POTENTIAL RESOURCES OF THE MOON

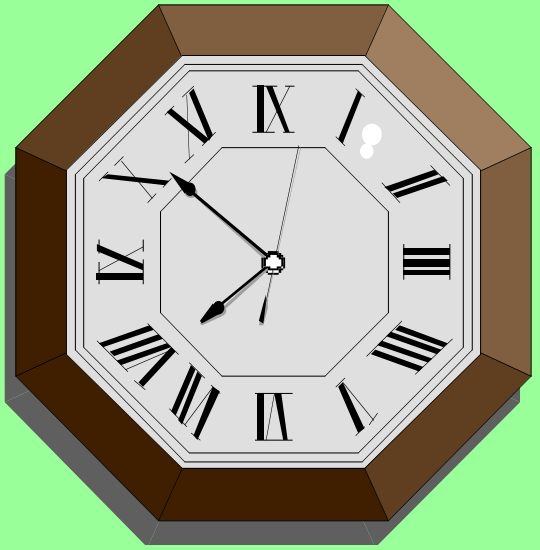
LUNAR RESOURSE ACCESSIBILITY

MAJOR FACTORS

- **ORIGINAL ROCK COMPOSTION**
- **REGOLITH FORMATION**
- **IGNEOUS CRYSTAL SETTLING**
- **ABSENCE OF FLUID WATER**

REGOLITH MATURATION

- **BEGINS WITH SURFACE STABLIZATION**
  - **MODIFICATION BY:**
    - **PRIMARY IMPACTS**
    - **SECONDARY IMPACTS**
    - **HYDROGEN REDUCTION OF FEO**
    - **SPACE RADIATION**
    - **INTERNAL VOLATILE MIGRATION**
- **SPACE RADIATION**
  - **COSMIC RAYS**
  - **SOLAR-WIND IONS**



REGOLITH SUMMARY - 1

- **REGOLITH (mantle of fragmental, unconsolidated material overlying bedrock)**
  - **>6M DEEP ON 3.8 BY OLD SURFACES**
- **CONSTITUENTS:**
  - **ROCK FRAGMENTS**
  - **AGGLUTINATES (IMPACT GLASS WELDING TOGETHER ROCK AND MINERAL FRAGMENTS)**
  - **MINERAL FRAGMENTS**
  - **VOLCANIC GLASS SPHERES AND FRAGMENTS**
  - **METEORITIC CONTAMINATION (<0.3%)**
  - **ADSORBED SOLAR WIND VOLATILES (H_2 AND HE)**
  - **PRODUCTS OF SOLAR AND COSMIC RADIATION**

REGOLITH SUMMARY - 2

- **LATERAL MIXING RATE**
  - **ON THE ORDER OF 10S OF METERS PER 100 MY**
  - **~100S OF METERS PER BILLION YEARS**
- **VERTICAL MIXING IRREGULAR**
  - **3M DRILL CORES INDICATE TEXTURAL LAYERING BUT NO SIGNIFICANT CHEMICAL CHANGE WITH DEPTH**

