Mineralogy and History of Mars

Les Houches, 29 / 03 / 2010

Mineralogy and History of Mars

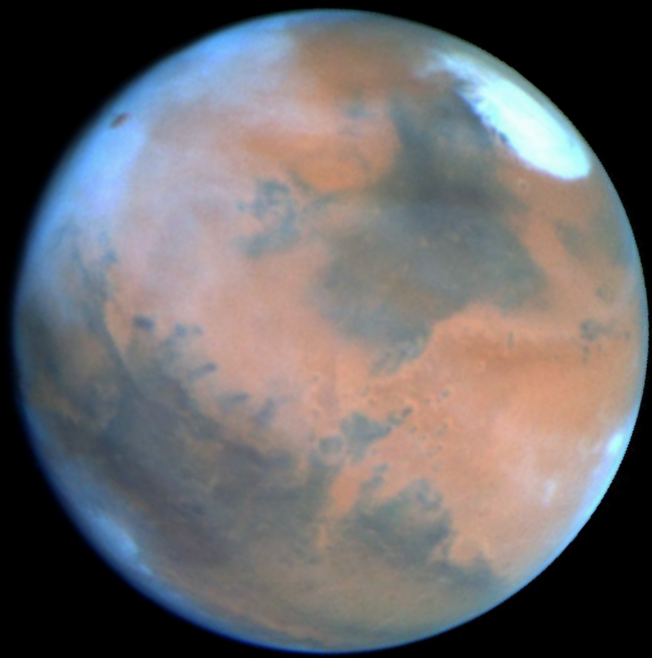
Jean-Pierre Bibring

IAS

Institut d'Astrophysique Spatiale

Orsay, France

on behalf of the entire OMEGA team



Les Houches, 29 / 03 / 2010

Mineralogy and History of Mars

Jean-Pierre Bibring

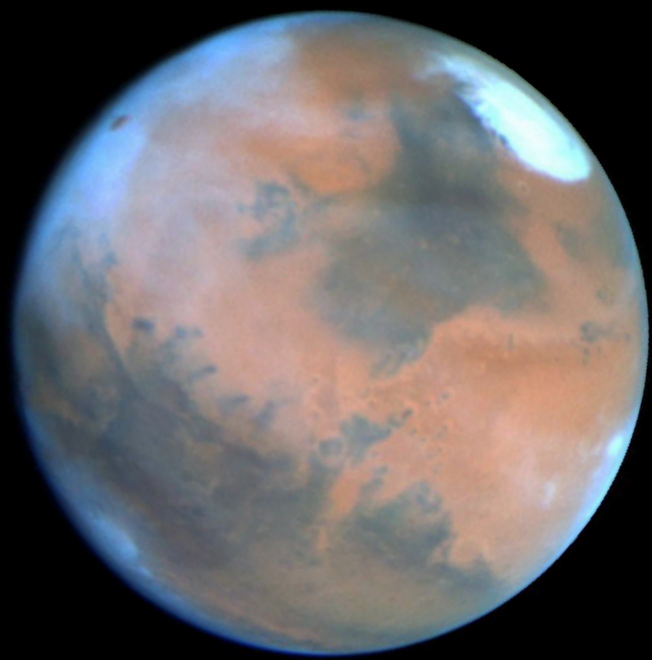
IAS

Institut d'Astrophysique Spatiale

Orsay, France

on behalf of the entire OMEGA team

Deep thanks to all @ CNES and ESA who made/make our venture a gorgeous reality



Les Houches, 29 / 03 / 2010

Mineralogy and History of Mars

Jean-Pierre Bibring

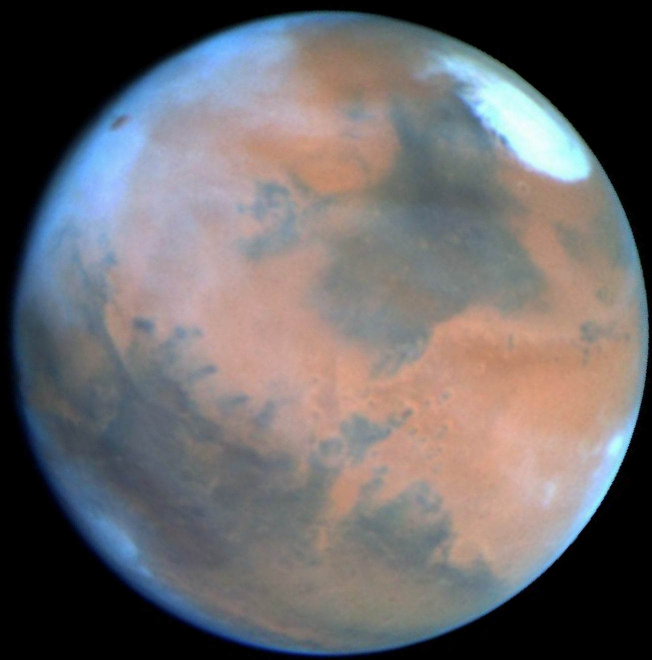
IAS

Institut d'Astrophysique Spatiale

Orsay, France

on behalf of the entire OMEGA team

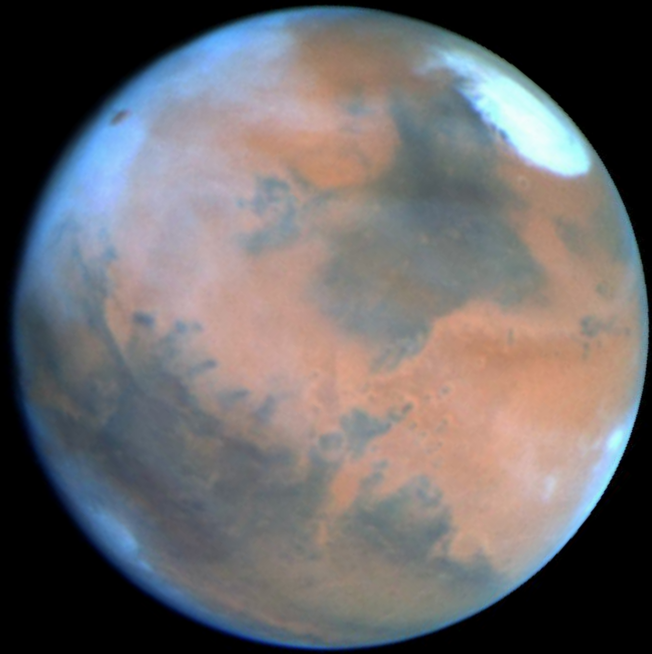
bibring @ ias.fr



Les Houches, 29 / 03 / 2010

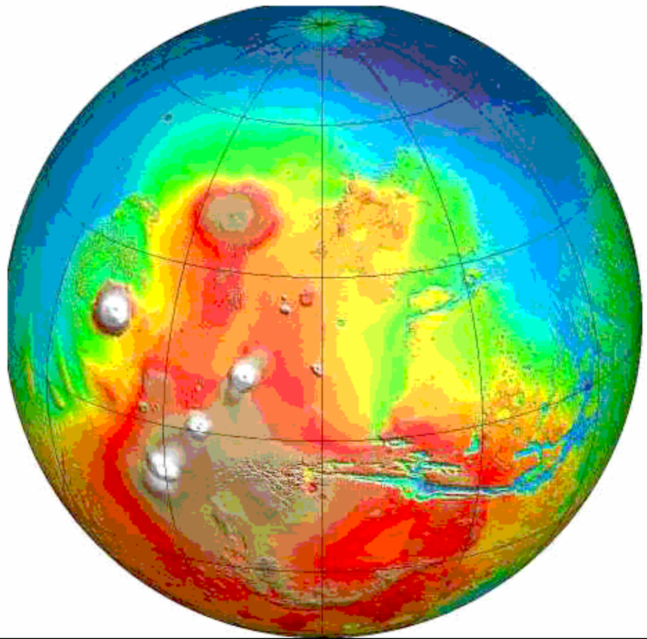
Mineralogy and History of Mars

Until recently, Mars History was primarily derived from optical images and topography, interpreted with reference to lunar (impacts) and terrestrial processes (volcanism, fluvial activity, erosion, frosting and ice deposition etc…).



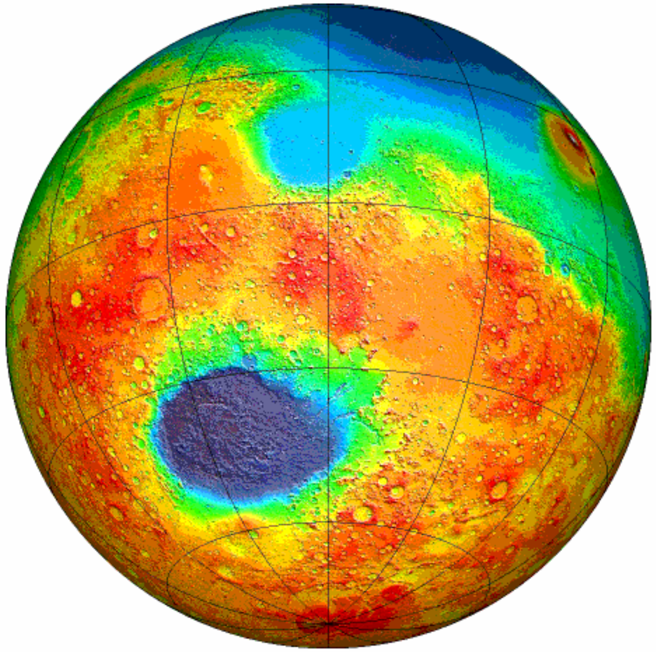
Mineralogy and History of Mars

Until recently, Mars History was primarily derived from optical images and topography, interpreted with reference to lunar (impacts) and terrestrial processes (volcanism, fluvial activity, erosion, frosting and ice deposition etc…).



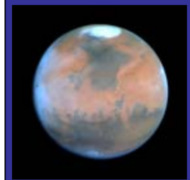
Mineralogy and History of Mars

Until recently, Mars History was primarily derived from optical images and topography, interpreted with reference to lunar (impacts) and terrestrial processes (volcanism, fluvial activity, erosion, frosting and ice deposition etc…).



Les Houches, 29 / 03 / 2010

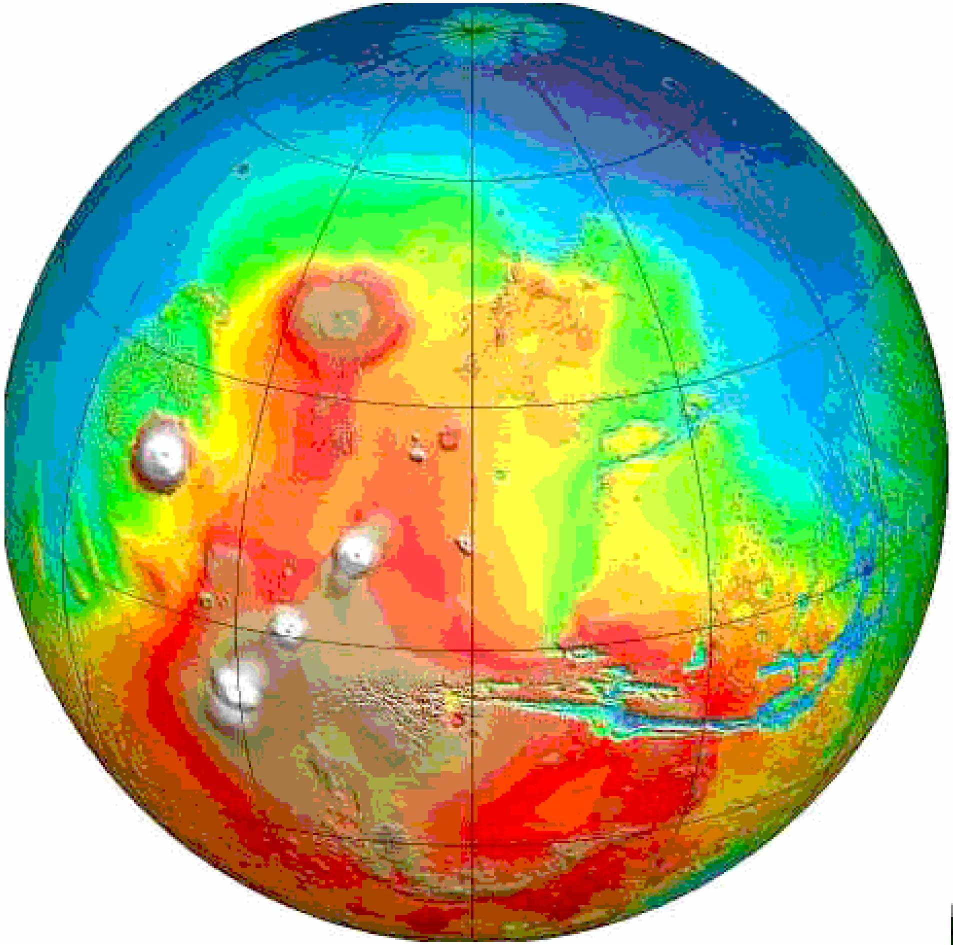
birth		now



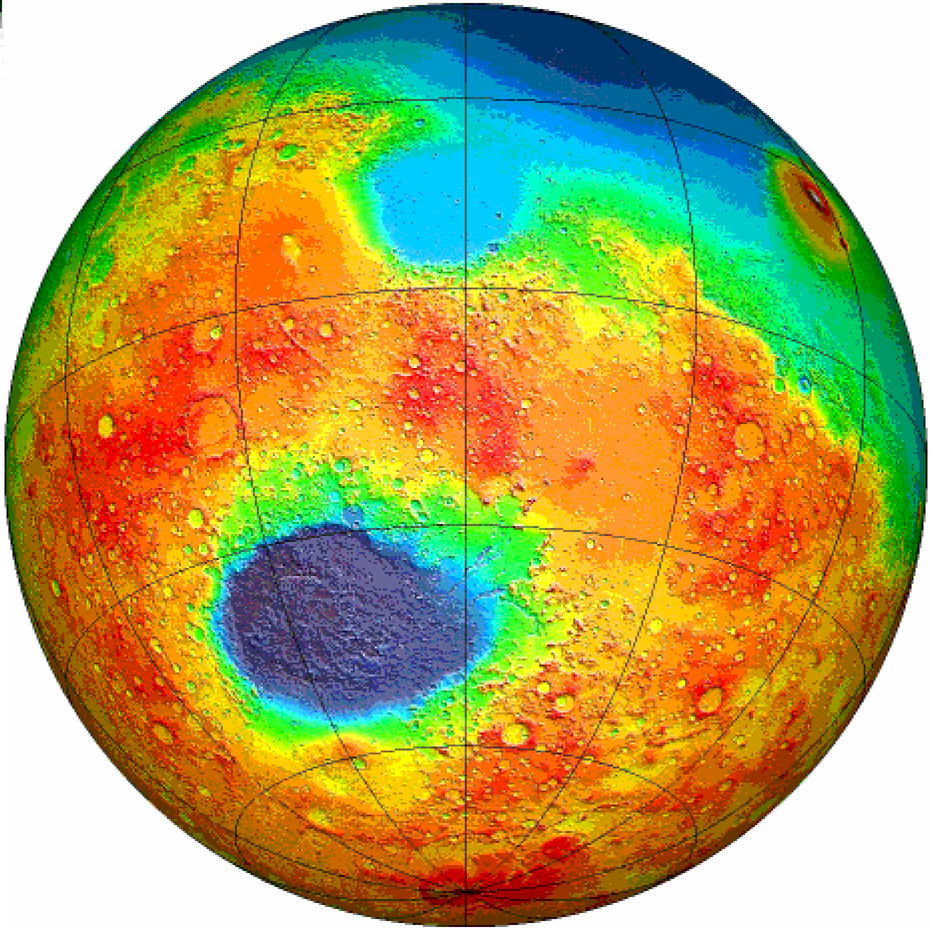
Noachian	Hesperian	Amazonian

heavy bombardment

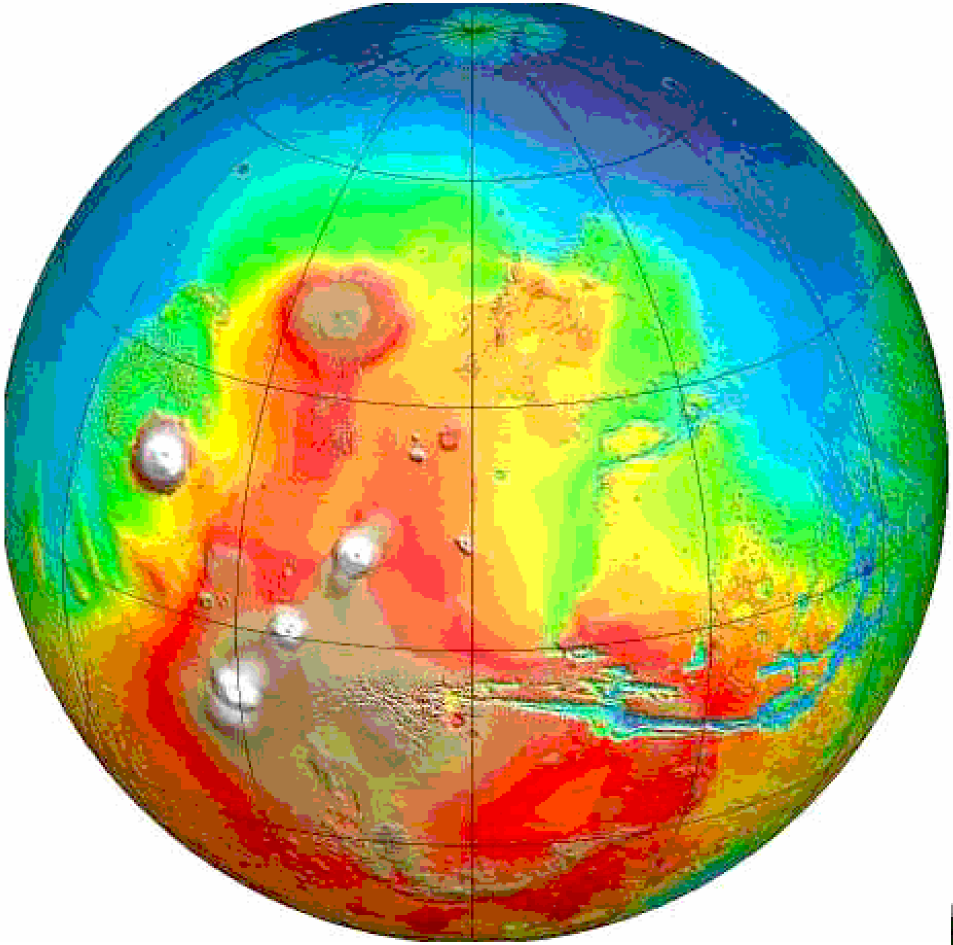
Mars History derived from surface structures
exhibits three long-standing eras,
defined by an exogenous trigger (impacts),
during which a variety of transient processes have occurred:
volcanism, fluvial an glacial activity...



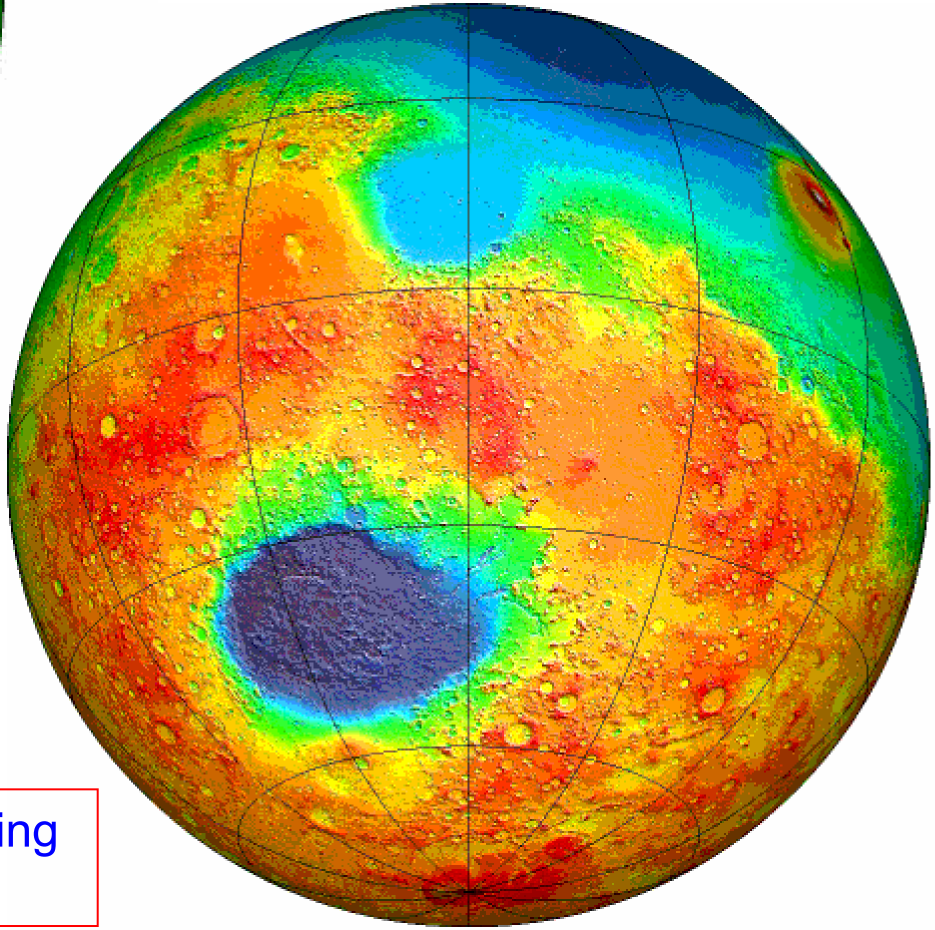
MGS / MOLA



Mars exhibits a variety of units, recording a sequence of processes, both long-standing/sustained and transient, preserved all along its History.

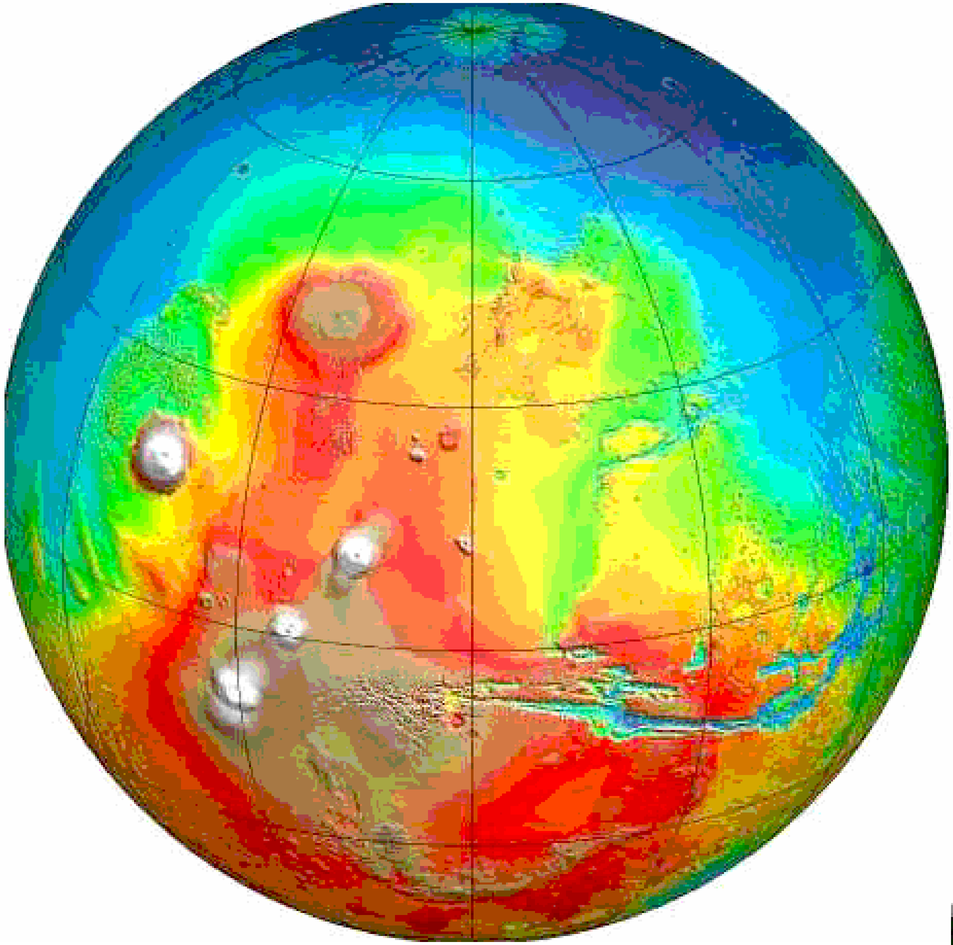


MGS / MOLA

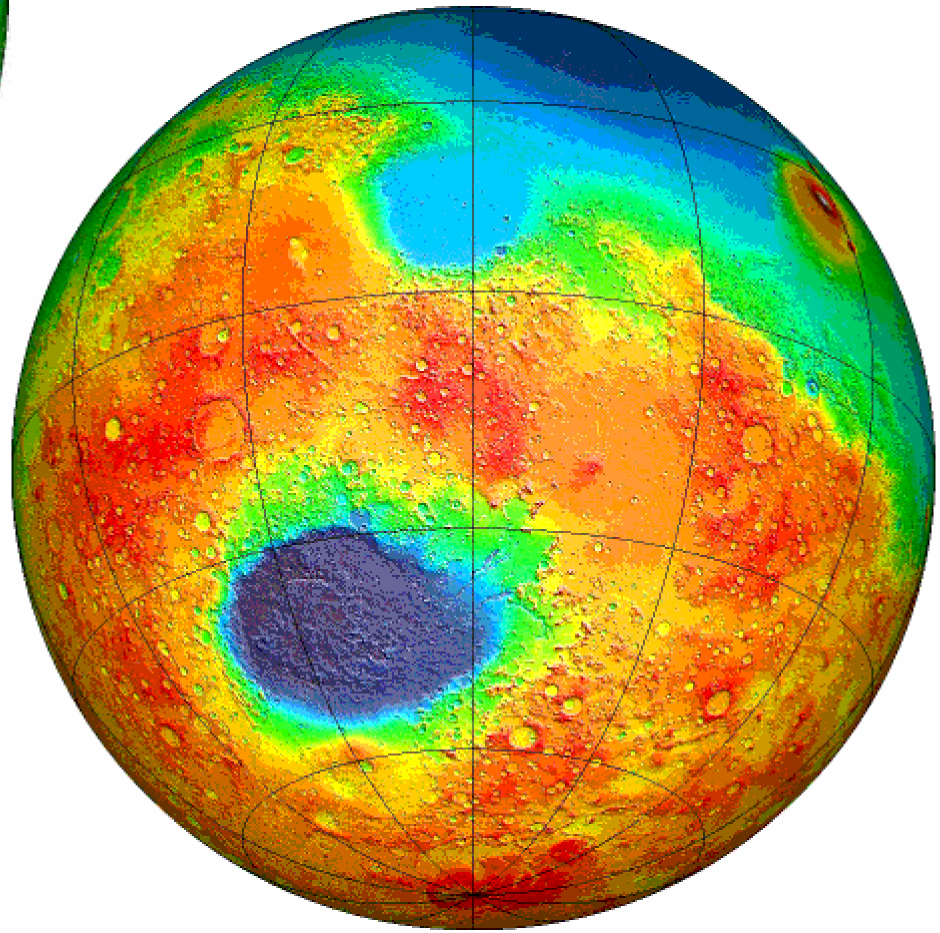


Mars exhibits a variety of units, recording a sequence of processes, both long-standing/sustained and transient, preserved all along its History.

To derive an History from units requires dating and characterizing the relevant processes.



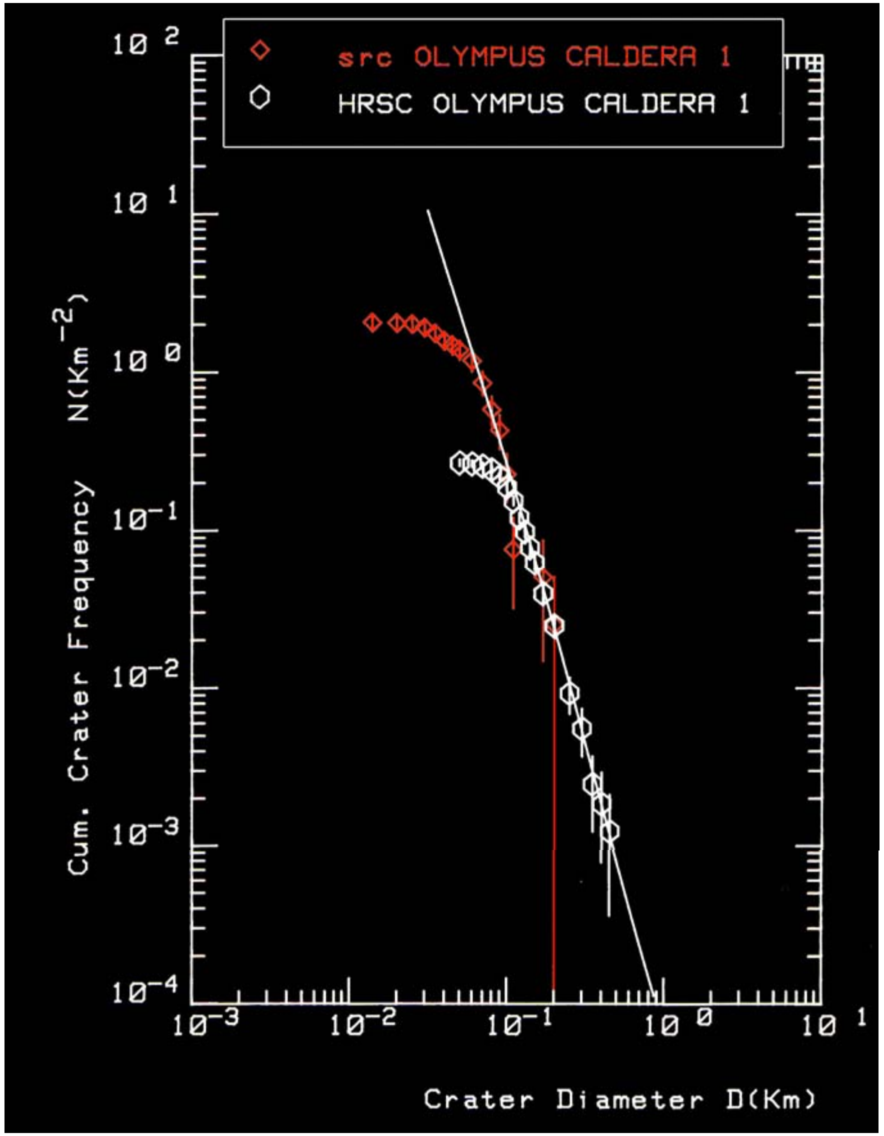
MGS / MOLA

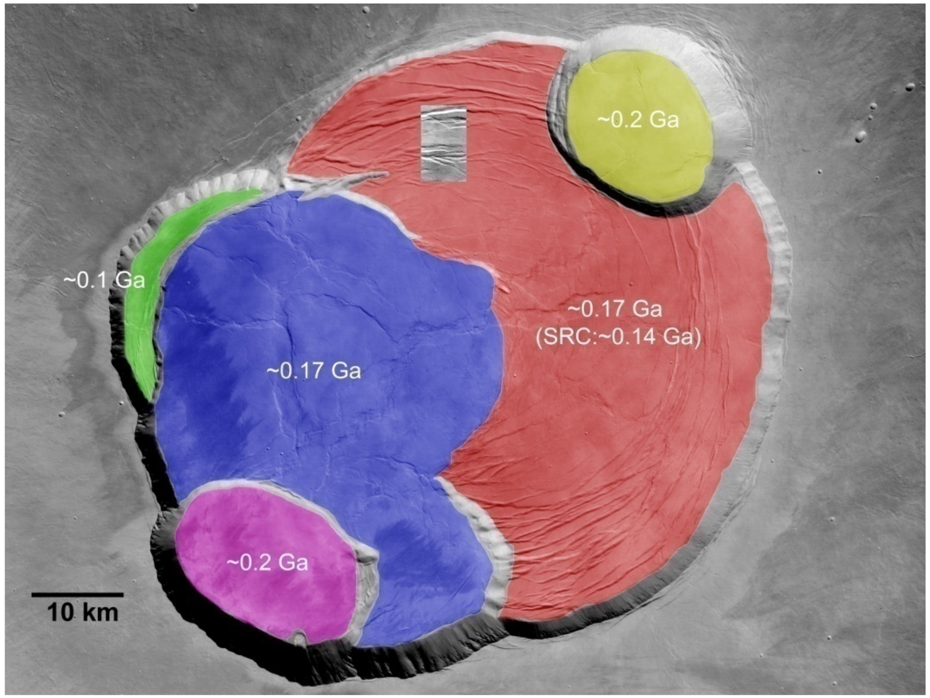


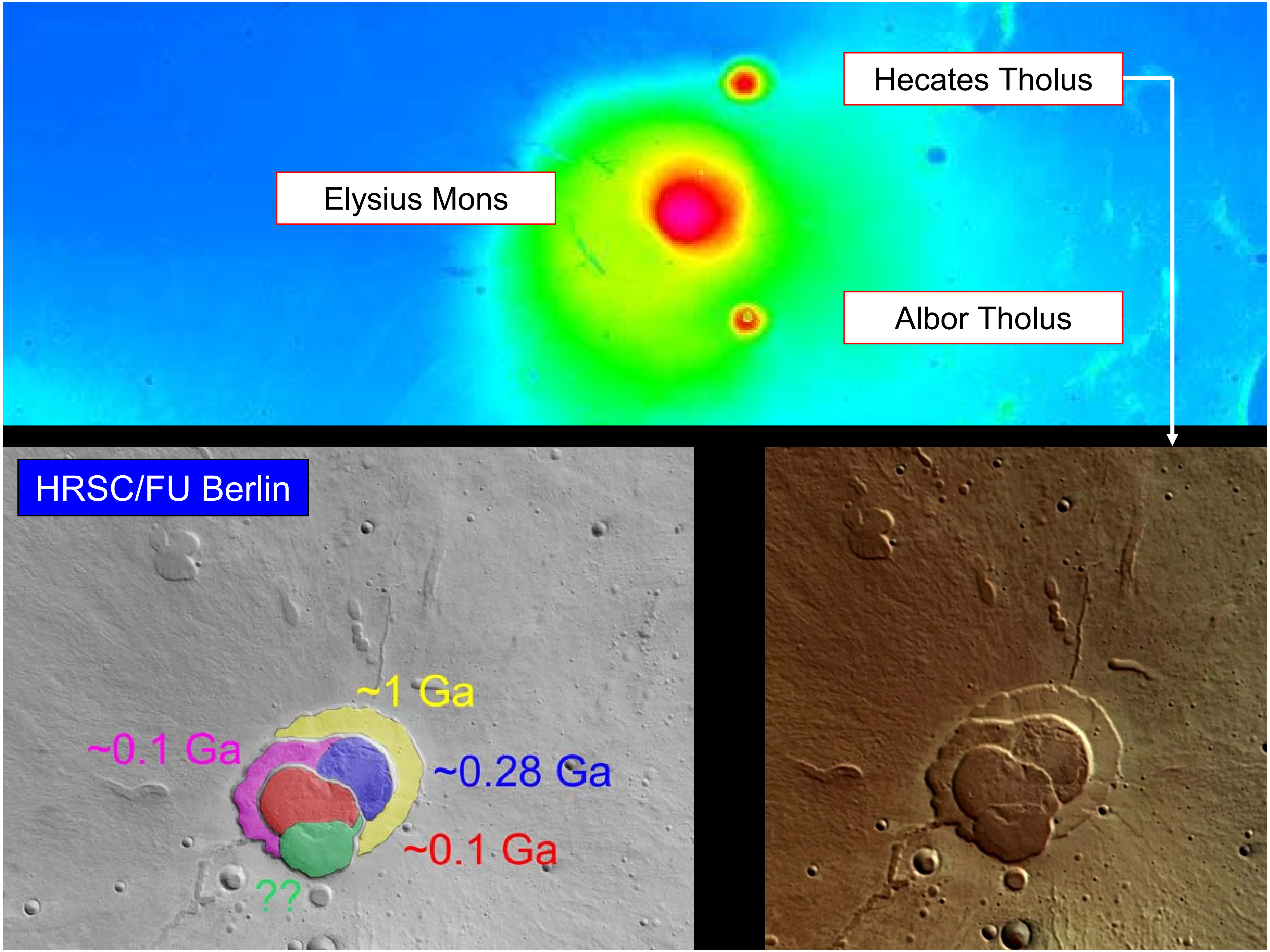
Dating and chronology are derived (primarily and efficiently) from crater sizing and counting, noticeably for transient processes (e.g. volcanism).

Olympus caldera

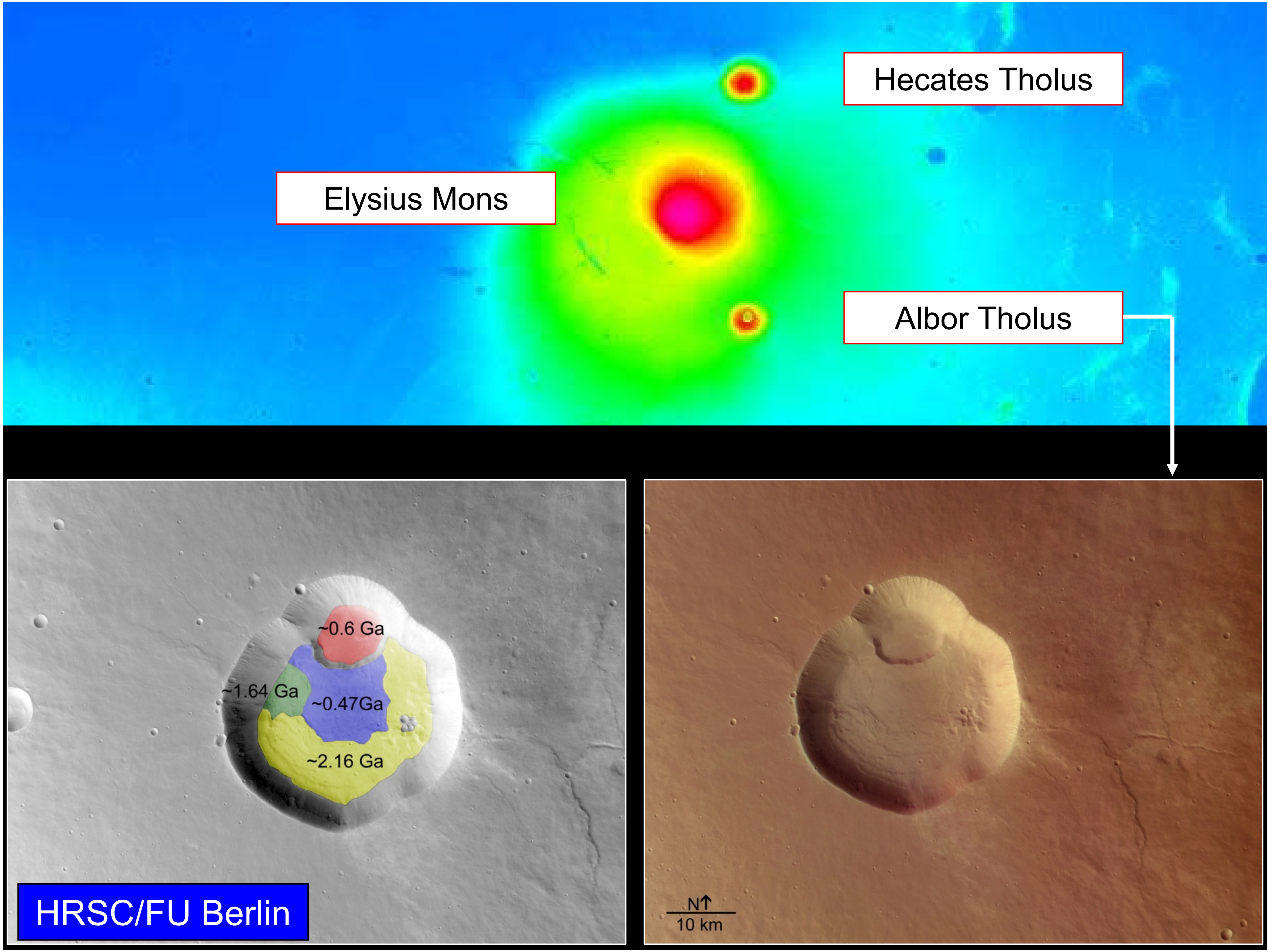
HRSC/FU Berlin



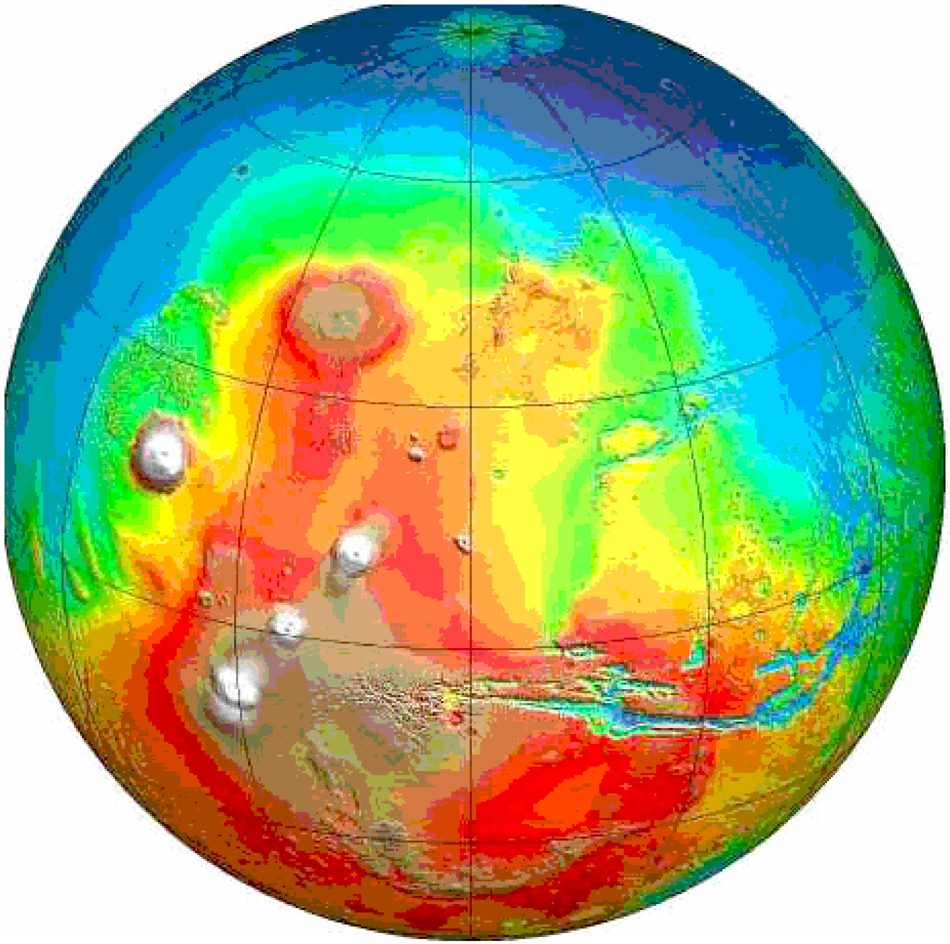




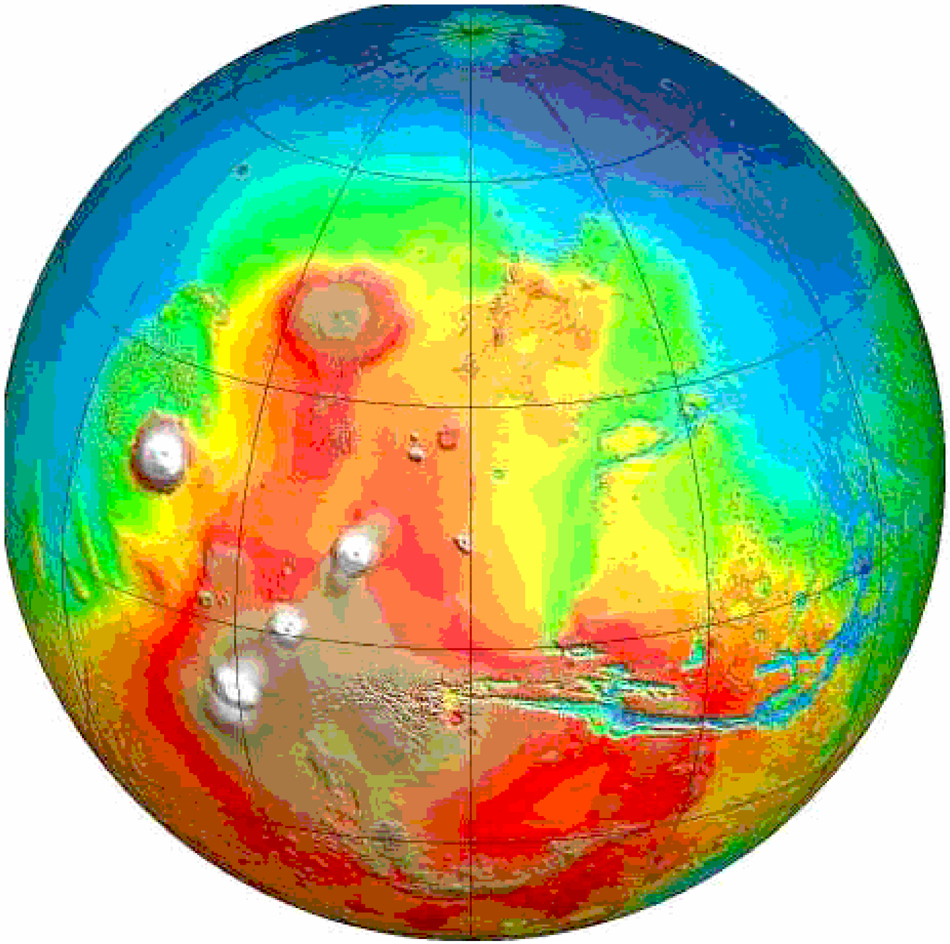
Hecates Tholus
Elysius Mons
Albor Tholus
HRSC/FU Berlin
~1 Ga
~0.1 Ga
~0.28 Ga
~0.1 Ga
??


Hecates Tholus
Elysius Mons
Albor Tholus
~0.6 Ga
~1.64 Ga
~0.47Ga
~2.16 Ga
HRSC/FU Berlin
N
10 km

Most volcanoes operated over the entire Mars lifetime, a small number of times, in a rather limited way, till ~ now

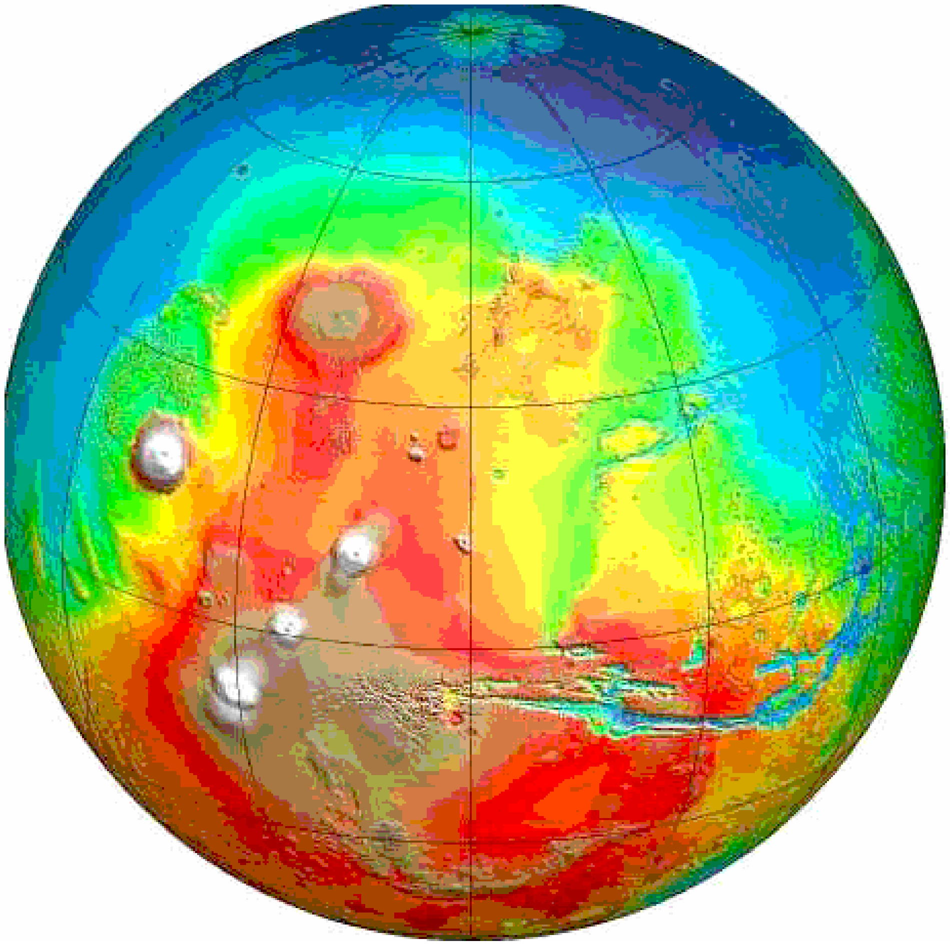


Most volcanoes operated over the entire Mars lifetime, a small number of times, in a rather limited way, till ~ now

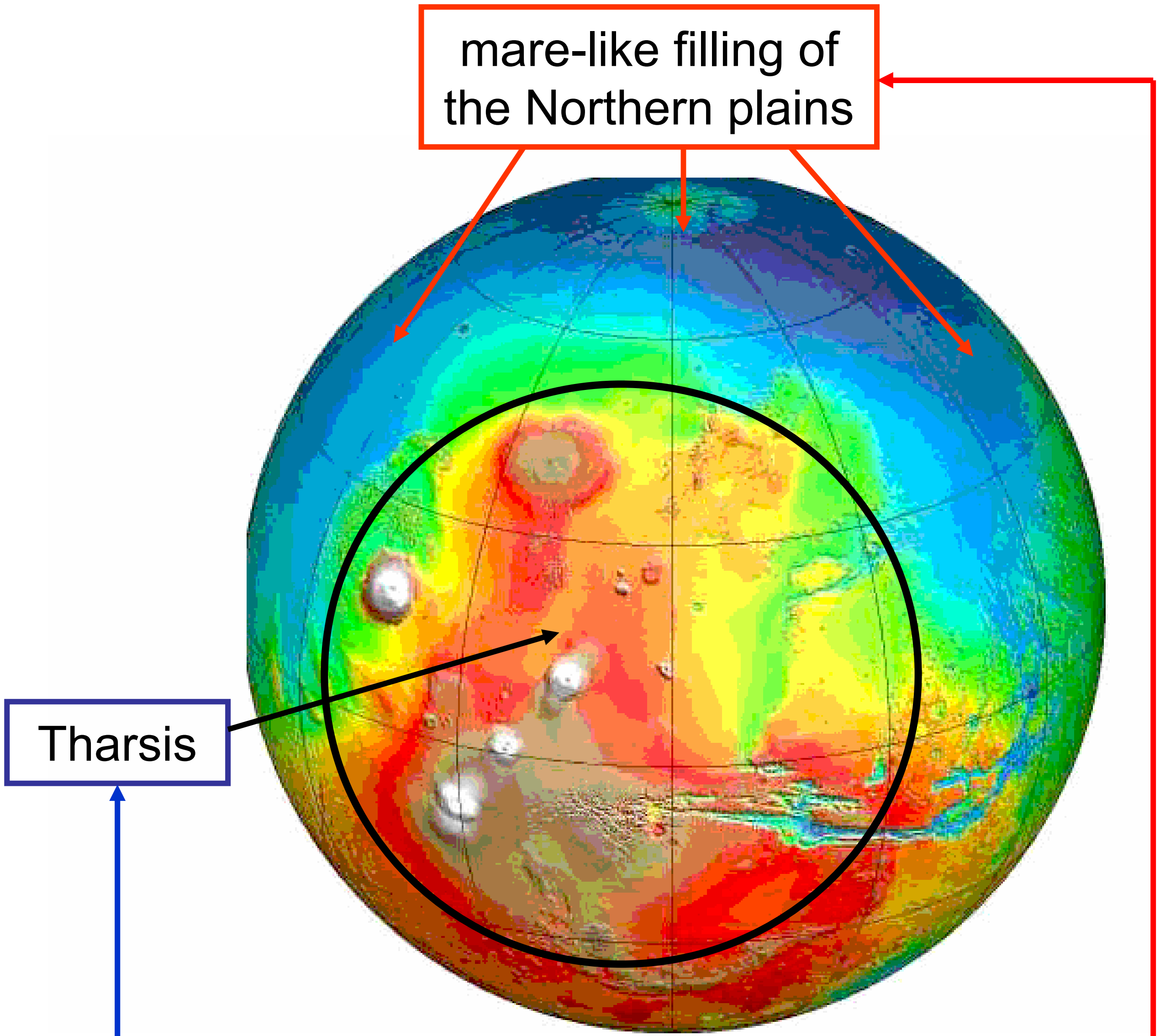


To assess the present level of internal activity (Mars degree of geological death), a seismological network mission should be implemented.

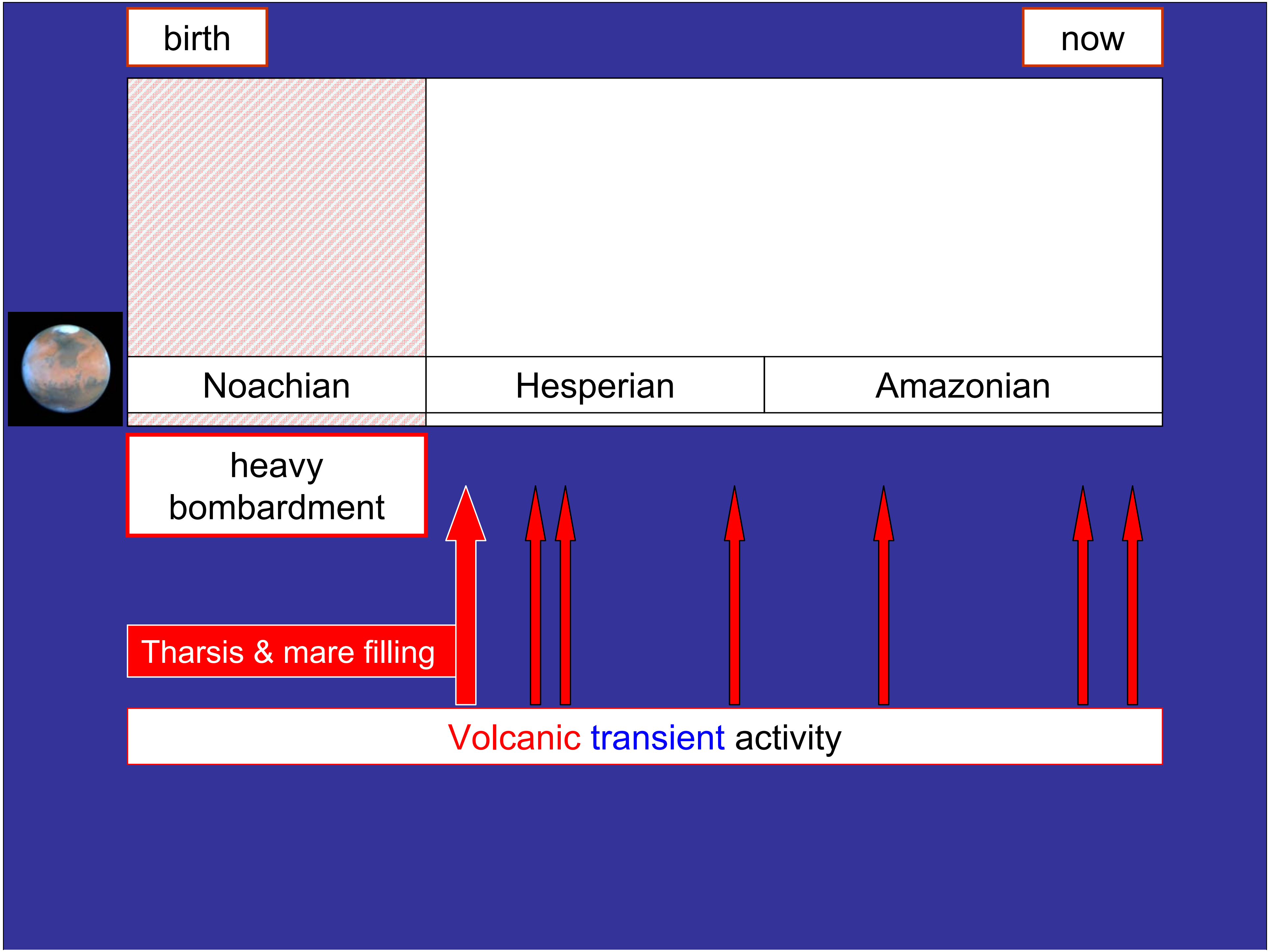
Most volcanoes operated over the entire Mars lifetime, a small number of times, in a rather limited way, till ~ now

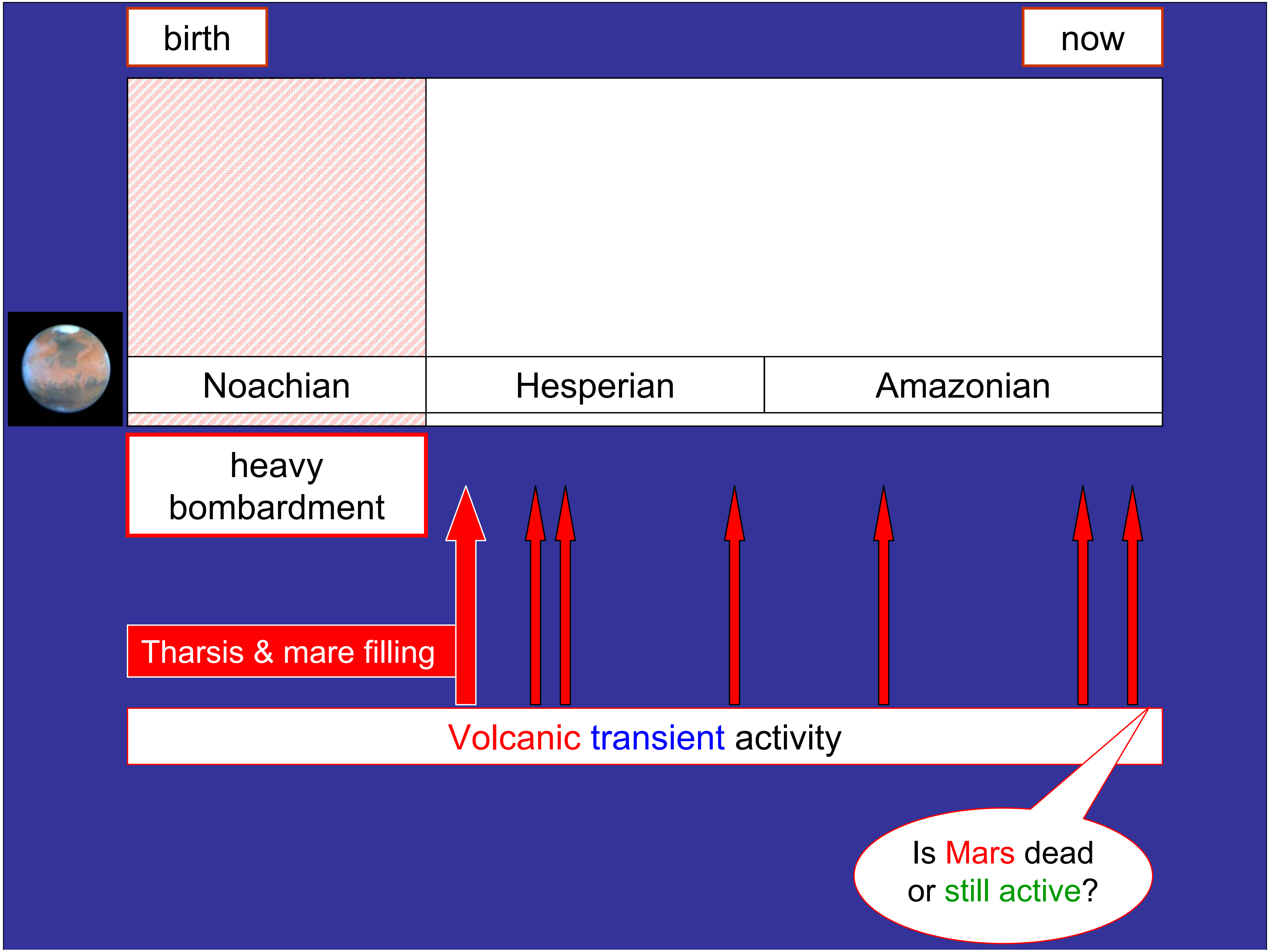


But, the utmost of volcanic activity, does not come from volcanoes…

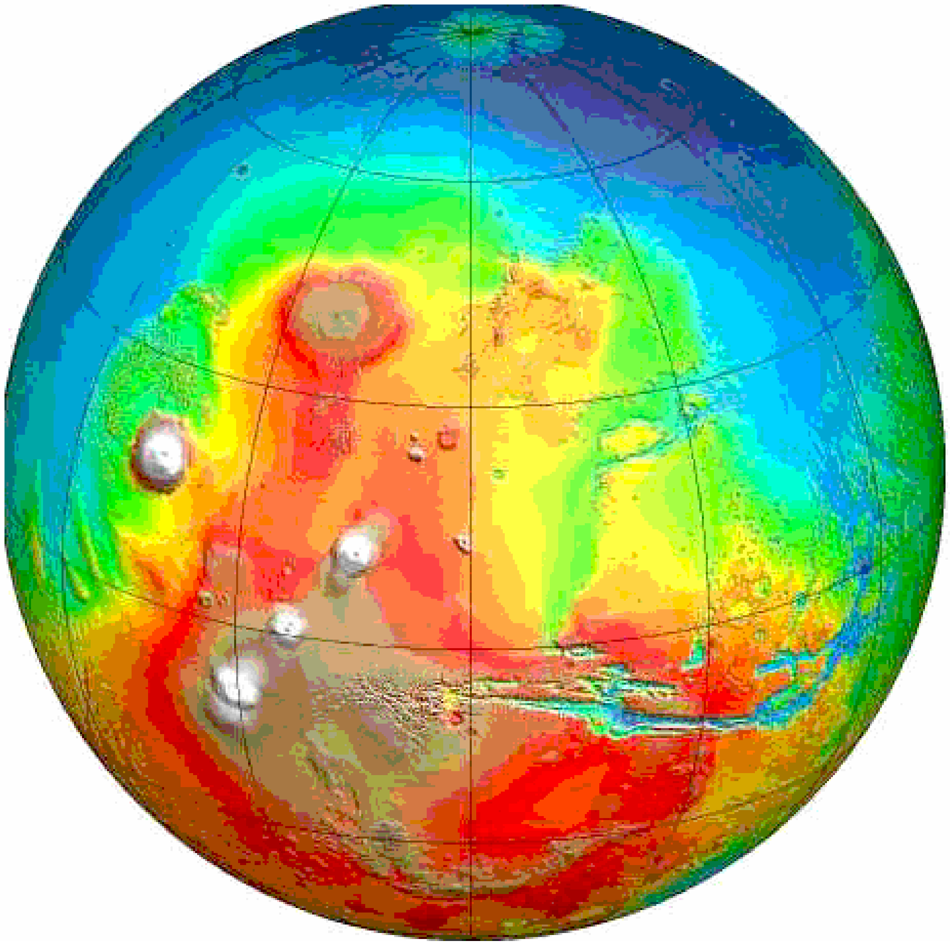


Tharsis building and filling the Northern plains constitute the major volcanic event, pre-dating the volcanoes activity, but post heavy bombardment.


birth
now
Noachian
Hesperian
Amazonian
heavy bombardment
Tharsis & mare filling
Volcanic transient activity

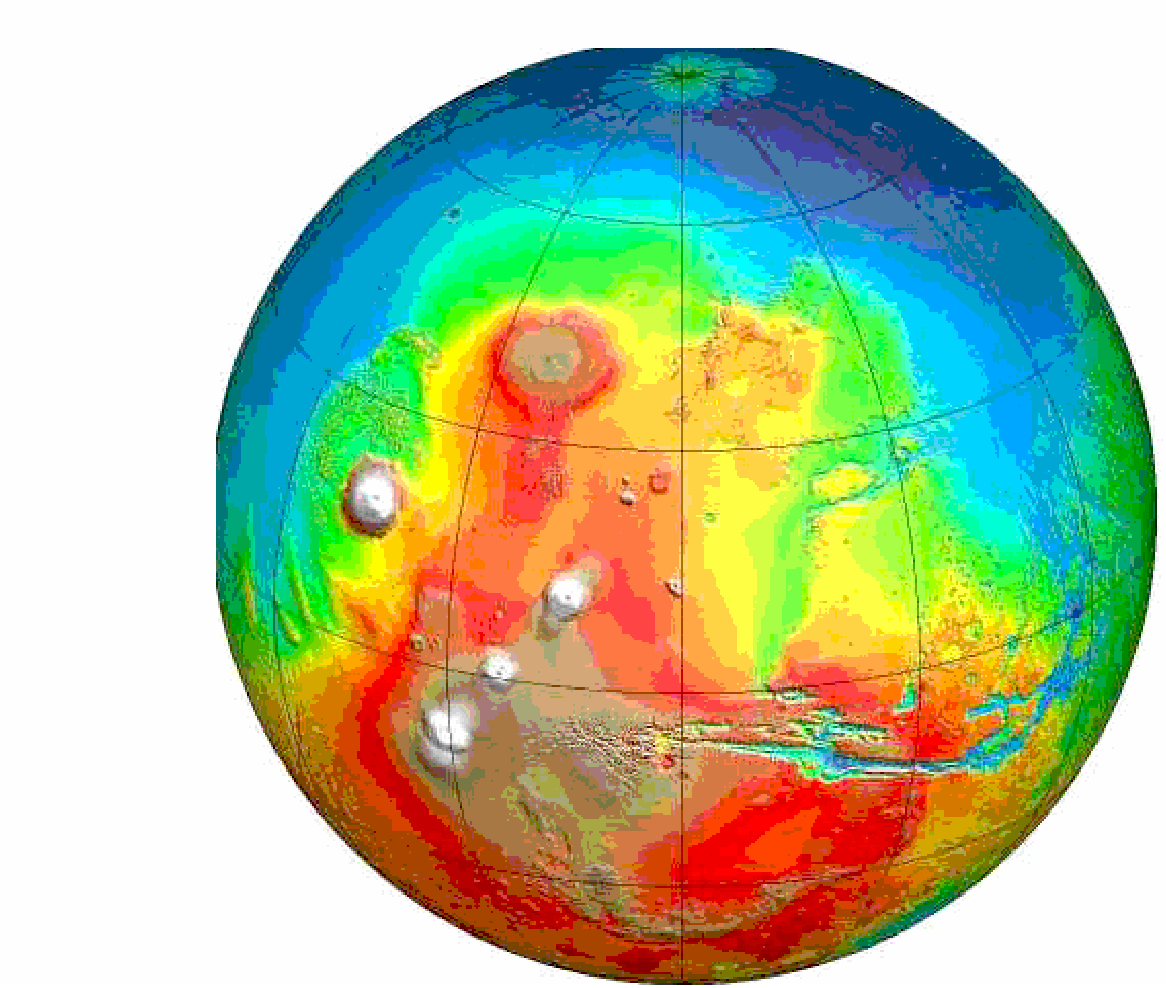

birth
now
Noachian
Hesperian
Amazonian
heavy bombardment
Tharsis & mare filling
Volcanic transient activity
Is Mars dead or still active?

is Mars still active?



Even if magma is no more surface supplied, is the outgassing also stopped, or is the present atmosphere still resulting from venting?

is Mars still active?

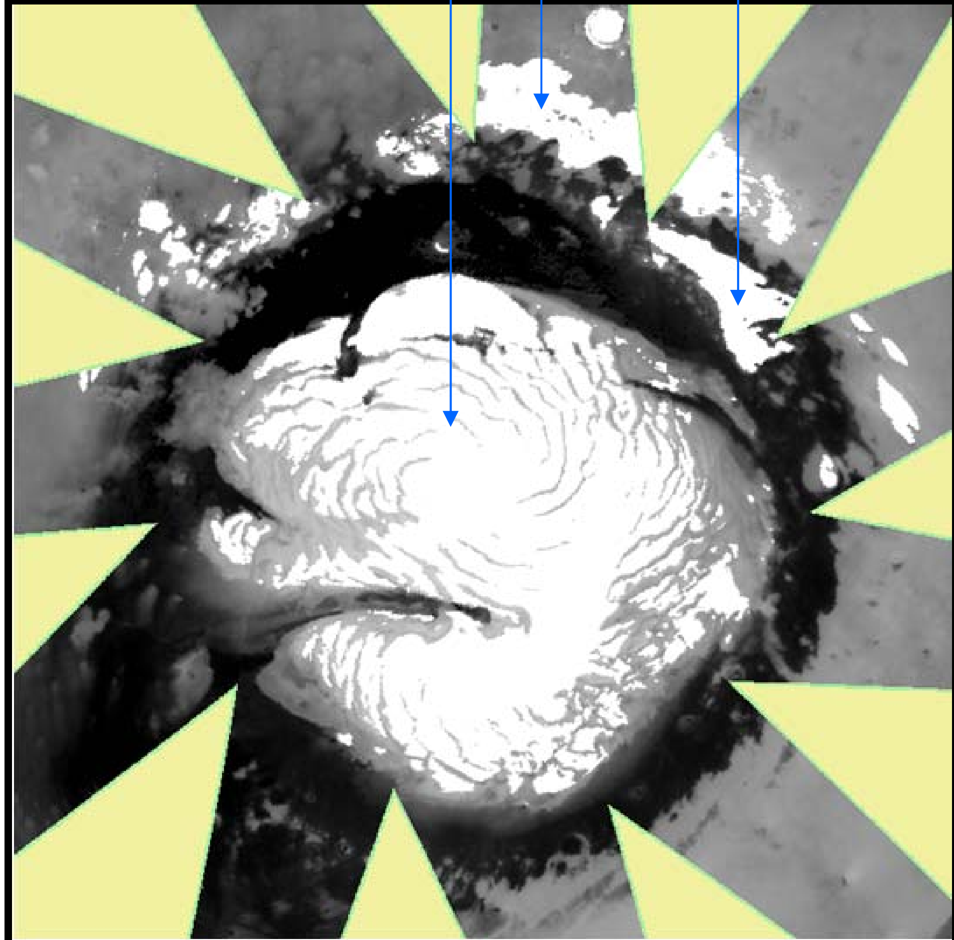


There are several lines of evidence (gypsum, methane?) that
Mars is still venting

Perennial northern polar cap

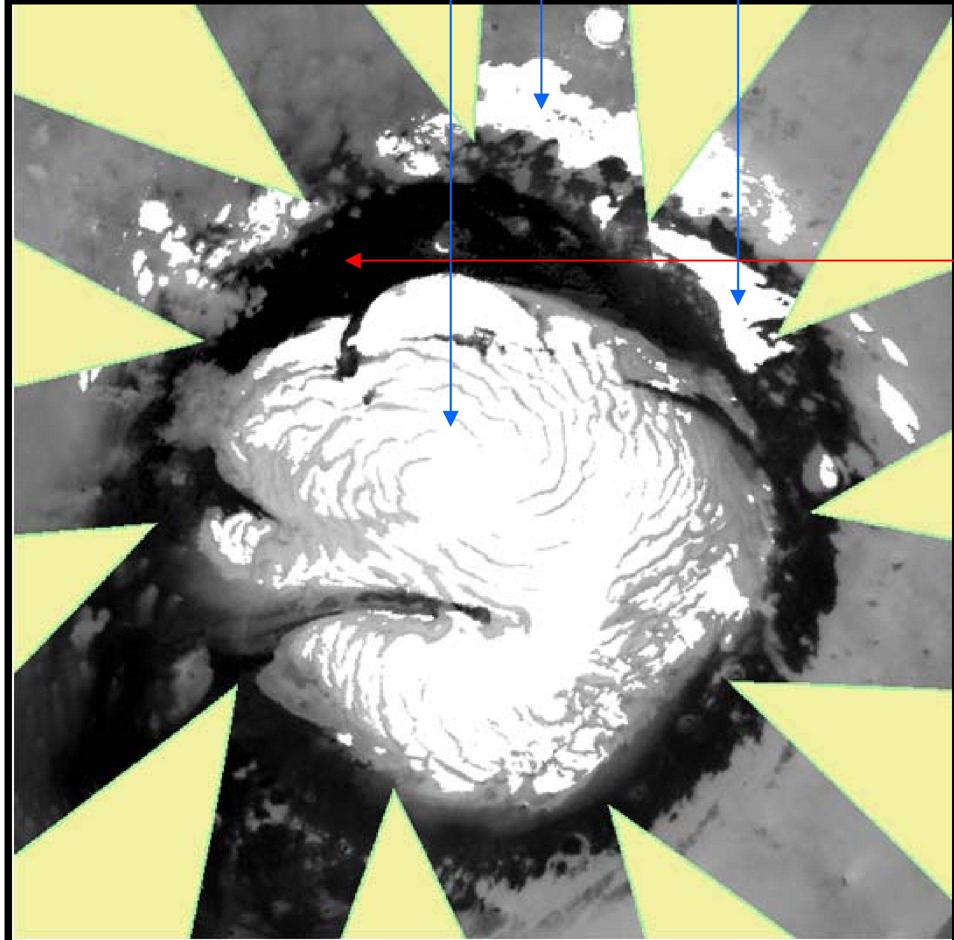
(Y. Langevin et al.)

