ORIGIN AND EVOLUTION OF THE MOON

NEEP 533 LECTURE 8

Harrison H. Schmitt

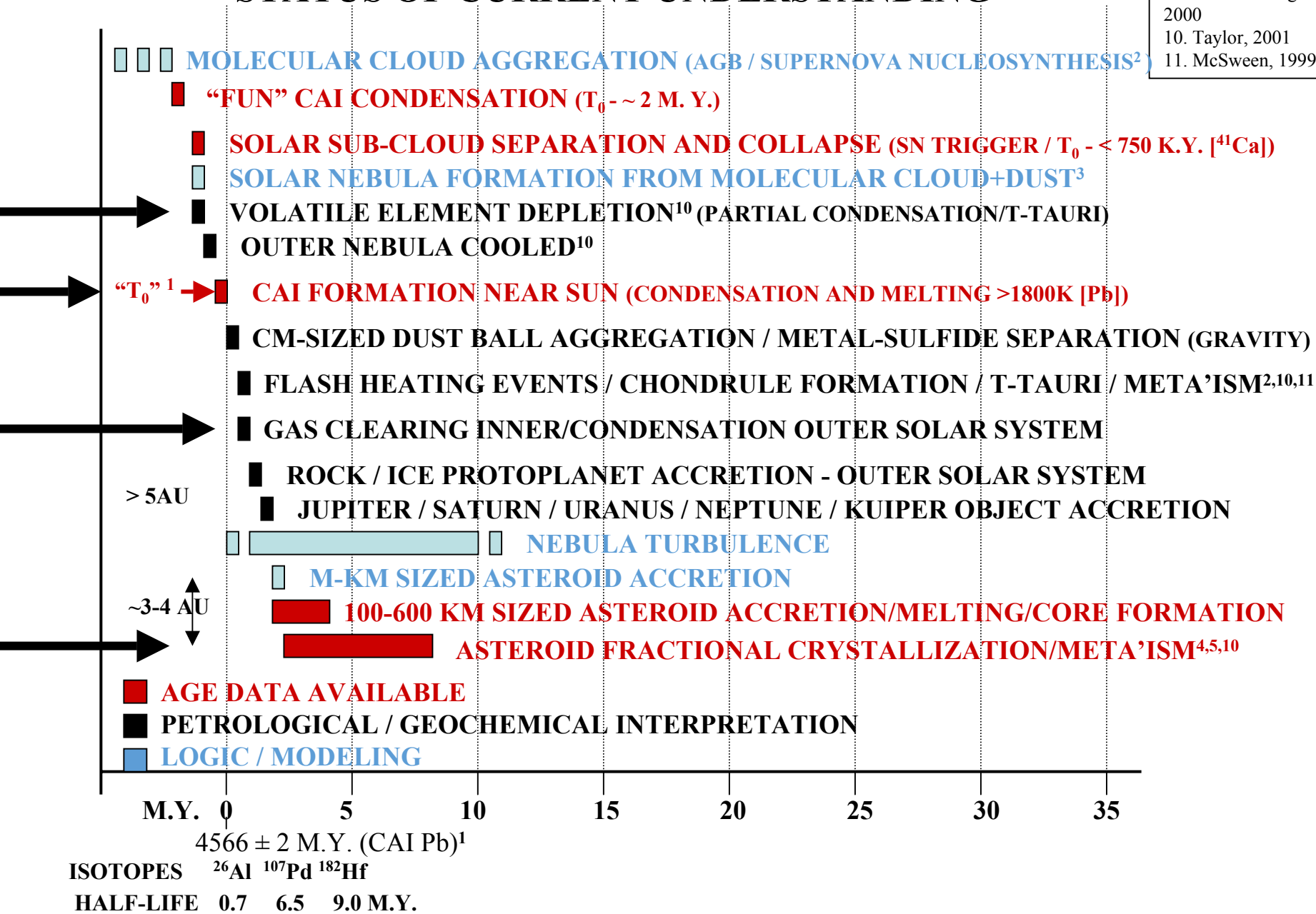
NASA GALILEO/MARS GLOBAL SURVEYOR

DEFINITIONS

- **MAGMA / LAVA** — MOLTEN SILICATES
- **OLIVINE** — Mg-RICH, LOW SILICA SILICATE
  - HIGH DENSITY VS. MAGMA
- **PYROXENE** — Mg-RICH, MID-SILICA SILICATE
  - HIGH DENSITY VS. MAGMA
- **PLAGIOCLASE** — Ca-RICH ALUMINUM SILICATE
  - LOW DENSITY VS. MAGMA
- **ILMENITE** — Fe-Ti OXIDE
  - HIGH DENSITY VS. MAGMA
- **GARNET** — Ca-Mg-RICH ALUMINUM SILICATE
  - HIGH DENSITY VS. MAGMA
- **BASALT** — FINE-GRAINED, Mg-Ca-RICH SILICATE ROCK
- **PYROCLASTIC** — EXPLOSIVELY ERUPTED
- **VOLATILES** — ELEMENTS/MOLECULES THAT VOLATILIZE AT LOW TEMP.

BEGINNING

STATUS OF CURRENT UNDERSTANDING



1. Allègre, et al, 1995
2. Busso,, et al, 1999
3. Vanhala & Boss, 2000
4. Carlson & Lugmire, 2000
10. Taylor, 2001
11. McSween, 1999

INNER SYSTEM ACCRETION
(LARGELY COMPLETE AT 30 M.Y.)

- DUST AGGREGATION
- METER SIZE PARTICLE AGGREGATION
- KILOMETER SIZE BODY AGGREGATION
- RUNAWAY GROWTH OF PLANETS
  - FRAGMENTATION NOT IN MODELS
- GIANT IMPACTS AND MAGMA OCEANS
  - ADDITIONAL LOSS OF LUNAR VOLATILE ELEMENTS
  - SEPARATION OF CORE-FORMING LIQUID
    - DELAYED CORE FORMATIONS ?

^{182}Hf / ^{182}W
AGES FOR CORE
MAT'L SEPARATION
(T_0 PLUS 30 M.Y.)

