Contrary Views of the Origin and Thermal Evolution of the Moon

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UWFDM-1122

Presented at the 31st Lunar and Planetary Science Conference, Houston TX, 13-17 March 2000.

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Introduction: The time-stratigraphic formulation of major events in lunar history has a long and continuing usefulness [1]. On the other hand, a descriptive formulation, based on the geological character of major lunar features [2] but consistent with the time-stratigraphic system, may enable broader multidisciplinary discussions of lunar and planetary evolution. The following is an updated general outline of such a perspective [3], the "Apollo Model 2000:"

- Stage 1: Beginning (Pre-Nectarian) – 4.57 b.y. before present
- Stage 2: Magma Ocean (Pre-Nectarian) – 4.57 - 4.2(?) b.y.
- Stage 3: Cratered Highlands (Pre-Nectarian) – 4.4(?) - 4.2(?) b.y.
- Stage 4: Large Basins –(Pre-Nectarian - Lower Imbrium) – 4.3(?) - 3.8 b.y.
  - Stage 4A: Old Large Basins and Crustal Strengthening (Pre- Nectarian) – 4.3(?) - 3.92 b.y.
  - Stage 4B: Young Large Basins (Nectarian - Lower Imbrium) – 3.92 - 3.80 b.y.
- Stage 5: Basaltic Maria (Upper Imbrium, primarily) – 4.3(?) - 1.0(?)
- Stage 6: Mature Surface (Upper Imbrium, Copernican and Eratosthenian) – 3.80 b.y. - Present.

This descriptive approach and details supporting it bring to light significant discrepancies within currently popular hypotheses relative to the origin of the Moon and its thermal evolution. These hypotheses are: (1) the giant Earth impact hypothesis for the origin of the Moon based largely on the Earth-Moon system's high angular momentum, and (2) a thermal evolution hypothesis based on an assumption that the present heterogeneous crustal distribution of radioactivity and related components reflects a primordial distribution. More likely explanations for lunar origin and thermal evolution, respectively, appear to be (1) post-accretion capture and (2) large impact initiated concentration of radioactivity and related components initially contained in a globally homogeneous zone at the base of the crust.

Lunar Origin: Evidence of a significantly undifferentiated lower lunar mantle [10,11,12,13] and constrained initial conditions for models of an Earth-impact origin for the Moon [4,5,6,7] suggest a lunar origin by capture [3,8] of an independently evolved small planet. Capture appears to better explain the geochemical and geophysical details related to the lower mantle of the Moon and to the present distribution of elements and their isotopes [3,9,10,11].

Geochemically, the source of the volatile components of the Apollo 17 orange glass and the Apollo 15 green glass apparently would require source regions below the degassed and differentiated magma ocean [3] in a relatively undifferentiated primordial lower mantle. In contrast to the differentiated upper mantle and crust of the Moon, the orange glass contains primitive (non-radiogenic) lead [10], chondritic tungsten [11], higher alumina [12], and distinctive ratios of Au/Ir and Zr/Y [13]. Constraints on the total lunar FeO additionally suggest that the Moon could contain only a small component of the Earth's mantle [14].

Geophysically, seismic data interpretations for the lower lunar mantle [12,15] define an upper mantle-lower mantle boundary at about 500 km and suggest increased aluminum below this depth as would be expected for largely undifferentiated chondritic material. Recent indications that an intrinsic lunar magnetic field [16,17,18] was not active before 3.92 b.y., the probable age of the Nectarius event [1], suggests delayed migration of core-forming materials which in turn suggests an initially cool lower mantle.

Finally, the mean model age for the now extinct lunar ^{182}Hf (half-life = 9 m.y.) and its daughter ^{182}W is 53 ± 4 m.y., essentially the same as the isochron age for the orange soil [11]. This allows only a very narrow window for a Mars-sized asteroid and the very early Earth to impact to form the Moon [3,19].

The above constraints increasingly support previous hypotheses [20,2] of lunar origin through capture of a previously accreted small planet, roughly co-orbital with the early Earth. The Moon's evolution after accretion would have occurred largely independently of the Earth's. Its capture probably took place relatively soon after accretion due to the many opportunities presented by the co-orbiting environment [20]; however, modern modeling techniques should be applied to further constrain the probability and time of capture and the resulting range of possible angular momentum.

Lunar Thermal Evolution: A significant number of workers are proposing a heterogeneous initial distribution of Th and other heat-producing isotopes in the Moon, along with associated components, with a major concentration in the vicinity of the 3200 km diameter Procellarum Basin [21,22,23,24,25,26]. It remains difficult to imagine how the differentiation of the lunar magma ocean could produce the postulated heterogeneity. On the other hand, such an initial distribution may not be necessary to explain the existing radioisotope distribution [27] if we consider the potential effects of an extremely large Procellarum impact event.

To evaluate the effects of a Procellarum event, the change from non-mascon basin formation to mascon basin formation during the Large Basin Stage of lunar evolution must be understood. This change in isostatic response indicates that the residual magma ocean liquid had not solidified at the beginning of this stage. Solidification and the resulting strengthening of the crust, however, took place during the Stage in response to deep crustal and upper mantle disruptions resulting from early large impacts. Once the residual liquid had moved into the crust and solidified, later basins would not have fully adjusted isostaticly and could become the loci of mascons [28]. Workers generally have concluded that this global residual magma ocean, enriched in radioisotopes, is equivalent to urKREEP [29], the precursor of the upper crustal KREEP component detected in Apollo samples [30] and by remote sensing [31] in the vicinity of the Imbrium Basin and its surrounding ejecta.

A Procellarum event specifically is suggested by lunar mapping [1], by unusually thin crust beneath the basin [32,33], by unusually thick crust west of the basin [32], and by an annulus of increased Fe+Ti along portions of the basin's postulated rim [27]. The above consideration of crustal strengthening during the Large Basin Stage and the later impact degradation of basin features indicate that the event would have taken place at about 4.3 b.y. during the Cratered Highland Stage and before solidification of the magma ocean's residual liquid (urKREEP). The response of the global shell of residual magma ocean liquid at the top of the mantle to the instantaneous release of lithostatic pressure would be to migrate toward the Procellarum region. Regional surface eruptions of residual liquid, contaminated with crustal debris, may well have occurred. Cryptomaria [34,35] exposures should be evaluated with this possibility of ~ 4.3 b.y. old KREEP eruptions in mind. The coincidental Imbrium event in the thin crust near the center of the Procellarum Basin excavated and possibly re-melted concentrations of KREEP, producing the major distribution patterns seen today.

Upper mantle regions surrounding Procellarum would be depleted in residual liquid in response to this event. This depletion, along with the absence of an Imbrium-scale coincidental event, probably explains the lack of a strong KREEP signal in the vicinity of the far side South Pole-Aitken Basin. The presence of a small, positive KREEP signature in South Pole-Aitken, however, supports a globally concentric distribution of urKREEP liquid at the end of magma ocean differentiation. Additionally, the absence of significant mare basalt in the South Pole-Aitken region [27] may be partially related to the depletion of upper mantle KREEP along with the removal of upper crustal, cratered highland's debris [3]. Without significant insulating crust and KREEP-related heat sources, a reverse wave of mantle melting to produce mare basalts would not occur.

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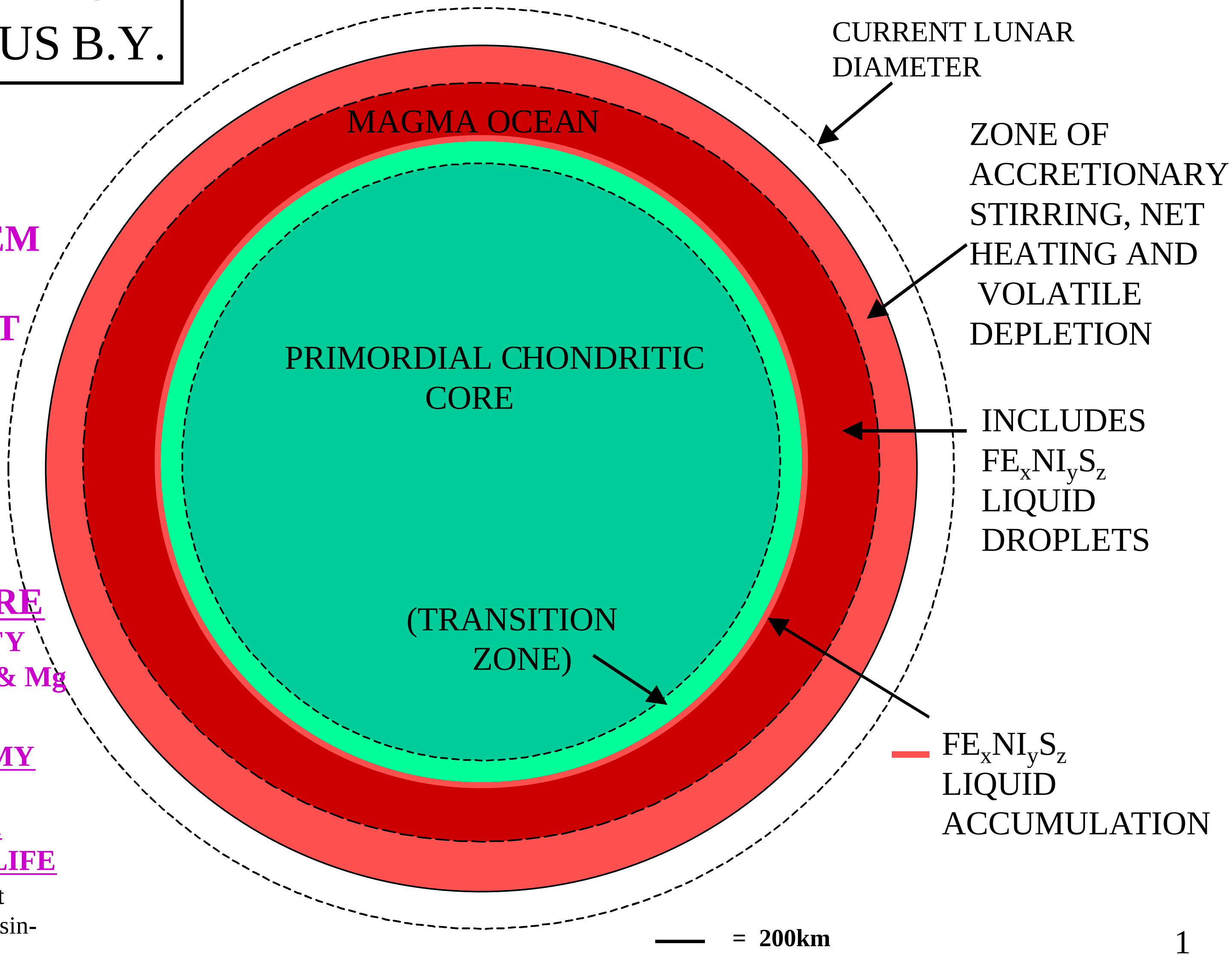
APOLLO MODEL OF LUNAR EVOLUTION

