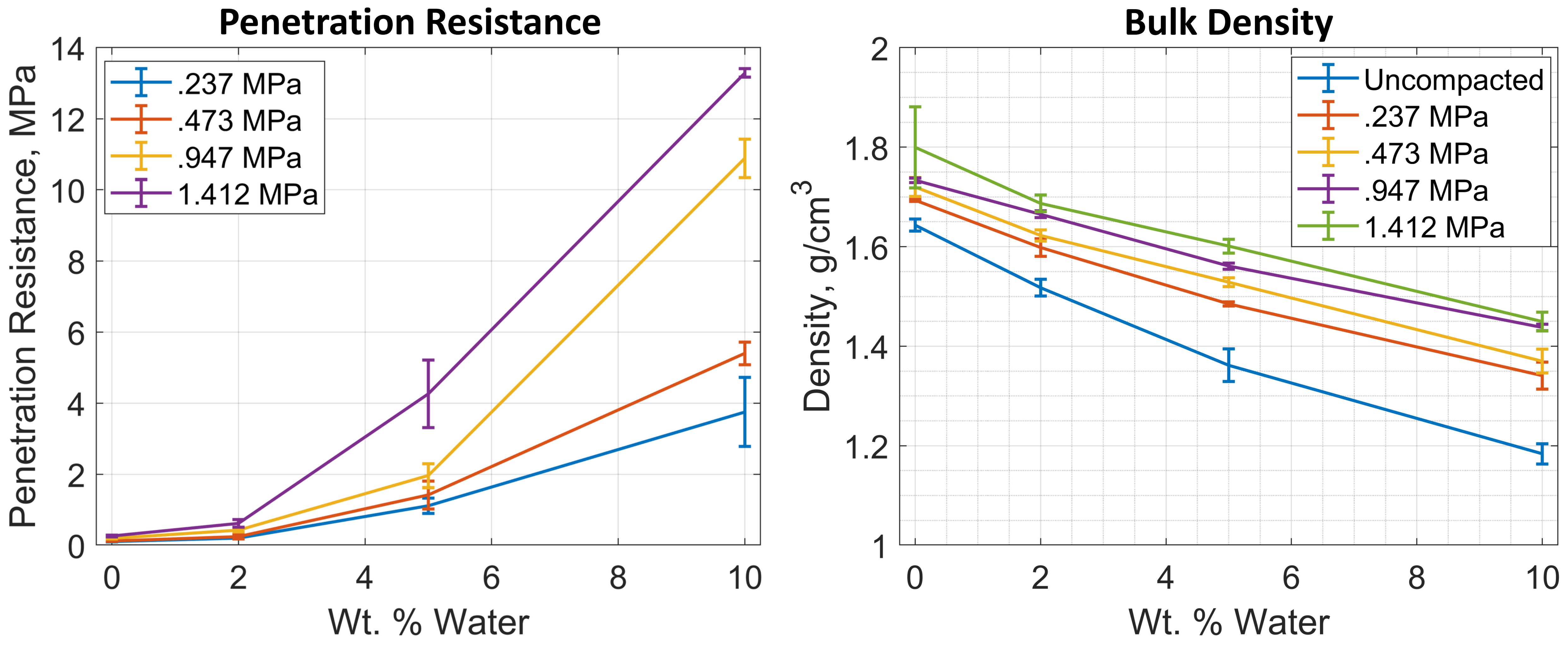
Gertsch et al., 2008

Pressure Sintered Icy Lunar Regolith Simulant (PSS)

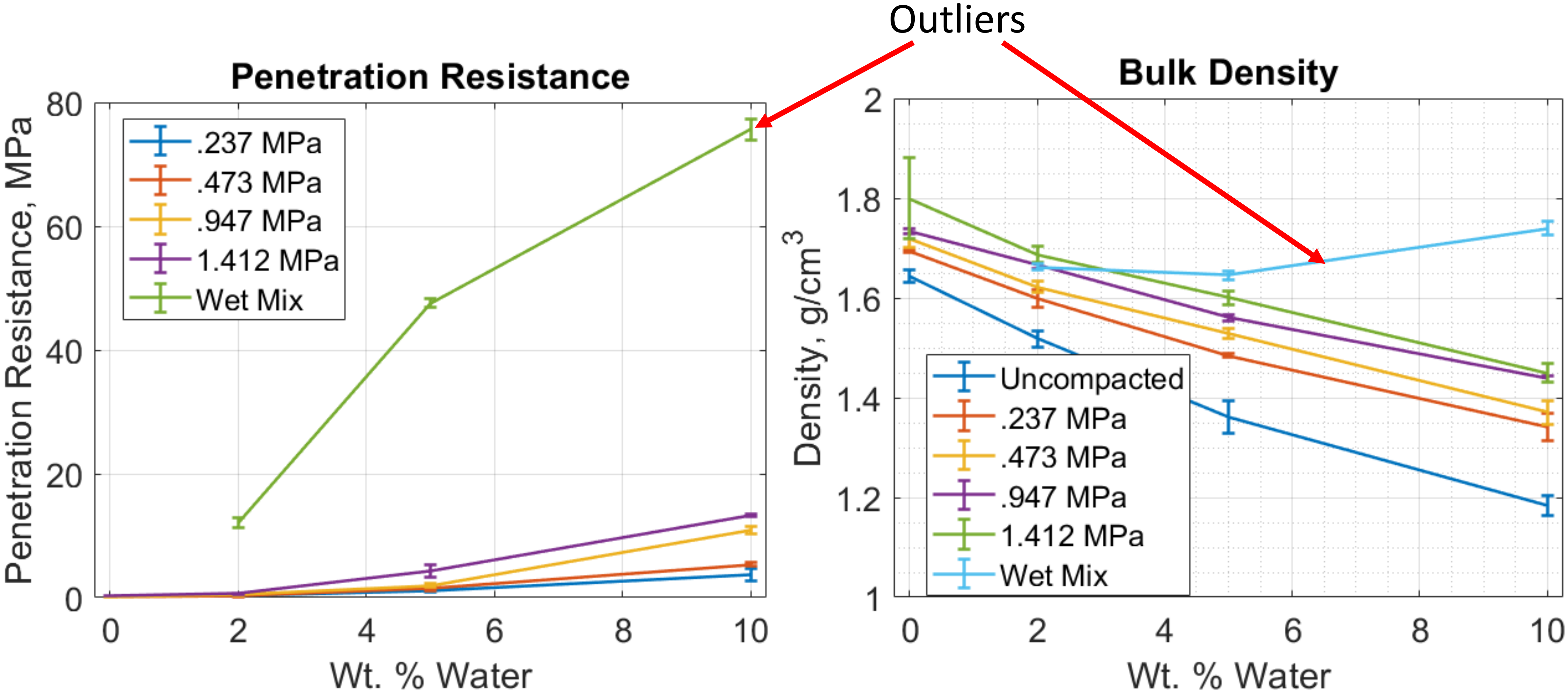
- Mixture of sieved ice grains and regolith simulant placed in cup
- Cup pressed with piston for 10 minutes
- Ice grains sinter the mixture together
- At -10˚C, melting pressure 150 MPa, Yield Strength ~1.5 MPa



