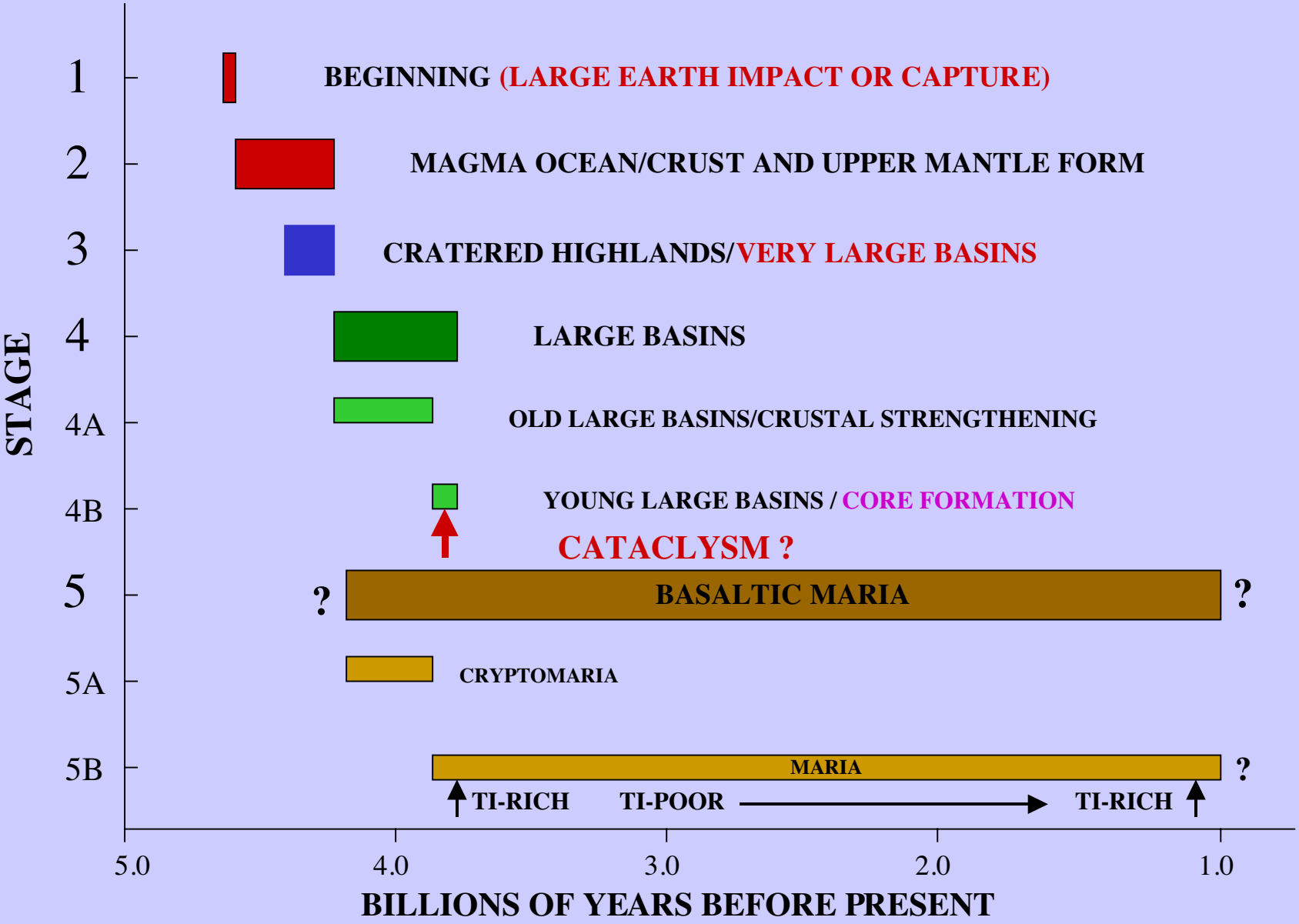
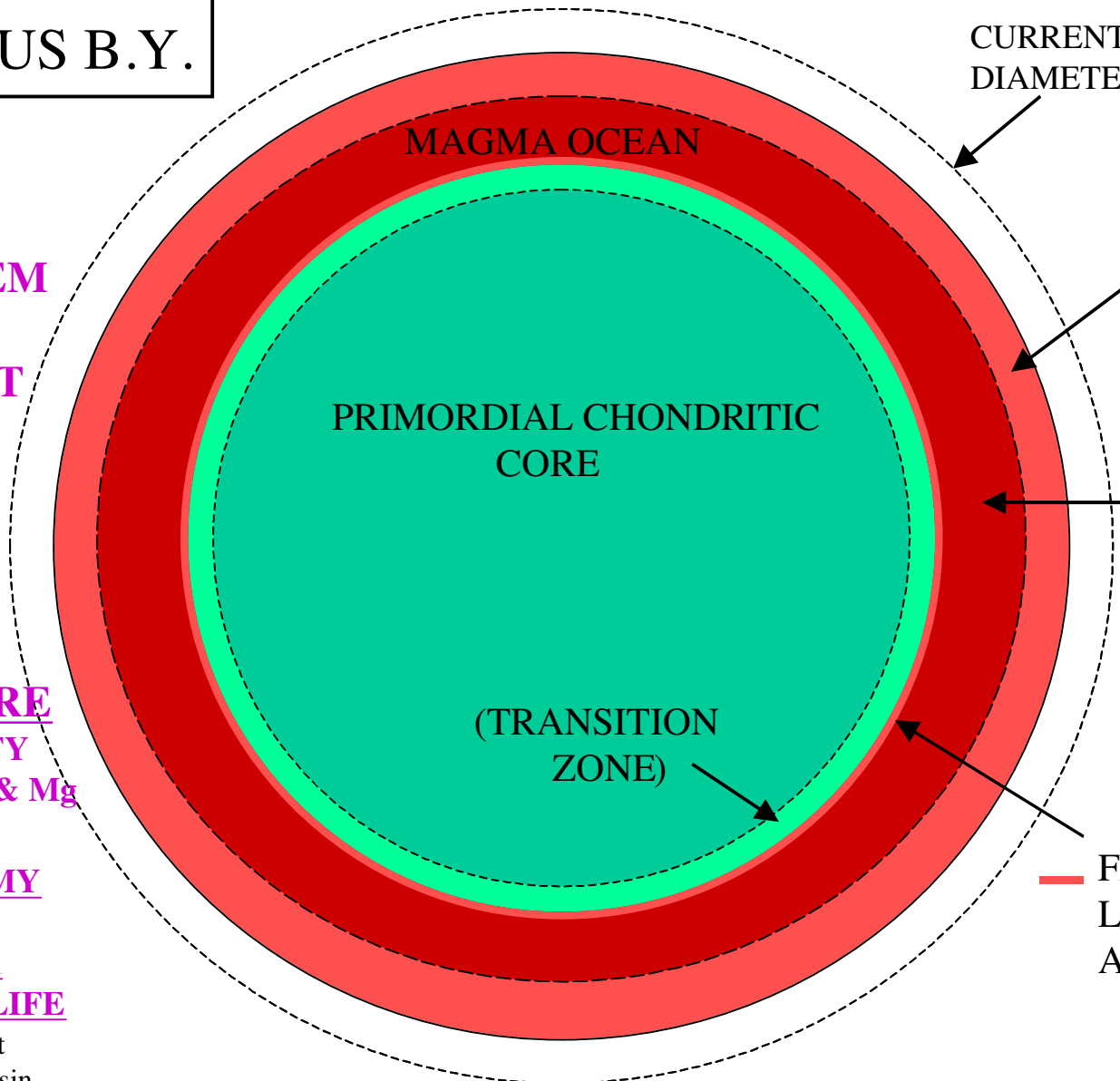
MAJOR STAGES OF LUNAR EVOLUTION



RED = MAJOR UNCERTAINTY

APOLLO MODEL OF LUNAR EVOLUTION

BEGINNING
~4.567 PLUS B.Y.

