Lunar Polar Regolith Thermal & Geotechnical Properties

Presented to the International Space Exploration Coordination Group (ISECG) Lunar Polar Volatiles Virtual Workshops

"Lunar Volatiles Acquisition Technologies"

Sept. 14, 2016

Overview compiled from many sources with attributions on each chart

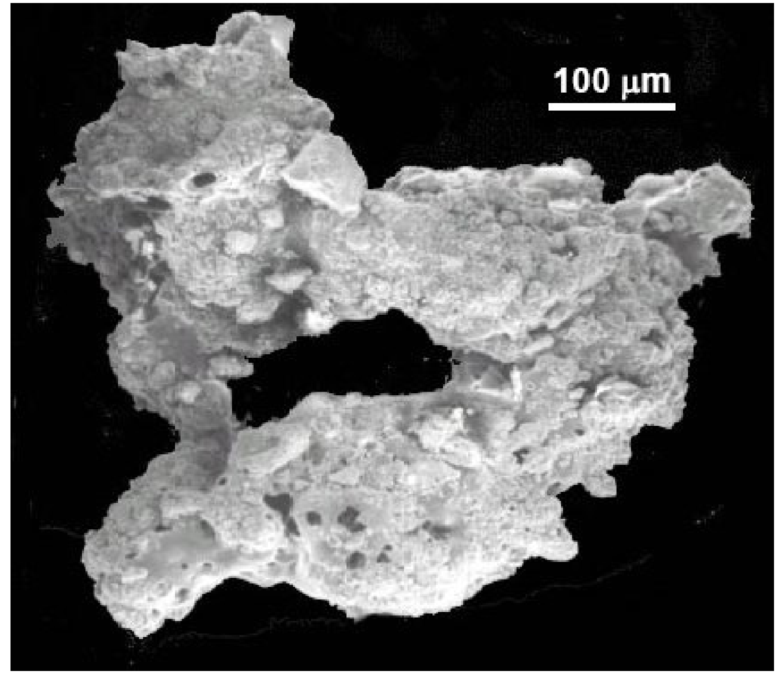
Philip Metzger, UCF

Polar vs. "Normal" Lunar Soil

- Most lunar geologic processes are globally isotropic
- To first-order, polar soil ought to be like equatorial or mid-latitude soil
- However, evidence exists for differences exist at the poles, which we do not understand
- We will review "normal" lunar soil first, then look at differences

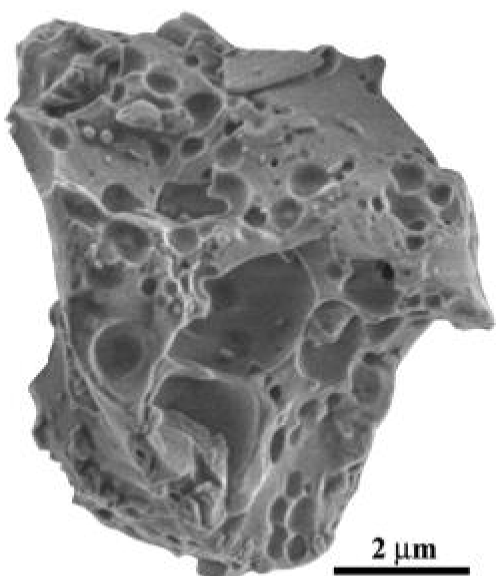
Regolith Formation

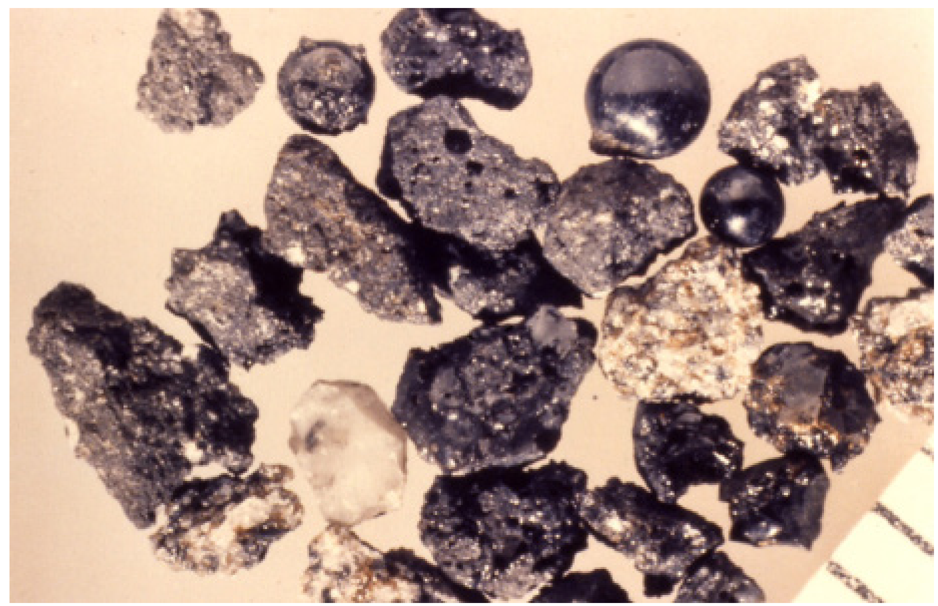
- Impacts are the dominant geological process
- Larger impacts (asteroids & comets)
  - Fracture bedrock and throw out ejecta blankets
  - Mix regolith laterally and in the vertical column
- Micrometeorite gardening
  - Wears down rocks into soil
  - Makes the soil finer
  - Creates glass and agglutinates
  - Creates patina on the grains via vapor deposition
- Lunar soil is completely unlike terrestrial soil
  - No lunar soil simulant can meet every need



Source: David McKay, NASA/JSC

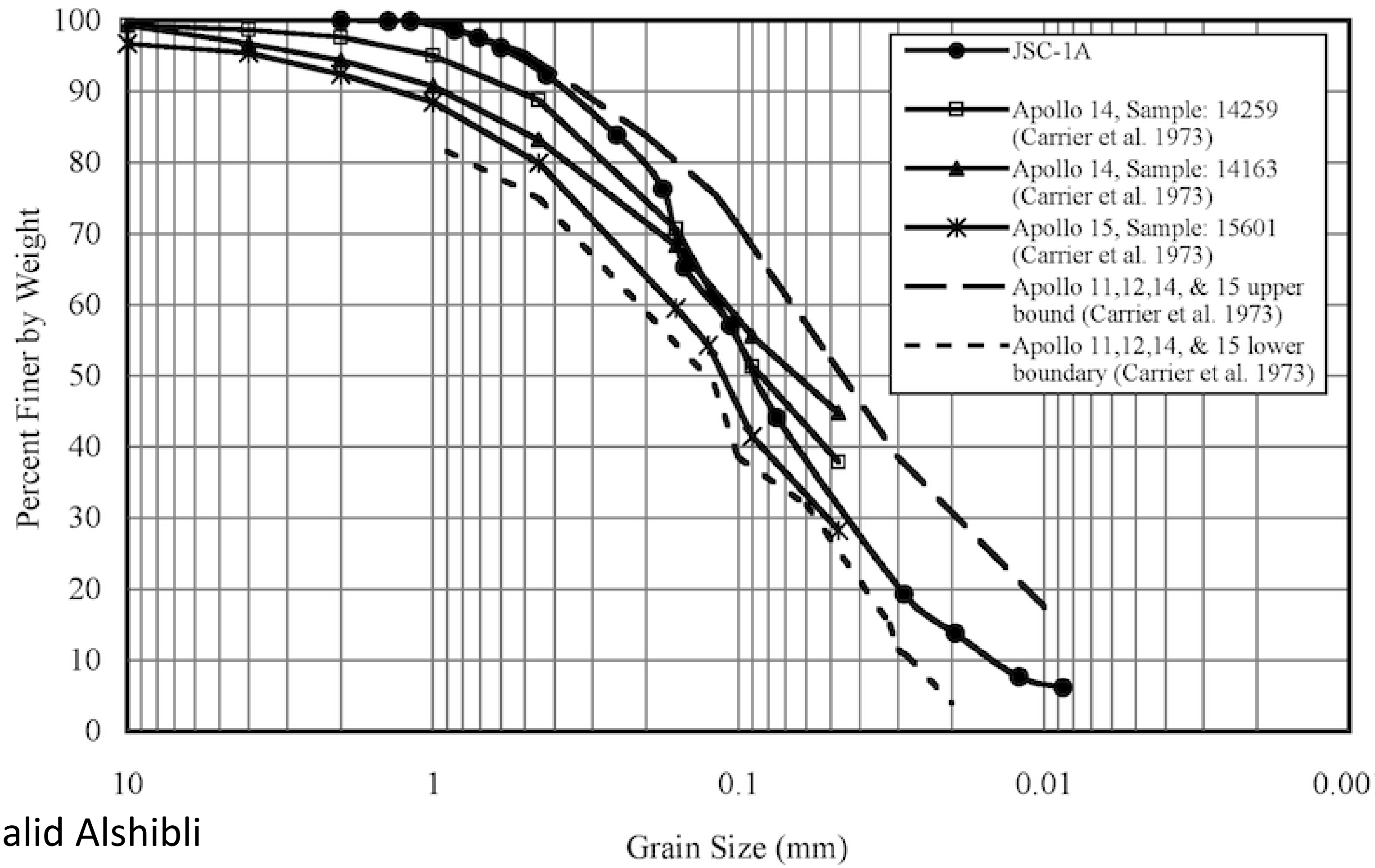
Source: Yang Liu





Source: Larry Taylor

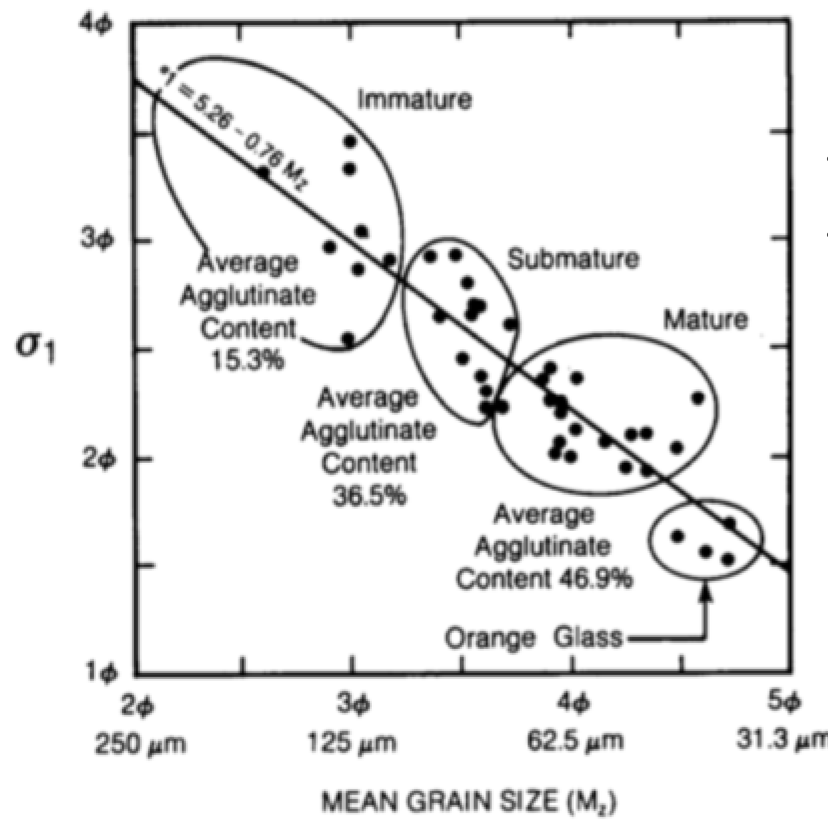
Soil Particle Size Distribution



Credit: Khalid Alshibli

Soil Maturity

- Soil formed by a recent impact is *immature*
  - Coarser, less glass content, fewer agglutinates, less nanophase iron
- Exposure to micrometeorite gardening makes it *submature* then *mature*

