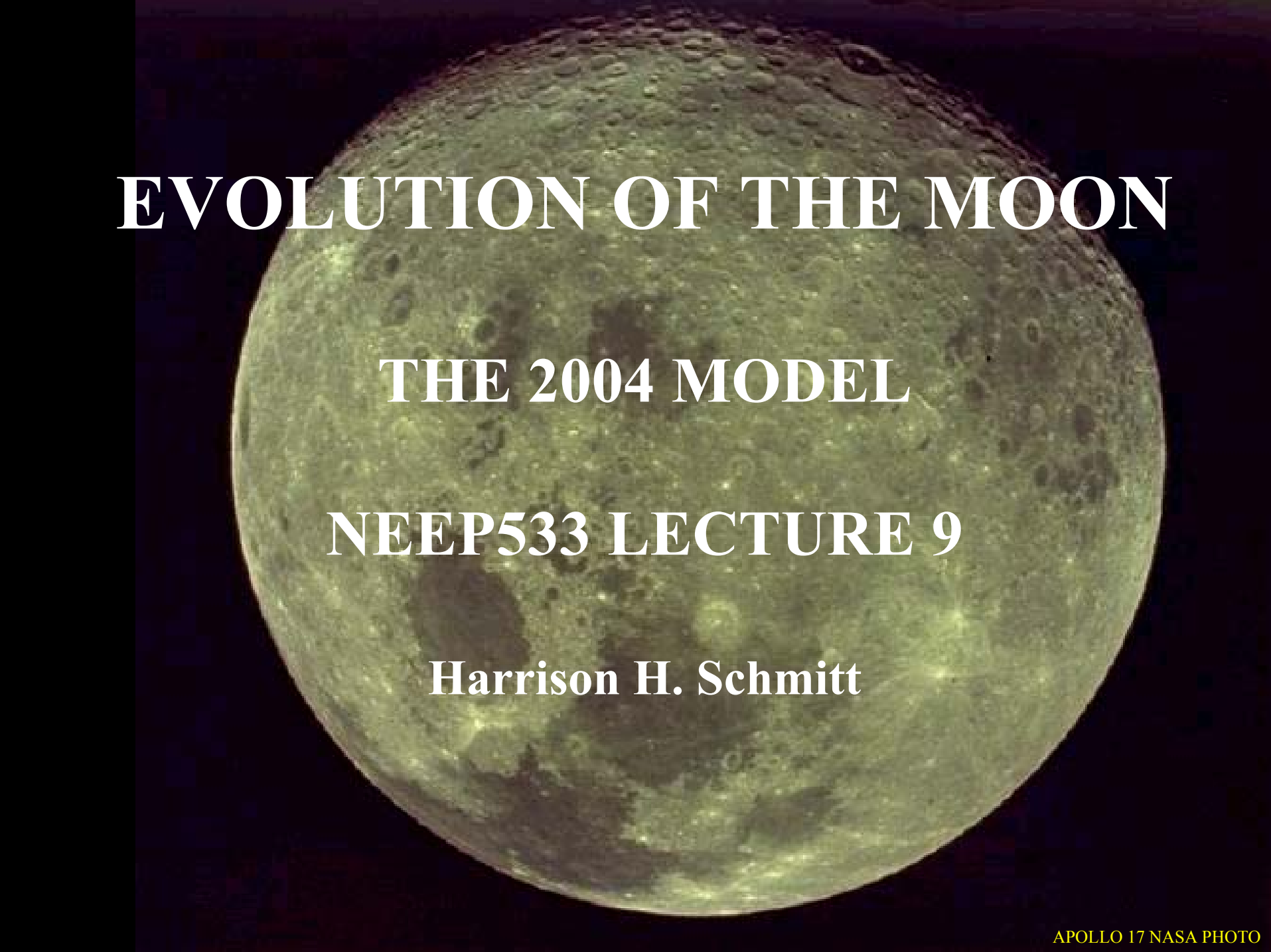


EVOLUTION OF THE MOON

THE 2004 MODEL

NEEP533 LECTURE 9

Harrison H. Schmitt

APOLLO 17 NASA PHOTO

DEFINITIONS-1

- **CHONDRULE**
  - **A VERY SMALL TO MARBLE SIZED PARTS OF CHONDRITIC METEORITES MADE UP LARGELY OF OLIVINE AND PYROXENE**
- **CARBONACEOUS CHONDRITE**
  - **A CLASS OF METEORITES CONTAINING CHONDRULES IN A CARBON-RICH MATRIX**
- **CHONDRITIC MATERIAL**
  - **MATERIAL CHEMICALLY OR ISOTOPICALLY RELATED TO CHONDRITES**
- **DIFFERENTIATION**
  - **GEOLOGICAL OR PLANETARY PROCESSES THAT RESULT IN A SEPARATION OF ELEMENTS**
- **FRACTIONAL CRYSTALLIZATION**
  - **DIFFERENTIATION BY THE SEPARATION OF MINERALS CRYSTALLIZING IN MAGMA ON THE BASIS OF DENSITY**

DEFINITIONS- 2

- **SIDEROPHILE**
- **LITHOPHILE**
- **CHALCOPHILE**
- **INCOMPATIBLE ELEMENT**
- **REFRACTORY MATERIAL**
- **CRYPTOMARIA**

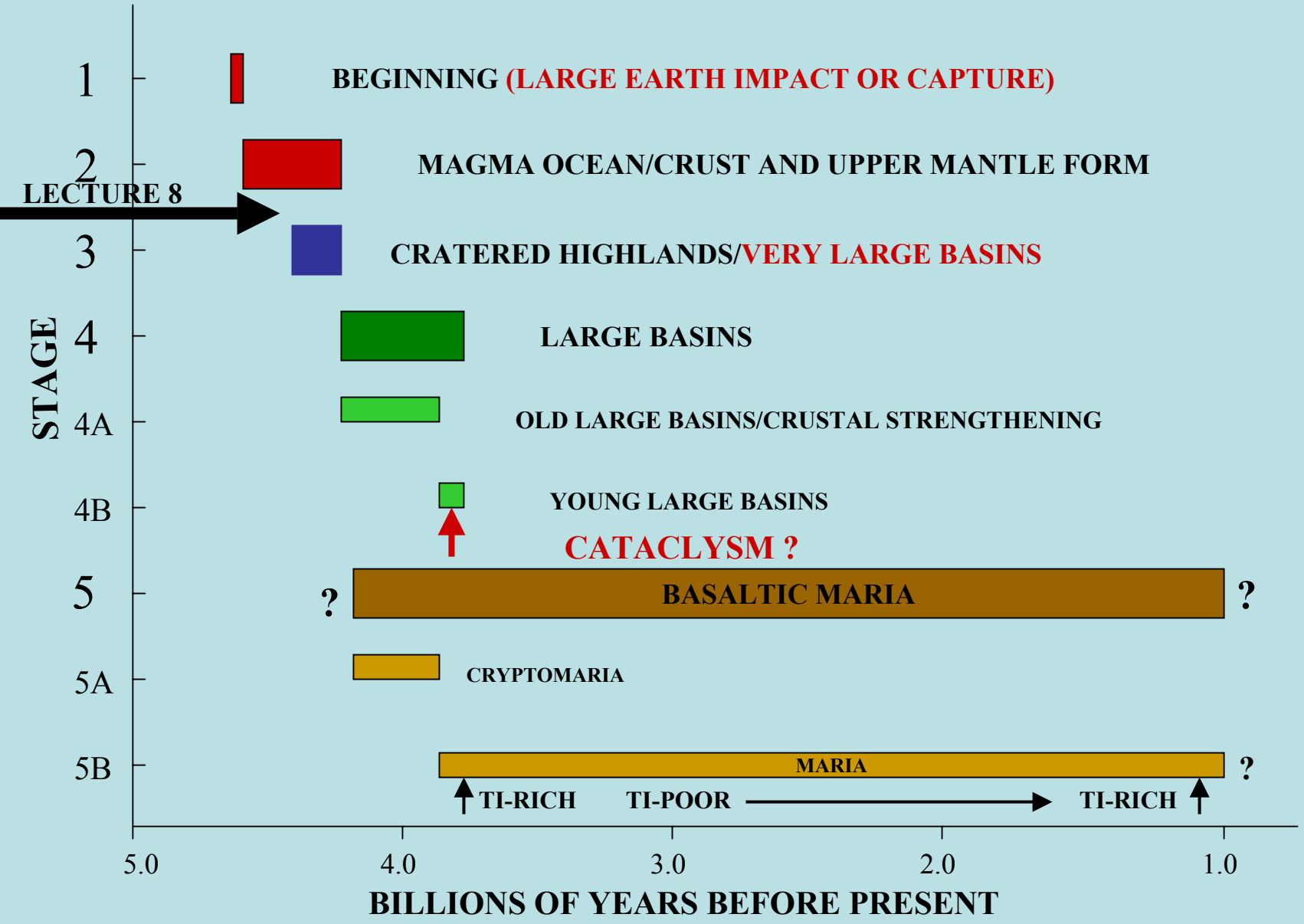
- **CHEMICALLY FOLLOWS (LOVES) IRON**
- **CHEMICALLY FOLLOWS (LOVES) SILICON**
- **CHEMICALLY FOLLOWS (LOVES) SULFUR**
- **IONIC SIZE OR CHARGE LIMITS INCLUSION IN COMMON MINERALS**
- **MELTS OR DECOMPOSES AT HIGH TEMPERATURE**
- **PROBABLE MARE-LIKE BASALT FLOWS NOW COVERED BY YOUNG, LARGE BASIN EJECTA. DEFINED BY IMPACTS THAT PENETRATE SUCH EJECTA**

DEFINITIONS - 3

- **KREEP**
- **urKREEP**
- **OLD LARGE BASINS**
- **YOUNG LARGE BASINS**
- **MG-SUITE**

- **COMPONENT OF SAMPLES RICH IN K, REE, P, U, AND Th**
- **SOURCE OF KREEP COMPONENT**
- **IRREGULAR BASINS WITHOUT MASCONS**
- **CIRCULAR BASINS WITH MASCONS**
- **FRAGMENTS OF CRYSTALLINE IGNEOUS ROCKS RICH IN Mg**

