Center for Lunar & Asteroid Surface Science
CLASS

UNIVERSITY OF CENTRAL FLORIDA

SWAMP WORKS
NASA KENNEDY SPACE CENTER

Compaction processes of lunar soil globally versus in the polar regions

Philip Metzger, UCF, CLASS

Lunar Soil Very Compacted

- At the equatorial and mid-latitude sites, lunar soil was found to be very compacted

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

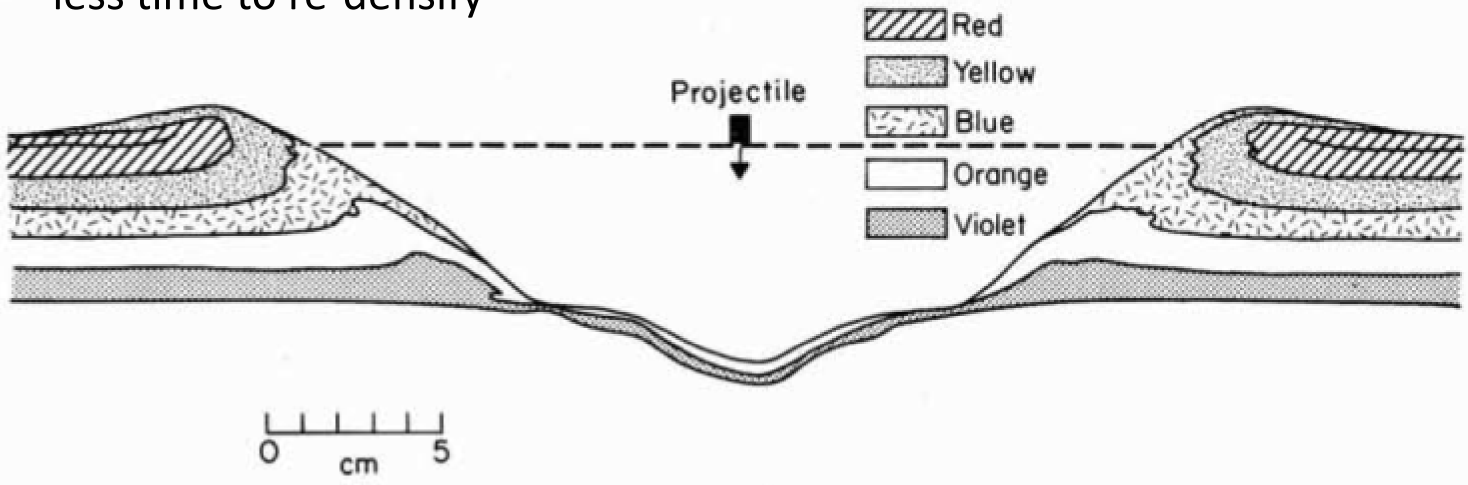
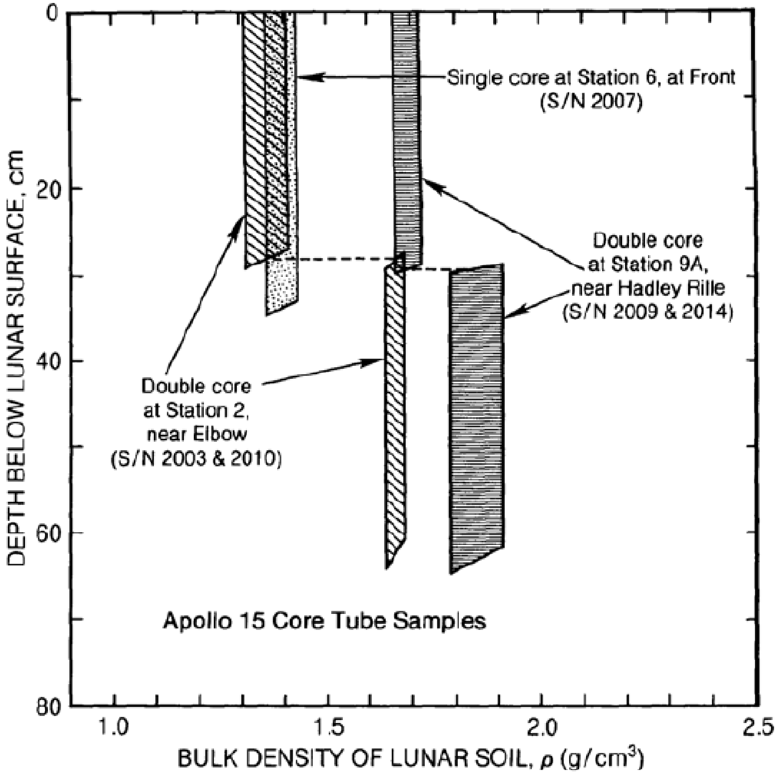


Fig. 3.13. A small experimental crater in a layered cohesionless substrate. The original stratigraphy is preserved as a thin inverted sequence in the ejecta deposit. Compare with figure 3.19 (after Stöffler, D., Gault, D. E., Wedekind, J. and Polkowski, G., *Jour. Geophys. Res.*, *80*: 4062-4077, 1975,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

Lunar Stratigraphy and Sedimentology, J.F. Lindsay

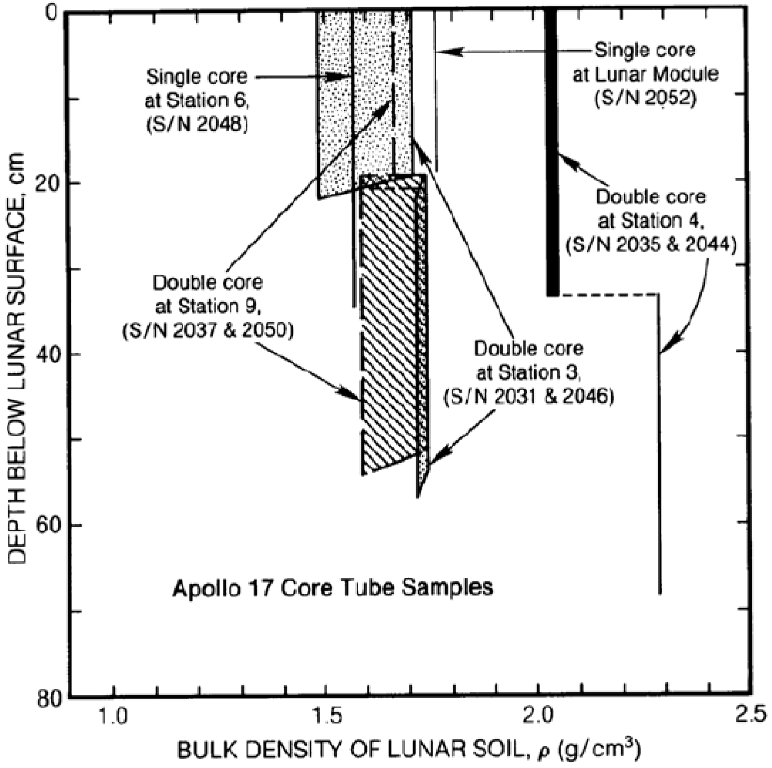
Core Tube Samples

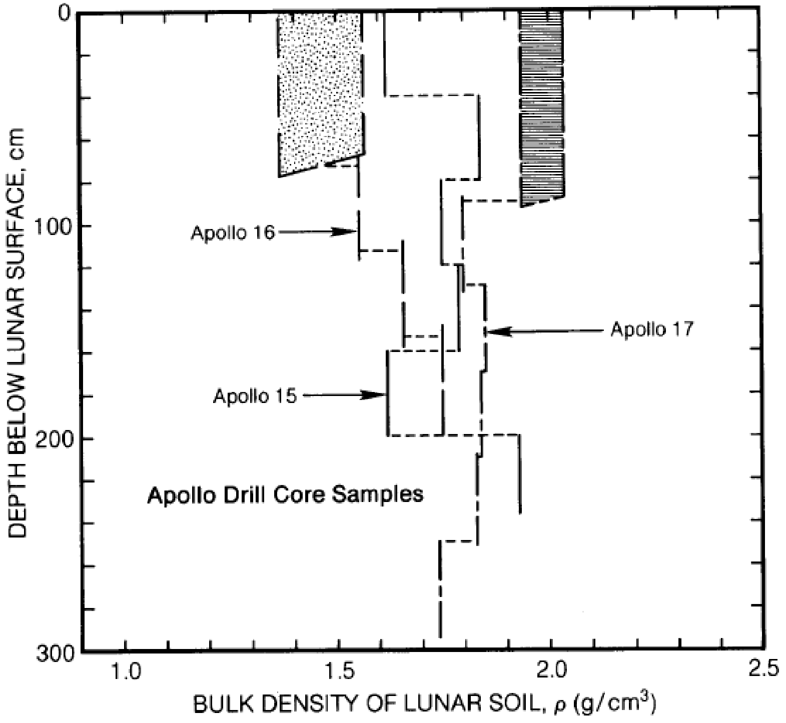
- Average density in upper half of double core tubes generally less than in lower half
- Note this is average density over ~30 cm
- Finer density variations would be lost in the averaging



Lunar Sourcebook
Heiken, Vaniman, and French, eds.

