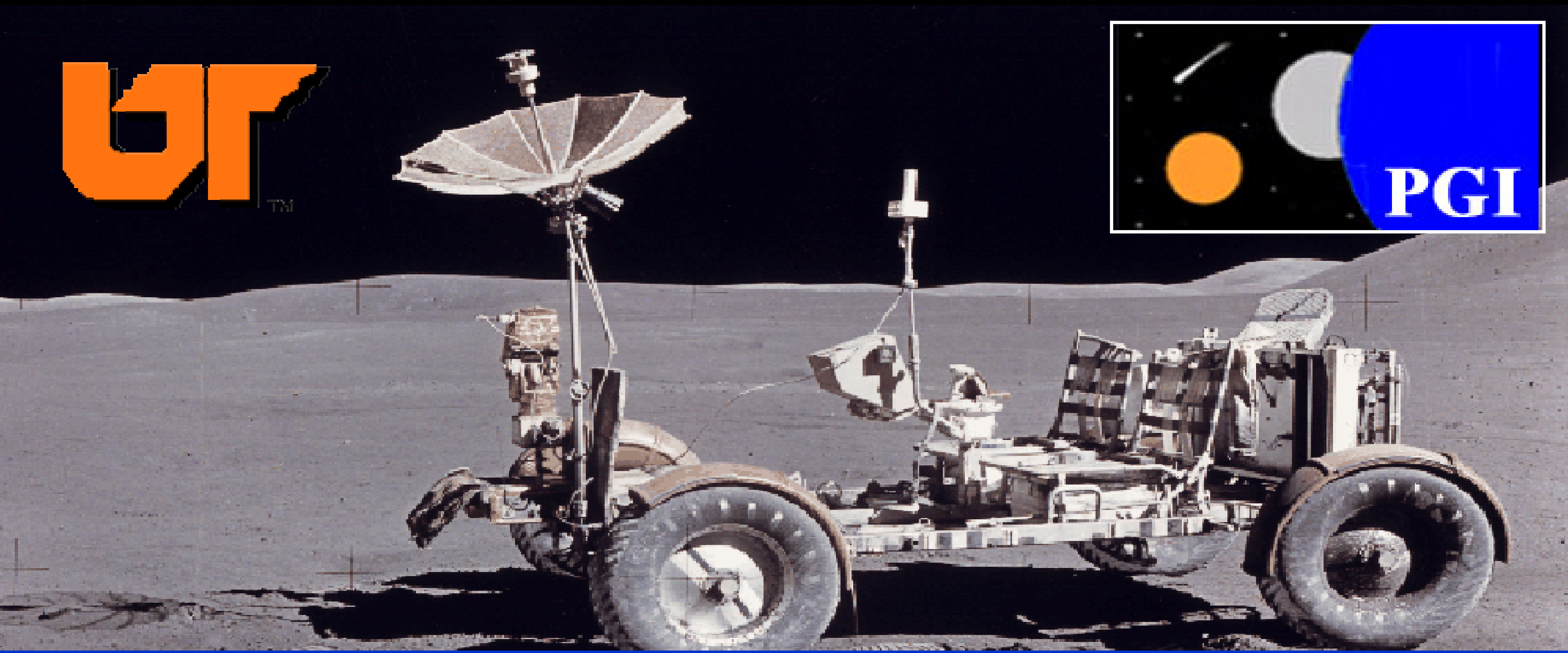
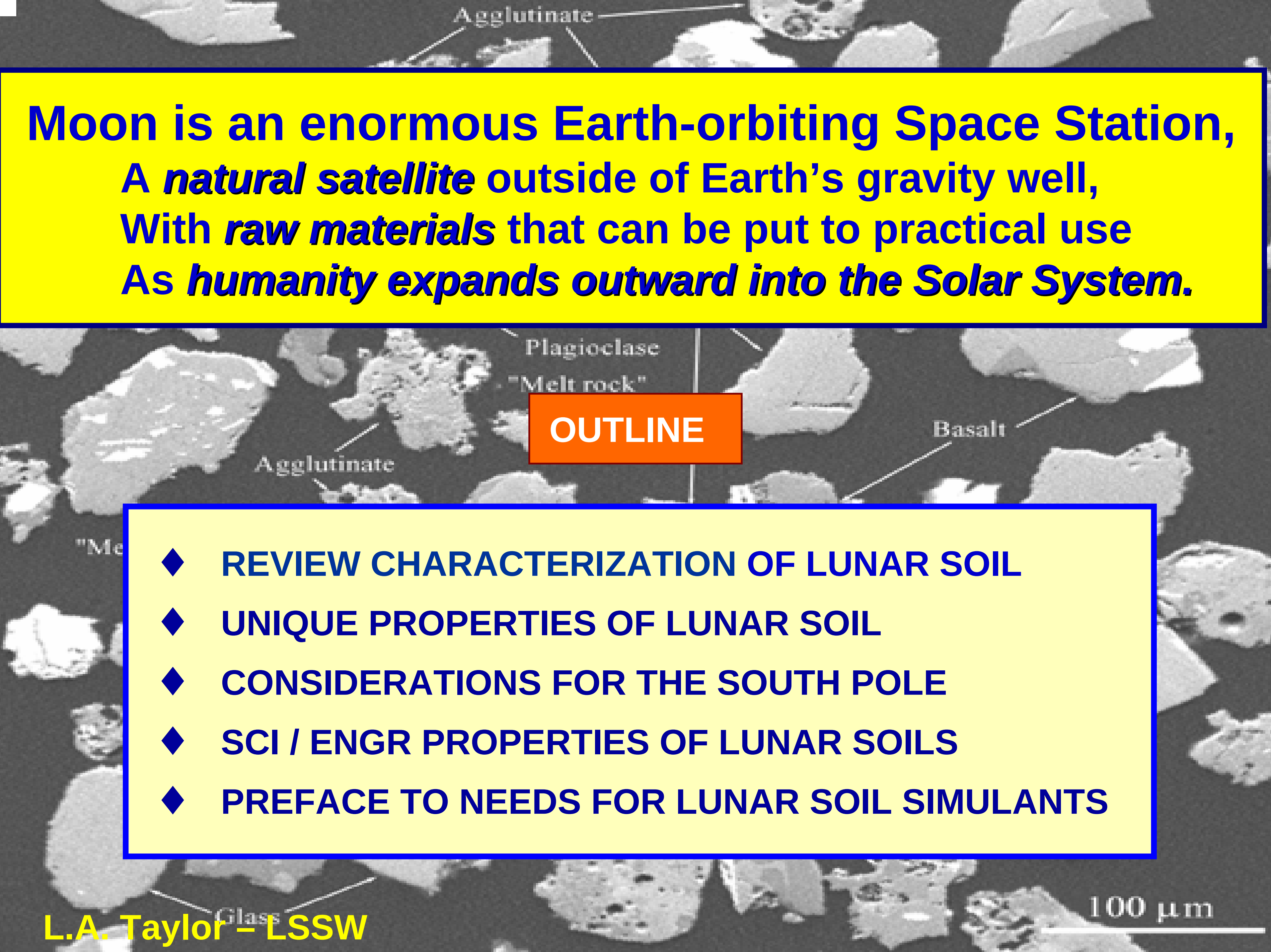
GEOTECHNICAL PROPERTIES OF LUNAR REGOLITH: FROM EQUATOR TO THE POLES



Larry Taylor (lataylor@utk.edu), David Carrier, and Jeff Taylor

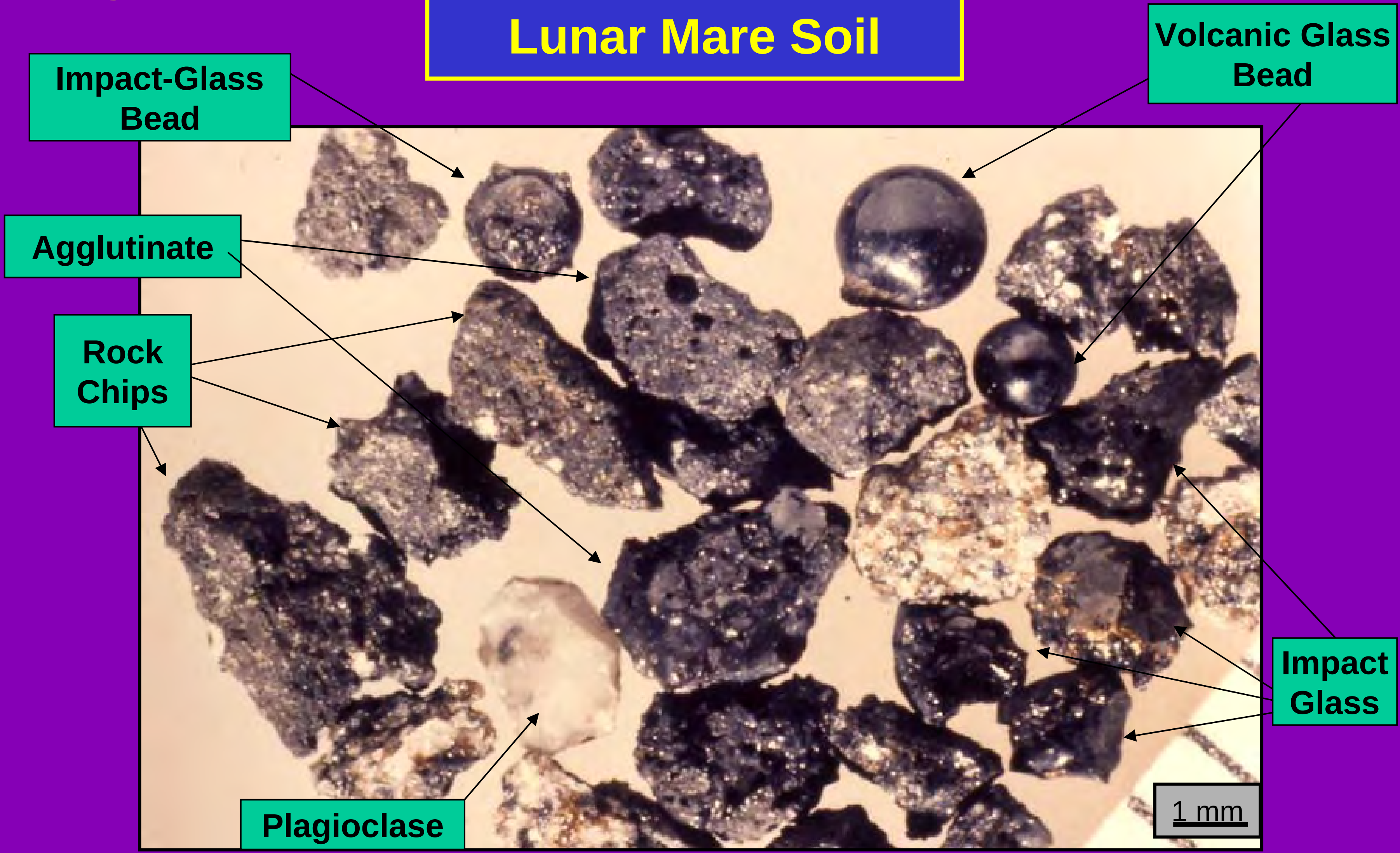


Moon is an enormous Earth-orbiting Space Station,
A *natural satellite* outside of Earth's gravity well,
With *raw materials* that can be put to practical use
As *humanity expands outward into the Solar System.*