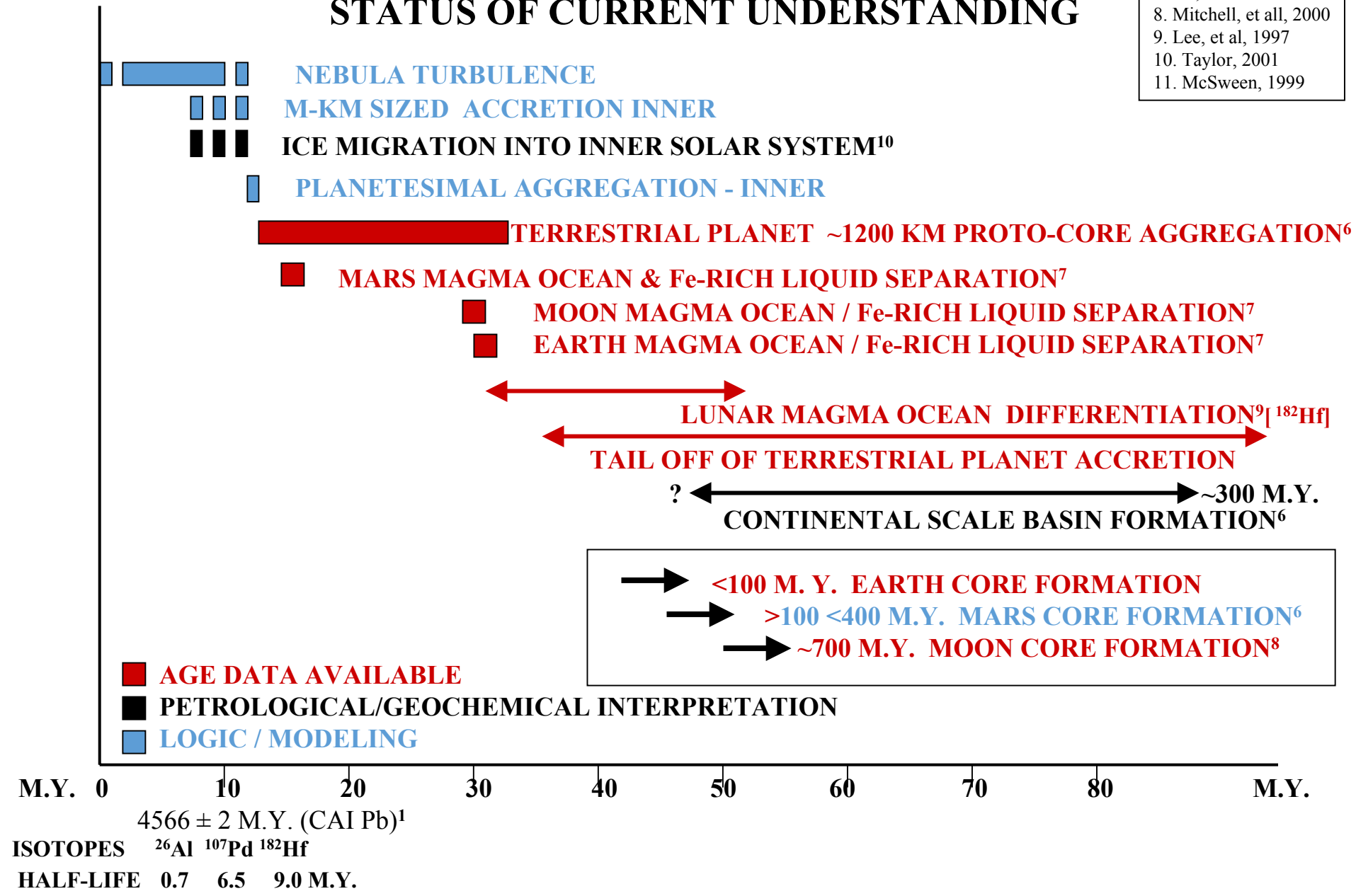
ORIGIN OF THE MOON
LUNAR CONSTRAINTS

- **OLDEST LUNAR ROCKS SAMPLED 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 RELATIVE TO THE EARTH'S CRUST**
- **THE MOON BEGAN WITH A GLOBAL SILICATE MAGMA OCEAN ABOUT 500 KM DEEP**
  - **SMALL MINORITY STILL WOULD ARGUE FOR WHOLE MOON MELTING**
- **EVIDENCE OF UNDIFFERENTIATED CHONDRITIC MATERIAL BELOW ABOUT 500 KM**
- **CRYSTALLIZATION OFTHE MAGMA OCEAN WAS ~95% COMPLETE ABOUT 50 MILLION YEARS AFTER T_0**
  - **^{182}Hf / W SYSTEMATICS**
- **AT LEAST 45 LARGE IMPACTS >300 KM IN DIAMETER OCCURRED ON THE MOON IN ITS FIRST 600 MILLION YEARS**
  - **AT LEAST ONE, POSSIBLY FIVE OR MORE, LARGE IMPACT BASINS >2500 KM IN DIAMETER**
  - **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 OUTER 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**
  - **3.41 X 10^{41} RAD · GM · CM^2/SEC VS.**
  - **4 HOUR ROTATION RATE IF ALL IN A MOLTEN EARTH, BUT FISSION WOULD NOT OCCUR**

BEGINNING: INNER SOLAR SYSTEM
STATUS OF CURRENT UNDERSTANDING

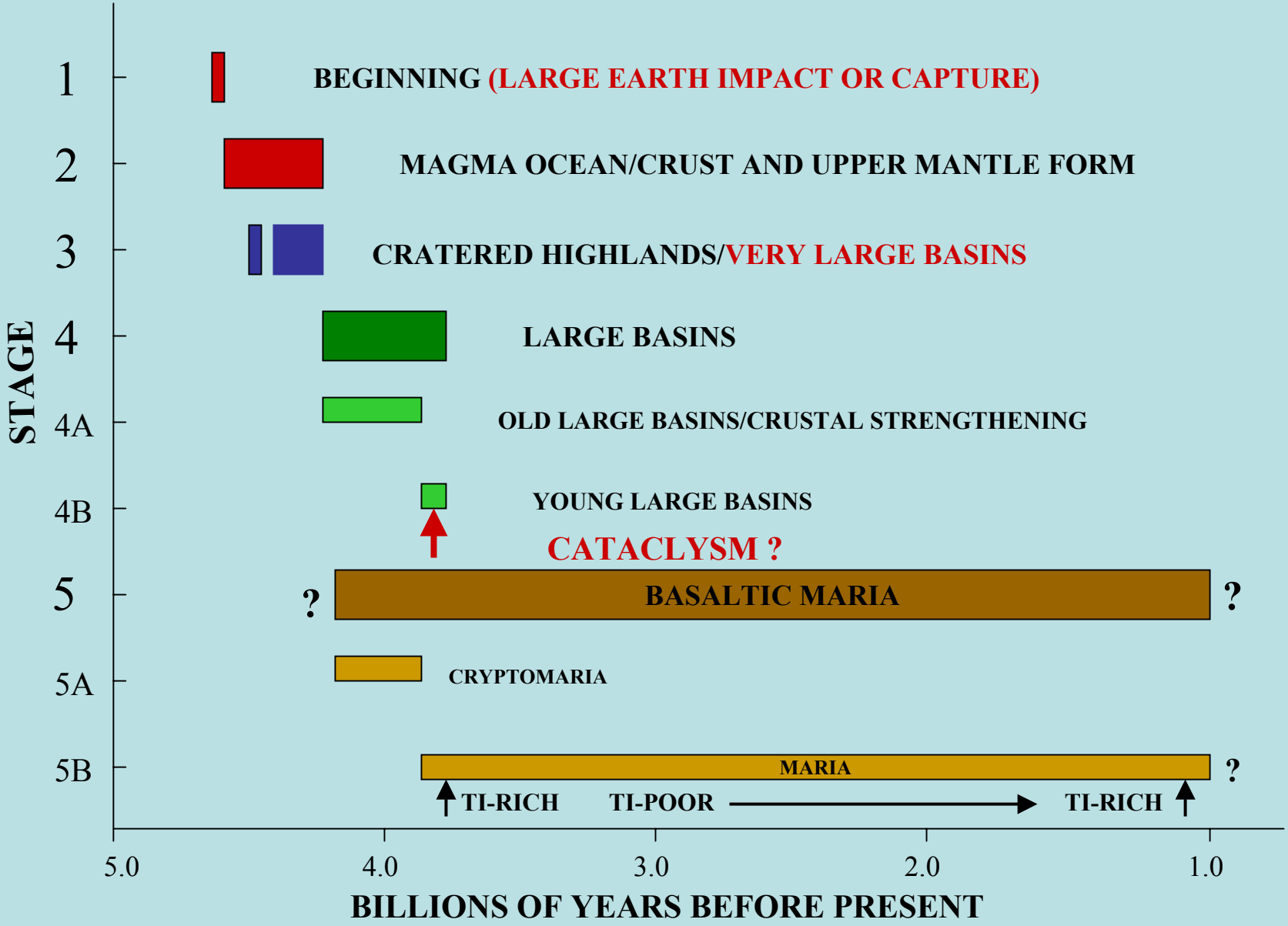


4566 ± 2 M.Y. (CAI Pb)[1]

ISOTOPES	^{26}Al	^{107}Pd	^{182}Hf
HALF-LIFE	0.7	6.5	9.0 M.Y.

