PHYSICAL & CHEMICAL CHARACTERIZATION OF LUNAR REGOLITH: CONSIDERATIONS FOR SIMULANTS

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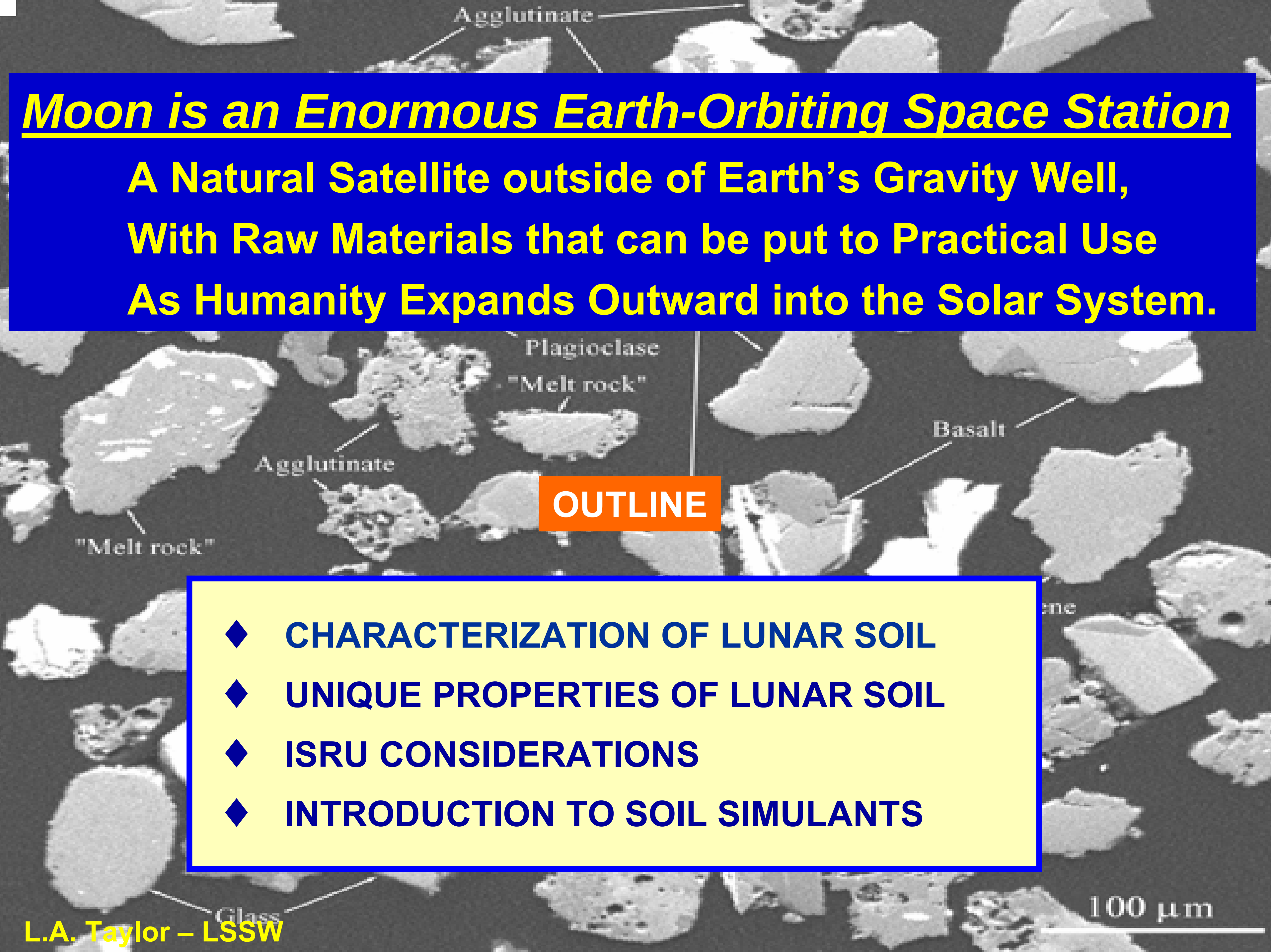


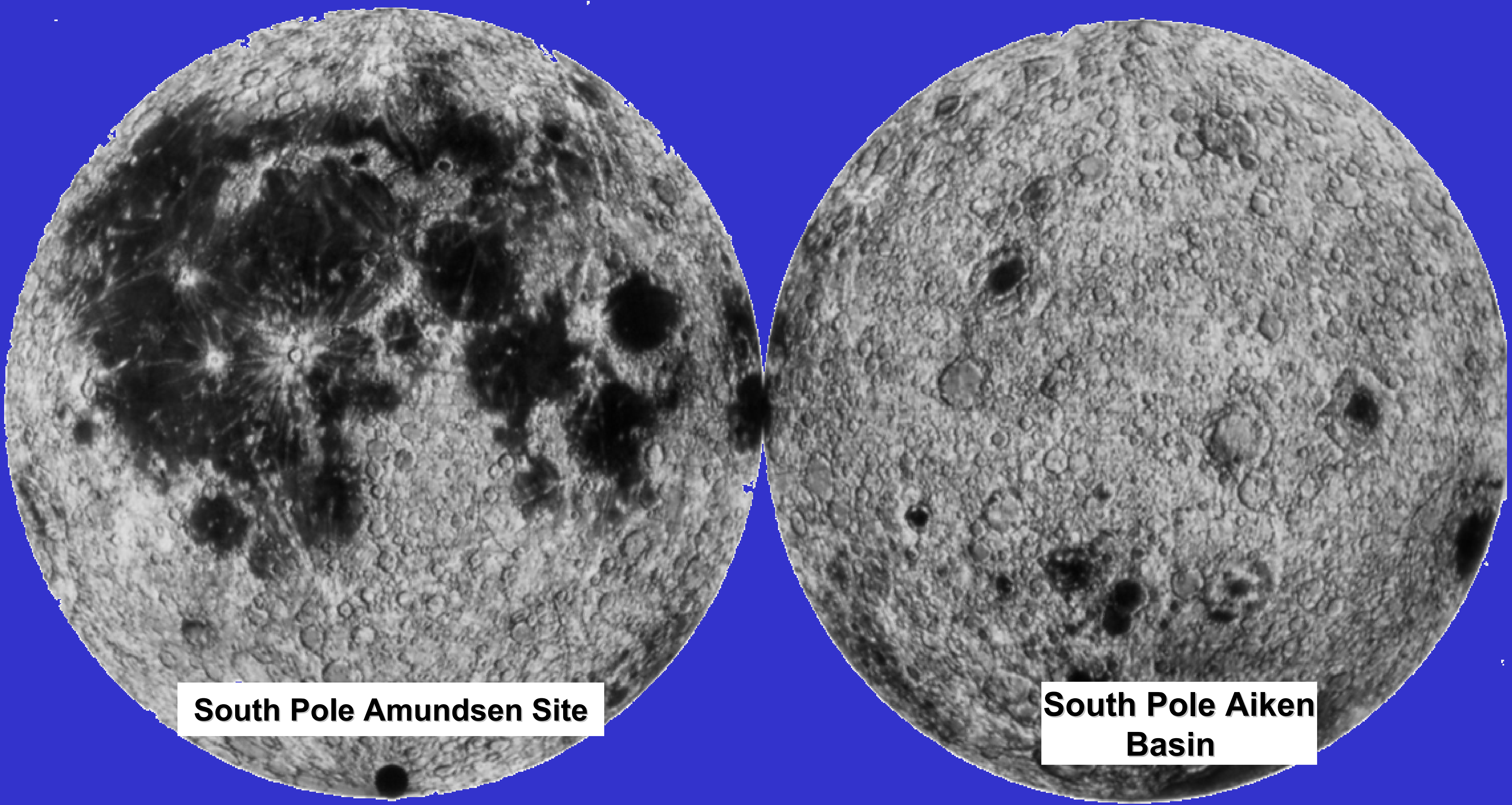
Moon is an Enormous Earth-Orbiting Space Station

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

- ♦ CHARACTERIZATION OF LUNAR SOIL
- ♦ UNIQUE PROPERTIES OF LUNAR SOIL
- ♦ ISRU CONSIDERATIONS
- ♦ INTRODUCTION TO SOIL SIMULANTS

16% Maria and 84% Highlands
Contrasting Regions of the Moon



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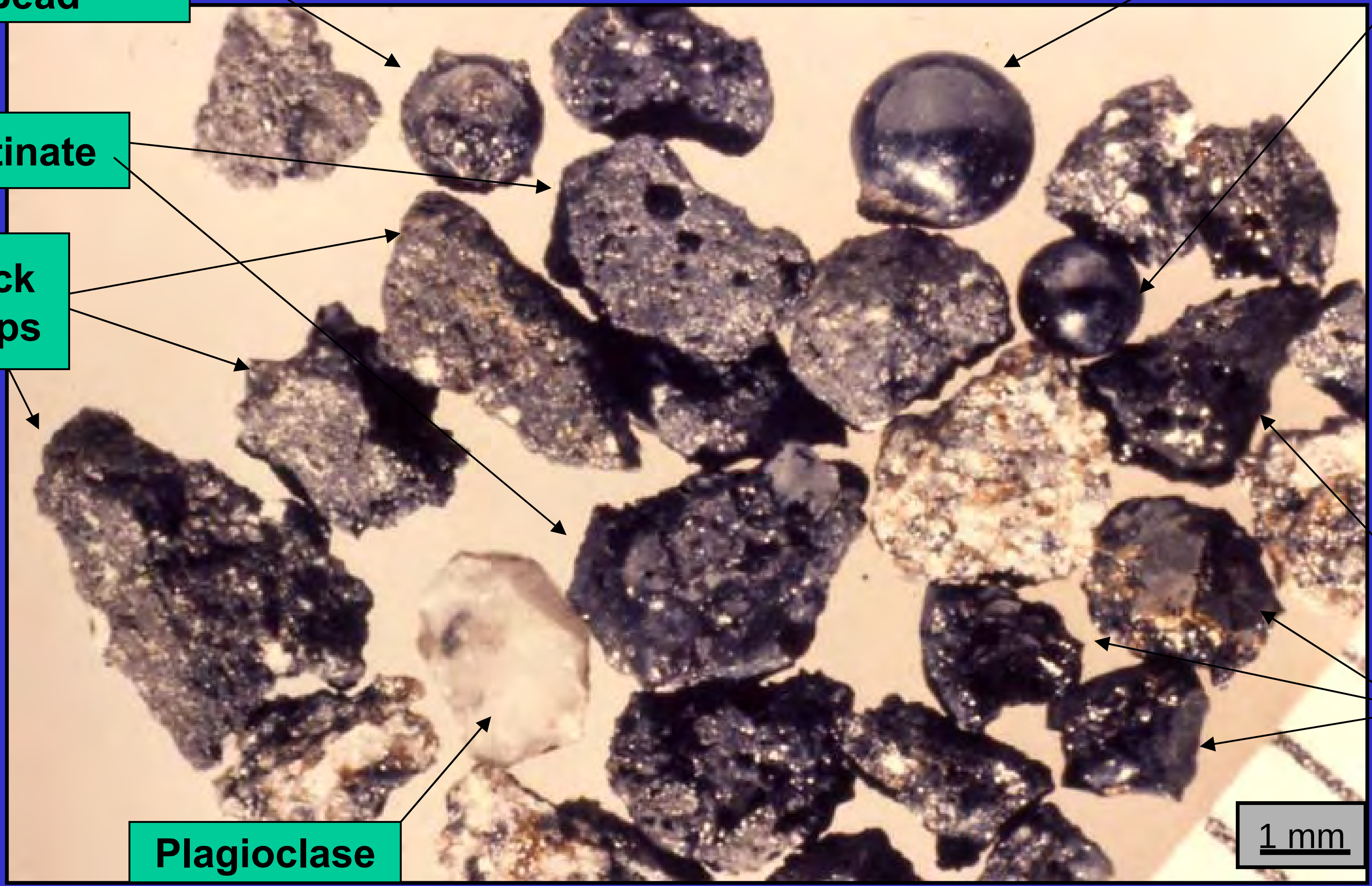
Lunar Mare Soil