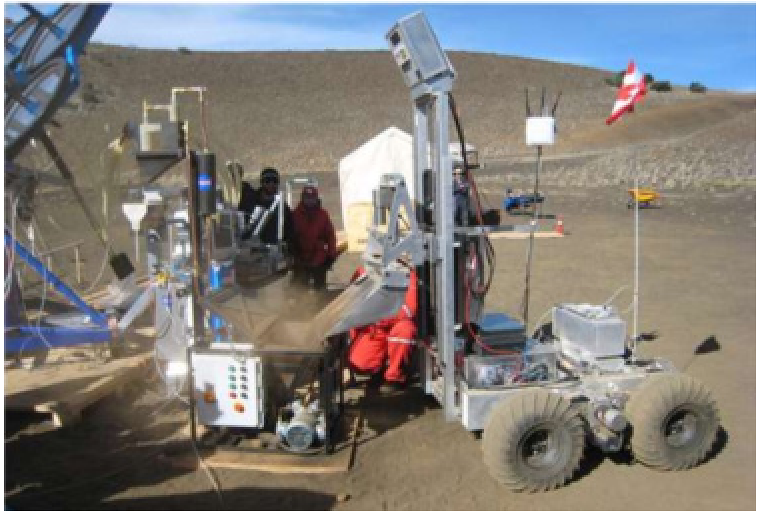


Source: Lunar Sourcebook

Source: W. David Carrier III, Gary R. Olhoeft, and Wendell Mendell, Lunar Source Book

Flowability of Lunar Soil

- Lunar soil does not flow well
  - Sharp, angular particles = high friction
  - Dust content = high cohesion
  - Low Gravity
- Lunar soil simulants often flow too easily
  - JSC-1A flows far too easily
  - NU-LHT series much better but very expensive



Cohesion

Cohesion of the orange and adjacent gray soil.
AS17-137-20989

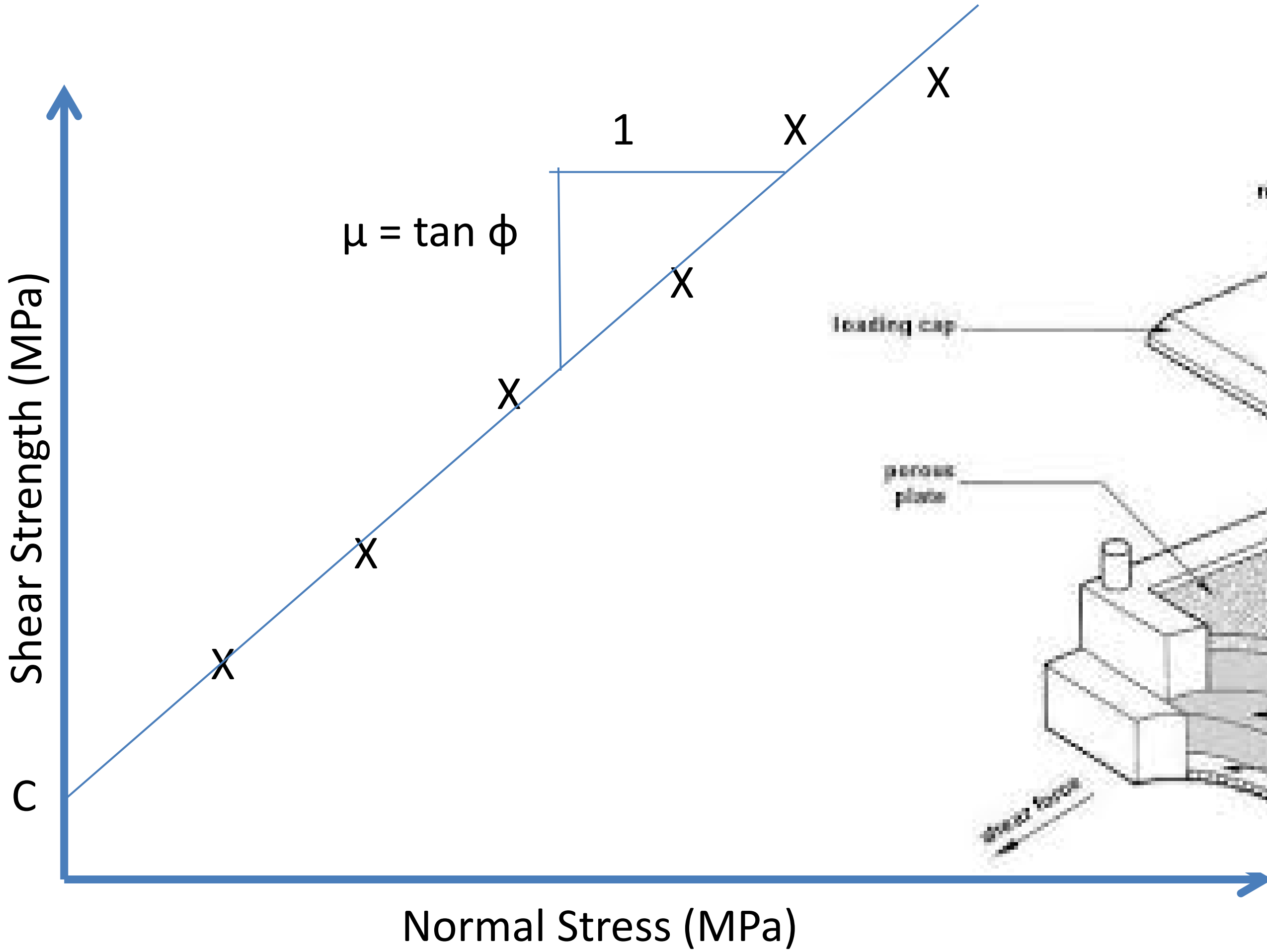
Average cohesion of 0.17 kN m^{-2} adopted for surficial material.

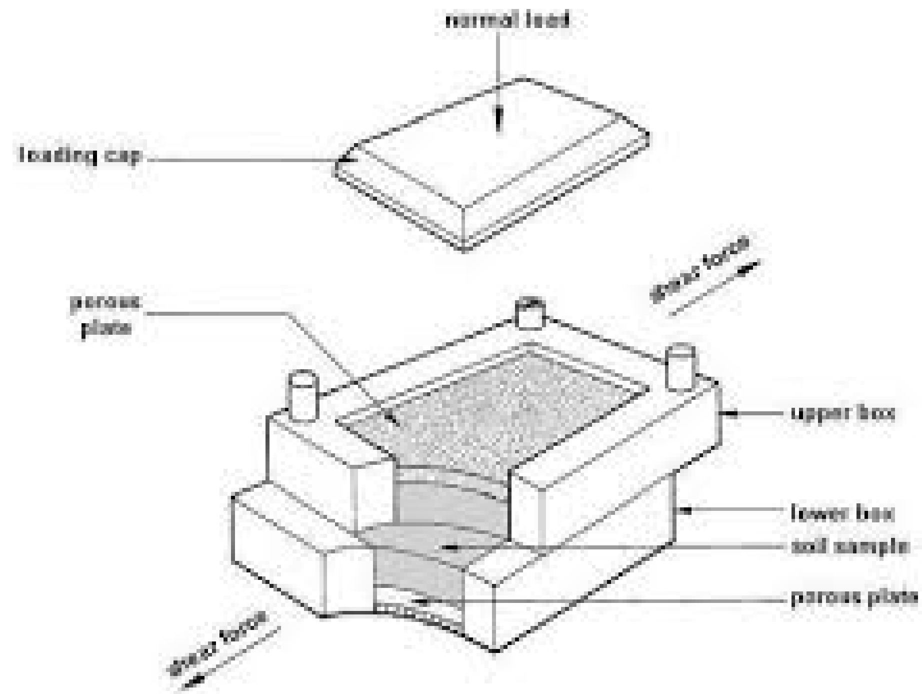
Varies from 0.1 to 1.0 kN m^{-2}

AS12-57-8448

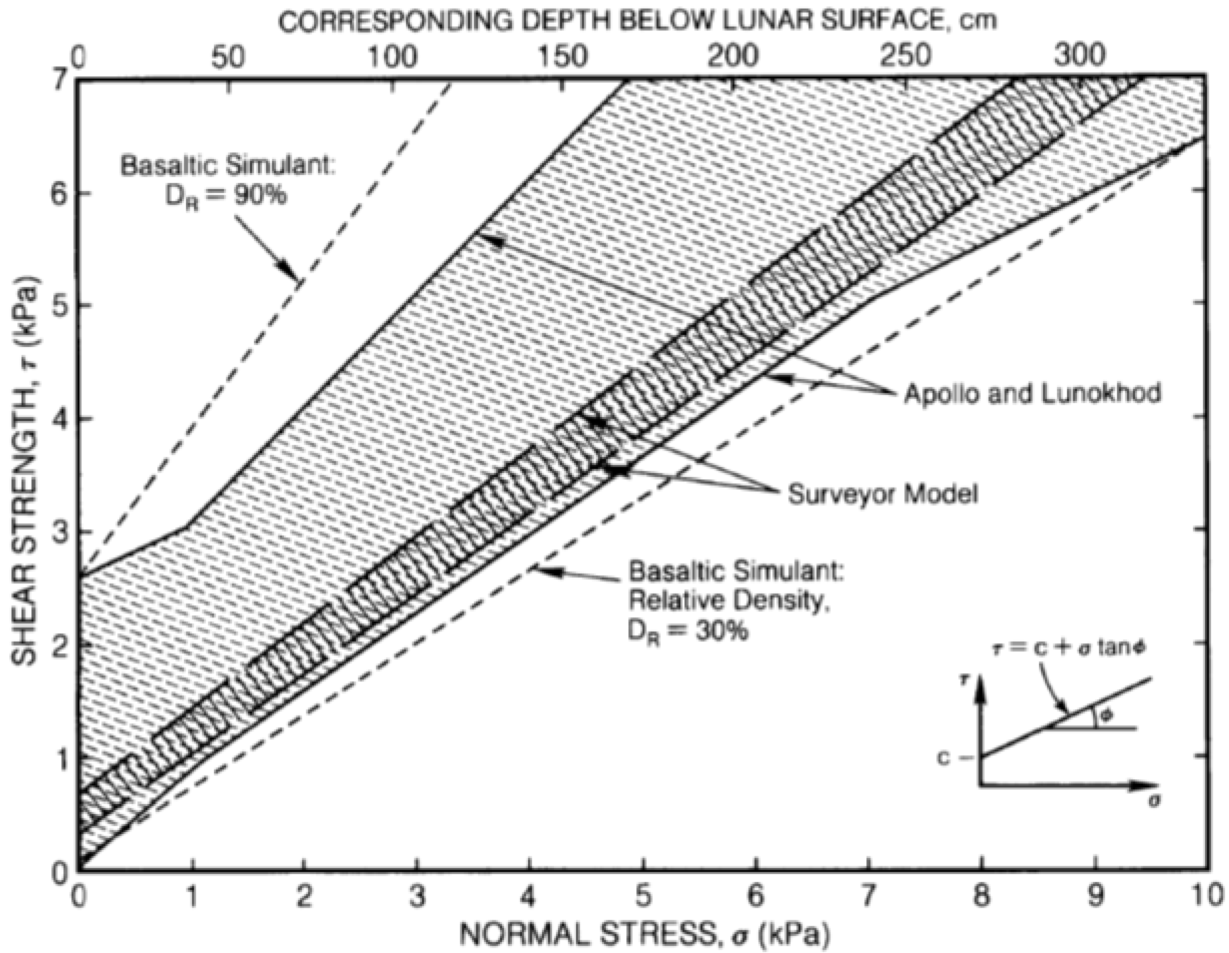
Chart Credit: Jeff Plescia, "The Lunar Surface" in Moon 101 course

Mohr-Coulomb Plot





Mohr-Coulomb Plot for Lunar Soil



<u>Apollo Best Model:</u>

Cohesion = 0.1 - 1 kPa

Friction angle = 30° - 50°

Source: W. David Carrier III, Gary R. Olhoeft, and Wendell Mendell, Lunar Source Book

