Lunar Regolith – Understanding for Science and Exploration

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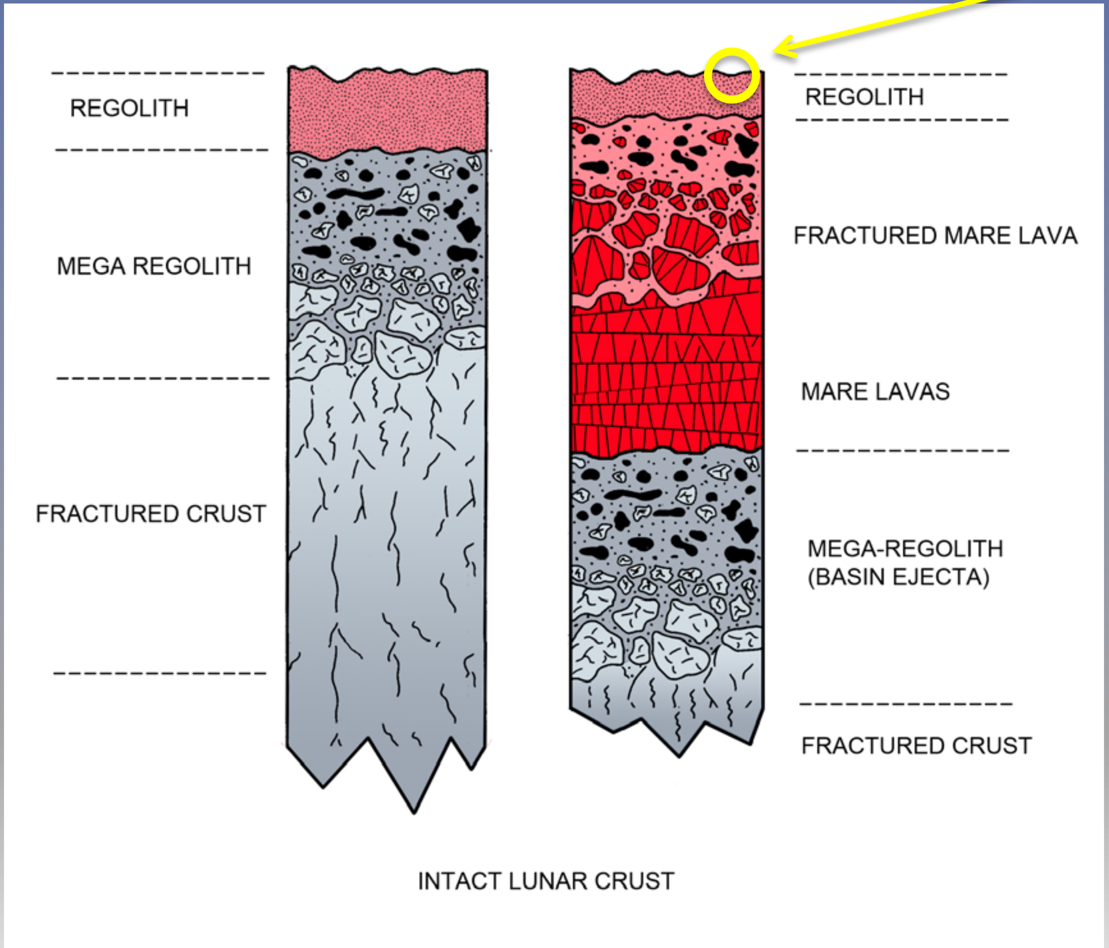
LEAG Annual Meeting

VORTICES
VOlatile Regolith Thermal Investigations Consortium for Exploration & Science

Overview

- What new advances have been made in understanding the properties of the lunar regolith?
- What are key outstanding questions with regard to the lunar regolith?
  - SRQ: Strategic Regolith Questions
  - RKG: Regolith Knowledge Gaps

Regolith Properties



This is where all of the action is:

Volatile adsorption, adhesion, formation
Micro-scale physics
Radiation interactions
Space weathering

Volatile storage
- Long term
- Short term

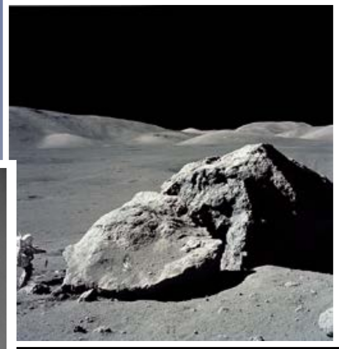
Regolith Definition

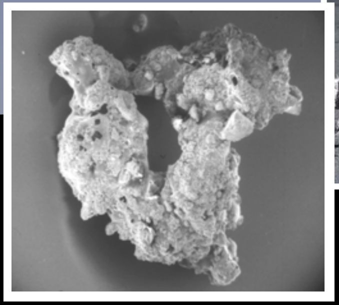
Regolith: *The layer or mantle of loose incoherent rock material, of whatever origin, that nearly everywhere underlies the surface of the land and rests on bedrock. A general term used in reference to unconsolidated rock, alluvium or soil material on top of the bedrock. Regolith may be formed in place or transported in from adjacent lands. – Terrestrial definition.*

Regolith*: S*urficial layer covering the entire lunar surface ranging in thickness from meters to tens of meters formed by physical desegregation of larger fragments into smaller ones over time (impact or thermal processes).

Particle size ranges from enormous boulders to micron-sized particles

The lunar regolith is not just JSC-1.





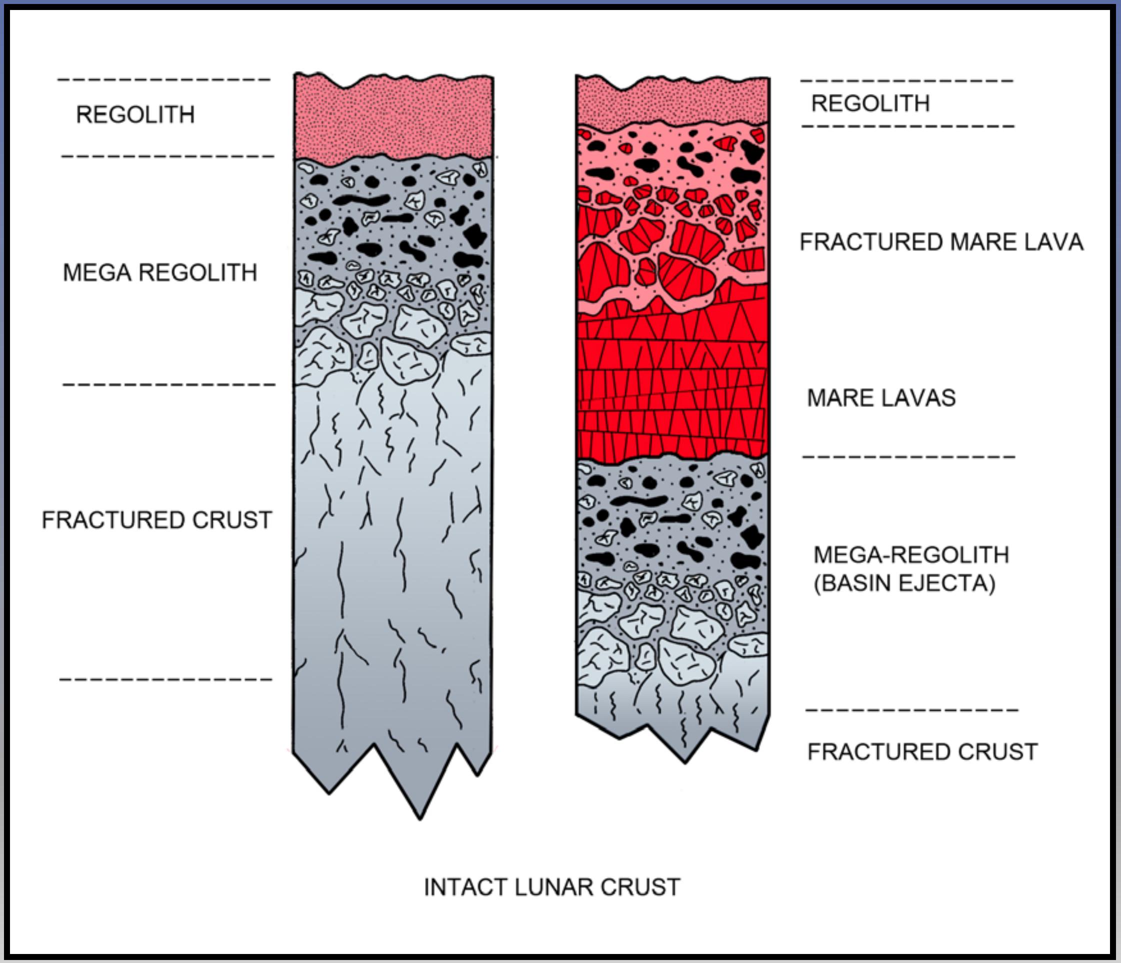
Regolith Properties 1 – Apollo Era

Property	Value	Units	Notes	Sources
Bulk density (ρ)	1.58 ± 0.05: 0-30 cm 1.74 ± 0.05: 30-60 cm	g/cm^3	Intercrater areas	p 492 LSB
Relative density (D_R)	74 ± 3: 0-30 cm 82 ± 3: 30-60 cm	%	Intercrater areas	T9.6 LSB
Porosity (n)	49 ± 2: 0-30 cm 44 ± 2: 30-60 cm	%		T9.5 :SB
Void ratio (e)	0.96 ± 0.07: 0-30 cm 0.78 ± 0.07: 30-60 cm			LSB
Permeability (Q)	$1 - 7 \times 10^{-12}$	m^2	Surveyor vernier engines	Choate et al. 1968
Diffusivity	7.7 He 2.3 Ar 1.8 Kr	cm^2 / sec	Function of gas species	Martin et al. 1973
Compression index (C_c)	0.3: loose 0.05: dense 0.01-0.11: range		sample mass 1.2 to 200 g	T9.9/9.10 LSB
Recompression index (C_r)	0.003 average 0.000-0.013 range			T9.9 LSB
Coefficient of lateral stress (K_o)	0.45:normally consolidated 0.70: recompacted			T9.9 LSB

