EVOLUTION OF MARS

LECTURE 17 NEEP 533

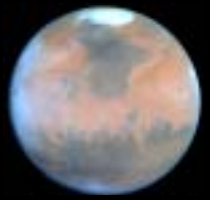
HARRISON H. SCHMITT

NASA HST IMAGE

DEFINITIONS

- **IGNEOUS**
- **NWA**
- **ANDESITE / ANDESITIC**

- **RELATED TO NATURALLY MELTED ROCK (MAGMA)**
- **NORTH WEST AFRICA**
- **LAVA COMPOSITION BETWEEN BASALT AND GRANITE**

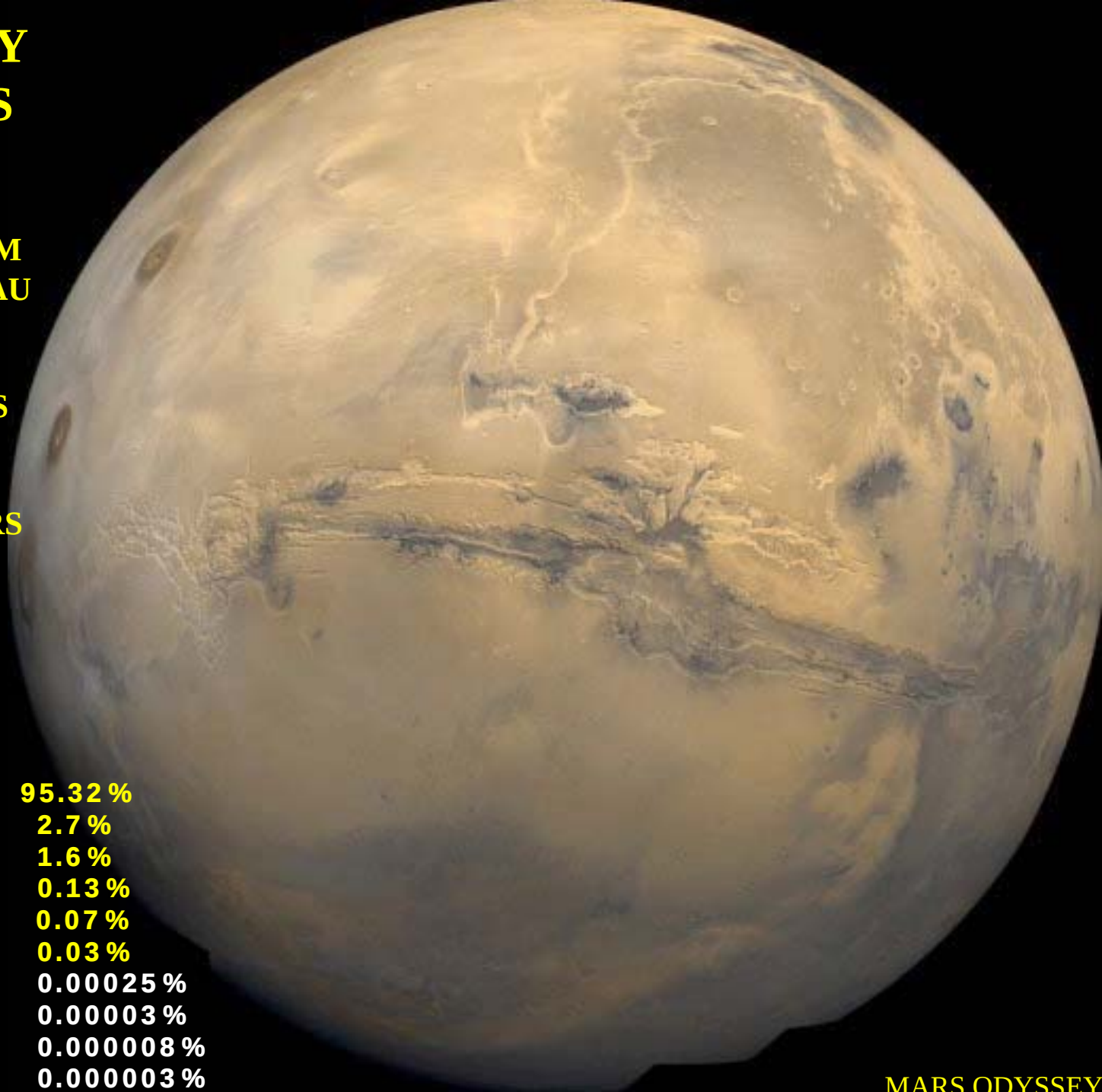


MARS/EARTH/MOON COMPARISONS

- **RADIUS: 3490 VS 6378-6275 VS 1735 KM**
  - **1200KM RADIUS CHONDRITIC PROTOCORE SMALLER RELATIVE TO TOTAL MASS THAN MOON**
- **GRAVITY: 3/8 VS 1 VS 1/6**
  - **MAGMA OCEAN MORE VIGOROUSLY CONVECTING THAN MOON'S**
- **DENSITY: 3.94 VS 5.5 VS 3.34 GM/CM^3**
- **SUN DISTANCE: 1.52 VS 1.0 VS ~1 AU (SEMIMAJOR AXIS)**
  - **NEBULA REGION HAD MORE WATER, SULFUR, SODIUM AND POTASSIUM THAN EARTH AND MOON**
  - **57% LESS INSOLATION TODAY (DISAGREEMENT ON LUMINOSITY OF EARLY SUN)**
- **OBLIQUITY: 0-60 DEGREES VS VERY SMALL VARIATIONS**
  - **EXTREME REGIONAL CLIMATE VARIATION**
- **OTHER: NO LARGE MOON TO STABILIZE MARS' DYNAMICS**

MARS ODYSSEY VIEW OF MARS

MEAN DENSITY: 3.94
MEAN RADIUS: 3397 KM
MEAN DISTANCE: 1.5 AU
“DAY”: 24.6 HOURS
“YEAR”: 687 DAYS
GRAVITY: 3/8 EARTH’S
TEMP: 20 TO -140 C.
MEAN TEMP: -68 C
ATM. PRESS: 1-9 MBARS



ATM. COMPOSTION

Carbon Dioxide (C02)	95.32%
Nitrogen (N2)	2.7%
Argon (Ar)	1.6%
Oxygen (O2)	0.13%
Carbon Monoxide (CO)	0.07%
Water (H2O)	0.03%
Neon (Ne)	0.00025%
Krypton (Kr)	0.00003%
Xenon (Xe)	0.000008%
Ozone (O3)	0.000003%

NASA GALILEO/MARS GLOBAL SURVEYOR

SNC METEORITES FROM MARS

METEORITE	XLL'TN AGE (B.Y.)	PETROLOGY (DESCRIPTION)
Shergotty	0.165-0.205 0.350	Shock-metamorphosed basalt with pyroxene and plagioclase
Zagami	0.116-0.230	Shock-metamorphosed basalt
Los Angeles	0.165	Differentiated basalt with significant concentrations of "KREEP" like components.
NWA 480		
*Nakhla	1.240-1.370	Pyroxene-olivine cumulate or coarse basaltic lava
*Lafayette	1.330 0.274-0.655 (iddingsite)	Pyroxene-olivine cumulate or coarse basaltic lava
*Gov. Valadares	1.320	Pyroxene-olivine cumulate or coarse basaltic lava
*Chassigny	1.230-1.390	Olivine cumulate
QUE 94201	Not available	Basaltic
DaG476	Olivine-rich	
SaU005	Olivine-rich, porphyritic	
Dhofar 019	Olivine-rich	
NWA 817		

SNC = Shergotty Nakhla Chassigny

Blue = Magma source is mantle depleted in incompatible elements with non-radiogenic Sr and excess 142Nd
Green = Magma source is crust enriched in incompatible elements and radiogenic Sr

SNC METEORITES FROM MARS

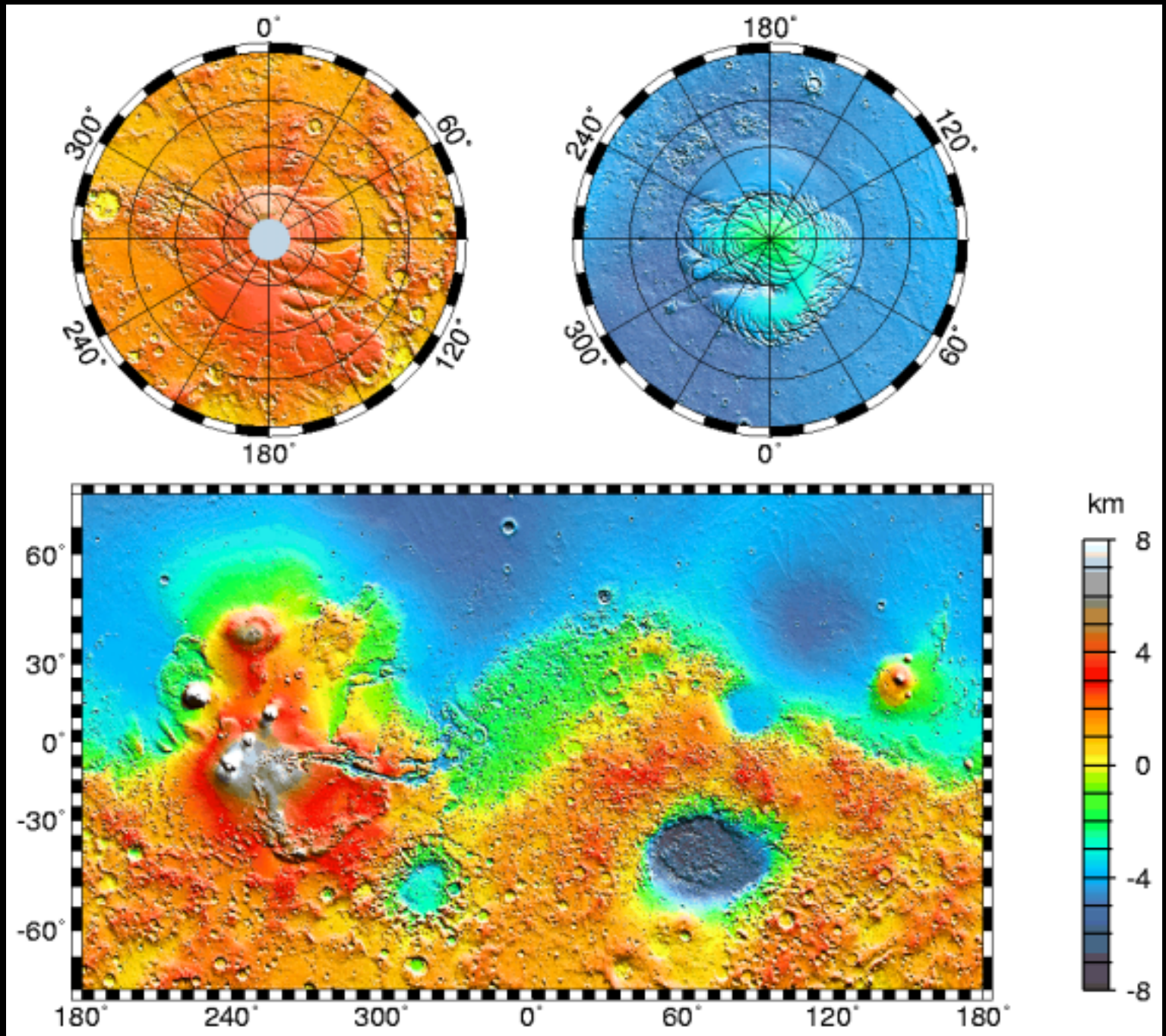
METEORITE	XLL'TN AGE (B.Y.)	PETROLOGY (DESCRIPTION)
ALHA77005	0.187	Shock-metamorphosed lherzolitic (olivine and pyroxene) basalt with cumulate minerals
EETA79001	0.150-0.185	Shock-metamorphosed basalt with light colored xenoliths, melt and cumulate minerals, porphyritic olivine
LEW88516	Not available	lherzolitic basalt
Y793605	Not available	lherzolitic basalt
ALH84001	4.5	Igneous orthopyroxenite cumulate with miner maskelynite, olivine, chromite, pyrite, and apatite

Black = Magma source in primitive, unfractionated mantle with intermediate Sr
Red = Magma source may be associated with magma ocean differentiation.

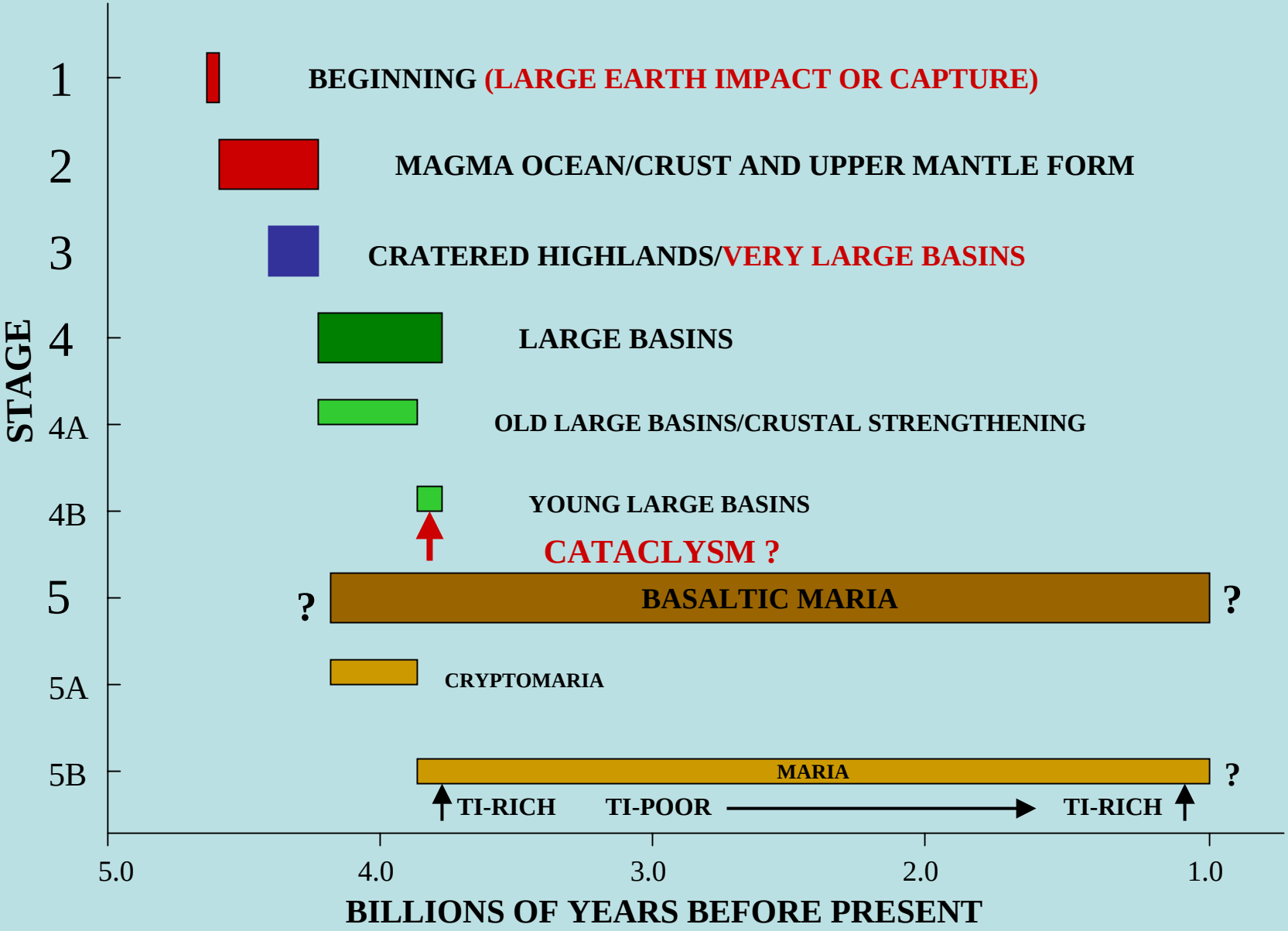
TIME-STRATIGRAPHIC SYSTEM

- **NOACHIAN SYSTEM**
  - **BEGINNING** — **4.567 B.Y.**
  - **MAGMA OCEAN**
  - **CRATERED HIGHLANDS / VERY LARGE BASINS** — **~4.5-4.2**
  - **GLOBAL BASALTIC VOLCANISM** — **4.5-?**
  - **GLOBAL MAGNETIC FIELD (PRE- VERY LARGE BASINS)** — **~4.3?**
  - **LIQUID WATER/DENSE ATMOSPHERE / EROSION**
  - **EARLY NORTHERN OCEAN (?)**
- **HESPERIAN SYSTEM**
  - **LARGE BASINS** — **4.2-3.8 OR 3.8**
  - **REGIONAL VOLCANISM / ANDESITIC MARIA** — **<1.3-0.65?**
  - **DENSE ATMOSPHERE / EROSION**
  - **LATE NORTHERN OCEAN(?)**
- **AMAZONIAN SYSTEM**
  - **MATURE CRUST**
  - **THIN ATMOSPHERE**

