POTENTIAL RESOURCES OF THE MOON

THEY START WITH THE MARE BASALTS!

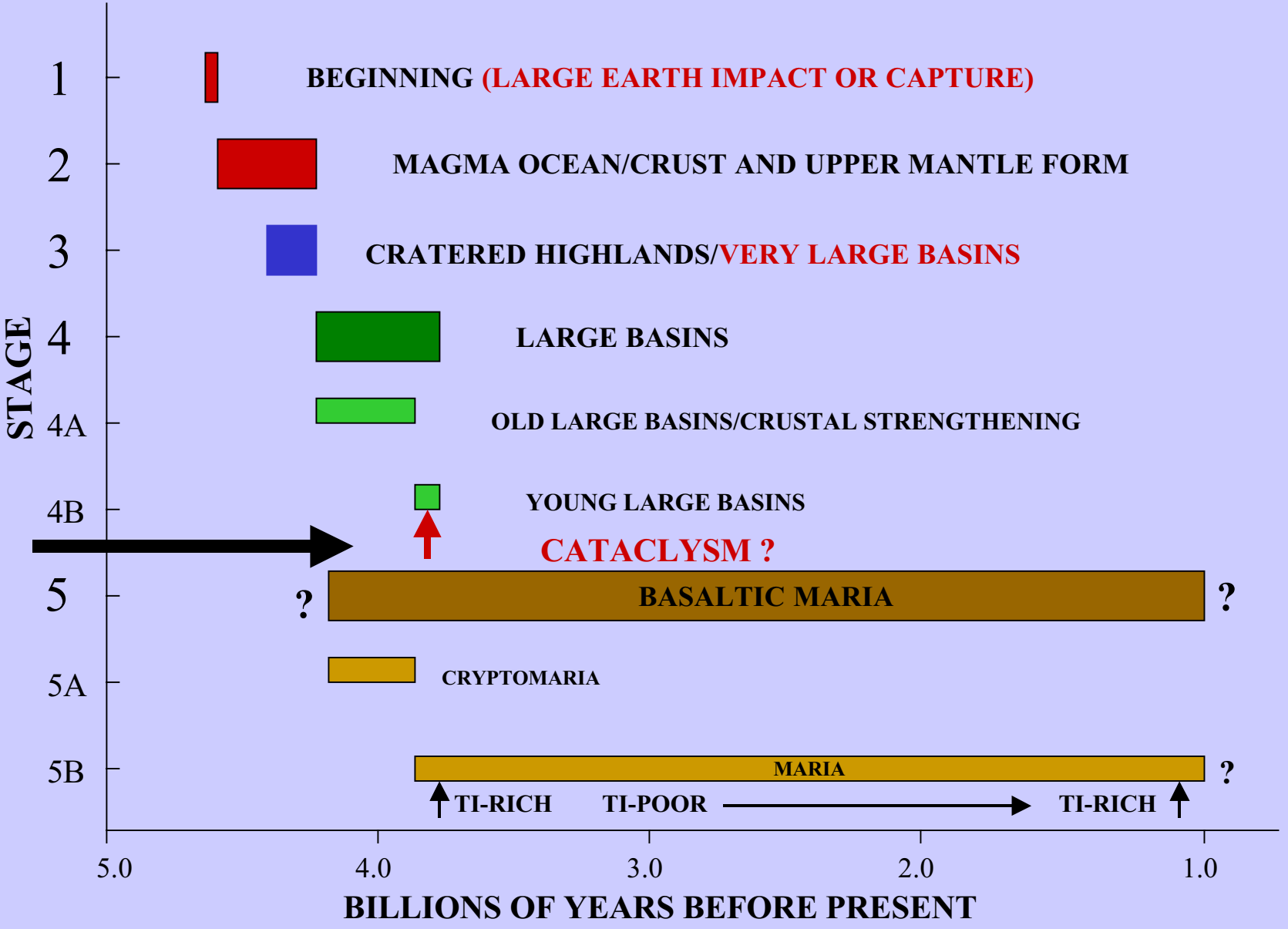
NEEP 533 LECTURE 10

Harrison H. Schmitt

DEFINITIONS

- **VESICULAR**
- **CONTAINS SMOOTH-WALLED HOLES (VESICLES) FORMED BY A GAS BUBBLE IN MAGMA**
- **FERROAN ANORTHOSITE**
- **IRON BEARING, Ca-RICH PLAGIOCLASE ROCK.**
- **$CaAl_2Si_2O_8$**

MAJOR STAGES OF LUNAR EVOLUTION



RED = MAJOR UNCERTAINTY

IN NEXT FOUR CARTOONS

WATCH HOW THE DEPTH OF MARE BASALT MAGMA GENERATION MOVES DOWNWARD

IN THE SEQUENCE,

BLACK

GREEN 

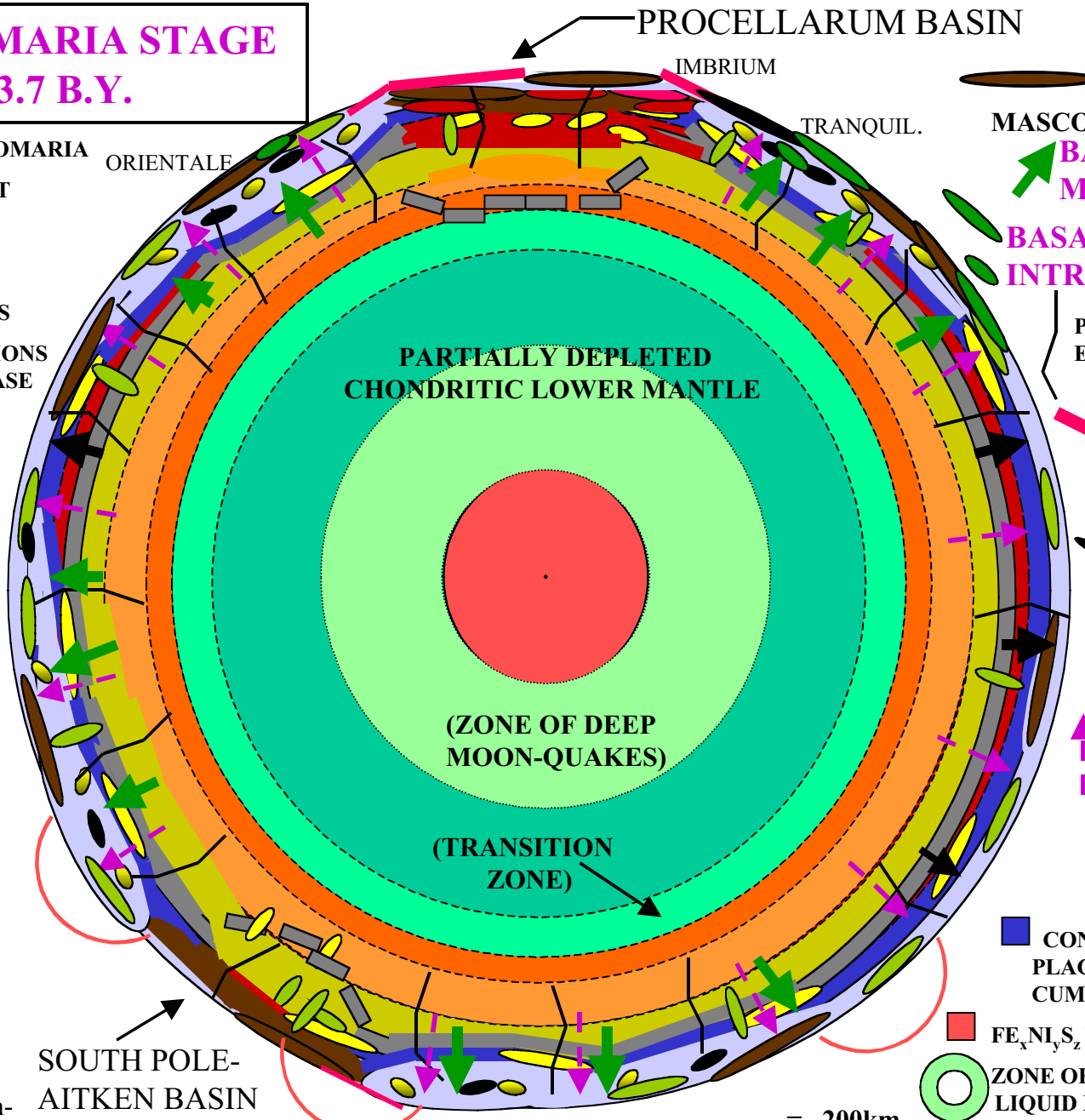
BROWN 

RED 

BLACK 

APOLLO MODEL OF LUNAR EVOLUTION

BASALTIC MARIA STAGE 3.8-3.7 B.Y.