Regolith Properties 2 – Apollo Era

Property	Value	Units	Notes	Sources
Friction angle (ϕ)	30-50	degrees		T9.11 LSB
Cohesion (c)	0.1-1.0	kPa		T9.11 LSB
Modulus of subgrade reactions (k)	1-200 range 8 average	kPa / cm		LSB p 519
Thermal conductivity	1.5×10^{-4} Apollo 15 $1.72\text{-}2.95 \times 10^{-4}$ Apollo 17 1.5×10^{-5} 0-2 cm	W / cm K		LSB p 37-38
Thermal diffusivity (κ)	$2\text{-}6 \times 10^{-3}$	cm^2 / sec	Temperature, density dependent	Horai et al. Langseth et al.
Heat capacity (specific heat)	$c = C_4{*}T^4 + C_3{*}T^3 + C_2{*}T^2 + C_1{*}T + C_0$ $C_4 = 3.8697908 \times 10^{-9}$ $C_3 = -4.1426332 \times 10^{-6}$ $C_2 = -2.0296199 \times 10^{-3}$ $C_1 = 3.6432101E{+}00$ $C_0 = -5.8395023 \times 10^{1}$	J/kg/K	Temperature dependent	D. Paige
DC electrical conductivity	see section TBD	mho / m	Temperature dependent	LSB9.2.1
Relative dielectric permittivity (k)	1.908		Function of density, temperature and frequency	LSB 9.2.4 Olhoeft and Strangway 1975
Loss tangent	$10^{(0.44, -2.943)}$ $10^{(0.045(\%TiO2 + \%FeO) - 2.754)}$		Function of density, temperature, frequency and chemistry	LSB 9.2.4 Olhoeft and Strangway 1975

Regolith Structure - Stratigraphy



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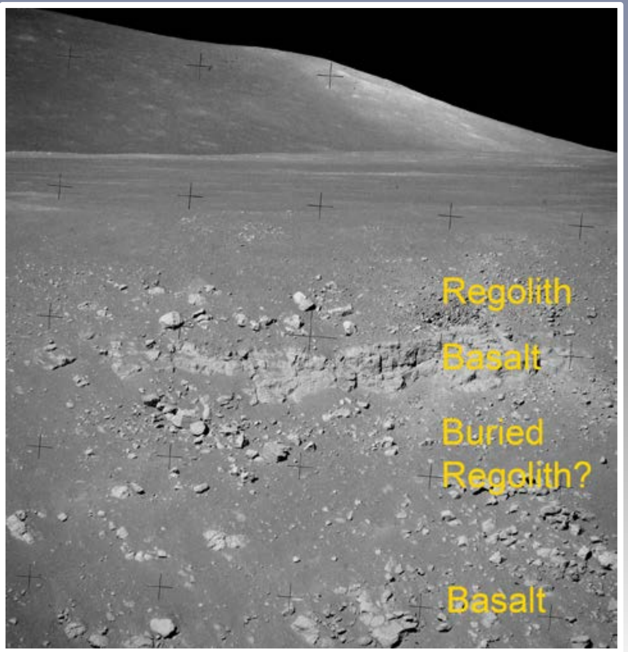


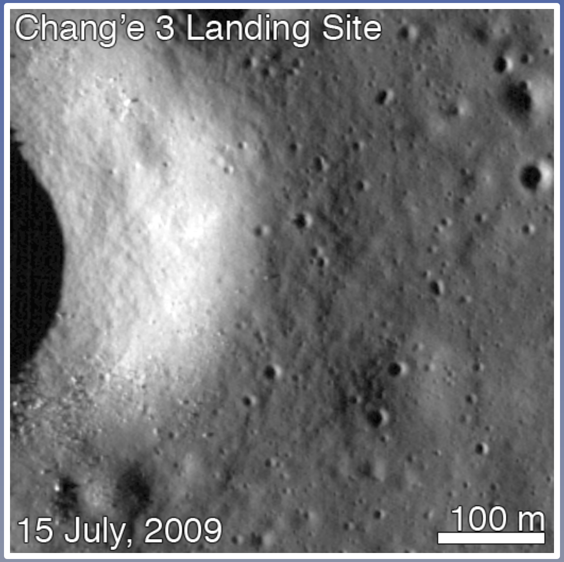
Regolith Structure Stratigraphy

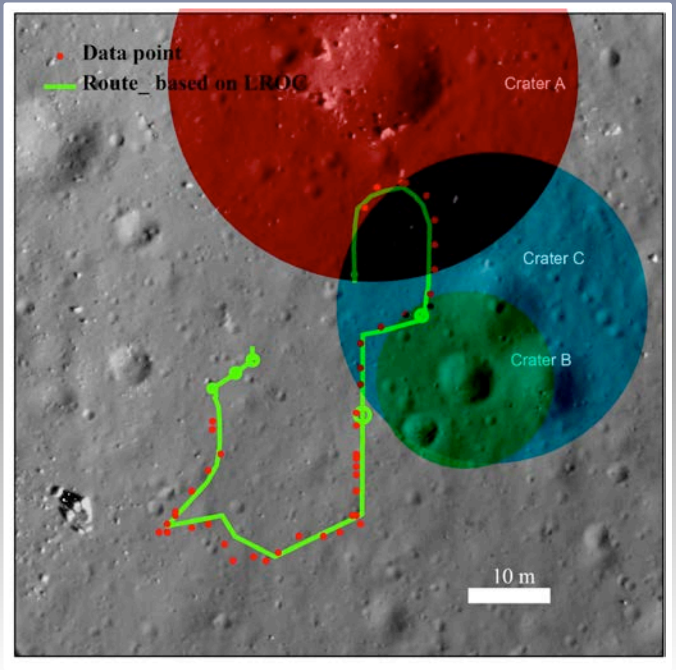
Chang'e Yutu Ground Penetrating Radar

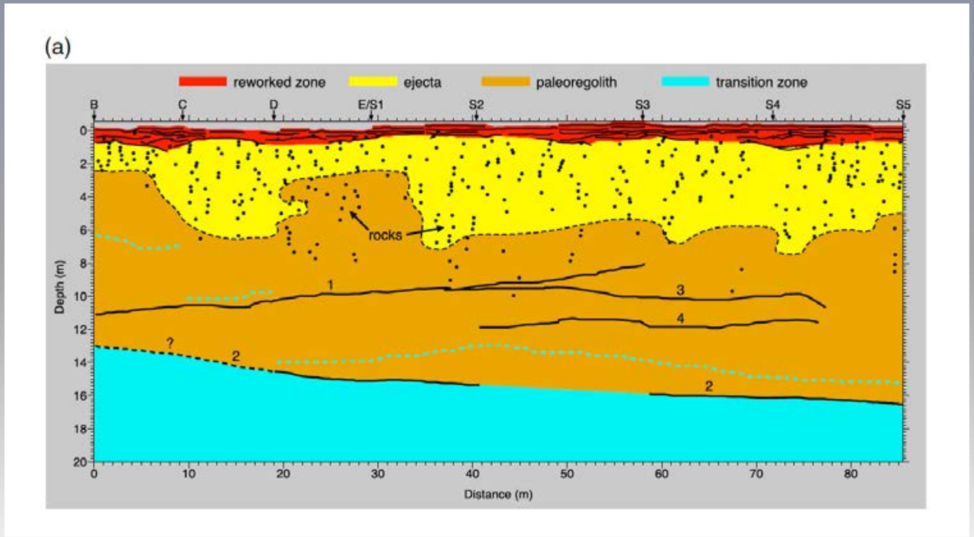
Multiple reflectors and scattering points

Identify multiple ejecta layers

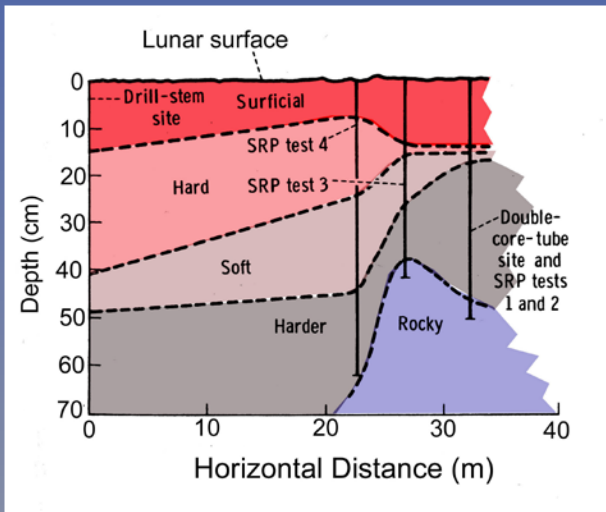
Reflectors have variable lateral continuity



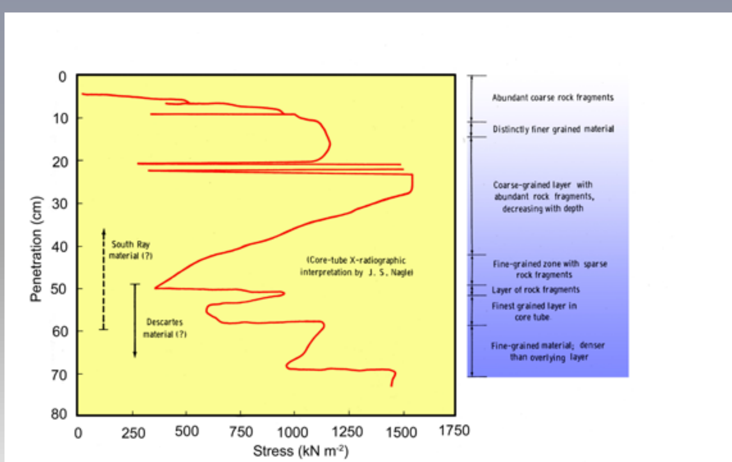




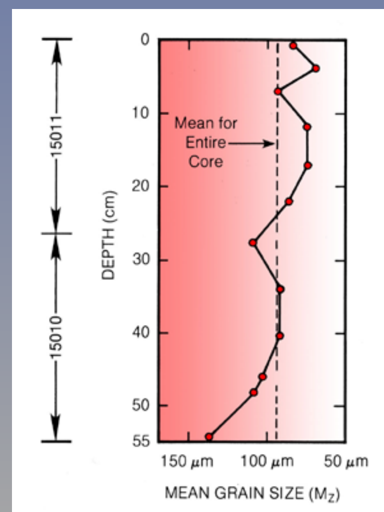
Regolith Stratigraphy



Apollo 16: Station 10 ALSEP



Station 4 double-core-tube stratigraphy / SRP test 4 (index 8)



Upper regolith composed of numerous, variable layers. Layering is highly localized and individual layers can not be traced for significant distances.