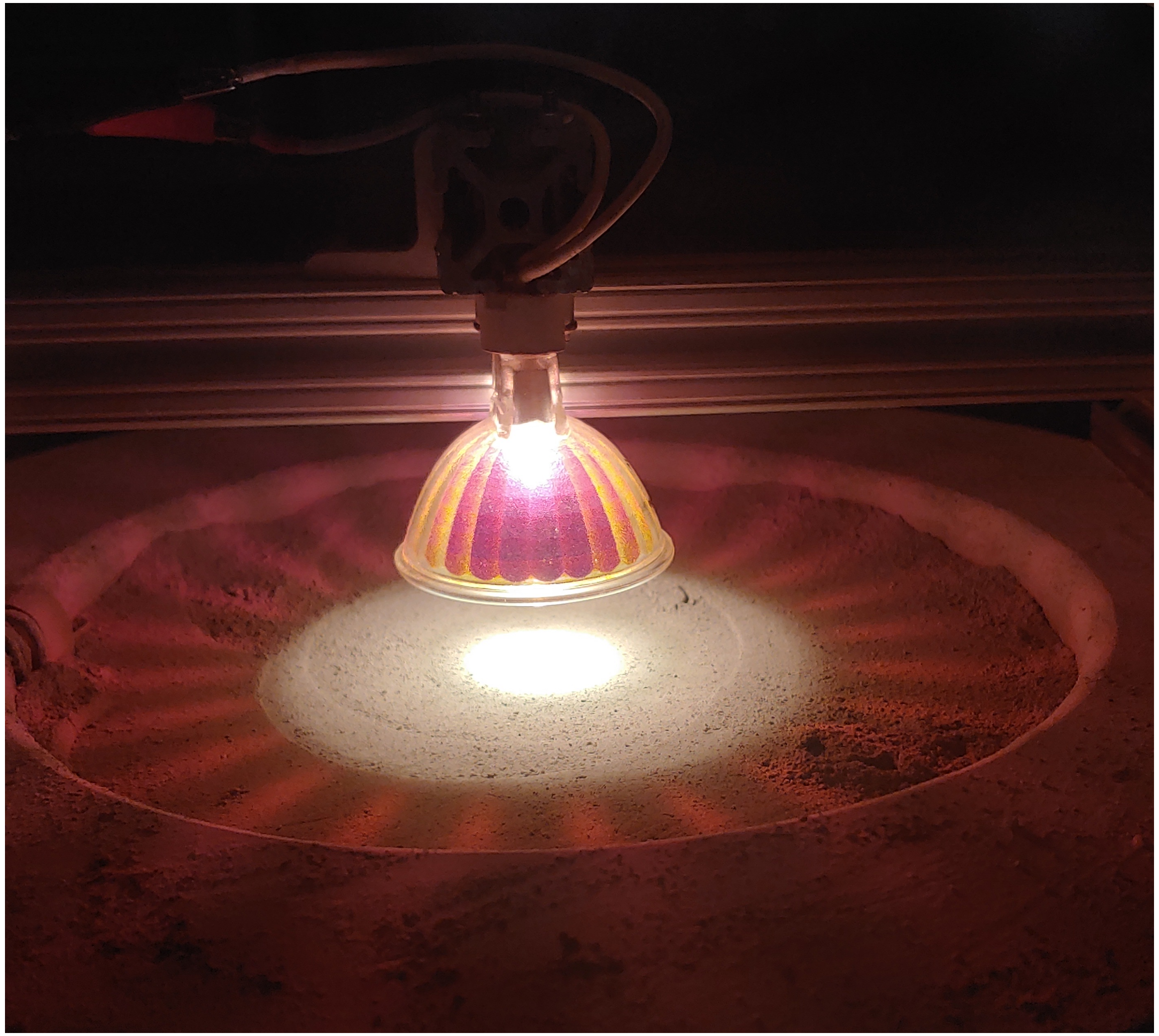
PSS Behavior



PSS Behavior Compared to Wet Mix

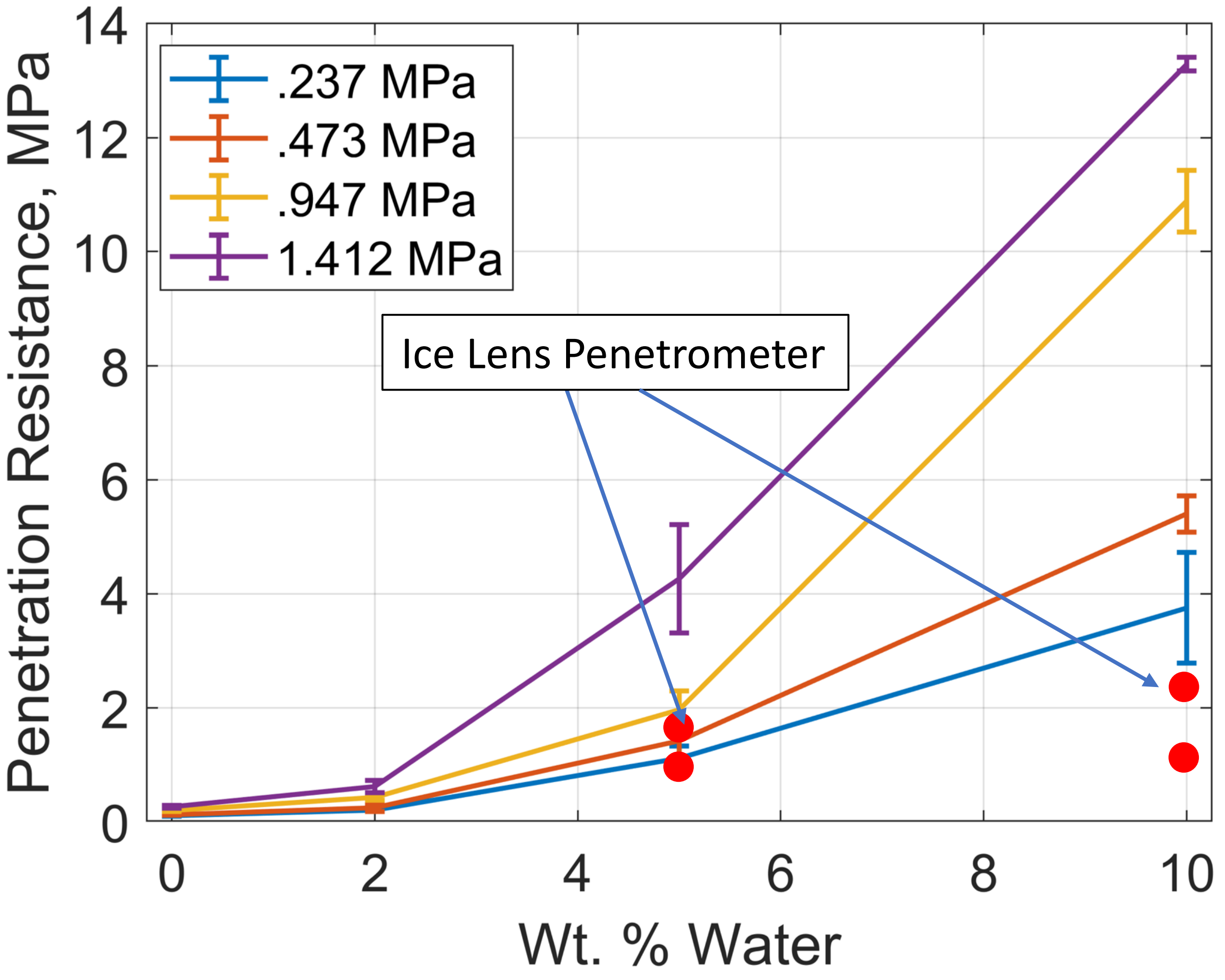


Vacuum Sintered Icy Regolith Simulant (VSS)