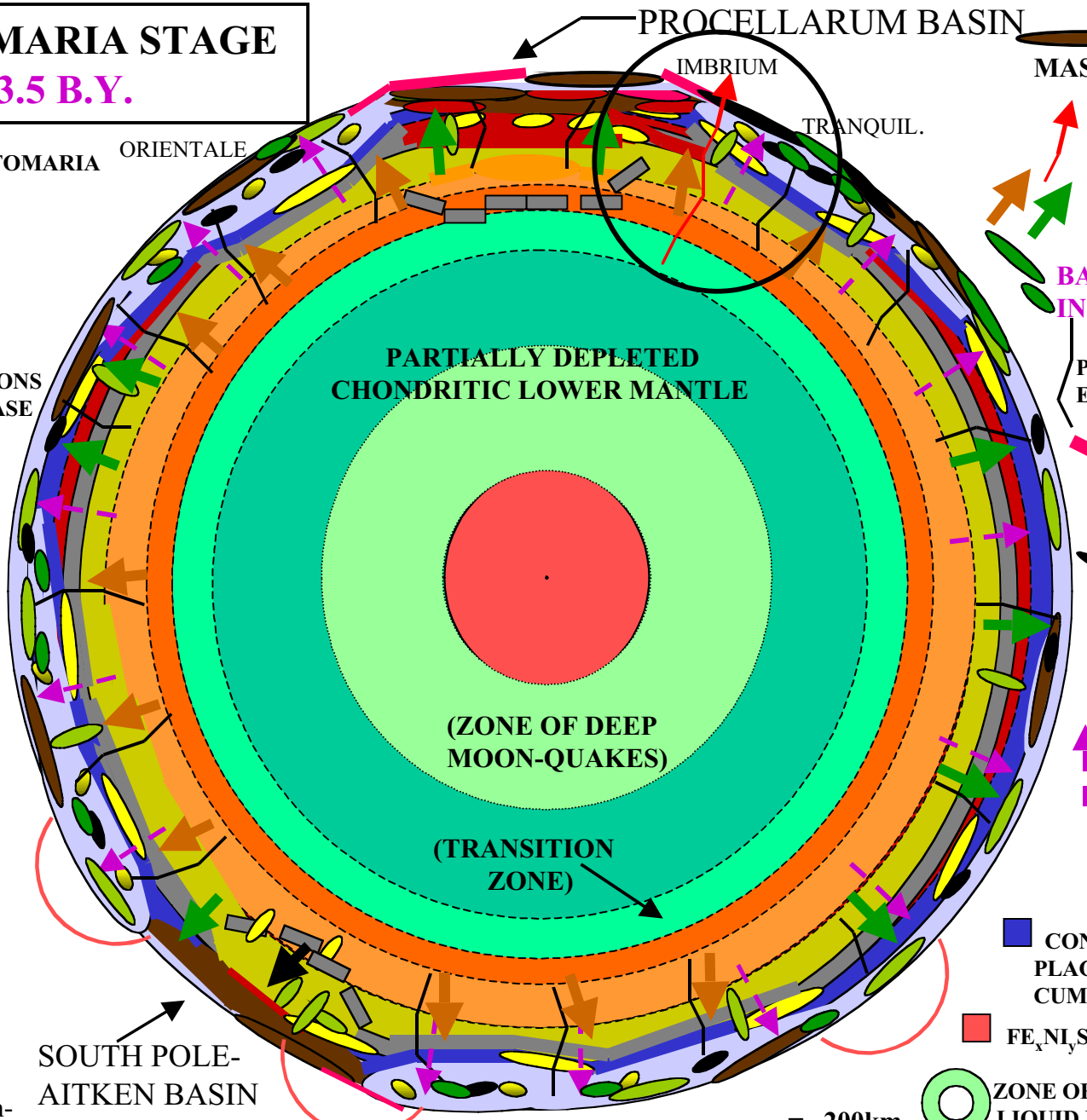
- BURIED CRYPTOMARIA
- KREEPY BASALT EXTRUSIVES
- MG-SUITE INTRUSIVES
- MG-SUITE DEBRIS
- BASALT INTRUSIONS OF PRESSURE-RELEASE MAGMAS
- SOLIDIFIED IMPACT MELT SHEET
- ILMENITE CUMULATE MASSES
- OLIVINE, HIGH CA-PYROXENE, AND ILMENITE CUMULATE
- KREEP BASALTS
- OLIVINE AND HIGH CA-PYROXENE CUMULATE
- OLIVINE AND LOW CA-PYROXENE CUMULATE
- OLIVINE CUMULATE

- YOUNG LARGE MASCON BASINS
- BASALT PARTIAL MELTS
- BASALT EXTRUSION/ INTRUSION
- PROGRADE THERMAL EXTENSION FRACTURE
- KREEPY IMBRIUM EJECTA
- TI-RICH BASALT PARTIAL MELTS
- TI-BASALT EXTRUSION/ INTRUSION
- MAGNETIC ANOMALY
- H_2 MIGRATION
- INSULATING CRATERED HIGHLANDS AND EJECTA
- CONSOLIDATED PLAGIOCLASE CUMULATE
- $FE_xNI_yS_z$ LIQUID CORE
- ZONE OF ISOLATED $FE_xNI_yS_z$ LIQUID MASSES

— = 200km

APOLLO MODEL OF LUNAR EVOLUTION

BASALTIC MARIA STAGE
3.7-3.5 B.Y.



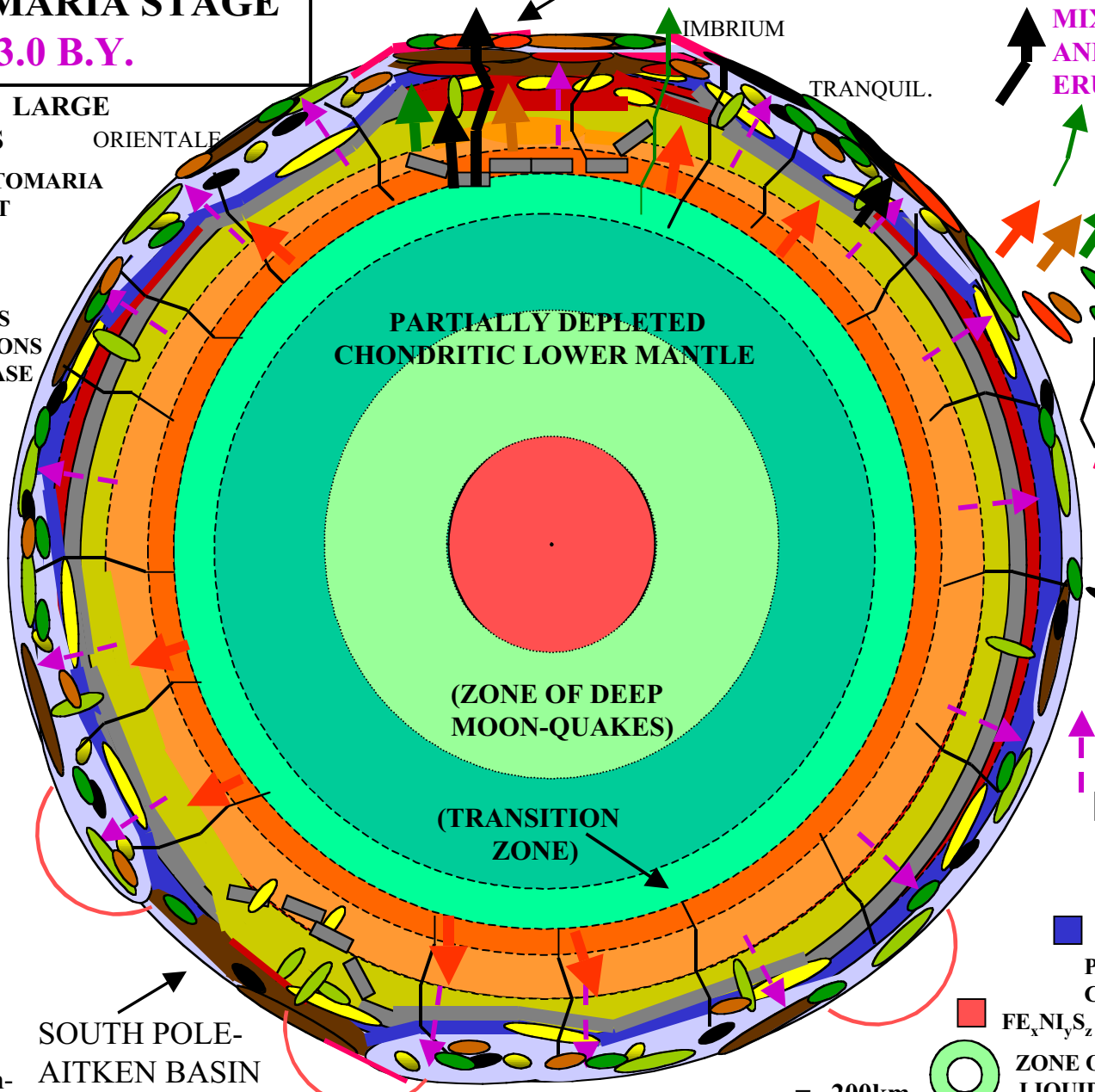
- BURIED CRYPTOMARIA
- KREEPY BASALT EXTRUSIVES
- MG-SUITE INTRUSIVES
- MG-SUITE DEBRIS
- BASALT INTRUSIONS OF PRESSURE-RELEASE MAGMAS
- SOLIDIFIED IMPACT MELT SHEET
- ILMENITE CUMULATE MASSES
- OLIVINE, HIGH CA-PYROXENE, AND ILMENITE CUMULATE
- KREEP BASALTS
- OLIVINE AND HIGH CA-PYROXENE CUMULATE
- OLIVINE AND LOW CA-PYROXENE CUMULATE
- OLIVINE CUMULATE

- YOUNG LARG MASCON BASINS
- PYROCLASTIC ERUPTIONS BASALT PARTIAL MELTS
- BASALT EXTRUSION/ INTRUSION
- PROGRADE THERMAL EXTENSION FRACTURE
- KREEPY IMBRIUM EJECTA
- TI-RICH BASALT PARTIAL MELTS
- TI-BASALT EXTRUSION/ INTRUSION
- MAGNETIC ANOMALY
- H_2 MIGRATION
- INSULATING CRATERED HIGHLANDS AND EJECTA
- CONSOLIDATED PLAGIOCLASE CUMULATE
- $FE_xNI_yS_z$ LIQUID CORE
- ZONE OF ISOLATED $FE_xNI_yS_z$ LIQUID MASSES

— = 200km

APOLLO MODEL OF LUNAR EVOLUTION

BASALTIC MARIA STAGE
3.5-3.0 B.Y.