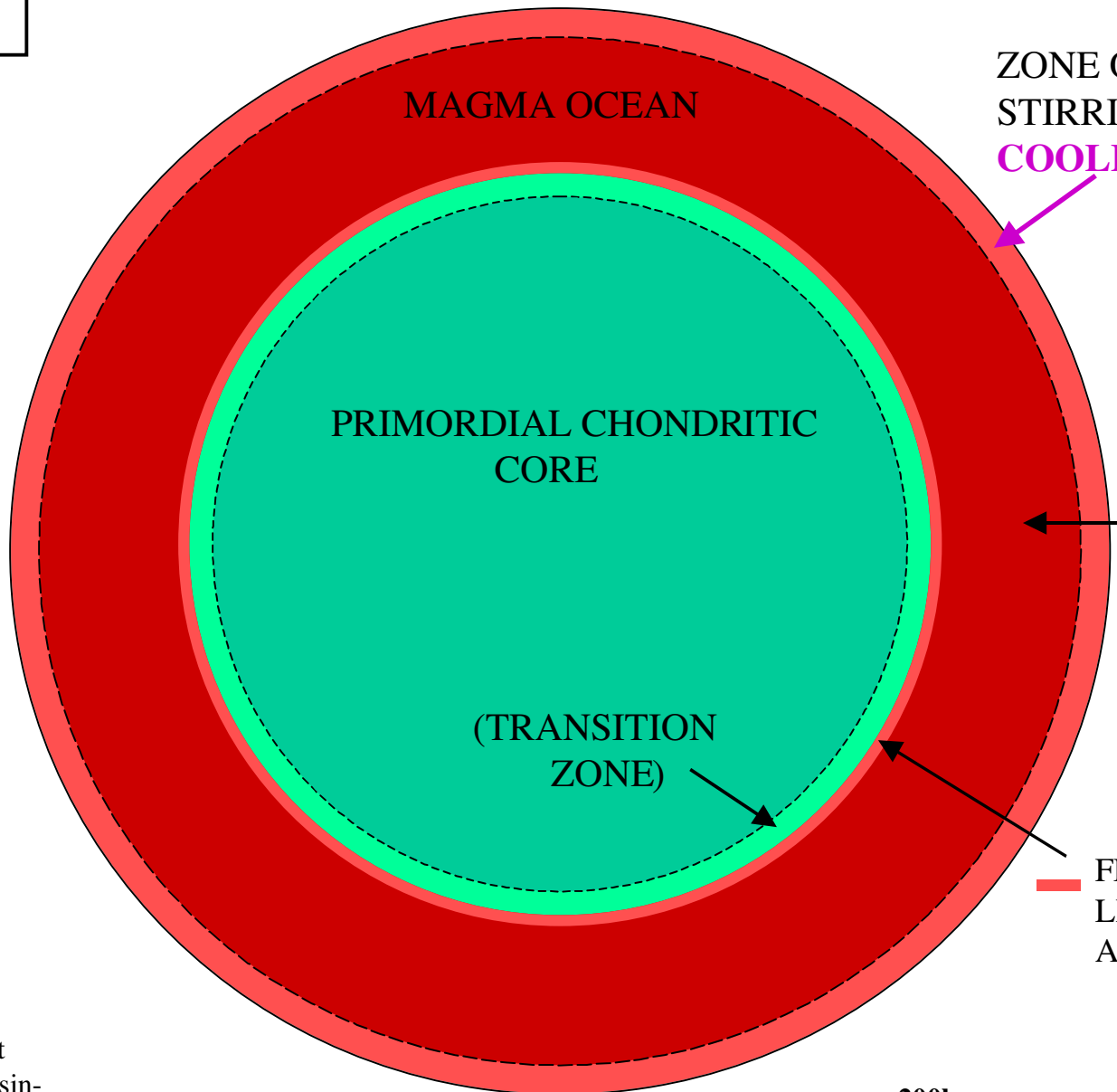


NOTE:
ASSUMES A SOLAR SYSTEM ORIGIN INDEPENDENT OF EARTH.

- **CORE**
  - **PRIMATIVE Pb**
  - **CHONDRITIC W**
  - **NON-MANTLE VOLATILES**
- **MANTLE/CORE**
  - **V DISCONTINUITY**
  - **INCREASE IN Al & Mg**
- **TIMING**
  - **Hf/W GIVES <40 MY AFTER NEBULA FORMATION FOR MAGMA OCEAN LIFE**

APOLLO MODEL OF LUNAR EVOLUTION

BEGINNING
~4.567 B.Y.



ZONE OF IMPACT STIRRING **AND NET COOLING**

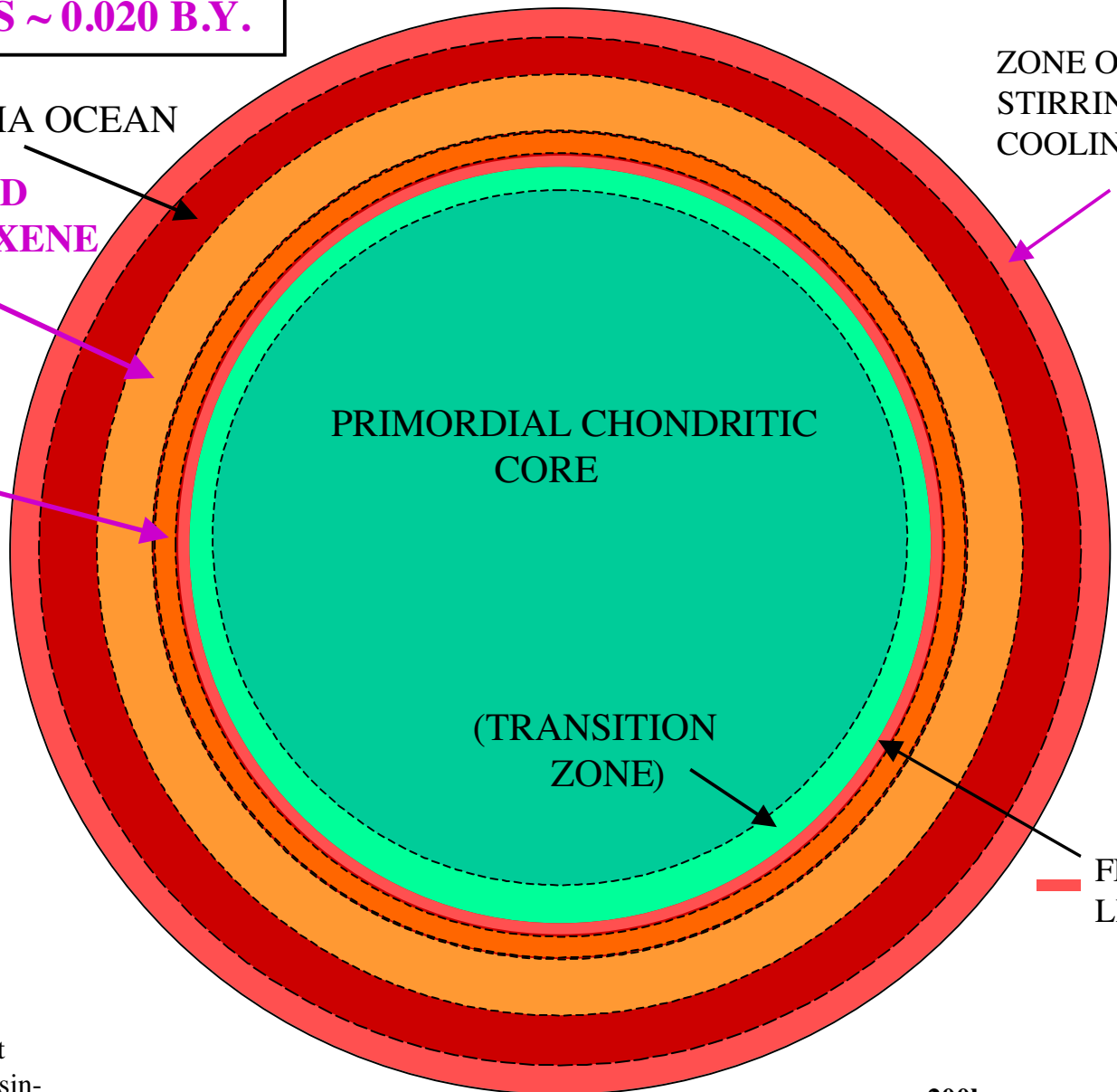
INCLUDES $FE_xNI_yS_z$ LIQUID DROPLETS

$FE_xNI_yS_z$ LIQUID ACCUMULATION

= 200km

APOLLO MODEL OF LUNAR EVOLUTION

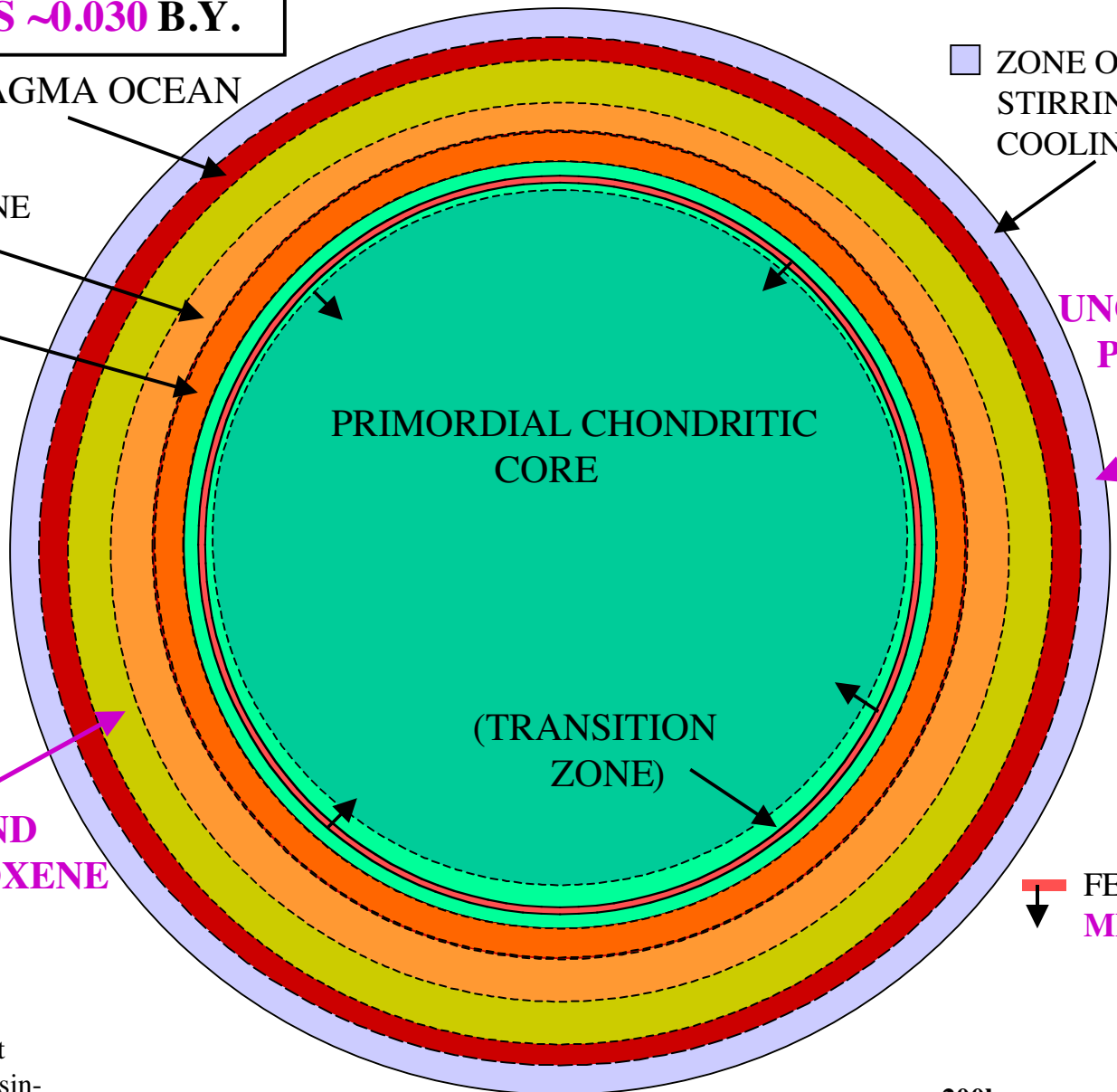
MAGMA OCEAN STAGE
~4.567 MINUS ~ 0.020 B.Y.