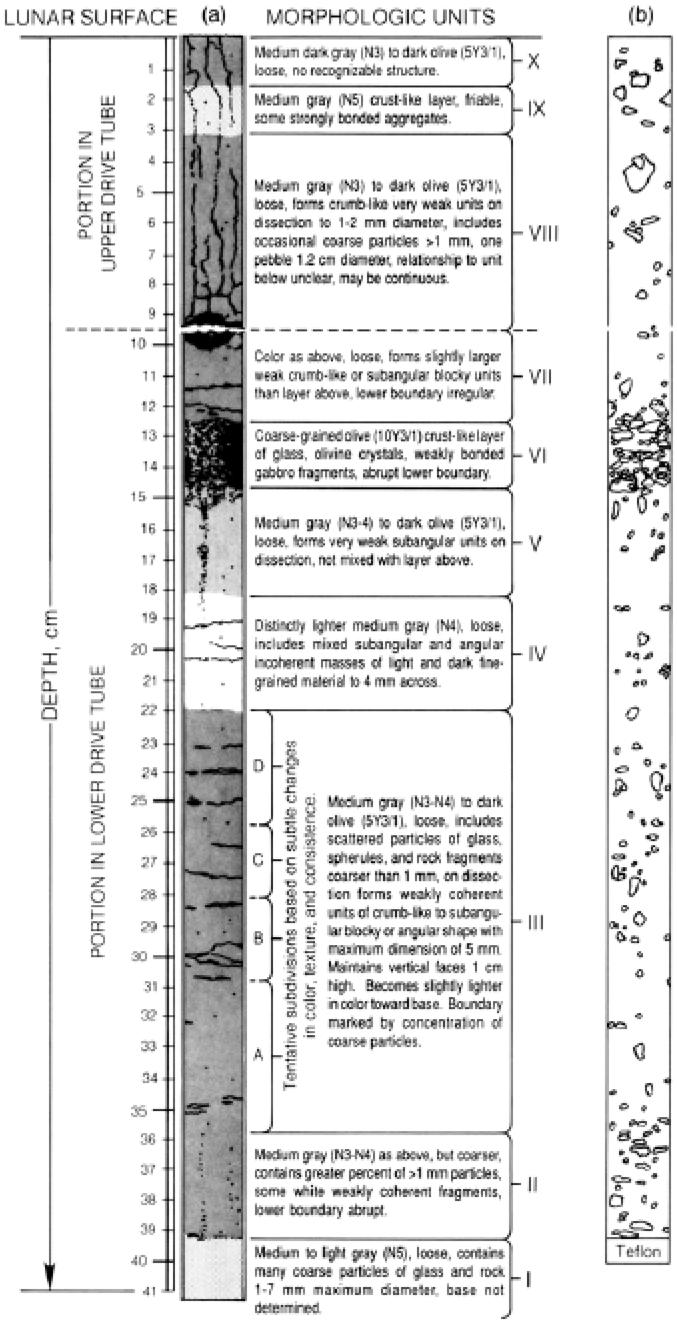
More Core Tubes & Drill Core Samples





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



X: Medium dark gray (N3) to dark olive (5Y3/1), loose, no recognizable structure.

IX: Medium gray (N5) crust-like layer, friable, some strongly bonded aggregates.

VIII: Medium gray (N3) to dark olive (5Y3/1), loose, forms crumb-like very weak units on dissection to 1-2 mm diameter, includes occasional coarse particles >1 mm, one pebble 1.2 cm diameter, relationship to unit below unclear, may be continuous.

VII: Color as above, loose, forms slightly larger weak crumb-like or subangular blocky units than layer above, lower boundary irregular.

VI: Coarse-grained olive (10Y3/1) crust-like layer of glass, olivine crystals, weakly bonded gabbro fragments, abrupt lower boundary.

V: Medium gray (N3-4) to dark olive (5Y3/1), loose, forms very weak subangular units on dissection, not mixed with layer above.

IV: Distinctly lighter medium gray (N4), loose, includes mixed subangular and angular incoherent masses of light and dark fine-grained material to 4 mm across.

III: Medium gray (N3-N4) to dark olive (5Y3/1), loose, includes scattered particles of glass, spherules, and rock fragments coarser than 1 mm, on dissection forms weakly coherent units of crumb-like to subangular blocky or angular shape with maximum dimension of 5 mm. Maintains vertical faces 1 cm high. Becomes slightly lighter in color toward base. Boundary marked by concentration of coarse particles.

II: Medium gray (N3-N4) as above, but coarser, contains greater percent of >1 mm particles, some white weakly coherent fragments, lower boundary abrupt.

I: Medium to light gray (N5), loose, contains many coarse particles of glass and rock 1-7 mm maximum diameter, base not determined.

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.

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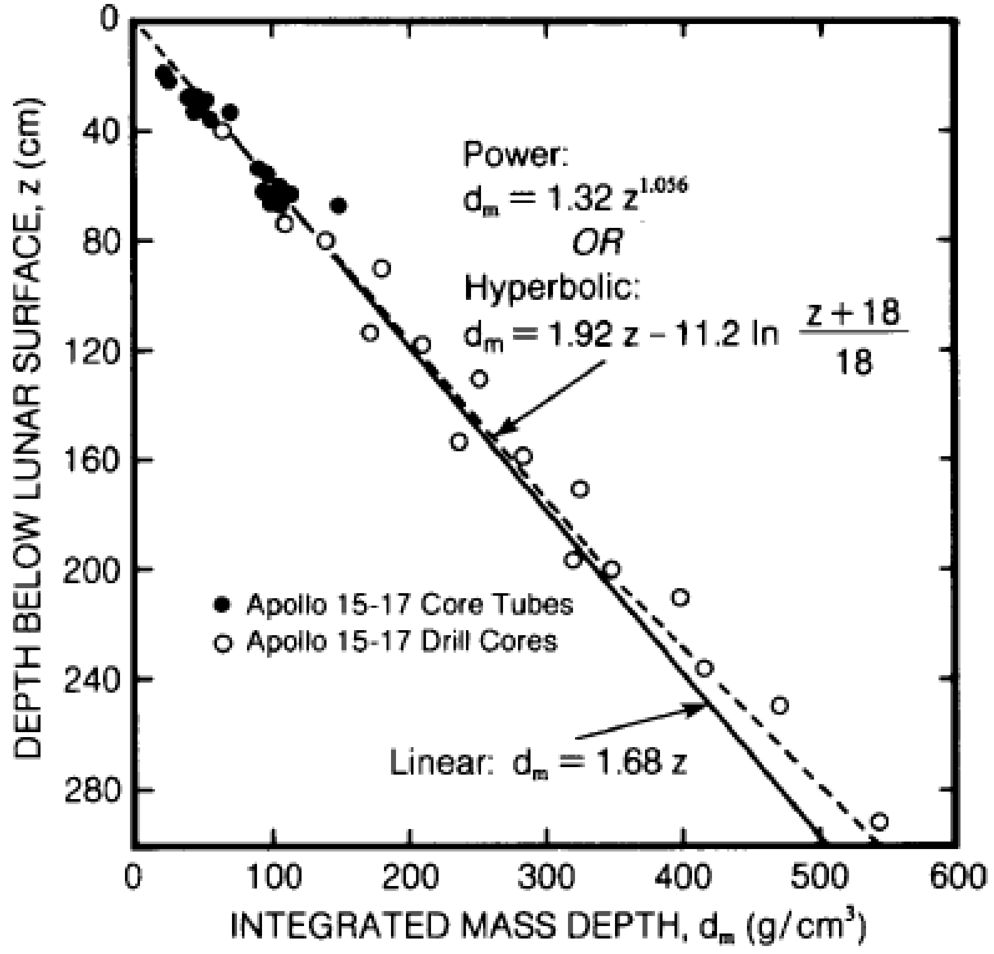
Heiken, Vaniman,
and French, eds.

Model of Bulk Density vs Depth



$$d_m = 1.92\, z - 11.2 \ln \left(\frac{z+18}{18} \right)$$

$$\rho = 1.92\, \frac{z + 12.2}{z + 18}$$

This is an inherently monotonic model. Fitting to the integrated mass depth smooths out any non-monotonic features.