MARS TOPOGRAPHY MOLA SCIENCE TEAM

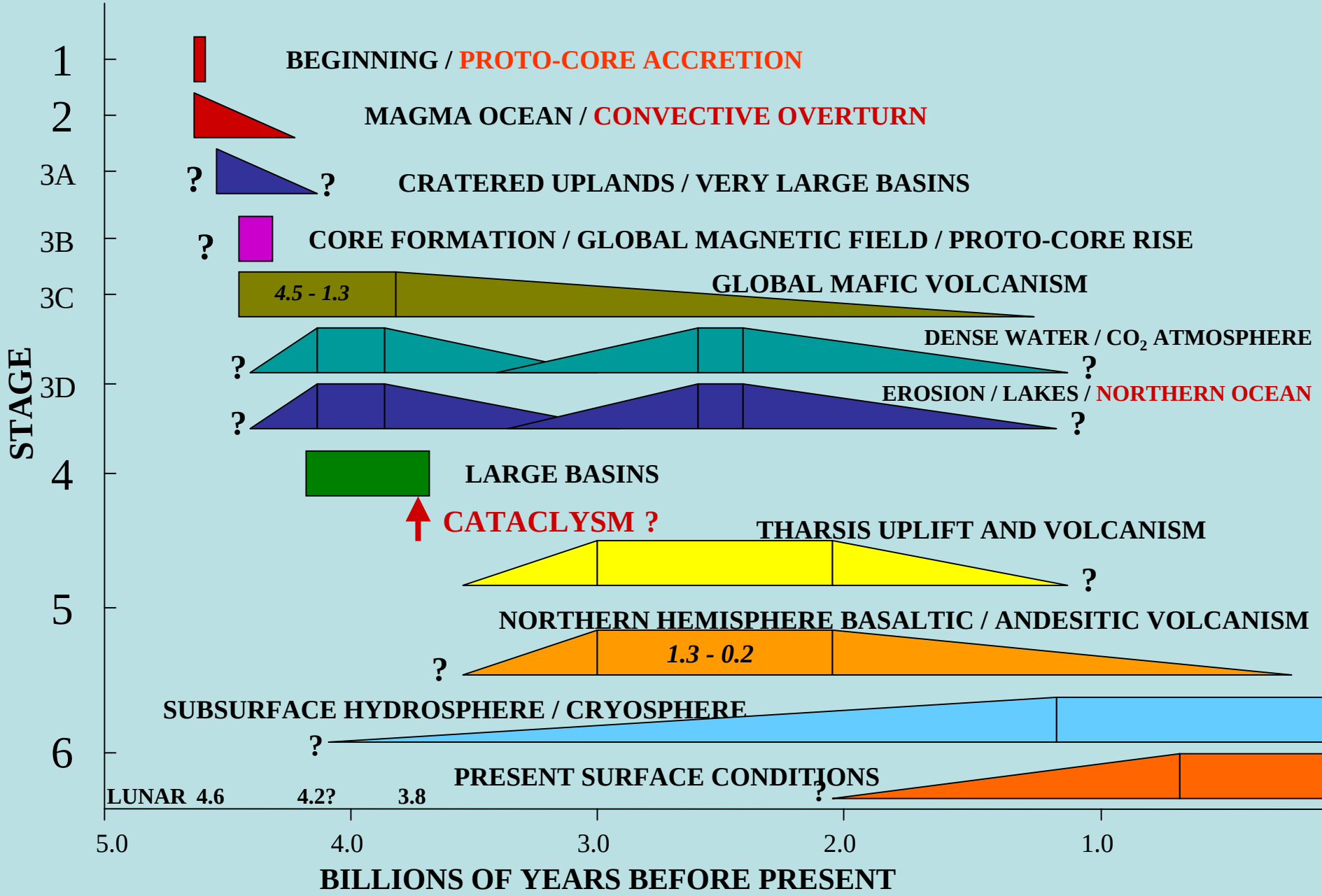


MAJOR STAGES OF LUNAR EVOLUTION



RED = MAJOR UNCERTAINTY

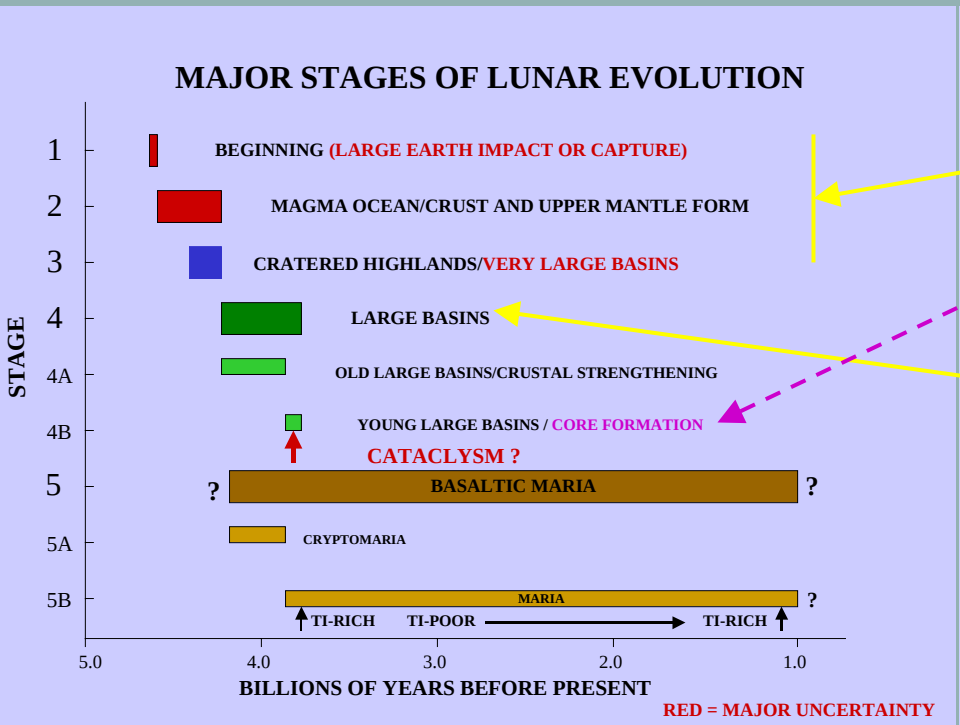
MAJOR STAGES OF MARTIAN EVOLUTION

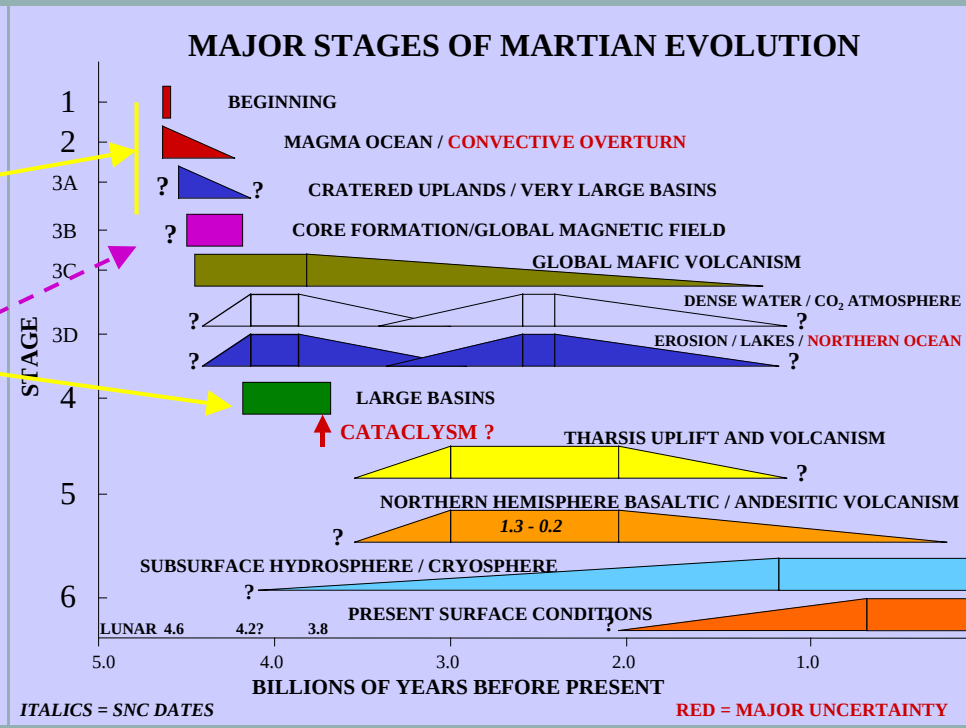


ITALICS = SNC DATES

RED = MAJOR UNCERTAINTY

COMPARISON OF LUNAR AND MARTIAN EVOLUTION





CRATERING HISTORY CORRELATION

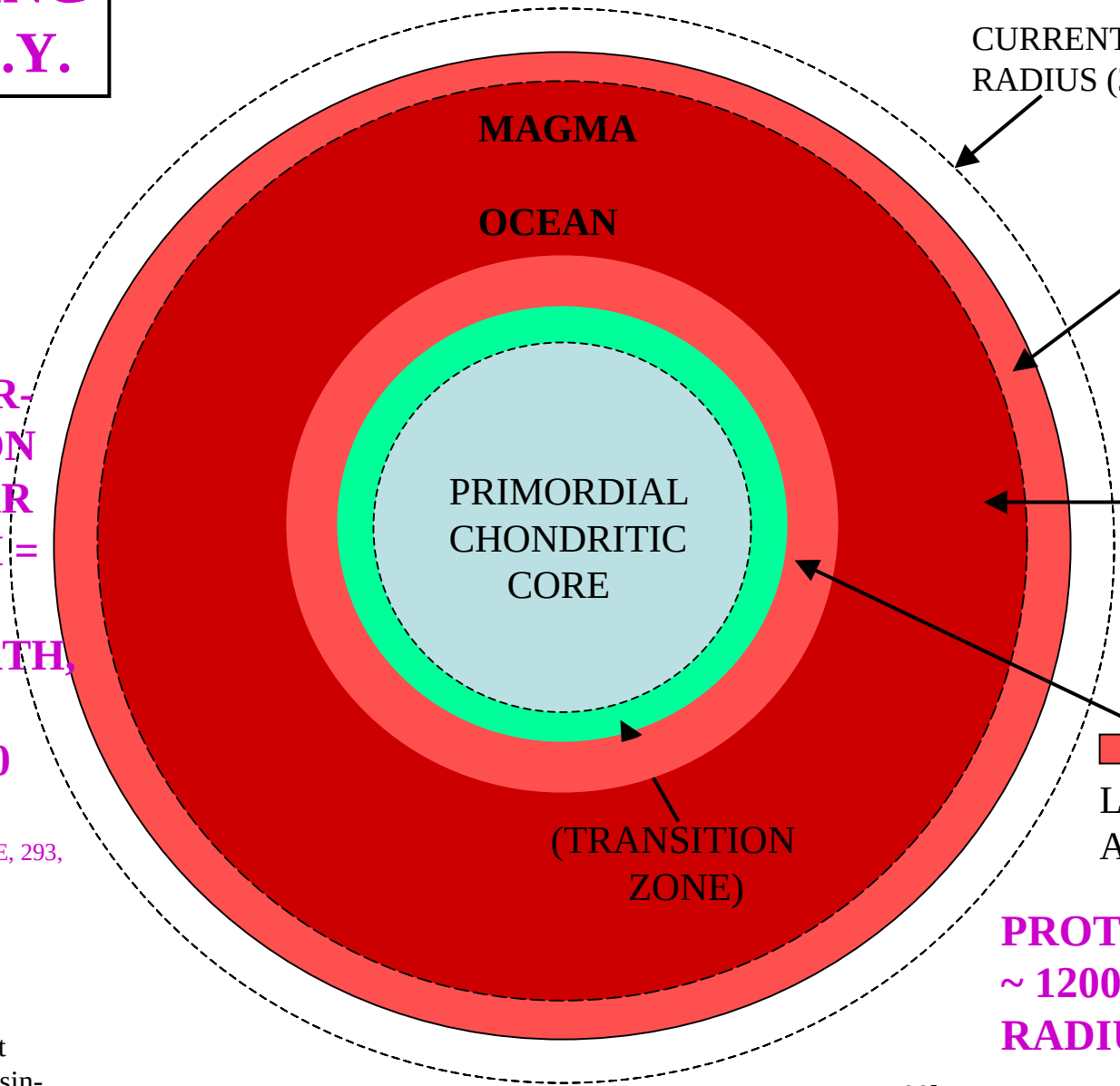
CORE FORMATION DIFFERENCE

APOLLO MODEL OF MARS EVOLUTION

BEGINNING >4.554+ B.Y.

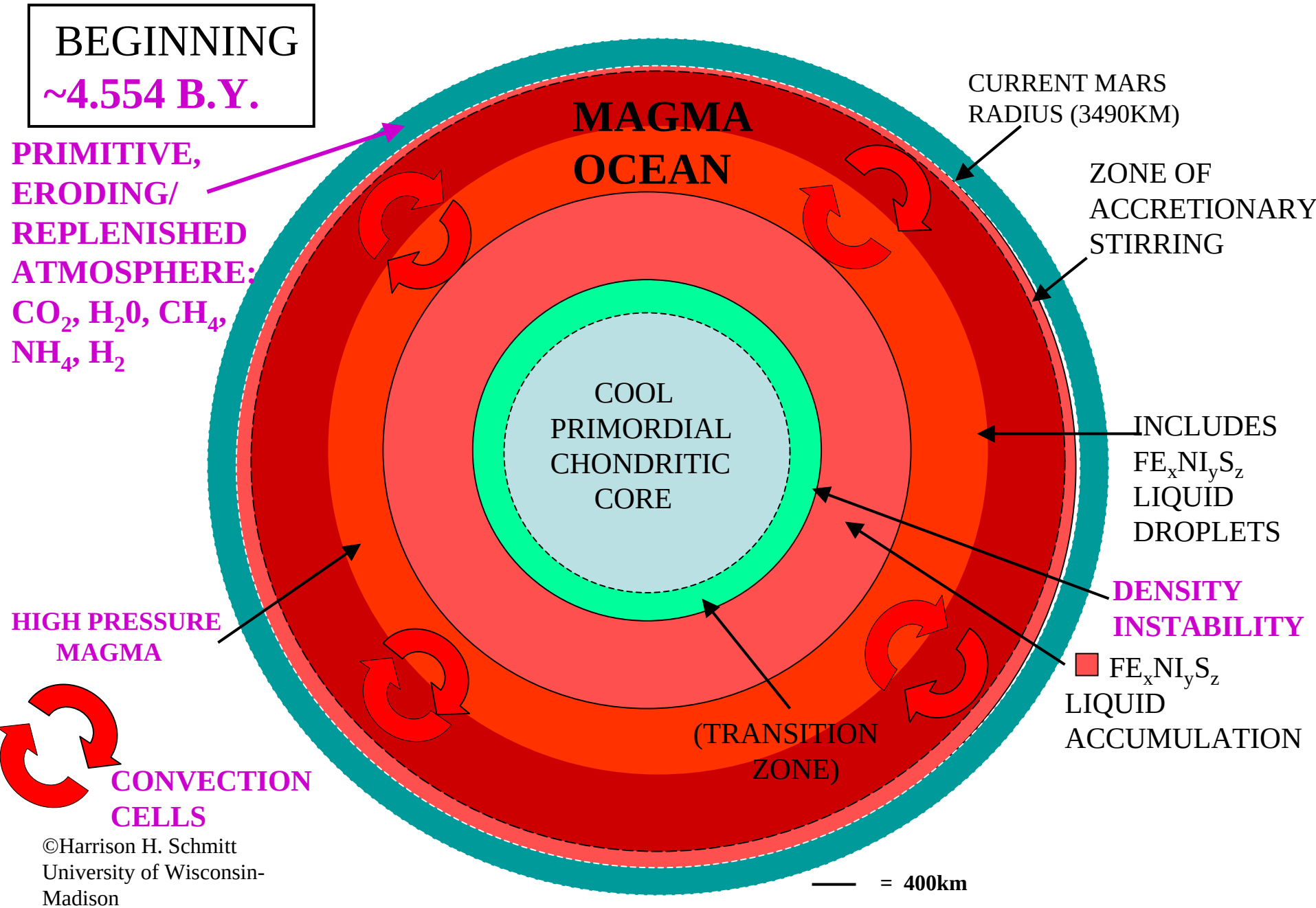
ASSUMES ACCRETION HISTORY SIMILAR TO MOON'S IN MORE WATER-RICH PORTION OF THE SOLAR NEBULA. (D/H = ~300 X 10^{-6} VS. ~150 FOR EARTH, ~20 FOR THE SUN, AND ~310 FOR COMETS

ROBERT, F., 2001, SCIENCE, 293, 1056-1058)



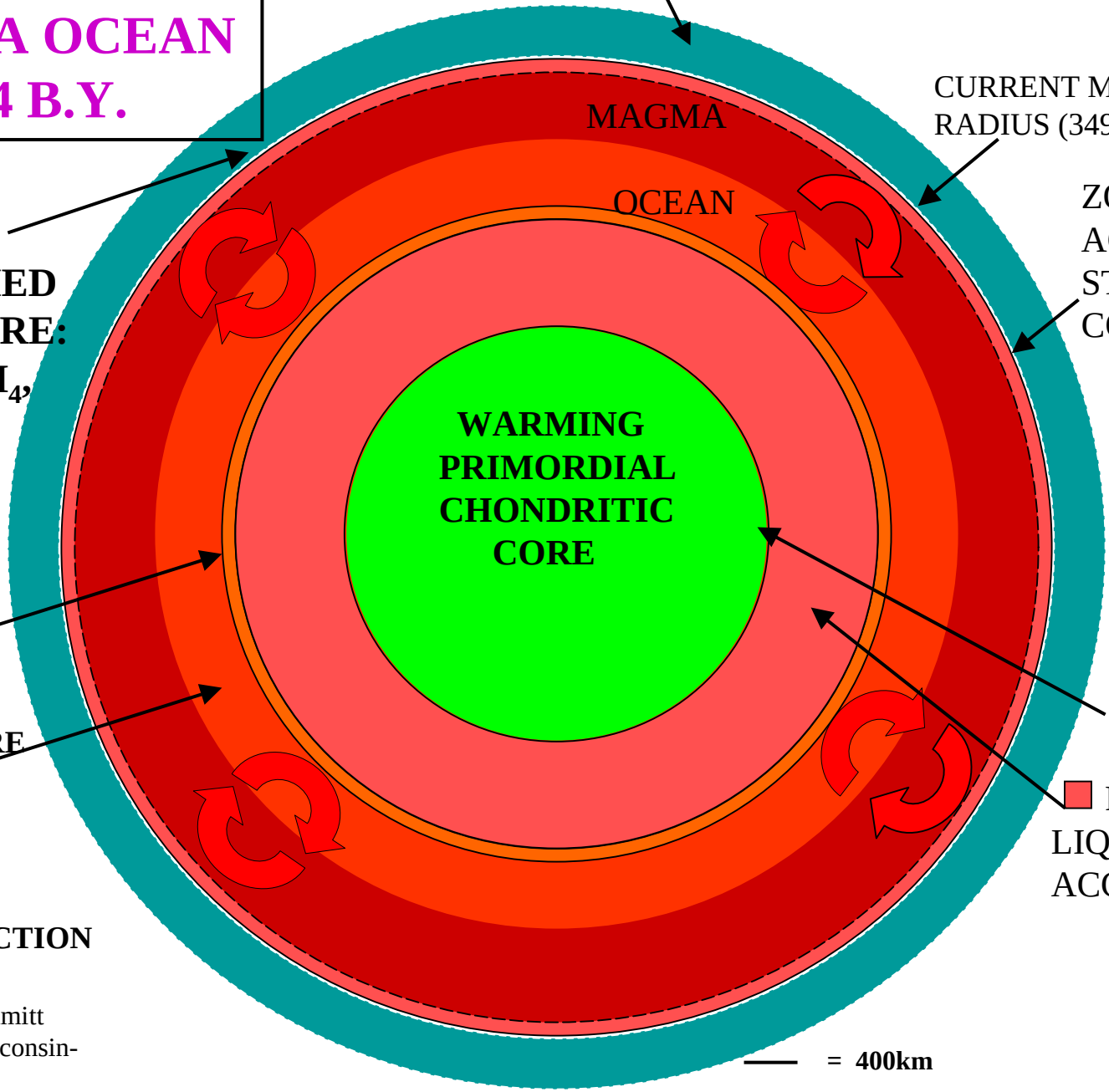
PROTO-CORE IS ~ 1200KM IN RADIUS

APOLLO MODEL OF MARS EVOLUTION



APOLLO MODEL OF MARS EVOLUTION

MAGMA OCEAN <4.554 B.Y.

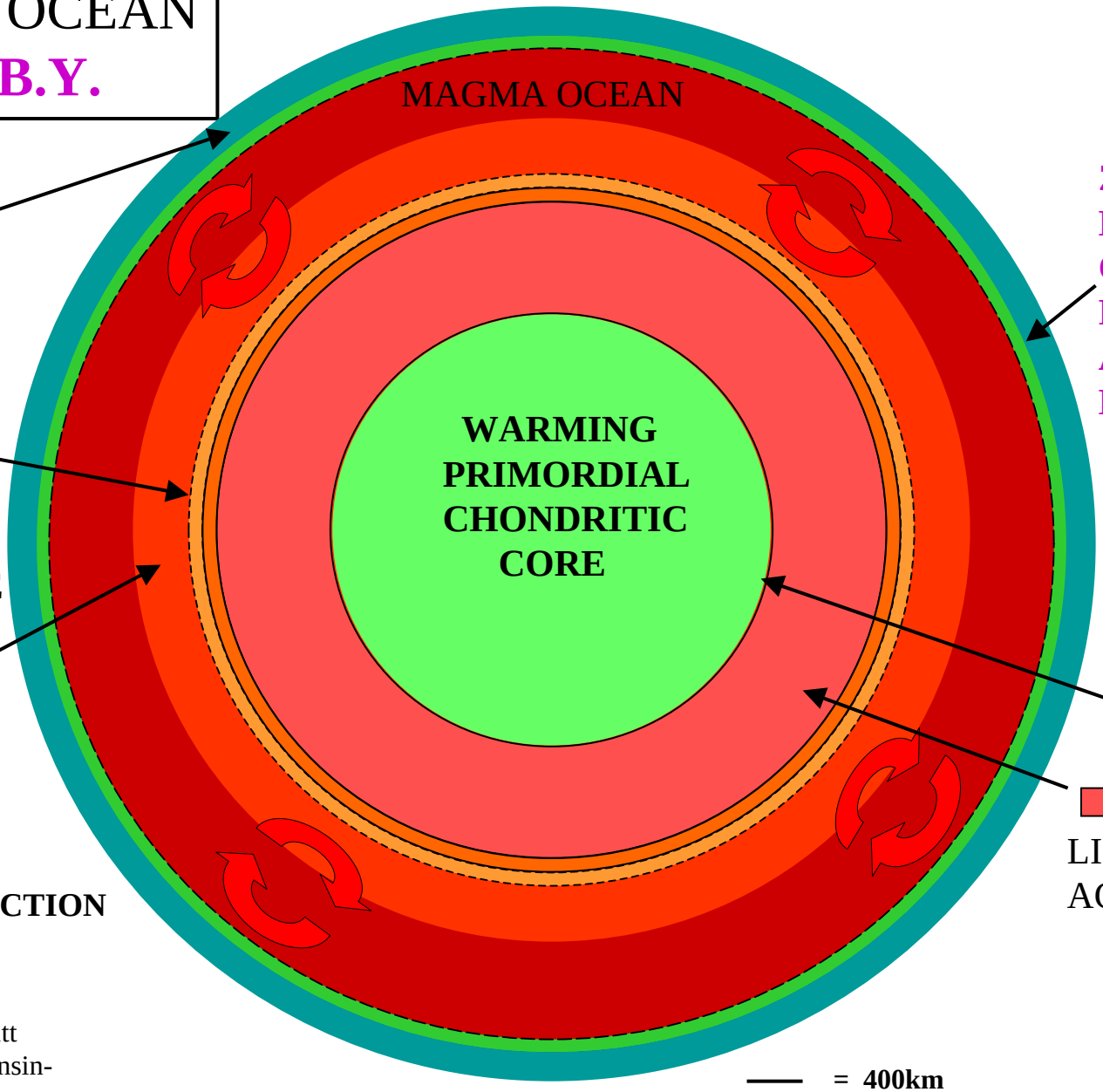


CRYSTALLIZATION OF HIGH PRESSURE MINERAL PHASES

- **PRIMARY HIGH PRESSURE MINERALS (MORE DENSE THAN LIQUID)**
  - **OLIVINE - MG**
  - **GARNET-MAJORITE - CA, MG, FE, AL, REE**
  - **CLINOPYROXENE - NA, CA, MG, AL**
  - **BIOTITE/HORNBLENDE - K, NA, MG, FE, AL, H_20**
  - **RUTILE - TI**
- **SIGNIFICANCE (PARTICULARLY WITH CONVECTIVE MIXING)**
  - **PLAGIOCLASE DOES NOT CRYSTALLIZE UNTIL VERY LATE**
    - **NO FLOATING CRUST**
  - **UPPER MANTLE POOR IN AL, NA, CA, K**
  - **LUNAR-LIKE KREEP PRODUCTION INHIBITED**
    - **RESIDUAL LIQUID IN UPPER MANTLE / LOWER CRUST RICH IN FE, SI, H_20, CO2, AND REMAINING INCOMPATIBLE ELEMENTS**
  - **RADIOACTIVE ^{40}K HELD IN HIGH PRESSURE MANTLE**
  - **WATER HELD IN HIGH PRESSURE MANTLE**
  - **TITANIUM HELD IN HIGH PRESSURE MANTLE**

APOLLO MODEL OF MARS EVOLUTION

MAGMA OCEAN
~4.54 B.Y.



