Extraction Techniques-Solar Wind Volatiles

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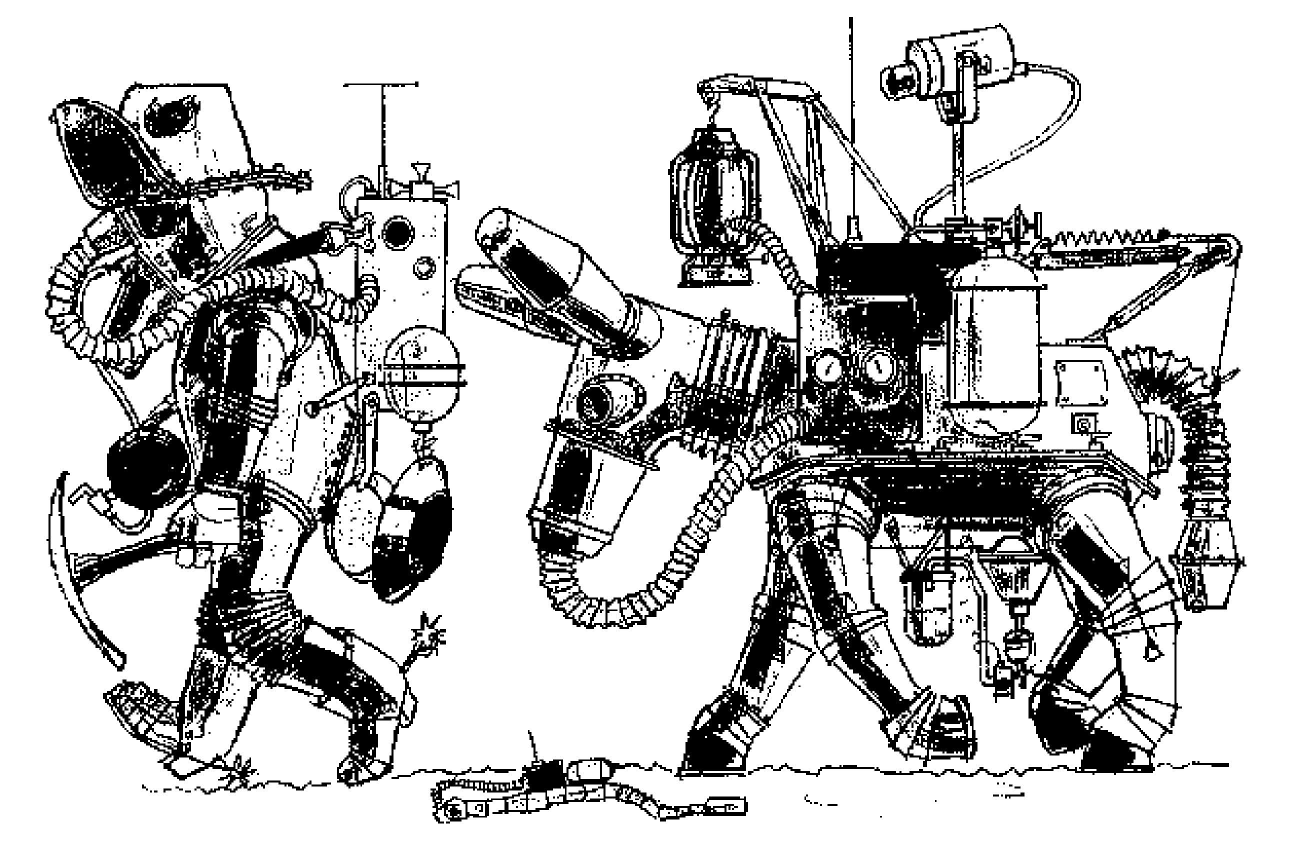
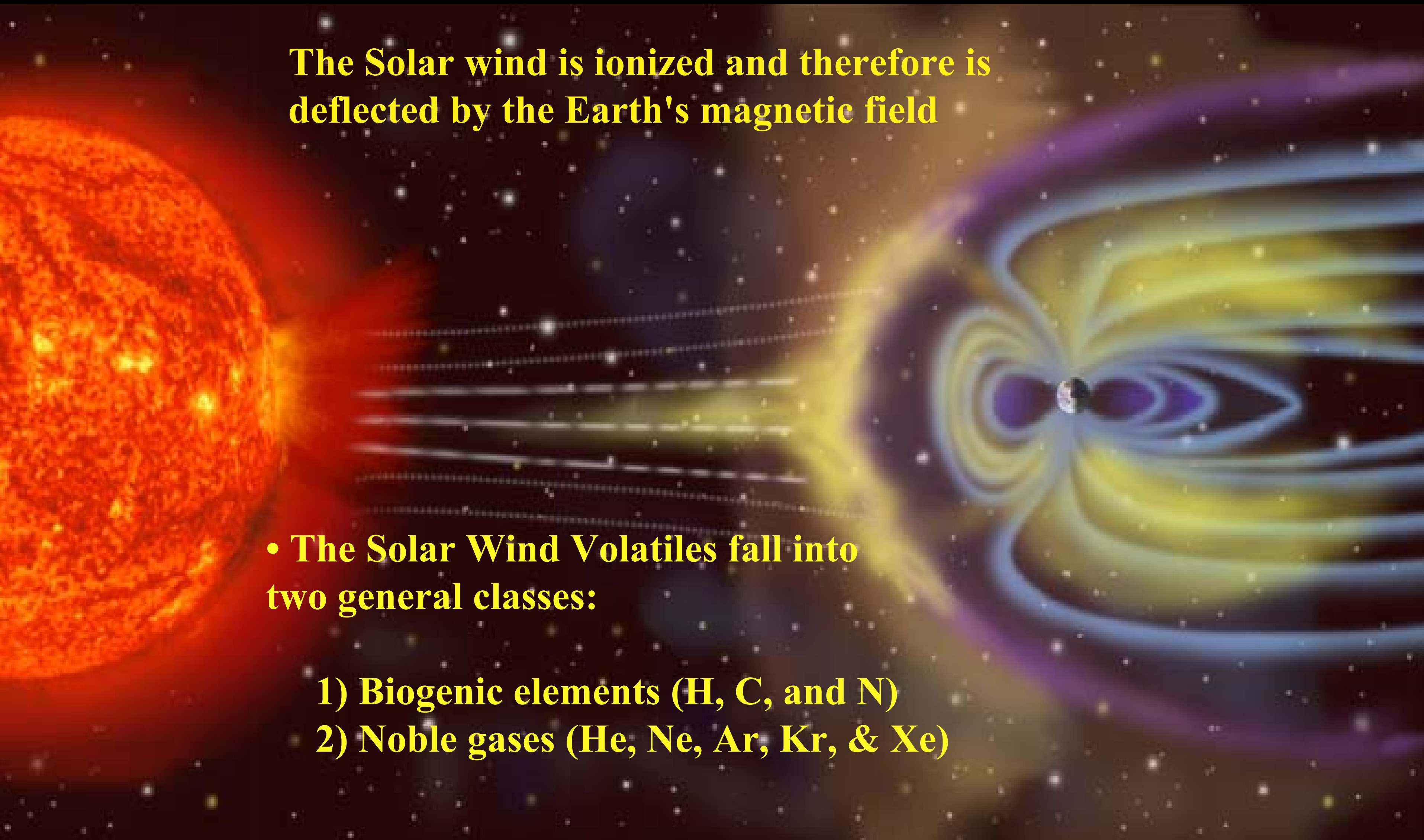
Feb. 16, 2004



The Solar Wind has been "blowing" on the planets (and Moons) of our solar system for some 4.5 billion years.



The Solar wind is ionized and therefore is deflected by the Earth's magnetic field

- The Solar Wind Volatiles fall into two general classes:

  1) Biogenic elements (H, C, and N)
  2) Noble gases (He, Ne, Ar, Kr, & Xe)

http://sec.gsfc.nasa.gov/sec_resources_imagegallery.htm

The Solar Wind Has Been an Important Source of Resources for the Moon

- **Composition of Solar Wind**:
  - 96% H, 4% He, traces (≈ 0.1%) of C, N, and O
- **Energy per particle**
  - 0.5-3 keV/amu (ave. ≈ 1 keV/amu)

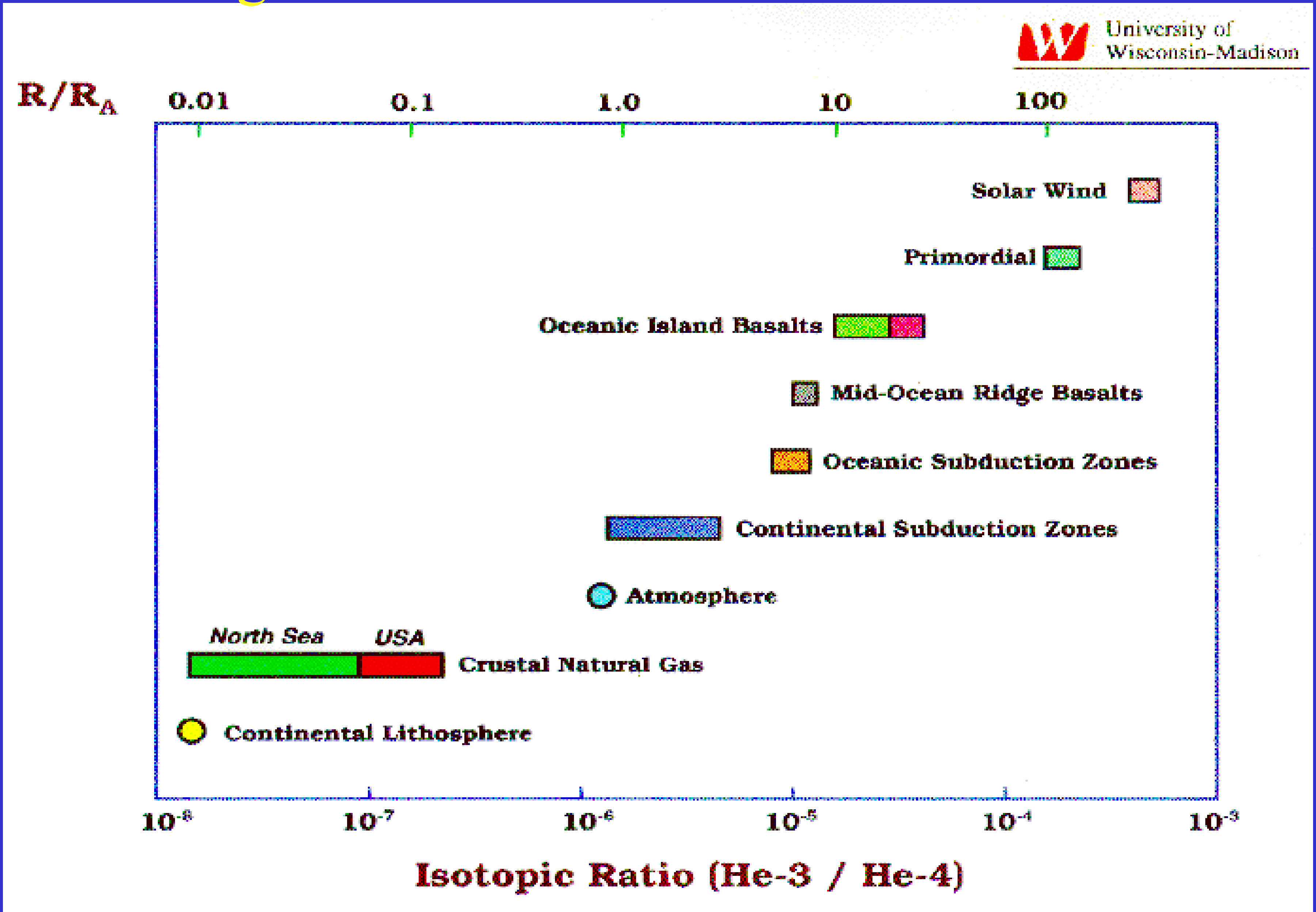
The Solar Wind Has Been an Important Source of Resources for the Moon

- Particle flux:
  - $\approx$ 1-8 x 10^8 $cm^{-2}s^{-1}$
  - ave. $\approx$ 3 x 10^8 $cm^{-2}s^{-1}$
- Number of solar wind particles that have hit the lunar surface in 4.5 billion years
  - 4 x 10^{25} particles/cm^2
- This number of atoms is equal to the number of atoms in the first 2 meters of lunar regolith.