BEGINNING
~4.567 PLUS B.Y.

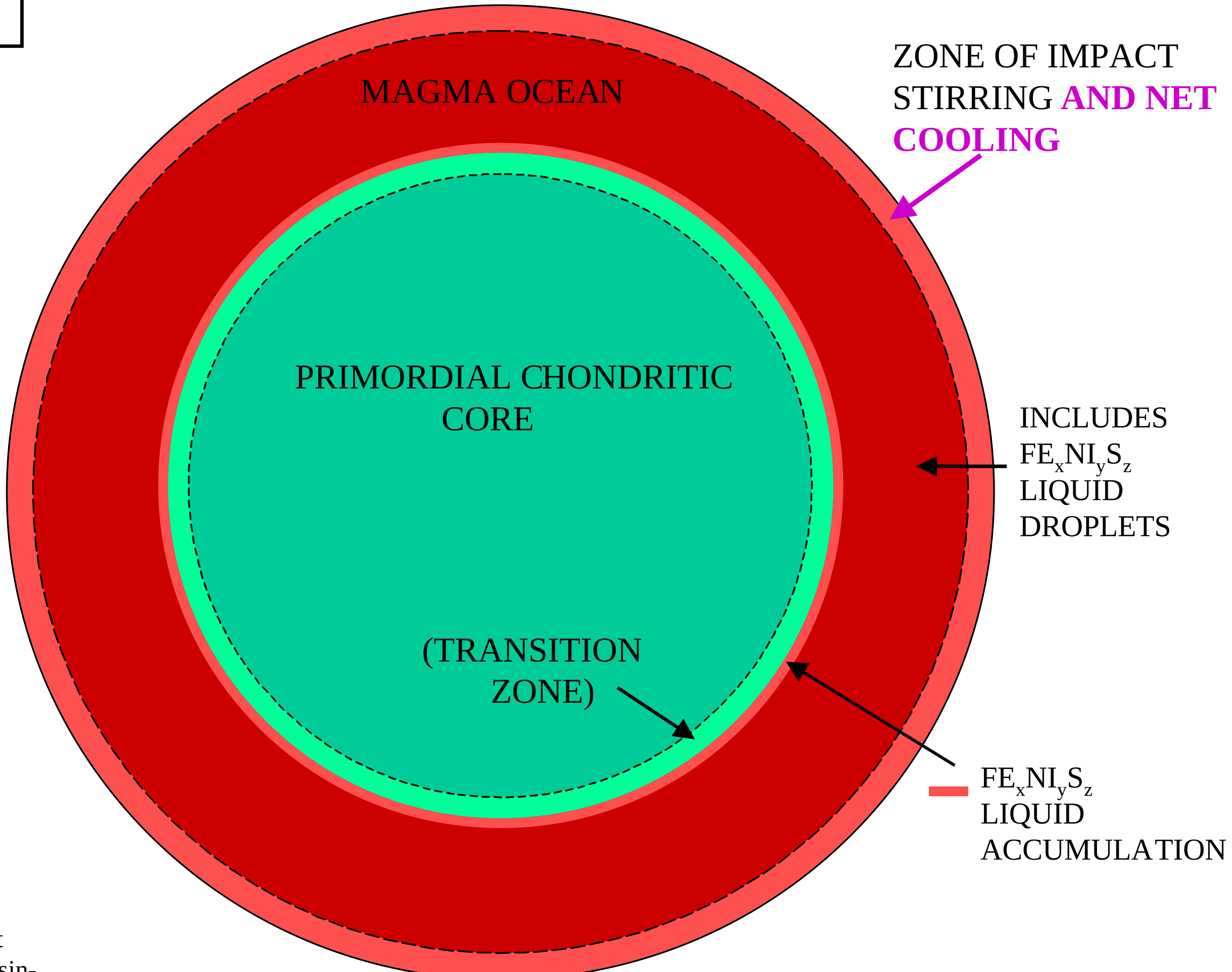


NOTE:
ASSUMES A SOLAR SYSTEM ORIGIN INDEPENDENT OF EARTH.

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

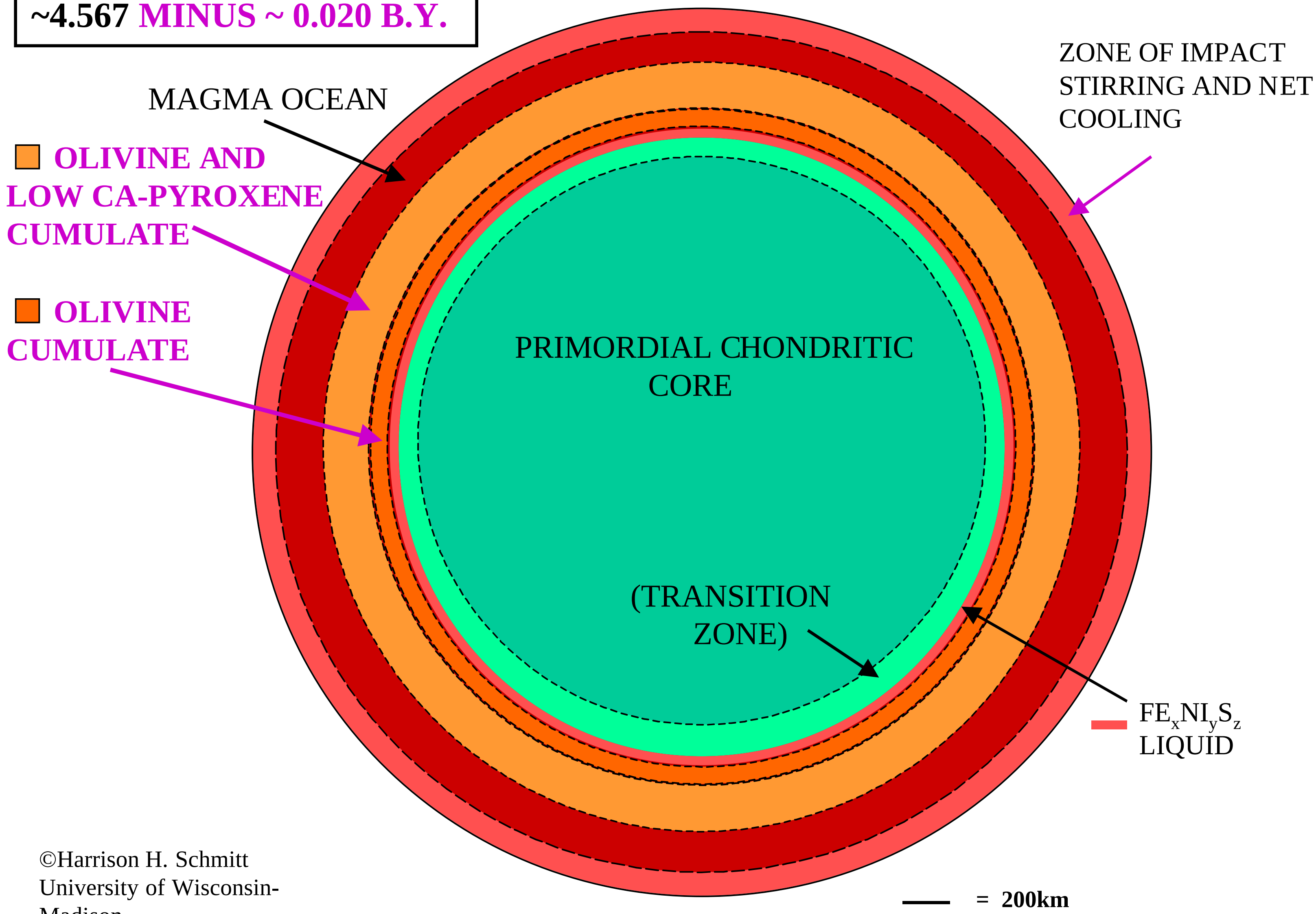
APOLLO MODEL OF LUNAR EVOLUTION

BEGINNING
~4.567 B.Y.