= 200km

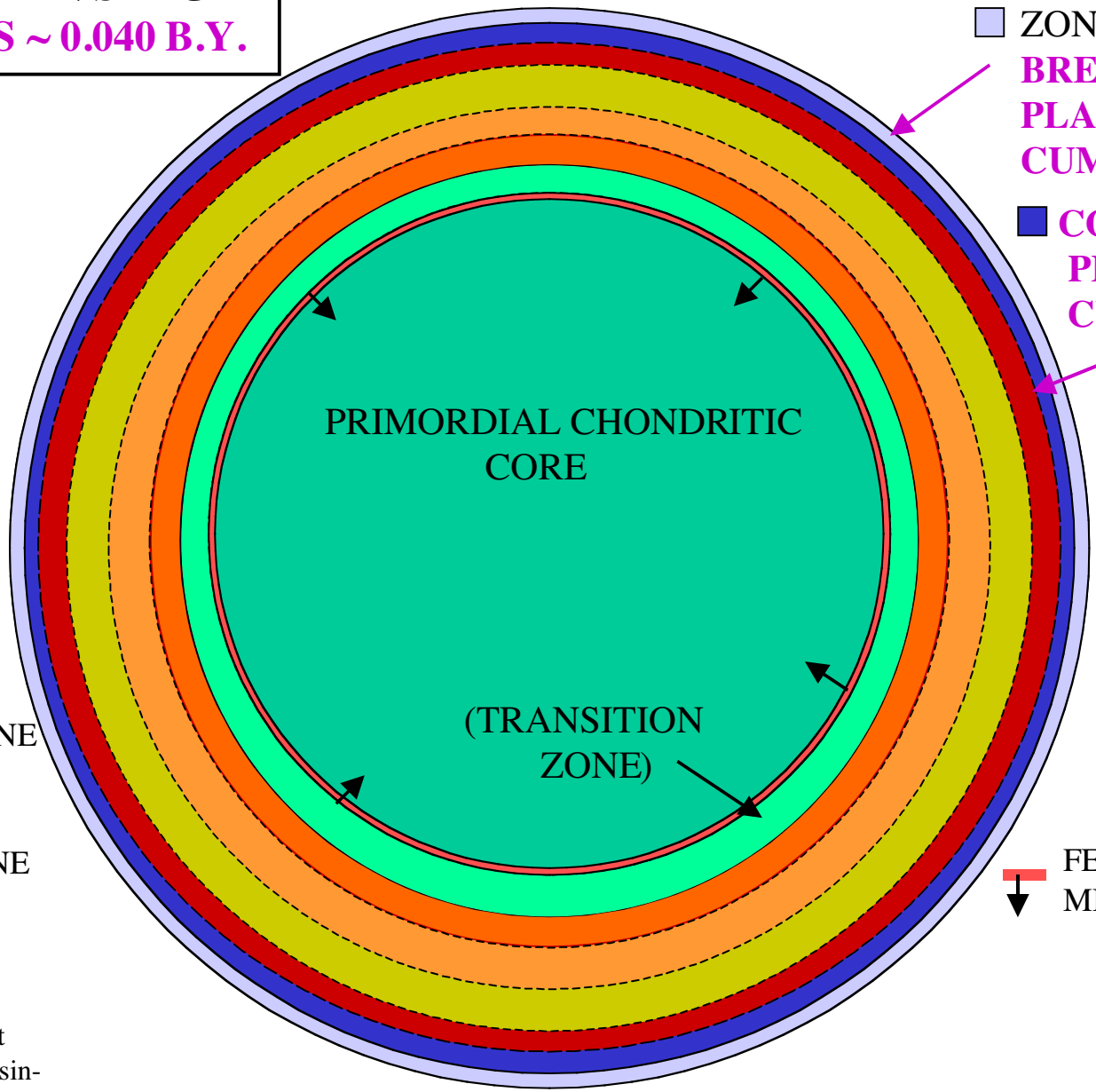
APOLLO MODEL OF LUNAR EVOLUTION

MAGMA OCEAN STAGE
~4.567 MINUS ~0.030 B.Y.



APOLLO MODEL OF LUNAR EVOLUTION

MAGMA OCEAN STAGE
~4.567 MINUS ~ 0.040 B.Y.



