Thermal and Dynamic History of Planets
Planetary Volcanism and Crustal Evolution

David Baratoux

University of Toulouse, Institut de Recherche pour le Développement
Institut Fondamental d'Afrique Noire

Day 2 – The thermal evolution of Mars

Part I – The mantle source
A geochemical model of the Martian mantle

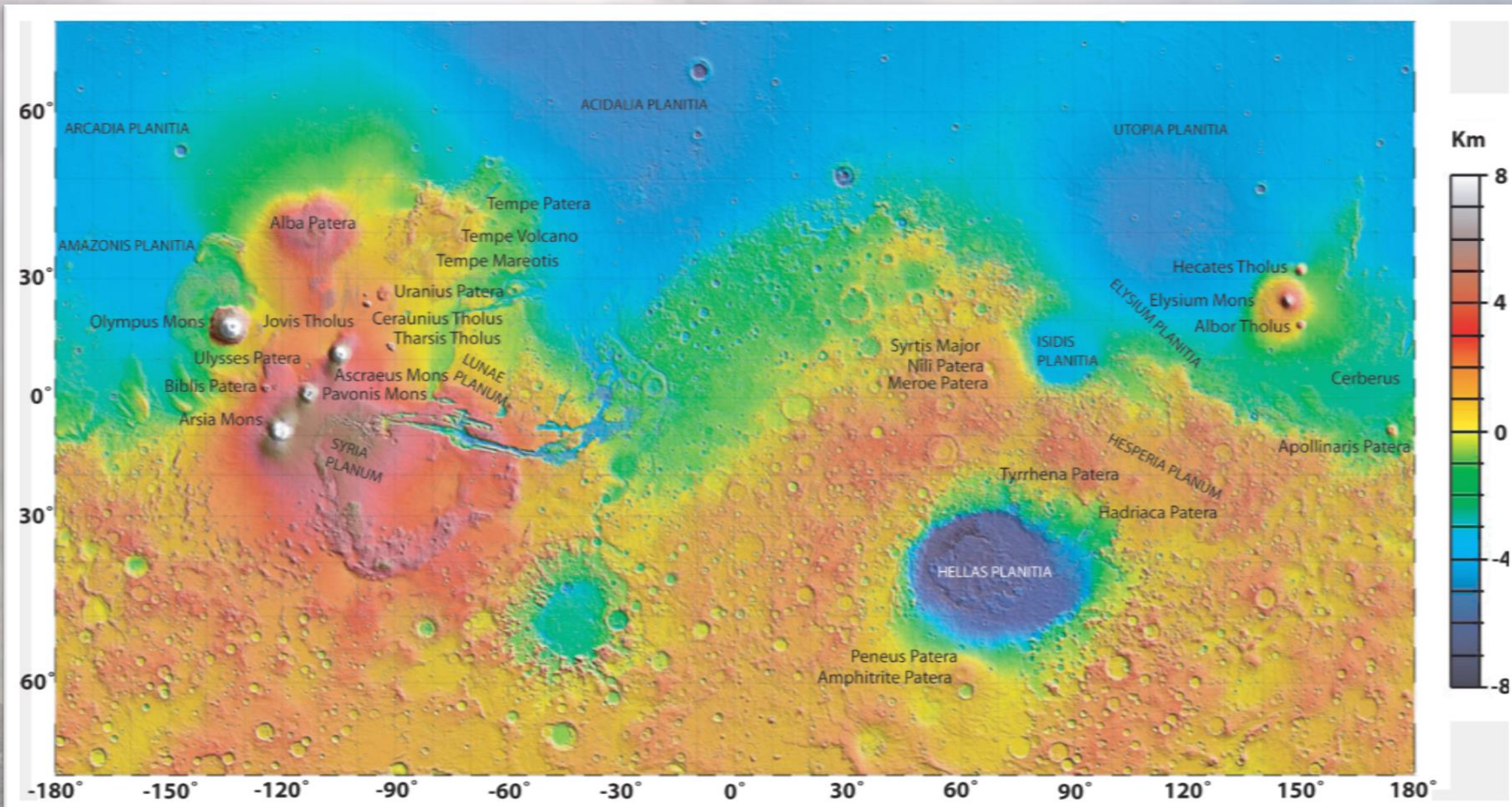
<u>Part II – Petrological constraints on the thermal evolution of the mantle</u>