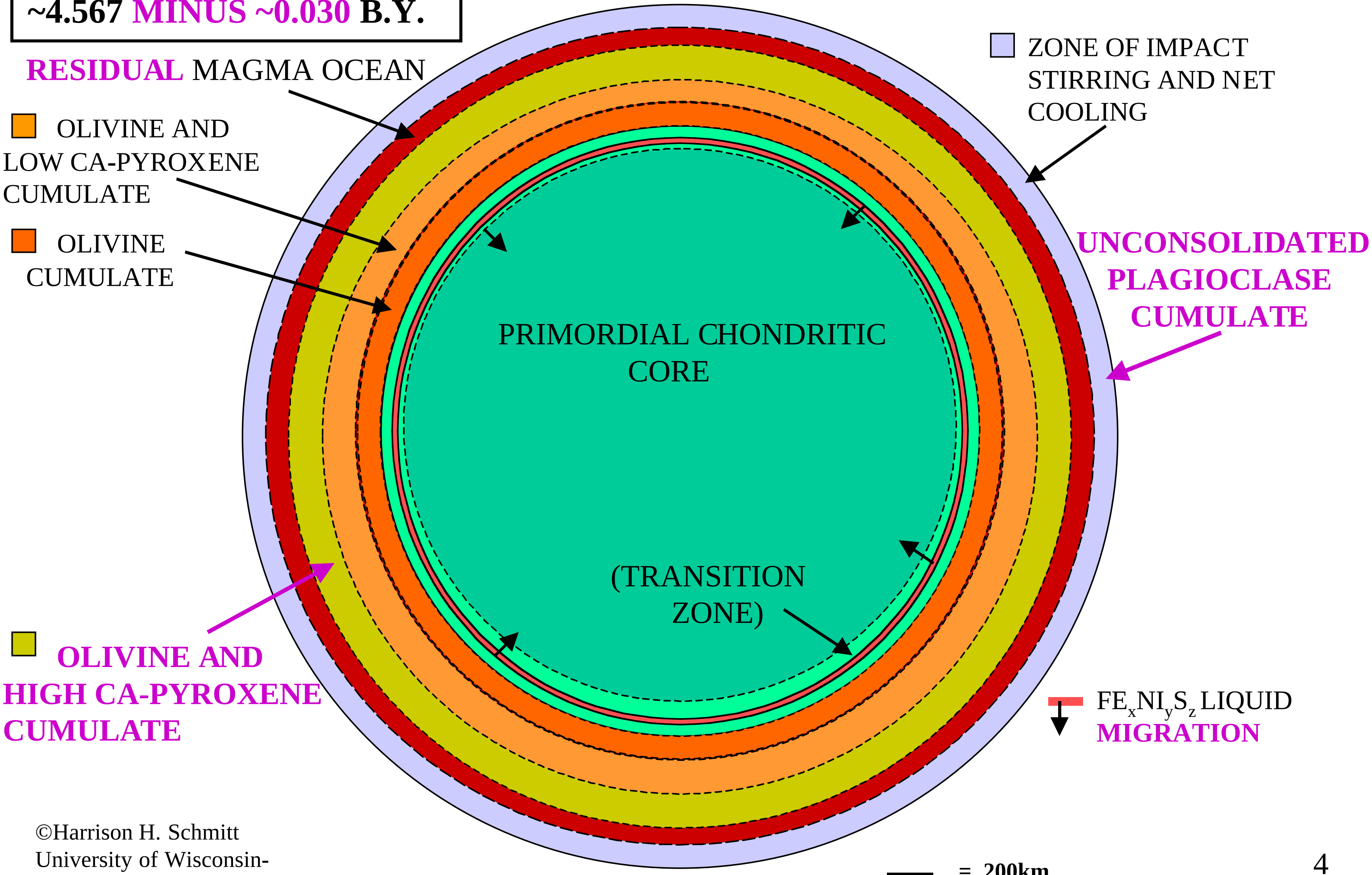
APOLLO MODEL OF LUNAR EVOLUTION

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



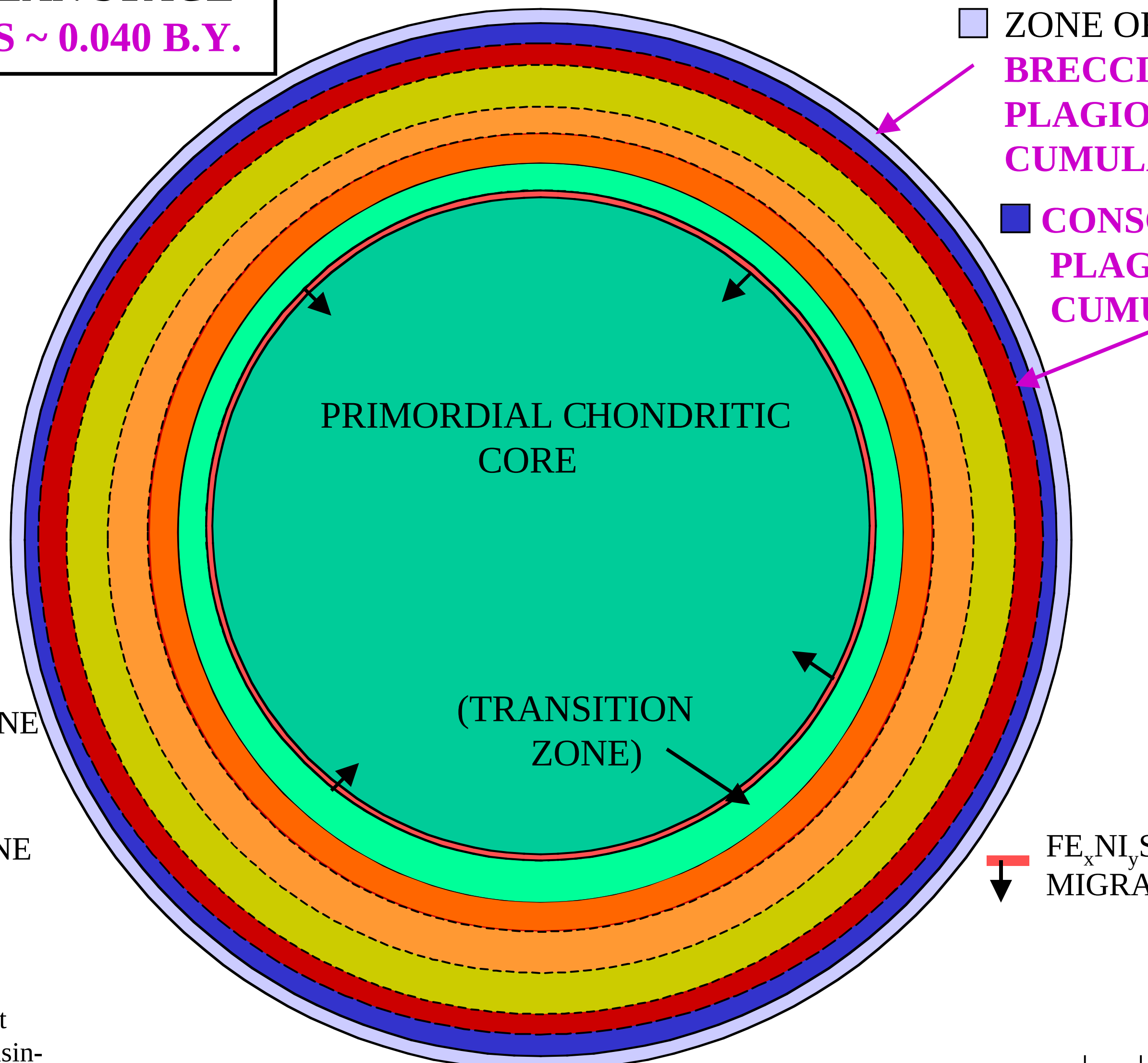
APOLLO MODEL OF LUNAR EVOLUTION

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

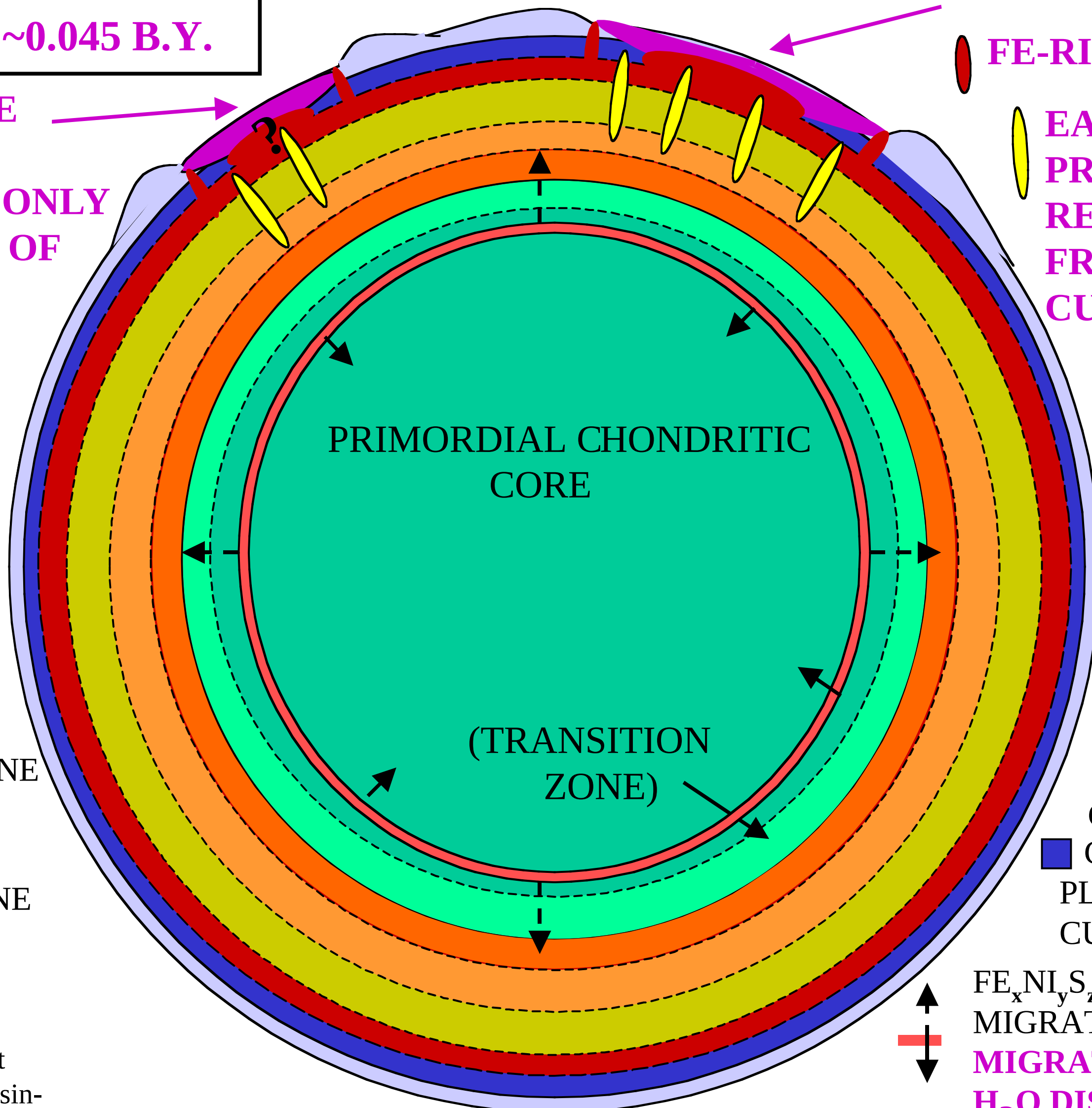
MAGMA OCEAN STAGE
4.567 MINUS ~0.045 B.Y.

PROSPECTUM EVENT (?)

FE-RICH INTRUSIONS

EXISTENCE OF EARLY MG-SUITE ONLY EVIDENCE OF EVENT(S)

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