Apollo 12

12015/12028: 42 cm long, 10 layers, 61-595 mm

Apollo 15

15001-15006: 236 cm long, 42 layers, all poorly sorted, median 44-89 mm

Near rille, 15010/15011, 60 cm long, coarser grained than elsewhere, mean 85 mm

Apollo 16

Drilling: 221 cm long, 3 major subdivisions, 46 textural units, poorly sorted, median 56-72 mm

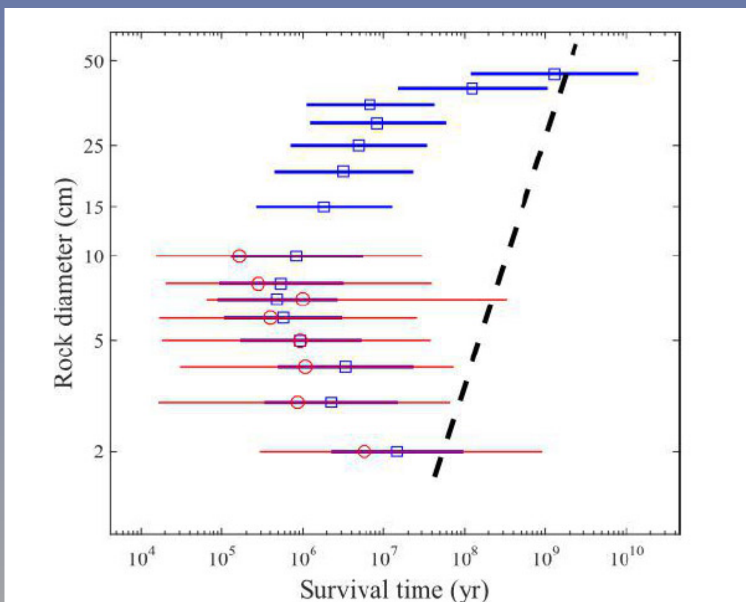
60009/60010: general increase with depth, 85 mm surface, 200 mm at 55 cm

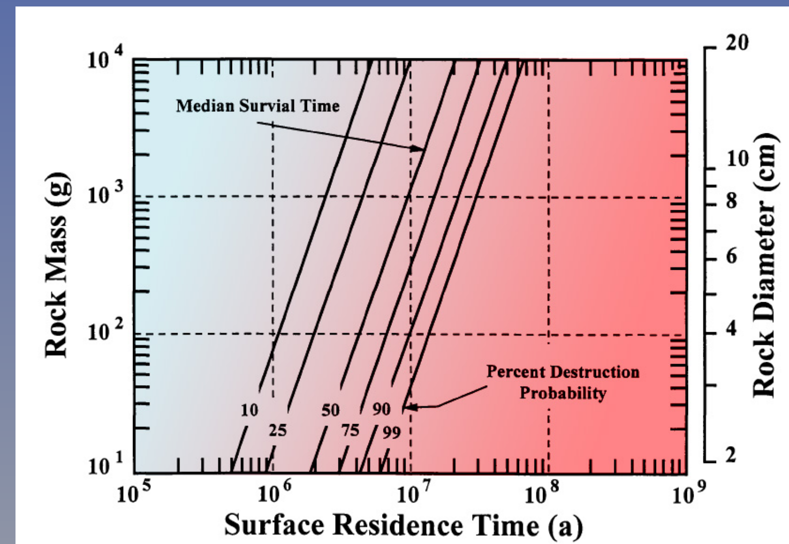
Apollo 17

70009-70002: 284 cm long, 5-8 stratigraphic units

Regolith Formation – Thermal Fatigue v. Catastrophic Disruption

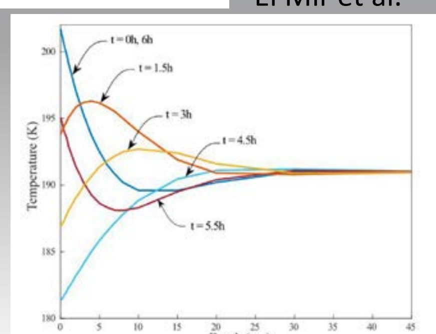
New models of thermally driven crack propagation shows that rock breaks down must faster due to thermal stress than impact.

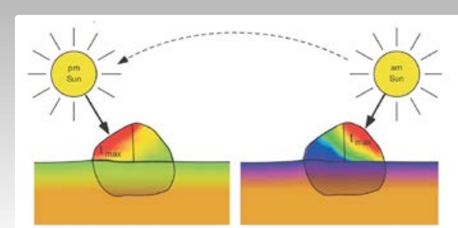




Survival times for different rocks size. Blue lines: new model, red line: model of Miyamoto et al. Dashed line: Impact induced breakdown

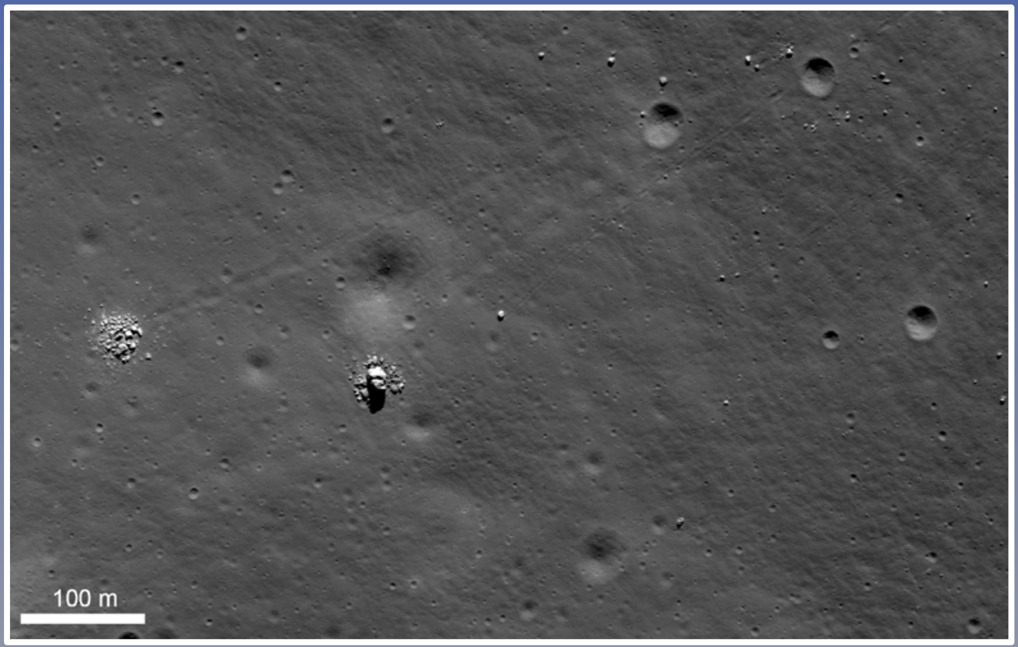
El Mir et al.

