Mineralogy and History of Mars

Les Houches, 29 / 03 / 2010
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Jean-Pierre Bibring
IAS
Institut d’Astrophysique Spatiale
Orsay, France

on behalf of the entire OMEGA team

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

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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...).
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<tr>
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</table>

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 and glacial activity...
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. Mars exhibits a variety of units, recording a sequence of processes, both long-standing/sustained and transient, preserved all along its History.
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
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.
<table>
<thead>
<tr>
<th>Time Period</th>
<th>Event Description</th>
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<tbody>
<tr>
<td>Noachian</td>
<td>Volcanic transient activity</td>
</tr>
<tr>
<td>Hesperian</td>
<td></td>
</tr>
<tr>
<td>Amazonian</td>
<td>Tharsis &amp; mare filling</td>
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<td></td>
<td>heavy bombardment</td>
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</table>

*Volcanic transient activity*
Is Mars dead or 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?**
is Mars still active?

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

H₂O ice

OMEGA: H₂O ice map

(Y. Langevin et al.)
Perennial northern polar cap

H₂O ice

OMEGA: H₂O ice map

OMEGA: which mineral?
Perennial northern polar cap

H₂O ice

large gypsum-rich dunes
latest S-rich hot spot vent?
MSL should answer, through accurate fractionation measurements $^{15}\text{N}/^{14}\text{N}$, $^{13}\text{C}/^{12}\text{C}$

Potentially responsible for major ($\text{CO}_2$), minor ($\text{N}_2$), trace (e.g. $\text{CH}_4$) atmospheric supply?

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

2013 & 2016 missions should search for $\text{S}$-rich compounds (in addition to $\text{CH}_4$ and other C-rich traces)
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.
Do these fluvial features imply that liquid water was stable?
Did they feed long standing bodies of water?
Do they record a sustained process?
audacious extrapolation
oceans would have been stable after Tharsis and the volcanoes were put in place, and Valles Marineris formed
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.
RGB-type image
hypespectral image-cube

100’s of λ’s

in all wavelength range
hyperspectral image-cube
hyperspectral image-cube
H₂O ice
gypsum
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

Les Houches, 29 / 03 / 2010
| Noachian | Hesperian | Amazonian |

Can one superimpose on a Mars History derived from surface structures a Mars History derived from surface mineralogy?
Has Mars evolution been frozen in distinct mineralogical units?
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:
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<tr>
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</tr>
<tr>
<td>heavy bombardment</td>
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</tbody>
</table>
Heavy bombardment

| Noachian | Hesperian | Amazonian |

Impact rate over time

Asteroidal bombardment used for crater dating
Heavy bombardment

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Asteroidal bombardment used for crater dating

Impact rate

- EHB
- LHB
<table>
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![Graph showing impact rate over time.](image)

- **EHB** (Early Heavy Bombardment)
- **LHB** (Late Heavy Bombardment)
Earth Moon impact formed
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.

<table>
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<tr>
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<tr>
<td>Had.</td>
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<tr>
<td>Archean</td>
<td></td>
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<tr>
<td>Proterozoic</td>
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Earth Moon formed
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**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?
The ancient crust has preserved its pristine magmatic composition. It has not been globally altered.
The ancient crust has preserved its pristine magmatic composition. It has not been globally altered.
Nili Fossae

Nili Patera
carte MOLA
- 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
If either or both OH and H₂O 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.
In hundreds of spots within the ancient crust, hydrated minerals have been identified, most requiring kilometer to sub-kilometer resolution.
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.
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

<table>
<thead>
<tr>
<th>Noachian</th>
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<th>Amazonian</th>
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impact rate

phylllos

time
<table>
<thead>
<tr>
<th>Era</th>
<th>Impact Rate</th>
</tr>
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<tbody>
<tr>
<td>Noachian</td>
<td>heavy bombardment</td>
</tr>
<tr>
<td>Hesperian</td>
<td>zircons</td>
</tr>
<tr>
<td>Amazonian</td>
<td>phyllos</td>
</tr>
</tbody>
</table>

Diagram:
- Heavy bombardment events (EHB and LHB) with corresponding impact rate.
- Phyllos layer highlighted.
Mars crust globally altered in hydrated phyllosilicates
Mars crust globally altered in hydrated phyllosilicates
Mars crust globally altered in hydrated phyllosilicates

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

The LHB has buried most of the altered crust with deeper pristine mafic material
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?
Why did the aqueous era end?
Where has the liquid water gone?