ZONE OF IMPACT
BRECCIATION OF PLAGIOCLASE CUMULATE

CONSOLIDATING PLAGIOCLASE CUMULATE

RESIDUAL MAGMA OCEAN

OLIVINE AND HIGH CA-PYROXENE CUMULATE

OLIVINE AND LOW CA-PYROXENE CUMULATE

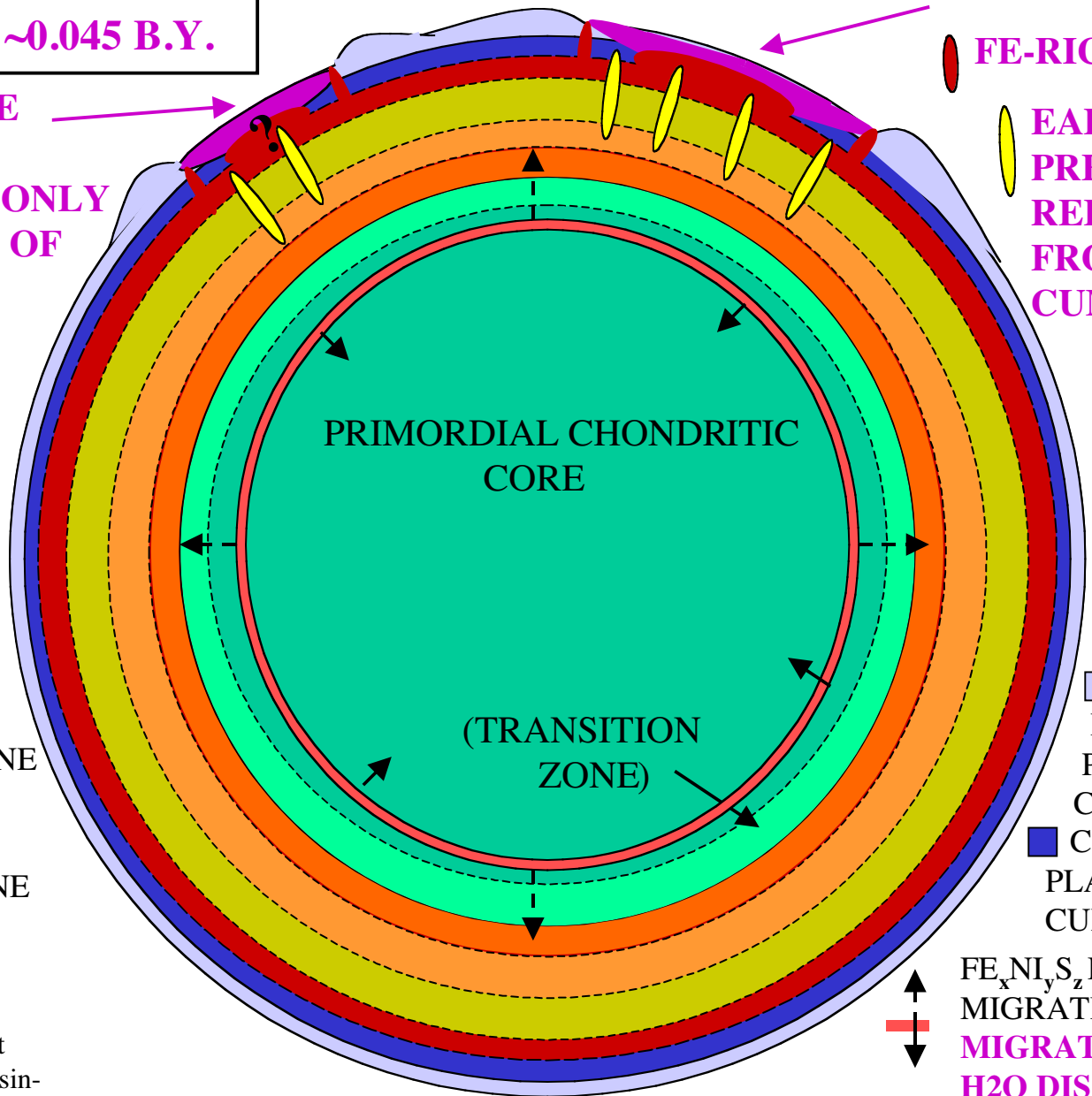
OLIVINE CUMULATE

$FE_xNI_yS_z$ LIQUID MIGRATION

= 200km

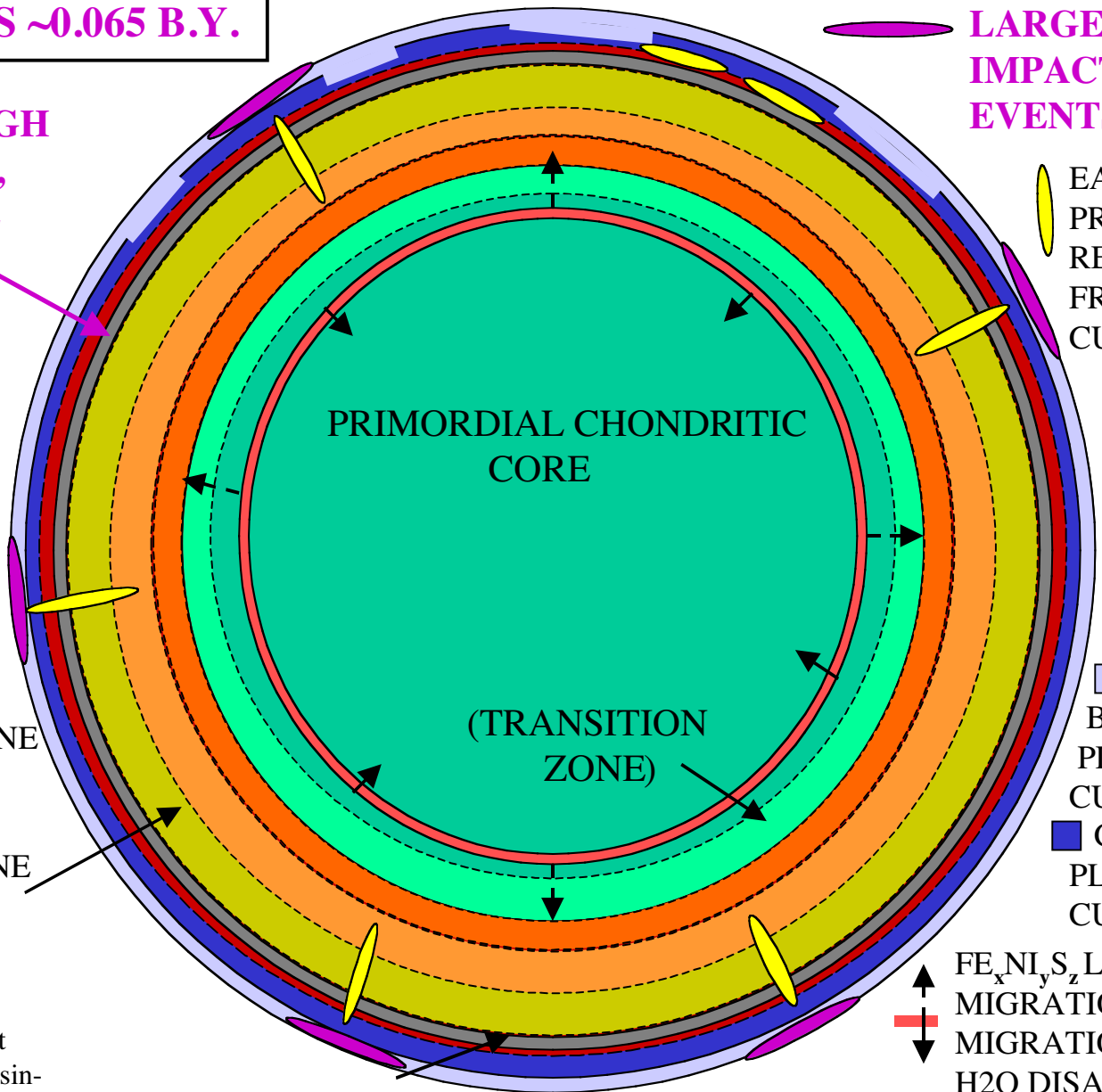
APOLLO MODEL OF LUNAR EVOLUTION

MAGMA OCEAN STAGE
4.567 MINUS ~0.045 B.Y.



APOLLO MODEL OF LUNAR EVOLUTION

MAGMA OCEAN STAGE
~4.567 MINUS ~0.065 B.Y.



LARGE IMPACT EVENTS

OLIVINE, HIGH CA-PYROXENE, AND ILMENITE CUMULATE

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

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

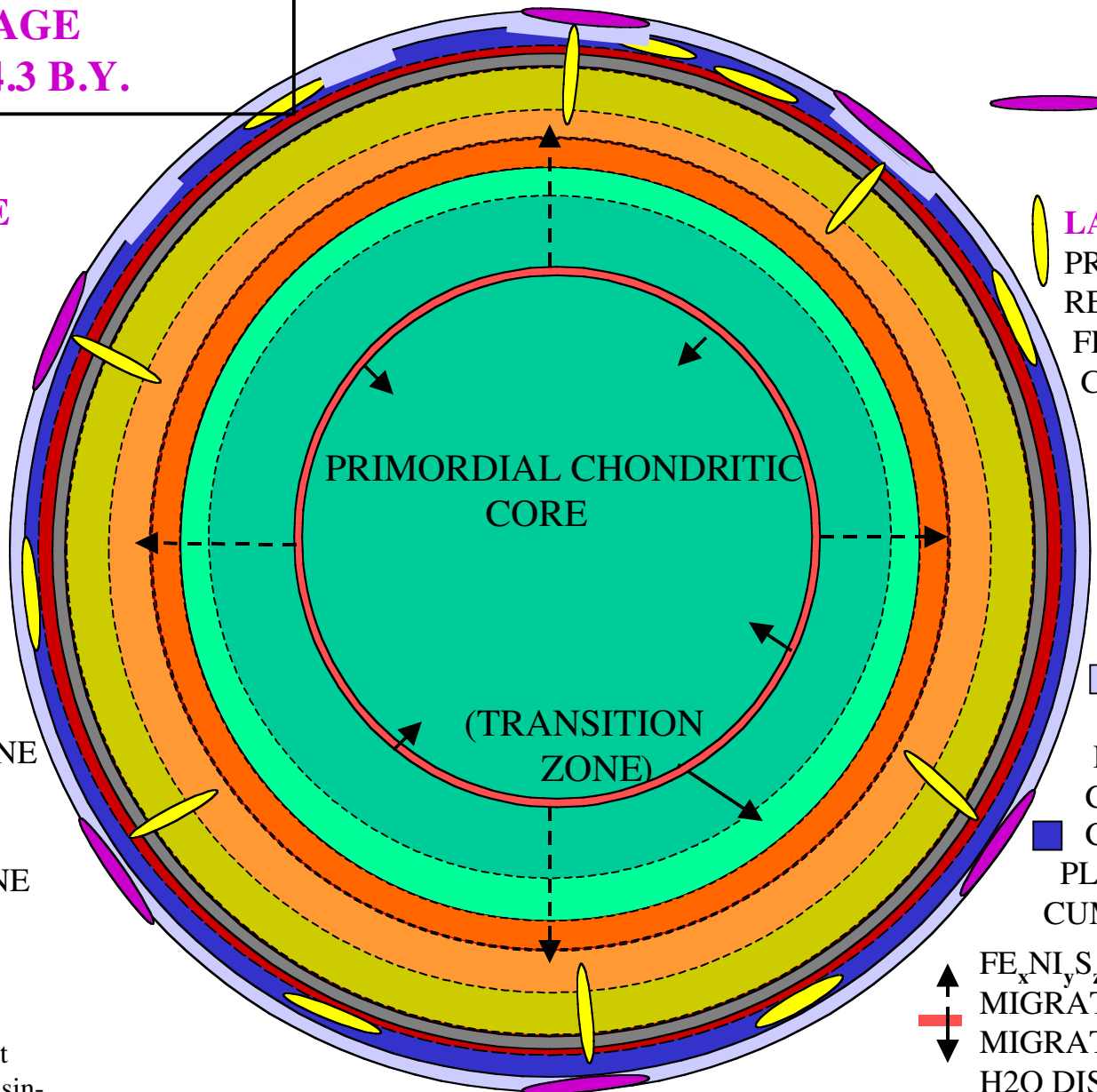
CONSOLIDATING PLAGIOCLASE CUMULATE

$FE_xNI_yS_z$ LIQUID MIGRATION AND H MIGRATION AFTER H2O DISASSOCIATION

— = **200km**

APOLLO MODEL OF LUNAR EVOLUTION

CRATERED HIGHLANDS STAGE
~4.5 - 4.3 B.Y.