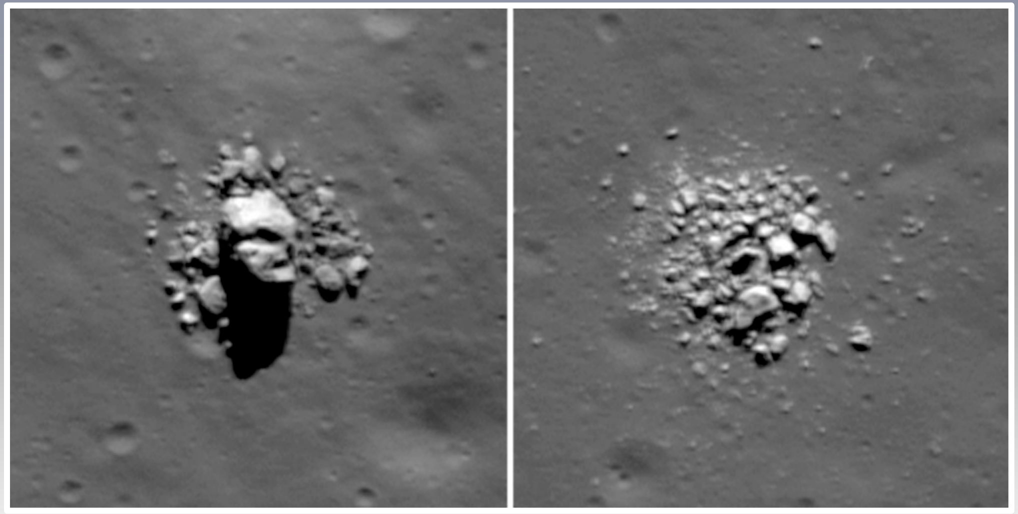


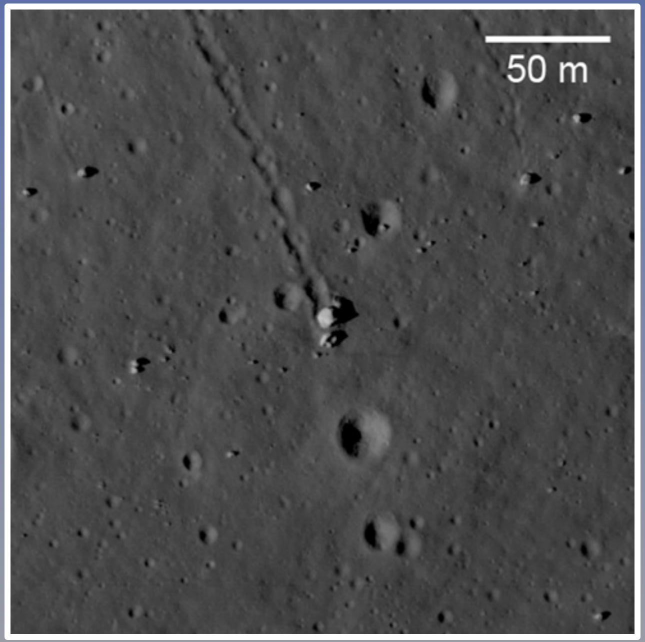


Shattered Boulders

Schiller Crater







Apollo 17 Station 6

Lunar Particle Size-Frequency Distribution

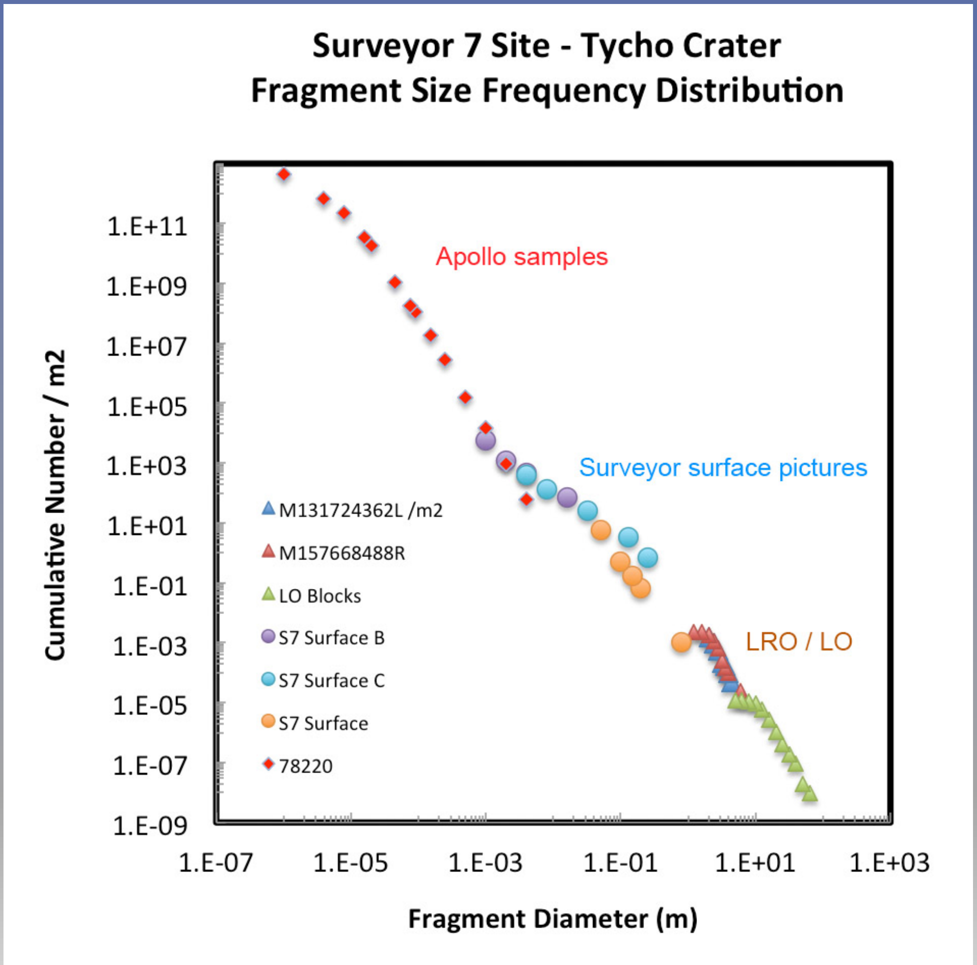
Origin of regolith on airless bodies

Micrometeorite impact

Thermal fatigue

Need to understand the observed size-frequency distribution of the regolith from boulders to micron-size particles for comparison against models and experiments.

No single source for all size ranges. Compiling data from modern to ancient sources: Surveyor, Apollo, Lunar Orbiter, and LRO to build a complete particle size-frequency distribution. Part of the problem is that original surface data from Surveyor and Apollo surface pictures is lost to history.



Regolith Gardening – Exposure of Immature Regolith

Recent impacts – resolved impact craters and splotches

1.36 × 10^5 splotches (D≥10 m) annually

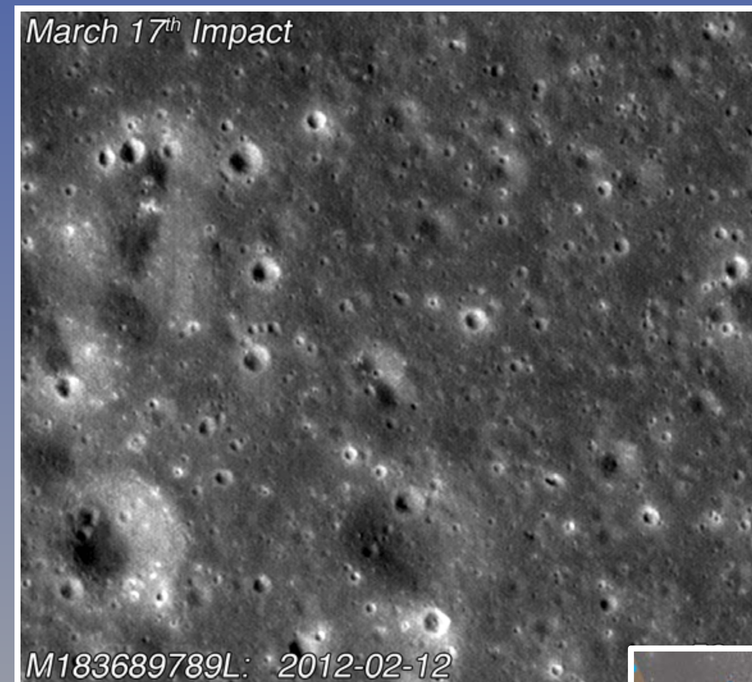
Splotches

- 1.09 x 10^5 ≥10 m / year
- ≥1 m 1.52 x 10^9 / year – 40.2 ± 1.6 km^{-2}

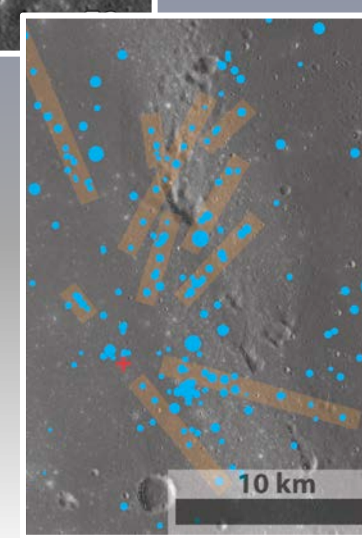
Overturn

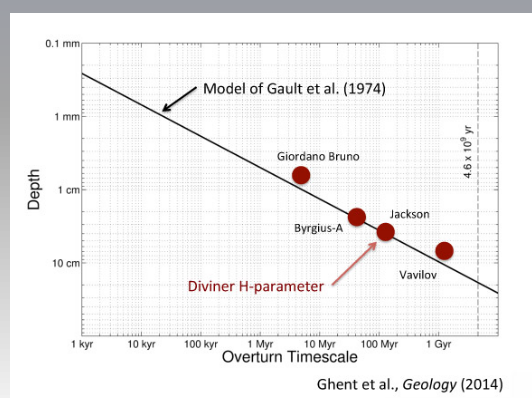
- 20 cm: 99% of surface overturned 1.0 x 10^7 yrs.
- 2 cm: 8 x 10^4 yrs.
- 100X faster than Gault et al. (1973) and Ghent et al. (2014)

Spreyerer et al. (2016)



17 March 2013 impact, 18 m crater, secondaries found >30 km distant

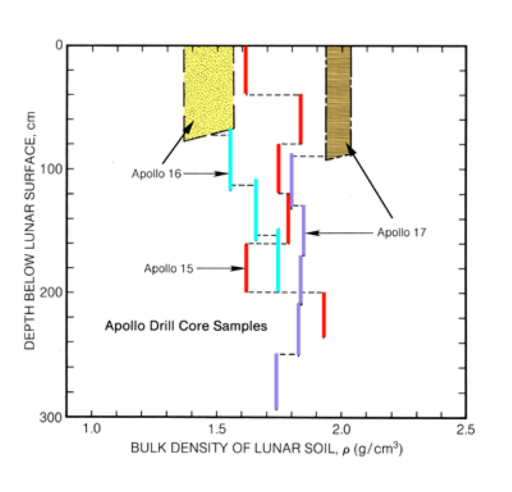


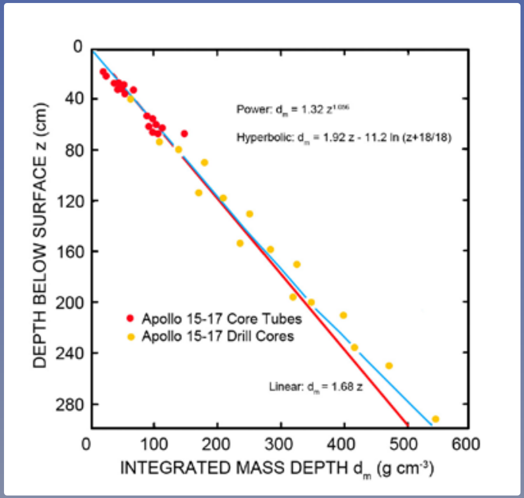


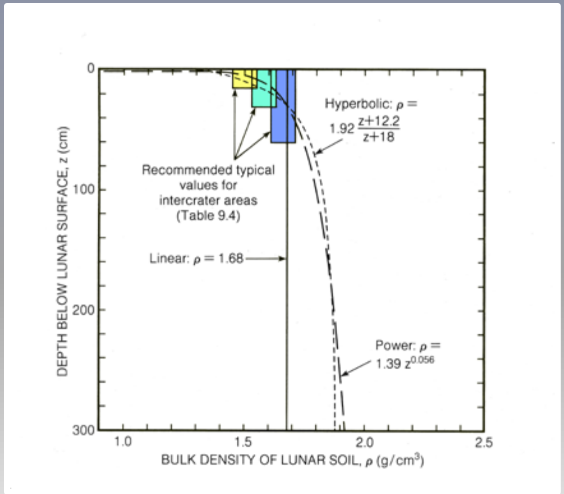
Ghent et al., *Geology* (2014)

Regolith Density

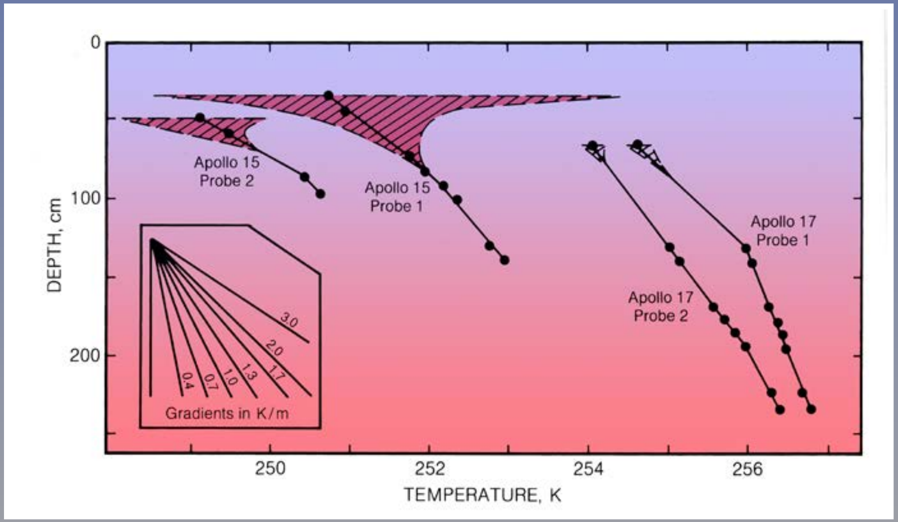
	Depth	Density (g cm^{-3})
Mare		
A11:	0-13 cm	1.54-1.75
A12:	0-9 cm	1.98
	9-41 cm	1.96
A15:	<30 cm	1.62-1.64
	>30 cm	1.75-1.91
A17:	0-90 cm	1.99
Highlands		
A15:	<30 cm	1.3-1.36
	>30 cm	1.66-1.8
A17:	0-35 cm	1.5
A14:	0-30 cm	1.6-1.7
Source Book		1.58