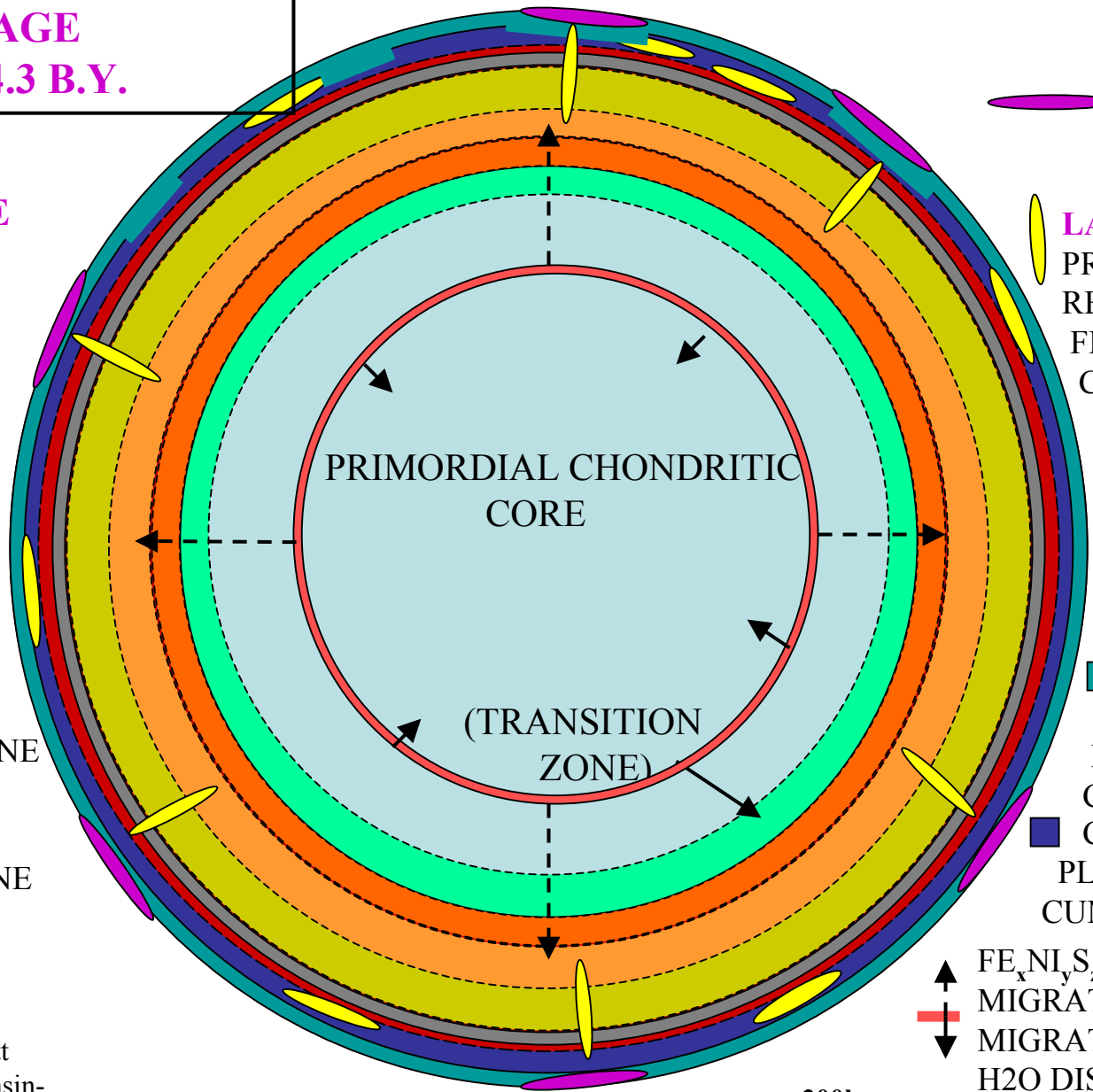
MAJOR STAGES OF LUNAR EVOLUTION



RED = MAJOR UNCERTAINTY

APOLLO MODEL OF LUNAR EVOLUTION

CRATERED HIGHLANDS STAGE
~4.5 - 4.3 B.Y.



LARGE IMPACT EVENTS

LATE MG-SUITE PRESSURE RELEASE MAGMAS FROM OLV-OPX CUMULATE LAYER

MG-SUITE INTRUSIVES

OLIVINE, HIGH CA-PYROXENE, AND ILMENITE CUMULATE

RESIDUAL MAGMA OCEAN (URKREEP LIQUID)

OLIVINE AND HIGH CA-PYROXENE CUMULATE

OLIVINE AND LOW CA-PYROXENE CUMULATE

OLIVINE CUMULATE

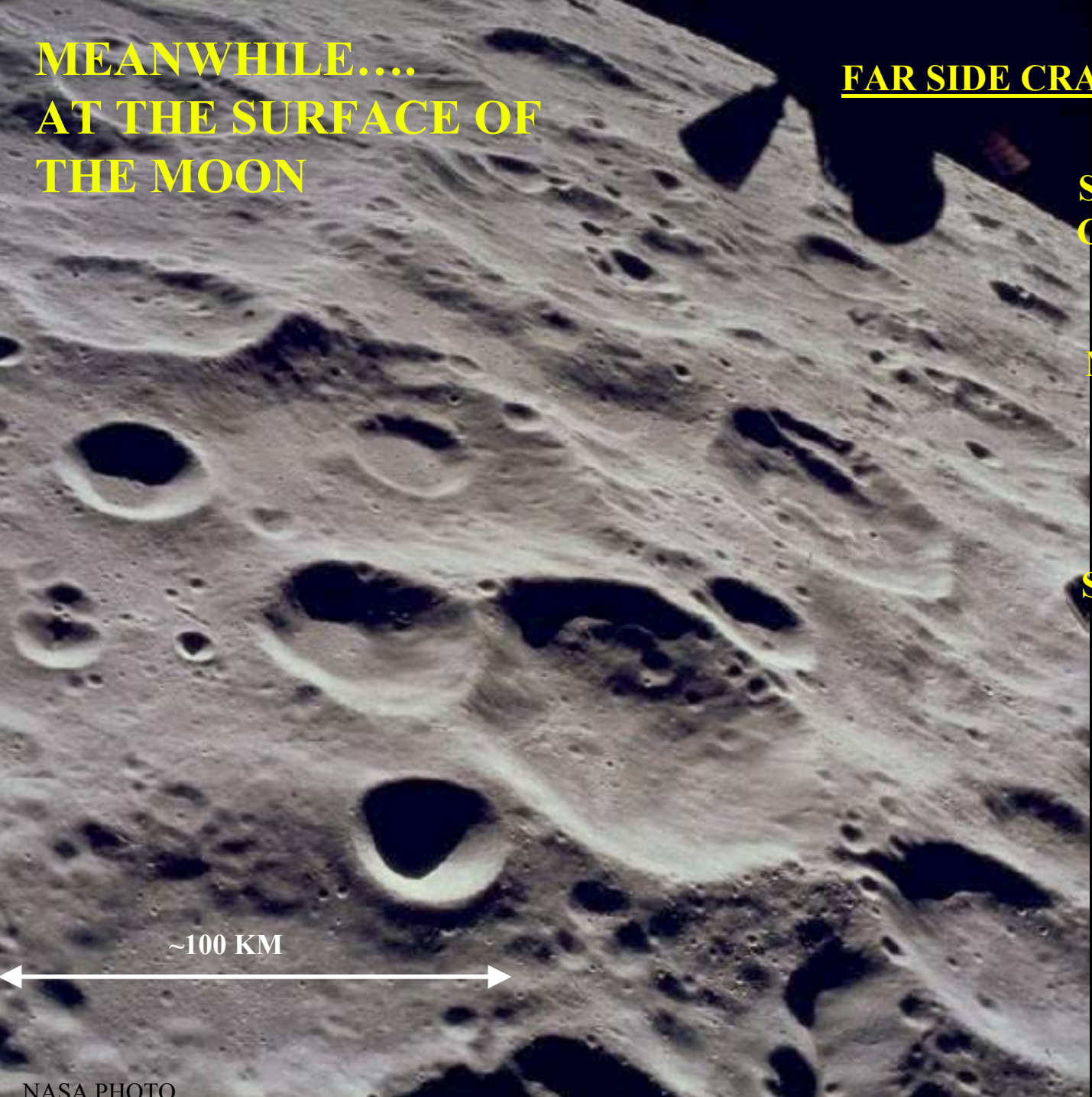
ZONE OF IMPACT BRECCIATION OF PLAGIOCLASE CUMULATE

CONSOLIDATING PLAGIOCLASE CUMULATE

$FE_xNI_yS_z$ LIQUID MIGRATION AND C0 & H MIGRATION AFTER H2O DISASSOCIATION

— = **200km**

MEANWHILE….
AT THE SURFACE OF THE MOON



NASA PHOTO

FAR SIDE CRATERED HIGHLANDS

SATURATED WITH CRATERS 60-70 KM DIAMETER

MEGA-REGOLITH ~25KM THICK

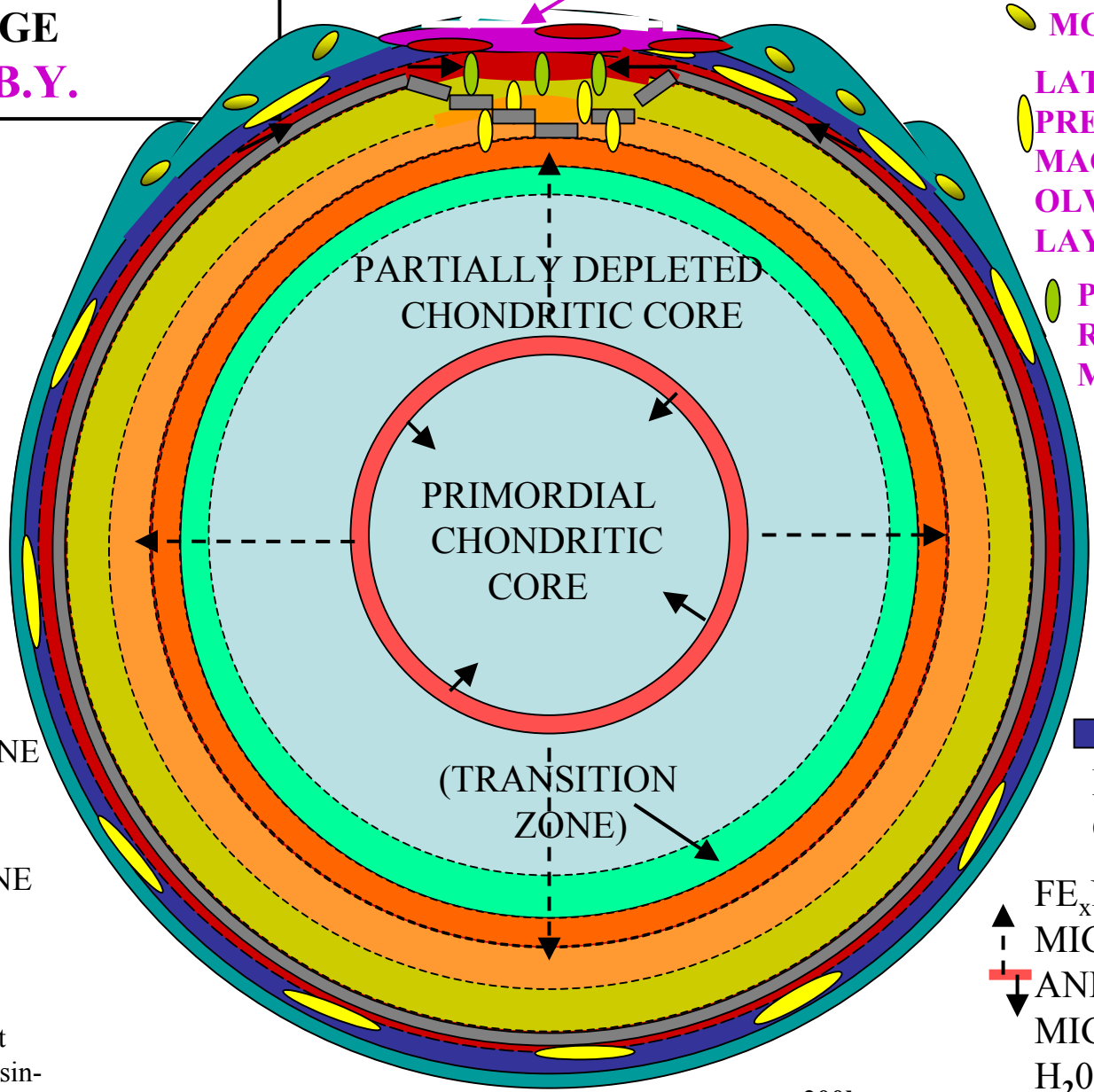
WELL-MIXED LATERALLY ON SCALE OF 100s KM

SIGNIFICANT EMBEDDED SOLAR WIND HYDROGEN

APOLLO MODEL OF LUNAR EVOLUTION

CRATERED HIGHLANDS STAGE

~4.3 B.Y.