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

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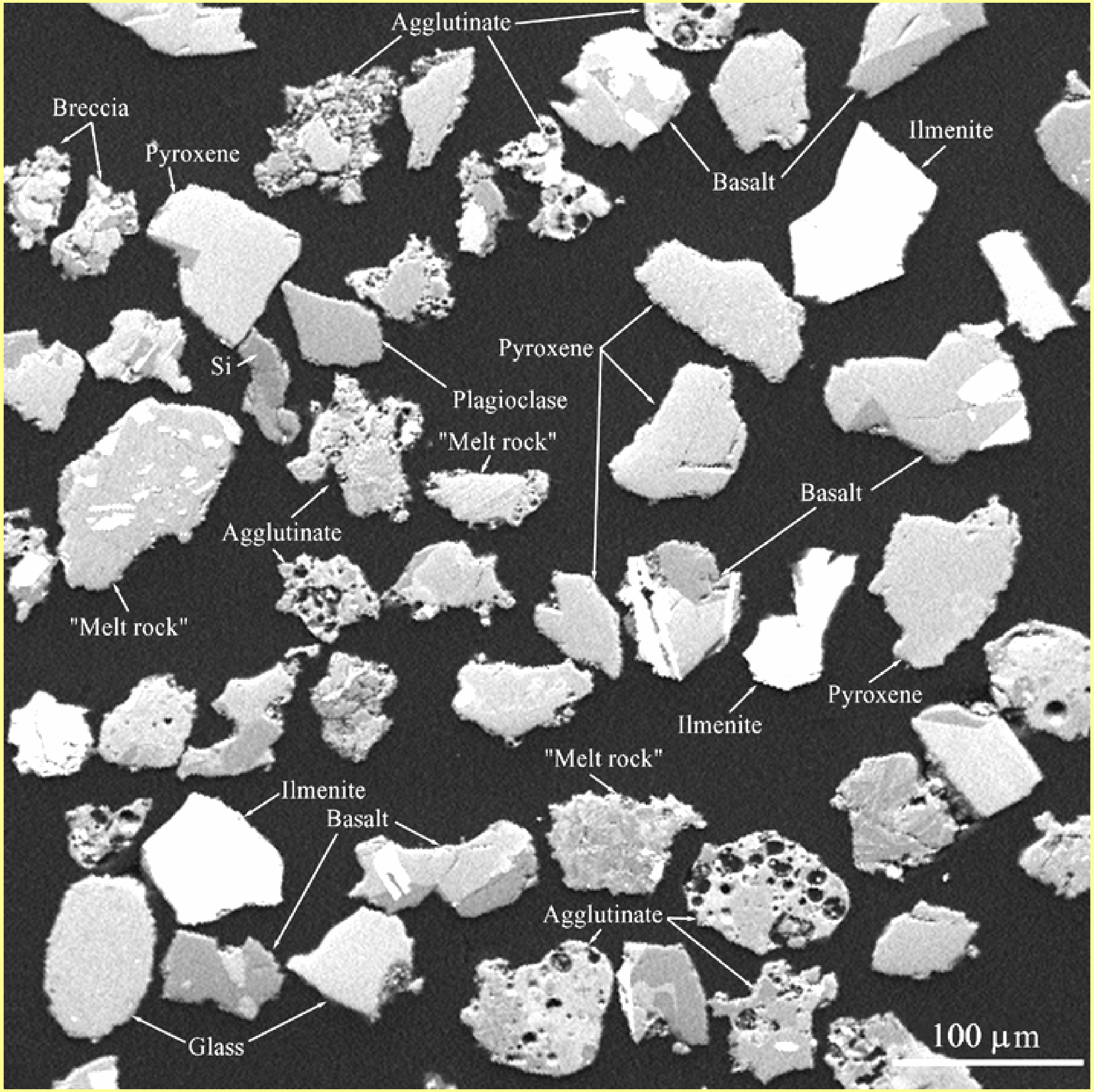
Major Components of Lunar Soils:

- Rock Fragments
- Mineral Fragments
- Glassy Particles
  - Agglutinates
  - Impact-Glass Droplets
  - Volcanic-Glass Beads

Lunar Mare Soil



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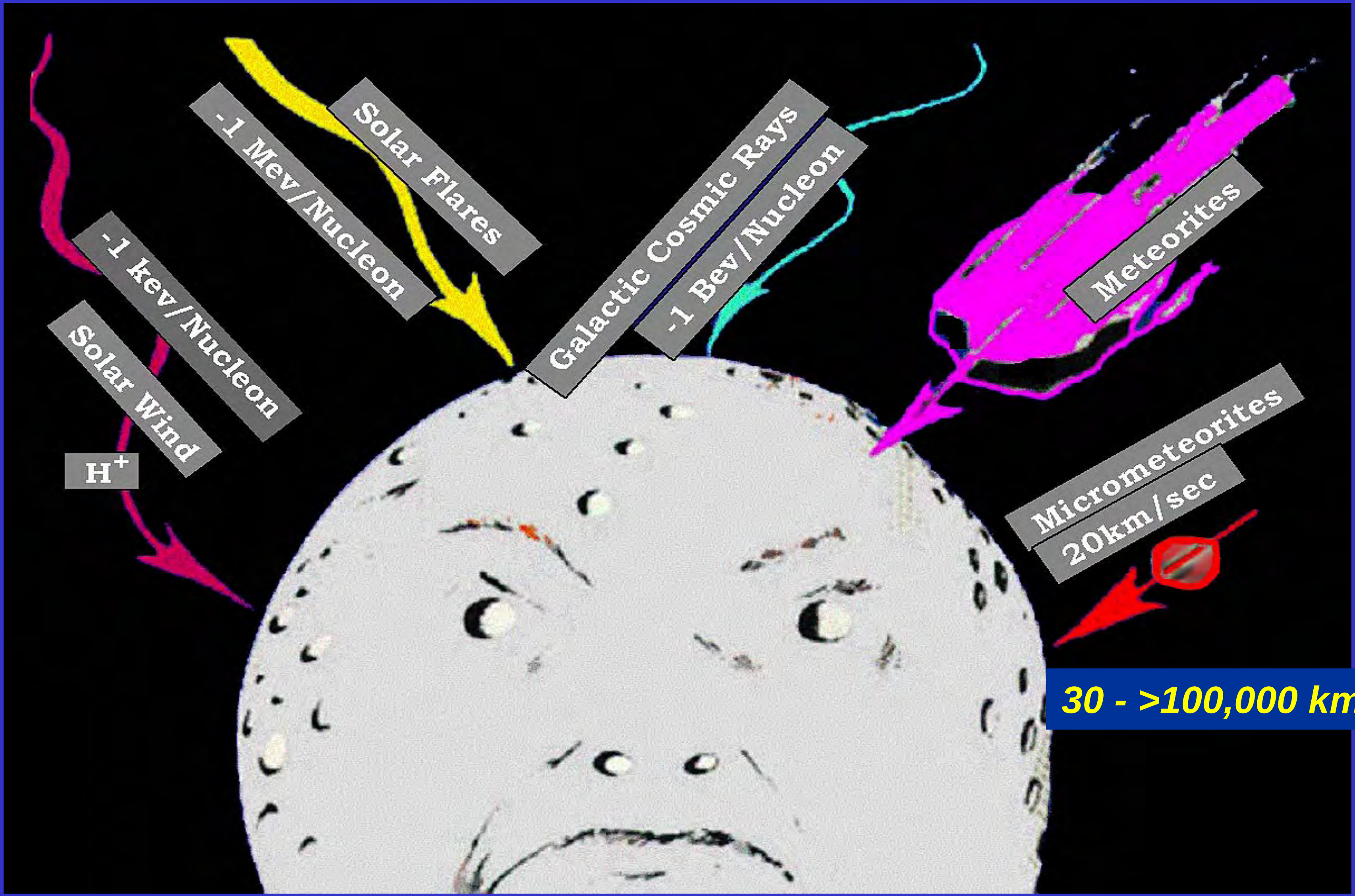
Space Weathering on the Moon

Cumulative Effects due to :

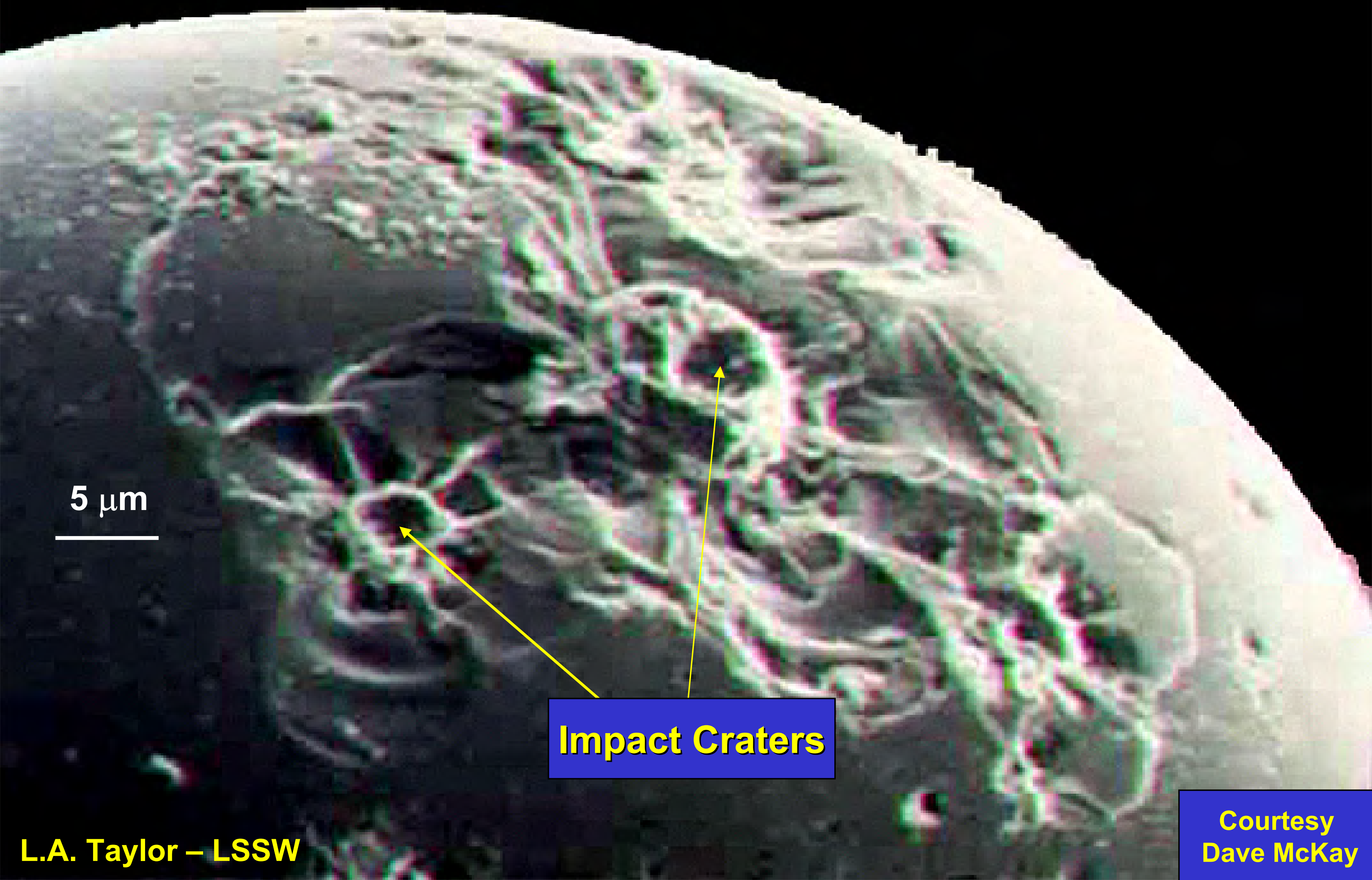
- **Deep Vacuum** : >10^{-12} torr
- **Micrometeorite Impact** : Velocities to >10^{5} km/hr
- **Radiation**: Galactic / Cosmic / Solar-ray Particles
- **Temperatures** : Equator: -20 °C ± 120 °C
  South Pole: Light -50 ^{0}C ± 20 ^{0}C
  Dark -220 ^{0}C ± 20 ^{0}C