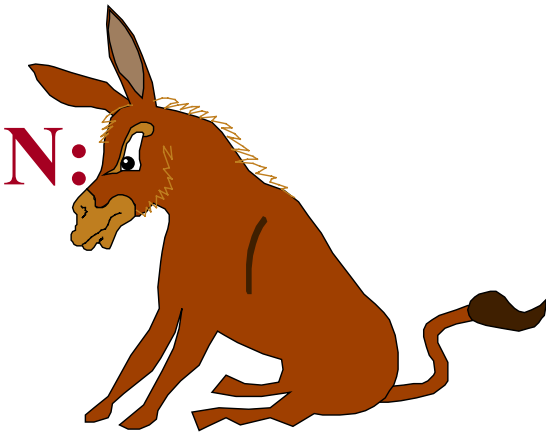
5. Lee, et all,
6. Schmitt, 2003
7. Yin, et al, 2001 and Kline, et al 2001
8. Mitchell, et all, 2000
9. Lee, et al, 1997
10. Taylor, 2001
11. McSween, 1999

MAJOR STAGES OF LUNAR EVOLUTION



RED = MAJOR UNCERTAINTY

LUNAR ORIGIN AND EVOLUTION: STANDARD HYPOTHESIS - 1

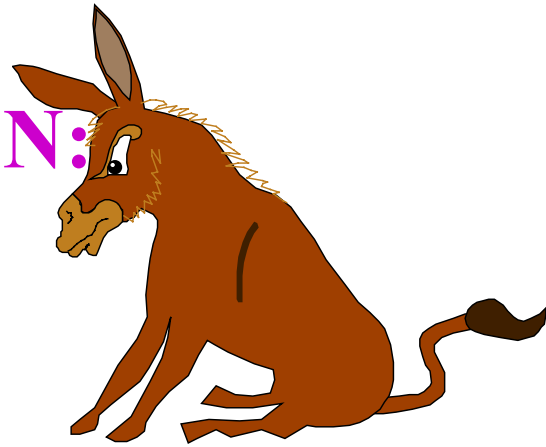


- GIANT IMPACT AT ~4.55 B.Y.
  - HIGH ANGULAR MOMENTUM
  - EARLY CORE FORMATION
  - GEOCHEMICAL ANOMALIES PROVIDED BY IMPACTOR
    - I.E., IMPACT ASSISTED CAPTURE OF MANTLE OF IMPACTOR
- MAGMA OCEAN FOR <50 M.Y.
  - OLIVINE-PYROXENE DOMINATED MANTLE
  - CA-RICH PLAGIOCLASE CRUST (~65KM THICK)
  - ILMENITE-RICH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

URKREEP: ORIGINAL RESIDUAL LIQUID FROM MAGMA OCEAN, RICH IN K, RARE EARTH ELEMENTS, PHOSPHOROUS, URANIUM, AND THORIUM.

ITEMS INDICATED IN RED ARE SUBJECT TO RE-INTERPRETATION

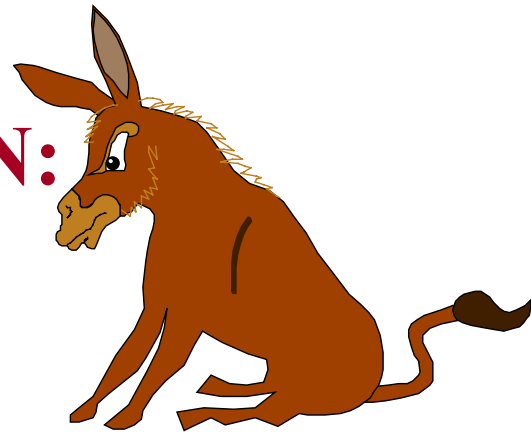
LUNAR ORIGIN AND EVOLUTION: STANDARD HYPOTHESIS - 2



- **EARLY BASALTIC MAGMATIC ACTIVITY**
  - **MG-SUITE OF PLUTONIC ROCKS (4.5-4.2 B.Y.)**
  - **KREEP-RICH BASALTIC LAVAS (4.3-? B.Y.)**
  - **CRYPTOMARIA (PRE 3.9 B.Y.)**
- **LUNAR CATACLYSM BETWEEN 3.9-3.8 B.Y.**
  - **~50 LARGE BASINS IN ~100 M.Y.**
  - **ONE, ONLY, EXTREMELY LARGE BASIN (SOUTH POLE-AITKEN)**
    - **PROCELLARUM BASIN IS ARTIFACT OF SEVERAL BASINS**
  - **AGES OF IMPACT GLASSES RESET TO > 3.9 B.Y.**
- **GLOBAL MAGNETIC FIELD**
  - **AT LEAST BETWEEN 3.9 AND 3.8 B.Y.**

ITEMS INDICATED IN RED ARE SUBJECT TO RE-INTERPRETATION

LUNAR ORIGIN AND EVOLUTION: STANDARD HYPOTHESIS - 3



- **MARE BASALT/PYROCLASTIC ERUPTIONS**
  - **3.9-1.0 B.Y.**
  - **LARGELY ON THE NEAR SIDE**
- **EXCEPT FOR MARE BASIN FILLING, MAJOR FEATURES LITTLE MODIFIED AFTER 3.9 B.Y.**
  - **~100 KM CRATERS AND SMALLER**
  - **SEVERAL METERS OF REGOLITH DEVELOPED**

ORIGIN OF THE MOON

OLD HYPOTHESES

- **SIMULTANEOUS FORMATION AS A DOUBLE PLANET SYSTEM**
  - **PROBLEM WITHCURRENT ANGULAR MOMENTUM AND DIFFERENCES IN DENSITIES AND COMPOSTIONS**
- **BREAK-UP OR FISSION FROM A RAPIDLY SPINNING EARTH**
  - **PROBLEM WITH TOO MUCH CURRENT ANGULAR MOMENTUM AND DISTINCT COMPOSITIONAL DIFFERENCES BETWEEN EARTH AND MOON**
- **DISINTEGRATION AND RE-AGGREGATION OF NEAR-EARTH CROSSING PLANETESIMALS**
  - **PROBLEM IN TESTING THIS HYPOTHESIS**
- **CAPTURE OF AN INDPENDENTLY EVOLVED PLANET**
  - **STILL UNDER CONSIDERATION, BUT MOST REJECT AS UNLIKELY**

ORIGIN OF THE MOON
NEW HYPOTHESES

- **GIANT EARTH IMPACT BY 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 PRIMORDIAL CIRCUMTERRESTRIAL DISK**
    - **(NO IN DEPTH EVALUATION AS YET, BUT ACCRETION DYNAMICS WOULD BE SIMILAR TO THOSE POST-GIANT IMPACT)**

ORIGIN OF THE MOON
EVIDENCE FOR GIANT IMPACT

- **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 CREATE MAGMA OCEANS ON THE MOON AND EARTH**
- **CAN ACCOUNT FOR THE MOON'S TOTAL IRON BEING HIGHER RELATIVE TO THE EARTH (PROVIDED THAT LESS THAN 10% OF EARTH'S MANTLE IS INCLUDED IN MOON)**
- **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 GIANT IMPACT

- **MAY REQUIRE THAT THE ENTIRE MOON BE INITIALLY MOLTEN**
  - **STRONG EVIDENCE THAT INITIAL, ACCRETIONARY MELTING EXTENDED ONLY TO ~500KM DEPTH**
    - **APOLLO SEISMIC VELOCITIES INDICATE UPPER MANTLE ~500 KM THICK**
    - **~ 60-70 KM THICKNESS OF Ca-ALUMINUM SILICATE CRUST CONSISTENT WITH LIMITED MELTING**
    - **CHONTRITIC ELEMENT AND ISOTOPIC SIGNATURES FROM LOWER MANTLE**
    - **INCREASED ALUMINUM (IN GARNET?) BELOW~ 500 KM**
    - **APPARENTLY DELAYED CORE FORMATION SUGGESTS INITIALLY COOL LOWER MANTLE**
- **IF MARS HAD A MAGMA OCEAN, AS APPEARS LIKELY, GIANT IMPACTWOULD NOT BE NECESSARY FOR THIS PURPOSE**
  - **DISSIPATION OF ACCRETIONARY POTENTIAL AND KINETIC ENERGY PROBABLY ENOUGH**
- **REQUIRES THAN THE ENTIRE MOON BE ACCRETED FROM LARGELY DEVOLATILIZED MATERIAL, OVER AND ABOVE PRE-T_0 DEVOLATILIZATION**
  - **DOES NOT ACCOUNT FOR THE PRESENCE OF CONCENTRATIONS OF VOLATILE ELEMENTS IN MOON'S LOWER MANTLE 10 TO 100 TIMES THOSE IN THE UPPER MANTLE AND CRUST**