Friction & Cohesion Depend upon Compaction

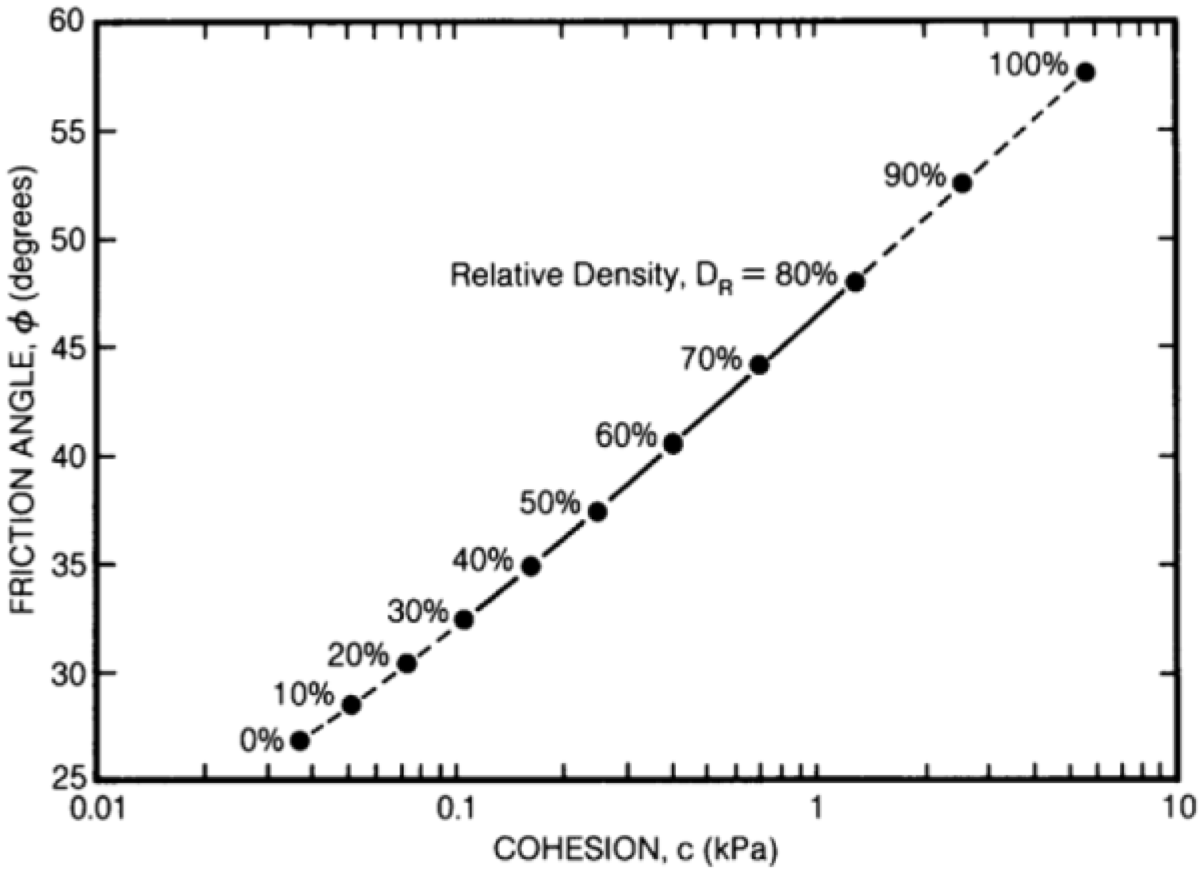


Fig. 9.27. Measured shear strengths of a basaltic simulant of lunar soil, showing the friction angle (vertical axis) and cohesion (horizontal axis) for different relative densities (after *Mitchell et al.*, 1972d, 1974).

Source: W. David Carrier III, Gary R. Olhoeft, and Wendell Mendell, Lunar Source Book

Lunar Soil Very Compacted

- At the equatorial and mid-latitude sites, lunar soil was found to be very compacted
- Surface was loose, easy to make boot prints
- Deeper soil was compacted, difficult to penetrate

Soil Less Dense on Crater Rims

- The crew encountered less dense soil on the rims of large, young impact craters
- This makes sense since overturned soil is deep on the rims and has had less time to re-densify

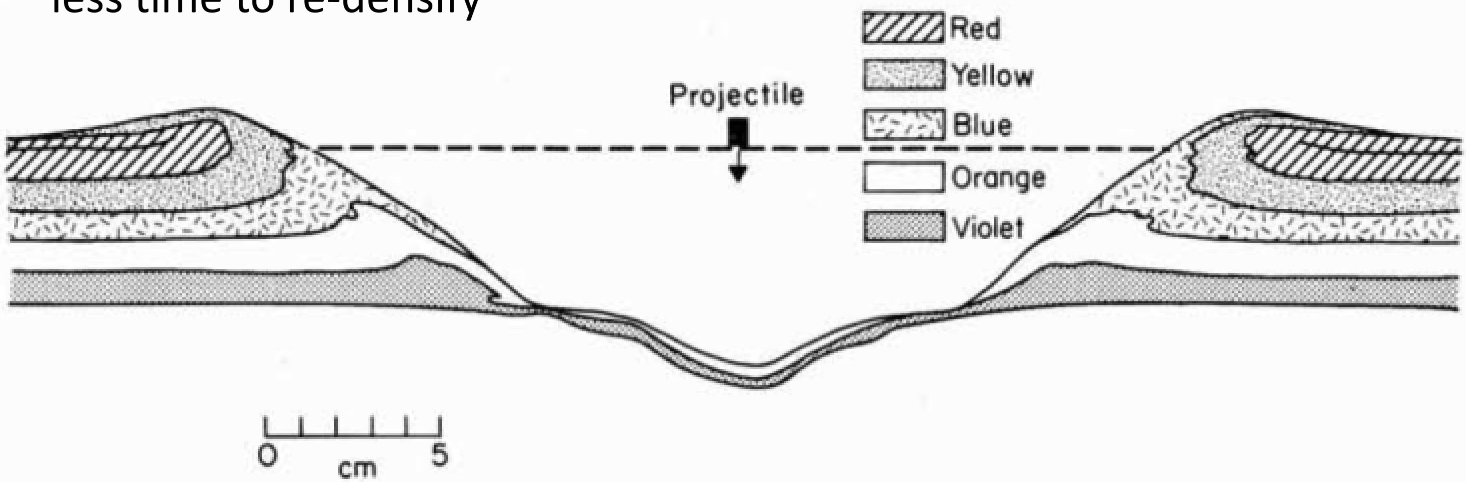
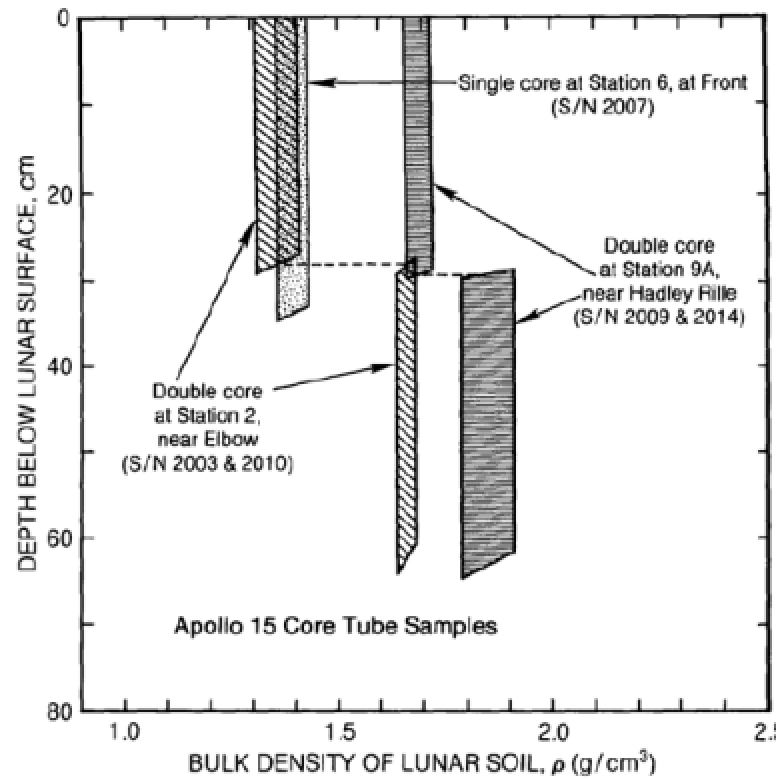


Fig. 3.13. A small experimental crater in a layered cohesionless substrate. The original stratigraphy is preserved as a thin inverted sequence in the ejecta deposit. Compare with figure 3.19 (after Stöffler, D., Gault, D. E., Wedekind, J. and Polkowski, G., *Jour. Geophys. Res., 80:* 4062-4077, 1975, copyrighted American Geophysical Union).

Lunar Stratigraphy and Sedimentology, J.F. Lindsay

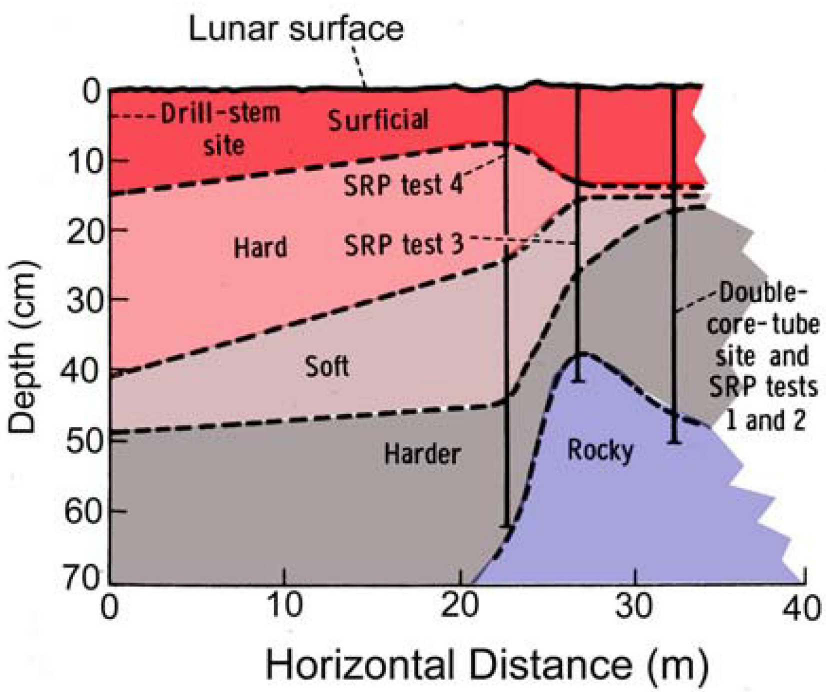
Core Tube Samples

- Average density in upper half of double core tubes generally less than in lower half
- Note this is average density over ~30 cm
- Finer density variations would be lost in the averaging

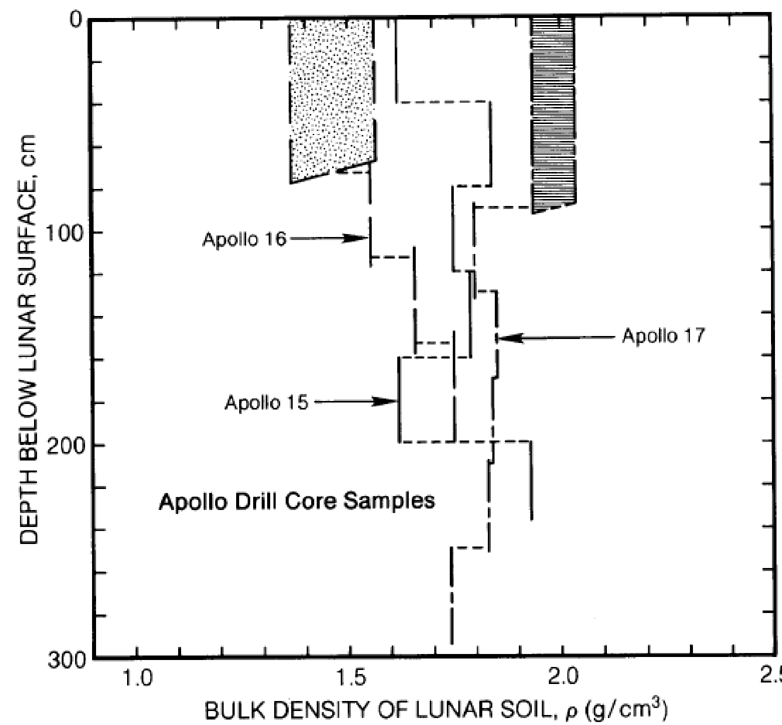


Source: W. David Carrier III, Gary R. Olhoeft, and Wendell Mendell, Lunar Source Book