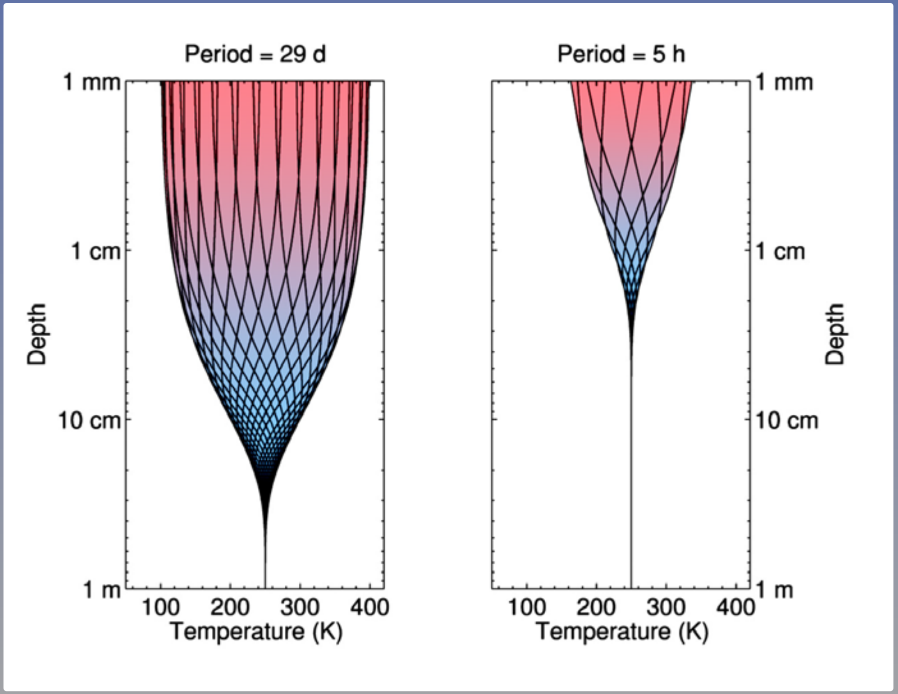




Regolith - Thermal Properties



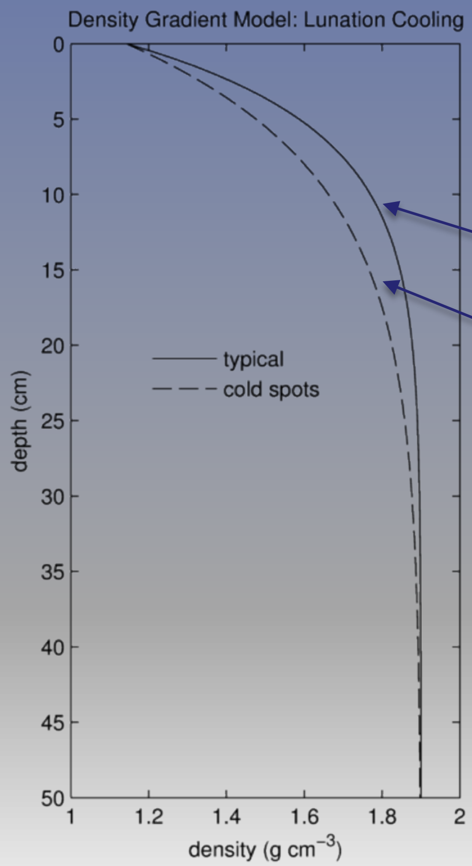
Apollo – Temperature vs. Depth



Temperature variation *f*(forcing period)
Greenhagen et al.

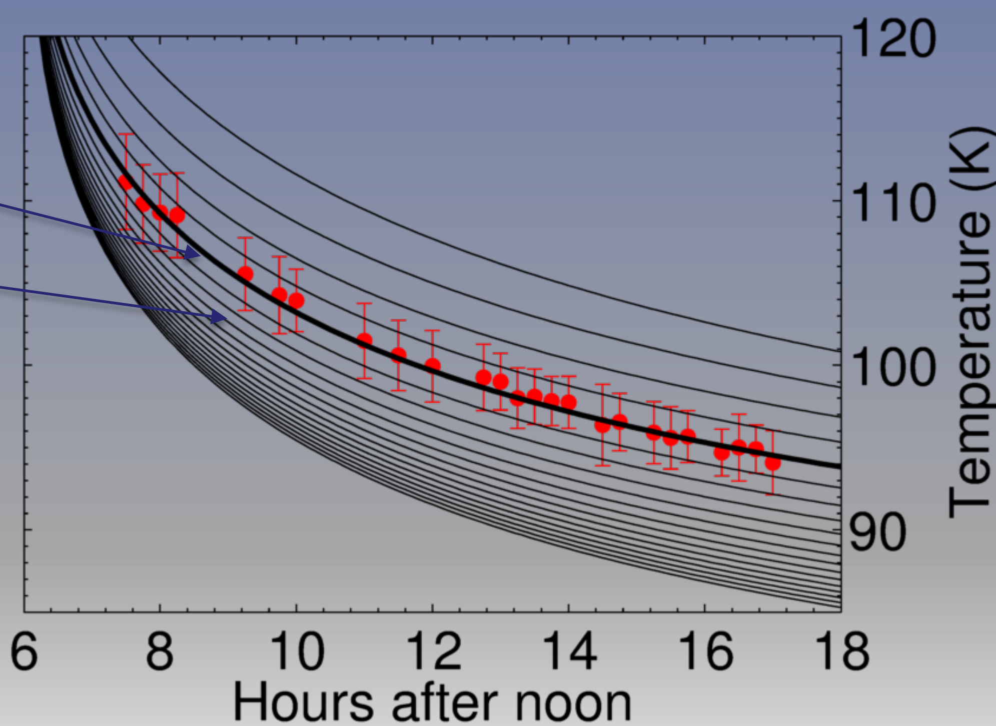
Regolith - Thermal Properties

$$\rho(z) = \rho_d - (\rho_d - \rho_s) e^{-z/H}$$



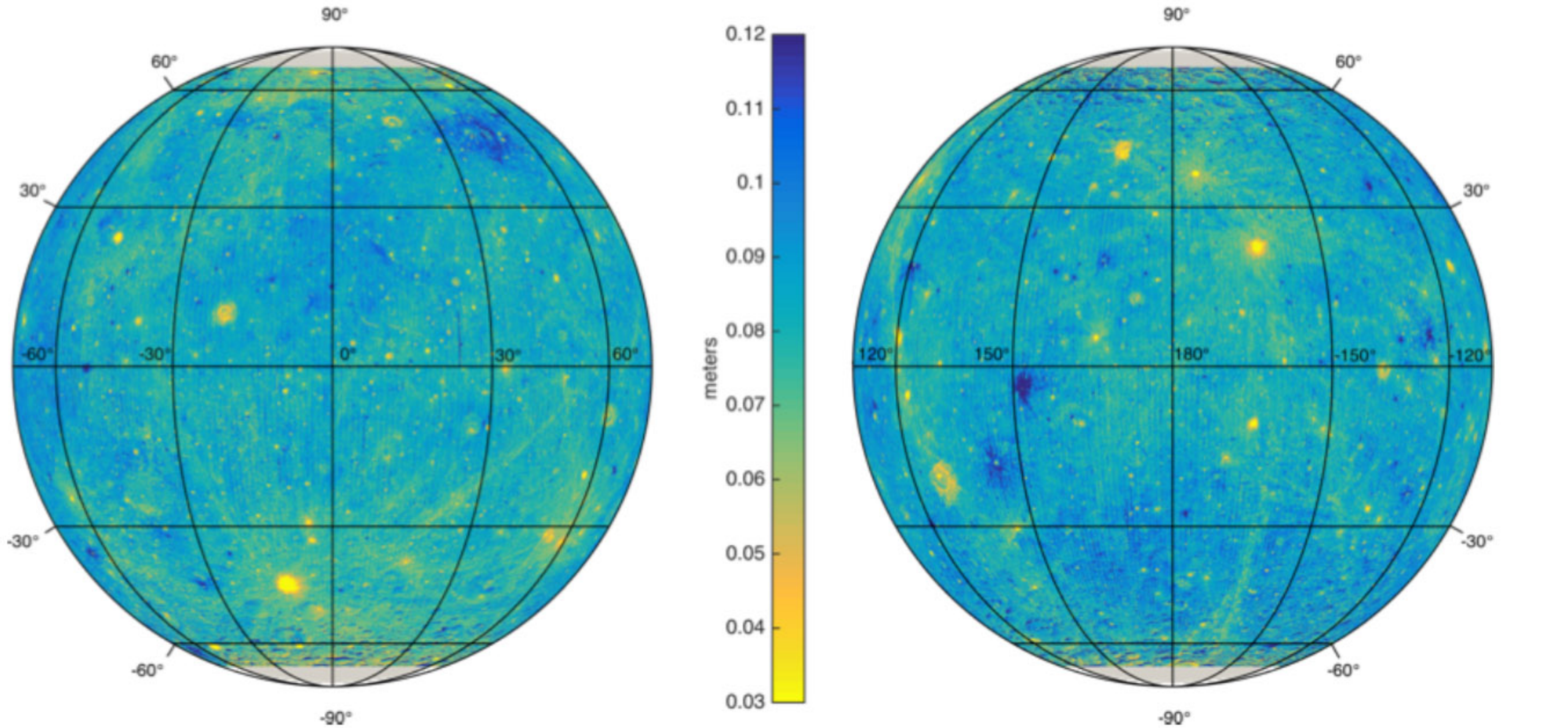
$H \approx 6$ cm

$H \approx 9$ cm



Profile Fits: “H-parameter”