OUTLINE

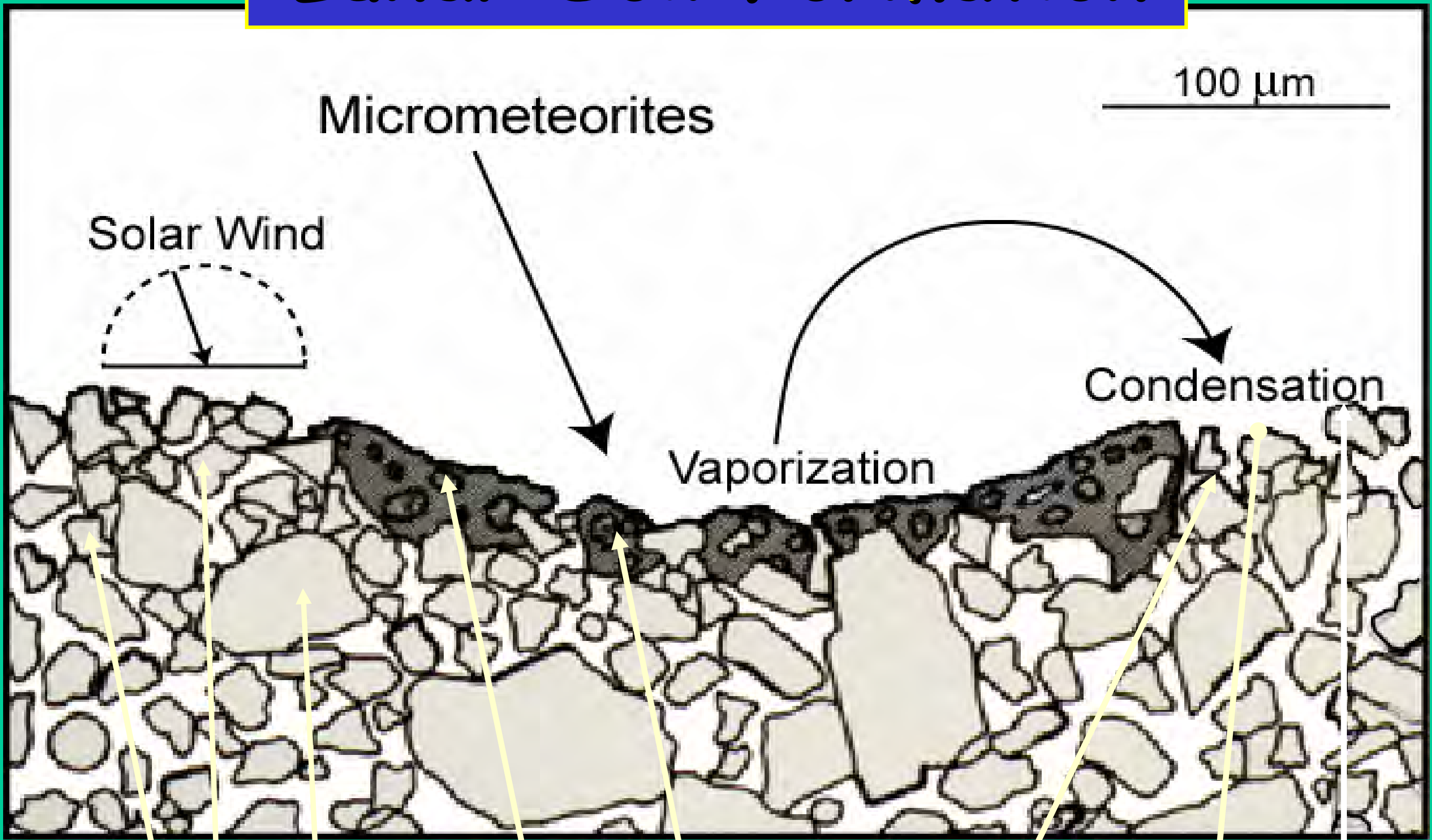
- **REVIEW CHARACTERIZATION OF LUNAR SOIL**
- **UNIQUE PROPERTIES OF LUNAR SOIL**
- **CONSIDERATIONS FOR THE SOUTH POLE**
- **SCI / ENGR PROPERTIES OF LUNAR SOILS**
- **PREFACE TO NEEDS FOR LUNAR SOIL SIMULANTS**

Lunar Mare Soil



Regolith: broken up rock material; **Soil:** <1 cm portion of the Regolith
Dust: < 50 µm portion of the Soil

Lunar Soil Formation



Comminution, Agglutination, & Vapor Deposition

The major Weathering and Erosional agent on the Moon is Meteorite and Micrometeorite Impact.

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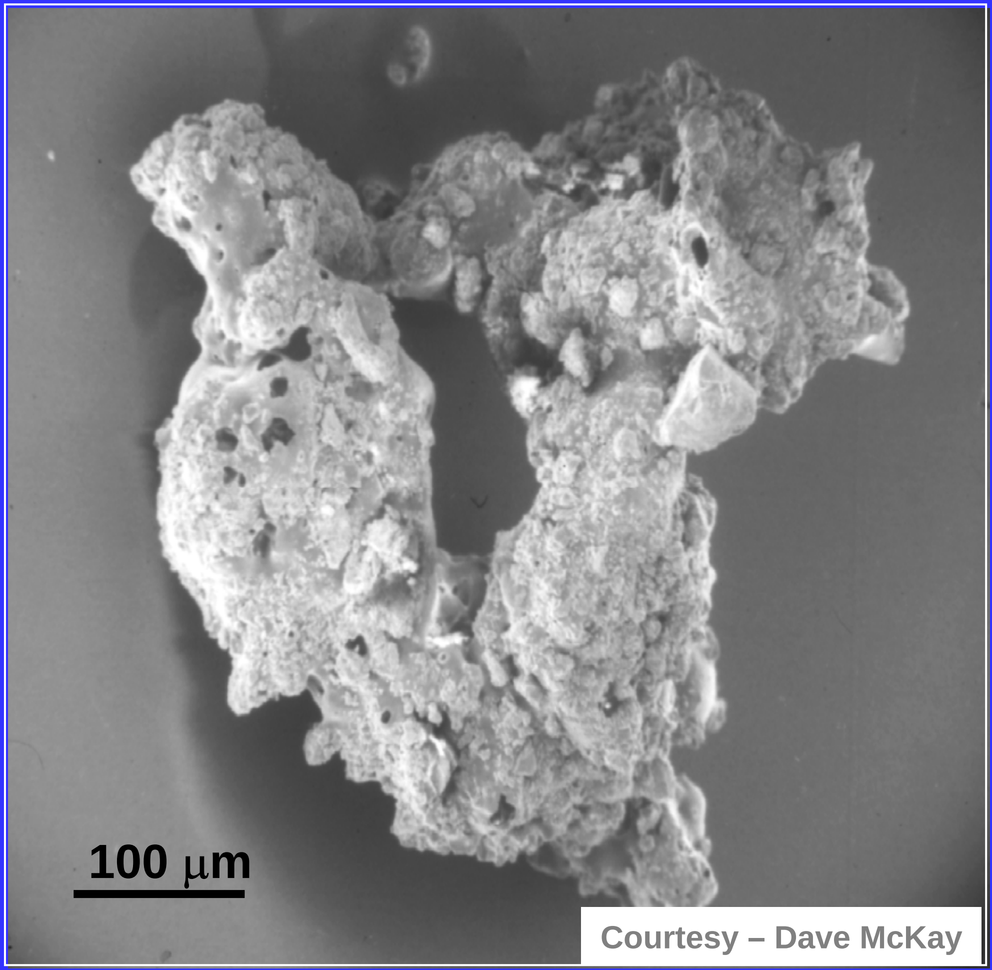
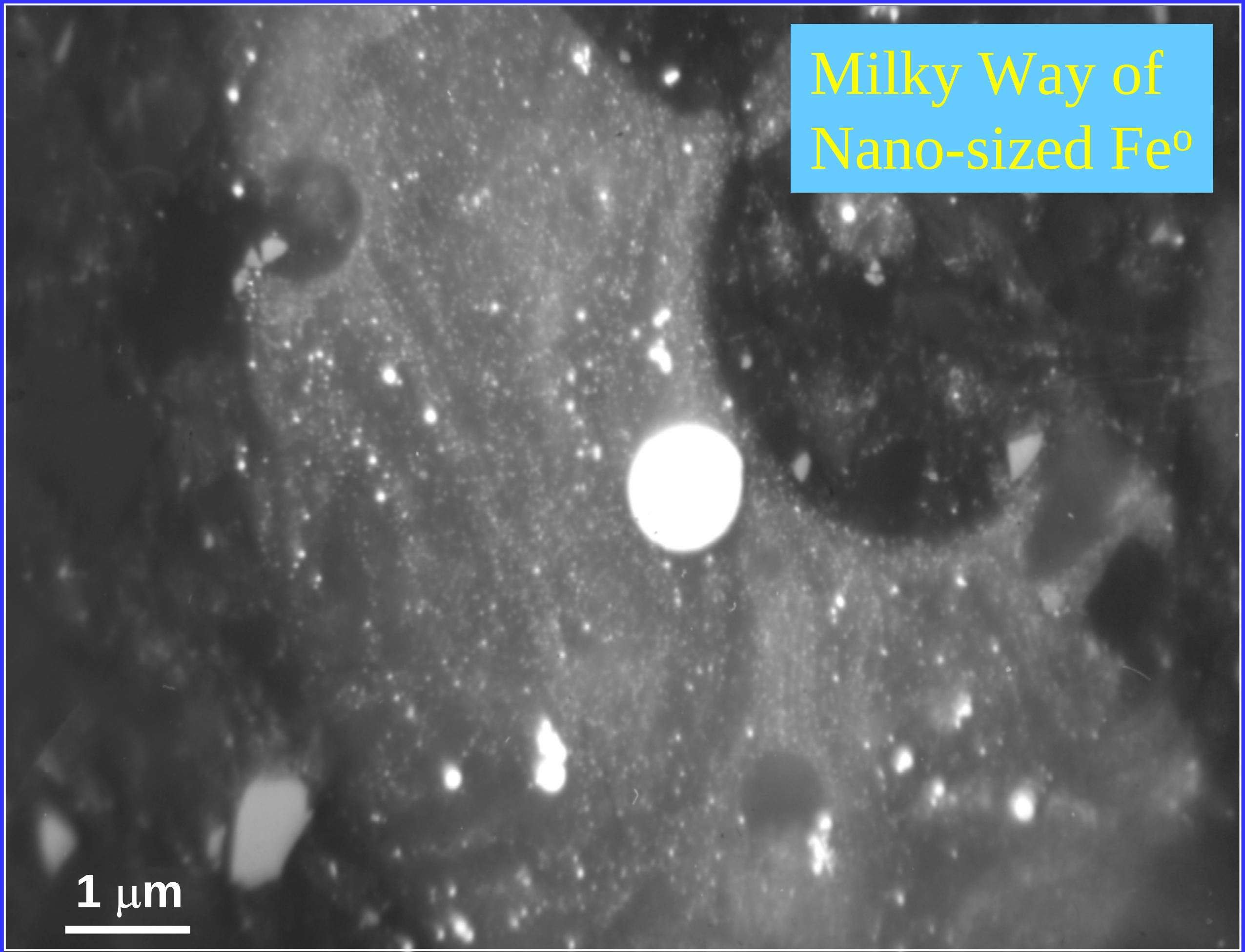
Mare-Soil Agglutinate