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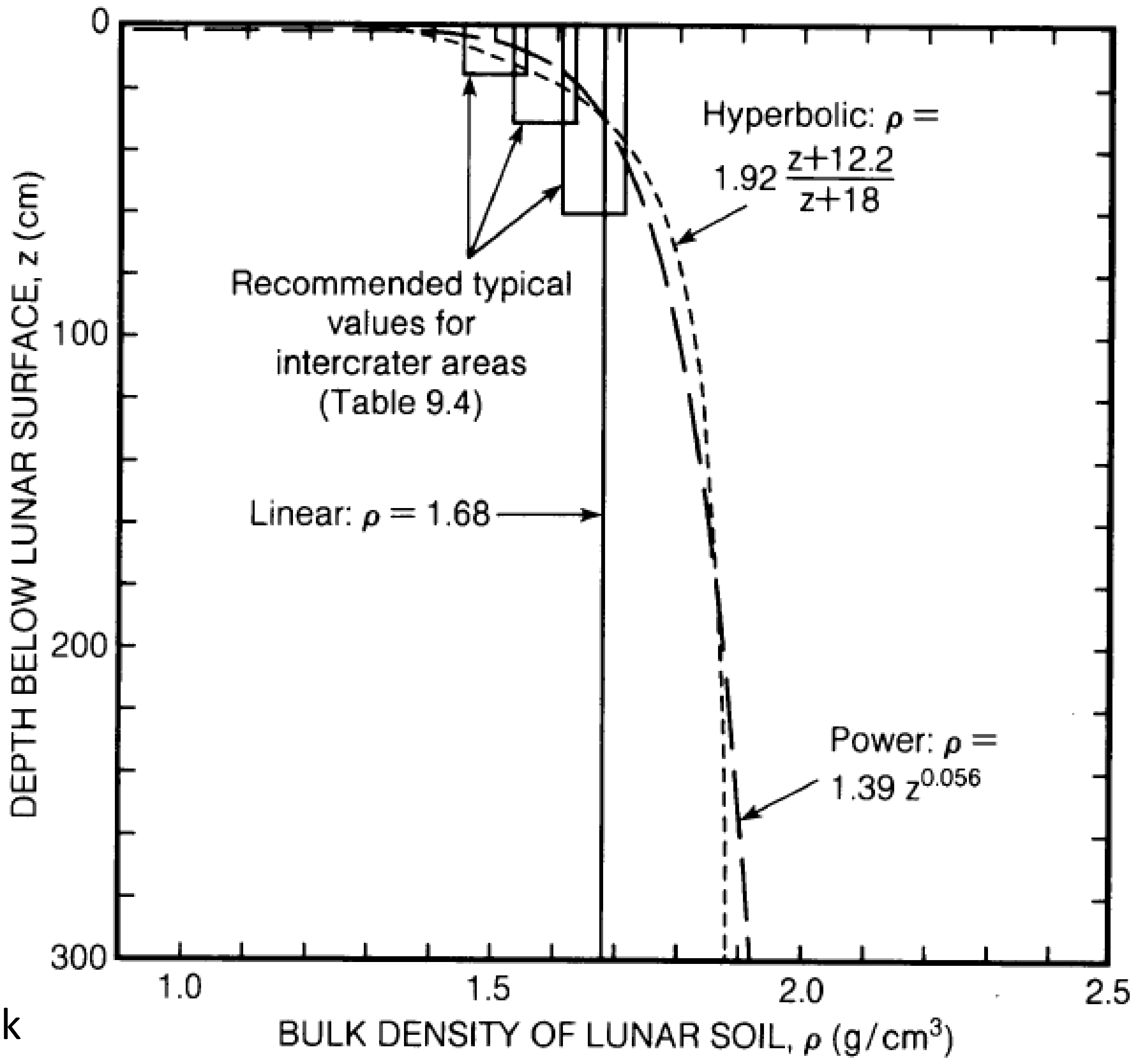

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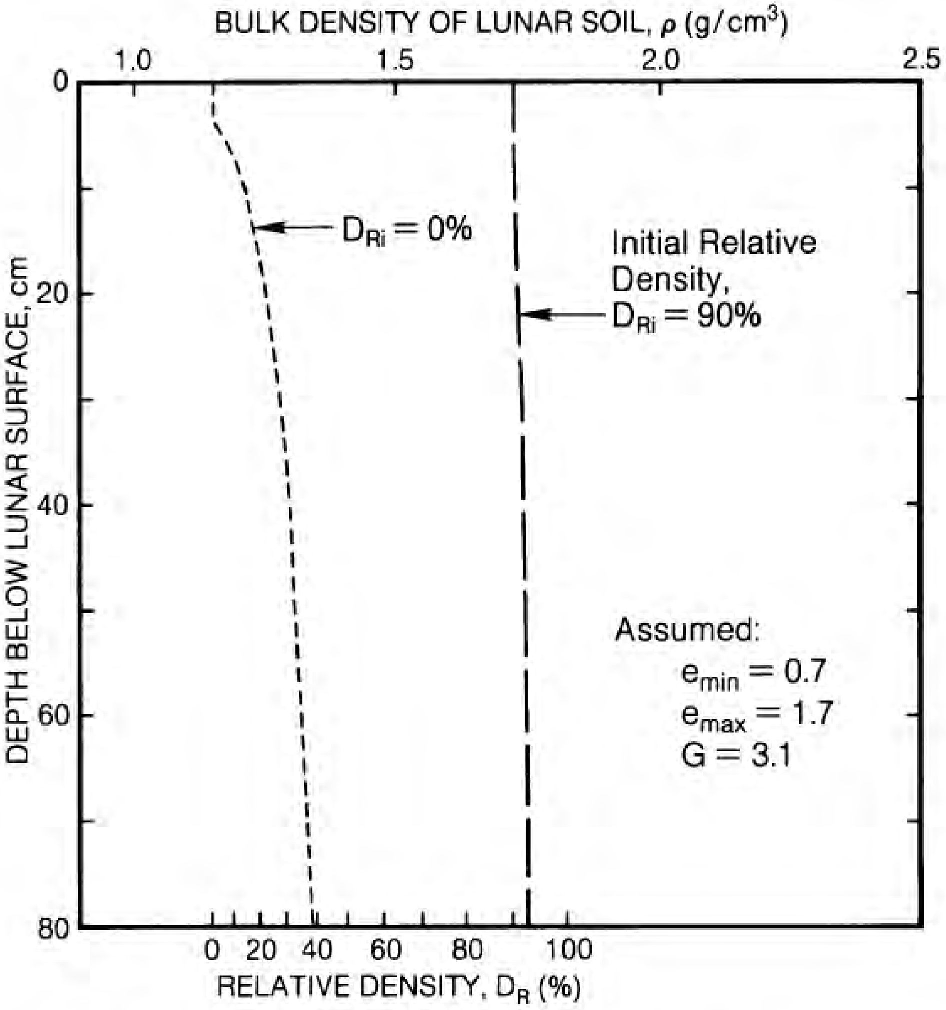
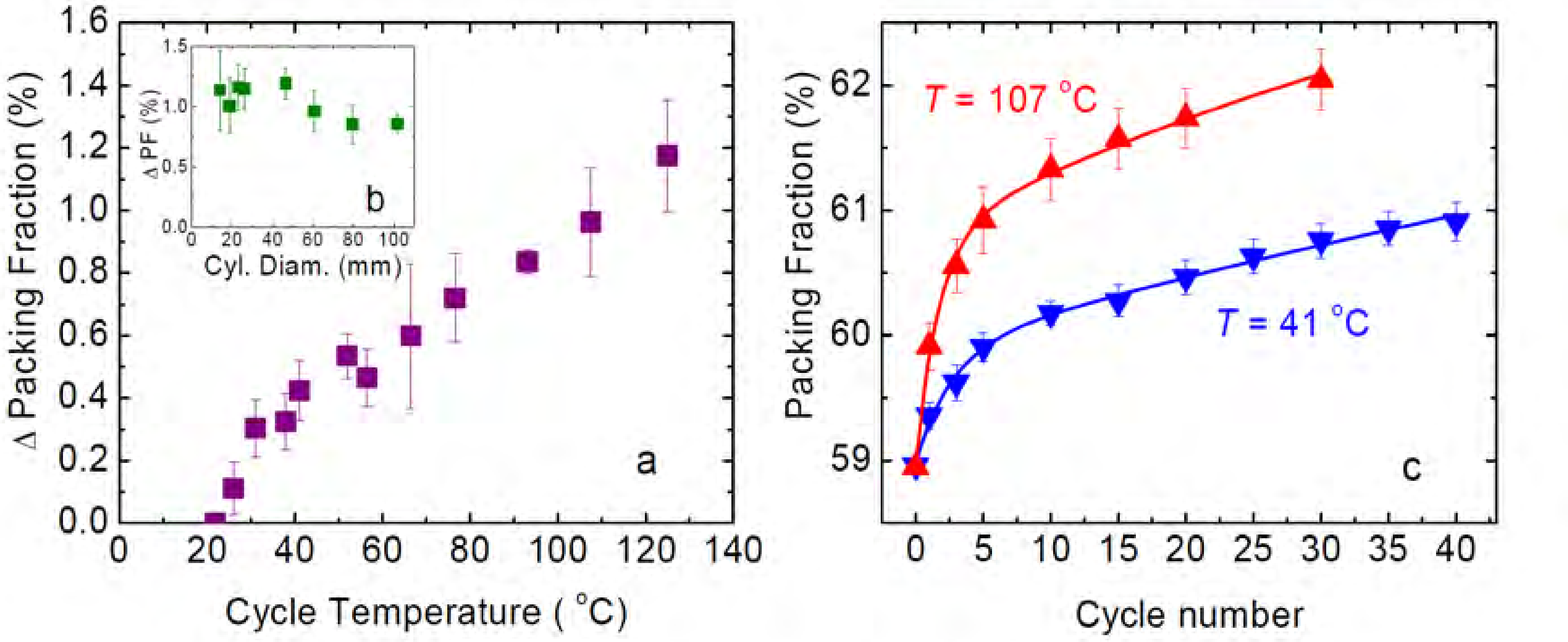


Fig. 9.23. Densification of lunar soil caused by self-weight compression in lunar gravity. The plot shows *in situ* bulk density (top horizontal axis) and relative density (bottom horizontal axis) as a function of depth below the surface (vertical axis). Self-compression of material with an initial relative density of 0% (light dashed curve, left) produces densities at depth that are much lower than those actually observed. Postdepositional vibration of the material (e.g., by seismic waves associated with meteorite impacts) could produce a material with an initial relative density of 90% or more (heavy dashed curve, right). The fact that lunar soil samples have relative densities of 60–100% (Fig. 9.20) indicates that such a vibration/compaction process has taken place. The steepness of both curves is related to the fact that the effects of self-compaction are limited because of the low lunar gravity.