MG-SUITE INTRUSIVES

ILMENITE CUMULATE MASSES

OLIVINE, HIGH CA-PYROXENE, AND ILMENITE CUMULATE

RESIDUAL MAGMA OCEAN (URKREEP LIQUID)

OLIVINE AND HIGH CA-PYROXENE CUMULATE

OLIVINE AND LOW CA-PYROXENE CUMULATE

OLIVINE CUMULATE

MG-SUITE DEBRIS

LATE MG-SUITE PRESSURE-RELEASE MAGMAS FROM OLV-OPX CUMULATE LAYER

PRESSURE-RELEASE BASALT MAGMAS FROM OLV-CPX CUMULATE LAYER

INSULATING CRATERED HIGHLANDS AND EJECTA

CONSOLIDATED PLAGIOCLASE CUMULATE

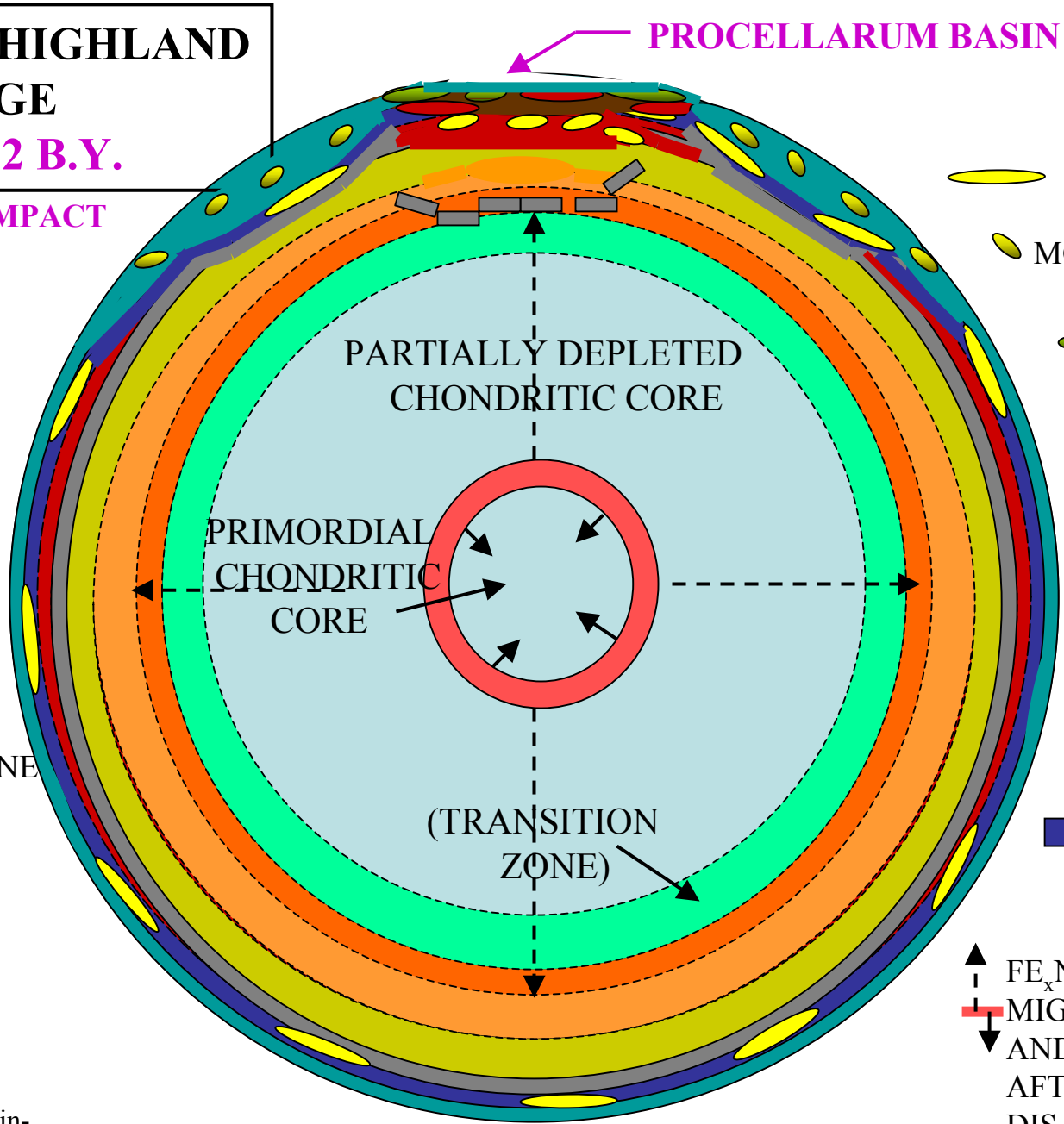
$FE_xNI_yS_z$ LIQUID MIGRATION AND CO & H MIGRATION AFTER H_20 DISASSOCIATION

— = **200km**

APOLLO MODEL OF LUNAR EVOLUTION

CRATERED HIGHLAND STAGE

PRE ~4.2 B.Y.



- SOLIDIFIED IMPACT MELT SHEET
- ILMENITE CUMULATE MASSES
- OLIVINE, HIGH CA-PYROXENE, AND ILMENITE CUMULATE
- RESIDUAL URKREEP LIQUID+KREEP BASALTS
- OLIVINE AND HIGH CA-PYROXENE CUMULATE
- OLIVINE AND LOW CA-PYROXENE CUMULATE
- OLIVINE CUMULATE

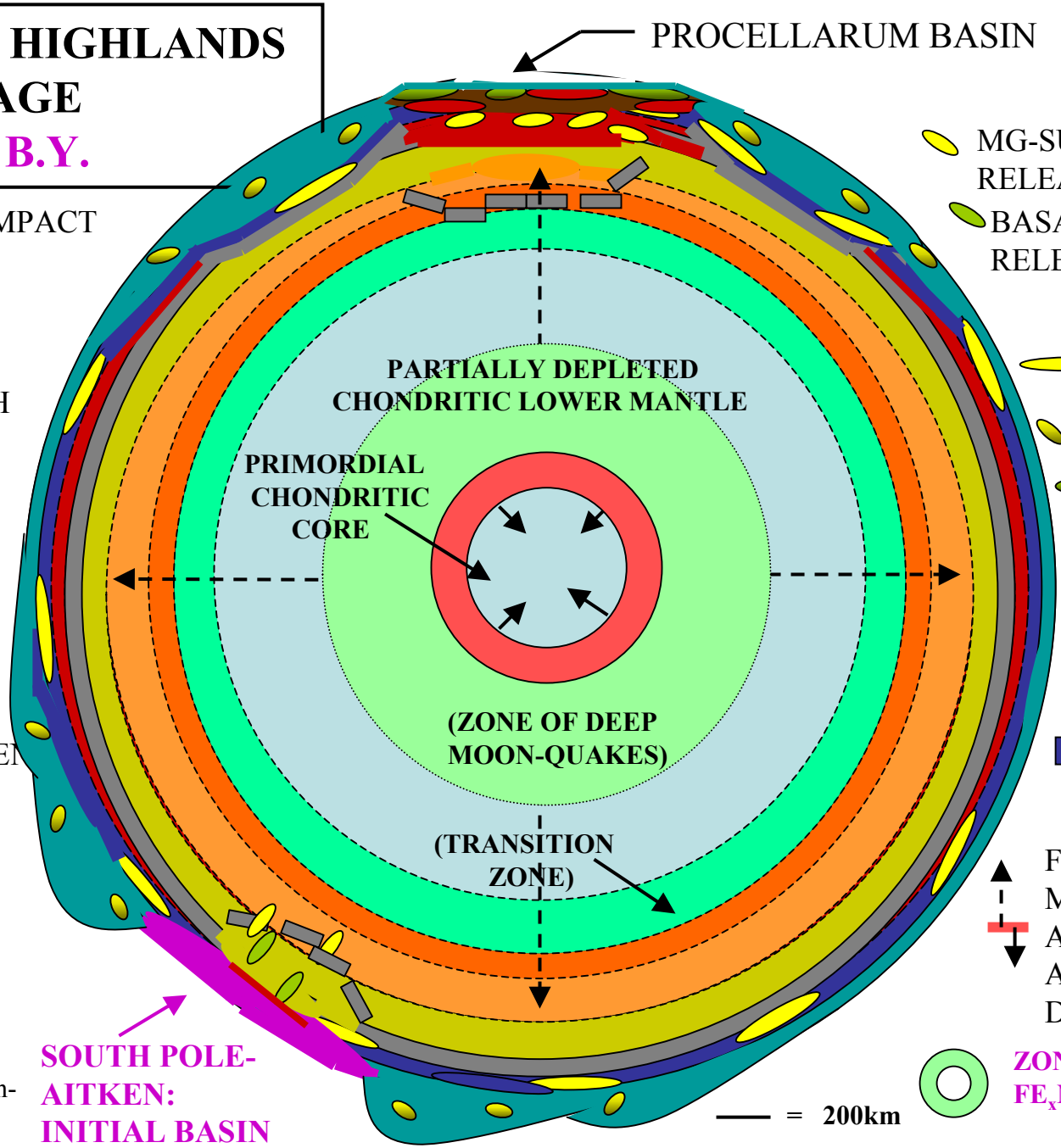
- MG-SUITE INTRUSIVES
- MG-SUITE DEBRIS
- EARLY KREEPY BASALT EXTRUSIVES
- INSULATING CRATERED HIGHLANDS AND EJECTA
- CONSOLIDATED PLAGIOCLASE CUMULATE
- $FE_xNI_yS_z$ LIQUID MIGRATION AND H MIGRATION AFTER H_20 DISASSOCIATION

— = 200km

APOLLO MODEL OF LUNAR EVOLUTION

CRATERED HIGHLANDS STAGE

~4.2 B.Y.



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- OLIVINE CUMULATE

- MG-SUITE PRESSURE-RELEASE MAGMAS
- BASALT PRESSURE-RELEASE MAGMAS
- MG-SUITE INTRUSIVES
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- EARLY KREEPY BASALT EXTRUSIVES
- INSULATING CRATERED HIGHLANDS AND EJECTA
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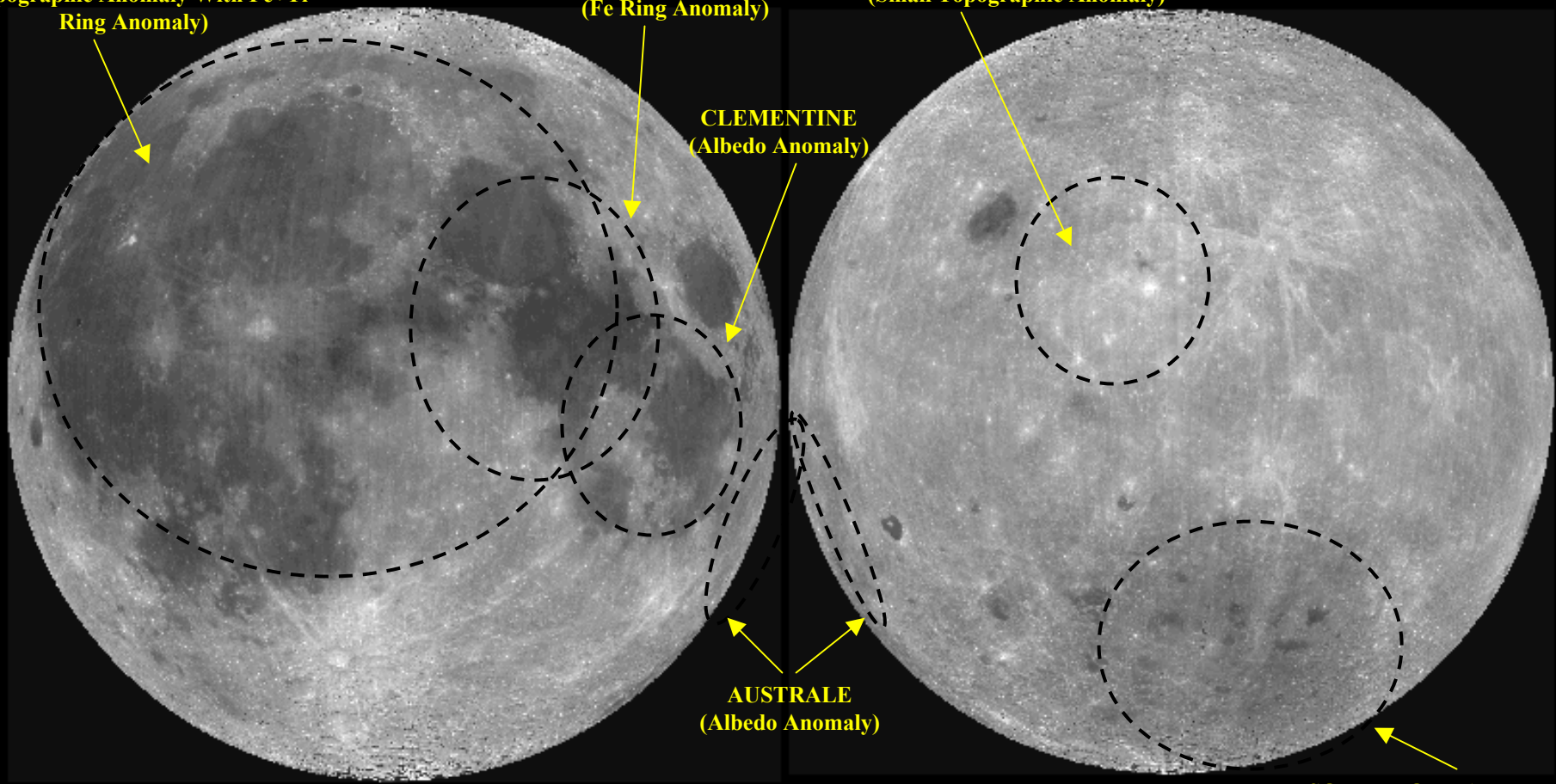
- $FE_xNI_yS_z$ LIQUID MIGRATION AND H MIGRATION AFTER H_20 DISASSOCIATION
- ZONE OF ISOLATED $FE_xNI_yS_z$ LIQUID MASSES