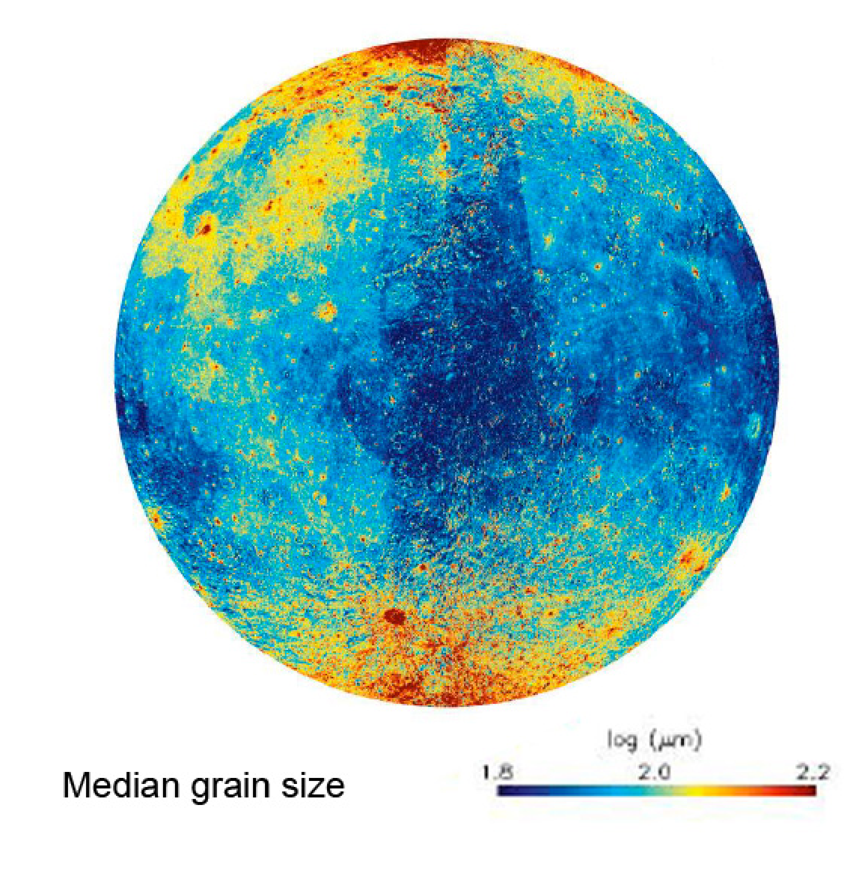
Latitude Variability



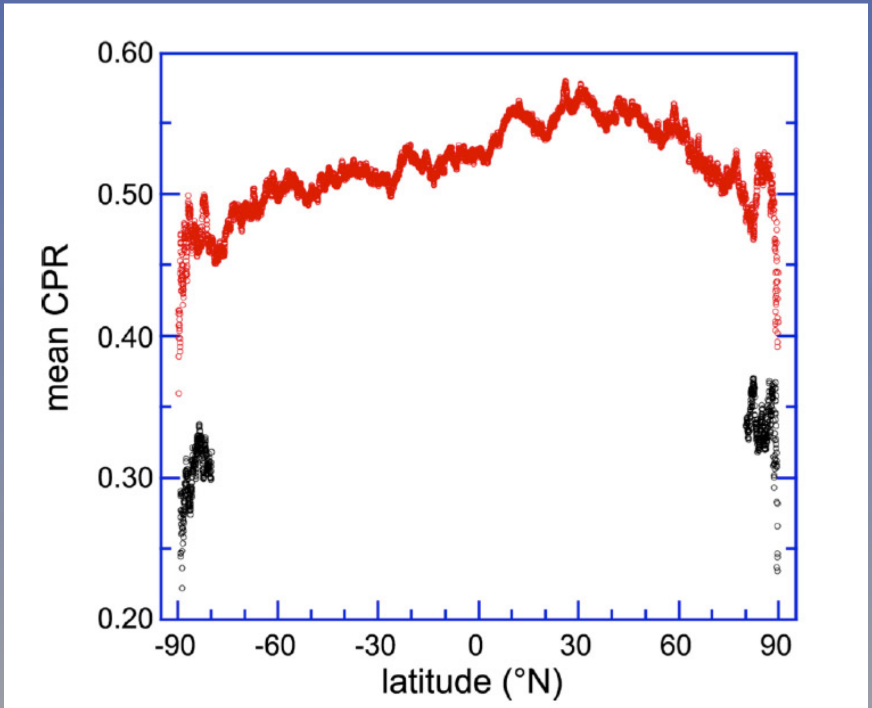
Hayne - H Parameter

Latitude Variability - Radar

Radar observations from the Earth
Decrease porosity with latitude



Jeong et al. 2016 – L Band Earth-based



Thompson et al. 2016 – Mini RF

Regolith Porosity

Surface Porosity

- 83±2%
  - Photometry (Hapke Sato, 2016)
  - Hapke and Van Horn (1963) 80-90%
- 70% PSR
  - Lyman α (Gladstone et al., 2012)
- 49±2% 0-30 cm: LSB
- 44±2% 30-60 cm: LSB

Duricrust – mm thick

Ultrafine particles (< 2 μm) dominate uppermost few grains (Noble, 2010)

Samples (Macke et al., 2012)

- Basalts 5-10%
- Imbrium Ejecta – Regolith Breccia 15-25%

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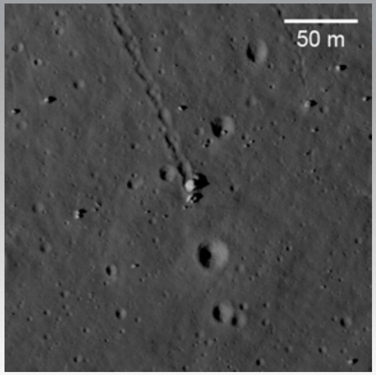
AS15-87-11777



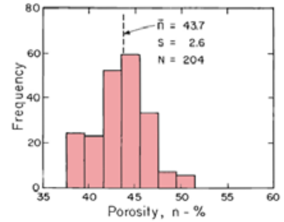


Fig. 3. Apollo 11, 14, and 15 footprint data.

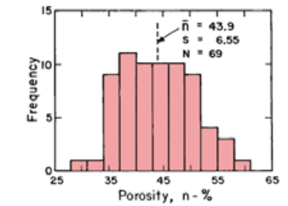


Fig. 4. Boulder track data from Orbiter photographs.

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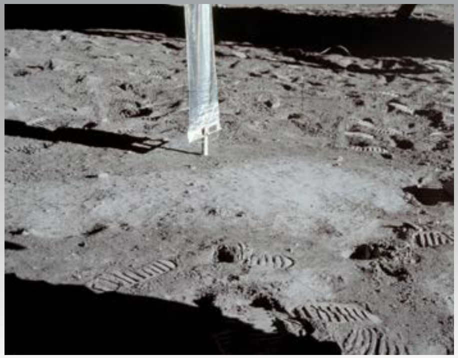