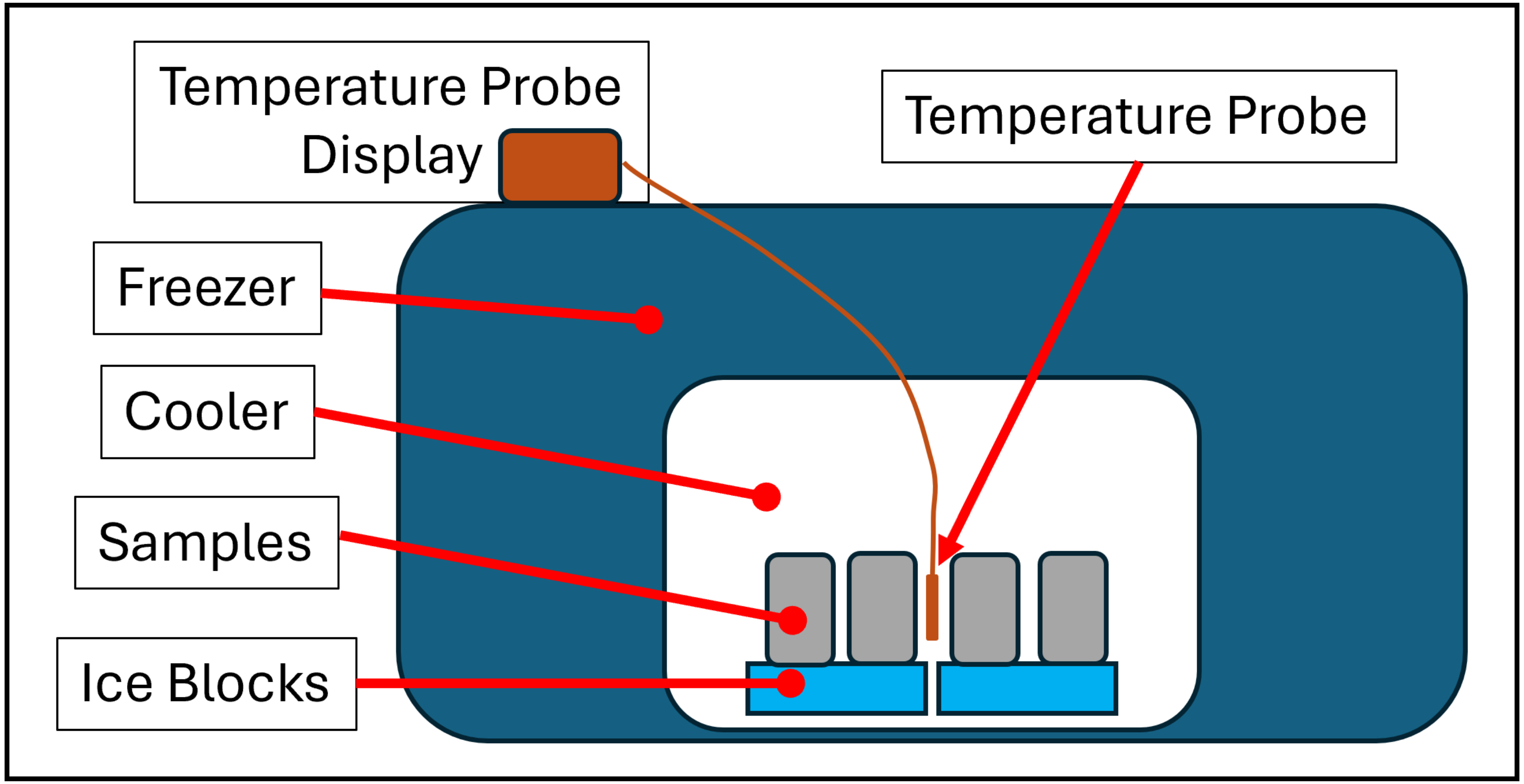
Results: Thermal Sintering

- Variable ice lens thicknesses observed
- Penetration resistance similar to lower-strength PSS
- 40-80x weaker than wet-mix
- No change in ice content observed in ice lens