PROBABLE VERY LARGE BASINS ON THE MOON



CLEMENTINE GLOBAL ALBEDO IMAGES (750 nm filter)

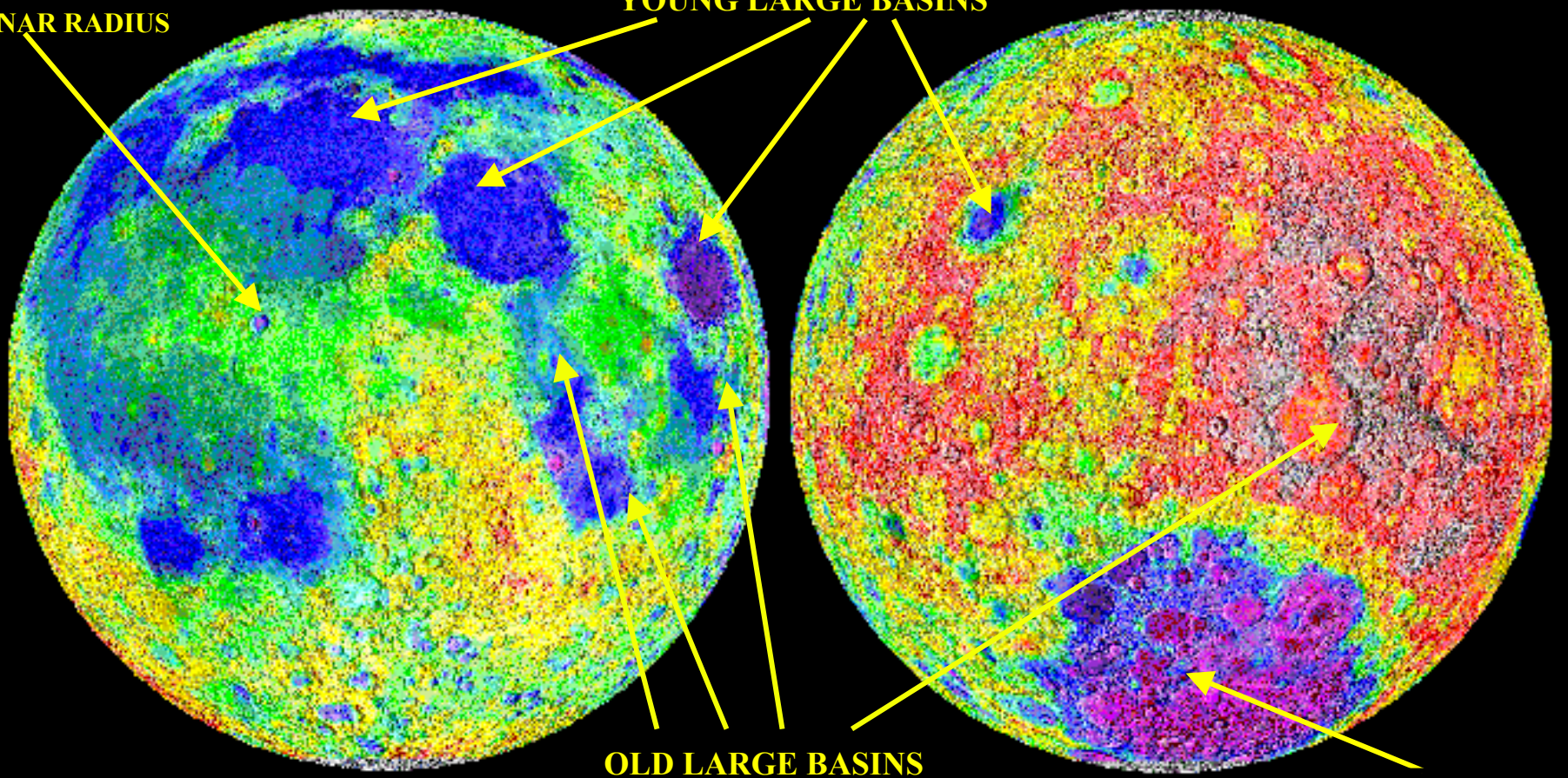
VERY LARGE BASINS

Clementine Topographic Map of the Moon

Contour Interval - 500 m

PROCELLARUM AVERAGE ~3KM BELOW MEAN LUNAR RADIUS

YOUNG LARGE BASINS



OLD LARGE BASINS

SOUTH POLE AITKEN 12 KM BELOW MEAN LUNAR RADIUS!