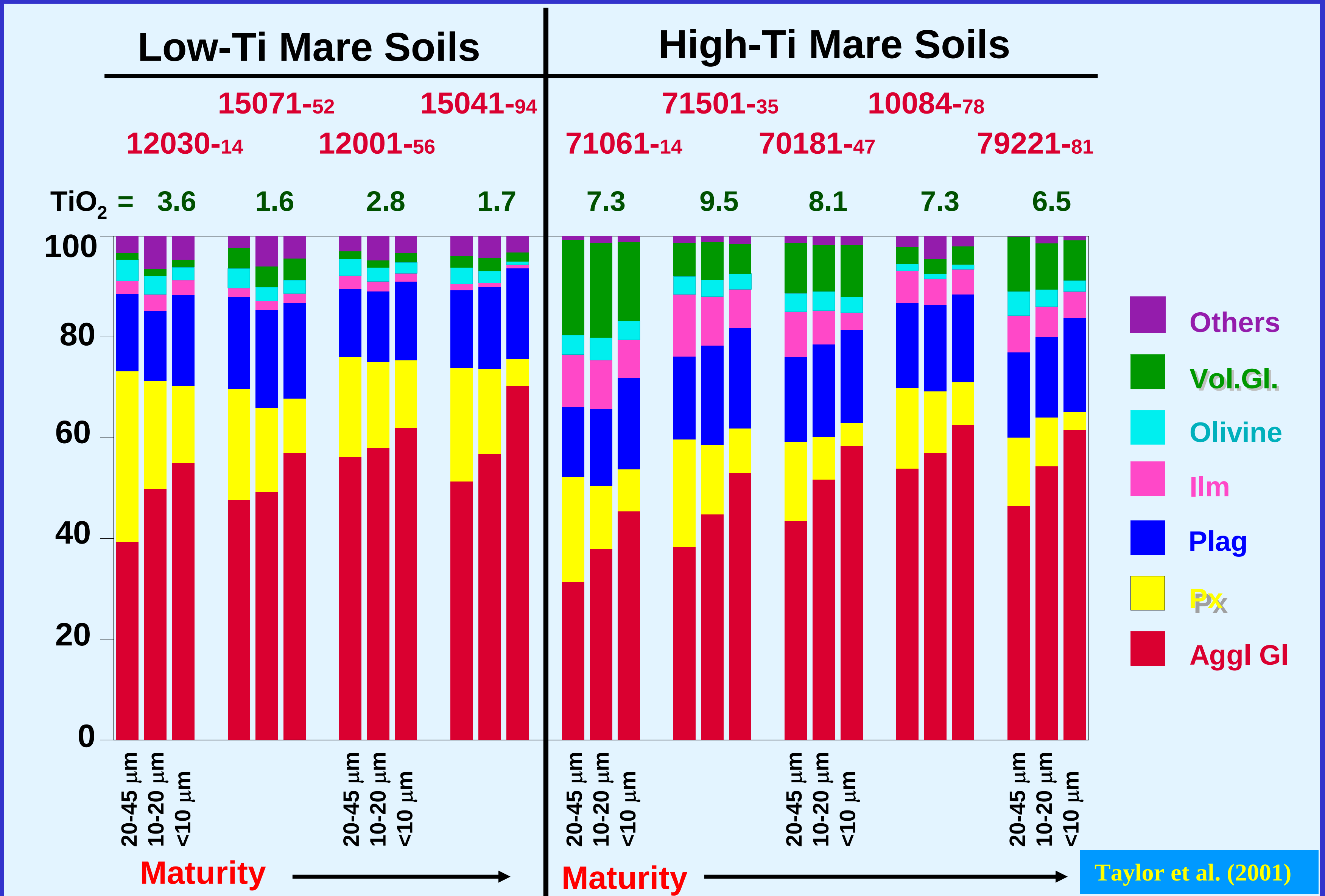
Pieces of minerals, rocklets, and glass welded together by shock-melt glass

SEM BSE-Image of Mare Agglutinitic Glass



Courtesy – Dave McKay

Cumulative Modal Abundances of Mare Soils



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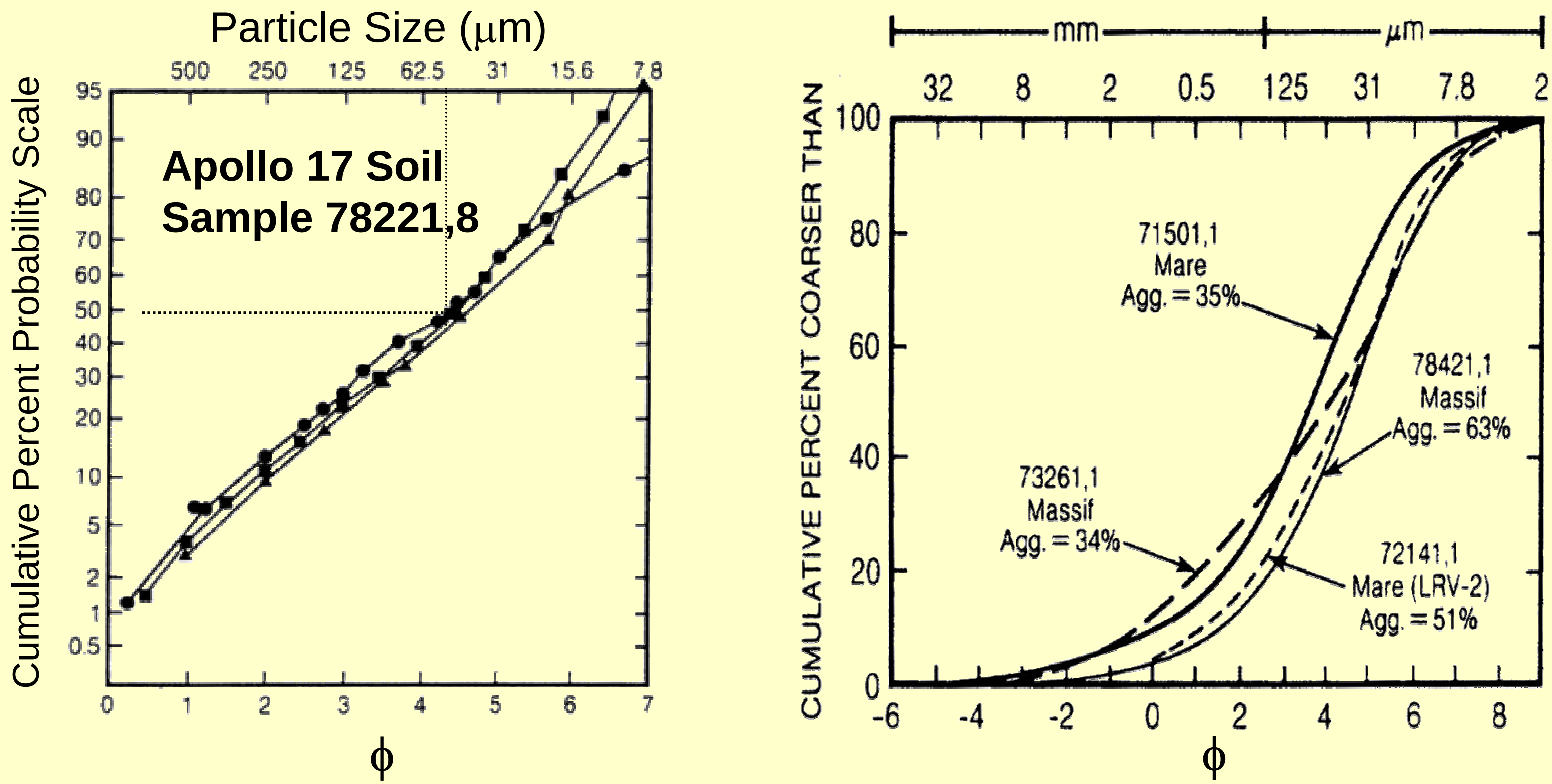
Particle Size Distribution

Fig. 9.1 (LSB, 1991); Distribution of particle sizes in separate splits of Apollo 17 soil 78221,8, analyzed by 3 different labs.