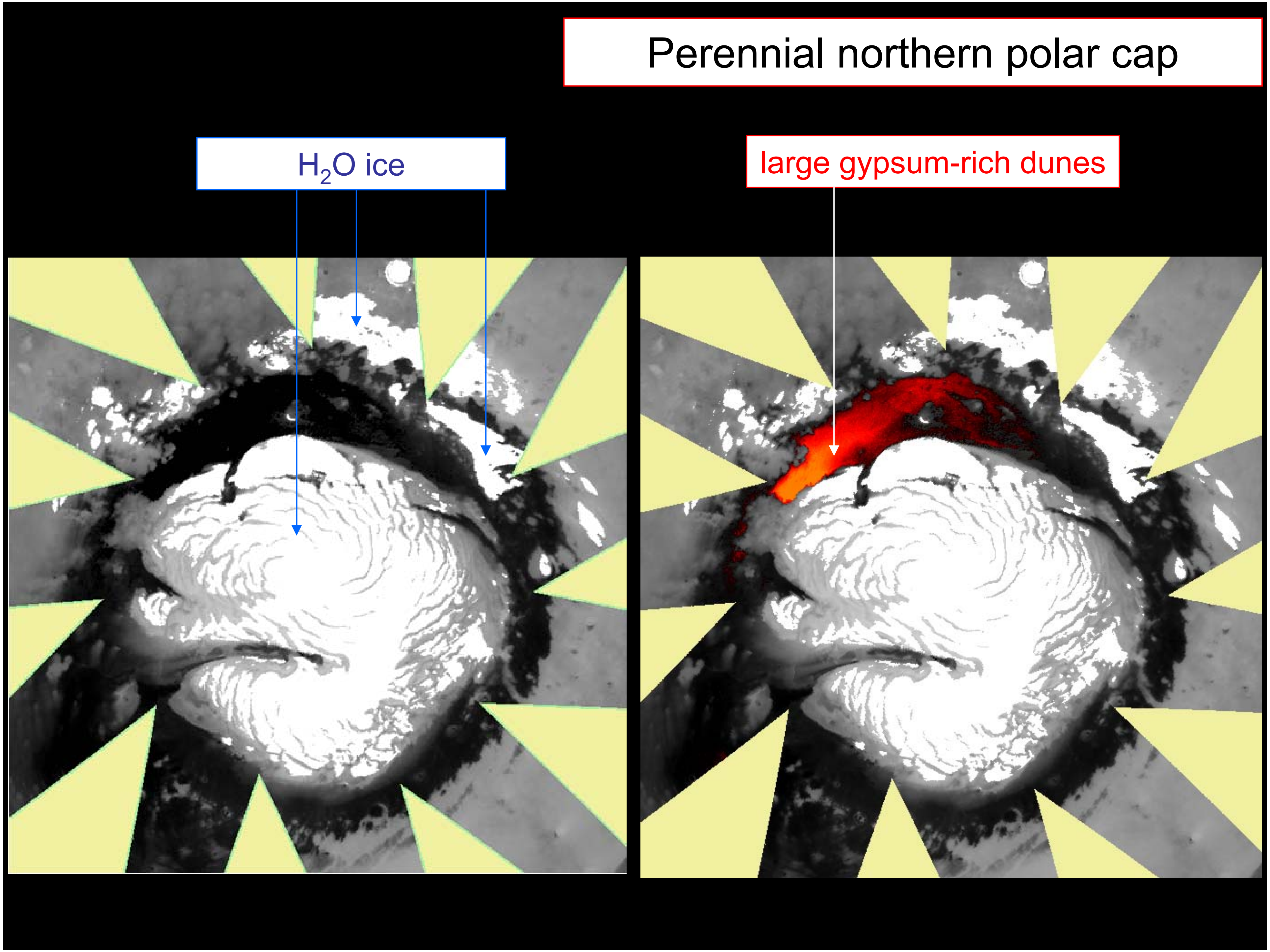
H_2O ice

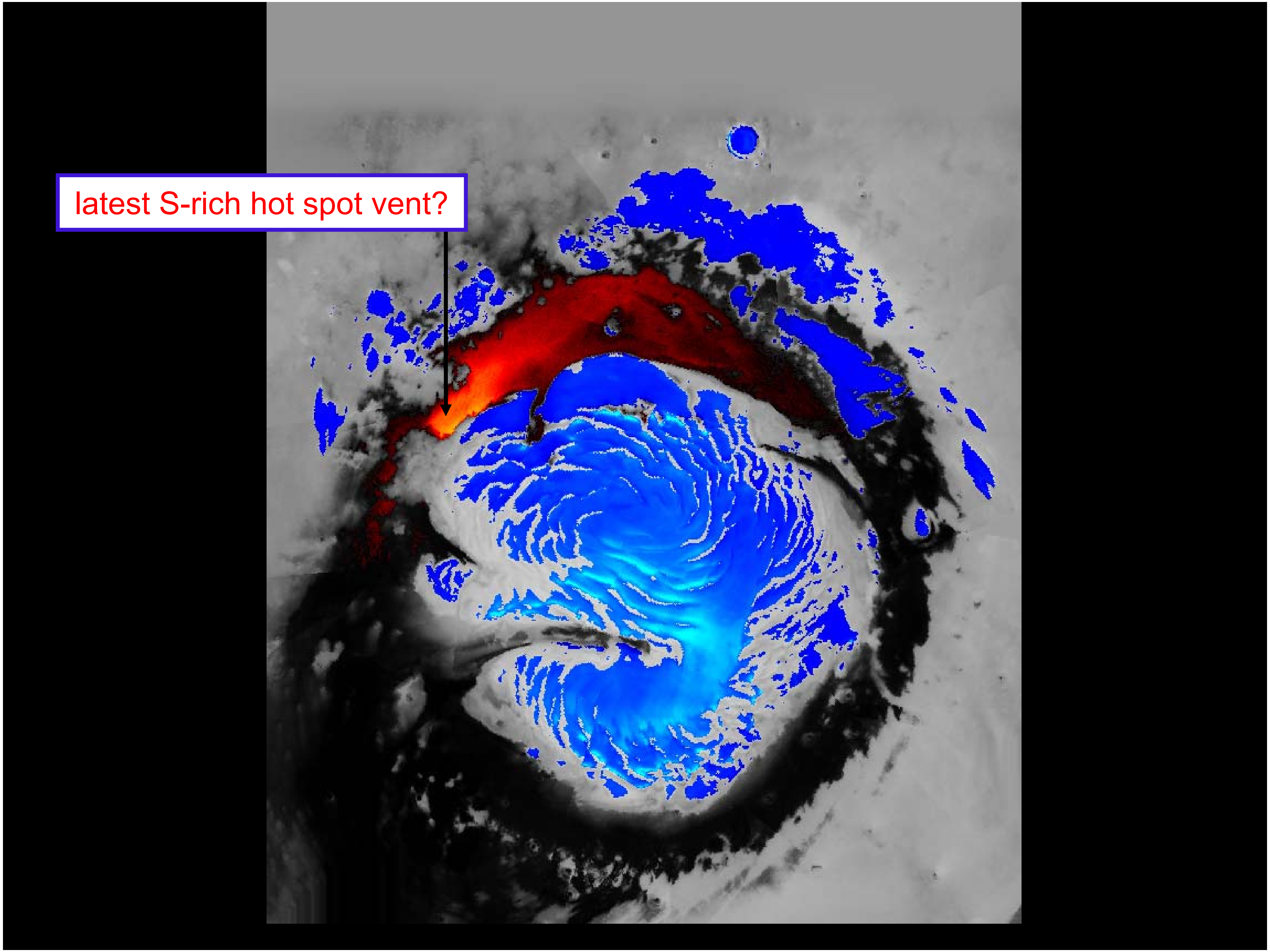


OMEGA: H_2O ice map

Perennial northern polar cap




Perennial northern polar cap
H_2O ice
large gypsum-rich dunes


latest S-rich hot spot vent?

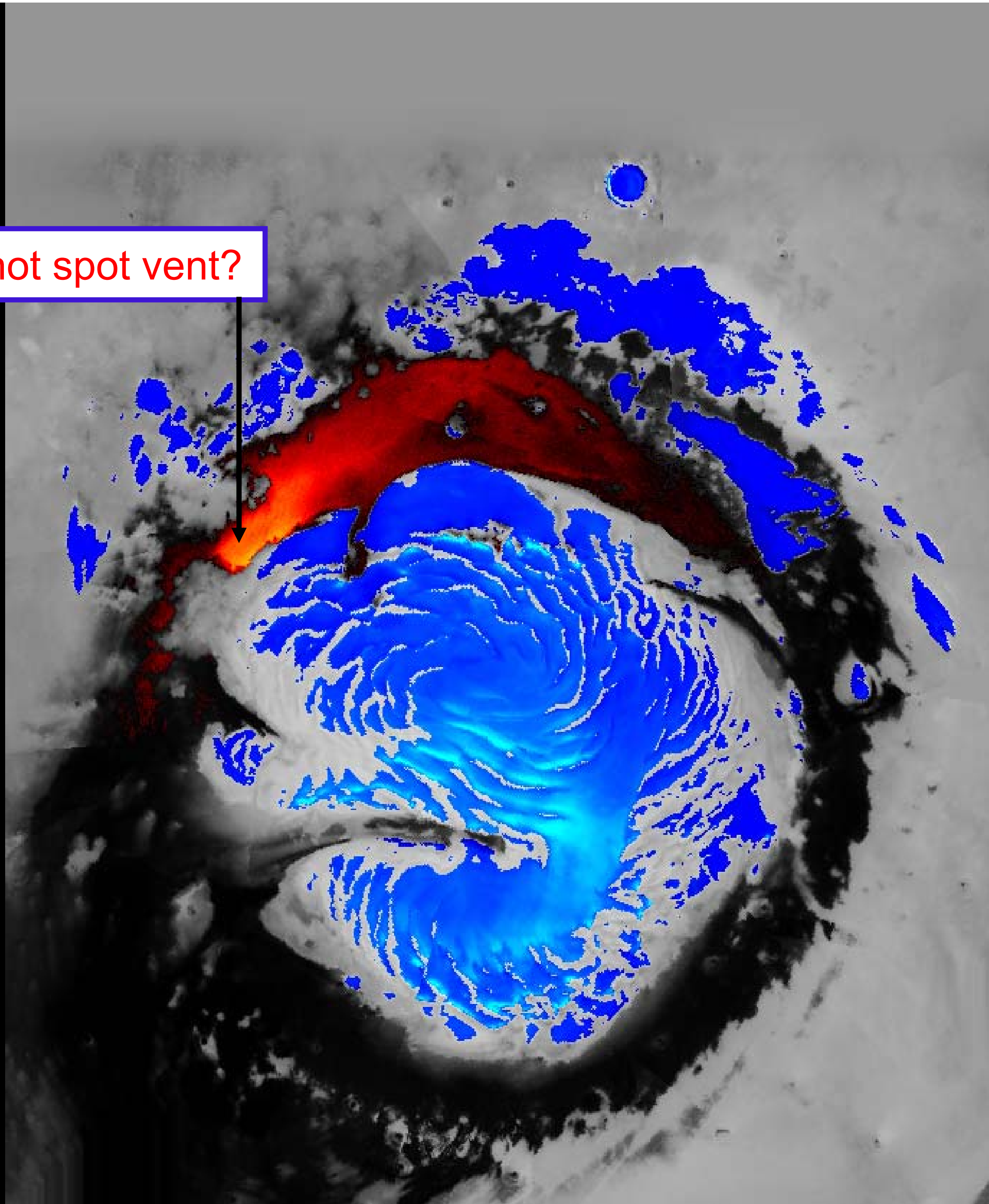
Potentially responsible for

major (CO_2), minor (N_2), trace (e.g. CH_4)

atmospheric supply?

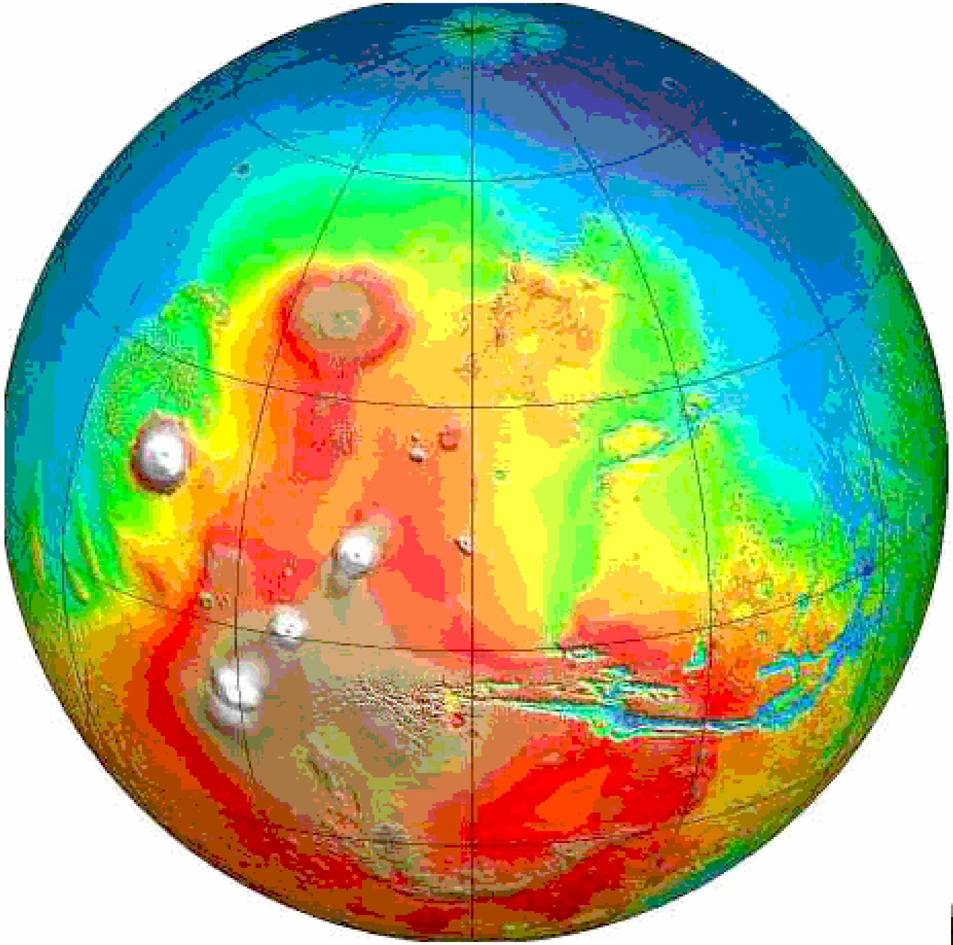
MSL should answer, through accurate fractionation measurements

$^{15}N/^{14}N$, $^{13}C/^{12}C$

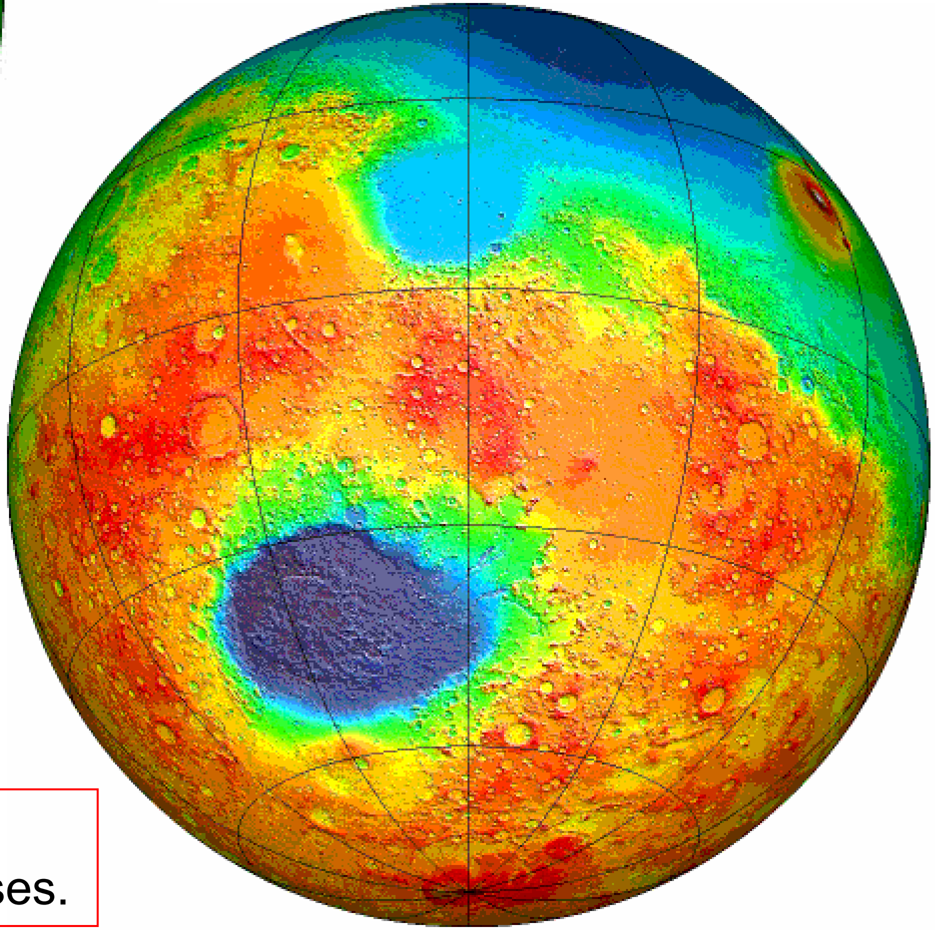


The 2013 MAVEN mission is key: detection of ongoing venting, and escape

2013 & 2016 missions should search for S-rich compounds (in addition to CH_4 and other C-rich traces)

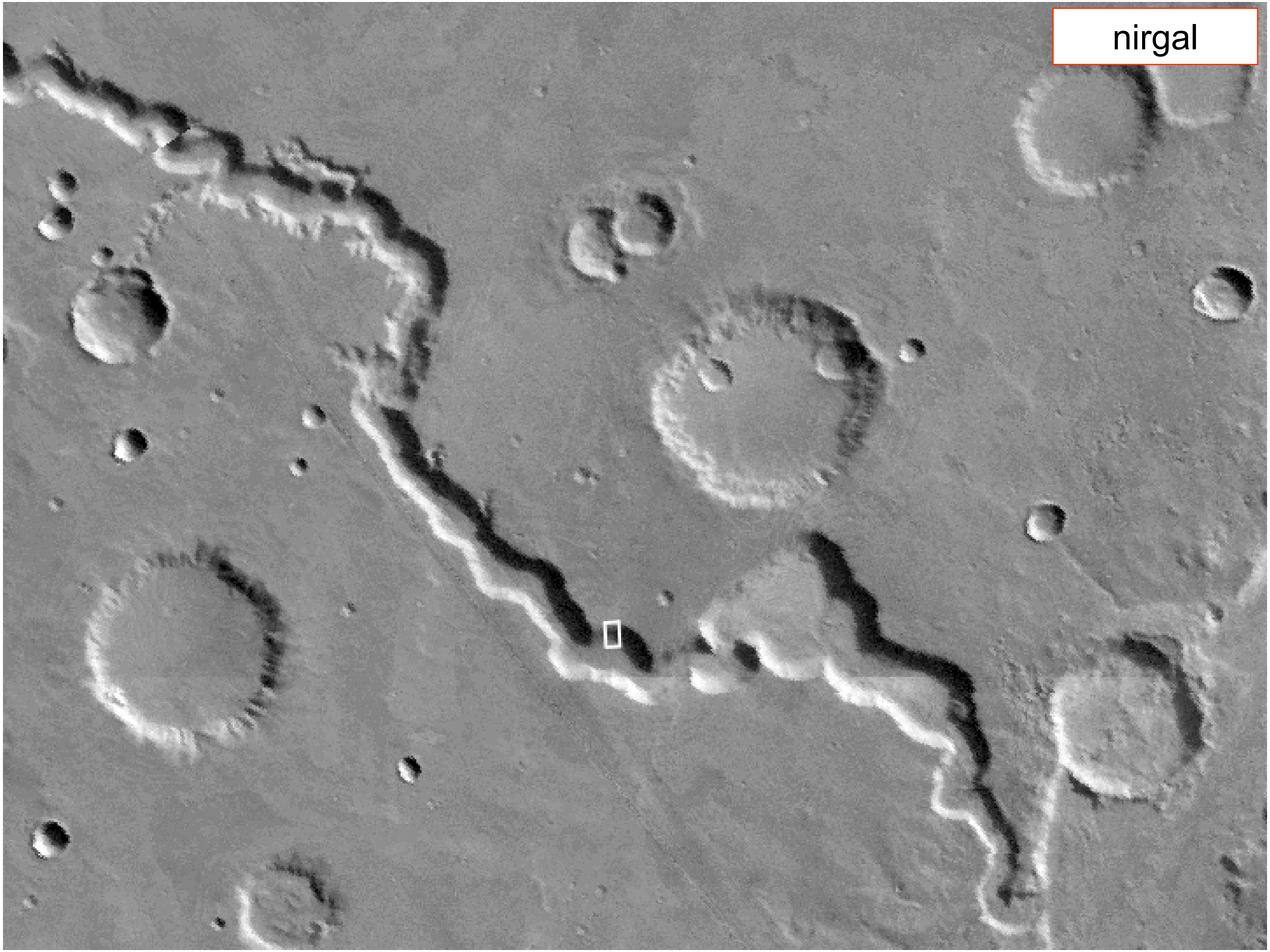


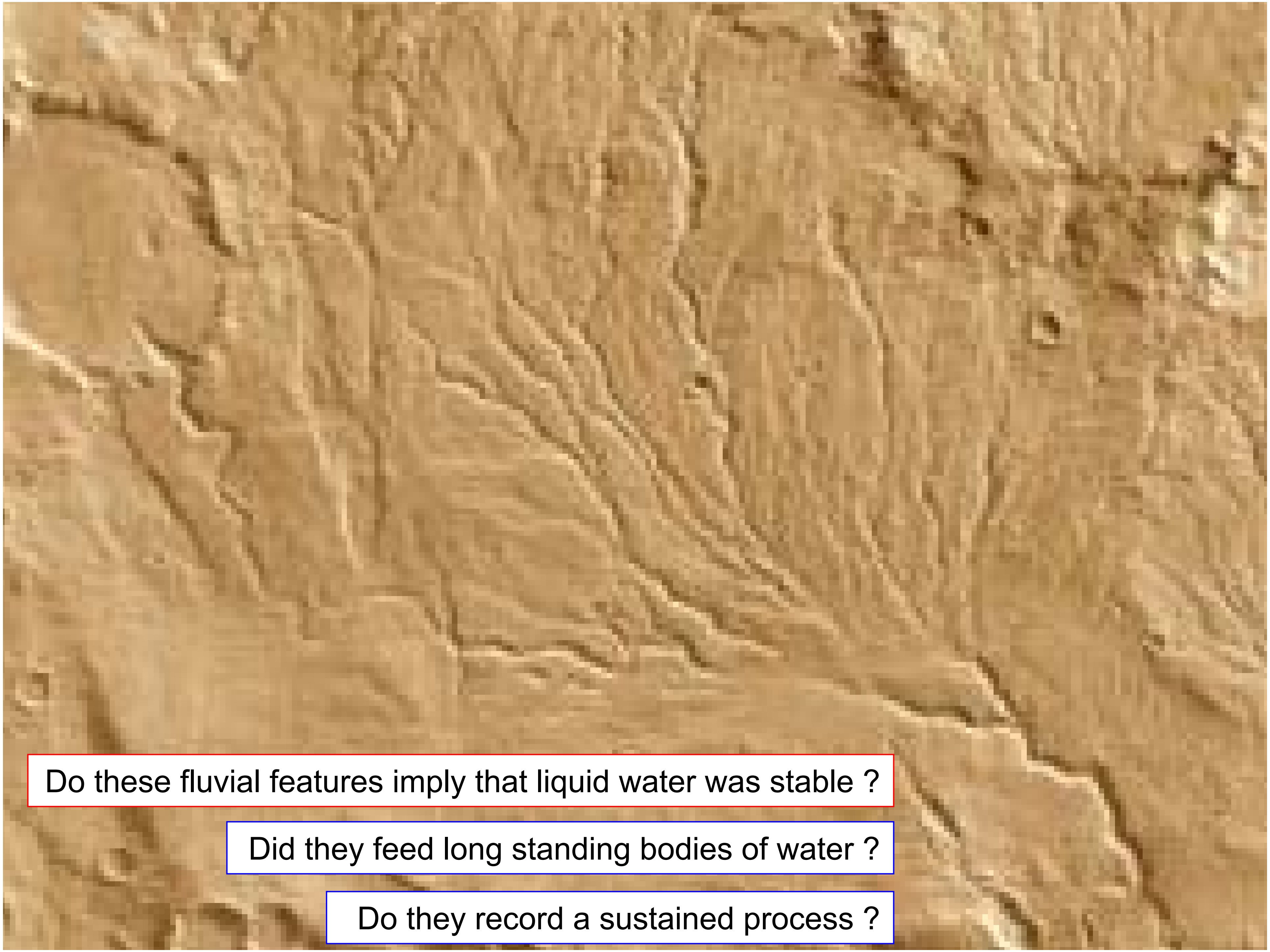
MGS / MOLA

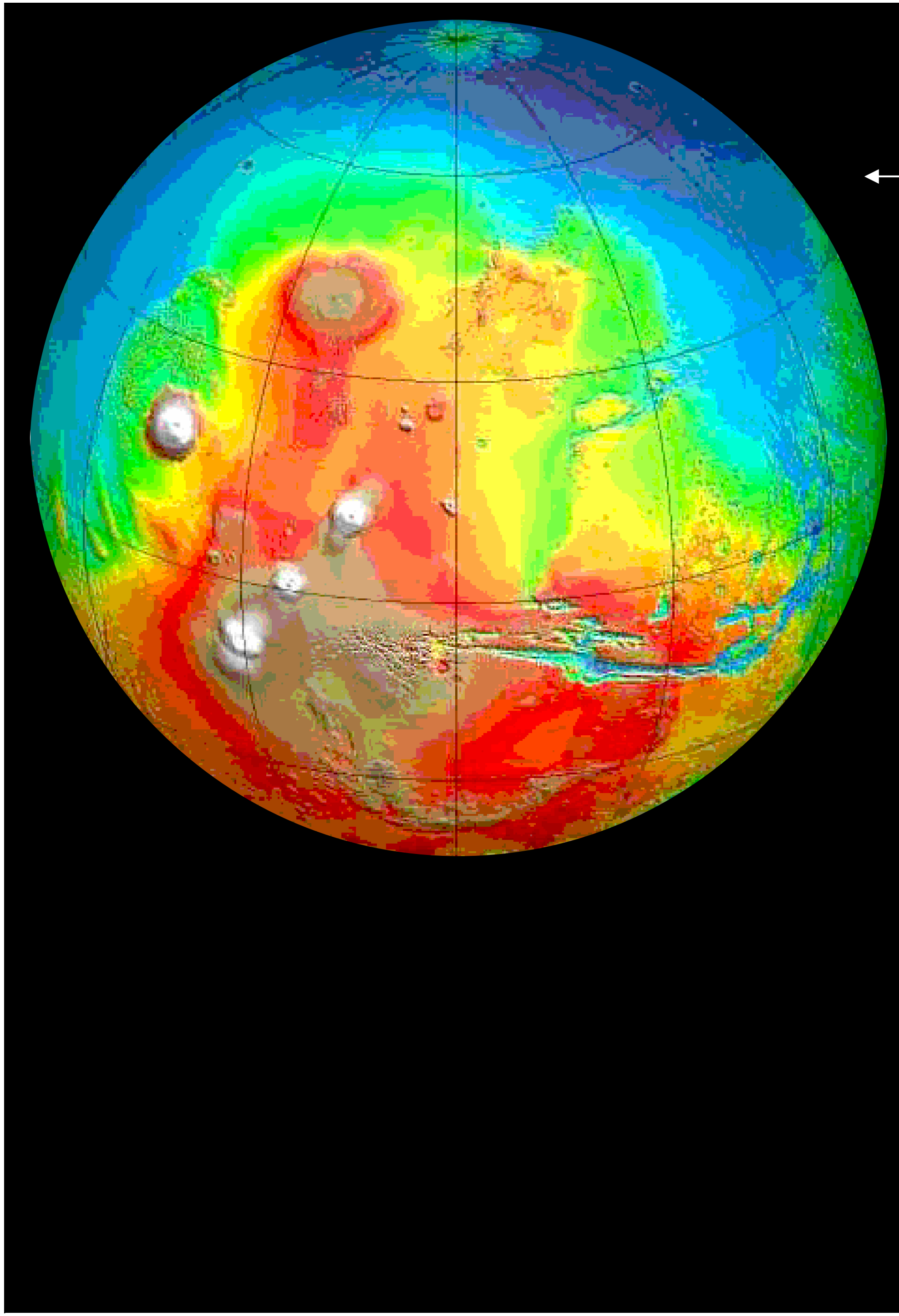


To decipher the processes from imaging / topography favors reference to terrestrial processes.

To derive an History from units requires deciphering and dating the relevant processes.

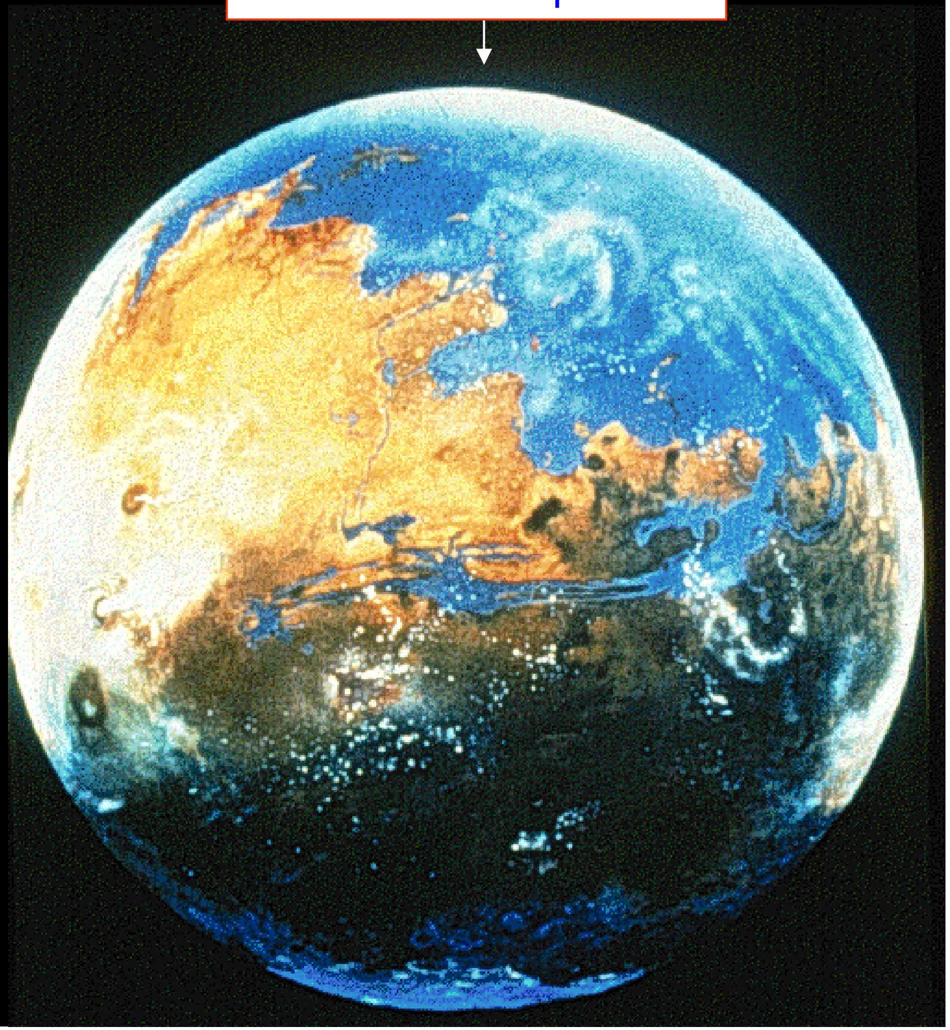

nirgal


Do these fluvial features imply that liquid water was stable ?
Did they feed long standing bodies of water ?
Do they record a sustained process ?



MGS / MOLA

audacious extrapolation



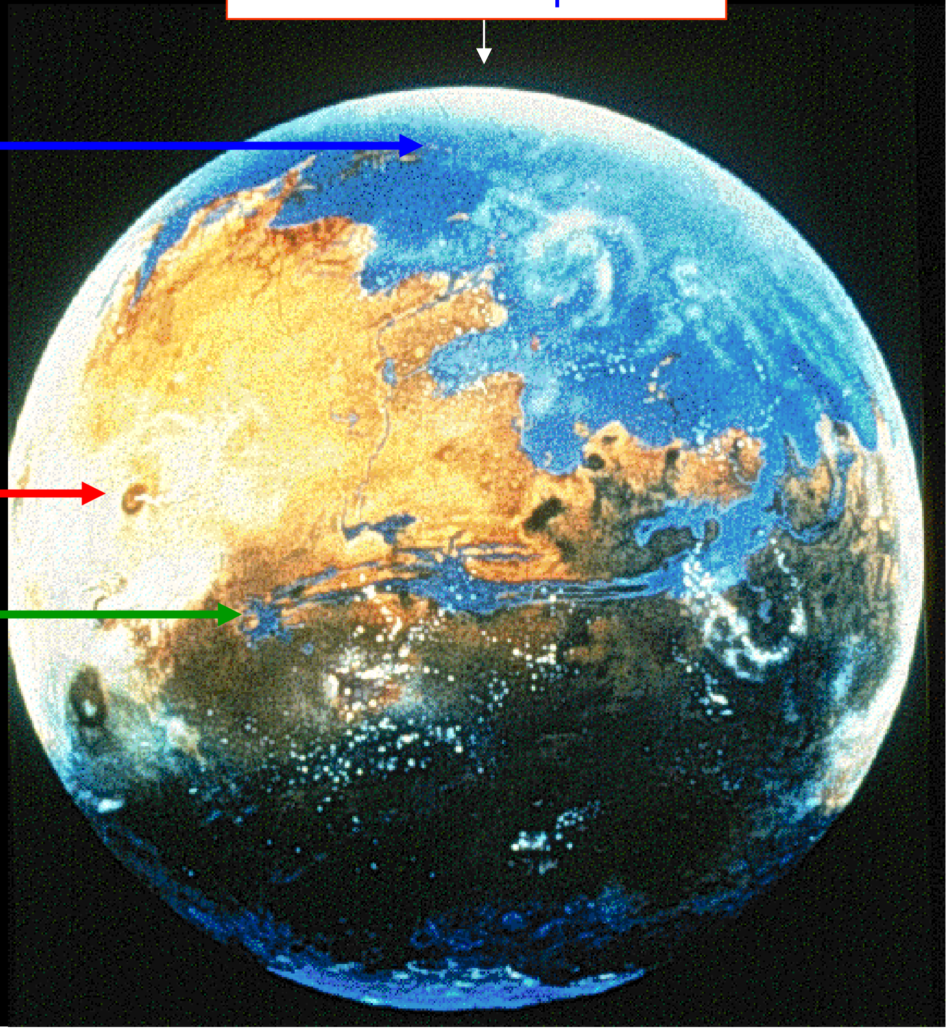
oceans would have been stable

<u>after</u>

Tharsis and
the volcanoes
were put in place,

and Valles Marineris
formed

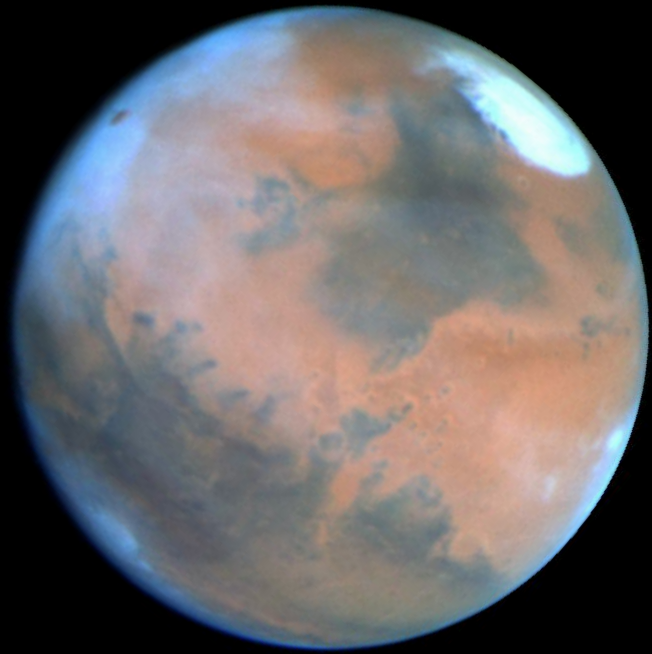
audacious extrapolation



Mineralogy and History of Mars

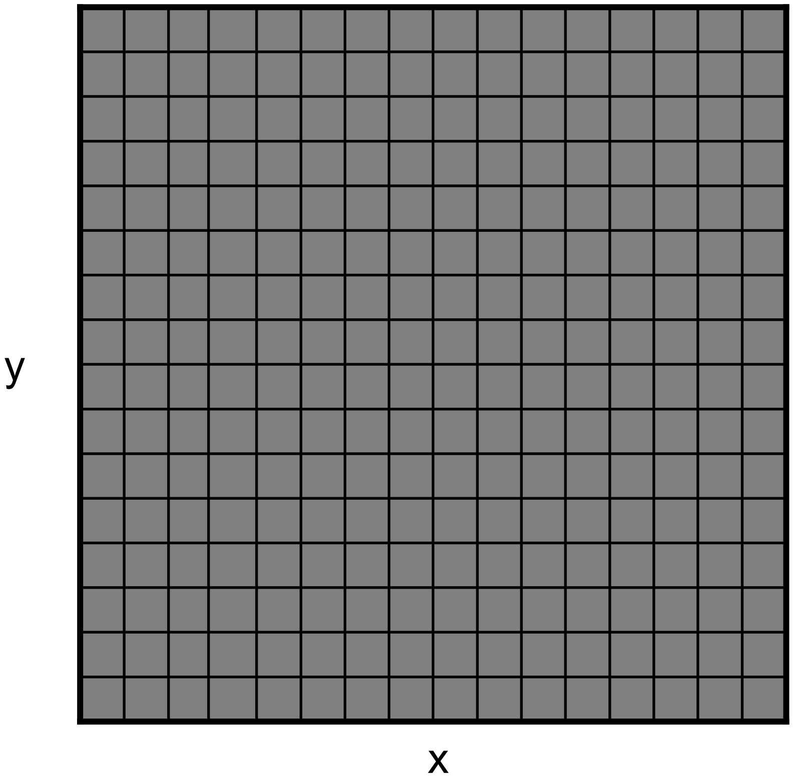
Until recently, Mars History was primarily derived from optical images and topography, interpreted with reference to lunar (impacts) and terrestrial processes (volcanism, fluvial activity, erosion, frosting and ice deposition etc…).

Within the past ten years, hyperspectral imagery, first in the thermal infrared, then in the VIS/NIR, has drastically modified our capability to understand the evolution of Mars at all timescales, from seasonal to climatic and geological variations.

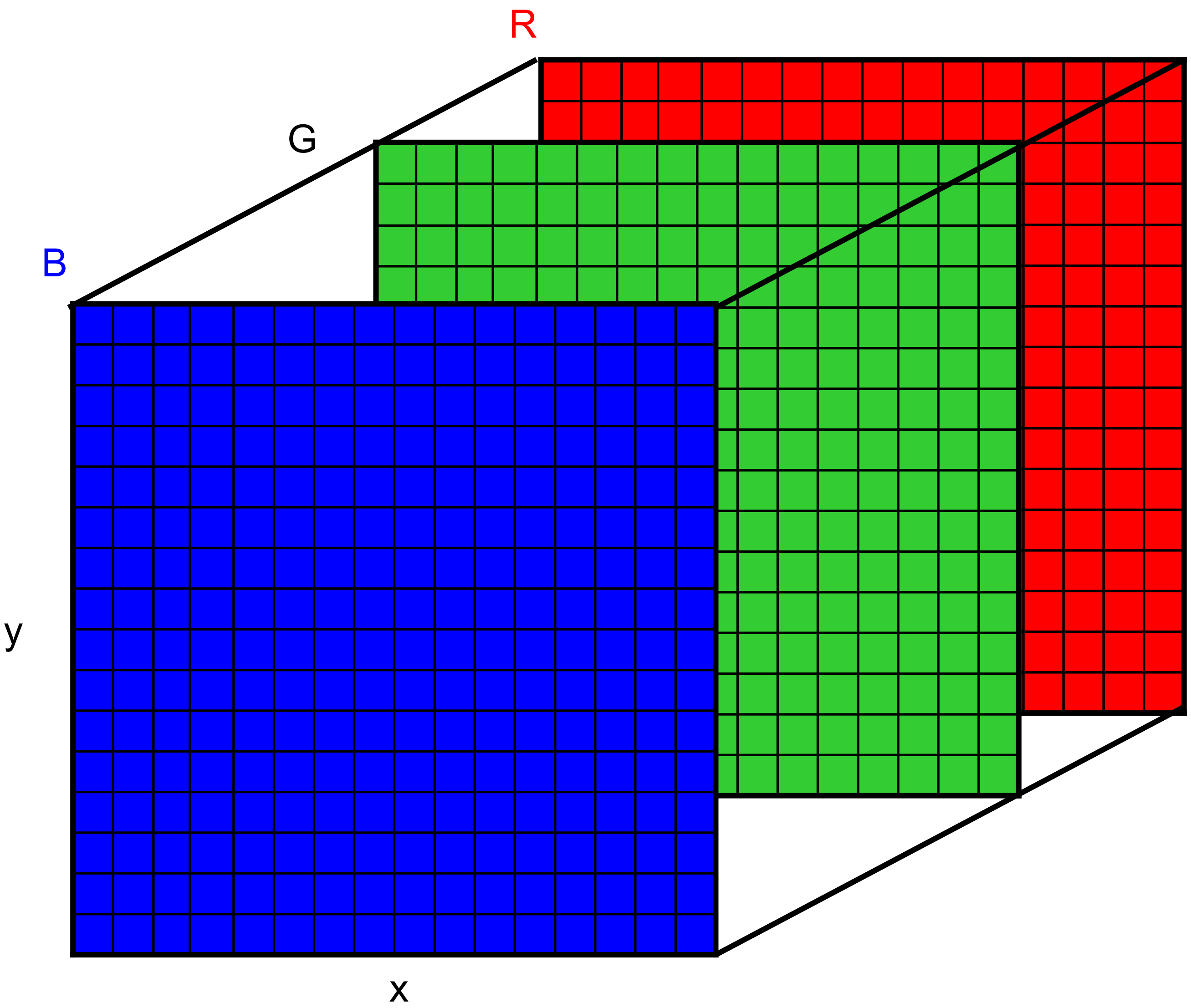


Les Houches, 29 / 03 / 2010

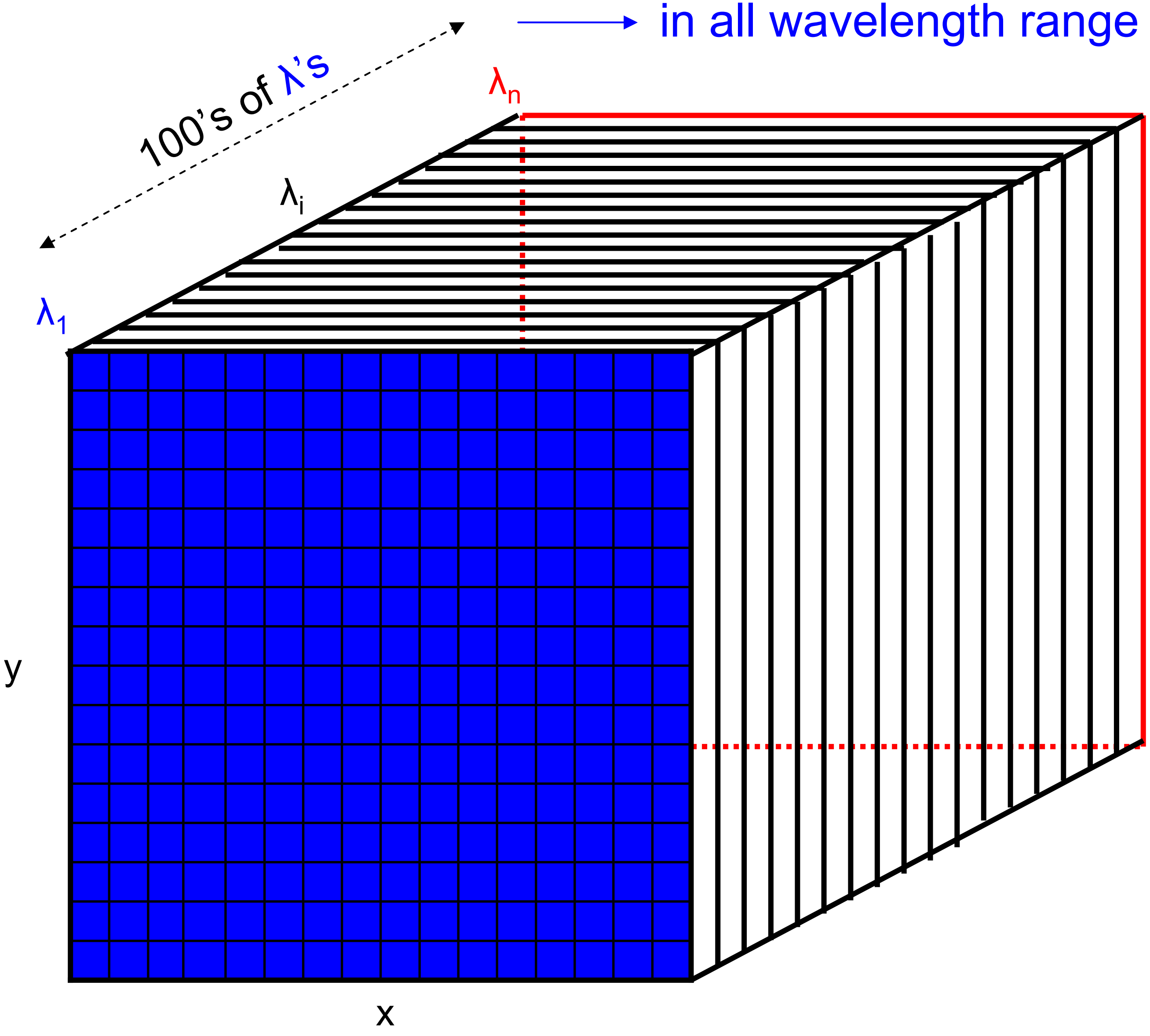
B&W image



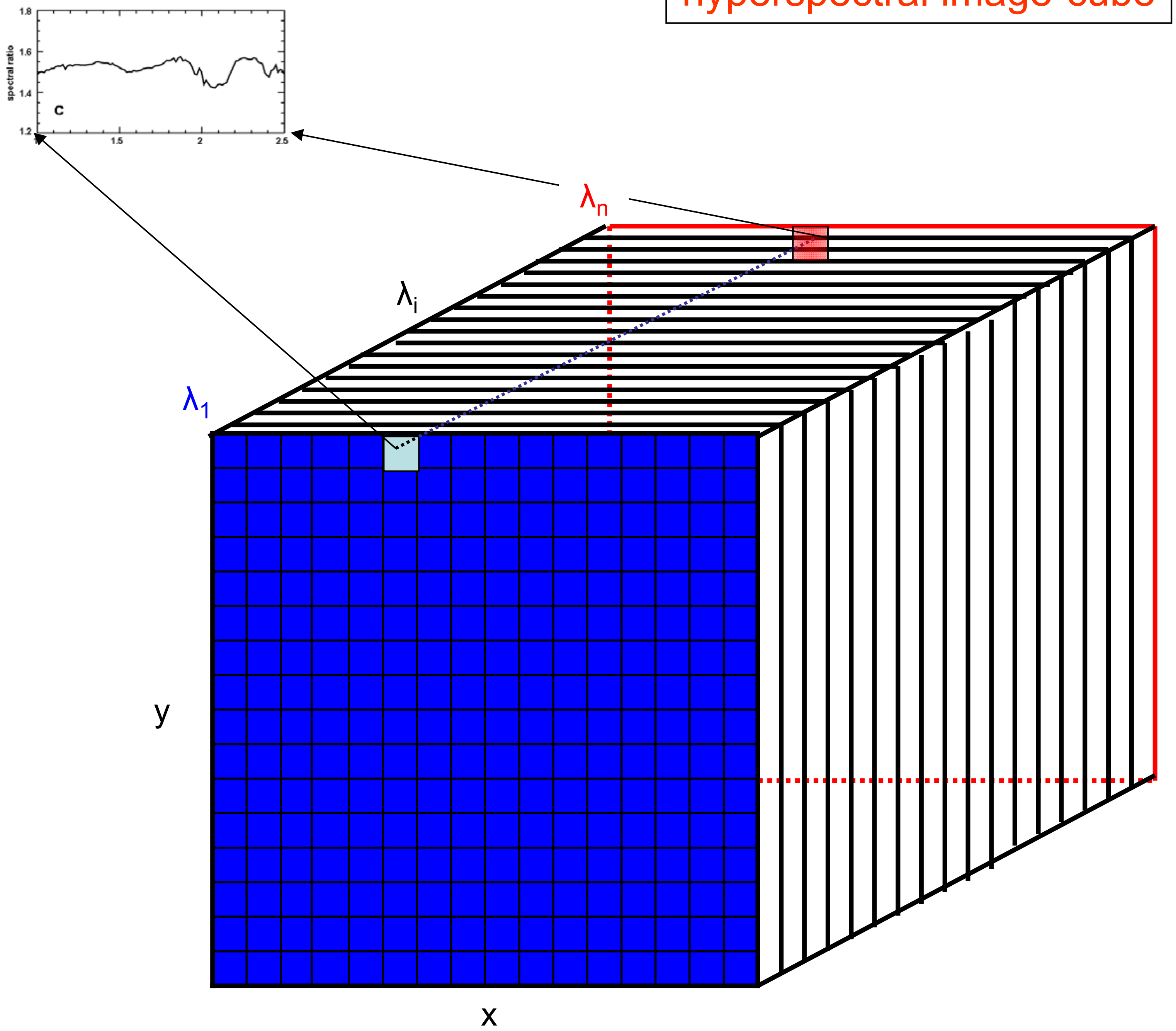
RGB-type image



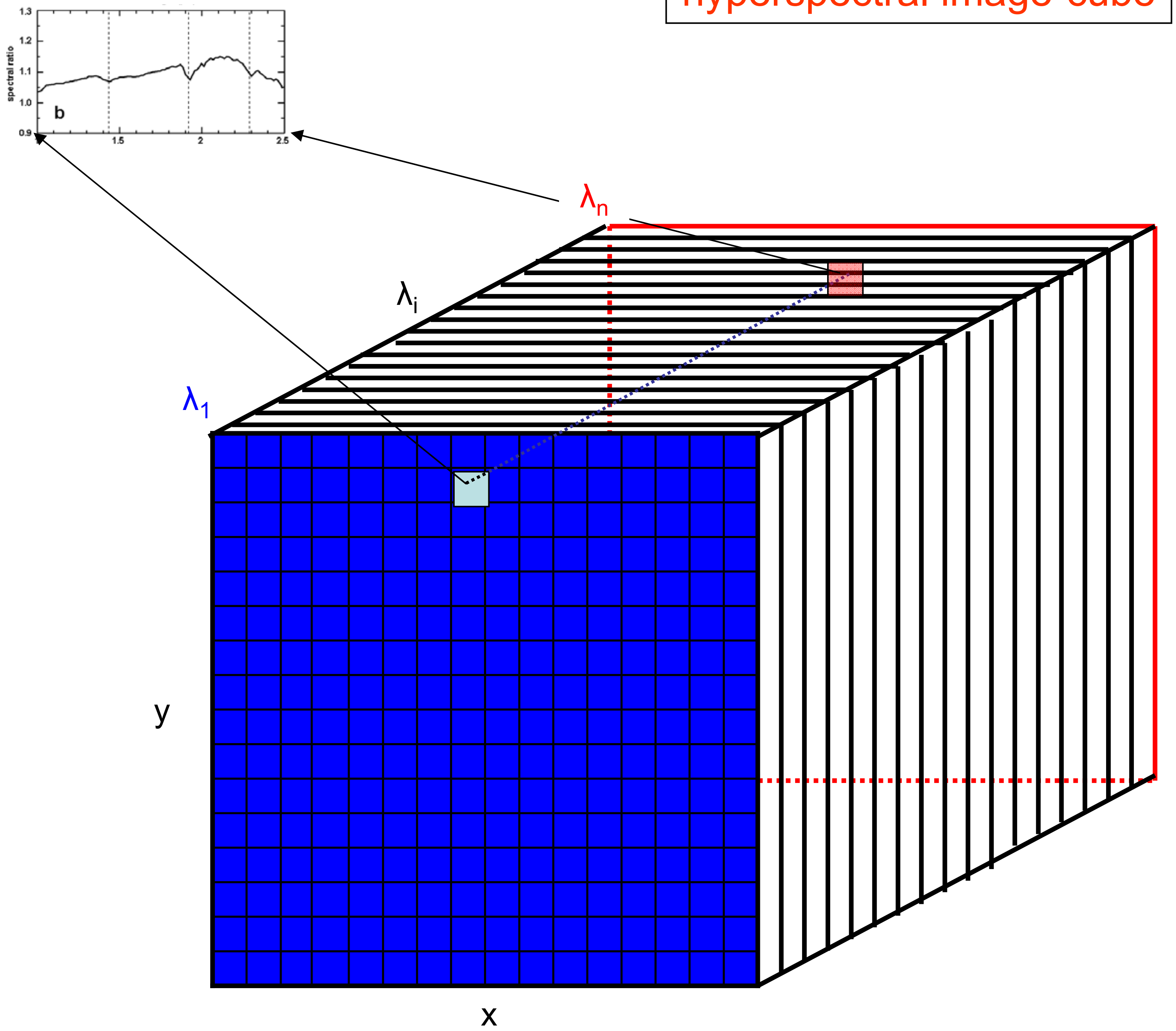
hyperspectral image-cube



hyperspectral image-cube

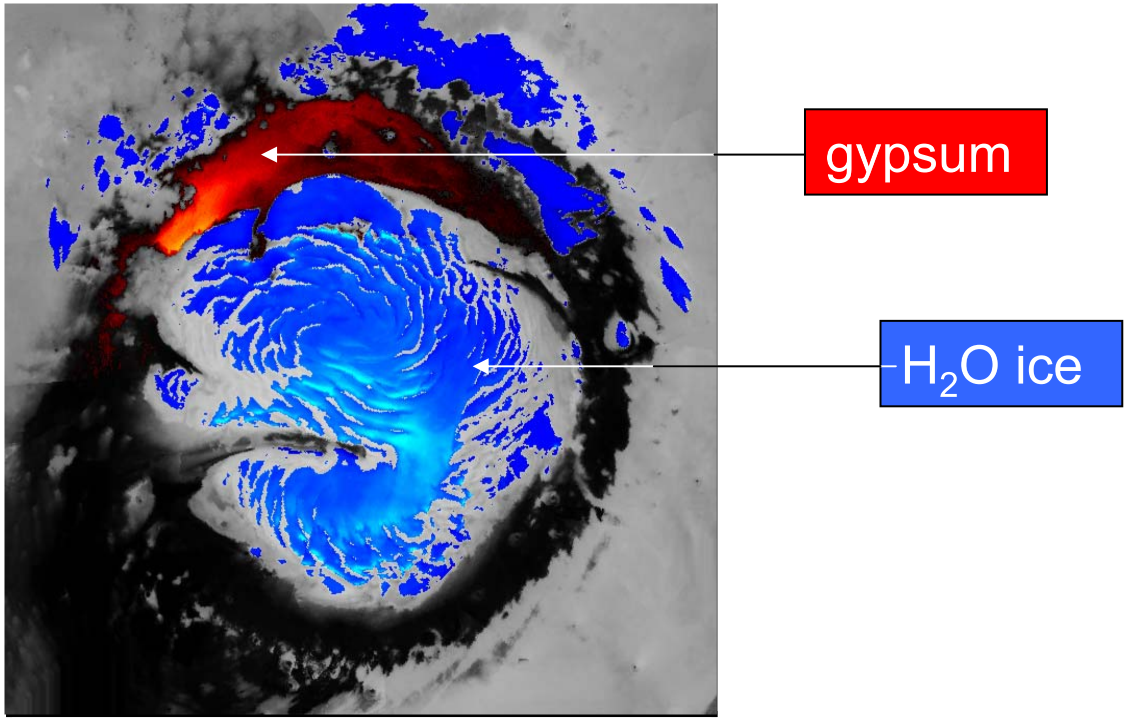


hyperspectral image-cube



hyperspectral image-cube

derived
false color
compositional map



Mineralogy and History of Mars

Minerals

- record sustained processes
- give access to the “enabling” environments

Hyper-spectral imagery of minerals

- spectrometry:
  identification (diagnostic spectral features) → processes
- imagery:
  mapping (distinct units) → chronology

Mineralogy and History of Mars

Minerals

- record sustained processes
- give access to the “enabling” environments

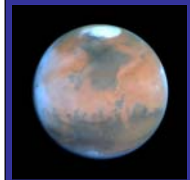
Hyper-spectral imagery of minerals

- spectrometry:
  identification (diagnostic spectral features) → processes
- imagery:
  mapping (distinct units) → chronology

⇩

characterization and mapping of minerals enable to derive an History birth

now



Noachian	Hesperian	Amazonian

Can one superimpose on a

Mars History derived from surface structures

a Mars History derived from surface mineralogy ?

Mineralogy and History of Mars

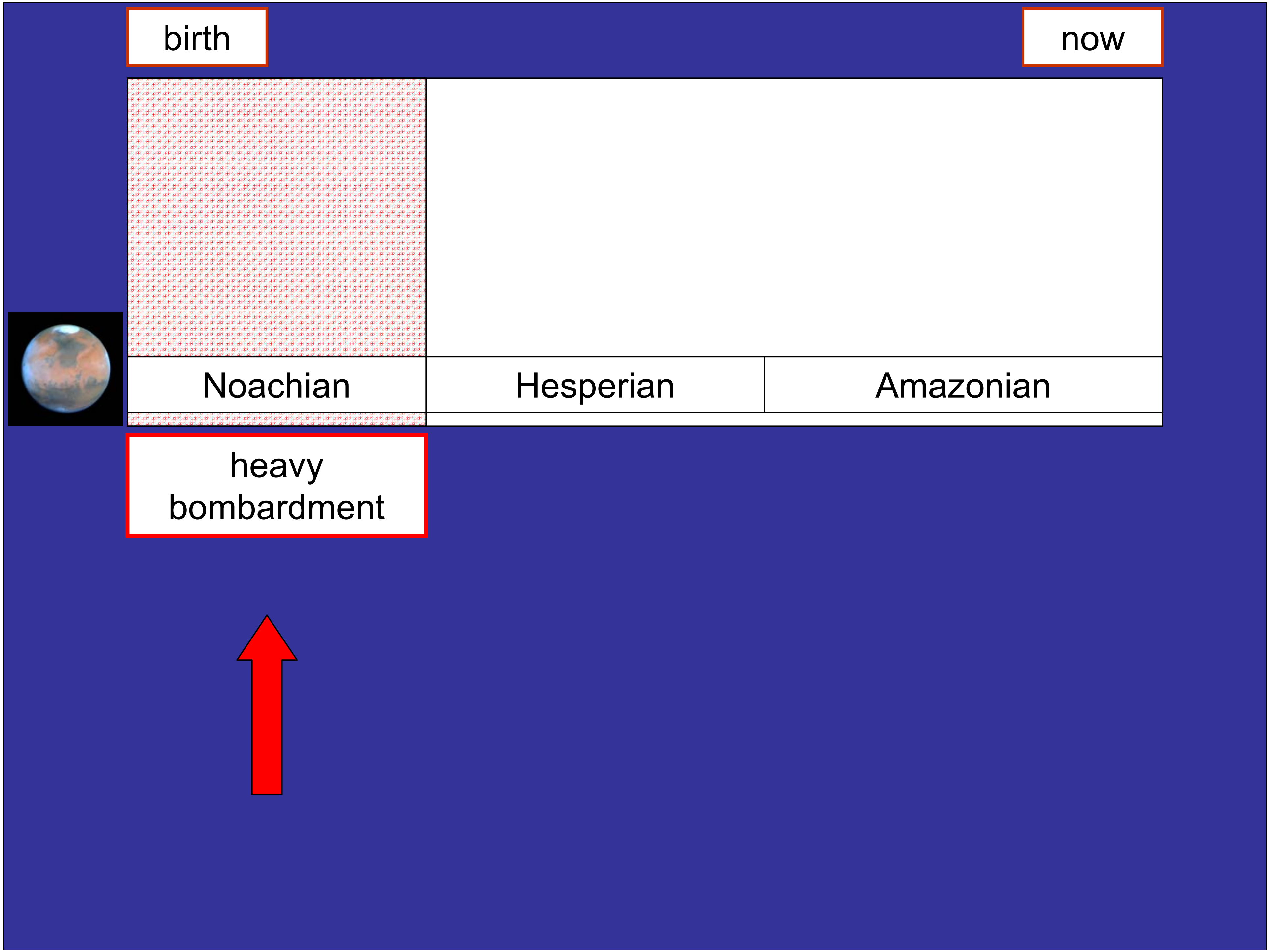
Has Mars evolution been frozen in distinct mineralogical units ?

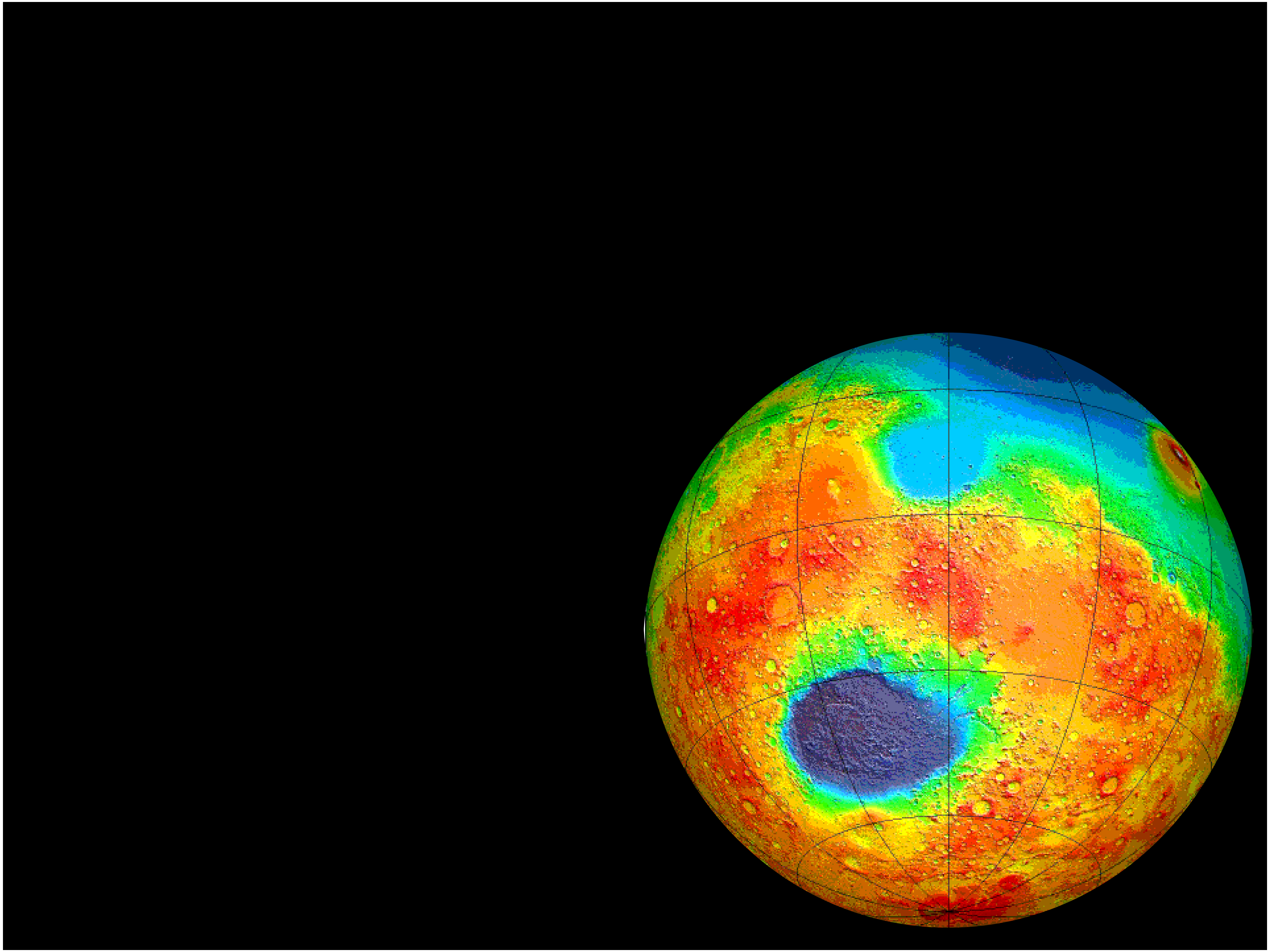
Les Houches, 29 / 03 / 2010

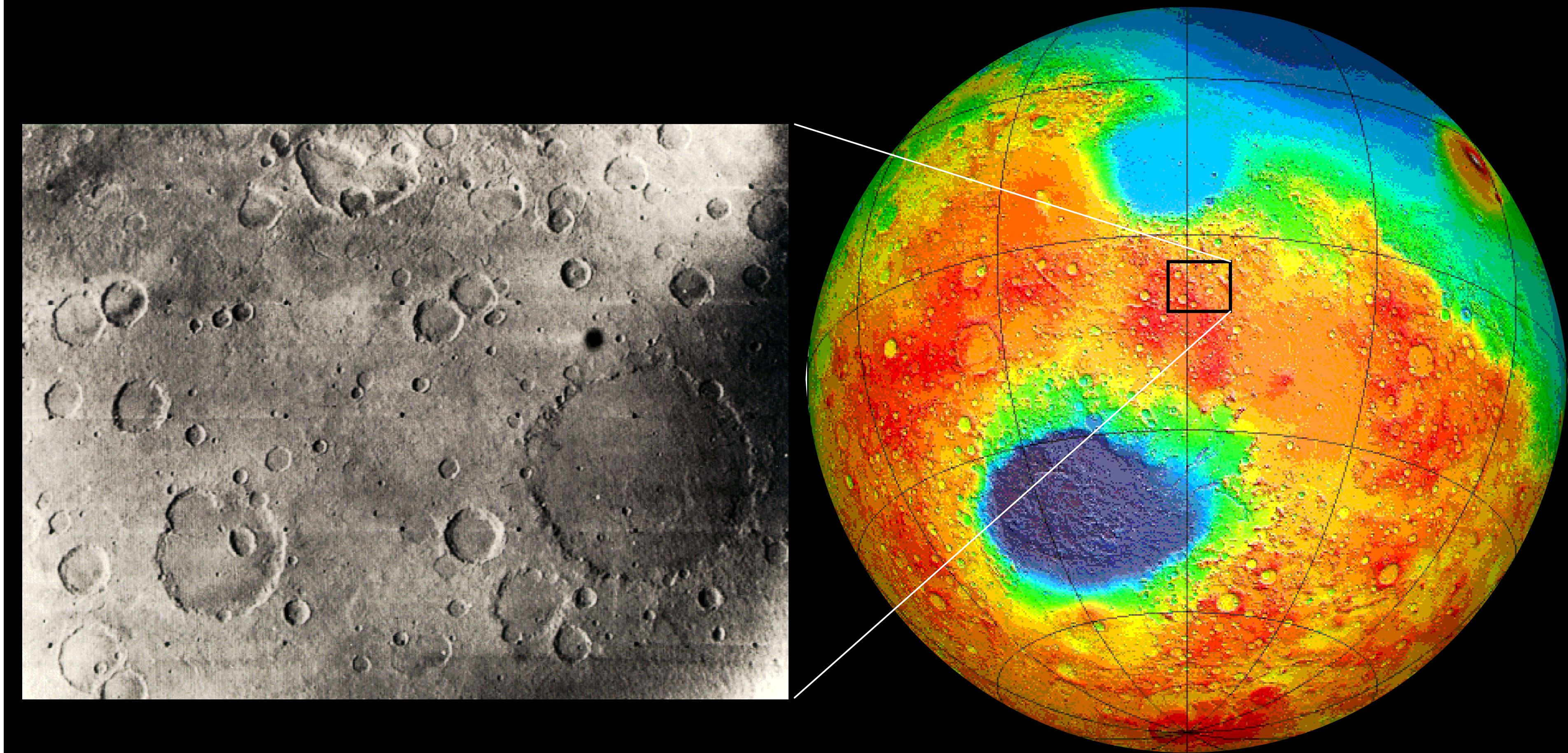
Mineralogy and History of Mars

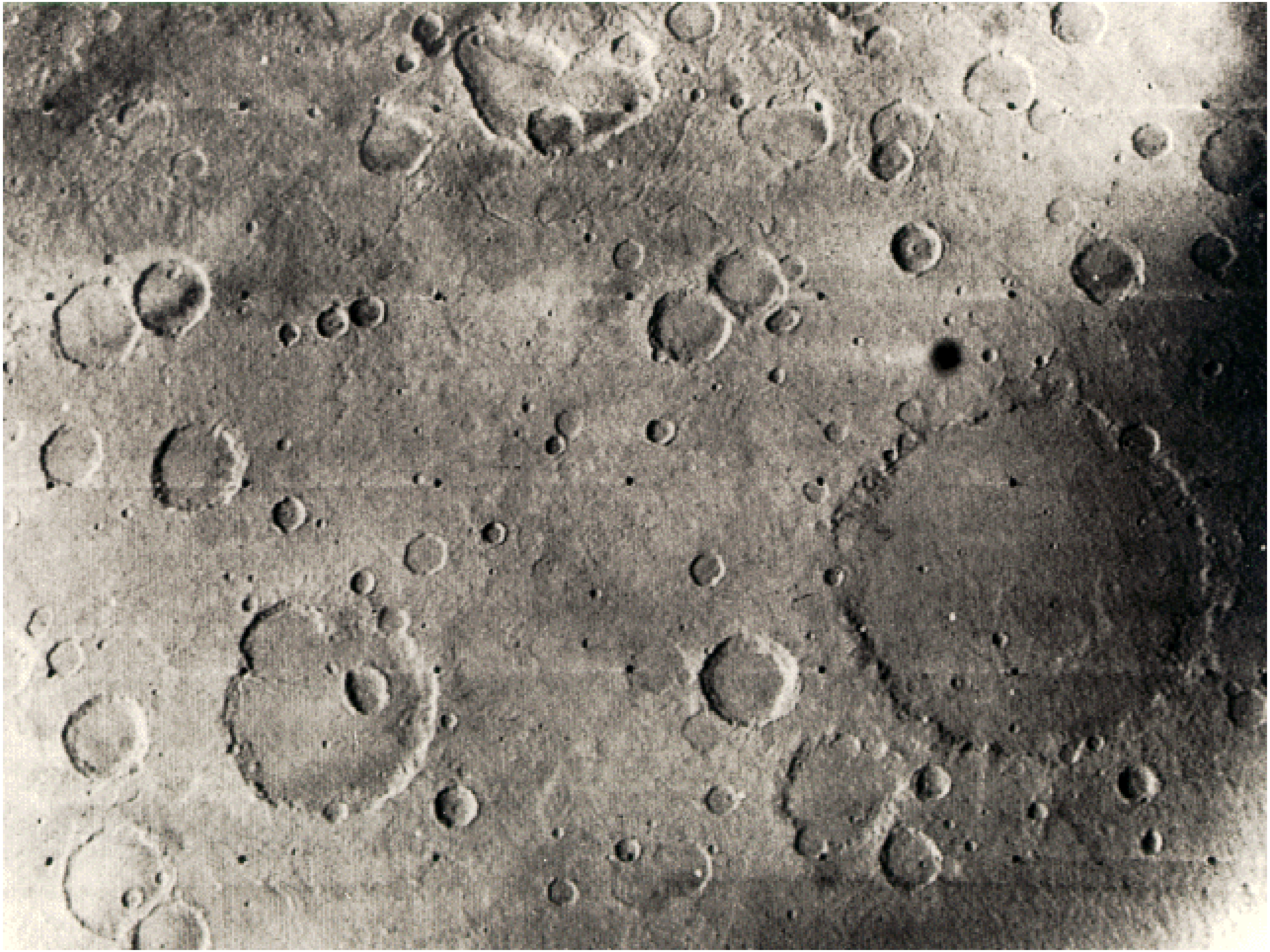
Has Mars evolution been frozen in distinct mineralogical units ?