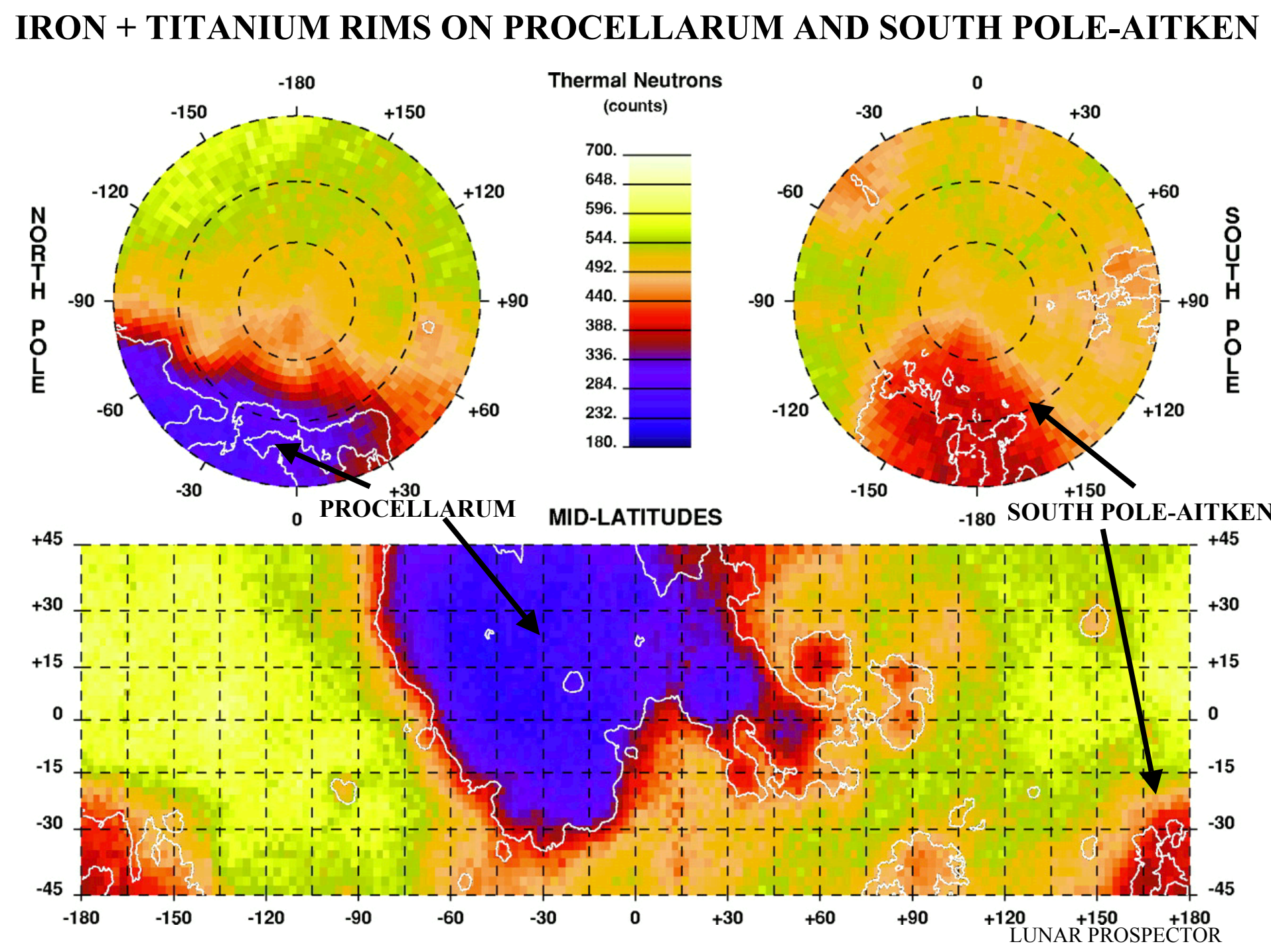
Near Side

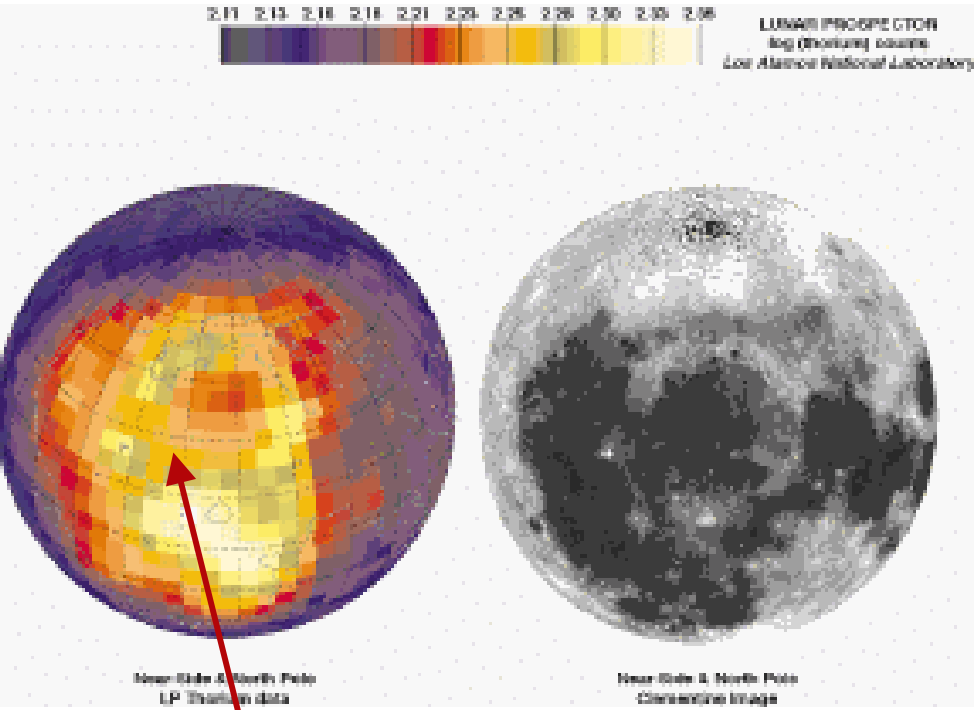
Far Side

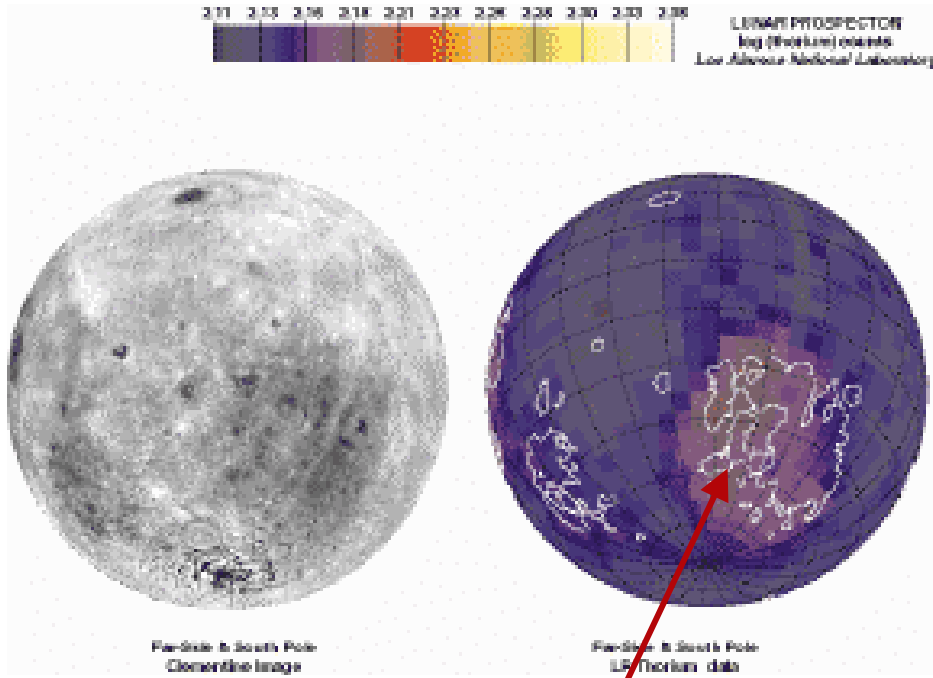
-8 -6 -4 -2 0 2 4 6 8

Kilometers

IRON + TITANIUM RIMS ON PROCELLARUM AND SOUTH POLE-AITKEN



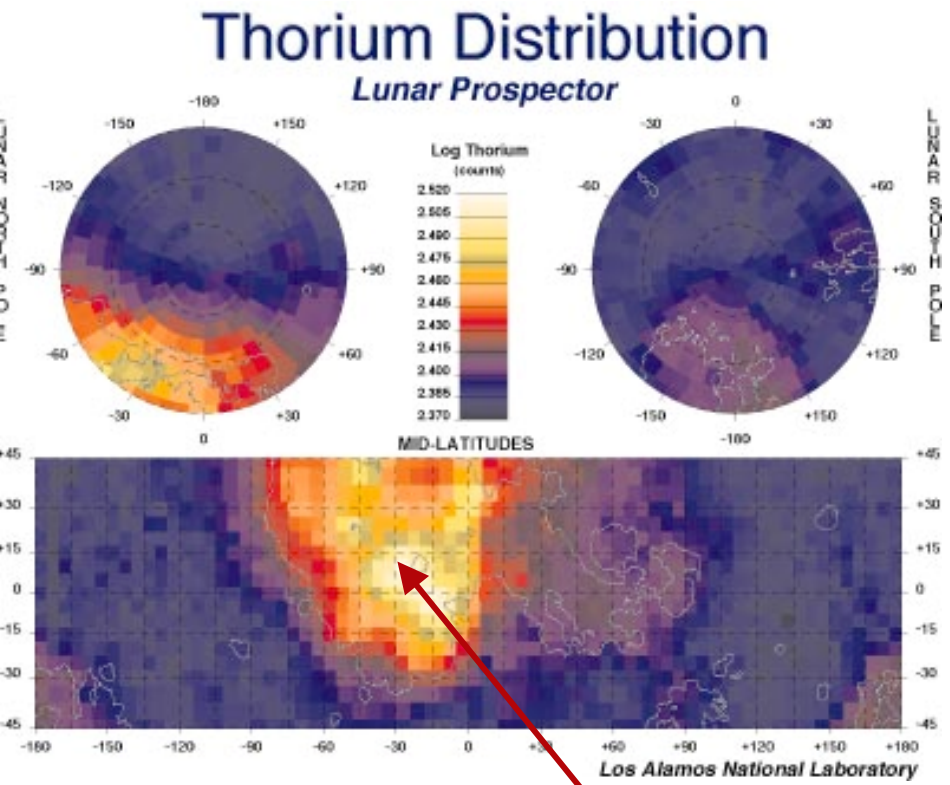


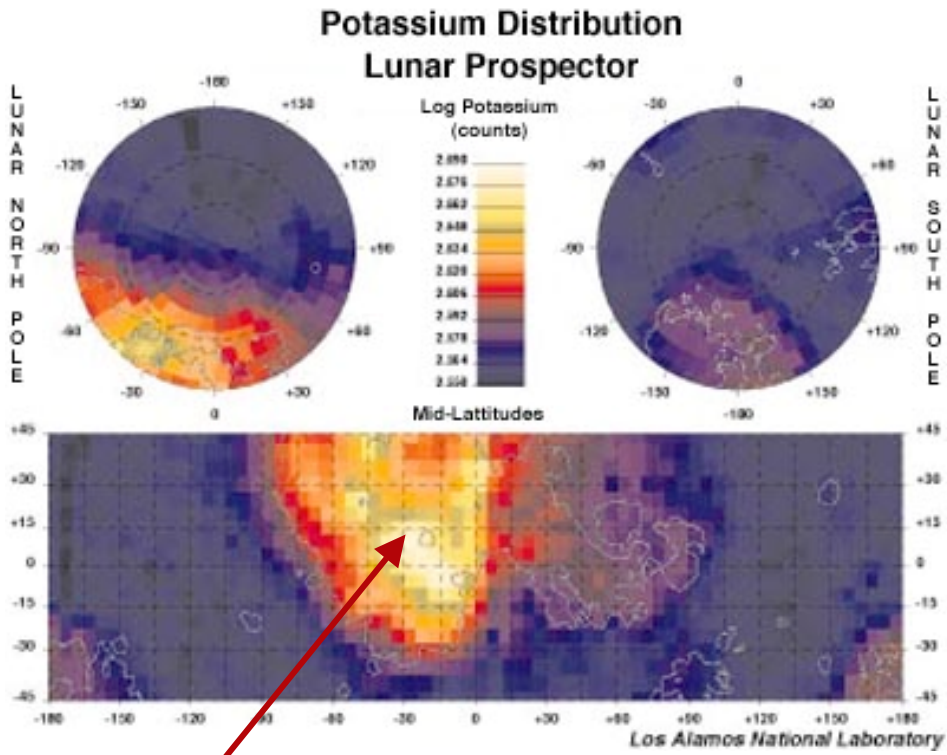


PROCELLARUM BASIN "THE KREEP HOT SPOT"

SOUTH POLE AITKEN BASIN

THORIUM CONCENTRATIONS AT THE LUNAR SURFACE





PROCELLARUM BASIN
"THE KREEP HOT SPOT"

COMPARISON OF LUNAR THORIUM AND POTASSIUM DISTRIBUTION

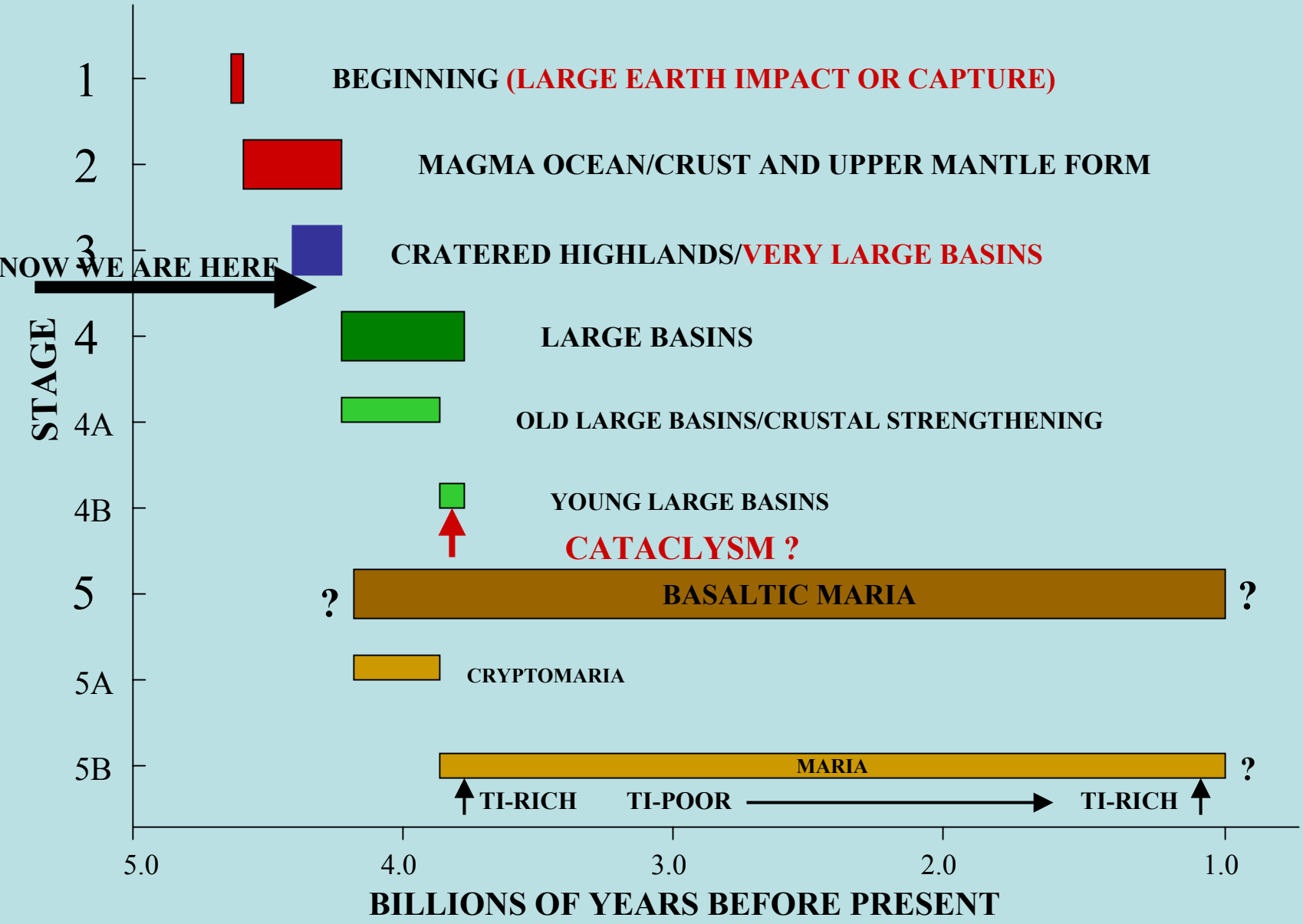
IMPORTANCE OF VERY LARGE BASINS

- ORIGIN OF KREEP HOT SPOT
  - PRESSURE RELEASE MIGRATION OF urKREEP TO PROCELLARUM REGION
    - LESS EXTENSIVE KREEP EXPOSURE IN SOUTH POLE AITKEN
- SOURCE OF OLD MG-SUITE
  - EJECTA FROM CRYSTALLINE INTRUSIVES IN DEEP CRUST
- ILMENITE CUMULATE OVERTURN
  - PERMITTED BY LOCAL DISRUPTION OF ILMENITE CUMULATE LAYER BENEATH BASIN