PRIMITIVE, ERODING/ REPLENISHING ATMOSPHERE: CO_2, H_20, CH_4, NH_4, H_2

OLIVINE/ MAJORITE CUMULATE

OLVINE CUMULATE

ZONE OF CRYSTAL-LIZATION OF HIGH PRESSURE PHASES

CONVECTION CELLS

ZONE OF BASALTIC ? CRUST FORMATION AND BRECCIATION

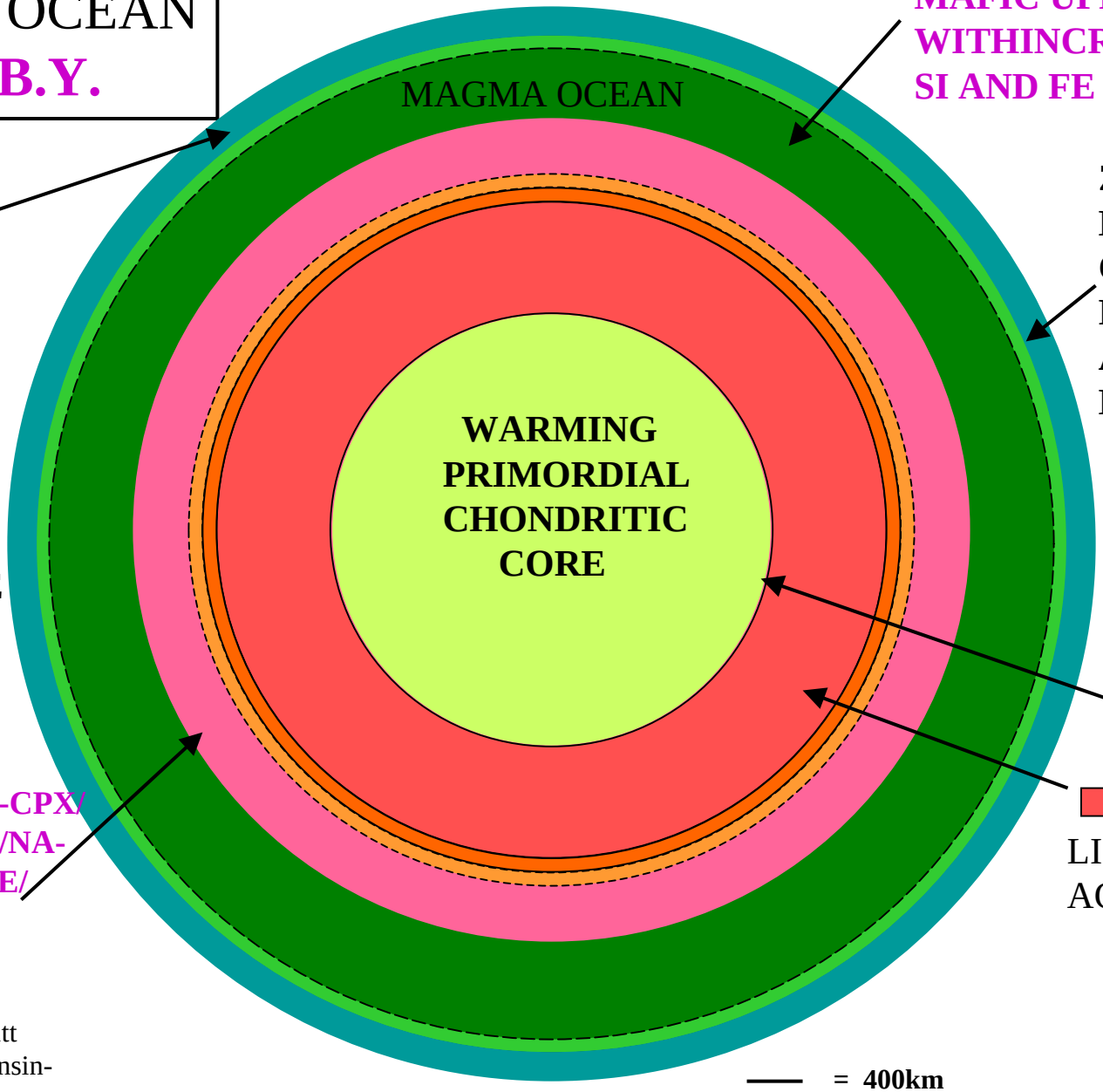
DENSITY INSTABILITY

$FE_xNI_yS_z$ LIQUID ACCUMULATION

— = 400km

APOLLO MODEL OF MARS EVOLUTION

MAGMA OCEAN
~4.52 B.Y.



MAFIC UPPER MANTLE WITHINCREASING SI AND FE UPWARDS

PRIMITIVE, ERODING/ REPLENISHING ATMOSPHERE: CO_2, H_20, CH_4, NH_4, H_2

ZONE OF BASALTIC ? CRUST FORMATION AND BRECCIATION

OLIVINE/ MAJORITE CUMULATE

OLVINE CUMULATE

DENSITY INSTABILITY

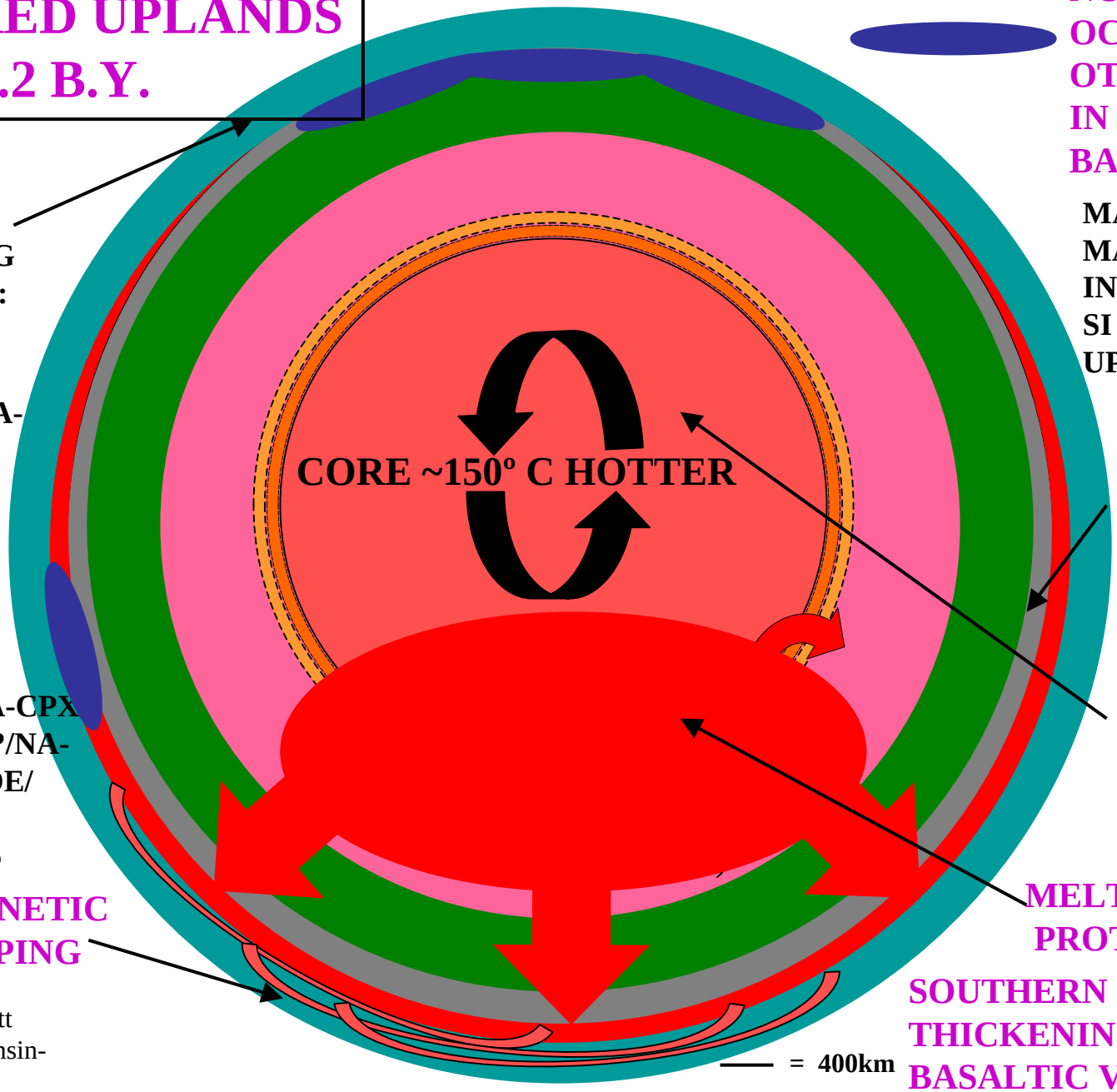
$FE_xNI_yS_z$ LIQUID ACCUMULATION

GARNET / NA-CPX/ NA-BIOTITE?/NA-HORNBLENDE/ "RUTILE" CUMULATES

= 400km

APOLLO MODEL OF MARS EVOLUTION

CRATERED UPLANDS
~4.5 - 4.2 B.Y.



NORTHERN OCEAN AND OTHER LAKES IN VERY LARGE BASINS

DENSE ERODING/ REPLENISHING ATMOSPHERE: CO_2, H_20

MAFIC UPPER MANTLE WITH INCREASING SI AND FE UPWARDS

OLIVINE/ NA-PYROXENE CUMULATE

OLIVINE CUMULATE

ZONE OF INTENSE CRATERING AND EROSION

GARNET / NA-CPX NA-BIOTITE?/NA-HORNBLENDE/ "RUTILE" CUMULATES

$FE_xNI_yS_z$ LIQUID CORE

MAGNETIC STRIPING

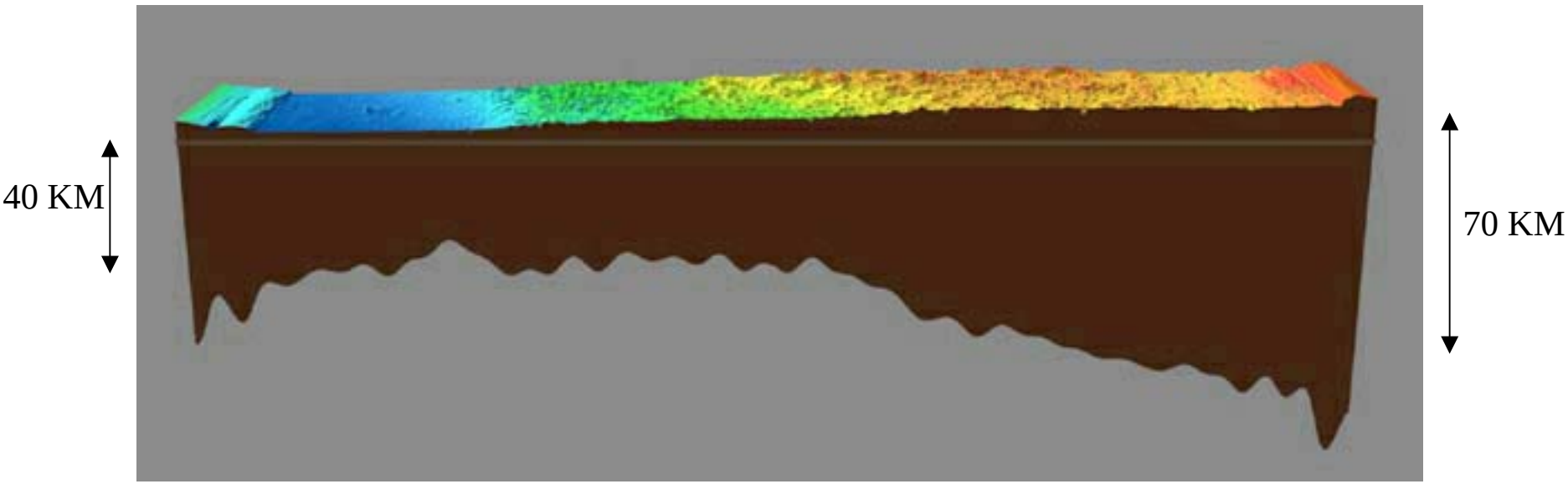
MELTING/RISING PROTO-CORE

SOUTHERN CRUSTAL THICKENING AND BASALTIC VOLCANISM

= 400km

CRUSTAL STRUCTURE - 0° LONGITUDE

NORTH POLE **SOUTH POLE**



NORTHERN LOWLANDS SOUTHERN HIGHLANDS

ARABIA TERRA

NOTE: LUNAR LOWLAND CRUST IS ~40-60KM THICK AND
LUNAR HIGHLAND CRUST IS ~60-120KM THICK

NEW SNC EVIDENCE OF DISPLACED PROTO-CORE

- **Rb-Sr AND Pb-Pb ISOTOPES INDICATE THREE DISTINCT RESERVOIRS: TWO MANTLE/ONE CRUST**
  - **MAJOR ELEMENTS ALSO SUGGEST THREE RESERVOIRS**
- **OXYGEN FUGACITIES INDICATE HETEROGENEOUS MANTLE**
- **^{142}Nd (^{146}Sm) RELATIONS INDICATE TWO DISTINCT MANTLE SOURCES**
- **EVIDENCE THAT PORTIONS OF MANTLE HAVE PRIMORDIAL Xe ISOTOPES**

SNC METEORITES FROM MARS

METEORITE	XLL'TN AGE (B.Y.)	PETROLOGY (DESCRIPTION)
Shergotty	0.165-0.205 0.350	Shock-metamorphosed basalt with pyroxene and plagioclase
Zagami	0.116-0.230	Shock-metamorphosed basalt
Los Angeles	0.165	Differentiated basalt with significant concentrations of "KREEP" like components.
NWA 480		
*Nakhla	1.240-1.370	Pyroxene-olivine cumulate or coarse basaltic lava
*Lafayette	1.330 0.274-0.655 (iddingsite)	Pyroxene-olivine cumulate or coarse basaltic lava
*Gov. Valadares	1.320	Pyroxene-olivine cumulate or coarse basaltic lava
*Chassigny	1.230-1.390	Olivine cumulate
QUE 94201	Not available	Basaltic
DaG476	Not available	Olivine-rich
SaU005	Not available	Olivine-rich, porphyritic
Dhofar 019	Not available	Olivine-rich
NWA 817	Not available	?

Blue = Magma source is mantle - depleted in incompatible elements with non-radiogenic Sr and excess 142Nd

Green = Magma source is crust - enriched in incompatible elements and radiogenic Sr

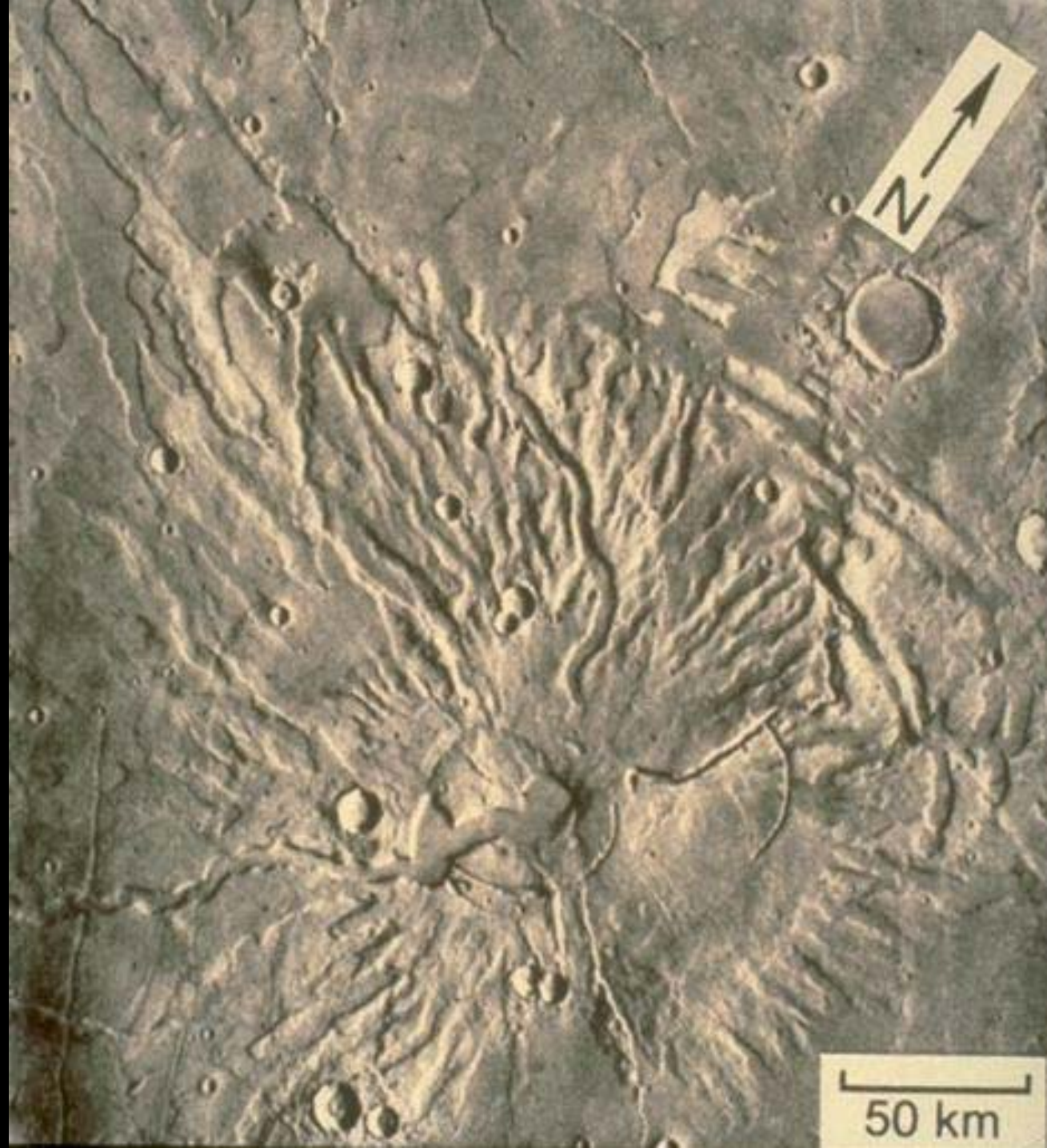
SNC METEORITES FROM MARS

METEORITE	XLL'TN AGE (B.Y.)	PETROLOGY (DESCRIPTION)
ALHA77005	0.187	Shock-metamorphosed lherzolitic (olivine and pyroxene) basalt with cumulate minerals
EETA79001	0.150-0.185	Shock-metamorphosed basalt with light colored xenoliths, melt and cumulate minerals, porphyritic olivine
LEW88516	Not available	lherzolitic basalt
Y793605	Not available	lherzolitic basalt
ALH84001	4.5	Igneous orthopyroxenite cumulate with miner maskelynite, olivine, chromite, pyrite, and apatite

Black = Magma source in primitive, unfractionated mantle with intermediate Sr

Red = Magma source may be associated with magma ocean differentiation.