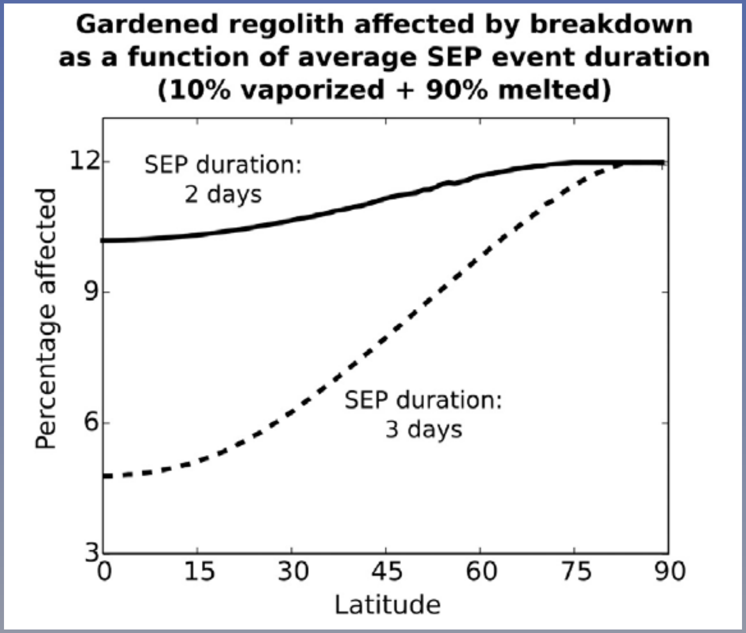
Dielectric Breakdown

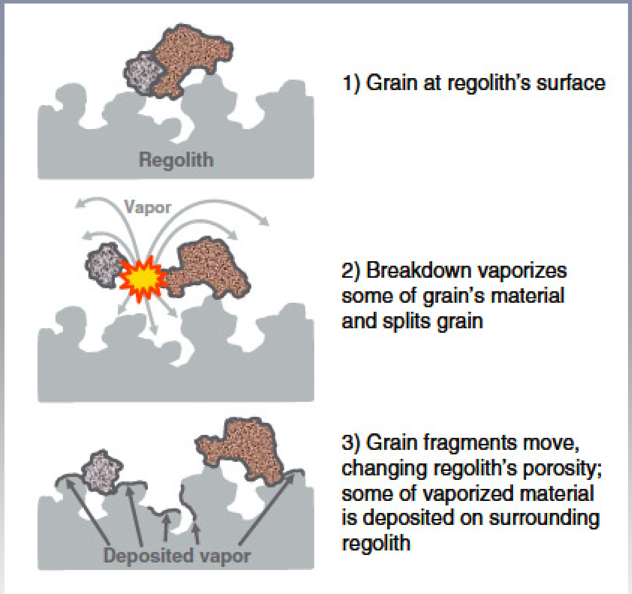
SEP induced electrical discharge

Breakdown results in narrow channels current causing melting and vaporization

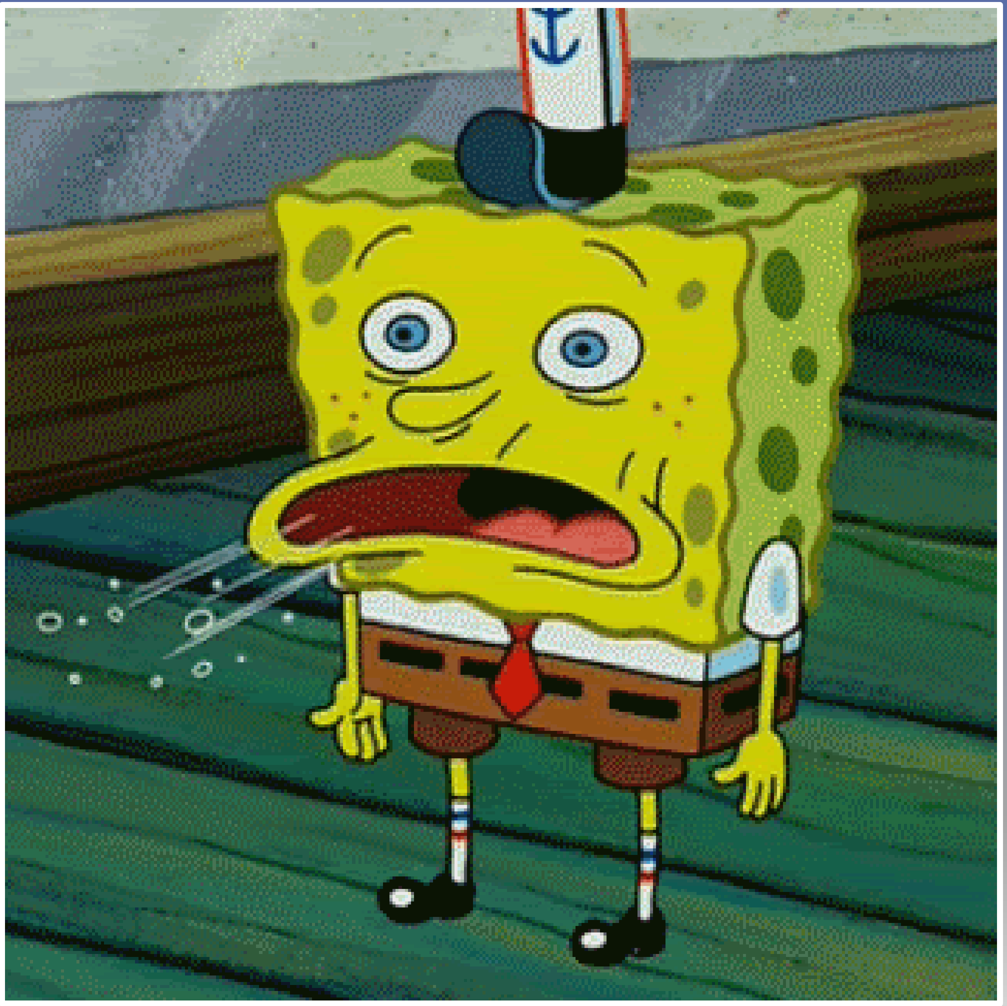
Weathering of regolith – increase surface porosity

Jordon et al. (2015, 2016)

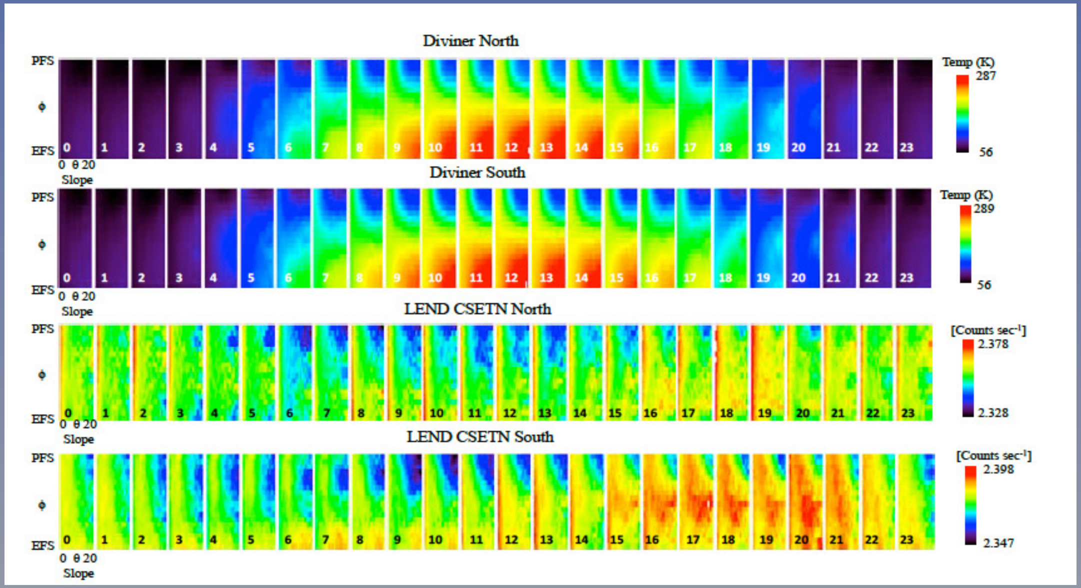




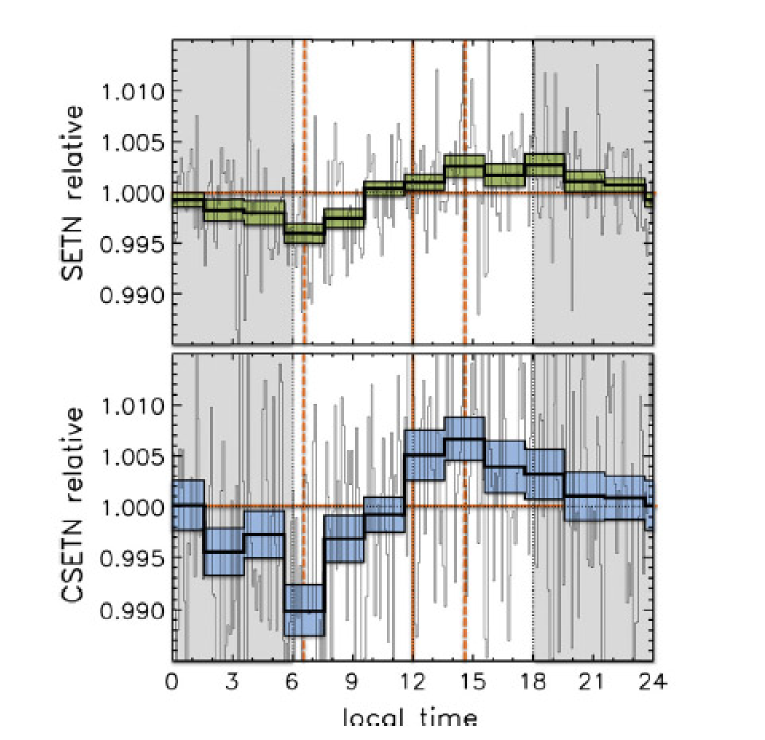
Volatile Cycling – Regolith Breathing



LEND – Hydrogen Sequestration



McClanahan et al., 2016



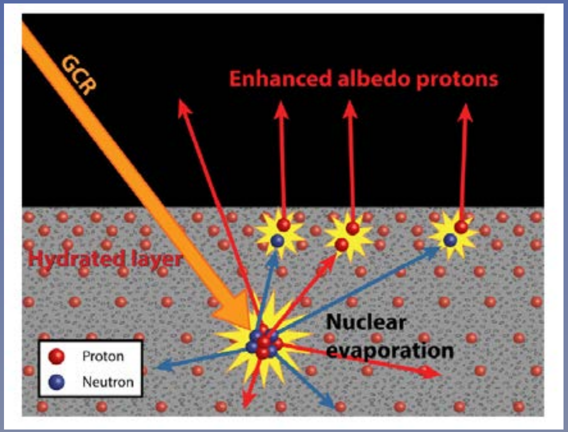
Livengood et al., 2015

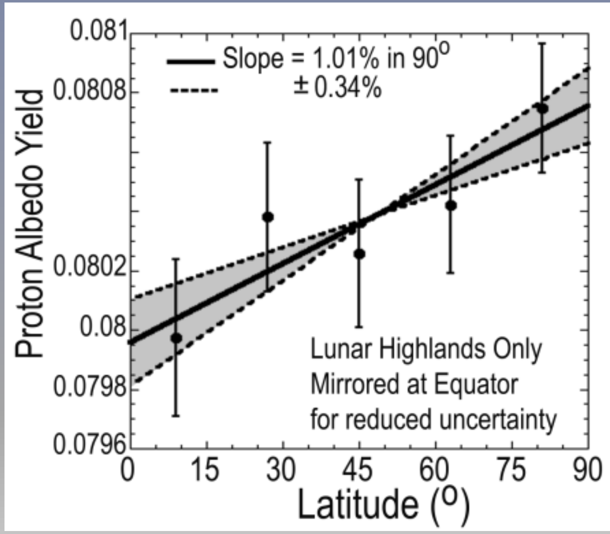
Shallow Regolith Hydrogen

Hydration of surface layer
Indications of dirunal variation

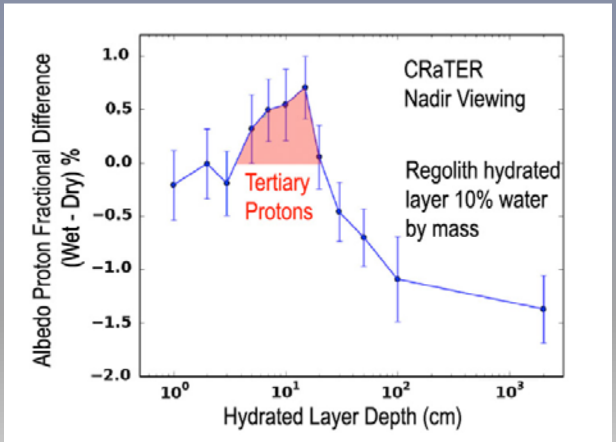
Scattering of protons and interaction with H enhancement of albedo protons

Schwadron et al. (2016), Wilson et al. (2016), Looper et al. (2016)





The latitude trend in the proton albedo suggests a 1-10 cm layer of hydrated regolith that is more prevalent near the poles *Schwadron et al.,* 2016).