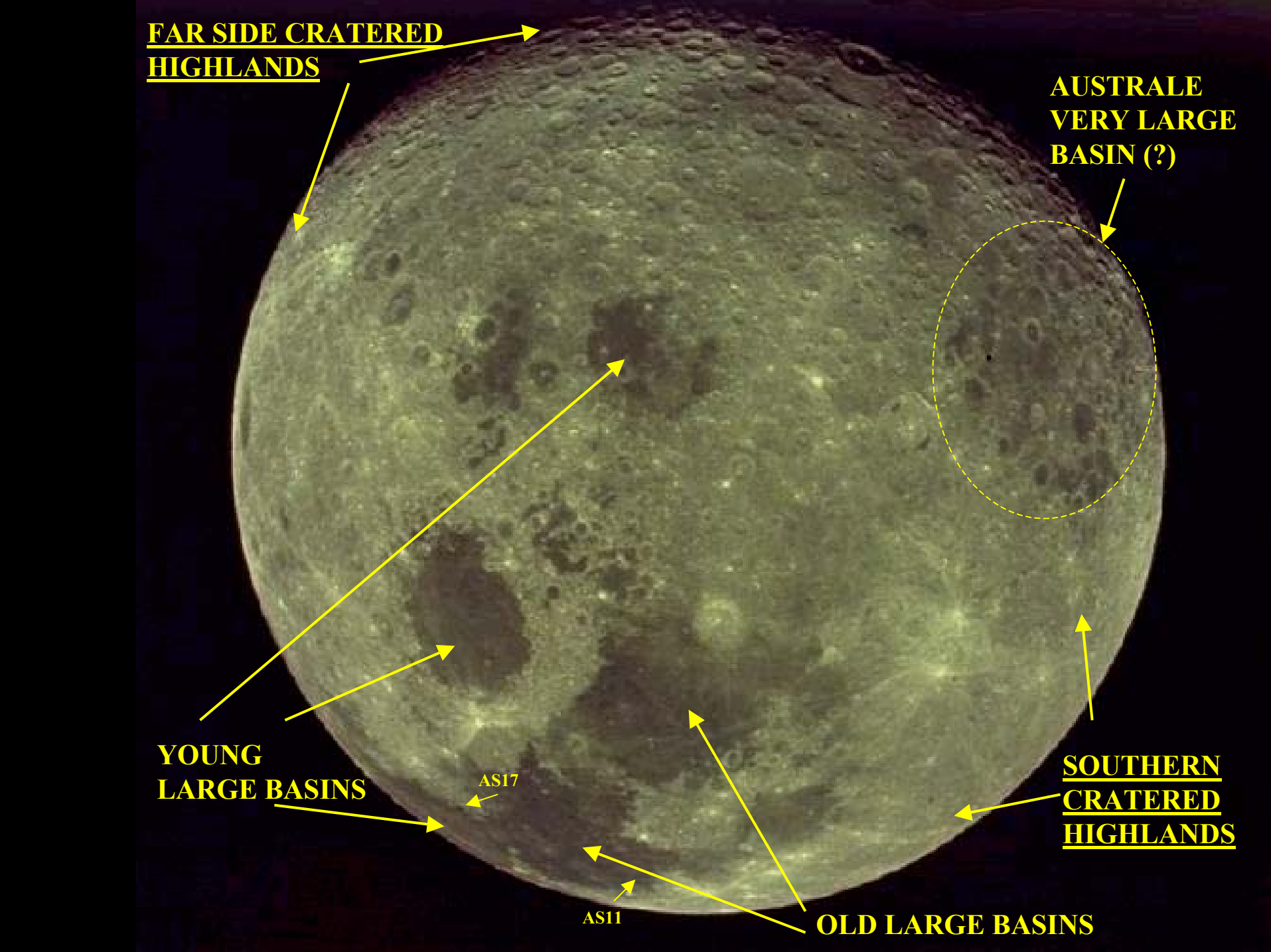
EARTH CONTINENTS AND VERY LARGE BASIN EVENTS

- **VERY LARGE IMPACT BASINS FORMED ON TERRESTRIAL PLANETS**
- **WATER INCREASES IMPACT MELT VOLUME**
- **~ 4.4 B.Y. TERRESTRIAL ZIRCON AGES CONSISTENT WITH ESTIMATES FOR VERY LARGE BASIN FORMATION AGES (SCHMITT, 1999, 2001; MOJESIS, ET AL, 2001;WILDE, ET AL, 2001)**
- **ZIRCON ($ZrSiO_4$) IS PRODUCT OF LATE STAGE MAGMA DIFFERENTIATION BY FRACTIONAL CRYSTALLIZATION**
- **ZIRCON OXYGEN ISOTOPES CONSISTENT WITH WATER IN MAGMA (WILDE, ET AL, 2001)**

MAJOR STAGES OF LUNAR EVOLUTION



RED = MAJOR UNCERTAINTY

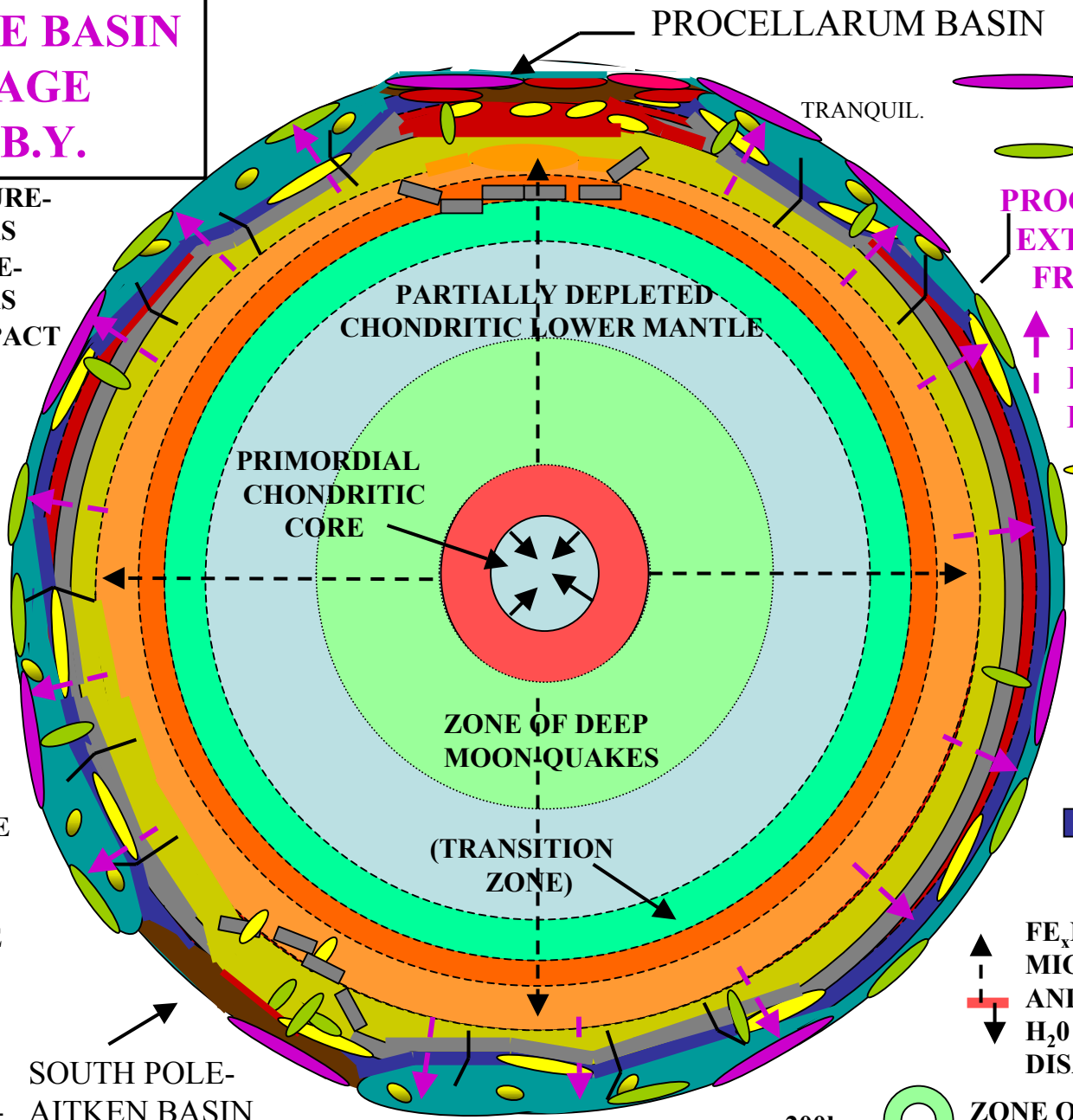

FAR SIDE CRATERED HIGHLANDS
AUSTRALE VERY LARGE BASIN (?)
YOUNG LARGE BASINS
AS17
AS11
SOUTHERN CRATERED HIGHLANDS
OLD LARGE BASINS

IMPORTANCE OF OLD LARGE BASIN FORMATION

- ORIGIN OF YOUNG MG-SUITE
  - PRESSURE RELEASE MELTING
- SOURCE OF MG-SUITE SAMPLES
  - EJECTA FROM LOWER CRUST
- GENESIS OF CRYPTOMARIA
  - PRESSURE RELEASE MELTING / FRACTURING PERMITTED ERUPTION AT SURFACE
- REASON FOR DISTINCTION BETWEEN NON-MASCON AND MASCON BASINS
  - CRUSTAL STRENGTHENING BY MIGRATION AND SOLIDIFICATION OF UNDERLYING URKREEP

APOLLO MODEL OF LUNAR EVOLUTION

OLD LARGE BASIN SUB STAGE ~4.2-3.9 B.Y.



- MG-SUITE PRESSURE-RELEASE MAGMAS
- BASALT PRESSURE-RELEASE MAGMAS
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- ILMENITE CUMULATE MASSES
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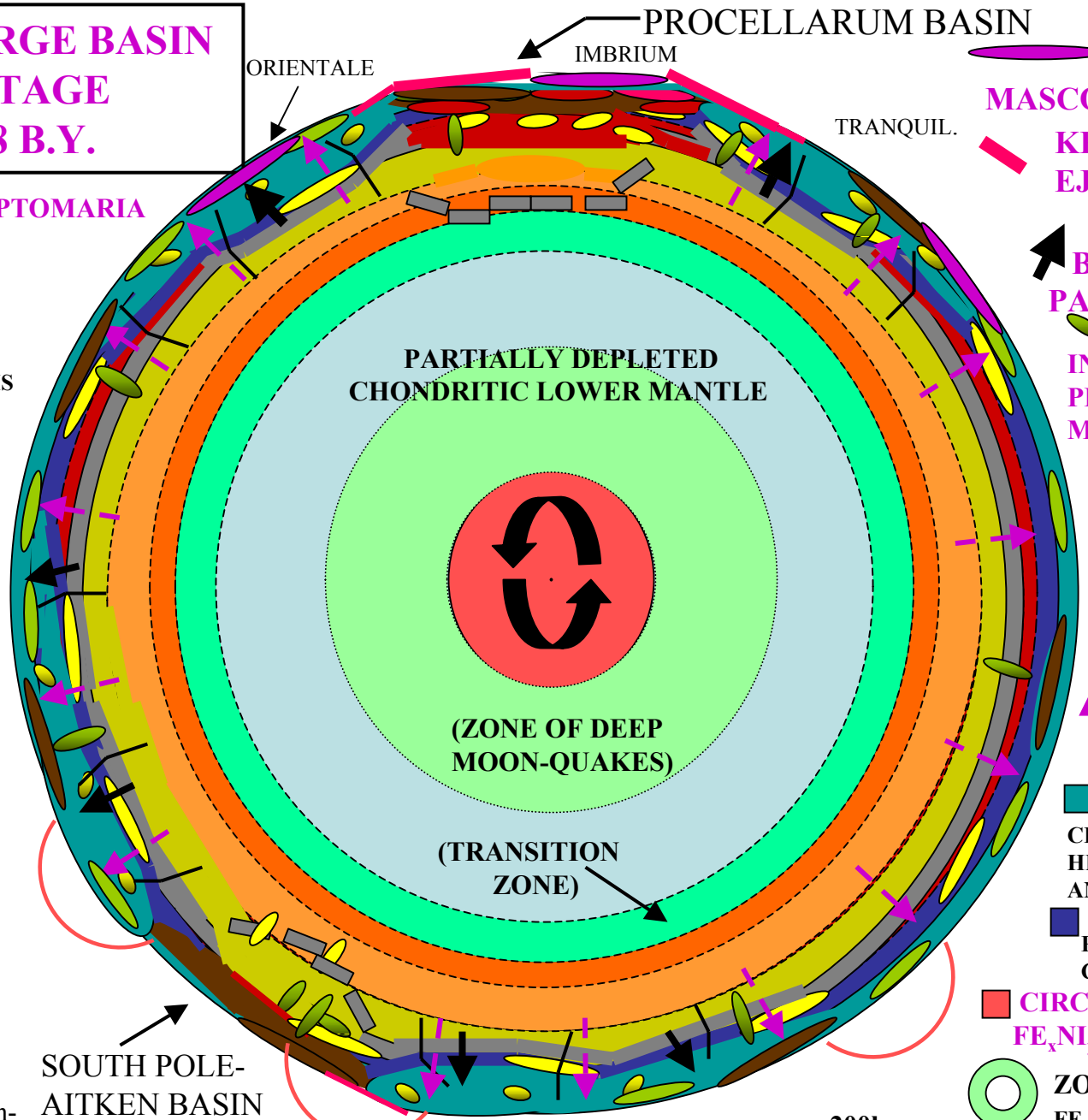
- OLIVINE AND HIGH CA-PYROXENE CUMULATE
- OLIVINE AND LOW CA-PYROXENE CUMULATE
- OLIVINE CUMULATE

- OLD LARGE BASINS
- CRYPTOMARIA
- PROGRADE THERMAL EXTENSION FRACTURES
- H_2 / CO DRIVEN LIGHT PLAINS DEBRIS ERUPTION
- MG-SUITE INTRUSIVES
- MG-SUITE DEBRIS
- LATE KREEPY BASALT EXTRUSIVES
- INSULATING CRATERED HIGHLANDS AND EJECTA
- CONSOLIDATED PLAGIOCLASE CUMULATE
- $FE_xNI_yS_z$ LIQUID MIGRATION AND H MIGRATION AFTE H_20 DISASSOCIATION
- = 200km
- ZONE OF ISOLATED $FE_xNI_yS_z$ LIQUID MASSES

APOLLO MODEL OF LUNAR EVOLUTION

YOUNG LARGE BASIN SUB STAGE 3.9-3.8 B.Y.