Our Unhappy Moon

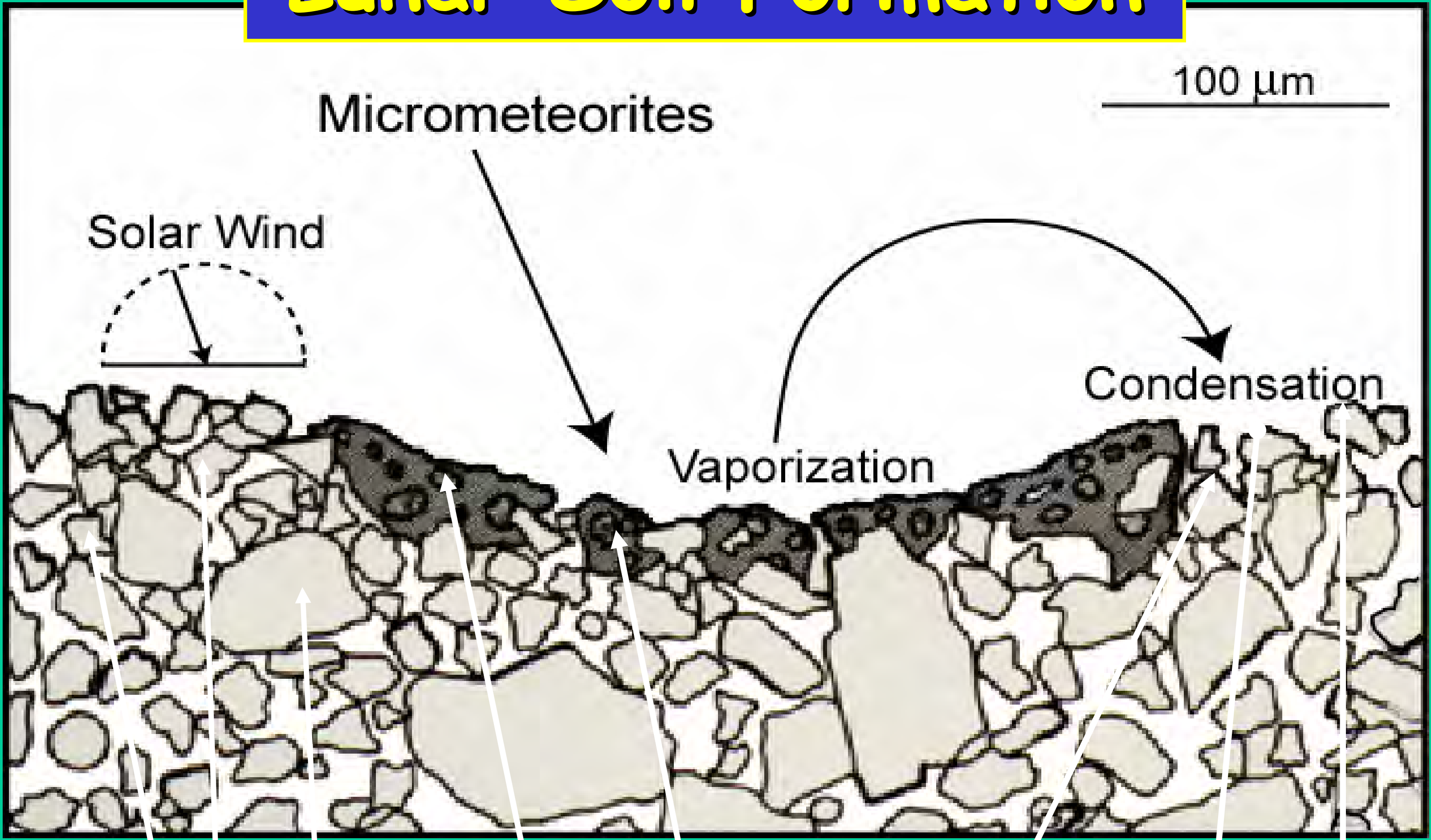


30 - >100,000 km/hr

Micrometeorite Impacts on Lunar a Glass Bead



Lunar Soil Formation



Comminution, Agglutination, & Vapor Deposition

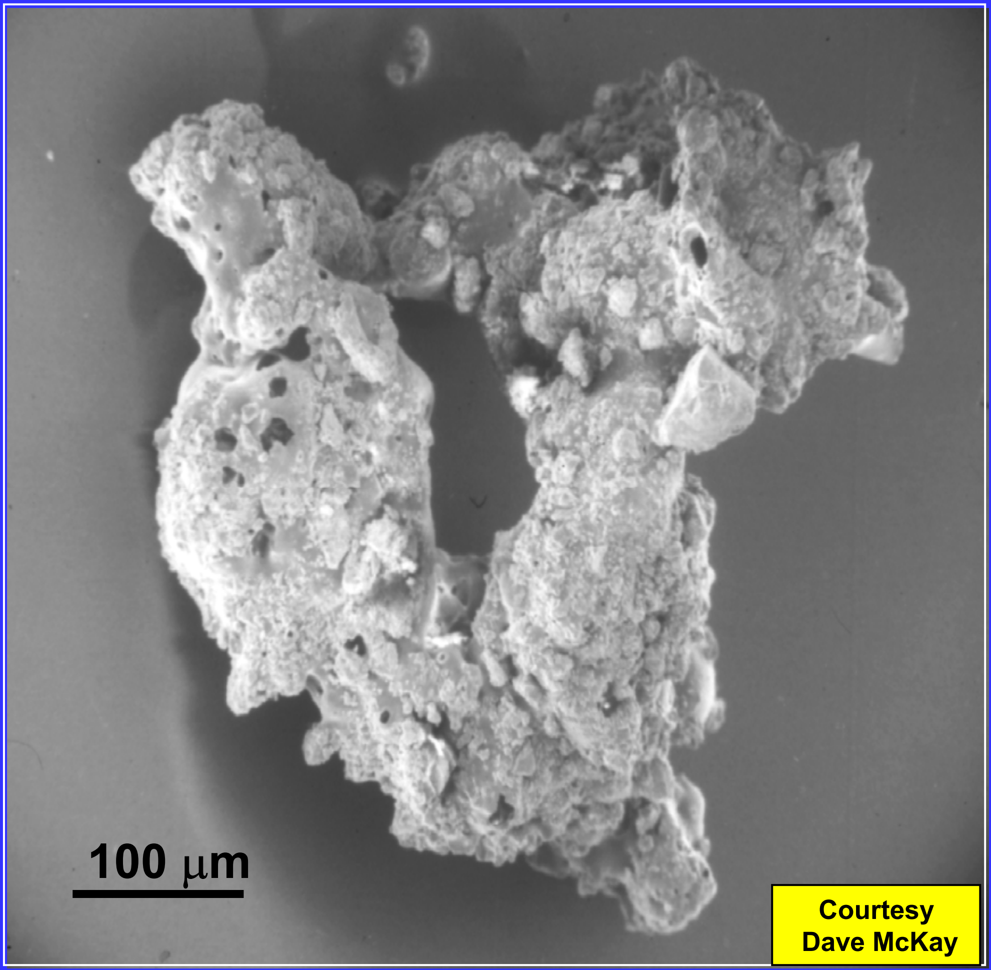
The major Weathering and Erosional agent on the Moon is Meteorite and Micrometeorite Impact

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

BASIC PROCESSES IN LUNAR SOIL FORMATION

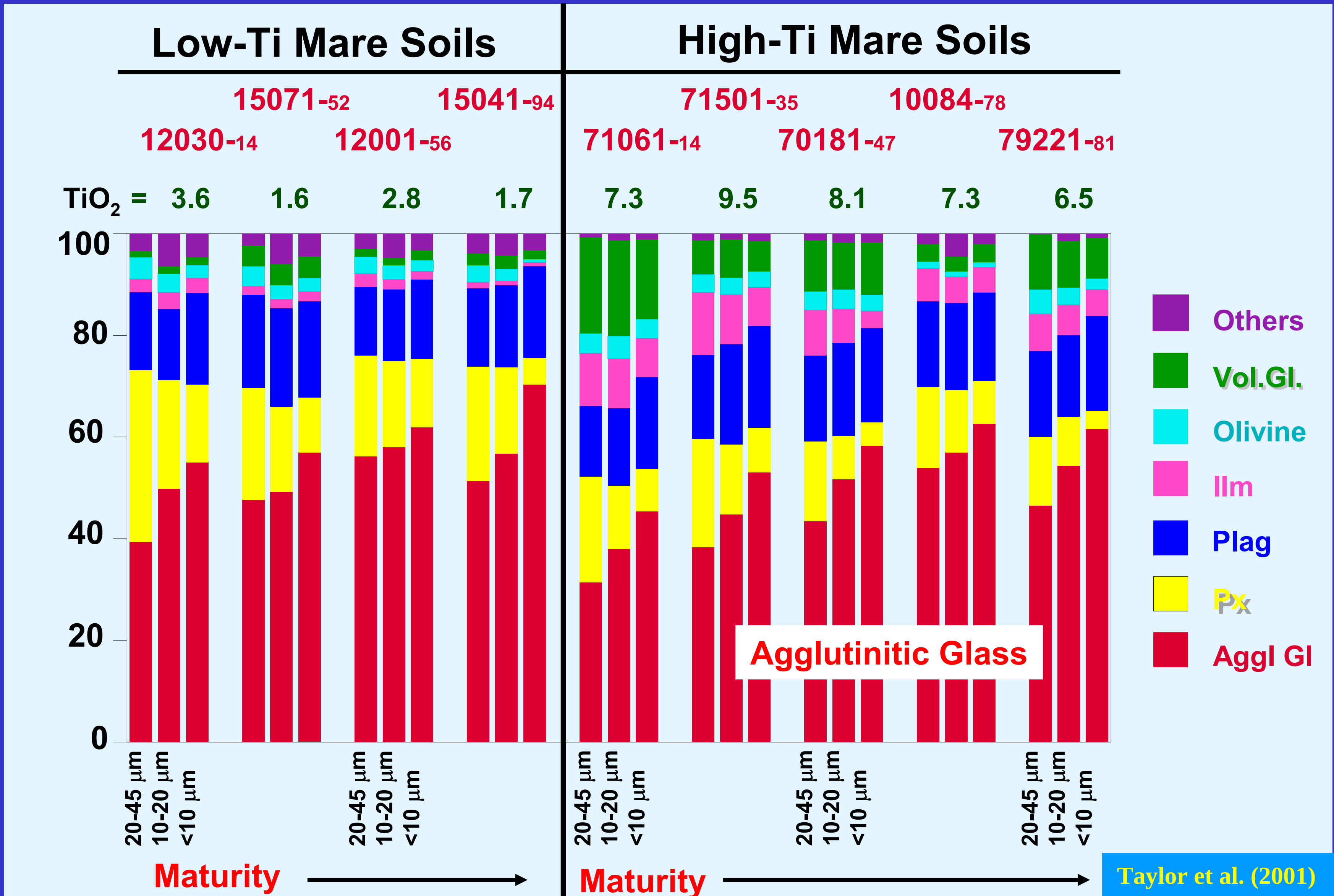
- ***COMMINUTION:*** breaking of rocks, minerals, and glasses into smaller particles;
- ***AGGLUTINATION:*** welding of rock, mineral, and glass fragments together by micrometeorite-produced, impact-generated melt (quenched to glass);
- ***IMPACT-MELT VAPORIZATION AND DEPOSITION:*** Vaporization of volatile components in the micro-meteorite-produced, impact- generated melt.
- ***SOLAR-WIND SPALLATION AND PARTICLE IMPLANTATI ON:*** Erosion and vaporization caused by sputtering from impacting high-energy particles;