Discovery of a New Densification Mechanism: Thermal Cycling



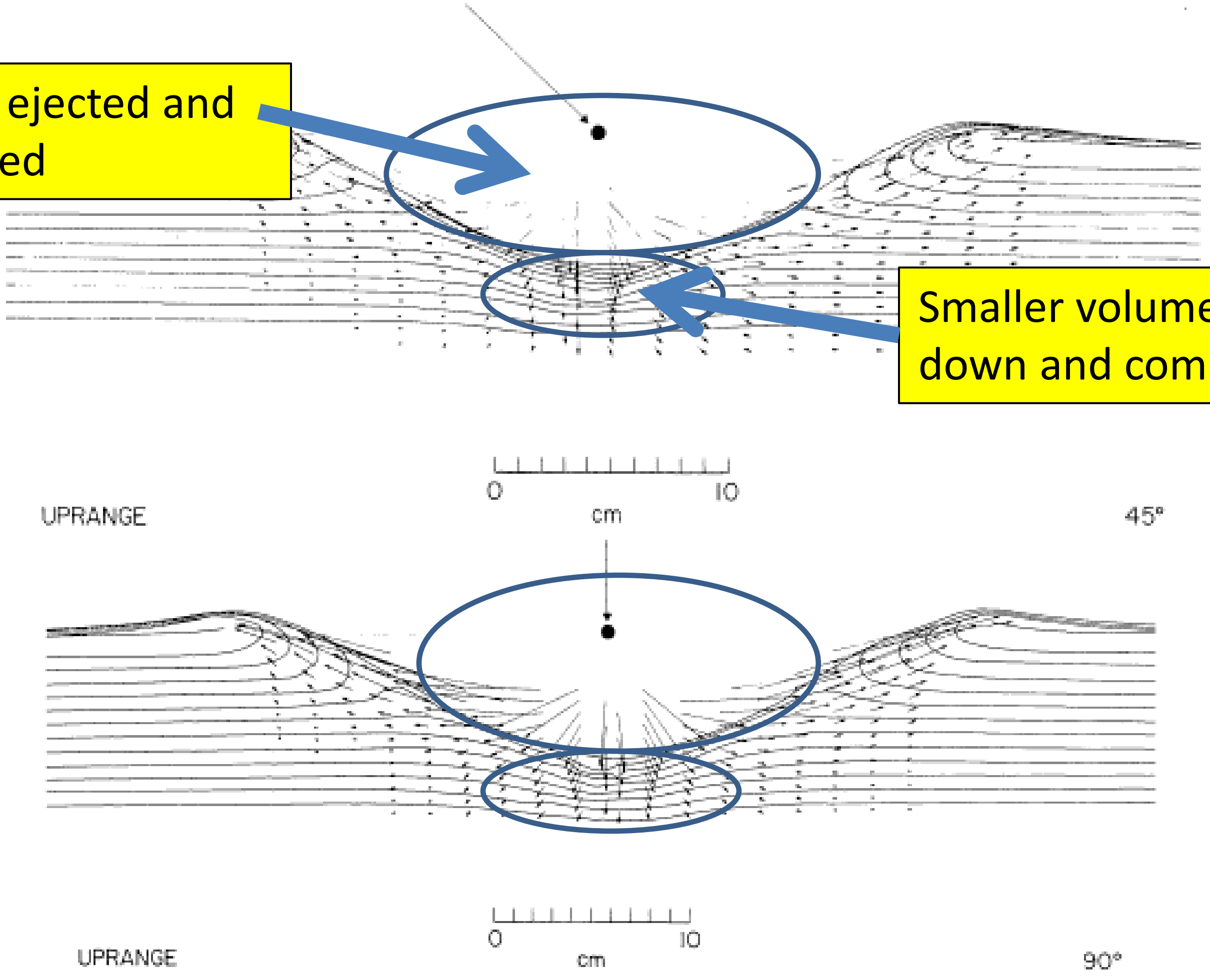
$$y = y_0 - A_1 e^{-\frac{x}{\tau_1}} - A_2 e^{-\frac{x}{\tau_2}}$$

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.

Why is Lunar Regolith Densified?

1. Impact Tamping?
2. Vibration?
    - Deep Moonquakes – No
    - Nearby Impact Events
    - Diurnal Vibrations (nearby sloped regolith slumping or nearby boulders fracturing)
    - Shallow Moonquakes
        - May be magnitude 5 on a 100-year timescale
        - Epicenters may be in the rims of ancient impact basins
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?

Hypervelocity Impact Experiments



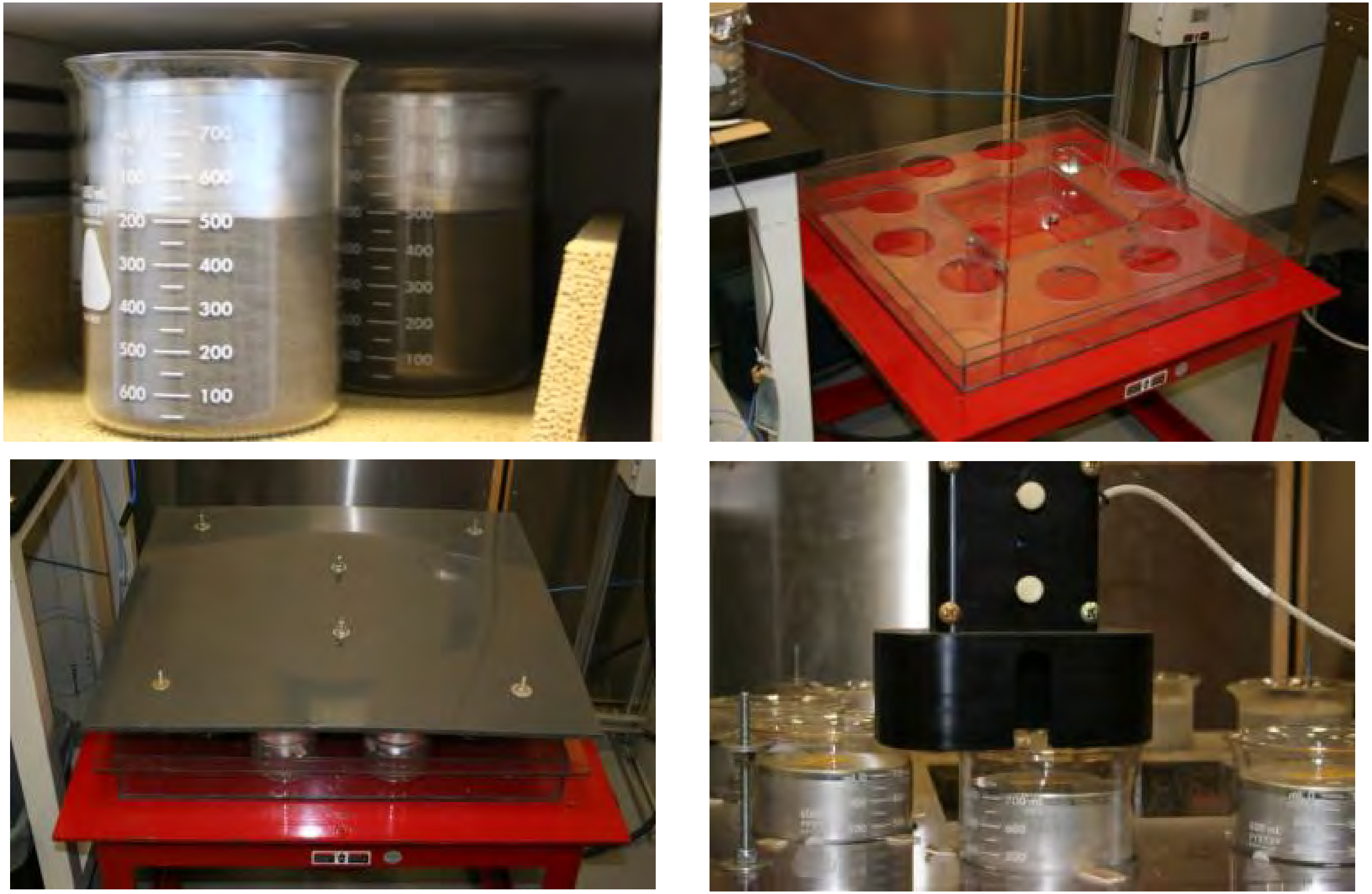
Larger volume ejected and thus re-loosened