Non-Monotonic Densities



Apollo 16 Station 10 ALSEP



Note: bulk density is non-monotonic in the Apollo 15 drill core samples, for example

- Complex stratigraphy in the column
- Complex depositional history
- Densification history must also be complex

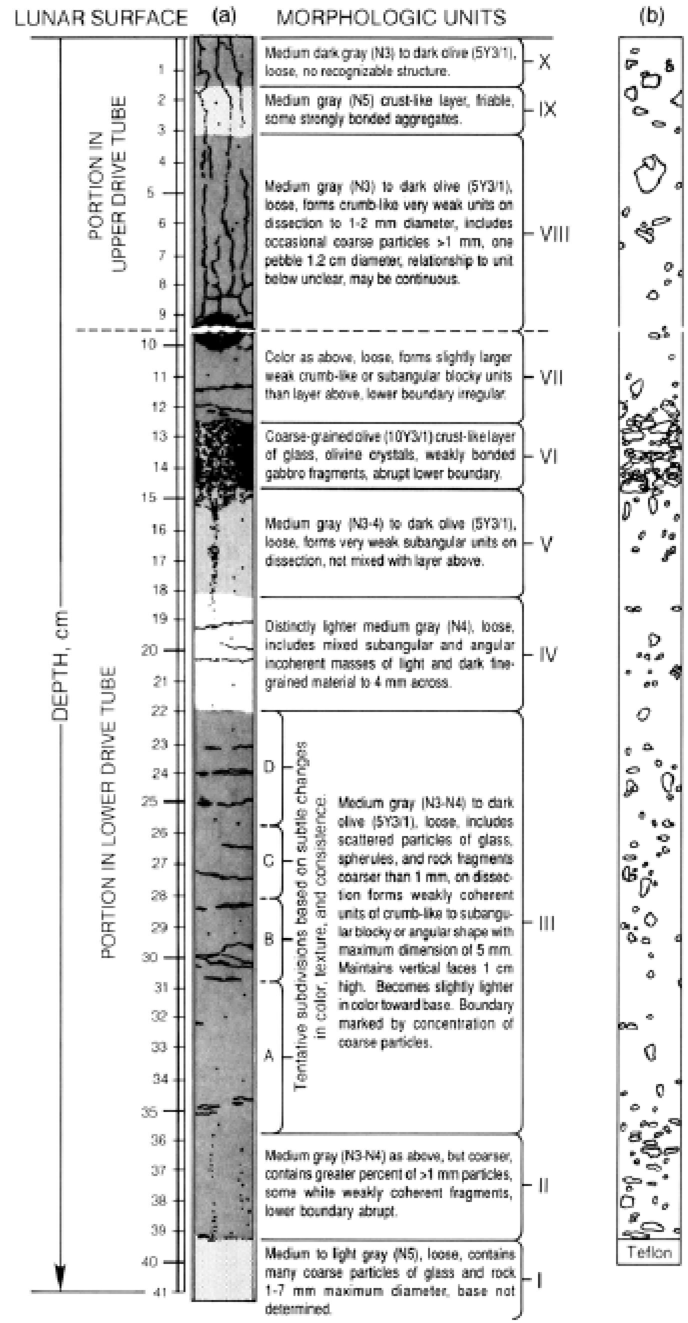
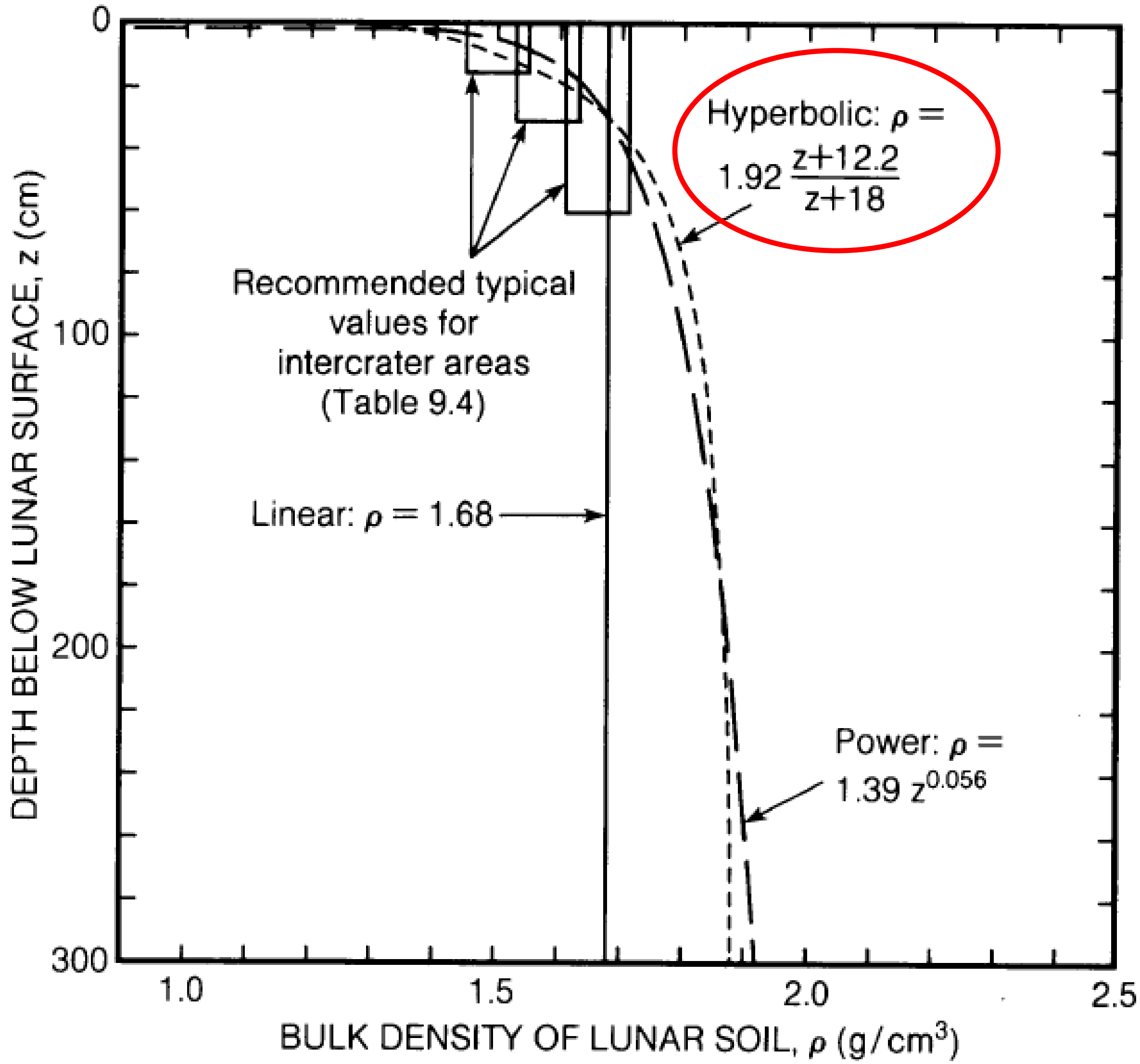


Fig. 7.16. Drawing of the Apollo 12 double drive-tube core (samples 12025-12028). **(a)** Within the core, 10 discrete layers have been identified, mostly on the basis of sharp changes in grain size and grading between adjacent layers (stratigraphic diagram by R. Fryxell; *Fryxell and Heiken*, 1974). Color designations are according to the Munsell standard. **(b)** Location of coarser lithic fragments.

Source: W. David Carrier III, Gary R. Olhoeft, and Wendell Mendell, Lunar Source Book

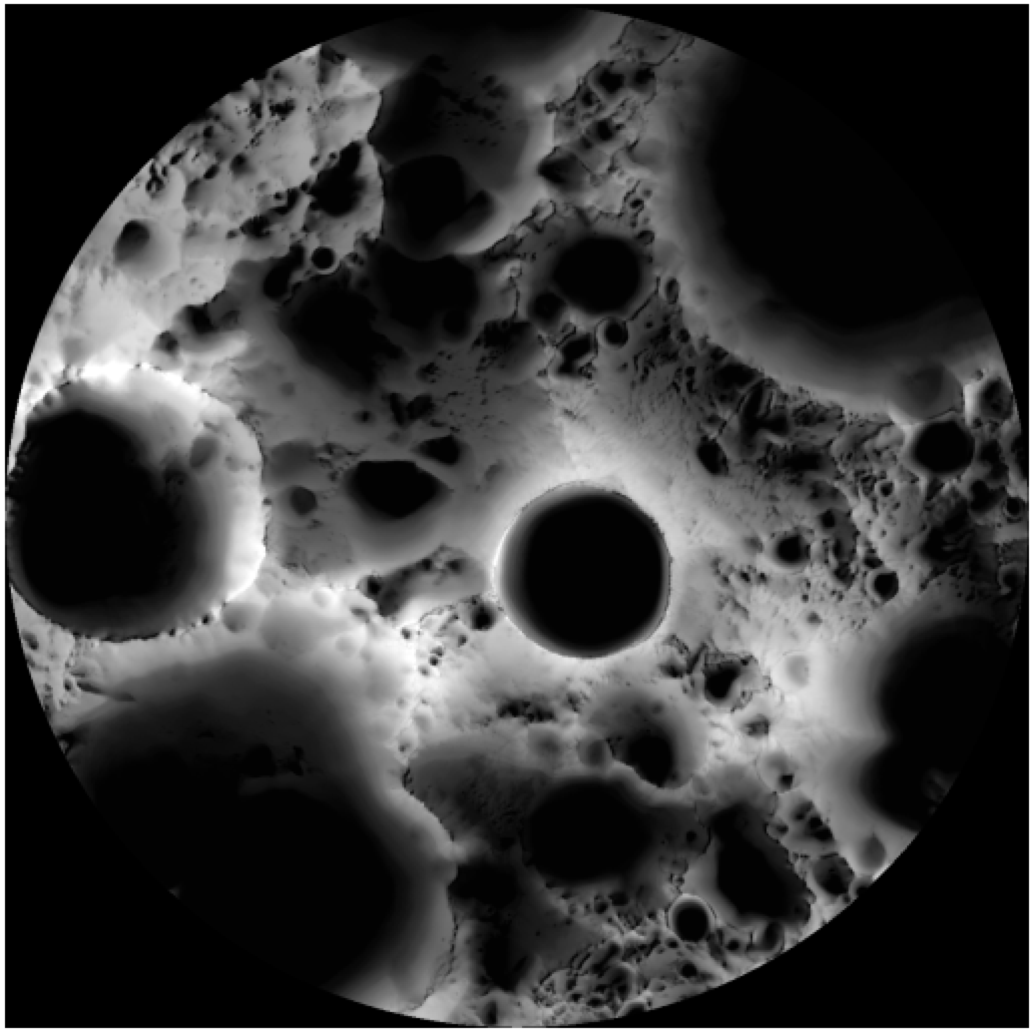


Source: W. David Carrier III, Gary R. Olhoeft, and Wendell Mendell, Lunar Source Book