McKay et al., 1974

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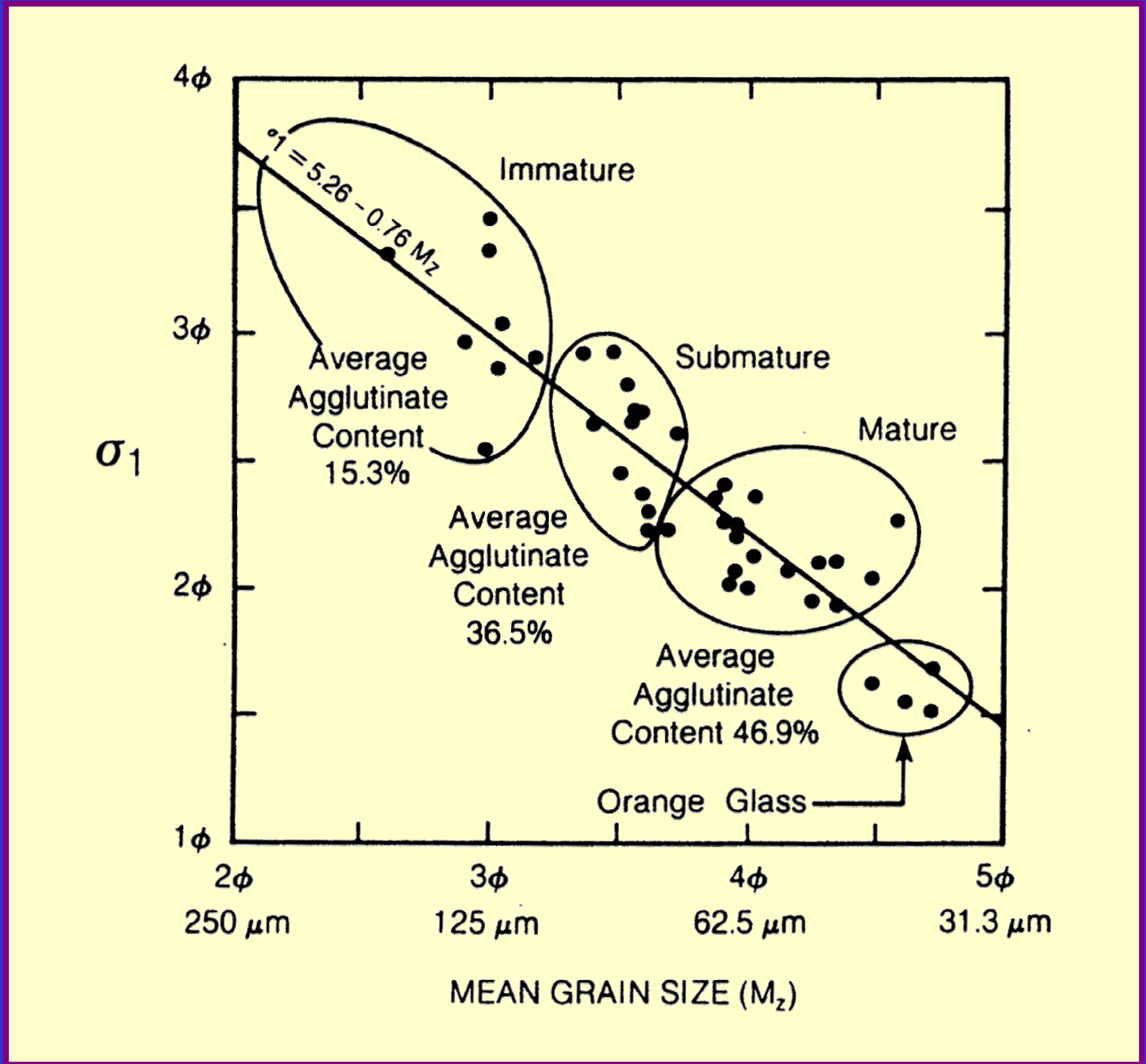
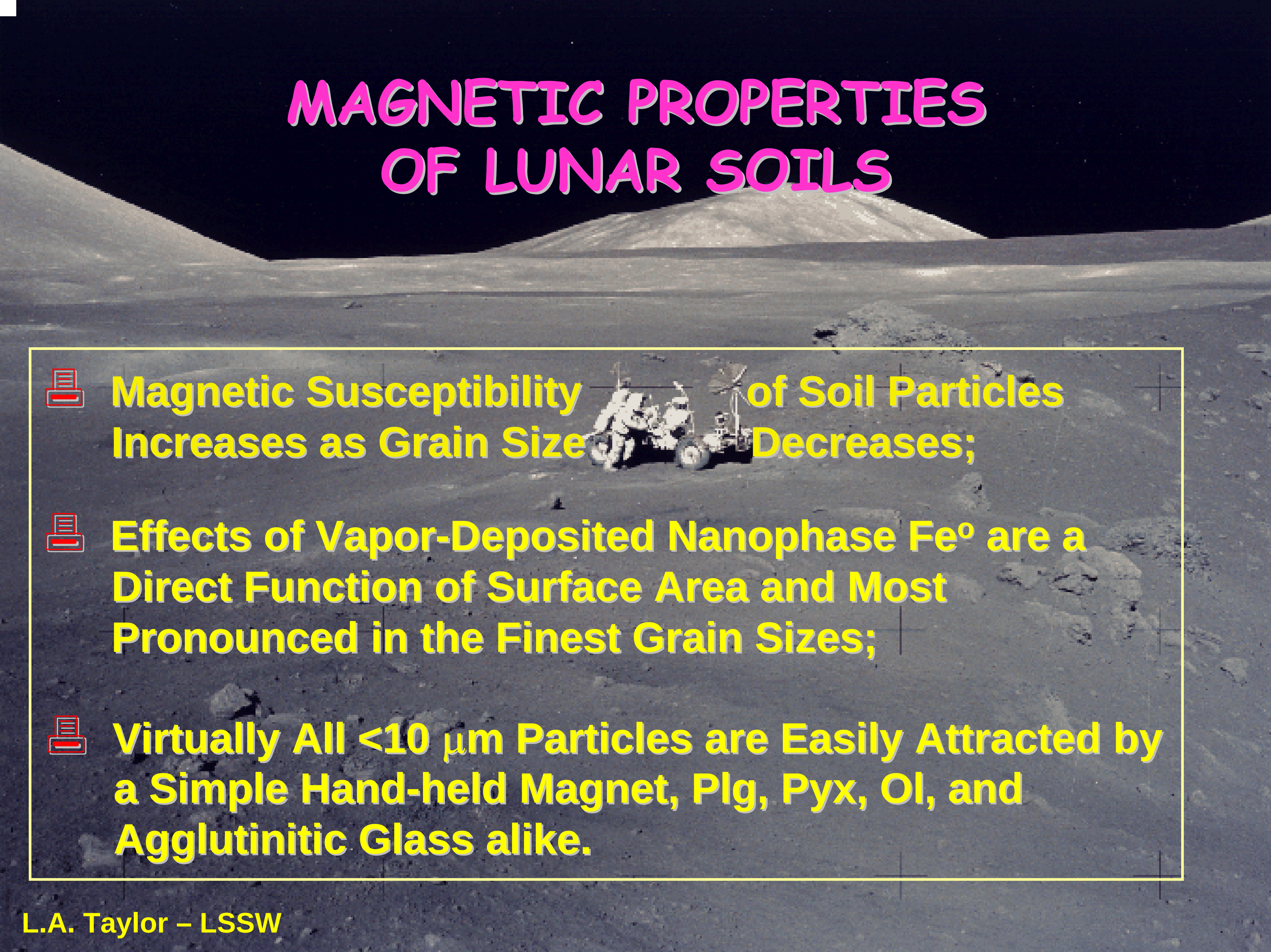
Diagram showing the relationship between grain size, sorting, and agglutinate content for 42 Apollo 17 soils (McKay et al, 1974)



Weight Distribution

Table 9.1 (LSB, 1991); Weight distribution in size fractions of scooped surface soils.

	Size Fraction					Mean Size, M_z	
Soil	>1 cm	4-10 mm	2-4 mm	1-2 mm	<1 mm	<1cm	<1mm
	(weights in grams)					(mm)	(mm)
14163	0.0	196.5	197.1	288.7	4444.0	76	56
15220	0.0	7.0	5.8	2.4	290.0	-	43
68500	1.3	17.3	25.1	37.8	521.1	106	68
72140	1.3	2.7	1.9	5.3	225.9	57	50
72500	3.1	8.0	12.9	24.1	687.2	67	57
73240	1.6	22.3	14.4	14.9	192.7	127	51
74220***	0.0	0.98	0.17	0.68	7.77	-	41
78220	0.0	1.5	2.7	5.2	227.1	50	45



MAGNETIC PROPERTIES OF LUNAR SOILS

- Magnetic Susceptibility of Soil Particles Increases as Grain Size Decreases;
- Effects of Vapor-Deposited Nanophase Fe° are a Direct Function of Surface Area and Most Pronounced in the Finest Grain Sizes;
- Virtually All <10 μm Particles are Easily Attracted by a Simple Hand-held Magnet, Plg, Pyx, Ol, and Agglutinitic Glass alike.

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Lunar Dust Effects: Must be Addressed before any Commercial Presence on the Moon can be Fully Evaluated.