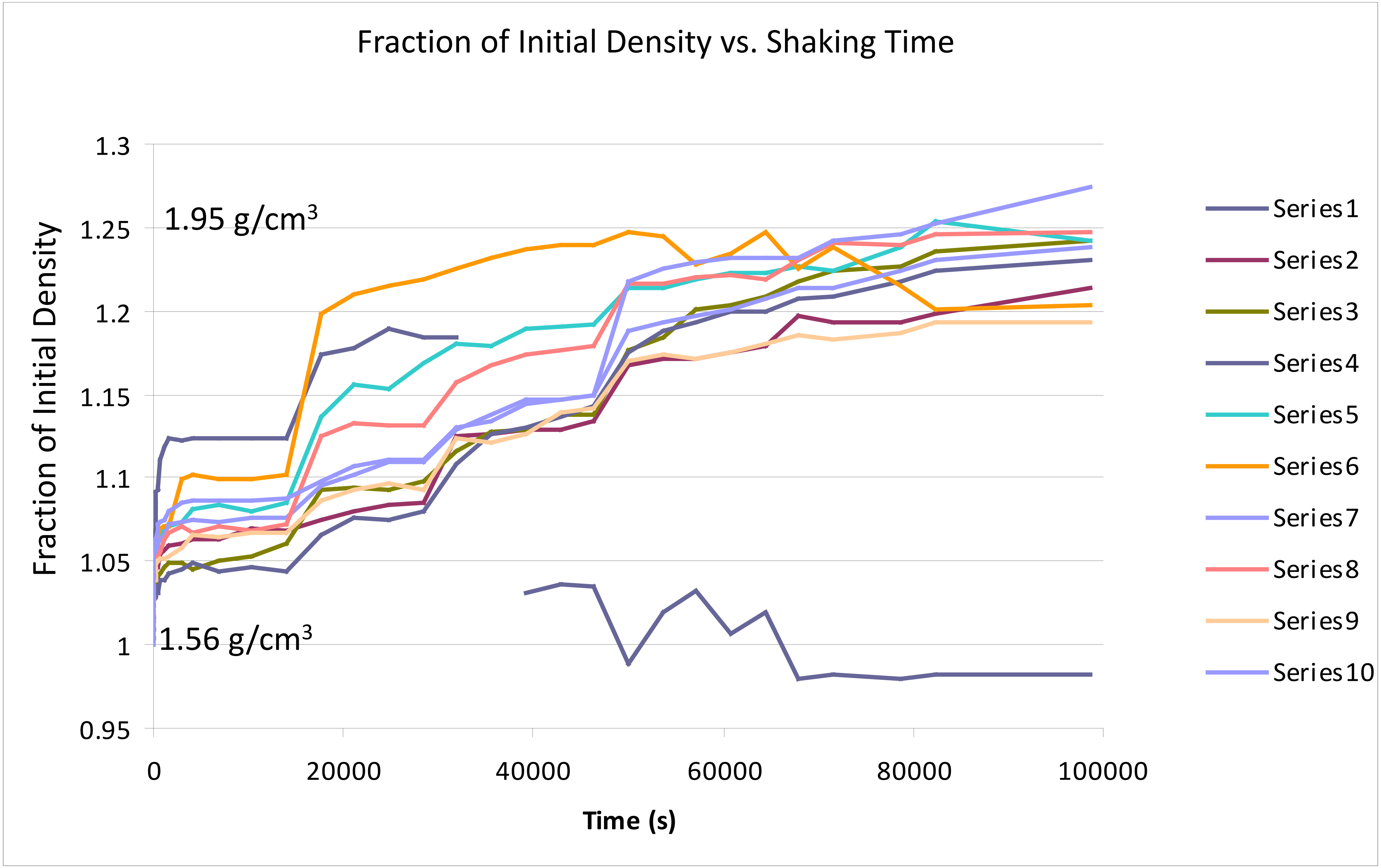
Smaller volume tamped down and compacted

Gault, D. E., F. Hörz, D. E. Brownlee, and J. B. Hartung. "Mixing of the lunar regolith." In *Lunar and Planetary Science Conference Proceedings*, vol. 5, pp. 2365-2386. 1974.

Vibration Experiments

Jake Gamsky and Phil Metzger




Fraction of Initial Density vs. Shaking Time
Fraction of Initial Density
Time (s)
1.3
1.25
1.2
1.15
1.1
1.05
1
0.95
0
20000
40000
60000
80000
100000
1.95 g/cm3
1.56 g/cm3
Series1
Series2
Series3
Series4
Series5
Series6
Series7
Series8
Series9
Series10

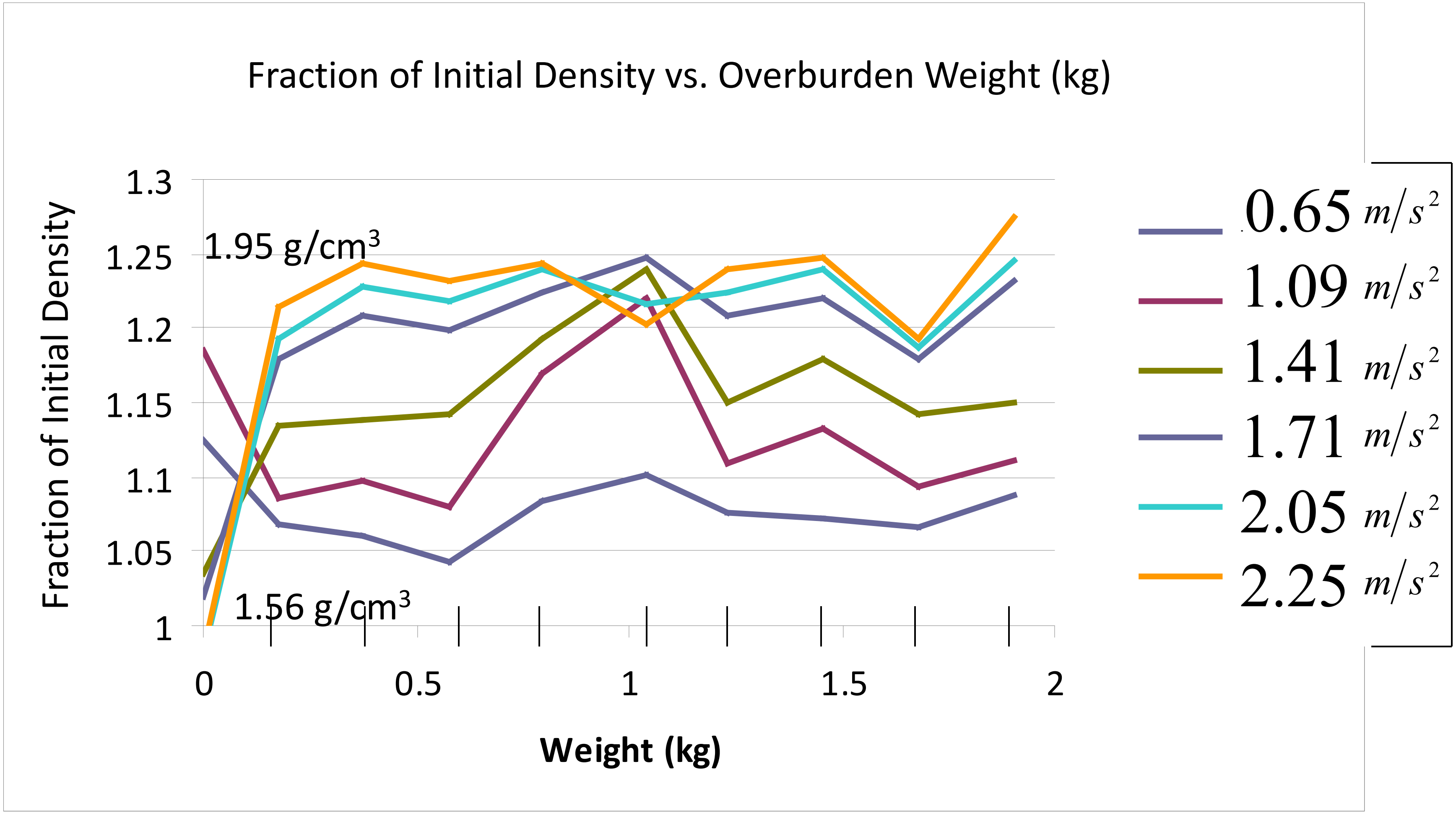


Figure 2. Steady State relative density vs. overburden weight at each acceleration value.

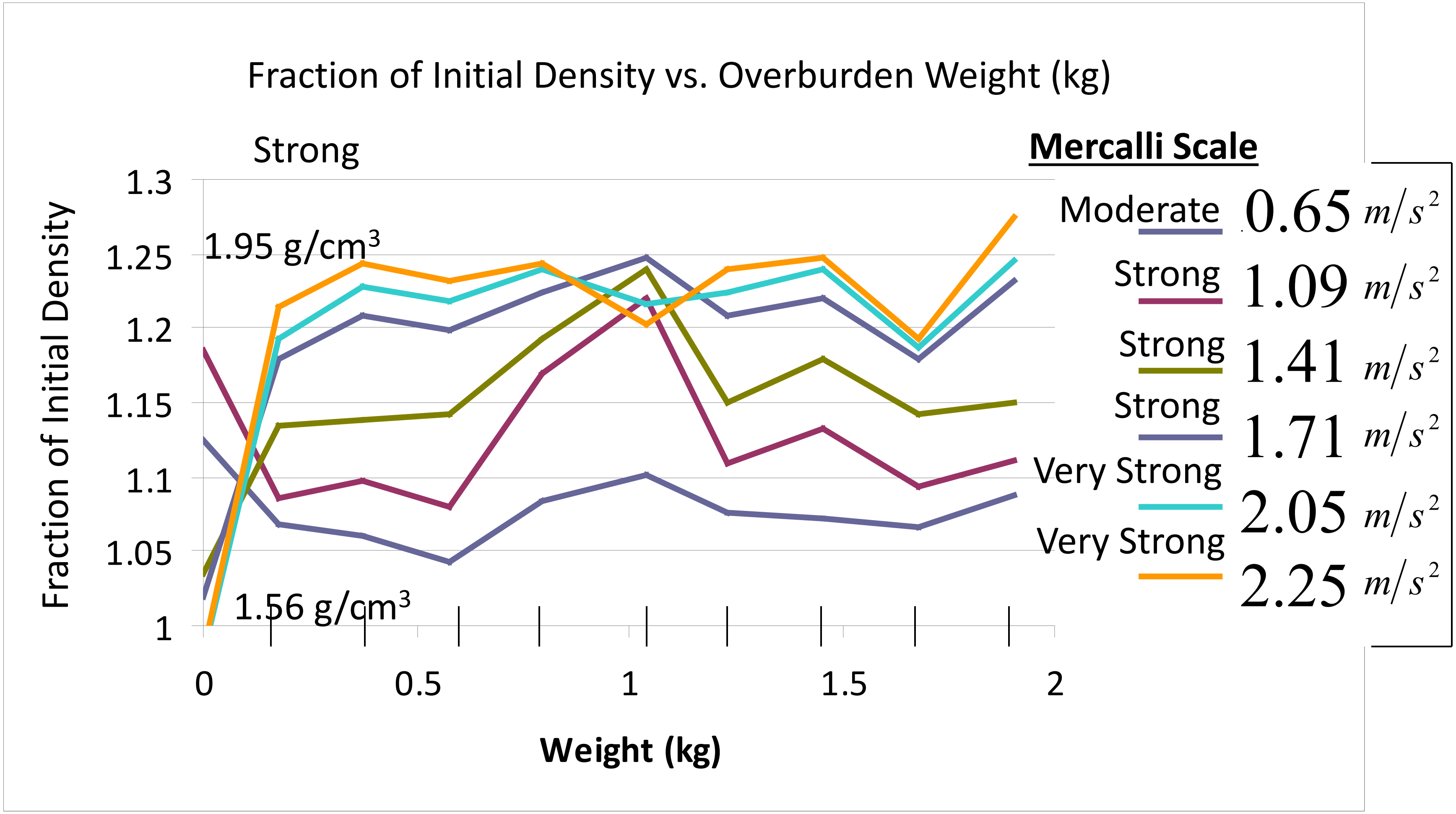


Figure 2. Steady State relative density vs. overburden weight at each acceleration value.