FE-RICH RESIDUAL MAGMA OCEAN

OLIVINE AND HIGH CA-PYROXENE CUMULATE

OLIVINE AND LOW CA-PYROXENE CUMULATE

OLIVINE CUMULATE

ZONE OF IMPACT BRECCIATION OF PLAGIOCLASE CUMULATE

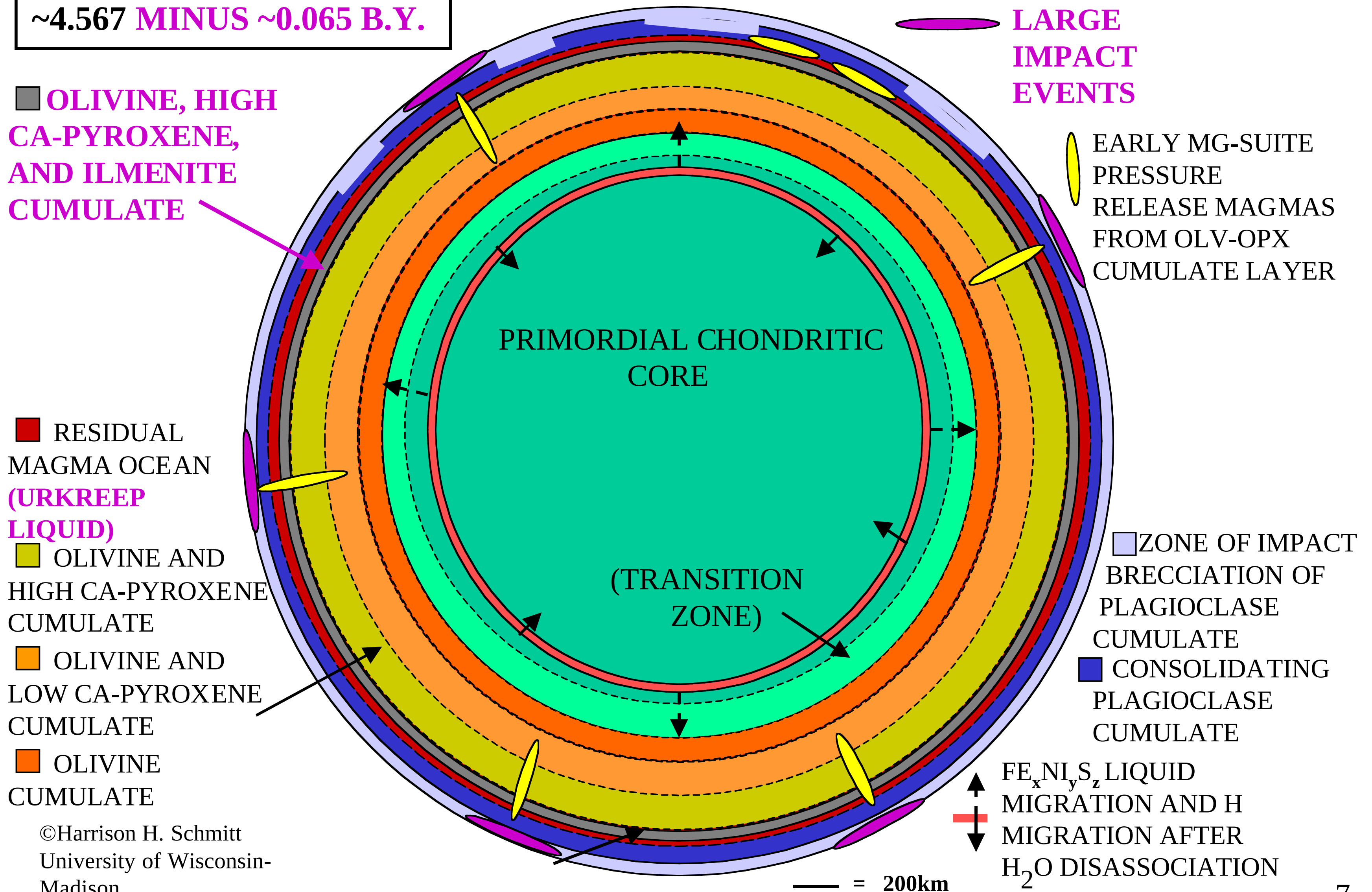
CONSOLIDATING PLAGIOCLASE CUMULATE

$Fe_xNi_yS_z$ LIQUID MIGRATION AND H MIGRATION AFTER H_2O DISASSOCIATION

— = 200km

APOLLO MODEL OF LUNAR EVOLUTION

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



APOLLO MODEL OF LUNAR EVOLUTION

CRATERED HIGHLANDS STAGE
~4.5 - 4.3 B.Y.