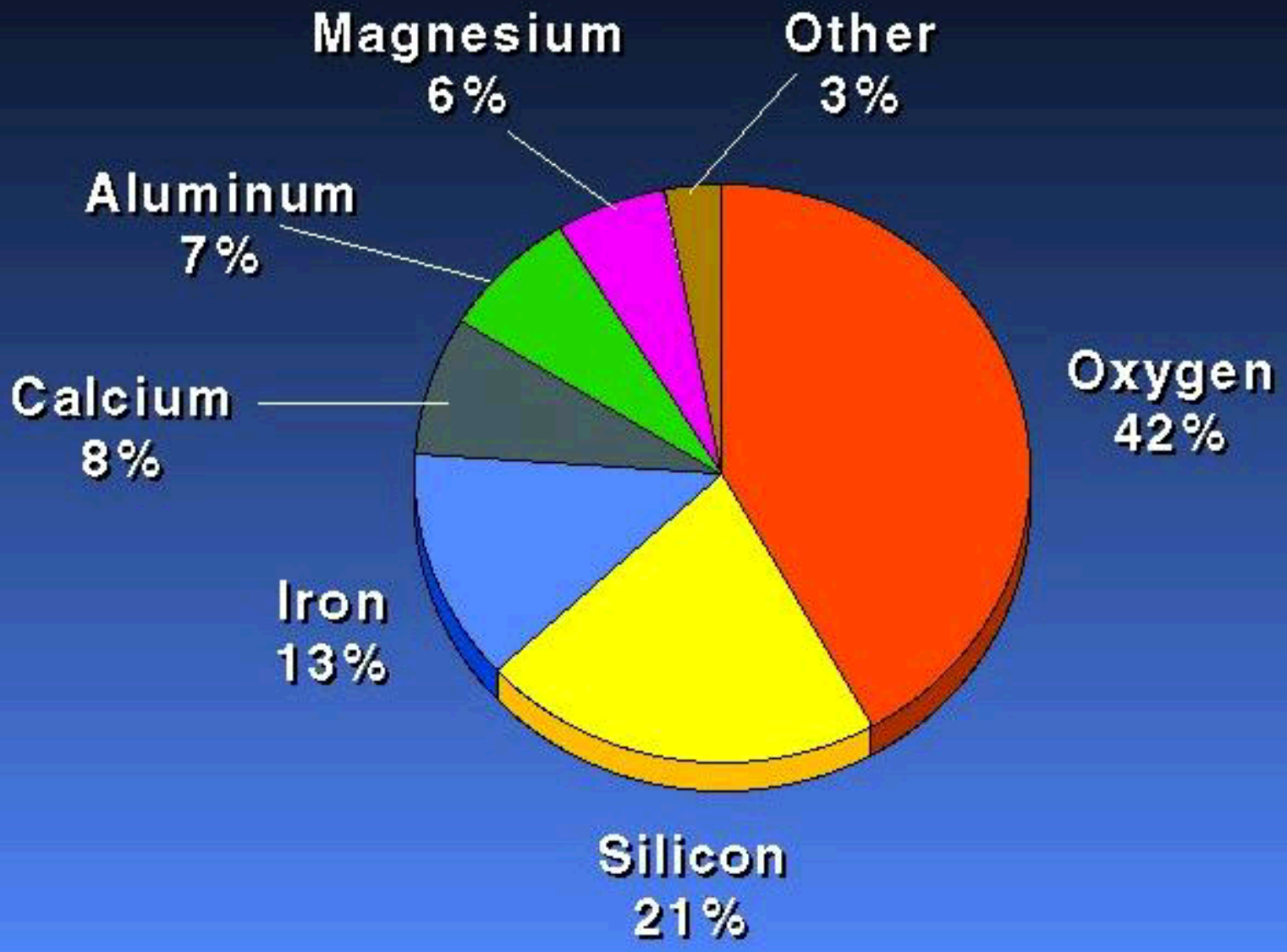
REGOLITH SUMMARY - 3

- **GEOTECHNICAL PARAMETERS**
  - **DENSITY ~1.9 GM/CM3**
  - **HIGH BEARING STRENGTH**
  - **MODERATE COHESION**
  - **>60% PARTICLES <100m (THAT IS, PENETRATING DUST!!!!!)**
  - **HIGHLY ABRASIVE (THAT IS, RELIABLE SEALS REQUIRED!!!!)**
  - **DISSEMINATED, FINE GRAIN NATIVE IRON**
  - **DISSEMINATED, FINE GRAIN IRON SULFIDE**
  - **HIGHLY REDUCING (HYDROGEN)**

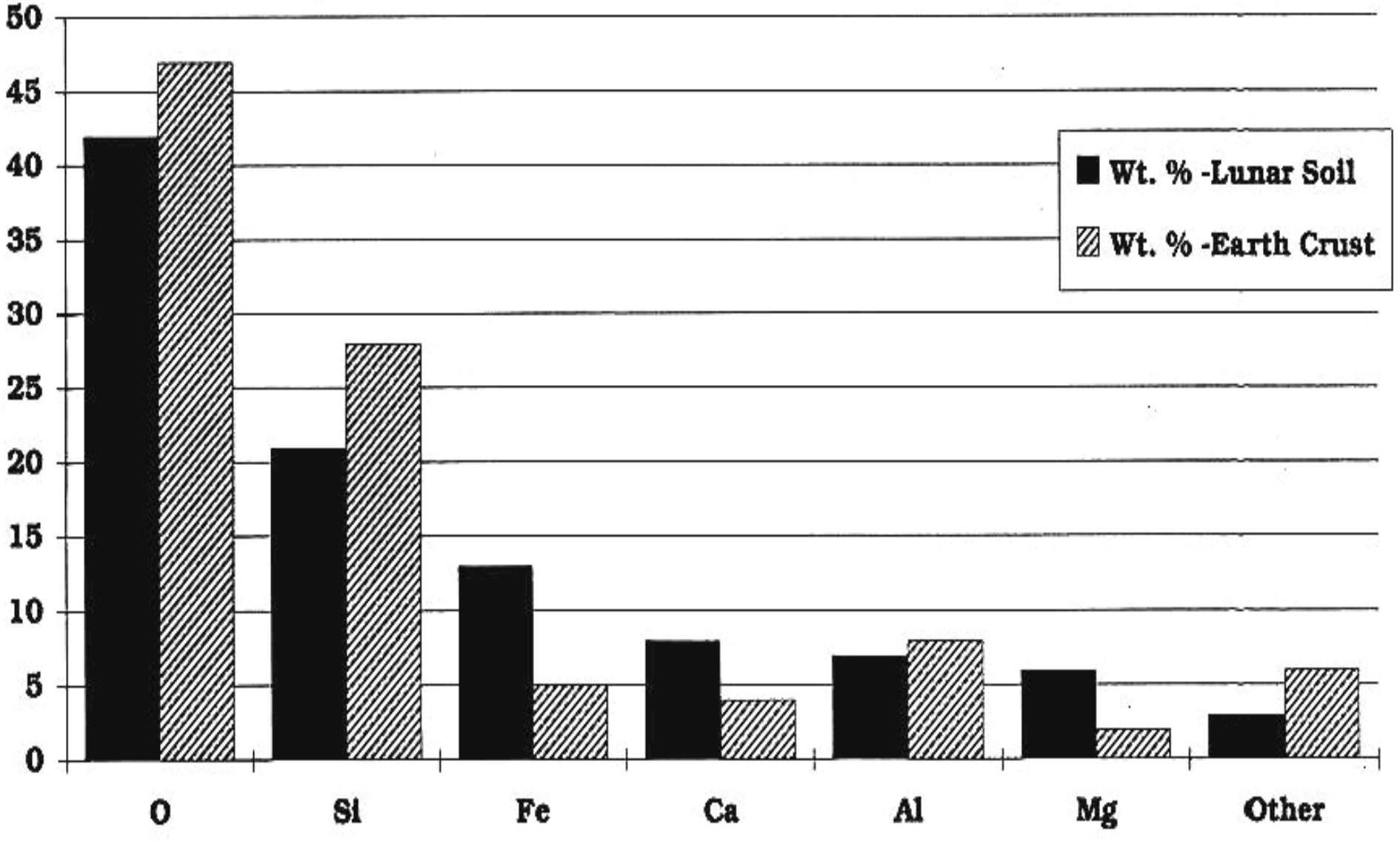
LUNAR CONSTRUCTION
NON-METALLIC MATERIALS

- **REGOLITH**
  - **INSULATION**
  - **RADIATION PROTECTION**
- **COARSE REGOLITH FRACTION**
  - **ROAD AGGREGATE**
  - **CONCRETE**
- **FINE REGOLITH FRACTION**
  - **COMPACTED “BRICK”**
  - **SINTERED “BRICK”**
  - **REGOLITH/METAL COMPOSITES**
  - **SOLAR PHOTOVOLTAIC CELLS**

Lunar Soil Composition



The Surface of the Moon is Slightly Richer in Fe, Ca, and Mg Compared to the Earth's Crust