  - Sintering much faster than diffusion, desiccation

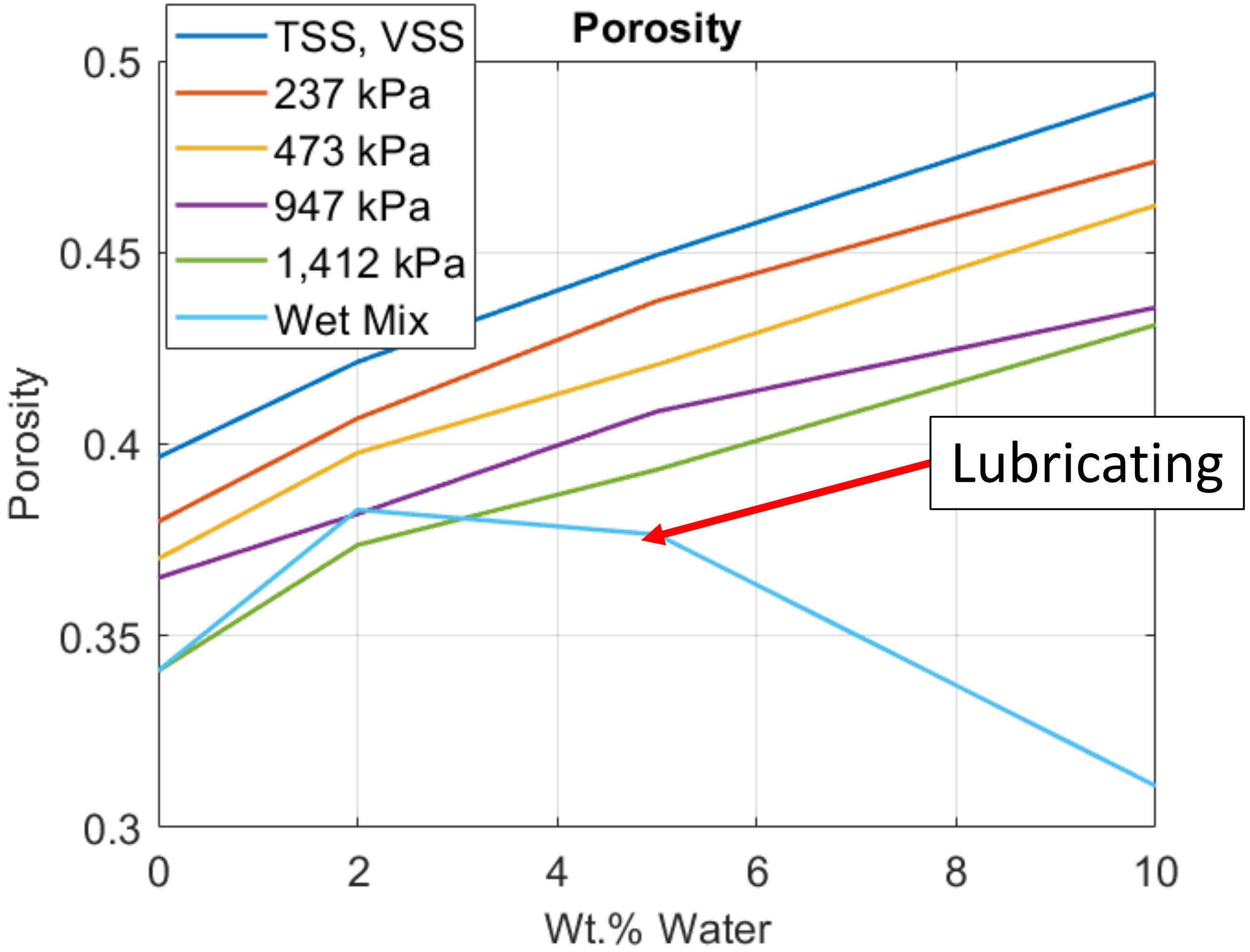


Thermally Sintered Simulant (TSS)

- Temperatures maintained between -2.5C and -6C
  - Ensure no melting
- 7 day duration
- Reproduce vacuum sintering without a vacuum chamber