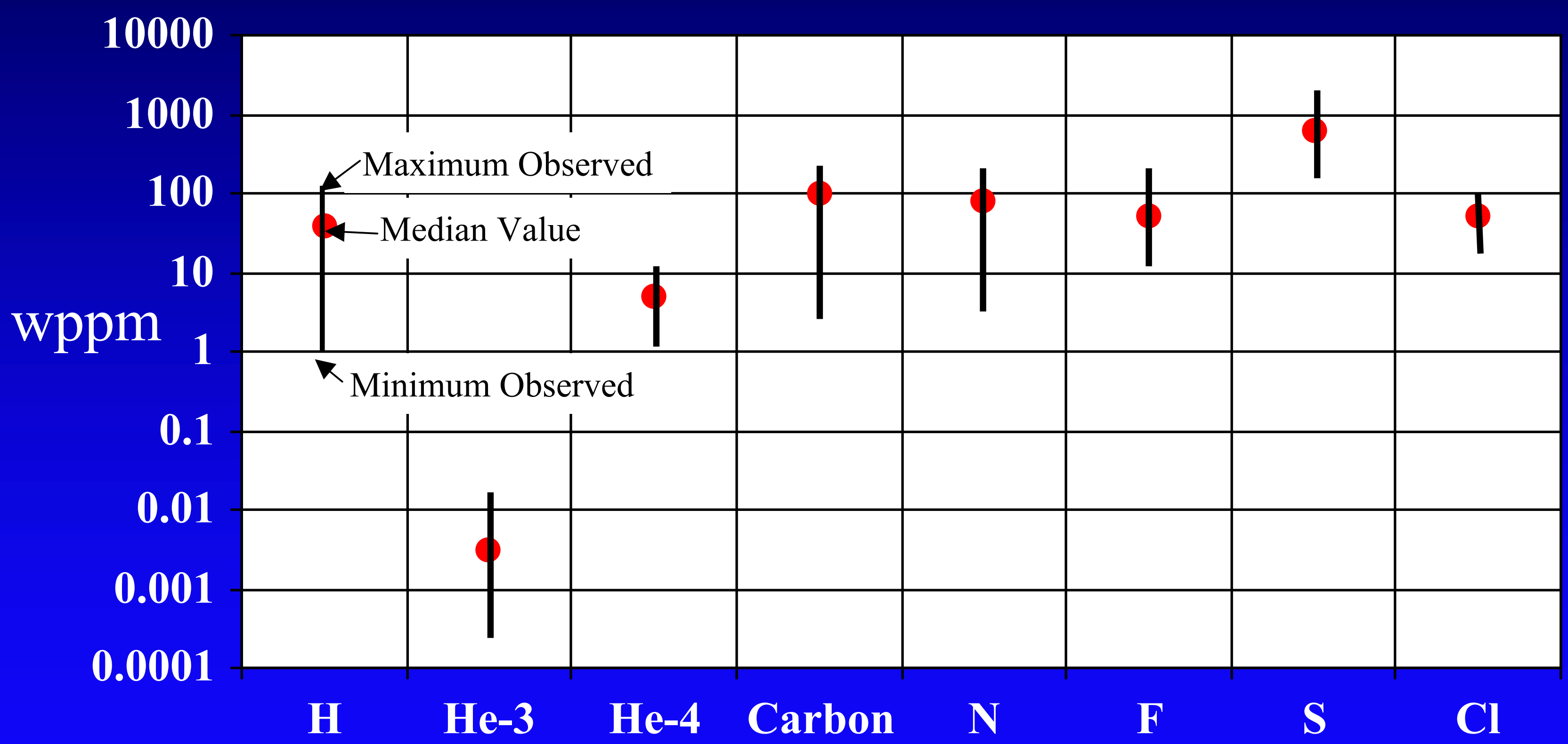
The Solar Wind Has Been an Important Source of Resources for the Moon

- The $^{3}He/^{4}He$ ratio in the solar wind is:
  - 4×10^{-4} atomic
  - 3×10^{-4} by weight
- This ratio is much different than on the Earth
  - (see Figure)
  - Source Wittenberg, 1989

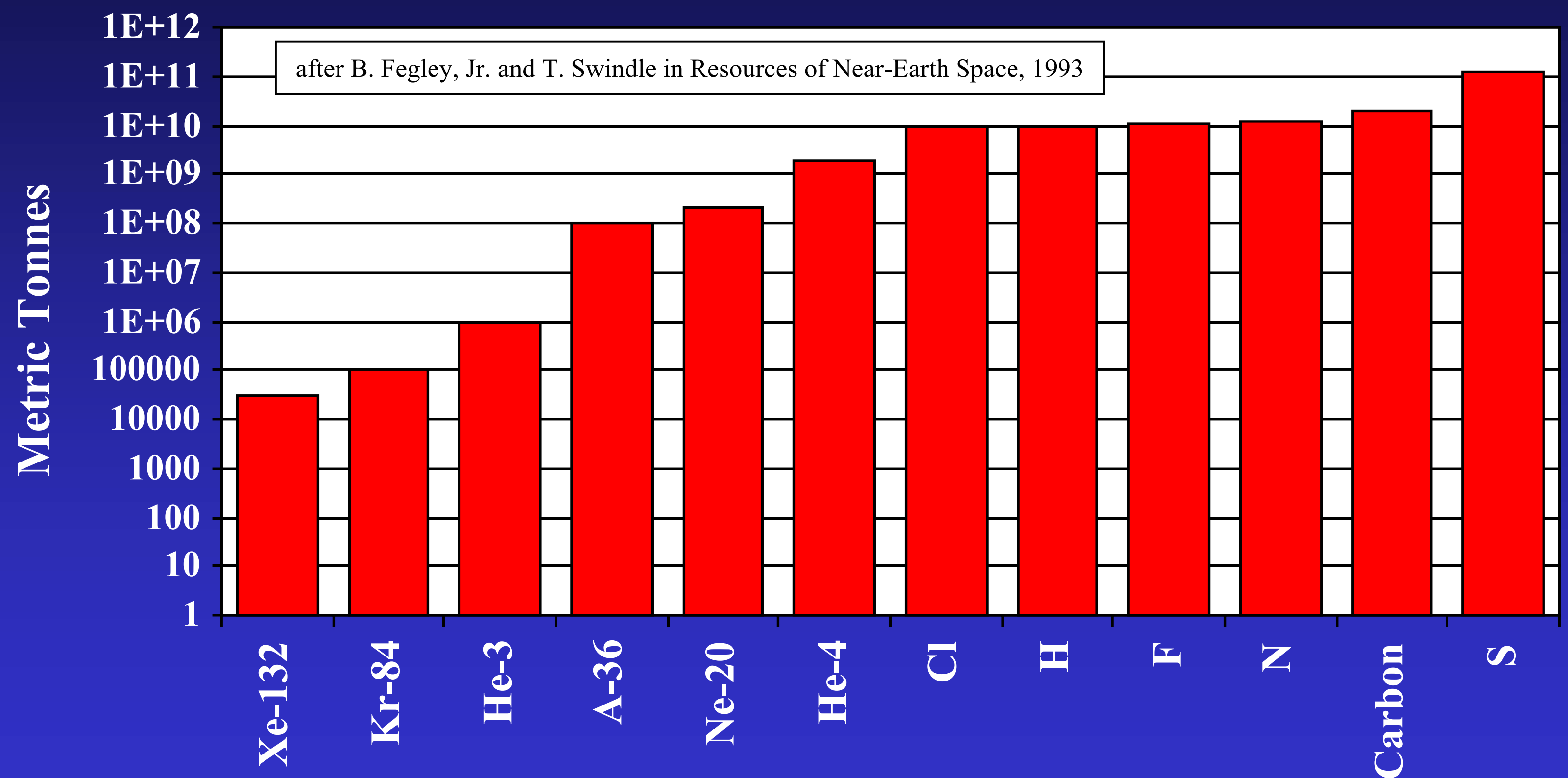
The $^3He/^4He$ ratio on the Earth can vary by orders of magnitude from the solar wind concentration



The Concentration of Lunar Volatiles in the Apollo Soil Samples Covers a Wide Range of Values

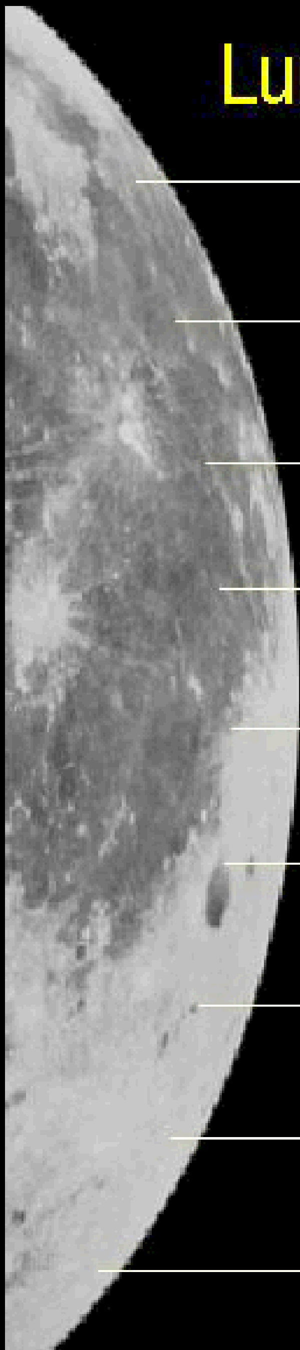


The Inventory of Volatiles in the First 3 Meters of the Lunar Regolith Can be Substantial



Note: at the present SW flux, over 500 million tonnes of ^{3}He hit the Moon over 4.5 billion years

Lunar Volatiles Have Many Applications



- **Hydrogen** Water, Rocket Fuel, Hydrocarbons, Oxygen
- **Helium-3** Fusion Energy (Propulsion, Electric Power, ...)
- **Helium-4** Atmosphere Control, Cryogenics
- **Water** Life Support, Oxygen
- **Nitrogen** Food, Atmosphere Control, Reagents
- **CO, CO_2, CH_4** Food, Hydrocarbons, Fuel
- **F_2** Oxygen & Metal Production, Teflon
- **Cl_2** Oxygen & Metal Production, Reagents
- **SO_2** Metal Extraction, H_2SO_4, Explosives, Binder for Bricks

What is Needed for Plants and Humans to Survive?

Plants

Gaseous Component	Pressure-mbar	Explanation
CO_2	>0.15	Lower limit set by photosynthesis, no upper limit
N_2	>1-10	Nitrogen Fixation
O_2	>1	Plant Respiration
Total	>10	Water + O_2 + N_2 + CO_2

Humans

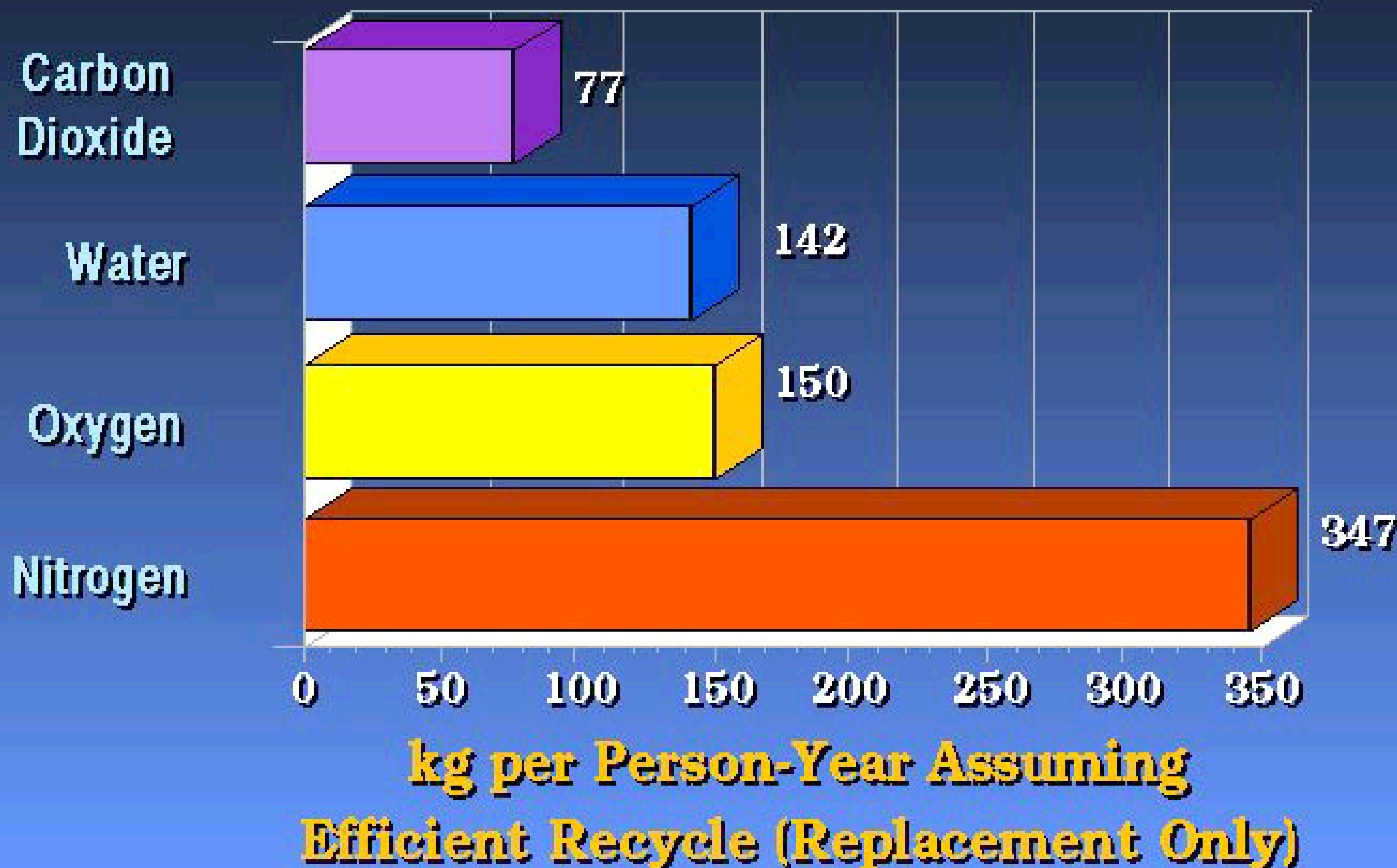
Gaseous Component	Pressure-mbar	Explanation
CO_2	<10	Set by Toxicity
N_2	>300	Buffer Gas
O_2	>130	Lower limit set by hypoxia
	<300	Upper limit set by flammability
Total	500-5,000	Lower limit based on high elevations and upper limit based on buffer gas narcosis

After E. P. McKay, Nature, 252, p. 489 (1991)