TYRRENUM PATERNA UPLANDS VOLCANO

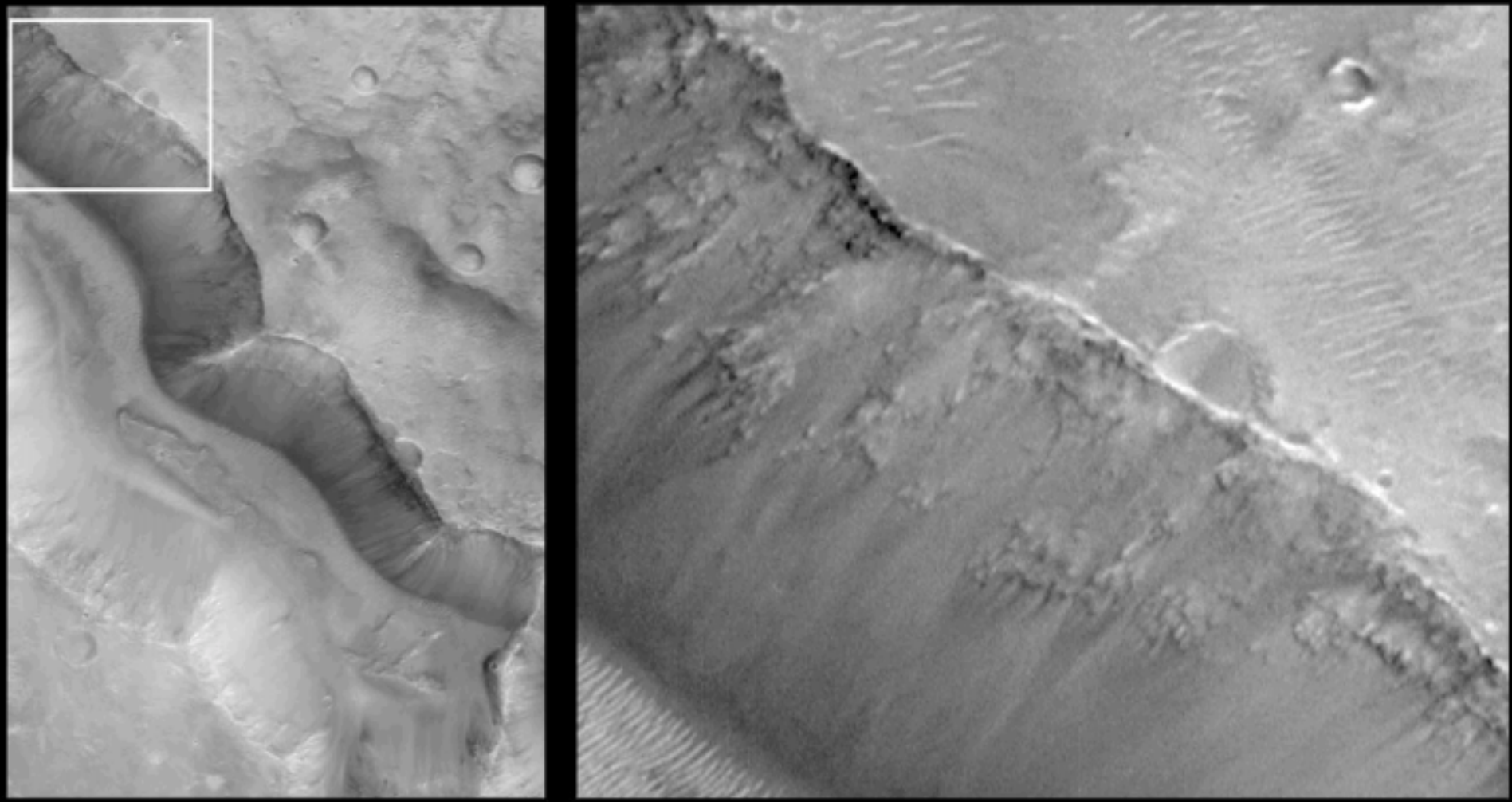


NASA VIKING IMAGE

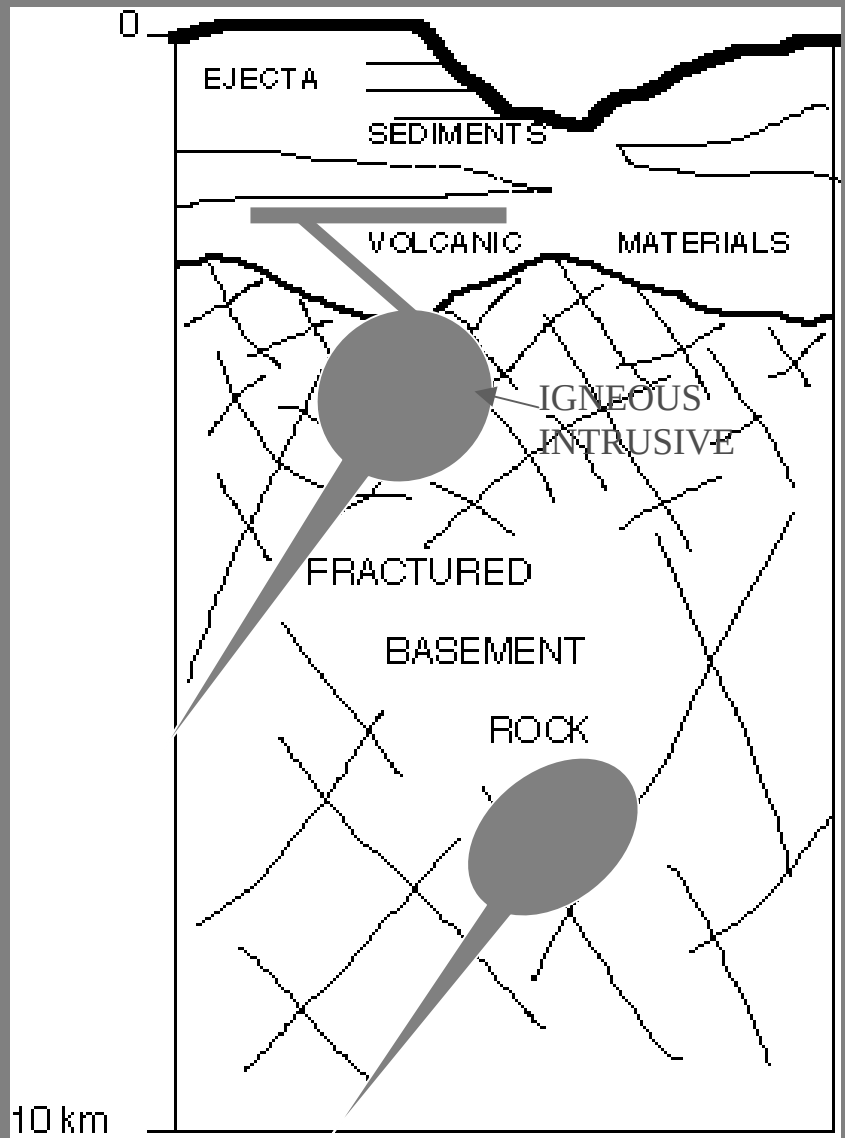
CRATERED UPLANDS

NASA VIKING IMAGE

CLIFF THROUGH CRATERED UPLANDS
TAGUS VALLIS



NASA/JPL/MALIN SPACE SCIENCE SYSTEMS



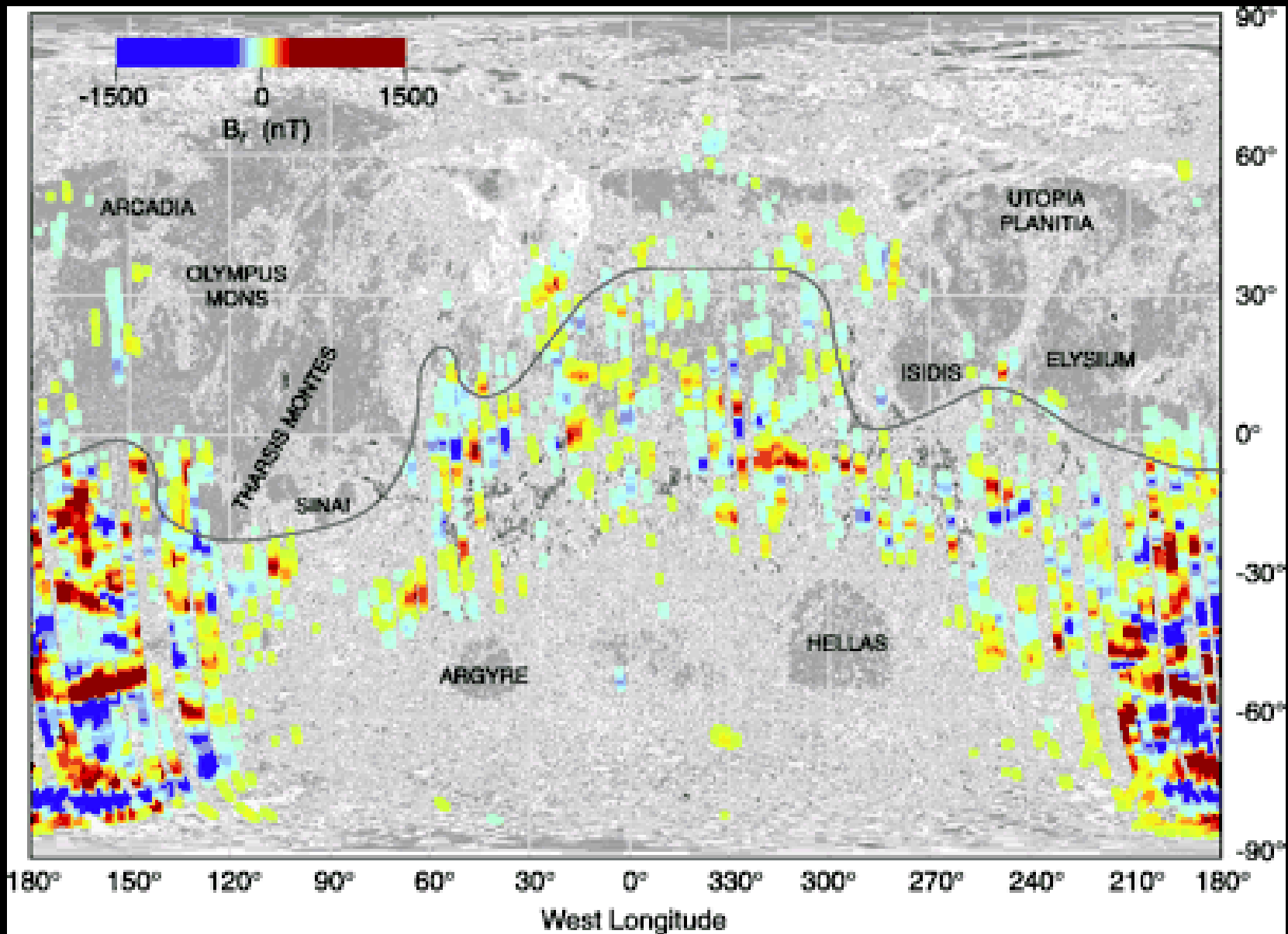
MEGAREGOLITH OF MARS

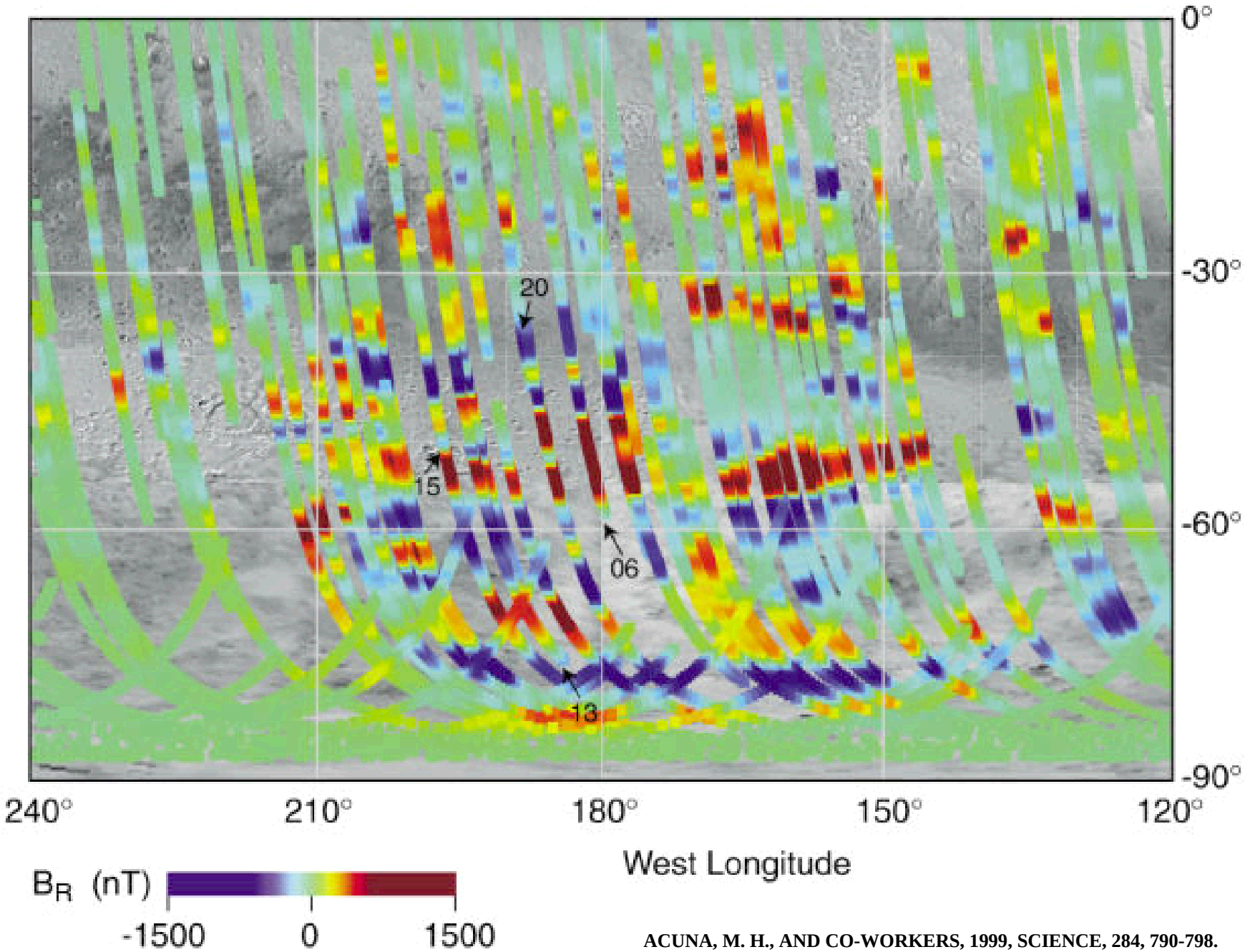
(After Carr, 1996)

LOCATION AND INTENSITY OF CRUSTAL MAGNETIC SOURCES

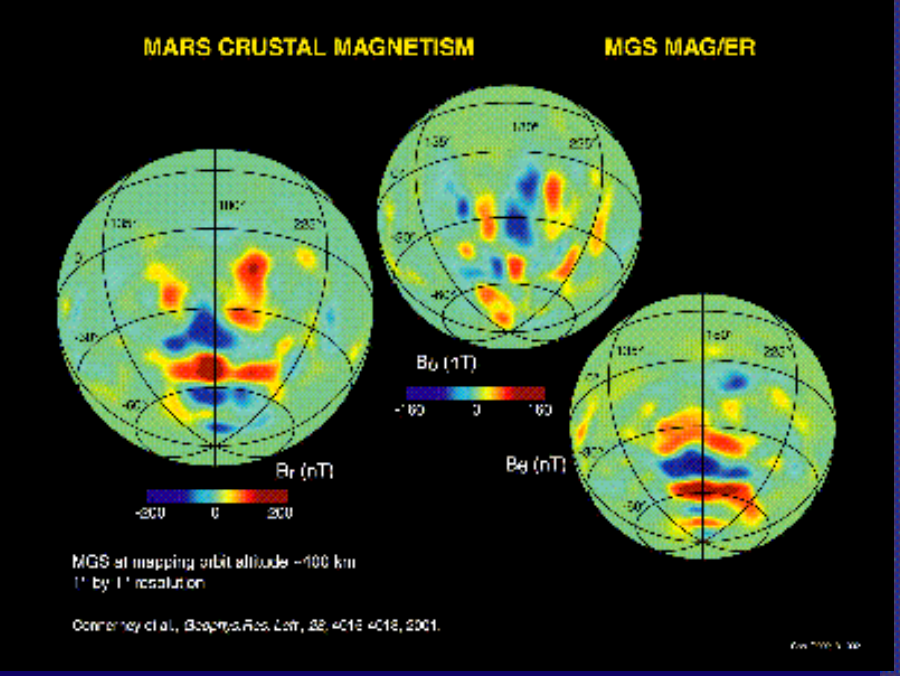
SUPERIMPOSED ON A TOPOGRAPHIC IMAGE OF MARS

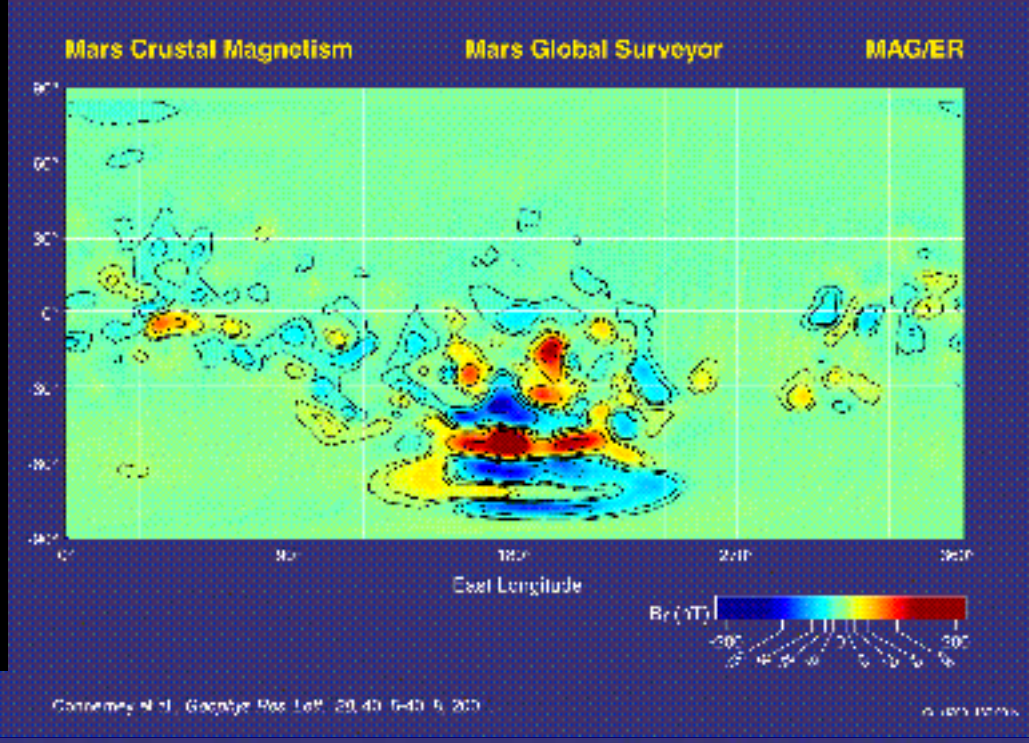
ACUNA, M. H., AND CO-WORKERS, 1999, SCIENCE, 284, 790-798.





ACUNA, M. H., AND CO-WORKERS, 1999, SCIENCE, 284, 790-798.

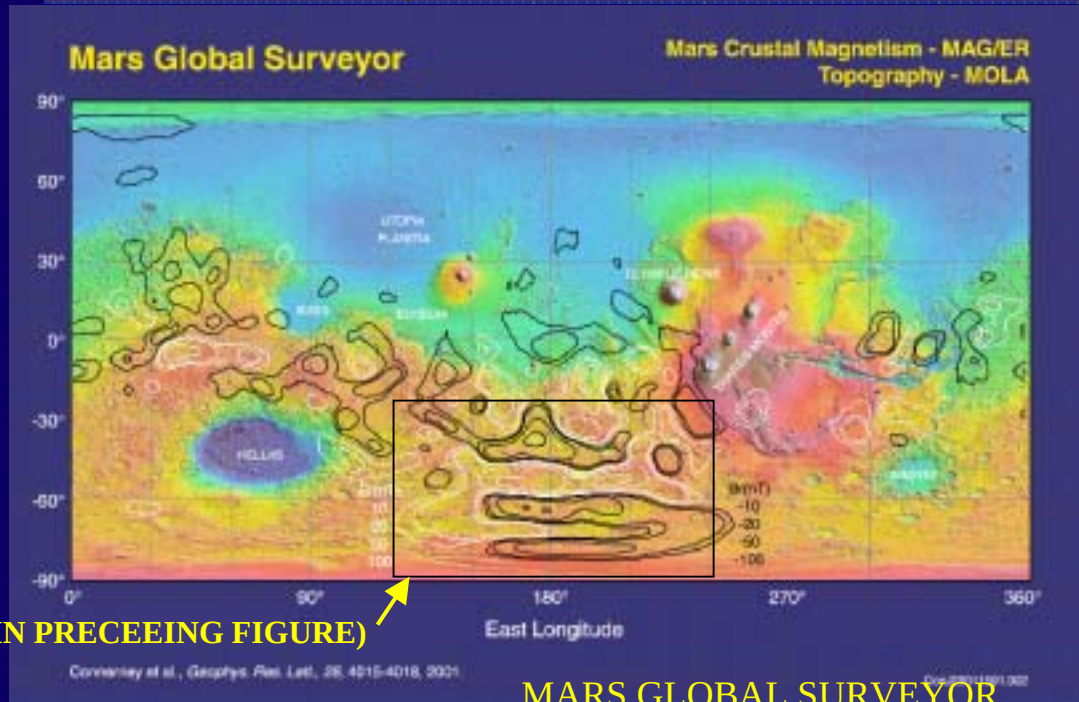




MARS CRUSTAL MAGNETISM

NOTE:

- **CONFINED TO CRATERED, SOUTHERN HEMISPHERE**
- **DESTROYED BY VERY LARGE BASIN EVENTS, I.E., PRE 4.2 B.Y.?**

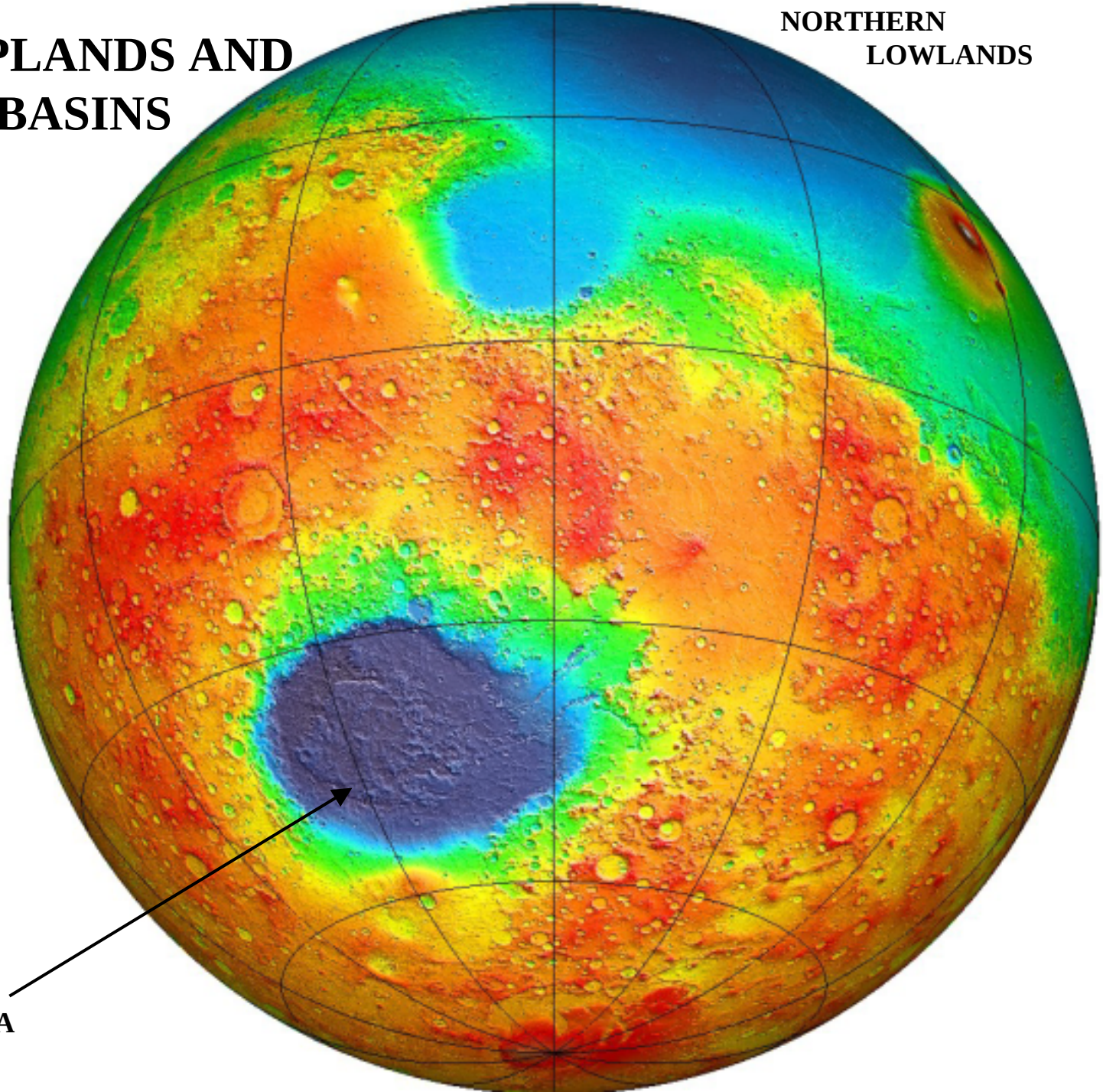


(AREA IN PRECEEING FIGURE)

MARS GLOBAL SURVEYOR

CRATERED UPLANDS AND VERY LARGE BASINS

MOLA SCIENCE TEAM



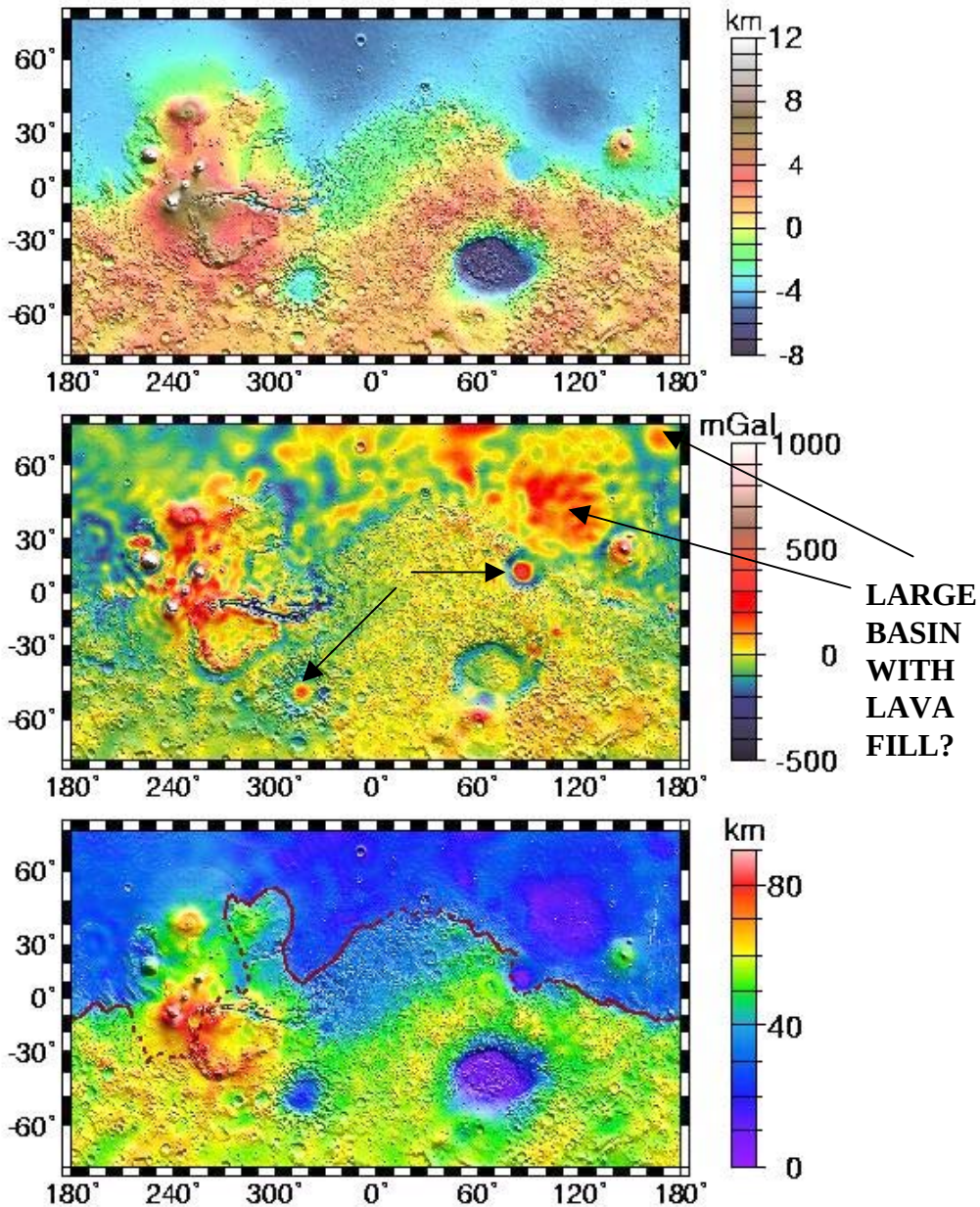
MARS GLOBAL SURVEYOR

TOPOGRAPHY

GRAVITY

NOTE: SEVERAL MASCONS AND HELAS -ve RING SUGGEST CRUSTAL STRENGTHENING AFTER VERY LARGE BASIN STAGE ~ MOON

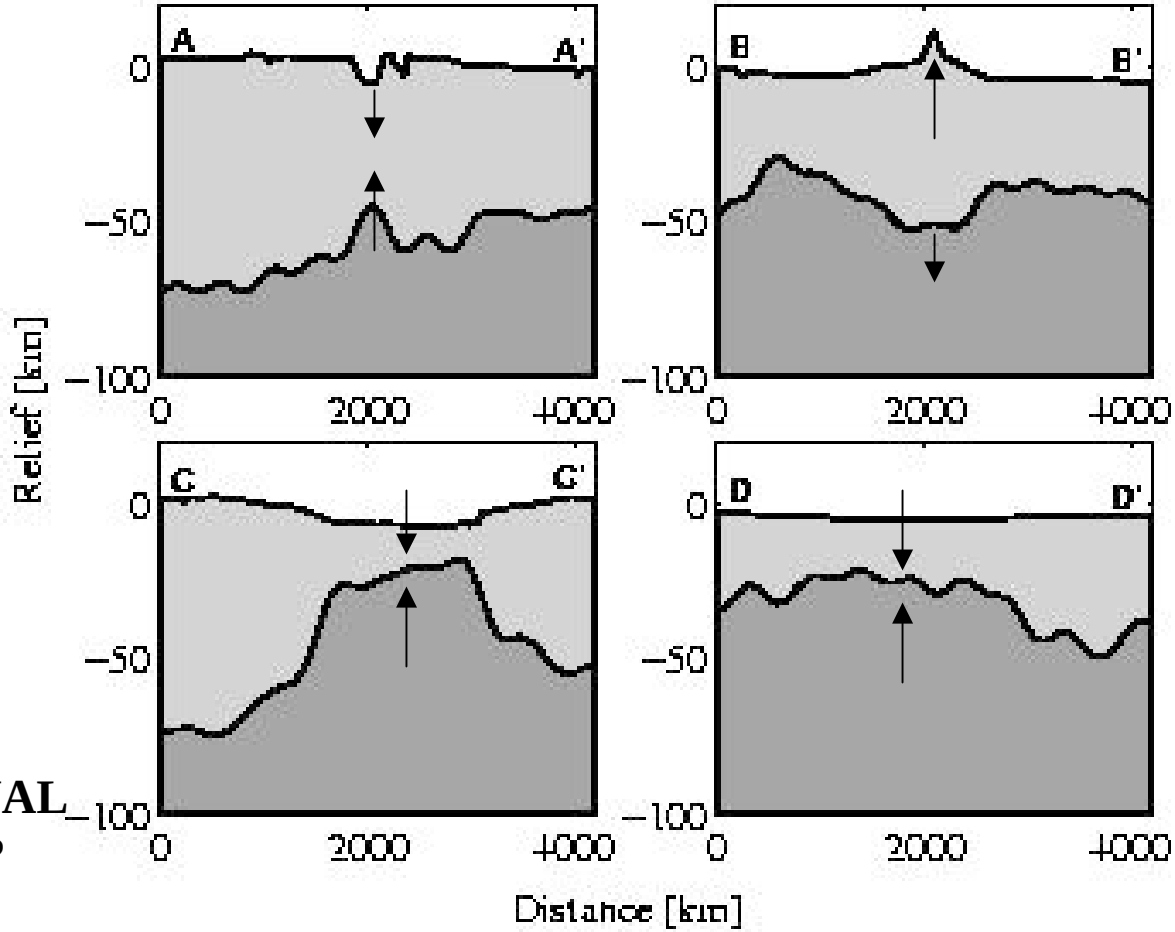
CRUSTAL THICKNESS



“ISOSTATIC” COMPENSATION IN MARS

VALLES MARINERIS

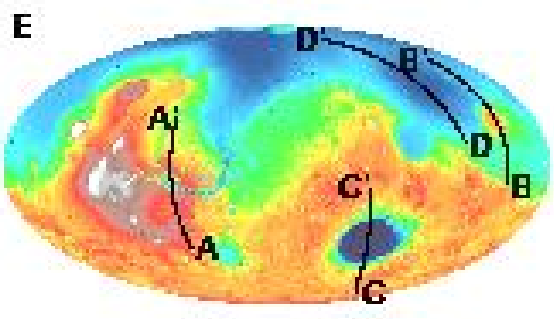
ELYSIUM MONS



HELLAS BASIN

ALSO AN ARTIFACT OF ORIGINAL REBOUND?

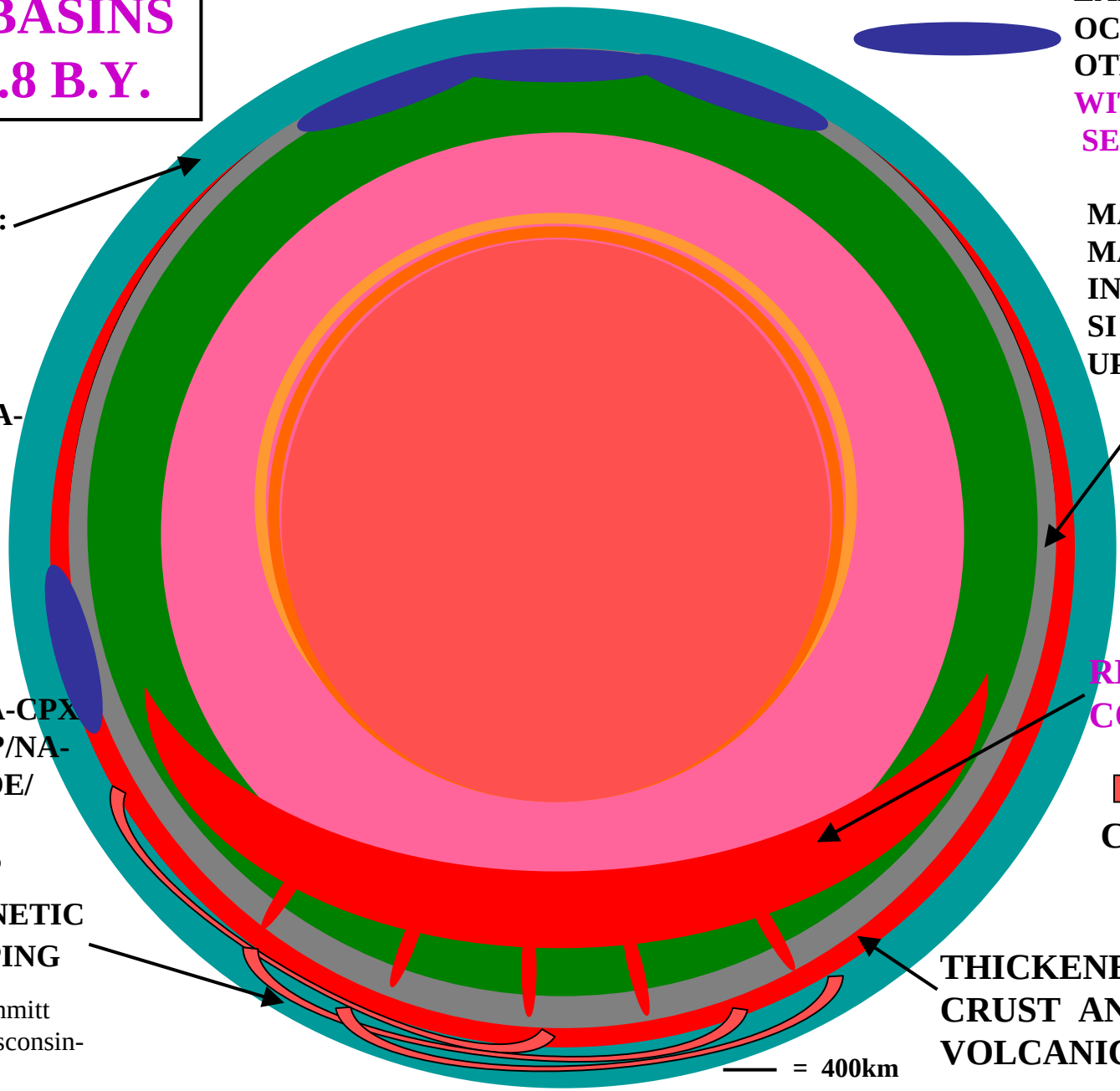
UTOPIA BASIN



GENERALLY INDICATES WEAK CRUST AND UPPER MANTLE AT TIME SURFACE FEATURES FORMED

APOLLO MODEL OF MARS EVOLUTION

LARGE BASINS
~4.2 - 3.8 B.Y.



EARLY NORTHERN OCEAN AND OTHER LAKES WITH CYCLIC SEDIMENTATION

THINNING ATMOSPHERE: CO_2, H_20

MAFIC UPPER MANTLE WITH INCREASING SI AND FE UPWARDS

OLIVINE/ NA-PYROXENE CUMULATE

OLIVINE CUMULATE

ZONE OF MEGA-REGOLITH AND EROSION

GARNET / NA-CPX NA-BIOTITE?/NA-HORNBLENDE/ "RUTILE" CUMULATES

RELIC PROTO-CORE ?

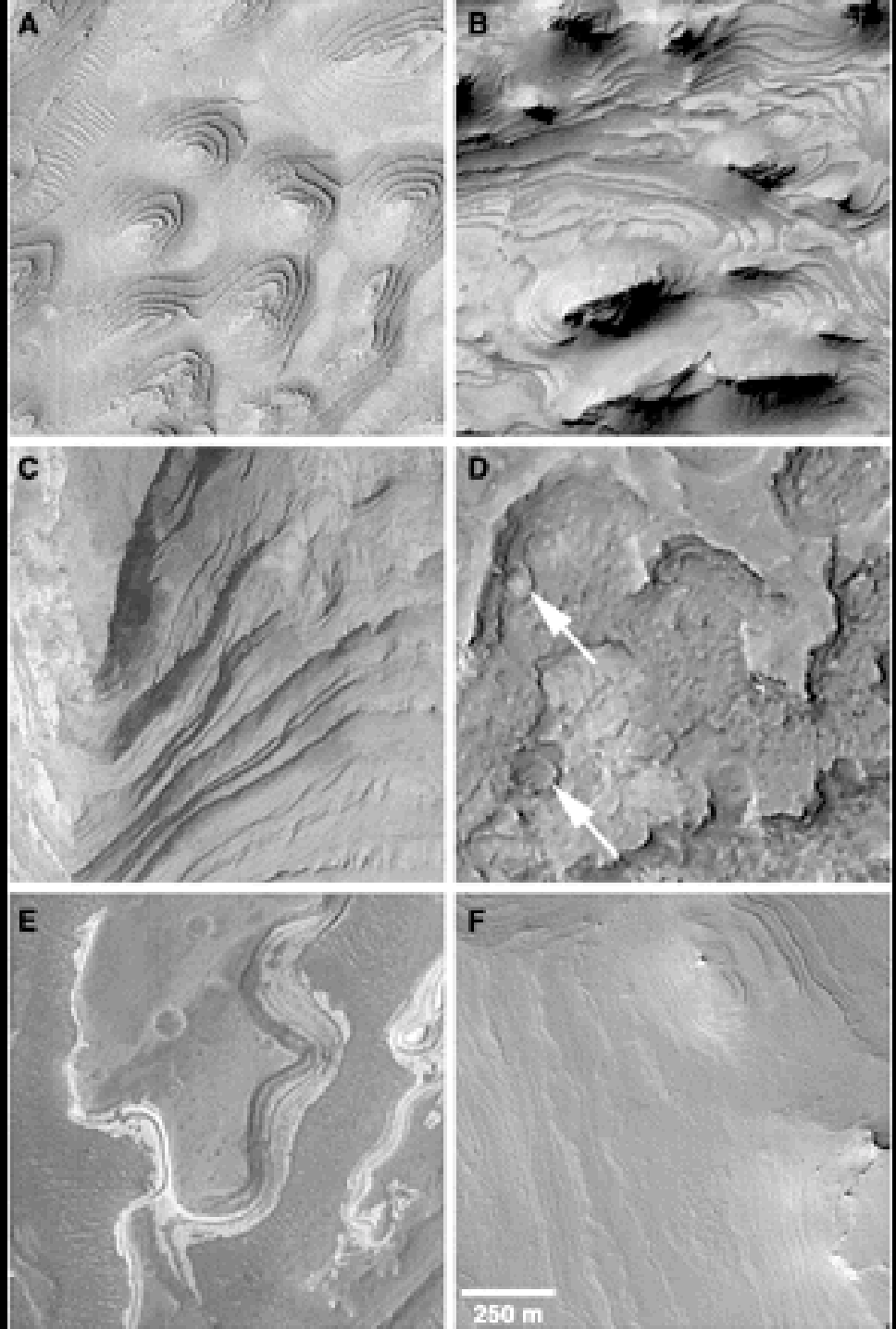
$FE_xNI_yS_z$ CORE

MAGNETIC STRIPING

THICKENED SOUTHERN CRUST AND BASALTIC VOLCANICS

= 400km

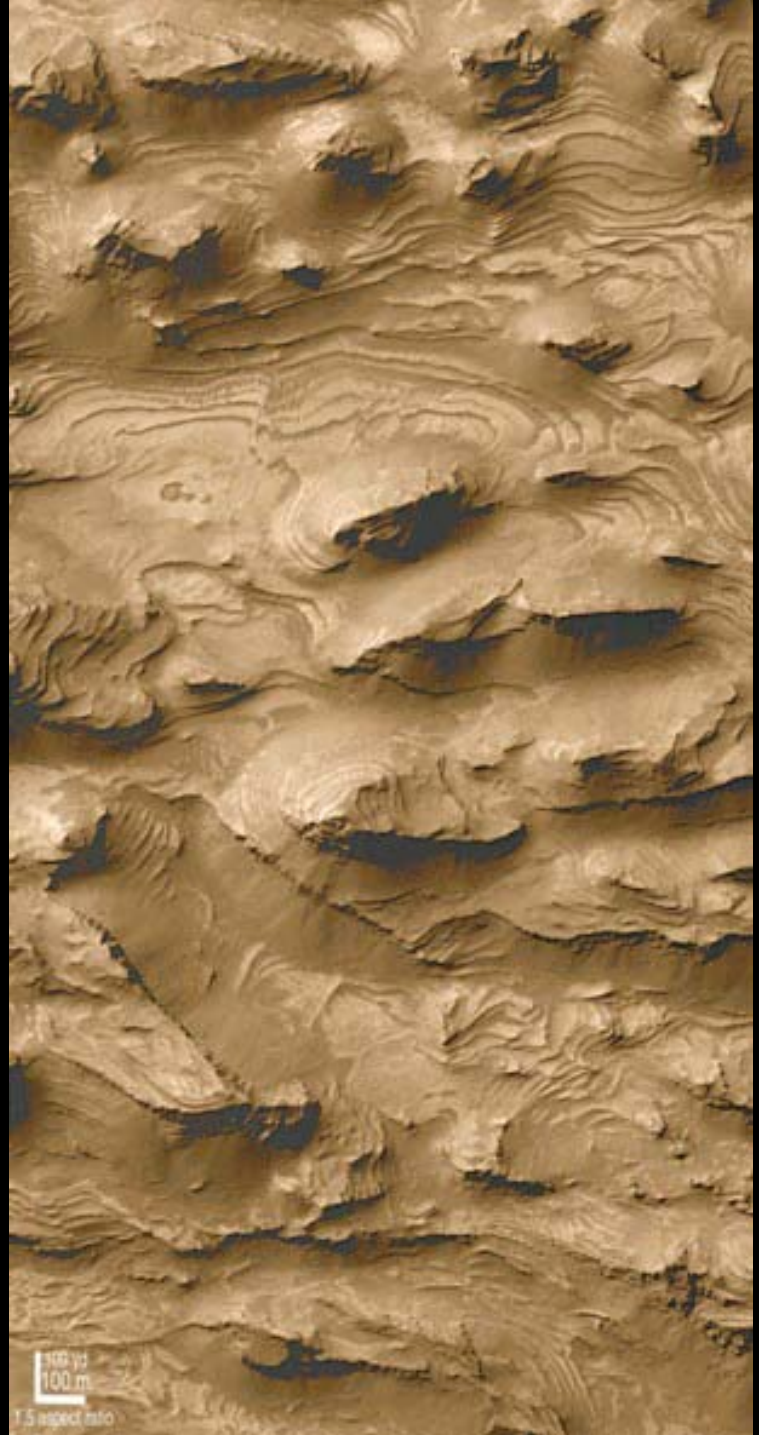
VARIOUS EXPOSURES OF LAYERED BEDROCK ON MARS (MGS)