CHALLENGES FOR GIANT IMPACT HYPOTHESIS

- **UNDIFFERENTIATED, PRIMORDIAL COMPONENTS IN LOWER MANTLE**
  - **VOLATILE ELEMENT CONCENTRATIONS IN APOLLO 17 ORANGE AND APOLLO 15 GREEN VOLCANIC GLASS >>MARE BASALTS (MEYER, ET AL, 1989)**
  - **PRIMITIVE LEAD IN ORANGE VOLCANIC GLASS (NUNES, ET AL 1974)**
  - **CHONDRITIC TUNGSTEN IN ORANGE VOLCANIC GLASS (LEE, ET AL 1997)**
  - **DISTINCTIVE AU/IR AND ZR/Y IN ORANGE VOLCANIC GLASS (NEAL, 2000)**
- **SEISMIC AND TRACE ELEMENT DATA SUGGESTS INCREASED ALUMINIUM AS GARNET BELOW 500KM (HAHN, 2000; NEAL, 2001)**
  - **LEAST SOME OF THE ORANGE AND GREEN VOLCANIC GLASSES INITIAL MELT APPARENTLY FORMED WITH GARNET PRESENT (NEAL, 2001)**
  - **INDICATES LOWER MANTLE DID NOT MELT (GOINS, ET AL, 1981; NEAL, 2001)**
- **REMANENT MAGNETISM ANTIPODAL TO YOUNG BASINS (LIN, ET AL, 1998, MITCHELL, ET AL, 2000) SUGGESTS METALLIC CORE FORMATION DELAYED TO ~3.9 B.Y.**
  - **COOL, LARGELY SILICATE PROTO-CORE IN THE WAY?**
- **LUNAR FEO AND HF/W SUGGESTS SMALL EARTH MANTLE COMPONENT, IF ANY (TAYLOR/ESAT, 1996; JONES/PALME, 2000)**
  - **$^{87}SR/^{86}SR$ SUGGESTS LARGE EARTH MANTLE COMPONENT (CARSON AND LUGMAIR, 2000)**

ORIGIN OF THE MOON
CAPTURE ALTERNATIVE TO GIANT IMPACT HYPOTHESIS

- **CAPTURE HYPOTHESIS:**
  - **The Moon and the Earth formed as independent planets in the same part of the solar system (same oxygen isotopic feeding zone of ~1 AU±0.5) with the Moon being captured by the Earth prior to at least 2.5 billion years ago, the age of the oldest known evidence of tidal interaction.**
- **EVIDENCE**
  - **MOON'S LOWER MANTLE IS PARTIALLY CHONDRITIC AND ALUMINOUS INDICATING PRIMORDIAL ACCRETION OF A PROTO-CORE (~1200 KM RADIUS)**
- **OTHER CONSIDERATIONS**
  - **CAN ACCOUNT FOR HIGHER Fe IN THE MOON RELATIVE TO THE EARTH**
    - **GRAVITATIONAL EFFECTS DURING PLANETARY ACCRETION**
  - **CAN ACCOUNT FOR ADDITIONAL DEVOLATILIZATION RELATIVE TO THE EARTH BY IMPACT EFFECTS DURING FORMATION OF THE MAGMA OCEAN**
    - **EXTREMELY HIGH TEMPERATURES AT EACH POINT OF IMPACT**

ORIGIN OF THE MOON
PROBLEMS FOR CAPTURE HYPOTHESIS

- **NO MODERN MODELING STUDIES TO SUPPORT: CONSIDERED VERY LOW PHYSICAL PROBABILITY**
  - **CAPTURE IS A RELATIVELY COMMON PHENOMENOM IN THE SOLAR SYSTEM (MARS, ASTEROIDS, NEPTUNE, KUIPER BELT, AND POSSIBLY JUPITER.**
  - **NO SIGNIFICANT MODELING EFFORT SINCE 1972**

- **ACCOUNTING FOR THE HIGH ANGULAR MOMENTUM OF EARTH-MOON SYSTEM**
  - **POTENTIAL DYNAMICS OF CAPTURE OR**
  - **CUMMULATIVE EFFECT OF LARGE, POST-CAPTURE ACCRETION**

- **ACCOUNTING FOR OUT-OF-ECLIPITIC ORBIT AND NON-PARALLEL ROTATIONAL AXIS**
  - **CUMMULATIVE EFFECT OF LARGE, POST-CAPTURE IMPACTORS ?**

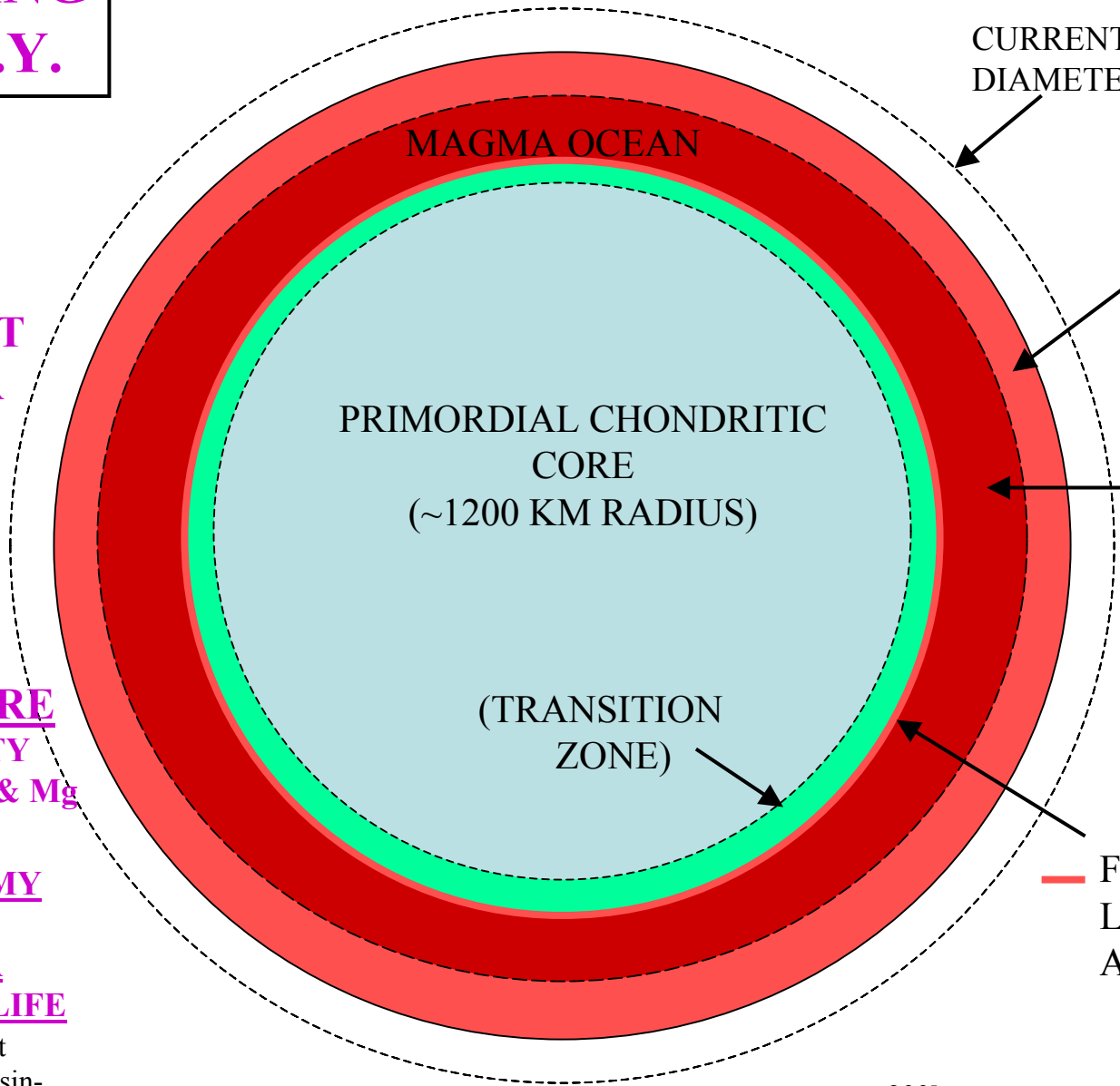
- **ACCOUNTING FOR TOTAL IRON DEPLETION OVER CHONDRITES AND THE EARTH**
  - **POOR GRAVITATIONAL COMPETITOR FOR DENSE IRON METAL SOURCE MATERIAL?**