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

LARGE IMPACT EVENTS

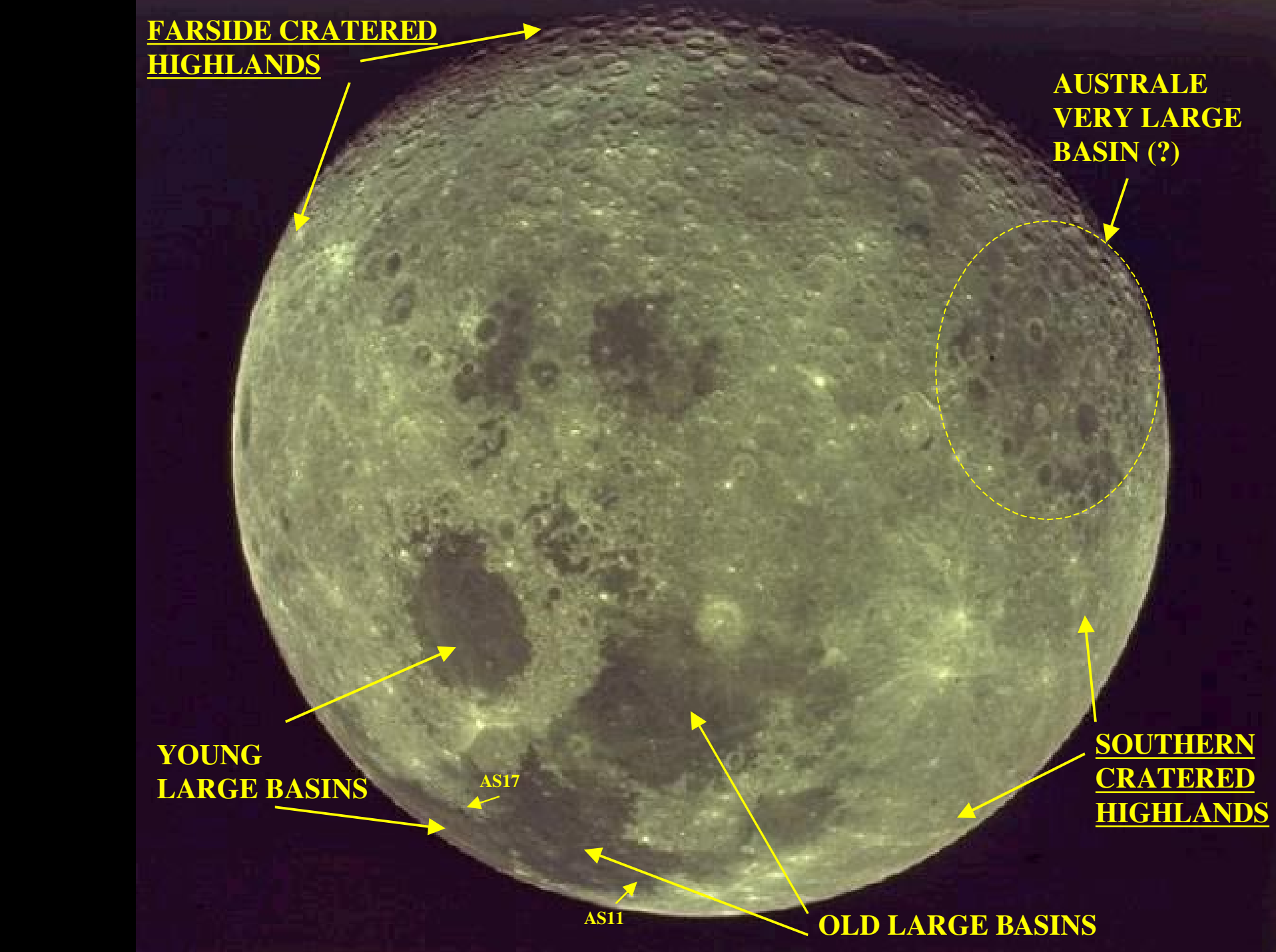
LATE MG-SUITE PRESSURE RELEASE MAGMAS FROM OLV-OPX CUMULATE LAYER

ZONE OF IMPACT BRECCIATION OF PLAGIOCLASE CUMULATE

CONSOLIDATING PLAGIOCLASE CUMULATE

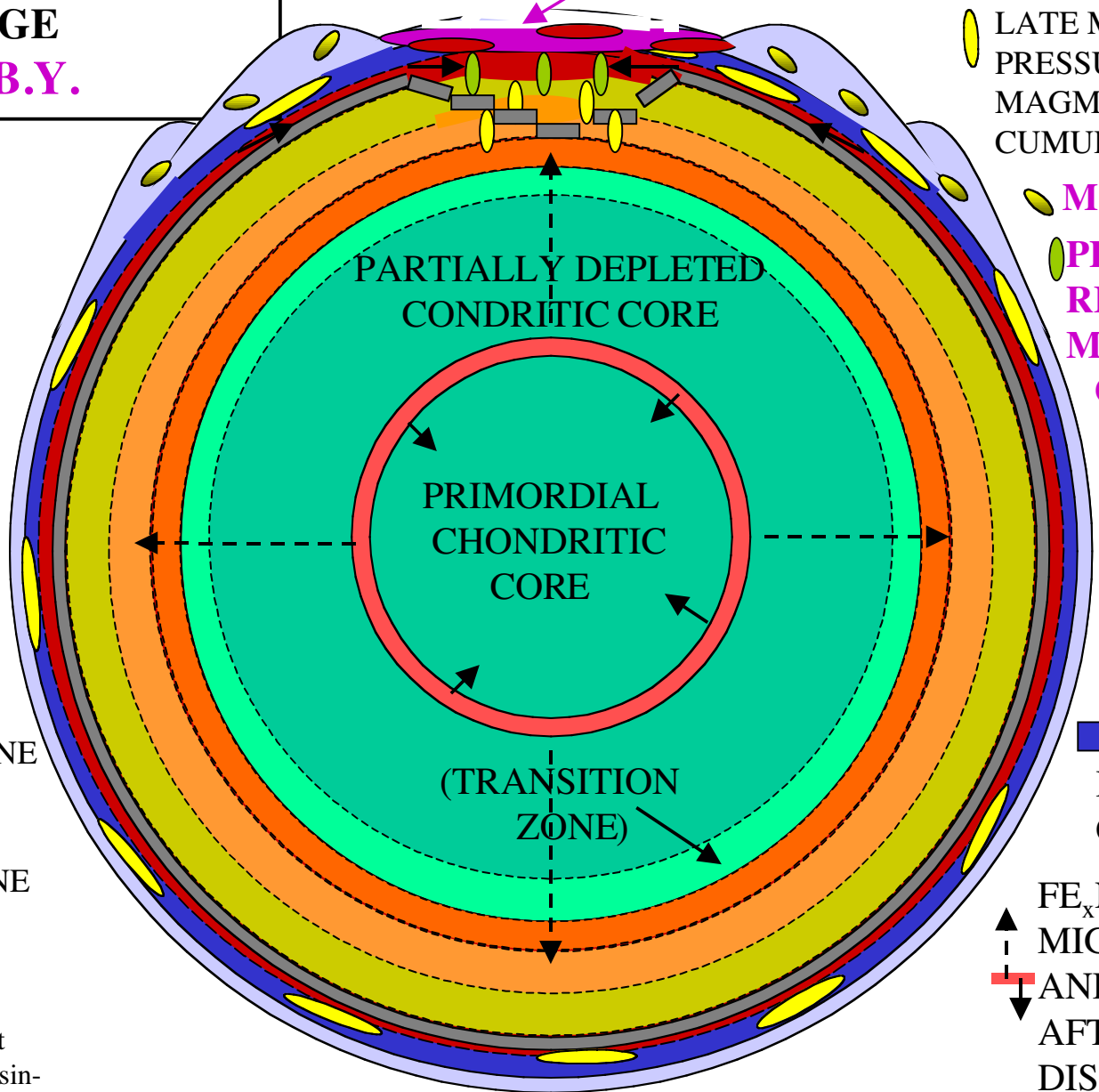
$FE_xNI_yS_z$ LIQUID MIGRATION AND H MIGRATION AFTER H2O DISASSOCIATION

= 200km


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

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

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

MG-SUITE DEBRIS

PRESSURE-RELEASE BASALT MAGMAS FROM OLV-CPX CUMULATE LAYER

INSULATING CRATERED HIGHLANDS AND EJECTA

CONSOLIDATED PLAGIOCLASE CUMULATE

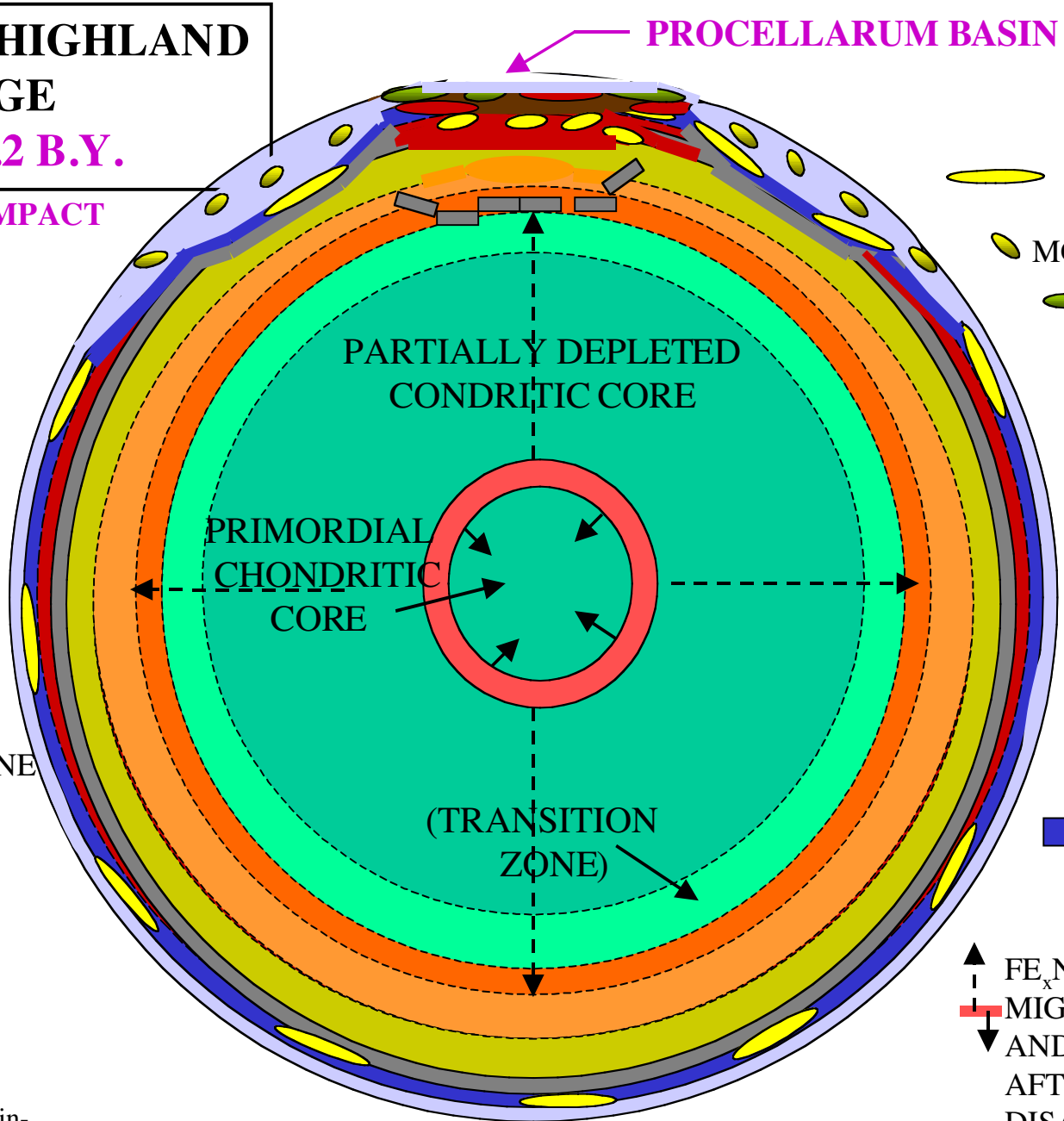
$FE_xNI_yS_z$ LIQUID MIGRATION AND H MIGRATION AFTER H_20 DISASSOCIATION

— = **200km**

APOLLO MODEL OF LUNAR EVOLUTION

CRATERED HIGHLAND STAGE

PRE ~4.2 B.Y.