MG-SUITE INTRUSIVES

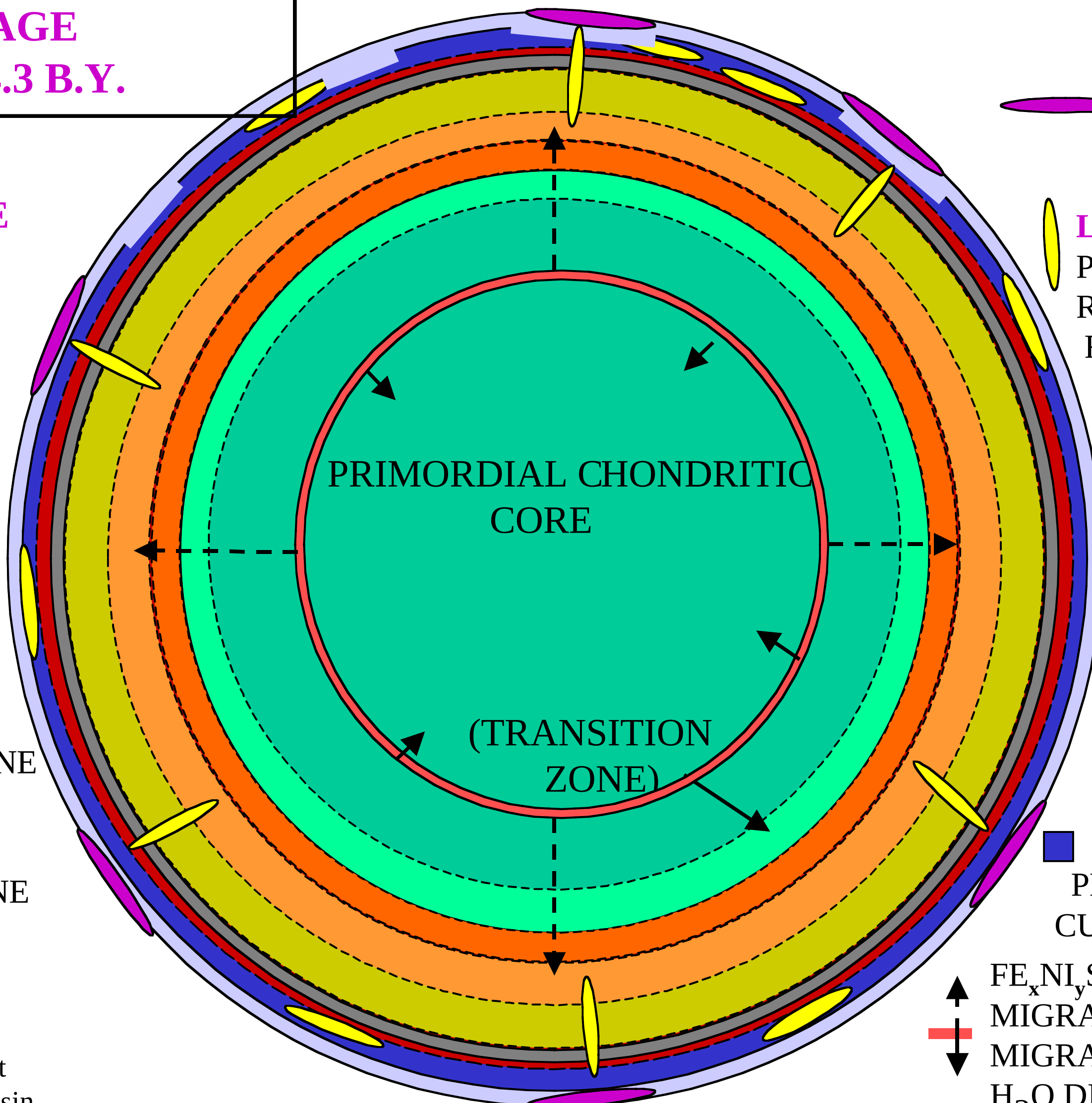
OLIVINE, HIGH CA-PYROXENE, AND ILMENITE CUMULATE

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 H_2O DISASSOCIATION

= **200km**

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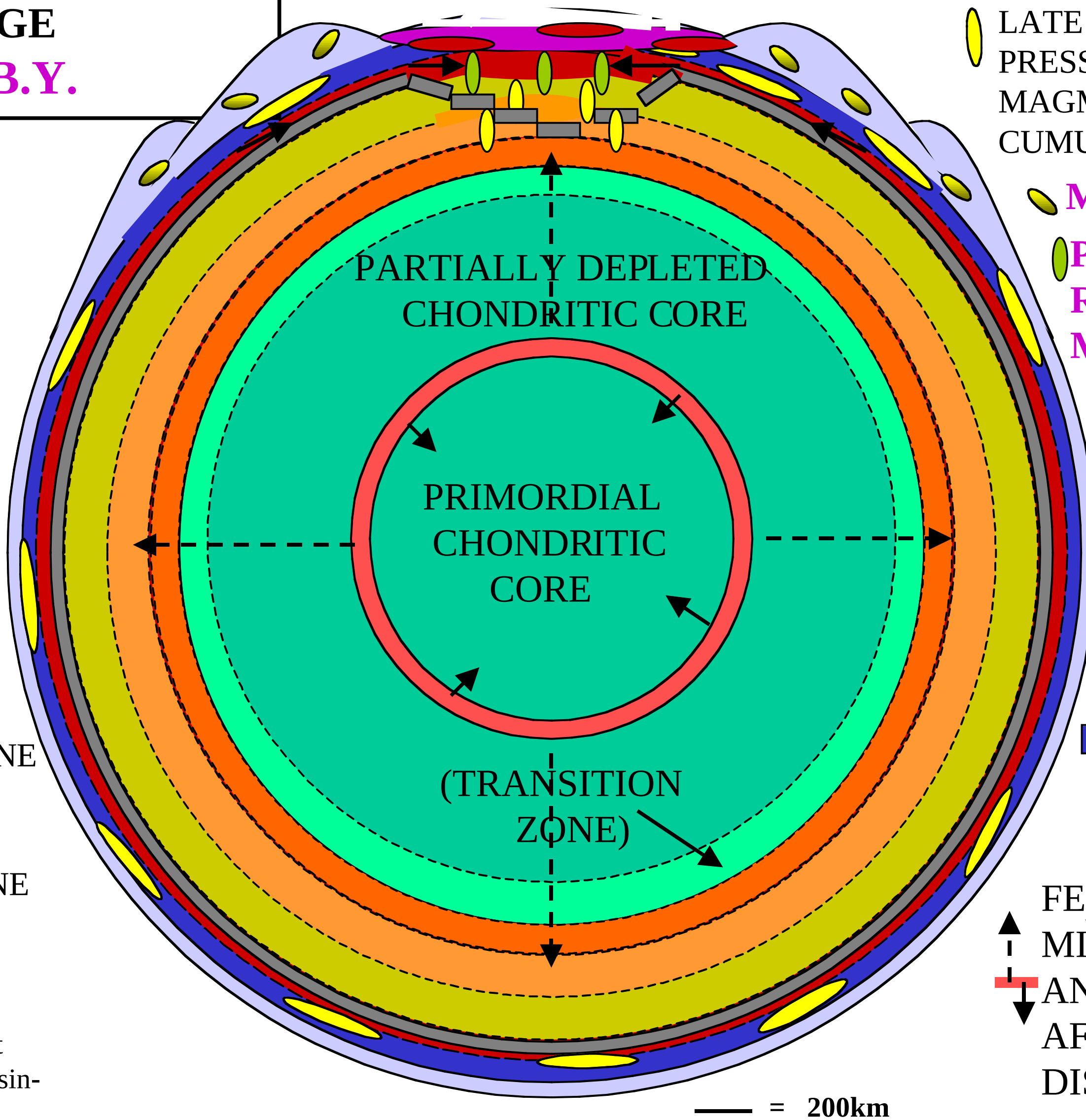
APOLLO MODEL OF LUNAR EVOLUTION

CRATERED HIGHLANDS STAGE

~4.3 B.Y.