- The atmosphere dropped (escaped)
- Liquid water in part percolated (and in part evaporated)
  → Eventually, this subsurface ice emerged later on, as
    - sulfates
    - outflow channels
steady loss?

few mbars

time

pressure
early massive loss followed by steady recycling

Few mbars

Pressure vs. time graph
- The atmosphere dropped (escaped)
- Liquid water in part percolated (and in part evaporated)

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

Mars global *climatic* change
- 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)

Impact rate

- EHB
- LHB

Time
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

Time

Dynamo drop
The magnetization is

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

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basin formation (and most other craters)

impact rate

Dynamo drop
heavy bombardment

| Noachian | Hesperian | Amazonian |

Tharsis formation

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

Noachian  |  Hesperian  |  Amazonian

dynamo drop

basin formation (and most other craters)

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

Noachian | Hesperian | Amazonian

Mars global climatic change
oceans would have been stable

after

Tharsis and the volcanoes were put in place,

and Valles Marineris formed

audacious extrapolation
Amazonian Tharsis rise, North plains mare-filled basin formation (and most other craters) dynamo drop

Noachian

Hesperian

Amazonian

Phyllos

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

Phyllosian

Phyllos

Noachian  Hesperian  Amazonian

Mars global climatic change
Eventually, geothermal front raises induced supplies of surface water from percolated ice.

Tharsis rise, North plains mare-filled.

Mars global climatic change.
Eventually, geothermal front raises induced supplies of surface water from percolated ice.

Tharsis rise, North plains mare-filled.

Mars global climatic change.
Eventually, geothermal front raises induced supplies of surface water from percolated ice.

Tharsis rise, North plains mare-filled.

Mars global climatic change.
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?
A large fraction of Mars surface has been altered; rusted?

nanophase hematite: $\alpha$ - Fe$_2$O$_3$
nanophase hematite: $\alpha - \text{Fe}_2\text{O}_3$
nanophase hematite: $\alpha - \text{Fe}_2\text{O}_3$
If either or both OH or/and H₂O 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.

- 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\textsubscript{2}O\textsubscript{2}) interaction, which constitutes a very slow process (it operates over billions of years) and only affects a very shallow (sub mm) depth.
<table>
<thead>
<tr>
<th>Noachian</th>
<th>Phyllosian</th>
</tr>
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<tbody>
<tr>
<td>Hesperian</td>
<td>Sulfates</td>
</tr>
<tr>
<td>Amazonian</td>
<td>Theiikian</td>
</tr>
<tr>
<td>Phyllosian</td>
<td>Theiikian</td>
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<tr>
<td>Phyllos</td>
<td></td>
</tr>
<tr>
<td>Noachian</td>
<td>Hesperian</td>
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</table>
Mars History derived from surface mineralogy
Mars global climatic change

Phyllosian

Theiikian

Siderikian

Phyllos

Sulfates

Anhydrous ferric oxides

Noachian

Hesperian

Amazonian

Alcaline

Stable

Liquid $\text{H}_2\text{O}$

Acidic

Tenuous atmosphere
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?

Mars global climatic change

P / T boundary
Mars global climatic change

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 greenhouse gases, disabling liquid water stability. Descending mantle cold plumes → core/mantle instabilities → ascending plumes + local/transient dynamo reactivation.
Hesperian

Amazonian

Sulfates

Anhydrous ferric oxides

Phyllos

Theiikian

Siderikian

Phyllosian

Noachian

Hesperian

Amazonian

Mars global climatic change

P / T boundary

extinction of Martian life?
Was Mars ever habitable?

extinction of Martian life?

Mars global climatic change

P / T boundary

extinction of Martian life?