Lunations and Seasons

- The lunation is 29.53 Earth days
- The Moon's axis is less tilted than the Earth's: only 1.5 deg (versus 23.44 deg)
- "(Ant)arctic Circle" is thus at 88.5 deg N or S. For a perfect sphere, inside that circle there would be 6 months of daylight followed by 6 months of darkness
- However, terrain dominates
  - high points of terrain get more sunlight and bottoms of craters get less
  - Peaks of Eternal Light vs. Perennially Shadowed Regions

Illumination Map – South Pole

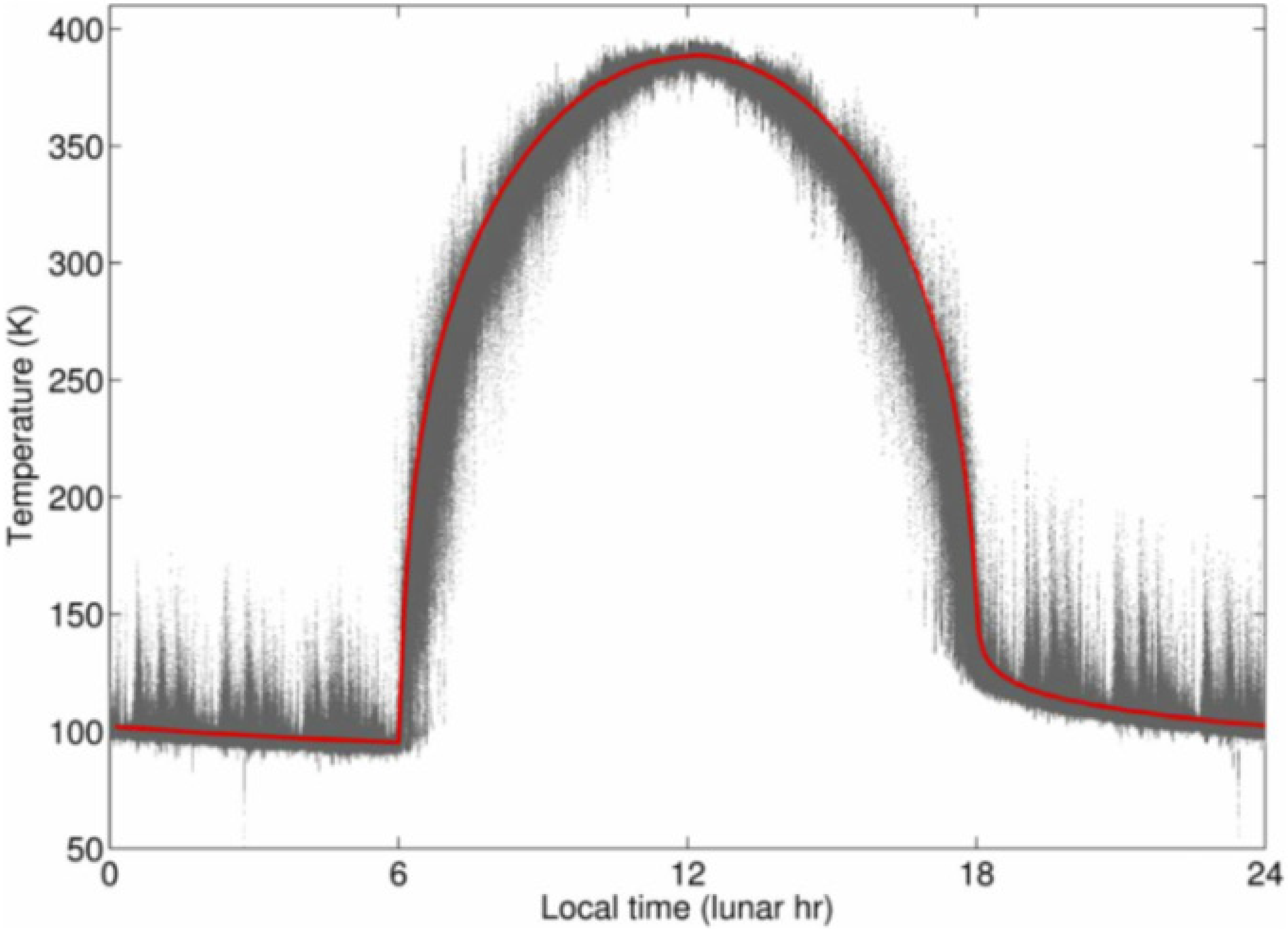


Credit: LROC Wide Angle Camera, NASA/GSFC/Arizona State University

Thermal Environment

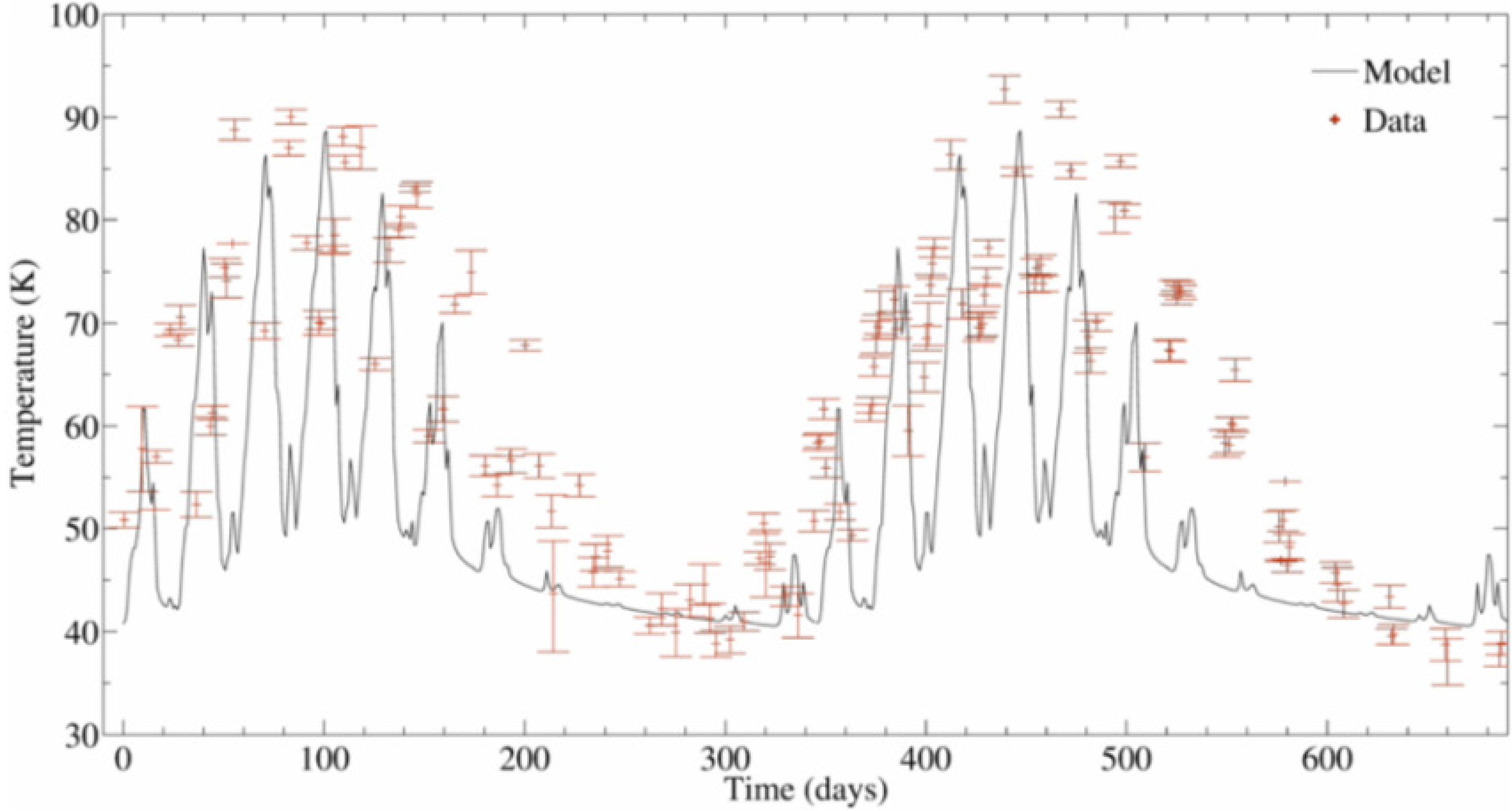
- Primary thermal drivers are hot sunlight (5777 K) and cold background radiation in space (2.7K).
- Not enough atmosphere to mediate temperature swings
- Temperature is cyclic with the lunations
- Equatorial temp range ~114 to 394K
- Polar temp range (not in PSRs) ~210 to 230K
- PSRs as low as 26K