APOLLO MODEL OF LUNAR EVOLUTION

BEGINNING ~4.535 B.Y.

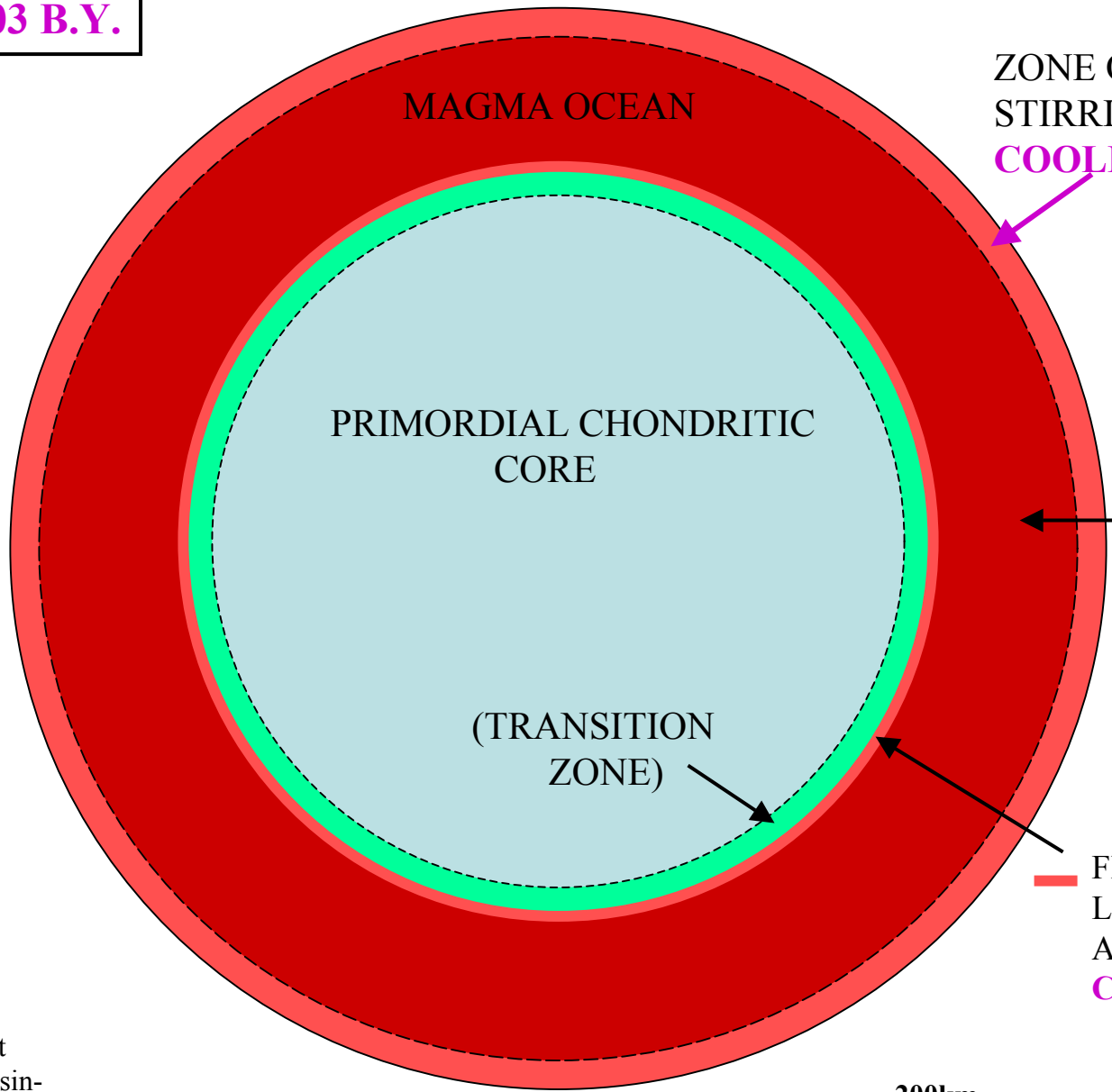
NOTE: ASSUMES AN ORIGIN INDEPENDENT OF BUT NEAR EARTH.

- **"CORE"**
  - **PRIMATIVE Pb**
  - **CHONDRITIC W**
  - **NON-MANTLE VOLATILES**
- **MANTLE-CORE**
  - **V DISCONTINUITY**
  - **INCREASE IN Al & Mg**
- **TIMING**
  - **Hf/W GIVES <50 MY AFTER NEBULA FORMATION FOR MAGMA OCEAN LIFE**



APOLLO MODEL OF LUNAR EVOLUTION

BEGINNING
~4.535 ± 0.003 B.Y.