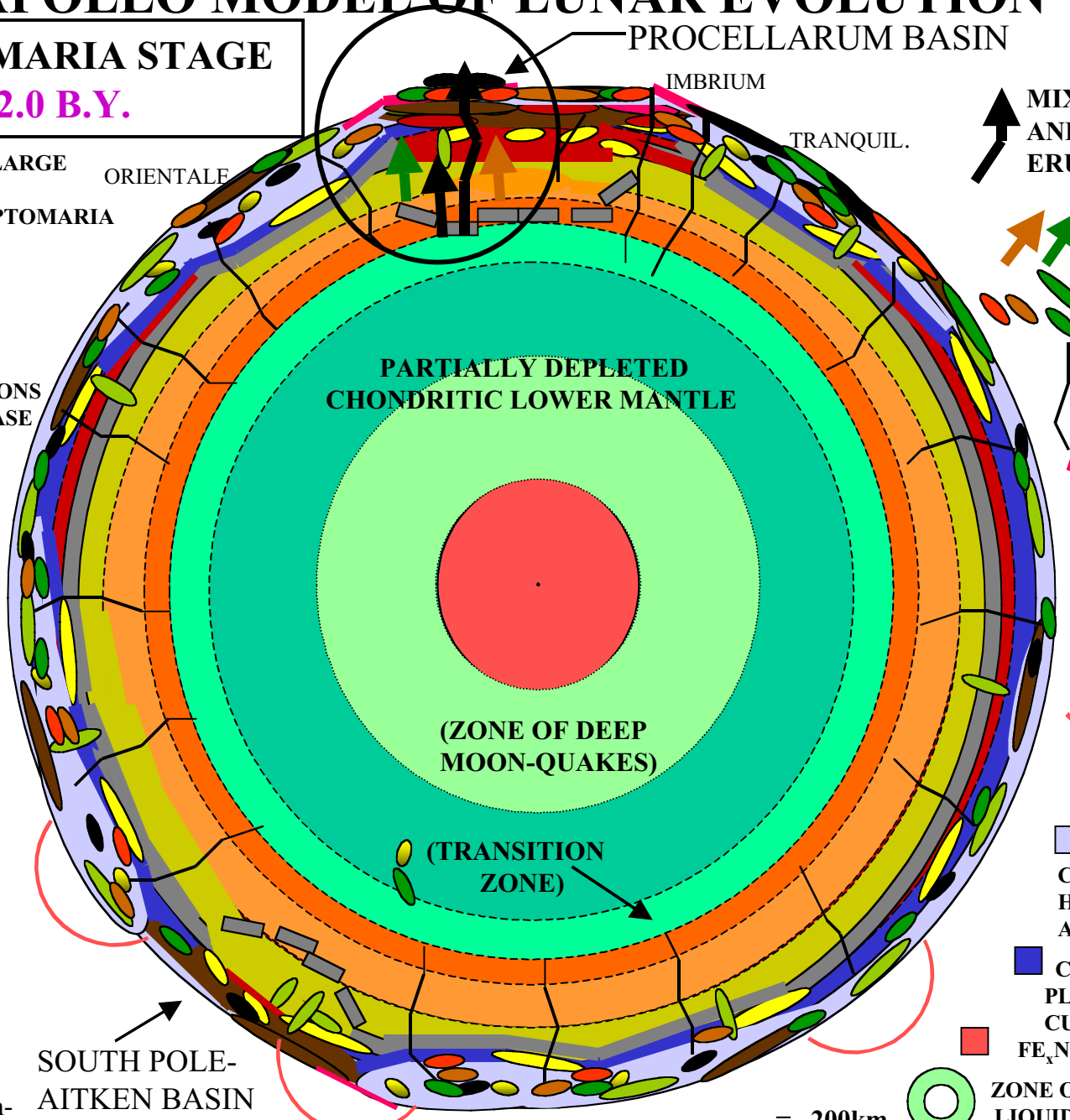
- YOUNG LARGE MASCON BASINS
- BURIED CRYPTOMARIA
- KREEPY BASALT EXTRUSIVES
- MG-SUITE INTRUSIVES
- MG-SUITE DEBRIS
- BASALT INTRUSIONS OF PRESSURE-RELEASE MAGMAS
- SOLIDIFIED IMPACT MELT SHEET
- ILMENITE CUMULATE MASSES
- OLIVINE, HIGH CA-PYROXENE, AND ILMENITE CUMULATE
- KREEP BASALTS
- OLIVINE AND HIGH CA-PYROXENE CUMULATE
- OLIVINE AND LOW CA-PYROXENE CUMULATE
- OLIVINE CUMULATE

- MIXED PYROCLASTIC AND LAVA ERUPTIONS
- PYROCLASTIC ERUPTIONS
- BASALT PARTIAL MELTS
- BASALT EXTRUSION/ INTRUSION
- PROGRADE THERMAL EXTENSION FRACTURE
- KREEPY IMBRIUM EJECTA
- TI-RICH BASALT PARTIAL MELTS
- TI-BASALT EXTRUSION/ INTRUSION
- MAGNETIC ANOMALY
- H_2 MIGRATION
- INSULATING CRATERED HIGHLANDS AND EJECTA
- CONSOLIDATED PLAGIOCLASE CUMULATE
- $FE_xNI_yS_z$ LIQUID CORE
- ZONE OF ISOLATED $FE_xNI_yS_z$ LIQUID MASSES

— = 200km

APOLLO MODEL OF LUNAR EVOLUTION

BASALTIC MARIA STAGE
3.0-2.0 B.Y.

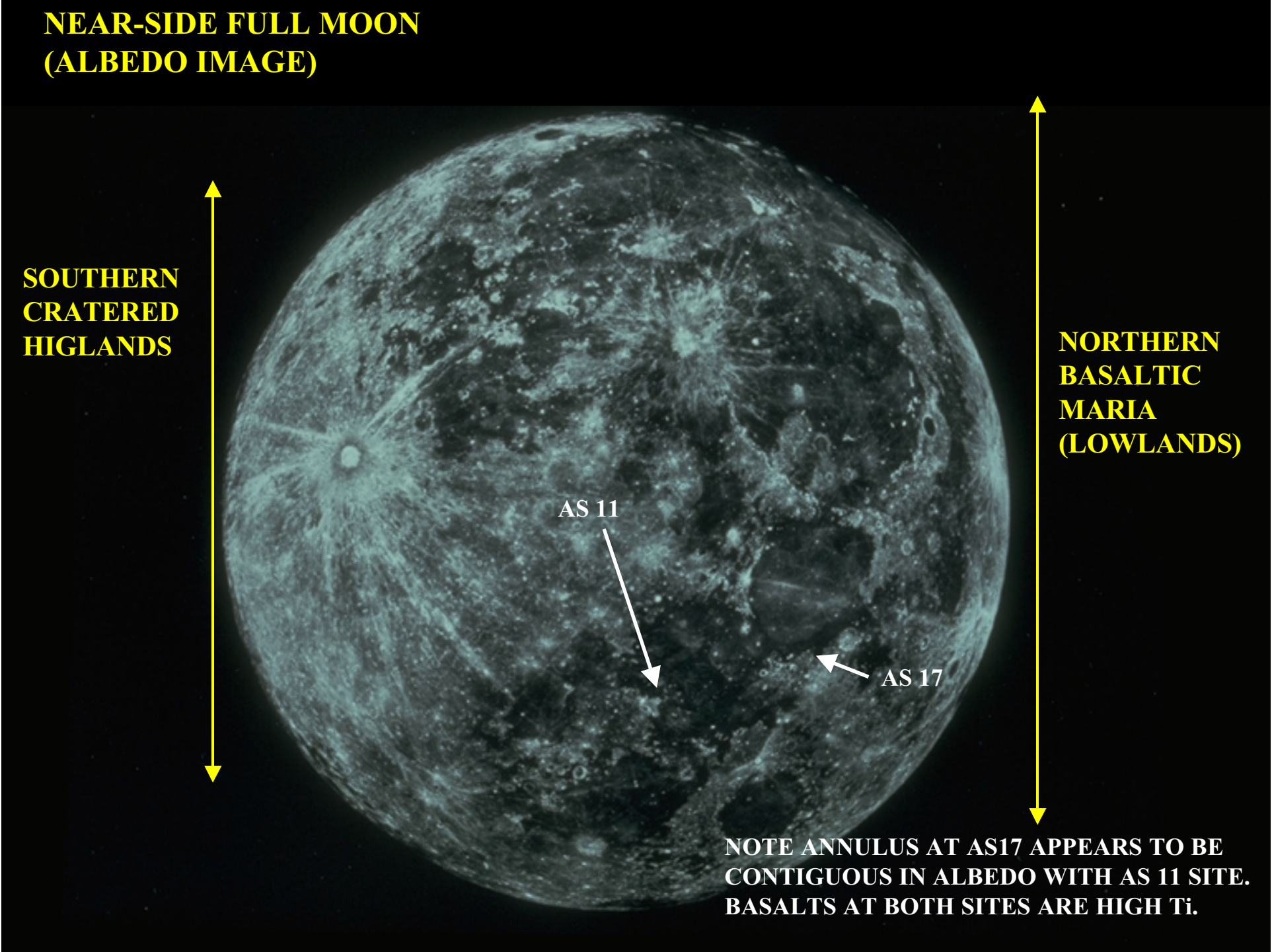


- YOUNG LARGE MASCON BASINS
- BURIED CRYPTOMARIA
- KREEPY BASALT EXTRUSIVES
- MG-SUITE INTRUSIVES
- MG-SUITE DEBRIS
- BASALT INTRUSIONS OF PRESSURE-RELEASE MAGMAS
- SOLIDIFIED IMPACT MELT SHEET
- ILMENITE CUMULATE MASSES
- OLIVINE, HIGH CA-PYROXENE, AND ILMENITE CUMULATE
- KREEP BASALTS
- OLIVINE AND HIGH CA-PYROXENE CUMULATE
- OLIVINE AND LOW CA-PYROXENE CUMULATE
- OLIVINE CUMULATE