PROCELLARUM: INITIAL BASIN



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

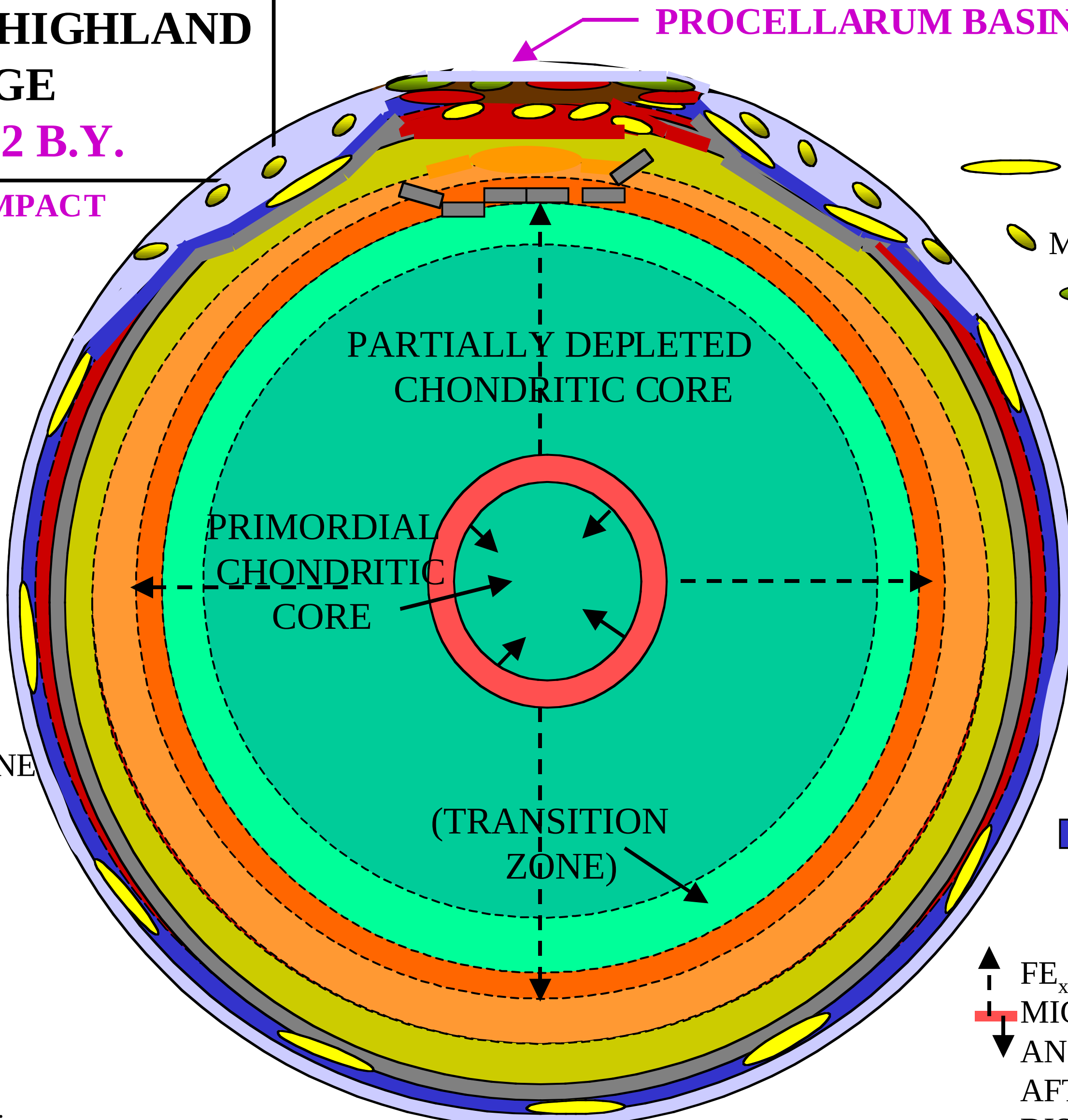
$FE_xNI_yS_z$ LIQUID MIGRATION

AND H MIGRATION AFTER H_2O DISASSOCIATION

APOLLO MODEL OF LUNAR EVOLUTION

CRATERED HIGHLAND STAGE

PRE ~4.2 B.Y.



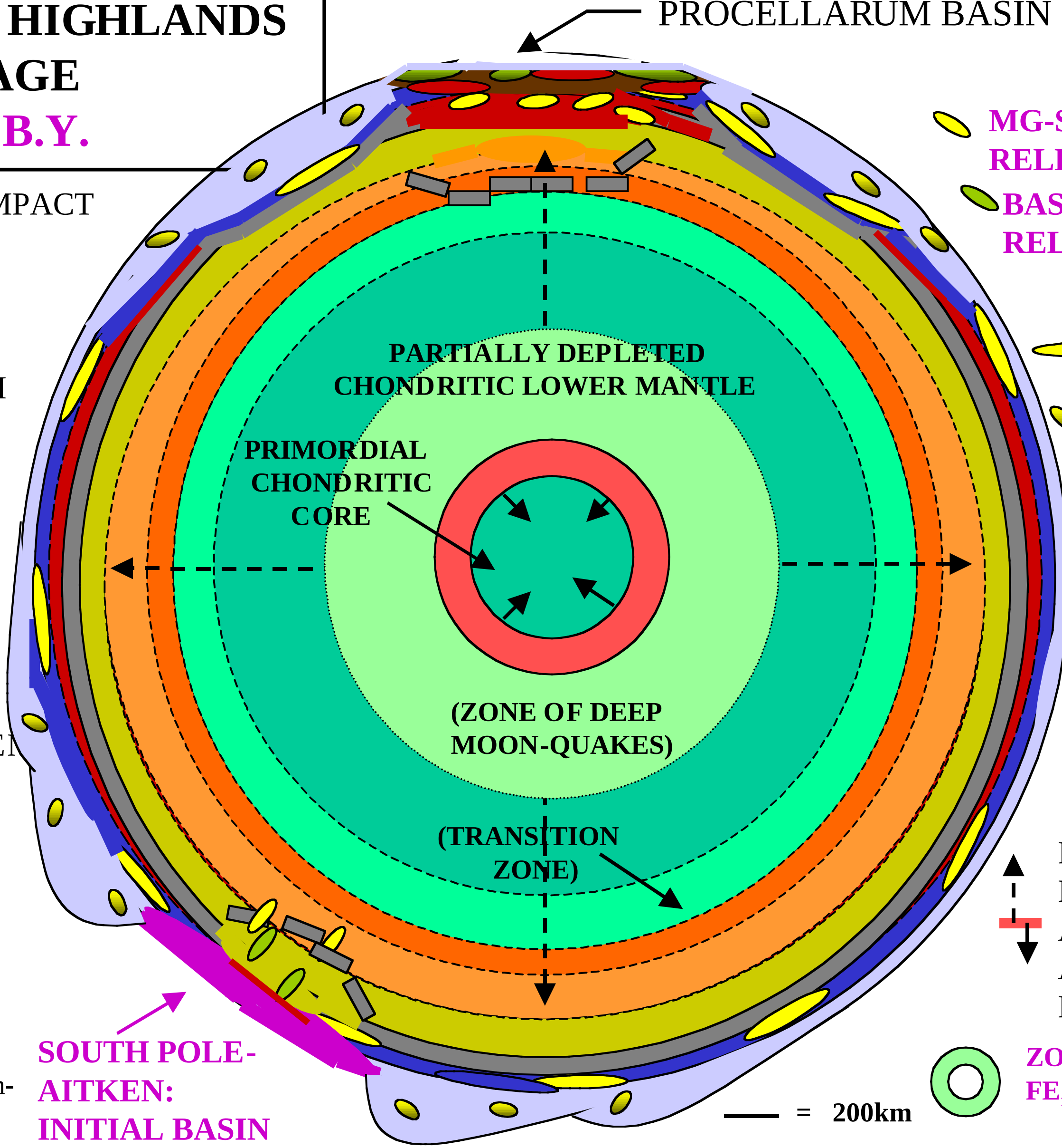
- SOLIDIFIED IMPACT MELT SHEET
- ILMENITE CUMULATE MASSES
- OLIVINE, HIGH CA-PYROXENE, AND ILMENITE CUMULATE
- RESIDUAL URKREEP LIQUID+KREEP BASALTS
- OLIVINE AND HIGH CA-PYROXENE CUMULATE
- OLIVINE AND LOW CA-PYROXENE CUMULATE
- OLIVINE CUMULATE
- MG-SUITE INTRUSIVES
- MG-SUITE DEBRIS
- EARLY KREEPY BASALT EXTRUSIVES
- INSULATING CRATERED HIGHLANDS AND EJECTA
- CONSOLIDATED PLAGIOCLASE CUMULATE
- $FE_xNI_yS_z$ LIQUID MIGRATION AND H MIGRATION AFTER H_2O DISASSOCIATION

— = **200km**

APOLLO MODEL OF LUNAR EVOLUTION

CRATERED HIGHLANDS STAGE

~4.2 B.Y.