It is Important to Minimize the Per Capita Loss Rate of Solar Wind Volatiles

Compound	Use	Loss/Makeup Conditions	Loss Rate, kg/y
Nitrogen	**Food Production**	**10%/y of waste not recoverable**	**<3**
	Atmospheric Component	**Earth-like atmosphere, 1% leakage/d**	**344**
Oxygen	**Food Production, Processing & Waste Recycling**	**10%/y loss of food waste**	**55**
	Atmospheric Component	**Earth-like atmosphere, 1% leakage/d**	**95**
CO_2	Food processing and waste recycling	10%/y loss in processed food	77
Water	Drinking, Food Production, Processing and Waste Recycling	10% loss of potable water/y	142
		Total	716

The Total Amount of Volatiles Required to Support 1 Person-Year on the Lunar Surface Exceeds 700 kg/year

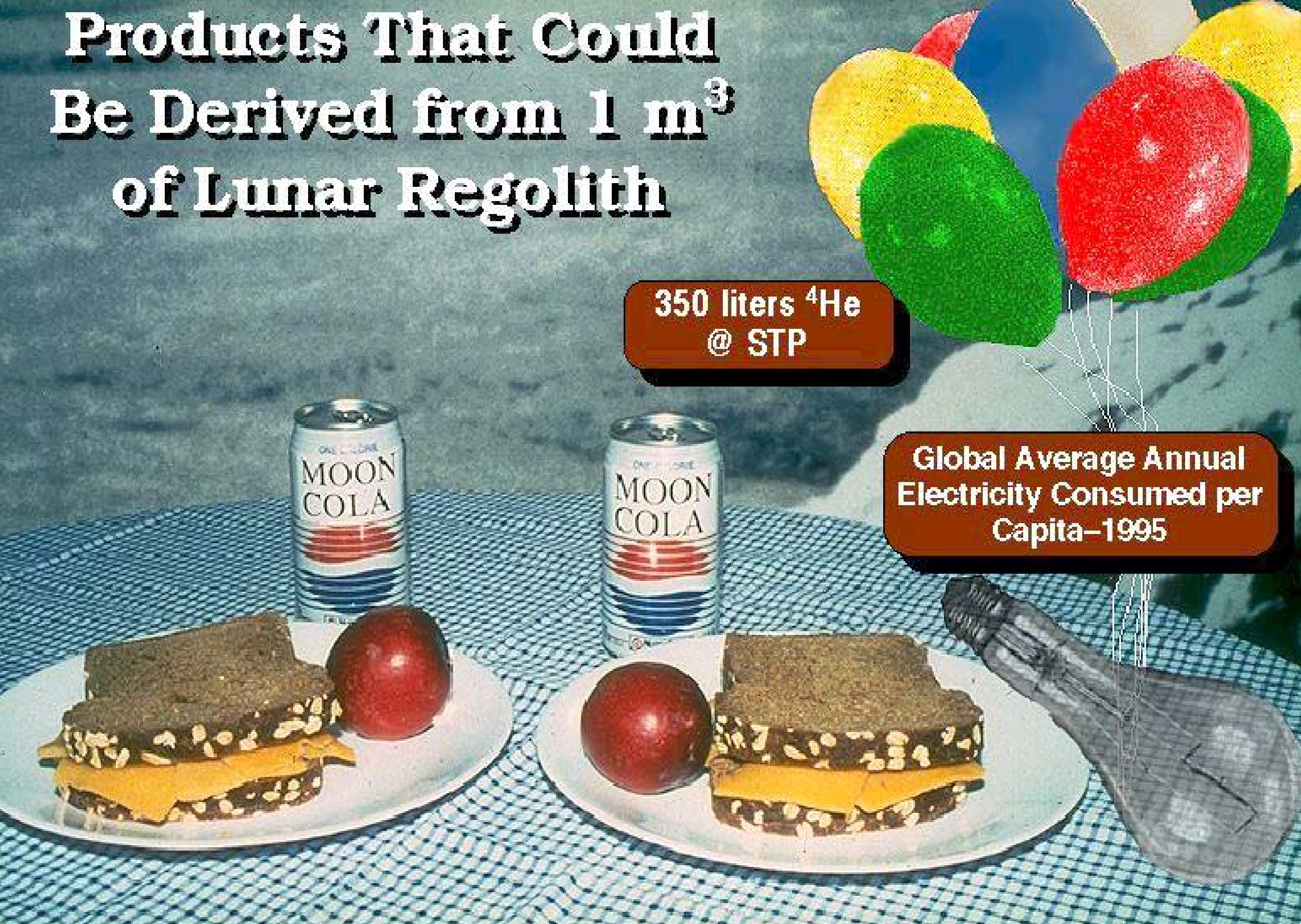


It is Important to Minimize the Per Capita Loss Rate of Solar Wind Volatiles

Element	Use	Loss Rate kg/y
N_2	Food, Atmosphere	347
O_2	Food, Water, Atmosphere	332
C	Food	21
H_2	Water, Food	16
	Total	716

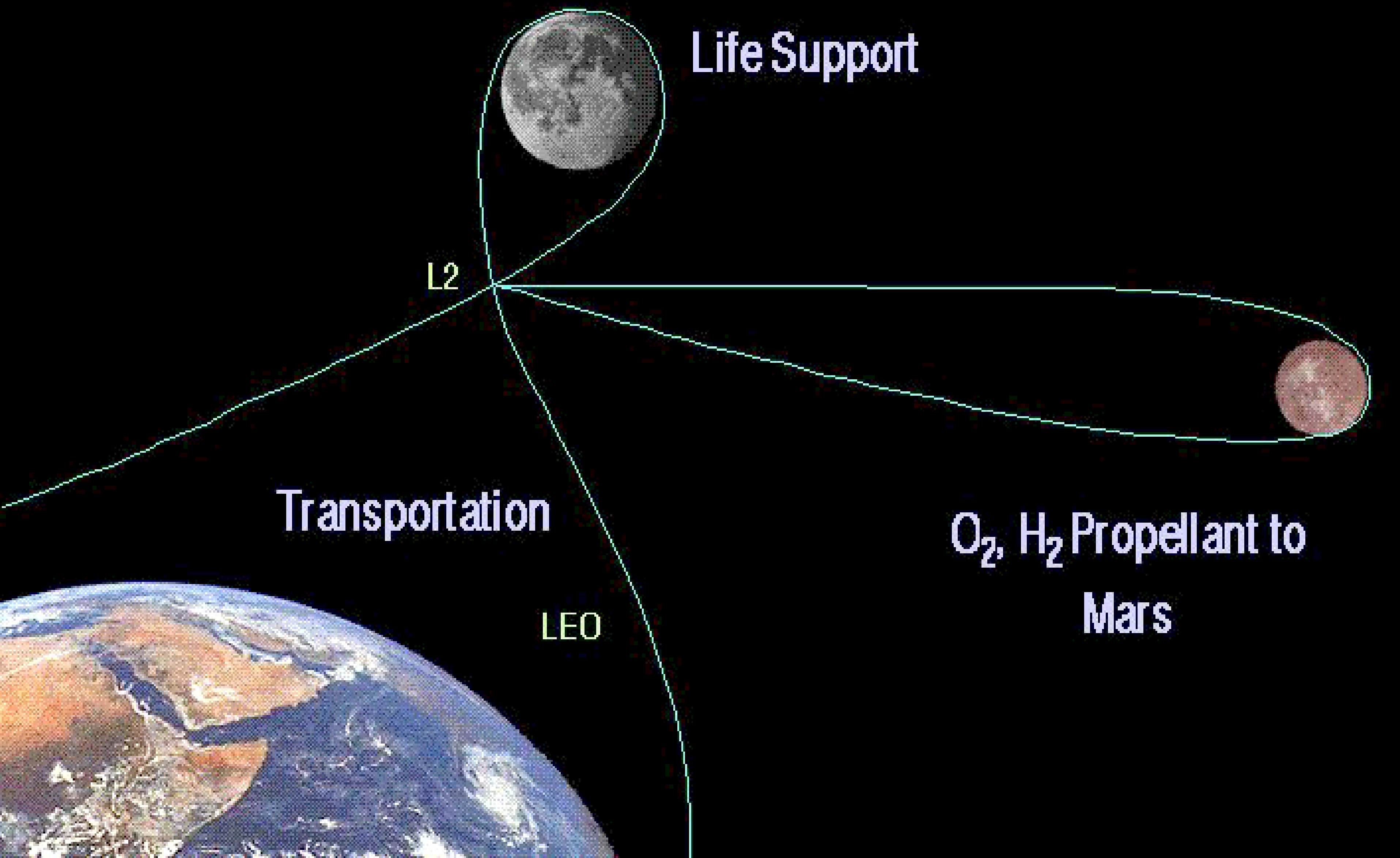
The Cost to Supply All the Volatiles Needed by a Base Camp of 10 People on the Moon is ≈ $1 Billion/y

- Present cost to LEO is ≈ 10-20,000 $/kg
- Sherwood and Woodcock, Boeing--1993, calculate that it will cost 7-10X as much to place cargo on the Moon
- The minimum life support mass (volatiles) is ≈ 700 kg/person-y
- The total cost to supply volatiles ranges from 50 to 150 $M per person year (today)
- A reasonable average cost is ≈ 100 $M /person-y times 10 persons is ≈ 1 $B/y



modified from Jeff Taylor and Larry Haskin

There are at Least 3 Areas That Could Benefit from Lunar Volatiles in the Near Term

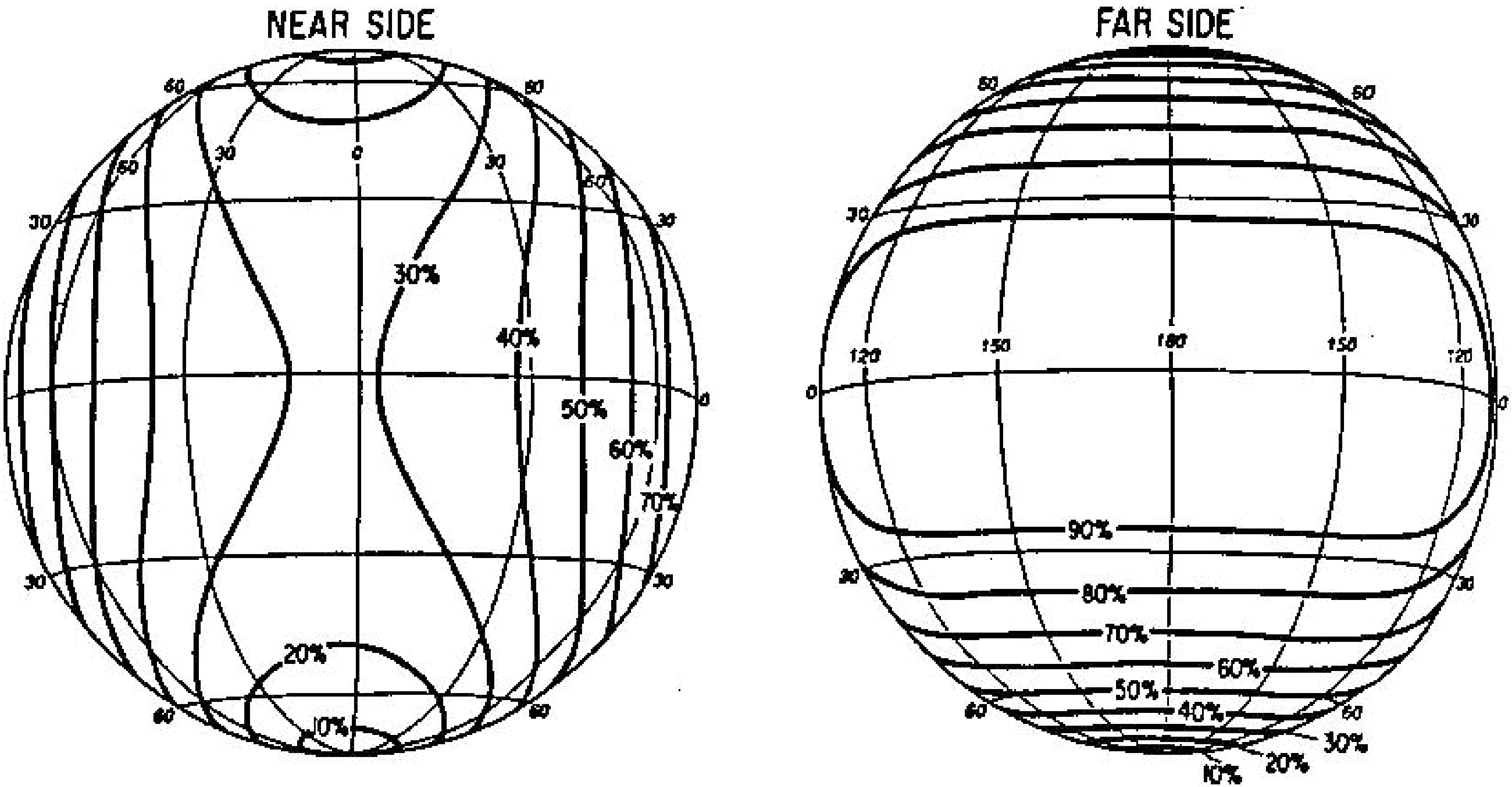


Many Factors go into the Calculation of the Amount of Solar Wind Volatiles That Can Be Recovered from the Moon

- Flux of $(SWV)_i$ to the lunar surface
  - *f(latitude, longitude, t)*
- Geographic location of $(\text{host material})_j$ on the Moon
  - *f(latitude, longitude, depth, t)*
- Fraction of $(SWV)_i$ retained by $(\text{host material})_j$
  - *f(t, T)*
- Fraction of $(\text{host material})_j$ that can be readily mined
  - *f(depth, location, obstacles, grain size)*
- Fraction of $(SWV)_i$ released from $(\text{host material})_j$ after mining
  - $f(T, t_{anneal})$