Thermal Cycling

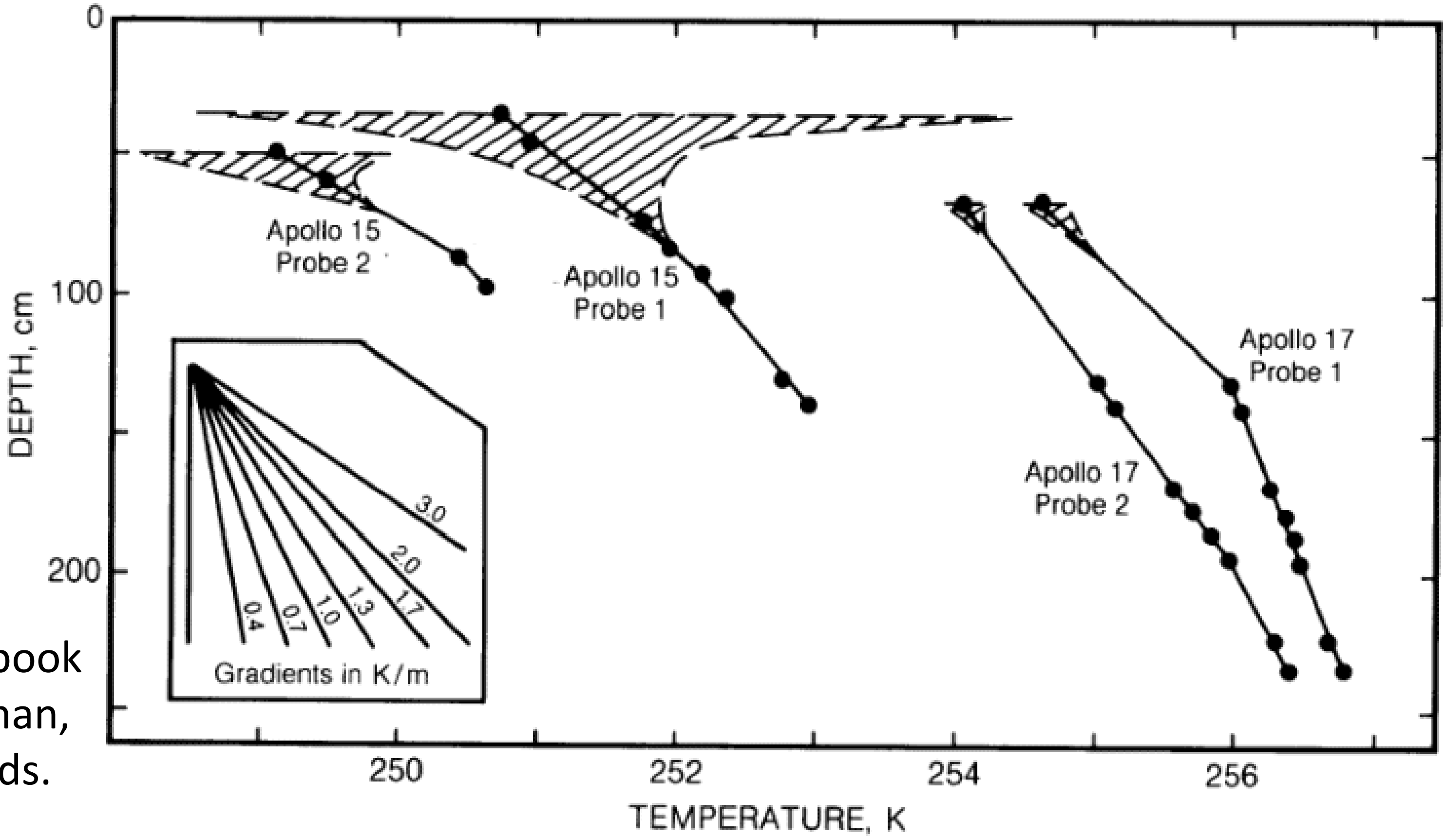


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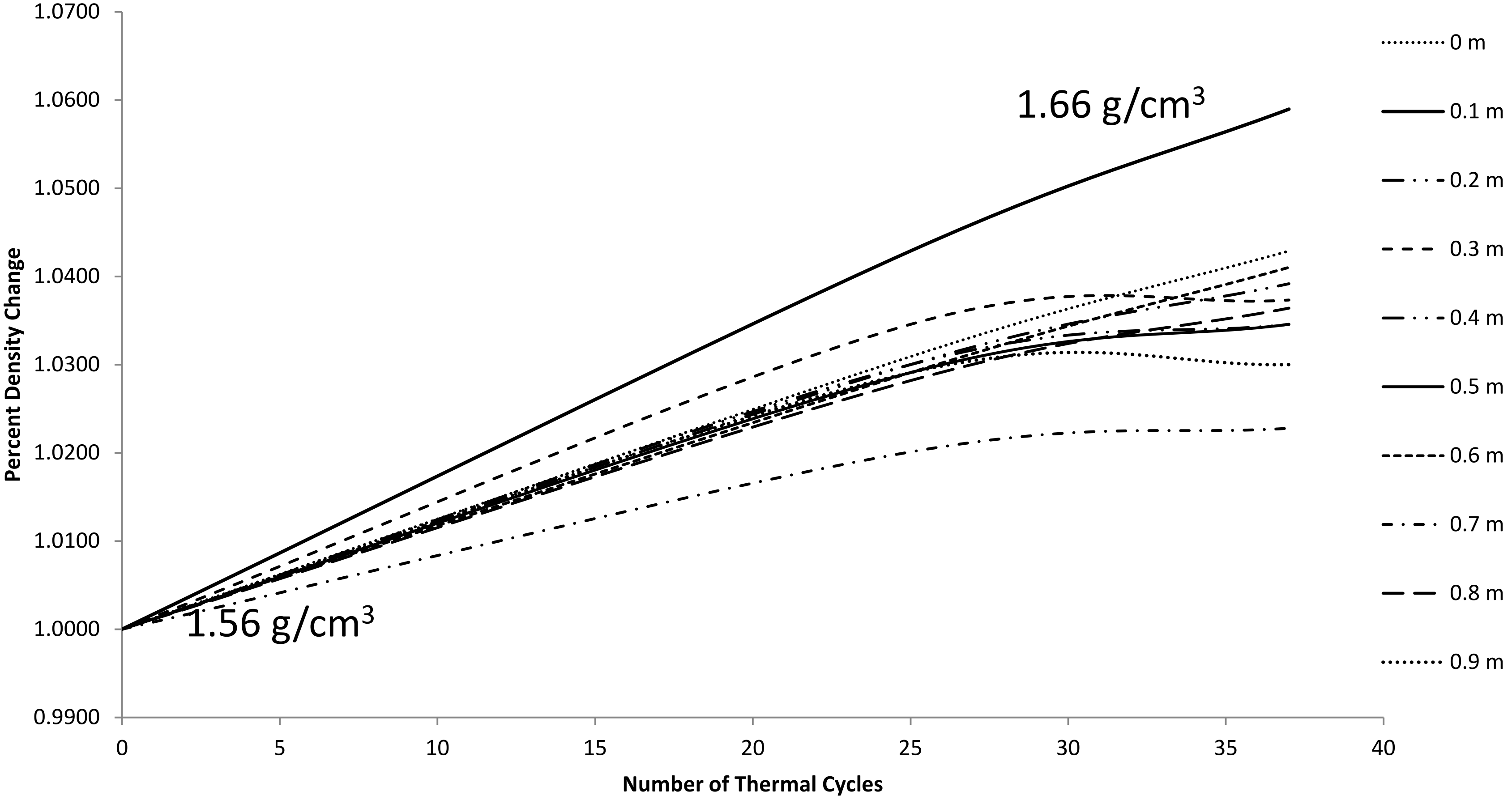
Fig. 3.9. Temperature fluctuations in the lunar regolith as a function of depth (after *Langseth and Keihm,* 1977). Note that the small temperature scale at the bottom of the diagram does not permit plotting of the extreme temperature fluctuations at depths less than ~30 cm; this region is left blank. Hatched areas show day-night temperature fluctuations below ~30 to 70 cm. Below ~50 cm there is essentially no temperature fluctuation due to the lunar day-night temperature cycles, and the steady temperature gradients recorded are due to internal lunar heat flow.