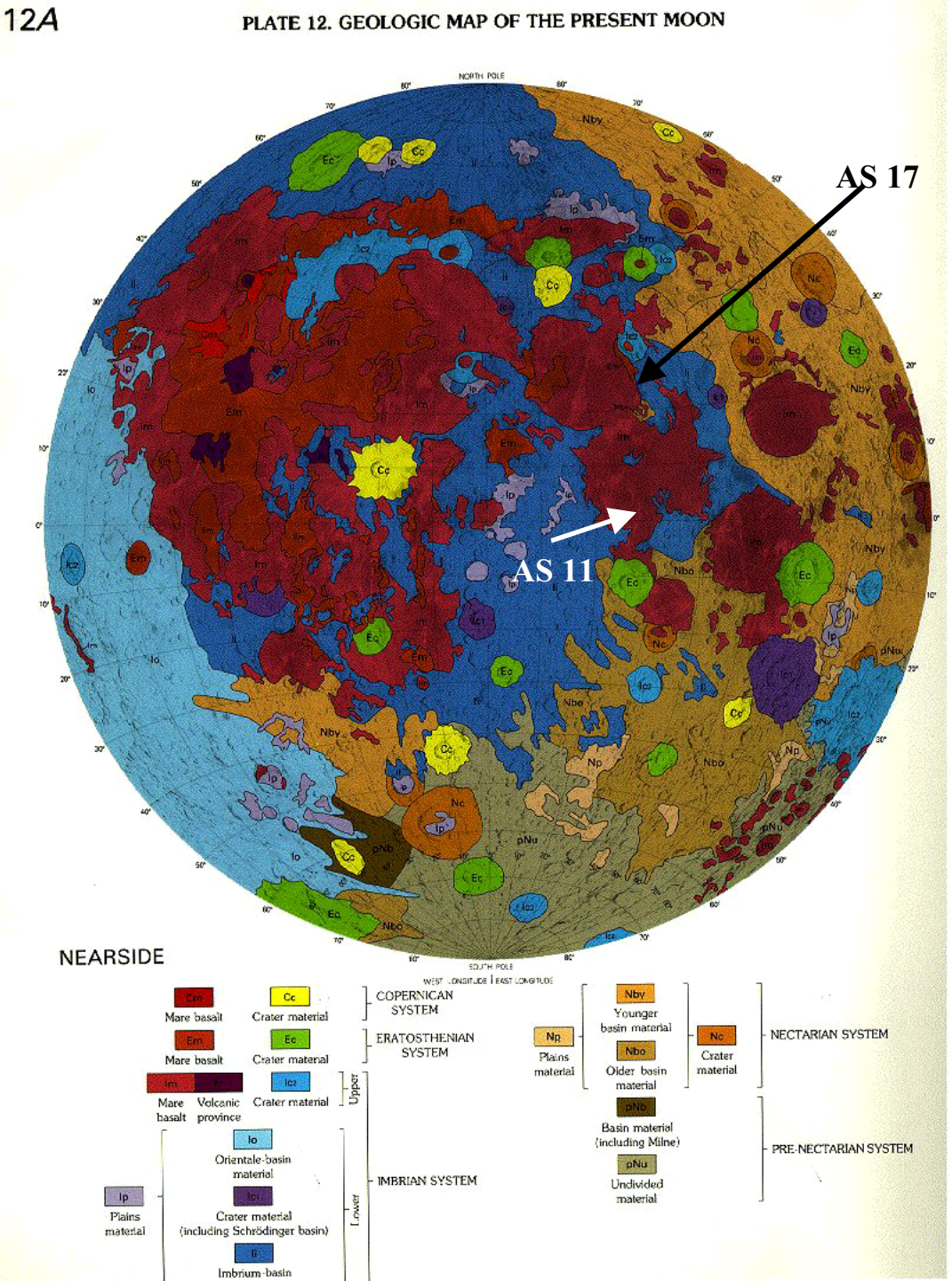
- MIXED PYROCLASTIC AND LAVA ERUPTIONS
- BASALT PARTIAL MELTS
- BASALT EXTRUSION/ INTRUSION
- CLOSED EXTENSION FRACTURE
- KREEPY IMBRIUM EJECTA
- TI-RICH BASALT PARTIAL MELTS
- TI-BASALT EXTRUSION/ INTRUSION
- REMANENT MAGNETIC ANOMALY
- INSULATING CRATERED HIGHLANDS AND EJECTA
- CONSOLIDATED PLAGIOCLASE CUMULATE
- $FE_xNI_yS_z$ LIQUID CORE
- ZONE OF ISOLATED $FE_xNI_yS_z$ LIQUID MASSES

— = 200km

NEAR-SIDE FULL MOON (ALBEDO IMAGE)



MAJOR BASALTIC MARIA UNITS MAPPED BY THE USGS.

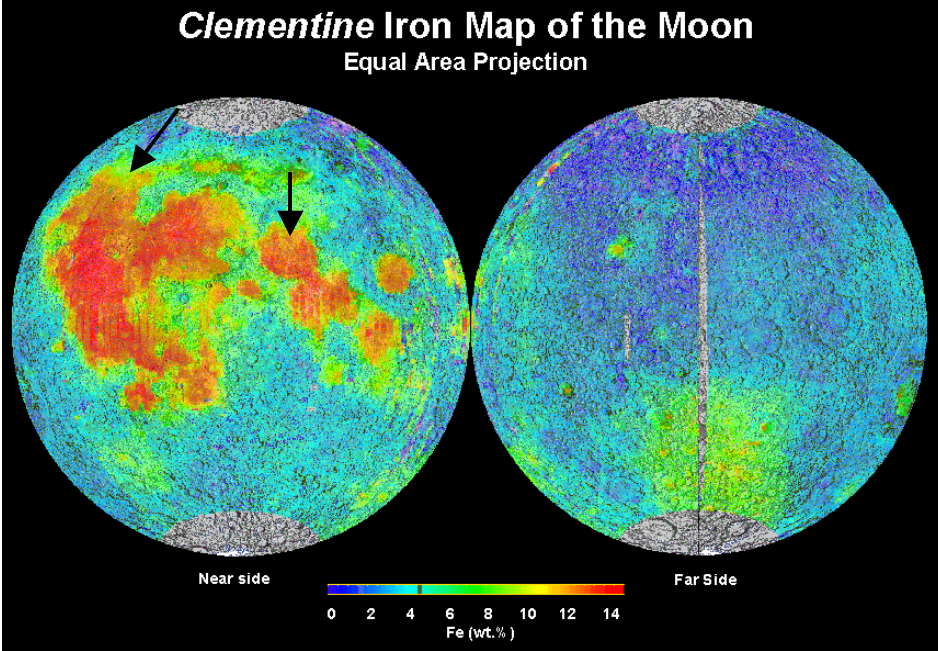


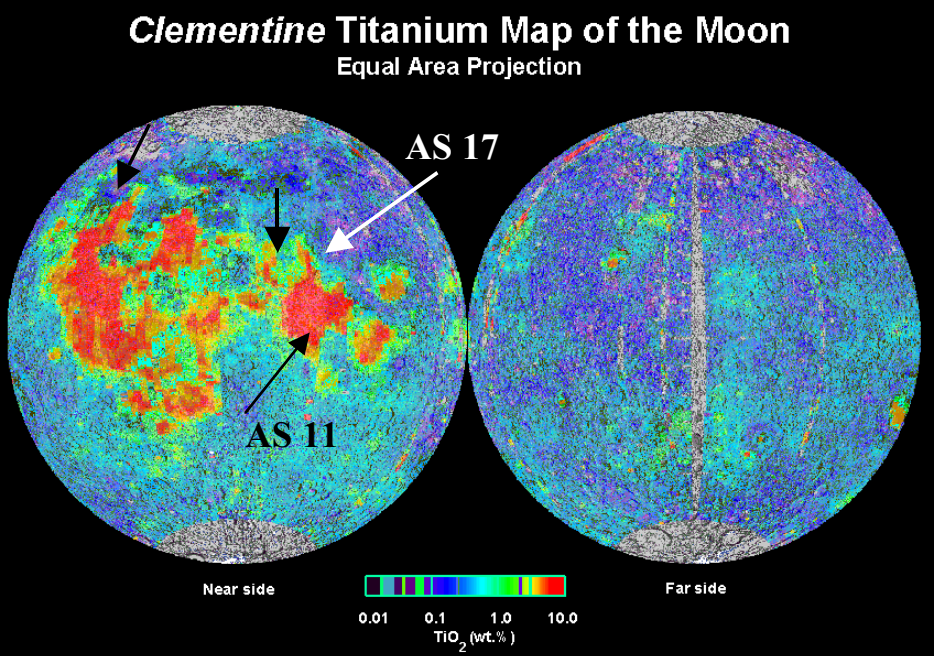
BASALTIC MARIA

WILHELMS, 1984

DISTRIBUTION OF BASALTIC MARIA

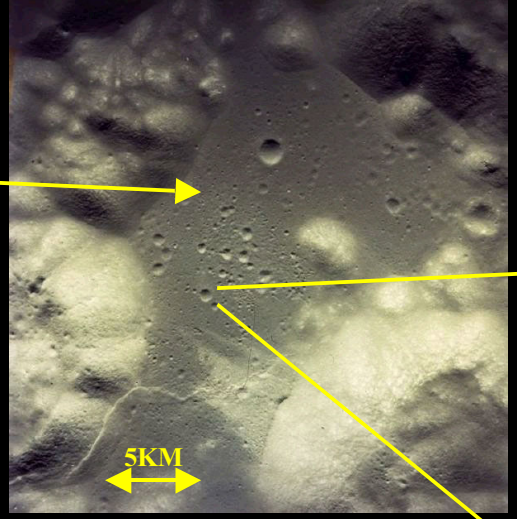
SHOWN BY IRON DISTRIBUTION (LEFT)
CONTRAST WITH VARIABILITY OF TITANIUM DISTRIBUTION (RIGHT)
(ARROWS INDICATE DIFFERENCES IN CENTRAL SERENITATIS MARIA AND NORTERN OCEANUS PROCELLARUM)