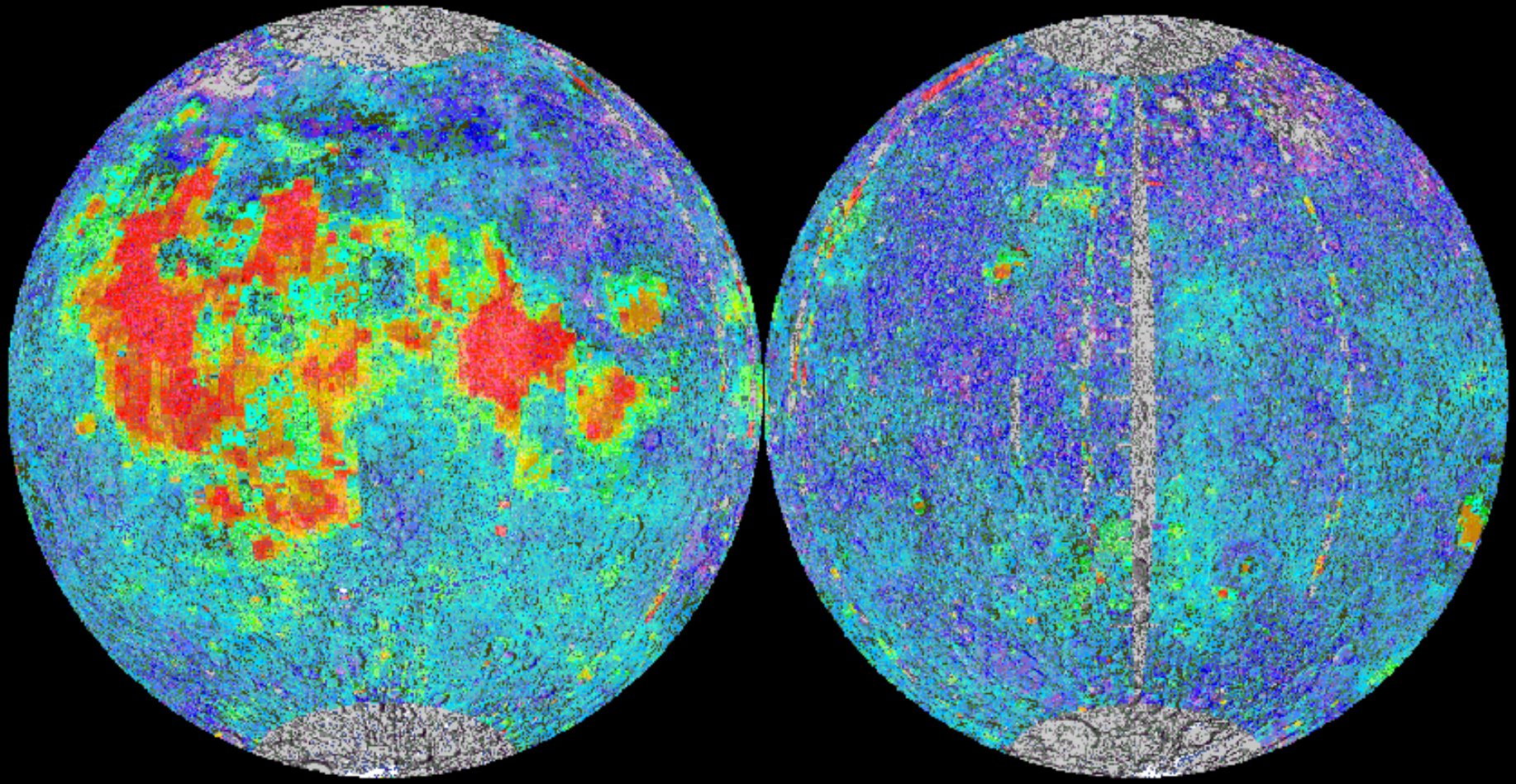
LUNAR MANUFACTURING

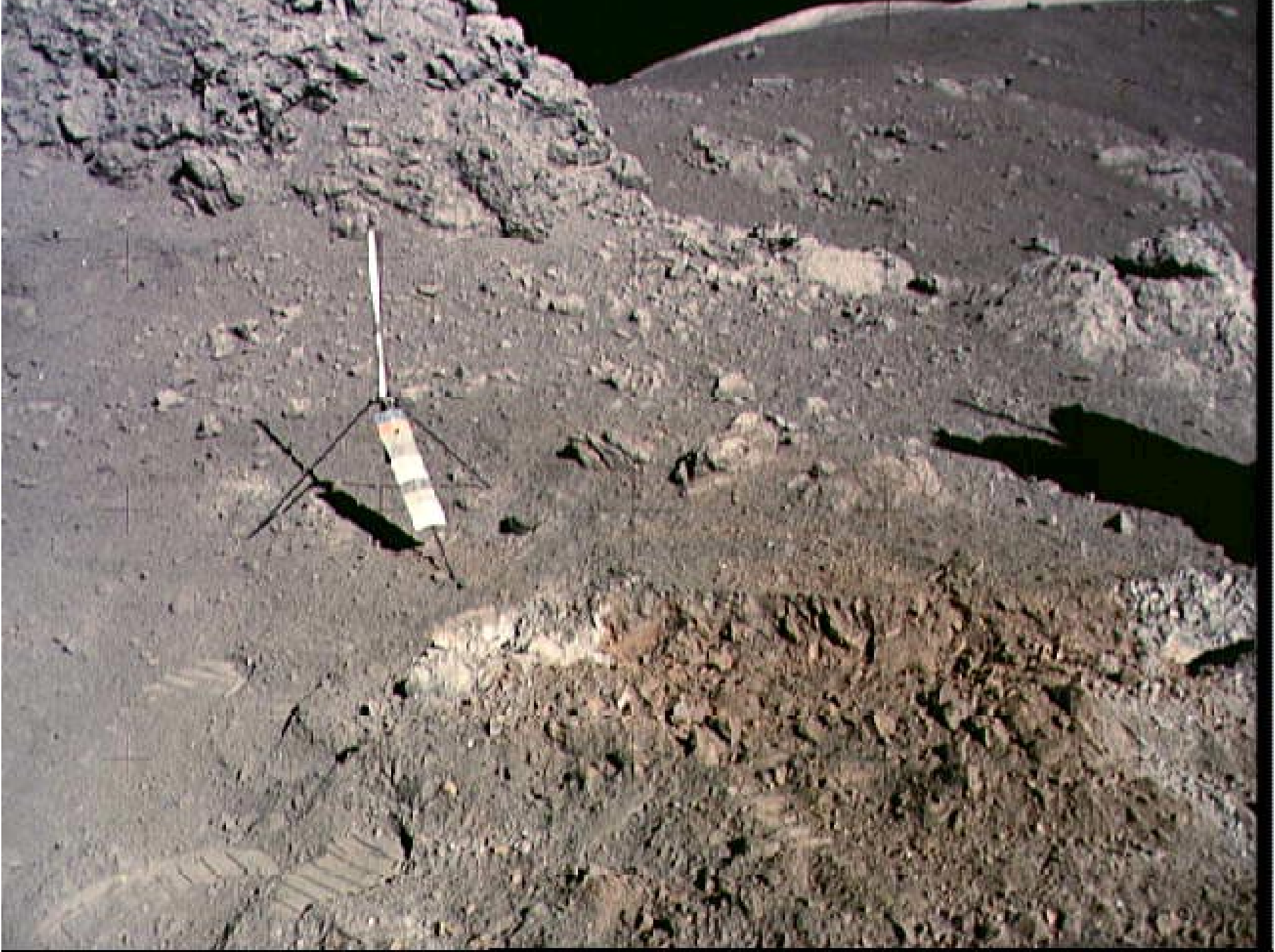
METALLIC MATERIALS (HIGH TI BASALTS)