Mare-Soil Agglutinate

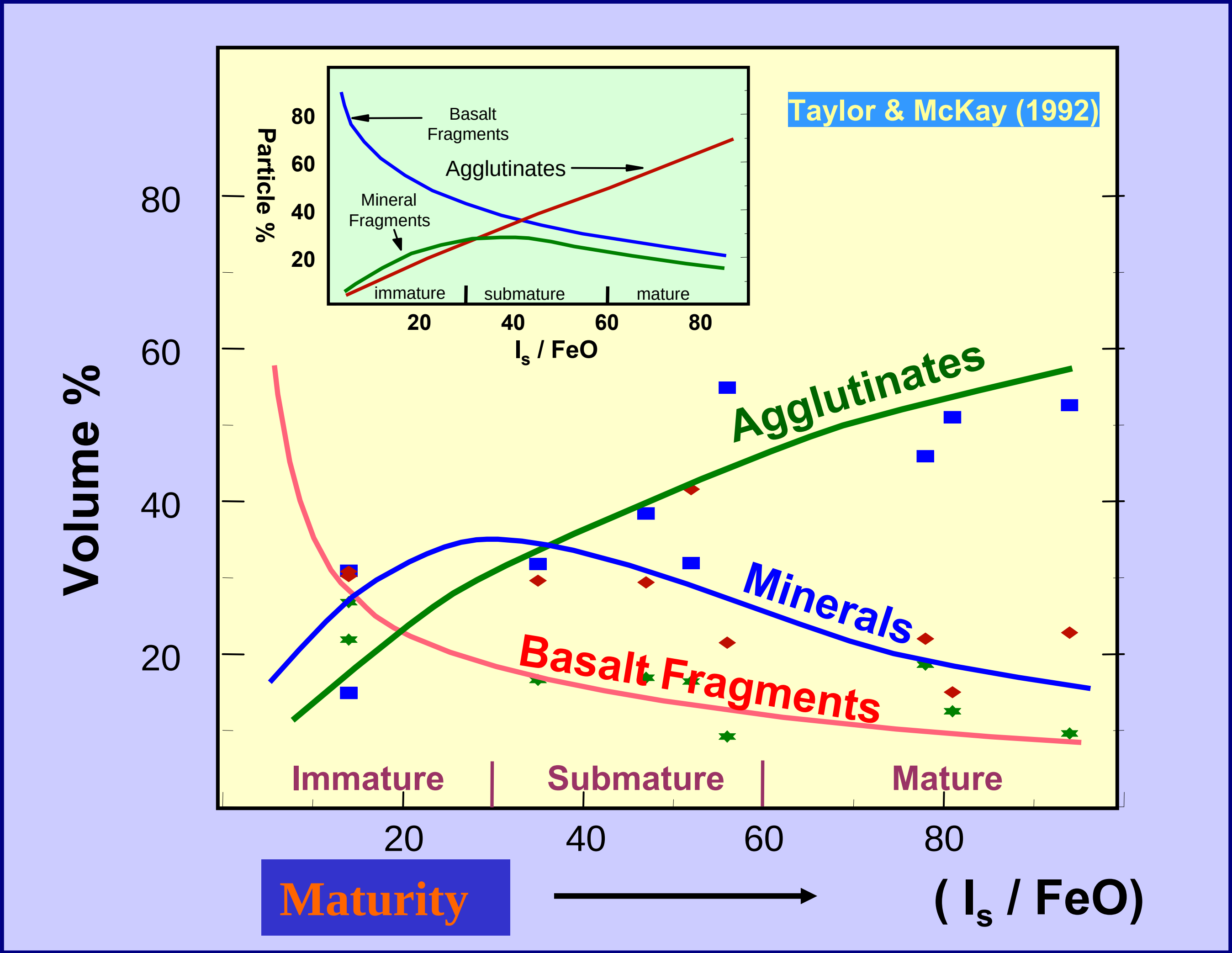


Pieces of minerals, rocklets, and glass cemented together by shock-melt glass

Cumulative Modal Abundances of Mare Soils



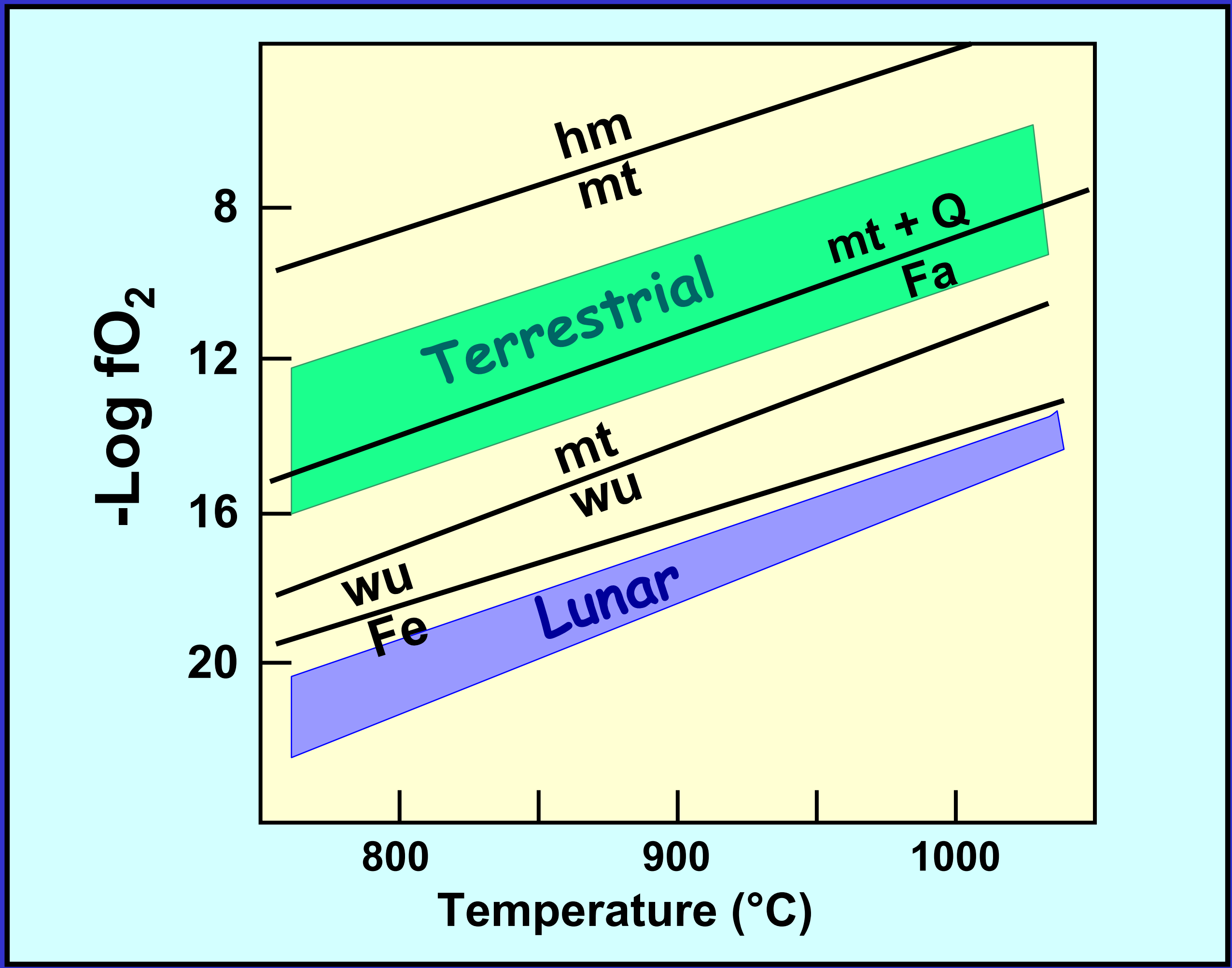
Mare Soil Maturation



What are the differences between Lunar Soils and the Rocks from which they were derived ??

Major Difference = ~ 10 X more native Fe^{o} in the soil

Oxygen Partial Pressures



All Lunar Rocks have Elemental Fe^0 as a Stable Mineral

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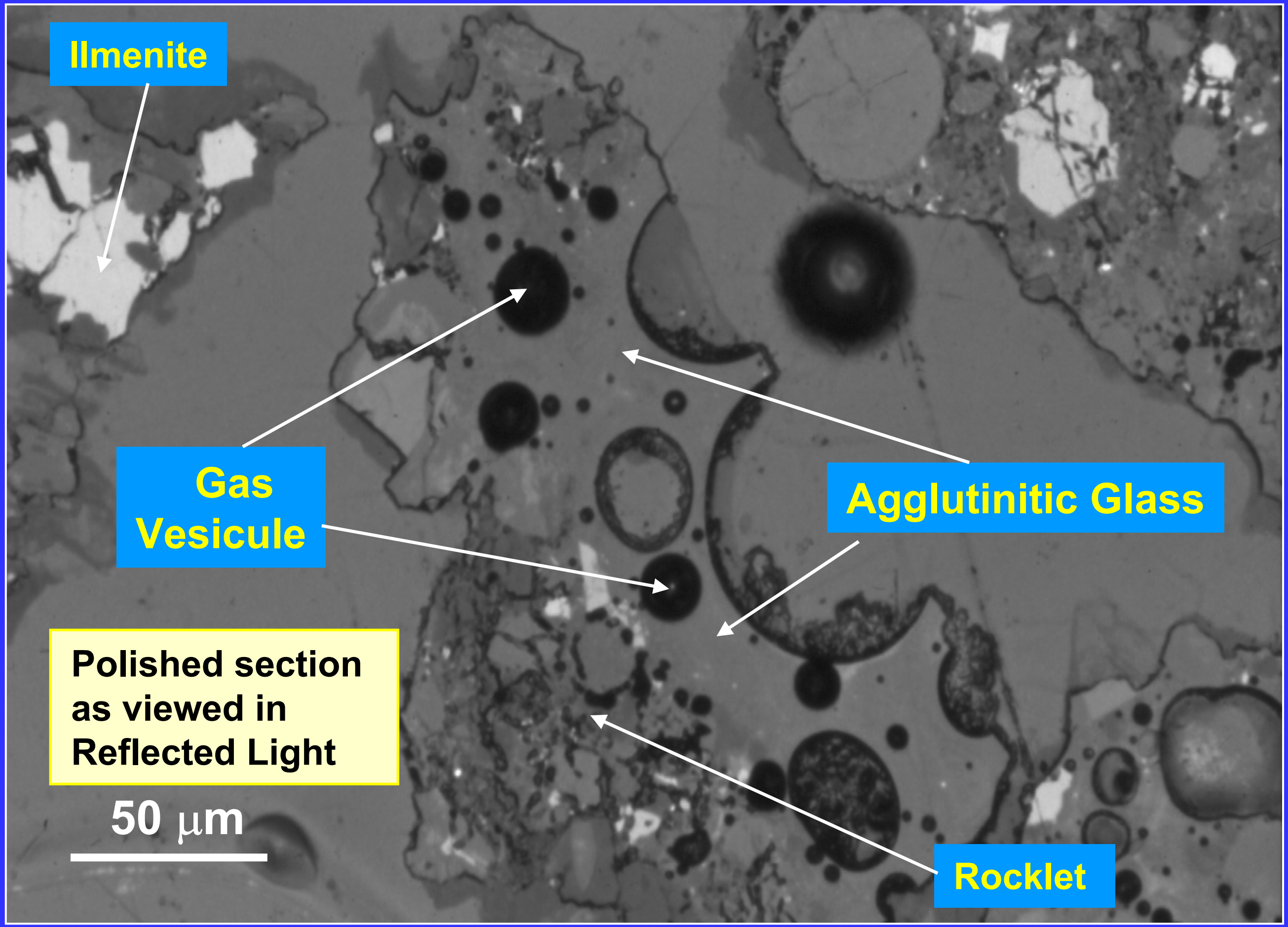
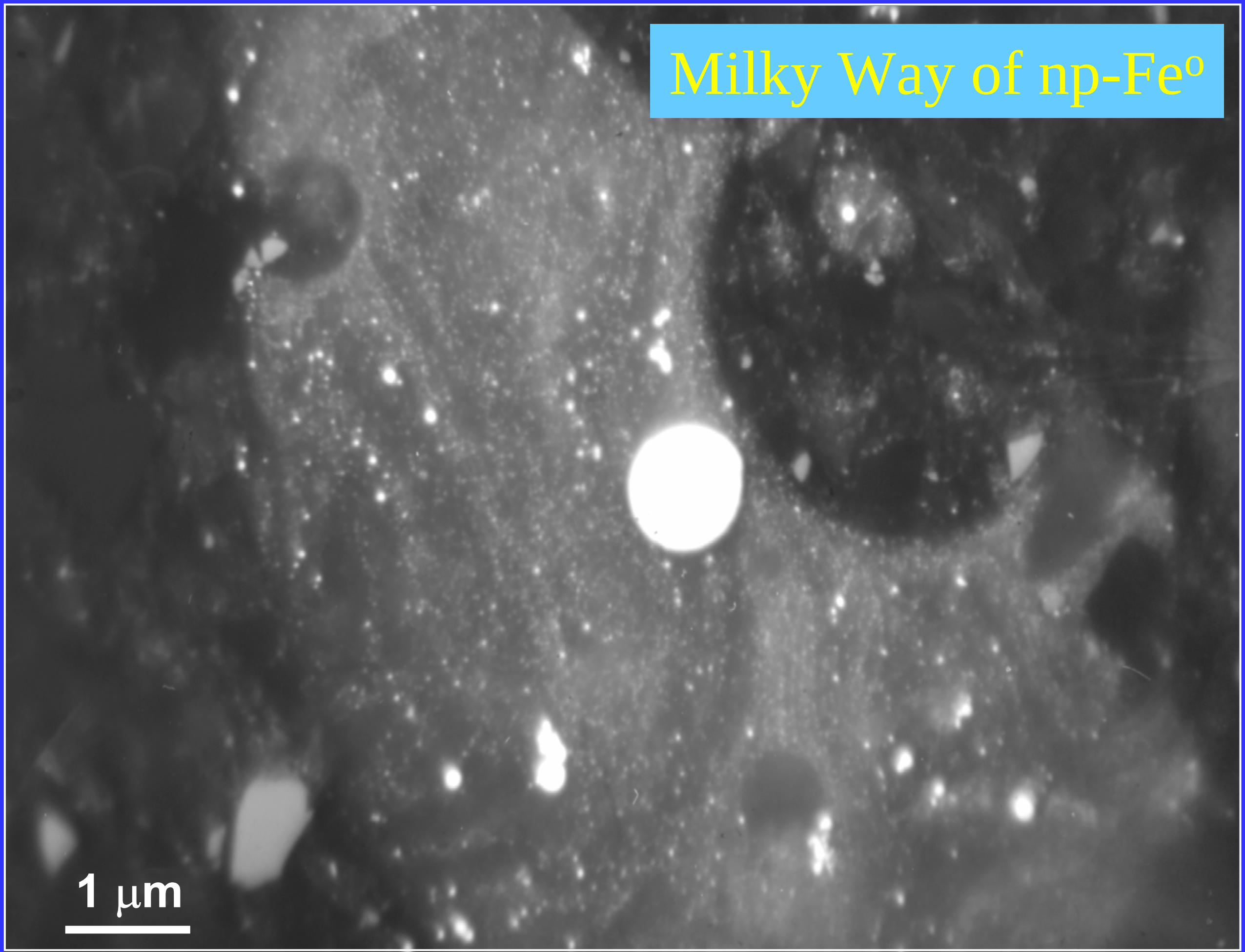
Mare-Soil Agglutinates