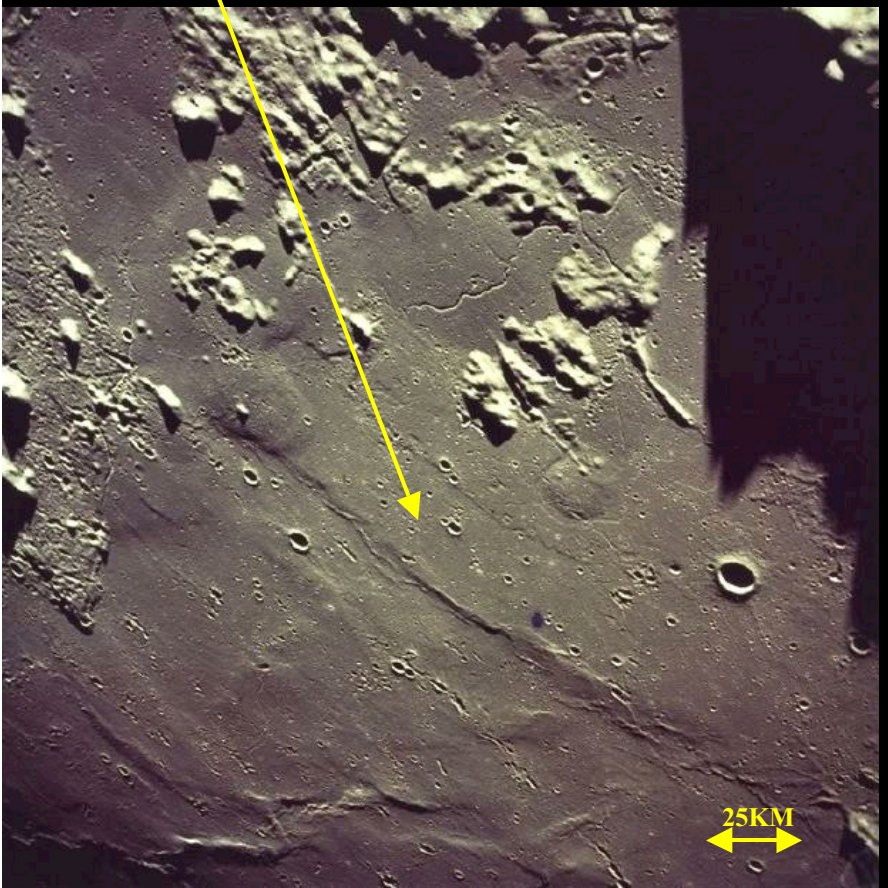


BASALTIC MARIA

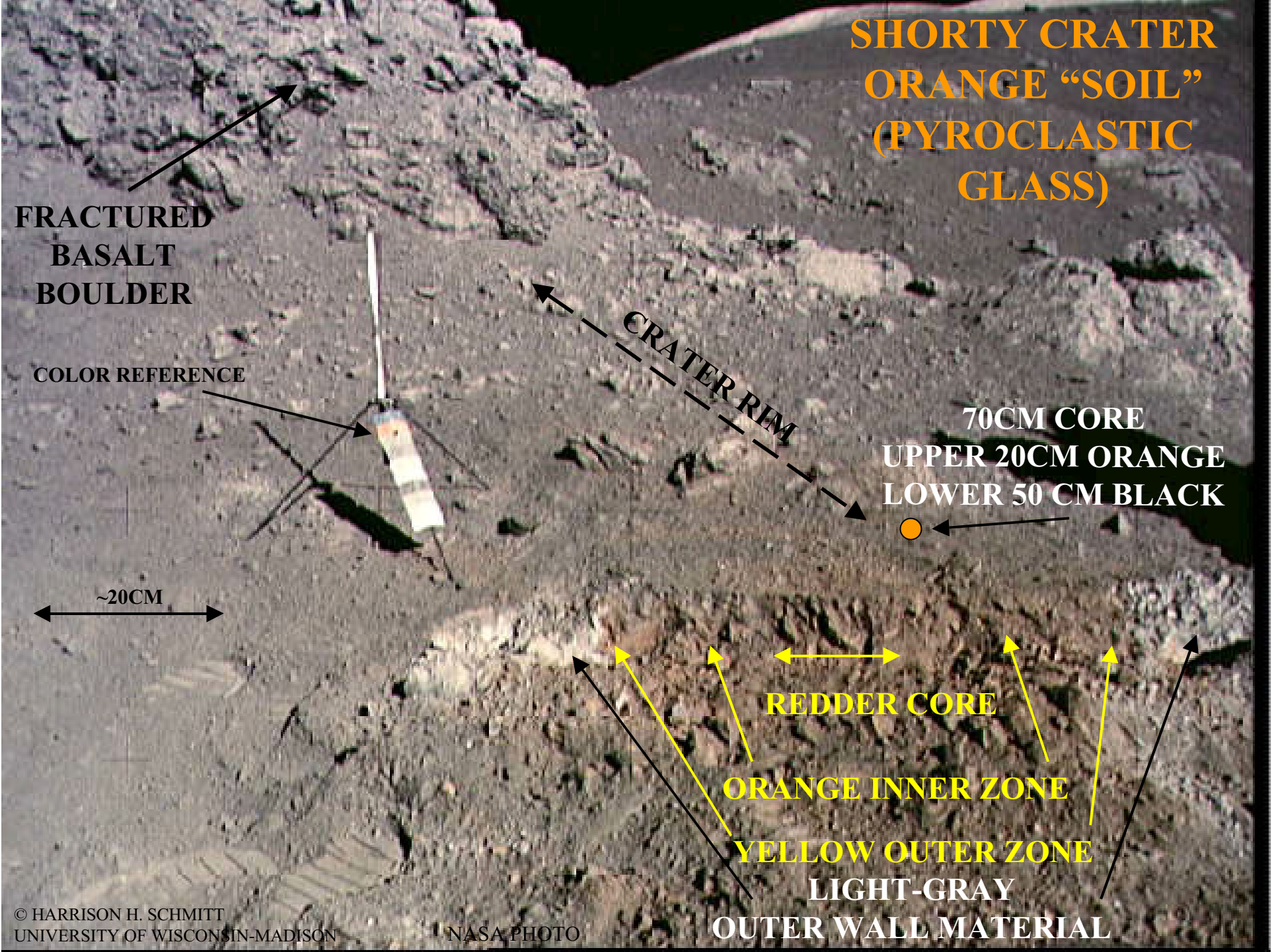
TAURUS LITTROW MARE



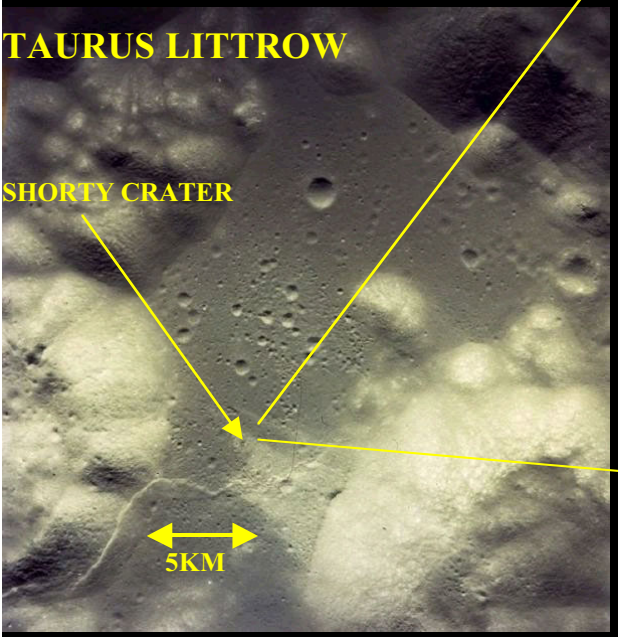
EASTERN IMBRIAN MARE

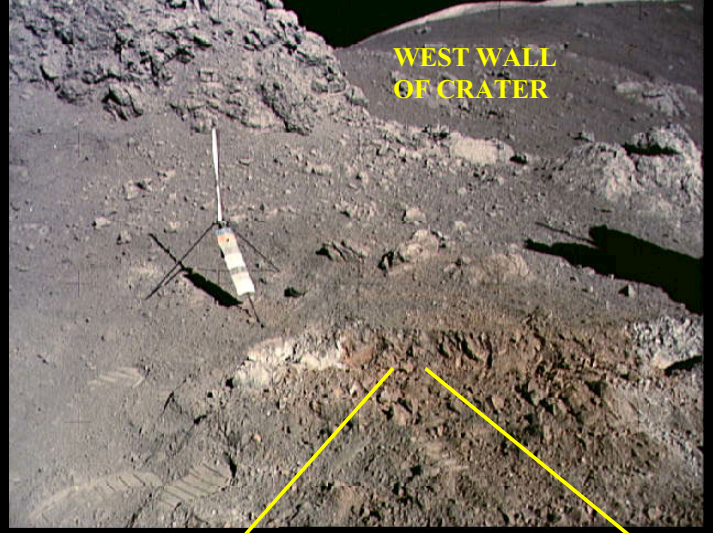


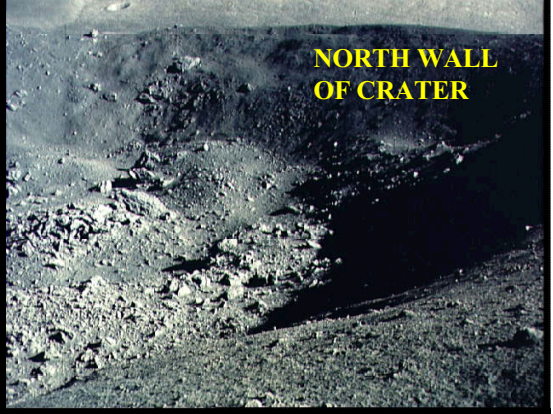
MARE BASALT TEXTURES

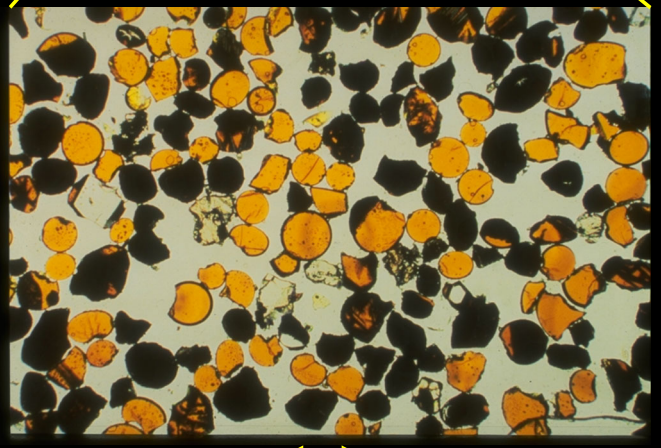


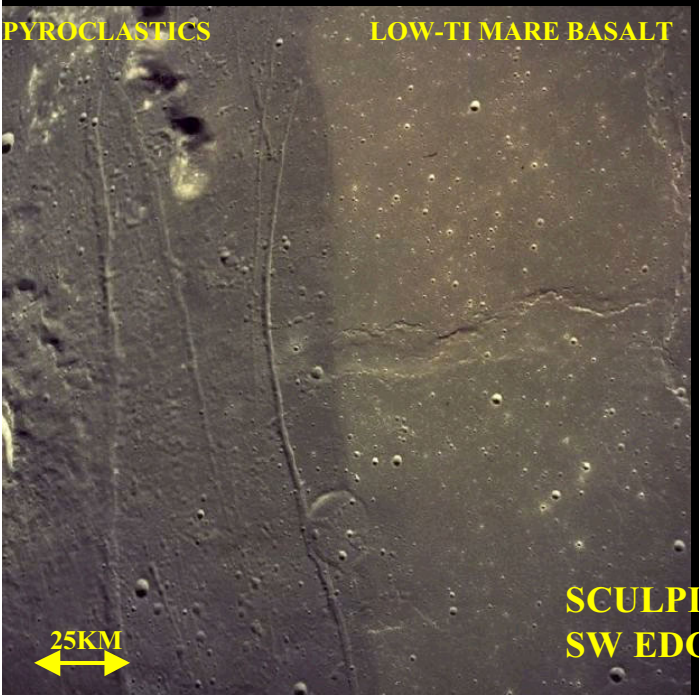
NASA PHOTO











SCULPICCIUS GALLES REGION
SW EDGE SERENITATIS BASIN

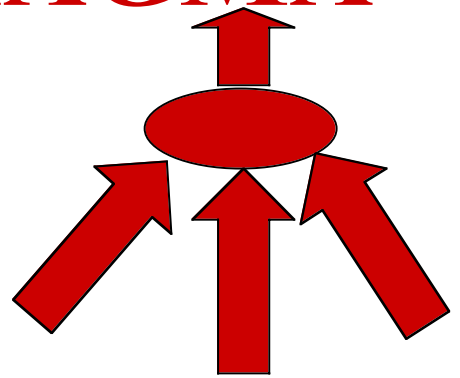
PYROCLASTIC GLASS DEPOSITS

NASA PHOTOS

SOURCES OF MARE MAGMA DIVERSITY -1

- **MAGMA OCEAN FRACTIONAL CRYSTALLIZATION TO PRODUCE UPPER MANTLE LAYERING**
- **LOCAL ILMENITE CUMULATE OVERTURN TO PRODUCE Ti AND urKREEP VARIABILITY WITH DEPTH**
- **DEPTH OF PENETRATION OF TENSIONAL FRACTURES DUE TO GLOBAL INTERNAL HEATING**
- **VERY LARGE AND OLD LARGE BASIN DISRUPTION OF KREEP DISTRIBUTION**
- **DEPTHS OF VERY LARGE AND LARGE BASIN PRESSURE RELEASE MELTING**

SOURCES OF MARE MAGMA DIVERSITY -2



- **RELATIVE VOLUMES OF KREEP ASSIMILATION**