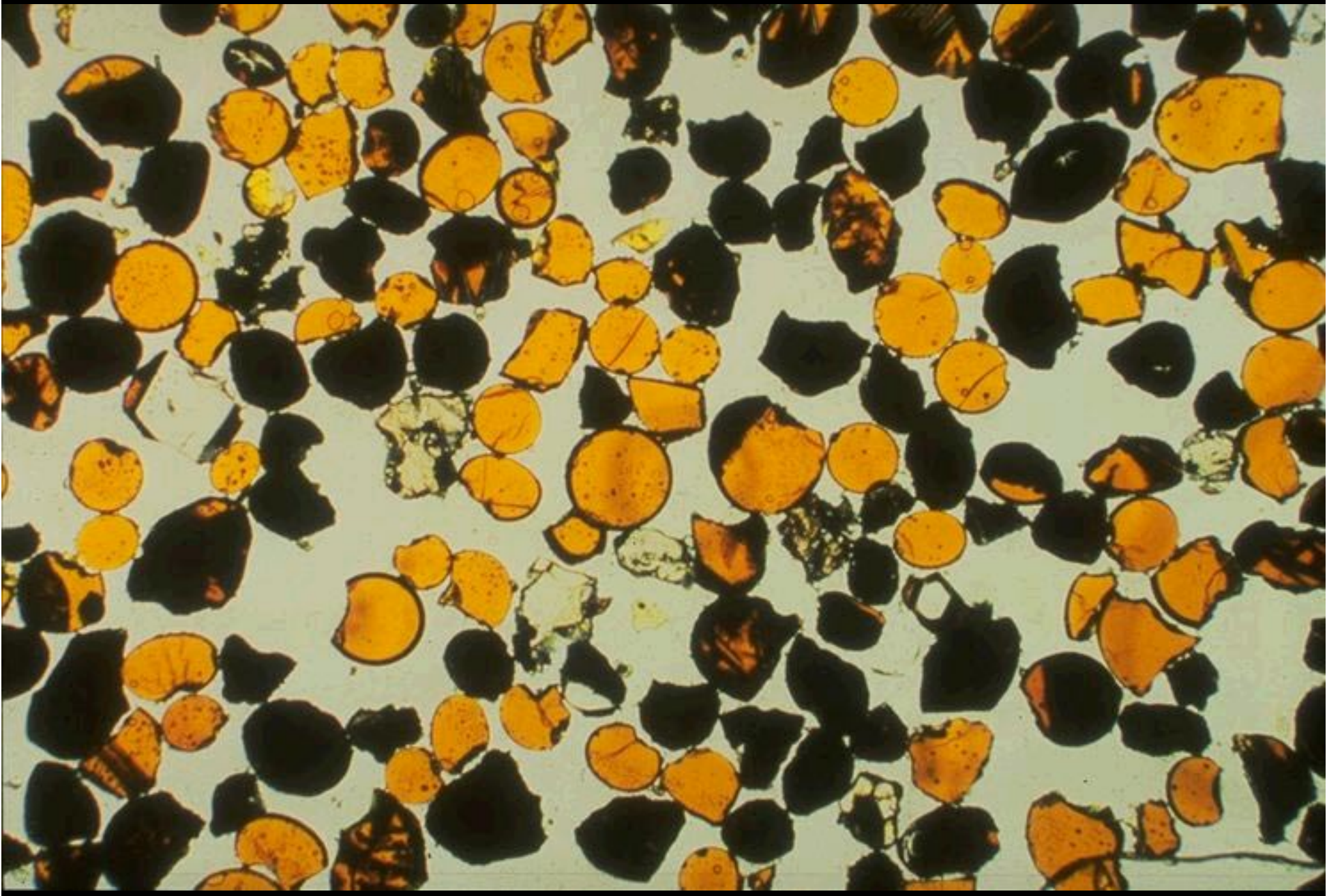
- **FINE REGOLITH FRACTION/MAJOR ELEMENTS**
  - **IRON IN IRON-TITANIUM OXIDE (22 WT % FEO AND 1 WT % NATIVE IRON)**
  - **TITANIUM IN IRON-TITANIUM OXIDE (11 WT % TiO_2 IN ILMENITE)**
  - **MAGNESIUM IN MAGNESIUM-IRON SILICATES (7 WT % MGO)**
  - **ALUMINUM IN CALCIUM-ALUMINUM SILICATES (9 WT % AL_2O_3)**
  - **SILICON IN CALCIUM-ALUMINUM SILICATES (40 WT % SiO_2)**
- **FINE REGOLITH FRACTION/MINOR ELEMENTS**
  - **PLATINUM GROUP IN METEORITIC DEBRIS**
  - **CHROMIUM IN CHROMIUM-IRON OXIDE**
- **PYROCLASTIC GLASSES**
  - **MAGNESIUM (16 WT % MGO)**
- **GRAVITY CONCENTRATIONS IN BASALT FLOWS**
  - **TITANIUM (ILMENITE)**
  - **ALUMINUM/SILICON (PLAGIOCLASE)**
  - **CHROMIUM (CHROMITE)**
  - **IRON/SULFUR (TROILITE)**

Clementine Titanium Map of the Moon

Equal Area Projection







LUNAR SPECIAL COMPOUNDS

- **LUNAR KREEP (NOT NORMALLY ASSOCIATED WITH BASALTIC REGOLITH)**
  - **PHOSPHATE (P_2O_5)**
  - **POTASH (K_2O)**
  - **SODA (Na_2O)**