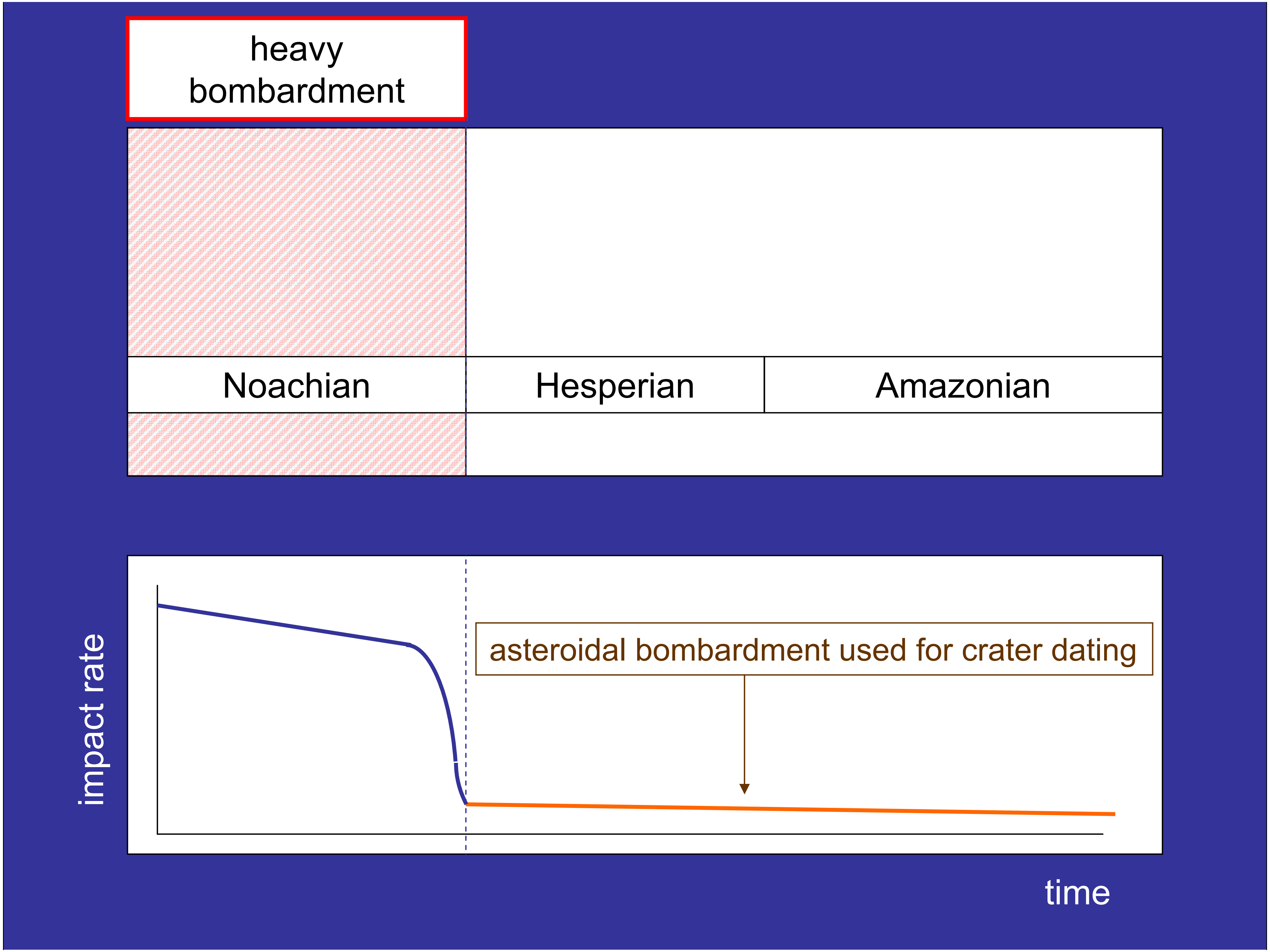
Key results have been obtained several years ago, and already reported in Les Houches II. A reminder, and some add-ons:

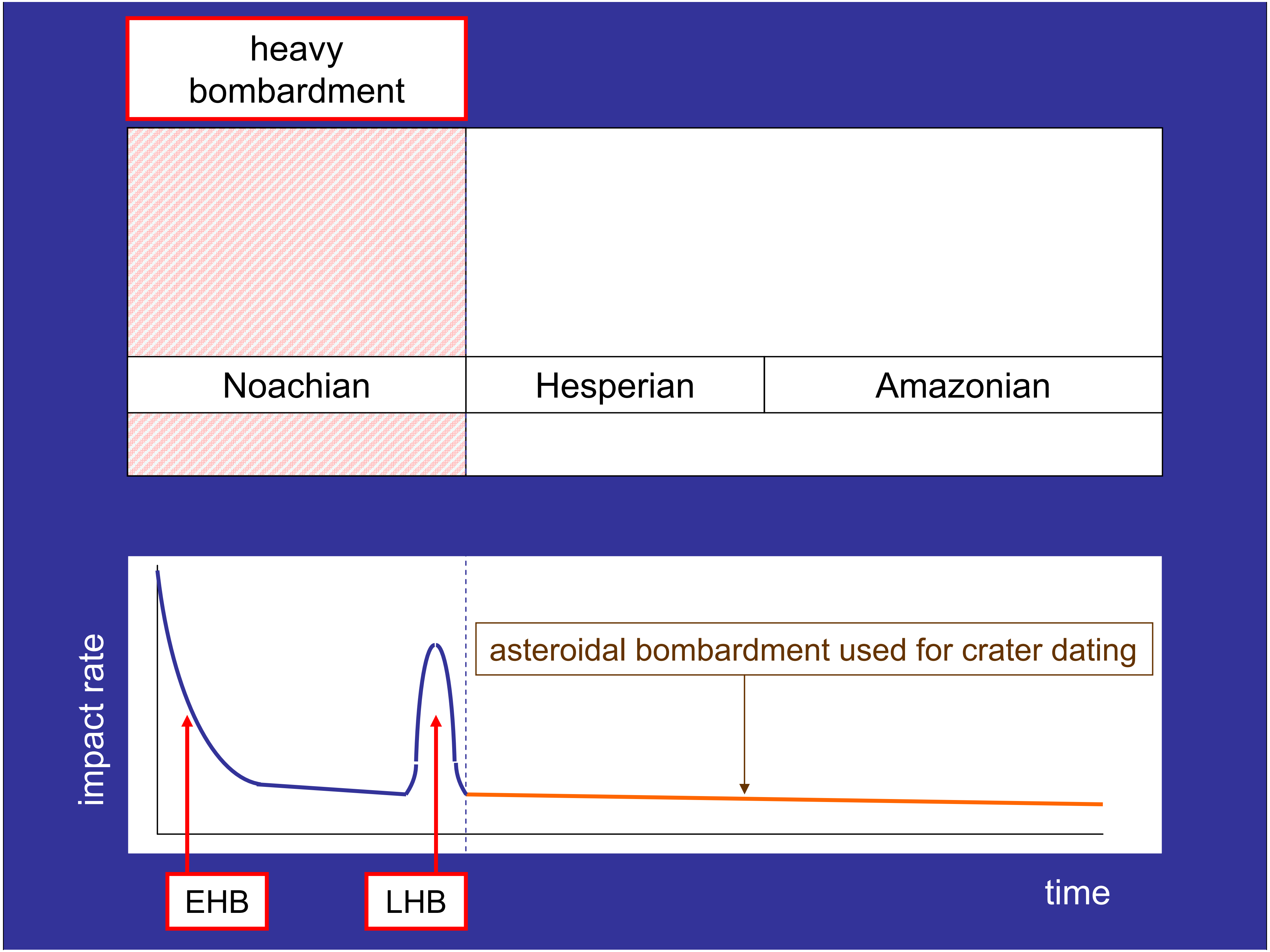

birth
now
Noachian
Hesperian
Amazonian
heavy
bombardment

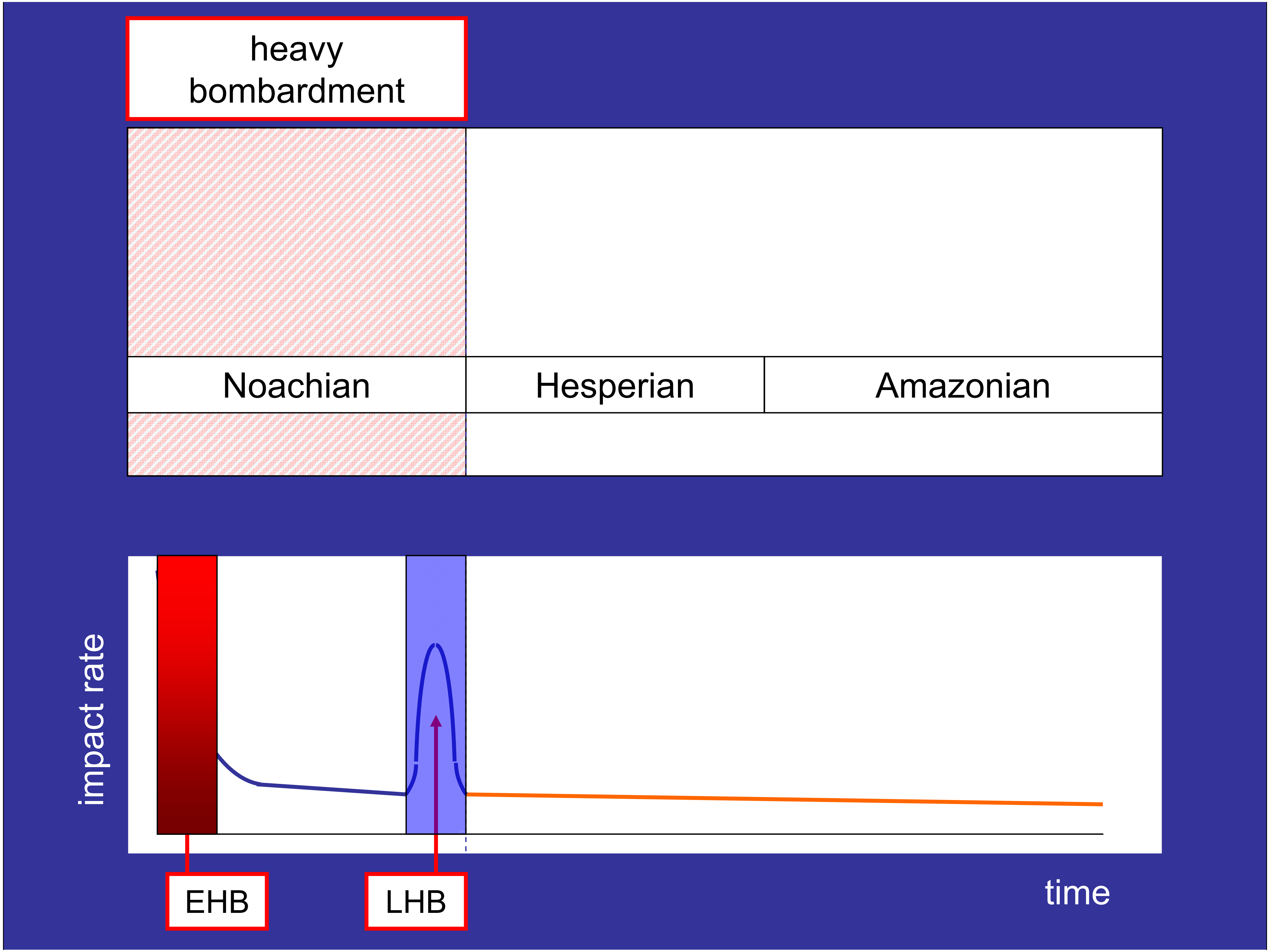




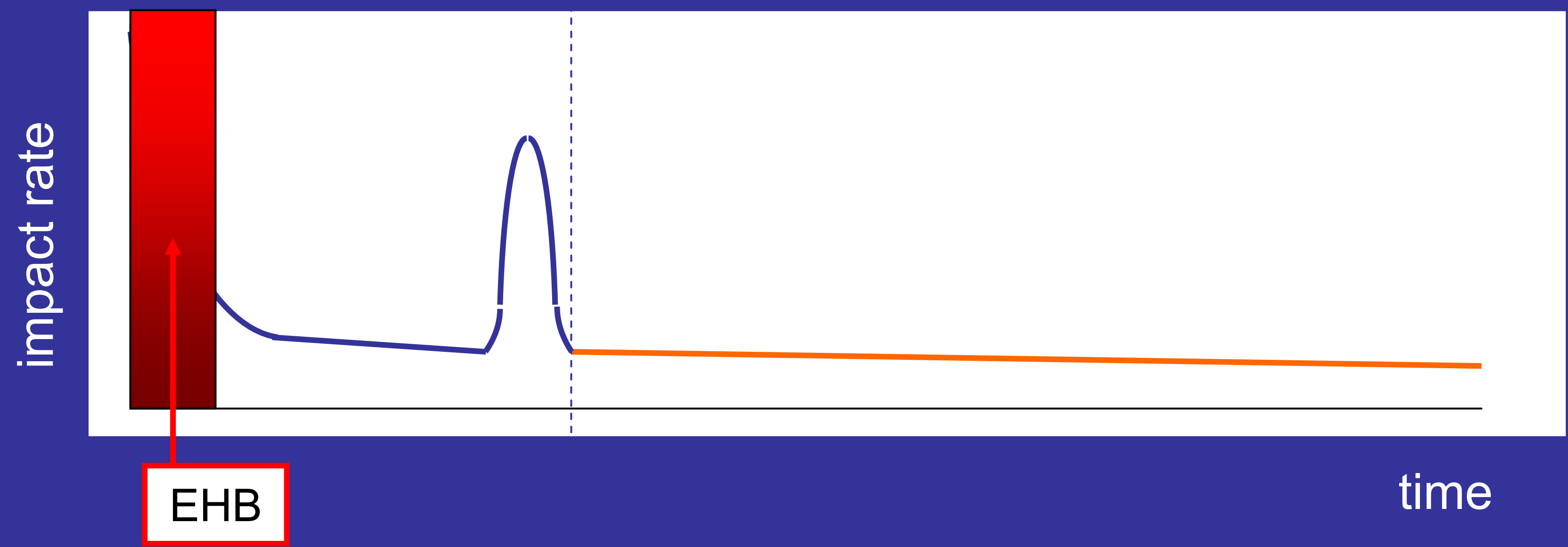


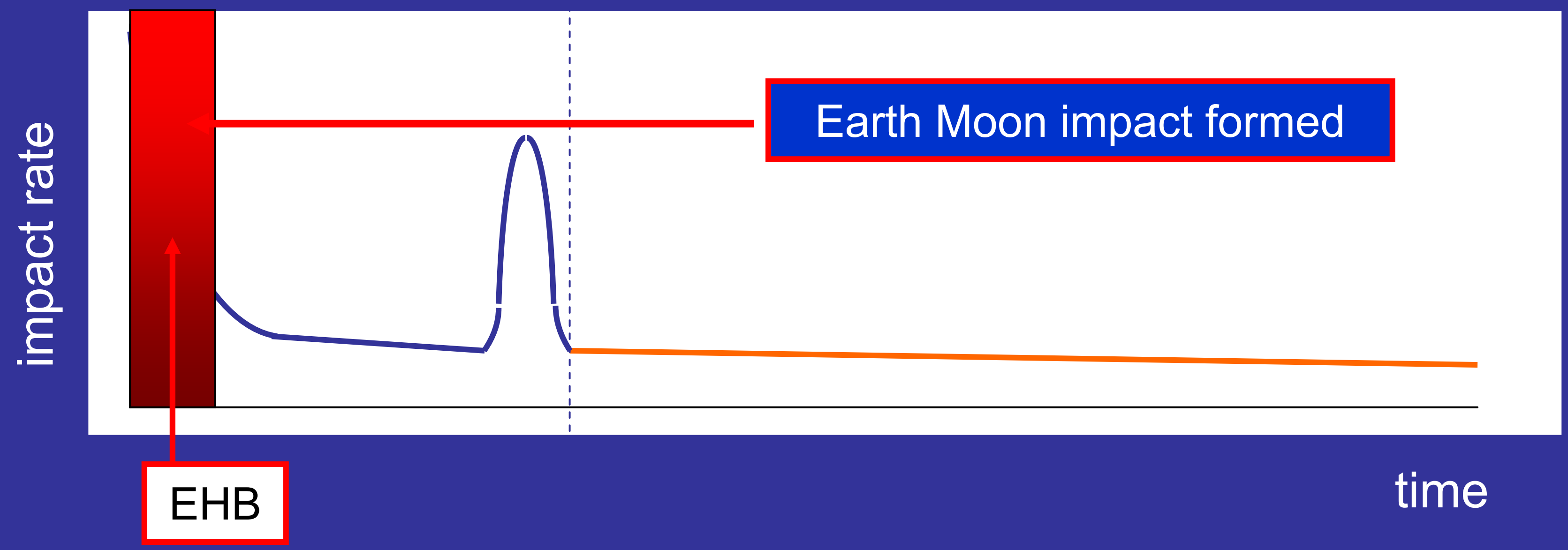

heavy bombardment
Noachian
Hesperian
Amazonian
asteroidal bombardment used for crater dating
impact rate
time


heavy bombardment
Noachian
Hesperian
Amazonian
impact rate
asteroidal bombardment used for crater dating
EHB
LHB
time

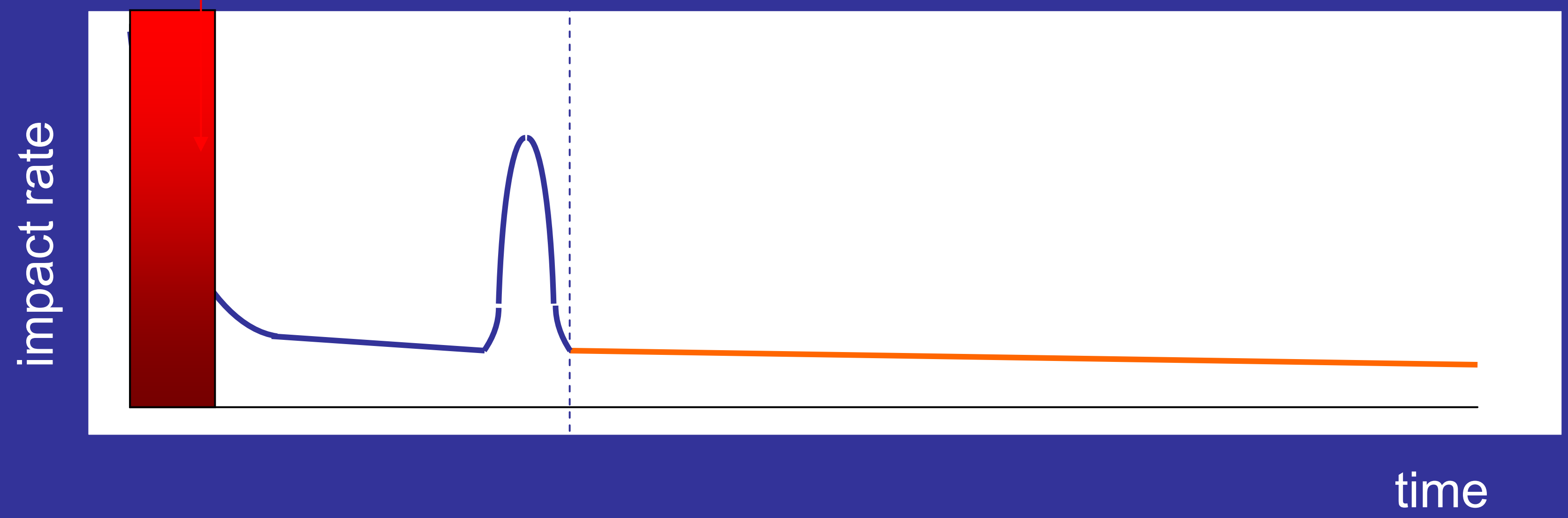


heavy bombardment
Noachian
Hesperian
Amazonian
impact rate
EHB
LHB
time


impact rate
EHB
time


Earth Moon impact formed
impact rate
EHB
time

Did Mars suffered a giant impact, similar to the Earth Moon forming one?



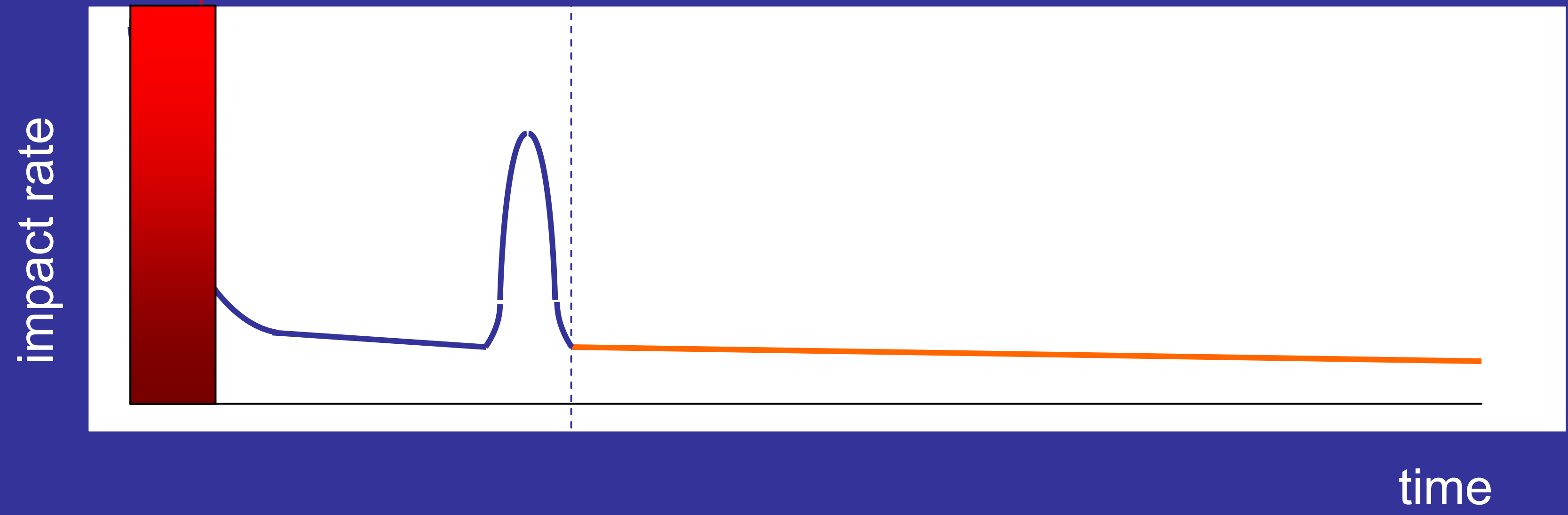
Did Mars suffered a giant impact, similar to the Earth Moon forming one?

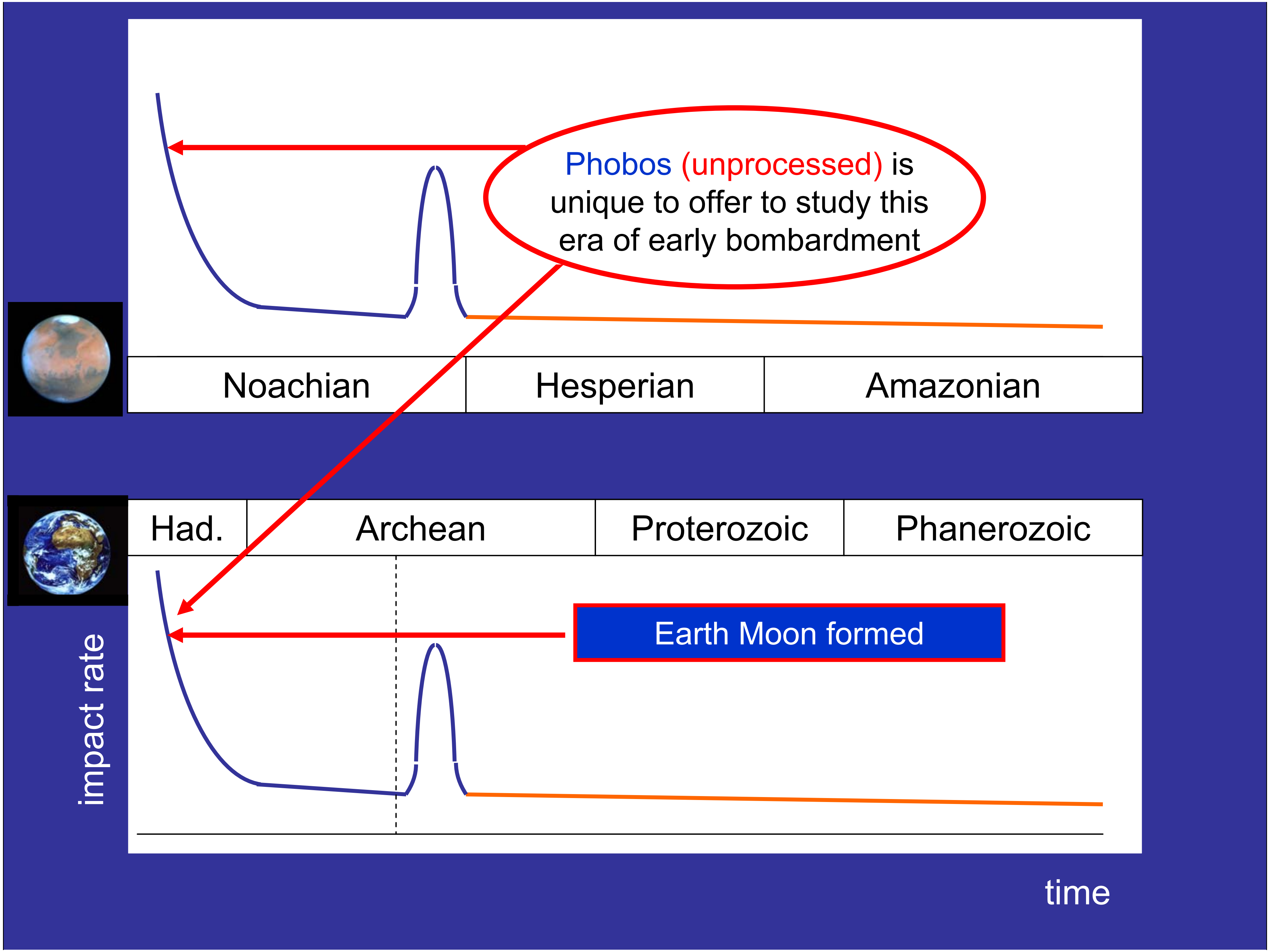
- The dichotomy might result from it
- Phobos and Deimos may be the latest remnants of re-accreted moons

→ Phobos may be (in part) martian in composition

→ Phobos analyses are of utmost importance to study the EHB

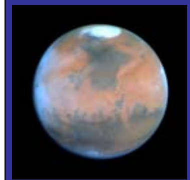
→ Phobos Grunt mission (in situ science + return sample)




Phobos (unprocessed) is unique to offer to study this era of early bombardment
Noachian
Hesperian
Amazonian
Had.
Archean
Proterozoic
Phanerozoic
Earth Moon formed
impact rate
time

birth

now

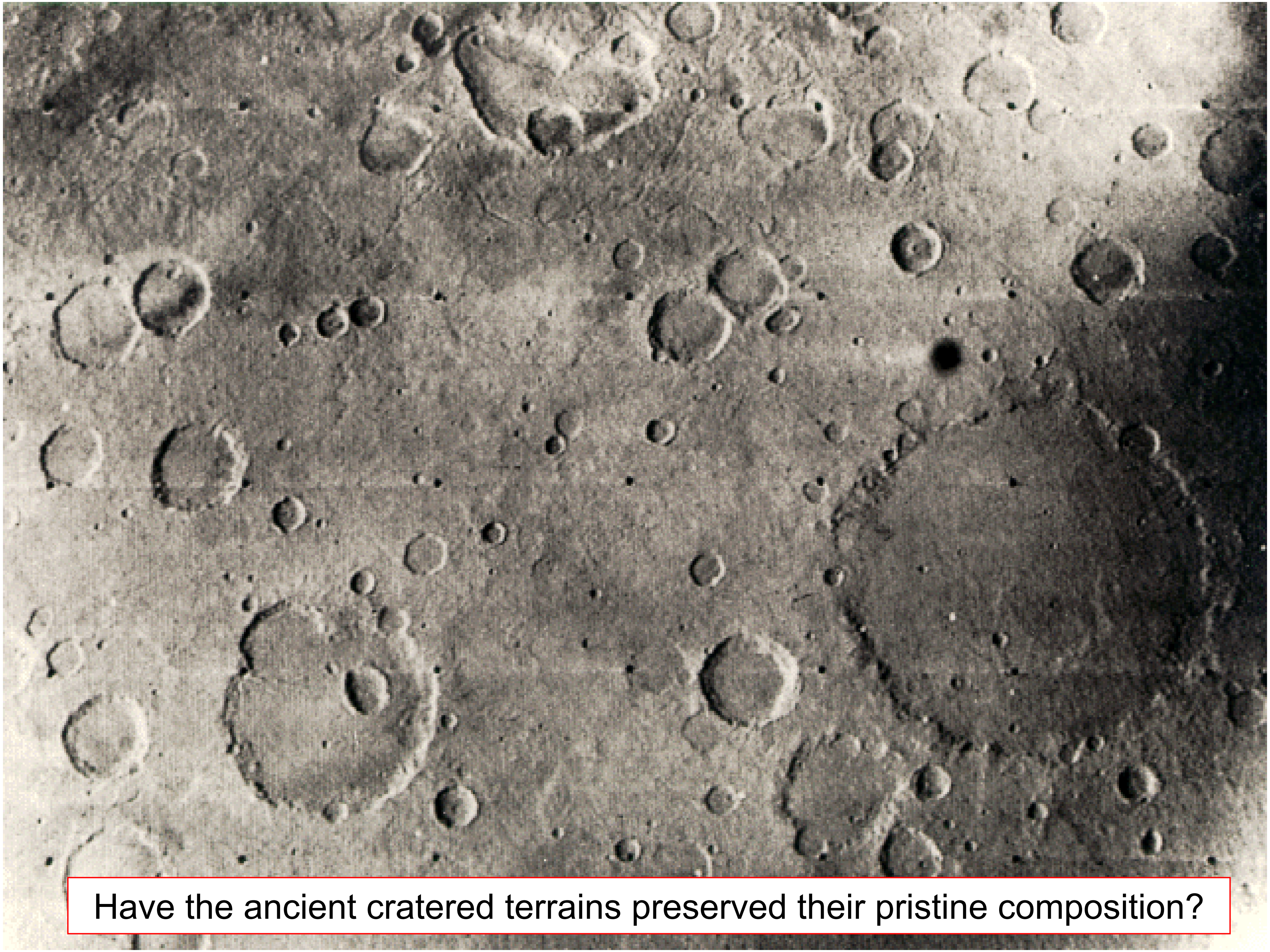


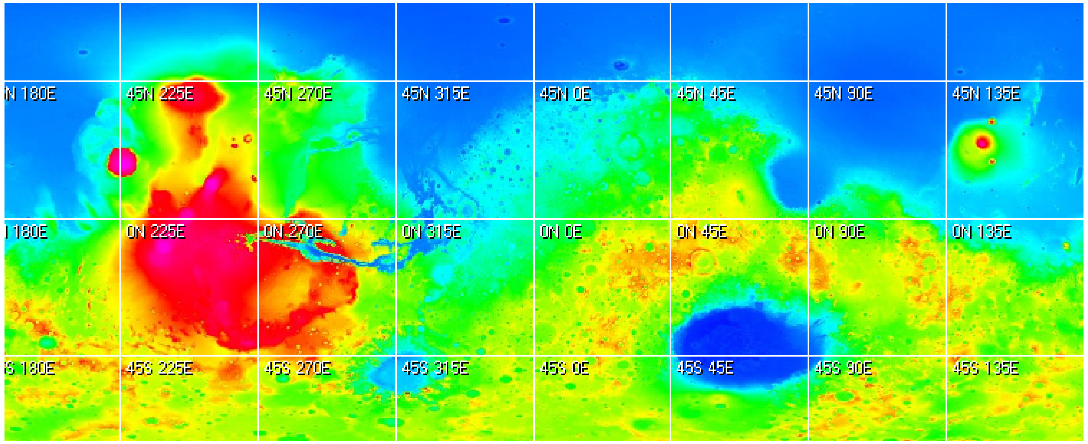
Noachian	Hesperian	Amazonian

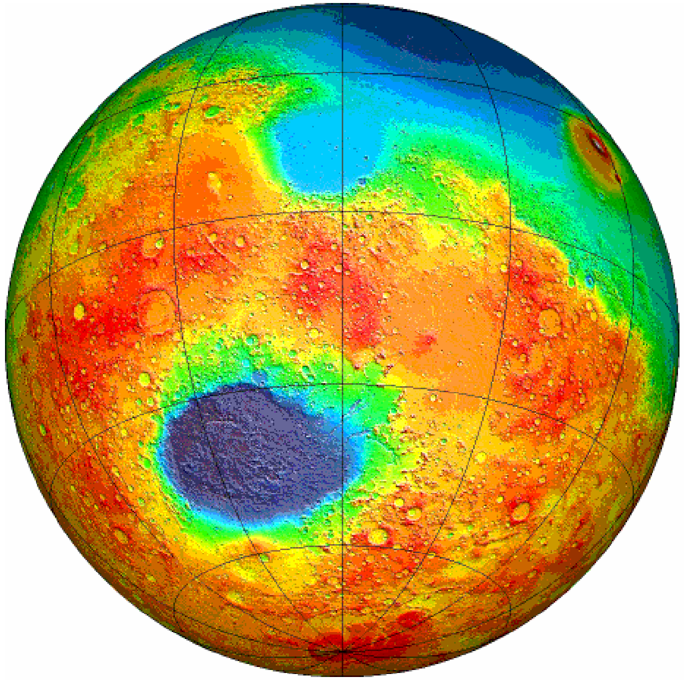
heavy bombardment

Is Noachian an era of similar properties over its entire duration?

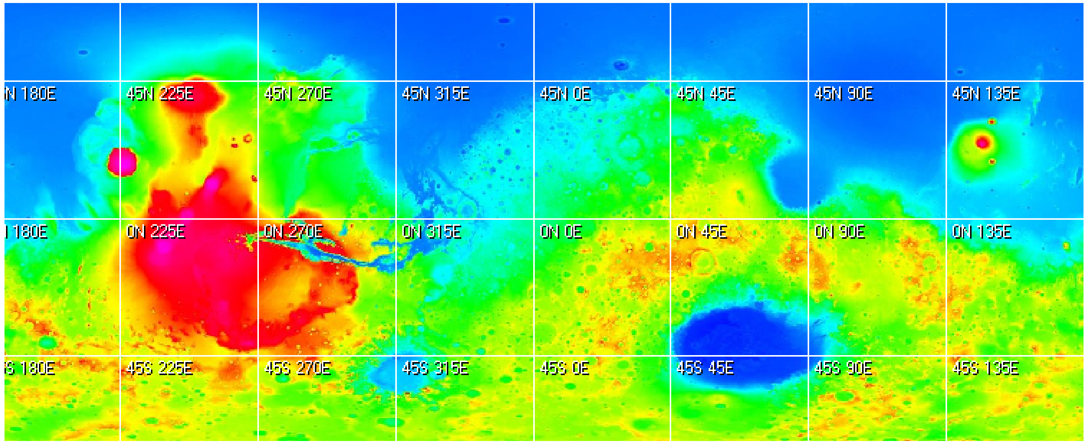
Noachian constitutes a sequence of distinct Martian conditions, the deciphering of which highly fruitful in comparative planetology

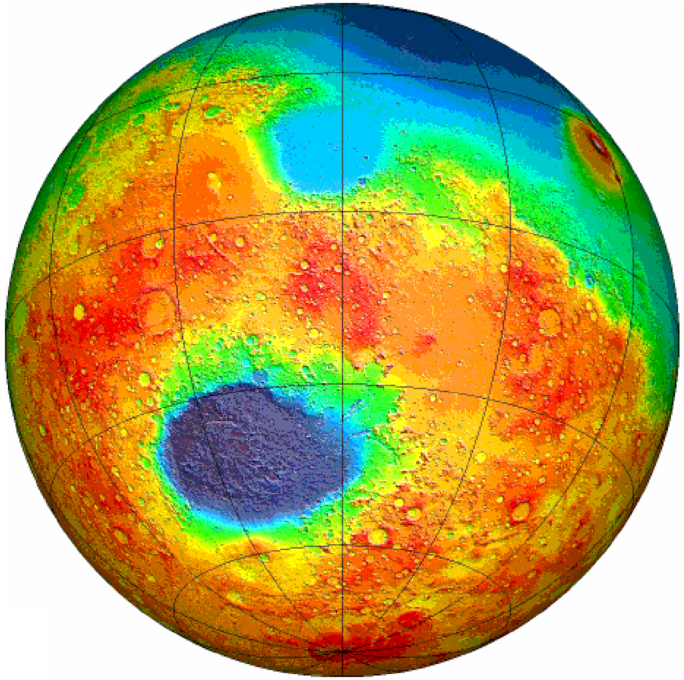

Have the ancient cratered terrains preserved their pristine composition?


N 180E
45N 225E
45N 270E
45N 315E
45N 0E
45N 45E
45N 90E
45N 135E
I 180E
0N 225E
0N 270E
0N 315E
0N 0E
0N 45E
0N 90E
0N 135E
S 180E
45S 225E
45S 270E
45S 315E
45S 0E
45S 45E
45S 90E
45S 135E

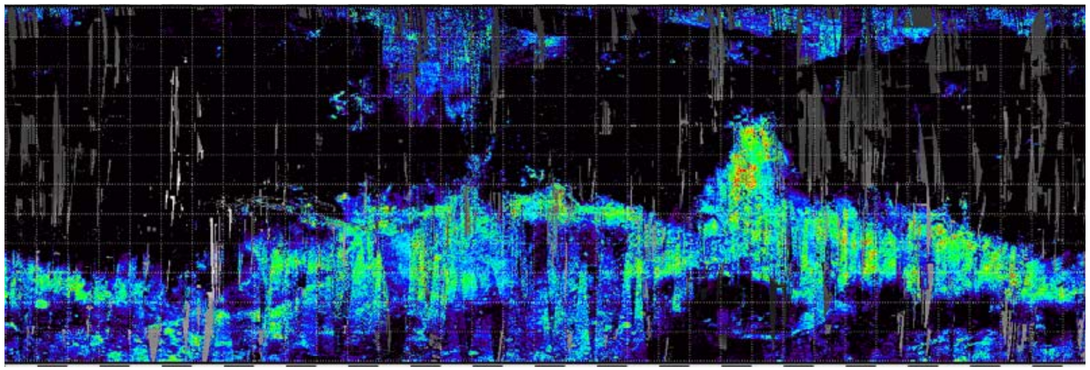


MOLA





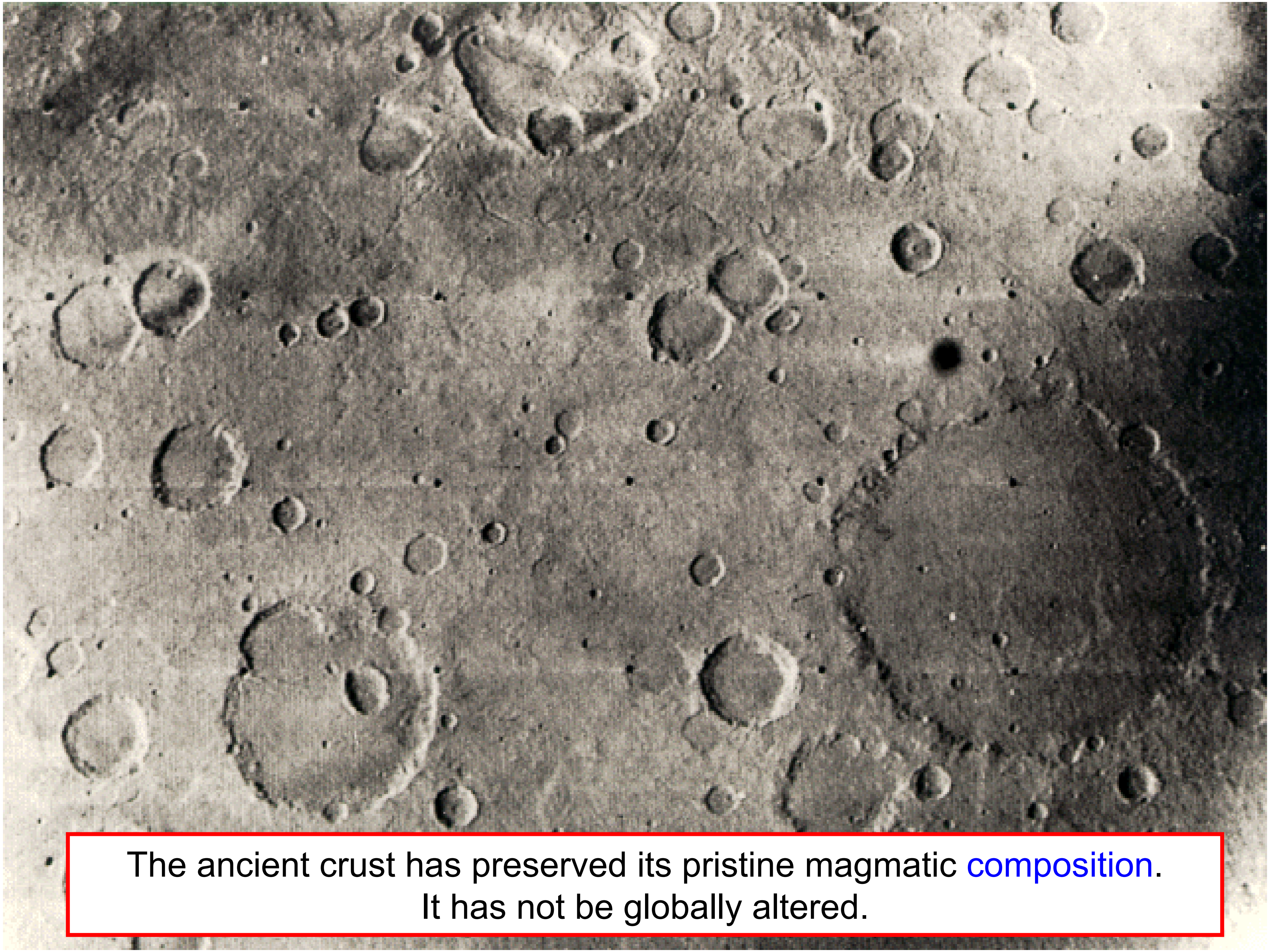
MOLA



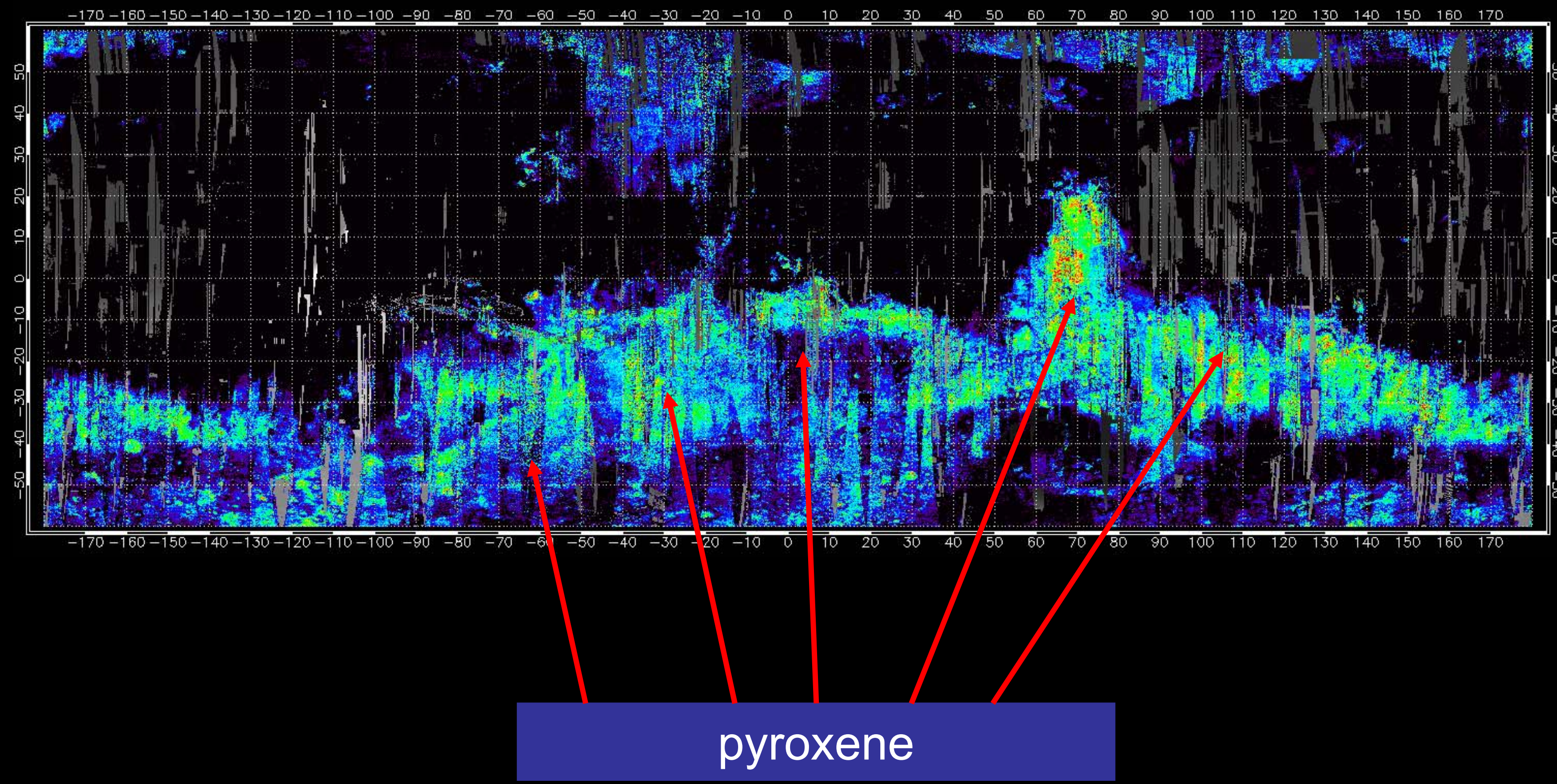
OMEGA

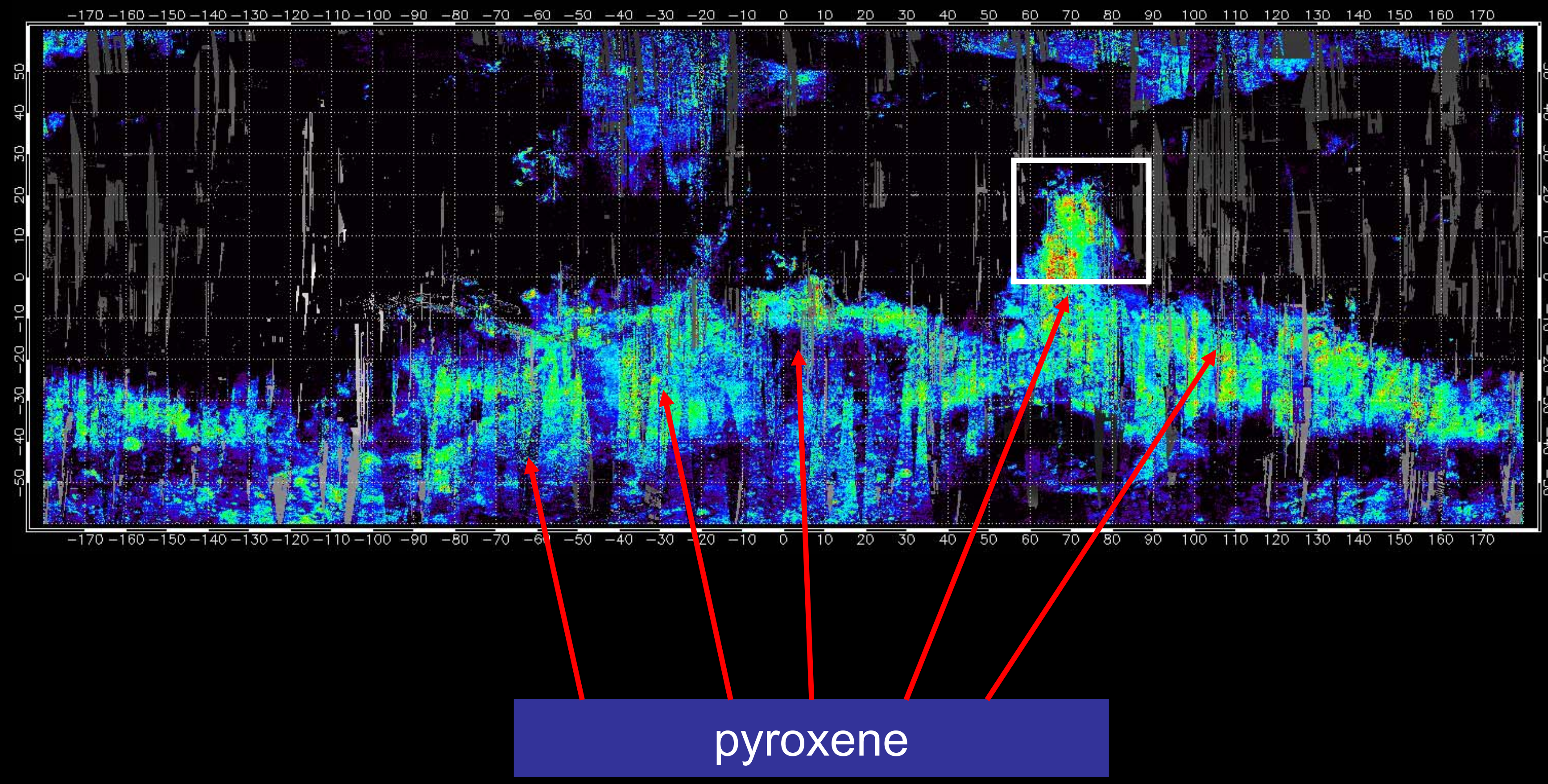
Pyroxenes

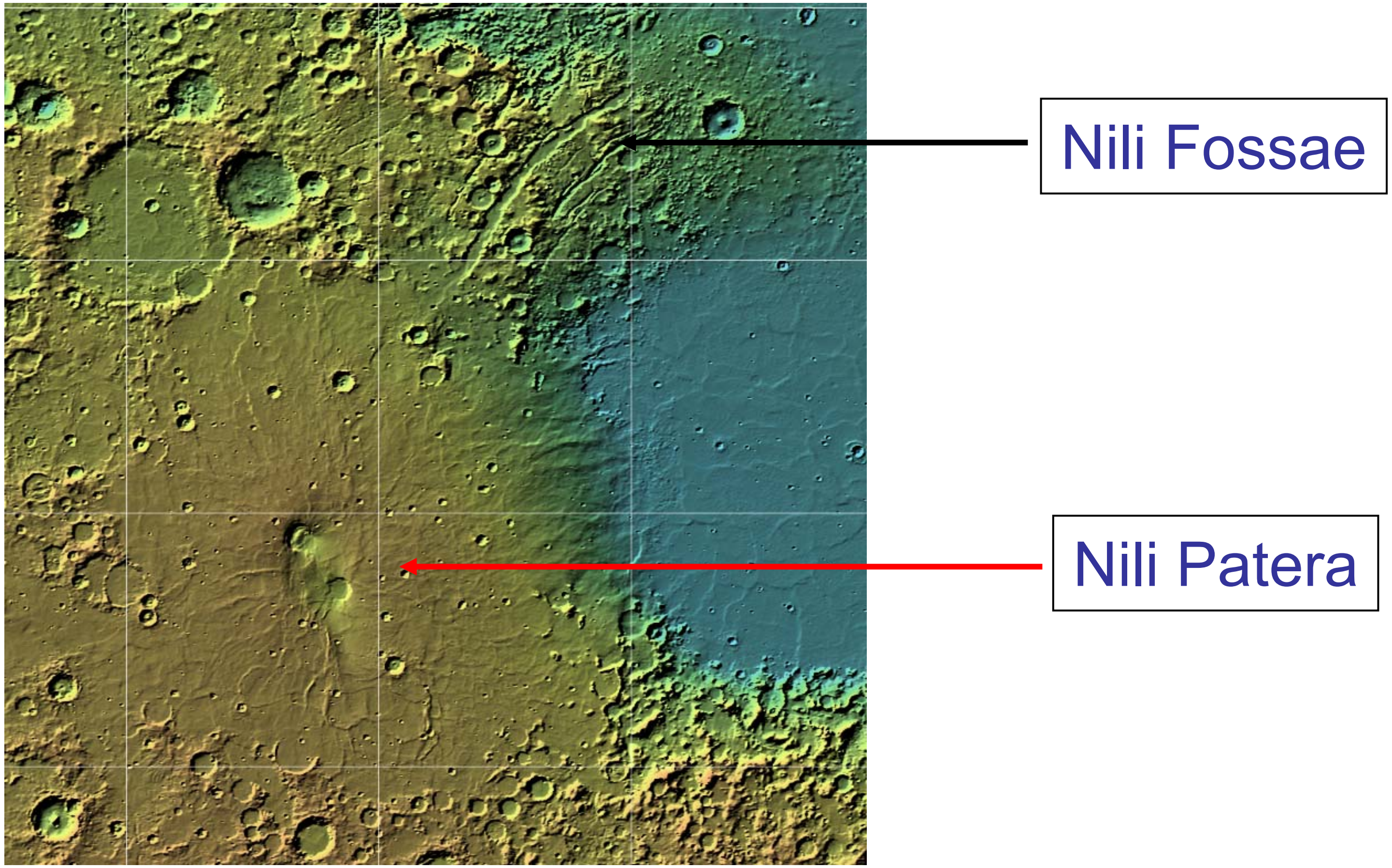
The ancient crust has preserved its pristine magmatic composition.
It has not be globally altered.



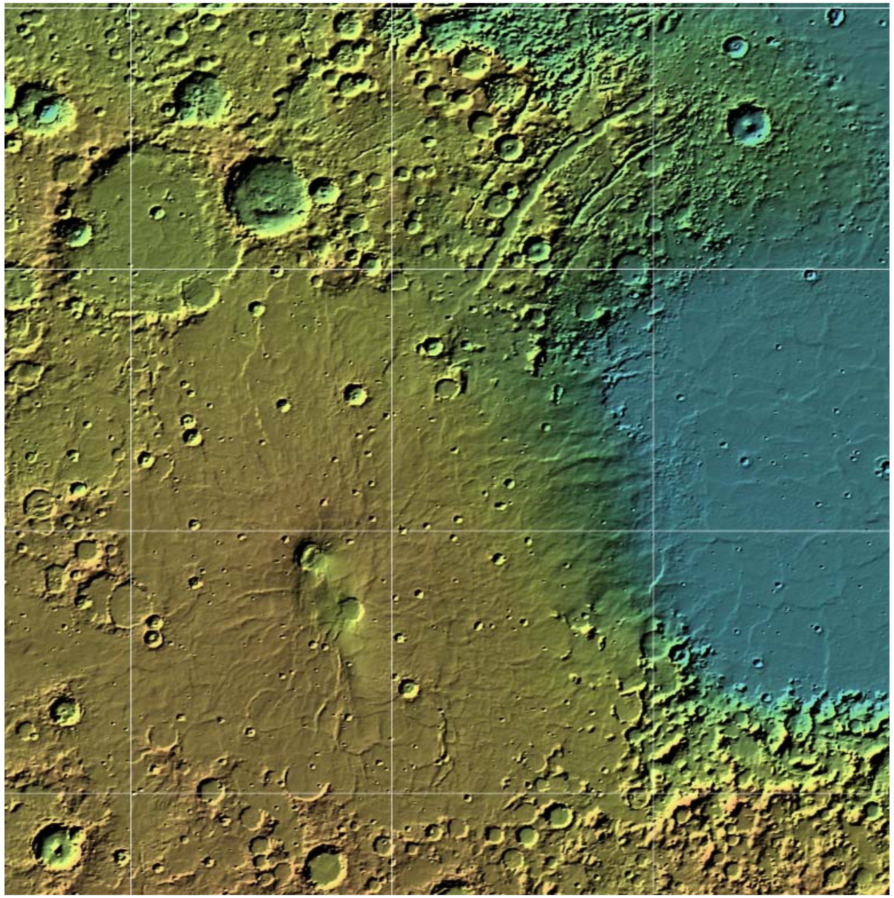
The ancient crust has preserved its pristine magmatic composition.
It has not be globally altered.


pyroxene

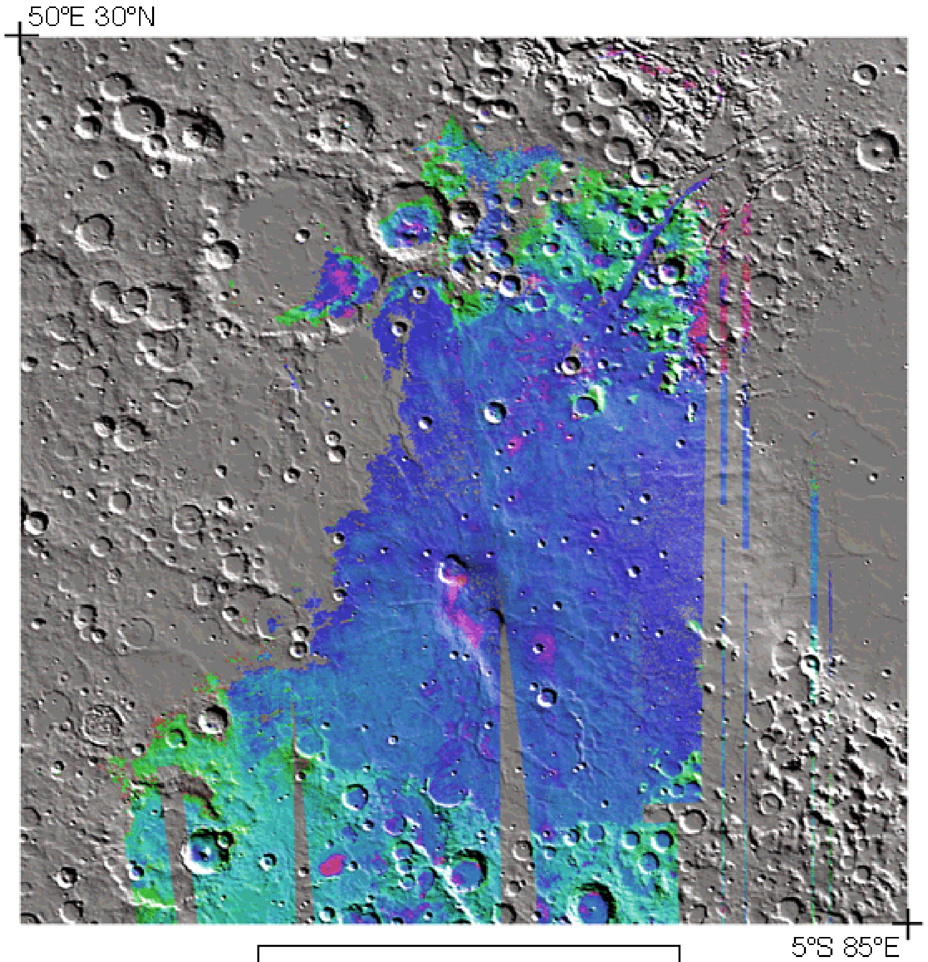

pyroxene



carte MOLA



MOLA map

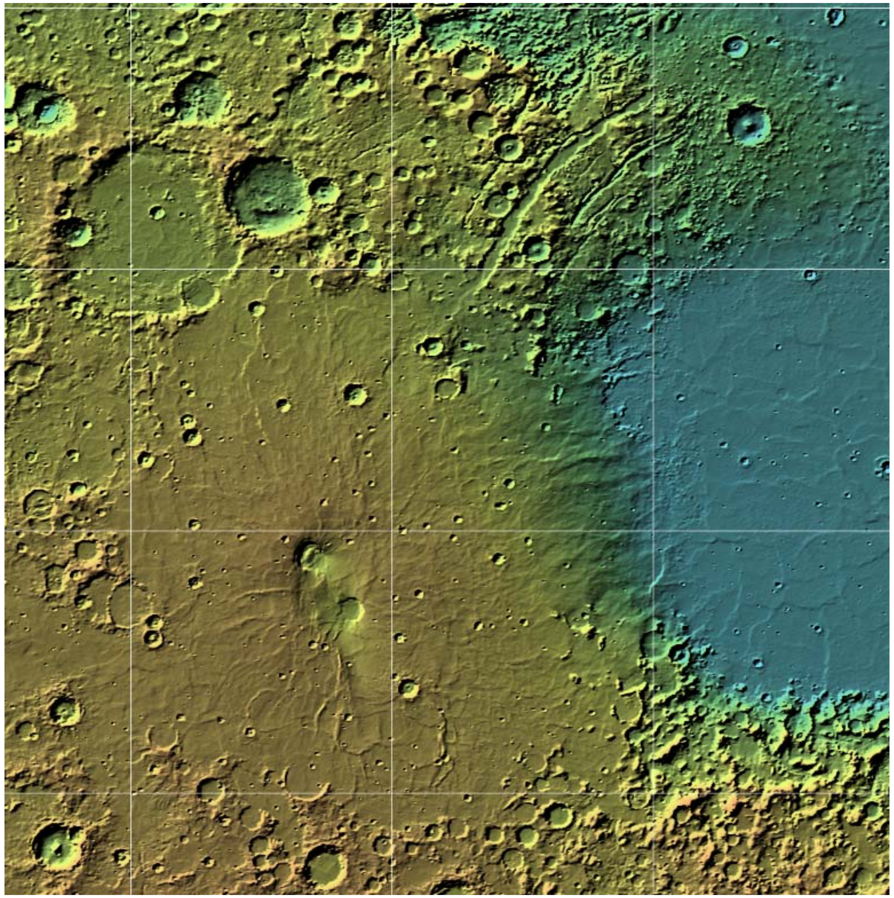


OMEGA map

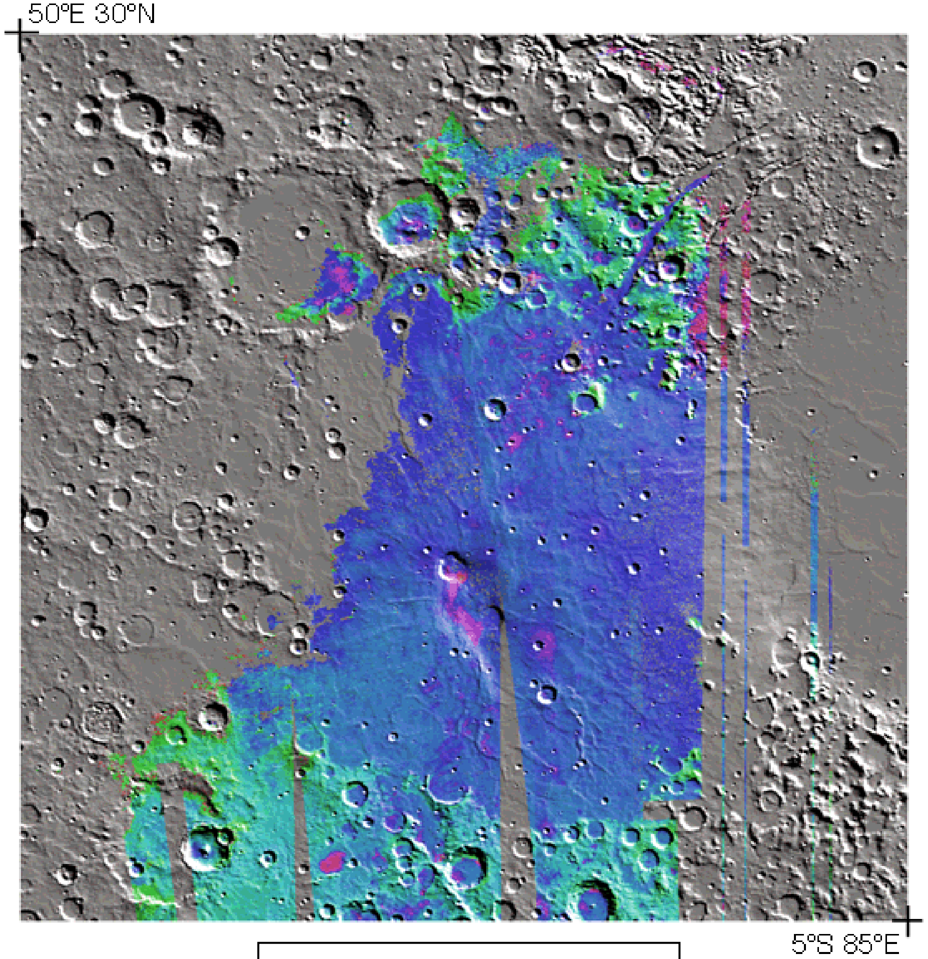
olivine: red

LCP: green

HCP: blue



MOLA map



OMEGA map

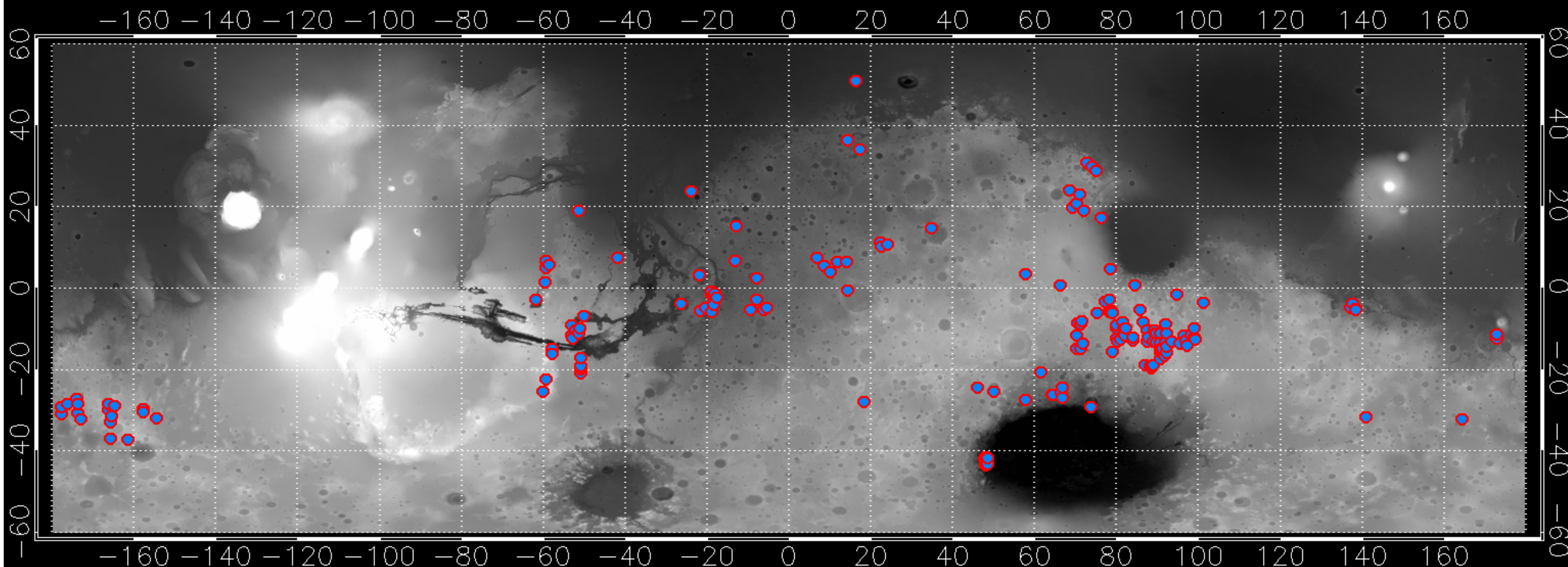
- The ancient crust solidified out of a fully melted magma.
- The volcanic outflows originate from partially melted magma (low level of fusion).

Mineralogy and History of Mars

Has Mars evolution been frozen in distinct mineralogical units ?

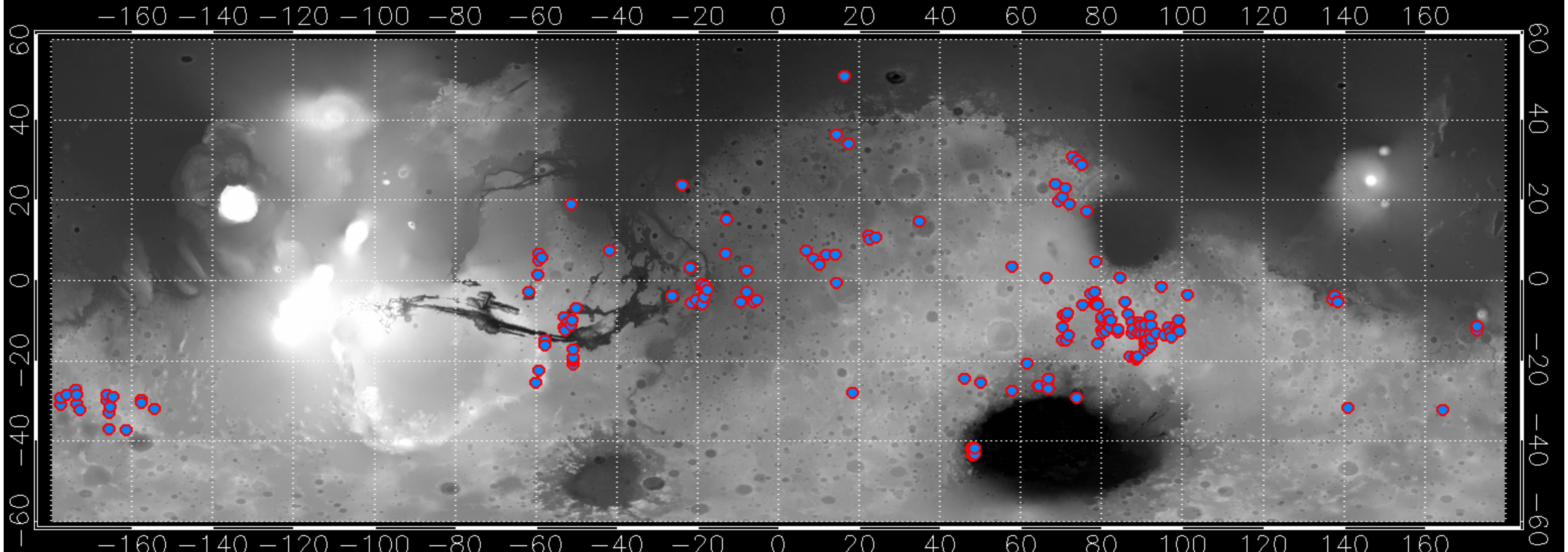
- Pristine crust, enriched in LCP
- Volcanic outflows, enriched in HCP

OMEGA map of hydrated minerals



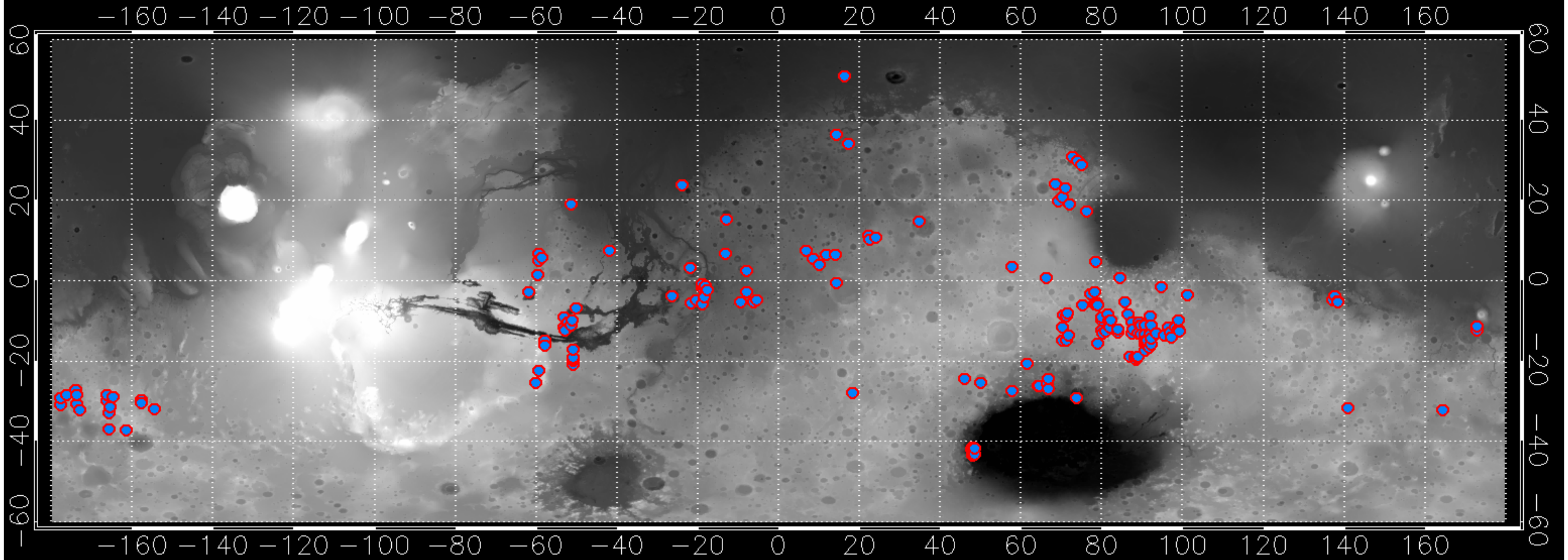
If either or both OH and H_2O is (are) present in a sample, in almost whatever physical state, OMEGA / Mars Express and CRISM / MRO can readily identify it: no one can hide its being hydrated.

OMEGA map of hydrated minerals



In hundreds of spots within the ancient crust, hydrated minerals have been identified, most requiring kilometer to sub-kilometer resolution.