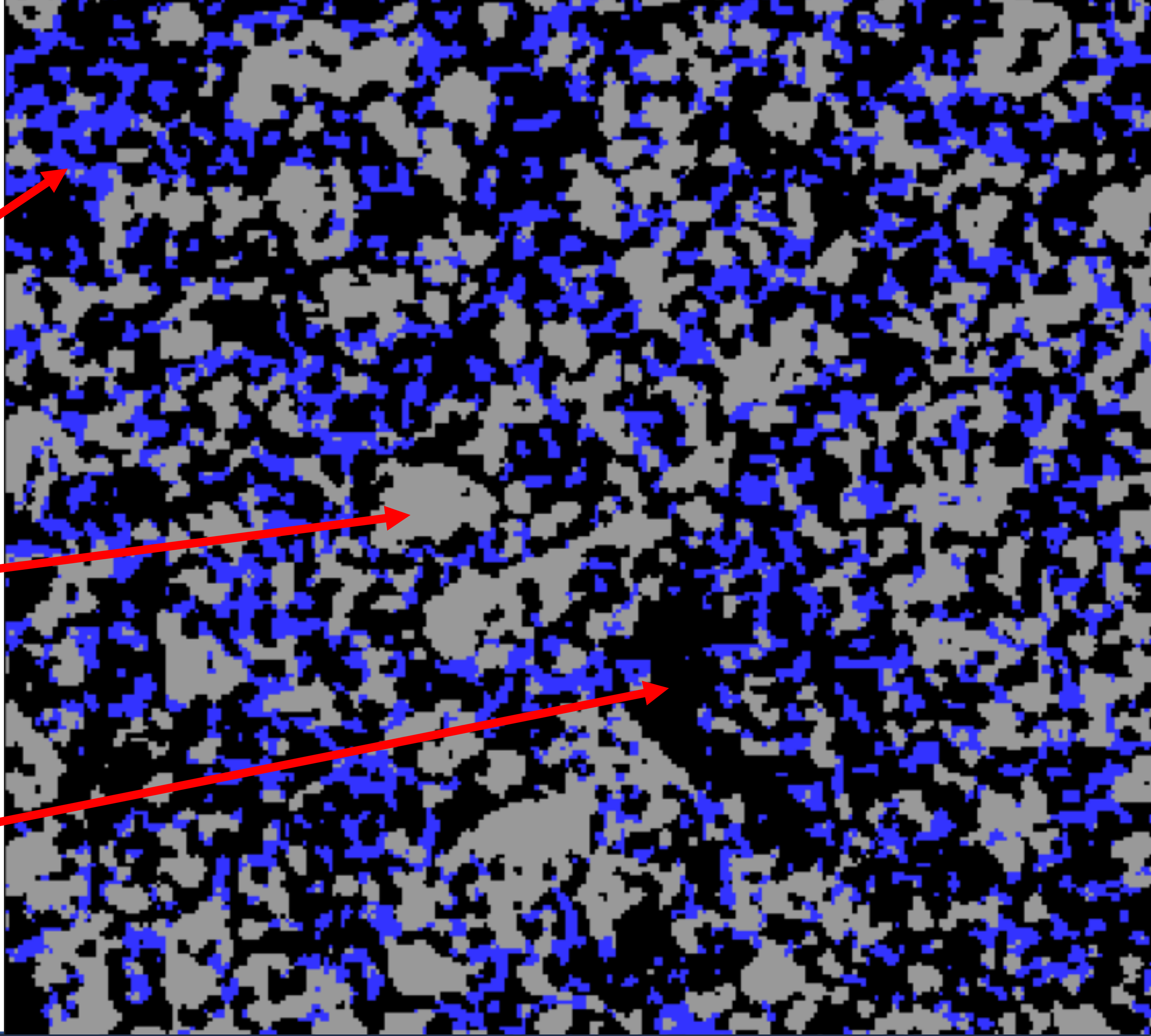
Porosity



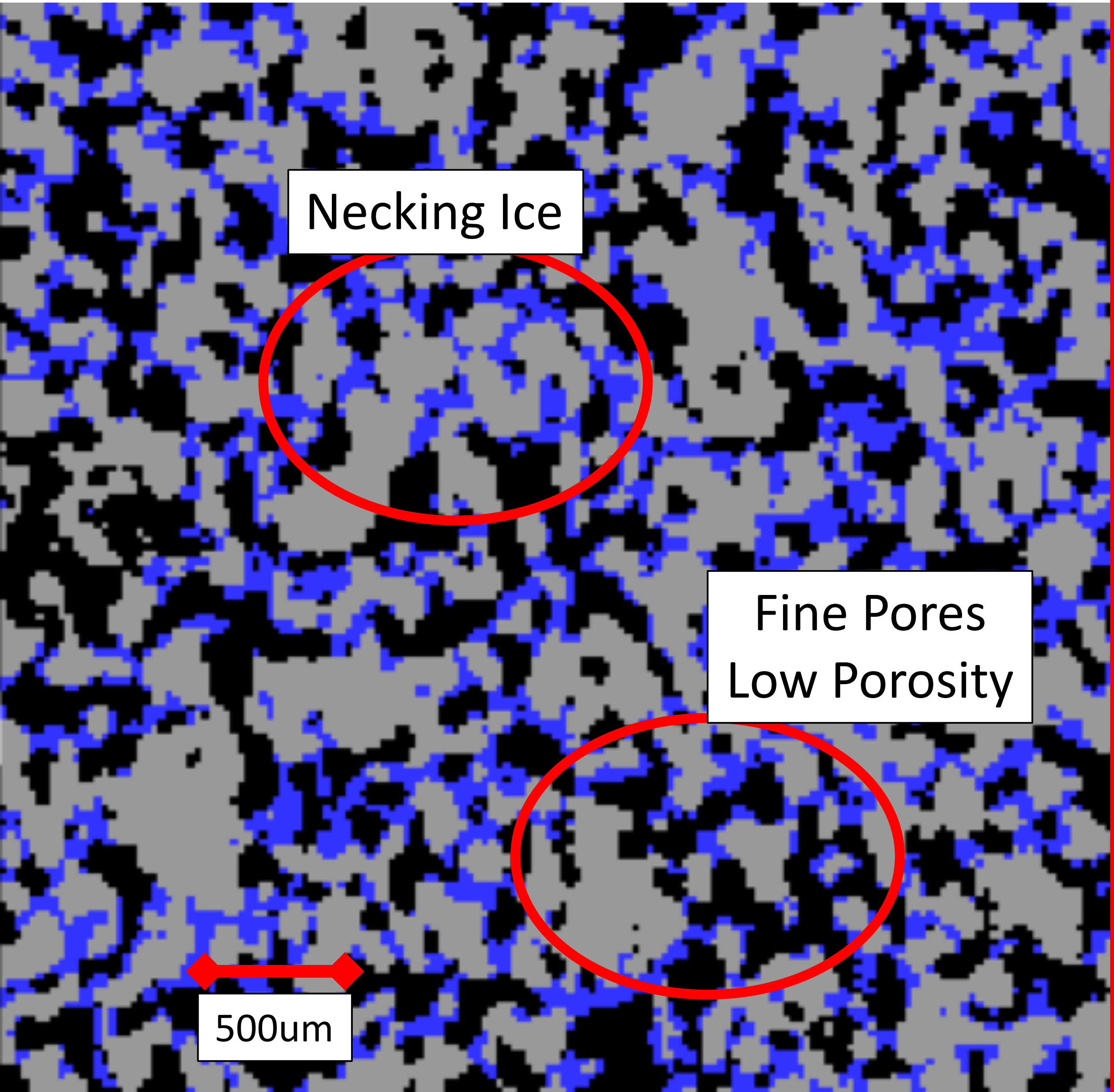
- Dry-mixed ice and regolith cannot densify like wet-mix
  - Even with applied pressure
- Divergent behavior
  - Wet mix decreases in porosity with increased water content