INDIGENOUS LUNAR VOLATILES

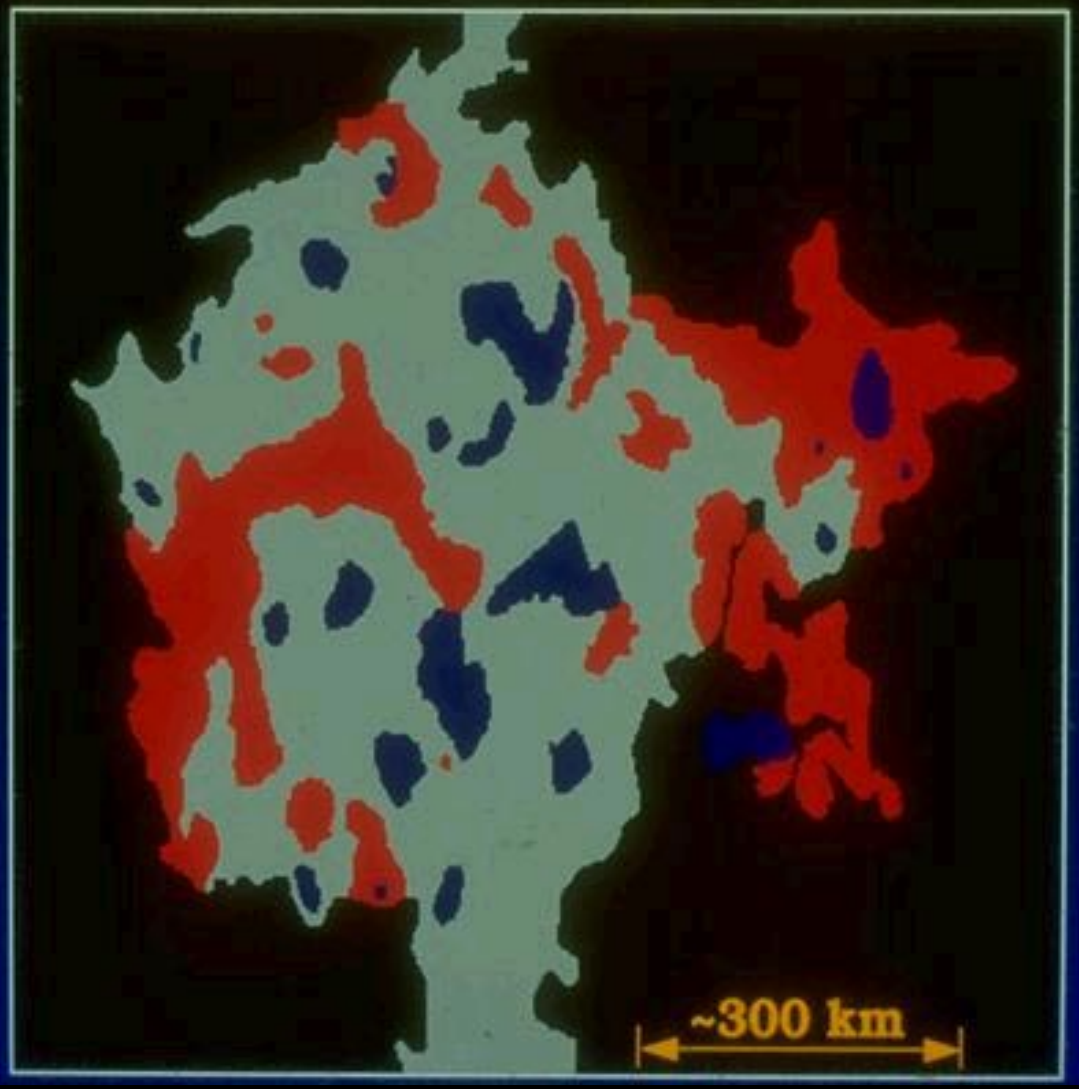
- **FROM PYROCLASTIC GLASSES**
  - **OXYGEN (ELECTROLYSIS OF H_2O PRODUCED BY HYDROGEN REDUCTION)**
- **ADSORBED ON PYROCLASTIC GLASSES (LARGE VOLUME PROCESSING)**
  - **FLUORINE**
  - **CHLORINE**
  - **VOLATILE METALS (COPPER, ZINC, LEAD)**
- **FROM REGOLITH (LARGE VOLUME PROCESSING)**
  - **SULFUR (IRON SULFIDE)**

SOLAR WIND VOLATILES

REGOLITH FINES

- **HYDROGEN**
  - **96% OF SOLAR WIND IONS**
  - **30 PPM AVE.**
    - **HIGHER IN REGOLITH DERIVED FROM TITANIUM-RICH BASALTS AND ANORTHOSITE**
  - **UP TO ALMOST 150 PPM IN SOME APOLLO 16 SAMPLES**
- **HELIUM**
  - **4% OF SOLAR WIND IONS**
  - **UP TO 70 PPM IN REGOLITH DERIVED FROM TITANIUM-RICH BASALTS**
    - **UP TO 30 PPB ^{3}HE**
- **NITROGEN**
- **CARBON**
- **TRACE NOBLE GASES (KR, XE, AR)**