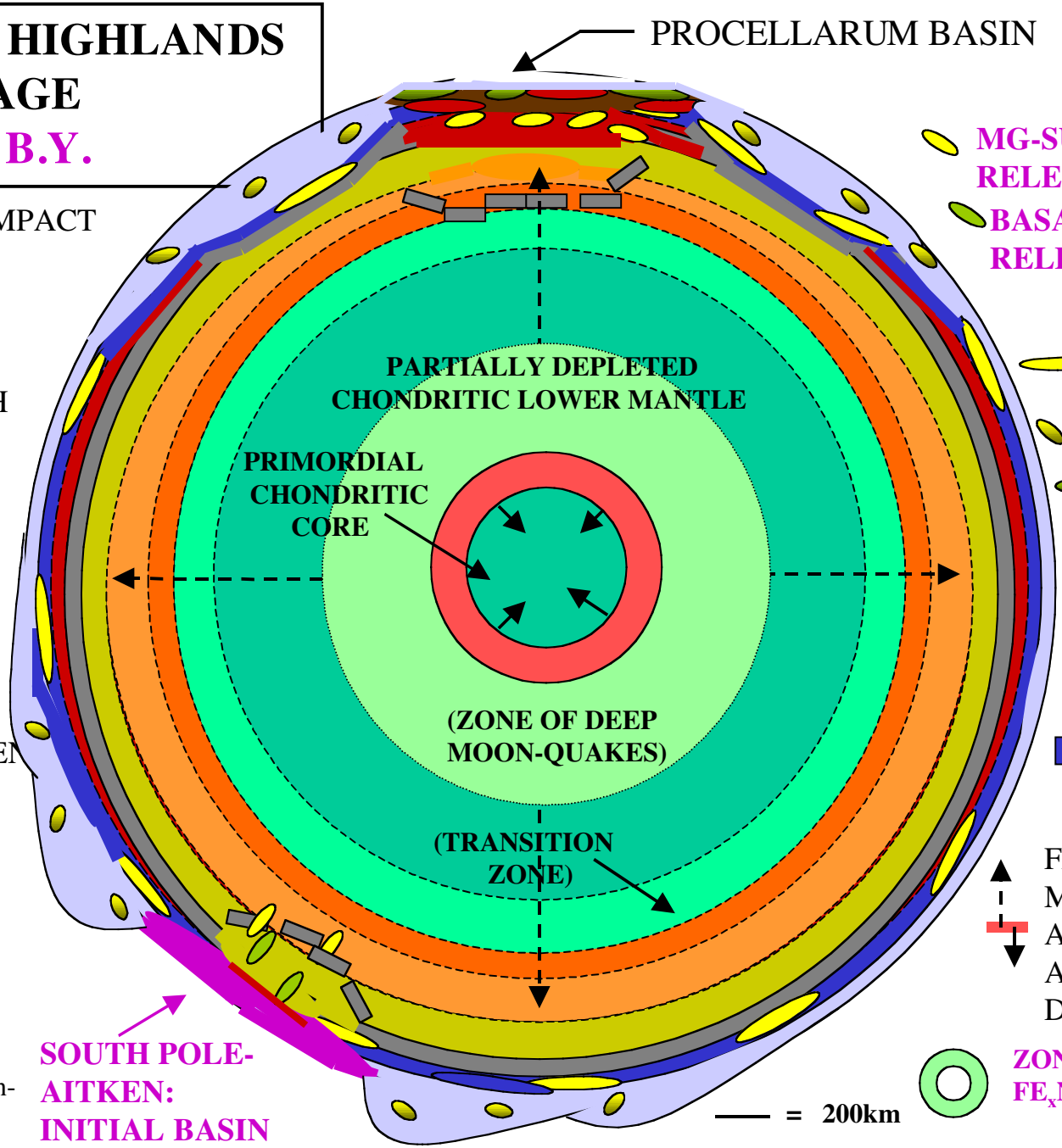
- SOLIDIFIED IMPACT MELT SHEET
- ILMENITE CUMULATE MASSES
- OLIVINE, HIGH CA-PYROXENE, AND ILMENITE CUMULATE
- RESIDUAL URKREEP LIQUID+KREEP BASALTS
- OLIVINE AND HIGH CA-PYROXENE CUMULATE
- OLIVINE AND LOW CA-PYROXENE CUMULATE
- OLIVINE CUMULATE

- 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

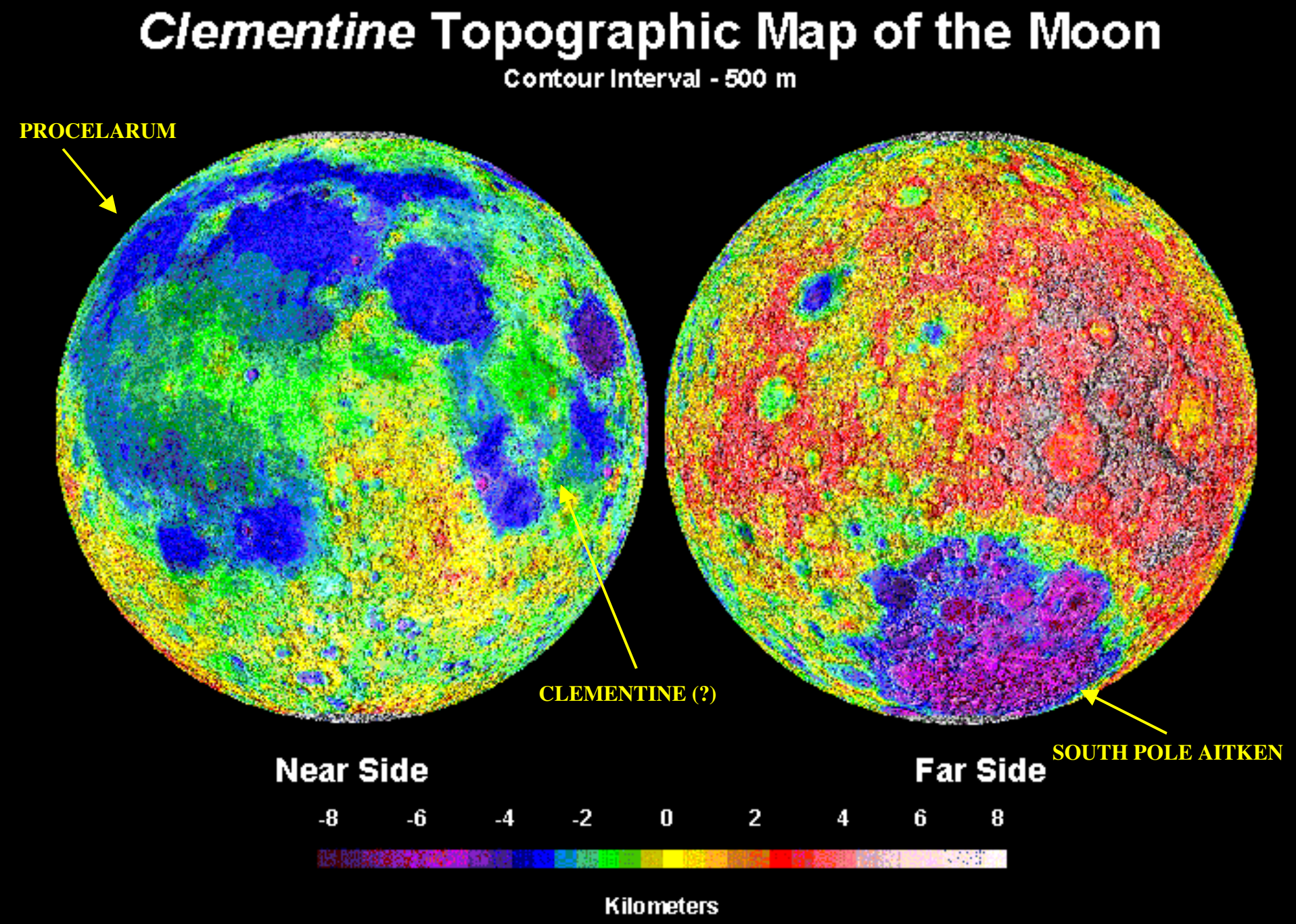
CRATERED HIGHLANDS STAGE
~4.2 B.Y.