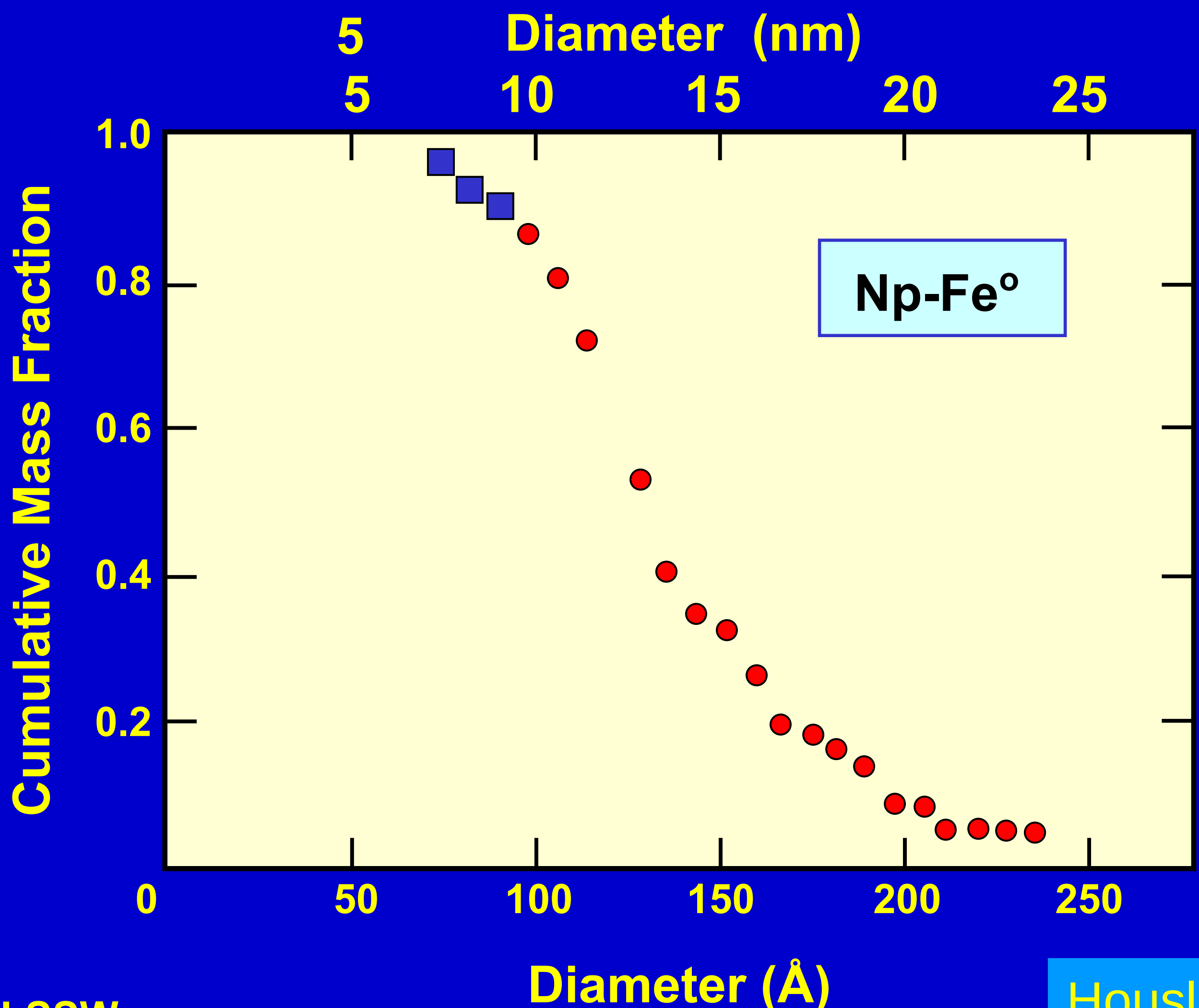


SEM BSE-Image of Mare Agglutinitic Glass



Courtesy – Dave McKay

TEM-measured Size Distribution of Fe Metal Spheres in Agglutinitic Glass of Apollo 11 Soil 10084



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Housley et al., 1974

FORMATION OF NANOPHASE Fe^{0} in AGGLUTINITIC GLASS:

Auto-Reduction Reaction in Impact-Soil Melt

$$\text{“}FeO_{melt}\text{”} + H_2 = Fe^0 + H_2O \uparrow$$

Solar-Wind Implanted H^{+} in Lunar Soil
Causes Reduction of Fe^{2+} to Fe^{o}
in Micrometeorite-Produced Impact Melt

FERROMAGNETIC RESONANCE (FMR):

- Measurement of Single-Domain, Nanophase Fe^0 (I_S)
- Normalized I_S for Iron Content: I_S / FeO
- I_S / FeO = amount of total iron present as Fe^o
- I_S / FeO is a Function of Agglutinate Abundance
- Agglutinate Abundance is a Function of Maturity

I_s / FeO = Soil Maturity

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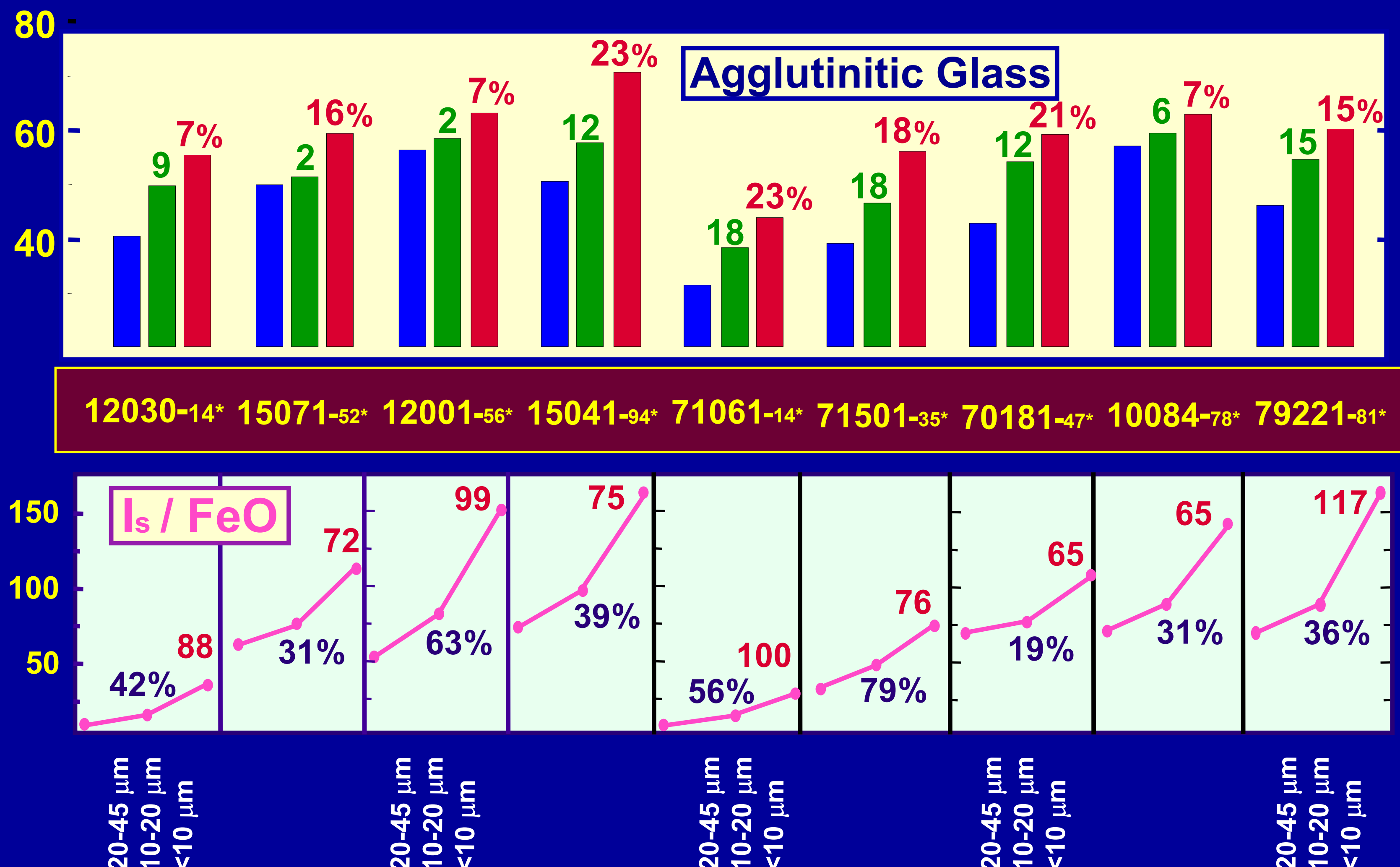
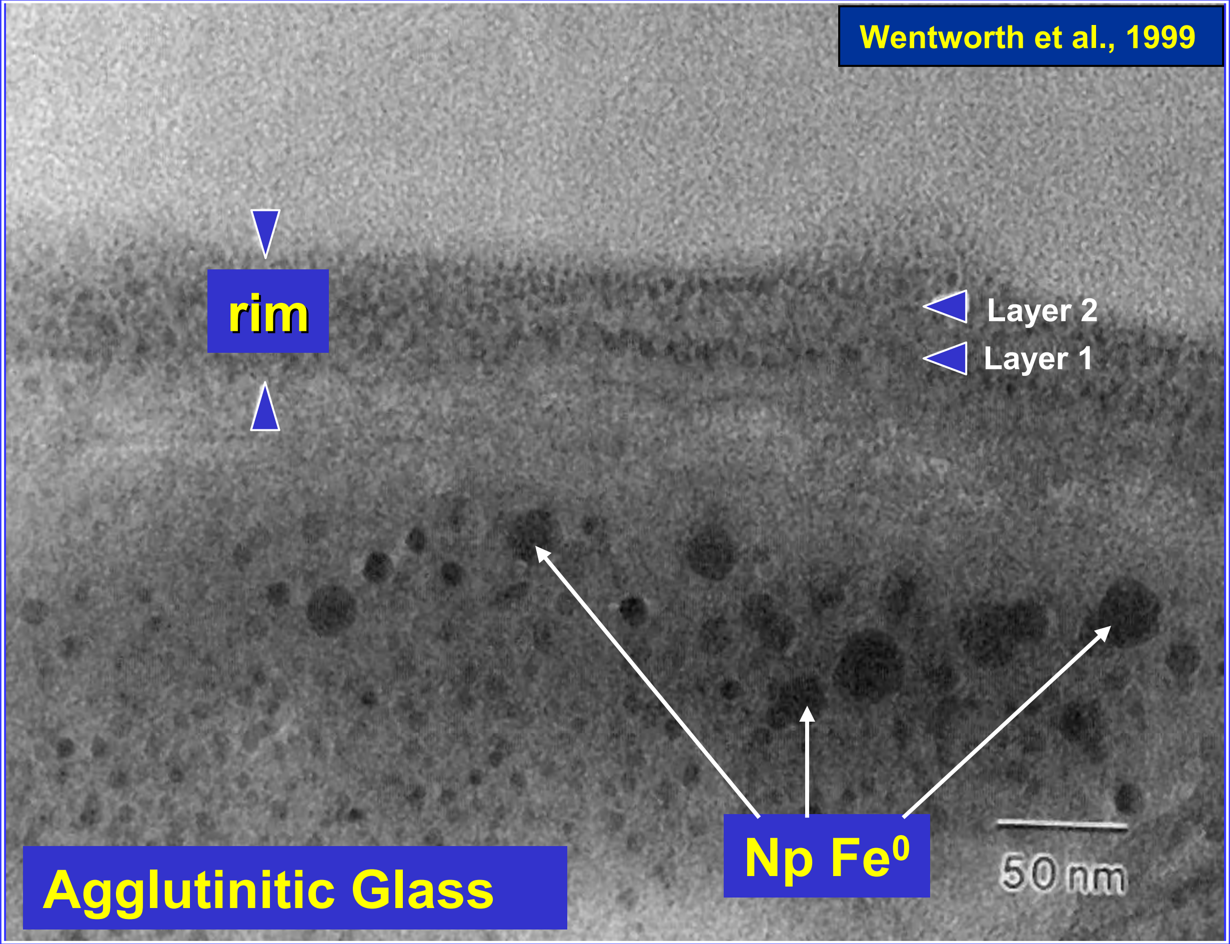
Is/FeO Values Versus Agglutinitic Glass Contents