Equator



Credit: Paul Hayne

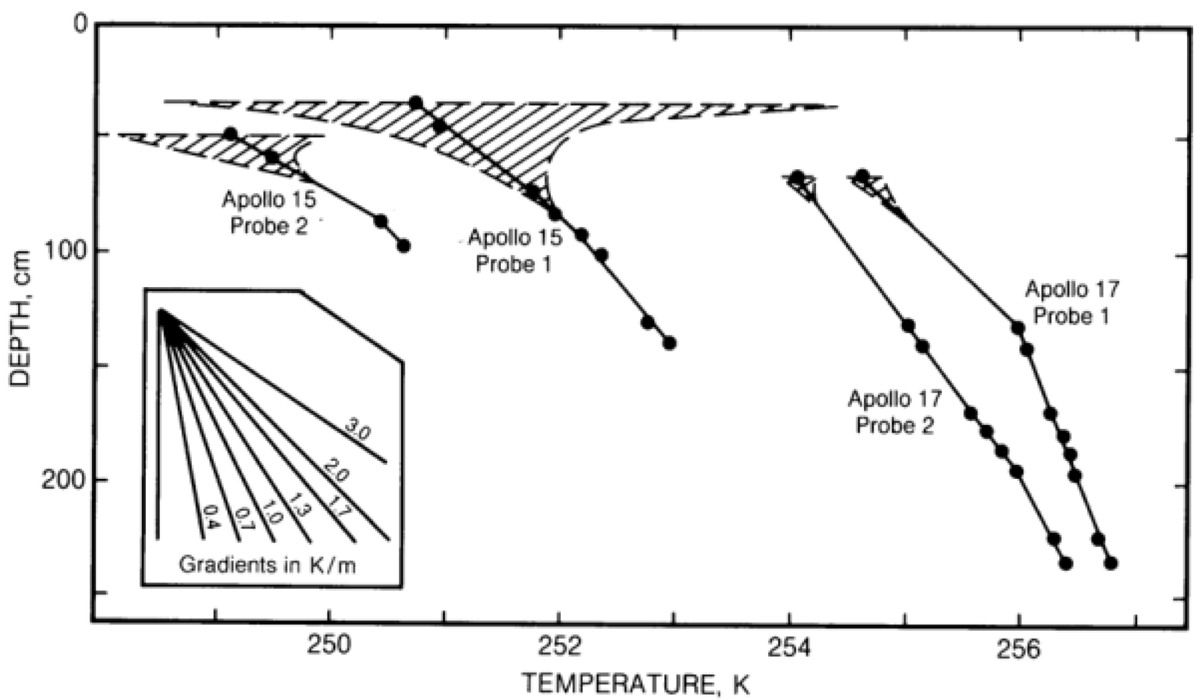
88° S



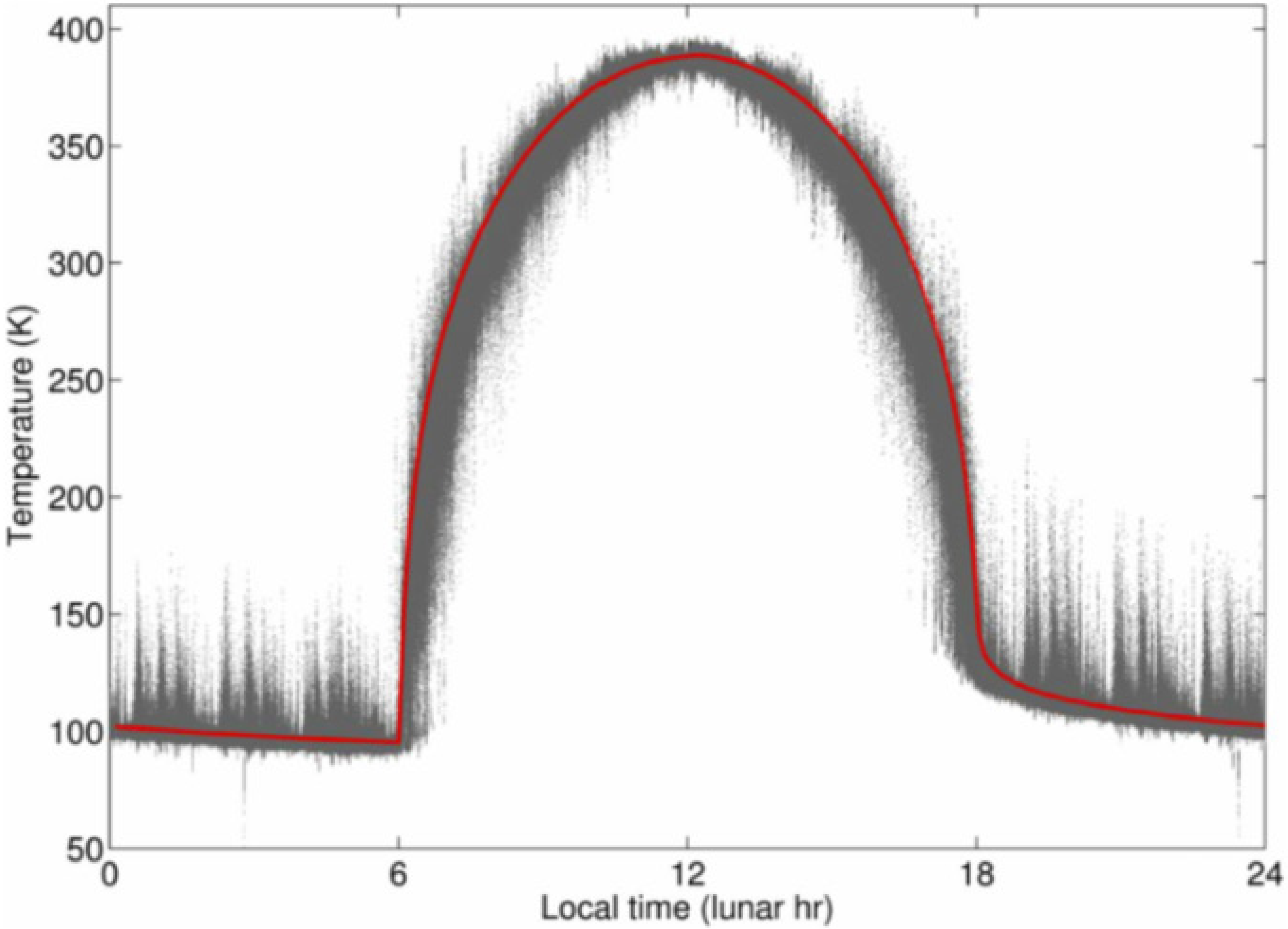
Credit: Paul Hayne

Subsurface Thermal Environment

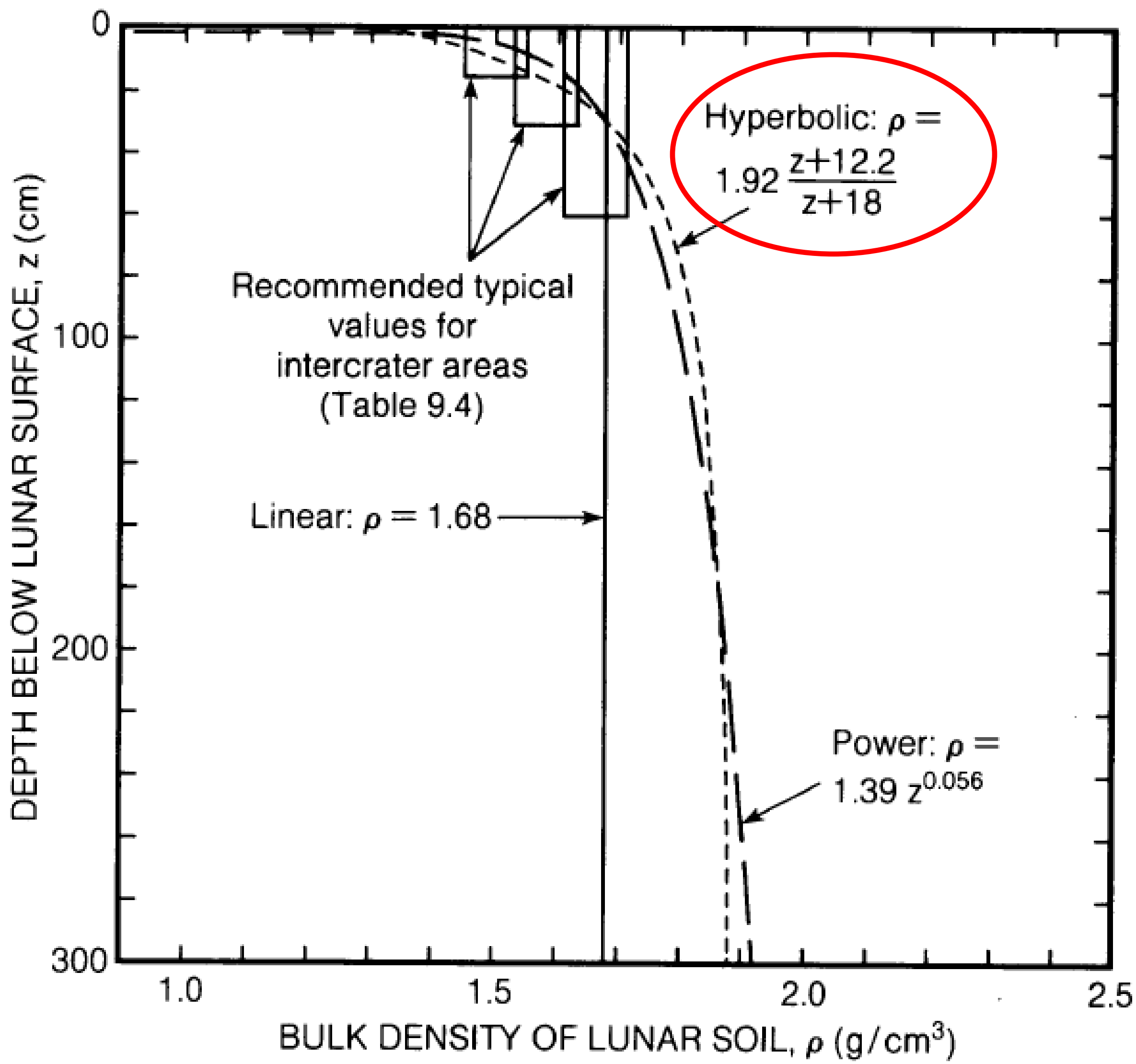
- Thermal inertia in the regolith causes the cyclic oscillation (thermal wave) to get smaller with depth
- Regolith is a poor heat conductor so this also reduces amplitude of the thermal wave with depth
- Essentially no temperature swing below 80 cm
- Low thermal inertia of the dry regolith allows it to heat up very quickly when the sun is on it again
- Wide range of temperatures in shadowed or sunlit topography



Equator



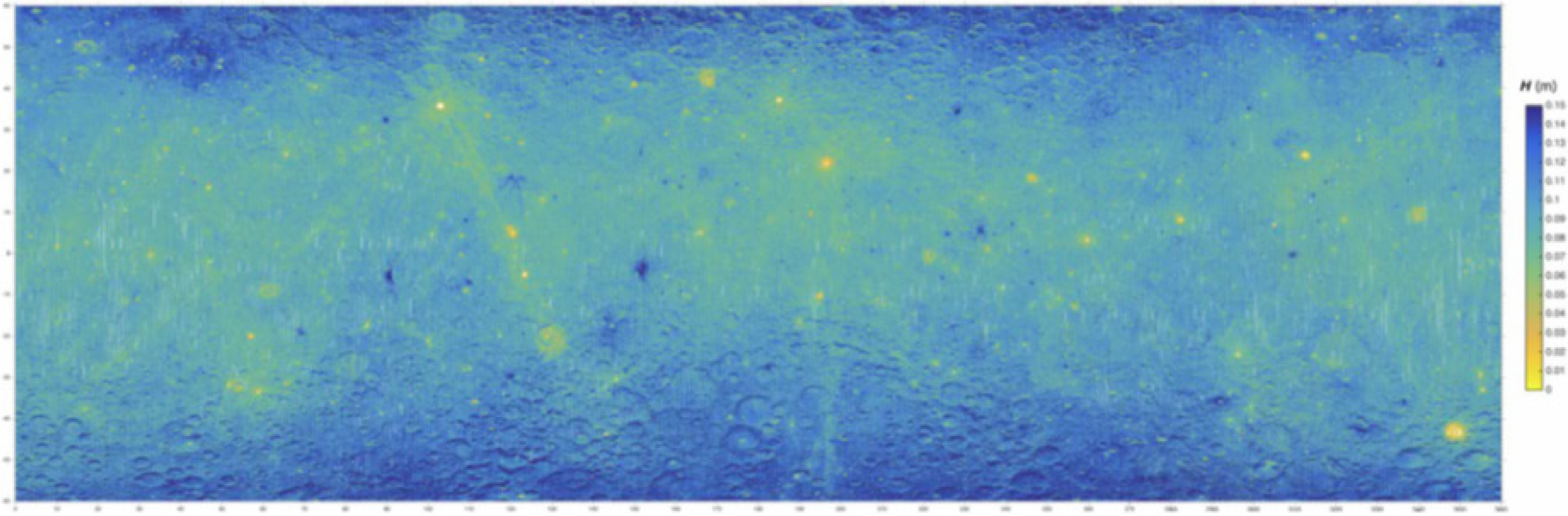
Credit: Paul Hayne



Source: W. David Carrier III, Gary R. Olhoeft, and Wendell Mendell, Lunar Source Book

Global H-parameter Map
(no latitude correction)