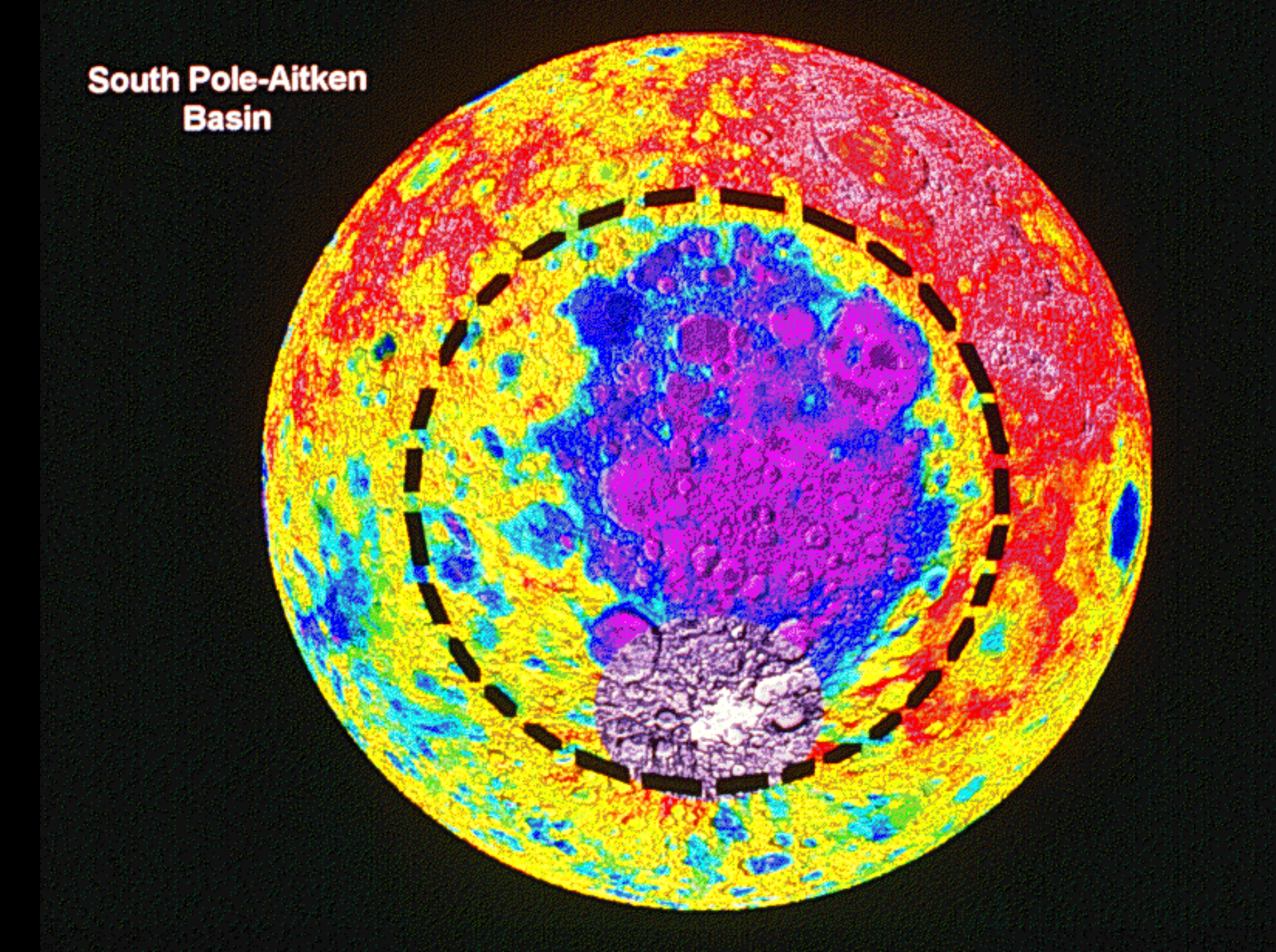


- SOLIDIFIED IMPACT MELT SHEET
- ILMENITE CUMULATE MASSES
- OLIVINE, HIGH CA-PYROXENE, AND ILMENITE CUMULATE
- RESIDUAL URKREEP LIQUID+KREEP BASALTS
- OLIVINE AND HIGH CA-PYROXEN CUMULATE
- OLIVINE AND LOW CA-PYROXENE CUMULATE
- OLIVINE CUMULATE

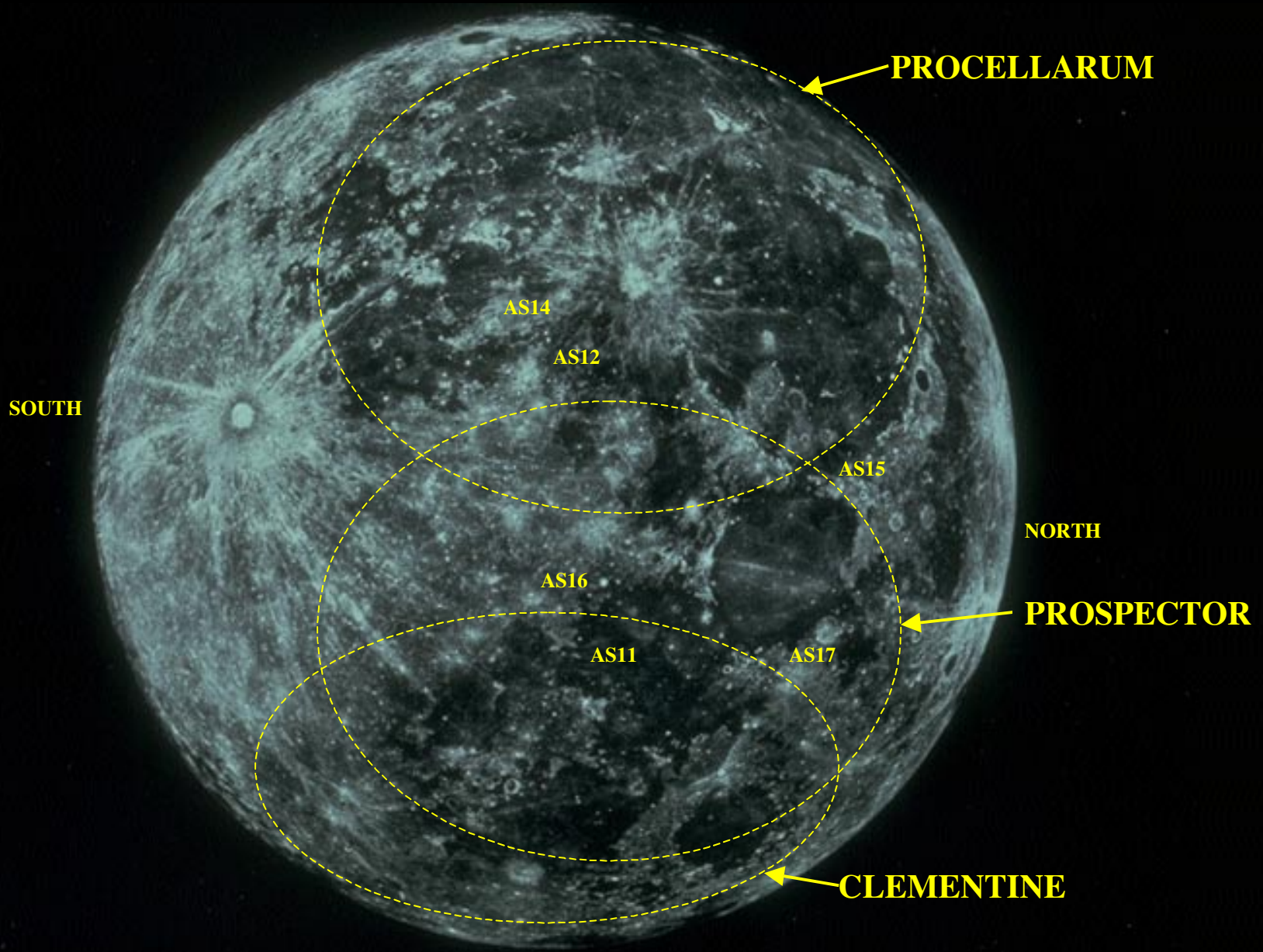
- MG-SUITE PRESSURE-RELEASE MAGMAS
- BASALT PRESSURE-RELEASE MAGMAS
- MG-SUITE INTRUSIVES
- MG-SUITE DEBRIS
- EARLY KREEPY BASALT EXTRUSIVES
- INSULATING CRATERED HIGHLANDS AND EJECTA
- CONSOLIDATED PLAGIOCLASE CUMULATE
- $FE_xNI_yS_z$ LIQUID MIGRATION AND H MIGRATION AFTER H_20 DISASSOCIATION
- ZONE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