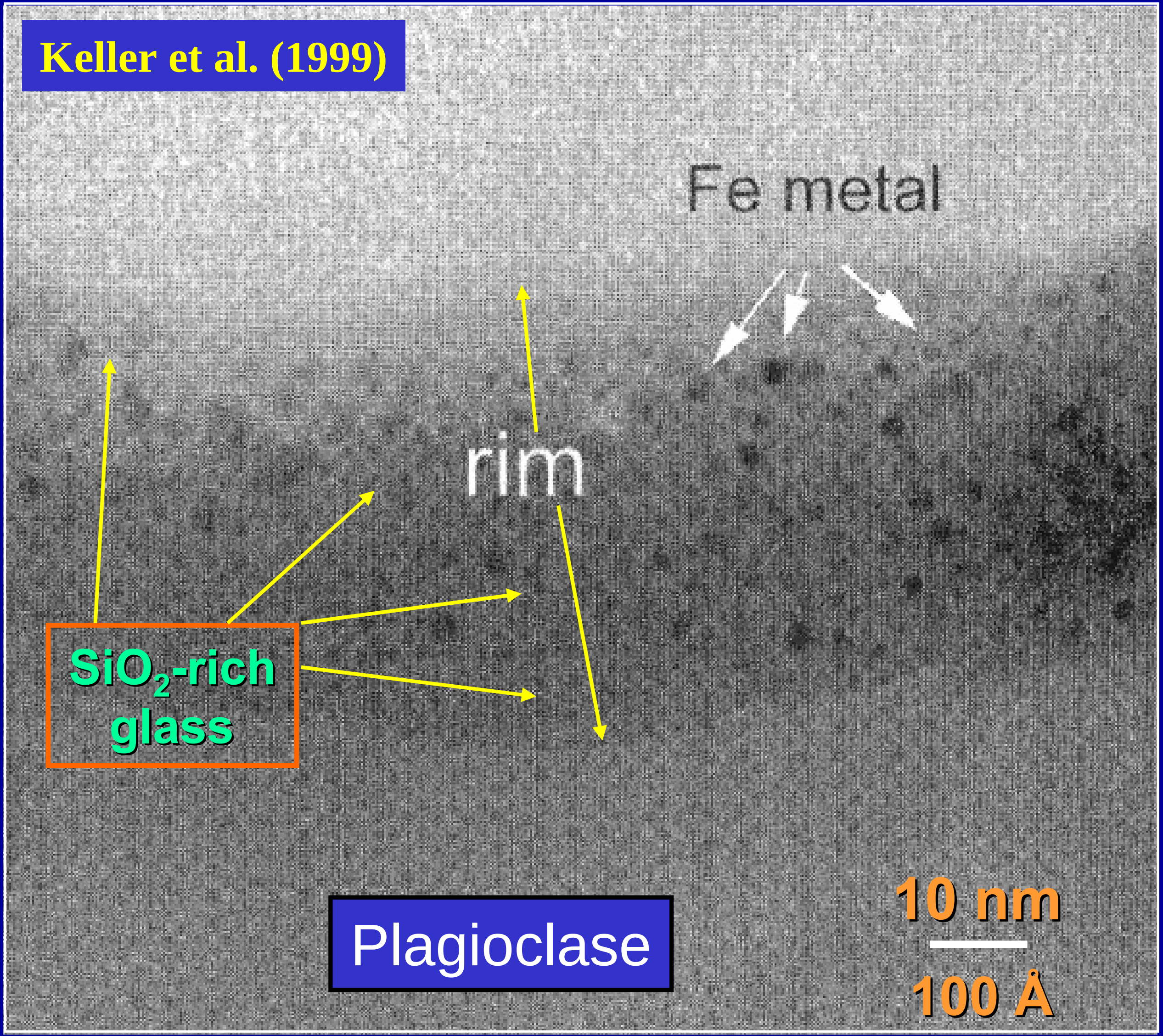
Small increases in Agglutinitic Glass, BUT Large increases in Is/FeO (Fe^0)

Taylor et al. (2001)

Multiple Layers of Vapor Deposition



Vapor-Deposited Nanophase Fe° on Plagioclase



NANOPHASE Fe° in VAPOR-DEPOSITED PATINAS (RIMS) on VIRTUALLY ALL GRAINS of a MATURE MARE SOIL PROVIDES an ADDITIONAL and ABUNDANT SOURCE for the

GREATLY INCREASED I_s/FeO VALUES for the FINEST GRAIN SIZES.

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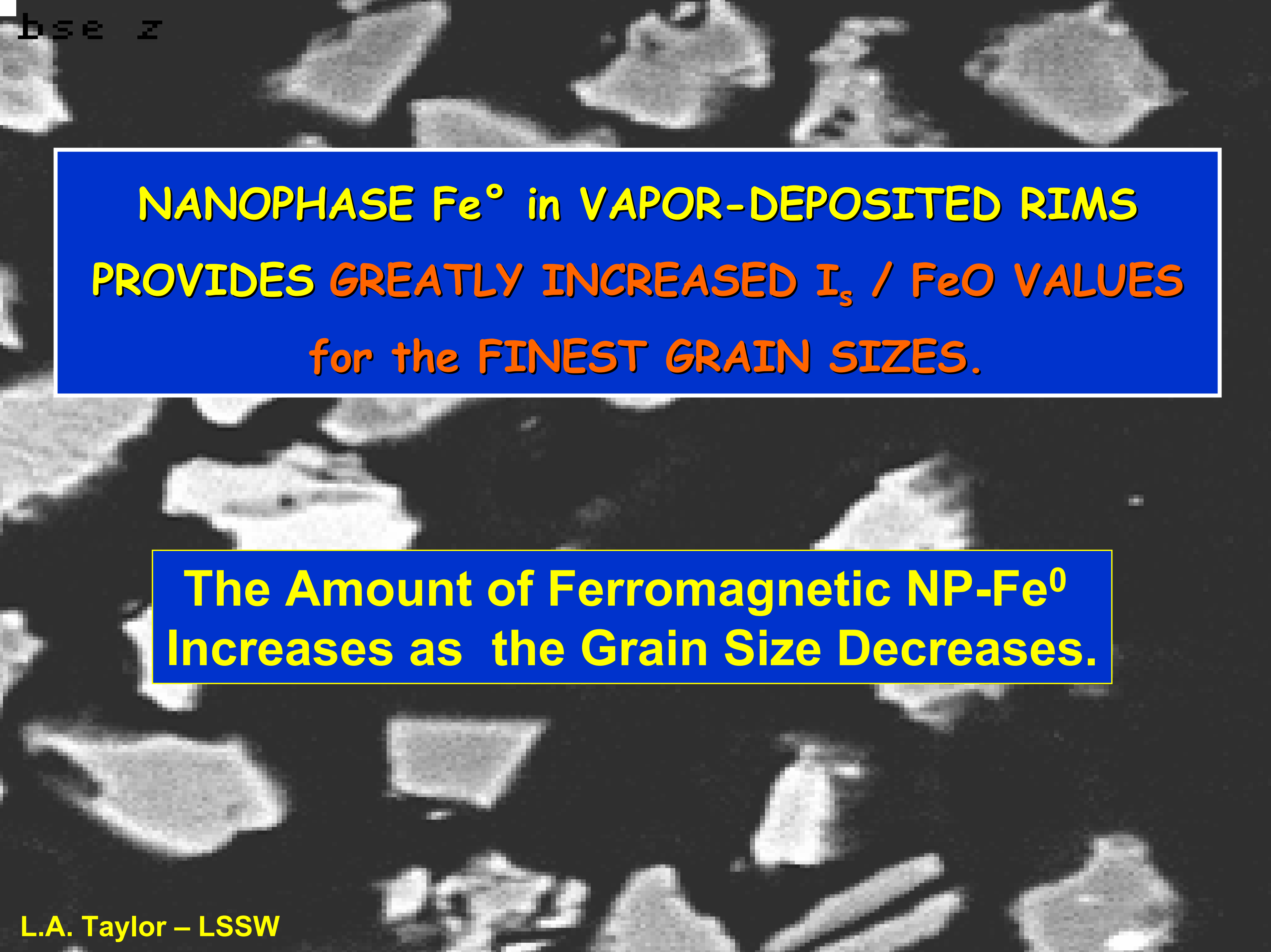
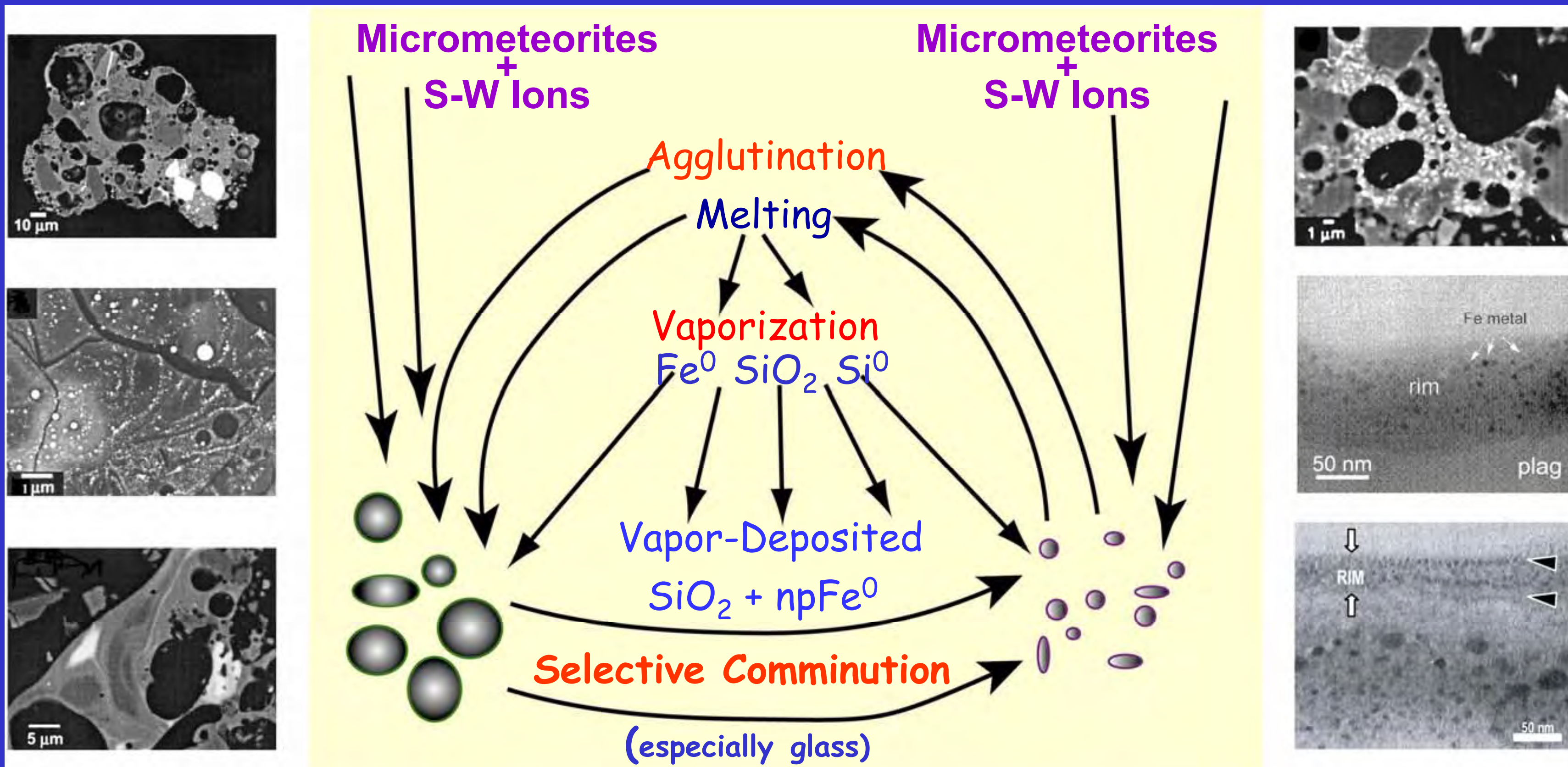