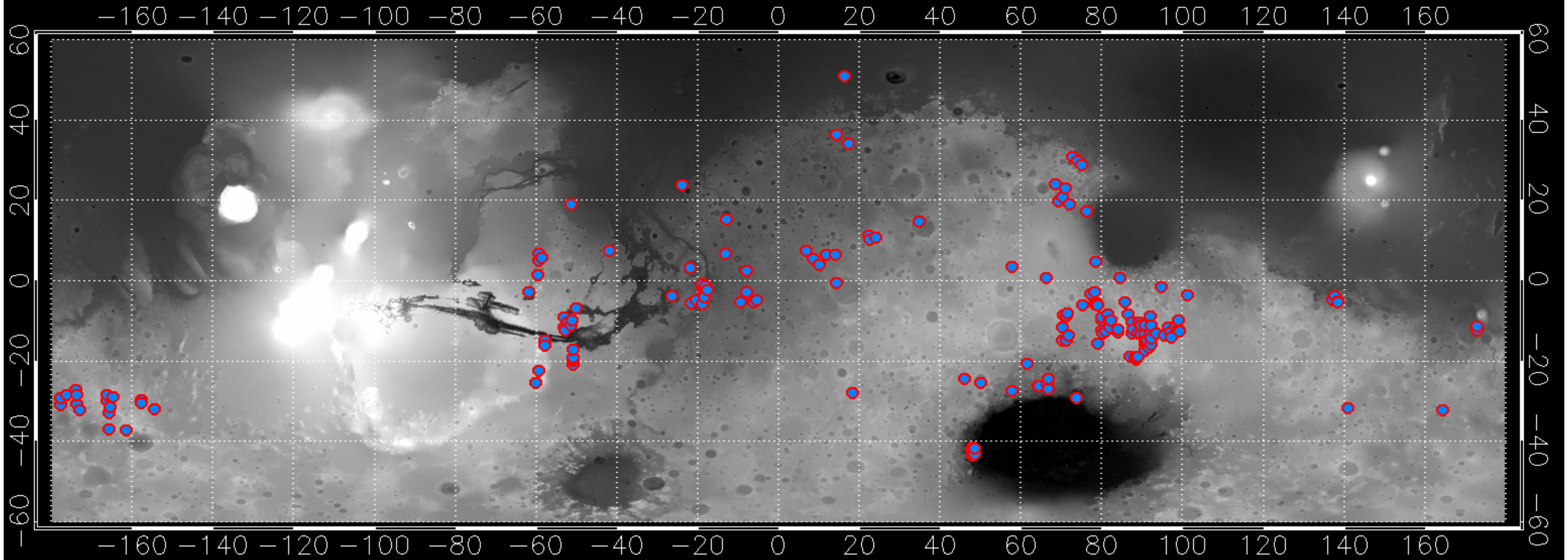
OMEGA map of hydrated minerals



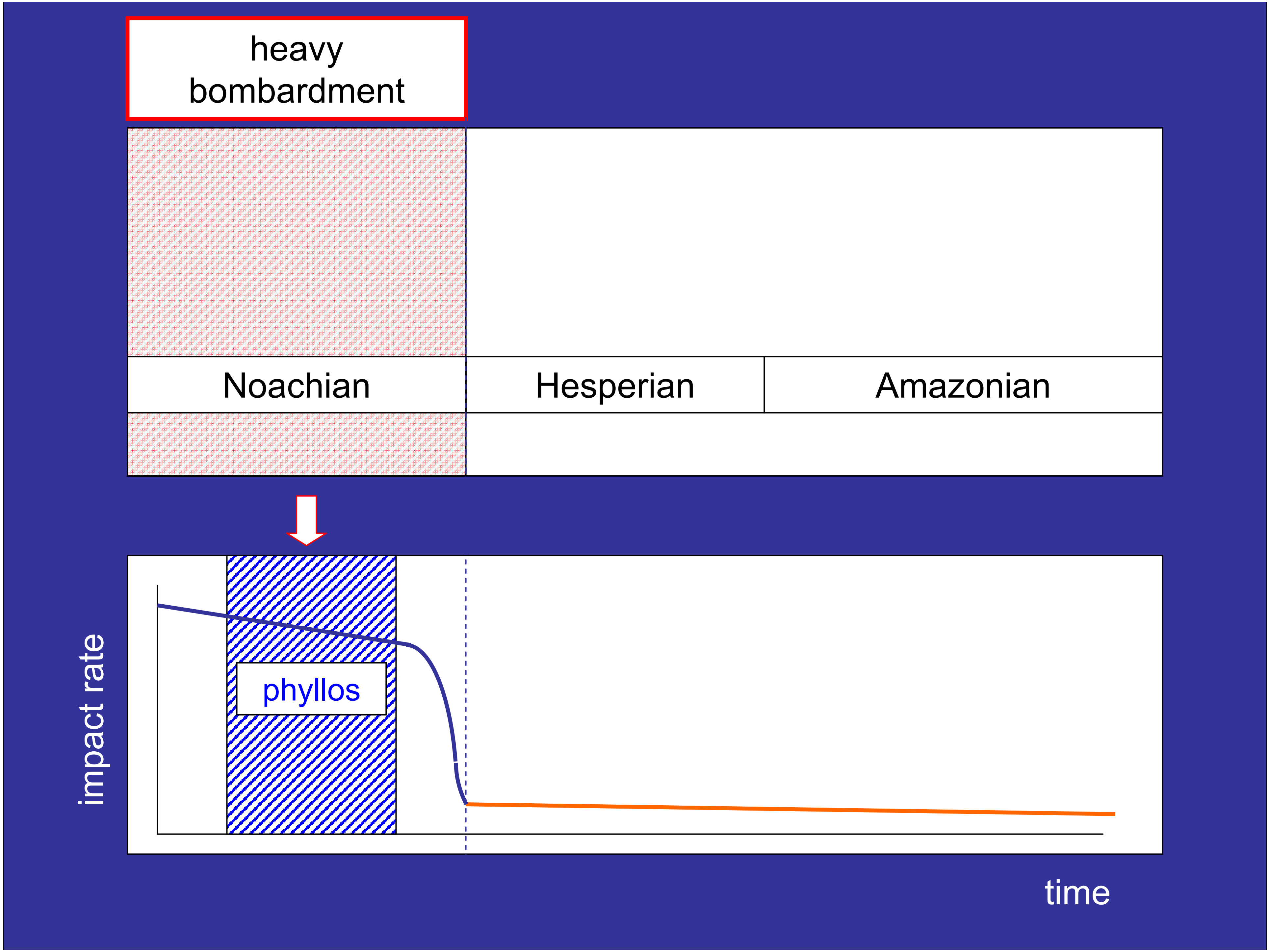
In hundreds of spots within the ancient crust, hydrated minerals have been identified, most requiring kilometer to sub-kilometer resolution.

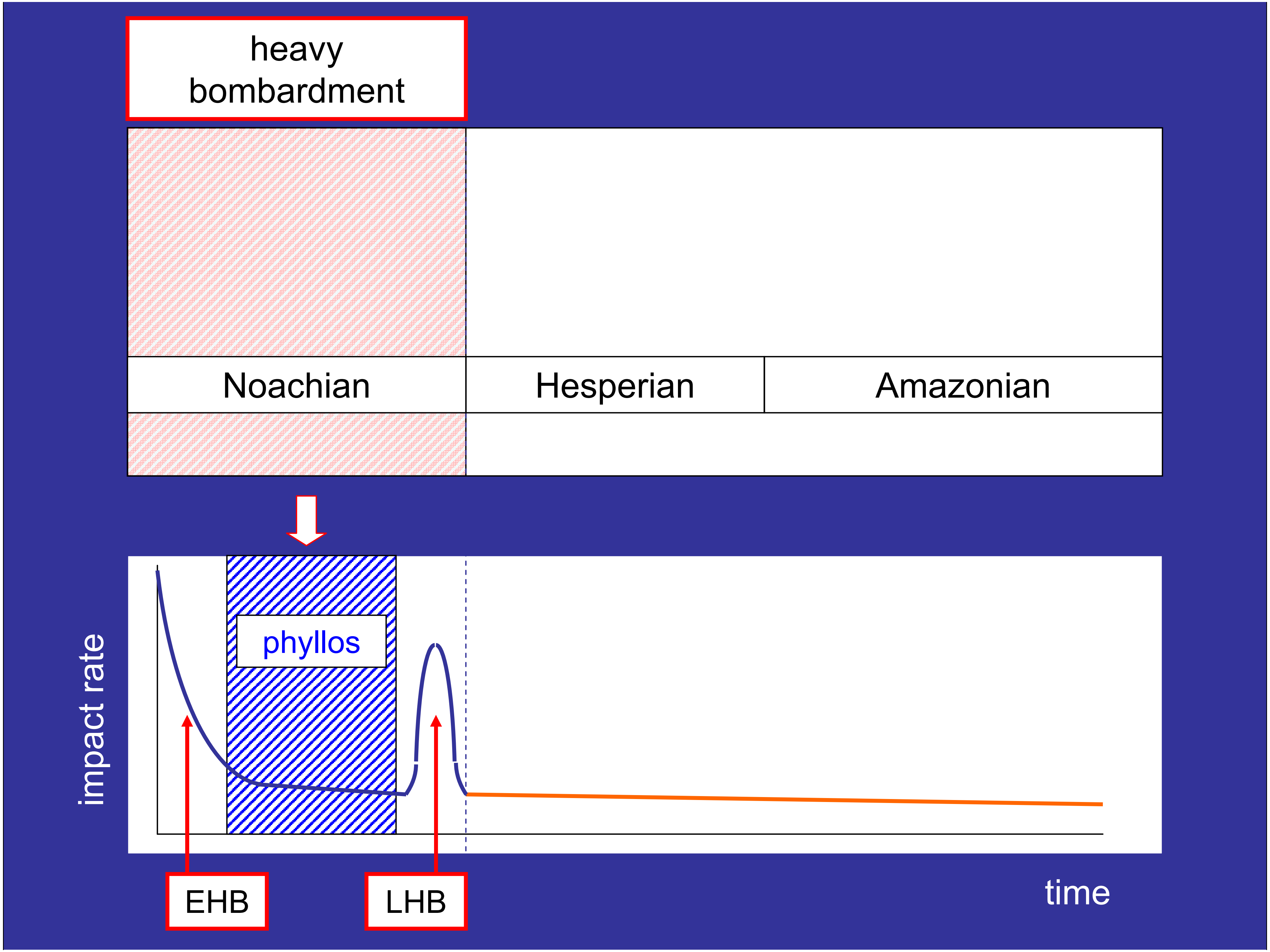
Phyllosilicates are amongst the most diagnostic of an ancient aqueous era, which happened during the heavy bombardment.

OMEGA map of hydrated minerals



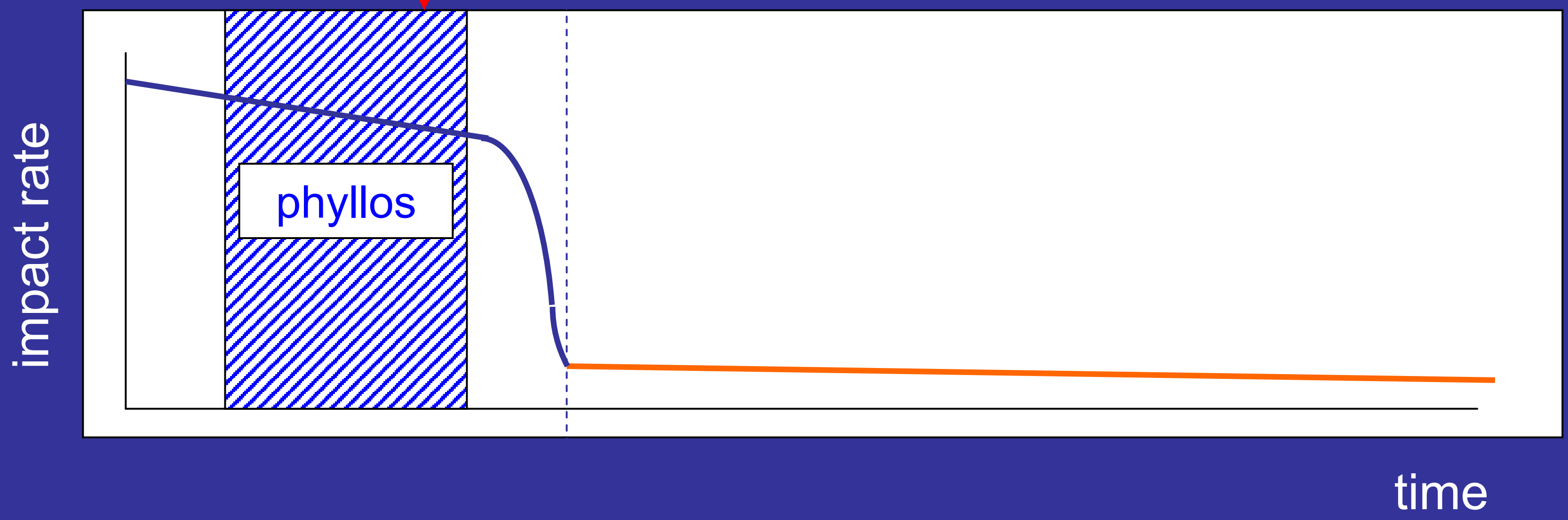
How to account for an ancient crust, still exhibiting its mafic pristine composition, with a number of isolated areas having been altered by liquid water over long durations, and having preserved this record over the heavy bombardment until now?

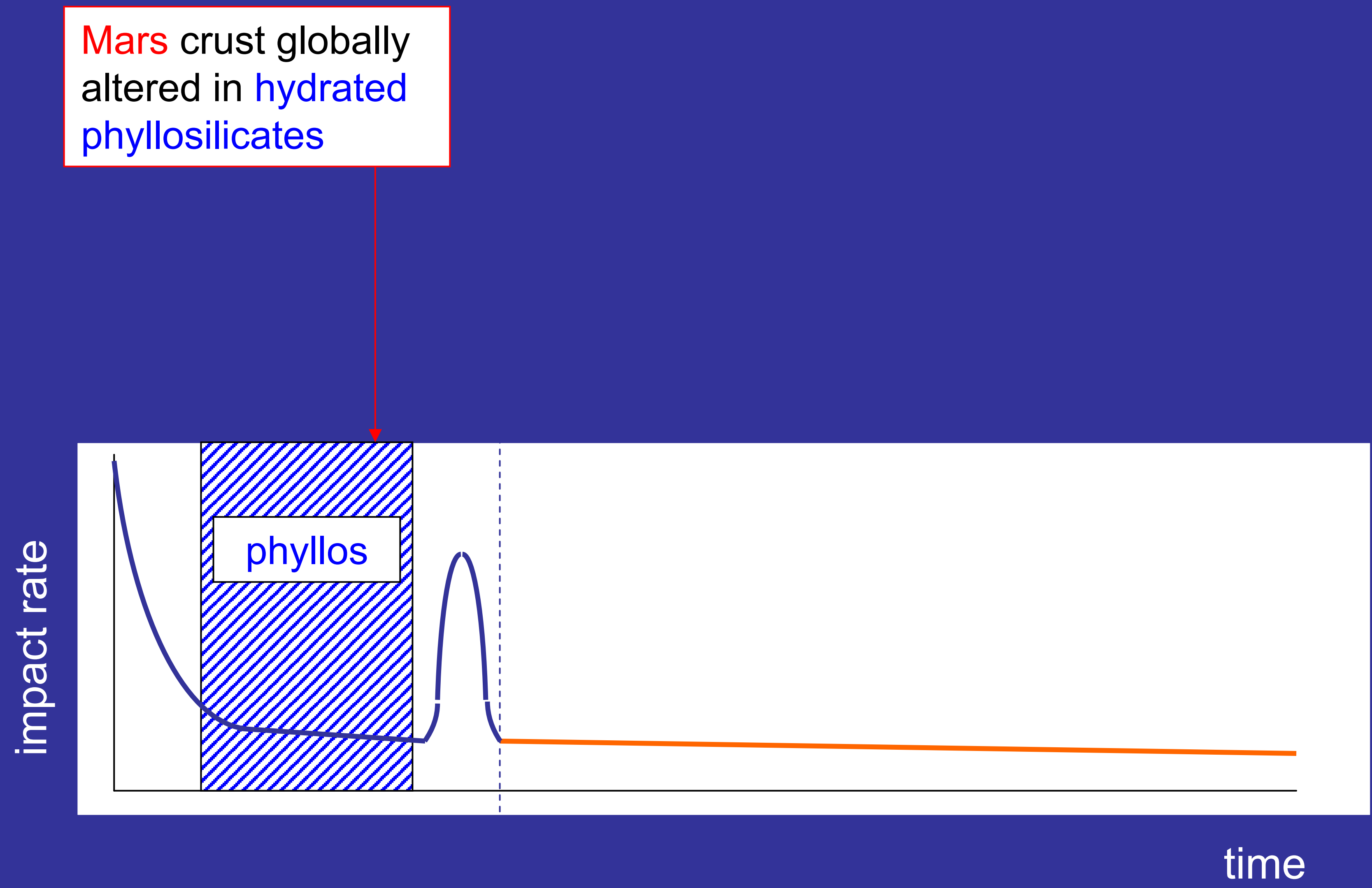

heavy
bombardment
Noachian
Hesperian
Amazonian
phyllos
impact rate
time

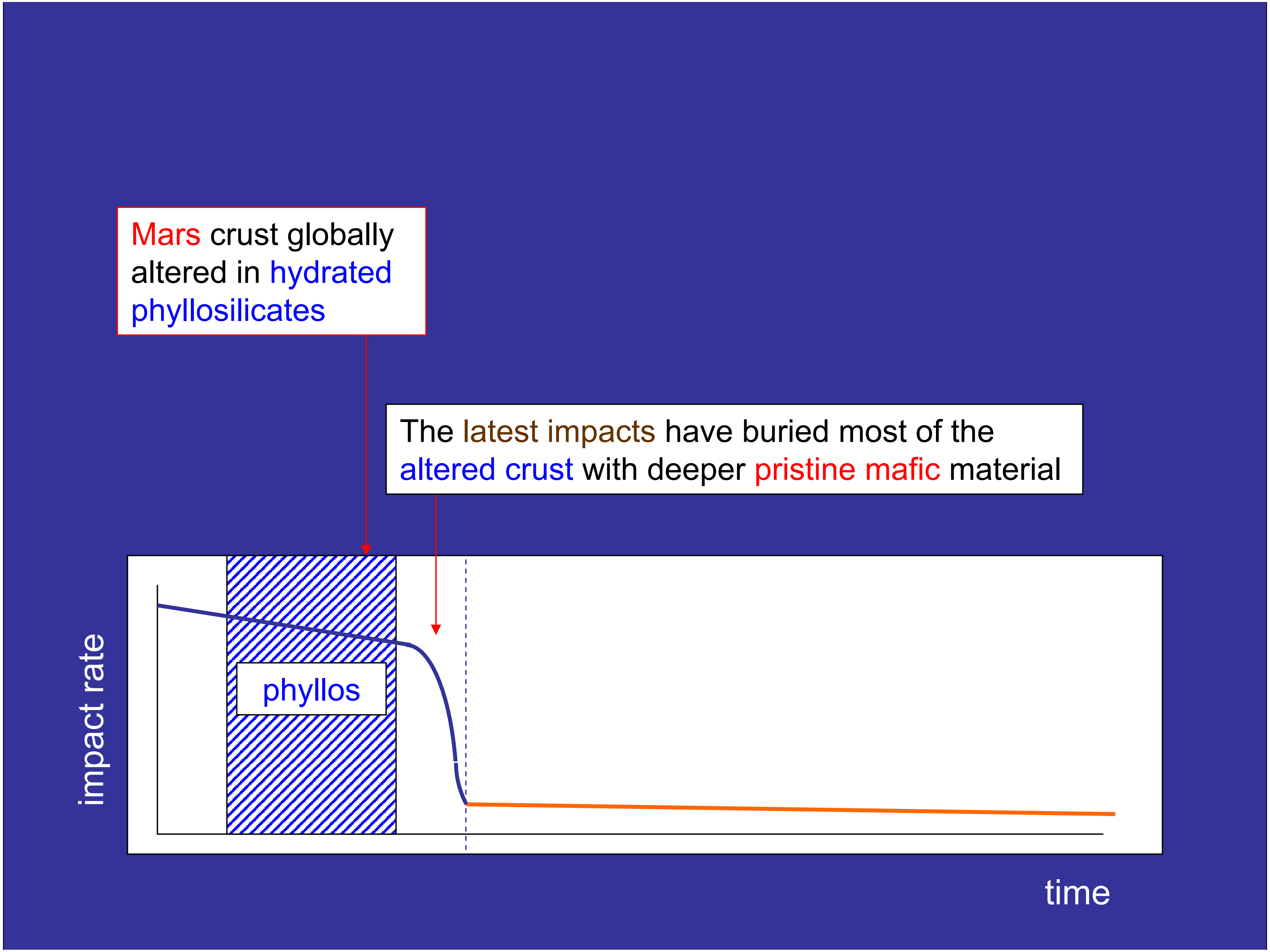


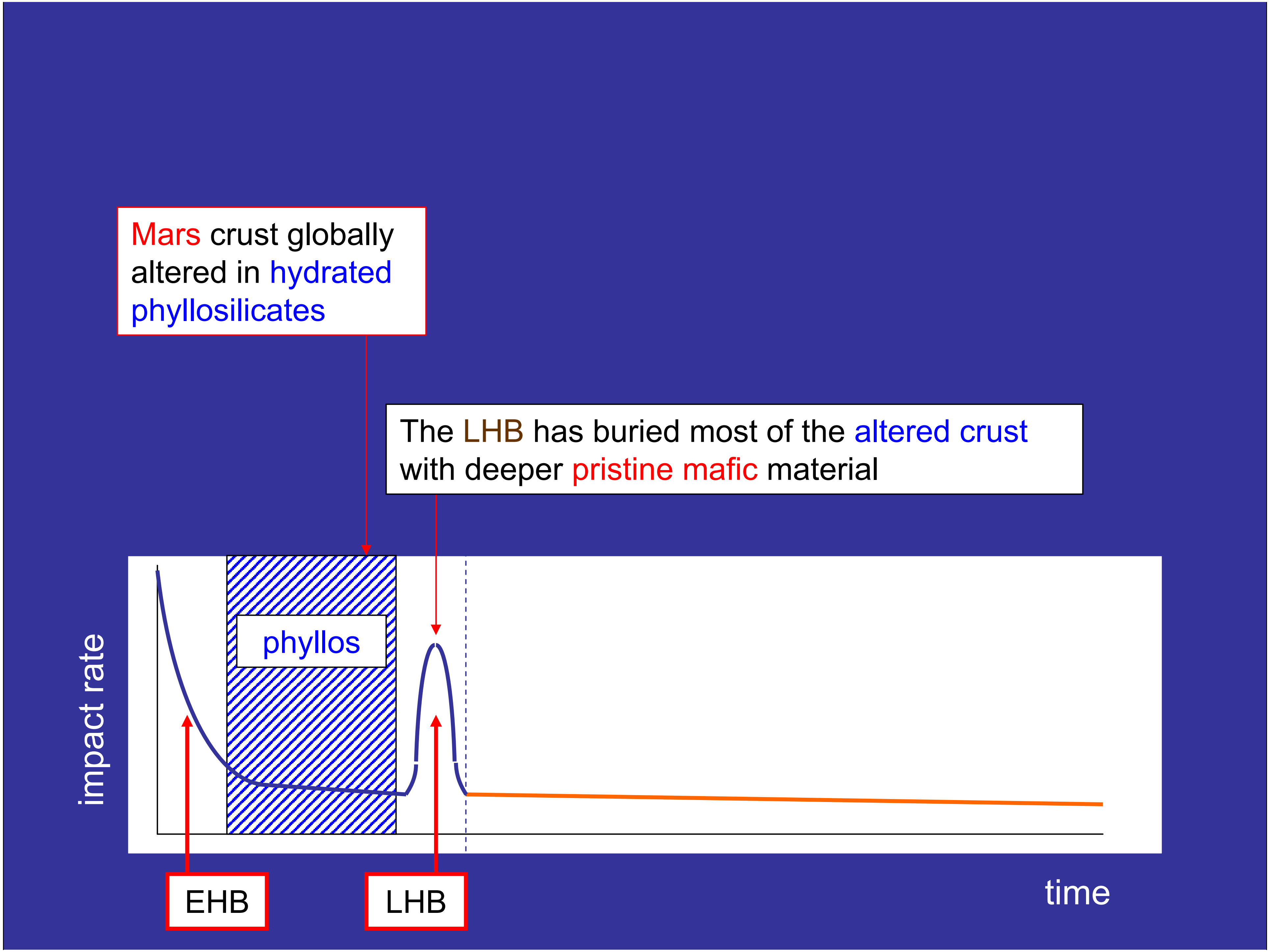
heavy bombardment
Noachian
Hesperian
Amazonian
phyllos
impact rate
time
EHB
LHB

Mars crust globally altered in hydrated phyllosilicates



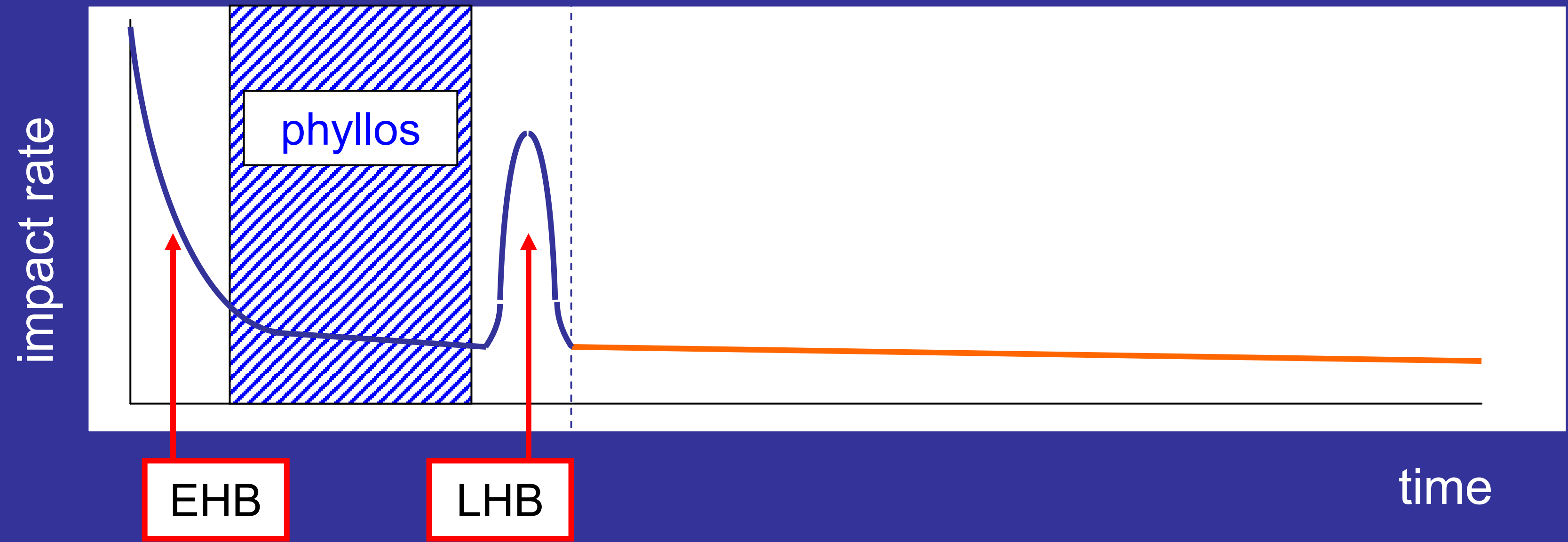

Mars crust globally altered in hydrated phyllosilicates
phyllos
impact rate
time

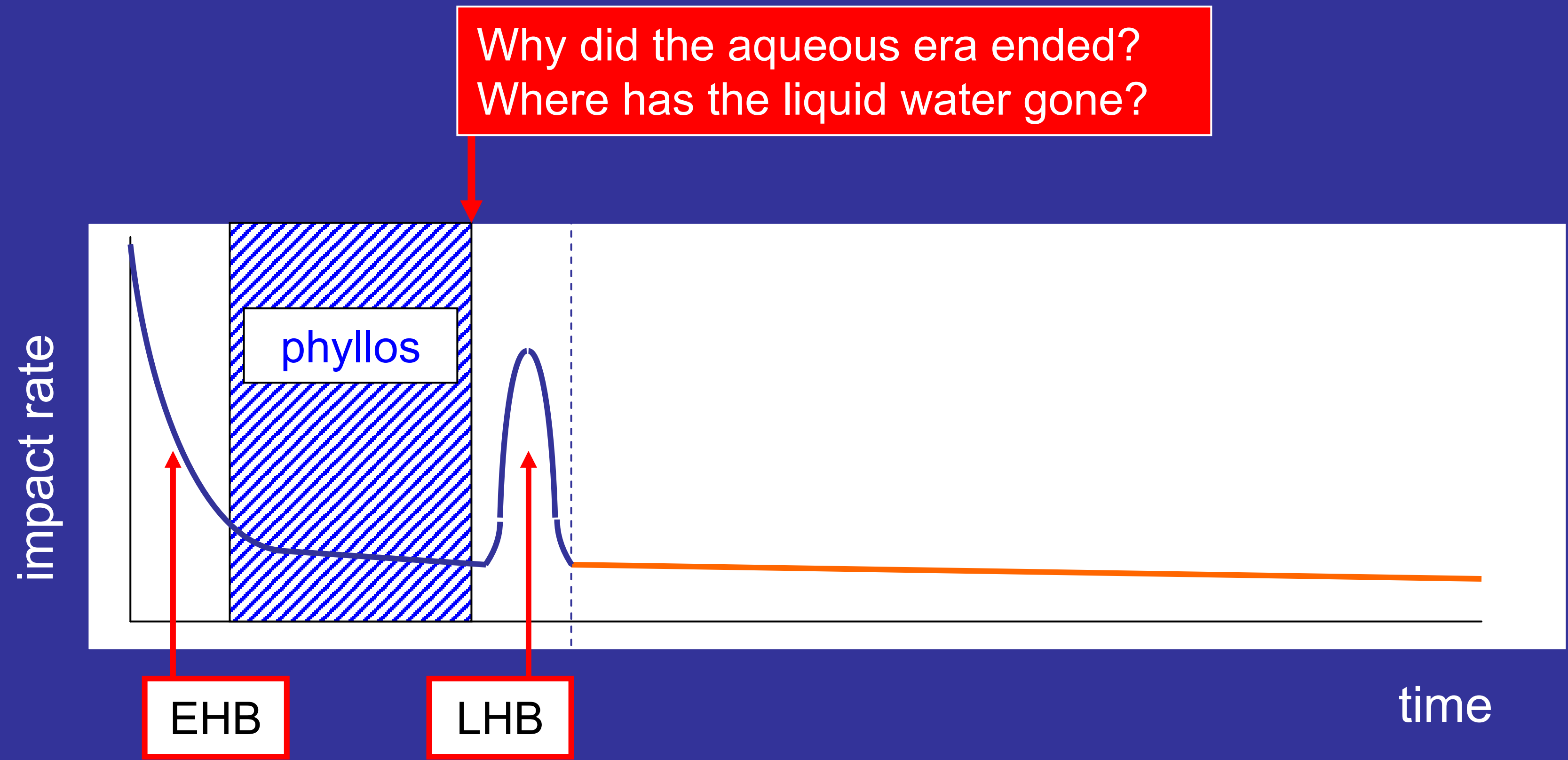

Mars crust globally altered in hydrated phyllosilicates
The latest impacts have buried most of the altered crust with deeper pristine mafic material
phyllos
impact rate
time



Mars crust globally altered in hydrated phyllosilicates
The LHB has buried most of the altered crust with deeper pristine mafic material
phyllos
impact rate
EHB
LHB
time

In both cases,
the aqueous era ended prior to the heavy bombardment drop.



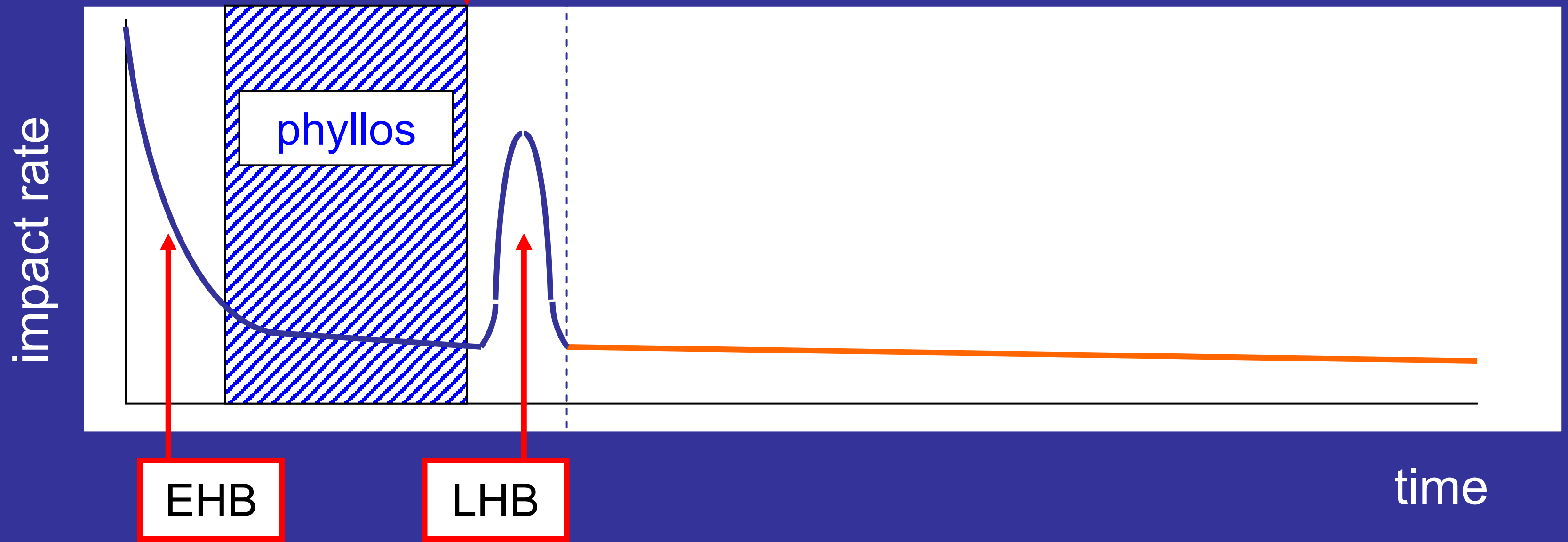

Why did the aqueous era ended?
Where has the liquid water gone?
phyllos
impact rate
EHB
LHB
time

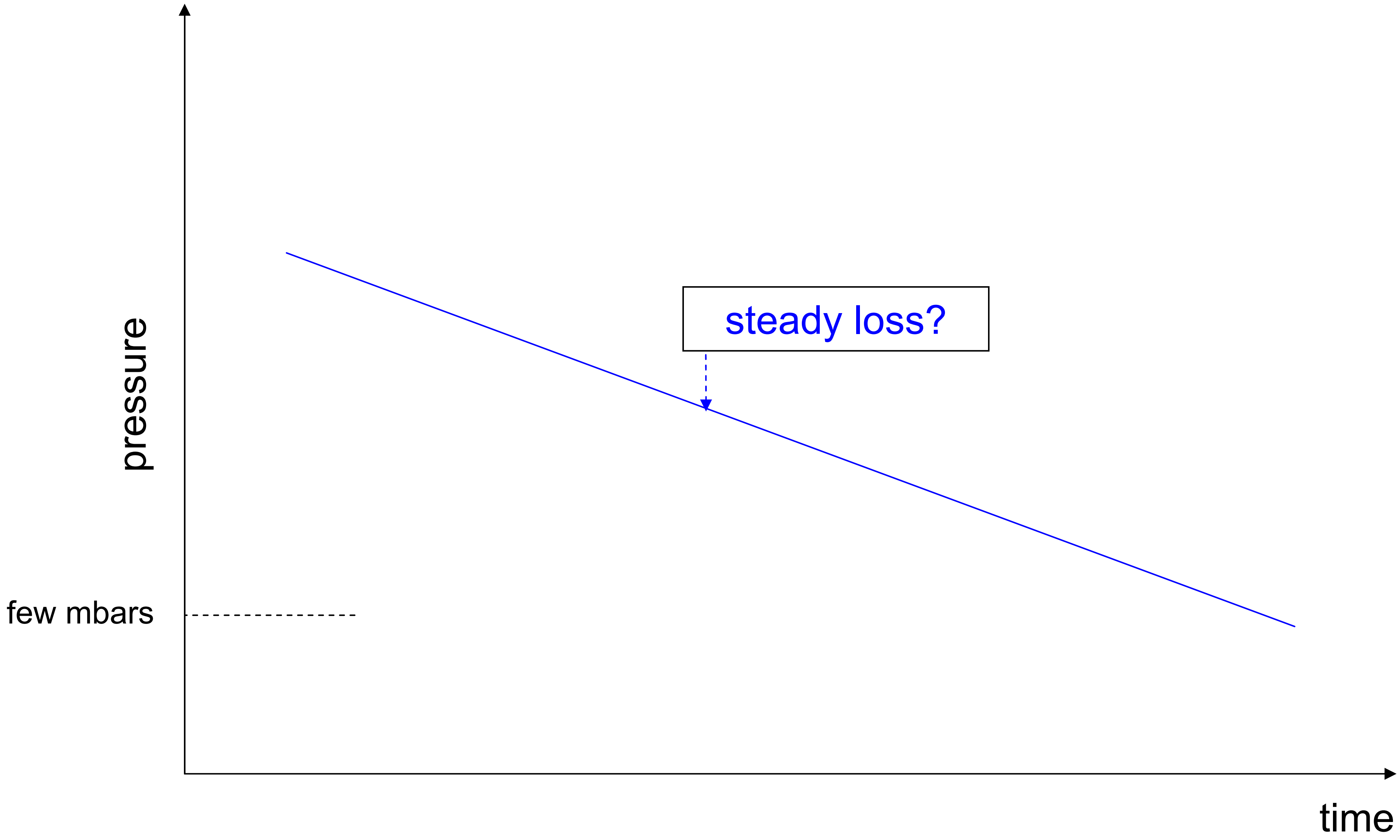
- The atmosphere dropped (escaped)
- Liquid water in part percolated (and in part evaporated)

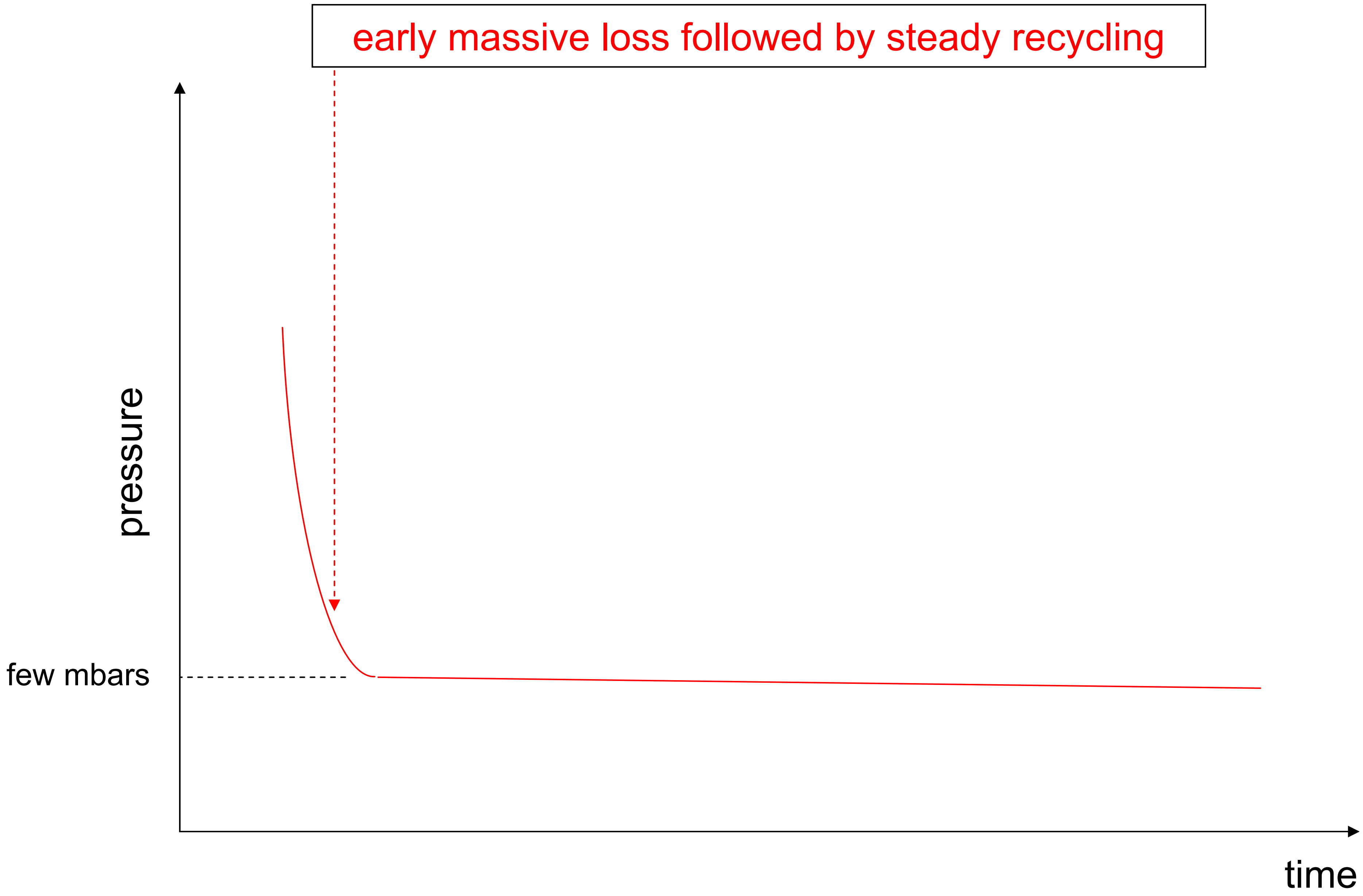
→ Eventually, this subsurface ice emerged later on, as

- sulfates
- outflow channels

Why did the aqueous era ended?
Where has the liquid water gone?



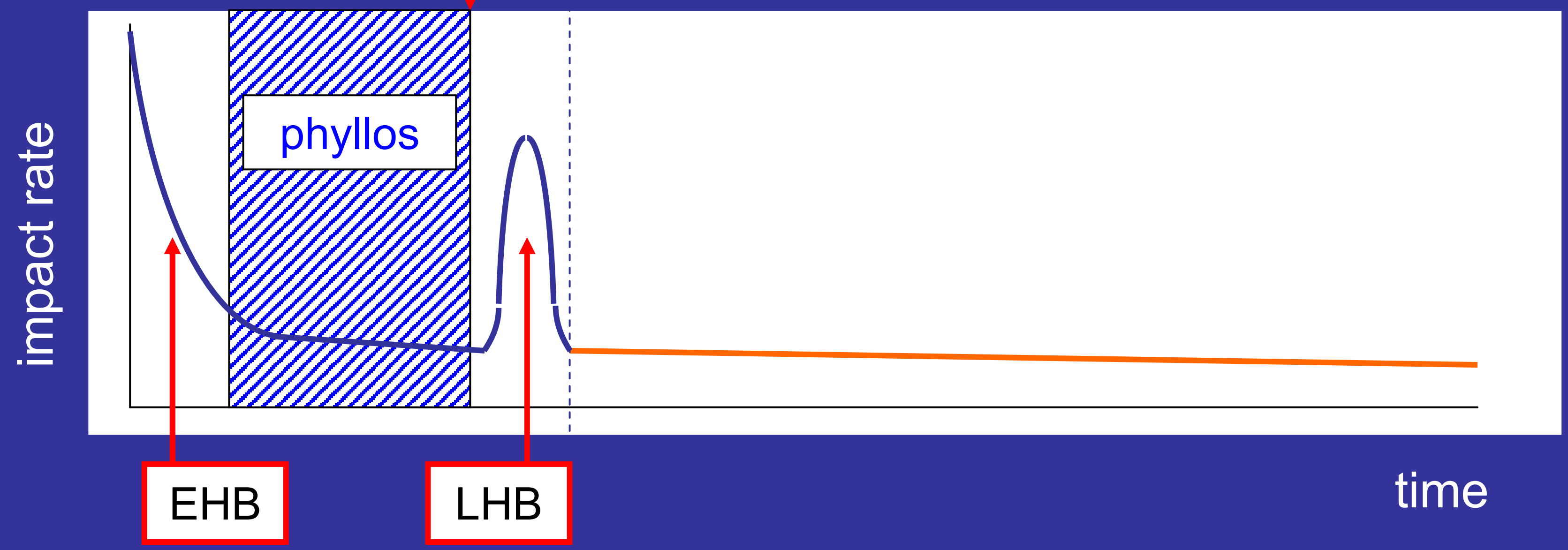

pressure
few mbars
steady loss?
time


early massive loss followed by steady recycling
pressure
few mbars
time

- The atmosphere dropped (escaped)
- Liquid water in part percolated (and in part evaporated)

Mars global climatic change

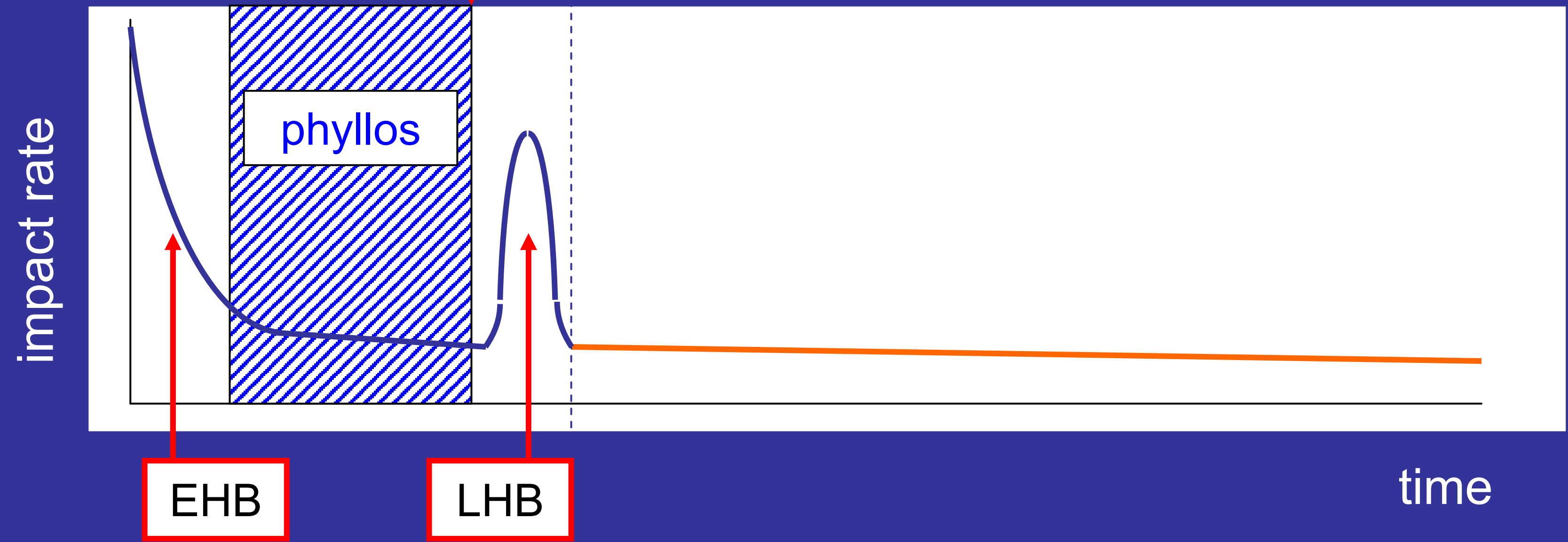
Why did the aqueous era ended?
Where has the liquid water gone?



- The atmosphere dropped (escaped)
- Liquid water in part percolated (and in part evaporated)

Mars global climatic change

What triggered the atmospheric escape ?

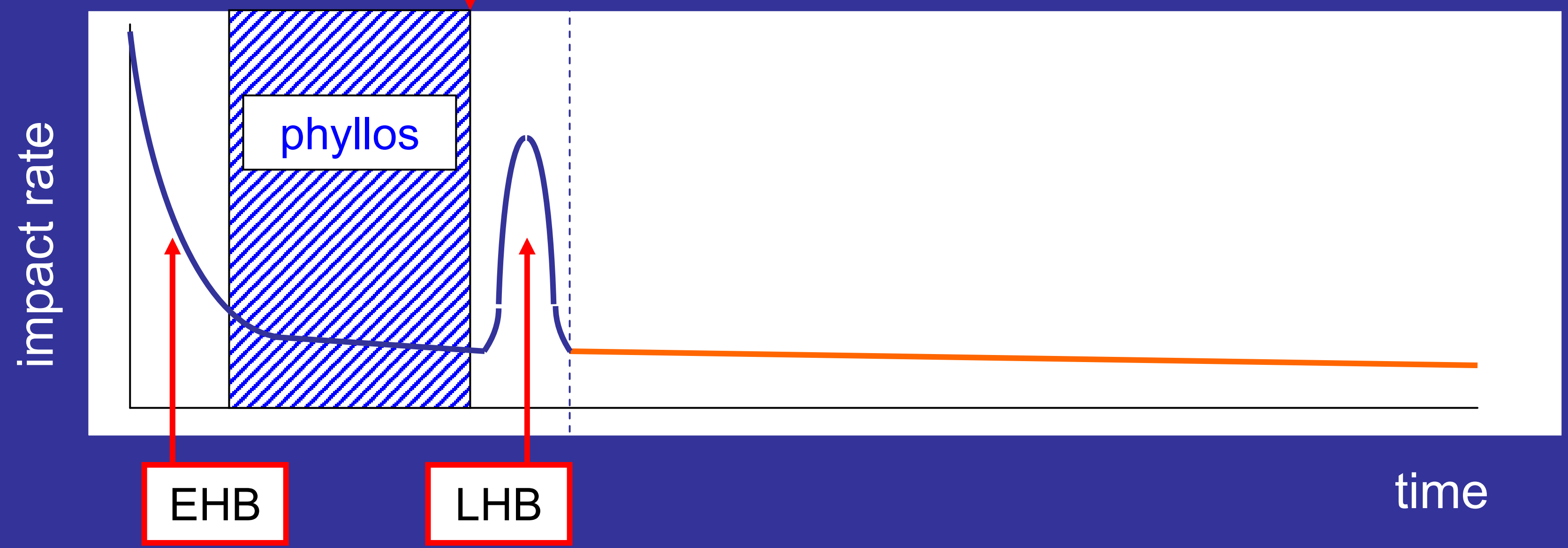


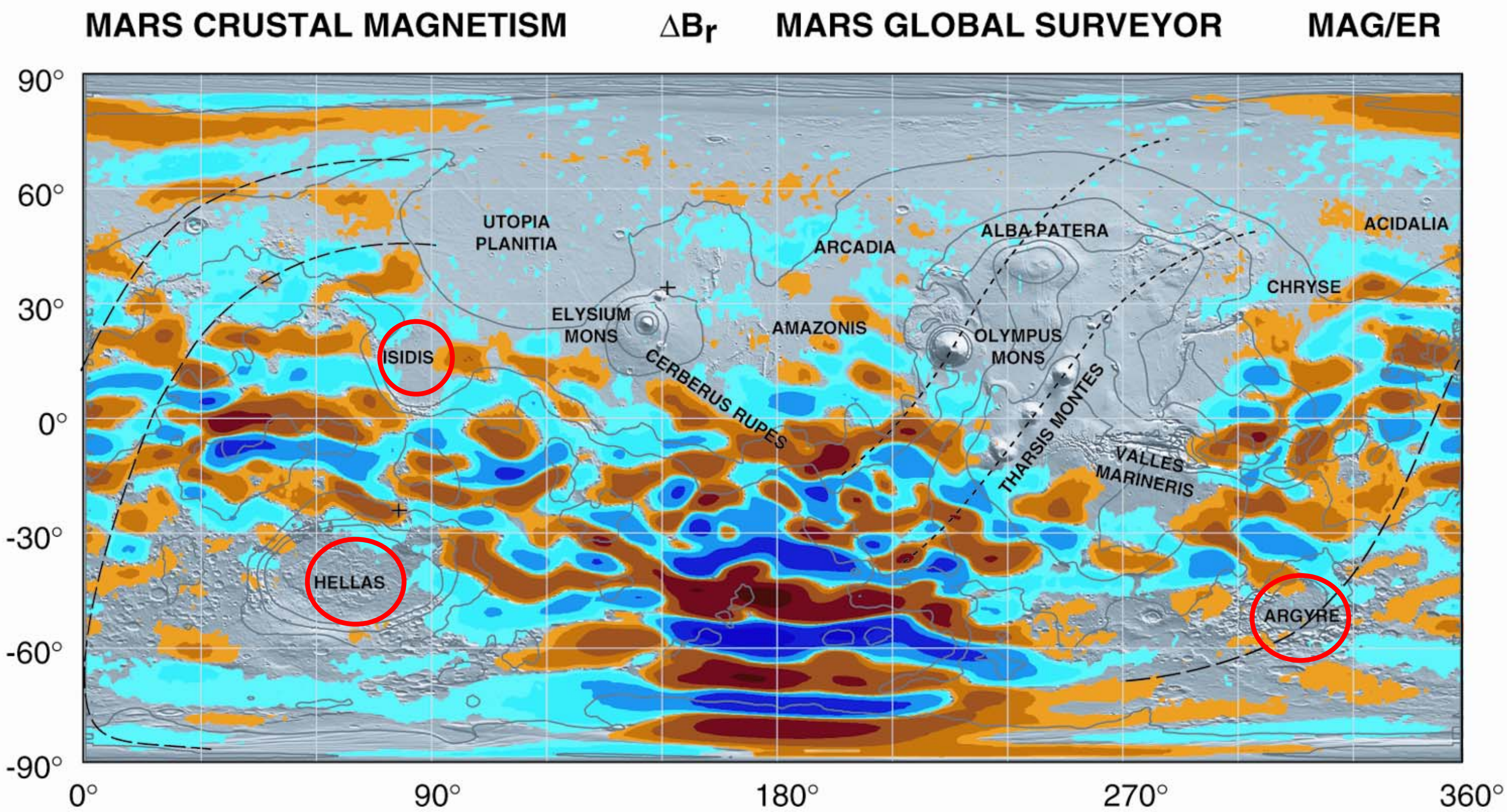
- The atmosphere dropped (escaped)
- Liquid water in part percolated (and in part evaporated)

Mars global climatic change

What triggered the atmospheric escape ?

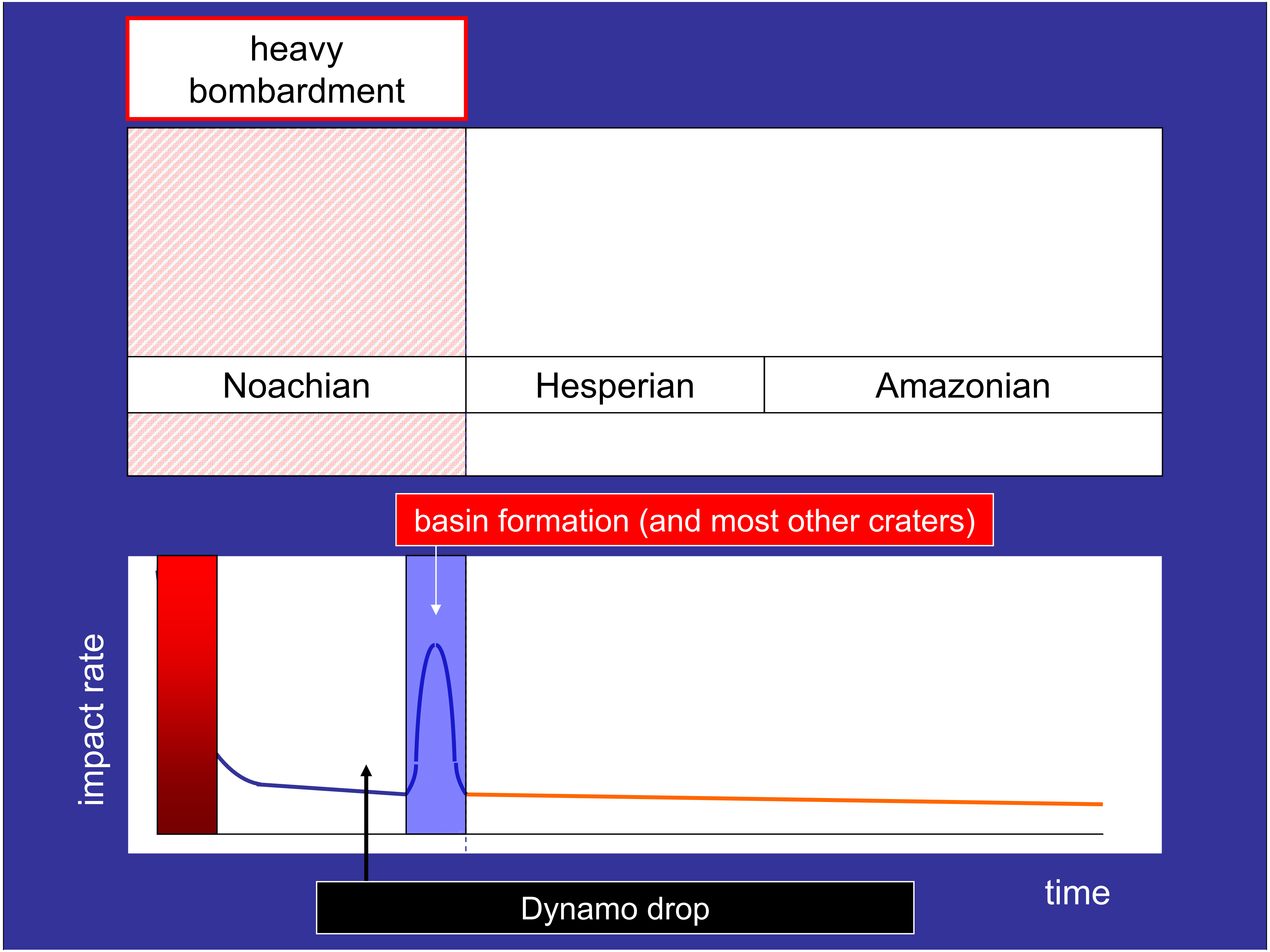
TBC: the drop of the dynamo (magnetic shield)

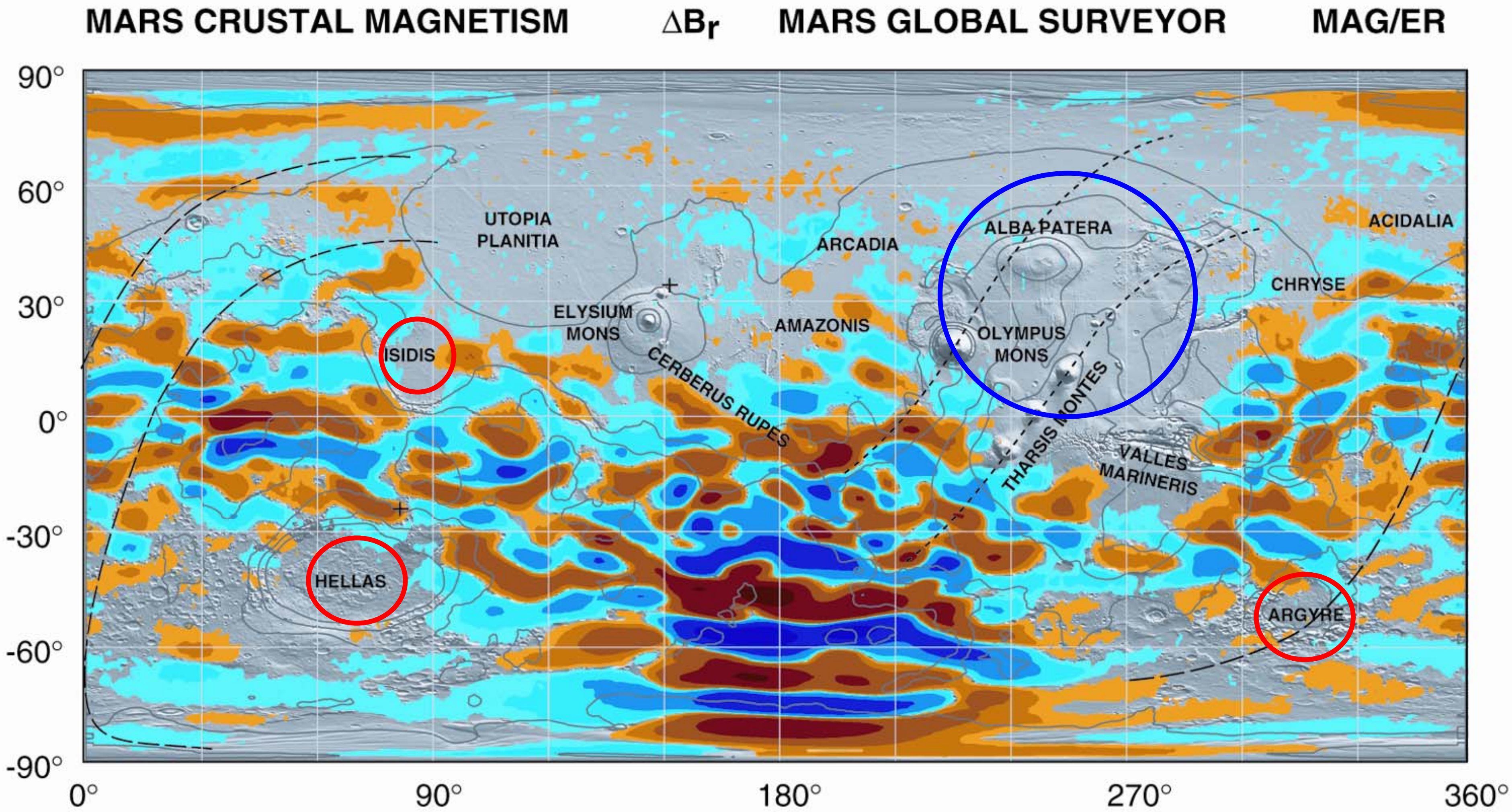




The magnetization is

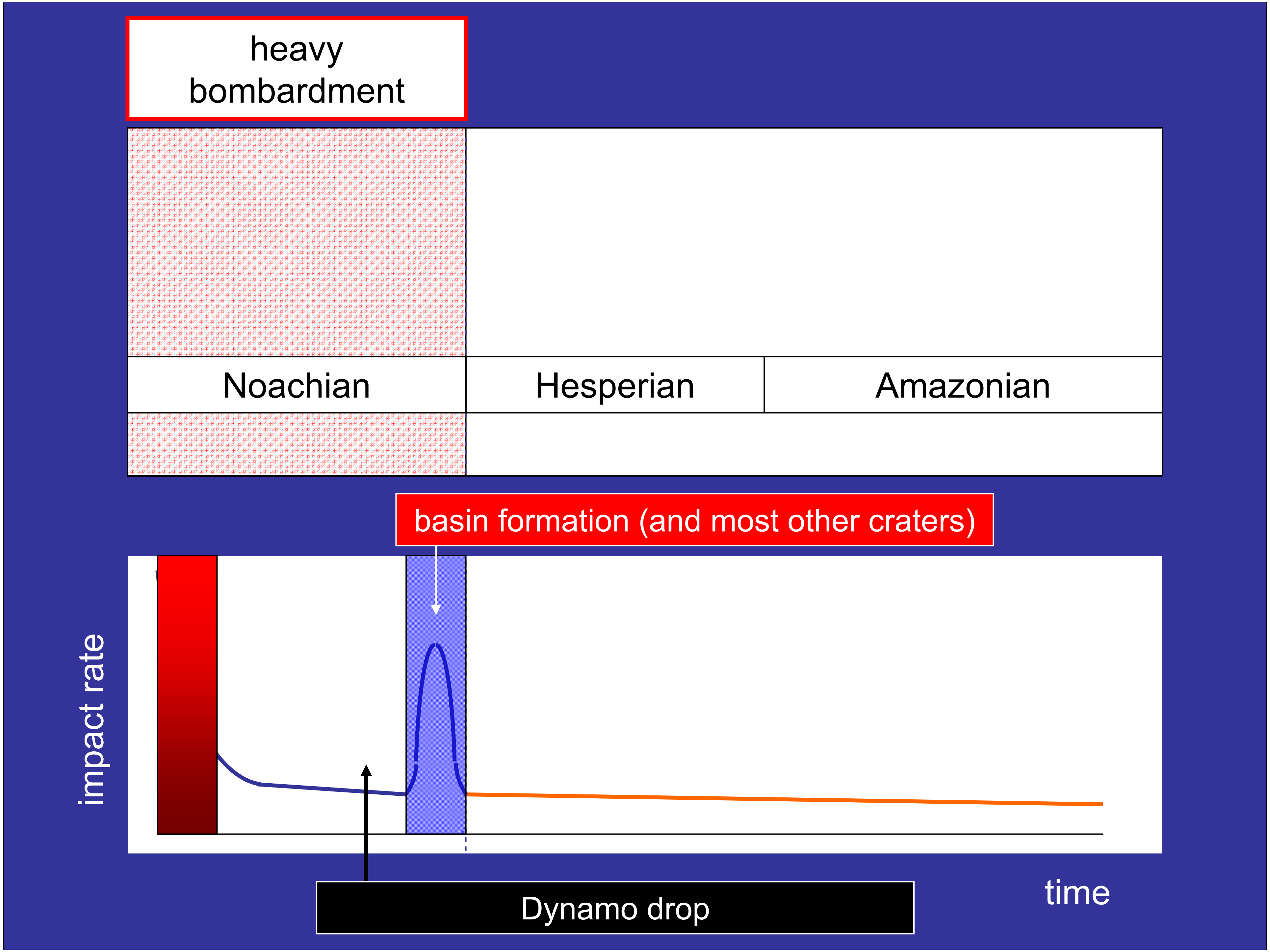
- remnant
- restricted to the crust
- inhomogeneous within the crust
- large basins excluded

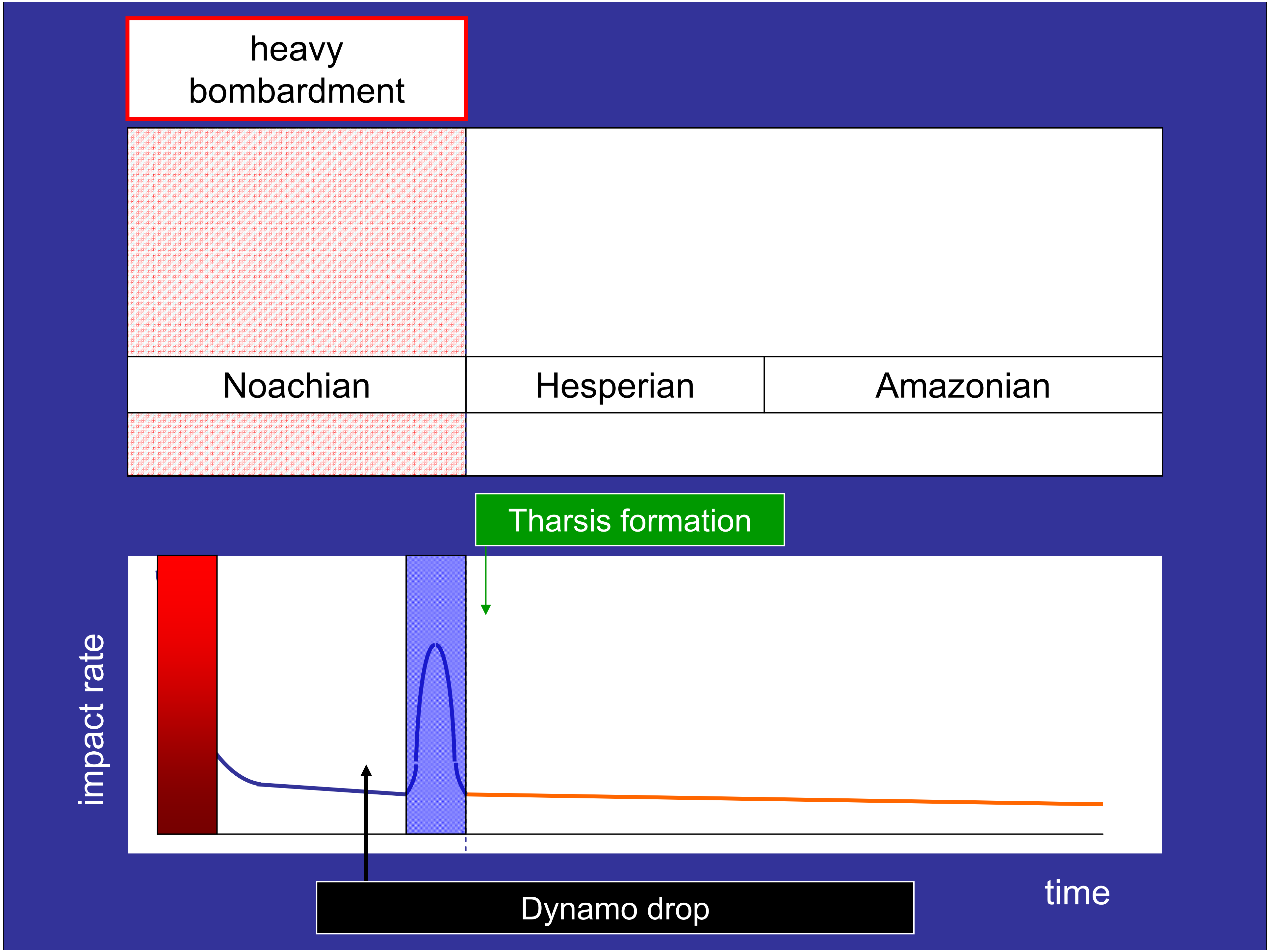

heavy
bombardment
Noachian
Hesperian
Amazonian
basin formation (and most other craters)
impact rate
Dynamo drop
time

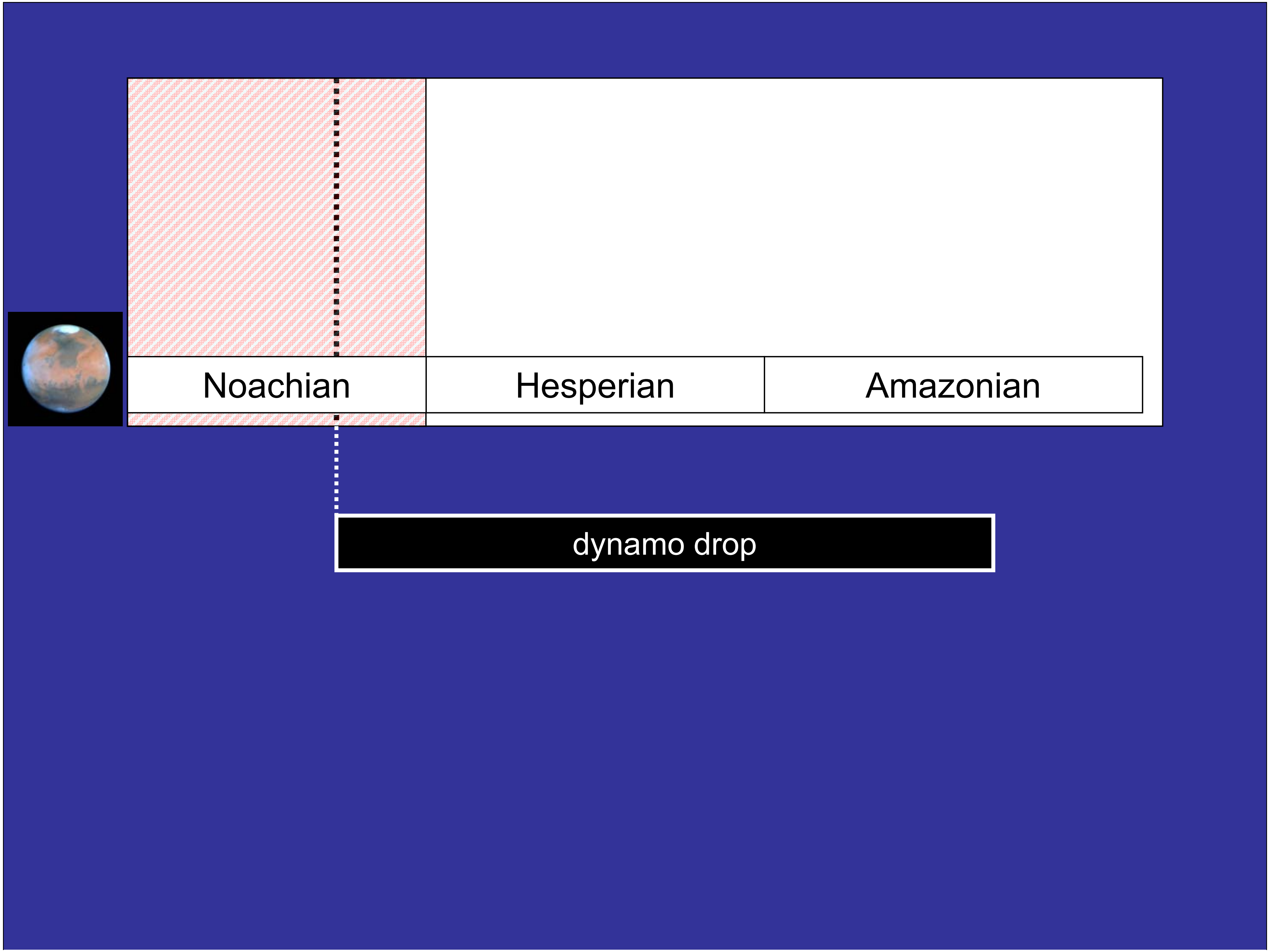


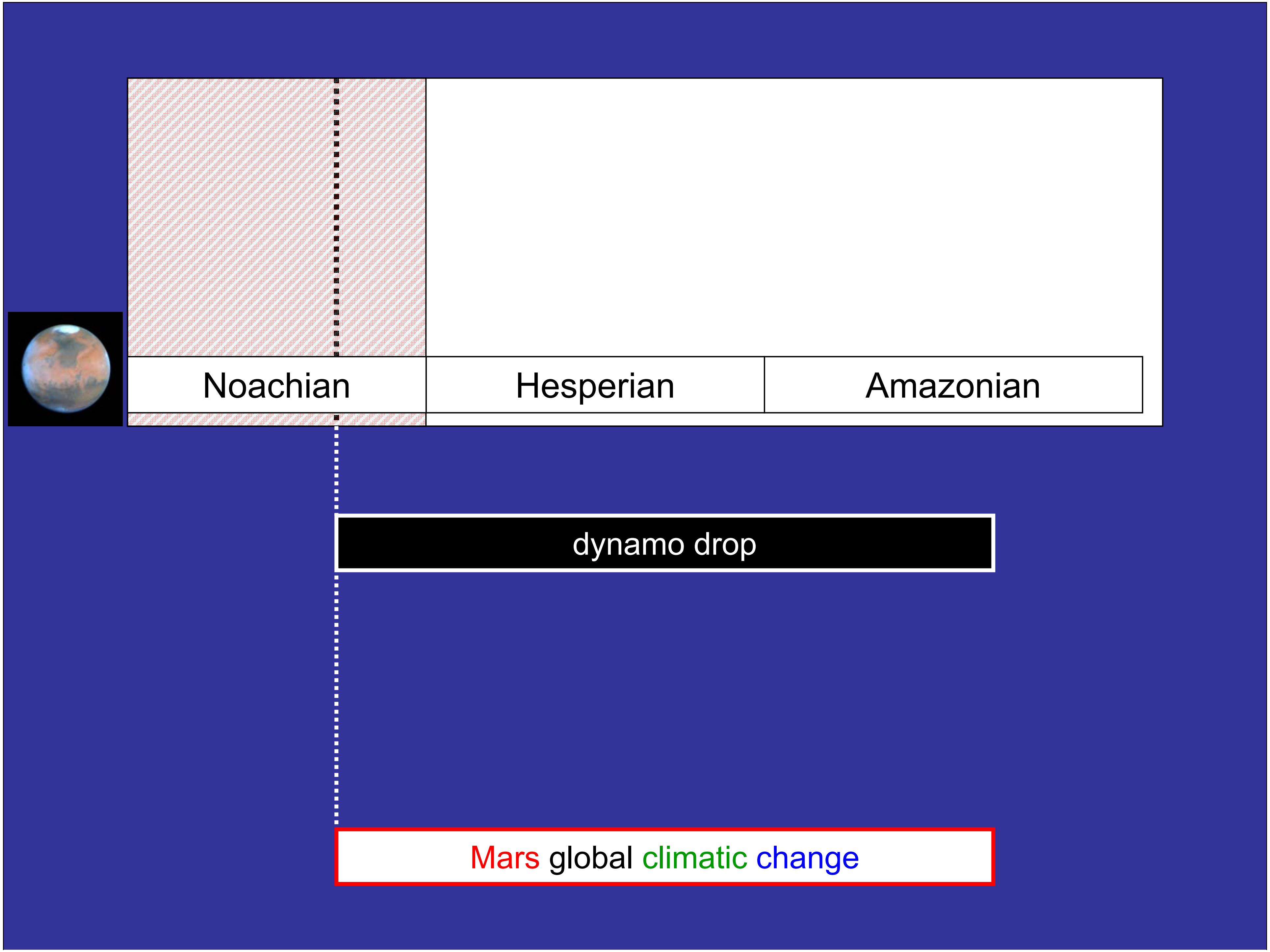
The magnetization is

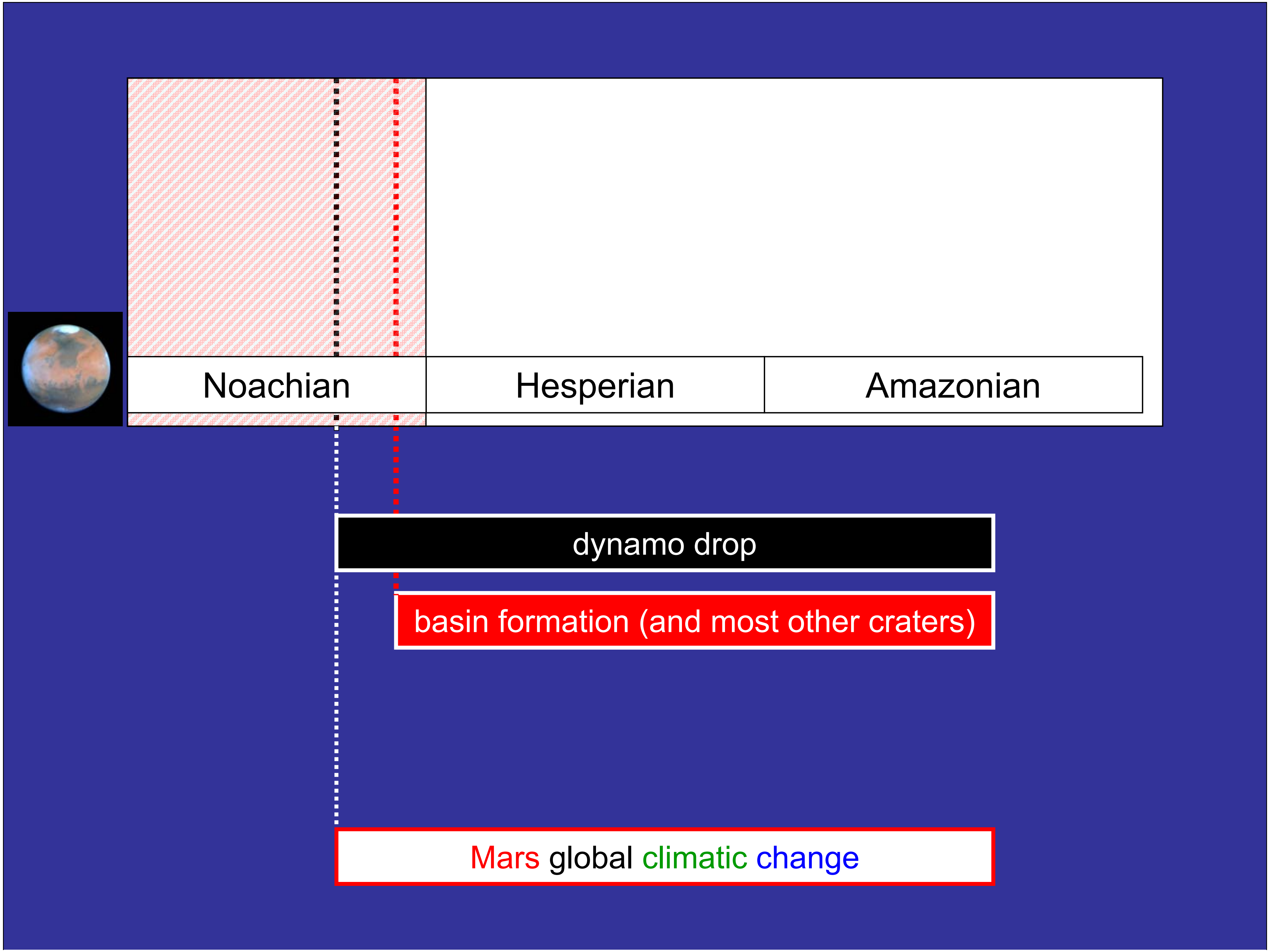
- remnant
- restricted to the crust
- inhomogeneous within the crust
- Tharsis, N lowlands & large basins excluded