VERY LARGE BASINS

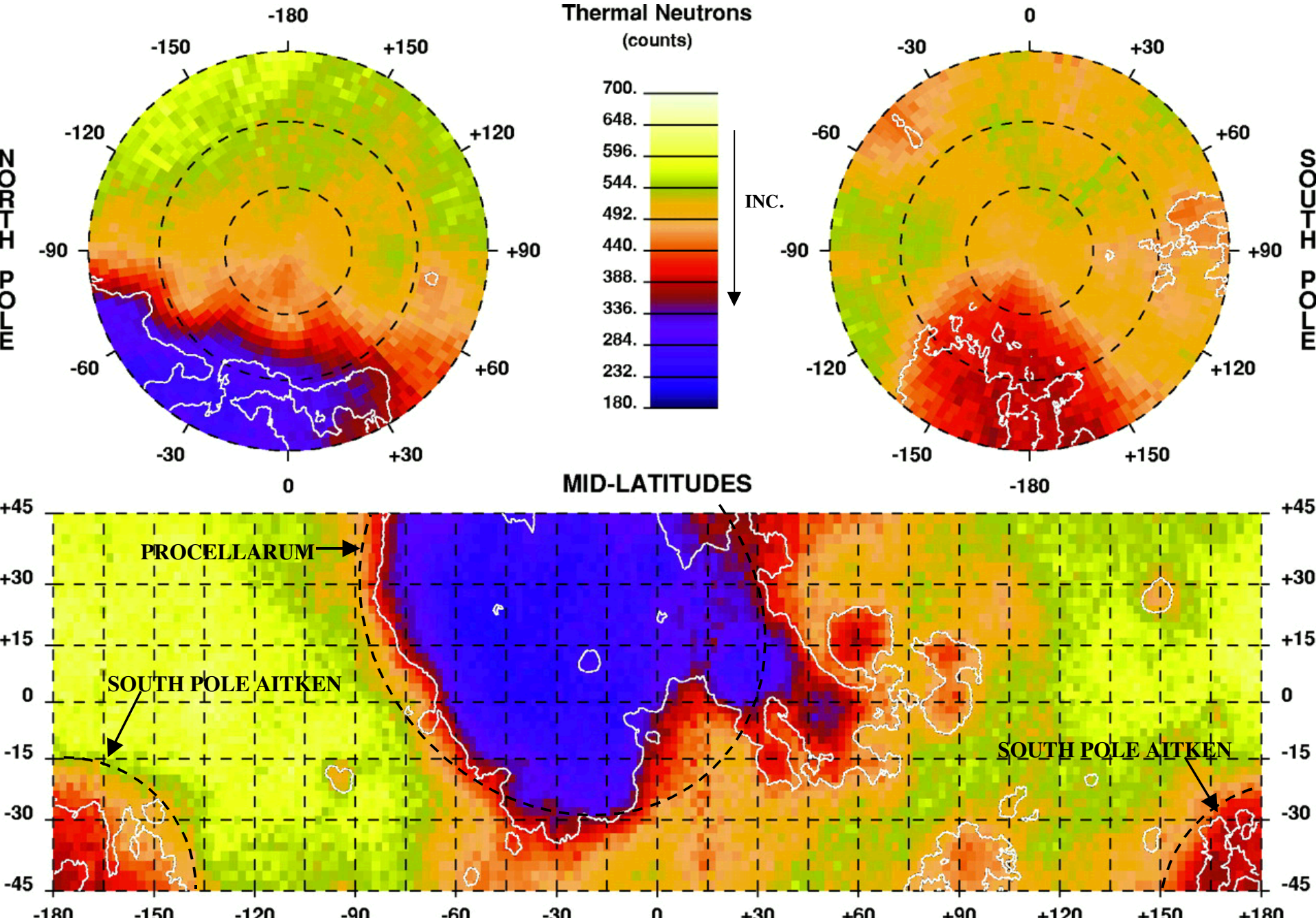



South Pole-Aitken
Basin

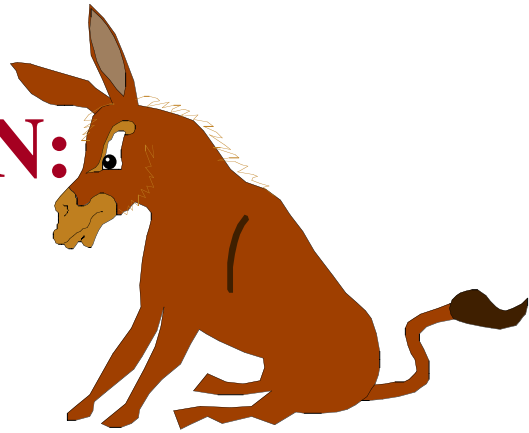
POSSIBLE VERY LARGE BASINS



IRON + TITANIUM CONCENTRATIONS



LUNAR ORIGIN AND EVOLUTION: STANDARD HYPOTHESIS - 1



- GIANT IMPACT AT ~4.55 B.Y.
  - EARLY CORE FORMATION
  - HIGH ANGULAR MOMENTUM
  - GEOCHEMICAL ANOMALIES PROVIDED BY IMPACTOR
- MAGMA OCEAN FOR <50 M.Y.
  - OLIVINE-PYROXENE DOMINATED MANTLE
  - CA-RICH PLAGIOCLASE CRUST (~65KM THICK)
  - ILMENITE-RICH CUMULATES SANK TO MANTLE BASE
  - URKREEP RESIDUAL LIQUID AT BASE OF CRUST
    - ASYMETRICALLY BENEATH IMBRIUM REGION

ORIGIN OF THE MOON
LUNAR CONSTRAINTS

- **OLDEST LUNAR ROCKS CRYSTALLIZED FROM SILICATE MELTS BETWEEN 4.5 AND 4.6 BILLION YEARS AGO.**
- **ELEMENTS OF THE ATOMIC NUMBER OF SODIUM (22) OR LESS ARE DEPLETED IN SAMPLES OF THE MOON'S CRUST AND MANTLE**
- **THE MOON BEGAN WITH A GLOBAL SILICATE MAGMA OCEAN ABOUT 500 KM DEEP**
- **THERE IS EVIDENCE OF UNDIFFERENTIATED CHONDRITIC MATERIAL BELOW ABOUT 500 KM**
- **Hf/W SYSTEMATICS INDICATE THAT CRYSTALLIZATION OF THE MAGMA OCEAN WAS LARGELY COMPLETE ABOUT 50 MILLION YEARS AFTER THE SOLAR NEBULA FORMED**
- **AT LEAST 45 LARGE IMPACTS OCCURRED ON THE MOON IN ITS FIRST 600 MILLION YEARS AND SOME WOULD HAVE AFFECTED ANGULAR MOMENTUM AND ROTATIONAL AXIS ORIENTATION**

ORIGIN OF THE MOON
EARTH/MOON CONSTRAINTS

- **RATIOS OF OXYGEN ISOTOPES IN THE EARTH AND THE MOON ARE THE SAME**
- **THE DENSITY OF THE EARTH IS 5.5 G/CM^3 AND OF THE MOON IS 3.3 G/CM^3**
- **THE MOON IS ~12% IRON WHILE THE EARTH'S MANTLE IS ~8%**
- **THE MANTLES OF THE EARTH AND THE MOON HAVE DISTINCTLY DIFFERENT SIDEROPHILE ELEMENT SIGNATURES**
- **REFRACTORY ELEMENT CONCENTRATIONS ARE HIGHER IN THE MOON THAN IN THE EARTH, HOWEVER, THEIR RATIOS ARE THE SAME**
- **THE MOON AND THE EARTH HAVE DISTINCT DIFFERENCES IN VARIOUS OTHER ISOTOPIC RATIOS**
- **ANGULAR MOMENTUM OF THE EARTH-MOON SYSTEM IS HIGHER THAN ANY KNOWN PLANET-SATELLITE SYSTEMS**

ORIGIN OF THE MOON
OLD HYPOTHESES

- **SIMULTANEOUS FORMATION AS A DOUBLE PLANET SYSTEM**
  - **PROBLEM WITH ANGULAR MOMENTUM AND DIFFERENCES IN DENSITIES AND COMPOSTIONS**
- **BREAK-UP OR FISSION FROM A RAPIDLY SPINNING EARTH**
  - **PROBLEM WITH TOO MUCH ANGULAR MOMENTUM AND DISTINCT COMPOSITIONAL DIFFERENCES**
- **DISINTEGRATION OF NEAR-EARTH CROSSING PLANETESIMALS**
  - **PROBLEM IN MODELING THIS HYPOTHESIS**
- **CAPTURE OF AN INDPENDENTLY EVOLVED PLANET**
  - **STILL UNDER CONSIDERATION**

ORIGIN OF THE MOON
NEW HYPOTHESES

- **EARTH IMPACT OF A MARS-SIZED PLANETESIMAL**
    - **Mars-sized planetesimal impacted a young Earth after separation of their iron-rich cores, i.e., impact assisted capture of the impactor's mantle.**
- **AGGREGATION OF CIRCUMTERRESTRIAL DISK**
    - **(NO EVALUATION AS YET)**

ORIGIN OF THE MOON
EVIDENCE FOR EARTH IMPACTOR

- **COMPUTER MODELS APPEAR TO PRODUCE A MOON WITHIN FEW MILLION YEARS**
- **CAN ACCOUNT FOR THE HIGH ANGULAR MOMENTUM OF EARTH-MOON SYSTEM**
- **CAN ACCOUNT FOR THE MOON'S OUT-OF-ECLIPITIC ORBIT AND NON-PARALLEL ROTATIONAL AXIS**
- **CAN GIVE A MAGMA OCEAN**
- **CAN ACCOUNT FOR THE MOON'S TOTAL IRON DEPLETION OVER CHONDRITES AND THE EARTH (PROVIDED THAT LESS THAN 10% OF EARTH'S MANTLE IS INCLUDED)**
- **CAN ACCOUNT FOR COMPOSITIONAL DIFFERENCES BETWEEN THE EARTH AND THE MOON BY DIFFERENCES BETWEEN THE EARTH AND THE IMPACTOR**
- **MAY ACCOUNT FOR THE LOSSES IN ELEMENTS BELOW THE ATOMIC NUMBER OF 23 IN THE MOON'S CRUST AND UPPER MANTLE**

ORIGIN OF THE MOON
PROBLEMS WITH EARTH IMPACTOR

- **MAY REQUIRE THAT THE ENTIRE MOON BE INITIALLY MOLTEN**
- **REQUIRES THAN THE ENTIRE MOON BE ACCRETED FROM DEVOLATILIZED MATERIAL, I.E., DOES NOT ACCOUNT FOR THE GEOCHEMISTRY OF MOON'S LOWER MANTLE**

ORIGIN OF THE MOON
EVIDENCE FOR CAPTURE

- **EARTH CAPTURE HYPOTHESIS:**
  - **The Moon and the Earth formed as independent planets in the same part of the solar system with the Moon being captured by the Earth prior to at least 2.5 billion years ago, the age of the oldest evidence of tidal interaction.**
- **EVIDENCE**
  - **MOON'S LOWER MANTLE PARTIALLY CHONDRITIC**
  - **CAN ACCOUNT FOR COMPOSITIONAL DIFFERENCES BETWEEN THE EARTH AND THE MOON BY DIFFERENT GRAVITATIONAL EFFECTS DURING PRIMARY ACCRETION**

ORIGIN OF THE MOON
PROBLEMS FOR CAPTURE

- **NO MODERN MODELING STUDIES OF CAPTURE**
- **ACCOUNTS FOR THE HIGH ANGULAR MOMENTUM OF EARTH-MOON SYSTEM ONLY BY THE ASSIMILATION SEVERAL LARGE IMPACTORS AFTER CAPTURE**
- **ACCOUNTS FOR THE MOON'S OUT-OF-ECLIPITIC ORBIT AND NON-PARALLEL ROTATIONAL AXIS ONLY BY THE CUMMULATIVE EFFECT OF MANY LARGE IMPACTORS**
- **ACCOUNTS FOR THE MOON'S TOTAL IRON DEPLETION OVER CHONDRITES AND THE EARTH ONLY BY BEING NON-COMPETITIVE WITH THE ACCRETION OF A MORE MASSIVE, CO-ORBITING EARTH**