Part III – Outstanding questions

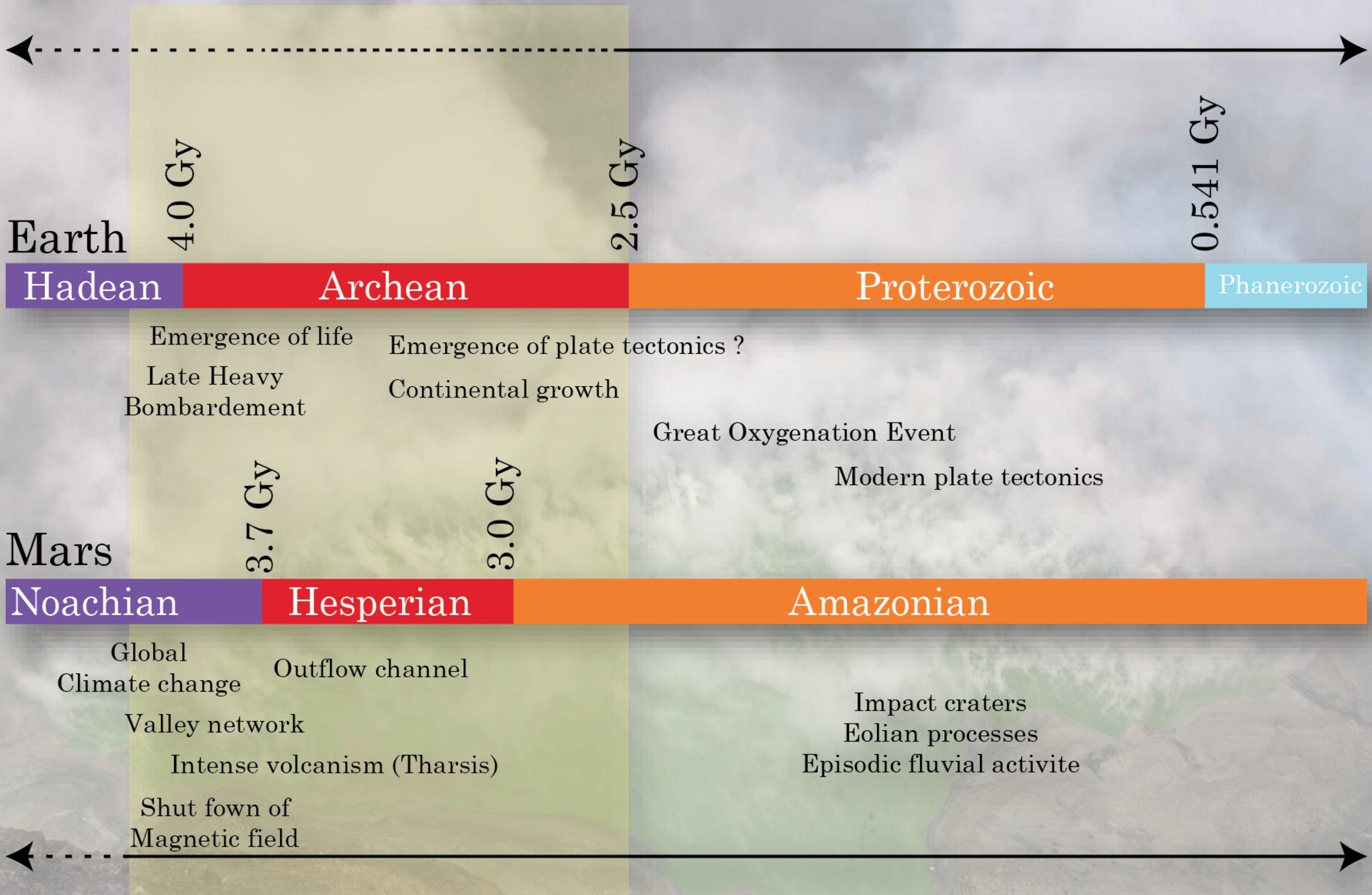
Mars Topography and Ages

Ages from crater counts
calibrated from Apollo samples