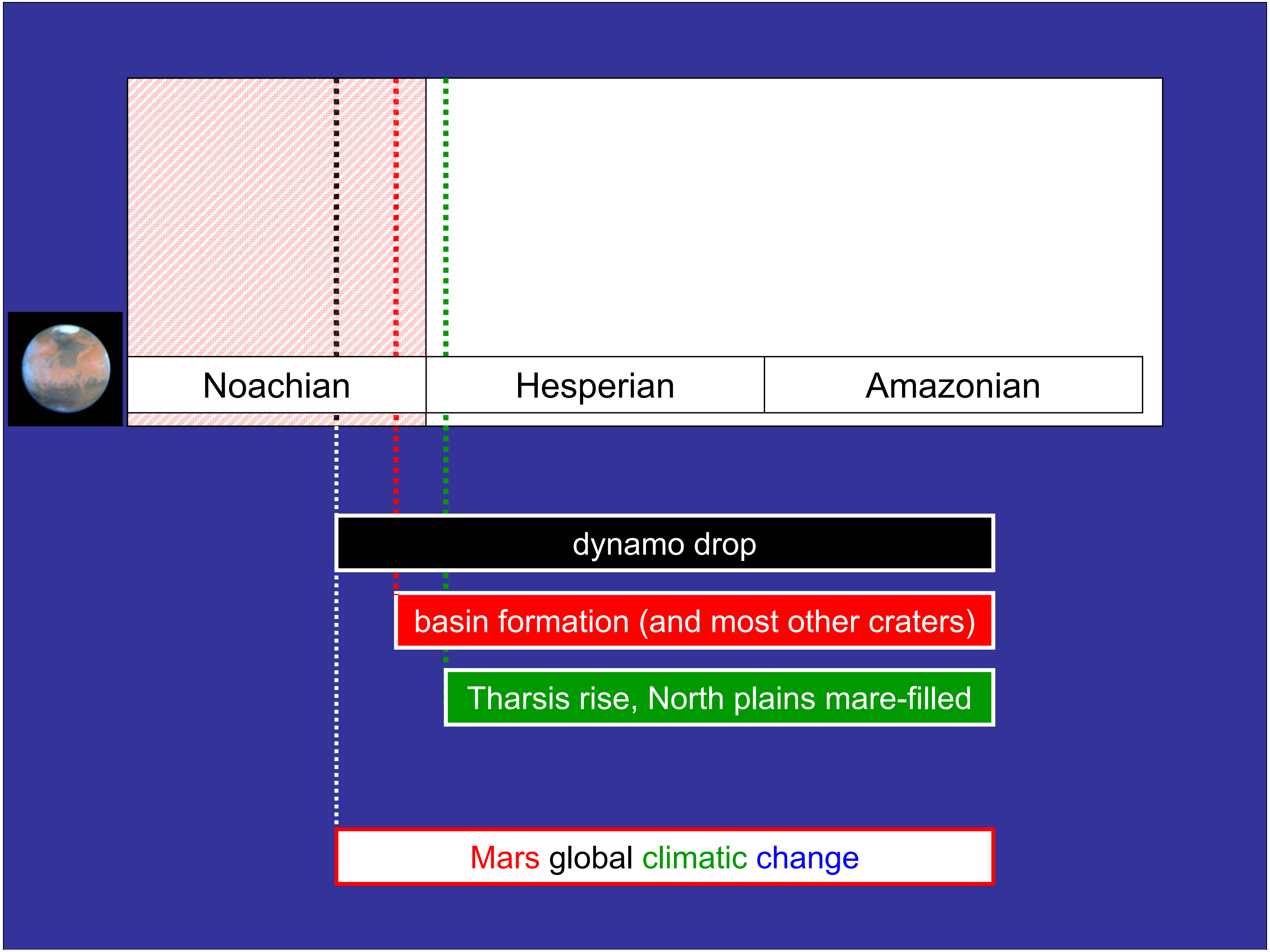

heavy bombardment
Noachian
Hesperian
Amazonian
basin formation (and most other craters)
impact rate
Dynamo drop
time


heavy
bombardment
Noachian
Hesperian
Amazonian
Tharsis formation
impact rate
time
Dynamo drop


Noachian
Hesperian
Amazonian
dynamo drop


Noachian
Hesperian
Amazonian
dynamo drop
Mars global climatic change


Noachian
Hesperian
Amazonian
dynamo drop
basin formation (and most other craters)
Mars global climatic change



Noachian
Hesperian
Amazonian
dynamo drop
basin formation (and most other craters)
Tharsis rise, North plains mare-filled
Mars global climatic change

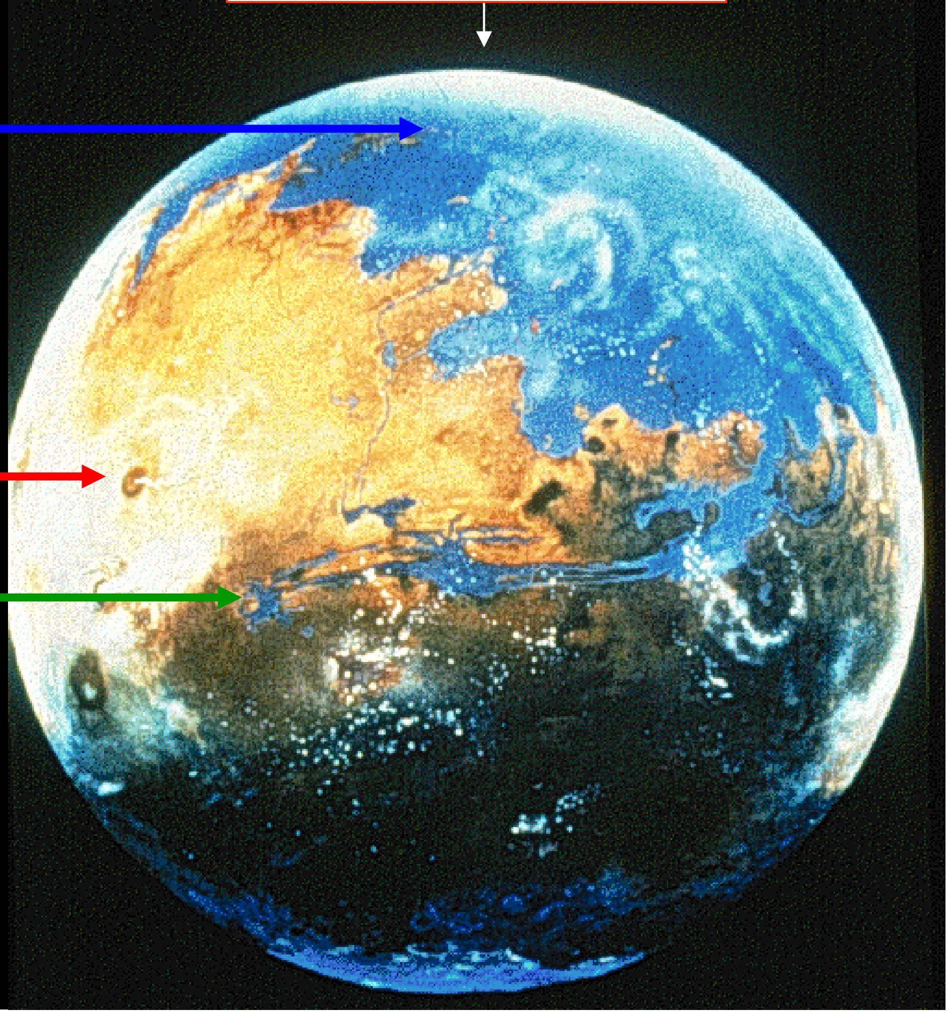
oceans would have been stable

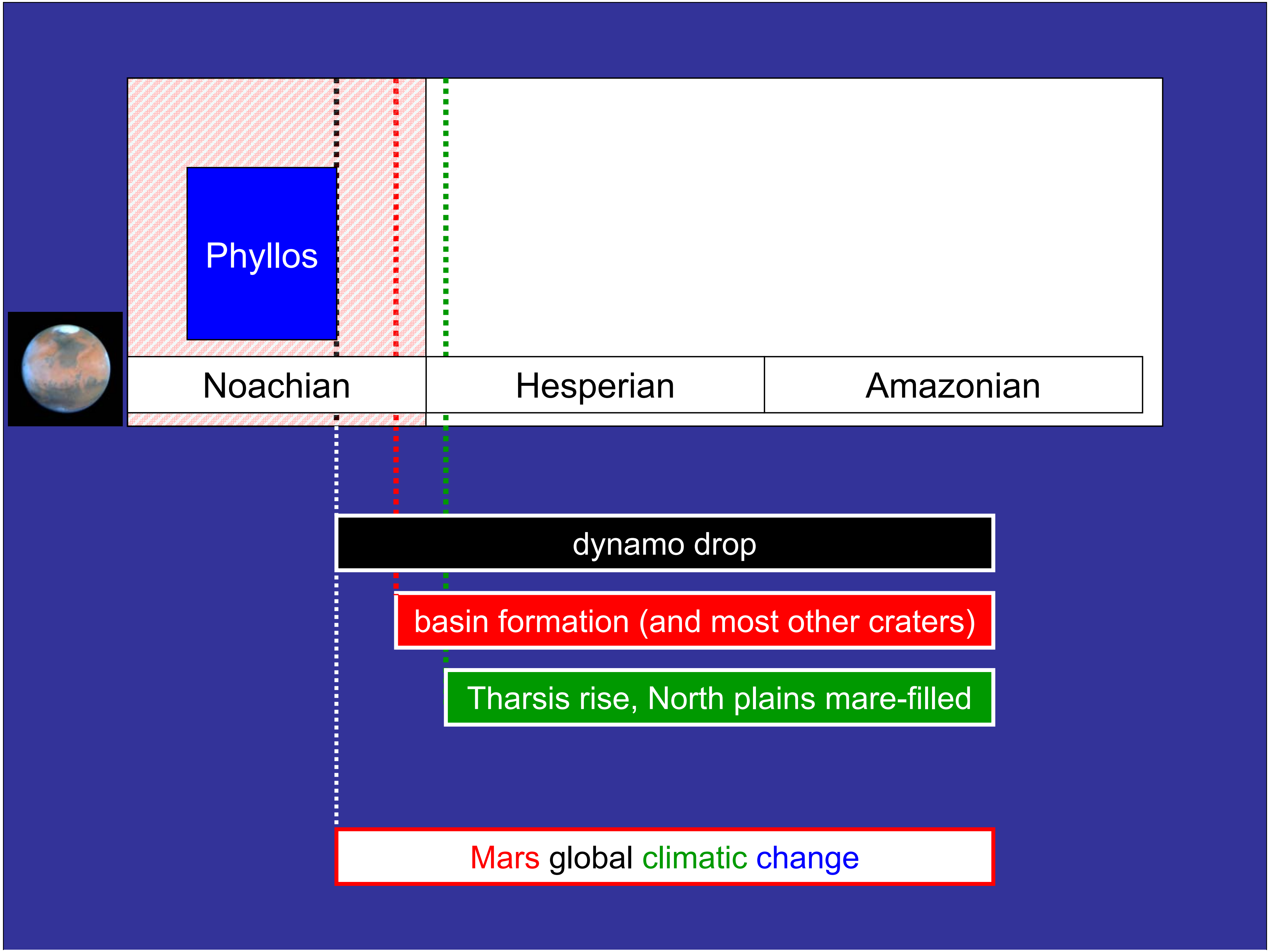
<u>after</u>

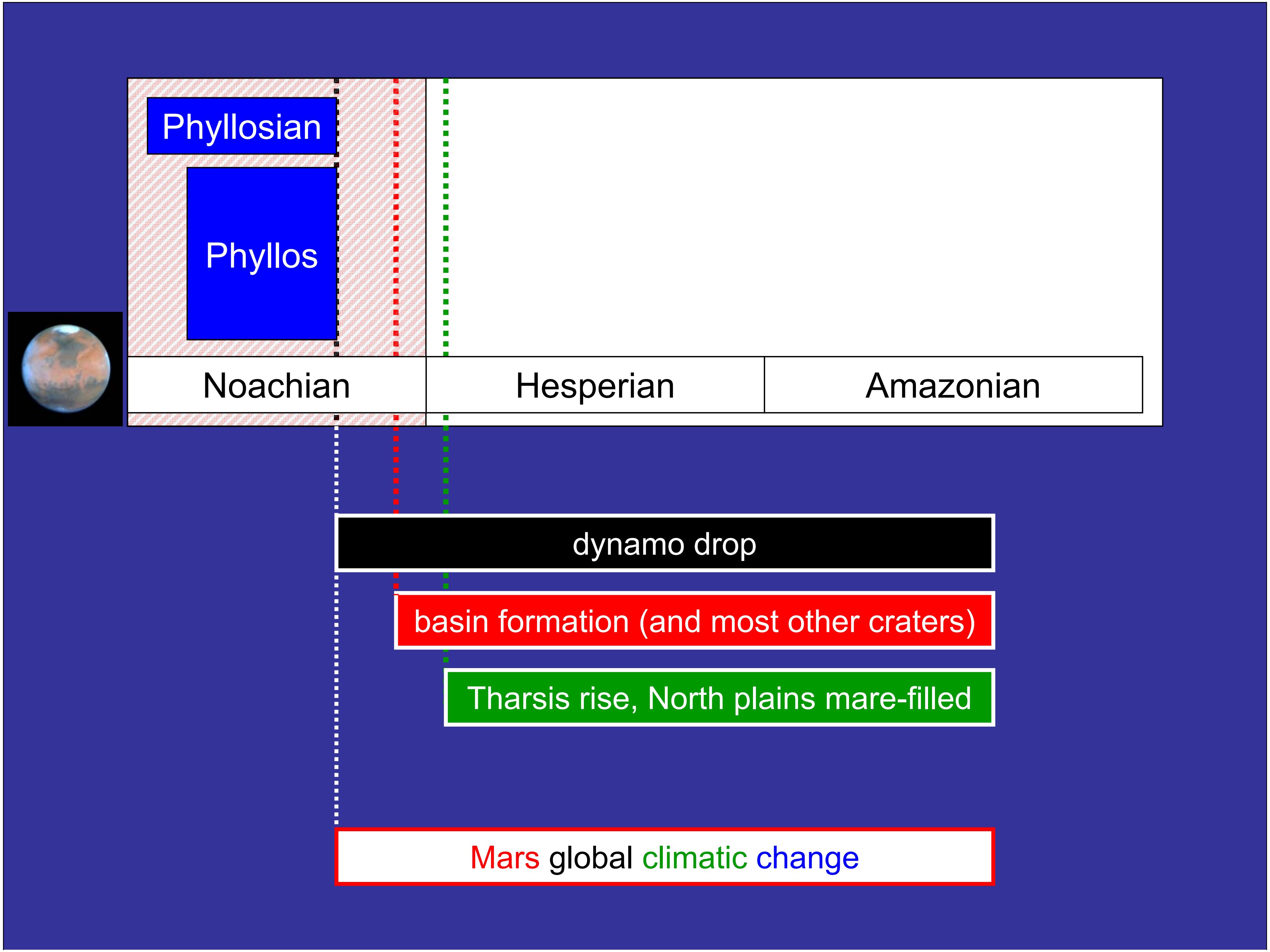
Tharsis and
the volcanoes
were put in place,

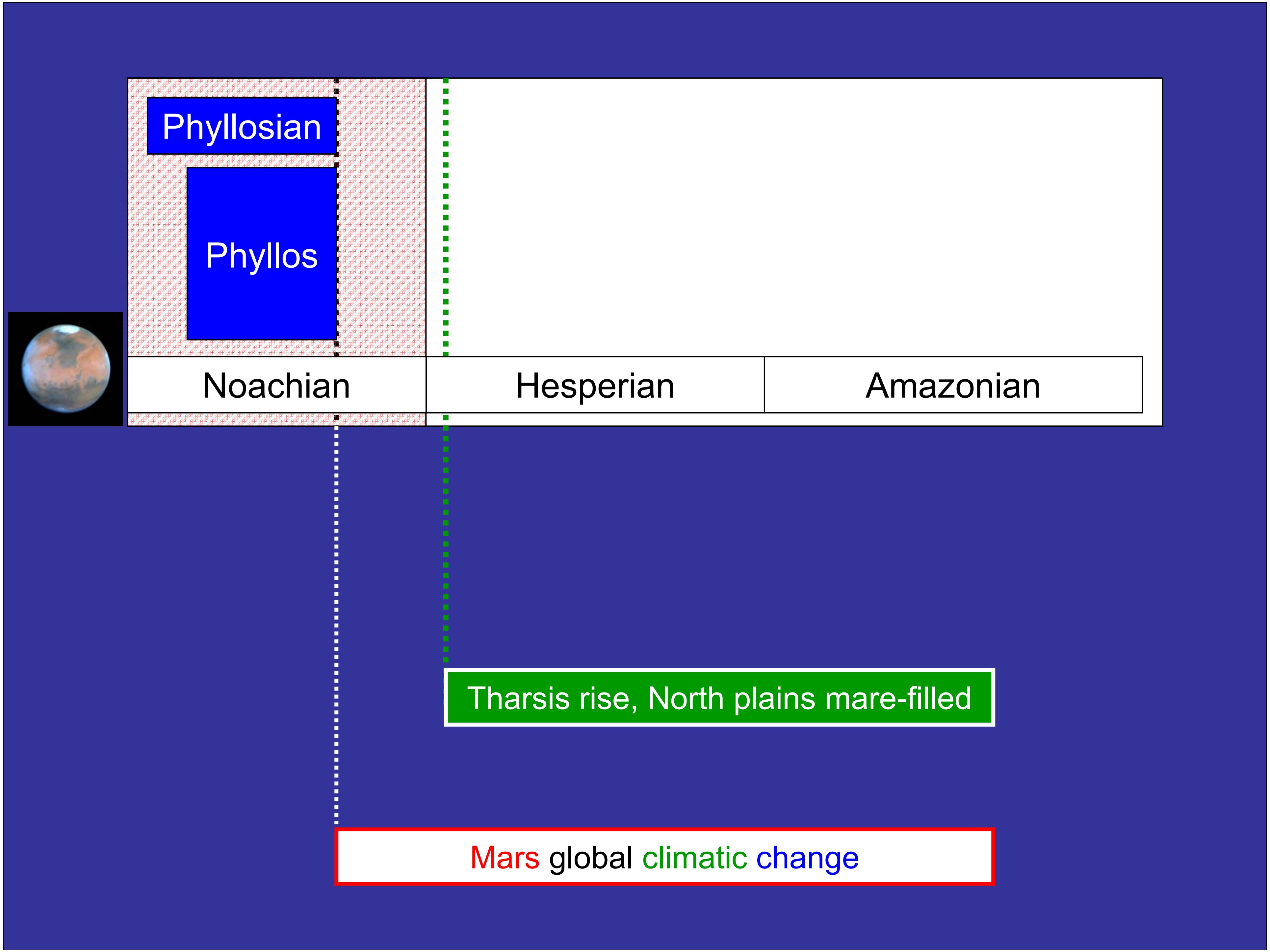
and Valles Marineris
formed

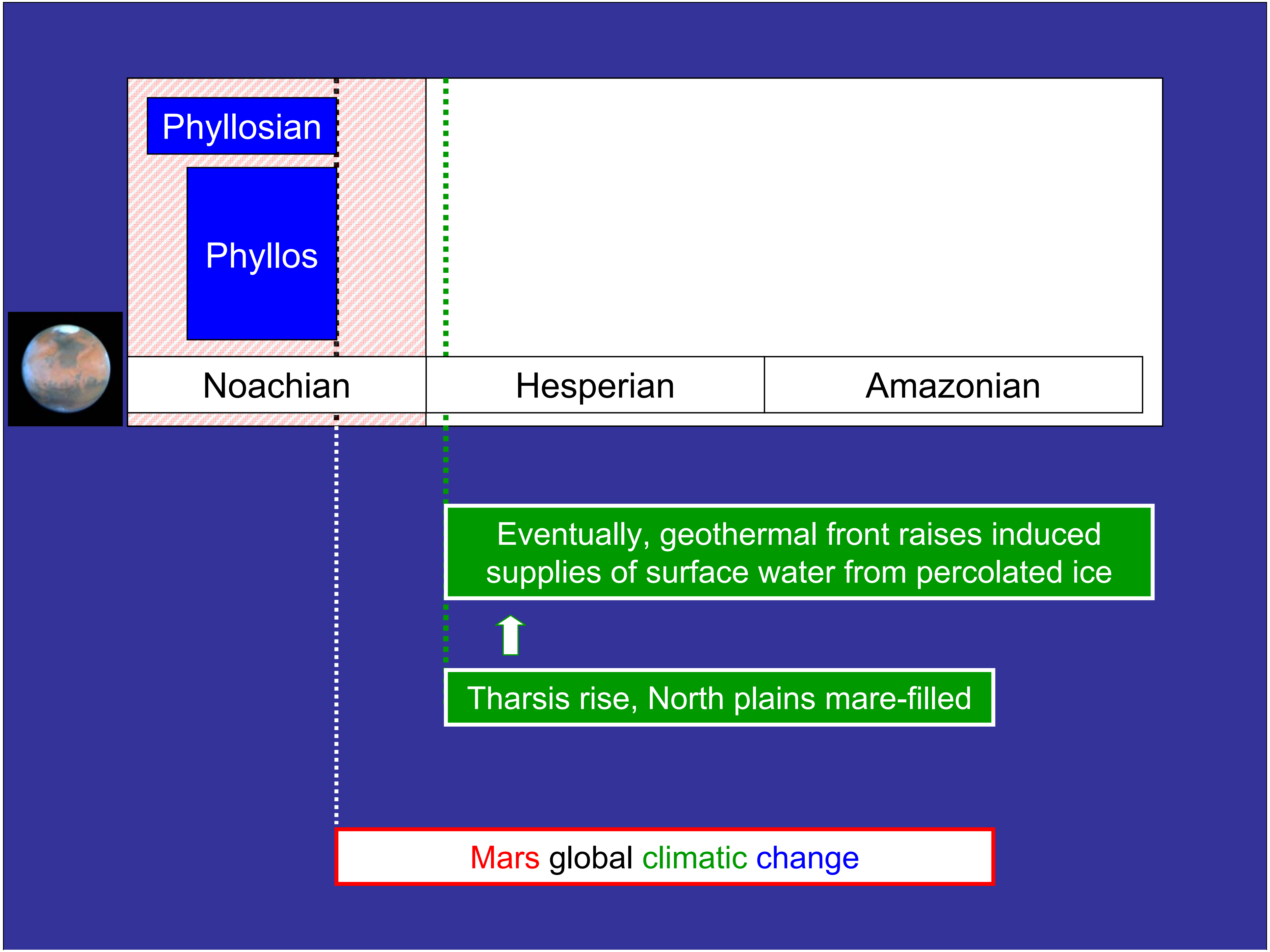
audacious extrapolation

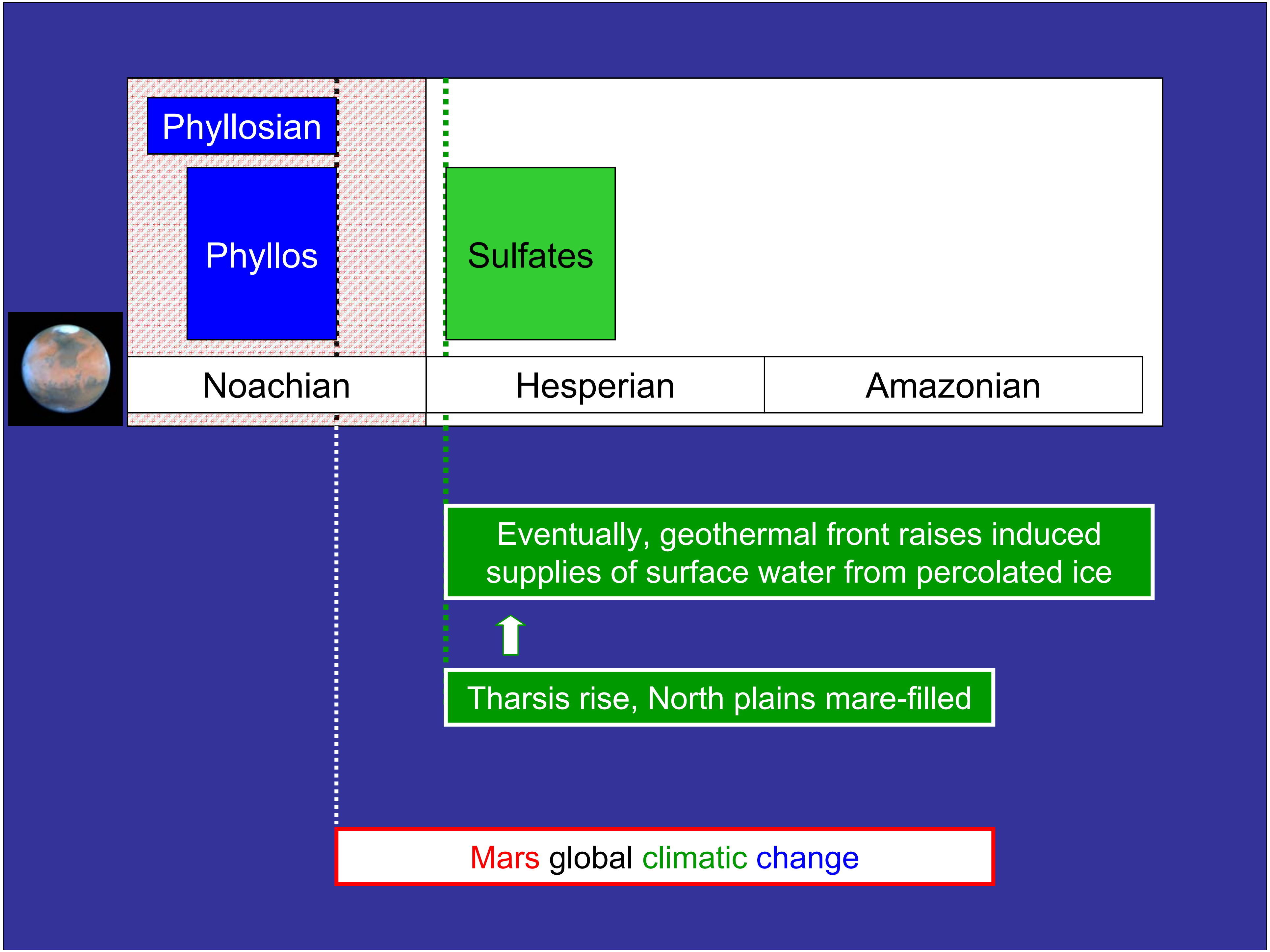


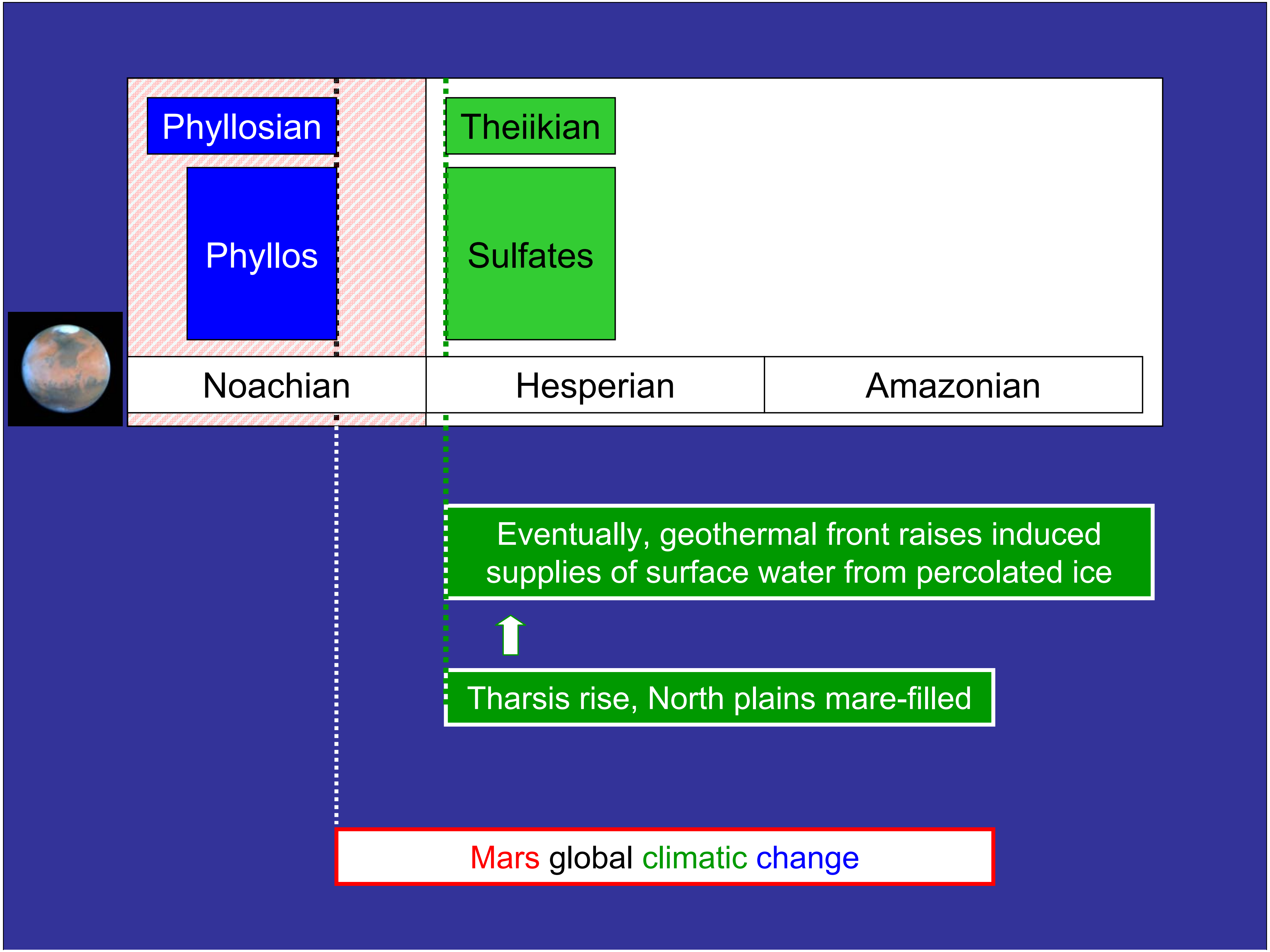

Phyllos
Noachian
Hesperian
Amazonian
dynamo drop
basin formation (and most other craters)
Tharsis rise, North plains mare-filled
Mars global climatic change

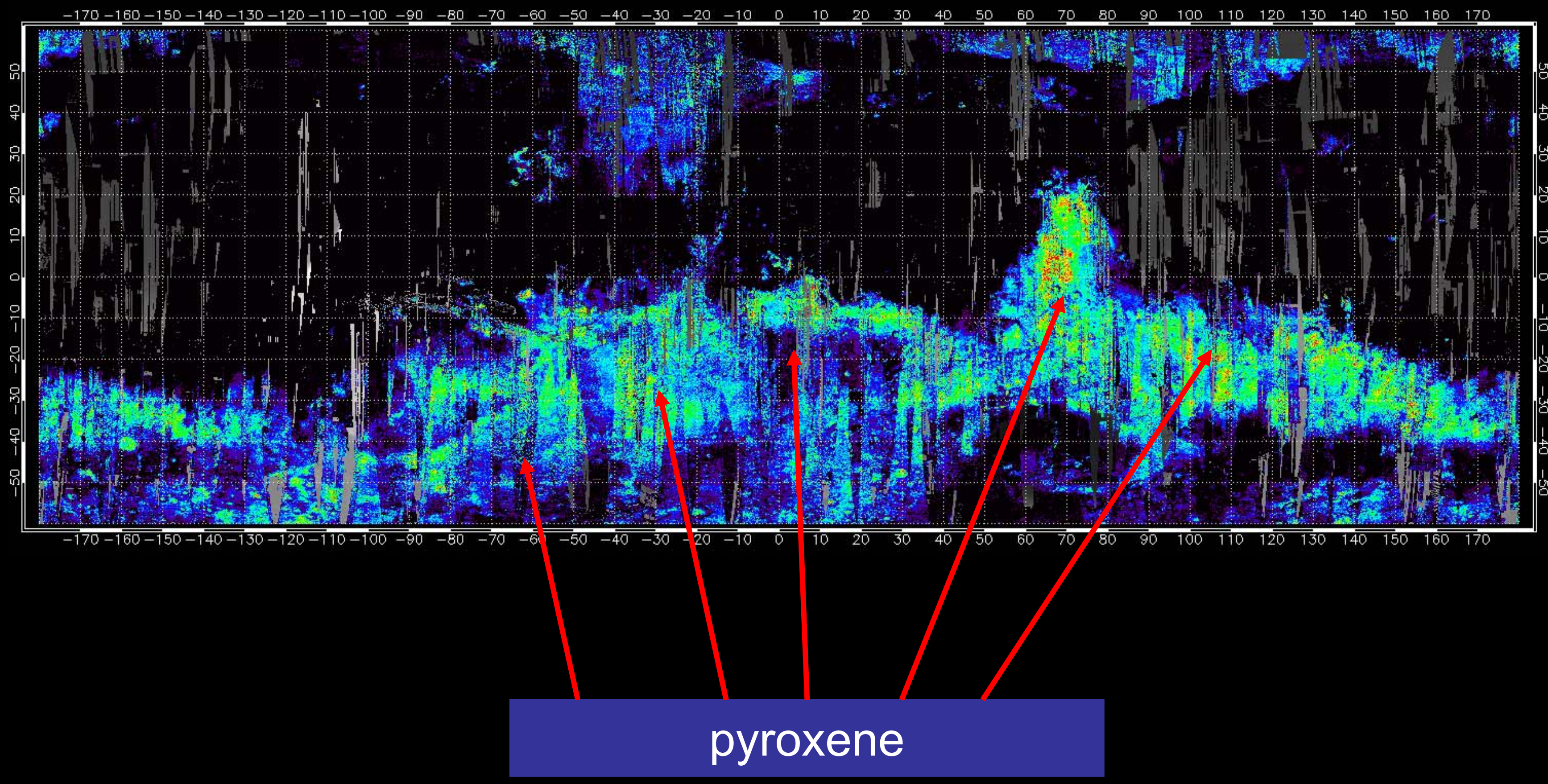

Phyllosian
Phyllos
Noachian
Hesperian
Amazonian
dynamo drop
basin formation (and most other craters)
Tharsis rise, North plains mare-filled
Mars global climatic change


Phyllosian
Phyllos
Noachian
Hesperian
Amazonian
Tharsis rise, North plains mare-filled
Mars global climatic change

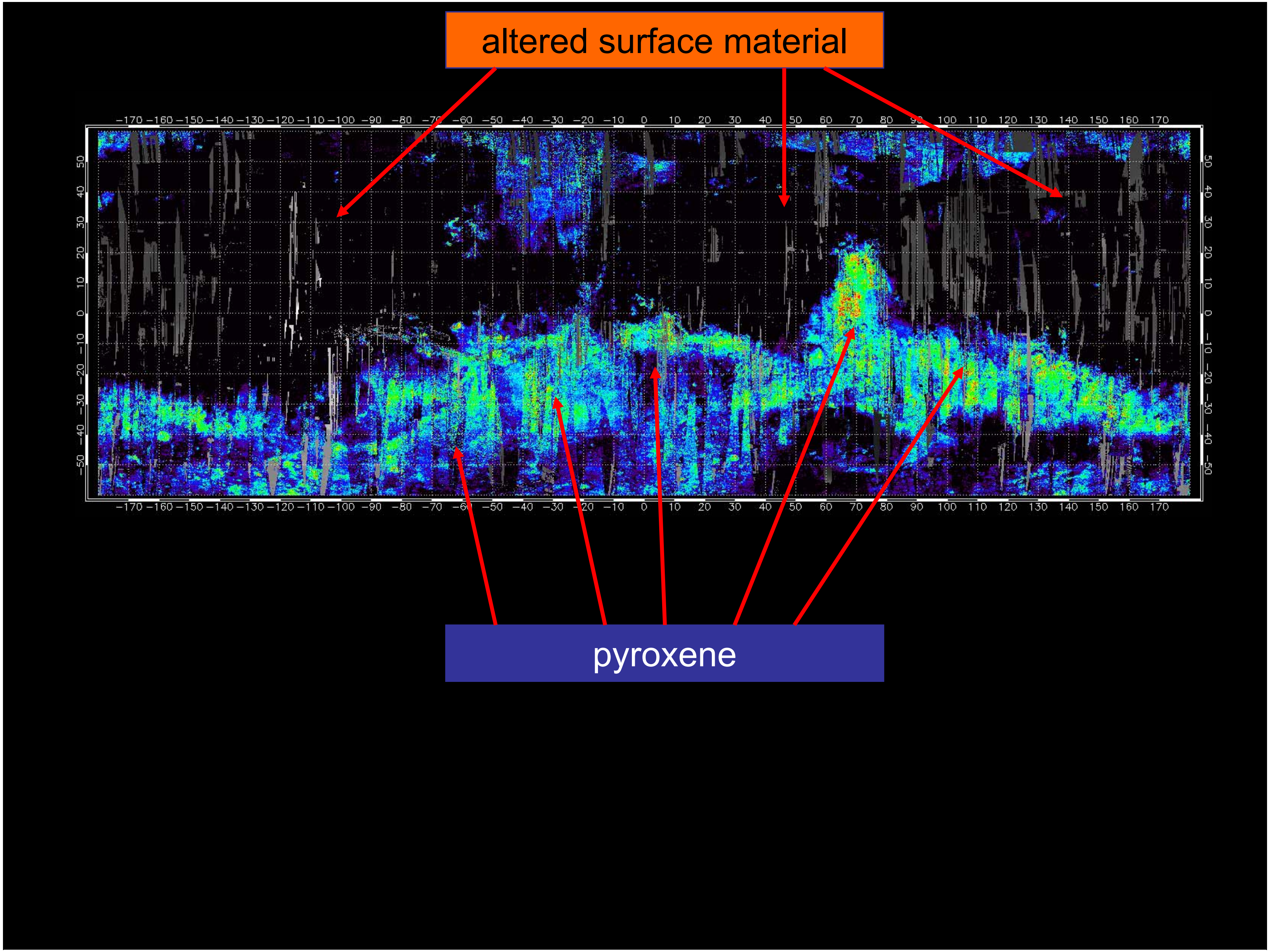

Phyllosian
Phyllos
Noachian
Hesperian
Amazonian
Eventually, geothermal front raises induced supplies of surface water from percolated ice
Tharsis rise, North plains mare-filled
Mars global climatic change


Phyllosian
Phyllos
Sulfates
Noachian
Hesperian
Amazonian
Eventually, geothermal front raises induced supplies of surface water from percolated ice
Tharsis rise, North plains mare-filled
Mars global climatic change

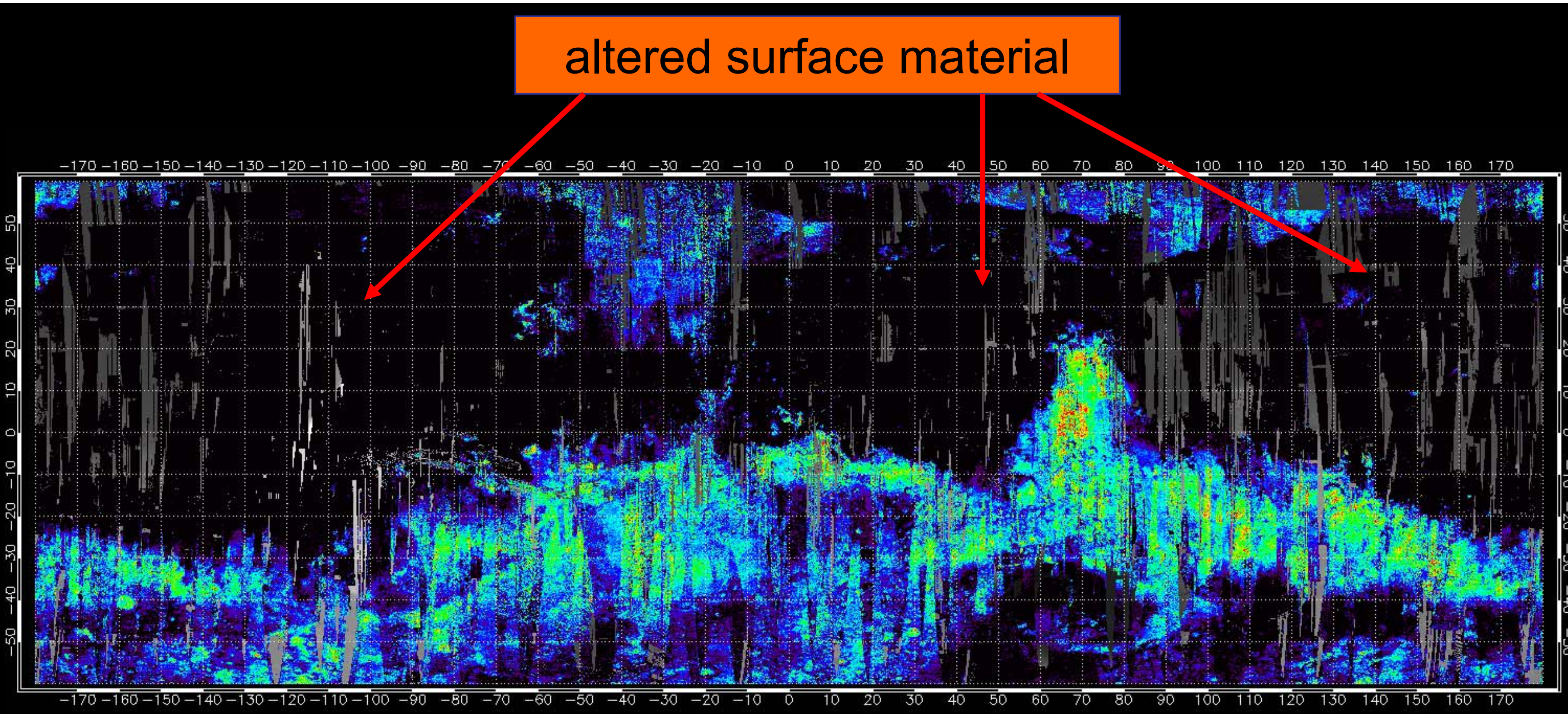

Phyllosian
Phyllos
Theiikian
Sulfates
Noachian
Hesperian
Amazonian
Eventually, geothermal front raises induced supplies of surface water from percolated ice
Tharsis rise, North plains mare-filled
Mars global climatic change



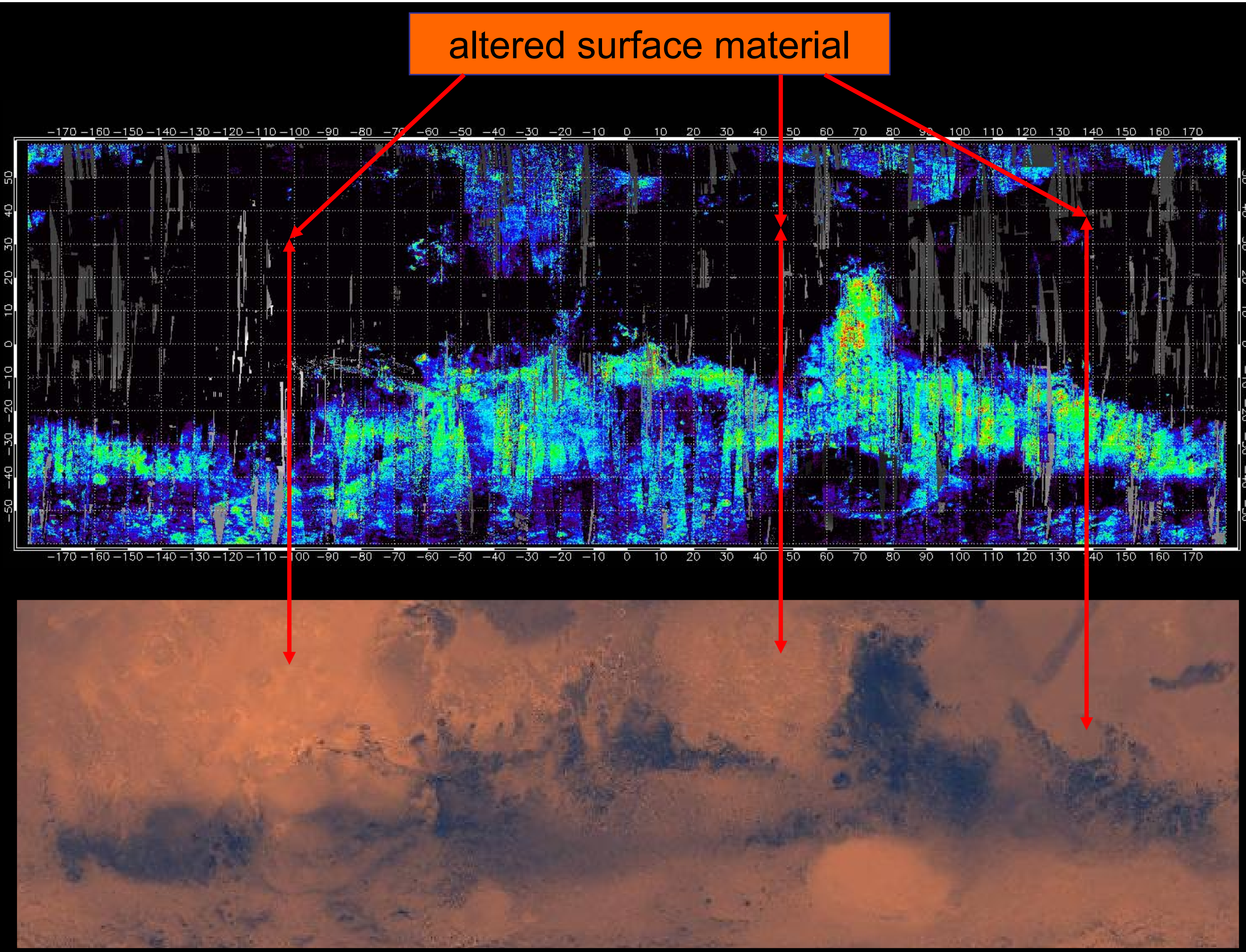
pyroxene



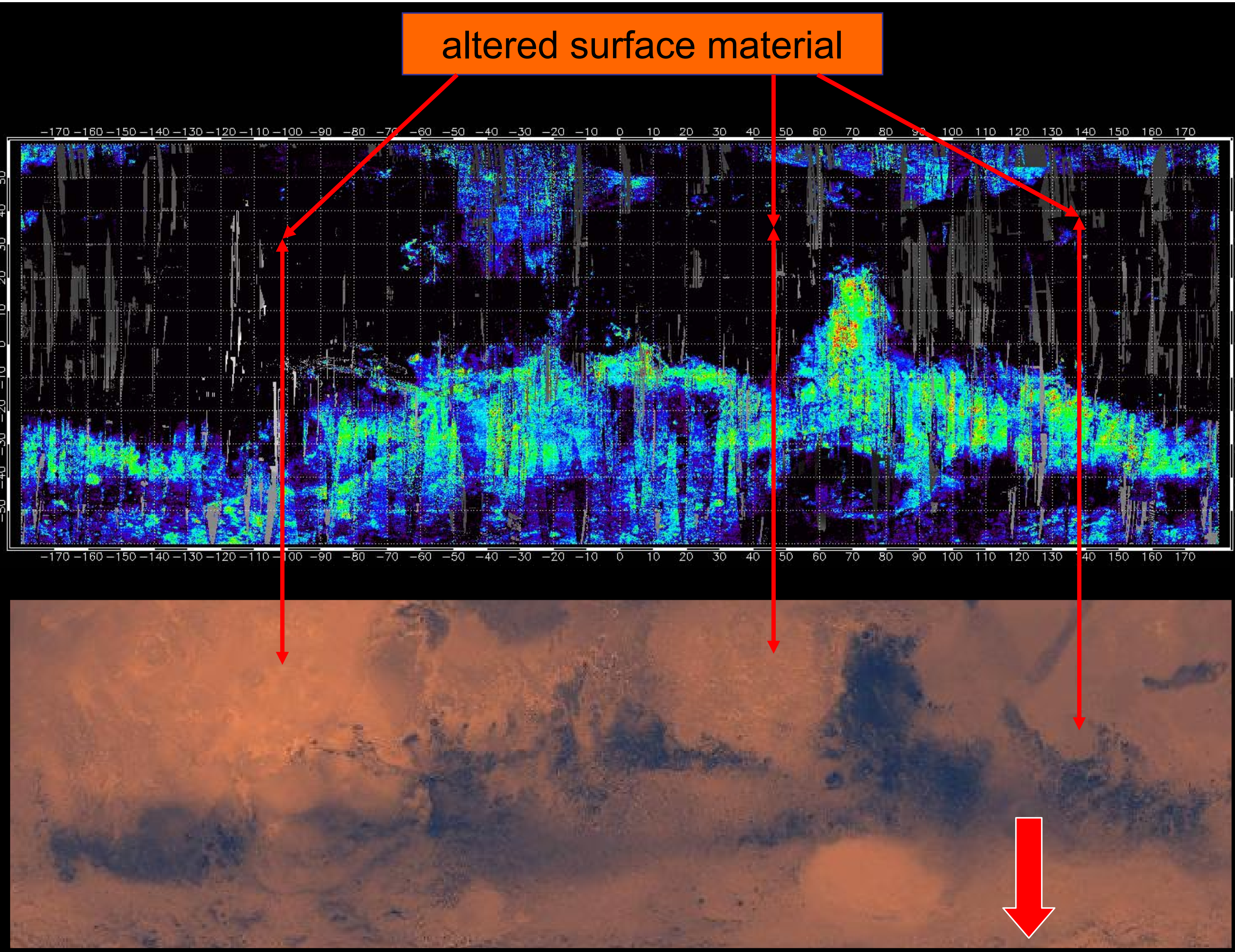
altered surface material
pyroxene



A large fraction of Mars surface has been altered

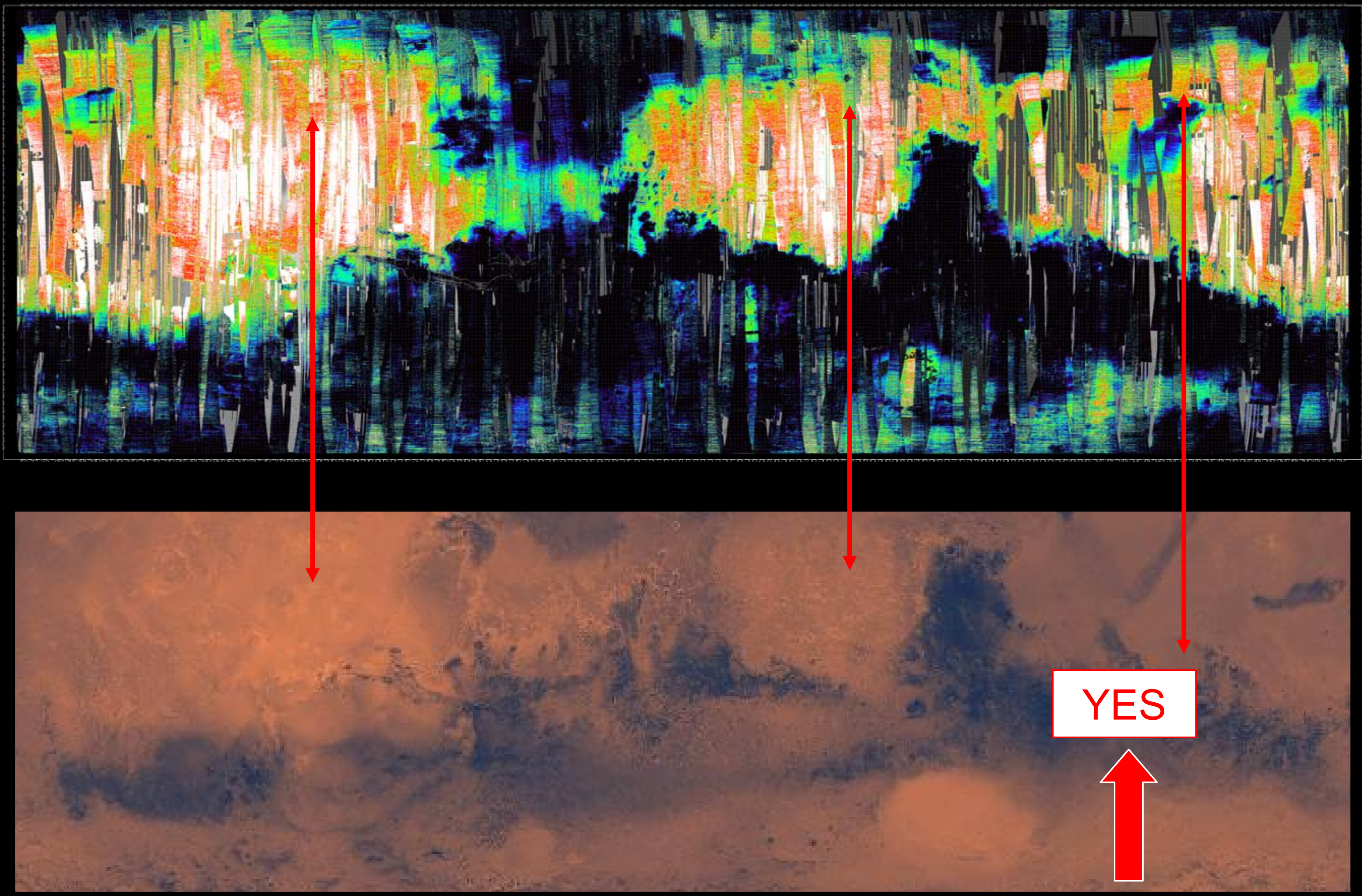


A large fraction of Mars surface has been altered



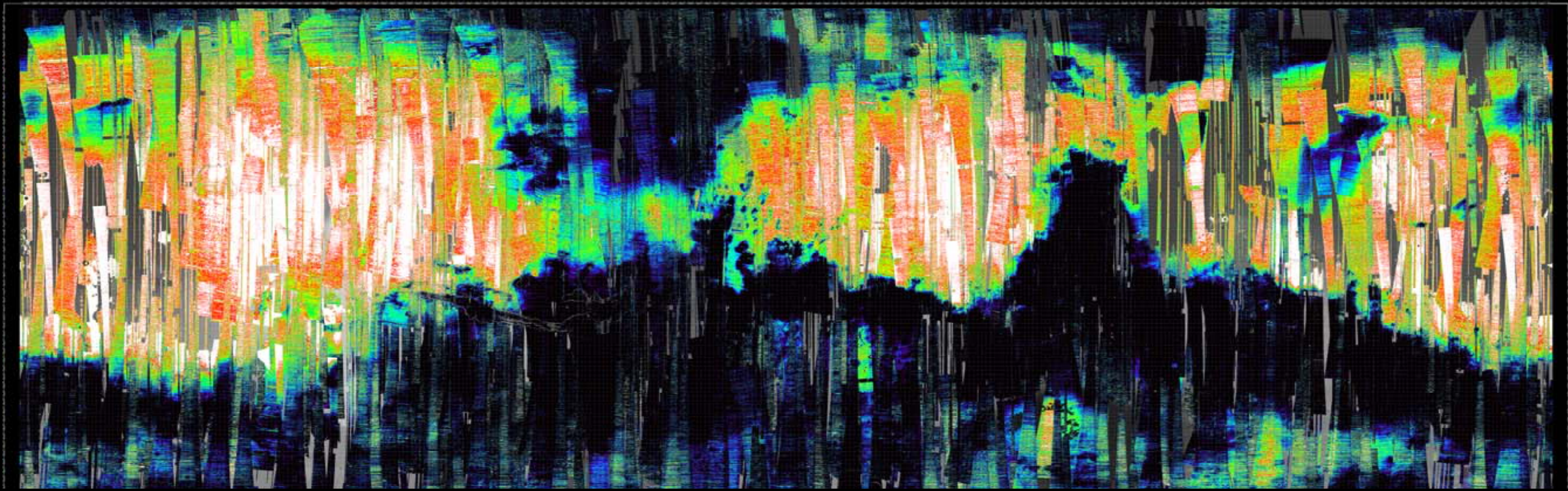
A large fraction of Mars surface has been altered; rusted ?

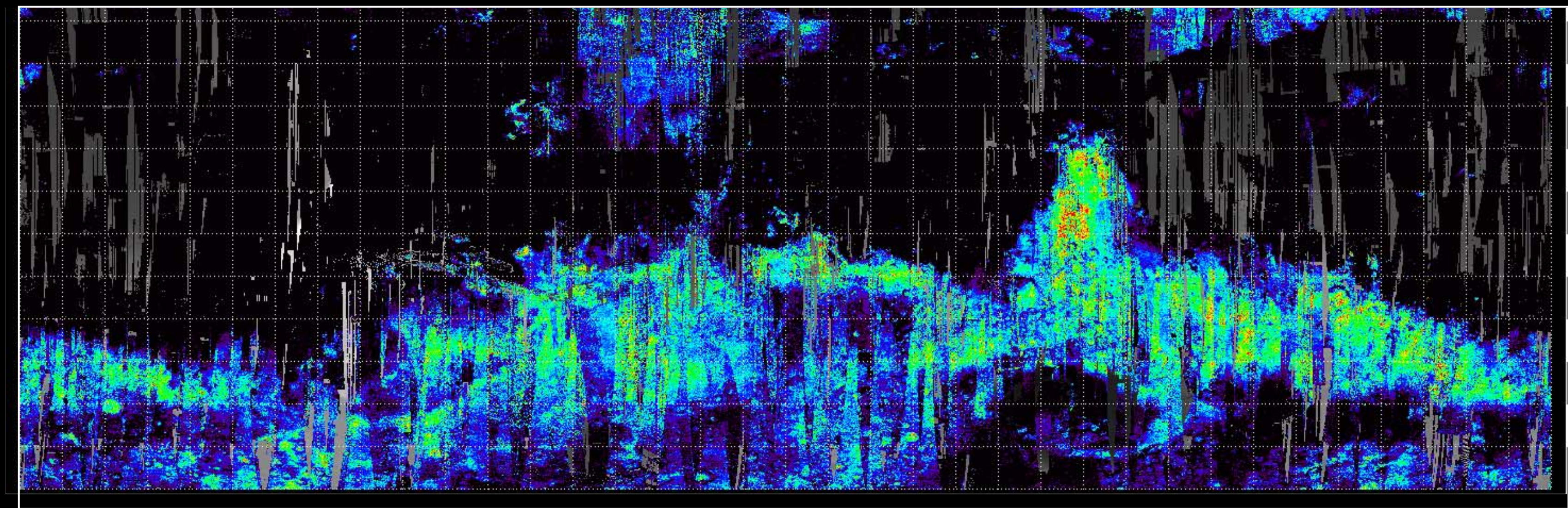
nanophase hematite : α - Fe_2O_3



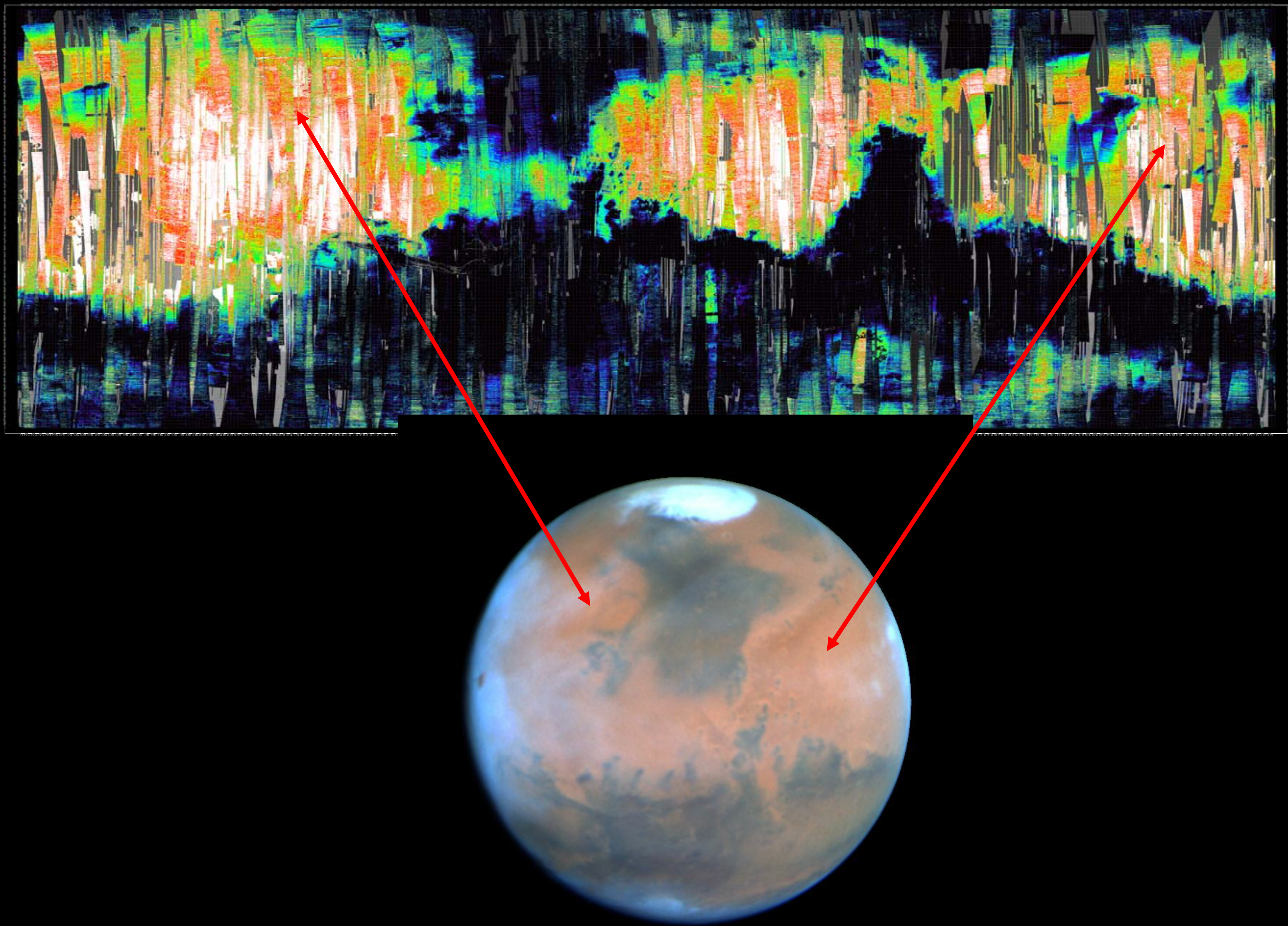
A large fraction of Mars surface has been altered; rusted ?