NANOPHASE Fe° in VAPOR-DEPOSITED RIMS PROVIDES GREATLY INCREASED I_s / FeO VALUES for the FINEST GRAIN SIZES.

The Amount of Ferromagnetic NP-Fe^0 Increases as the Grain Size Decreases.

Lunar Soil Cycle



Course (>100 µm)

Fine (<10µm)

Grain size decreases →

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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 Attracted by a Hand-held Magnet, Plg, Pyx, Ol, and Agglutinitic Glass alike.

Lunar Dust Effects: Must be Addressed before any Human 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 ??

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APOLLO 17

Microwave Heating of Lunar Soil:

NanoPhase Fe^0 in Silicate Glass

Fe^0 grain size is so small as to be below the effective "skin depth" of microwave penetration;

System is basically one of :

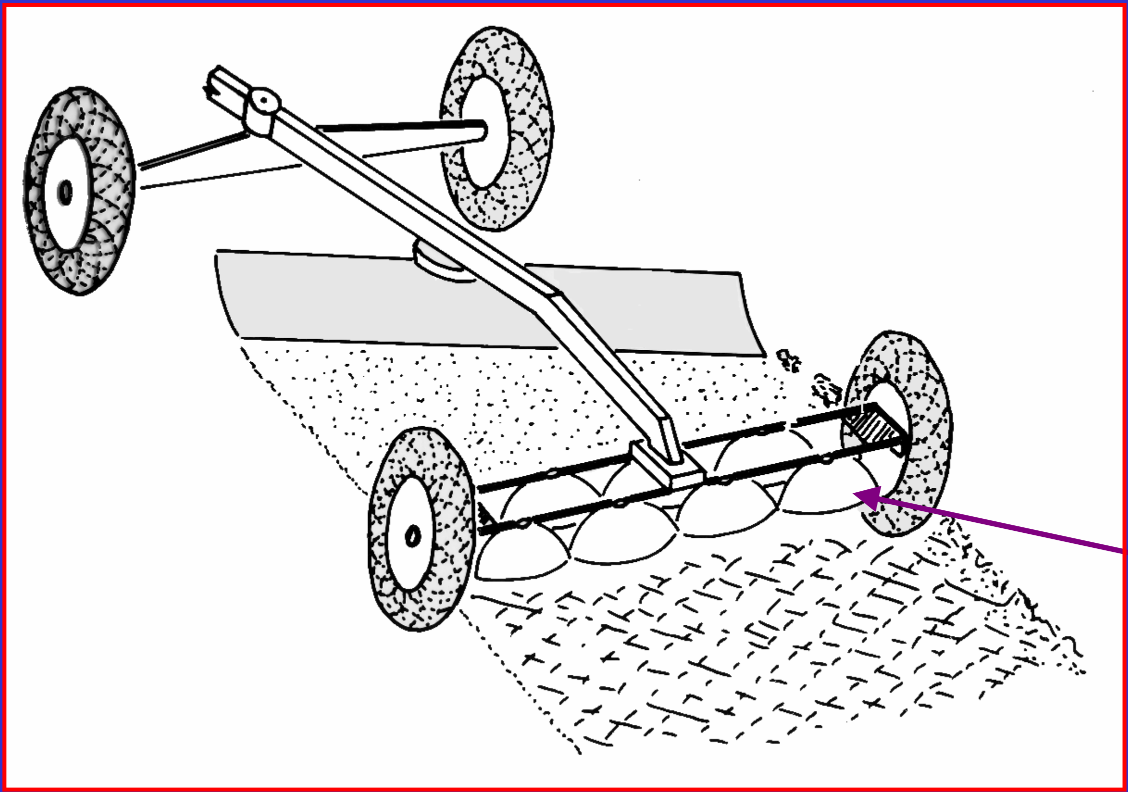
Small conductors of Fe^0 insulated by Intervening dielectric glass

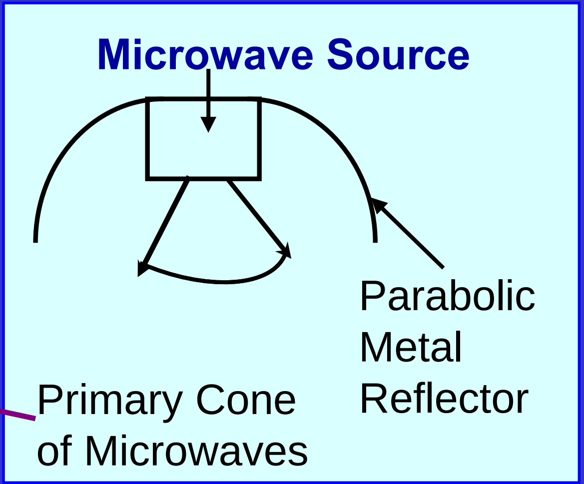
GREAT MICROWAVE COUPLING!

LUNAR SOIL PROCESSING & PRODUCTS

SINTERING and MELTING

Creating Smooth-Sintered to Glassy Surfaces on the Moon

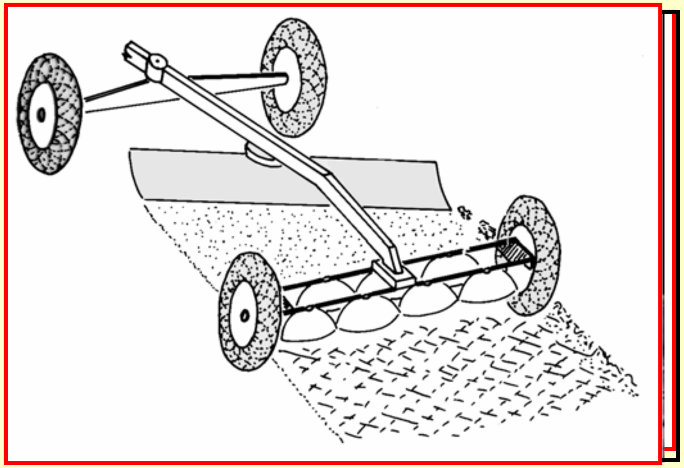




LUNAR SOIL PROCESSING & PRODUCTS

SINTERING and MELTING

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



SUGGESTIONS ??

Polar Regions

Two cases:

❖ **Hydrogen enrichment: solar-wind hydrogen only**

Properties of regolith may be similar to elsewhere on the Moon, from our Apollo studies; new information may not be needed; possibility of unexpected effects of extreme cold (25-100 K); major considerations for processing tools at 50 K.

❖ **Hydrogen enrichment: H_2O-dominated ice**

In this case, physical properties of the regolith might be very different from those at Apollo sites

Concentrations of Solar-Wind Volatile Species in Lunar Regolith Samples, in ppm

	H	He	C	N	Ne	Ar
Apollo 11	**20-100**	20-84	96-216	45-110	2-11	1.3-12
Apollo 12	**2-106**	14-68	23-170	46-140	1.2-6	0.5-4.6
Apollo 14	**67-105**	5-16	42-225	25-130	0.14-1.6	0.4-2.2
Apollo 15	**13-125**	5-19	21-186	33-135	0.6-108	0.5-2.7
Apollo 16	**4-146**	3-36	31-280	4-209	0.4-1.2	0.6-3
Apollo 17	**0.1-206**	13-41	4-200	7-94	1.2-2.7	0.6-2.6