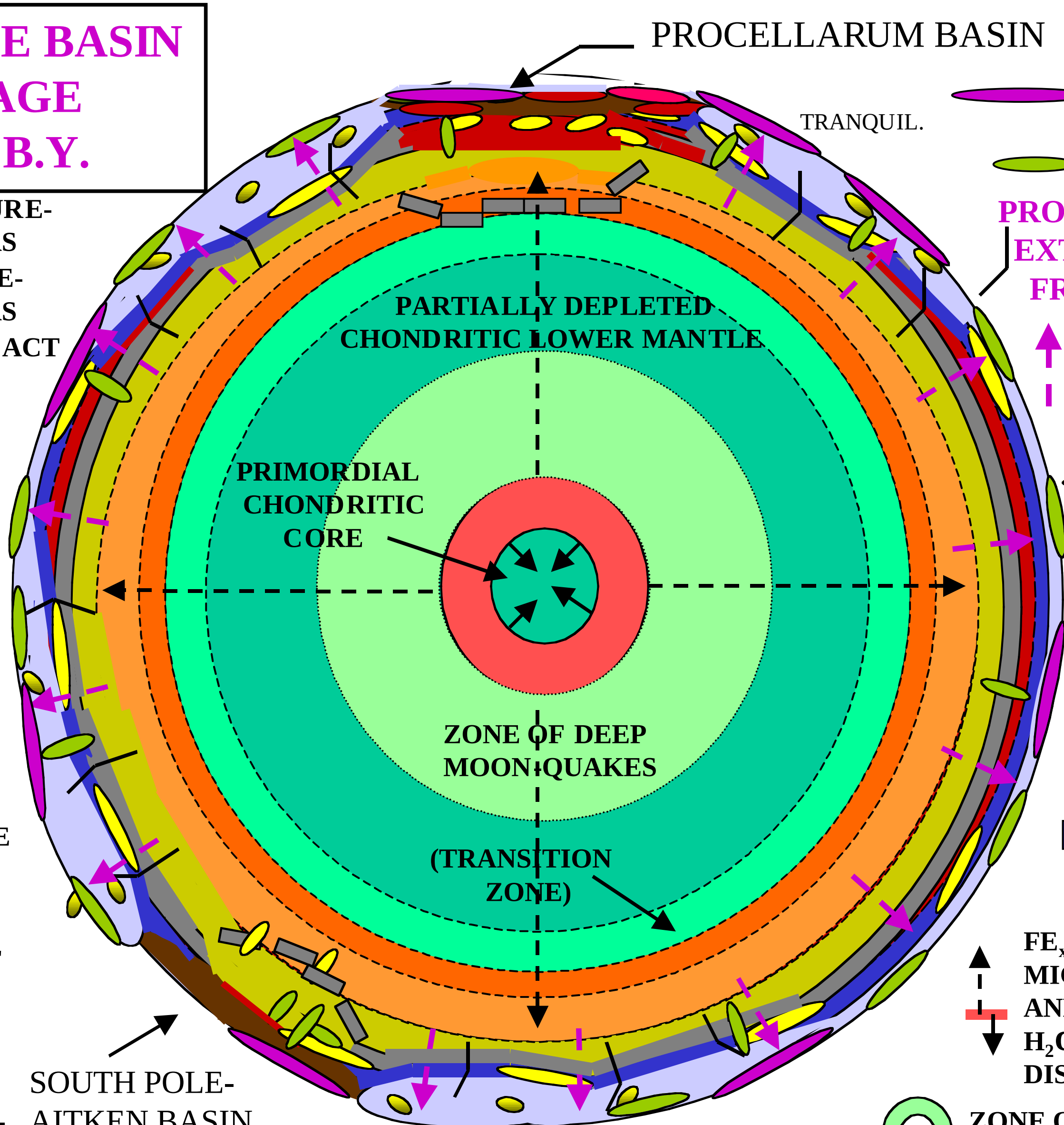


- SOLIDIFIED IMPACT MELT SHEET
- ILMENITE CUMULATE MASSES
- OLIVINE, HIGH CA-PYROXENE, AND ILMENITE CUMULATE
- RESIDUAL URKREEP LIQUID+KREEP BASALTS
- OLIVINE AND HIGH CA-PYROXENE CUMULATE
- OLIVINE AND LOW CA-PYROXENE CUMULATE
- OLIVINE CUMULATE
- MG-SUITE PRESSURE-RELEASE MAGMAS
- BASALT PRESSURE-RELEASE 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_2O DISASSOCIATION
- ZONE OF ISOLATED $Fe_xNi_yS_z$ LIQUID MASSES

— = 200km

APOLLO MODEL OF LUNAR EVOLUTION

OLD LARGE BASIN SUBSTAGE
~4.2-3.9 B.Y.



- MG-SUITE PRESSURE-RELEASE MAGMAS
- BASALT PRESSURE-RELEASE MAGMAS
- 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
- OLD LARGE BASINS
- CRYPTOMARIA
- PROGRADE THERMAL EXTENSION FRACTURES
- H_2 DRIVEN LIGHT PLAINS DEBRIS ERUPTIONS
- 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 AFTER H_2O DISASSOCIATION
- ZONE OF ISOLATED $FE_xNI_yS_z$ LIQUID MASSES

— = 200km

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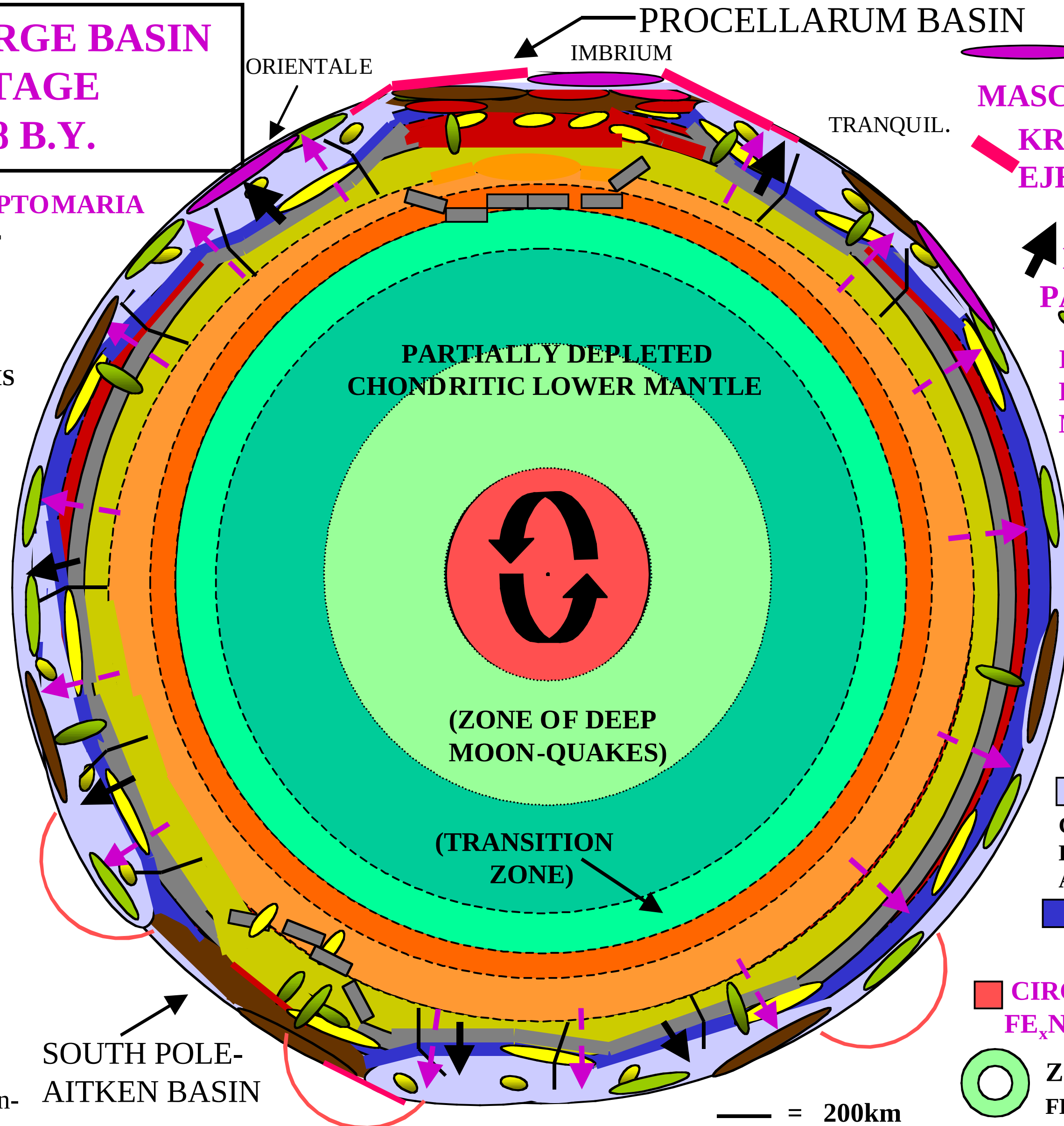
APOLLO MODEL OF LUNAR EVOLUTION