BURIED CRYPTOMARIA

KREEPY BASALT EXTRUSIVES

MG-SUITE INTRUSIVES

MG-SUITE DEBRIS

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

KREEPY IMBRIUM EJECTA

TI-RICH BASALT PARTIAL MELTS

BASALT INTRUSIONS OF PRESSURE-RELEASE MAGMAS

PROGRADE THERMAL EXTENSION FRACTURE

REMNANT MAGNETIC ANOMALY

H_2 DRIVEN LIGHT PLAINS DEBRIS ERUPTIONS

INSULATING CRATERED HIGHLANDS AND EJECTA

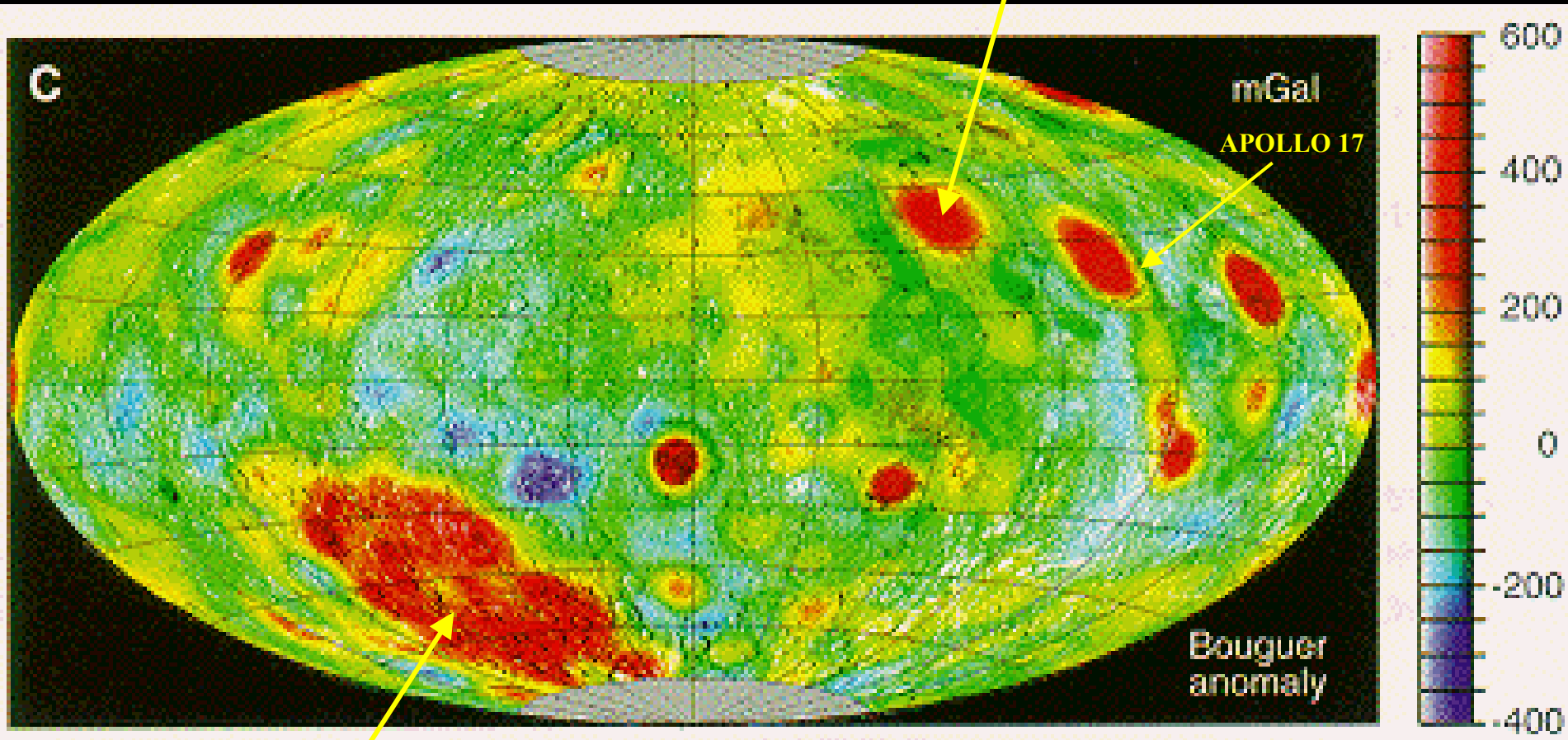
CONSOLIDATED PLAGIOCLASE CUMULATE

CIRCULATING $FE_xNI_yS_z$ LIQUID CORE

ZONE OF ISOLATED $FE_xNI_yS_z$ LIQUID MASSES

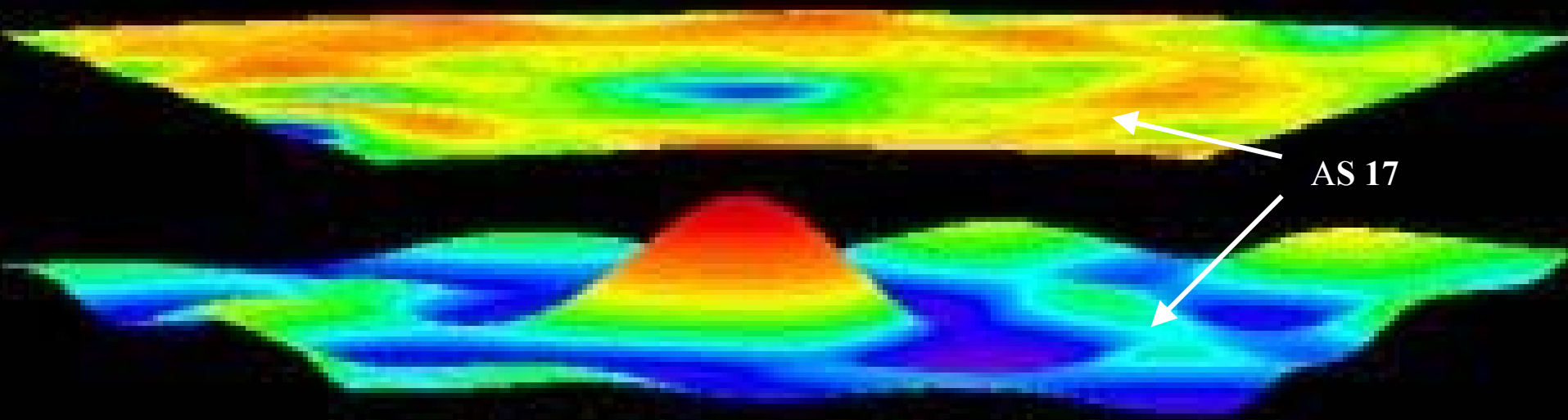
= 200km

MASS CONCENTRATIONS



(SOUTH POLE-AITKEN
NOT YOUNG BASIN)

EFFECTS OF YOUNG MASCON BASIN IMPACTS EXTEND TO SEVERAL BASIN DIAMETERS AND NEAR THEIR ANTIPODES



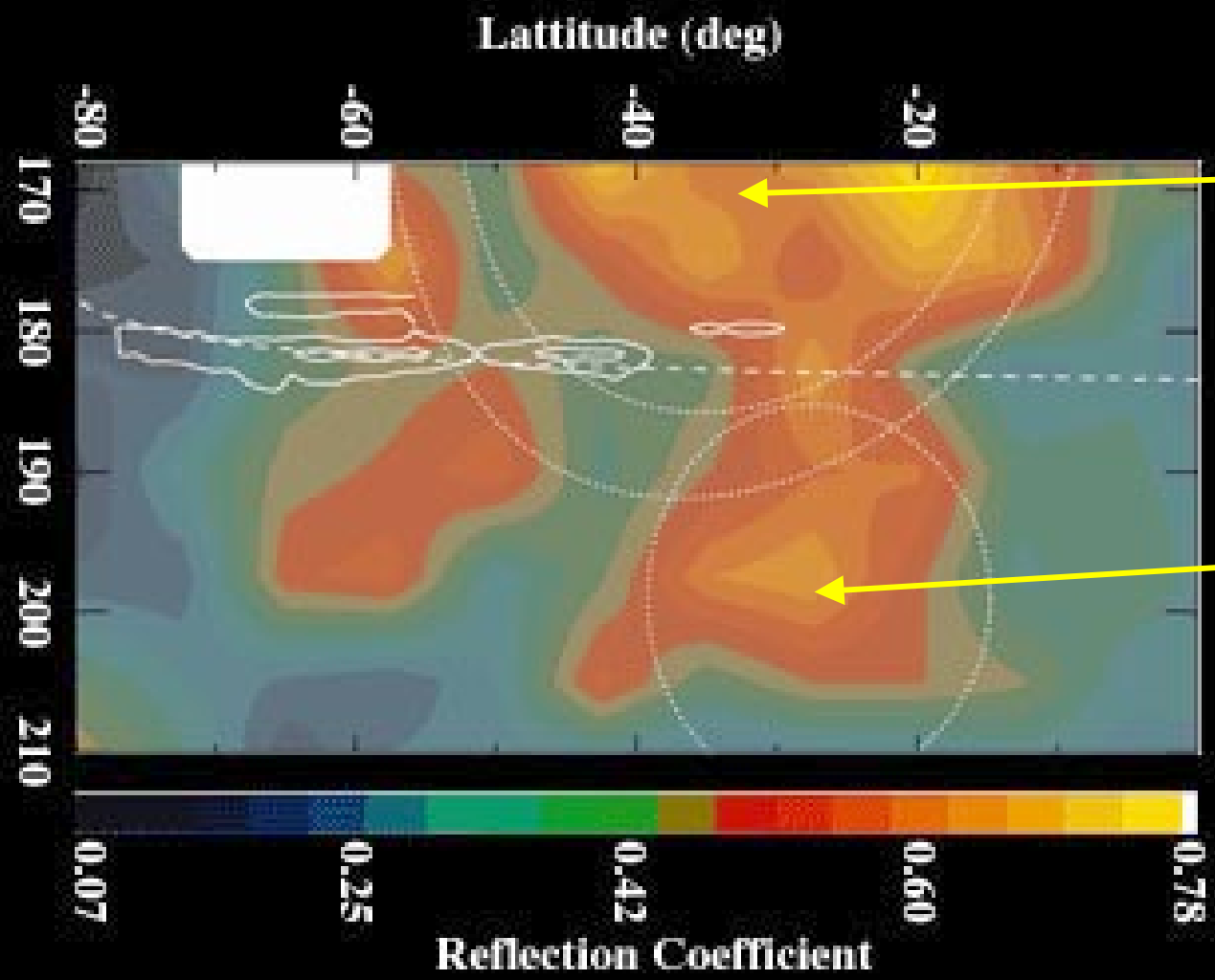
MASS CONCENTRATION OR "MASCON" (LOWER) IN SERENITATIS BASIN COMPARED WITH TOPOGRAPHY (UPPER)