- **RELATIVE VOLUMES OF LOWER CRUSTAL MG-SUITE/FERROAN ANORTHOSITE ASSIMILATION**
- **RELATIVE VOLUMES OF UPPER CRUSTAL FERROAN ANOTTHOSITE ASSIMILATION**
- **LOWER MANTLE CONTRIBUTIONS OF CHONDRITIC PARTIAL MELTS AND VOLATILES**
- **DENSITY, VISCOSITY AND VOLATILE EFFECTS ON RATE OF ASCENT OF MAGMAS**

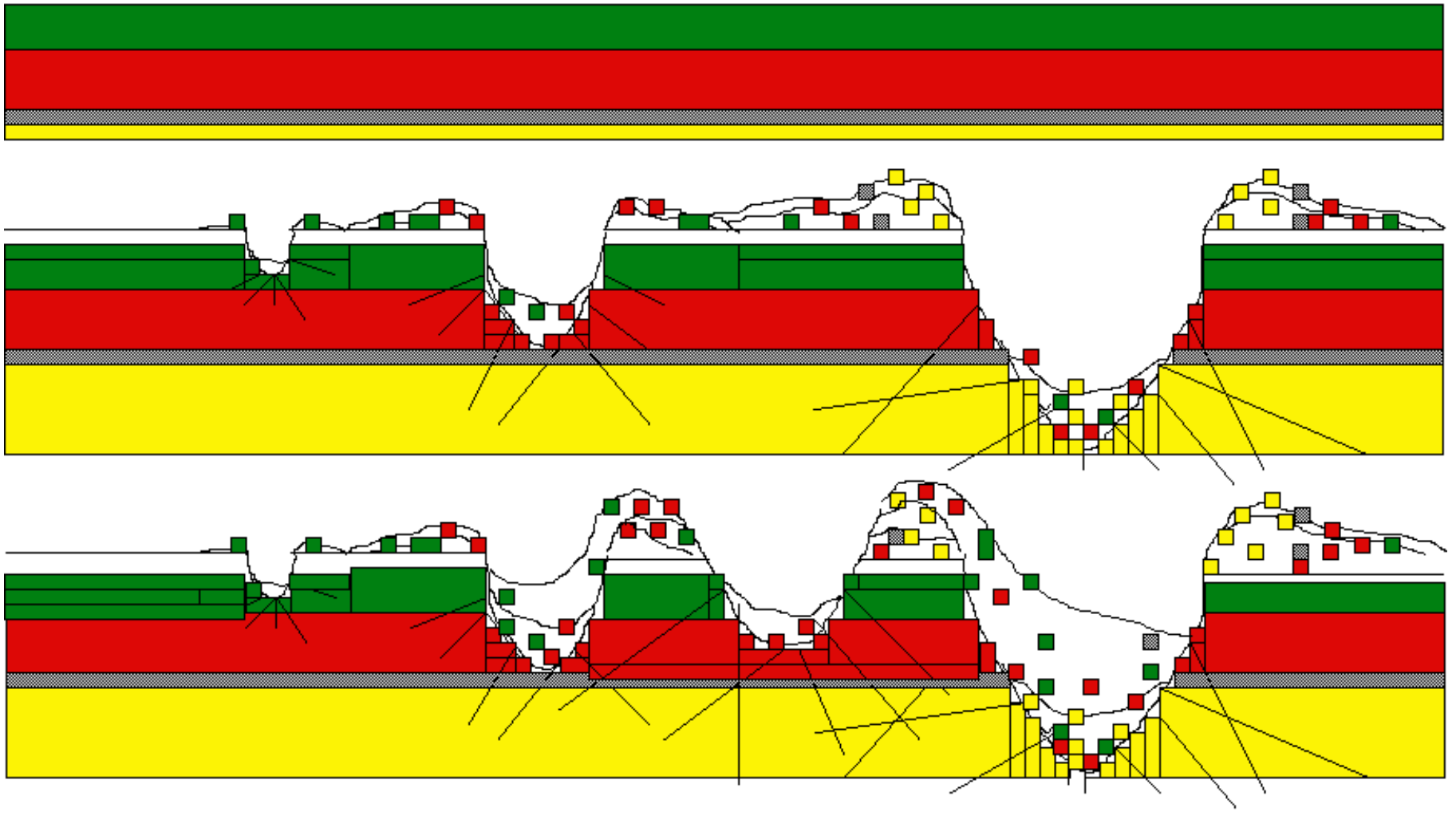
LUNAR RESOURSE AVAILABILITY

MAJOR FACTORS

- ORIGINAL ROCK COMPOSTION AND AGE
- REGOLITH FORMATION AND DISTRIBUTION OF BLOCKY RIM CRATERS
- ABSENCE OF WATER DURING LUNAR EVOLUTION
- FRACTIONAL CRYSTALLIZATION

THE REGOLITH……..

DISTURBED REGOLITH……



CONCEPTUAL DEVELOPMENT OF LUNAR REGOLITH IN MARE BASINS

APPROXIMATE SCALE 1CM = 10 M

BASALT UNITS

REGOLITH UNITS

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 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)

LUNAR SPECIAL COMPOUNDS

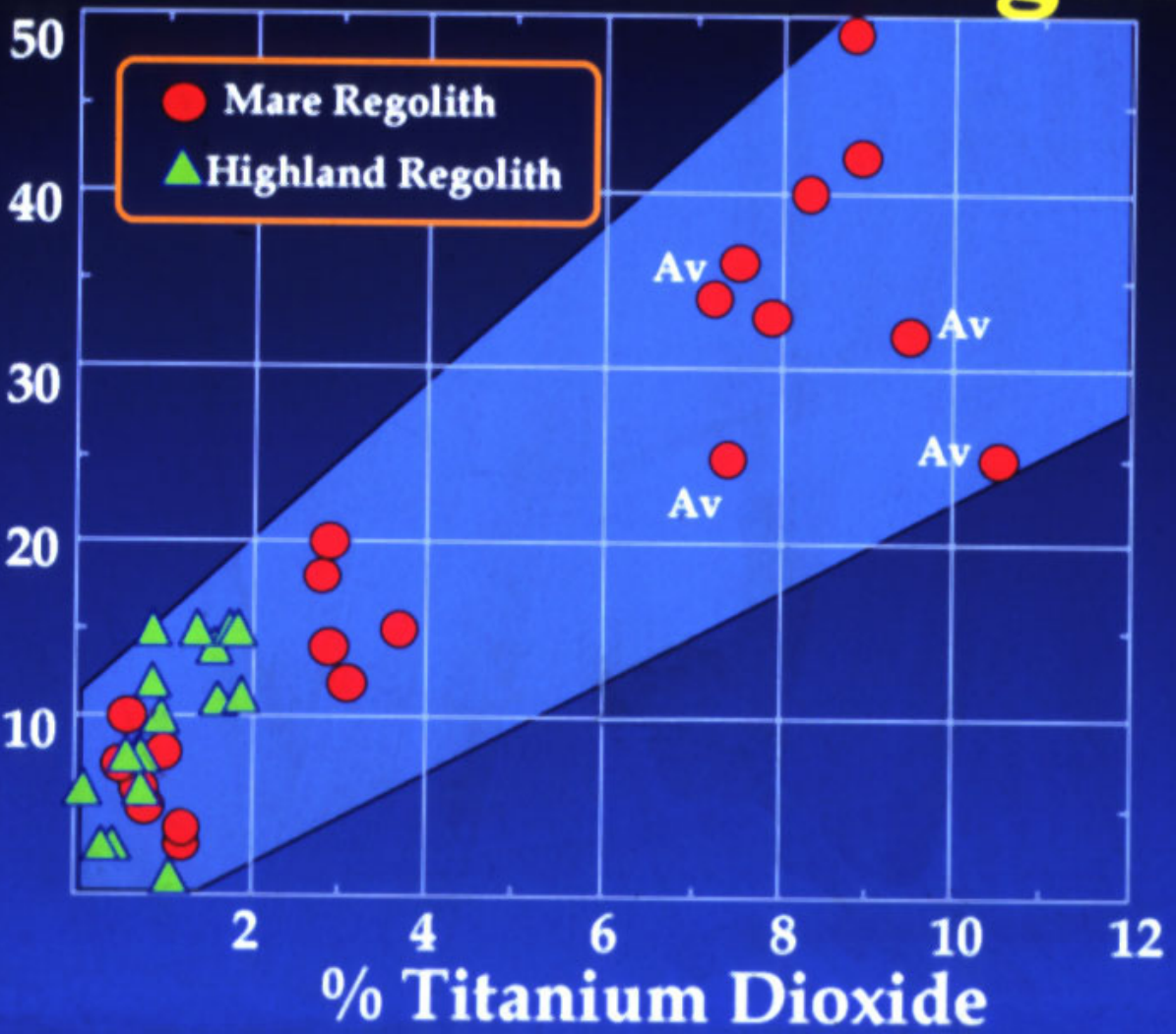
- **LUNAR KREEP (NOT NORMALLY ASSOCIATED WITH BASALTIC REGOLITH)**
  - **PHOSPHATE (P_2O_5)**
  - **POTASH (K_2O)**
  - **SODA (Na_2O)**