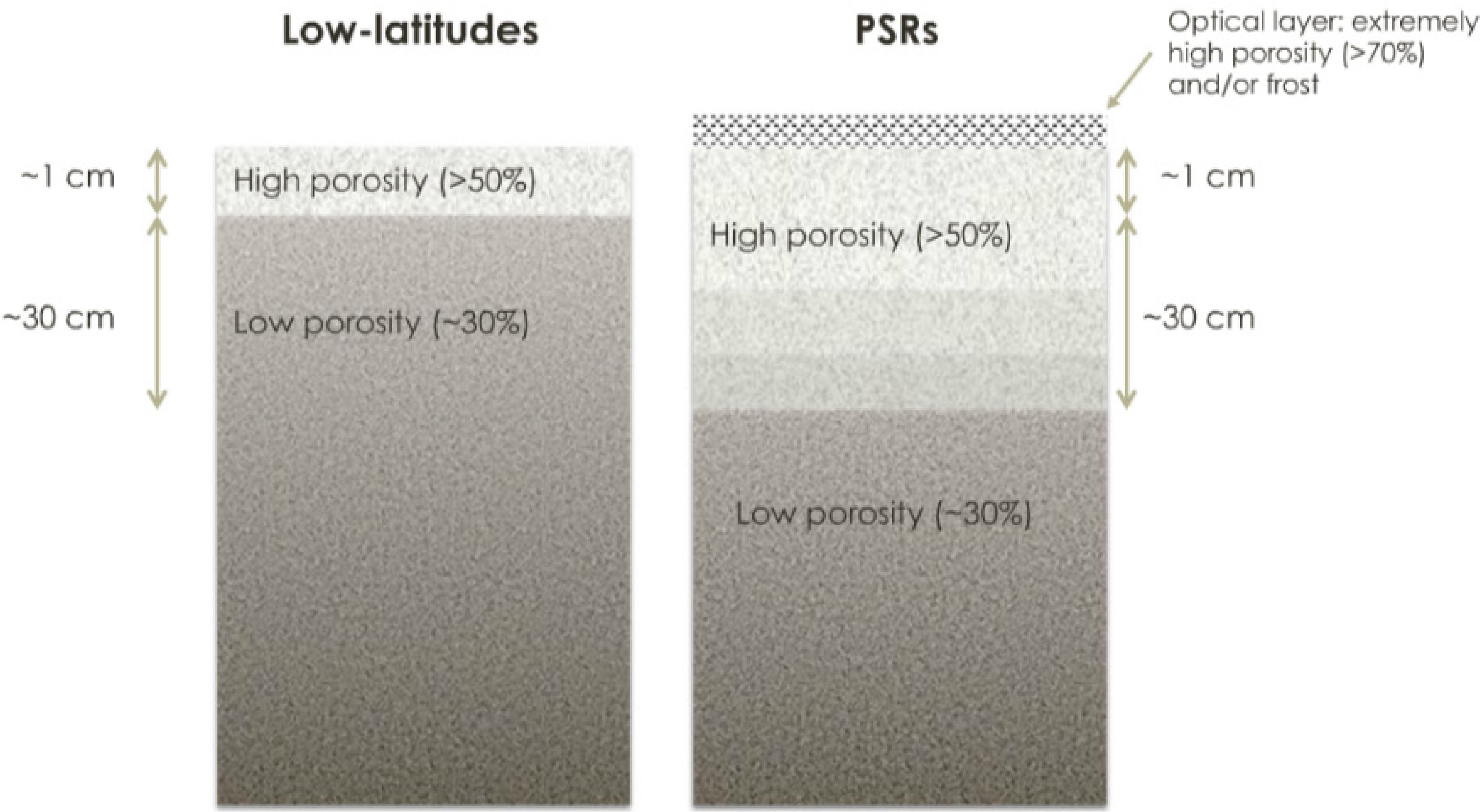
Lower thermal inertia in the regolith at high latitudes



Higher thermal inertia in the regolith at mid latitudes

Credit: Paul Hayne

One Possible Model:



Credit: Paul Hayne

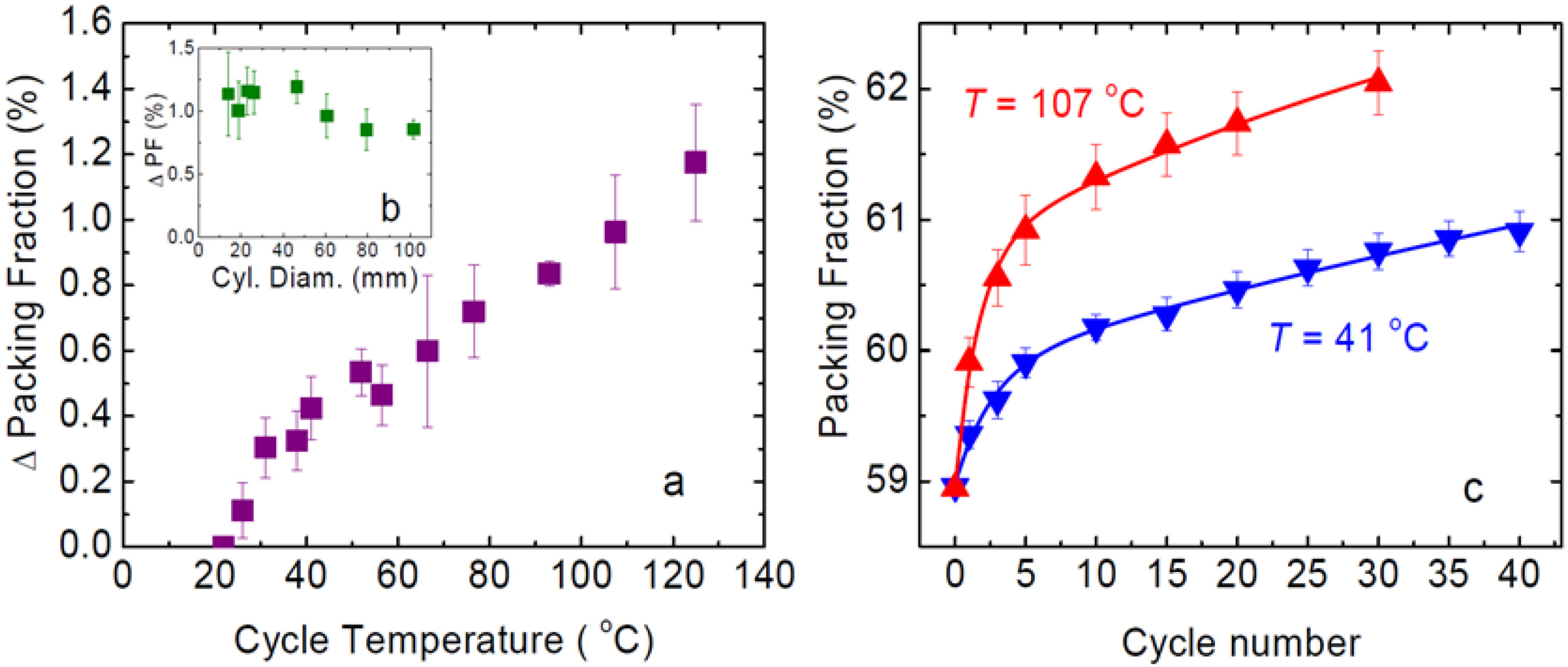
Evidence that polar soil may be different

- LCROSS ejecta blanket angle
- LCROSS delayed flash
- LRO Diviner “H” values (IR)
- LRO LAMP (FUV)
- LRO Mini-RF
- Lab experiments with thermal cycling

Why is Lunar Regolith Densified?

1. Impact Tamping?
2. Vibration?
   - Shallow Moonquakes
3. Thermal Cycling?
4. Combination?
   - What is the relative contribution of each?
   - How does this relate to the complex history of overturning and depositing layers?

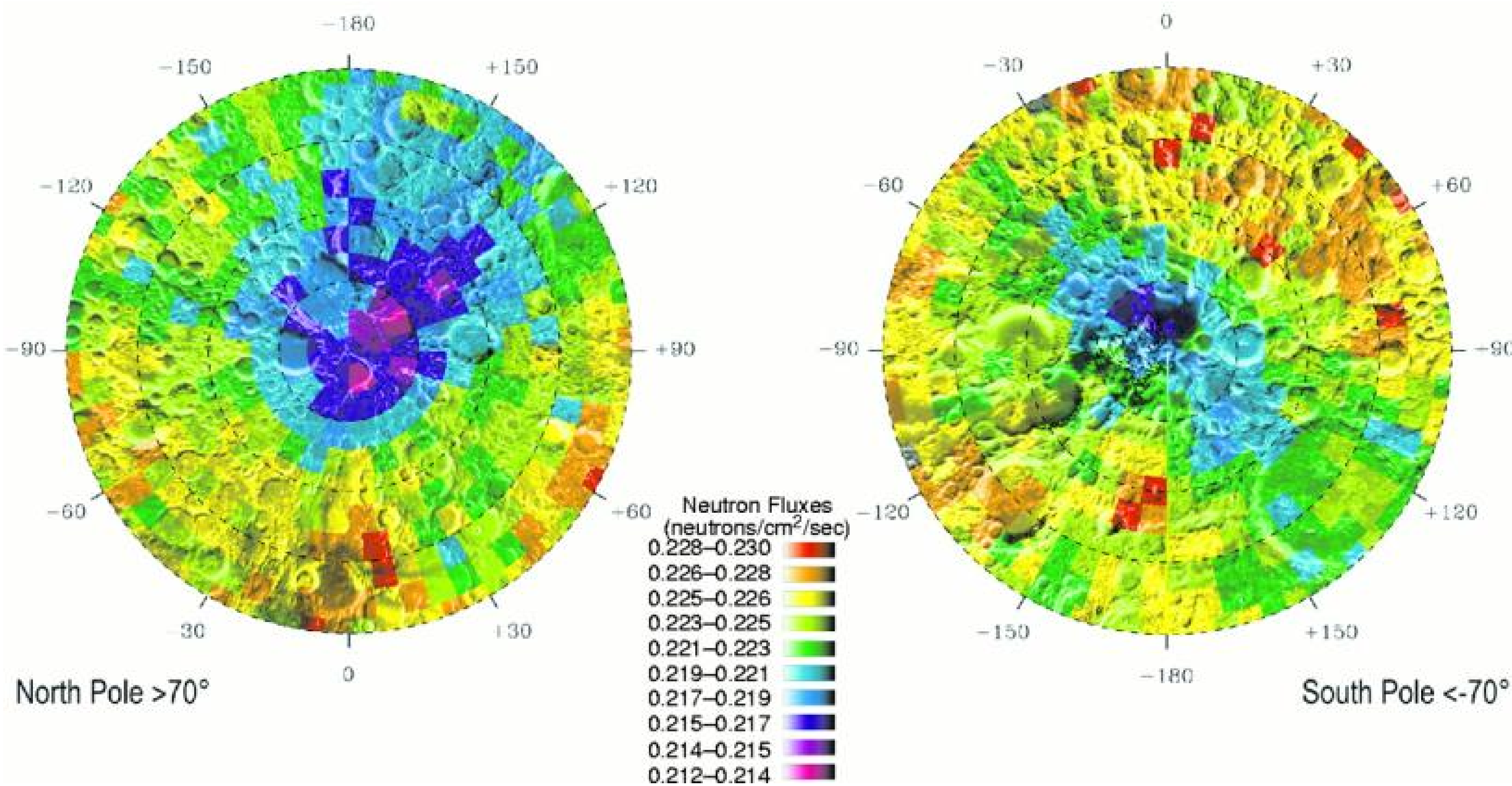
Thermal Cycling



$$y = y_0 - A_1 e^{-\frac{x}{\tau_1}} - A_2 e^{-\frac{x}{\tau_2}}$$

Chen, K., J. Cole, C. Conger, J. Draskovic, M. Lohr, K. Klein, T. Scheidemantel, and P. Schiffer. "Granular materials: Packing grains by thermal cycling." *Nature* 442, no. 7100 (2006): 257-257.

Figure 8 Overlay of epithermal* counting rates in each 2° by 2° equal area pixel poleward of ±70° with surface relief maps of the lunar poles (28).