ARROWS POINT TO BURIED CRATERS

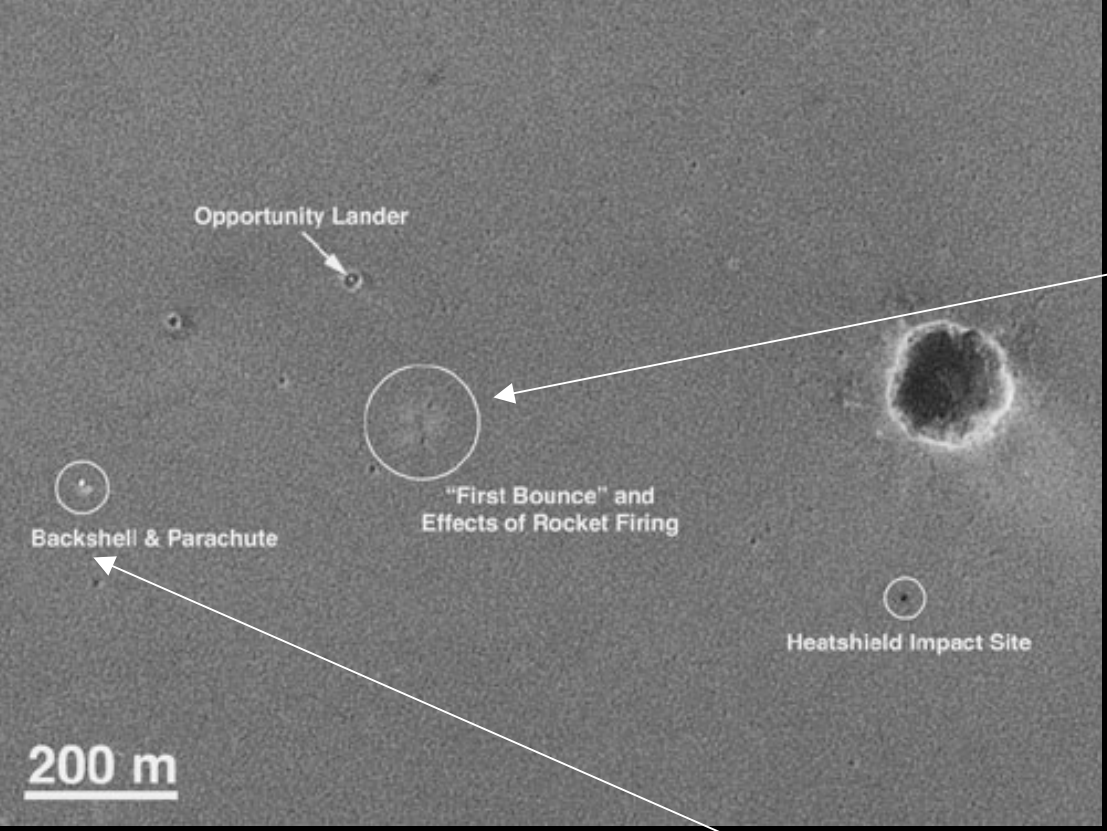
LIGHT AND DARK LAYERED UNIT COVERED BY MESA-FORMING UNIT

MALIN,M.C., AND K.S. EDGETT
2000, SCIENCE, 290,
PP. 1927-1937



CANDOR CHASMA

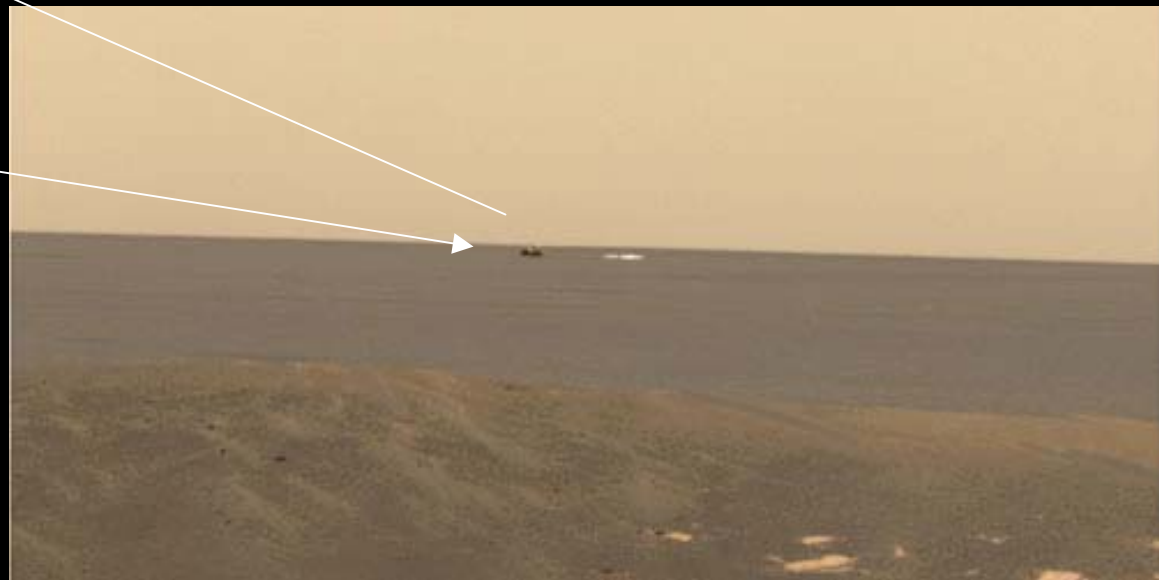
NASA/JPL/MALIN SPACE SCIENCE SYSTEMS



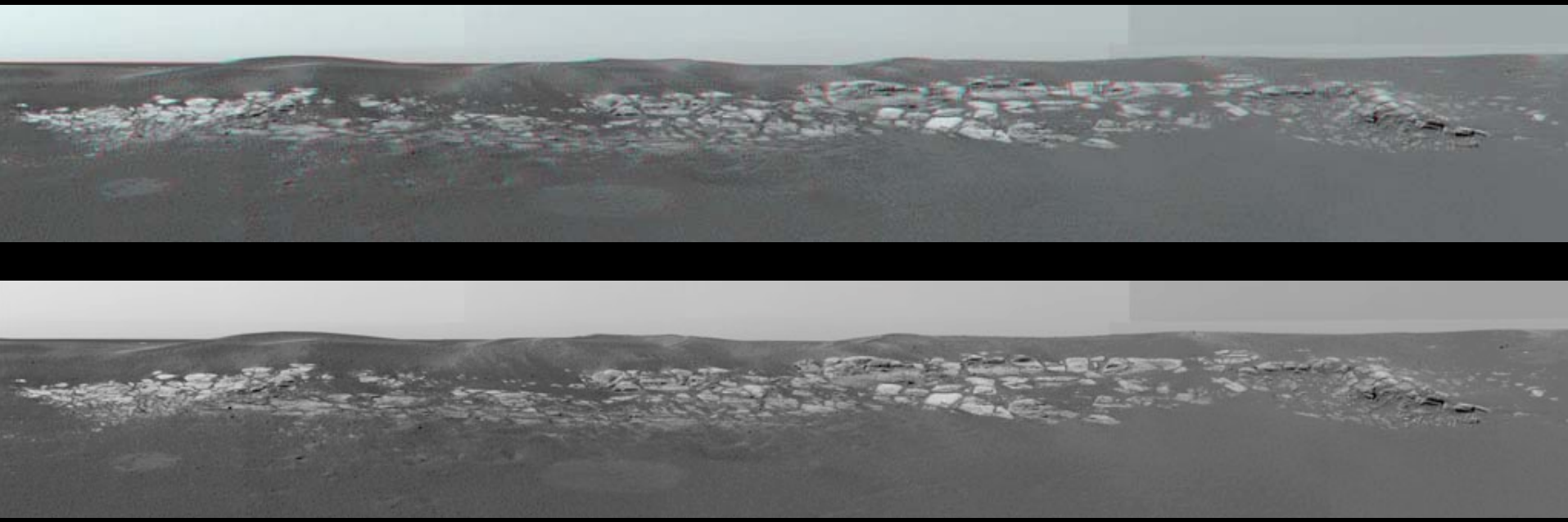
OPPORTUNITY KNOCKS: LAYERED ROCKS AT MERIDIANI PLANUM, MARS

A HEMATITE (Fe_2O_3) - RICH REGION

~350 M AWAY

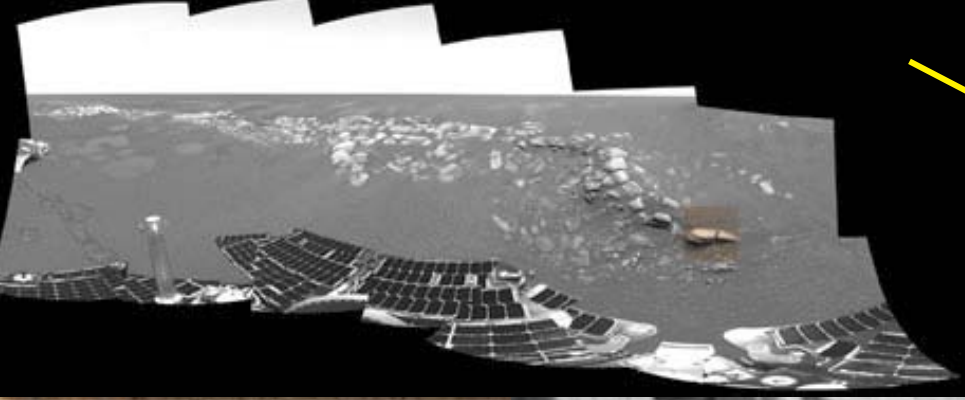


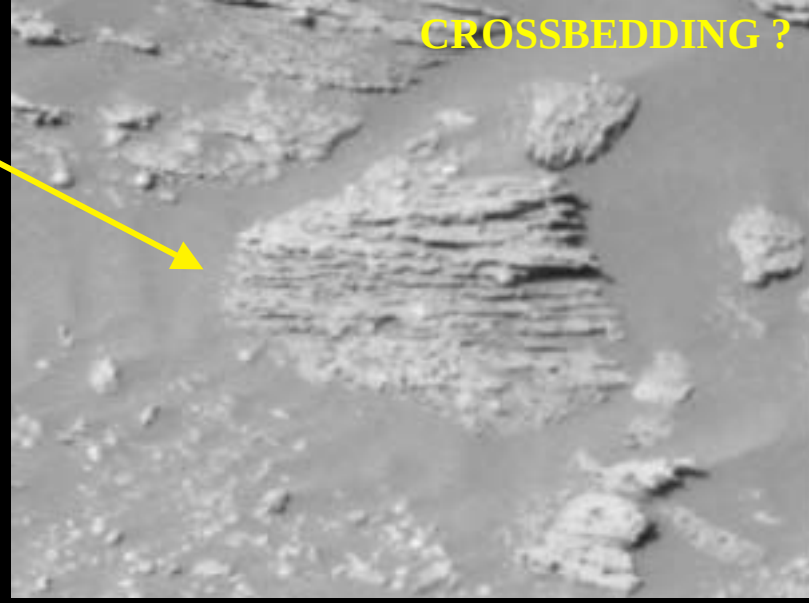
VIEWS OF ROCK OUTCROPS IN OPPORTUNITY'S CRATER (8-10 METERS FROM VIEWER)



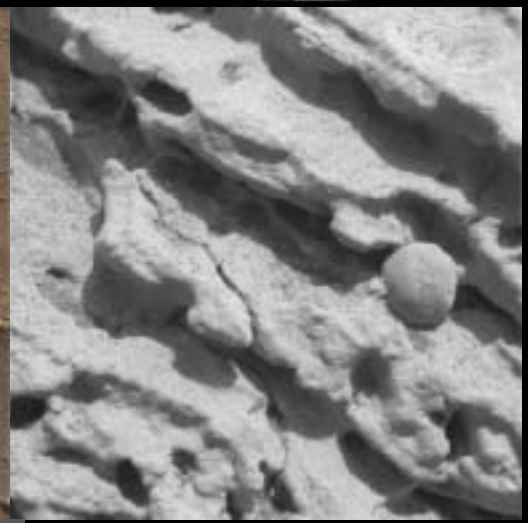
NOTE LAYERING OR FOLIATION

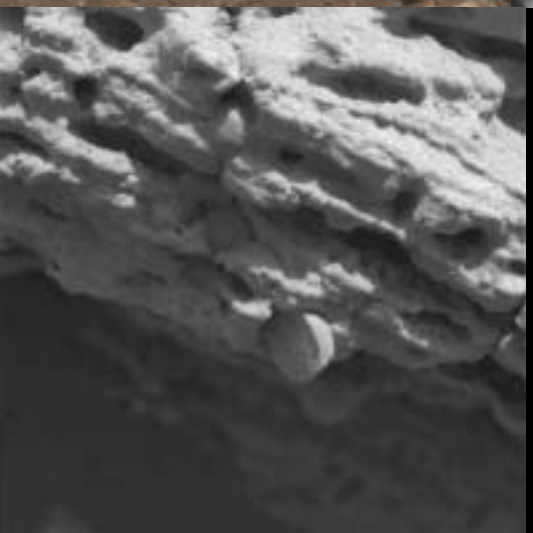
FOLIATION: GENERAL TERM FOR ROUGHLY PARALLEL PLANAR FEATURES IN ROCKS



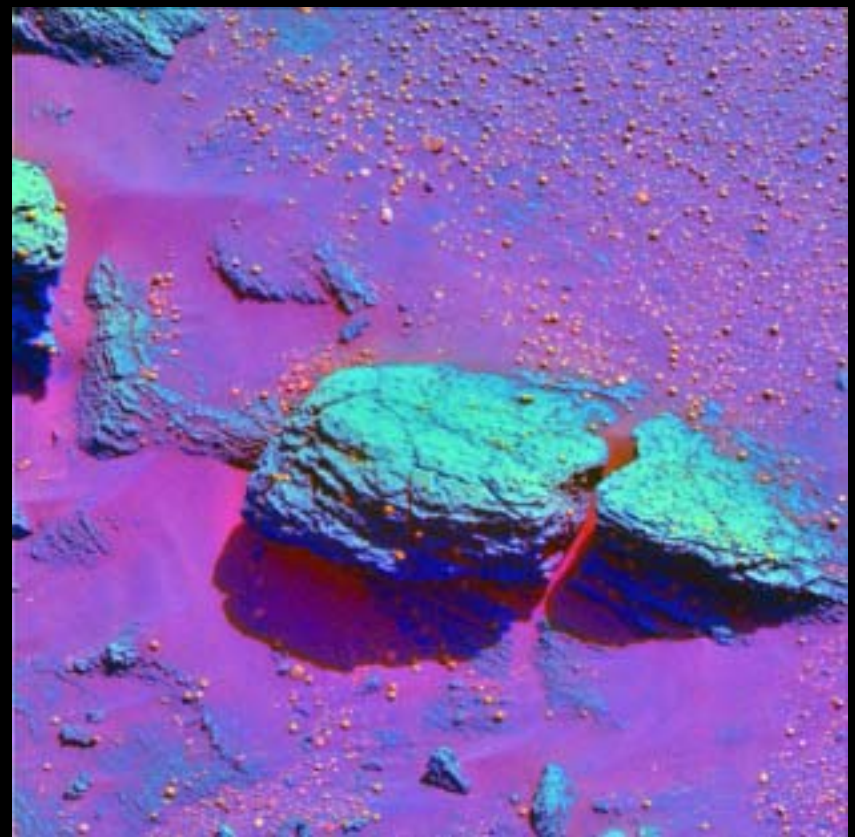


CROSSBEDDING ?

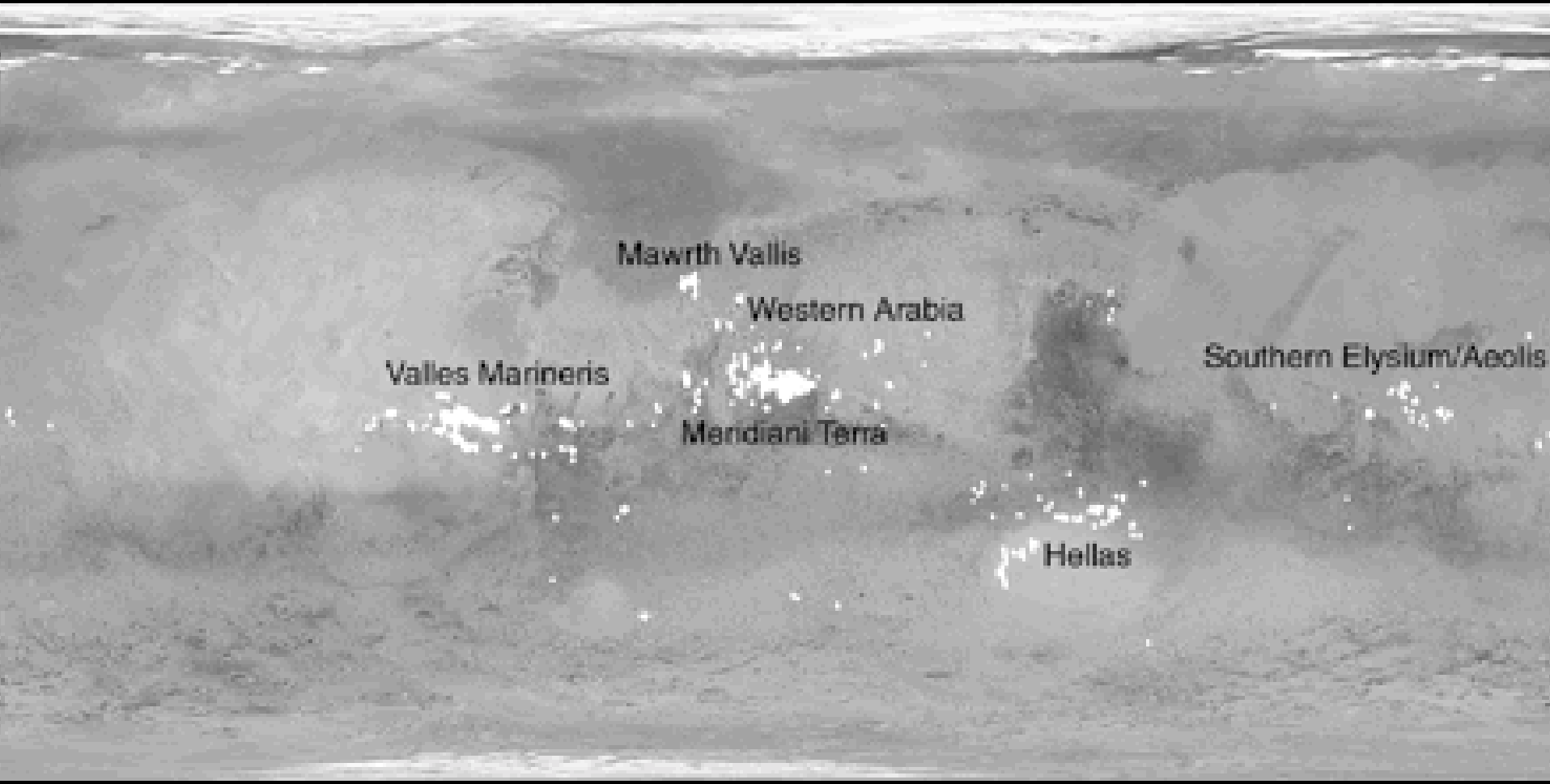




OPPORTUNITY'S LAYERED / FOLIATED ROCKS WITH SPHERULES (FEW TENTHS CM IN DIAMETER)