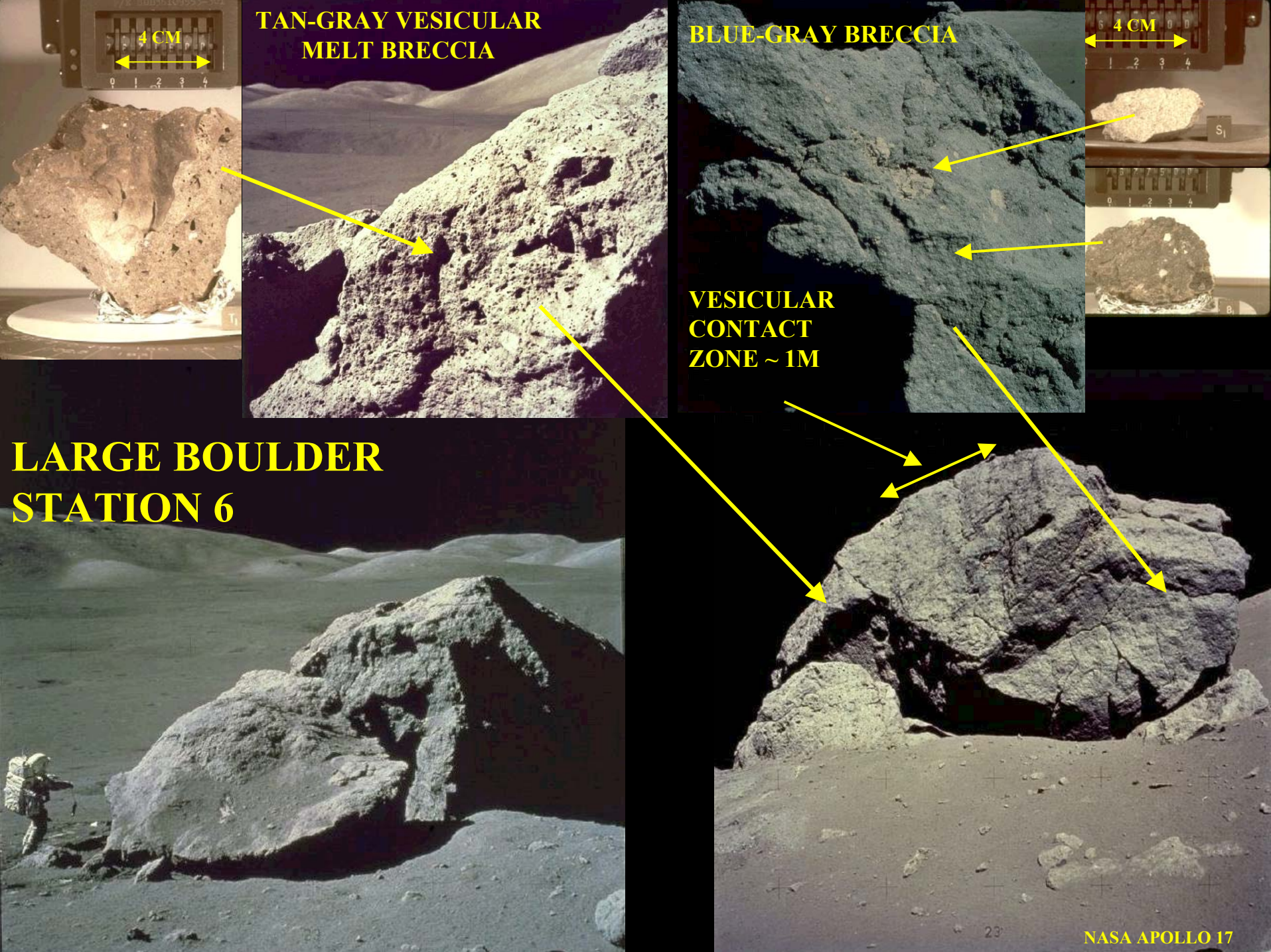
NOTE MASS DEFICIENCIES JUST OUTSIDE RIM OF BASIN

BEST MODEL FIT IS COMBINATION OF A PLATE OF MARE BASALT AND SOME UPWELLING OF MANTLE MATERIAL (WITH RING OF DOWN-WELLING) RELATIVE TO LESS DENSE CRUSTAL ROCKS

LUNAR PROSPECTOR DOPPLER GRAVITY

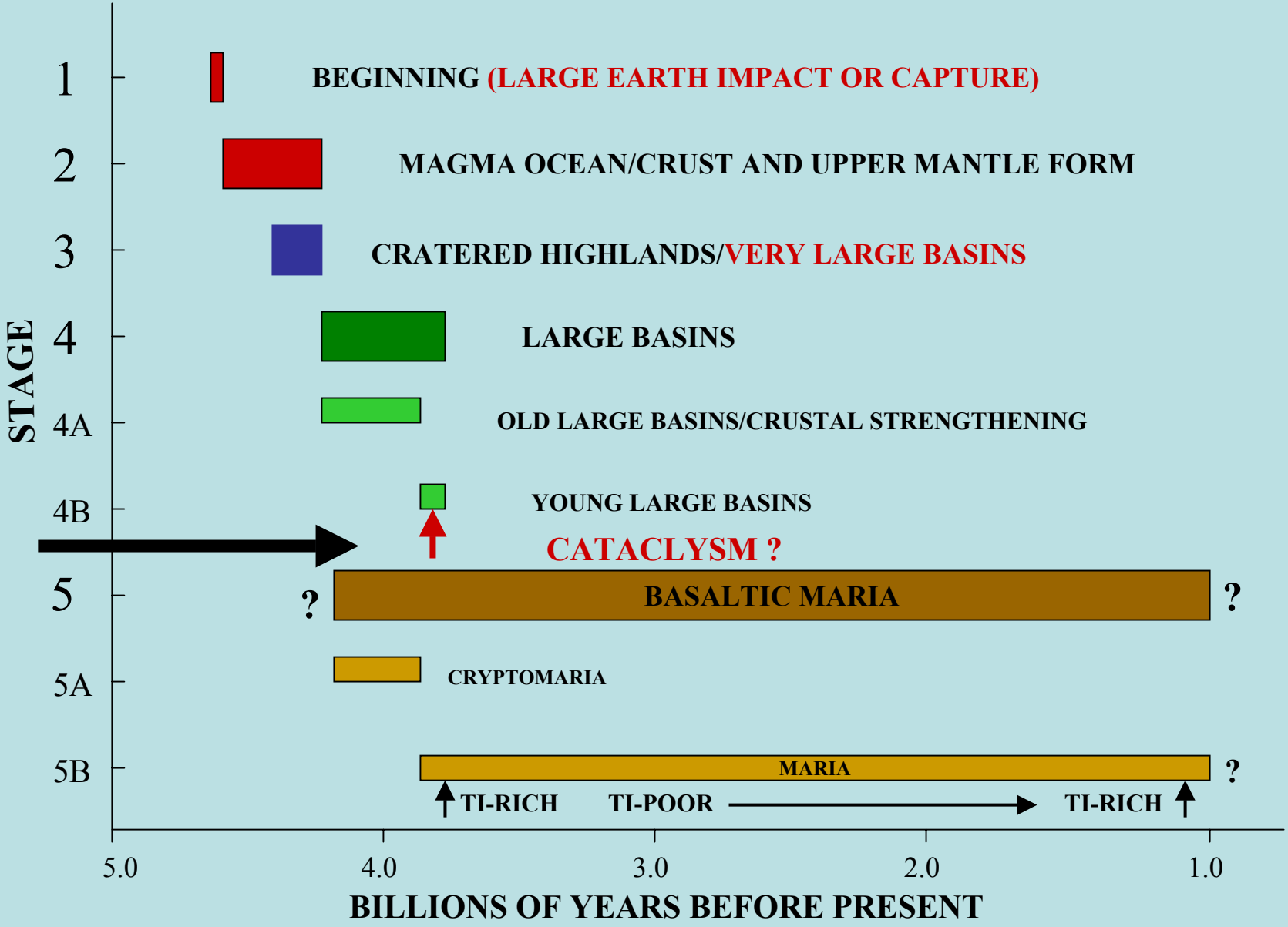
FAR SIDE MAGNETIC ANOMALIES




4 CM
TAN-GRAY VESICULAR
MELT BRECCIA
BLUE-GRAY BRECCIA
4 CM
VESICULAR
CONTACT
ZONE ~ 1M
LARGE BOULDER
STATION 6
NASA APOLLO 17

NASA APOLLO 17

MAJOR STAGES OF LUNAR EVOLUTION



RED = MAJOR UNCERTAINTY

LUNAR CATACLYSM OF IMPACTS

~100 M.Y. "CATACLYSM" AT 3.85 BY

OR

~400 M.Y. "CATACLYSM" BETWEEN 4.2 AND 3.8 BY?

EVIDENCE FOR SHORT CATACLYSM AT ~3.85 B.Y.

- **FEW UNEQUIVOCAL APOLLO IMPACT AGES OLDER THAN 3.9 B.Y. ($^{40}K/^{40}Ar$ AGES)**

- **AS YET, NO IMPACT AGES FROM LUNAR METEORITES OLDER THAN 3.9 B.Y.**

REASONS FOR SUSPECTING POSSIBLE IMPACT AGE BIAS

- **GLOBAL EFFECTS OF FORMATION OF 14 YOUNG LARGE BASINS (14 OUT OF ~50)**
  - **EJECTA COVERING OF "CRYPTOMARIA" IS GLOBAL IN EXTENT**

- **THERE ARE A FEW APOLLO SAMPLES IMPACT AGES OLDER THAN 3.9 B.Y.**
  - **APOLLO 16 BRECCIAS**
  - **APOLLO 17 BOULDER 1 / STATION 2**

SOURCE OF CATACLYSM IMPACTORS

- **DISCRETE SOURCE**
  - APPEARED AFTER ACCRETIONARY RESERVOIR OF CRATERED HIGHLANDS IMPACTORS BECAME DEPLETED AT ~4.2 B.Y.
- **SOURCES TO CONSIDER**
  - 1. ÖORT CLOUD
    - INTERACTION OF LARGE COMETARY OBJECTS WITH PASSING STELLAR BODY
  - 2. PROTO-KUIPER BELT
    - INTERACTION WITH GAS GIANTS
    - OUTWARD MIGRATION OF NEPTUNE
  - 3. MAIN BELT ASTEROIDS
    - JUPITER-INDUCED BREAK-UP OF PARENT PLANETESIMALS AND EXPULSION OF FRAGMENTS
  - 4. COMBINATIONS OF ABOVE

IMPLICATIONS OF INTENSE CRATERING BETWEEN 4.5 AND 3.8 BY ON EARTH AND MARS

CLAY MINERALS DOMINATED EARTH AND MARTIAN SURFACES BEFORE LIFE APPEARED!

IMPACT GLASS AND DEBRIS MIXED WITH WATER ALTERS RAPIDLY TO CLAY

EARTH/MARS IMPLICATIONS

- INTENSE GENERAL IMPACT ENVIRONMENT 4.5-4.2 B.Y.
  - CLAYS (AND POSSIBLY SULFIDES) DOMINANT IN VARIOUS HYDROUS ENVIRONMENTS PRIOR TO 3.8 B.Y.
  - GLOBAL SOUP(S) FOR ORGANIC SYNTHESIS
  - ORGANIC MOLECULAR SYNTHESIS ON EARTH PRIOR TO 3.8 B.Y. (WITH MINERAL CATALYSTS?)

- GLOBAL HOSTILITY TO LIFE > 3.8 B.Y.
  - LARGE BASIN FORMATION 4.5-3.8 B.Y.
  - EVIDENCE FOR EARLY, VERY LARGE IMPACTS ON EARTH
    - GEOCHEMICAL HETEROGENEITY IN EARTH'S CRUST PRIOR TO AT LEAST 4.4 B.Y. (SHOWN BY ZIRCONS)

- GLOBAL COMPATIBILITY FOR LIFE < 3.8 B.Y.
  - OLDEST INDICATION OF LIFE PROCESSES IS 3.8 B.Y.

POSSIBLE TERM PAPER TOPICS

- LUNAR MAGNETIC ANOMALIES
- VERY OLD TERRESTRIAL ZIRCONS
- NEPTUNE AND THE KUIPER BELT