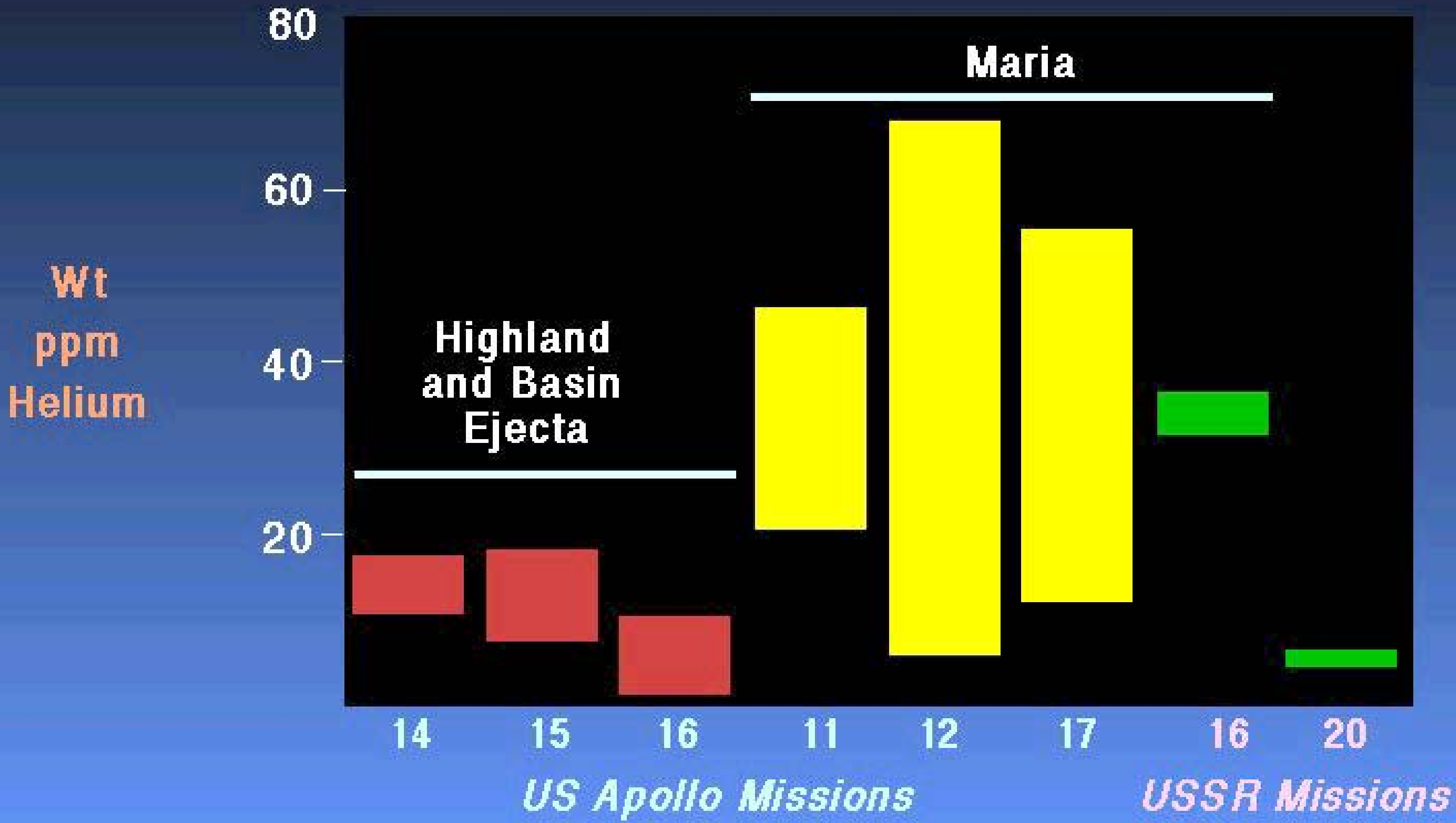
As the Moon passes in and out of the Solar Wind, and as a consequence of having one side always facing the Earth, the Solar Wind is distributed preferentially on the "far side" of the Moon. The "near side" collects only ~ 1/3 that of the "far side" (Swindle, 1992).