Inferred Titanium Content of Regolith of Mare Tranquillitatis



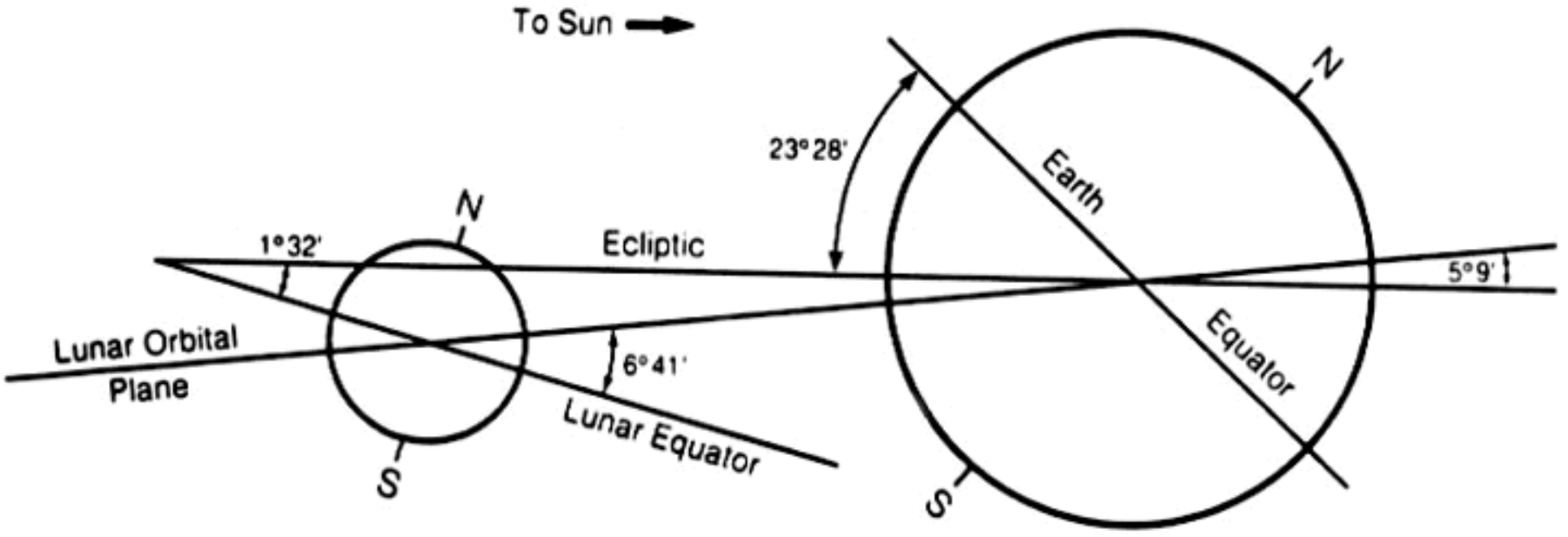
Minable Regolith and Helium Content of Mare Tranquillitatis

Regolith Category	Area, km^2	Avg. He Content, wppm	Regolith Minable, tonnes	He, tonnes	He3, tonnes
A	84,000	38	252×10^9	9.58×10^6	3,635
B	195,000	25	598×10^9	14.96×10^6	5,754
Totals	279,000		850×10^9	24.54×10^6	9,439

Note: He-3 content based on He/He-3 = 2600.
Average depth of regolith = 3 m.

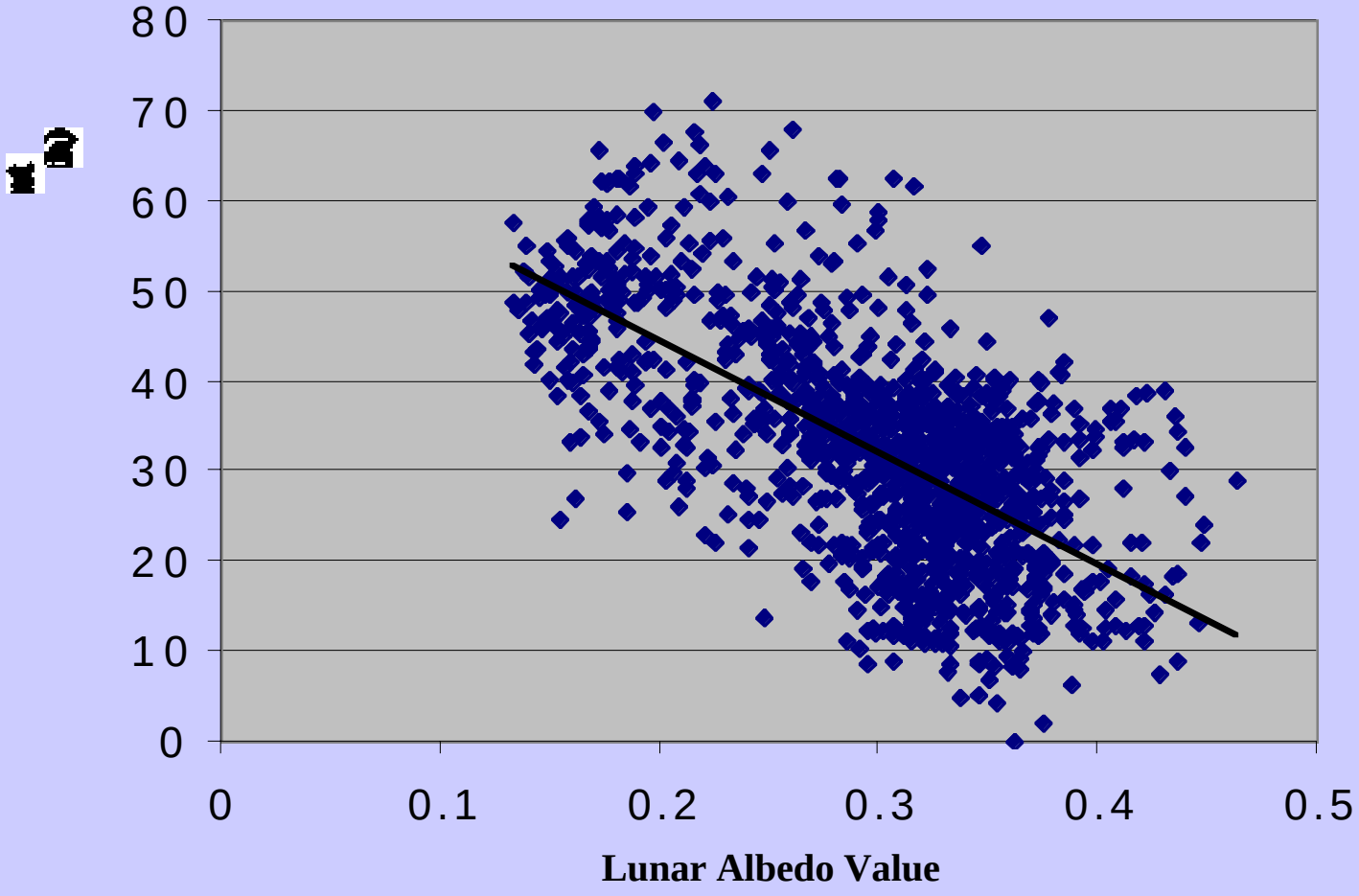
COMETARY VOLATILES
POLAR DEPOSITS?