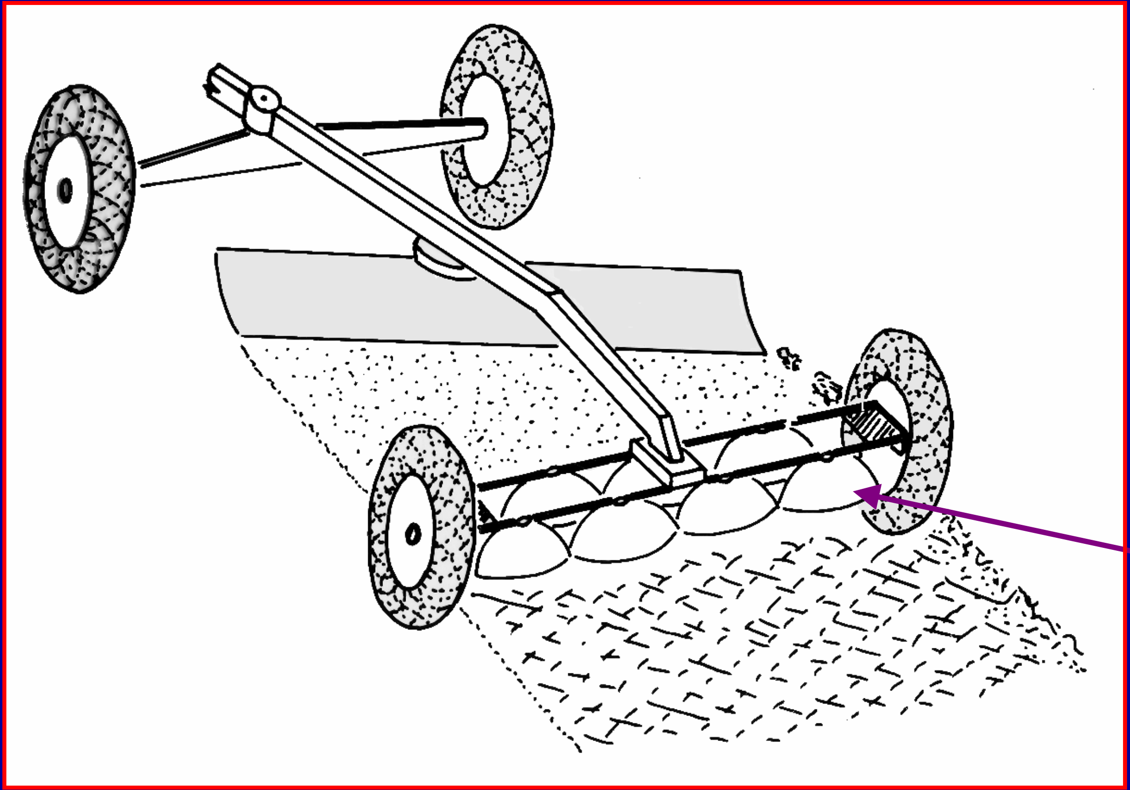
- ✓ Potential for **coatings**, on seals, gaskets, optical lens, windows, electrical components, et cetera;
- ✓ **Abrasiveness**, with regards to friction-bearing surfaces;
- ✓ Potential for **settling** on all thermal and optical surfaces, such as Solar cells and mirrors; and
- ✓ **Physiological effects** on humans, especially with respect to the lungs, the lymph system, and potentially the cardiovascular system, in the case of extremely fine particles.

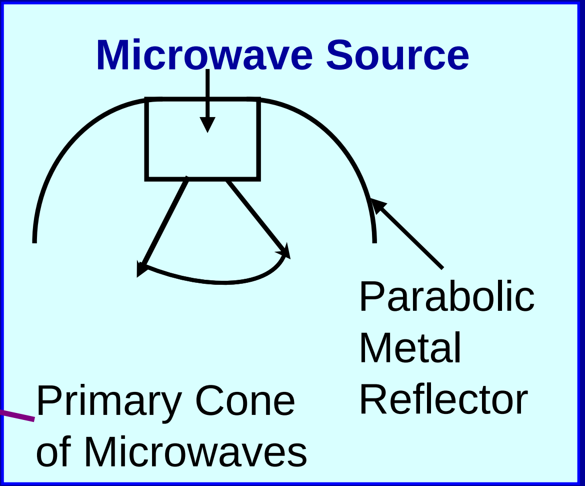
SOLUTION: Magnetic brushes ??

MICROWAVE PROCESSING OF LUNAR SOIL

SINTERING and MELTING

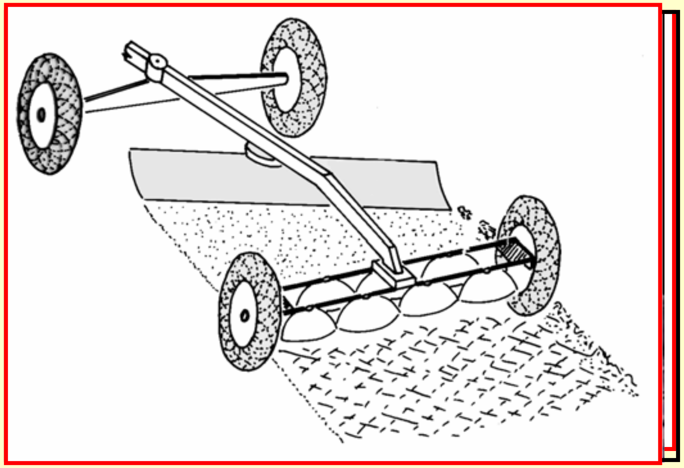
Creating Smooth-Sintered to Glassy Surfaces on the Moon





MICROWAVE PROCESSING OF LUNAR SOIL

SINTERING and MELTING



- Roads
- Satellite Dishes
- Shielding
- Welding
- Recovery of Volatiles
- Glass Fiber Production
- Solar Cells (Ilmenite)

SUGGESTIONS ??

Potential Sources of Polar Hydrogen

- Solar-wind deposited
- H_2O-ICE (in addition to solar-wind H_2)
  - Impact of Comets
  - Impact of hydrous Meteorites

KEY POINT: Still an Unknown!

(and LRO will not provide definitive answer)

Cometary Gases

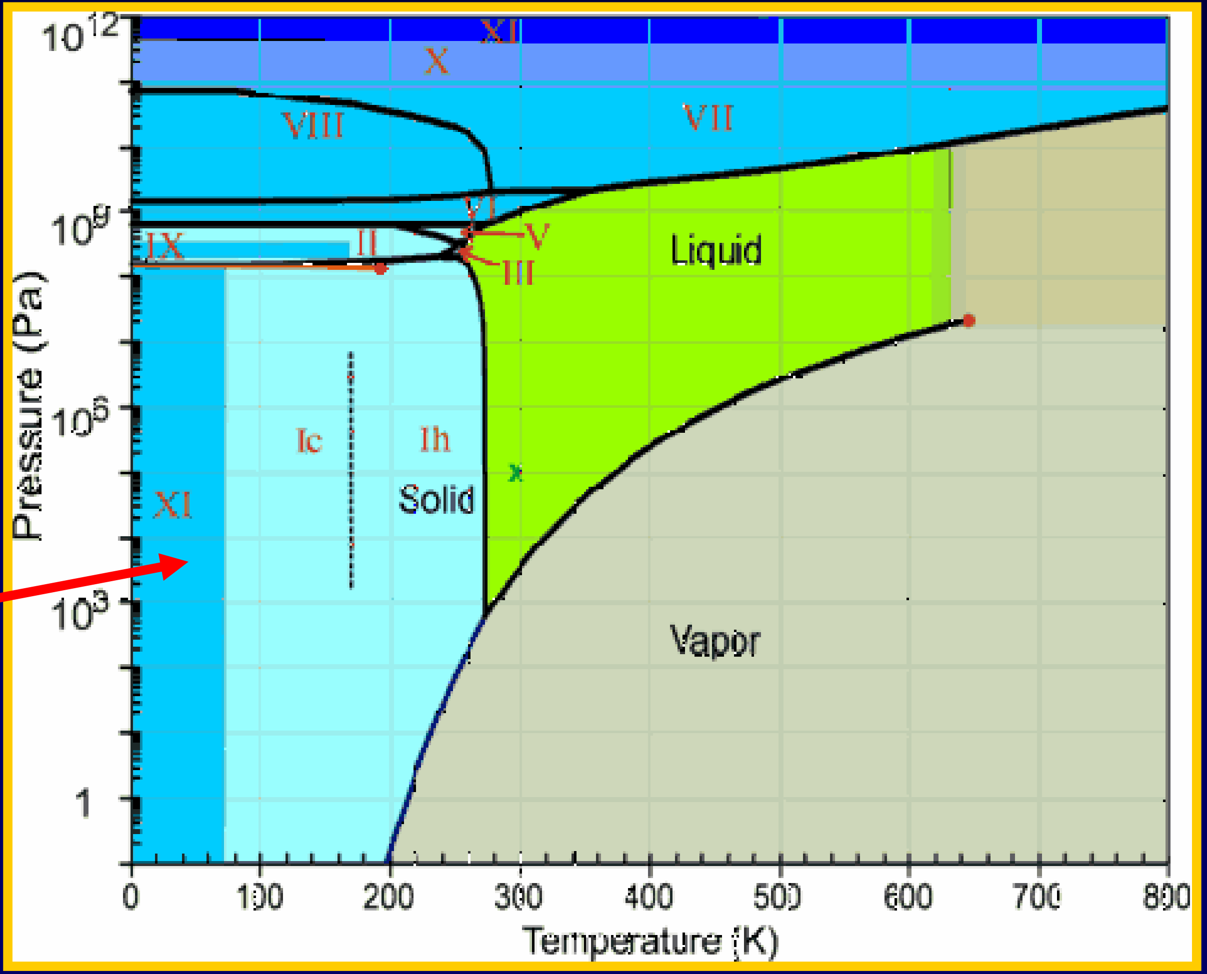
- We do not have solid data on compos-ition of polar volatile deposits;
- A good guess is that they contain gases from comets. For example, in Hale Bopp:

H_2O: 100	CO_2: 6
CO: 20	NH_3: 0.7
CH_3OH: 2	CH_4: 0.6

- These could result in deposits of H_2O and other gases.