The Relative Solar Wind Exposure Depends on the Lunar Latitude and Longitude

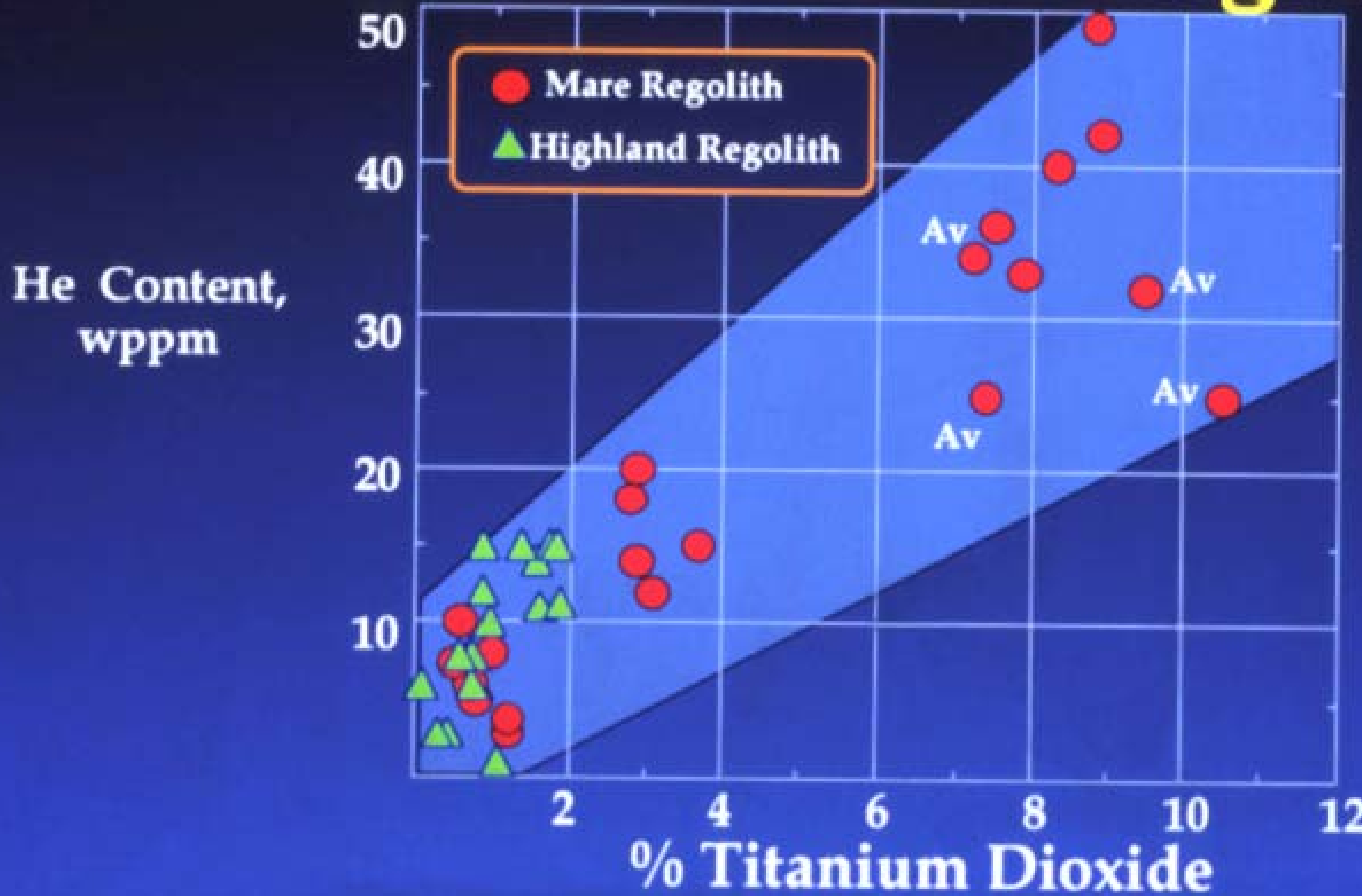


Source: T. D. Swindle et. al., Lunar & Plantary Science, XXIII:1395, 1992

Measured Helium Content in Lunar Samples

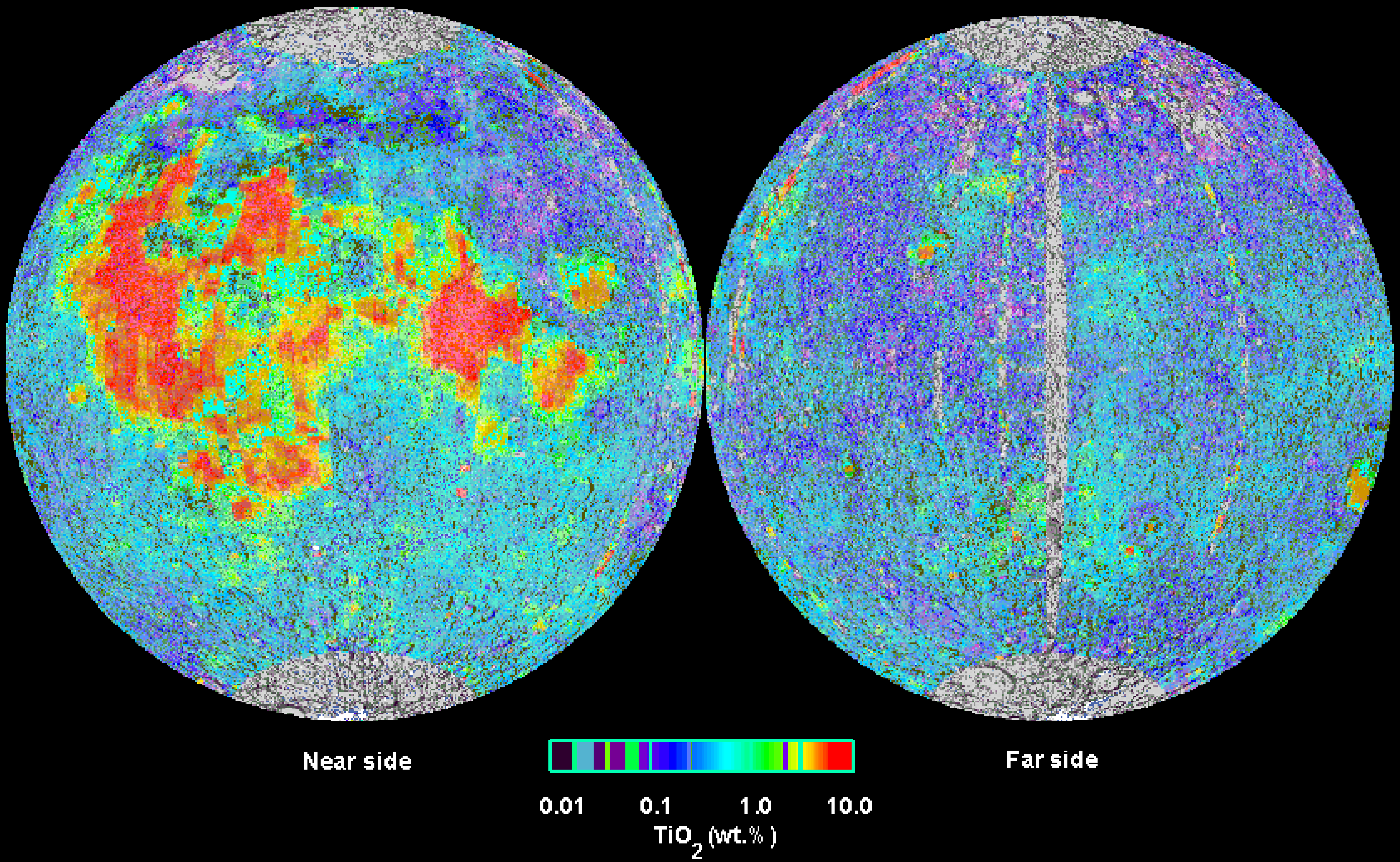


Correlation of Helium Content With TiO2 in Lunar Regolith

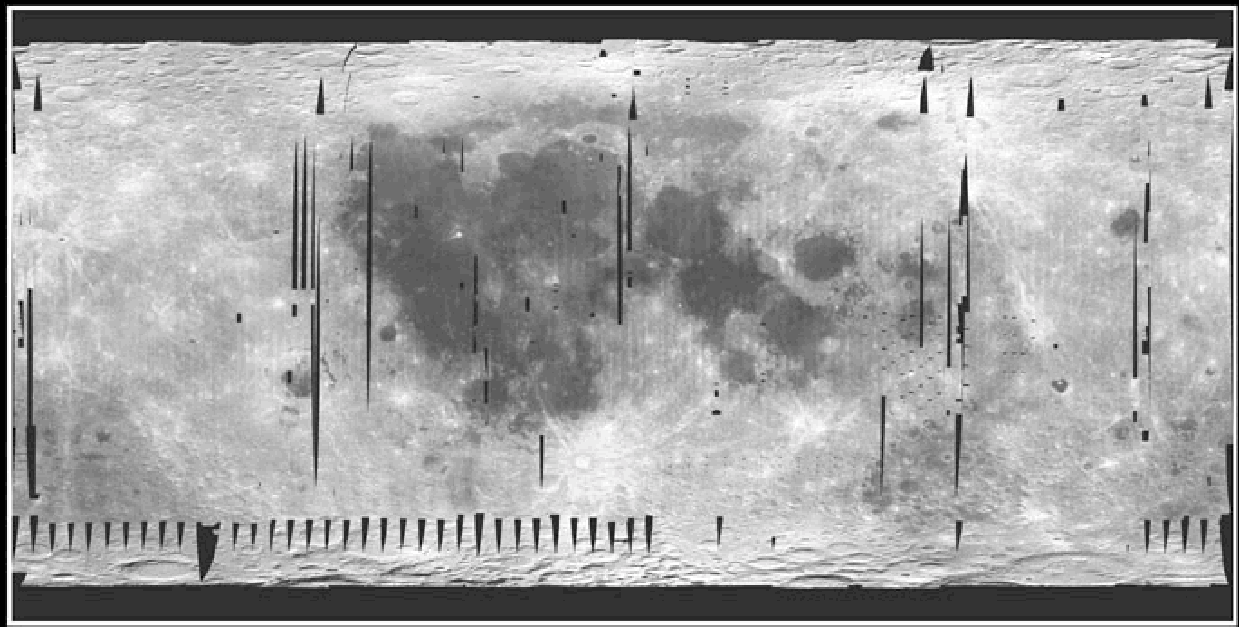


Clementine Titanium Map of the Moon

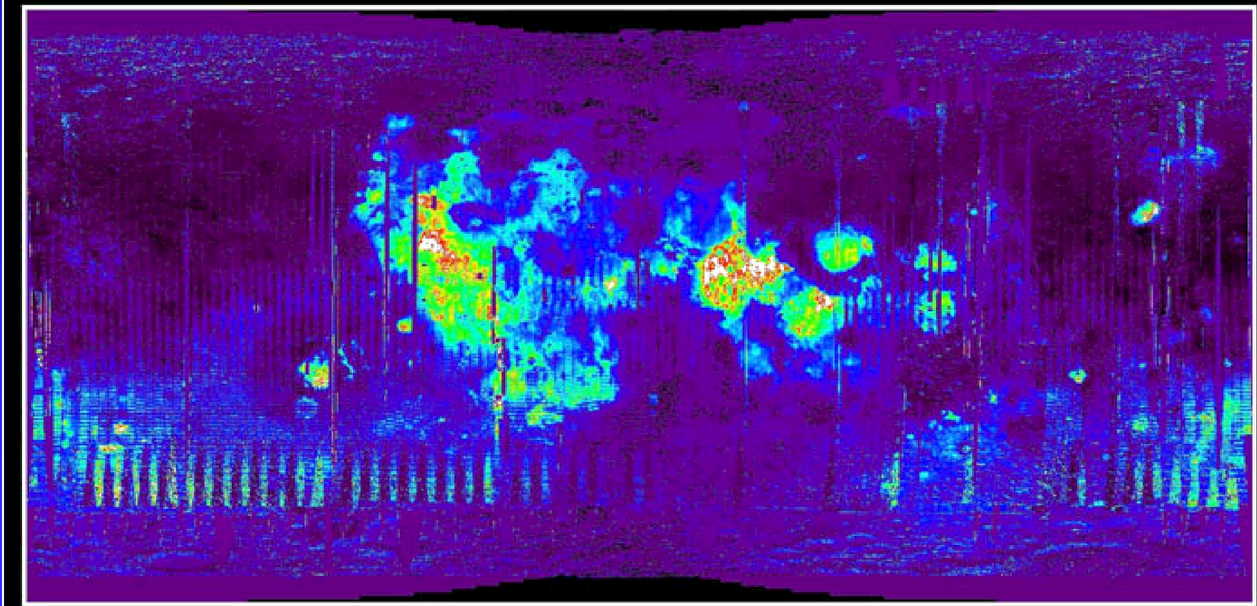
Equal Area Projection



J. Johnson et al. (1999) show that the Ti and maturity index can help identify potential locations of He-3.

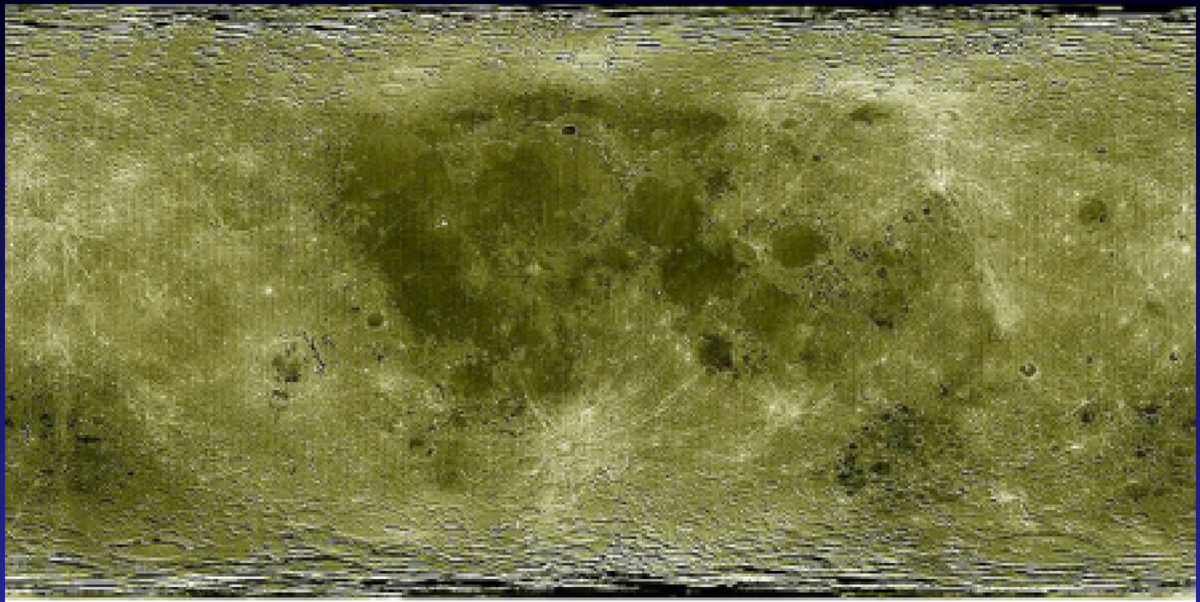


Clementine Lunar Mosaic

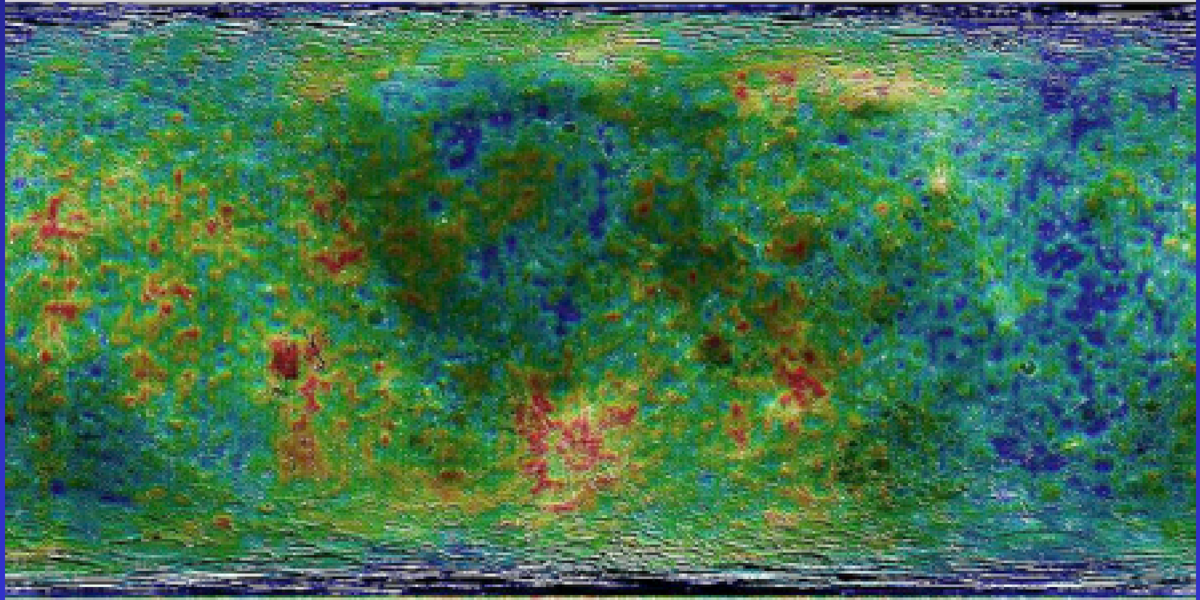


Estimated Helium-3 Abundance

Lunar Prospector data shows the distribution of H on the surface of the Moon.