Was Mars ever habitable?
<table>
<thead>
<tr>
<th>Hadean</th>
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- heavy bombardment
- Hell
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- **Hell**
- **Heaven**
- **heavy bombardment**
heavy bombardment

Noachian  Hesperian  Amazonian

Hadean  Archean  Proterozoic  Phanerozoic

Hell  Heaven

start of Earth habitability

because impacts considered sterilizers

because impacts considered sterilizers
Both for Mars and the Earth, the heavy bombardment era was viewed "pre-biotic"

Water thought stable after the bombardment had ceased and after the volcanoes were put in place

Because impacts considered sterilizers

Start of Earth habitability

Heavy bombardment

Hell

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

<table>
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- stable Earth oceans
- 3.7 – 4.0 By
- zircons
  - ancient (> 4.1 By)
  - $^{18}$O / $^{16}$O
Proterozoic heavy bombardment

Hadean ➔ Archean ➔ Proterozoic ➔ Phanerozoic

Earth habitability

stable Earth oceans

zircons
- ancient (> 4.1 By)
- $^{18}\text{O} / ^{16}\text{O}$
heavy bombardment

Hadean | Archean | Proterozoic | Phanerozoic

Earth habitability

stable Earth oceans

zircons
- ancient (> 4.1 By)
- $^{18}$O / $^{16}$O

Proterozoic
could oceans be stable during the heavy bombardment?
heavy bombardment

Hadean  Archean  Proterozoic  Phanerozoic

Earth habitability
stable Earth oceans

zircons
- ancient (> 4.1 By)
- $^{18}\text{O} / ^{16}\text{O}$

The LHB did evaporate < 20 % of the oceans (Morbidelli et al.)
crust solidified (4.3 By ZrSiO$_4$), surface oceans stable ($^{18}$O)

Earth habitable
crust solidified (4.3 By ZrSiO₄), surface oceans stable (¹⁸O)
crust solidified (4.3 By ZrSiO$_4$), surface oceans stable ($^{18}$O)
life could start

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

zircons
Earth habitable

Hadean  Archean  Proterozoic  Phanerozoic
crust solidified (4.3 By ZrSiO₄), surface oceans stable (¹⁸O)
life could start

3 Fe₂SiO₄ + 2 H₂O → 3 SiO₂ + 2 Fe₃O₄ + H₂
fayalite magnetite

3 Mg₂SiO₄ + SiO₂ + 4 H₂O → 2 Mg₃Si₂O₅(OH)₄
forsterite serpentine
(then serpentine → talc + amphibole if T > 500°C)

CO₂ + 4 H₂ ↔ CH₄ + 2 H₂O

9 Fe₂SiO₄ + 6 H₂O +2 N₂ ↔ 9 SiO₂ + 6 Fe₃O₄ + 4 NH₃

Earth habitable

Hadean Archean Proterozoic Phanerozoic
crust solidified (4.3 By ZrSiO₄), surface oceans stable (¹⁸O)
life could start
crust solidified (4.3 By ZrSiO₄), surface oceans stable (¹⁸O)
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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
Impact rate over time:

- Archean: Higher impact rate with a peak in zircons formation.
- Proterozoic: Lower impact rate, leading to Earth becoming habitable.
- Phanerozoic: Further decrease in impact rate, maintaining habitability.
Martian phyllosilicates and terrestrial zircons play analogous roles.
Martian phyllosilicates and terrestrial zircons play analogous roles.
Impact rate vs. time:

- Proterozoic
- Hesperian
- Amazonian

Earth habitation timeline:

- Phyllos
- Had.
- Archean
- Proterozoic
- Phanerozoic

Mars habitable?

Earths habitation:

- Earth habitable
- Earth inhabited

Zircons:

Impact rate vs. time graph:

Time scale:

- Noachian
- Hesperian
- Amazonian
post-LHB Earth life → Mars habitability must have survived dynamo †

Earth habitable

Earth inhabited

Mars habitable ?

Mars inhabited ?

Phyllos

Noachian  Hesperian  Amazonian

Had.  Archean  Proterozoic  Phanerozoic

zircons

impact rate

time
If life on Earth emerged pre-LHB

<table>
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<td>zircons</td>
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<td>Earth habitable</td>
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<td>Earth inhabited</td>
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impact rate

time
If life on Earth emerged pre-LHB, Mars might also have been inhabited.

Earth habitable
Earth inhabited
Mars is totally unique in offering thanks to its clays to study this key era of early habitability.

Earth inhabited
The future in situ missions should:

GO Phyllosian!
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.
optical image indicates flooding

HRSC
no hydrated minerals

optical image indicates flooding

OMEGA → HRSC
no hydrated minerals

but...

hydrated clays

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.
OMEGA : volcanic lava
OMEGA: hydrated phyllosilicates
OMEGA : hydrated phyllosilicates

This is where future astrobiological rovers should go and explore
hopefully the first phyllosian rover
then ExoMars, the second phyllosian rover
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