- **HYDROGEN REGIONAL AVE. INCREASES TO 150 PPM**
  - **LUNAR PROSPECTOR EPITHERMAL NEUTRON SPECTRA**
- **VERY HIGH CONCENTRATIONS OF HYDROGEN IN THREE SOUTH POLE CRATERS**
  - **ASSUMED TO BE WATER-ICE BY PROSPECTOR TEAM**
  - **FAST NEUTRON SPECTRA CONFIRM?**
  - **CLEMENTINE BI-STATIC RADAR CONFIRM?**
- **HYDROCARBONS?**

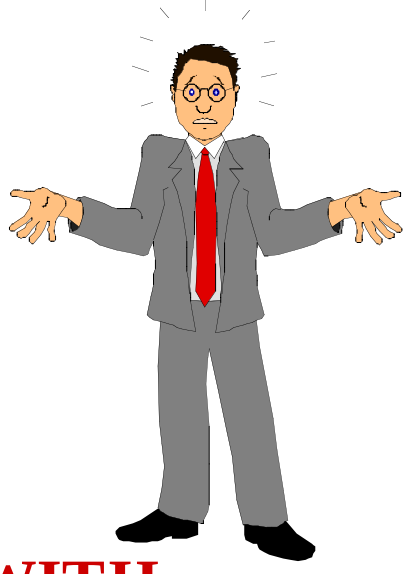

To Sun
23°28'
N
Earth
Equator
S
5°9'
N
1°32'
Ecliptic
Lunar Orbital
Plane
6°41'
Lunar Equator
S

COMETARY VOLATILES
DATA SOURCES

- **EPITHERMAL NEUTRON DATA (FELDMAN)**
  - **AVERAGE ~50 wppm HYDROGEN**
  - **~150 wppm IN POLAR REGIONS**
  - **1500 ± 800 wppm IN DEEP POLAR CRATERS**
- **CLEMENTINE 750nm ALBEDO VS. NEUTRON DATA (DING)**
  - **36 wppm NEARSIDE VS. 28 wppm FARSIDE**
- **CLEMENTINE BI-STATIC RADAR (NOZETTE)**
  - **CONTROVERSIAL INTERPRETATION OF ICE**


80
70
60
50
40
30
20
10
0
0
0.1
0.2
0.3
0.4
0.5
Lunar Albedo Value

INTERPRETATION?

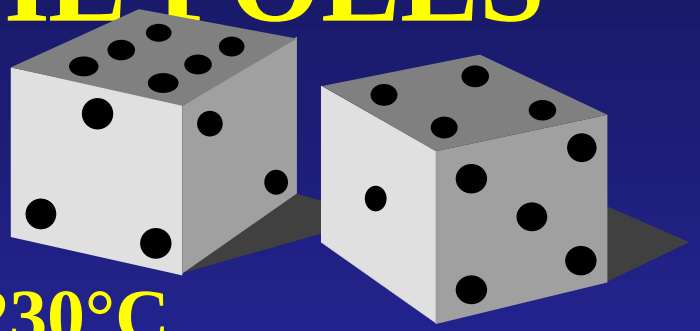


- **PROSPECTOR TEAM**
  - **LARGE QUANTITIES OF POLAR ICE WITH SOME SOLAR-WIND HYDROGEN**
  - **LATER, ICE ONLY IN 3 SOUTH POLE CRATERS**
  - **MORE RECENTLY, ICE ALSO IN REGOLITH**
- **ALTERNATIVE**
  - **LARGELY COLD TRAPPED SOLAR-WIND HYDROGEN**

SOLAR-WIND IONS

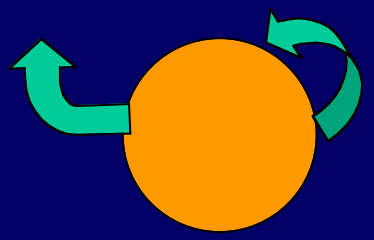
- **HYDROGEN (PROTONS)**
  - **~ 96% OF THE SOLAR-WIND**
  - **INITIALLY IMBEDDED IN MINERAL AND GLASS CONSTITUENTS**
  - **PARTIALLY RELEASED AS <u>PICKUP IONS</u>**
    - **MICROMETEORIOD IMPACT**
    - **DIURNAL HEATING**
  - **RETAINED BY BURIAL**

CONDITIONS AT THE POLES



- **PERMANENT SHADOW - ~230°C**
- **OUTSIDE PERMANENT SHADOW**
  - **AVERAGE SURFACE TEMPERATURE INCREASES WITH DECREASING LATITUDE**
- **MAXIMUM CONTRAST BETWEEN EQUATOR AND PERMANENT SHADOW**
  - **~350°C**

PICKUP IONS



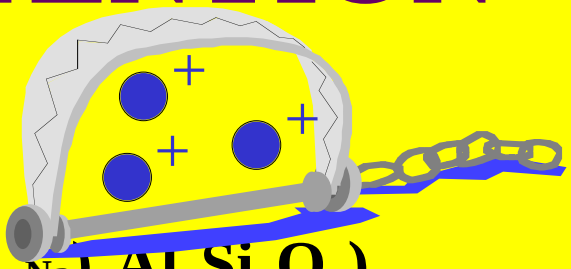
- **RELEASED REGOLITH VOLATILES**
  - **IONIZED AND ENTRAINED IN SOLAR-WIND**
  - **LOST ENTIRELY OR RE-IMPLANTED**

- **DEFINITIVE MODEL OF HISTORY OF PICKUP IONS NOT YET AVAILABLE**
  - **APOLLO, CLEMENTINE AND PROSPECTOR DATA DEFINE ~STEADY-STATE IN REGOLITH**
    - **SANTARIUS AND STUDENTS HAVE BEGUN TO MODEL OVER-ALL PROCESS**

STEADY-STATE HYDROGEN CONCENTRATION

- **APOLLO SAMPLES: 1OO ± 50 wppm**
  - **MAY BE LOW DUE TO HANDLING LOSSES**
- **PROSPECTOR DATA FOR REGIONS WITH PERMANENT SHADOW**
  - **~150 wppm (HIGH END OF APOLLO DATA)**
  - **X3 THAT SEEN FOR LOWER LATITUDES**
  - **GRADUAL CHANGE ACROSS PERMANENT SHADOW BOUNDARIES**
  - **1500 ± 800 wppm IN DEEP POLAR CRATERS**