INDIGENOUS LUNAR VOLATILES

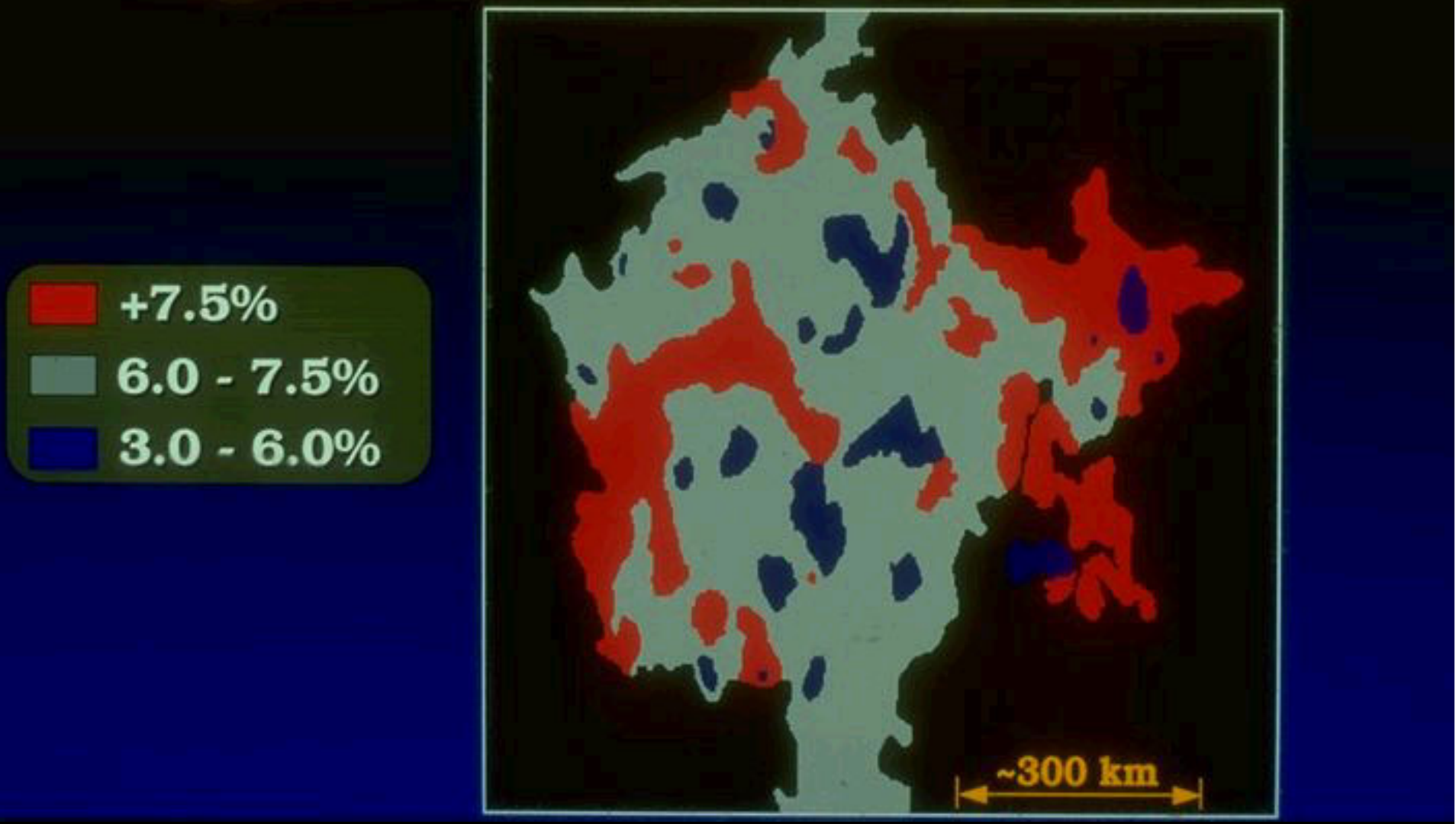
- **FROM PYROCLASTIC GLASSES**
  - **OXYGEN (ELECTROLYSIS OF H_2O PRODUCED BY HYDROGEN REDUCTION)**
- **ADSORBED ON PYROCLASTIC GLASSES (LARGE VOLUME PROCESSING)**
  - **FLUORINE**
  - **CHLORINE**
  - **VOLATILE METALS (COPPER, ZINC, LEAD)**
- **FROM REGOLITH (LARGE VOLUME PROCESSING)**
  - **SULFUR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


RED, ORANGE,
AND BLACK
PYROCLASTIC
GLASS DEPOSIT
IN SOUTHERN
SERENITATIS

Correlation of Helium Content With TiO2 in Lunar Regolith



Inferred Titanium Content of Regolith of Mare Tranquillitatis



CAMERON, 1986

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

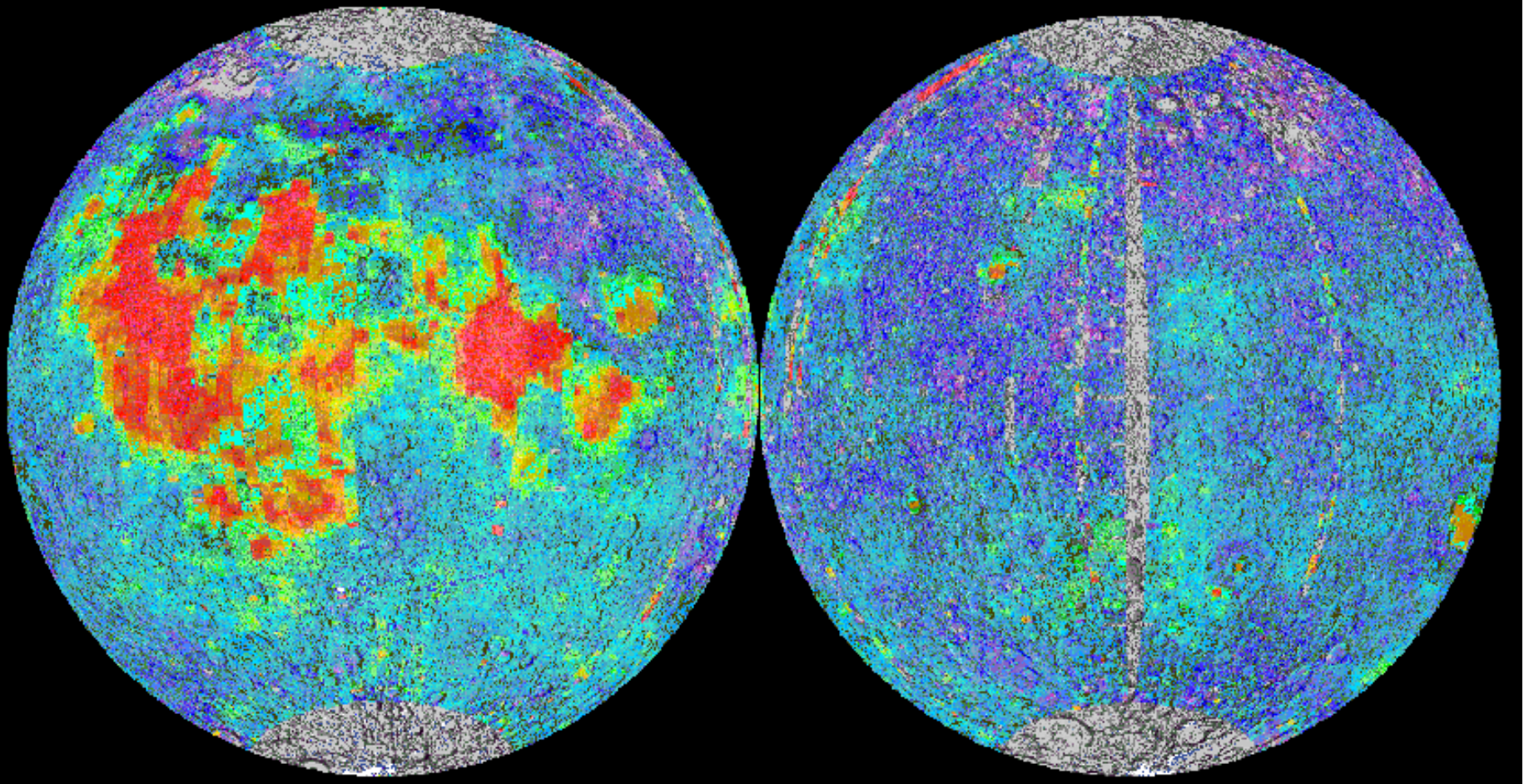
>60,000 1000MW PLANT YEARS !!!!