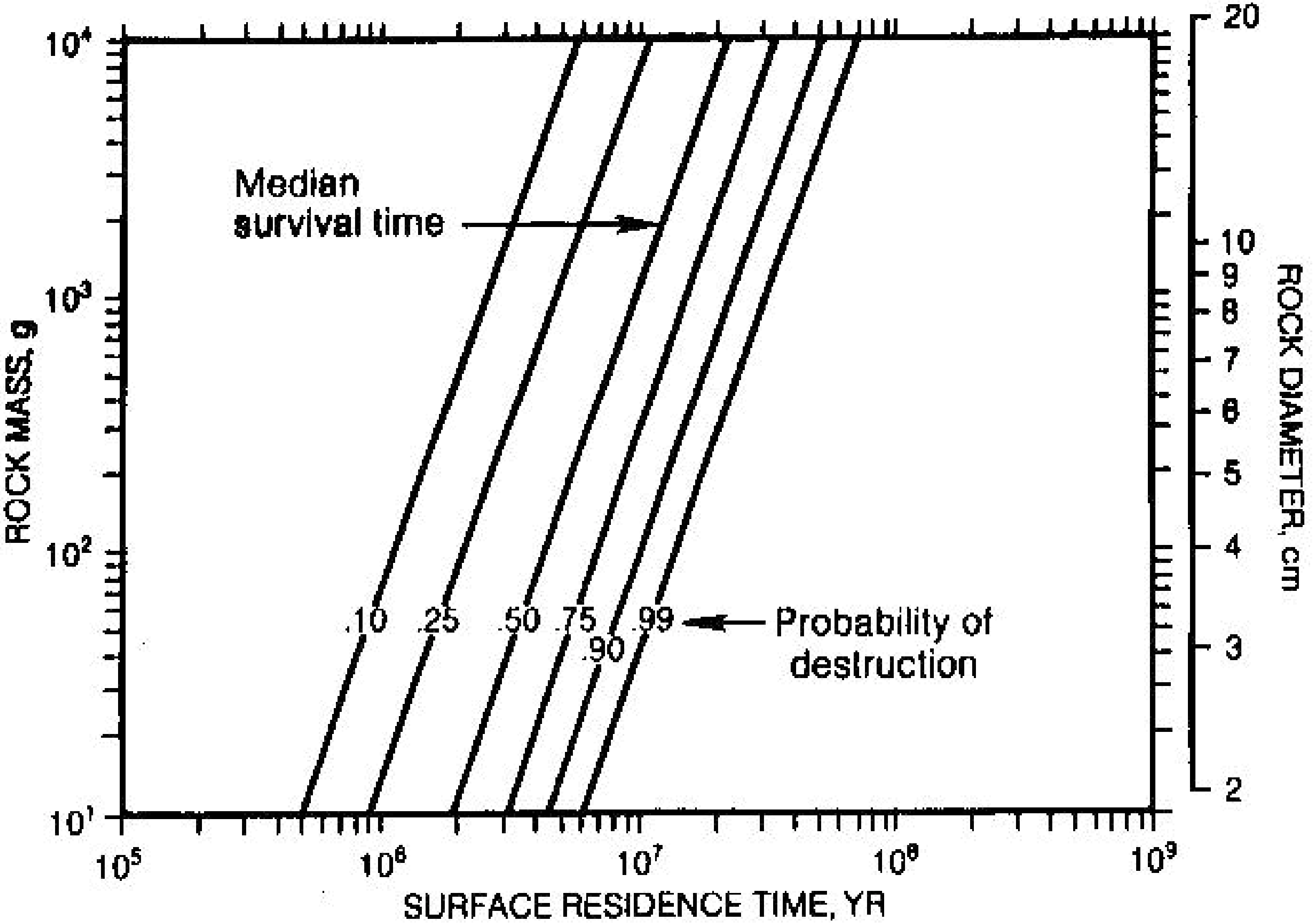
Surface



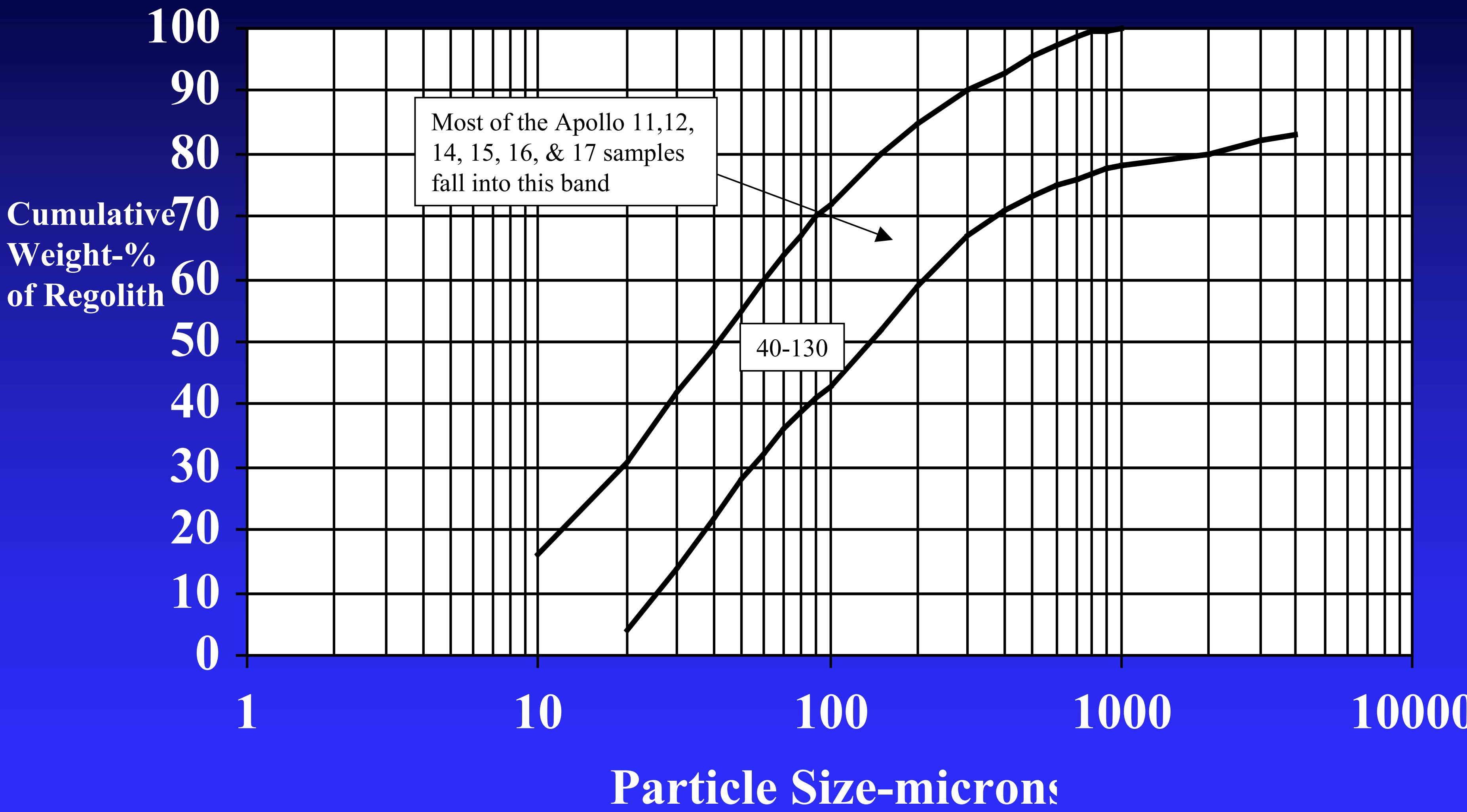
Hydrogen

The regolith in those regions is made up of very fine grains which has been gardened by meteorites over billions of years (NASA Photo).

The Median Survival Time of Most Rocks on the Lunar Surface is From 2-20 Million Years

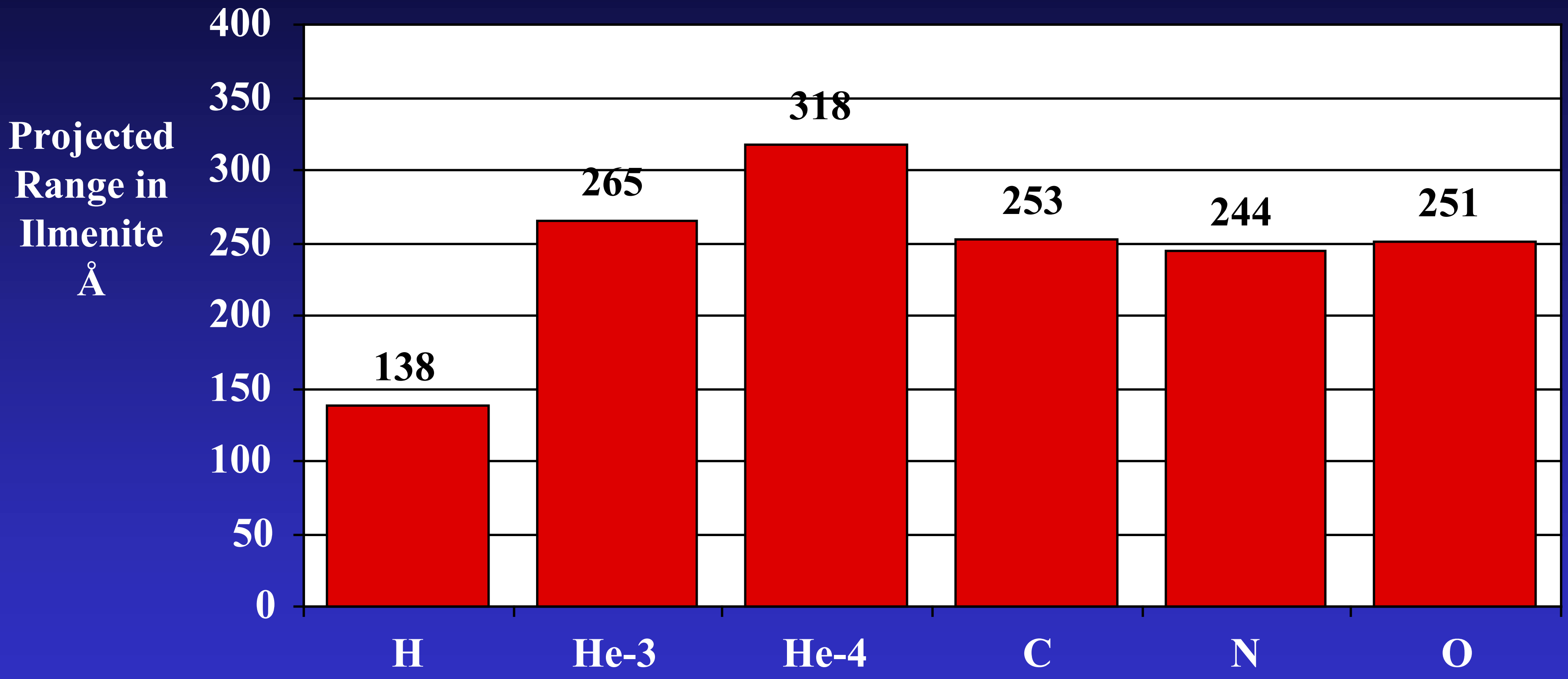


The Average Grain Size of Lunar Samples from the Apollo Missions Ranges from 40-130 Microns



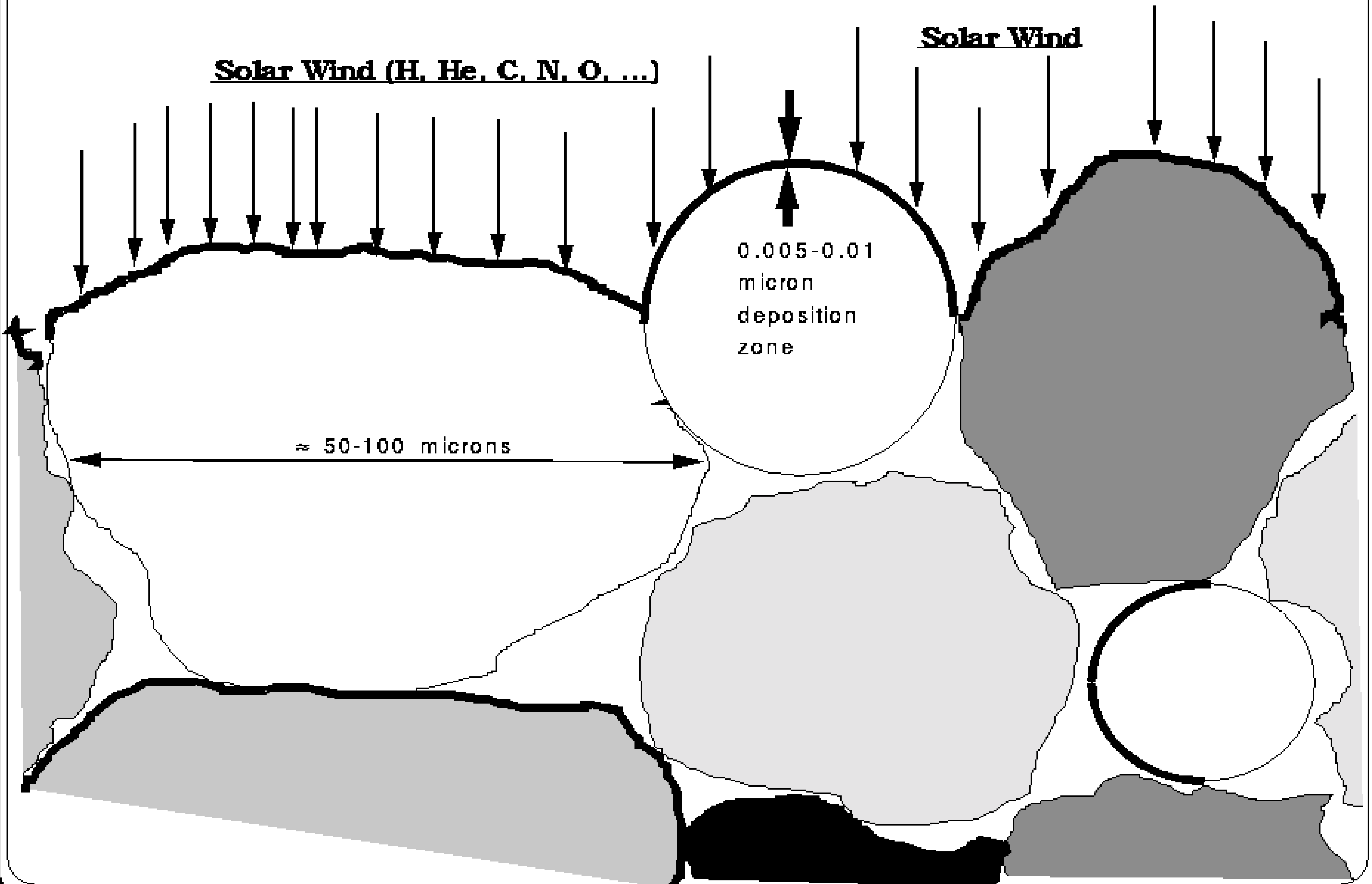
After Carrier and Mitchell, 1989

The Solar Wind Ions are Initially Depositied Within the First 320 Å of the Ilmenite Grains

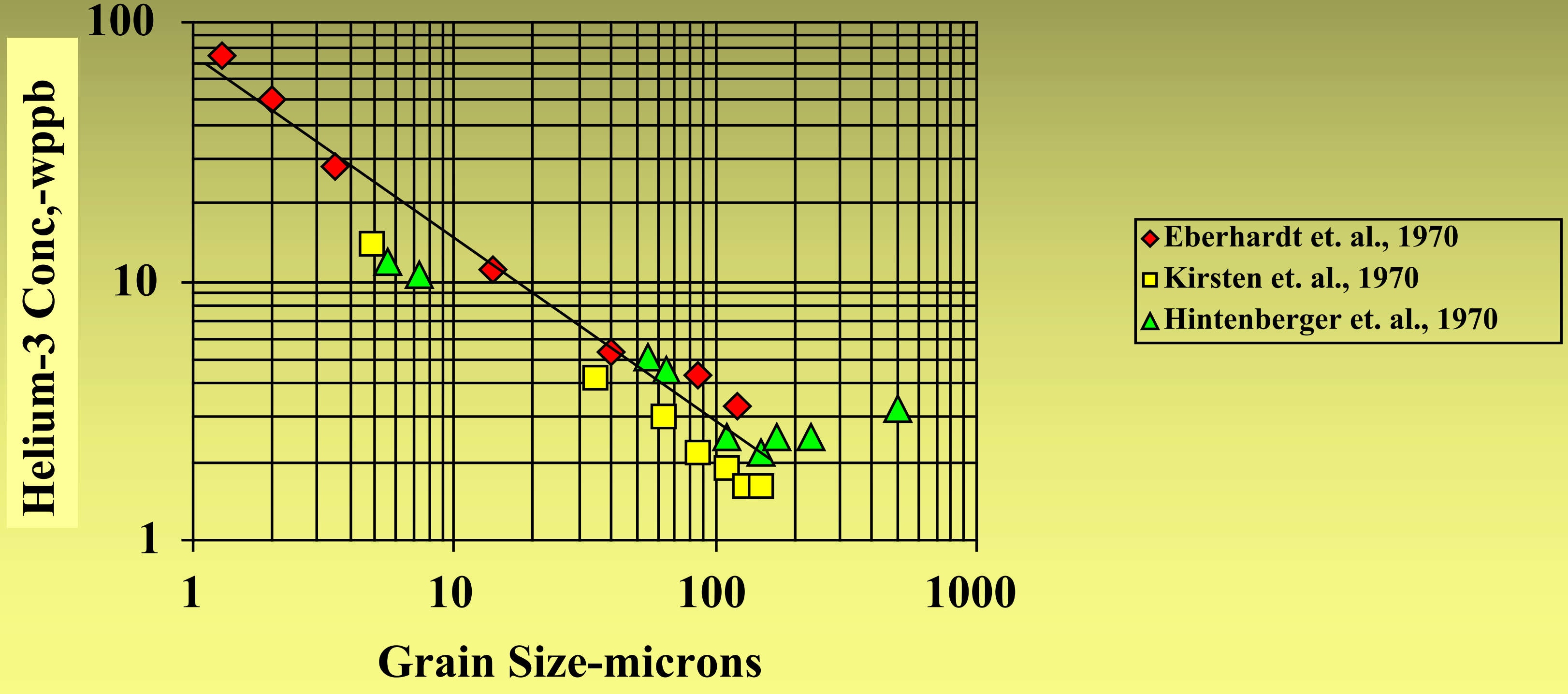


Ave. Energy 1 keV/amu, 500 Histories-TRIM Code (Kim Kuhlman-1996)