ZONE OF IMPACT STIRRING **AND NET COOLING**

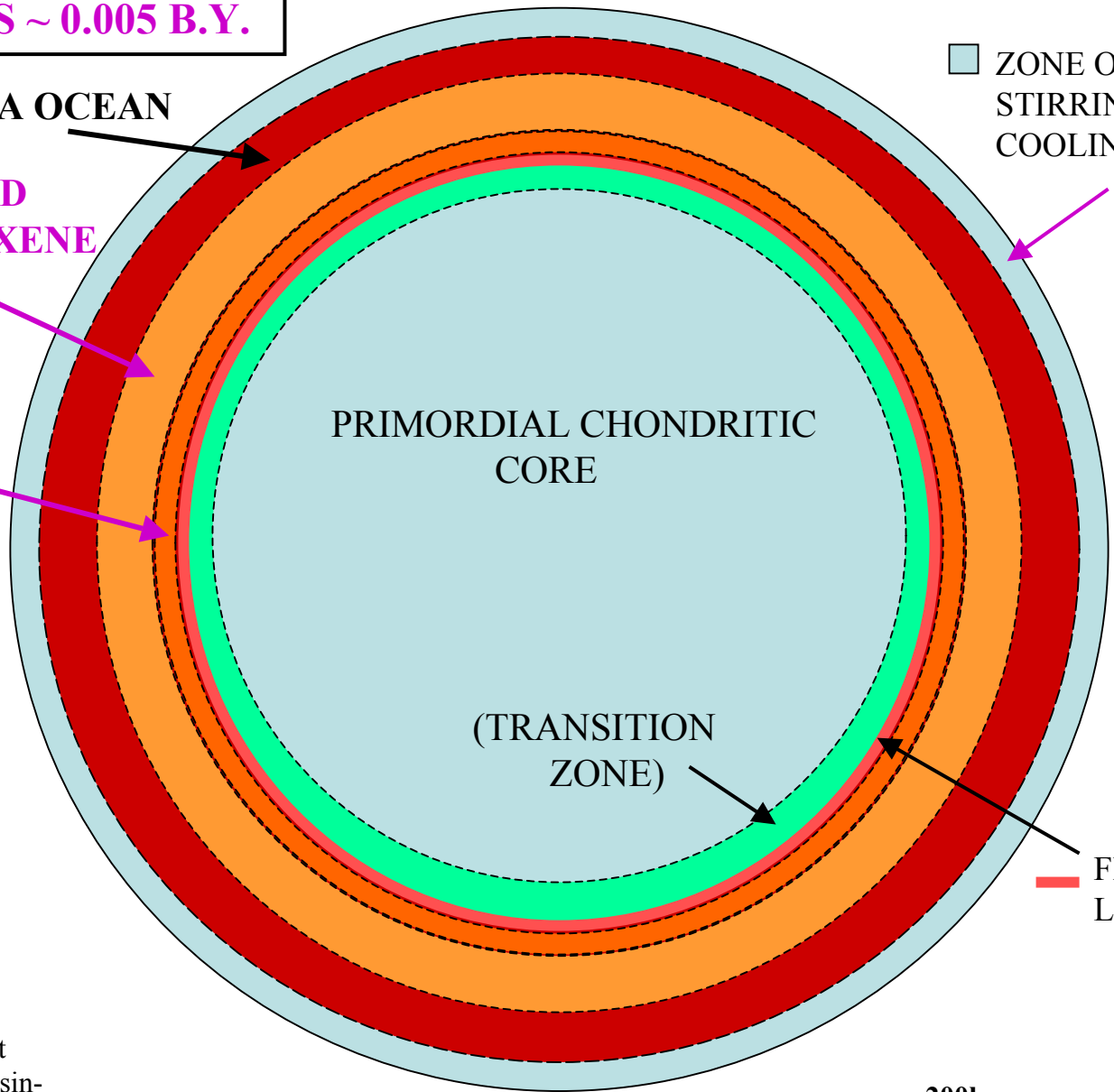
INCLUDES $FE_xNI_yS_z$ LIQUID DROPLETS

$FE_xNI_yS_z$ LIQUID ACCUMULATION **COMPLETE**

— = **200km**

APOLLO MODEL OF LUNAR EVOLUTION

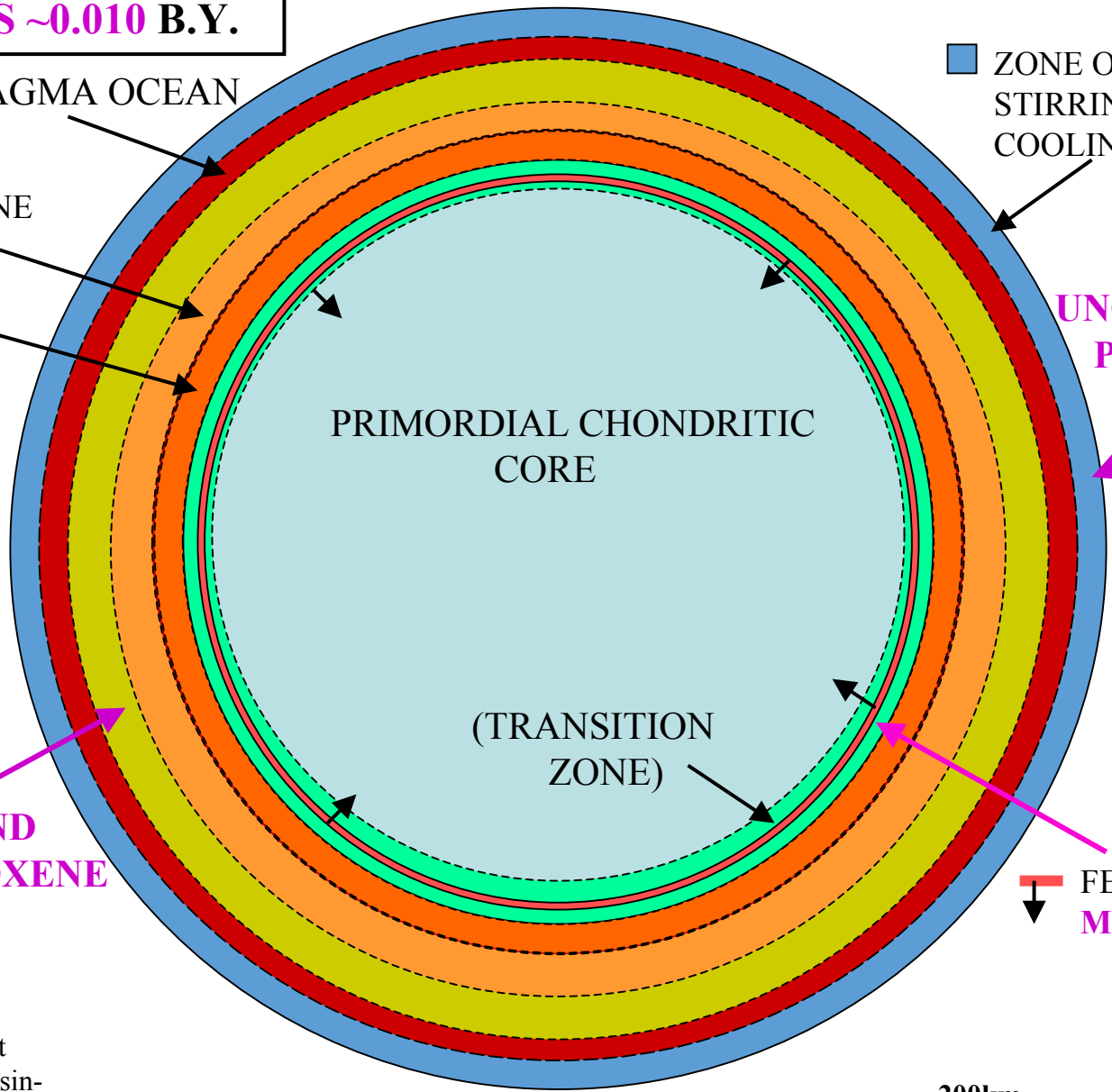
MAGMA OCEAN STAGE
~4.535 MINUS ~ 0.005 B.Y.