YOUNG LARGE BASIN SUBSTAGE
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

REMANANT 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

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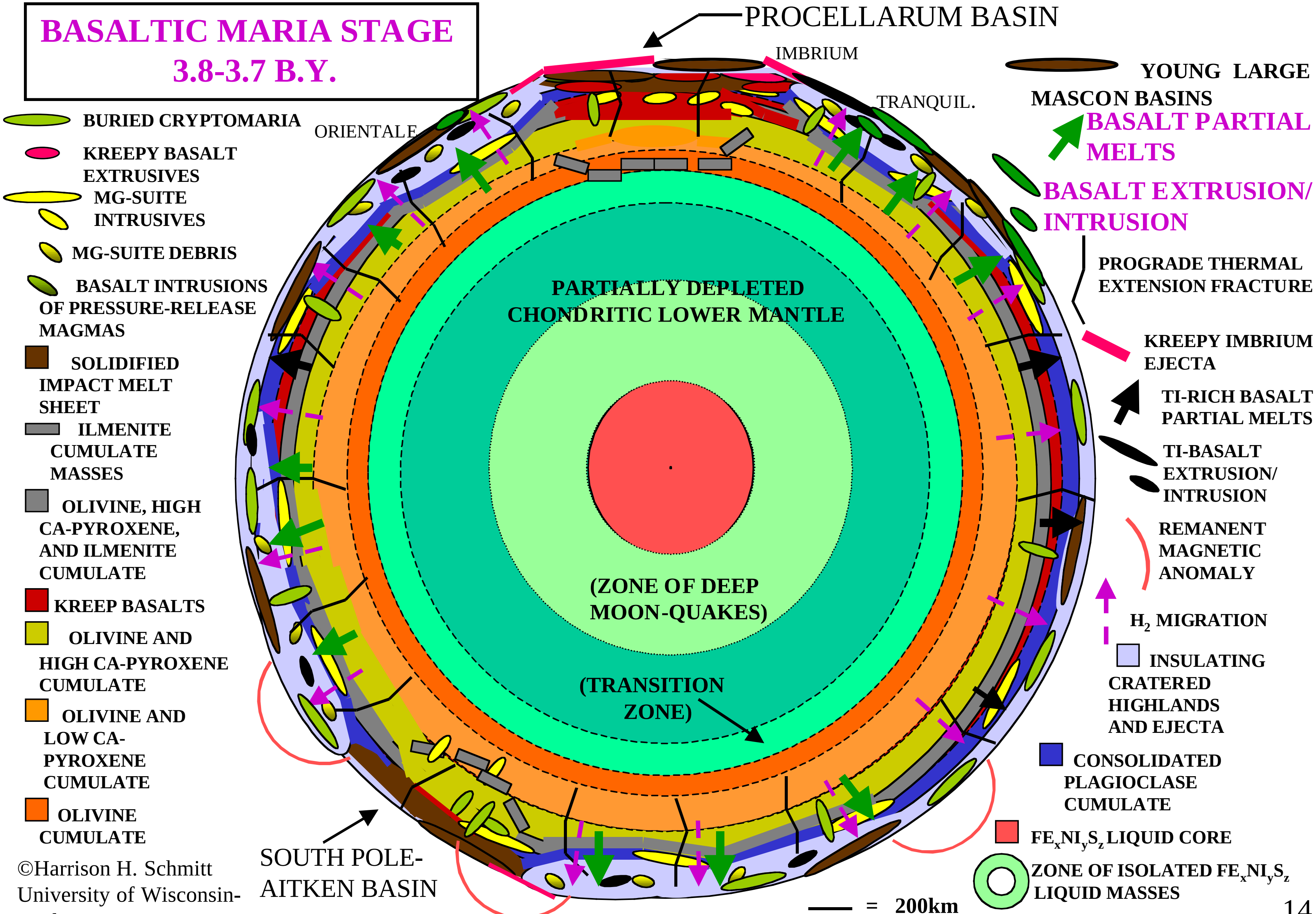
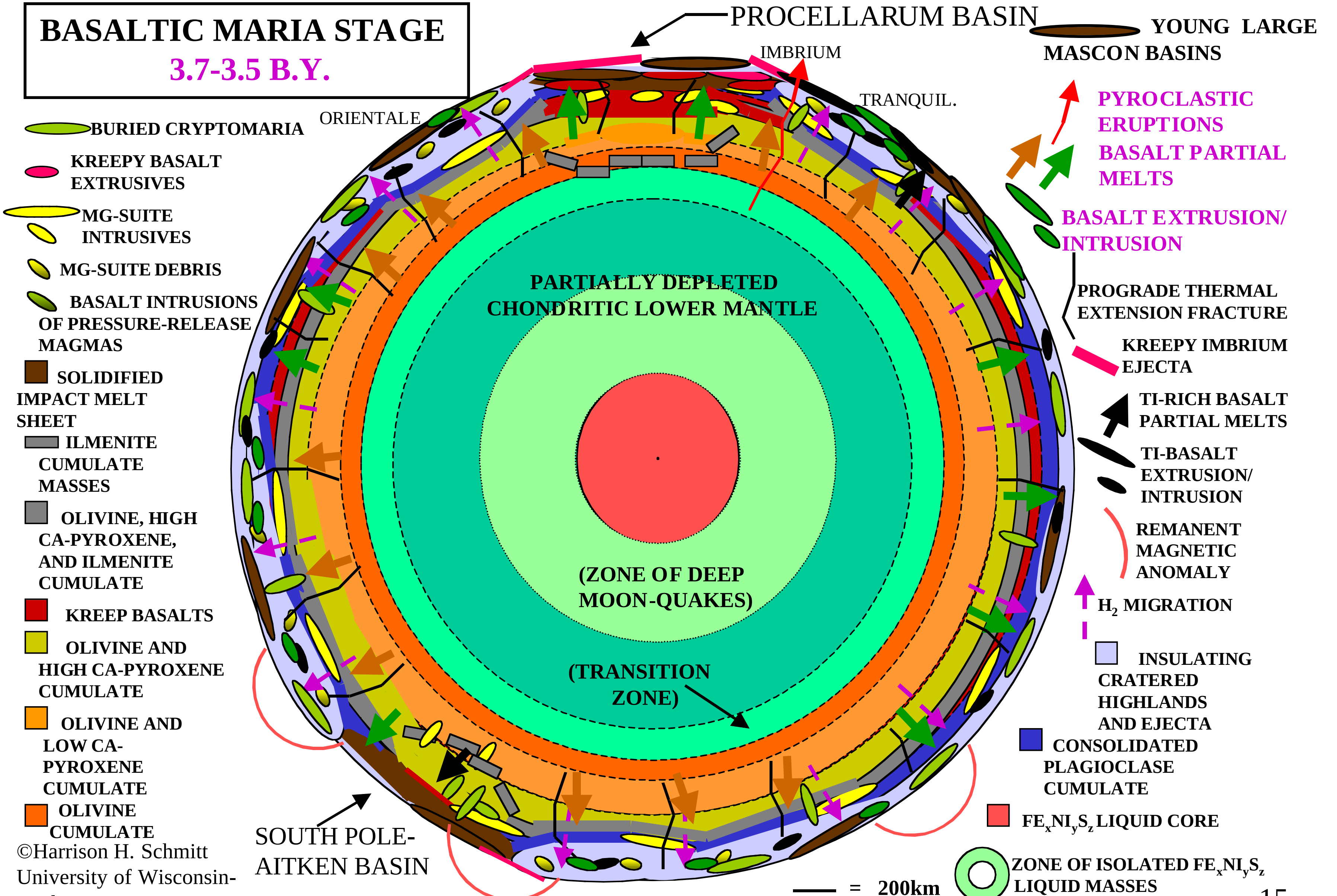
APOLLO MODEL OF LUNAR EVOLUTION

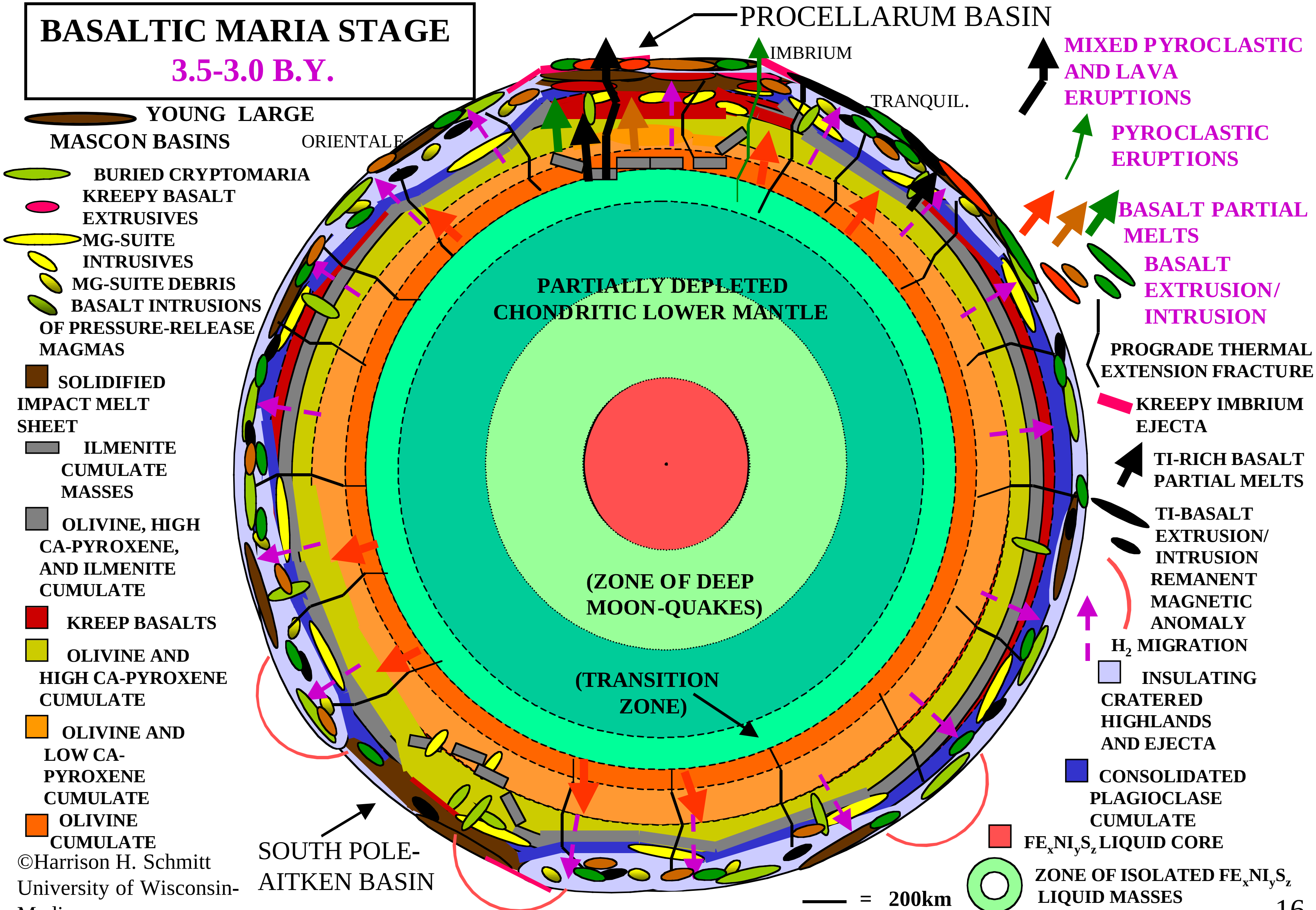
BASALTIC MARIA STAGE
3.8-3.7 B.Y.



APOLLO MODEL OF LUNAR EVOLUTION



APOLLO MODEL OF LUNAR EVOLUTION



APOLLO MODEL OF LUNAR EVOLUTION

BASALTIC MARIA STAGE

3.0-2.0 B.Y.