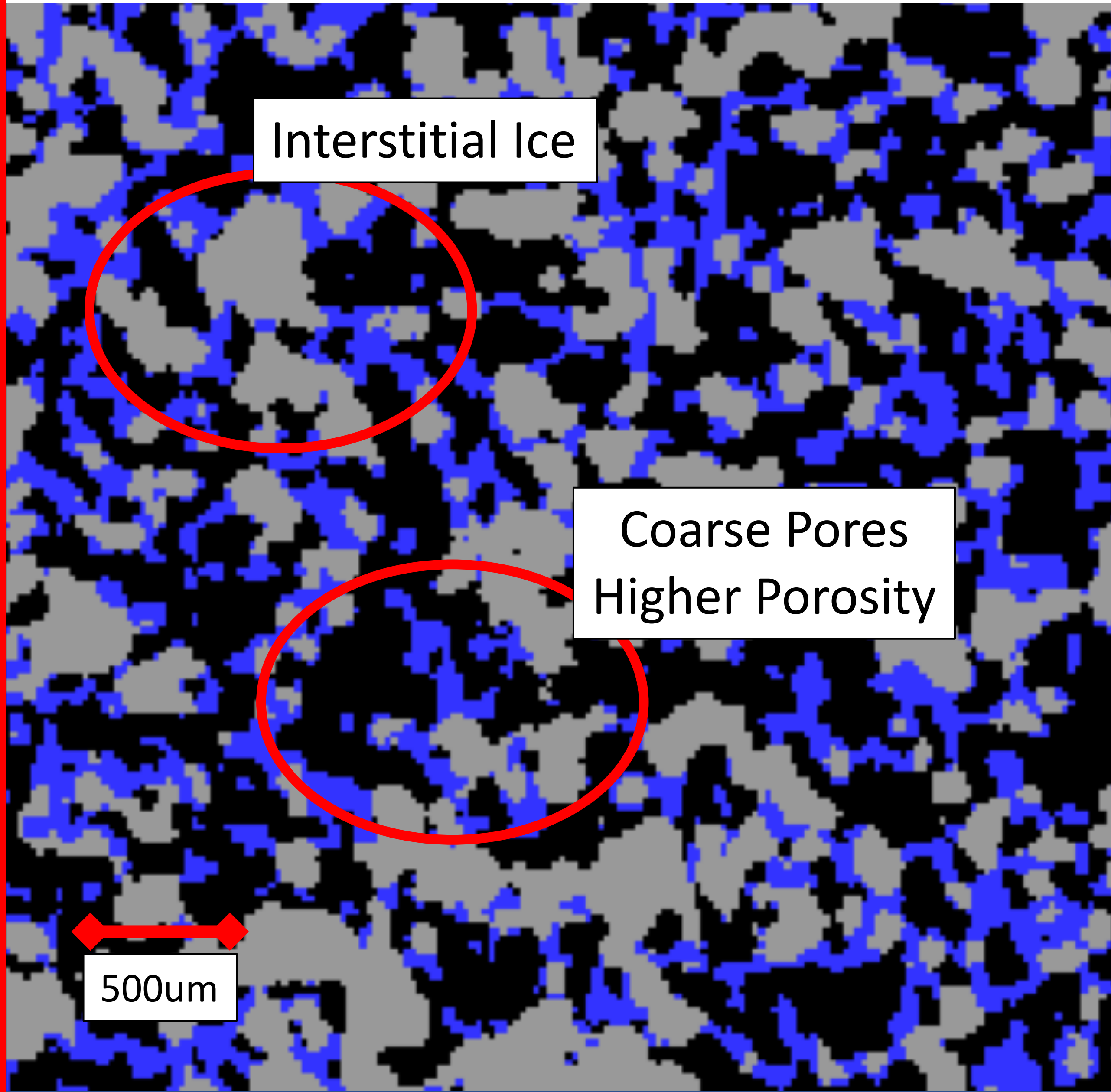
Micro CT Scans
Morphology Investigation

Micro CT Scans

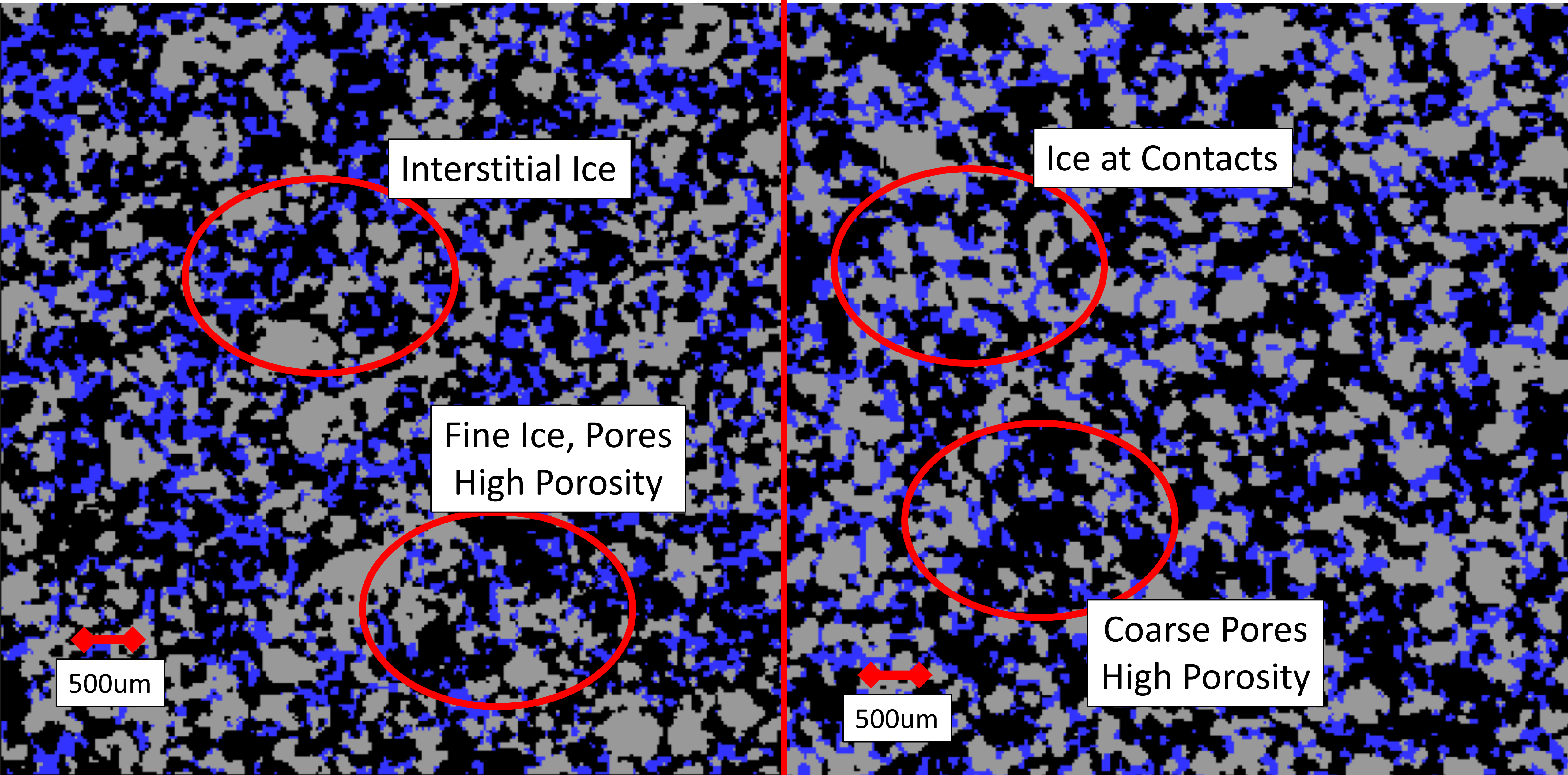


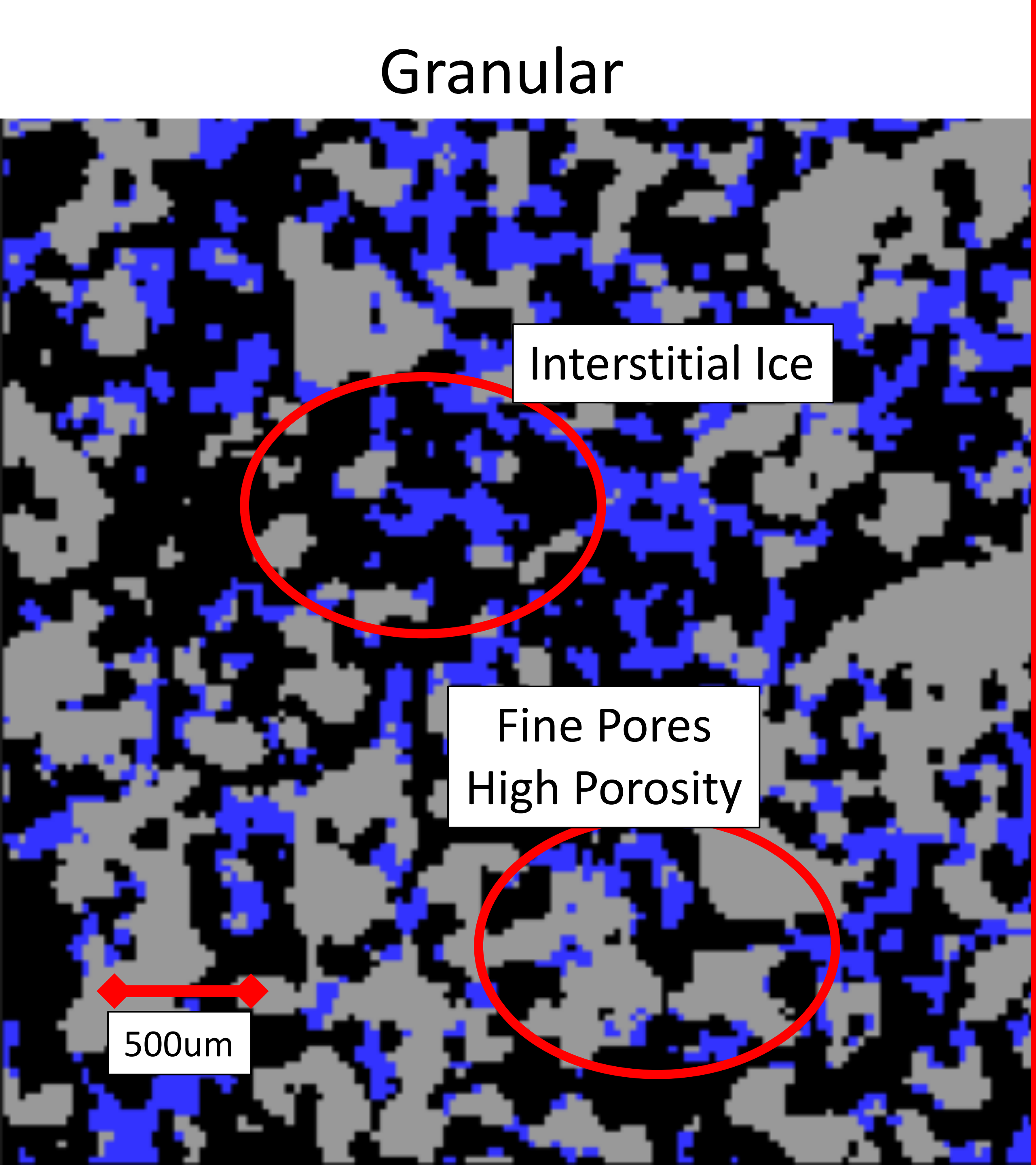
Wet Mix | Pressure Sintered

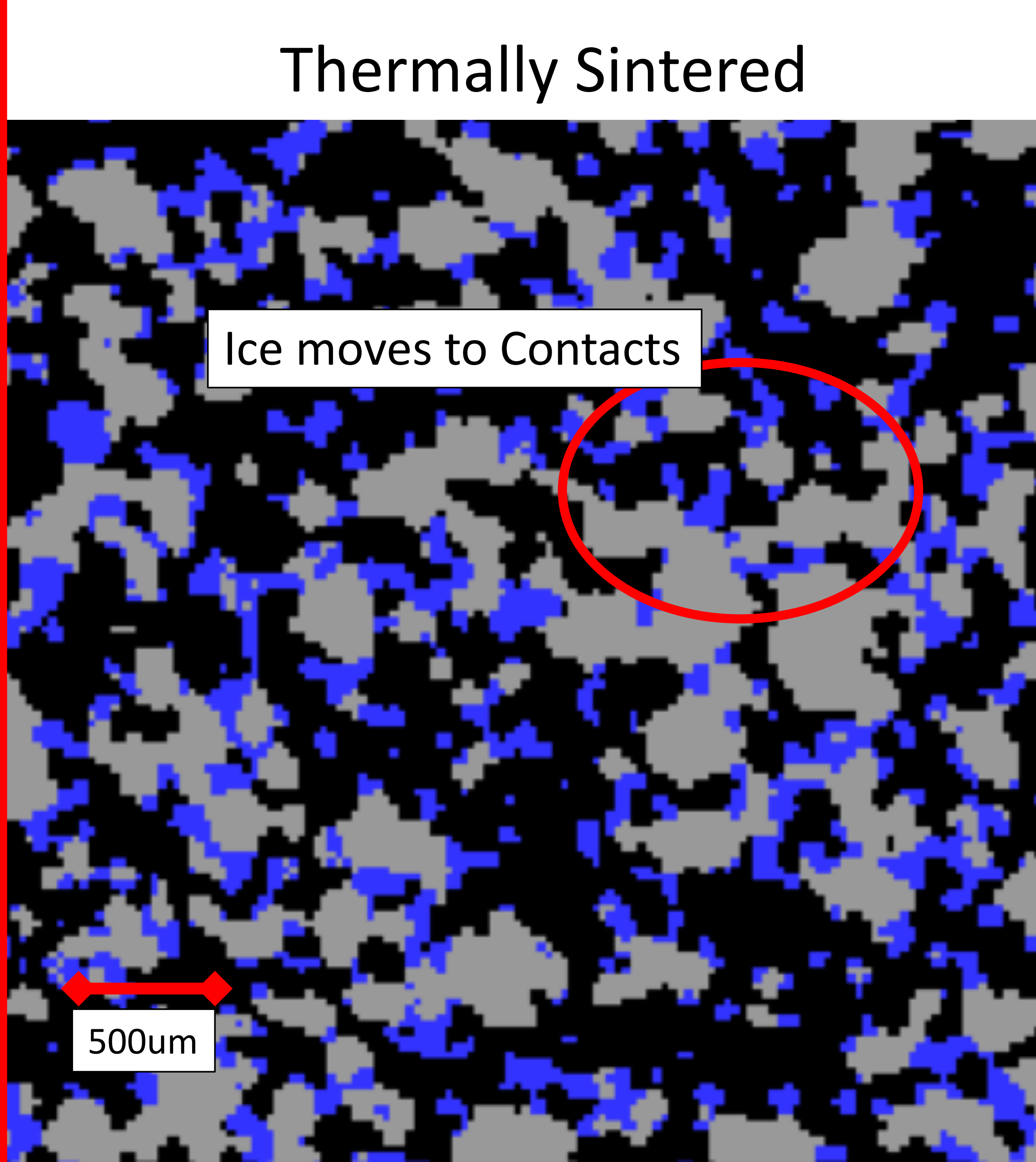




Granular | Thermally Sintered




Granular
Interstitial Ice
Fine Pores
High Porosity
500um


Thermally Sintered
Ice moves to Contacts
500um

Conclusions

- Sintering is a rapid, viable volatile modification mechanism on the Moon
- Sintering prevents densification, arrests high porosity (LCROSS)
- New suite of sintered icy regolith simulants available with geologic justification