nanophase hematite : α - Fe_2O_3

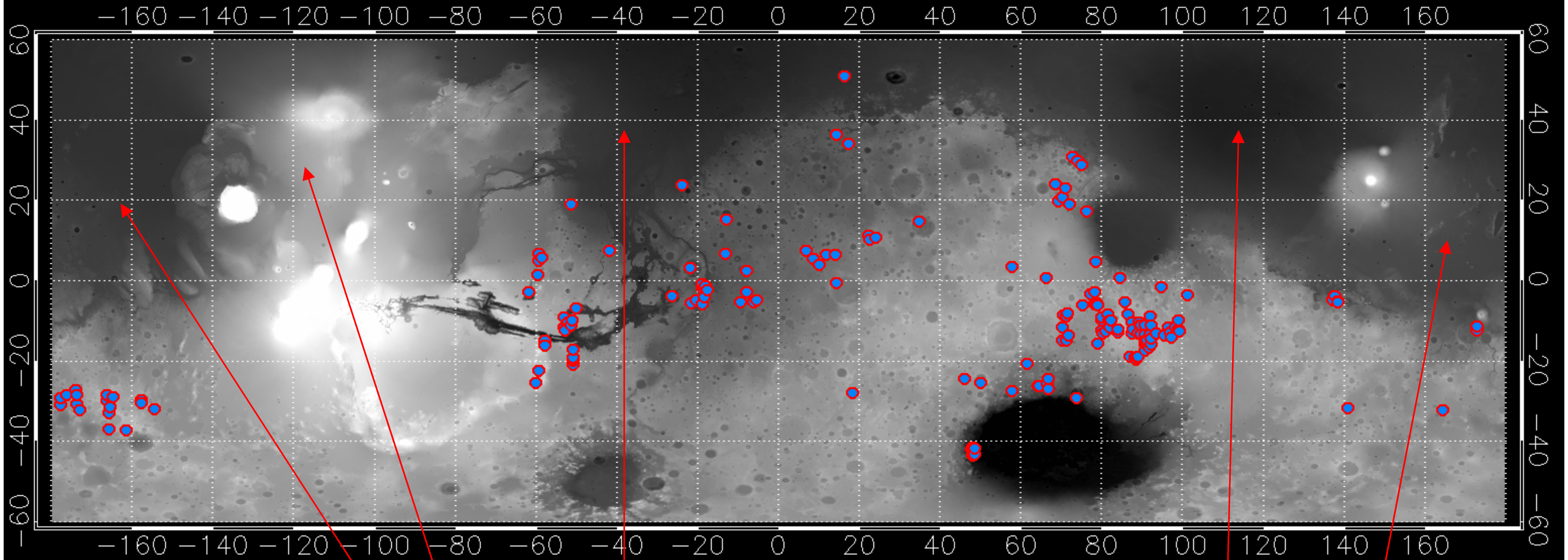




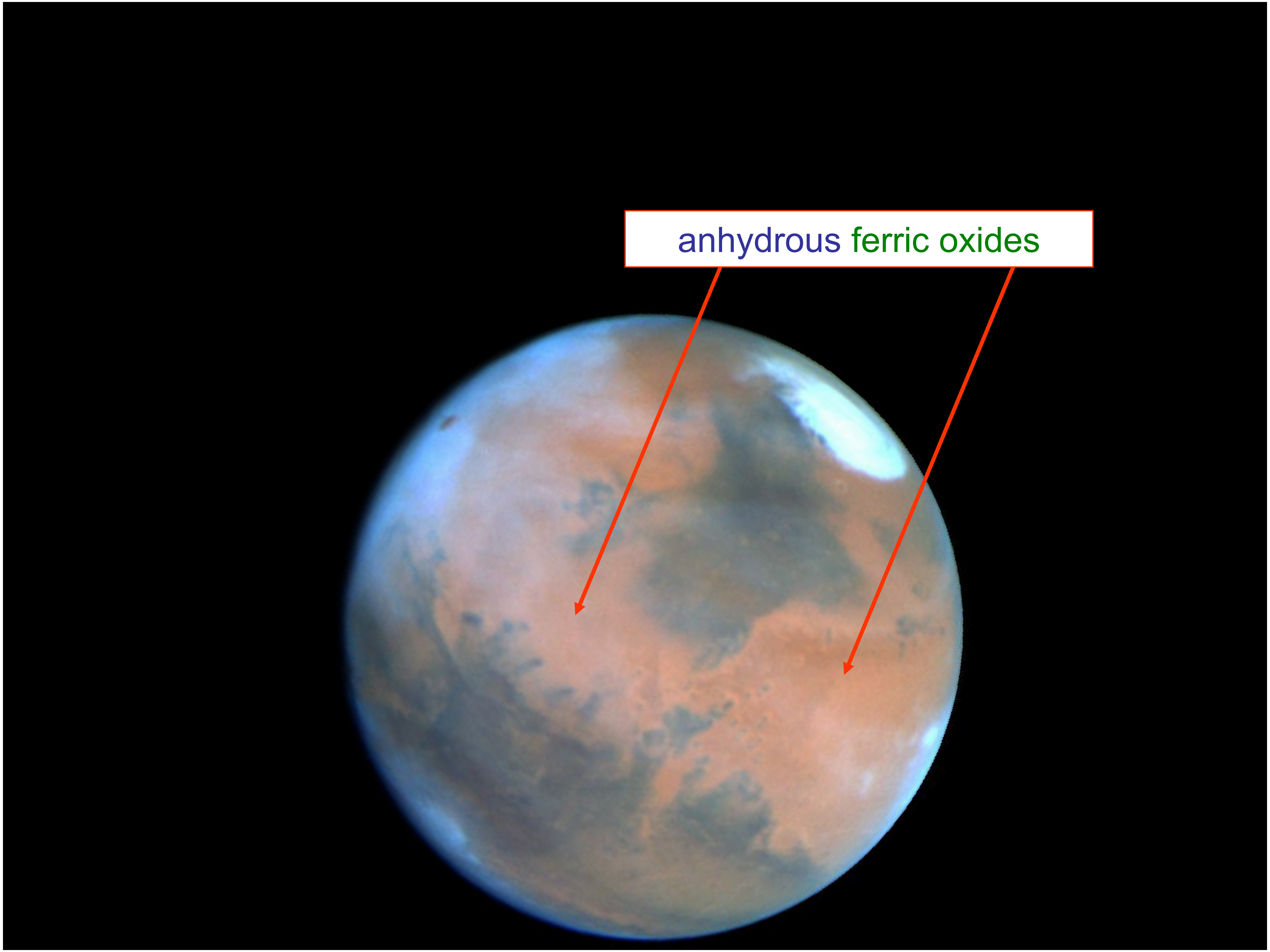
nanophase hematite : α - Fe_2O_3



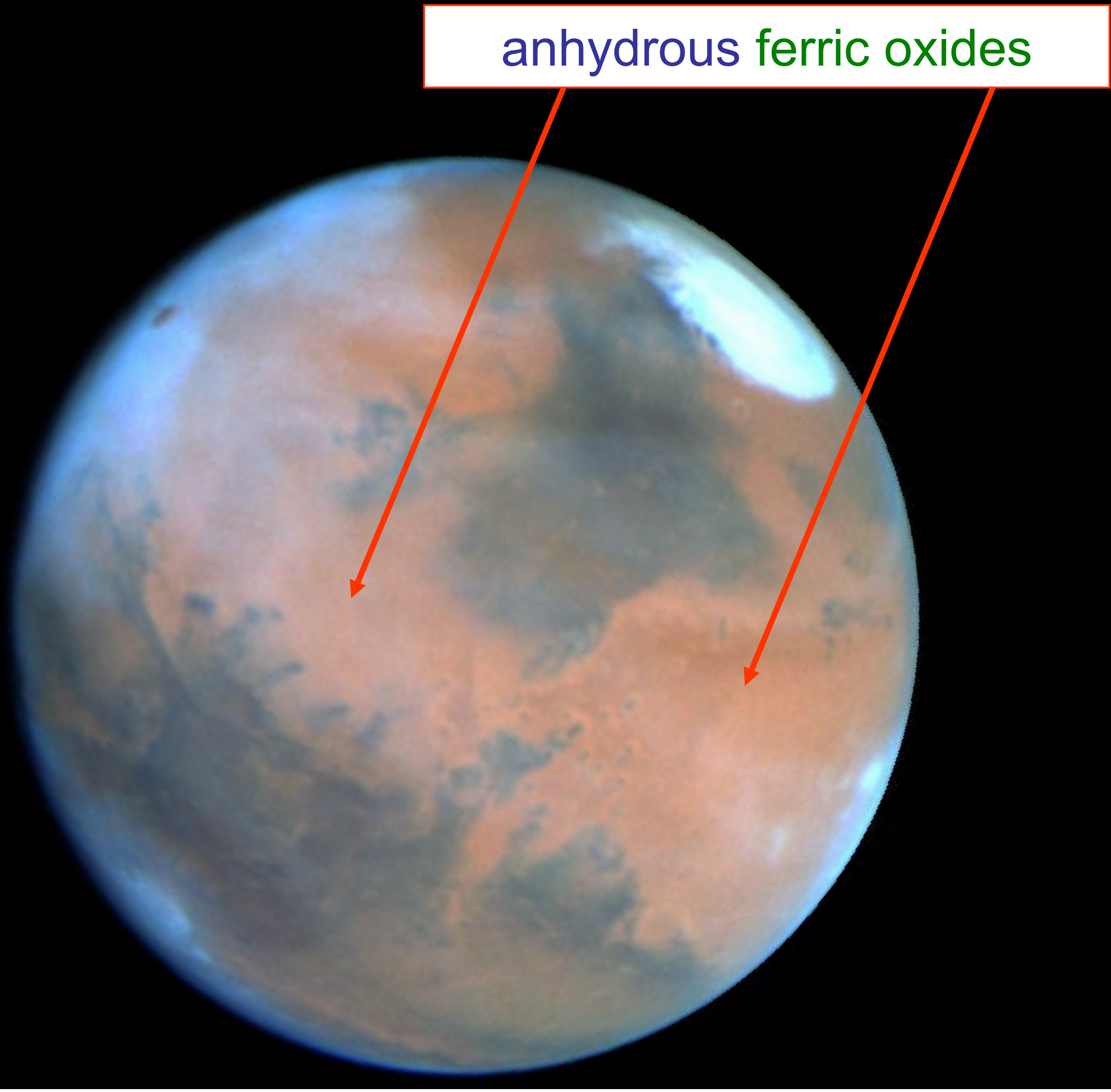
OMEGA map of hydrated minerals

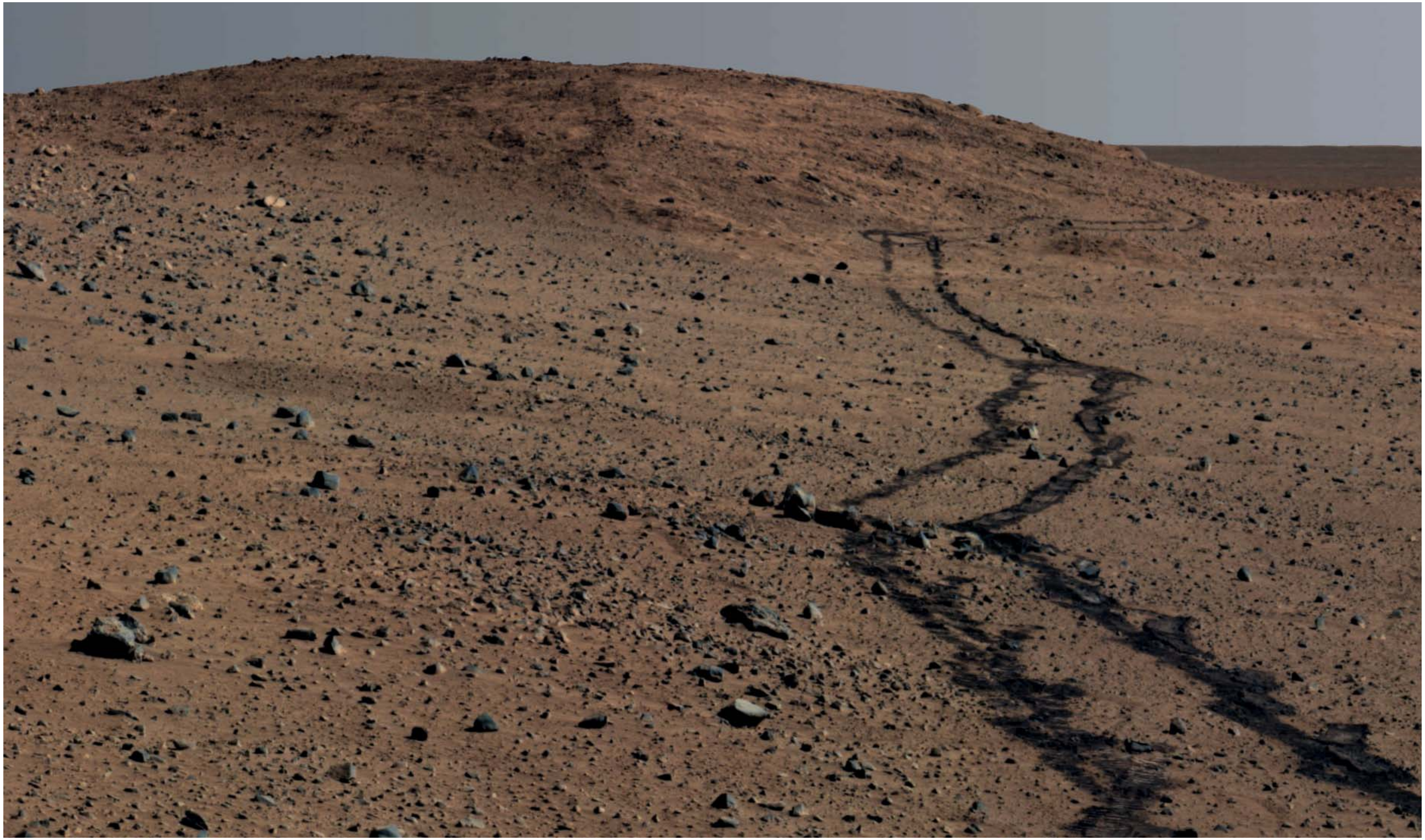


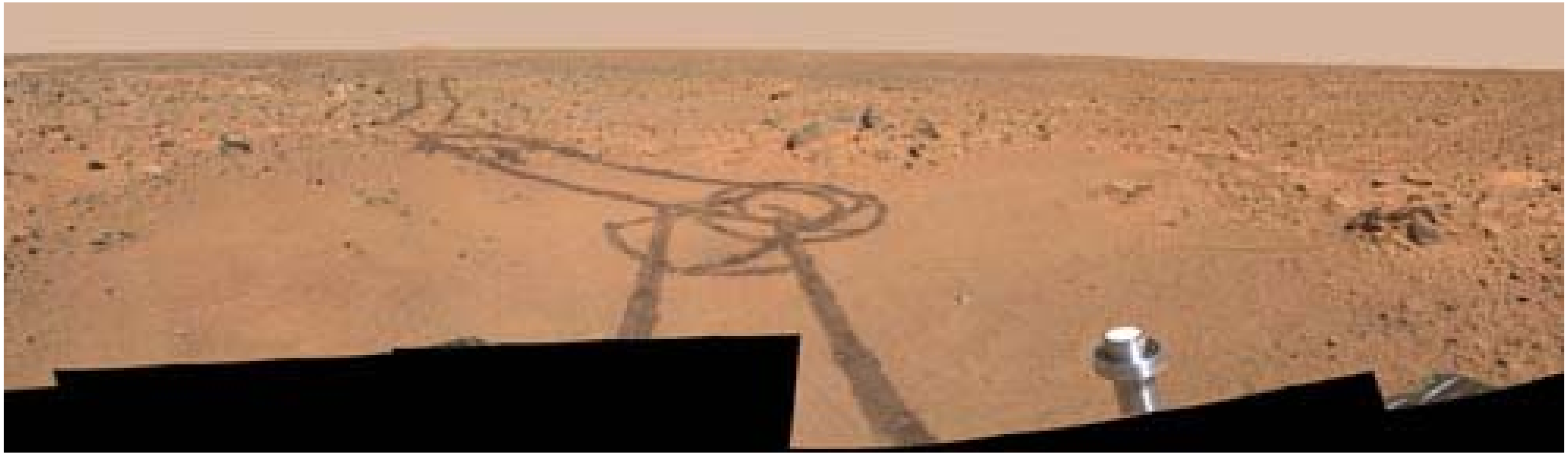
- the volcanic outflows are dry
- the bright (red) dust is anhydrous

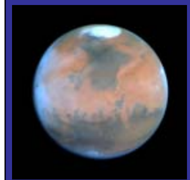

anhydrous ferric oxides

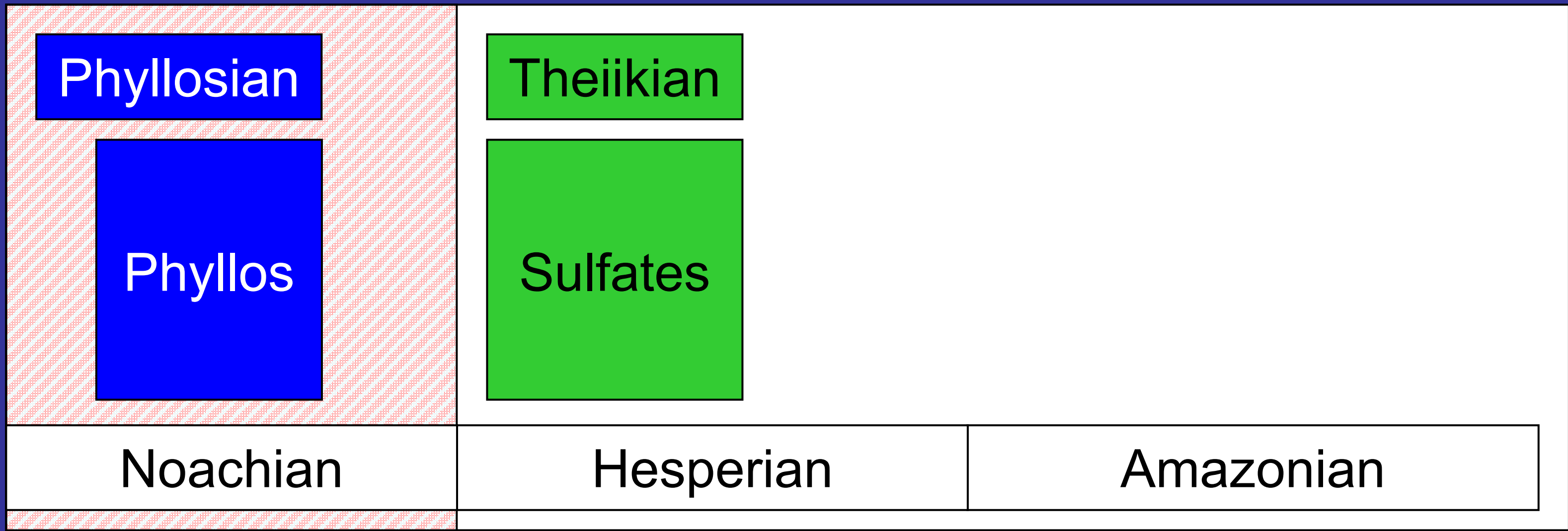
Liquid water is (likely) not responsible for Mars being rusted.
The surface oxidation (alteration) is mainly due to atmospheric peroxidic (H_2O_2) interaction, which constitutes a very slow process (it operates over billions of years) and only affects a very shallow (sub mm) depth.

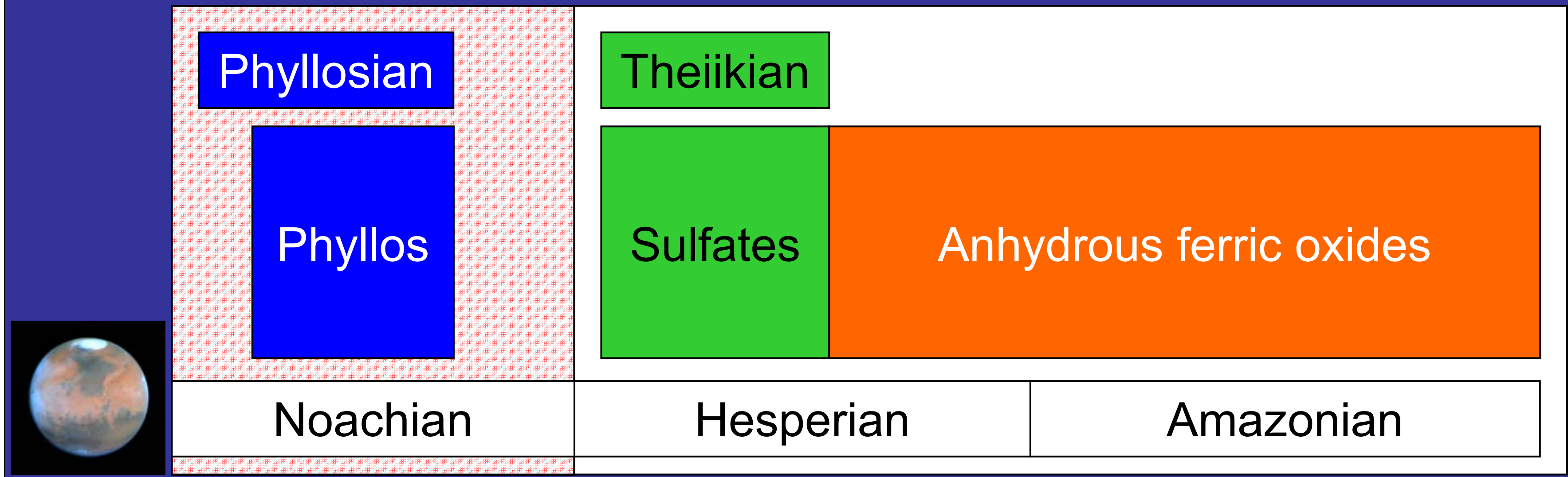




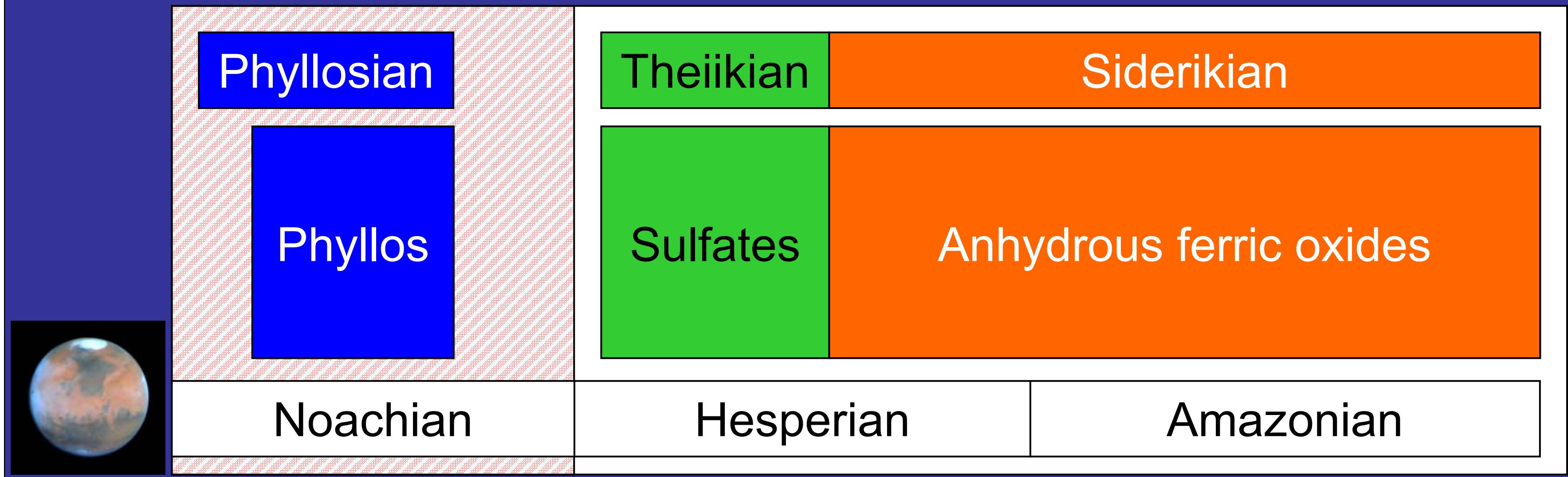


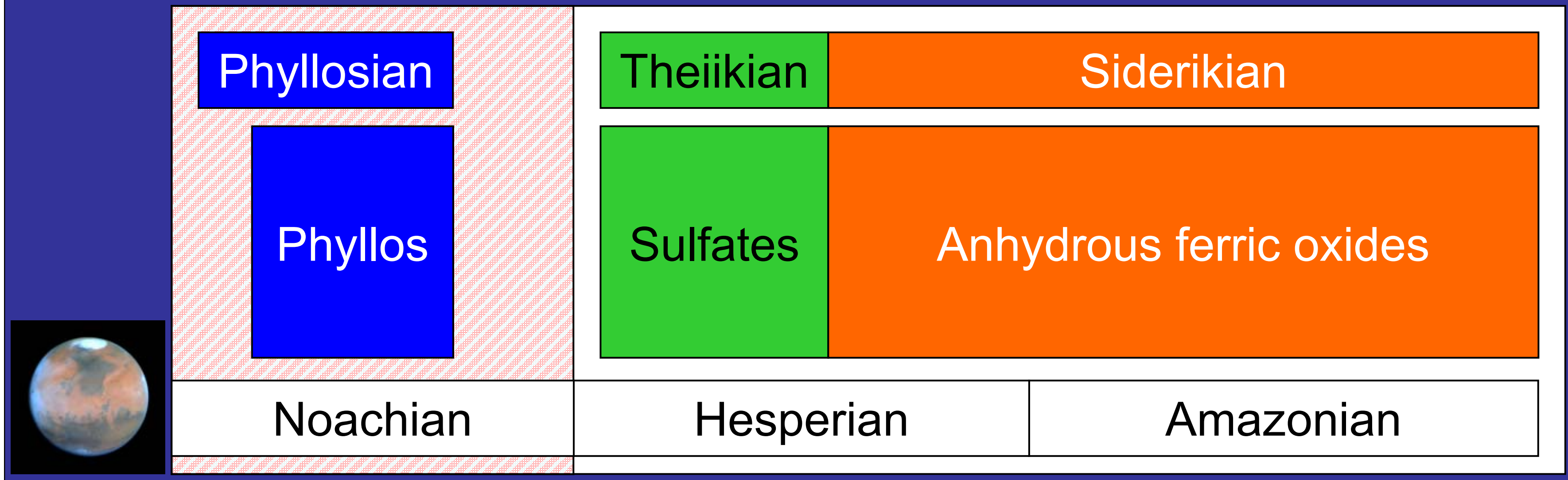



Phyllosian
Phyllos
Theiikian
Sulfates
Noachian
Hesperian
Amazonian



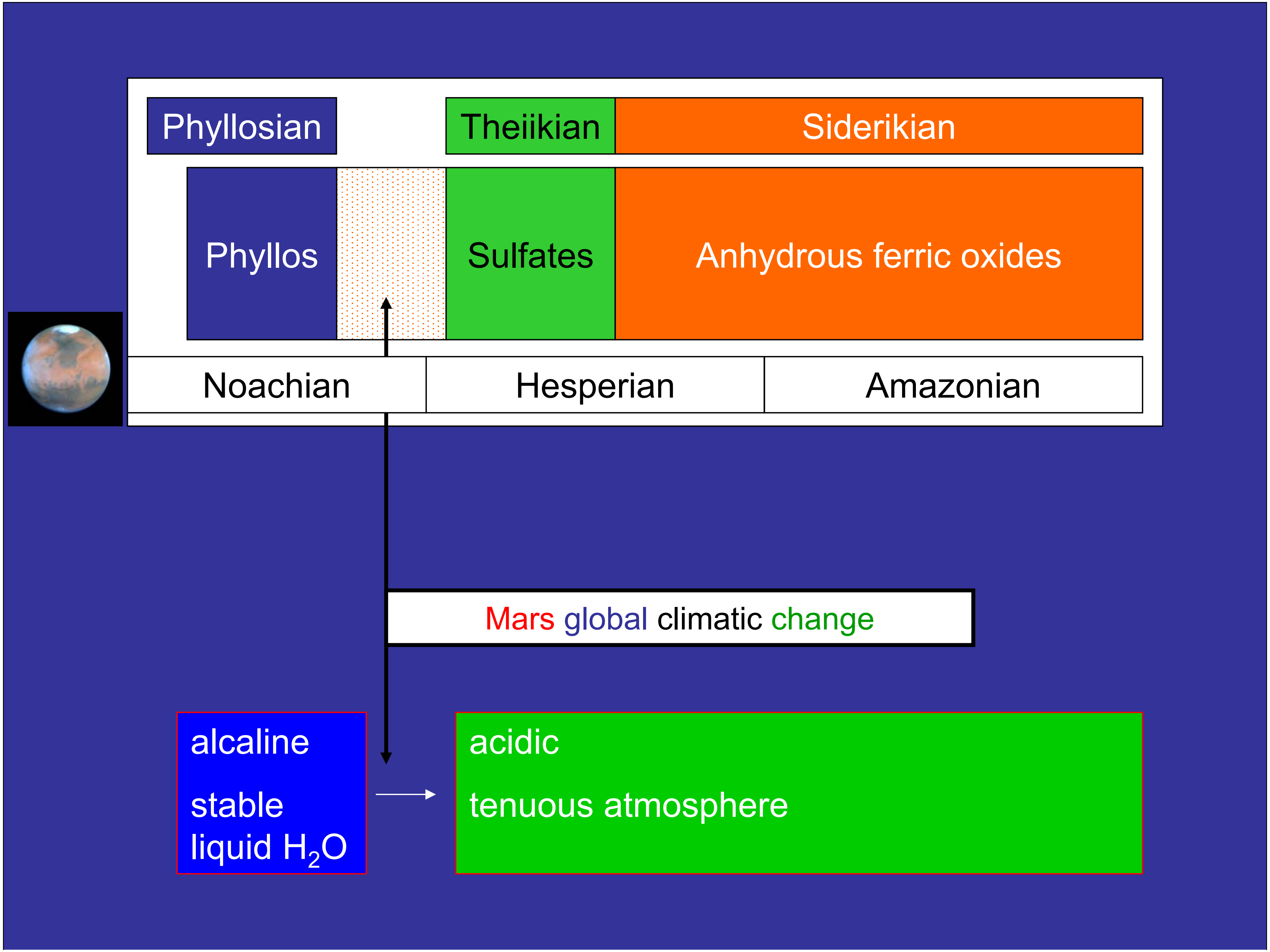
Phyllosian
Phyllos
Theiikian
Sulfates
Anhydrous ferric oxides
Noachian
Hesperian
Amazonian

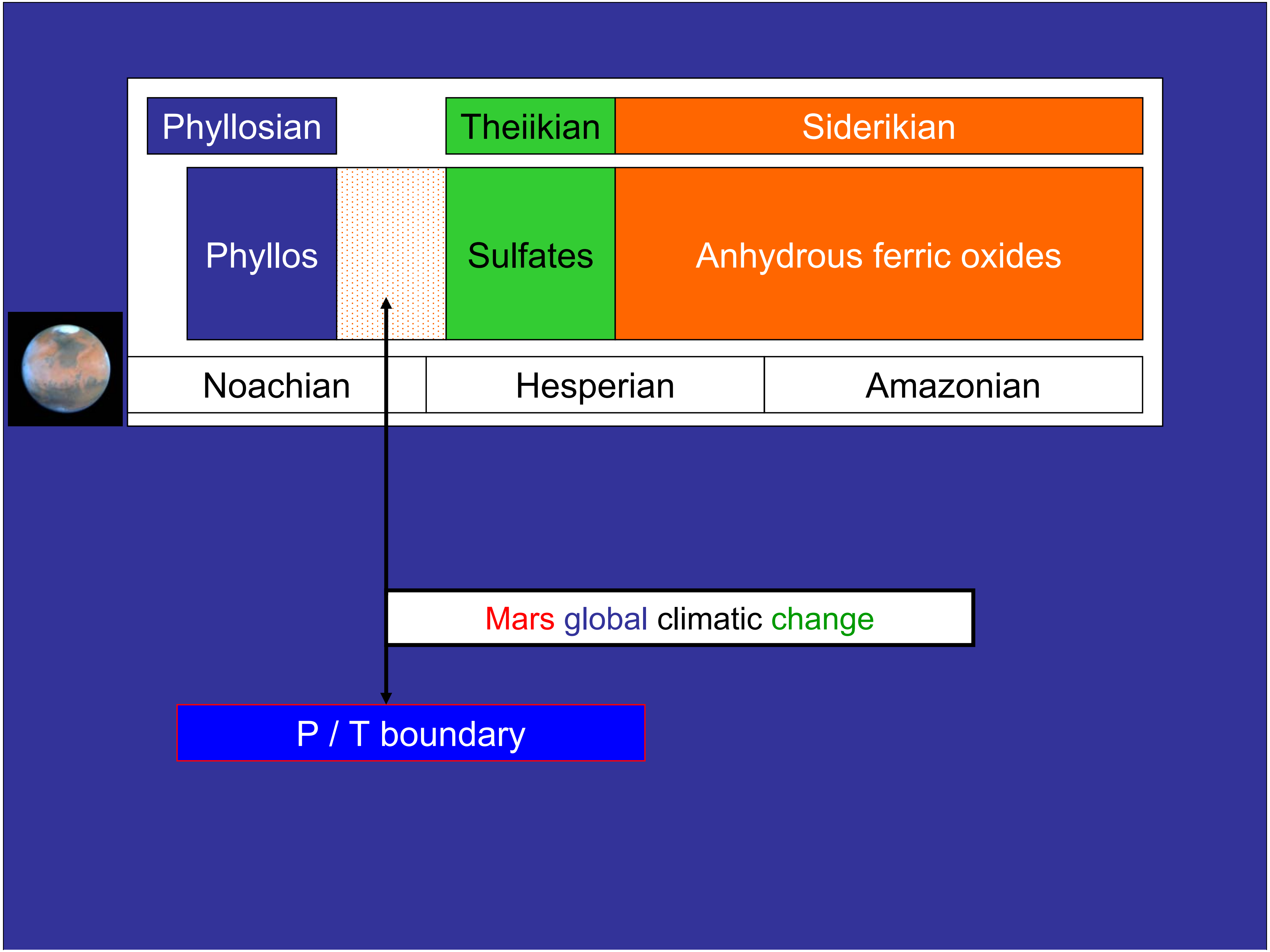

Phyllosian
Phyllos
Theiikian
Siderikian
Sulfates
Anhydrous ferric oxides
Noachian
Hesperian
Amazonian

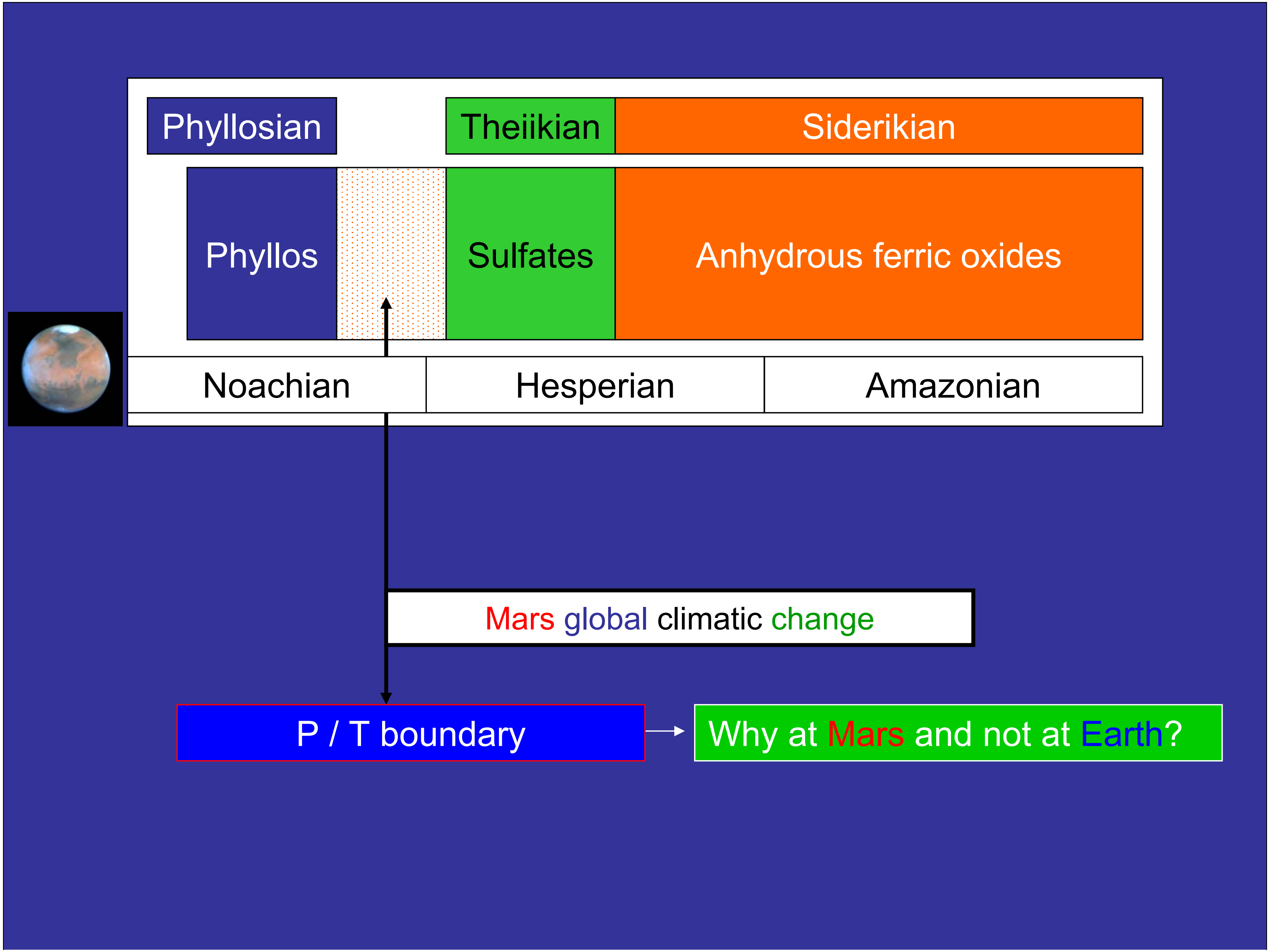


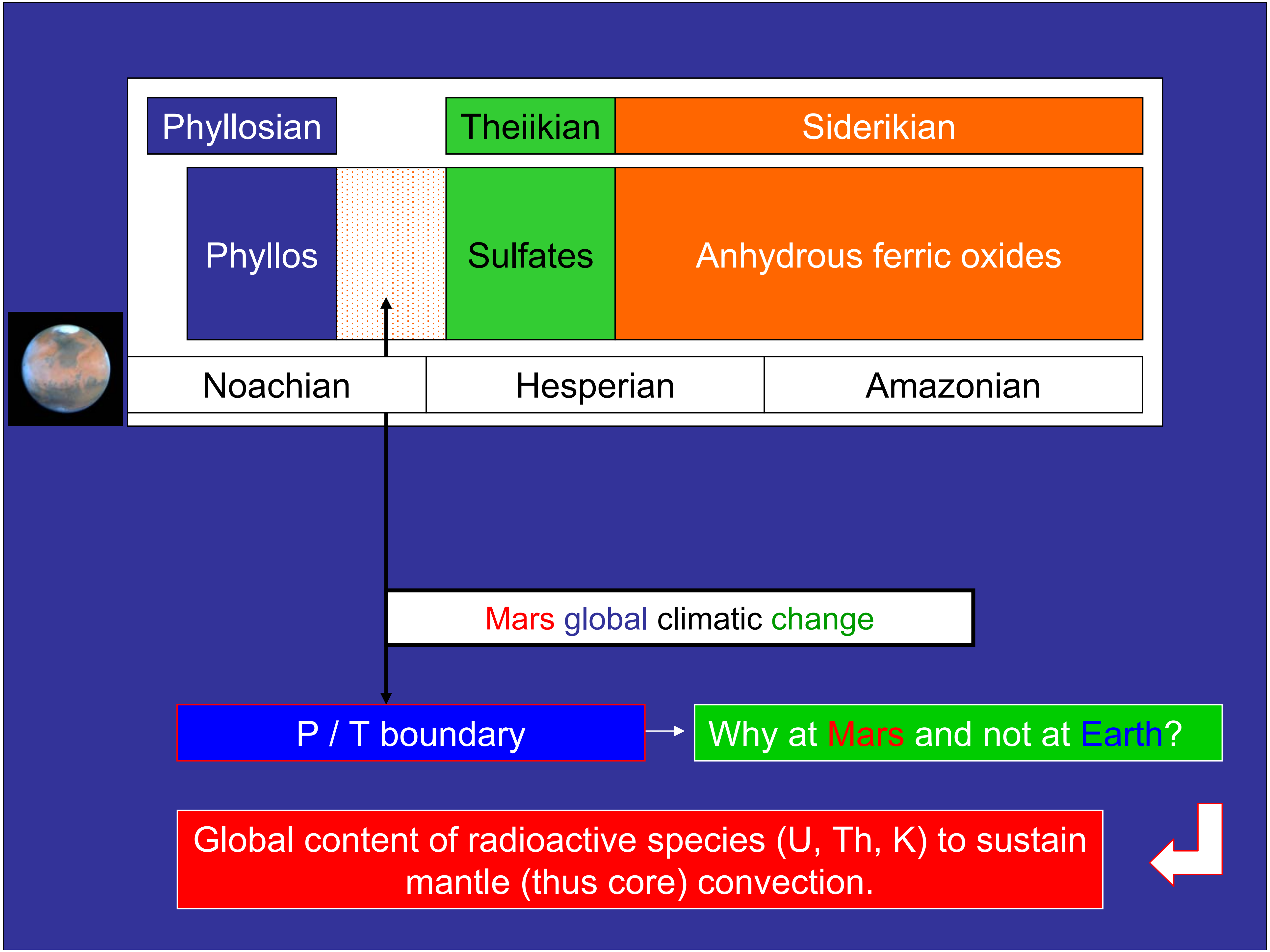
Mars History derived from surface structures

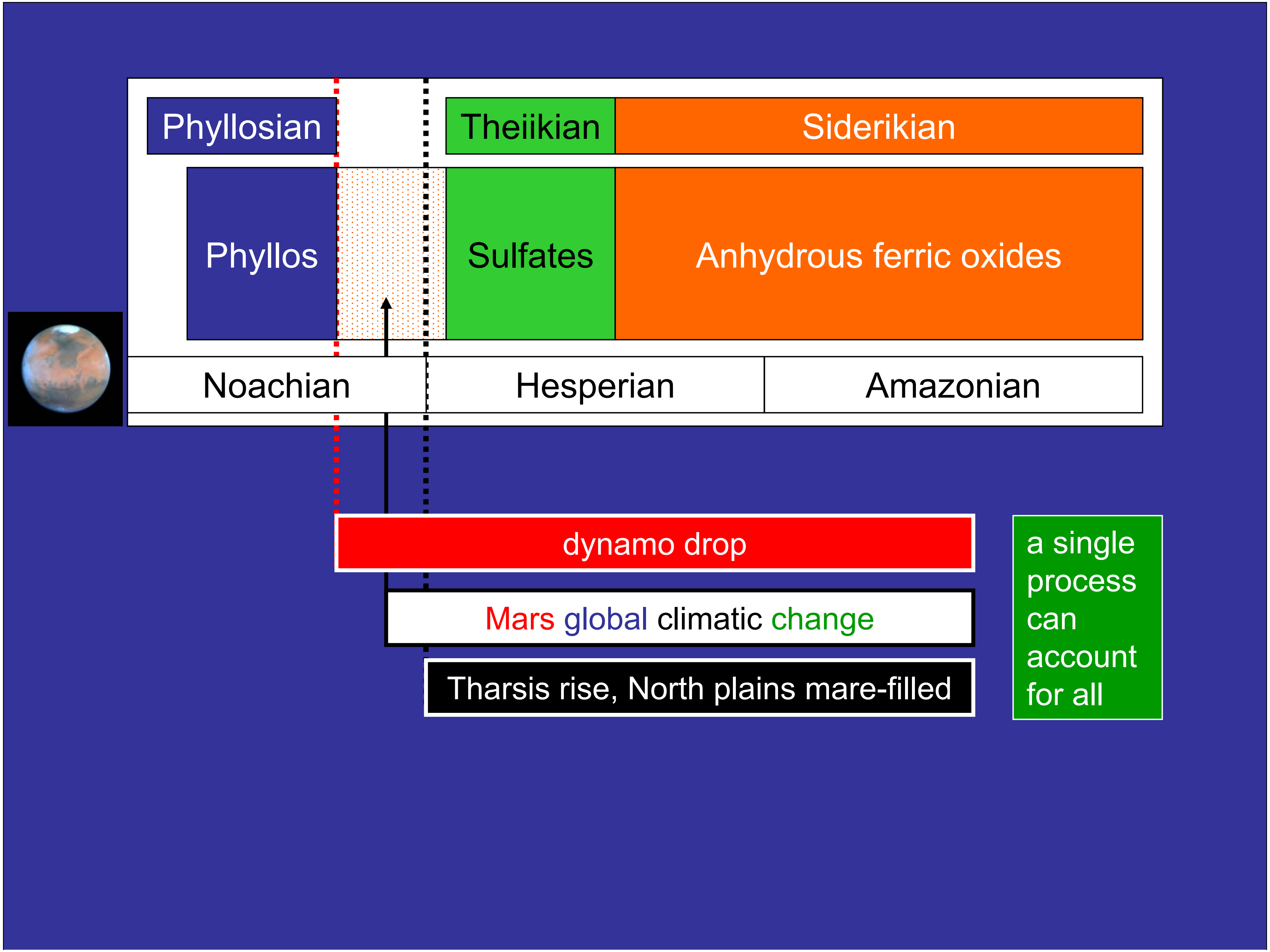
Mars History derived from surface mineralogy

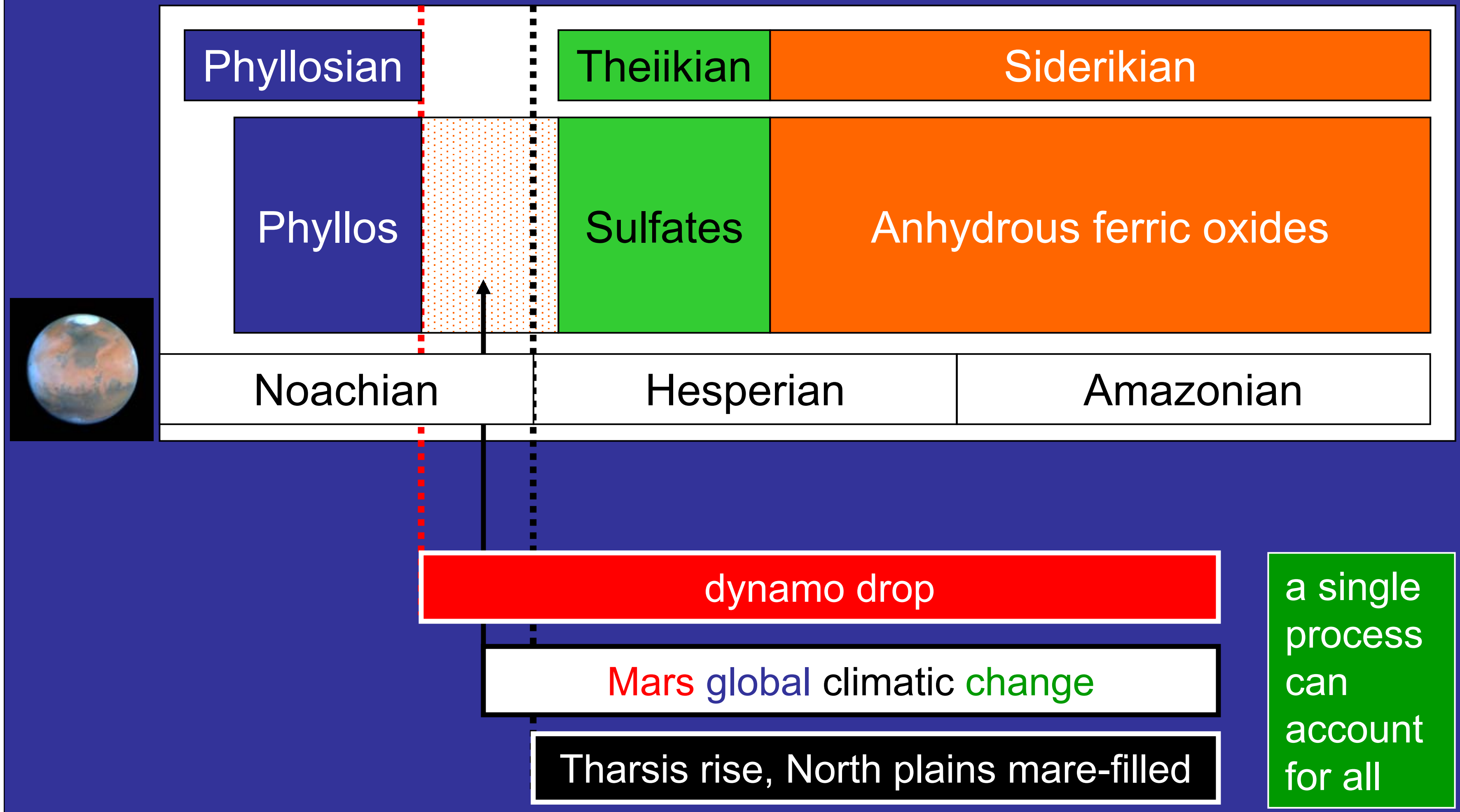

Phyllosian
Theiikian
Siderikian
Phyllos
Sulfates
Anhydrous ferric oxides
Noachian
Hesperian
Amazonian
Mars global climatic change
alcaline
stable
liquid H_2O
acidic
tenuous atmosphere


Phyllosian
Theiikian
Siderikian
Phyllos
Sulfates
Anhydrous ferric oxides
Noachian
Hesperian
Amazonian
Mars global climatic change
P / T boundary

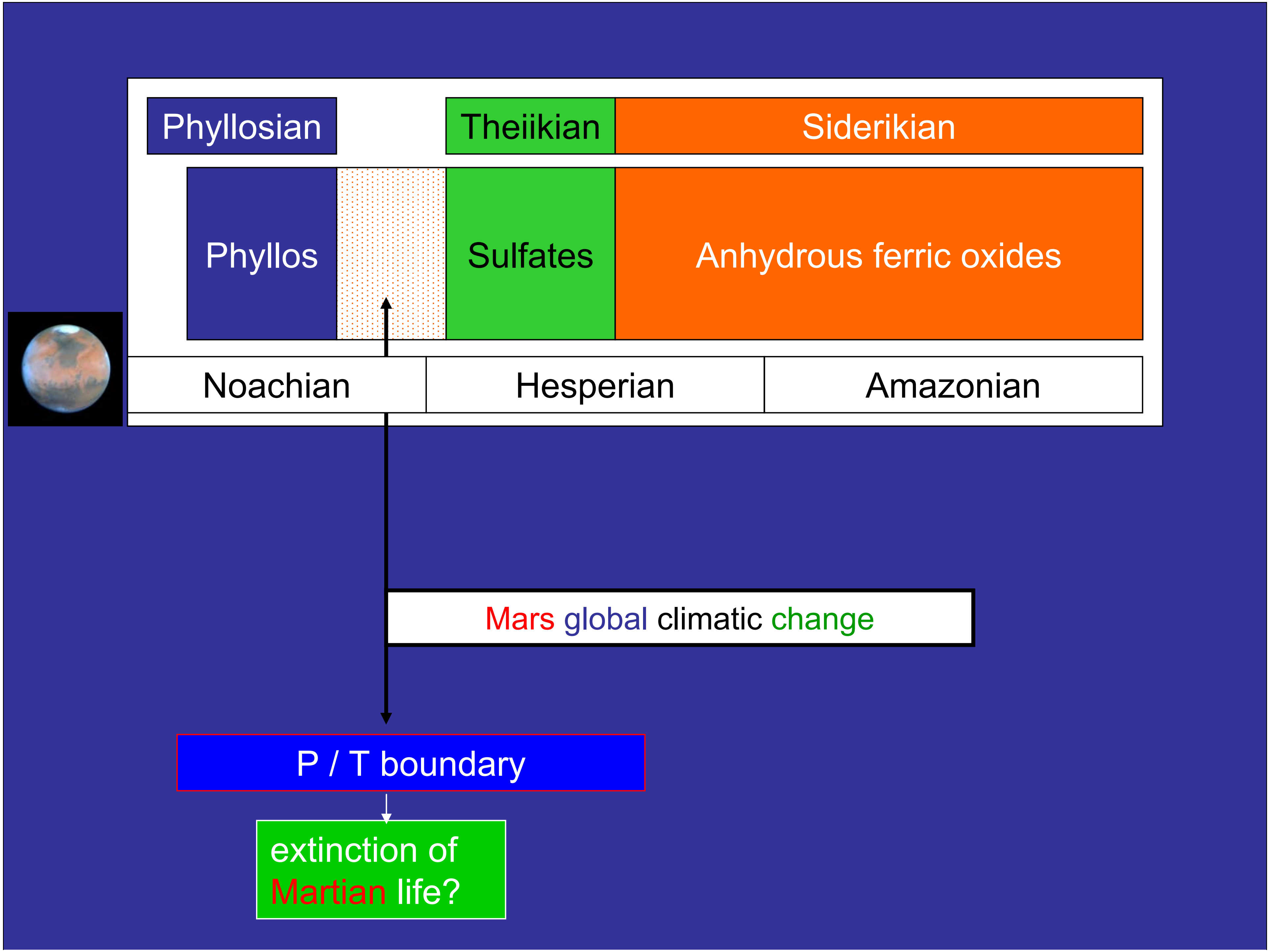

Phyllosian
Theiikian
Siderikian
Phyllos
Sulfates
Anhydrous ferric oxides
Noachian
Hesperian
Amazonian
Mars global climatic change
P / T boundary
Why at Mars and not at Earth?

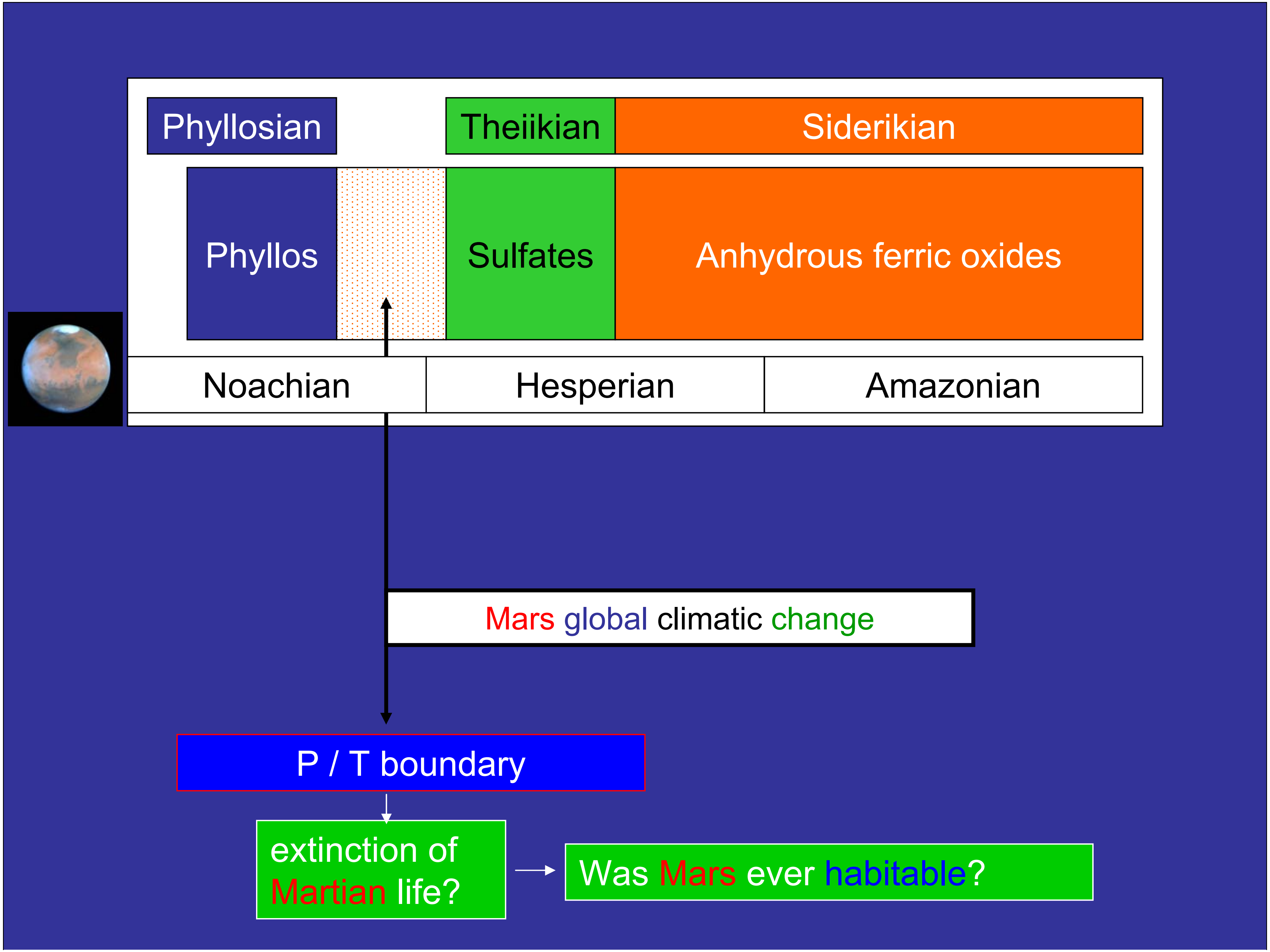

Phyllosian
Theiikian
Siderikian
Phyllos
Sulfates
Anhydrous ferric oxides
Noachian
Hesperian
Amazonian
Mars global climatic change
P / T boundary
Why at Mars and not at Earth?
Global content of radioactive species (U, Th, K) to sustain mantle (thus core) convection.

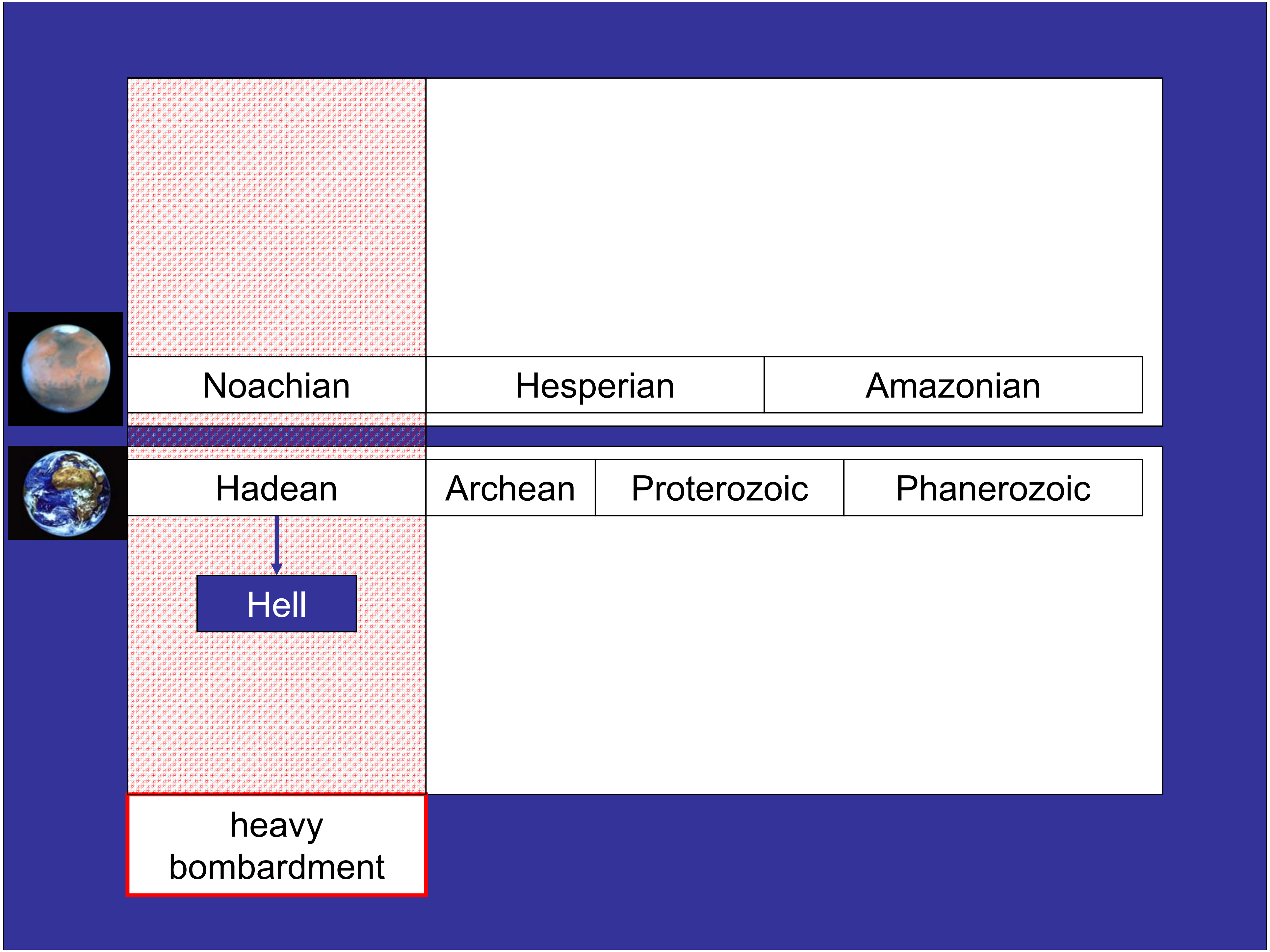

Phyllosian
Theiikian
Siderikian
Phyllos
Sulfates
Anhydrous ferric oxides
Noachian
Hesperian
Amazonian
dynamo drop
Mars global climatic change
Tharsis rise, North plains mare-filled
a single process can account for all

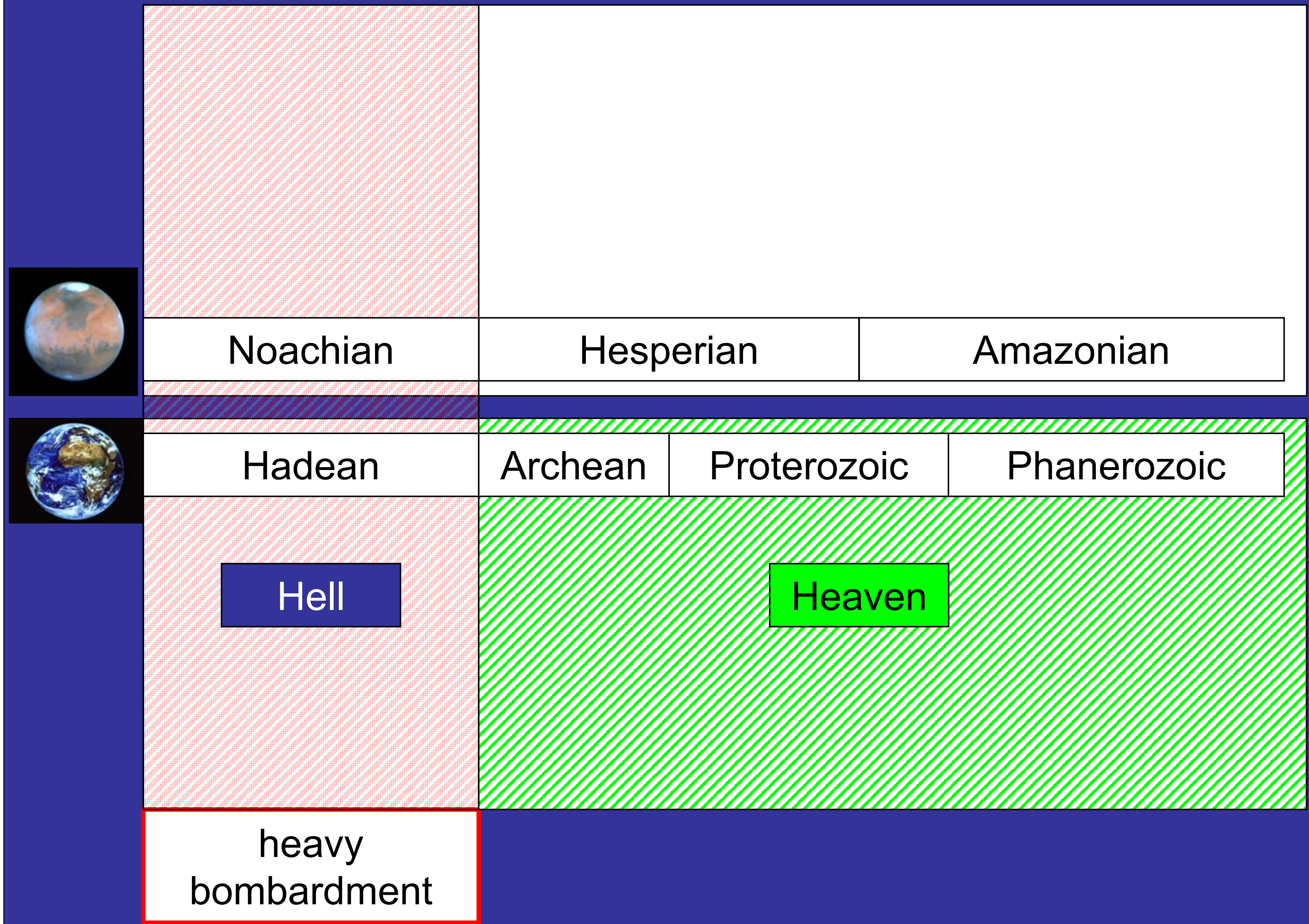


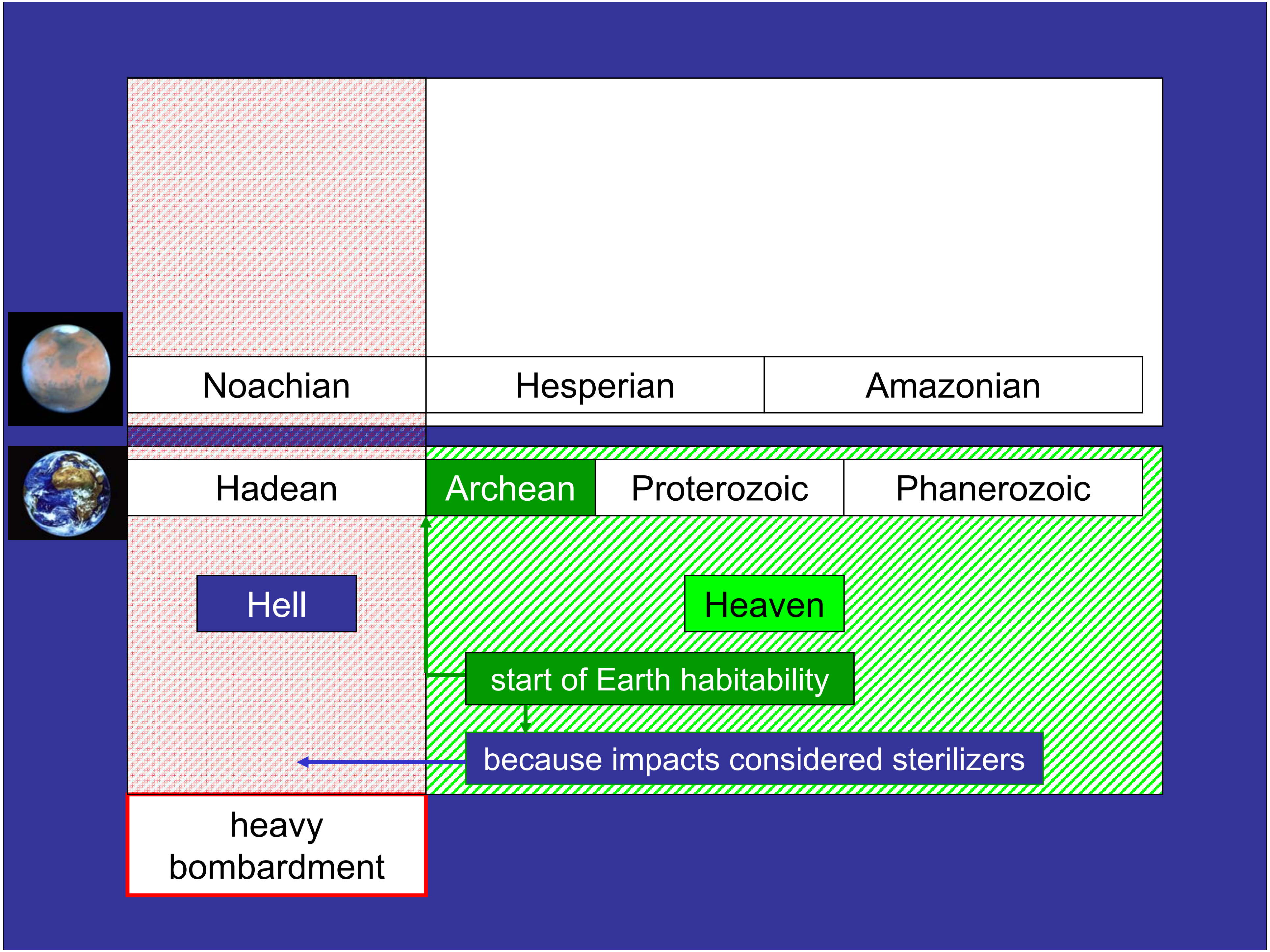
The decrease of mantle convection drove the drop of the core convection, thus of the magnetic shield against young Sun effects, leading to the escape of green house gases, disabling liquid water stability.
Descending mantle cold plumes → core/mantle instabilities → ascending plumes + local/transient dynamo reactivation.


Phyllosian
Theiikian
Siderikian
Phyllos
Sulfates
Anhydrous ferric oxides
Noachian
Hesperian
Amazonian
Mars global climatic change
P / T boundary
extinction of Martian life?

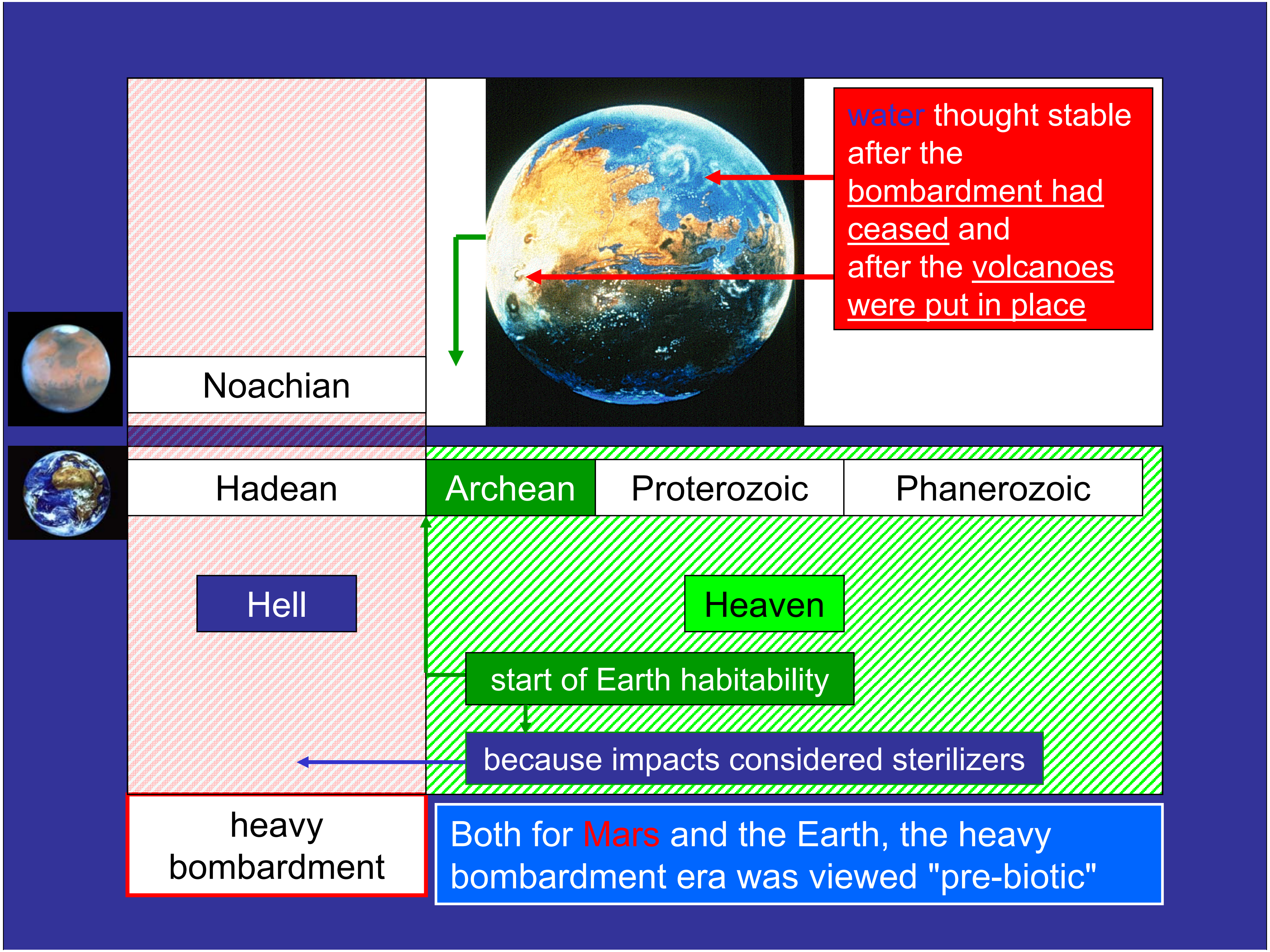

Phyllosian
Theiikian
Siderikian
Phyllos
Sulfates
Anhydrous ferric oxides
Noachian
Hesperian
Amazonian
Mars global climatic change
P / T boundary
extinction of Martian life?
Was Mars ever habitable?