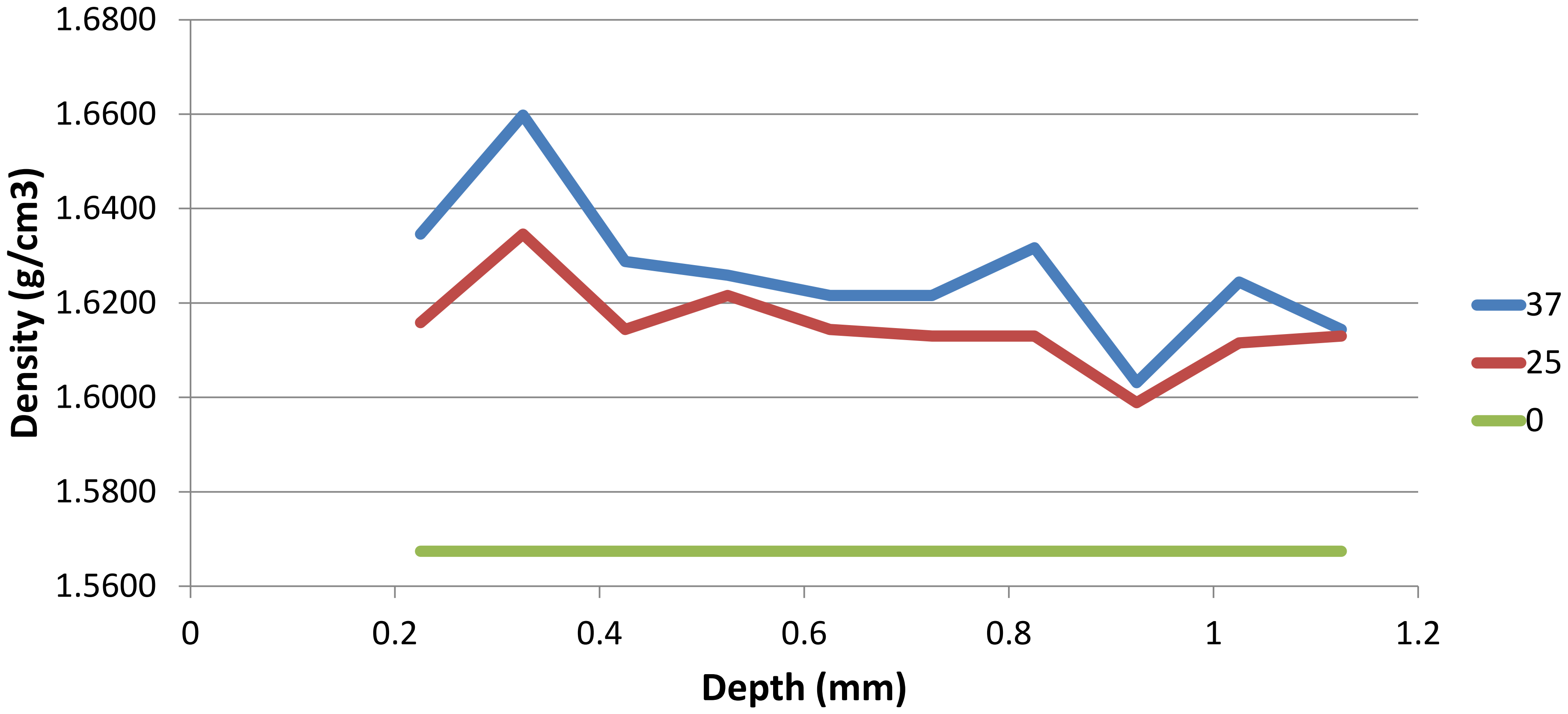
Thermal Cycling Experiments

- Jake Gamsky, Ryan Clegg-Watkins, Phil Metzger
- Samples with overburden (as in vibration tests)
- Placed in a furnace with simulated lunar thermal cycles
- Soaked at 250˚C for 4 hours, then cool to 100˚C for 4 hours and repeat.

Thermal Cycling



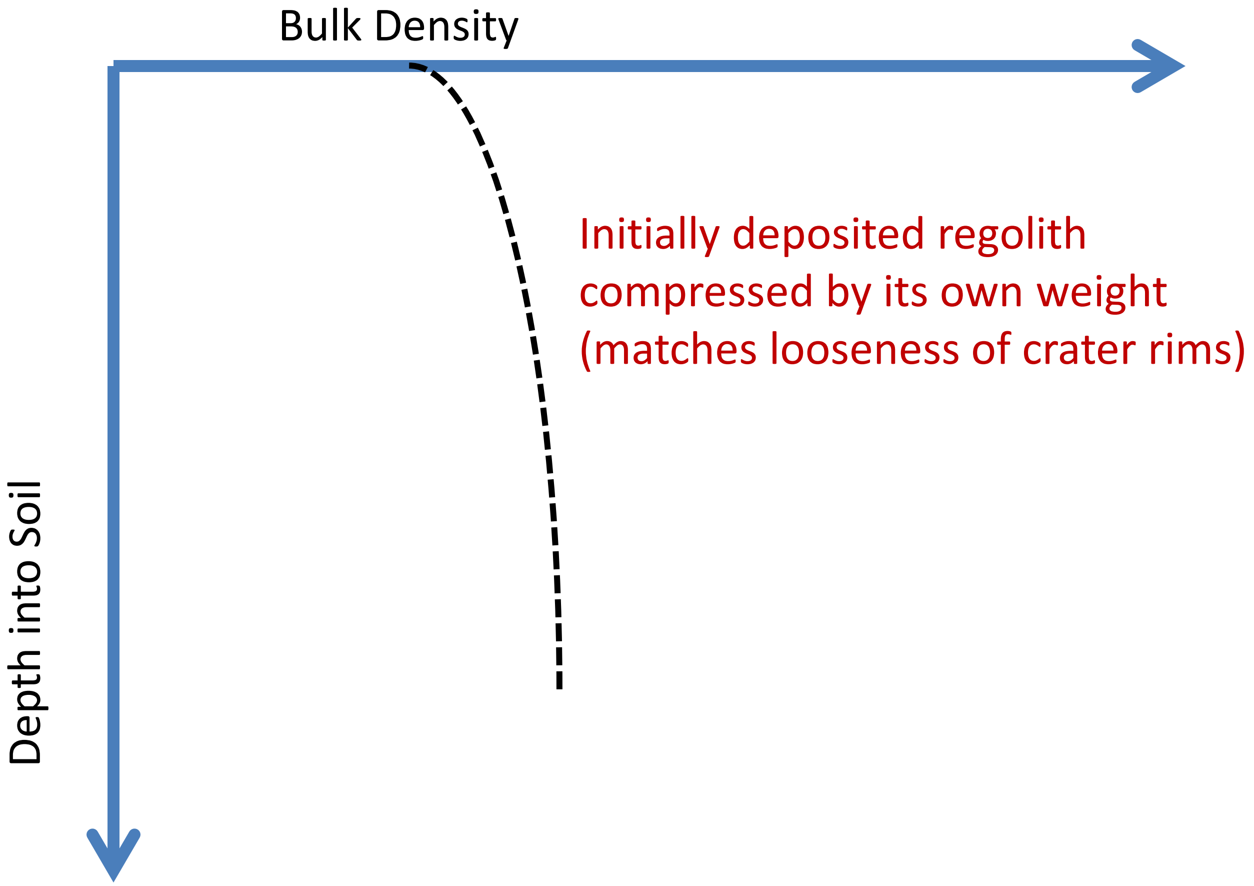
Thermal Cycling



Discussion

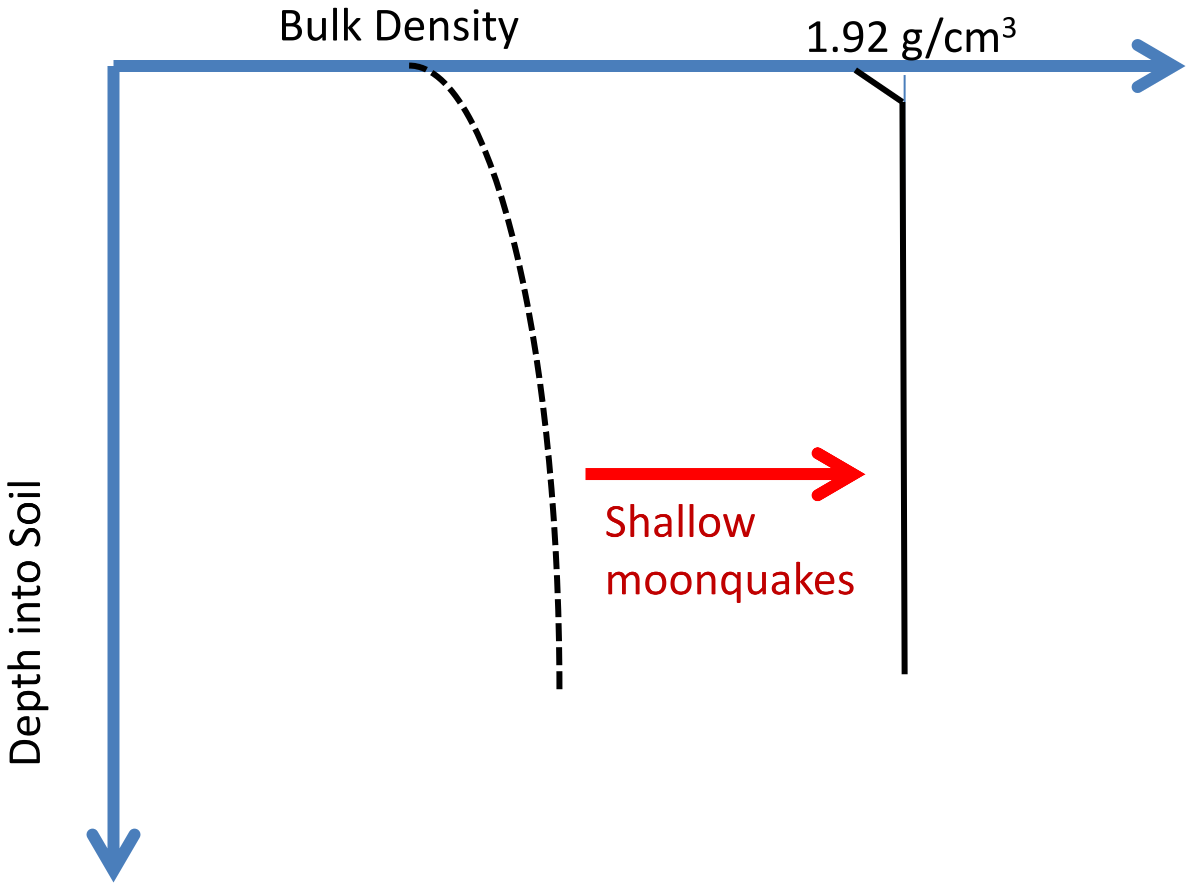
- Vibration requires extreme amplitudes and very long exposure but can achieve the highest compaction levels
- Over geologic timescales, if close enough to the epicenters of shallow moonquakes, then this mechanism may work but fails to predict the (average) hyperbolic curve
- Overturning soil produces net loosening, and more so near the surface
- Thermal cycling certainly compacts soil in the top 30-80 cm