Haskin and Warren, 1991

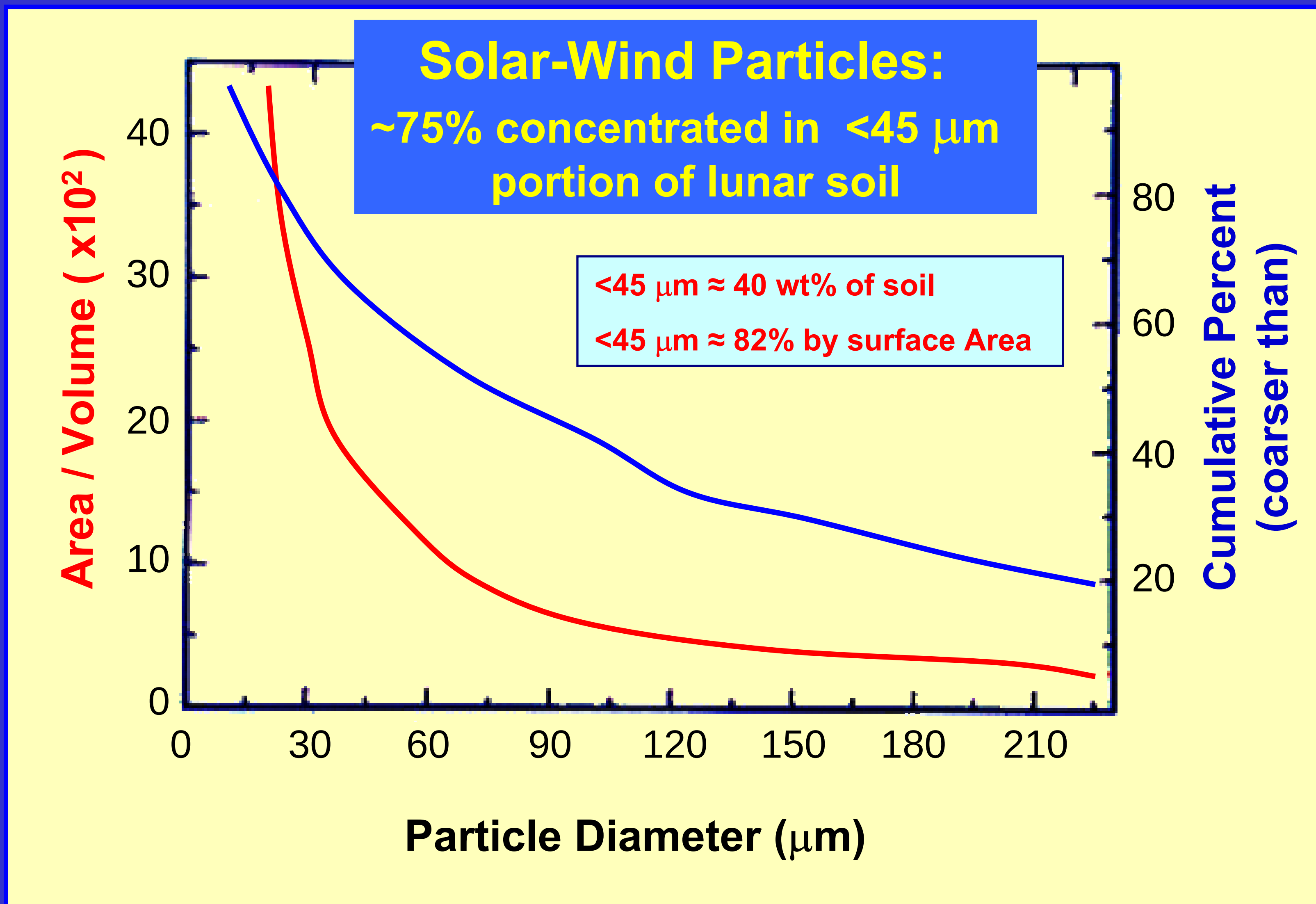
Regolith Properties

- **Liquidus Temperature**
  - Maria: 1200 - 1250ºC
  - Highlands: 1350 - 1380ºC
- **Viscosity (at liquidus)**
  - Maria: 9 Pa s (90 poise)
  - Highlands: 5 Pa s (50 poise)
- **Bulk Density**
  - Upper few mm: 800-1000 kg/m^3
  - 10-20 cm: 1500-1800 kg/m^3
- **Porosity: 35-45% at 10-20 cm depth**

- **Thermal diffusivity**
  - At 30 cm: 0.7-1.0 x 10^{-8} m^2/s
  - Very good insulator

- **CONCENTRATIONS OF SOLAR-WIND PARTICLES**
  - H, He, C, N;
  - Released as gases (H_2, O_2, CO_2, N_2, H_2O) when soil is agitated and/or heated;
  - Perhaps as much as 40-50% of SW lost by manipulation alone.
  - Peak gas release between 500 and 700oC

Lunar Mare Soils



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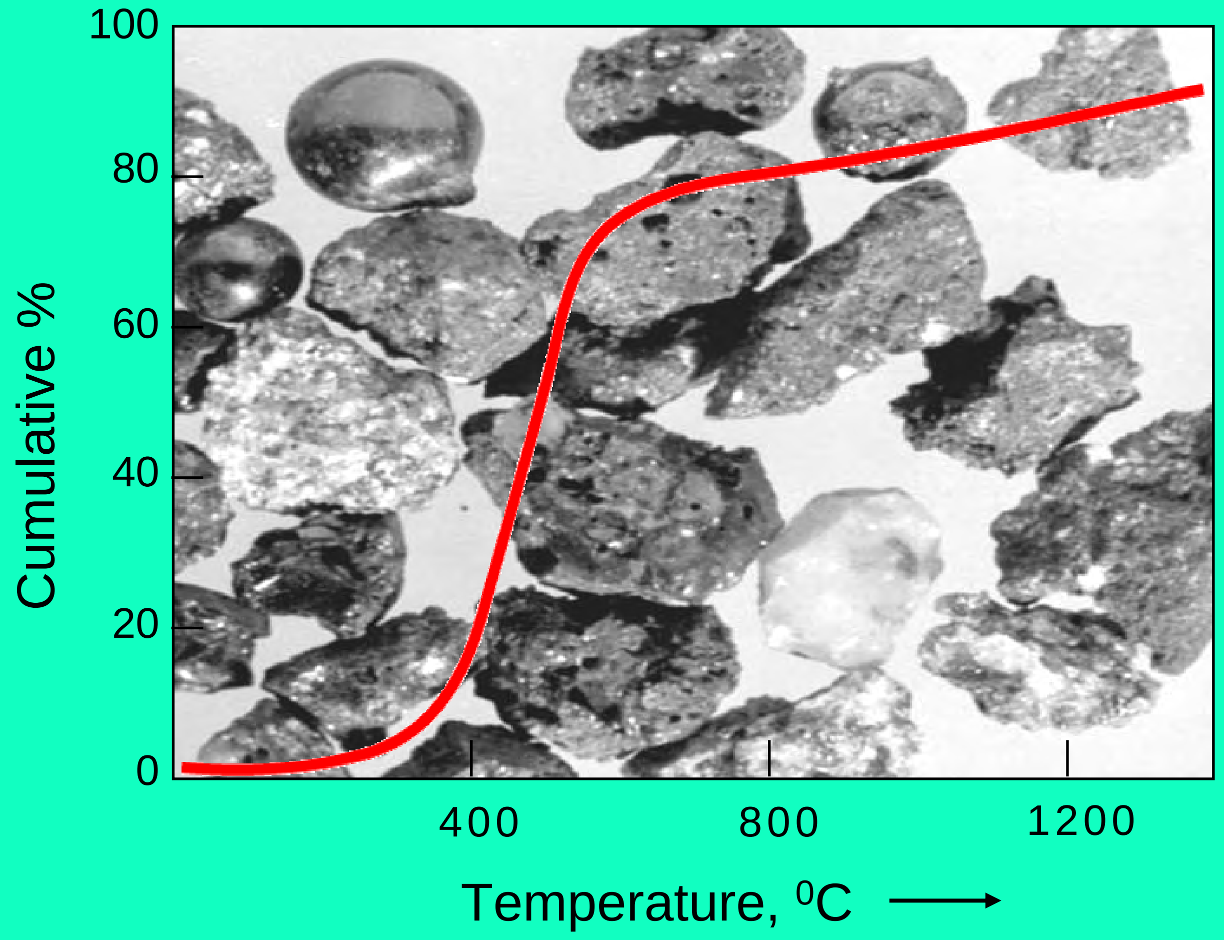
Gas Release from Lunar Mare Soil



Abundance of Hydrogen in Mare Soil

Premise : Need 20 tonnes of LLH hydrogen per year

Hydrogen in lunar soil = 200 ppm; <u>50% recovery</u> = 0.01 wt%

H in 1 m^3 = [2.0 g/cc] x [10^6 cc/m^3] X [1 x 10^{-4}] = 2.0 x 10^2 g/m^3

20 tonnes = 20t x 10^3 kg / t x 10^3 g/kg = 20 x 10^6 g

20 tonnes = 20 x 10^6g / 2.0 x 10^2 g/m^3 = 10 x 10^4 m^3 = 10^5 m^3

1 Football Field (Depth of 3m) = 5 x 10^3 m^2 x 3 = 15 x 10^3 m^3

20 t LH = 6.2 Football Fields to <u>3 m depth</u>

20 tonnes of LLH = ~6 Football Fields
0.03 km2 (1 / 30 th km^2)

= 180 TONNES OF WATER

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Potential Processes for Oxygen Production on the Moon

Process	Reference
Solid/Gas Interaction	**Solid/Gas Interaction**
X Ilmenite Reduction with Hydrogen	Gibson & Knudsen (1985)
Ilmenite Reduction with C/CO	Chang (1959); Shadman & Zhou (1988)
Ilmenite Reduction with Methane	Friedlander (1985)
x Glass Reduction with Hydrogen	McKay et al. (1991)
Reduction with Hydrogen Sulfide	Dalton & Hohmann (1972)
Extraction with Fluorine	Burt (1988)
X Carbothermal Reduction	Lynch (1989)
Chlorine Plasma Reduction	Lynch (1989)
Silicate/Oxide Melt	**Silicate/Oxide Melt**
X Molten Silicate Electrolysis	Haskin (1985)
x Fluxed Molten Silicate Electrolysis	Keller (1986)
Caustic Dissolution & Electrolysis	Dalton & Hohmann (1972)
Carbothermal Reduction	Rosenburg (1966); Cutler & Krag (1985)
Magma Partial Oxidation	Waldon (1989)
Li or Na Reduction Ilmenite	Sammells & Semkow (1987)
Pyrolysis	**Pyrolysis**
Vapor Pyrolysis	Steurer & Nerad (1983)
Ion Plasma Pyrolysis	Steurer & Nerad (1983)
Plasma Reduction of Ilmenite	Allen et al., (1988)
Aqueous Solutions	**Aqueous Solutions**
HF Acid Dissolution	Waldron (1985)
H_2SO_4 Acid Dissolution	Christiansen et al. (1988); Sullivan (1991)
Co-Product Recovery	**Co-Product Recovery**
Hydrogen-Helium-Water from Soil.	Christiansen et al. (1988)

Taylor & Carrier, 1992

Production of LLOX by H2 Reduction of Ilmenite

recycle

$$FeTiO_3 + H_2 \rightleftharpoons Fe + TiO_2 + H_2O \xrightarrow{\text{electrolysis}} H_2 + \tfrac{1}{2}\,O_2$$

Ilmenite feed

Solid Product

Oxygen Product

Mining Water on the Moon
Living- Off the-Land Concept

- H_2 is abundant in the Lunar Soil !
- O_2 is easily produced from Lunar Resources !
- Therefore, we can readily obtain rocket fuels and make H_2O !!!

BUSH FULL-SERVICE GAS STATION:

LLOX & LLH

- At BMB *
- L1 Station,
- LEO,
- Soon in a neighborhood near you!

* BUSH MOON BASE

STRAWMAN LIST OF SIMULANTS NEEDED FOR STUDIES OF:

	Chemistry	Geotech/Engr	Simulant
Facilities Construction		XX	JSC-2; MLS-2
Regolith Digging and Movin		XX	JSC-2; MLS-2
Trafficability (e.g., Roads)	XX	XX	JSC-2; MLS-2
Microwave Processing	X	X	NP-1; JSC-2; MLS-2
Conventional Heat Treatment	X	X	JSC-2; MLS-2
Oxygen Production	X	X	JSC-2; MLS-1; MLS-2
Dust Abatement	X	X	NP-1; JSC-2
Mineral Beneficiation	X	X	???
Solar-Wind Gas Release	XX	X	JSC-2; MLS-2; NP-1
Cement Manufacture	X		JSC-2; MLS-2
Radiation Protection		X	JSC-2; MLS-1; MLS-2

Mare Soil:	**JSC-2**	=	JSC-1 in chemistry + Geotech Prop.
	MLS-1	=	Chemistry only of Apollo 11 soil (no glass)
Highland Soil:	**MLS-2**	=	Anorthosite = Chemistry only
Magnetic Soil:	**NP-1**	=	Nanophase Magnetic properties only

JSC = Johnson Space Center; MLS = Minnesota Lunar Simulant