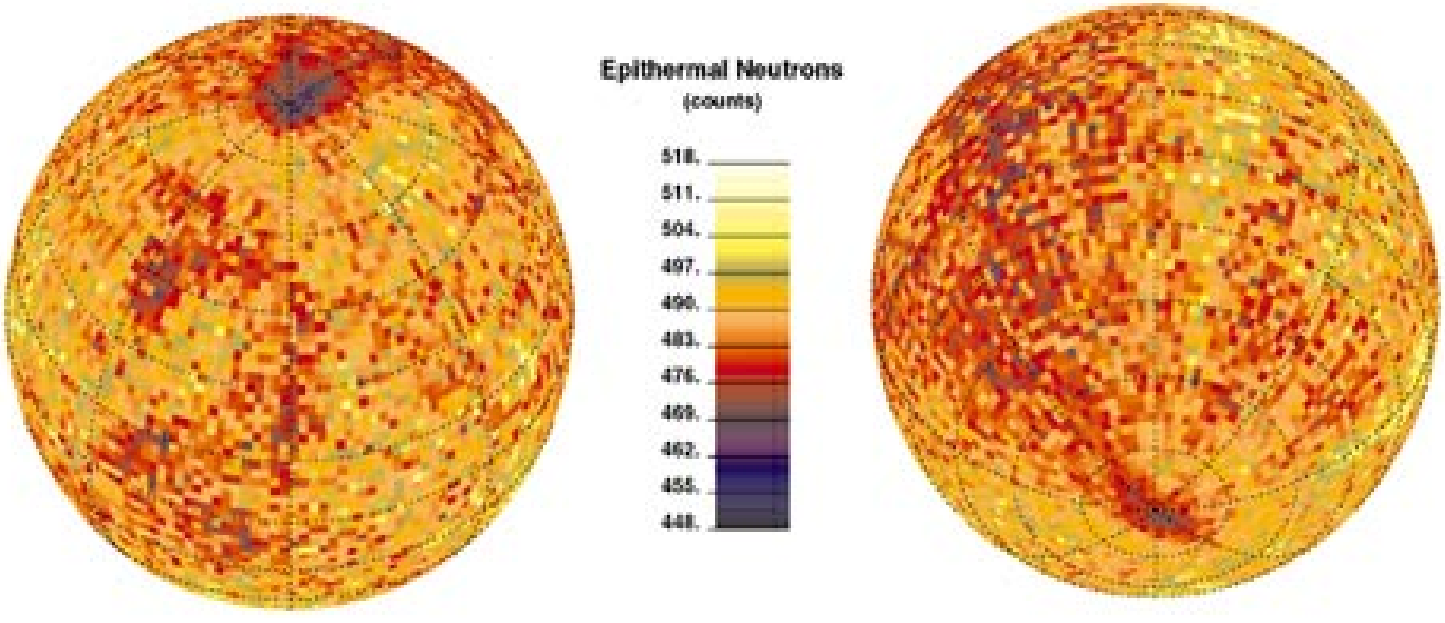
HYDROGEN RETENTION



- **PLAGIOCLASE FELDSPAR ($(Ca, Na)_2Al_2Si_2O_8$)**
  - **KNOWN TO ASSUME A CATION POSITION IN FELDSPAR - SODIUM SUBSTITUTE?**
    - **NOTE TRANSIENT LUNAR SODIUM ATMOSPHERE**
  - **SUPPORTED BY INHANCEMENT NEAR LARGE, YOUNG HIGHLAND CRATERS WHERE FRESH PLAGIOCLASE IS EXPOSED**

- **ILMENITE ($FeTiO_3$)**
  - **CLEMENTINE-PROSPECTOR COMPARISON BY DING**

Medium Energy Neutron Distribution
Lunar Prospector



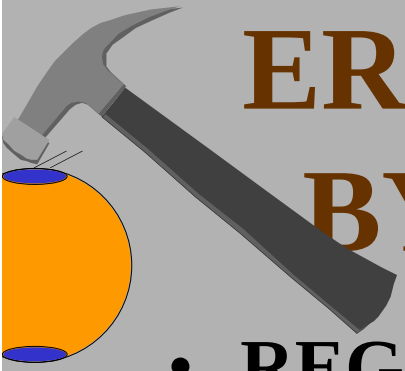
Near-Side & North Pole

Far-Side & South Pole

Los Alamos National Laboratory

POLAR SOLAR-WIND CONSIDERATIONS

- **VARIABLES AFFECTING ADDITIONS AND LOSSES OF HYDROGEN NEAR THE POLES**
  - **SOLAR-WIND FLUX VS. LATITUDE AND LONGITUDE**
  - **TILT OF MOON'S AXIS RELATIVE TO ECLIPTIC**
  - **NON-ECLIPTIC COMPONENT OF SOLAR-WIND**
  - **DIURNAL TEMPERATURE VARIATION VS. LATITUDE AND LONGITUDE**
  - **PICKUP-ION REDEPOSTION RATES VS. LATITUDE AND LONGITUDE**
  - **ABUNDANCES OF RETENTIVE MINERALS**
  - **MOON'S INTERACTION WITH THE MAGNETOSPHERE**
  - **FLUX OF MICRO-METEORITES IMPACTING THE MOON**



EROSION OF WATER ICE BY MICROMETEROIDS

- REGOLITH TURNOVER (GARDENING)
  - FEW CM EVERY 10 MILLION YEARS
- BLANKET OF COMETARY ICE WOULD ERODE AT COMPARABLE RATE
  - SPUTTERING DUE TO SOLAR-WIND WOULD ADD TO EROSION RATE
  - SOME PROTECTION POSSIBLE IN DEEP CRATERS OR BY FORTUITOUS EJECTA

SCIENCE CONCLUSIONS

- **THE HYDROGEN SIGNAL IN POLAR REGIONS IS LARGELY A CONCENTRATION OF SOLAR-WIND HYDROGEN BY COLD-TRAPPING**
  - **WATER ICE MAY BE PRESENT IN DEEP CRATERS WHERE PARTIALLY PROTECTED FROM EROSION**
  - **WATER ICE MAY BE LOCALLY MIXED INTO REGOLITH WHERE INITIALLY PROTECTED FROM EROSION BY IMPACT EJECTA**