Noachian
Hesperian
Amazonian
Hadean
Archean
Proterozoic
Phanerozoic
Hell
heavy bombardment


Noachian
Hesperian
Amazonian
Hadean
Archean
Proterozoic
Phanerozoic
Hell
Heaven
heavy bombardment

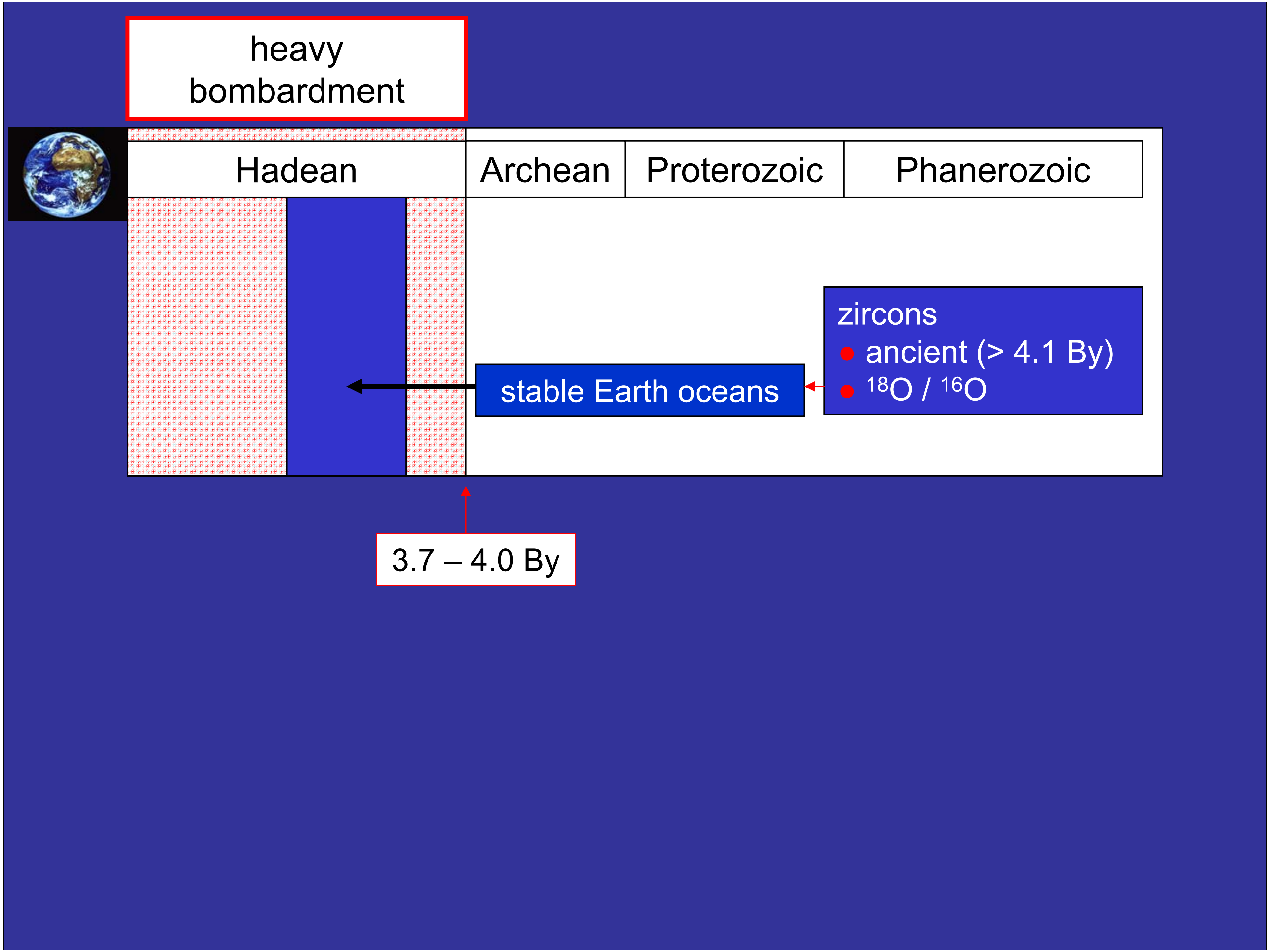


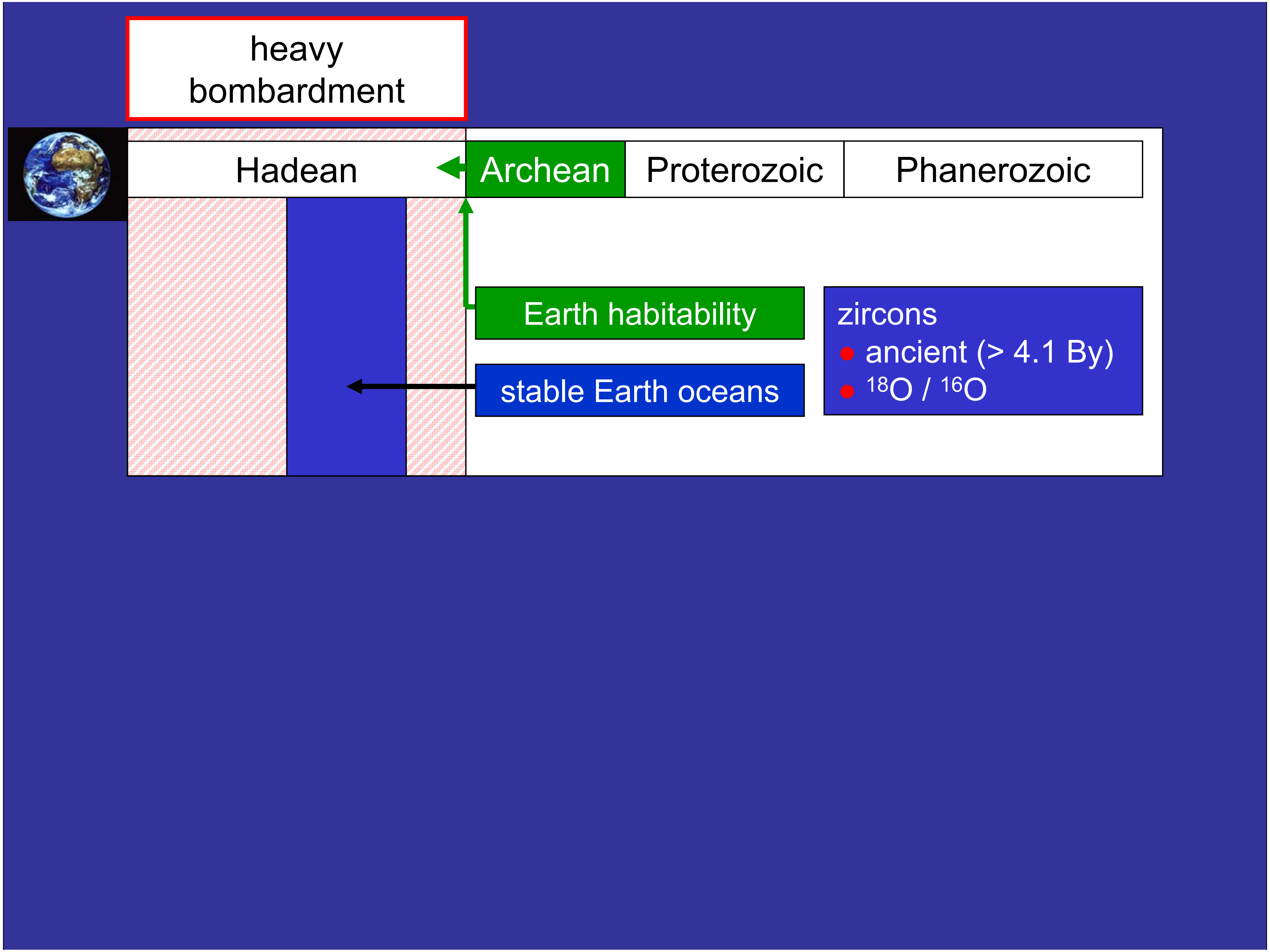
Noachian
Hesperian
Amazonian
Hadean
Archean
Proterozoic
Phanerozoic
Hell
Heaven
start of Earth habitability
because impacts considered sterilizers
heavy
bombardment

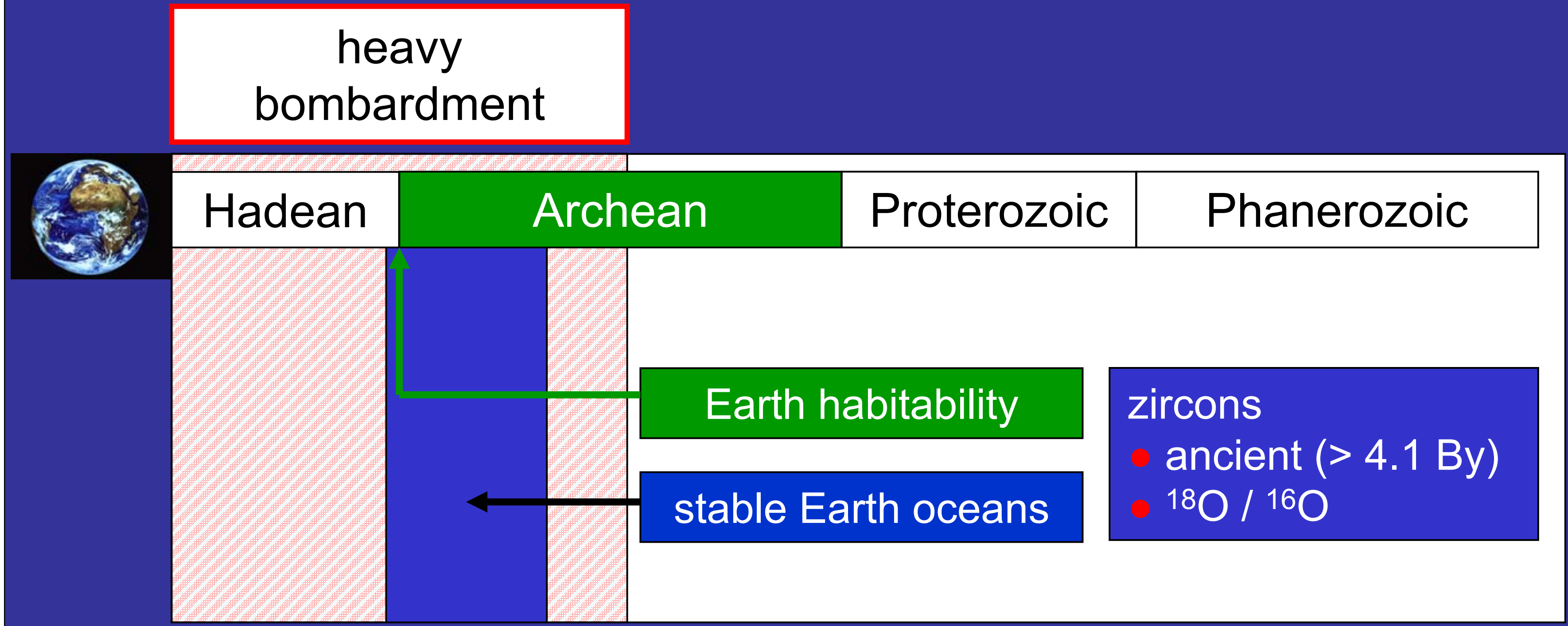


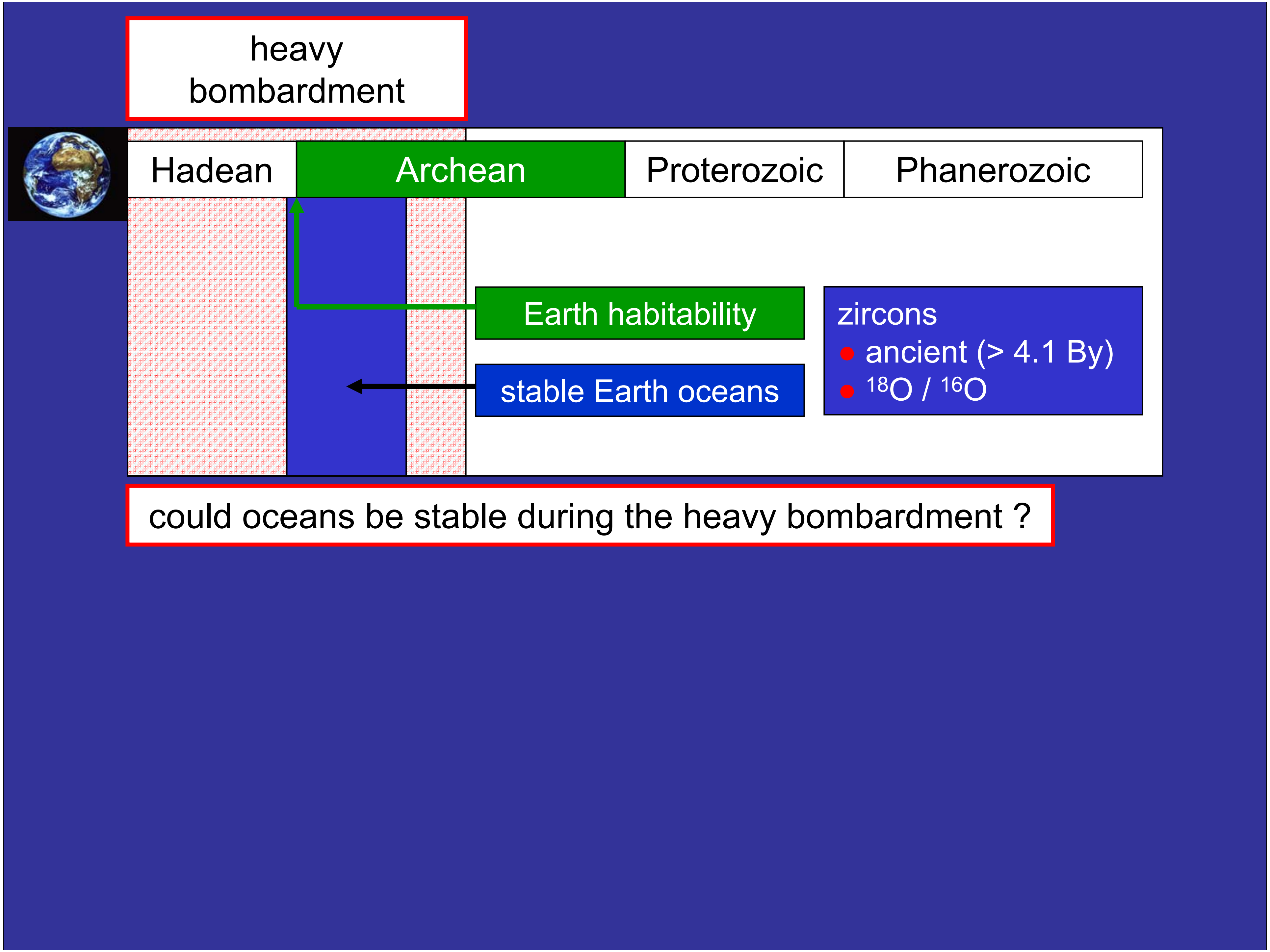
water thought stable after the bombardment had ceased and after the volcanoes were put in place
Noachian
Hadean
Archean
Proterozoic
Phanerozoic
Hell
Heaven
start of Earth habitability
because impacts considered sterilizers
heavy bombardment
Both for Mars and the Earth, the heavy bombardment era was viewed "pre-biotic"

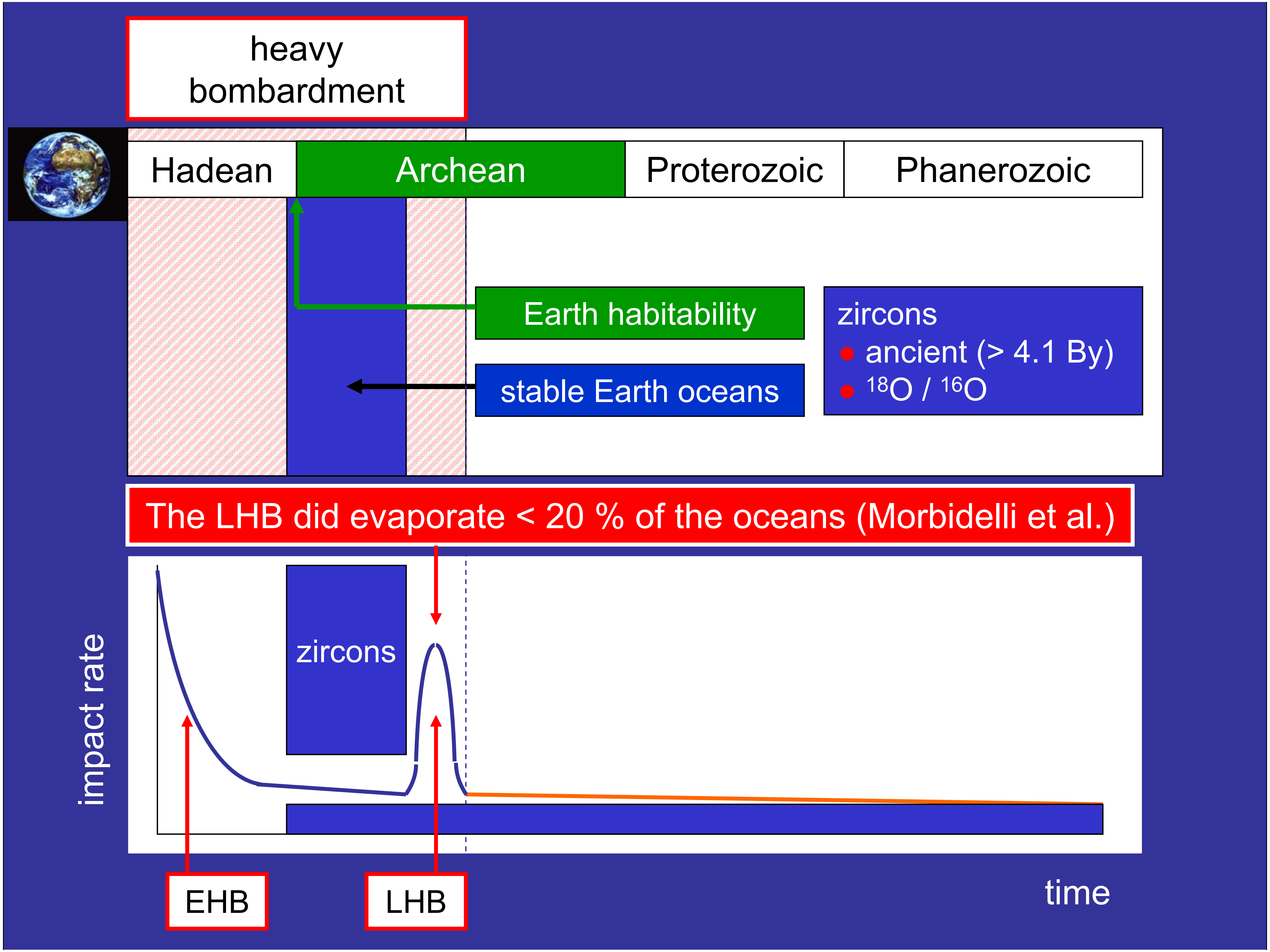
There are good reasons (results) to change this view, both for Mars and the Earth.

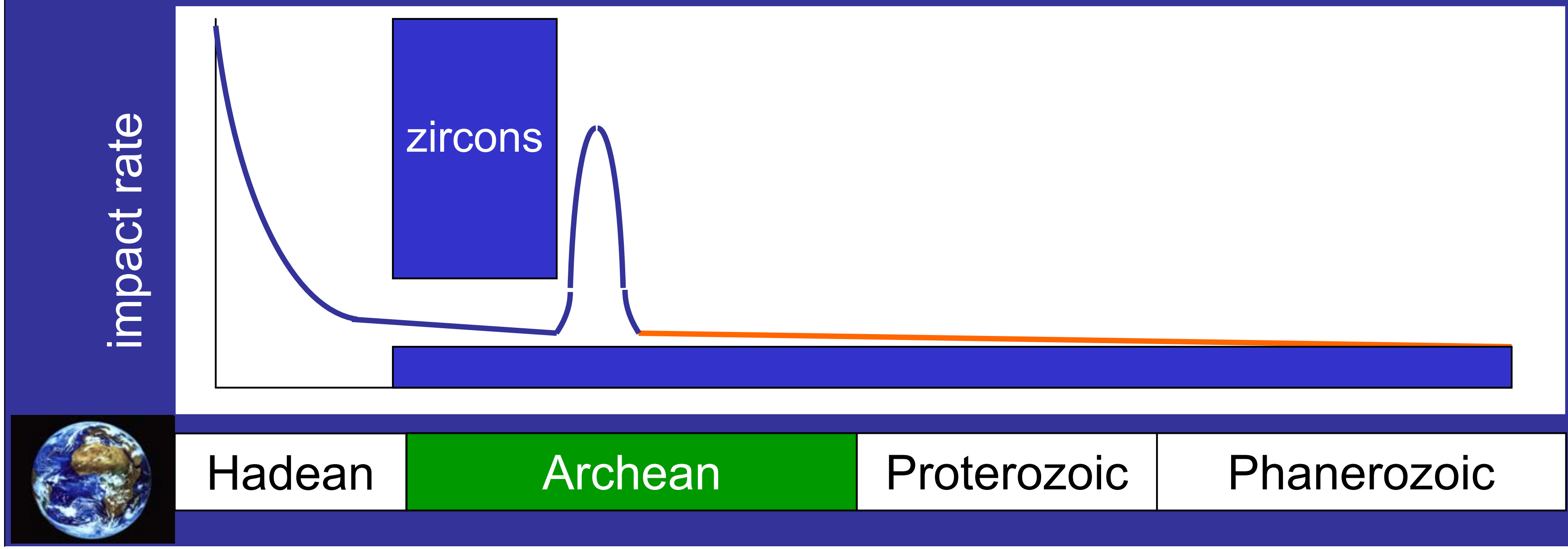

heavy bombardment
Hadean
Archean
Proterozoic
Phanerozoic
stable Earth oceans
zircons
ancient (> 4.1 By)
^{18}O / ^{16}O
3.7 – 4.0 By


heavy
bombardment
Hadean
Archean
Proterozoic
Phanerozoic
Earth habitability
stable Earth oceans
zircons
ancient (> 4.1 By)
^{18}O / ^{16}O

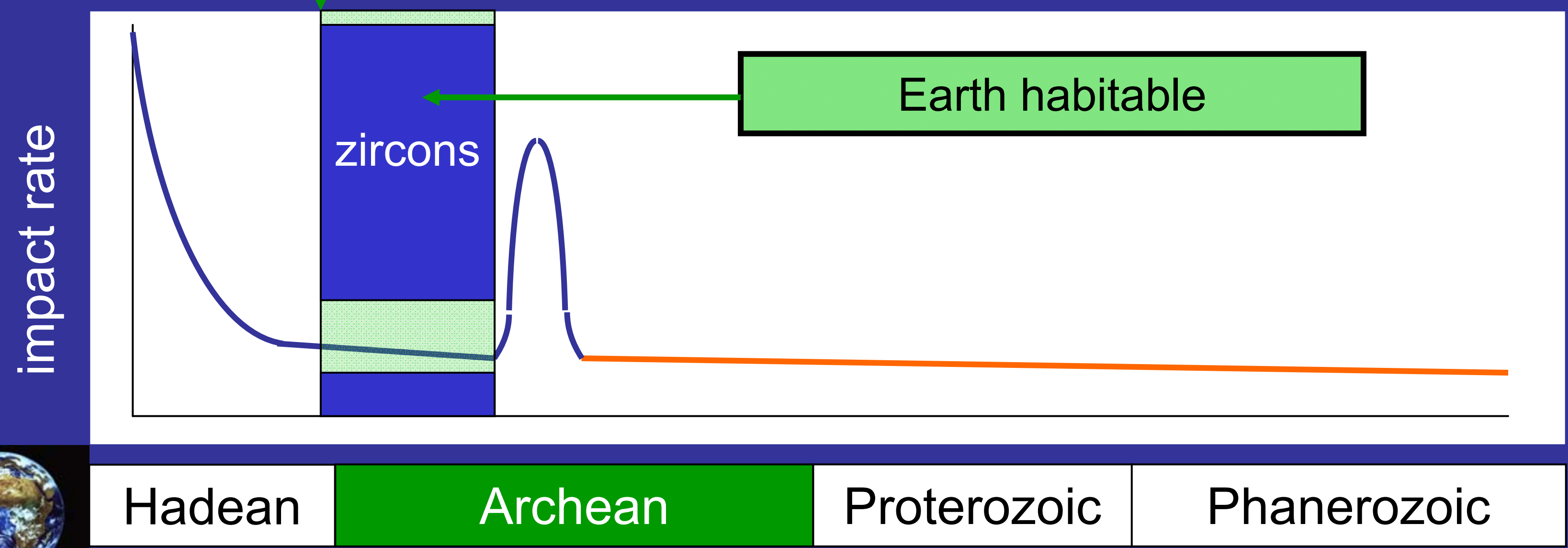

heavy bombardment
Hadean
Archean
Proterozoic
Phanerozoic
Earth habitability
stable Earth oceans
zircons
ancient (> 4.1 By)
18O / 16O


heavy bombardment
Hadean
Archean
Proterozoic
Phanerozoic
Earth habitability
stable Earth oceans
zircons
ancient (> 4.1 By)
^{18}O / ^{16}O
could oceans be stable during the heavy bombardment ?

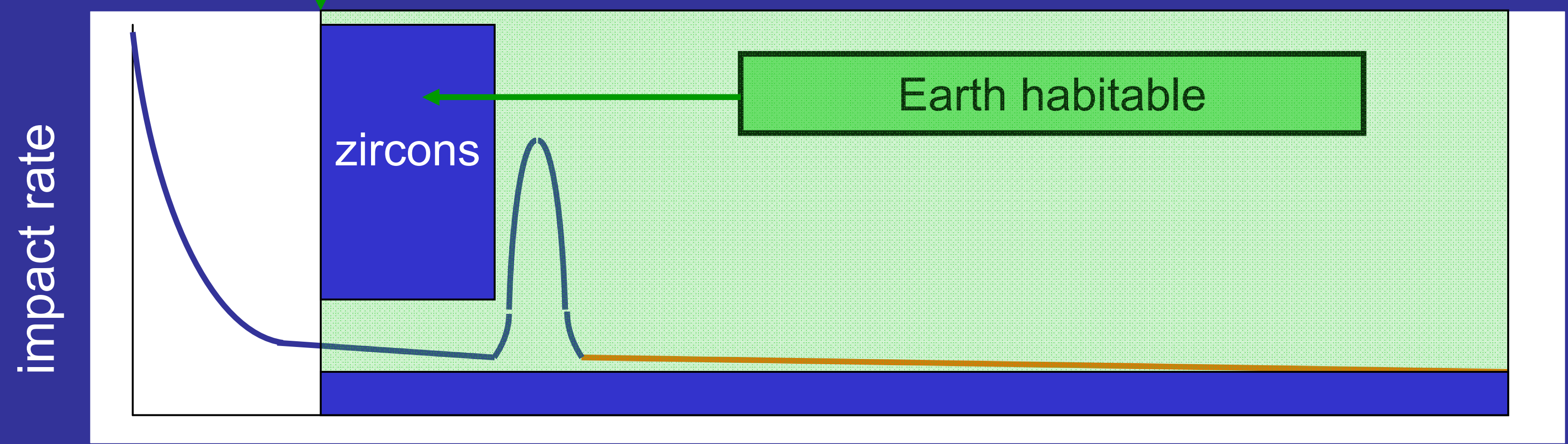

heavy bombardment
Hadean
Archean
Proterozoic
Phanerozoic
Earth habitability
stable Earth oceans
zircons
ancient (> 4.1 By)
18O / 16O
The LHB did evaporate < 20 % of the oceans (Morbidelli et al.)
impact rate
zircons
EHB
LHB
time


impact rate
zircons
Hadean
Archean
Proterozoic
Phanerozoic

crust solidified (4.3 By $ZrSiO_4$), surface oceans stable (^{18}O)



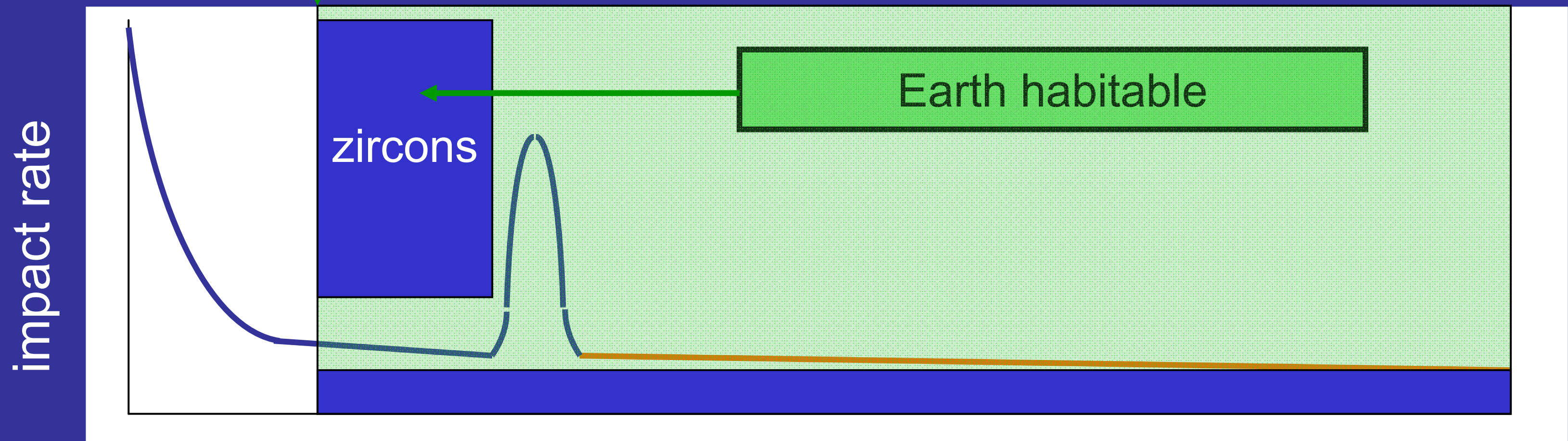
crust solidified (4.3 By $ZrSiO_4$), surface oceans stable (^{18}O)



Hadean	Archean	Proterozoic	Phanerozoic

crust solidified (4.3 By $ZrSiO_4$), surface oceans stable (^{18}O)
life could start

C-rich species → from impacts (ocean surface)
C-rich species → from serpentinisation (ocean floor)



Hadean	Archean	Proterozoic	Phanerozoic

crust solidified (4.3 By $ZrSiO_4$), surface oceans stable (^{18}O)

life could start

reducing environment from serpentinisation

$$3\,Fe_2SiO_4 + 2\,H_2O \rightarrow 3\,SiO_2 + 2\,Fe_3O_4 + H_2$$

fayalite — magnetite

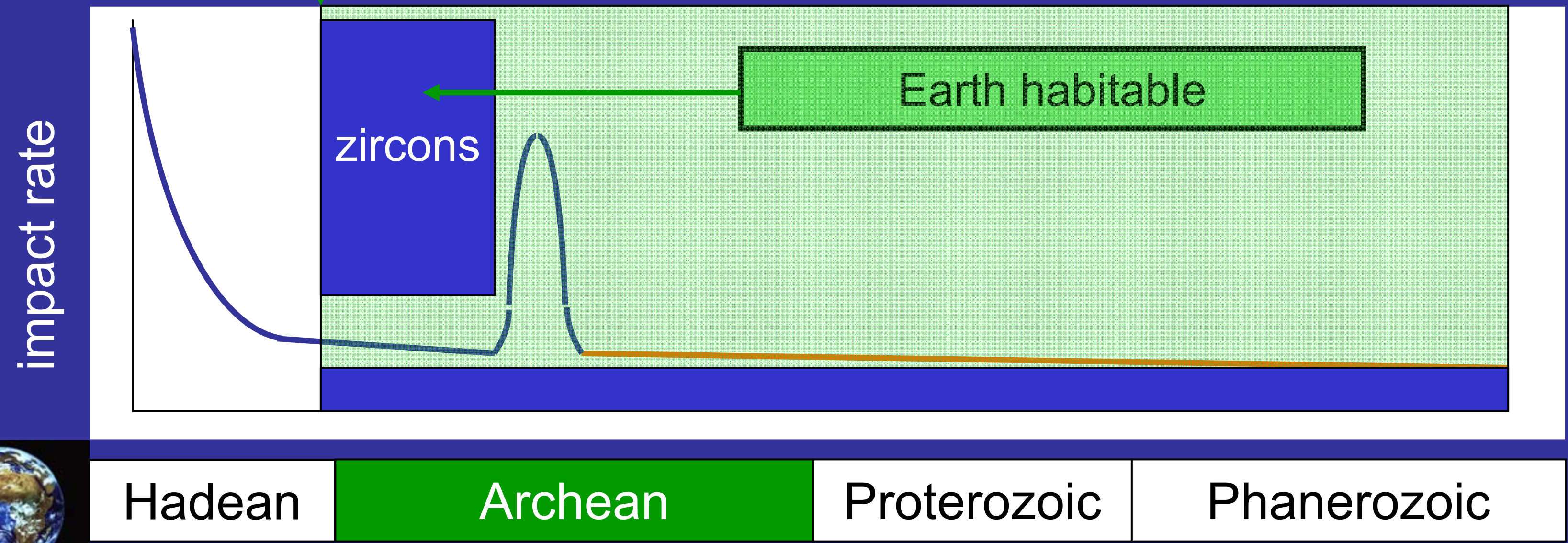
$$3\,Mg_2SiO_4 + SiO_2 + 4\,H_2O \rightarrow 2\,Mg_3Si_2O_5(OH)_4$$

forsterite — serpentine

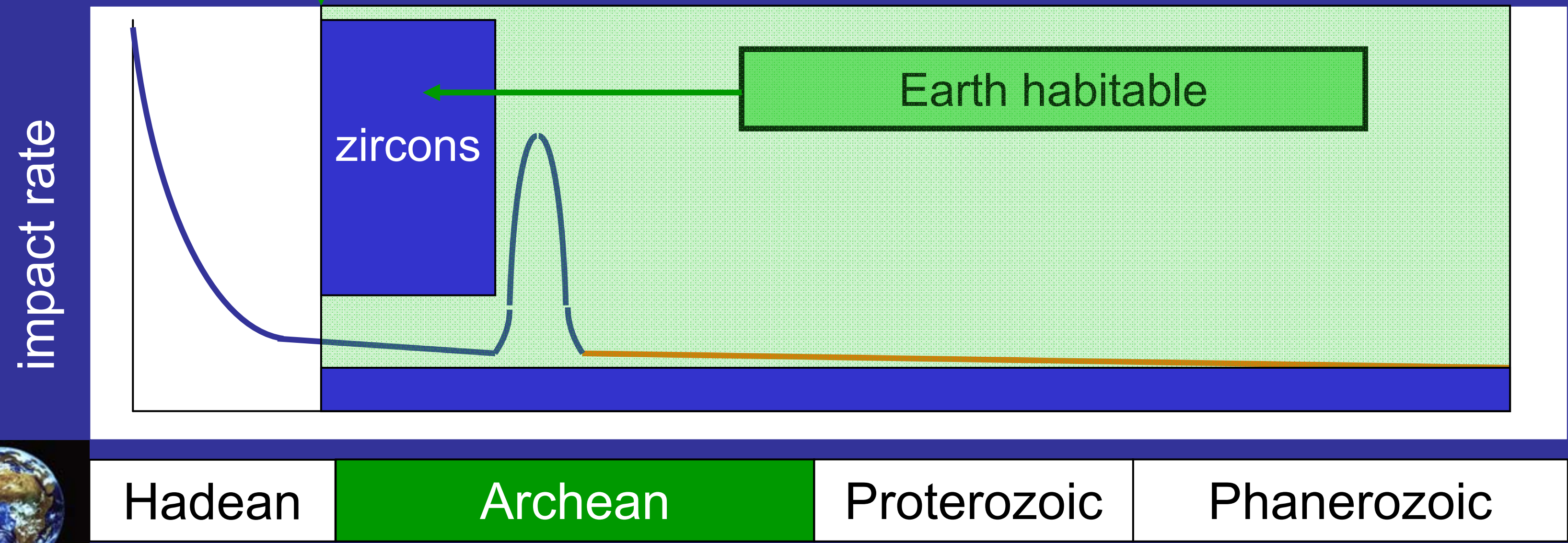
(then serpentine → talc + amphibole if T > 500°C)

$$CO_2 + 4\,H_2 \leftrightarrow CH_4 + 2\,H_2O$$

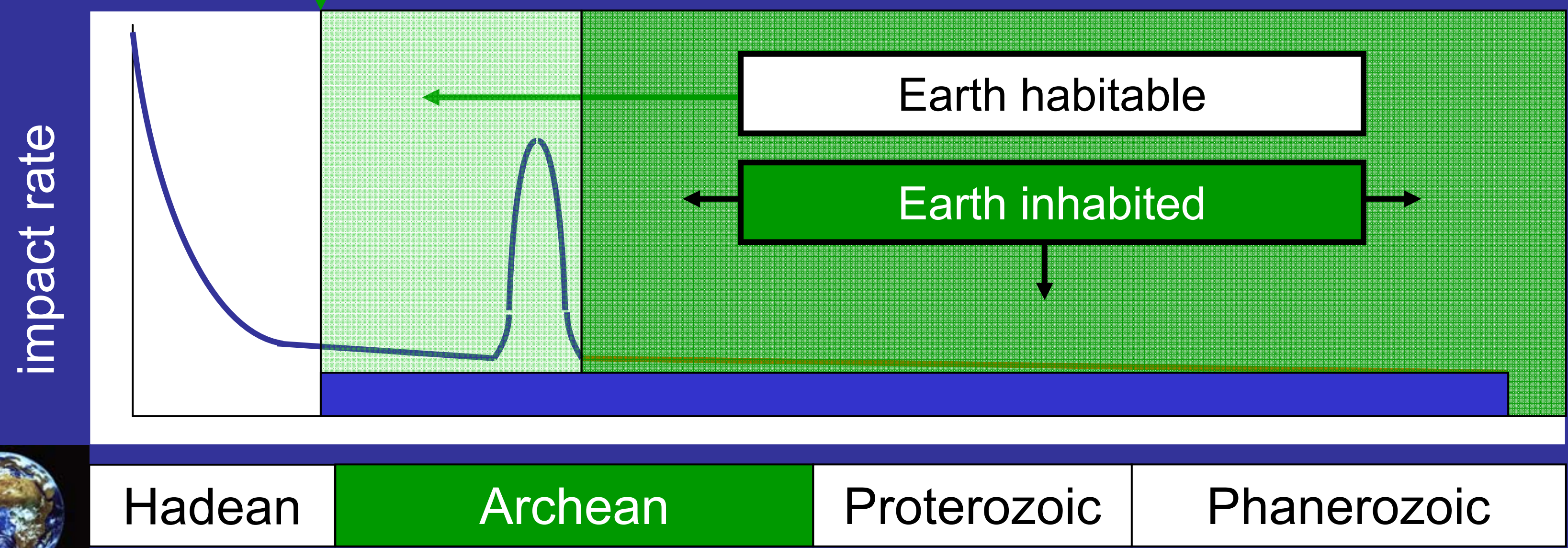
$$9\,Fe_2SiO_4 + 6\,H_2O + 2\,N_2 \leftrightarrow 9\,SiO_2 + 6\,Fe_3O_4 + 4\,NH_3$$



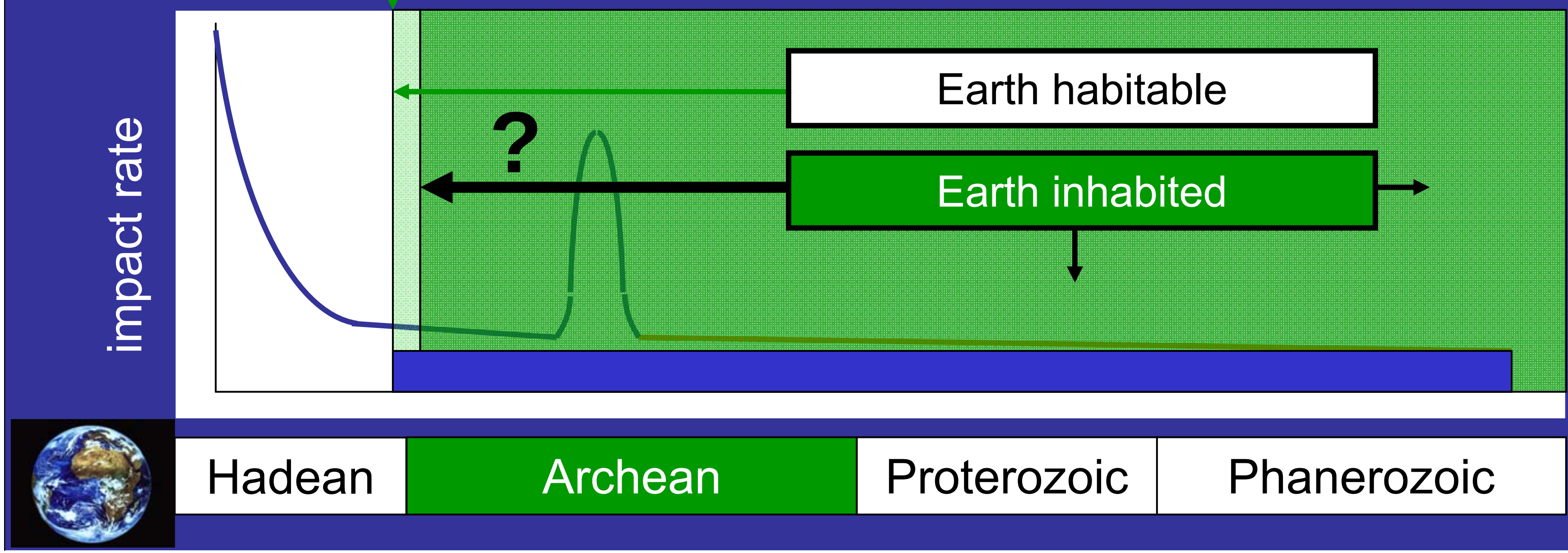
crust solidified (4.3 By $ZrSiO_4$), surface oceans stable (^{18}O)
life could start

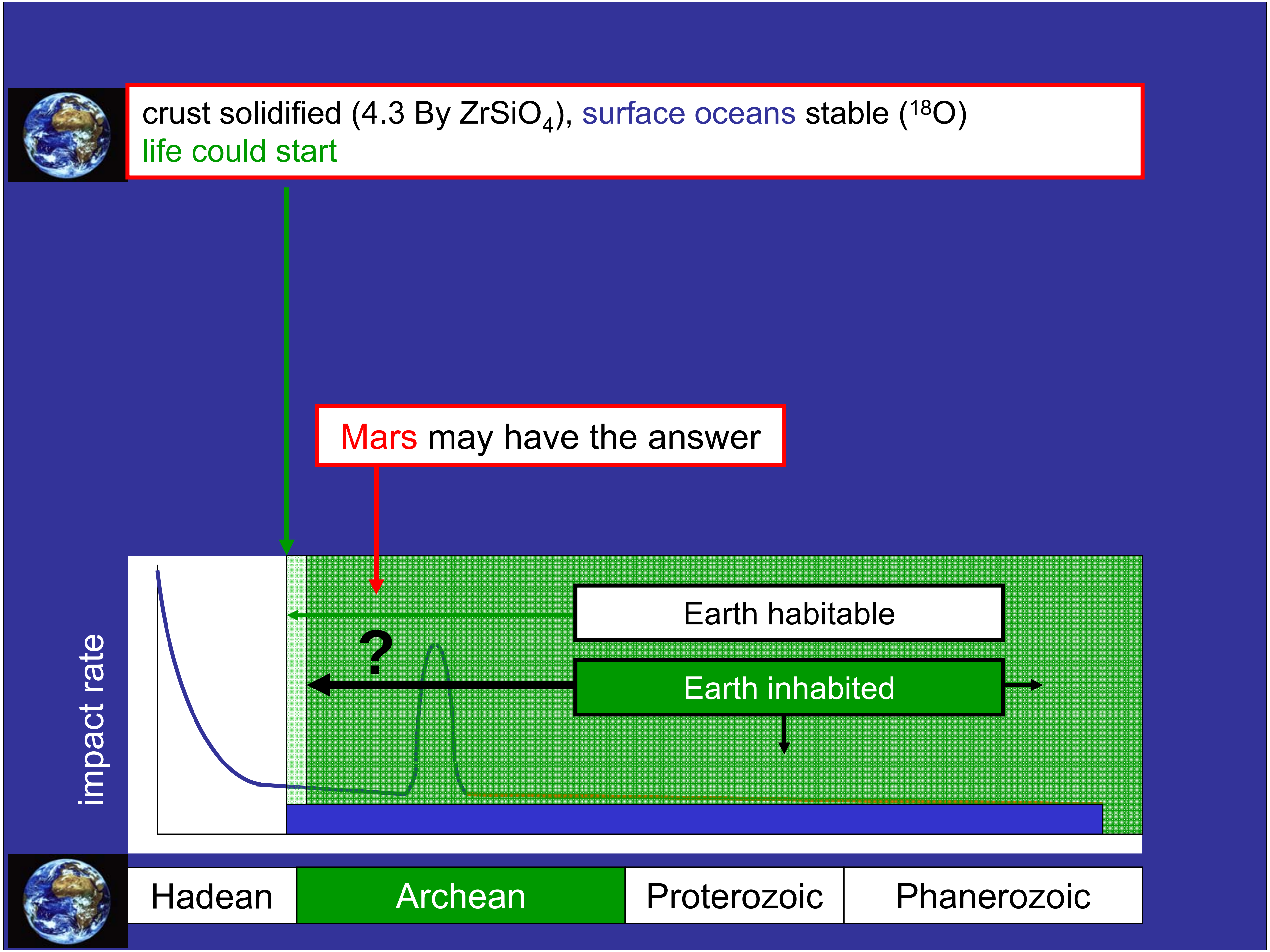


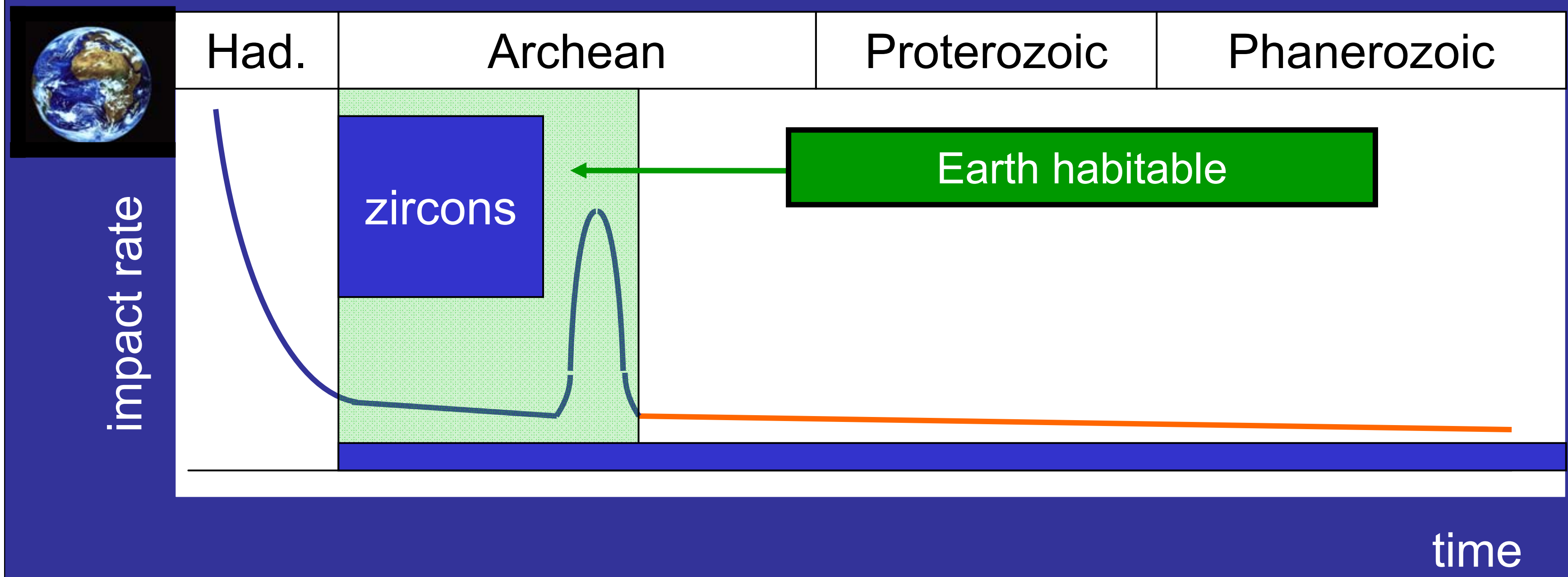
crust solidified (4.3 By $ZrSiO_4$), surface oceans stable (^{18}O)
life could start

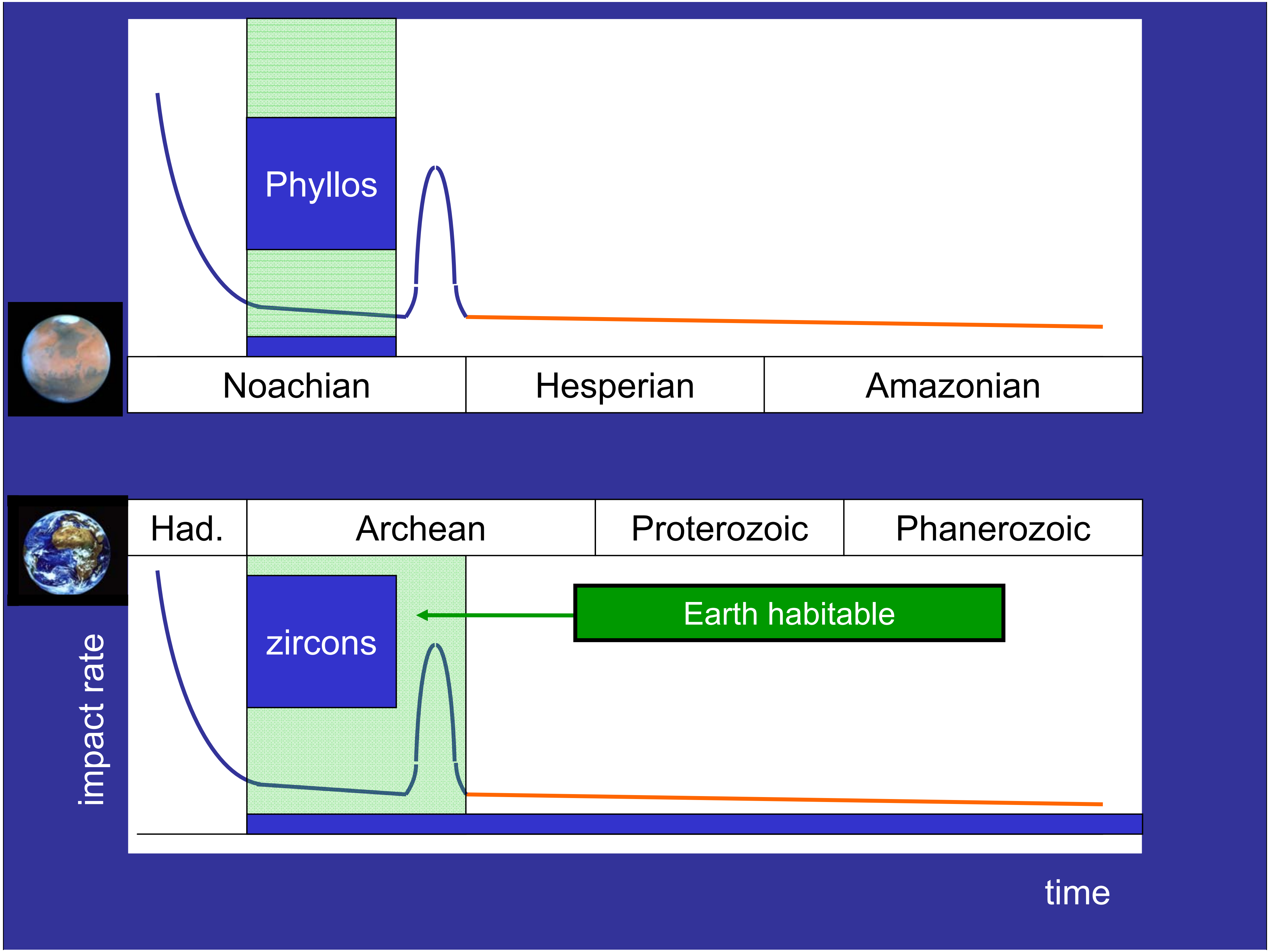


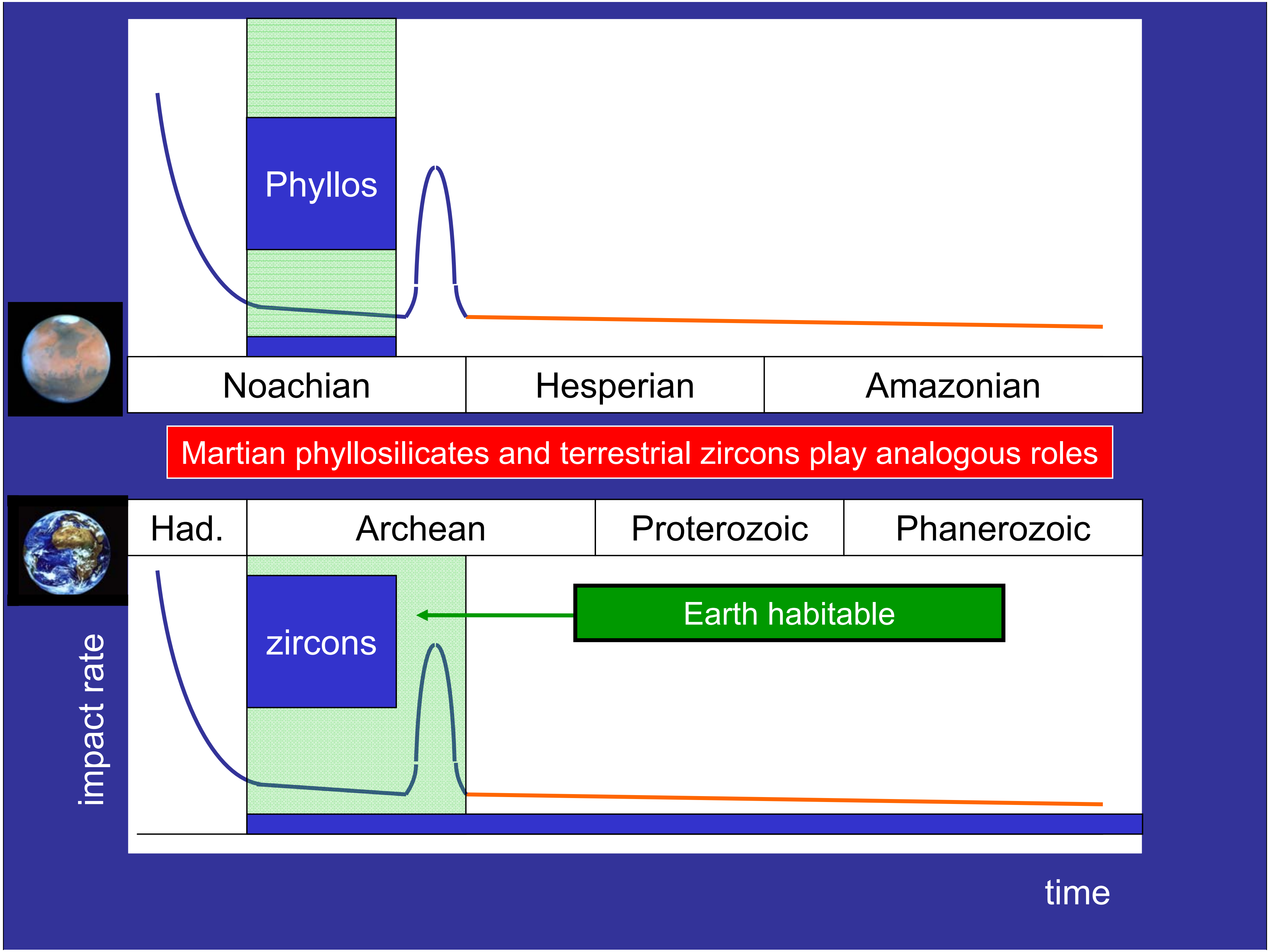
crust solidified (4.3 By $ZrSiO_4$), surface oceans stable (^{18}O)
life could start

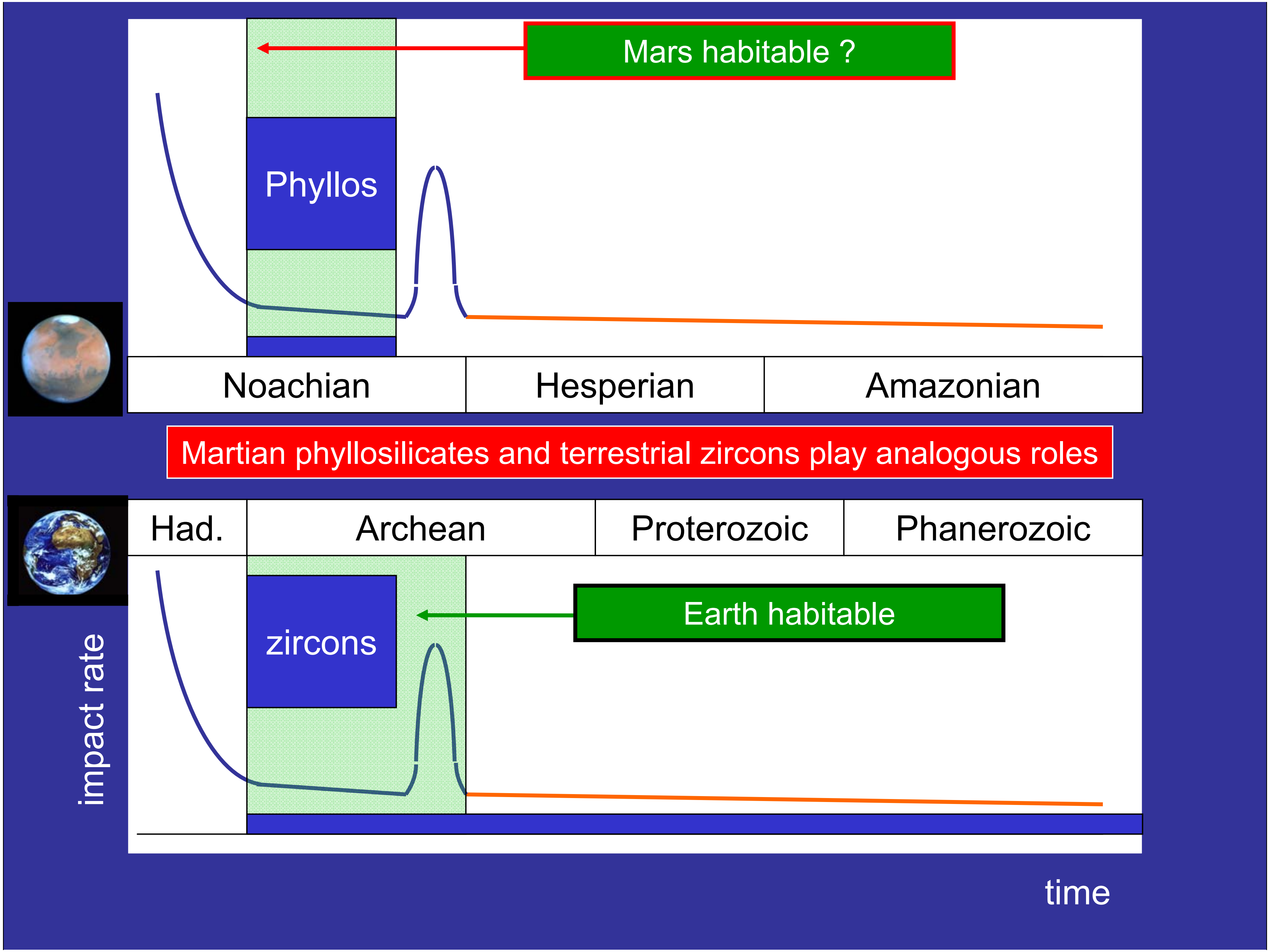


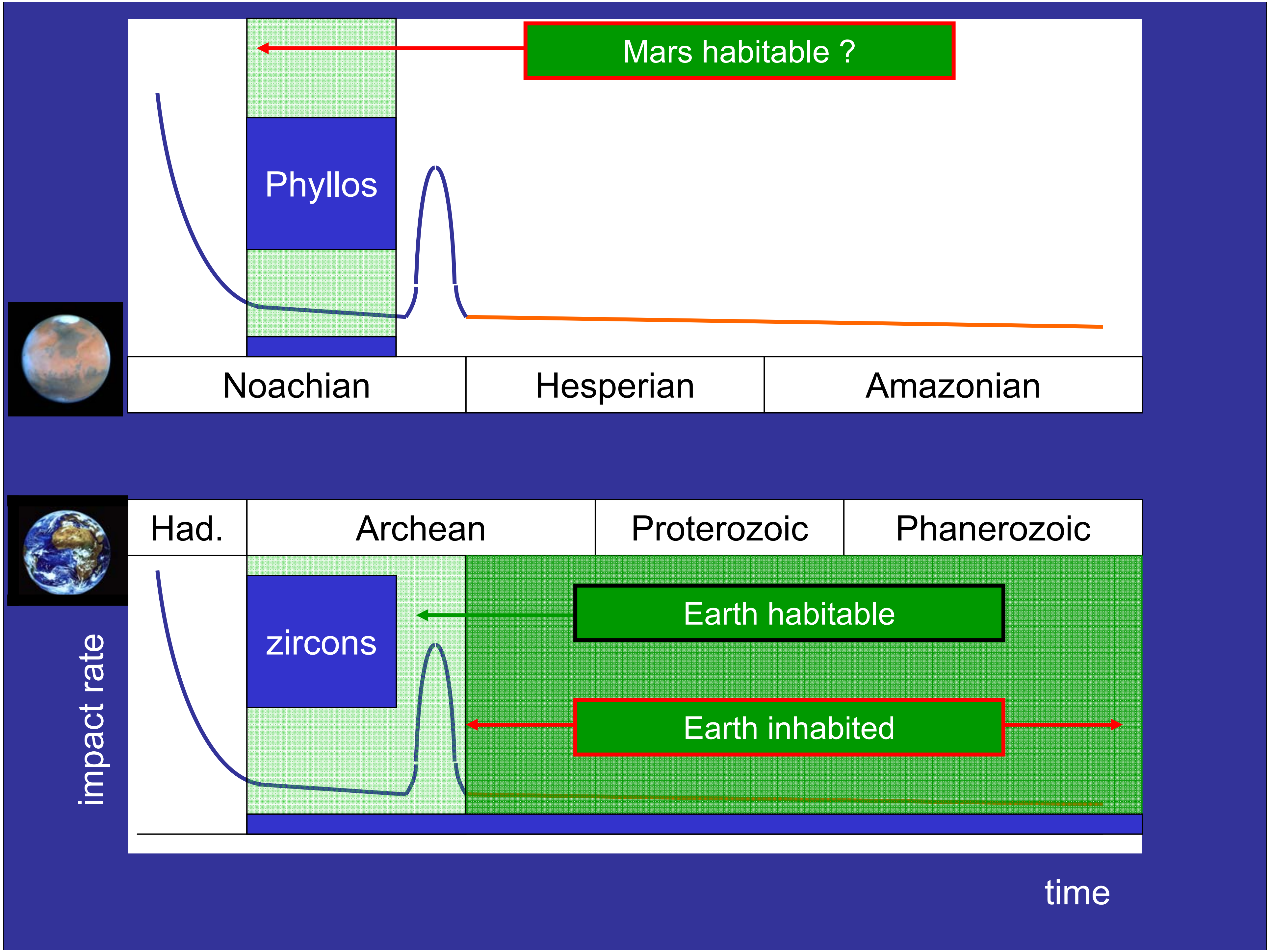

crust solidified (4.3 By $ZrSiO_4$), surface oceans stable (^{18}O)
life could start
Mars may have the answer
Earth habitable
?
Earth inhabited
impact rate
Hadean
Archean
Proterozoic
Phanerozoic


Had.
Archean
Proterozoic
Phanerozoic
Earth habitable
zircons
impact rate
time

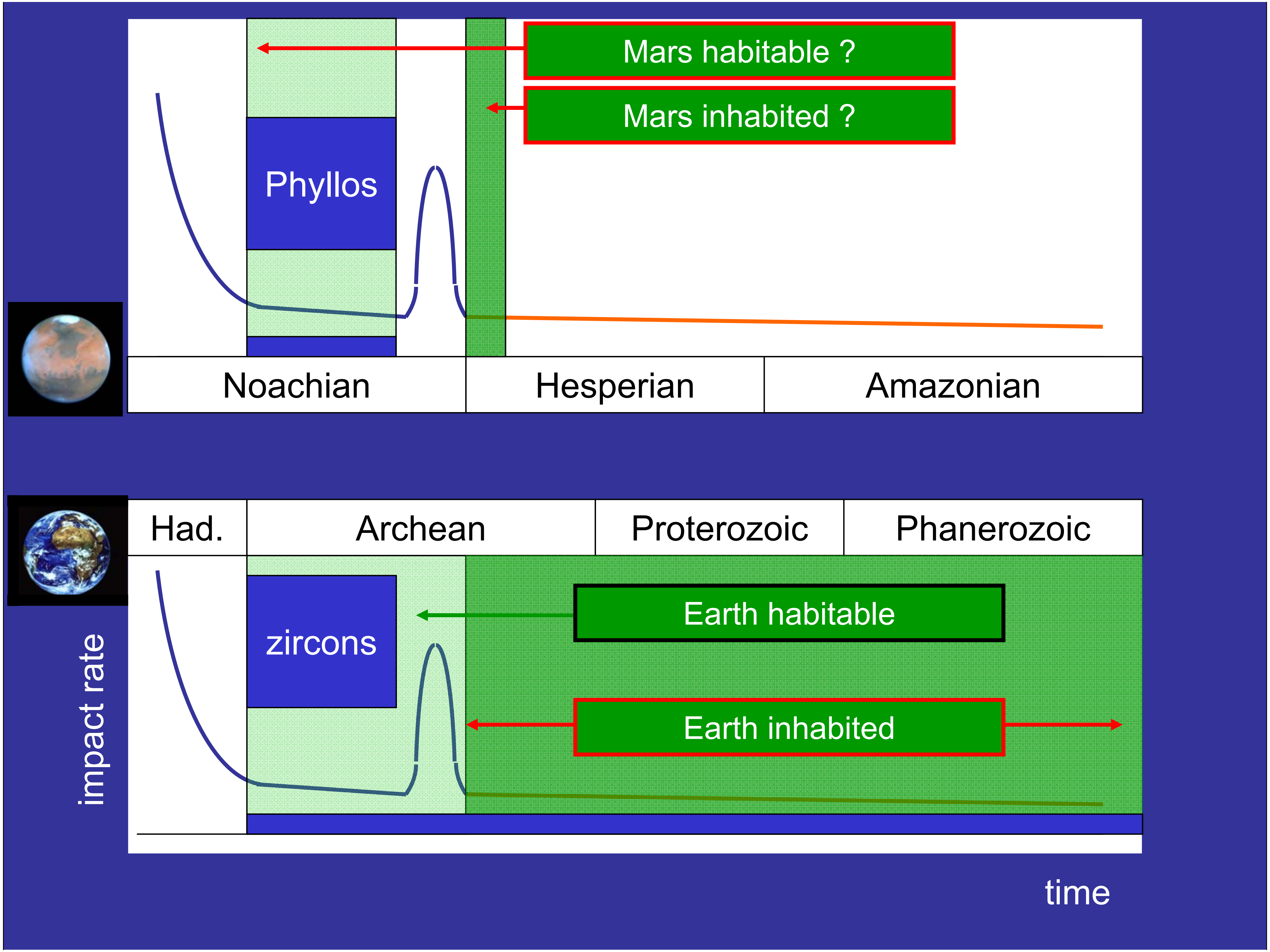

Phyllos
Noachian
Hesperian
Amazonian
Had.
Archean
Proterozoic
Phanerozoic
zircons
Earth habitable
impact rate
time


Phyllos
Noachian
Hesperian
Amazonian
Martian phyllosilicates and terrestrial zircons play analogous roles
Had.
Archean
Proterozoic
Phanerozoic
Earth habitable
zircons
impact rate
time

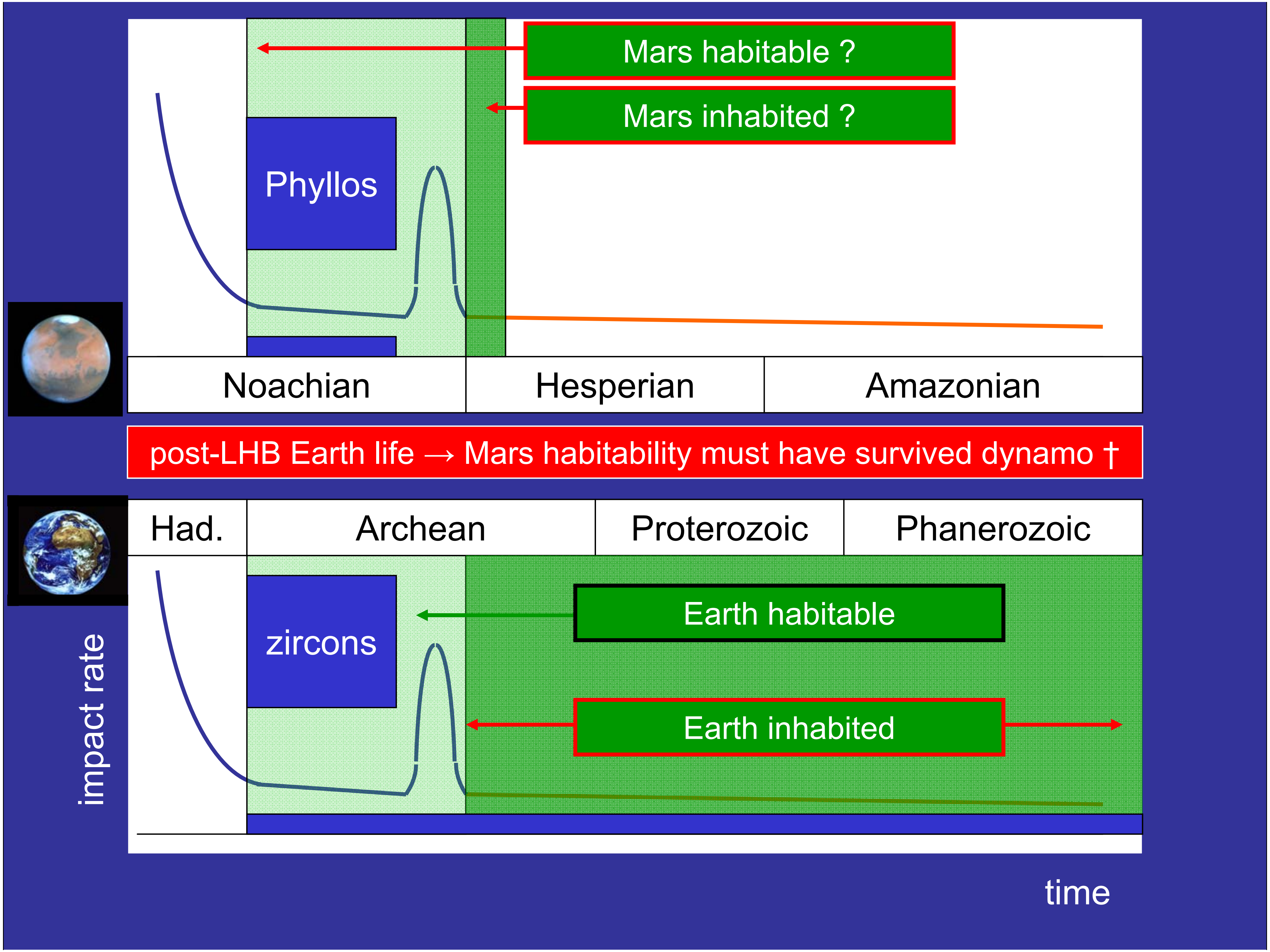

Mars habitable ?
Phyllos
Noachian
Hesperian
Amazonian
Martian phyllosilicates and terrestrial zircons play analogous roles
Had.
Archean
Proterozoic
Phanerozoic
Earth habitable
zircons
impact rate
time



Mars habitable ?
Phyllos
Noachian
Hesperian
Amazonian
Had.
Archean
Proterozoic
Phanerozoic
Earth habitable
zircons
Earth inhabited
impact rate
time

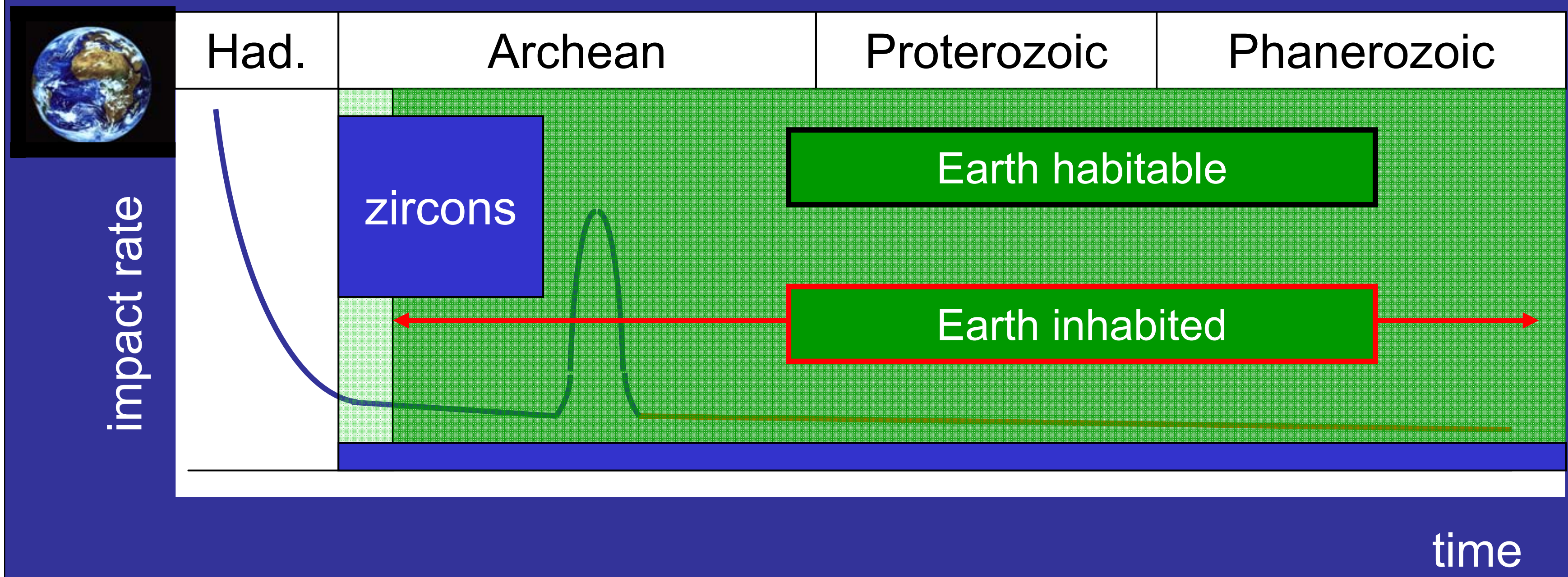


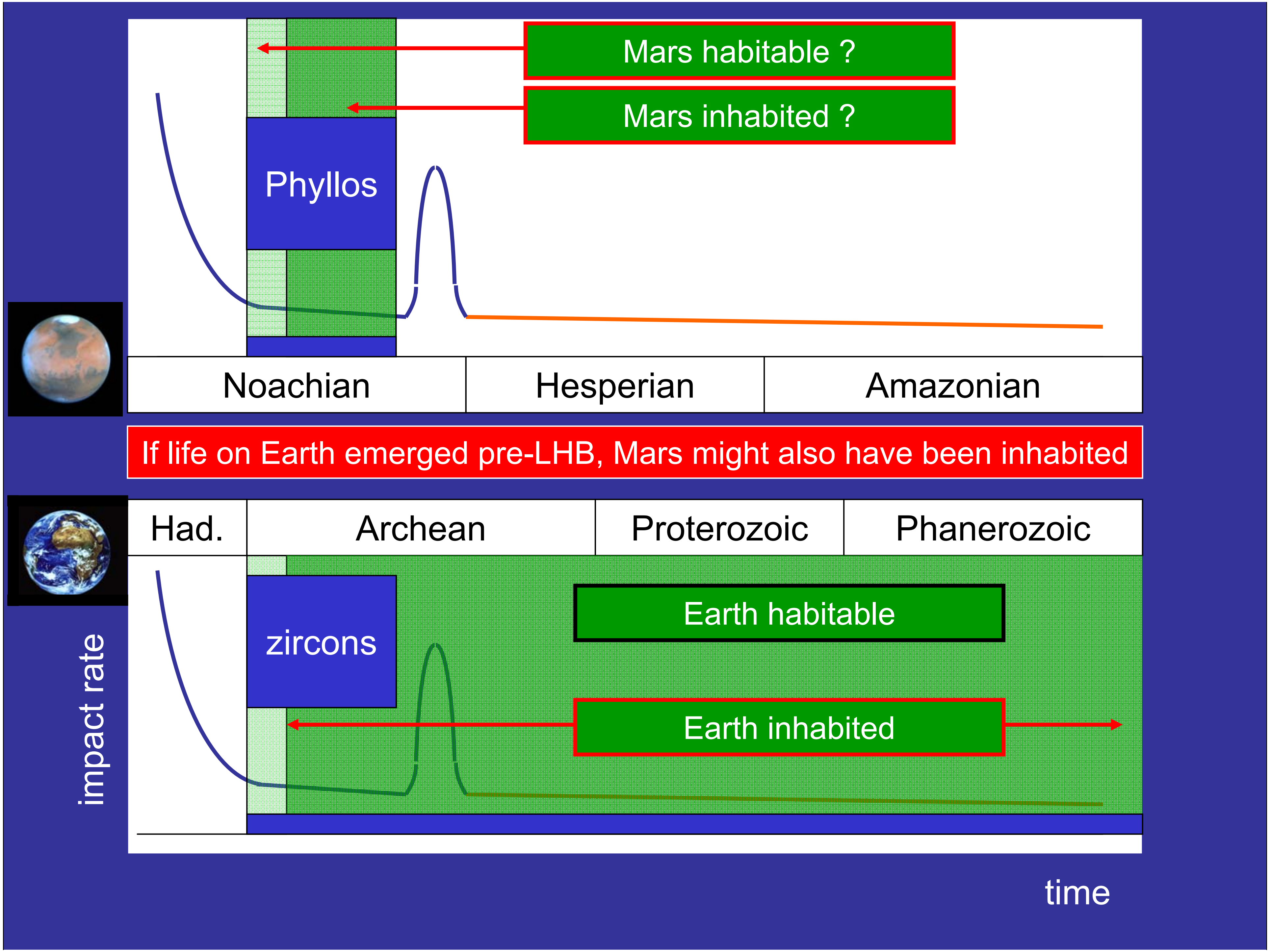
Mars habitable ?
Mars inhabited ?
Phyllos
Noachian
Hesperian
Amazonian
Had.
Archean
Proterozoic
Phanerozoic
zircons
Earth habitable
Earth inhabited
impact rate
time