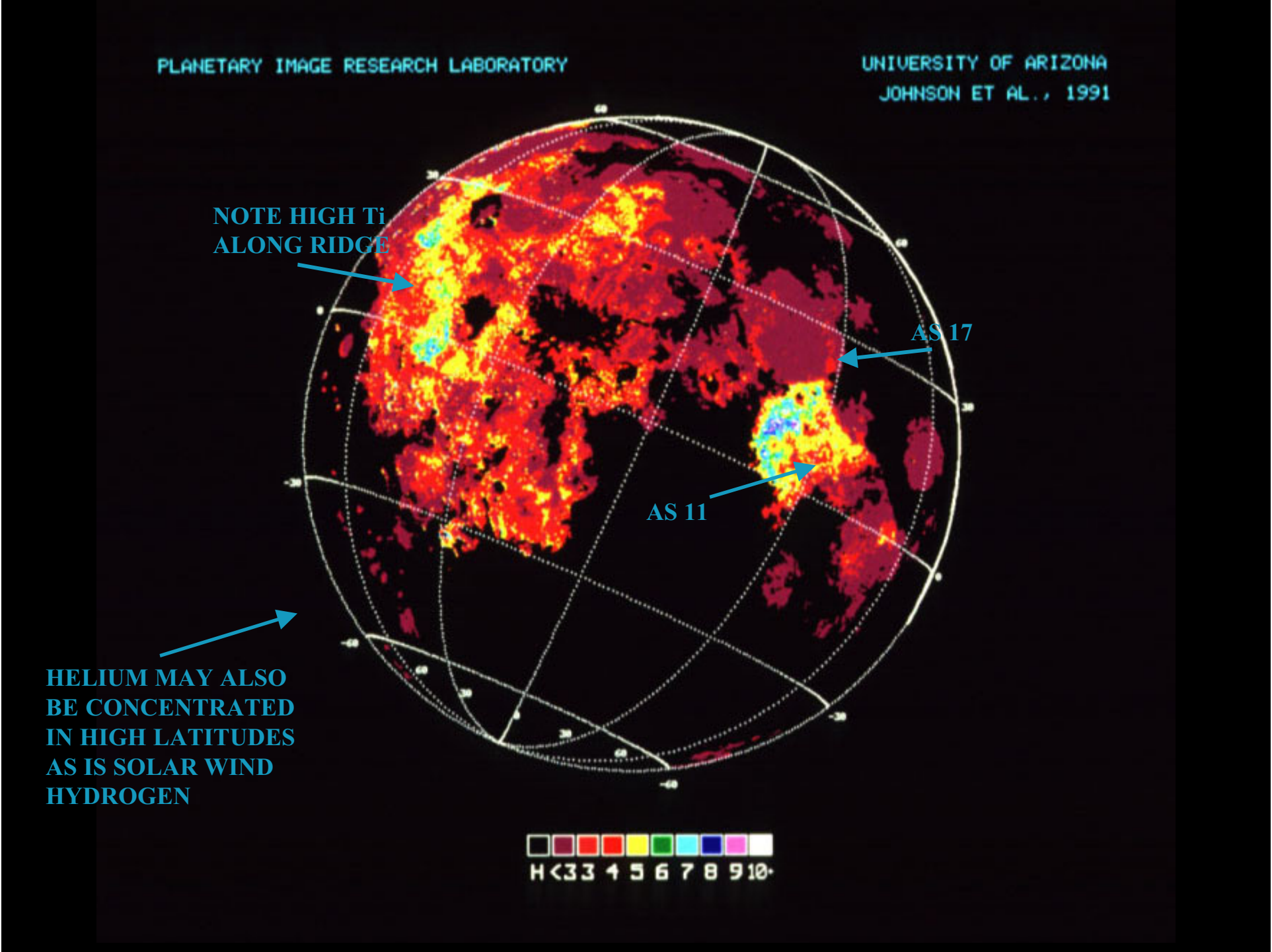
Note: He-3 content based on He/He-3 = 2600.
Average depth of regolith = 3 m.

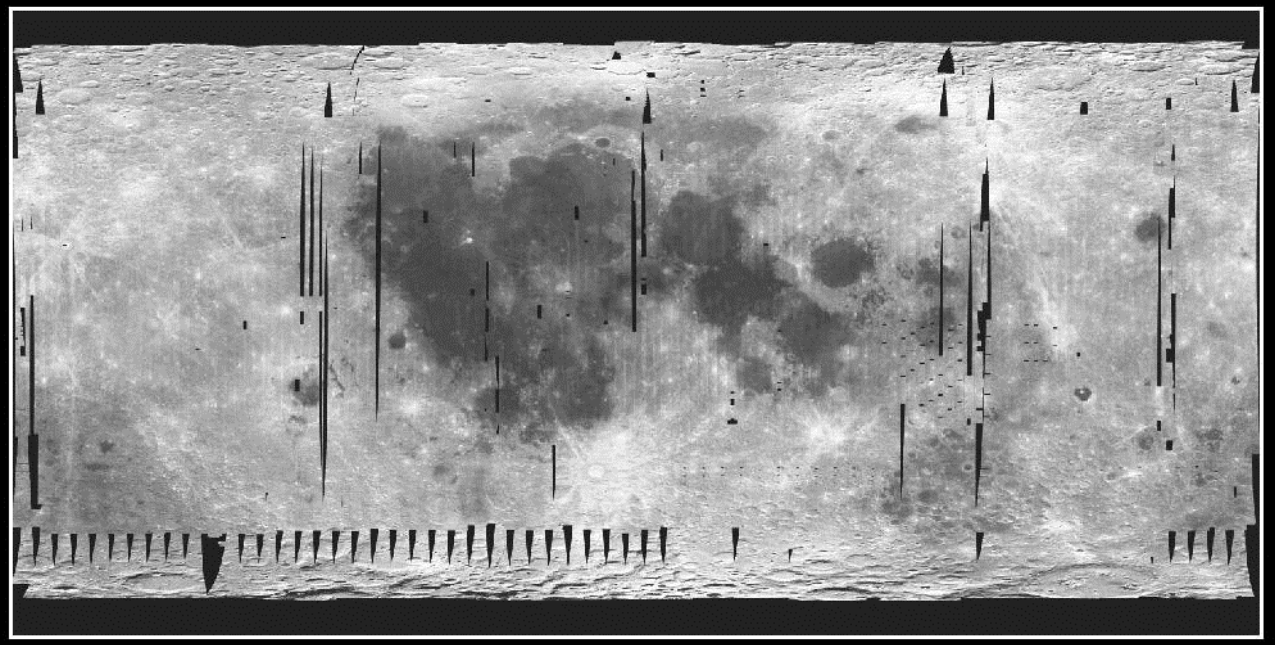
CAMERON, 1986

Clementine Titanium Map of the Moon

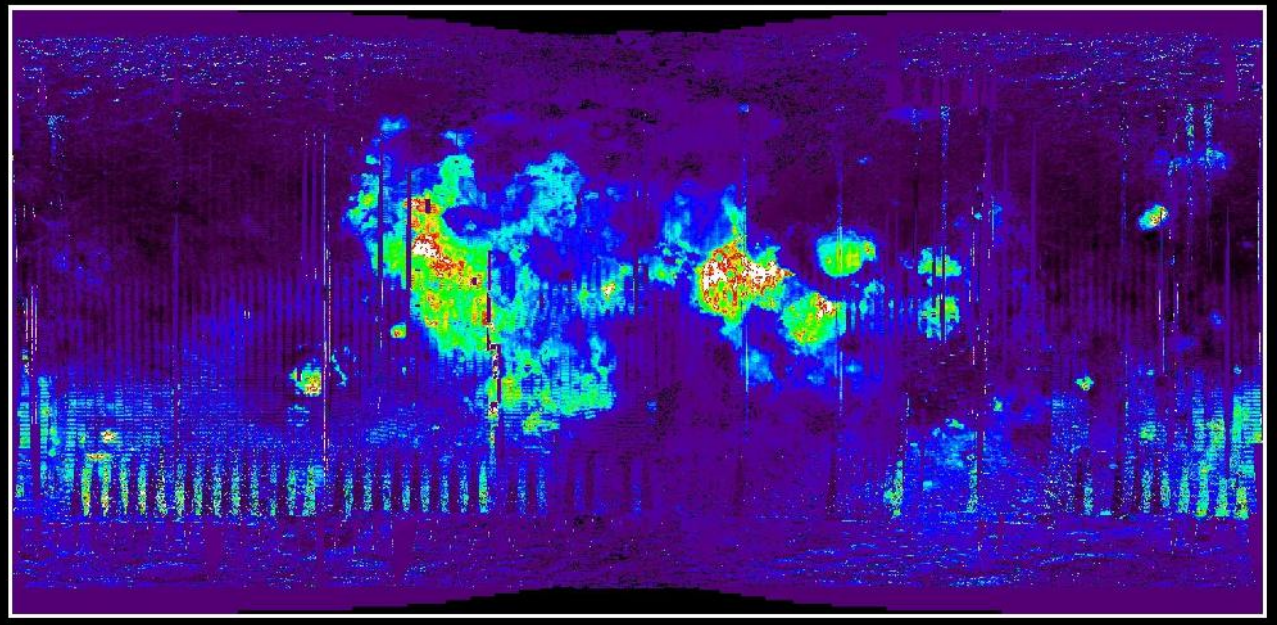
Equal Area Projection




PLANETARY IMAGE RESEARCH LABORATORY
UNIVERSITY OF ARIZONA
JOHNSON ET AL., 1991
NOTE HIGH Ti
ALONG RIDGE
AS 17
AS 11
HELIUM MAY ALSO
BE CONCENTRATED
IN HIGH LATITUDES
AS IS SOLAR WIND
HYDROGEN
H<3 3 4 5 6 7 8 9 10+



Clementine Lunar Mosaic



Estimated Helium-3 Abundance

COMETARY VOLATILES
POLAR DEPOSITS?

- **HYDROGEN REGIONAL AVE. INCREASES TO 150 PPM WITH DECREASE IN AVERAGE SURFACE TEMPERATURE**
  - **LUNAR PROSPECTOR EPITHERMAL NEUTRON SPECTRA**
- **HELIUM MAY INCREASE COMPARAB LY**
- **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?**
  - **ARACIBO RADAR INDICATES NOT WATER ICE**

DISCREPENCY UNRESOLVED

- **HYDROCARBONS?**

POSSIBLE TERM PAPER TOPICS

- **GENERAL REVIEW OF He DISTRIBUTION IN APOLLO CORES**
- **REVIEW OF THEORY OF VOLATILE DEPOSITION IN PERMANENT SHADOW**