H_2O Deposition as Amorphous Ice

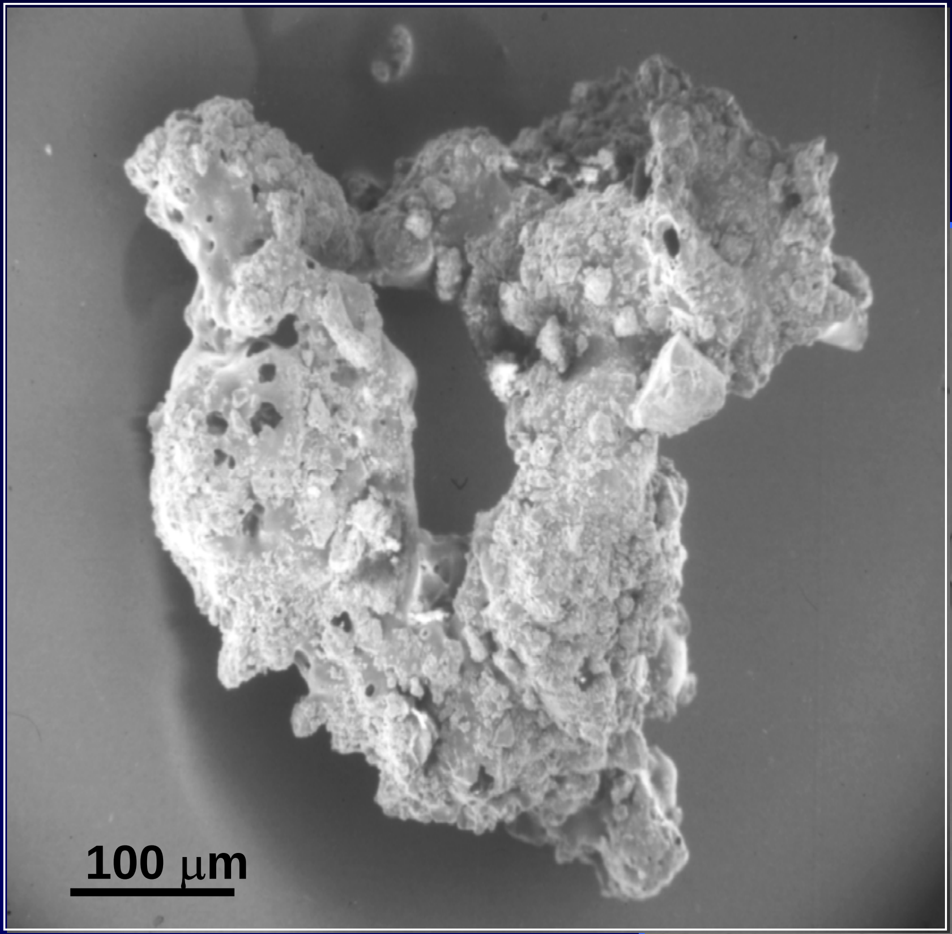
- Numerous H_2O phases;
- At low < 70 K & P < 2 x 10^8 Pa, H_2O occurs as an amorphous solid phase;

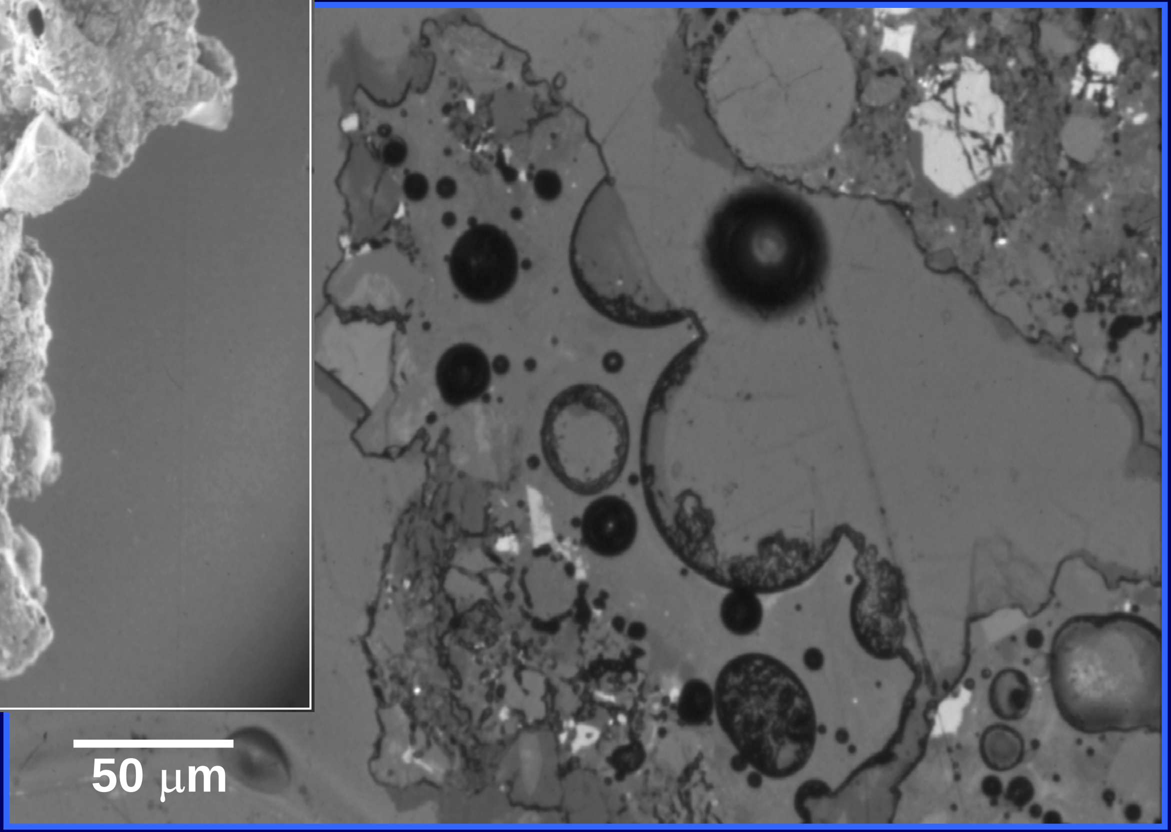


Gas Release from Amorphous Ice

- Amount of trapped gas depends on T
  - Can be up to 3.3 X more gas in ice at 20 K (Laufer et al., 1987);
  - Trapped CH_4/Ice and CO/Ice are ~ 0.01 at 70 K.
- Gas begins to be released at 120 K and increases exponentially as T rises to 135 K;
- Transformation to crystalline ice is exothermic, so there could be a runaway effect, resulting in huge gas losses.

Agglutinate Properties: Normal Dry Moon





Agglutinate Properties: Icy Moon

AGGLUTINATES FORMED IN ICY REGOLITH MIGHT BE EXTREMELY FROTHY!

Sample of RETICULITE: basaltic pumice in which cell walls of bubbles have burst—leaves a honeycomb-like structure..

Agglutinate Properties: At an Icy Pole

- Extremely porous agglutinates might lead to change in physical properties of bulk regolith:
  - Agglutinates make up > 50% of a mature soil;
  - Agglutinates are substantially weaker to both compressive and tensional forces;
  - Frothy Agglutinates would crush easier than ‘normal’ ones, leading to a finer-grained soil;
  - Net result would be substantially more glass for greater grain-to-grain friction.
- Could provide places for H_2O to precipitate

Polar Ice:
Extraction and Purification

- Once ice deposits are identified and characterized, **extraction experiments** are needed:
  - Heating methods
  - Volatile handling
  - Further processing of other gases
  - Gas storage
  - Separation of impurities from
  - Electrolysis of H_2O to produce LLH and LUNOX
  - **Demonstration Experiments on the Moon???**

Polar Ice

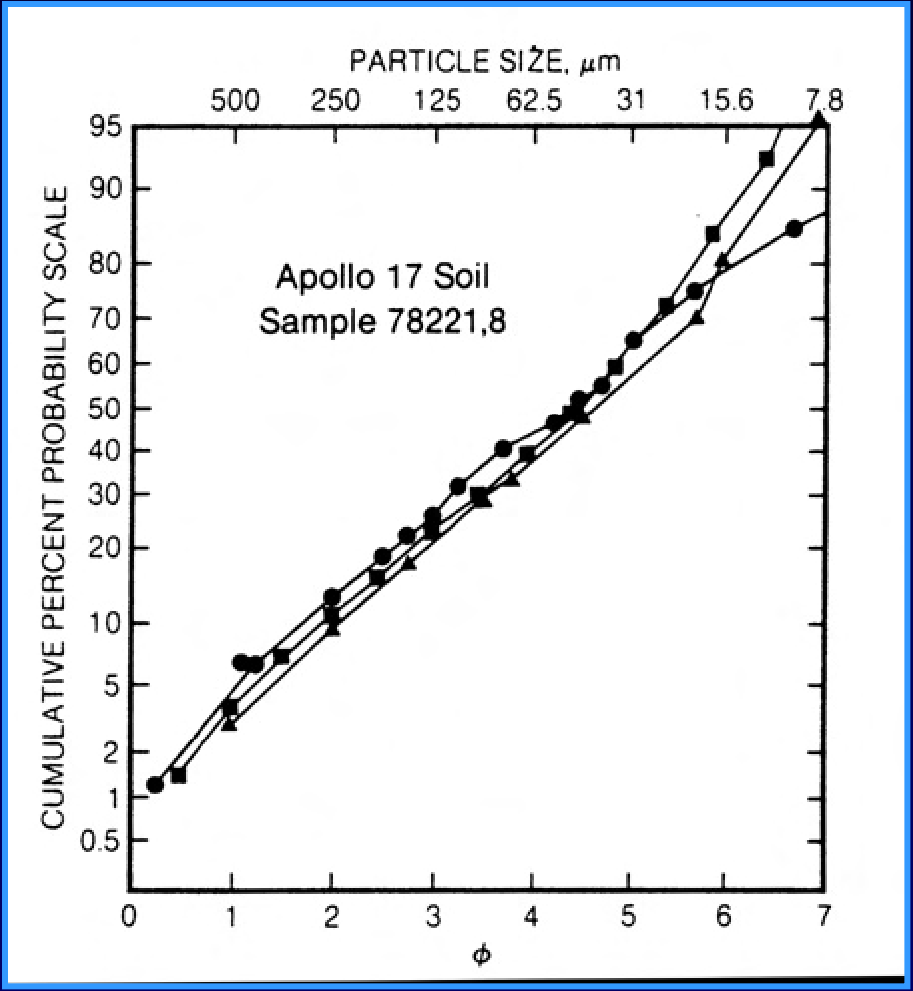
- ✱ **Effects of Ice on Regolith Physical Properties?**
  - **Composition of Ice:** Cometary? Lunar?
  - **Ice form:** Crystalline? Amorphous? Thin films? Pore-filling?;
  - **Soil Particles:** Binding by Ice? Loose? Granular? Coherent?
  - **Geotechnical Properties:** variations with depth (drill cores)? Ice Properties!
  - **Physical Properties of Regolith:** cohesion, shear strength, grain-size distribution, bulk density, porosity, etc.