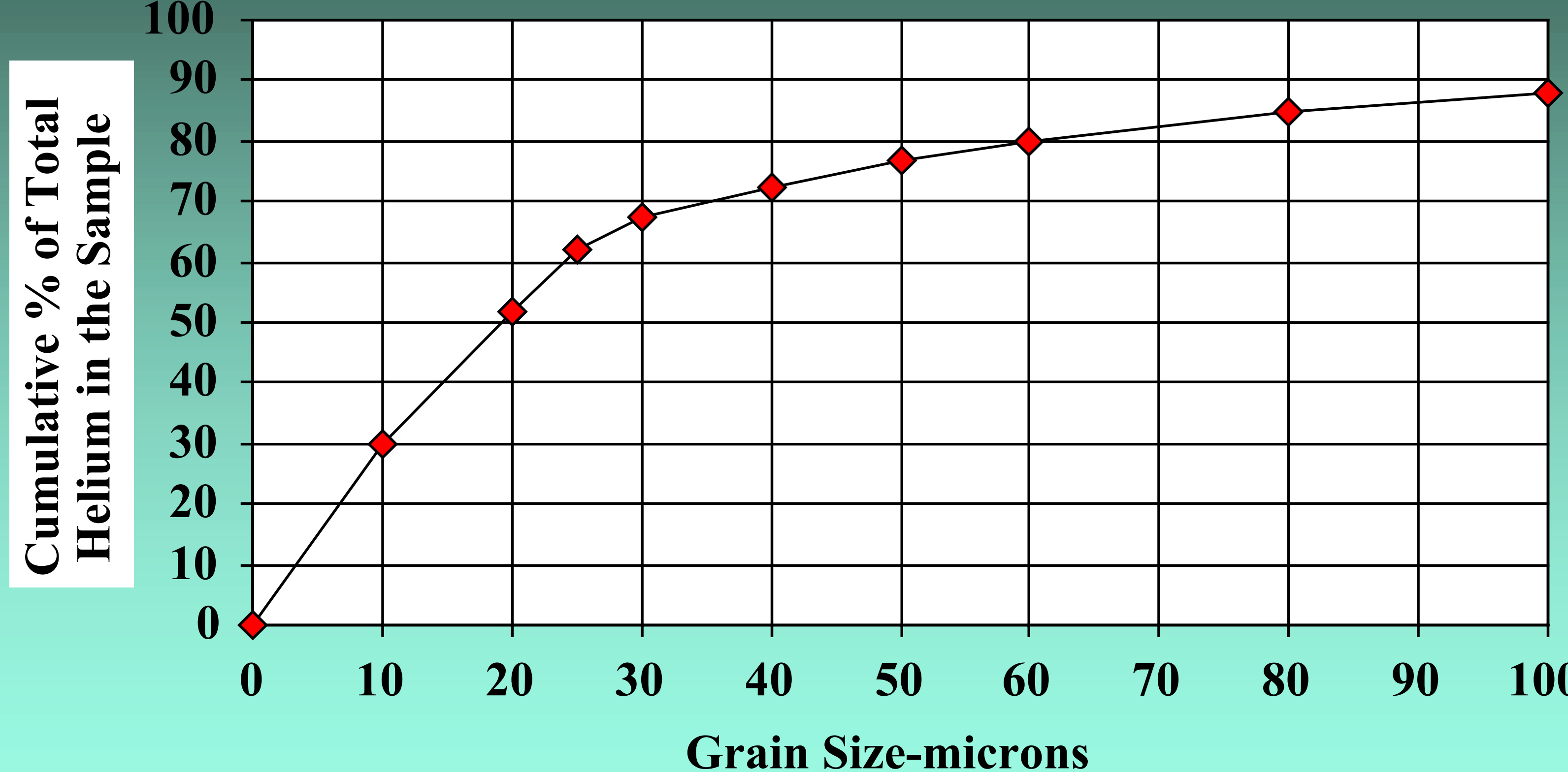
The Solar Wind ions Do Not Penetrate Very Deep Into the Lunar Regolith



The Concentration of Helium-3 in Apollo-11 Sample 10084 is Definitely Higher in Smaller Grains



Most of the Helium in the Apollo-11 Sample 10084 is Contained in Particles Below 50 Microns



After E. N. Cameron-1987

How Do We Calculate the Efficiency of Solar Wind Volatiles Evolution?

- One way is to maximize the amount of SWV's evolved divided by the energy used to release the SWV's

The Amount of Solar Wind Volatiles Available Depends on the Grain Size of the Host Material

- **Define**
  - **C_{SWV} = conc. of SWV's in implanted zone of the host material**
  - **f_i = fraction of particles with radii between r_i and r_{i+1}**
  - **Δx = depth of implanted zone**
  - **r_i = ave. radius of the particles with radii from r_i to r_{i+1}**

Then the maximum amount of SWV's is:

$$= C_{swv} \bullet \Delta x \bullet \sum_{i=1}^{N} f_i \bullet 4\pi r_i^2$$

The Energy Required for Solar Wind Volatiles Evolution Also Depends on the Grain Size of the Host Material

- **Define**
  - **C_p = Heat capacity of host material**
    ΔT = Temperature increase needed to evolve the SWV's

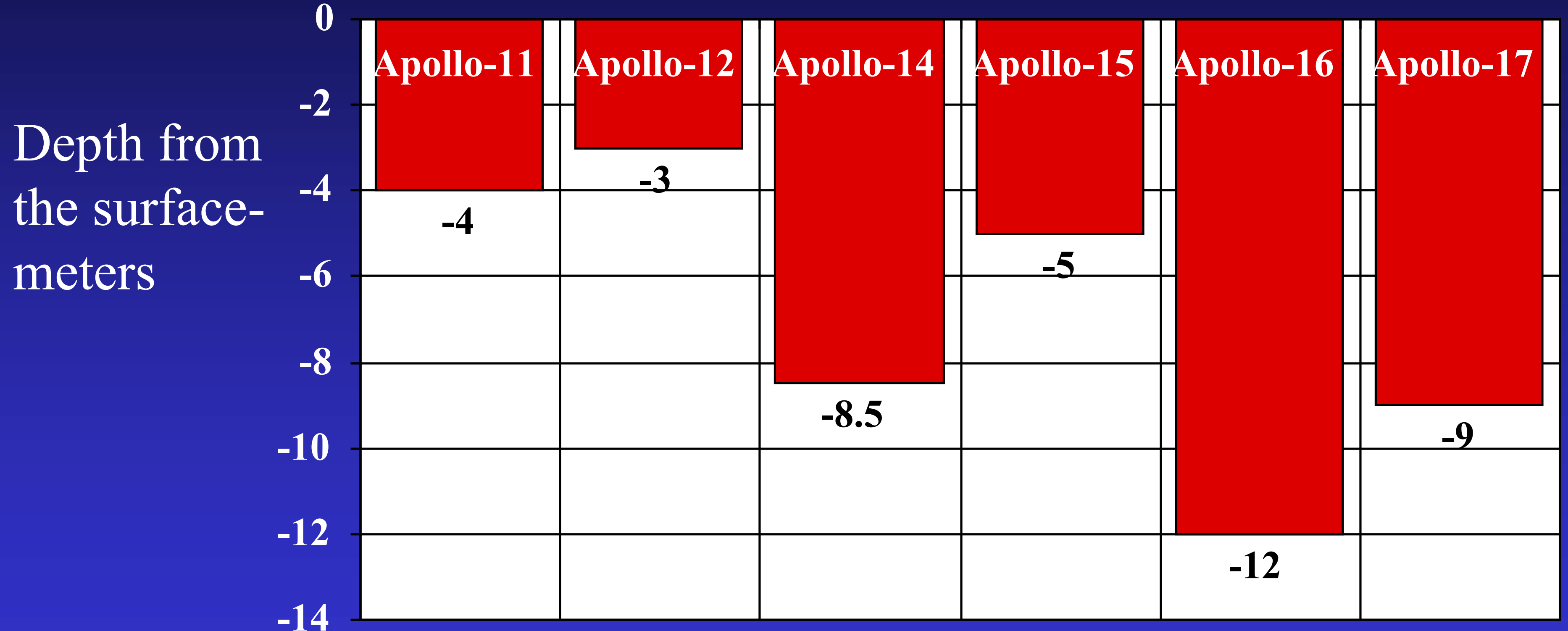
The energy needed to heat the SWV containing material to temperature T is:

$$= C_p \bullet \Delta T \bullet \sum_{i=1}^{N} f_i \bullet \frac{4\pi r_i^3}{3}$$

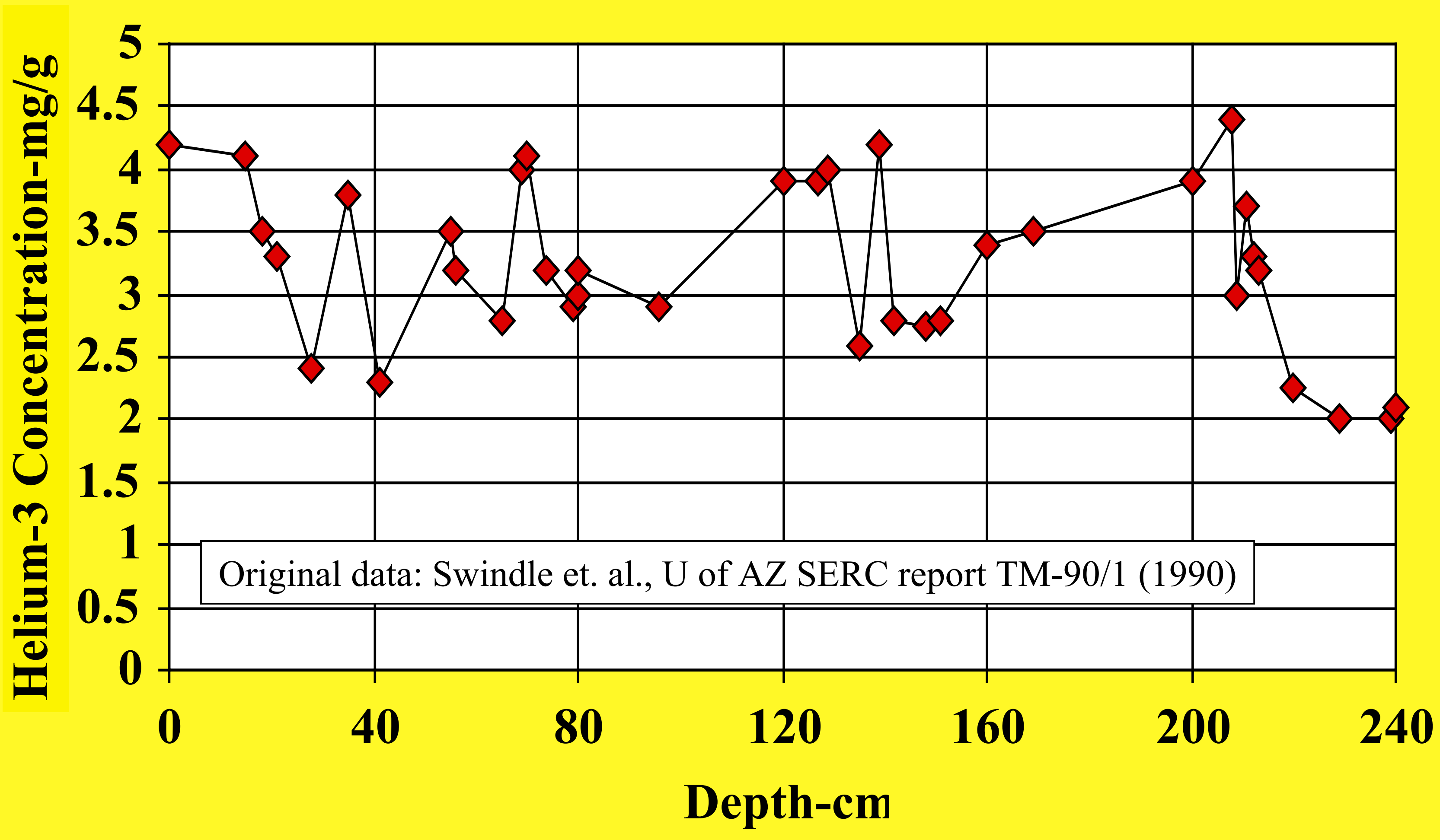
The Maximum SWV Return for a Given Energy Investment is Inversely Proportional to the Grain Size

$$\left(\frac{C_{swv} \bullet \Delta x}{C_{p} \bullet \Delta T}\right) \bullet \left(\frac{1}{r_{i}}\right)$$