GLOBAL DISTRIBUTION OF EXPOSURES OF PRE-THARSIS LAYERED UNITS



MALIN,M.C., AND K.S. EDGETT, 2000, SCIENCE, 290, PP. 1927-1937

FAULTED LIGHT AND DARK LAYERED UNITS WEST OF CANDOR CHASMA

MALIN,M.C., AND K.S. EDGETT,
2000, SCIENCE, 290,
PP. 1927-1937

THINLY LAYERED UNITS -1

- BEDS (TABULAR SUBUNITS) FROM <FEW METERS TO 2000M THICK
  - TRACEABLE (MAPABLE) OVER LARGE AREAS
  - ASSOCIATED WITH LARGE CRATERS AND BASINS
- CONSISTENT AND REPETITIVE DEPOSITION
- CONFORM TO WALLS OF CRATERS
- TRANSITION TO MASSIVE UNITS (UNLAYERED AT FEW METERS RESOLUTION)
- EXPOSED BY LATER FAULTING AND EROSION (WIND AND WATER?)
- RAPID DEGRADATION OF IMPACT CRATERS IMPOSED ON UNITS
  - CRATER COUNTS << THAN ON OVERLYING (YOUNGER) MESA UNITS
    - EASILY ERODED BY WIND
- OPPORTUNITY'S ROCKS VERY THINLY LAYERED OF FOLIATED

THINLY LAYERED UNITS -2

- **CONCLUSION: CYCLIC, VOLUMETRICALLY CONSISTENT DEPOSITION OF FINE-GRAINED MATERIAL; ONLY SLIGHTLY INDURATED AFTER DEPOSITION.**
  - **CYCLIC DEPOSITION DUE TO CLIMATE CYCLES AND/OR REPETITIVE PYROCLASTIC VOLCANISM**
    - **CYCLES IN AXIS INCLINATION TO ECLIPTIC (OBLIQUITY) ON FEW MILLION YEAR INTERVALS**
    - **CLAY AND/OR ASH TRANSPORTED BY CYCLIC PRECIPITATION RUNOFF**
    - **EVAPORITES: SALTS AND OR CARBONATES PRECIPITATED BY CYCLIC EVAPORATION OF STANDING WATER**
    - **WIND BLOWN DUST: CLAY AND/OR ASH SUPPLIED BY CYCLIC DUST STORMS AND/OR REPETITIVE VOLCANIC ERUPTIONS**

THINLY LAYERED UNITS -3 IMPLICATIONS

- **EROSION OF CRATERED UPLANDS**
  - **DURING AND/OR AFTER VERY LARGE AND LARGE BASIN FORMATION**
  - **BEFORE THARSIS ERUPTIONS AND RIFTING**

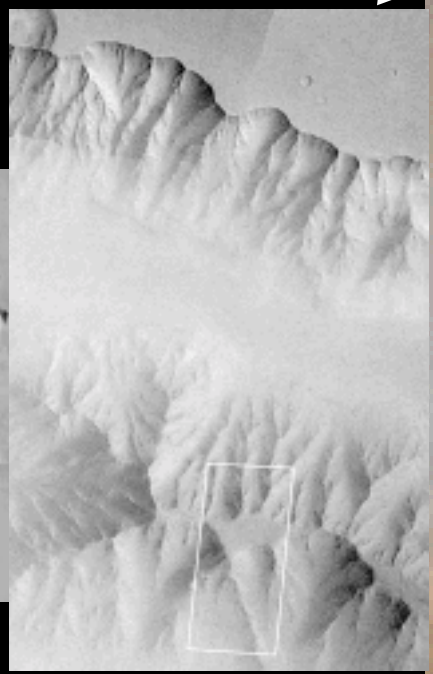
- **POSSIBLE ASSOCIATED VOLCANIC ACTIVITY**
  - **OLD VOLCANOES ERODED BY VALLEY NETWORKS**

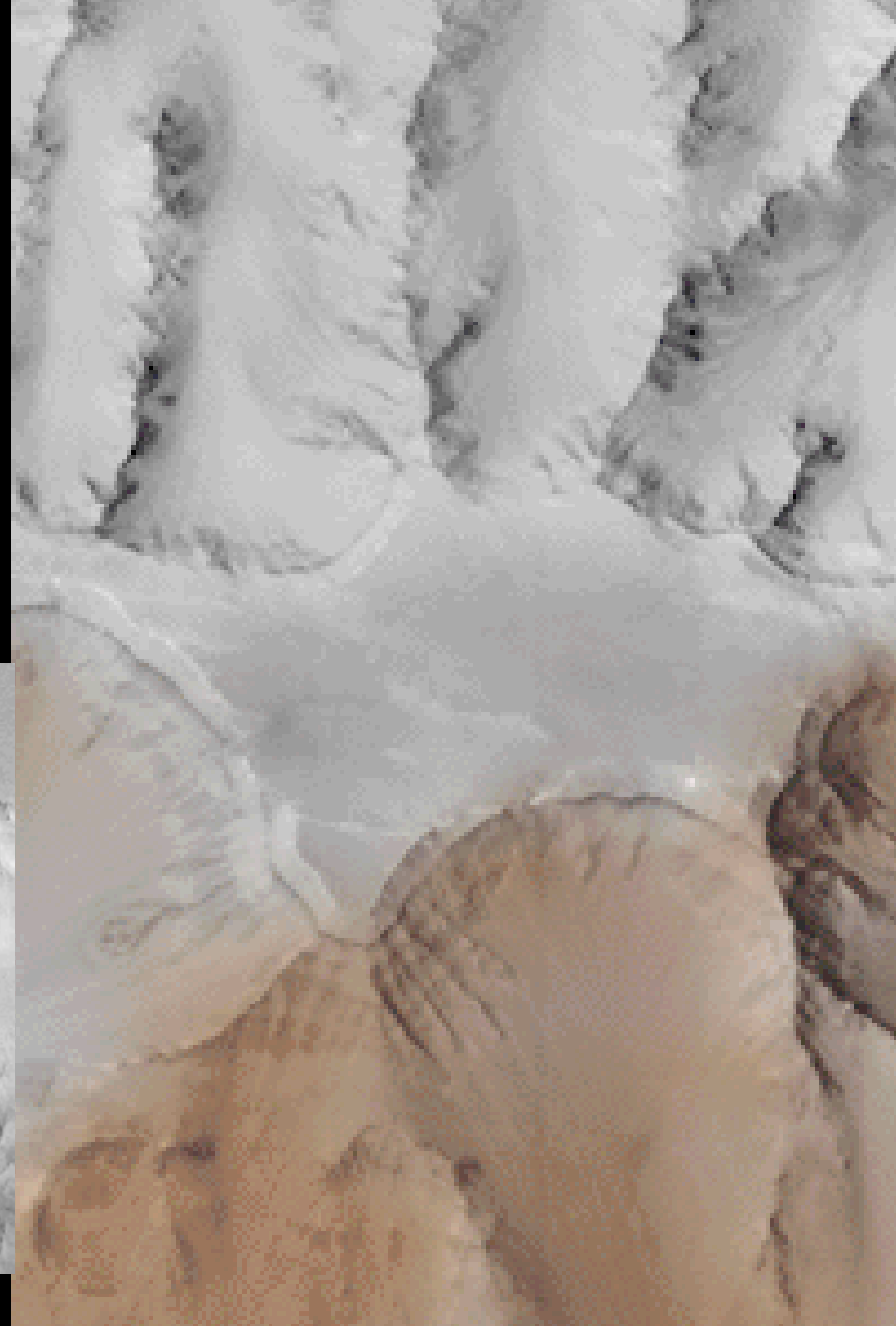
- **DENSE, WATER-RICH ATMOSPHERE PROBABLY REQUIRED**
  - **PRECIPITATION AND LAKES**

- **MINERAL CONCENTRATIONS (RESOURCES) BASED ON DENSITY, SIZE AND SHAPE DIFFERENCES HIGHLY PROBABLE**

- **EARLY OPPORTUNITY FOR ORGANIC SYNTHESIS**

LAYERED BEDROCK IN VALLES MARINERIS



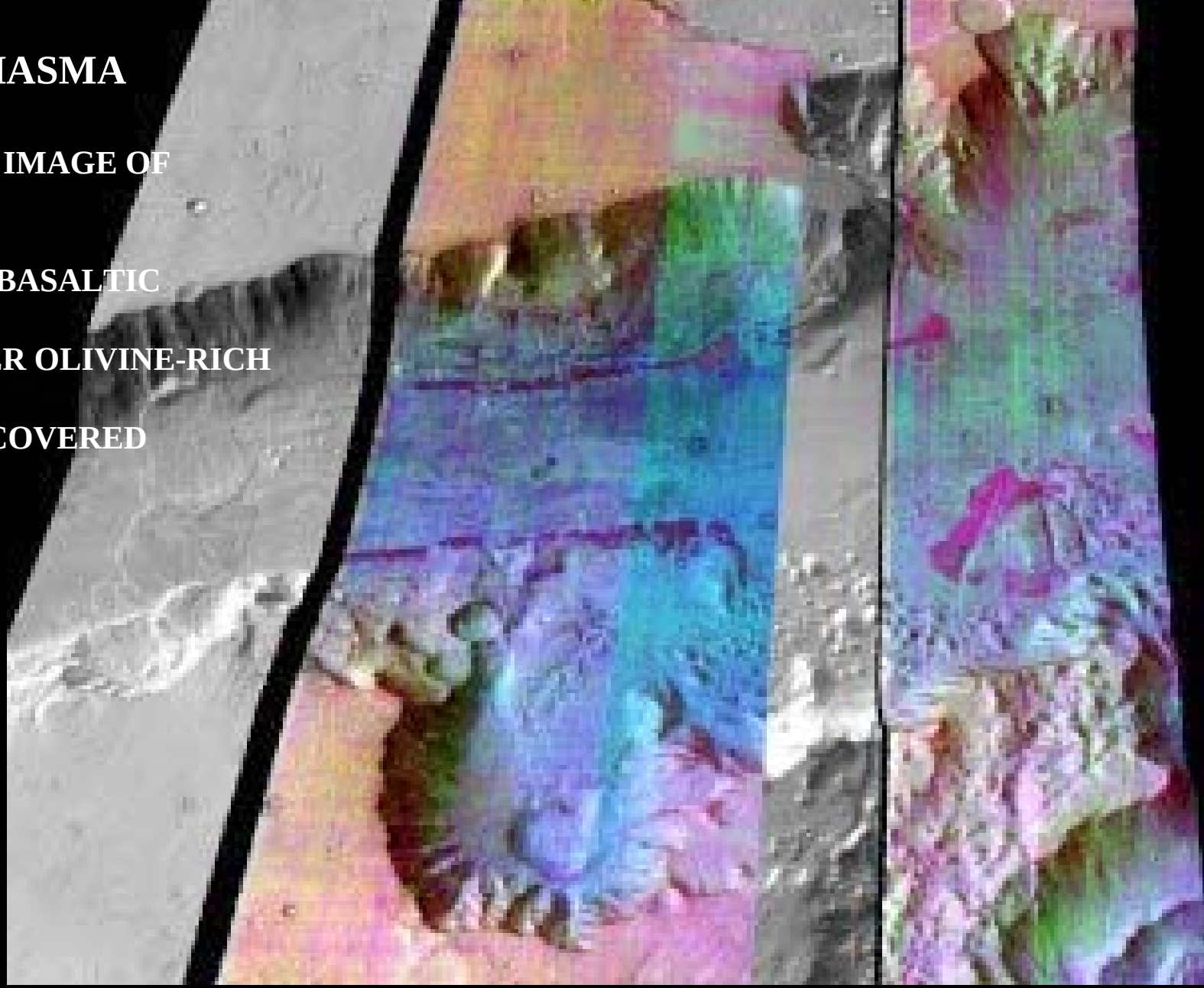


NASA/JPL/MALIN SPACE SCIENCE SYSTEMS.

GANGES CHASMA

FALSE COLOR IMAGE OF TES DATA

- **BLUE FLOOR BASALTIC**
- **PURPLE LAYER OLIVINE-RICH**
- **TAN IS DUST COVERED**



JET PROPULSION LABORATORY
UNIVERSITY OF ARIZONA'S LUNAR AND PLANETARY LAB
LOS ALAMOS NATIONAL LABORATORY
RUSSIA'S SPACE RESEARCH INSTITUTE.

TERM PAPER TOPICS

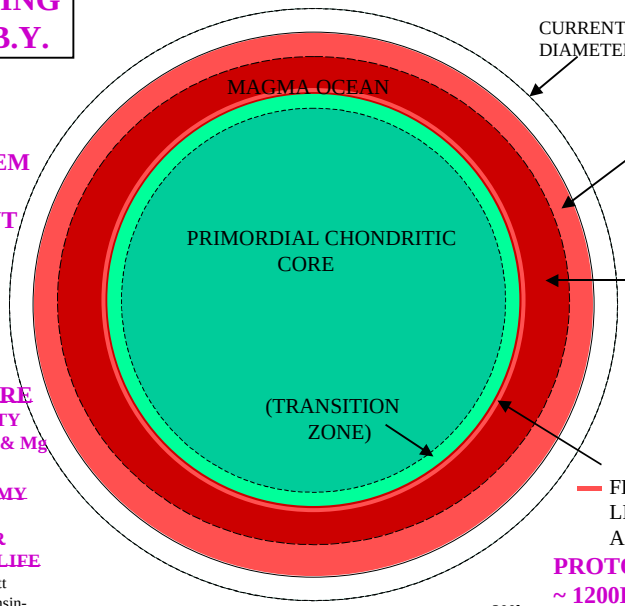
- **EVIDENCE FOR AND AGAINST TWO DISTINCT COMPOSITIONS (IGNEOUS RESERVOIRS) IN THE MARTIAN MANTLE**
- **RESOURCE SIGNIFICANCE OF THINLY LAYERED ROCKS**

APOLLO MODEL OF LUNAR EVOLUTION

BEGINNING ~4.542 + 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**

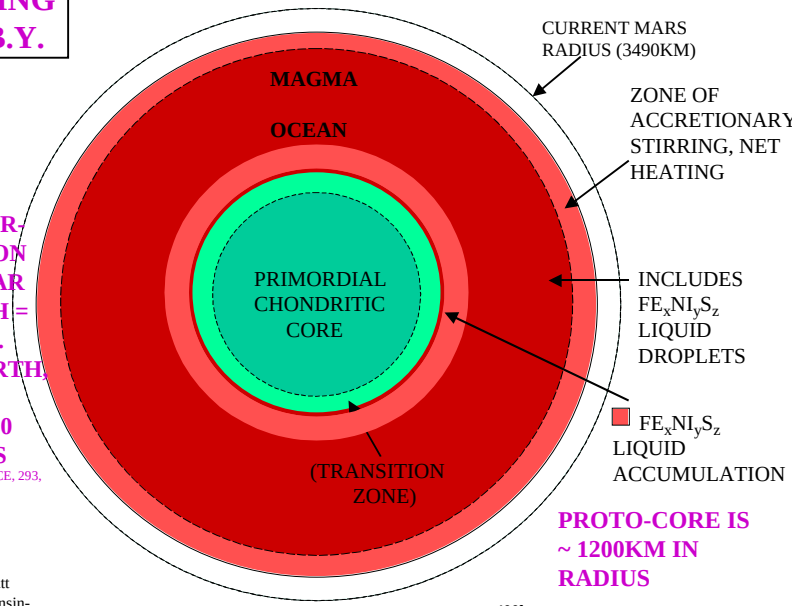


PROTO-CORE IS ~ 1200KM IN RADIUS

APOLLO MODEL OF MARS EVOLUTION

BEGINNING ~4.554+ B.Y.

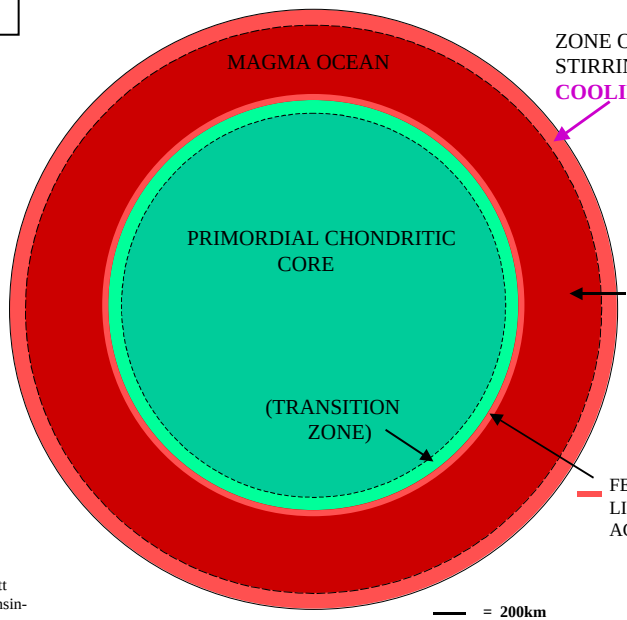
ASSUMES ACCRETION HISTORY SIMILAR TO MOON'S IN MORE WATER-RICH PORTION OF THE SOLAR NEBULA. (D/H = ~300 X 10^{-6} VS. ~150 FOR EARTH, ~20 FOR THE SUN, AND ~310 FOR COMETS ROBERT, F., 2001, SCIENCE, 293, 1056-1058)



PROTO-CORE IS ~ 1200KM IN RADIUS

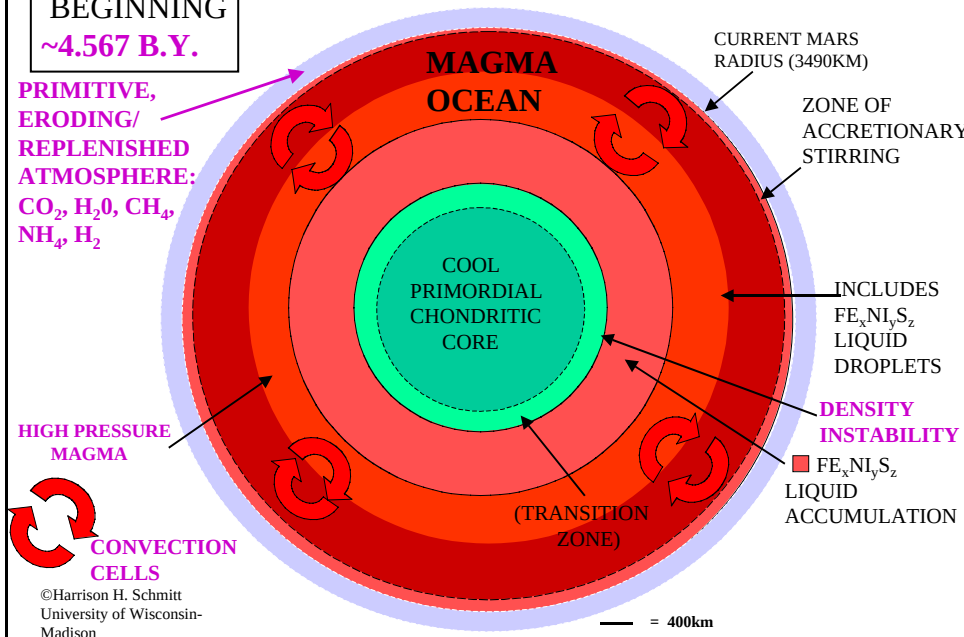
APOLLO MODEL OF LUNAR EVOLUTION

BEGINNING
~4.567 B.Y.



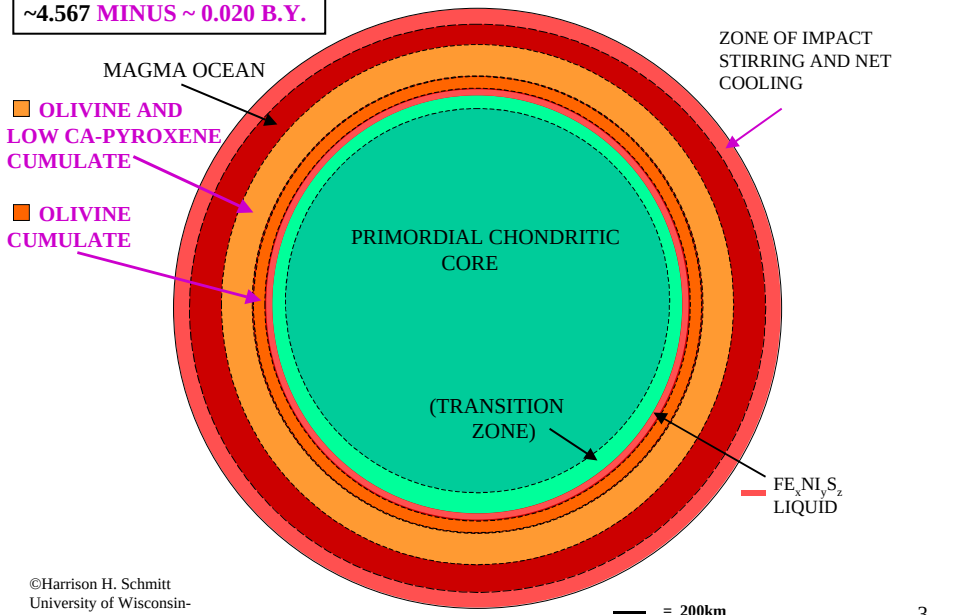
APOLLO MODEL OF MARS EVOLUTION

BEGINNING
~4.567 B.Y.