    - Thermally Sintered, Pressure Sintered, Vacuum Sintered
    - Highly tunable
- Wet mix icy simulant shown to be fundamentally different than sintered
    - Bulk properties: High strength, high density, low porosity
    - Microstructure: Small pores, grain bridging
    - No geologic justification
    - Not conservative, just different

Call to Action

- Prime-1, Viper (Trident, MSolo)
  - Calibrate needed on sintered high-porosity icy regolith simulants
  - Tunable, geologically relevant
- Use sintered icy simulants to develop new excavation, extraction, prospecting, instrumentation technologies

Journal paper, more to come!

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Backup Slides

Impact Gardening with Water Ice

- Secondary impacts 50x more flux than primary impacts
  - Primary ~20 km/s >> 10 GPa
  - Secondary 0.5 - 1.5 km/s: 1-4 GPa
    - Shock testing, ice melts completely at 4 Gpa
    - 9 – 50 GPa required for insipient, complete vaporization, respectively
- Cannon et al. (2020)
  - Primary impacts only, no thermal modifications
  - Ice concentration peak ~50 cm depth, 10s of cm plentiful ← Optimistic
- Costello et al. (2021)
  - Primary + secondary impacts
  - Complete desiccation by secondary impactors
  - Desiccated, 1Ga = 1m, 3 Ga = 3m ← Pessimistic

Costello et al., 2021; Cannon et al., 2020; Stewart and Ahrens, 2005