Regolith Grain Size

In non-polar regions:

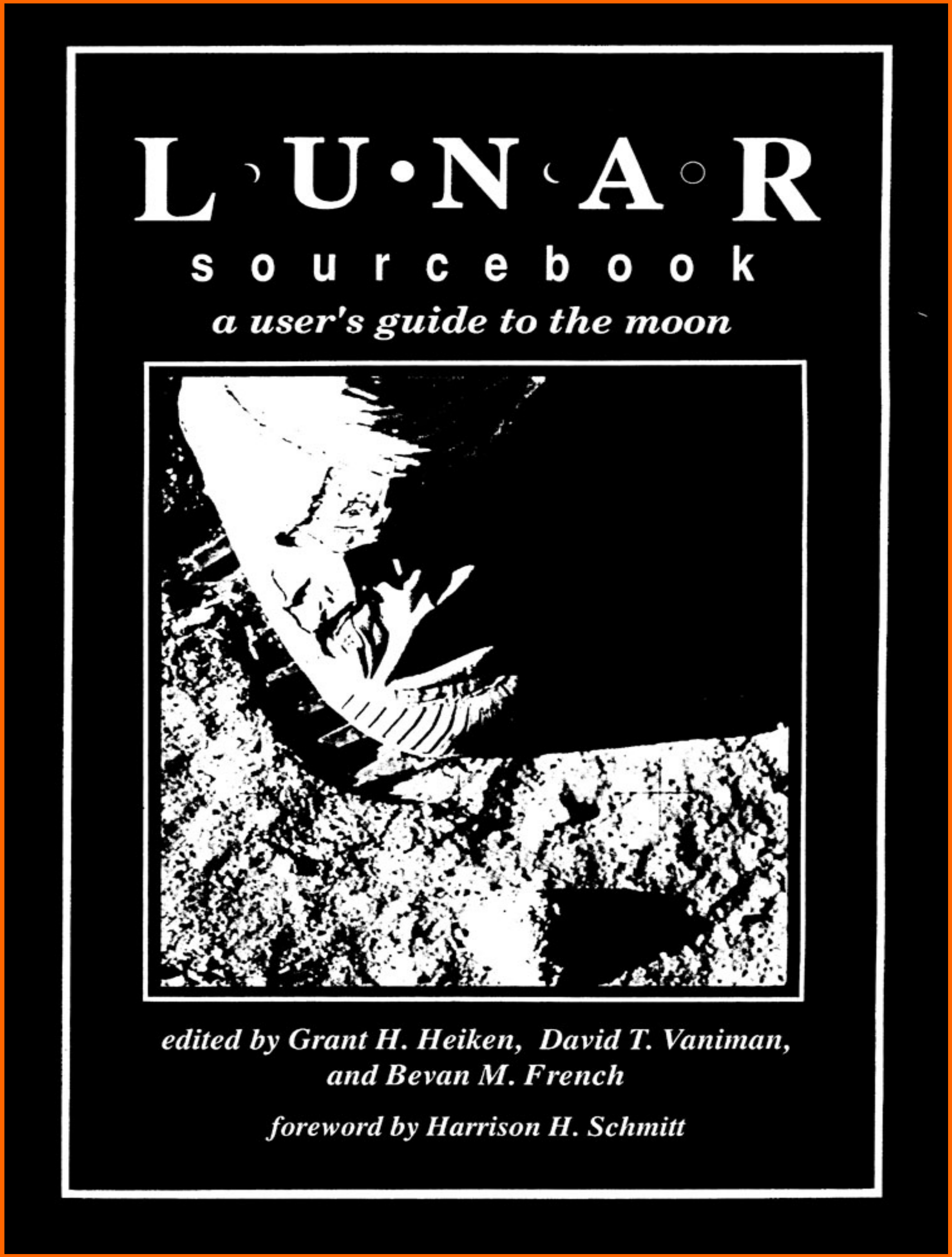
- Regolith is fine-grained
- Roughly:
  - 10% smaller than 10 μm
  - ~50% less than 50 μm
- Predictable physical properties (porosity, thermal conductivity, shear and bearing strength, angle of repose, tribology)

But, AT THE POLES???



Carrier et al. (1991)

The Lunar Bible



Cambridge University Press (1991)

Lunar Soil Properties

Specific Gravity: Range from 2.3 to >3.2; recommend 3.1 for Engr/Sci use.

Bulk Density: top 15 cm = 1.45-1.55 g/cm3; avg = 1.50 ±0.05 g/cm3
0-30 cm = 1.53-1.63 g/cm3; avg = 1.58 ±0.05 g/cm3
30-60 cm = 1.69-1.79 g/cm3; avg = 1.74 ±0.05 g/cm3
0-60 cm = 1.61-1.71 ±0.05 g/cm3; avg = 1.66 ±0.05 g/cm3
values up to 1.9 g/cm3 estimated at depth of cores to 2.98 m

Soil Porosity

Depth Range (cm)	Average Porosity n, (%)	Average Void Ratio, e
0-15	52 ± 2	1.07 ± 0.07
0-30	49 ± 2	0.96 ± 0.07
30-60	44 ± 2	0.78 ± 0.07
0-60	46 ± 2	0.87 ± 0.07

Lunar soil, >30 cm, has extremely high relative density [~90%], more than that which can be produced with mechanical compaction equipment!

– the lunar soil has experienced slow shaking over eons of time -

Compressibility:

Lunar soil is slightly more compressible than most simulants (except JSC-1), regardless of whether two soils are compared at the same void ratio or relative density - agglutinates.

Shear Strength (cone penetrometer measurements):

Mohr-Coulomb Equation: $\tau = c + \sigma \tan \phi$

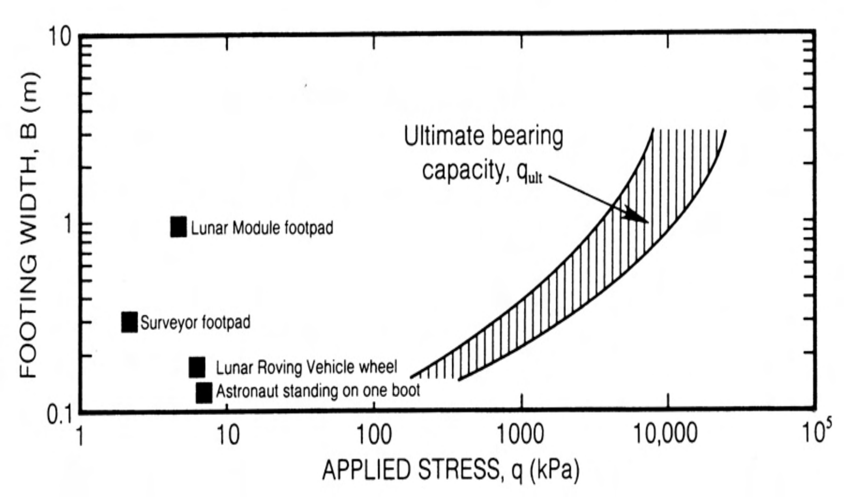
Friction Angle ϕ : 40-50°

Cohesion c : 0.1-1.0 kPa

σ : normal stress (kPa)

Bearing Capacity:

Fig. 9.36 (LSB, 1991) Ultimate bearing capacity data for lunar surface material. Data are plotted in terms of the applied stress (horizontal axis) produced by an object on the lunar surface and the footing width (essentially the footpad size) of the object.

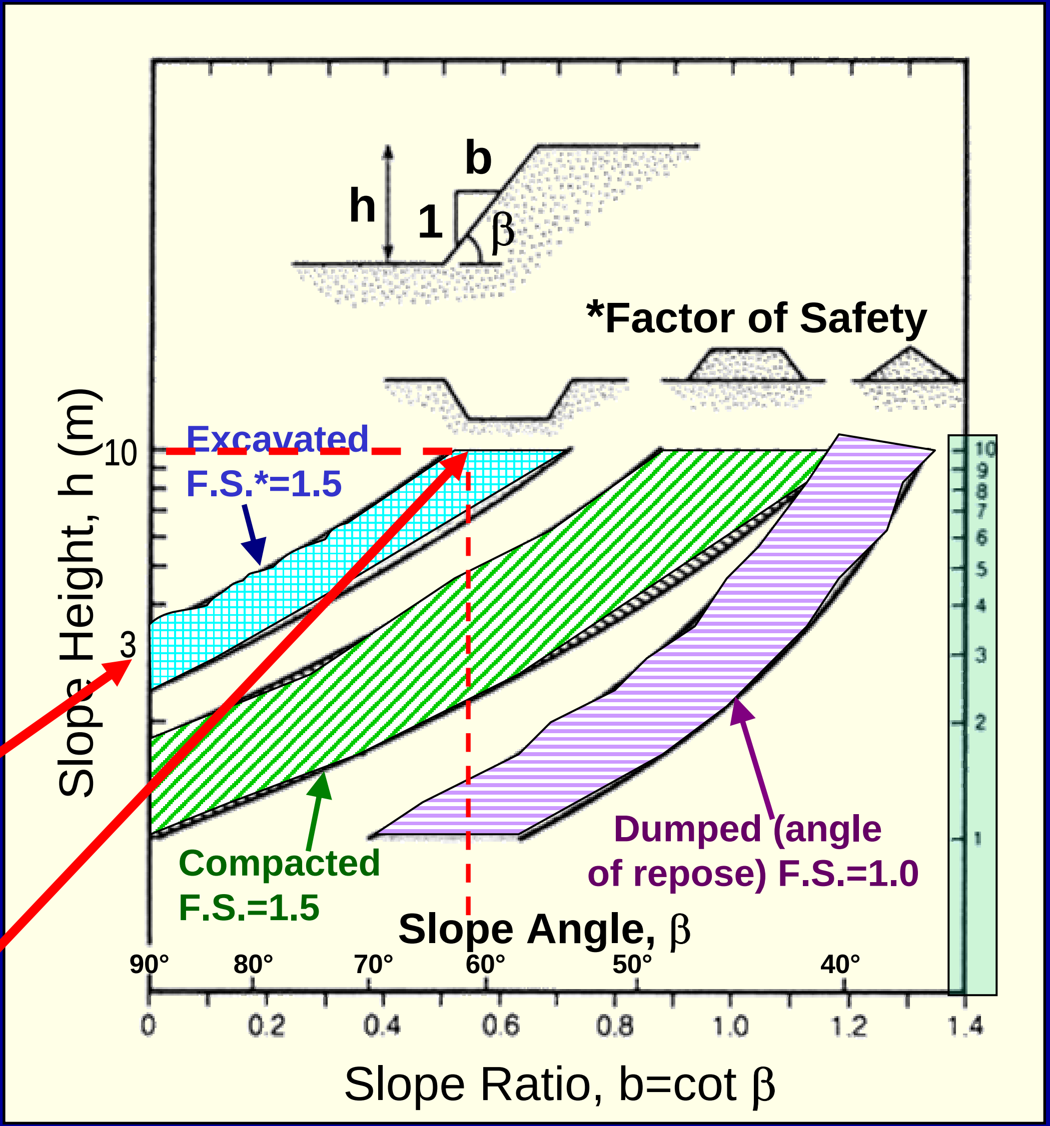


Slope Stability (Fig. 9.39; LSB, 1991)