Hypothesis

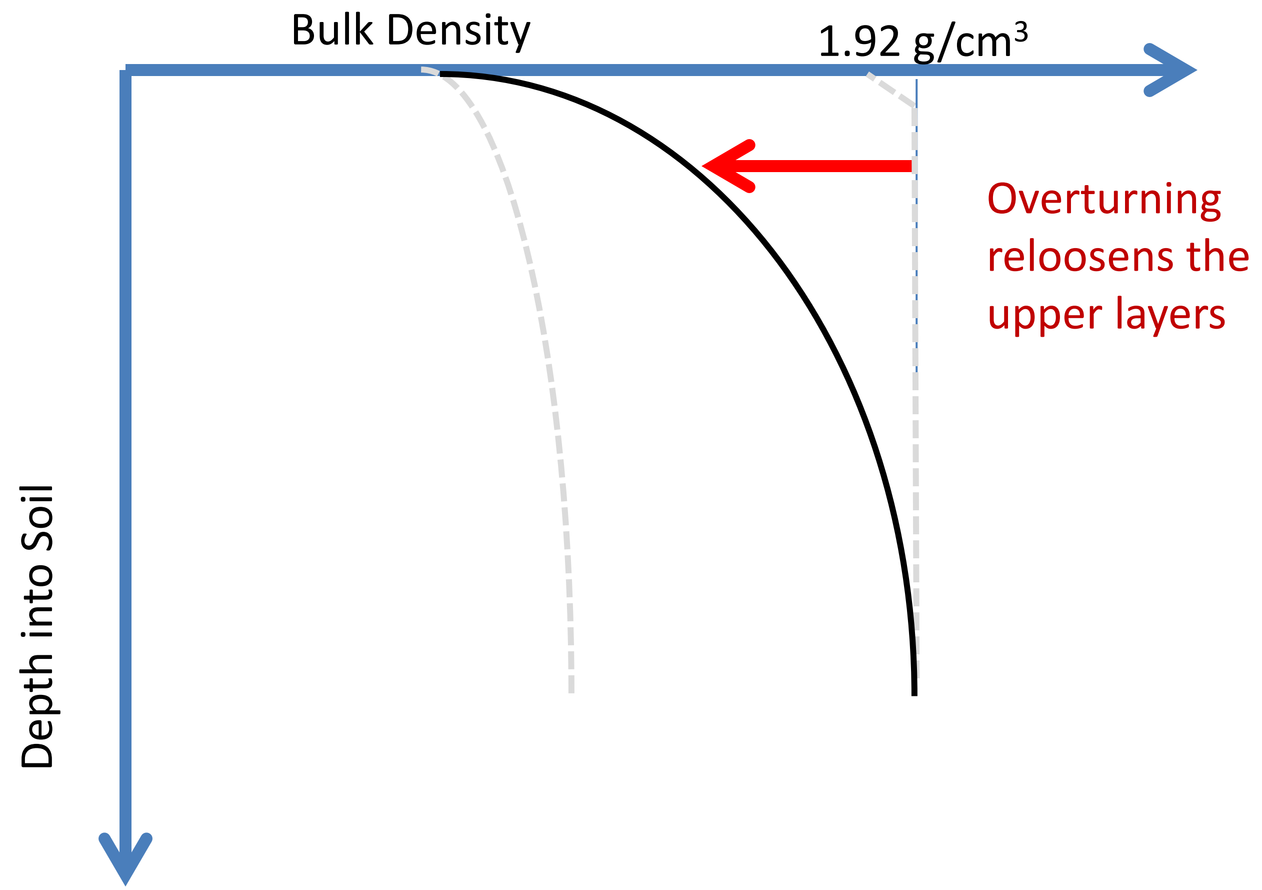


Initially deposited regolith compressed by its own weight (matches looseness of crater rims)

Hypothesis

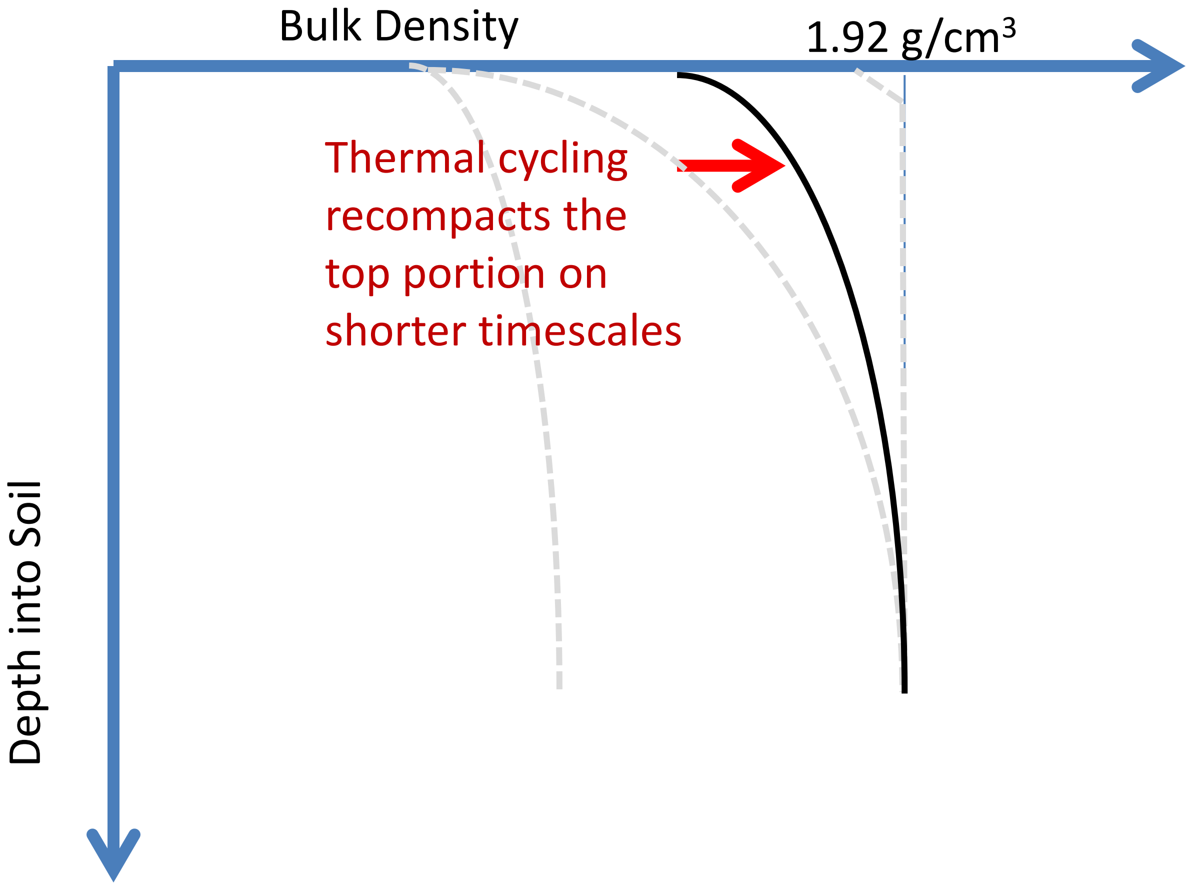


Hypothesis



Overturning reloosens the upper layers

Hypothesis



Thermal cycling recompacts the top portion on shorter timescales

Bulk Density in PSCs

- LCROSS Impact suggests loose to a depth of 2 meters
- Thermal cycling does not occur there
- Shallow Moonquakes may be significant there
- Overturning and tamping does occur there
- Soil could be cemented by ice, interfering with compaction processes

Summary

- Shallow moonquakes with “very strong” magnitude may compact the entire soil column over very long timescales
- Impacts overturn the soil and re-loosen it in the upper layers, but not homogeneously
- Thermal cycling re-compacts overturned soil on very short timescales but only to the depth of the thermal wave
- Since thermal cycling is absent in the polar regions, the upper layers may be somewhat looser than in the Apollo experience