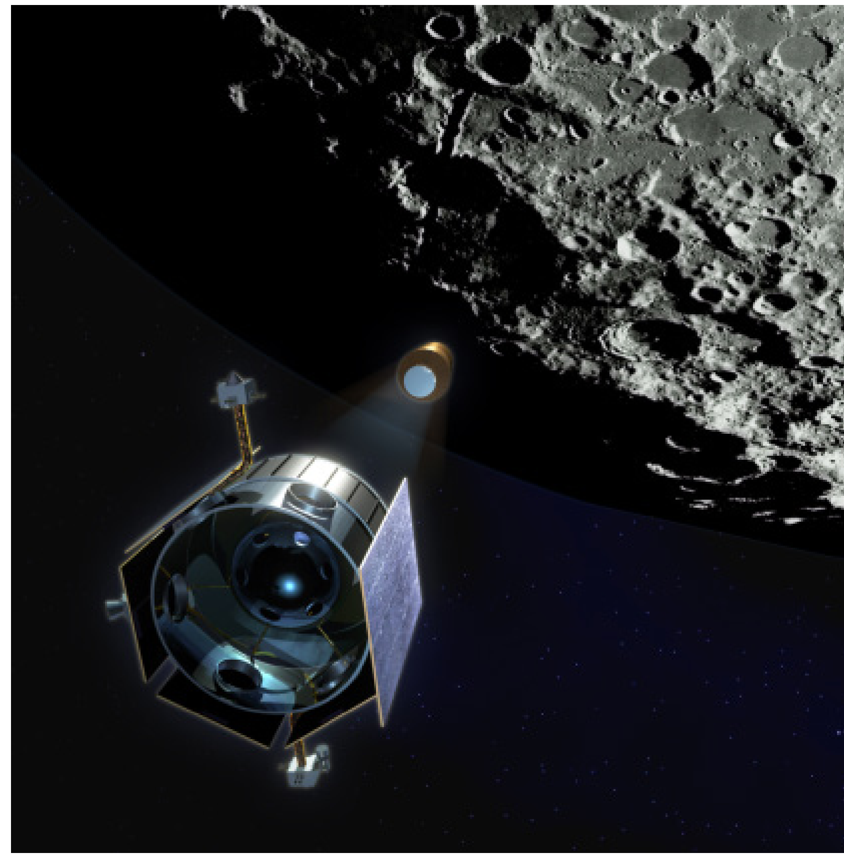


W. C. Feldman et al. Science 1998;281:1496-1500

Published by AAAS

LCROSS Impact

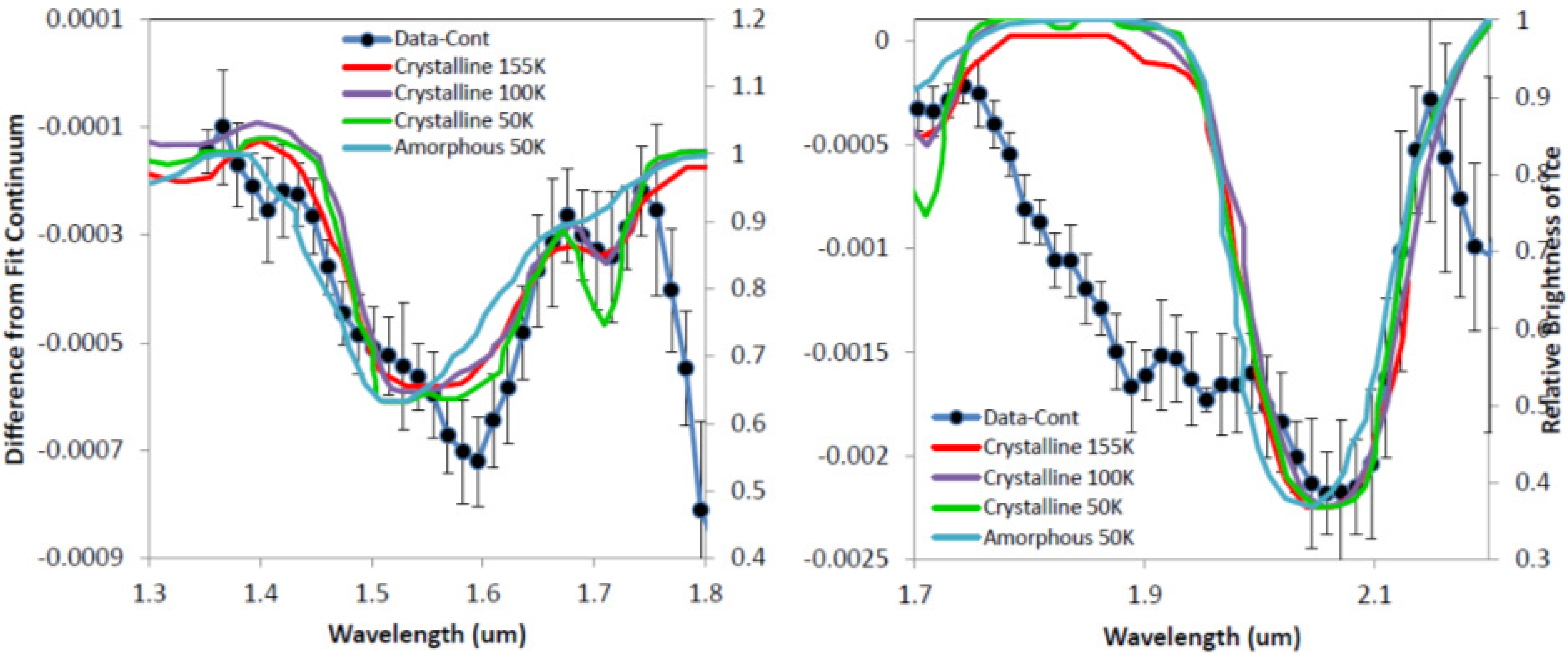
- 4 to 6 MT material ejected
- Volatiles comprised much as 20% of mass
- Not just water
  - CH_4, NH_3, H, CO_2, CO
  - Metals including sodium, silver and mercury
- Physical state of the ice is unknown



Source: NASA

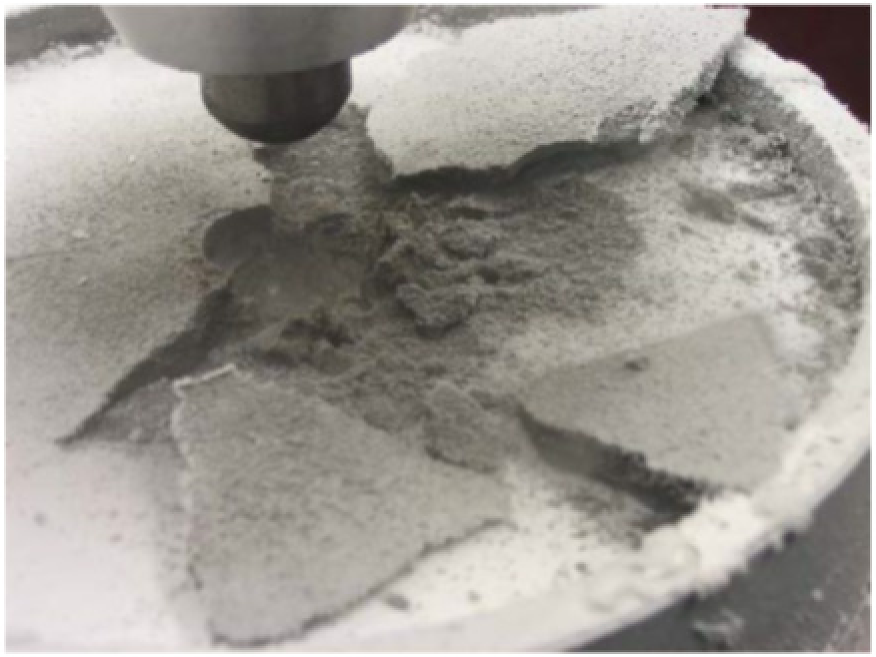
LCROSS Impact

- LCROSS NIR spectrometer suggests cold, crystalline ice:



Source: Anthony Colaprete, M. Shirley, J. Heldmann, D. Wooden, "The Final Minute: Results from the LCROSS Solar Viewing NIR Spectrometer," LEAG 2015

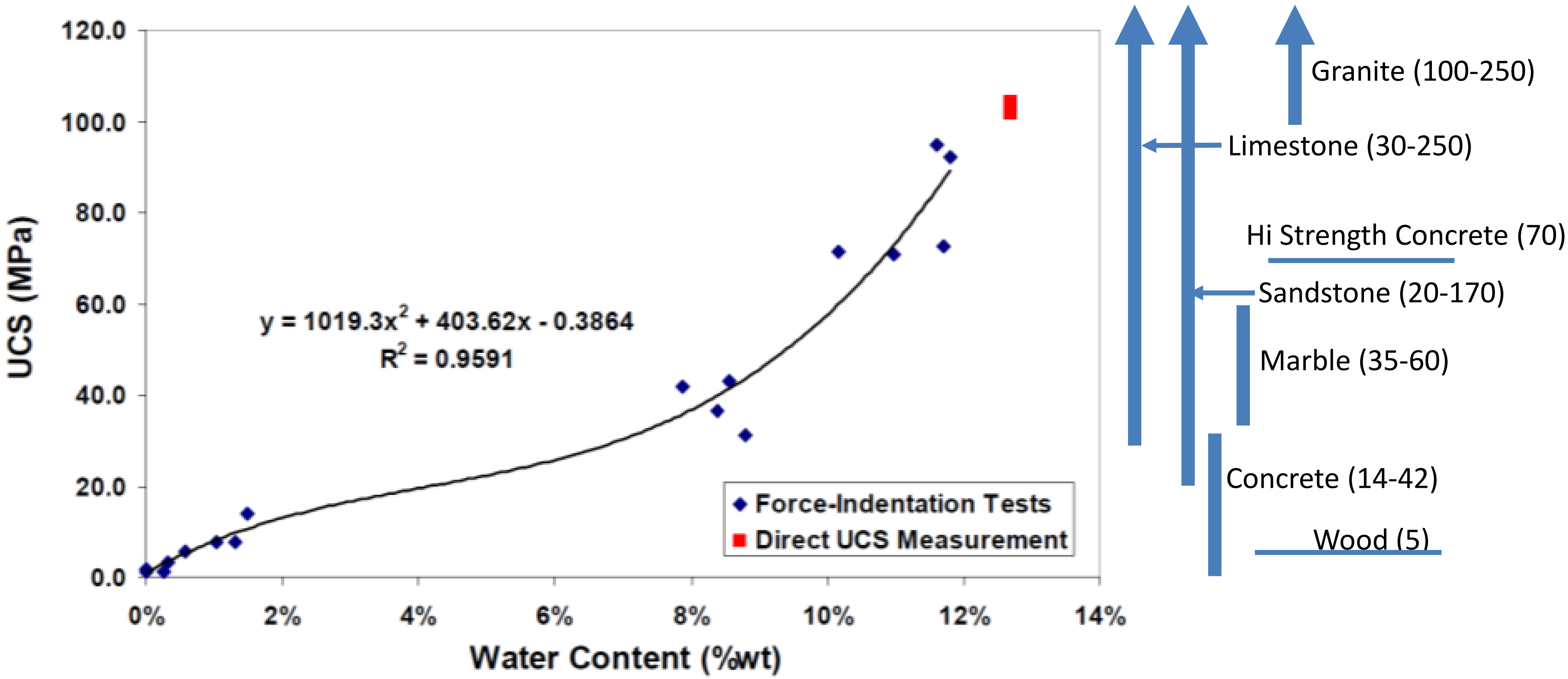
Strength of Icy Regolith



Water Content	Behaves Like
0-0.3%wt	Weak coal
0.6-1.5%wt	Weak shales & mudstones
7.9-8.8%wt	Moderate-strength limestones & sandstones
10-11.9%wt	Strong limestone, sandstone & high strength concrete

Source (chart on left): Gertsch, Leslie, Jamal Rostami, and Robert Gustafson. "Review of Lunar Regolith Properties for Design of Low Power Lunar Excavators." Sixth International Conference on Case Histories in Geotechnical Engineering (2008).

Strength of Icy Lunar Simulant



Source (chart on left): Gertsch, Leslie, Jamal Rostami, and Robert Gustafson. "Review of Lunar Regolith Properties for Design of Low Power Lunar Excavators." Sixth International Conference on Case Histories in Geotechnical Engineering (2008).

Mining Icy Regolith

Figure 2. RASSOR's bucket drum is shown excavating icy regolith formed by cryo-freezing BP-1 simulant mixed with water using a 10:1 ratio of regolith to water.

Source: Mantovani, James G., Adam Swanger, Ivan I. Townsend III, Laurent Sibille, and Gregory Galloway. "Characterizing the Physical and Thermal Properties of Planetary Regolith at Low Temperatures." In *Earth and Space 2014*, pp. 43-51. 2014.

Summary

- Lunar soil is poorly sorted silty-sand with rough particle shapes
  - High friction and cohesion
  - Flows poorly
- Generally is more compacted with depth
  - Therefore more frictional and cohesive with depth
  - Hard to penetrate
- There is evidence it is looser toward the poles
  - We do not understand these data
  - Be prepared to drive & dig in looser soil
- If it is sufficiently icy, it may behave like rock
  - Different sensors say maybe 1.5 - 20%wt ice in PSRs (???)
  - May have strength anywhere between weak shale & granite