University of Wisconsin-Madison

APOLLO MODEL OF LUNAR EVOLUTION

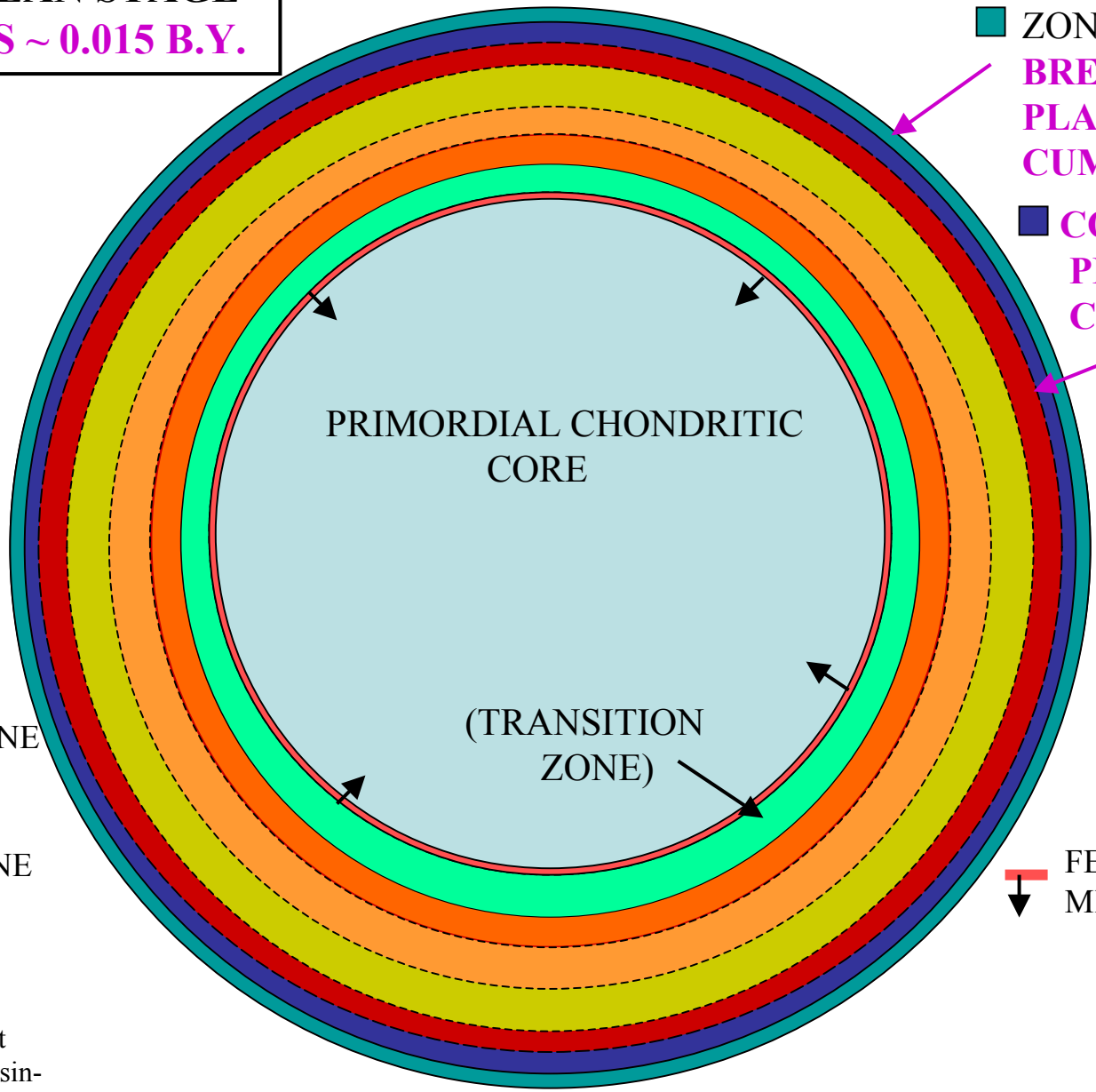
MAGMA OCEAN STAGE
~4.535 MINUS ~0.010 B.Y.



— = 200km

APOLLO MODEL OF LUNAR EVOLUTION

MAGMA OCEAN STAGE
~4.535 MINUS ~ 0.015 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