Simulation of proton albedo for wet v. dry regolith

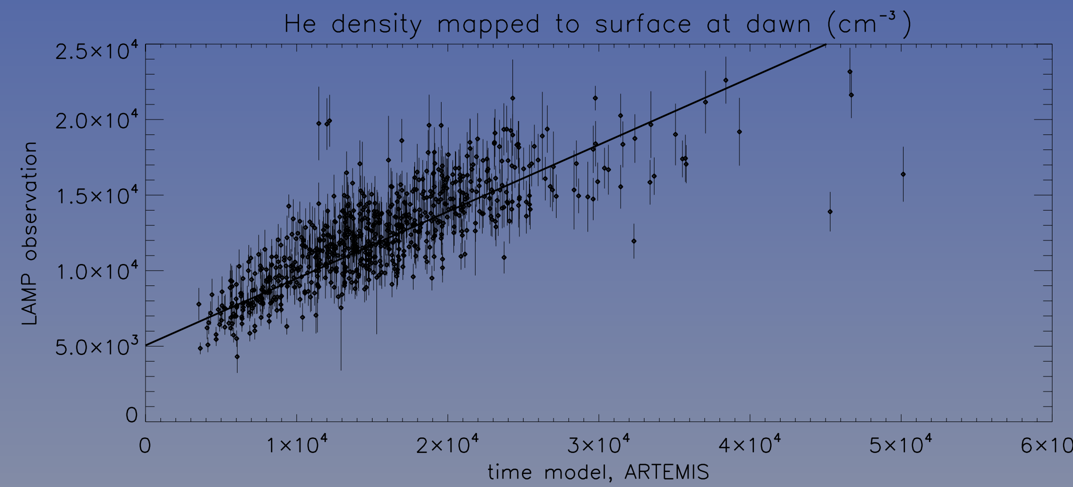
Helium Diffusion

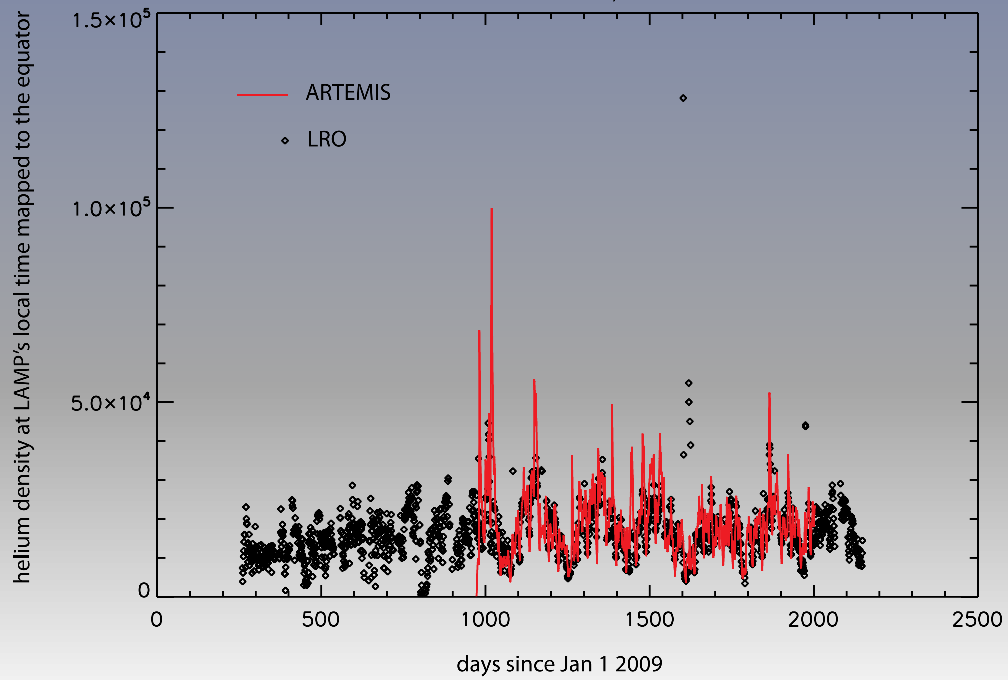
LAMP/LADEE/ARTEMIS

Strong correlation between solar wind alpha particle flux and the total content of the helium exosphere

Fraction of the exosphere is decoupled from the solar wind.

Slowly diffusing implanted solar wind helium or radiogenic helium from the interior.

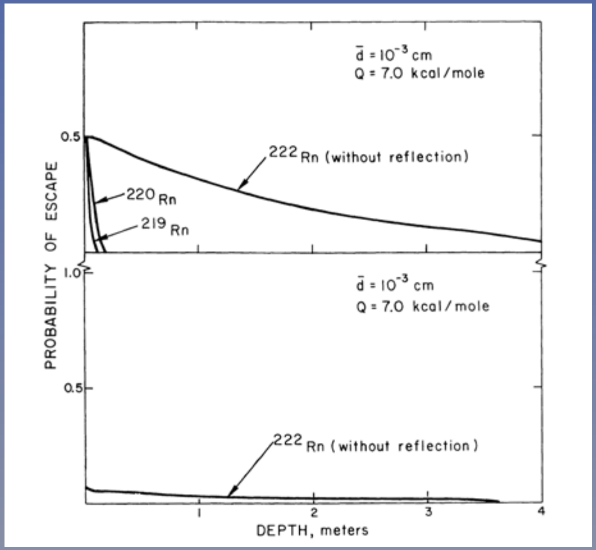




Knudsen Regolith Diffusion

Diffusion of gas into and out of the regolith

Porosity, permeability, density, grain size, molecular weight, sticking



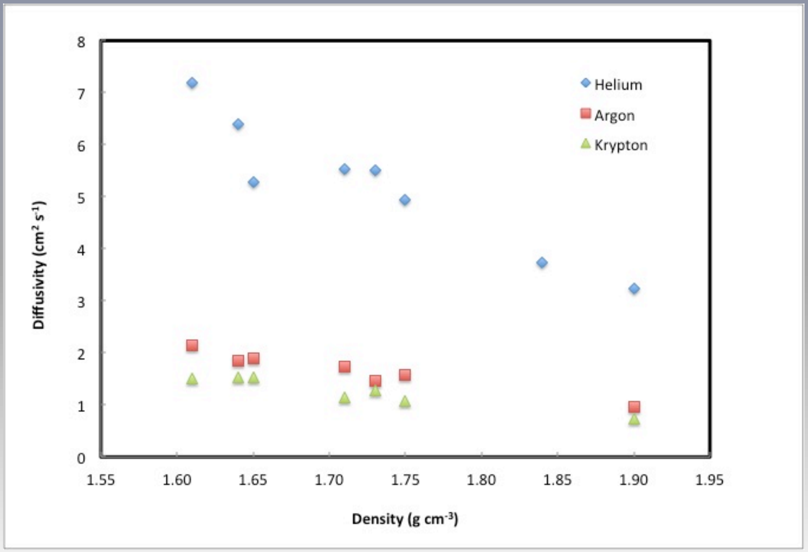
d mean free path between grains 10's microns

at low T, sticking becomes important Q

$\tau = \tau_0^{(Q/RT)}$

Permeability: 1-7 x 10^{-12} m^2 (< 25 cm)

~sand

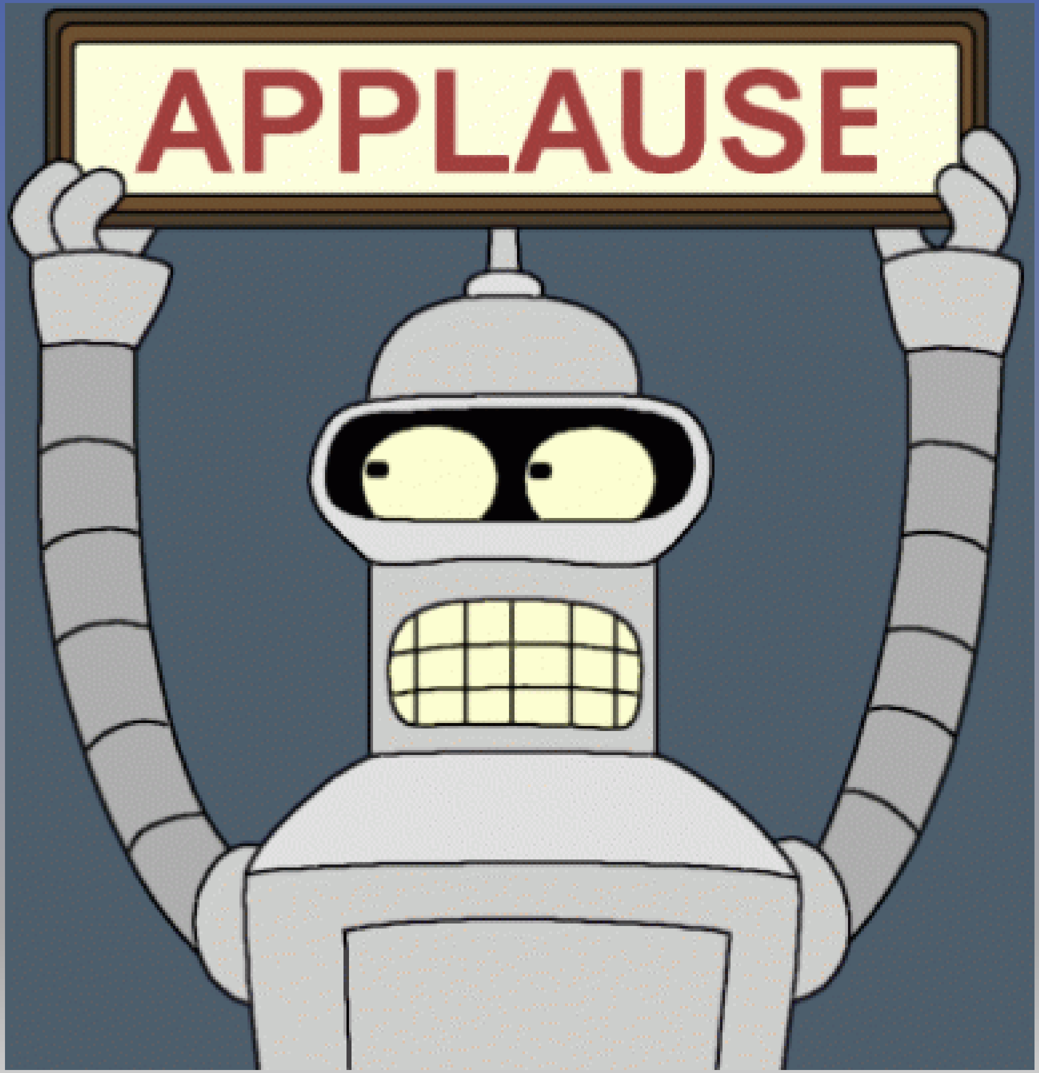


Friesen and Heymann (1972), Frisillo et al. (1974), Martin et al. (1973), LaMarche, et al. (2011)

RKGs

- Physical properties
  - Latitude
  - Geologic unit
  - Slope
  - PSRs
  - Optical surface*
- Diffusion / absorption properties
  - Porosity
  - Permeability
  - Diffusivity
  - Tortuosity
  - Defects
  - Activation energy

- Does the regolith really breathe?
- Thermal fatigue v. catastrophic disruption
- Turnover rate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