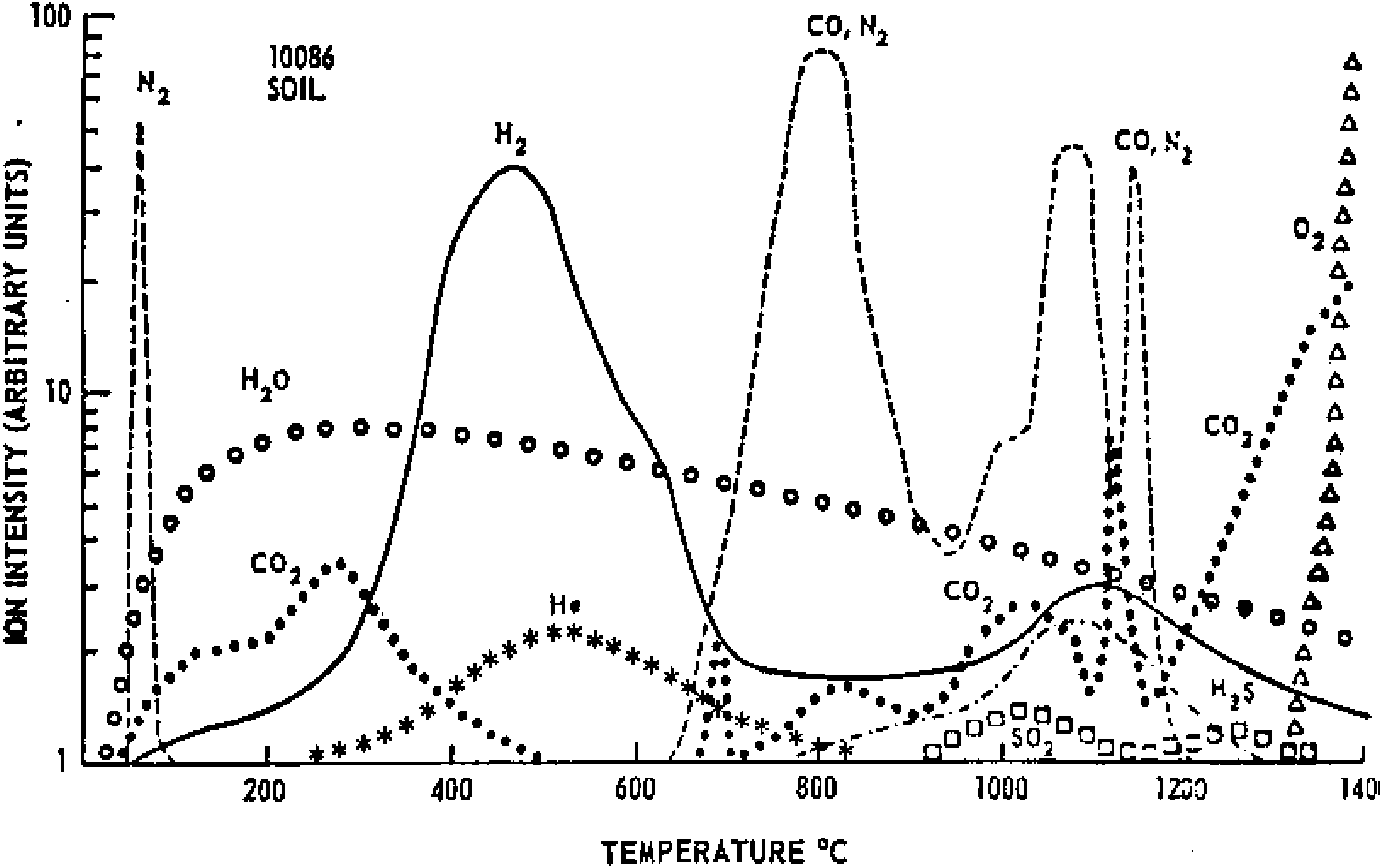
The Depth of the Regolith Varies Considerably from Site to Site



The Concentration of ^3He in Apollo-15 Drill Core Samples Remains Reasonably Constant With Depth

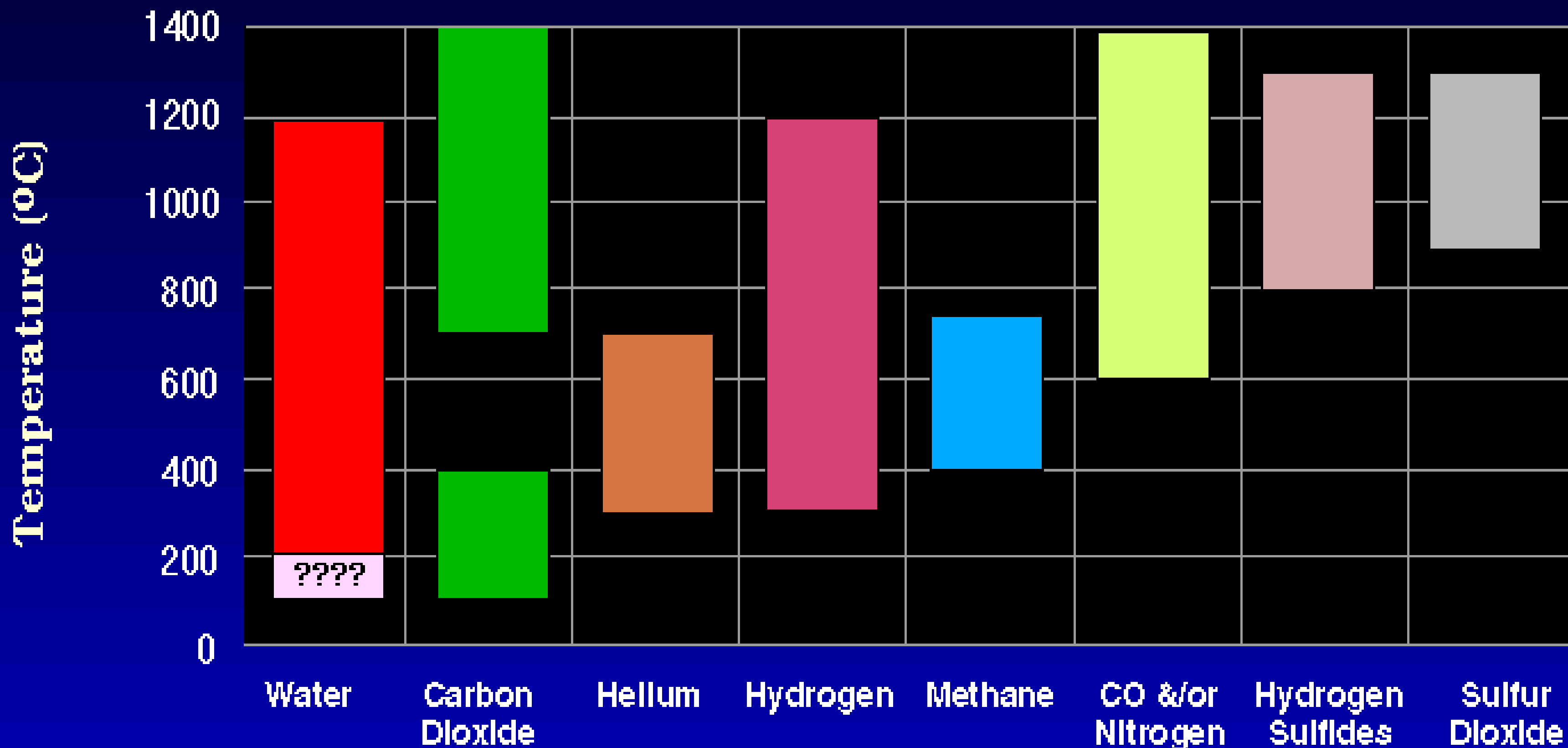


The Original Gas Release Pattern for the Apollo-11 Sample 10086,16 Was Very Complex



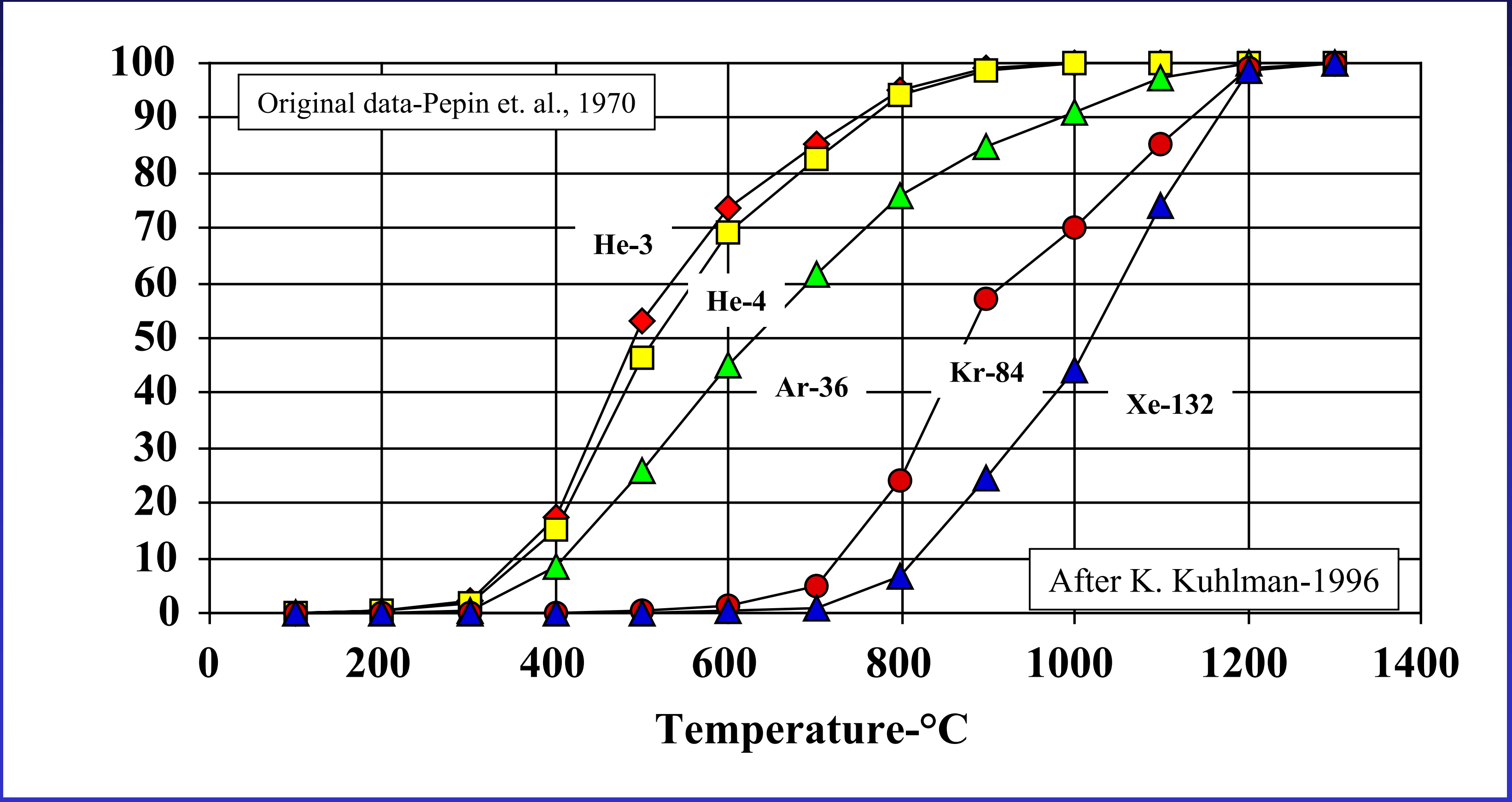
Source: Gibson and Johnson, Proc. 2nd Lunar Science Conf., 2, p. 1351(1971)

The Release of Lunar Volatiles (i.e. > 90%) Occurs Over a Wide Range of Temperatures

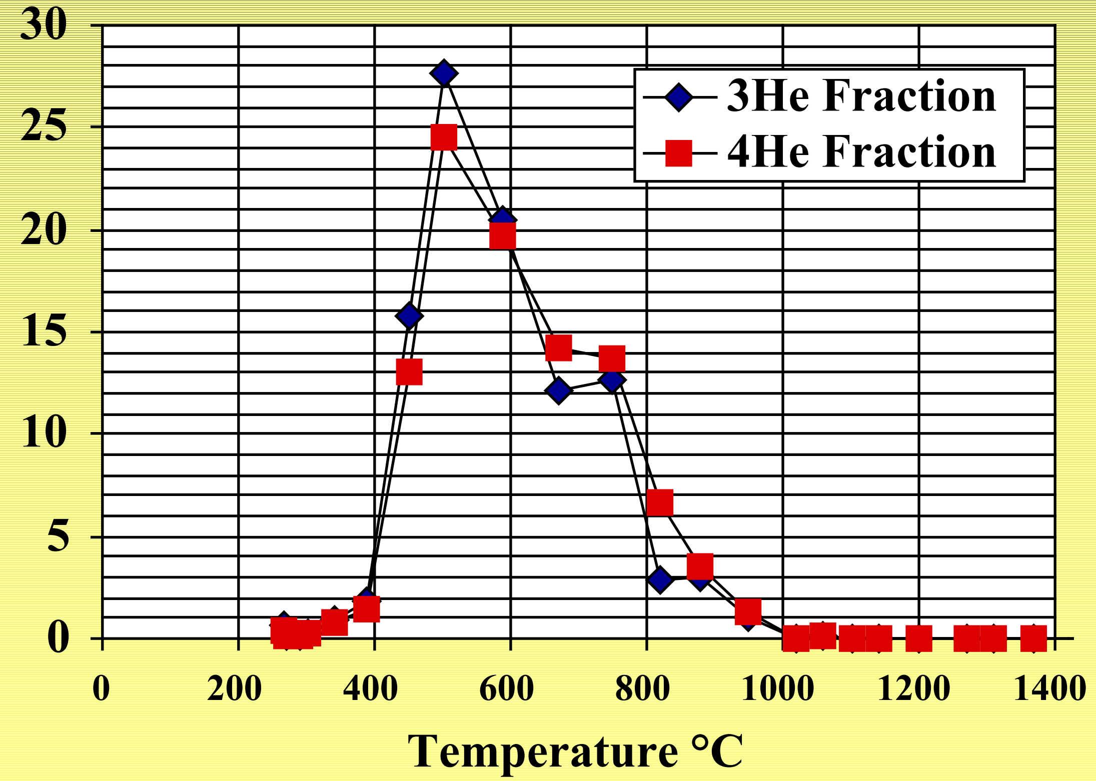


Source of Data: Gibson and Johnson, Proc. 2nd Lunar Sci. Conf. (1971)

Noble Gases Can be Removed from Lunar Regolith by Heating to 800-1,200 °C



The Peak Release Rate of Helium Isotopes from Apollo-11 Regolith Occurs at 500 °C



Original Data
Pepin et. al.,
(1970)

Observations

- The solar wind could be a major source of life supporting elements such as H, C, N, and O on the Moon.
- Heating the regolith to high enough temperatures could cause the H to react with the oxygen in the lunar regolith to supply the water needed for early settlers on the Moon.
- Other SWV's such as ^{3}He and ^{4}He could play important roles in the future of the Moon.
- Extraction of SWV's will require significant thermal energy sources (solar? nuclear?).