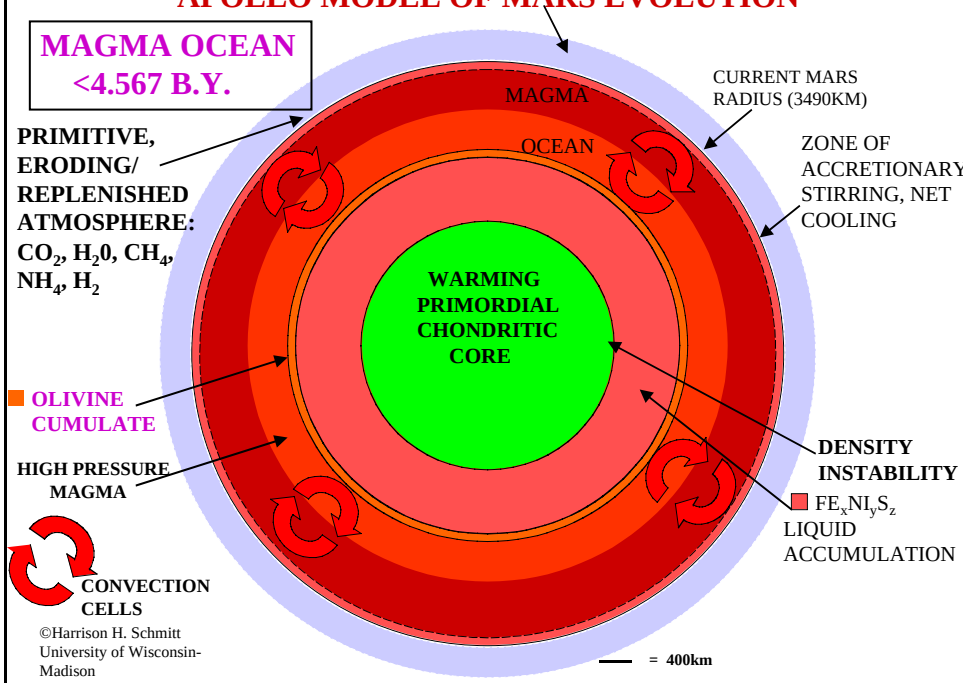
APOLLO MODEL OF LUNAR EVOLUTION

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



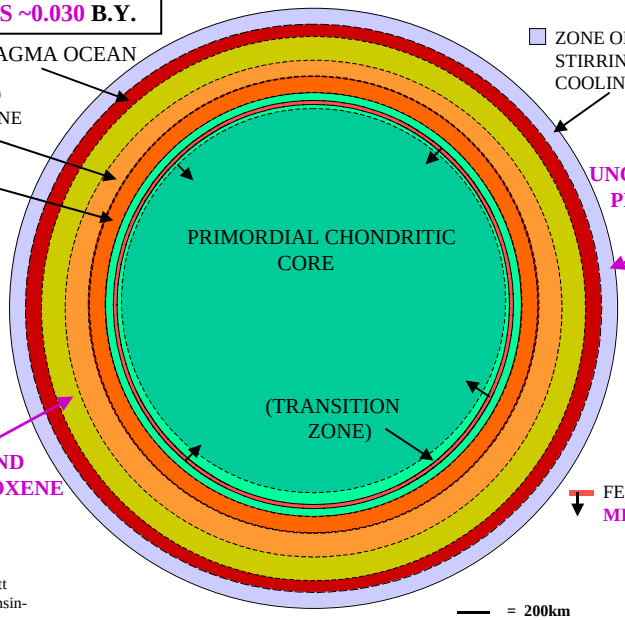
APOLLO MODEL OF MARS EVOLUTION

MAGMA OCEAN
<4.567 B.Y.



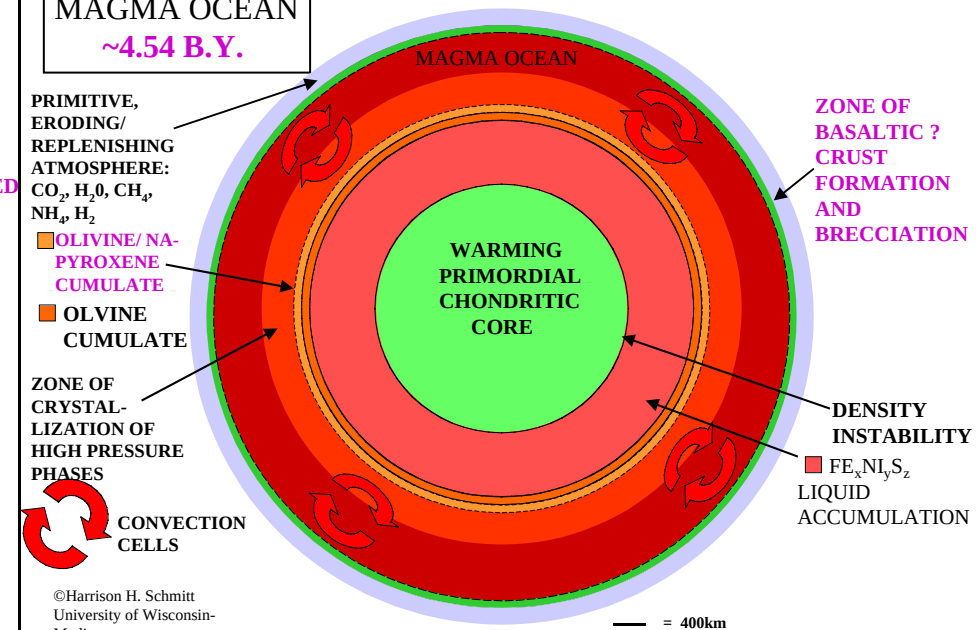
APOLLO MODEL OF LUNAR EVOLUTION

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



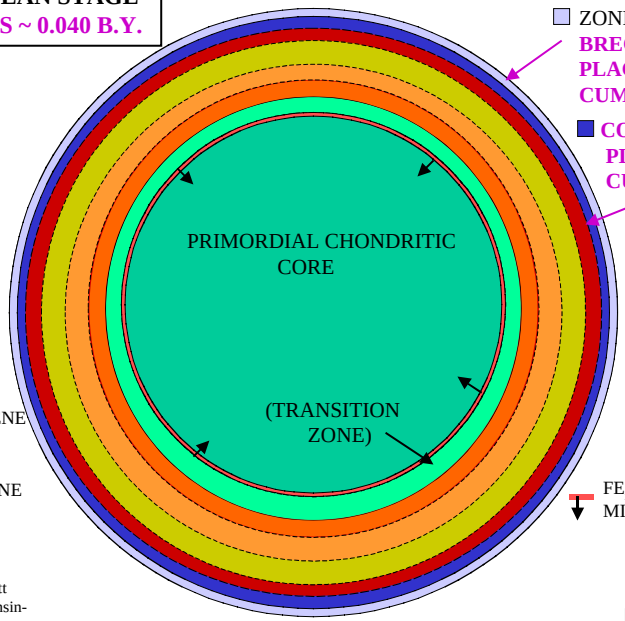
APOLLO MODEL OF MARS EVOLUTION

MAGMA OCEAN
~4.54 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

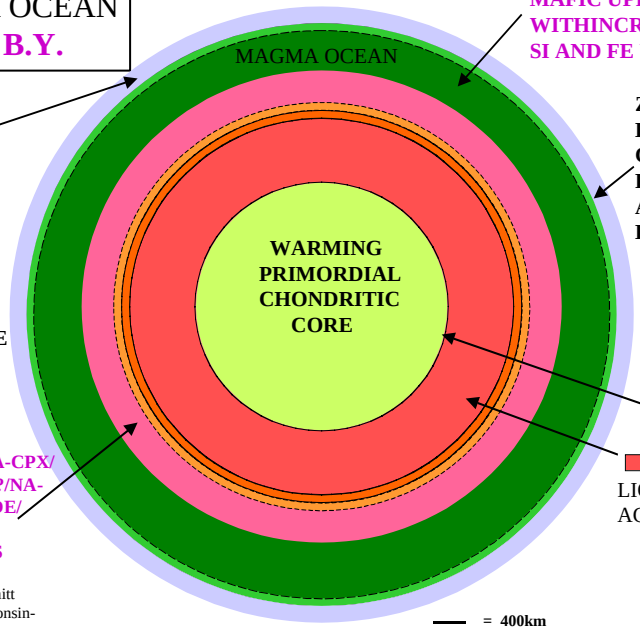
OLIVINE CUMULATE

$FE_xNI_yS_z$ LIQUID MIGRATION

= 200km

APOLLO MODEL OF MARS EVOLUTION

MAGMA OCEAN
~4.52 B.Y.



MAFIC UPPER MANTLE WITHINCREASING SI AND FE UPWARDS

PRIMITIVE, ERODING/ REPLENISHING ATMOSPHERE: CO_2, H_20, CH_4, NH_4, H_2

ZONE OF BASALTIC ? CRUST FORMATION AND BRECCIATION

OLIVINE/ NA-PYROXENE CUMULATE

OLVINE CUMULATE

DENSITY INSTABILITY

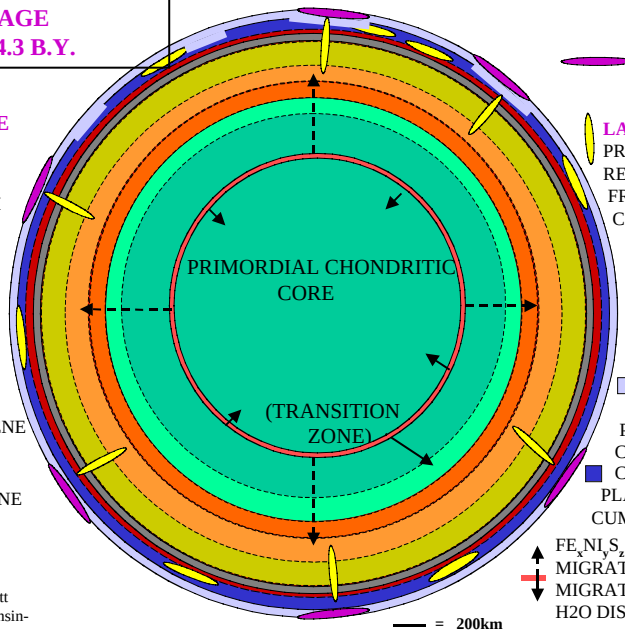
GARNET / NA-CPX/ NA-BIOTITE?/NA-HORNBLENDE/ "RUTILE" CUMULATES

$FE_xNI_yS_z$ LIQUID ACCUMULATION

= 400km

APOLLO MODEL OF LUNAR EVOLUTION

CRATERED HIGHLANDS STAGE ~4.5 - 4.3 B.Y.



MG-SUITE INTRUSIVES

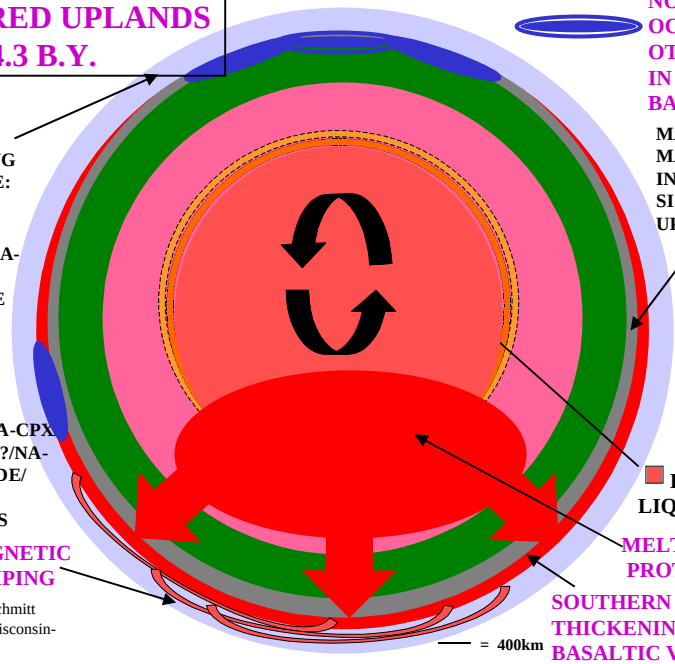
- OLIVINE, HIGH CA-PYROXENE, AND ILMENITE CUMULATE
- RESIDUAL MAGMA OCEAN (URKREEP LIQUID)
- OLIVINE AND HIGH CA-PYROXENE CUMULATE
- OLIVINE AND LOW CA-PYROXENE CUMULATE
- OLIVINE CUMULATE

- 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

APOLLO MODEL OF MARS EVOLUTION

CRATERED UPLANDS ~4.5 - 4.3 B.Y.



DENSE ERODING/ REPLENISHING ATMOSPHERE: CO_2, H_20

OLIVINE/ NA-PYROXENE CUMULATE

OLIVINE CUMULATE

GARNET / NA-CPX NA-BIOTITE?/NA-HORNBLENDE/ "RUTILE" CUMULATES

MAGNETIC STRIPING

NORTHERN OCEAN AND OTHER LAKES IN VERY LARGE BASINS

MAFIC UPPER MANTLE WITH INCREASING SI AND FE UPWARDS

ZONE OF INTENSE CRATERING AND EROSION

$FE_xNI_yS_z$ LIQUID CORE

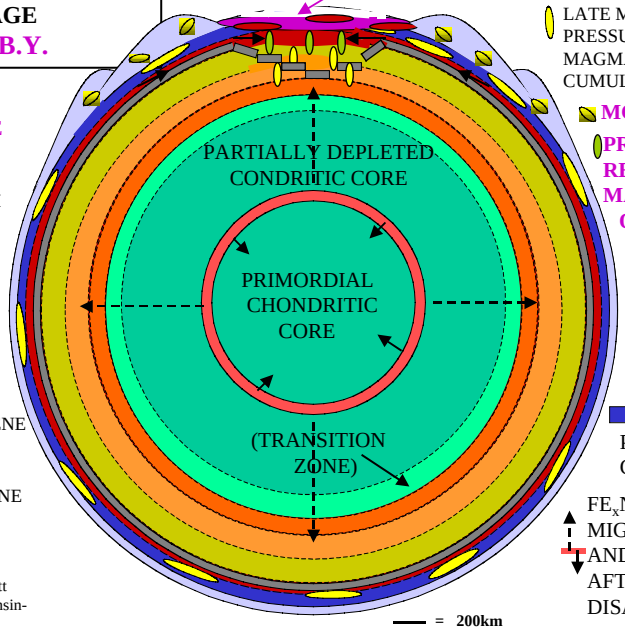
MELTING/RISING PROTO-CORE

SOUTHERN CRUSTAL THICKENING AND BASALTIC VOLCANISM

= 400km

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

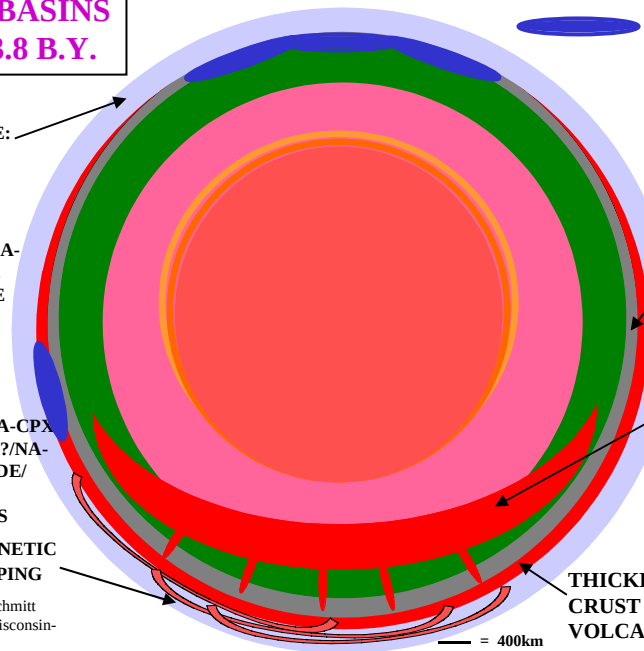
CONSOLIDATED PLAGIOCLASE CUMULATE

$FE_xNI_yS_z$ LIQUID MIGRATION AND H MIGRATION AFTER H_20 DISASSOCIATION

= 200km

APOLLO MODEL OF MARS EVOLUTION

LARGE BASINS
~4.2 - 3.8 B.Y.



EARLY NORTHERN OCEAN AND OTHER LAKES WITH CYCLIC SEDIMENTATION

THINNING ATMOSPHERE: CO_2, H_20

MAFIC UPPER MANTLE WITH INCREASING SI AND FE UPWARDS

OLIVINE/ NA-PYROXENE CUMULATE

OLIVINE CUMULATE

ZONE OF MEGA-REGOLITH AND EROSION

GARNET / NA-CPX NA-BIOTITE?/NA-HORNBLENDE/ "RUTILE" CUMULATES

RELIC PROTO-CORE ?

$FE_xNI_yS_z$ CORE

MAGNETIC STRIPING

THICKENED SOUTHERN CRUST AND BASALTIC VOLCANICS

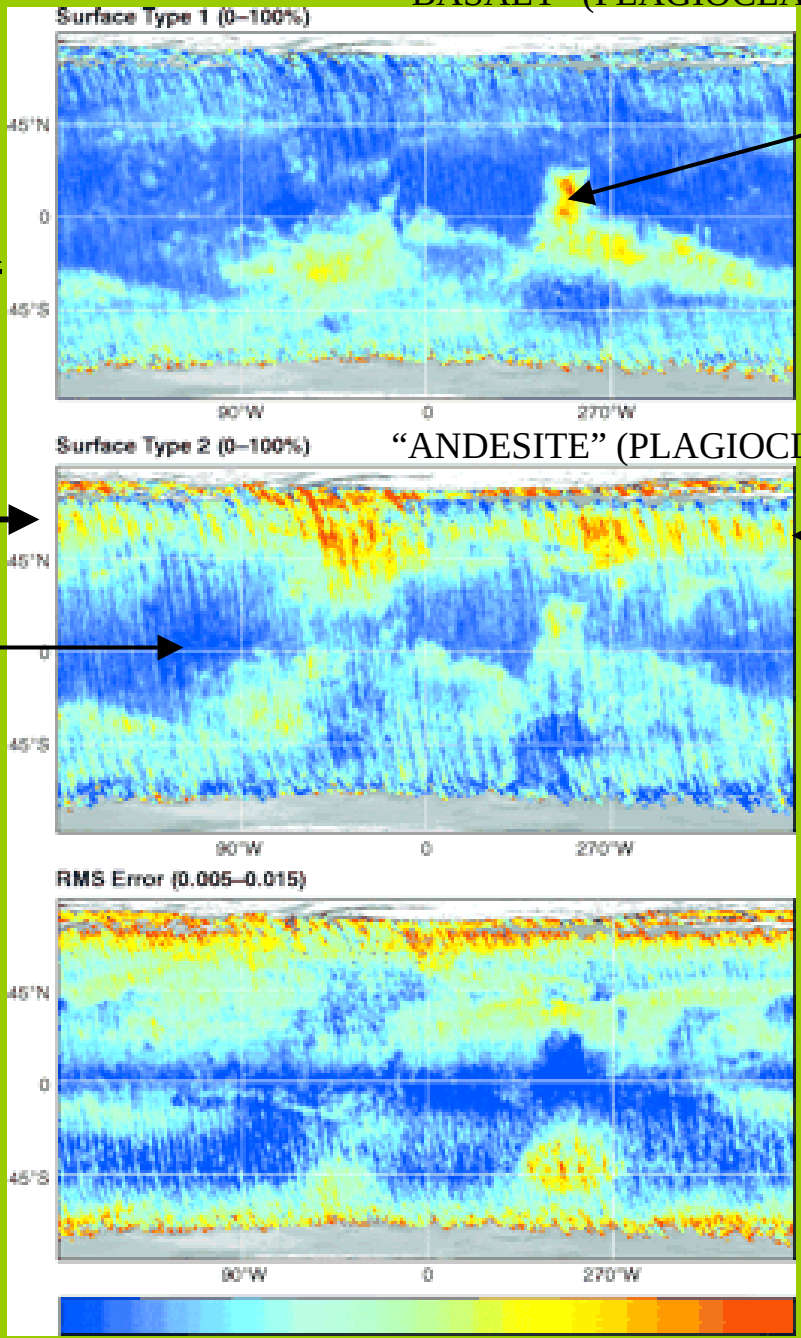
= 400km

COMPARISON OF THE EVOLUTION OF THE

HARRISON H. SCHMITT
UNIVERSITY OF WISCONSIN-MADISON

MGS THERMAL EMISSION SPECTROMETER DATA ON <u>BEDROCK</u> MINERALOGY

"BASALT" (PLAGIOCLASE AND CLINOPYROXENE)



ARABIA TERRA (CRATERED UPLAND)

"ANDESITE" (PLAGIOCLASE AND GLASS)

VASTITAS BOREALIS NORTHERN LOWANDS

THARSIS RISE

BANDFIELD, J.L., AND CO-WORKERS
2000, SCIENCE, 287, PP. 1626-1630