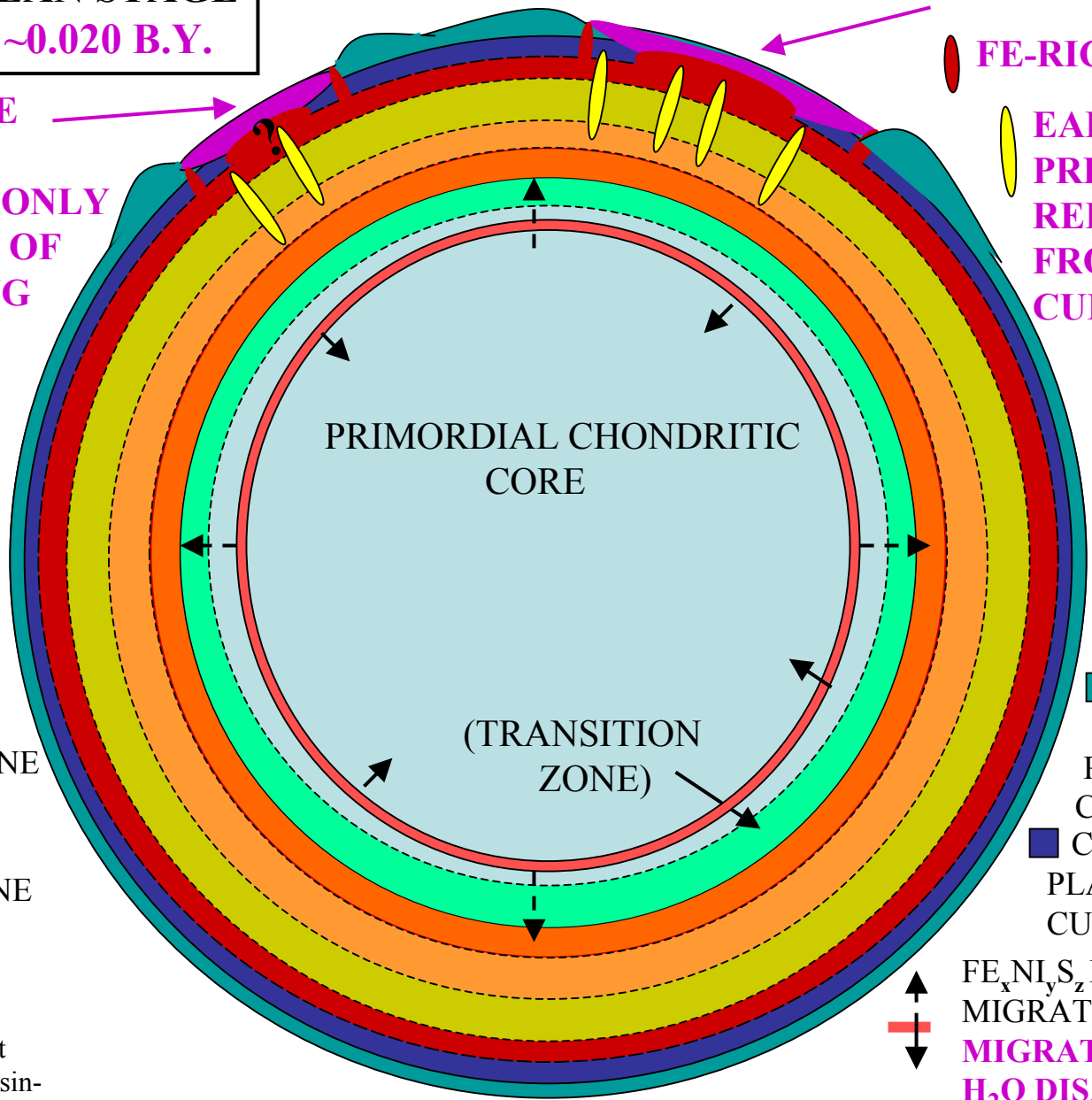
OLIVINE CUMULATE

$FE_xNI_yS_z$ LIQUID MIGRATION

= 200km

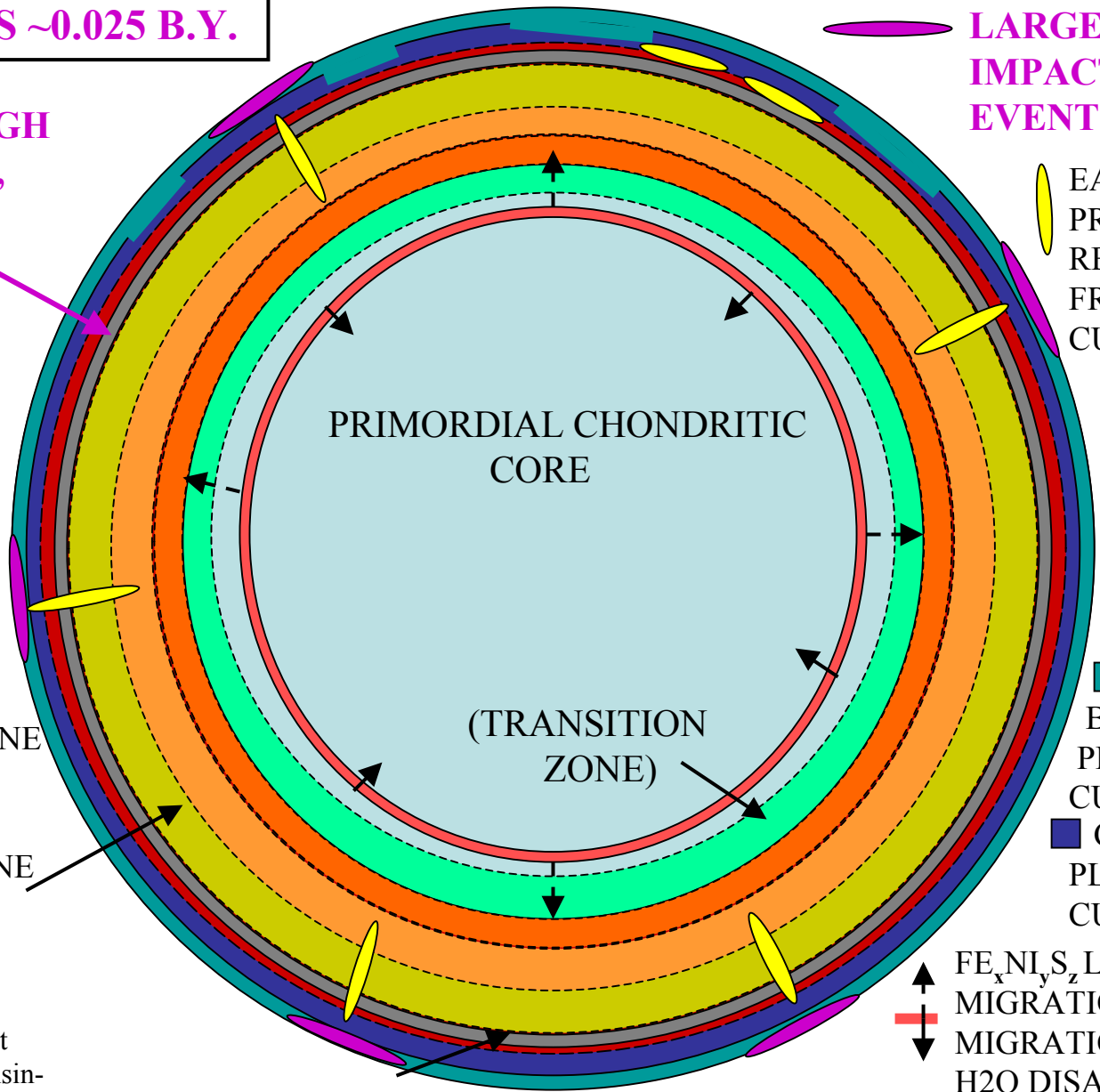
APOLLO MODEL OF LUNAR EVOLUTION

MAGMA OCEAN STAGE
4.535 MINUS ~0.020 B.Y.



APOLLO MODEL OF LUNAR EVOLUTION

MAGMA OCEAN STAGE
~4.535 MINUS ~0.025 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

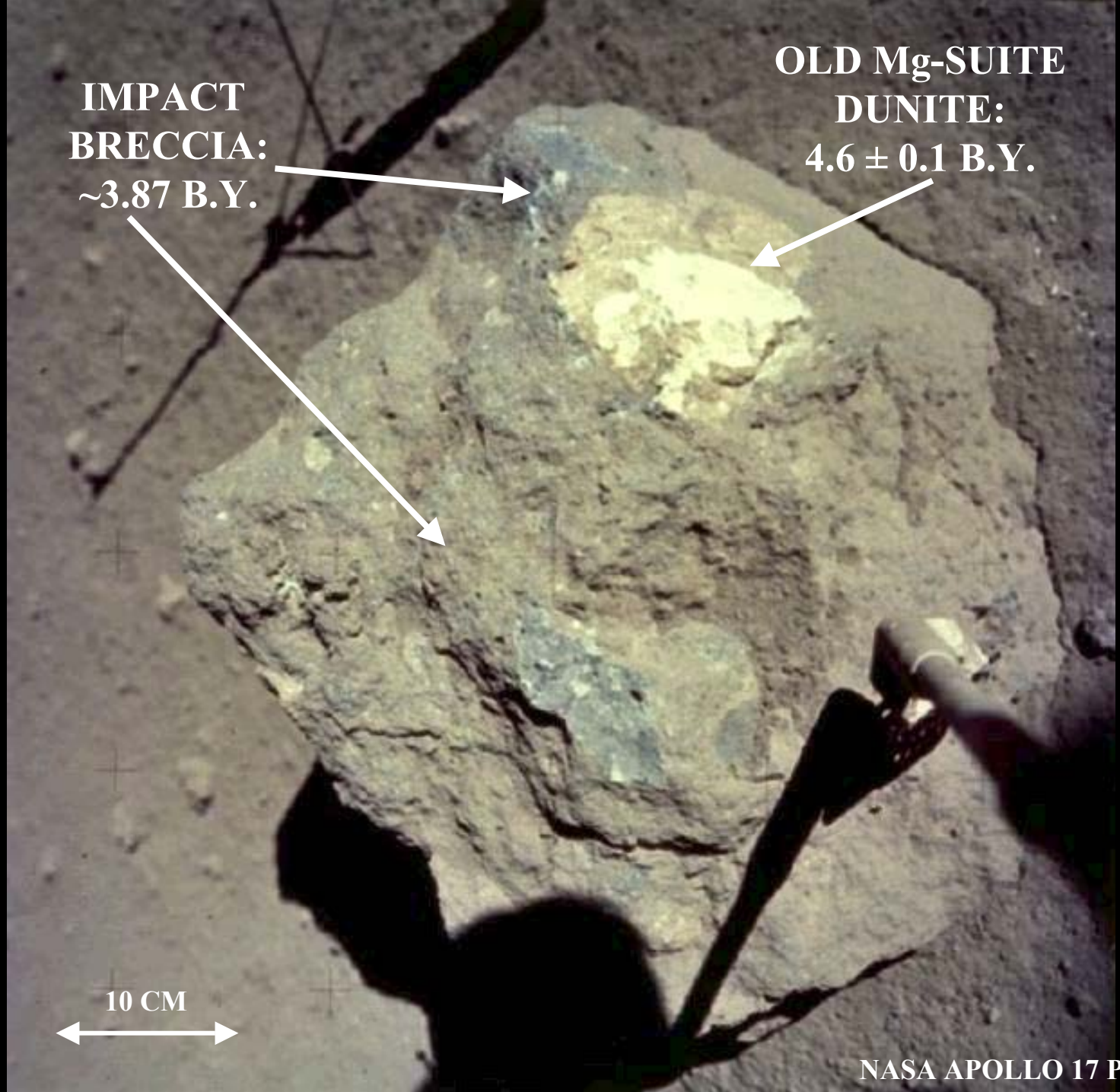
OLIVINE CUMULATE

ZONE OF IMPACT BRECCIATION OF PLAGIOCLASE CUMULATE

CONSOLIDATING PLAGIOCLASE CUMULATE

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

= **200km**


IMPACT
BRECCIA:
~3.87 B.Y.
OLD Mg-SUITE
DUNITE:
4.6 ± 0.1 B.Y.
10 CM
NASA APOLLO 17 PHOTO

POSSIBLE TERM PAPER TOPICS: LECTURE 8

- APPROACH TO CAPTURE MODELING
- COMPARISON OF ORANGE AND GREEN PYROCLASTIC GLASS CHEMICAL AND ISOTOPIC COMPOSITIONS
- SUMMARY OF ARGUMENTS FOR GIANT IMPACT ORIGIN OF THE MOON
- FACTORS LEADING TO WATER MIGRATION BACK INTO THE INNER SOLAR SYSTEM