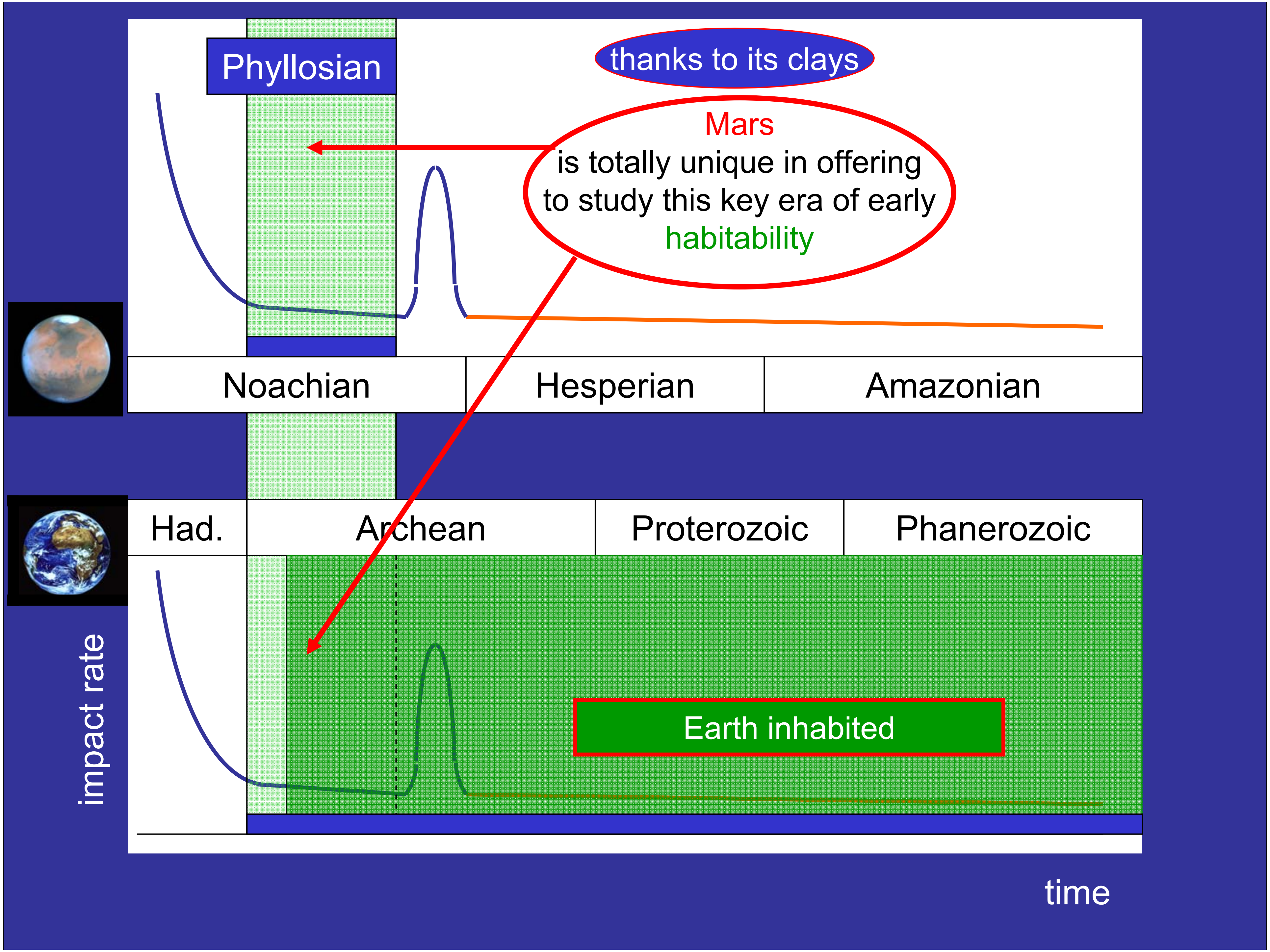
Mars habitable ?
Mars inhabited ?
Phyllos
Noachian
Hesperian
Amazonian
post-LHB Earth life → Mars habitability must have survived dynamo †
Had.
Archean
Proterozoic
Phanerozoic
Earth habitable
zircons
Earth inhabited
impact rate
time

If life on Earth emerged pre-LHB

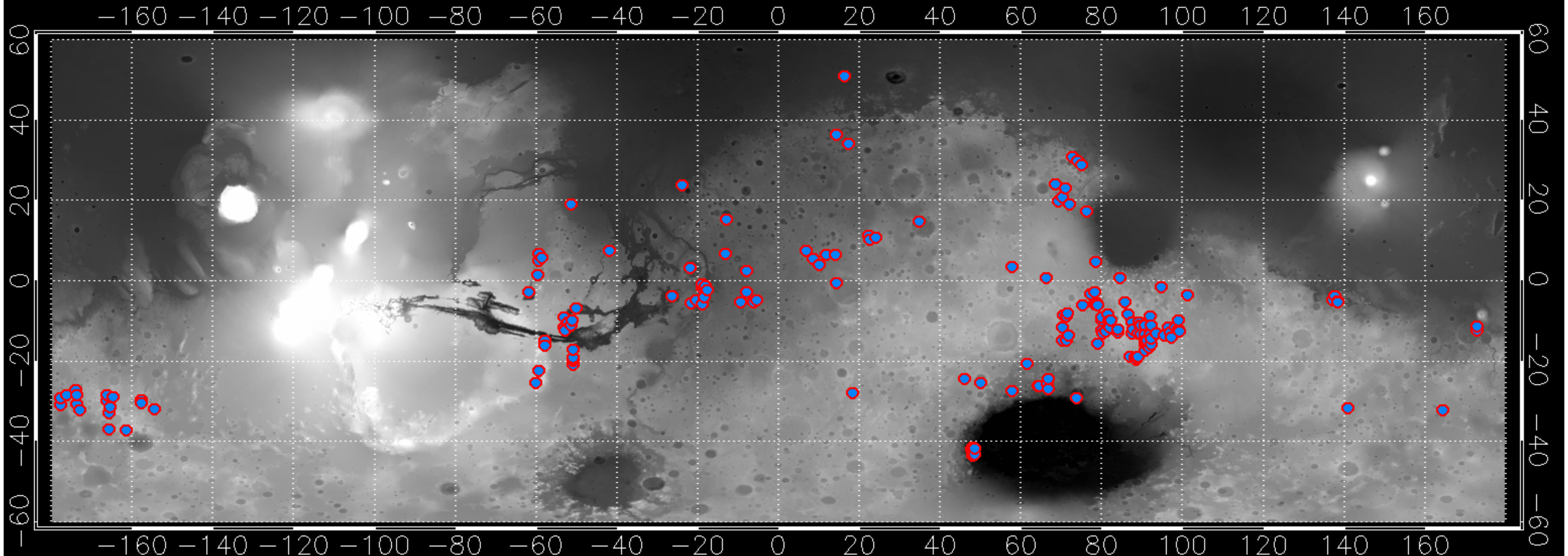




Mars habitable ?
Mars inhabited ?
Phyllos
Noachian
Hesperian
Amazonian
If life on Earth emerged pre-LHB, Mars might also have been inhabited
Had.
Archean
Proterozoic
Phanerozoic
zircons
Earth habitable
Earth inhabited
impact rate
time


Phyllosian
thanks to its clays
Mars
is totally unique in offering
to study this key era of early
habitability
Noachian
Hesperian
Amazonian
Had.
Archean
Proterozoic
Phanerozoic
Earth inhabited
impact rate
time

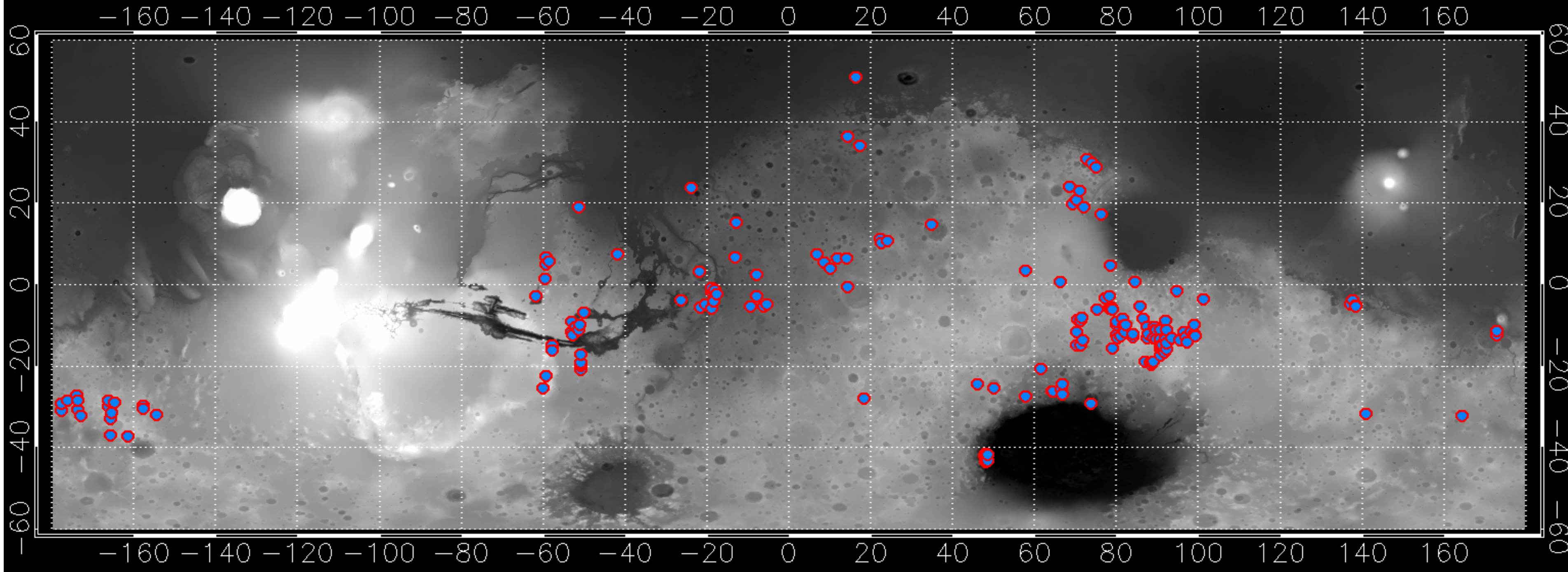
OMEGA map of hydrated minerals



The future in situ missions should:

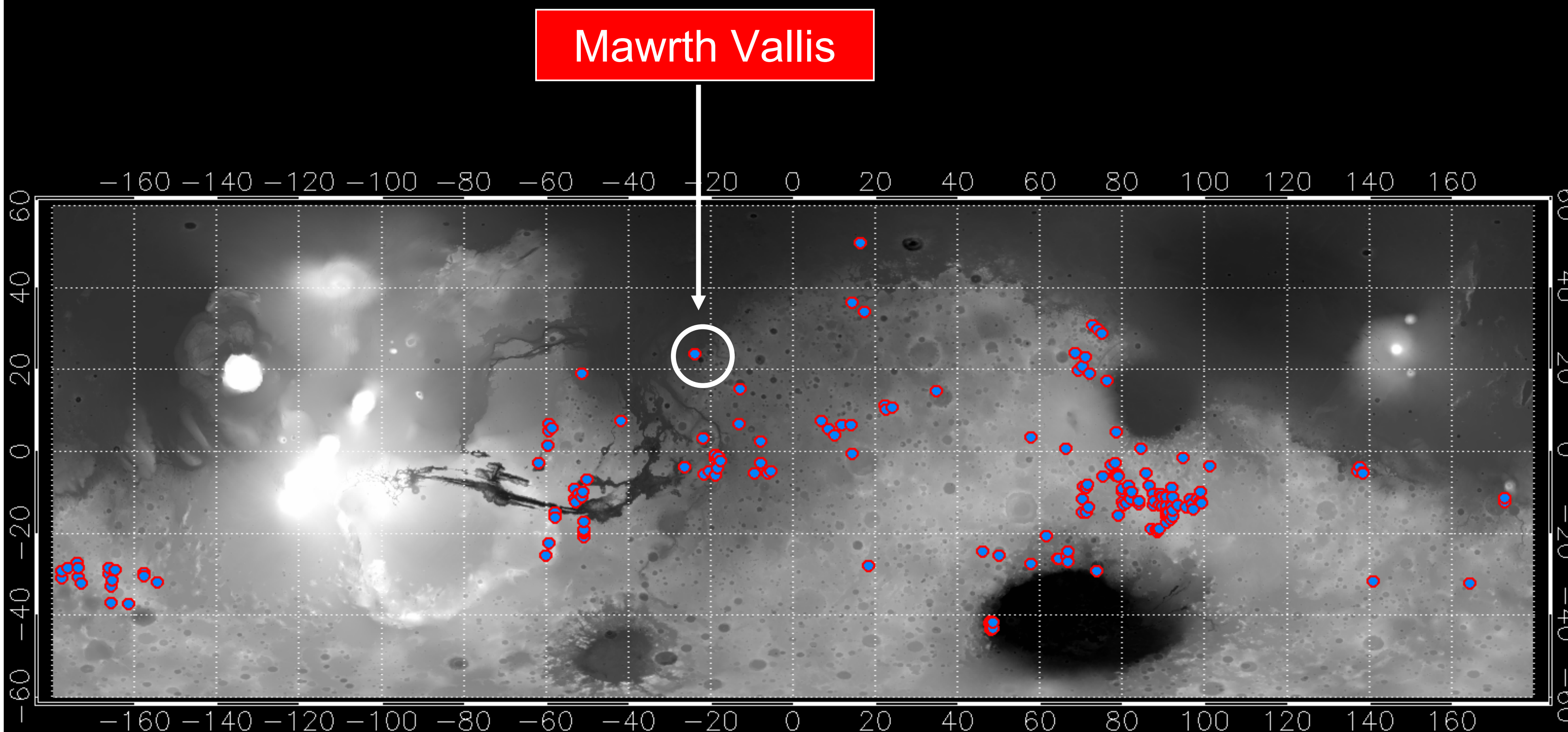
GO Phyllosian !

OMEGA map of hydrated minerals



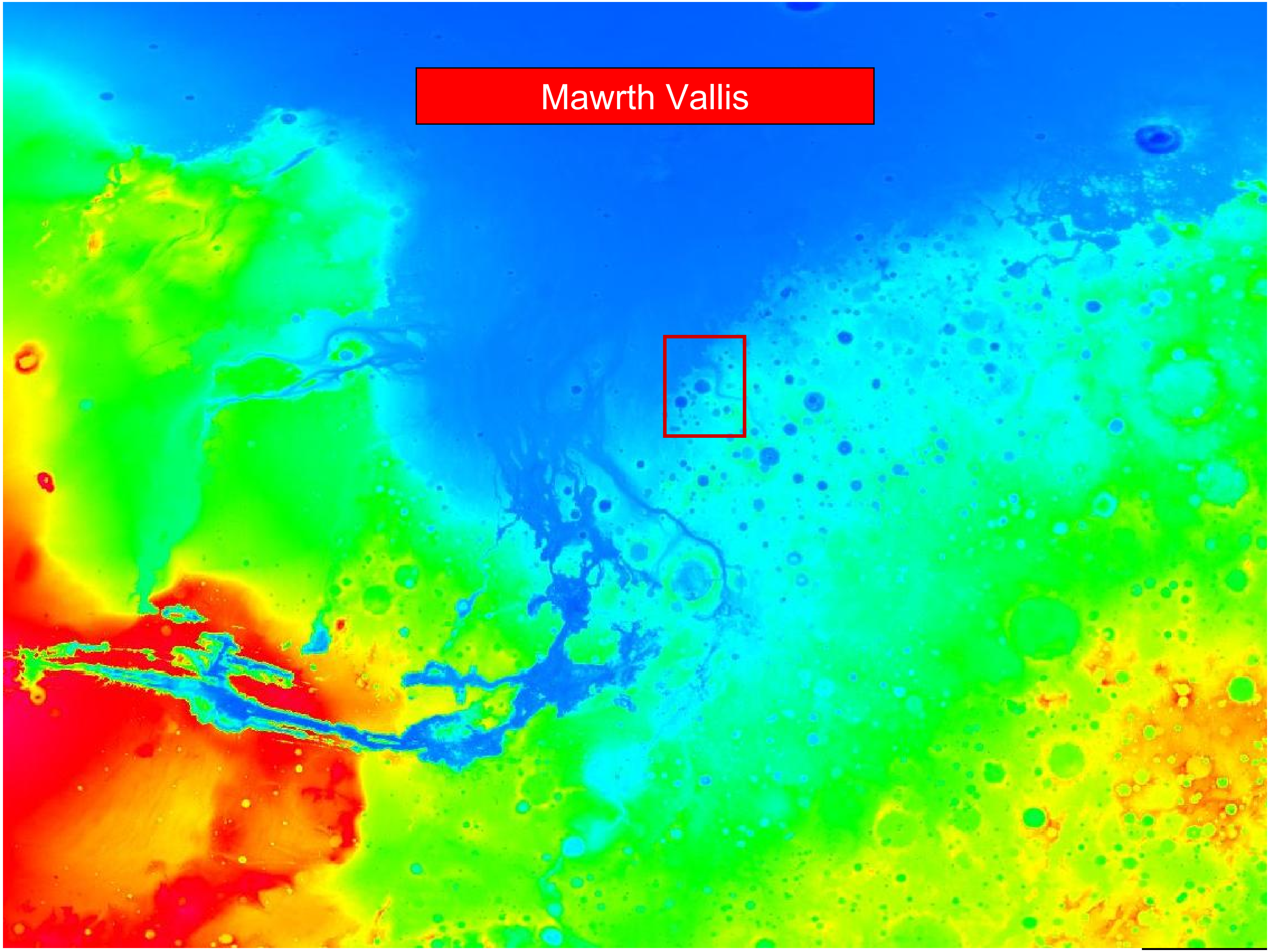
The future in situ missions should GO Phyllosian !

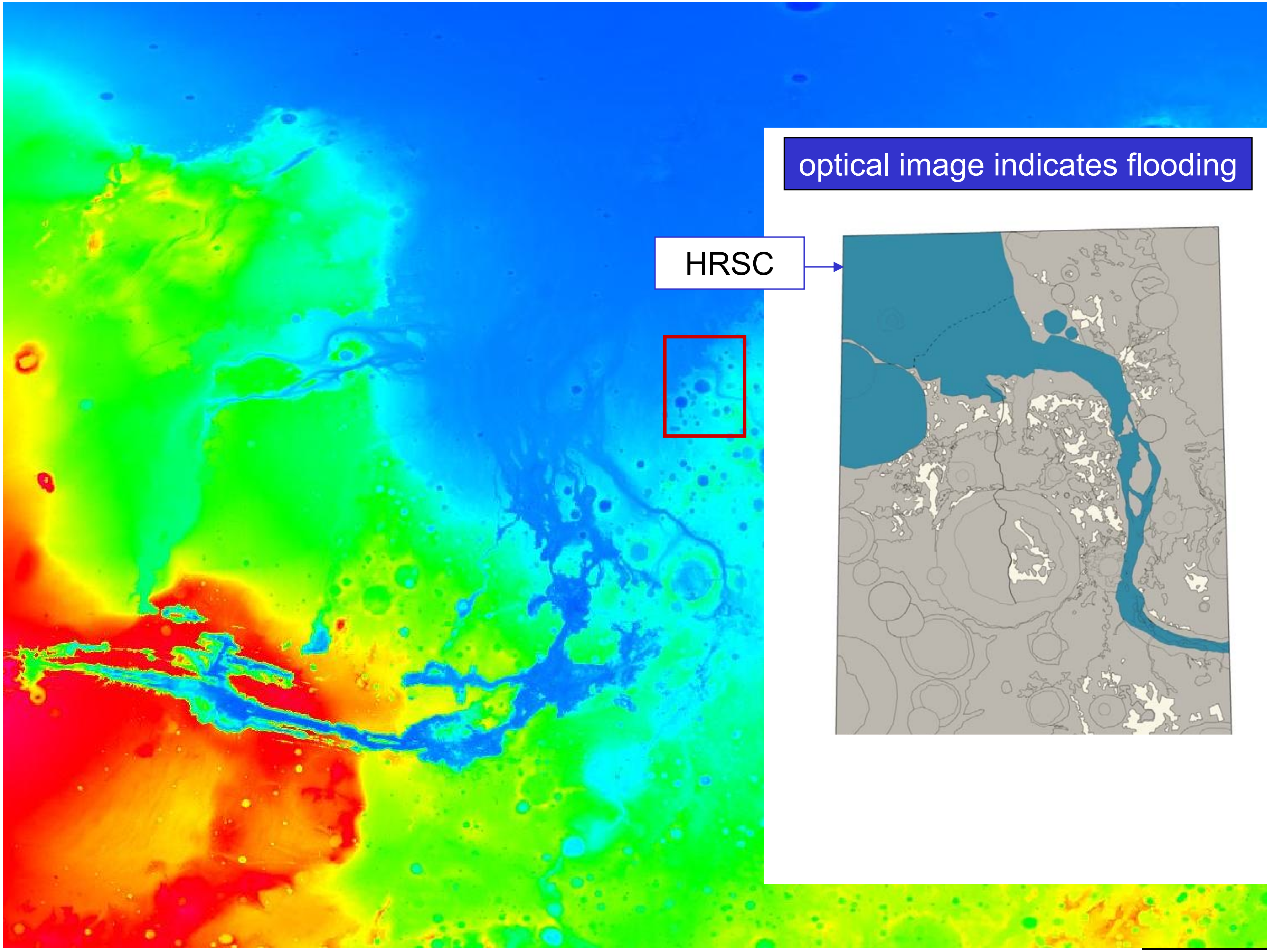
The widest & most favorable area phyllosilicate-rich is Mawrth Vallis.

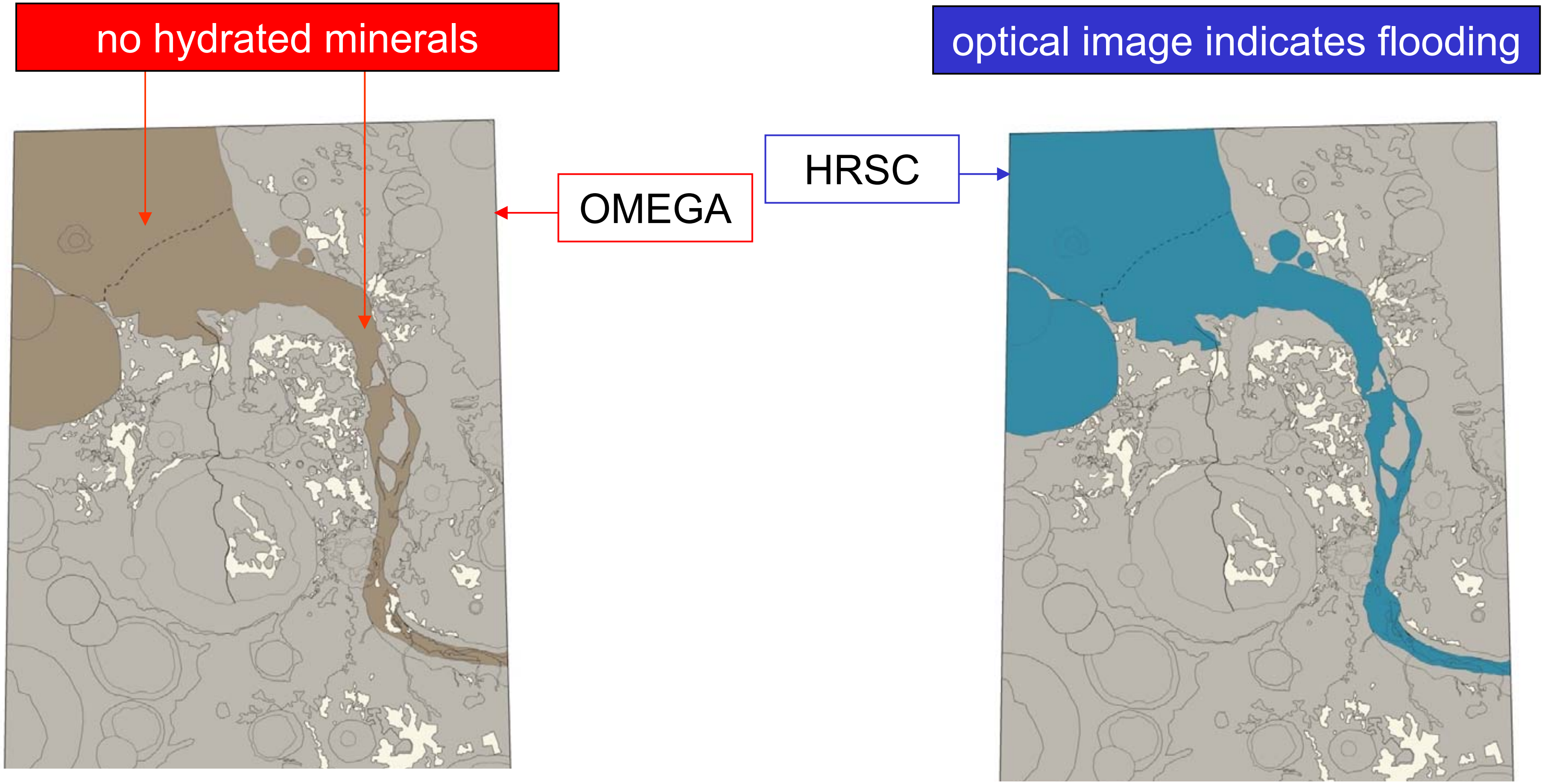


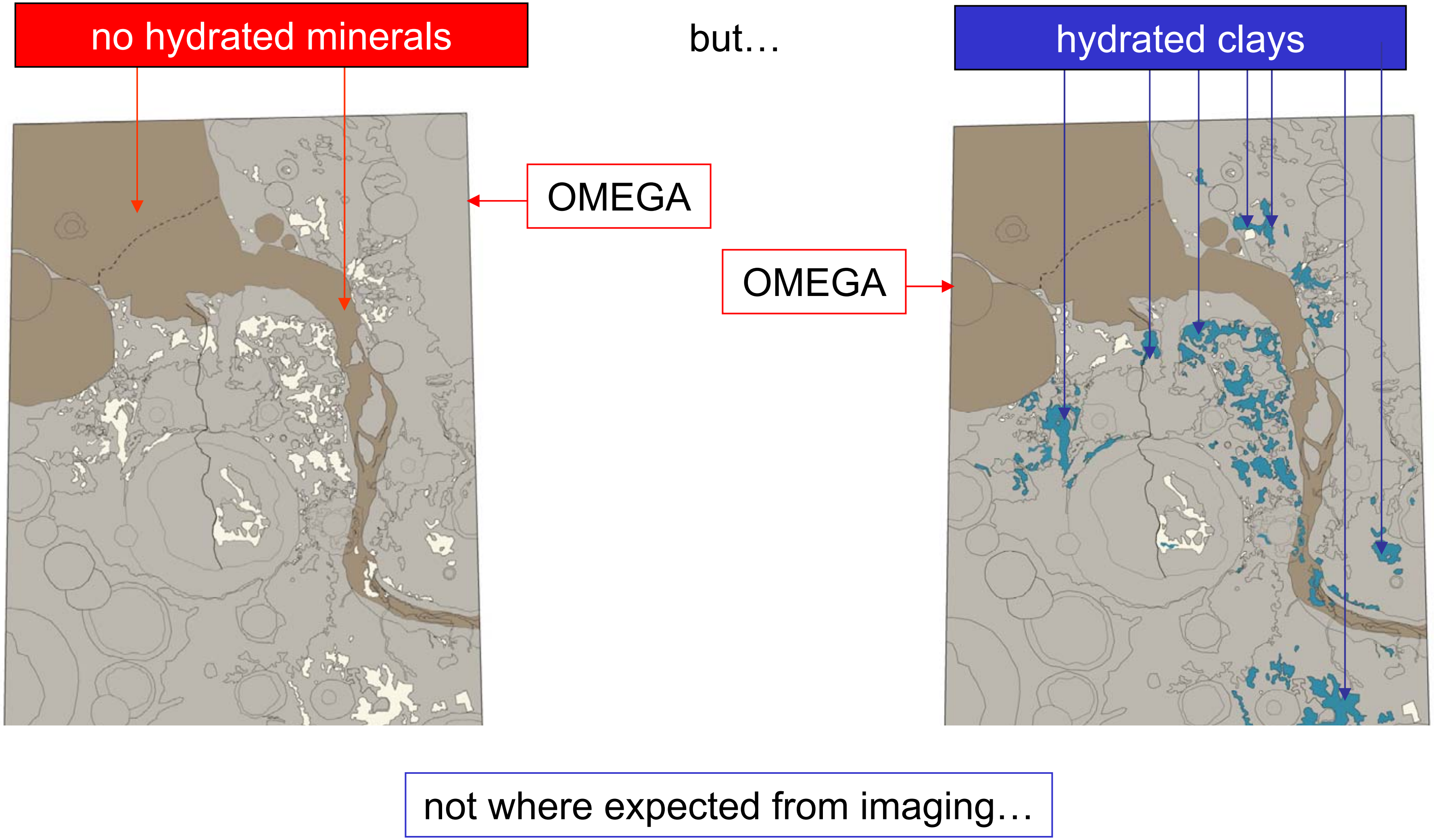
The future in situ missions should GO Phyllosian !

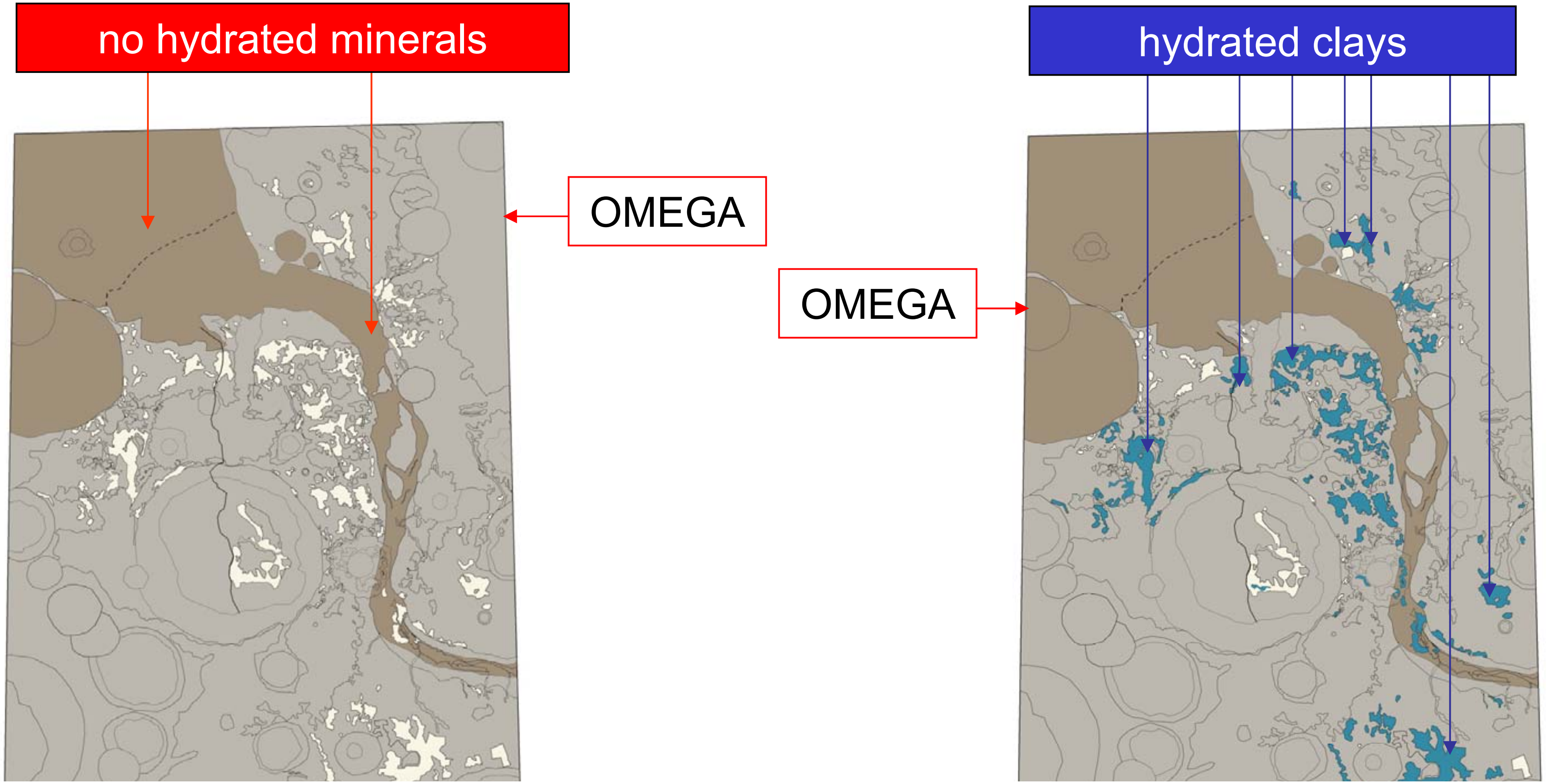
The widest & most favorable area phyllosilicate-rich is Mawrth Vallis.


Mawrth Vallis

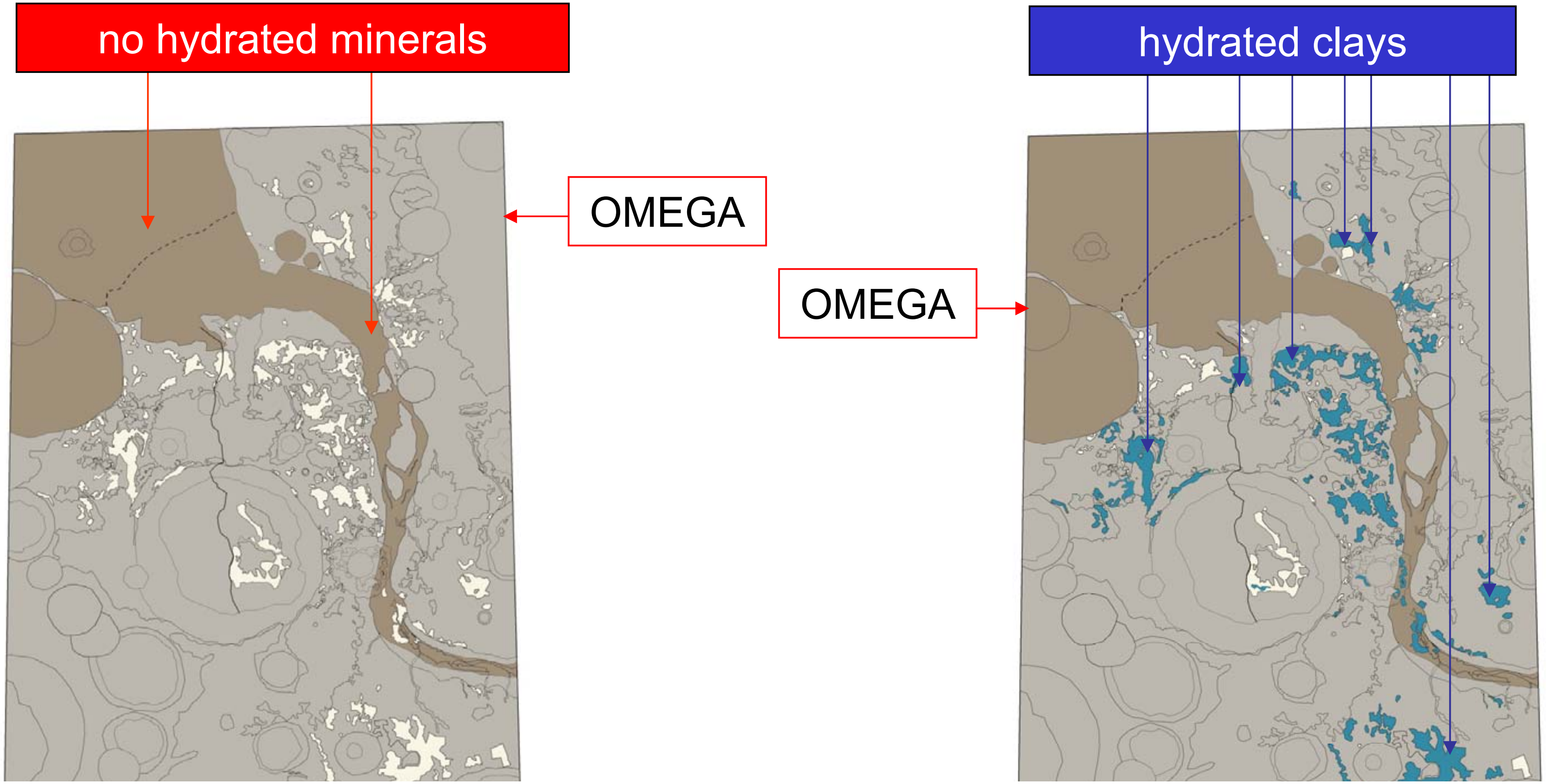

optical image indicates flooding
HRSC


no hydrated minerals
OMEGA
HRSC
optical image indicates flooding


no hydrated minerals
but…
hydrated clays
OMEGA
OMEGA
not where expected from imaging…

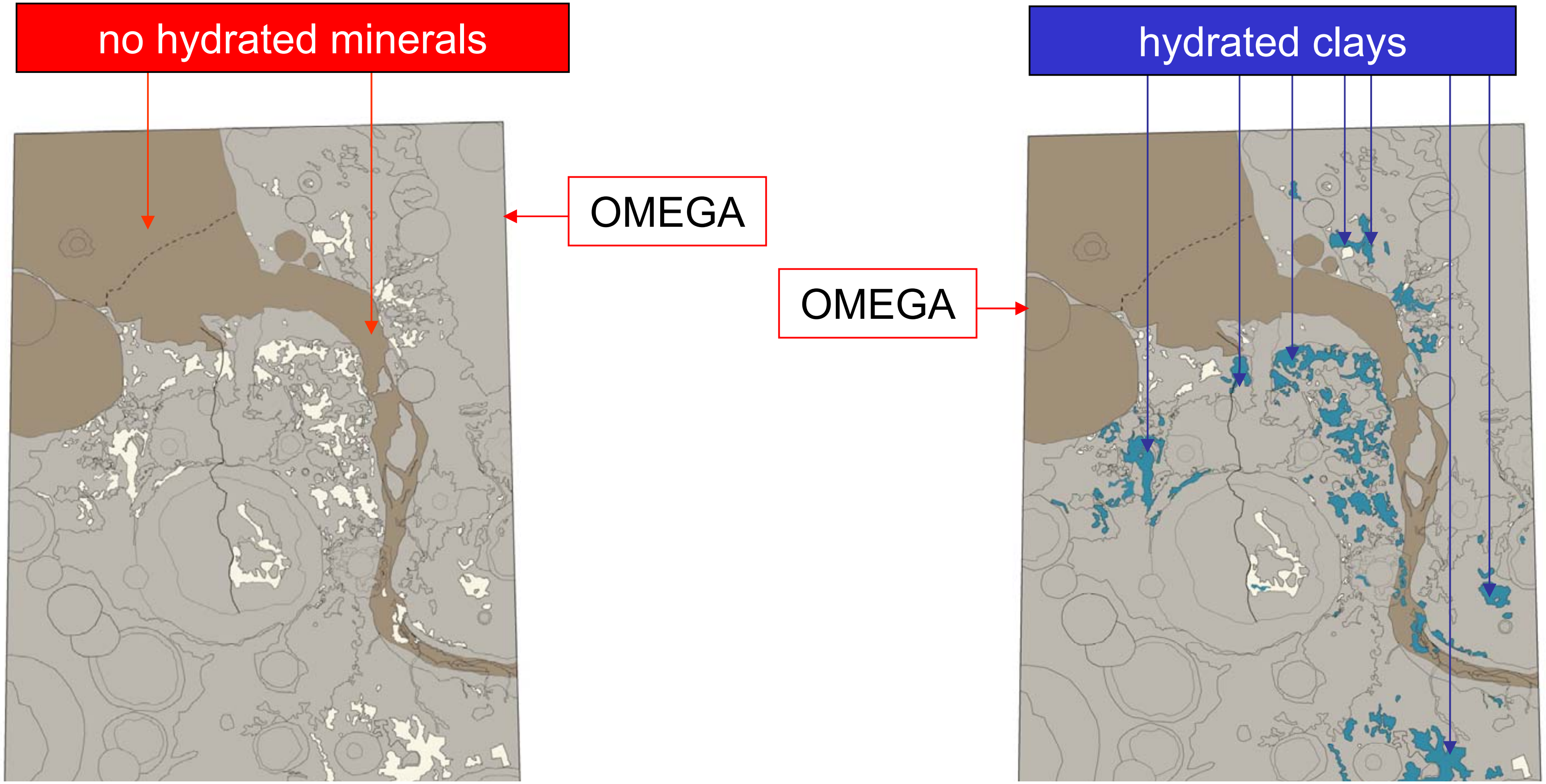


Violent but transient processes modeled channels without hydrating the rocks.
The erosion exposed ancient terrains containing clays, which traces episodes
during which liquid water might have been stable.



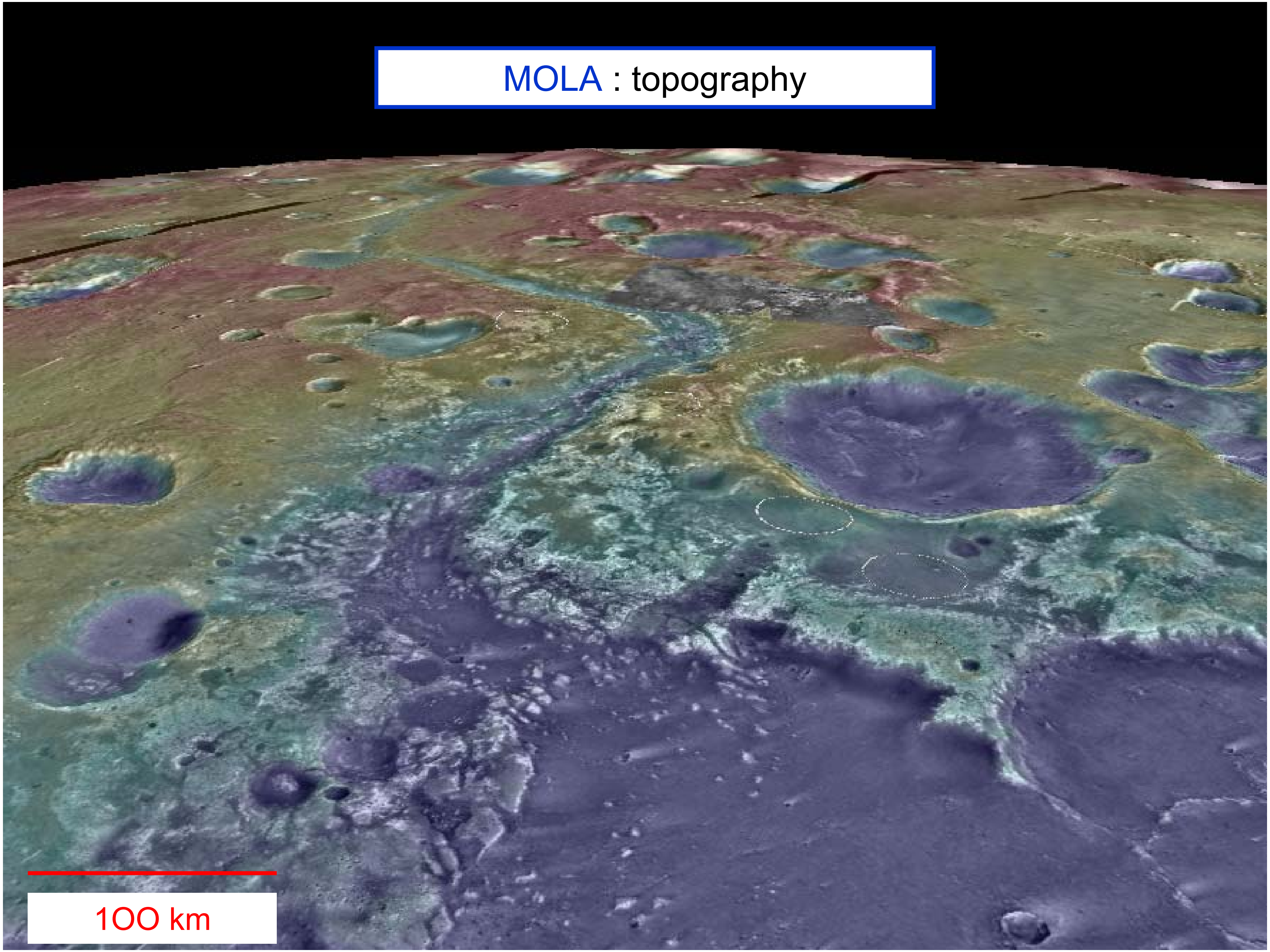
Violent but transient processes modeled channels without hydrating the rocks. The erosion exposed ancient terrains containing clays, which traces episodes during which liquid water might have been stable.

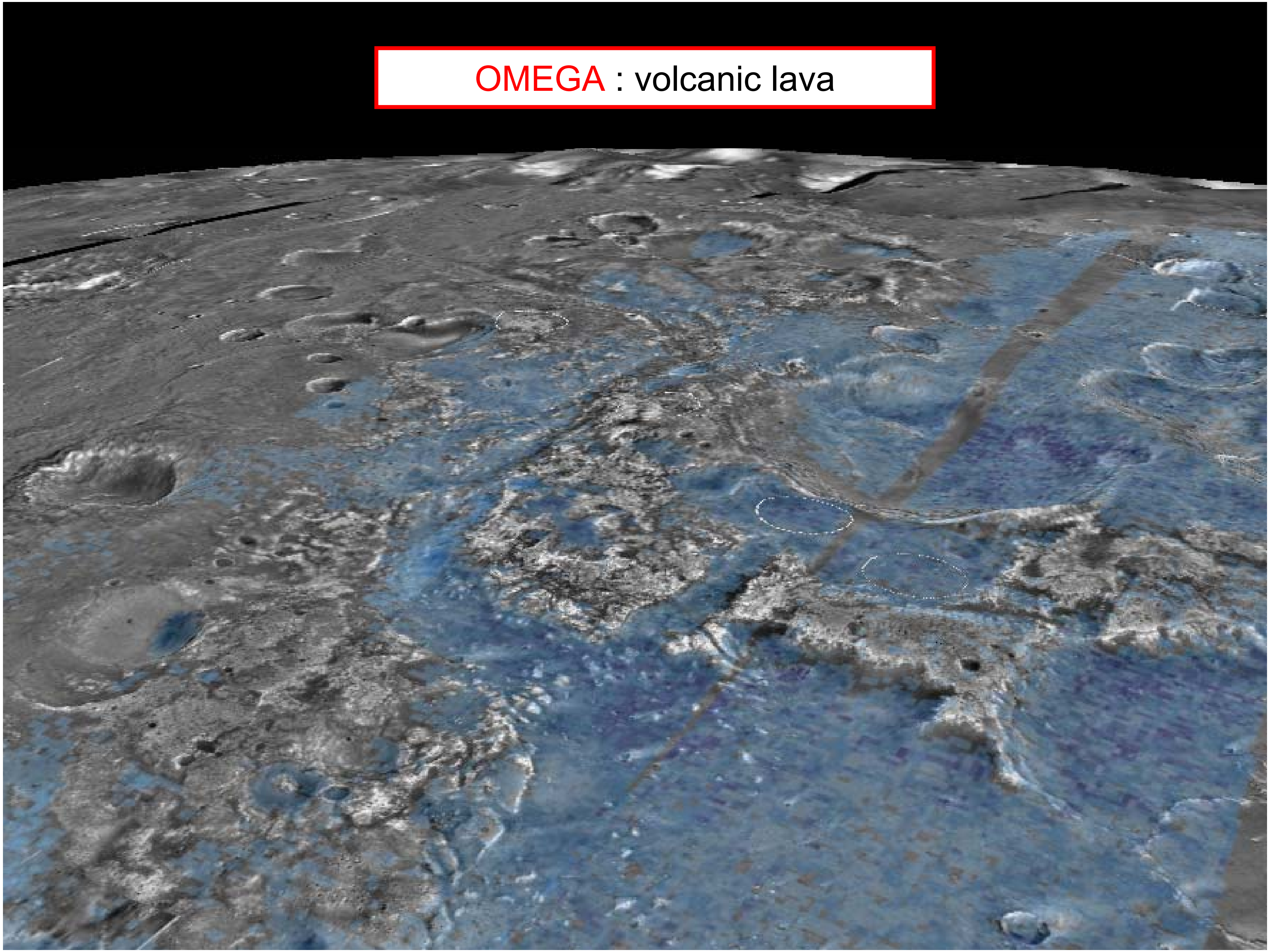
Most phyllosilicate formation predate the outflows

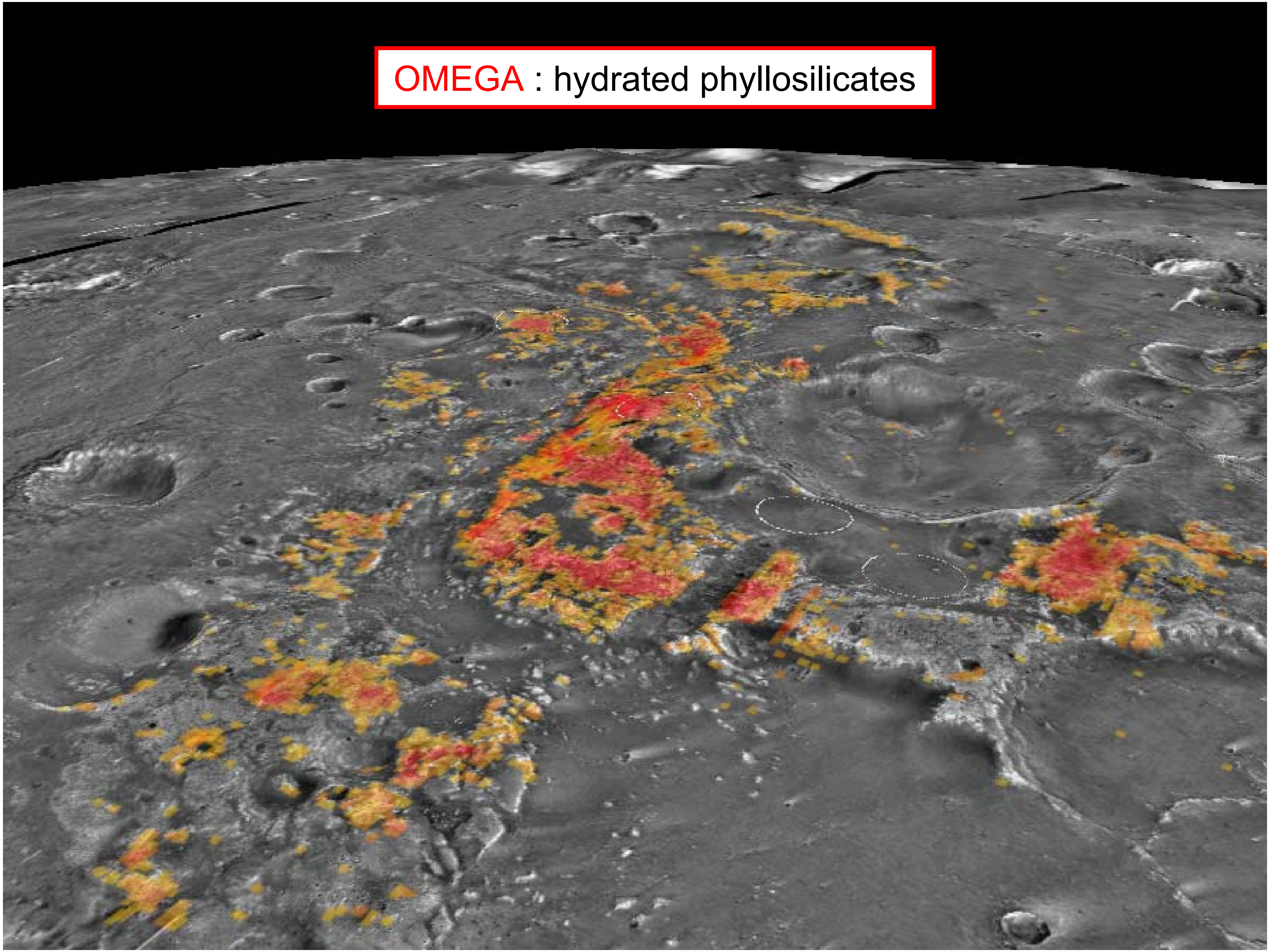


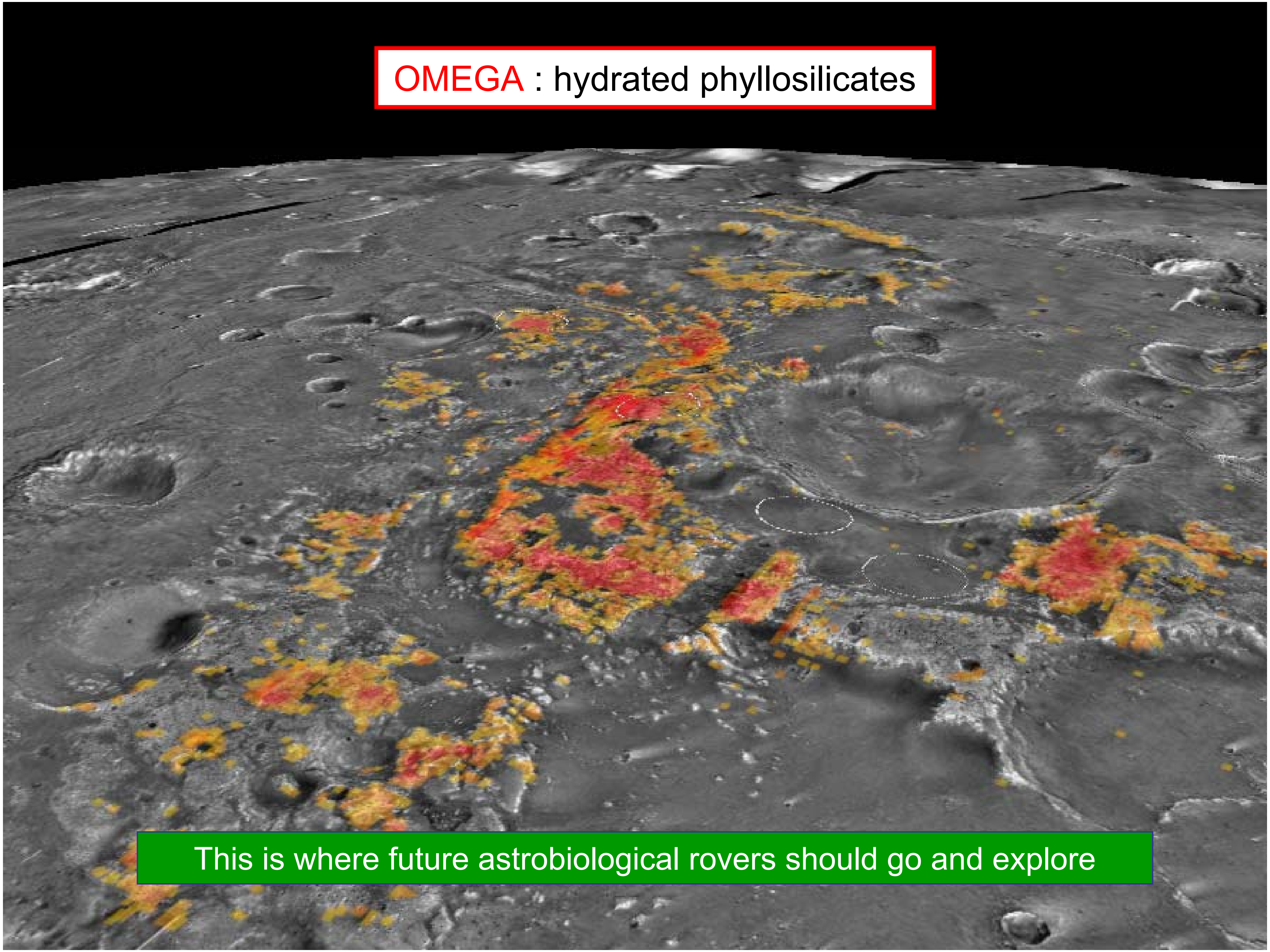
Most phyllosilicate formation took place before the end of the heavy bombardment, and remains recorded within the ancient cratered crust, in isolated spots.

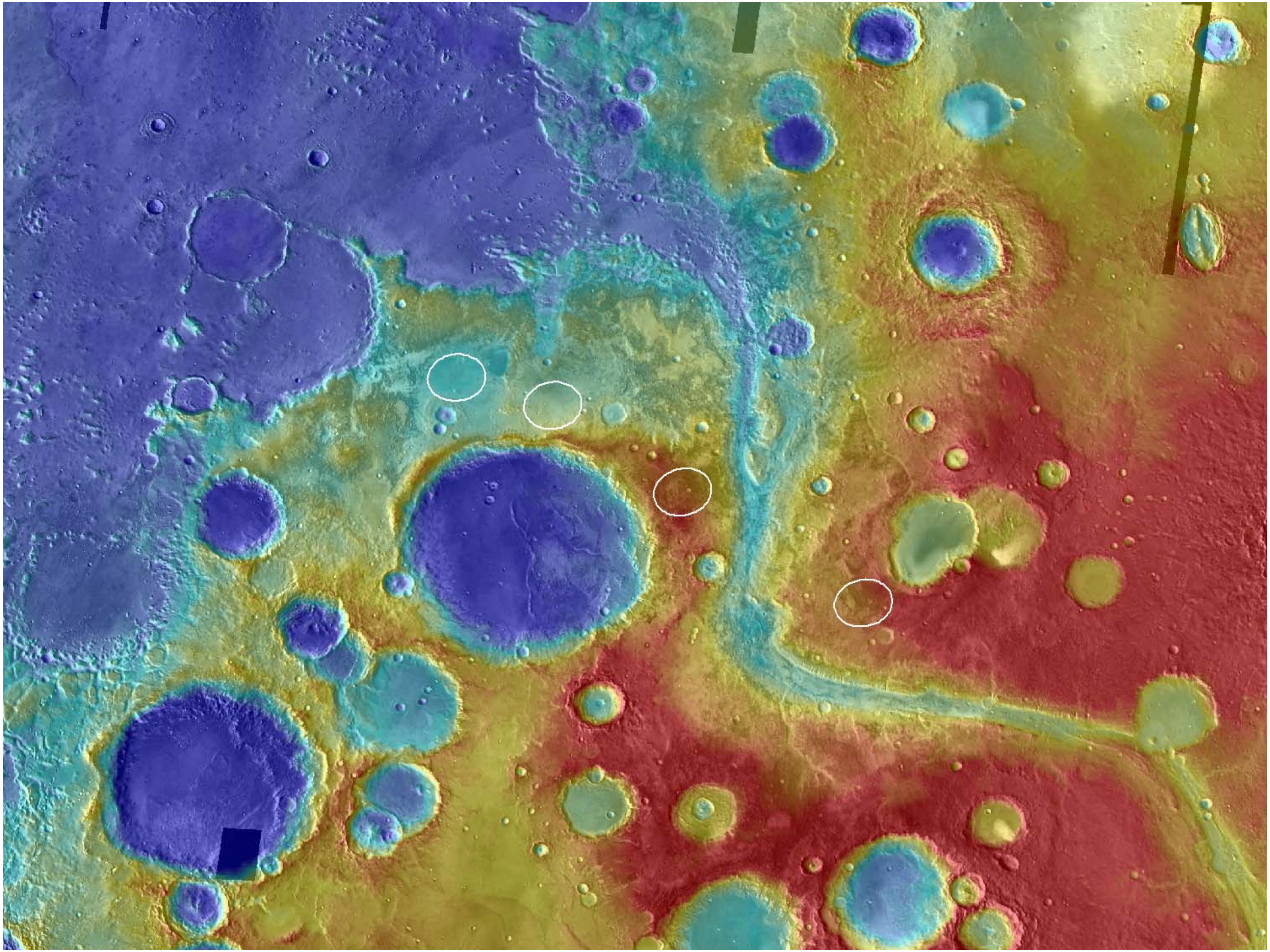
Most phyllosilicate formation predate the outflows

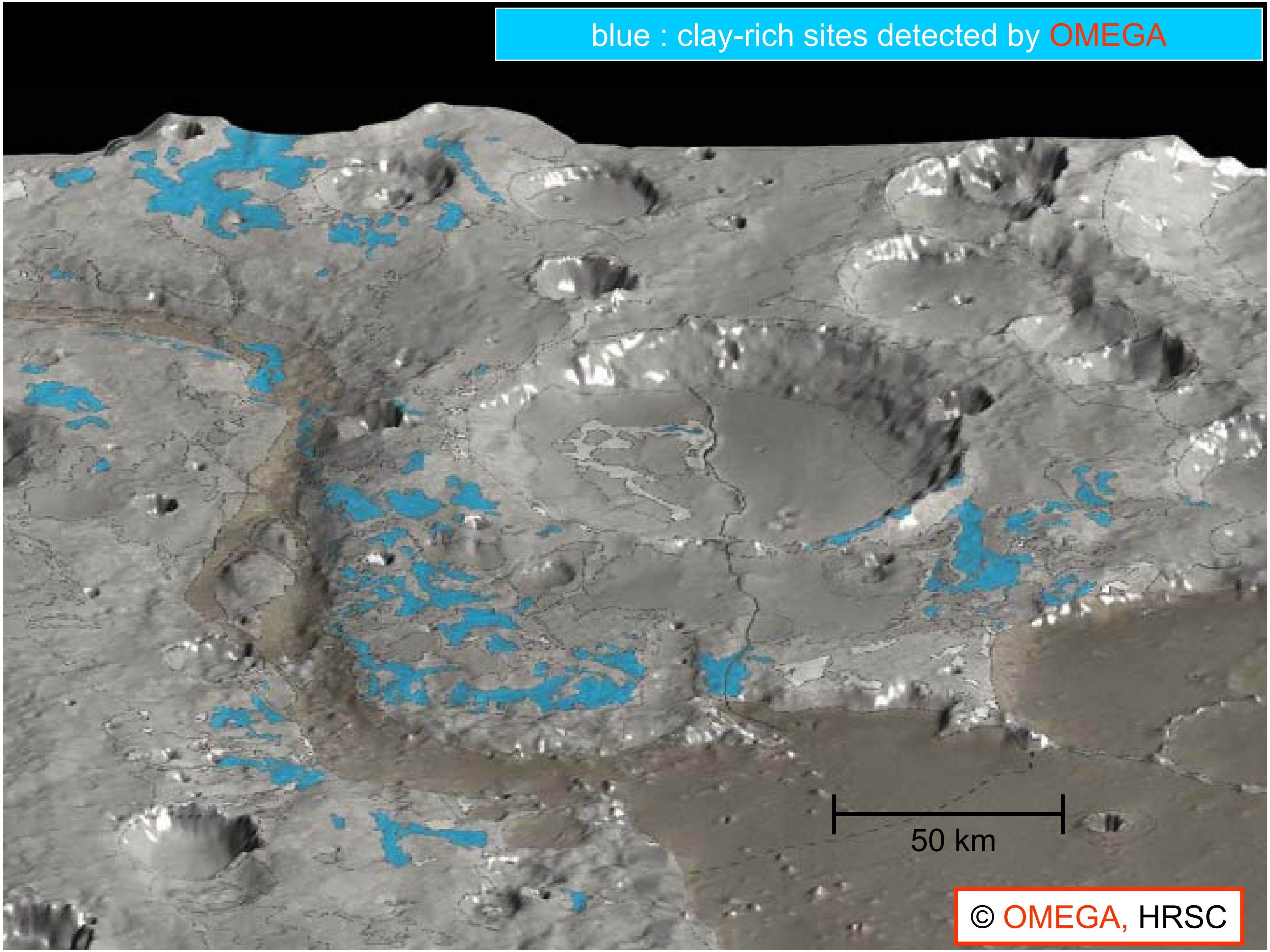

MOLA : topography
100 km


OMEGA : volcanic lava

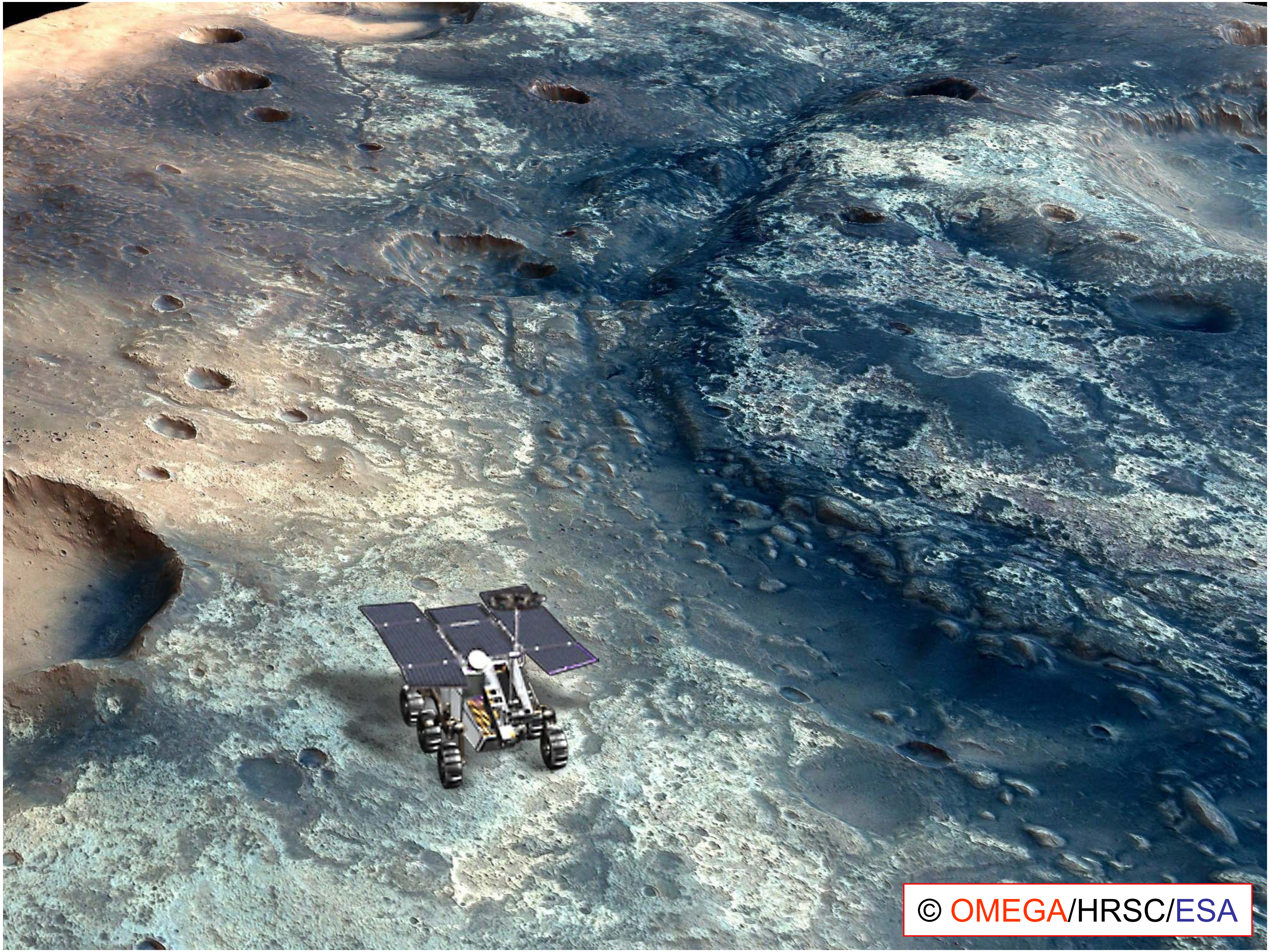

OMEGA : hydrated phyllosilicates


OMEGA : hydrated phyllosilicates
This is where future astrobiological rovers should go and explore

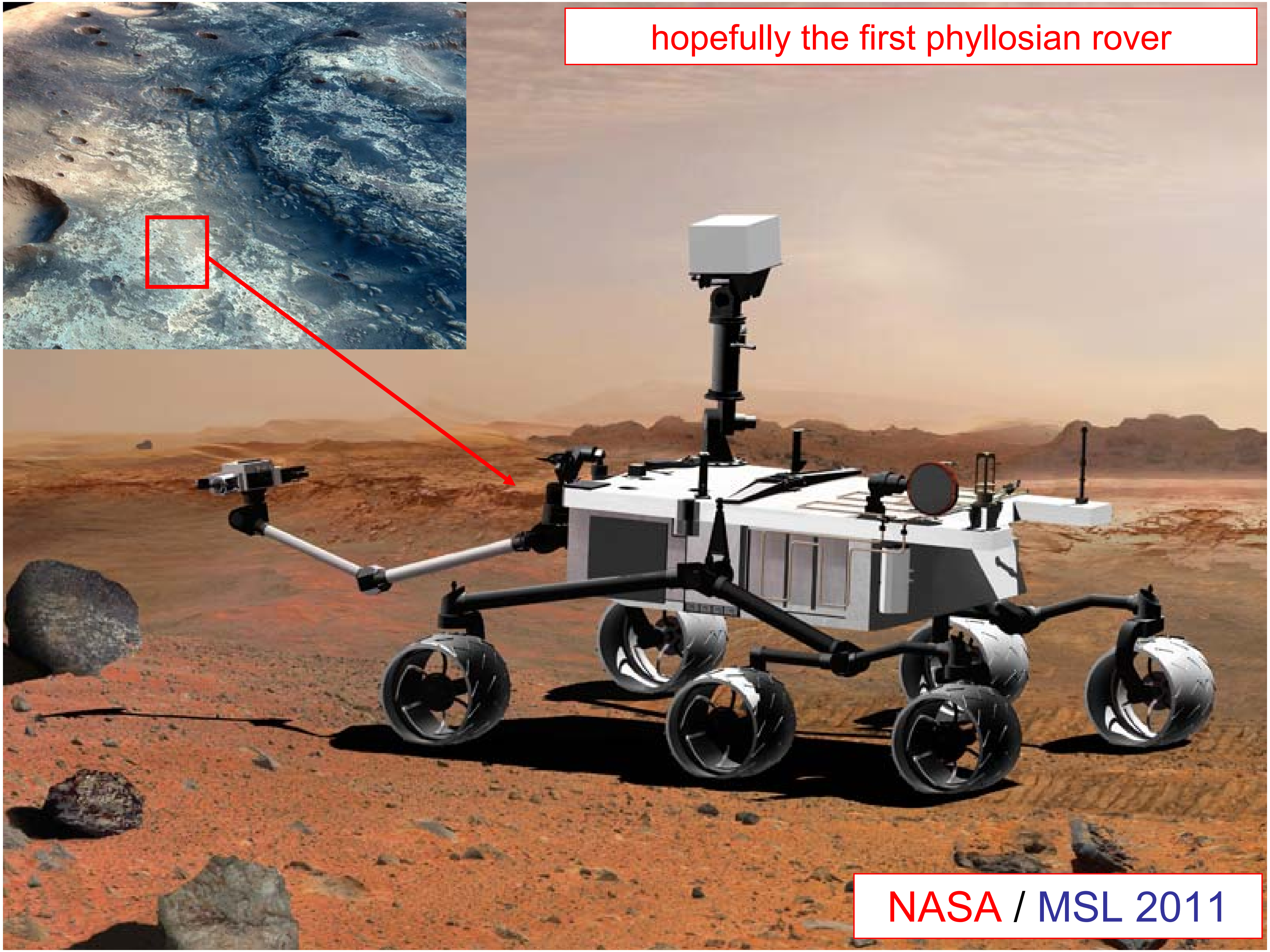




blue : clay-rich sites detected by OMEGA
50 km
© OMEGA, HRSC


© OMEGA/HRSC/ESA


NASA / MSL 2011


hopefully the first phyllosian rover
NASA / MSL 2011

then ExoMars, the second phyllosian rover

ESA / ExoMars 2018

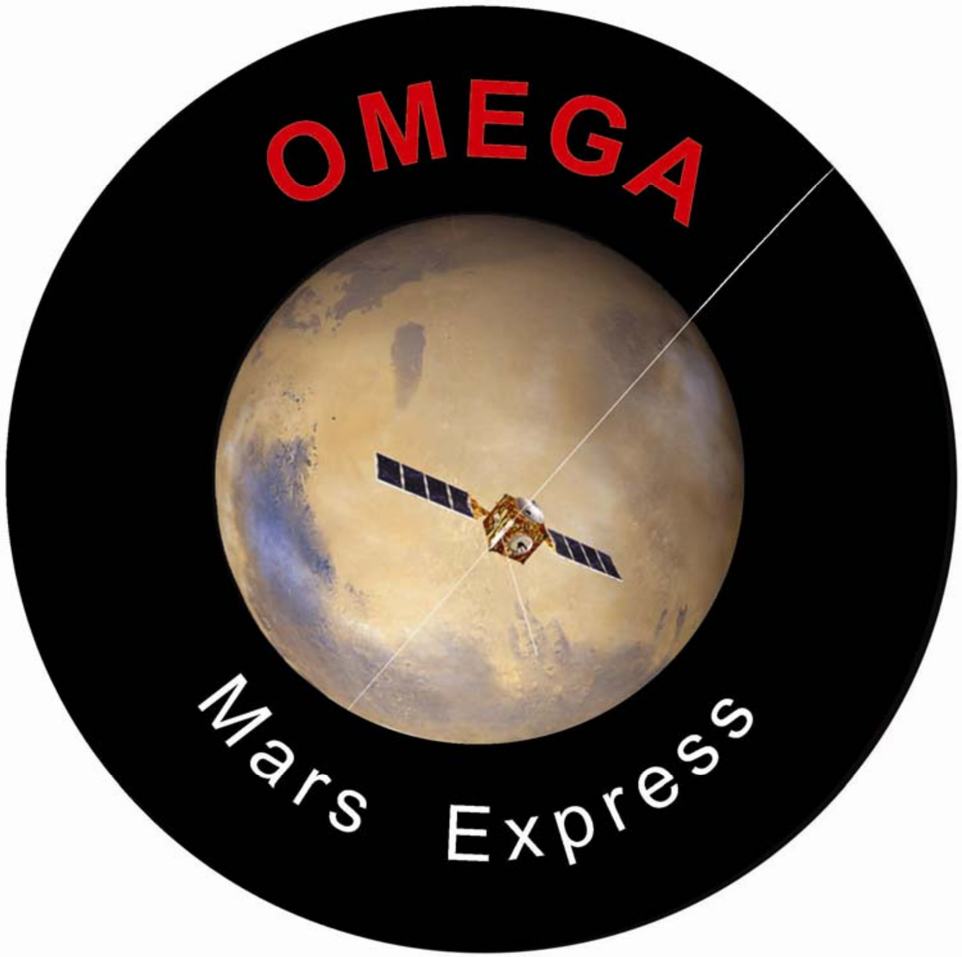
ESA / ExoMars 2018

Mineralogy and History of Mars

● It is remarkable that, 30 years after the pioneering Viking missions, an era of potential Martian habitability has been discovered, in its time and space.

● Mars uniquely offers to study the conditions that prevailed in the inner Solar system within the primordial bombardment, at a time life likely emerged on Earth.

● Exobiology is entering its scientific era, with the potential to help deciphering the conditions that enabled the birth of biology.



Les Houches, 29 / 03 / 2010