Calculated stability of artificial slopes constructed in lunar surface material. Data are presented for 3 situations:

(1) an excavation in lunar soil
(2) a compacted pile of excavated lunar soil;
(3) a dumped pile of lunar soil

***A vertical cut** can safely be made in lunar soil to a depth of about 3 m;*
***an excavated slope** of 60° can be maintained to a depth of about 10 m.*



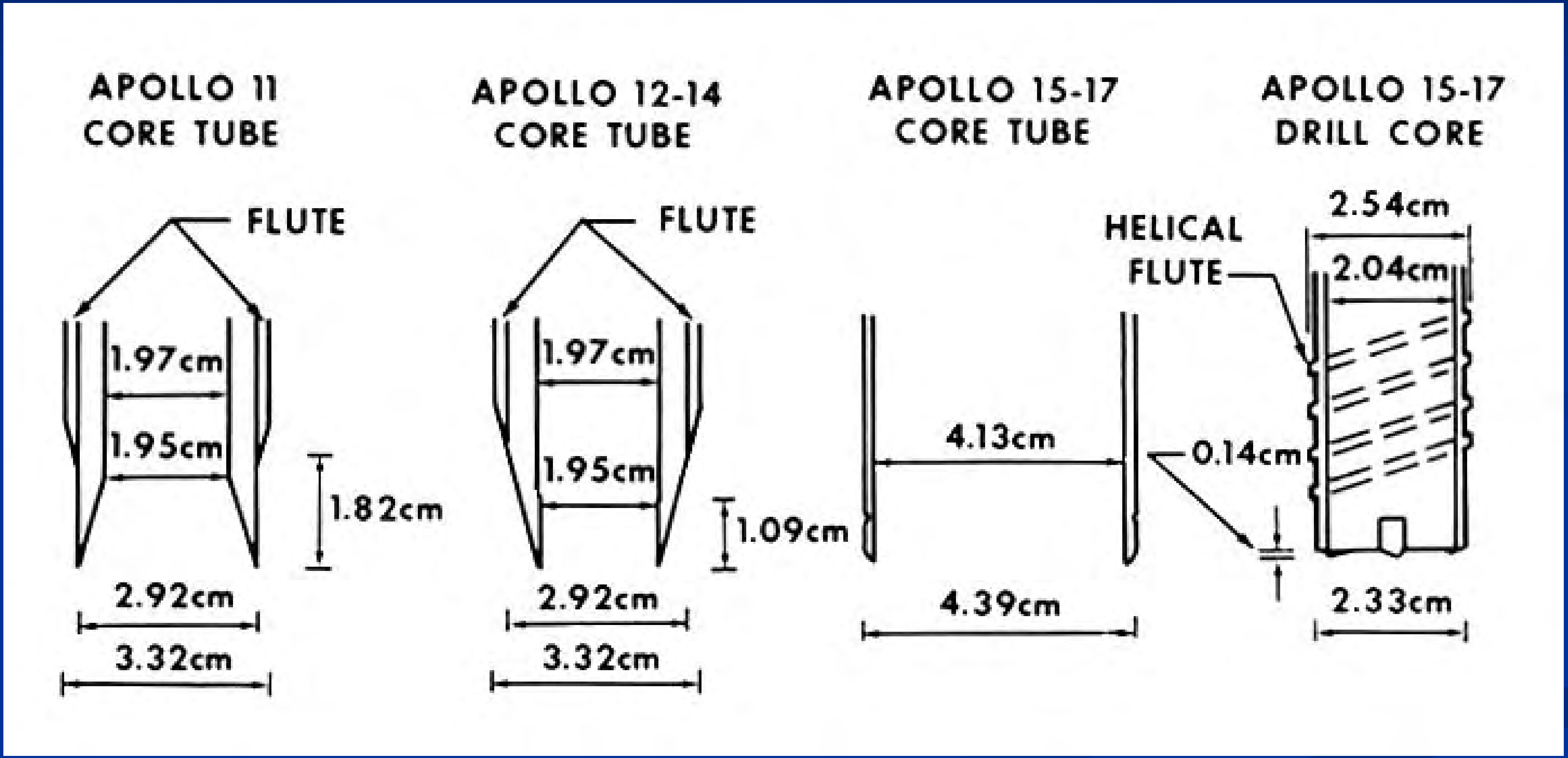
David Carrier

JSC,1971

LUNAR SOIL TEST BED

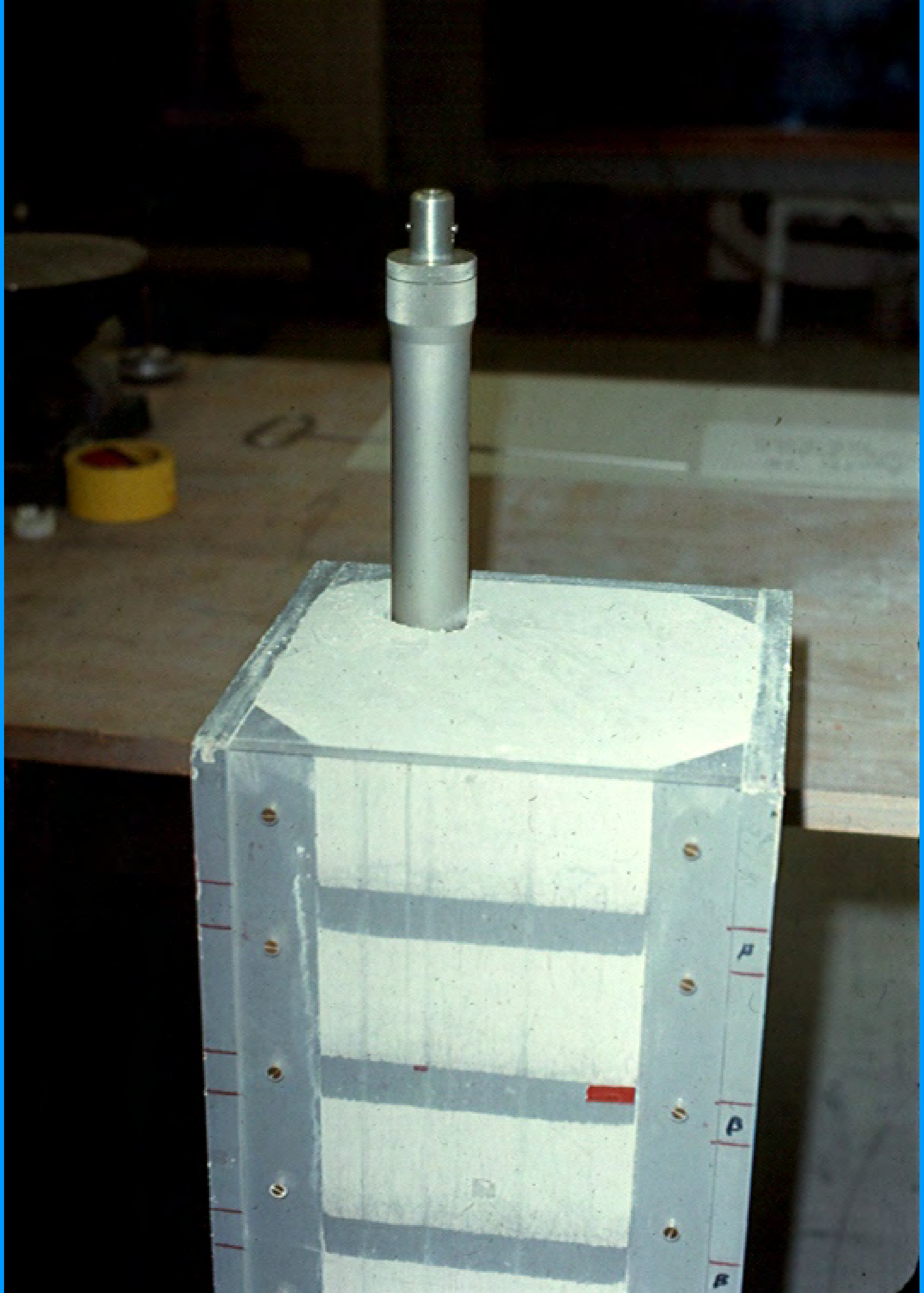
Kaolinite Clay
+
League City Sand
with
C-Black Markers

Comparison of Apollo Core Bits



(NASA-S-71-3961-S)

Drive-Tube Core Tube
driven into
Lunar soil simulant



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APOLLO 15 DRILL BIT

Stem With Helical Fluting for Augering

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APOLLO DRILLING PRACTICE

Don Burnett's Neutron-Flux Experiment

APOLLO 15
Backup Motorcycle

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SOIL PROPERTIES NEEDED FOR DIFFERENT PROCESSING

	CHEM-ISTRY	GRAIN SIZES	MINER-ALS	MAGNET-ICS	ELECTRO-STATICS	GEOTECH-NICS	Kg
Construction (sintering, melting,explosives)		X				X	?
Regolith Excavation and Handling		X				X	?
Trafficability (e.g., road building)		X				X	?
Microwave Processing	X		X	X			?
Conventional Heat Treatment	X		X				?
Oxygen Production (several processes + mineral beneficiation)	X	X	X				?
Dust Abatement (includes tribology)	X	X	X	X	X		?
Metals Extraction (several processes)	X	X	X	X	X		?
Solar-Wind Gas Extraction	X	X	X	X			?
Cement Manufacture	X		X				?
Radiation Protection	X		X				?
Biological Activity - Toxicity	X	X	X				?
Biol. Act. - Agriculture	X	X	X				?
???????????							


TIME FOR ANOTHER WALK ON THE MOON
L.A. Taylor – LSSW
NASA PHOTO