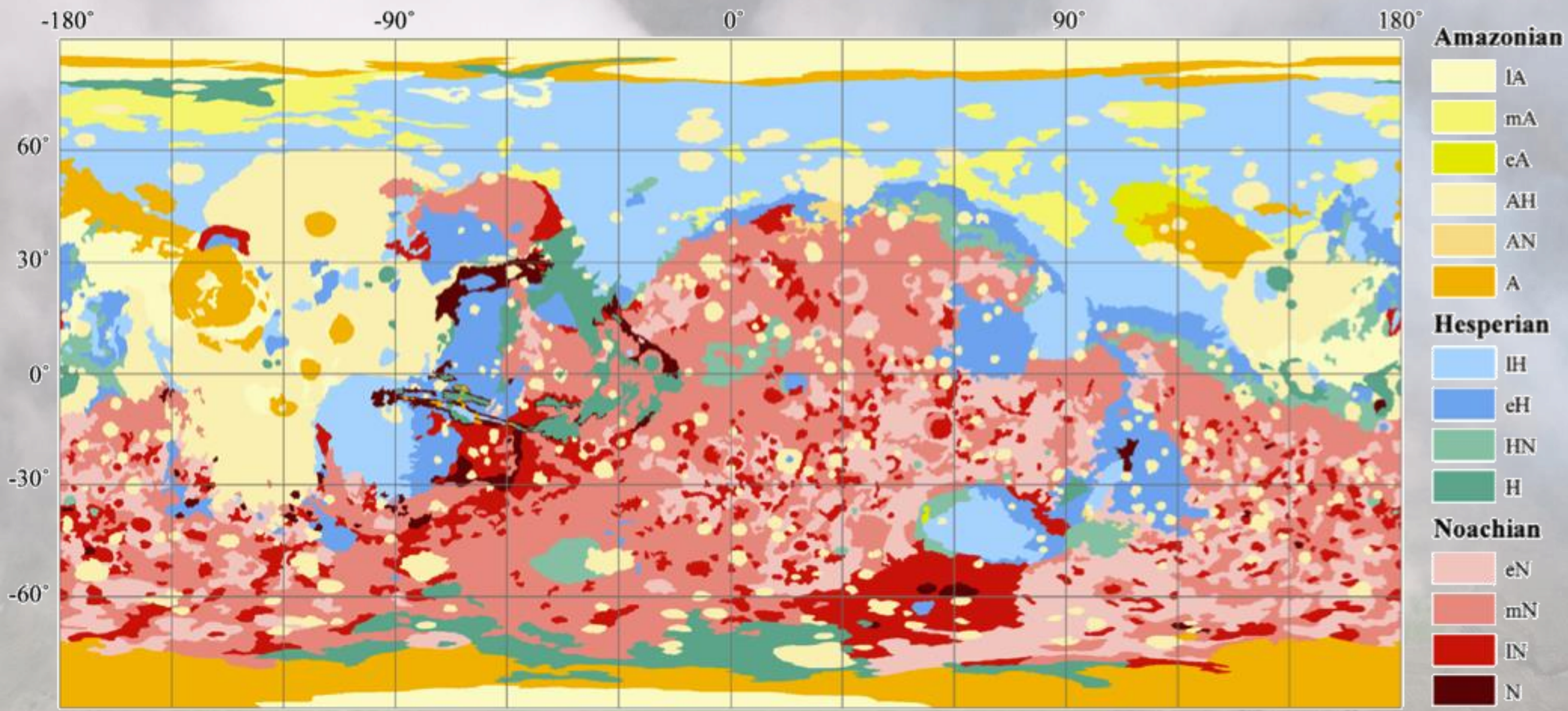
Main surface features
-Hemispheric dichotomy
-Large impact basins
-Volcanic provinces
-Valles Marineris



Stratigraphic scale of Mars

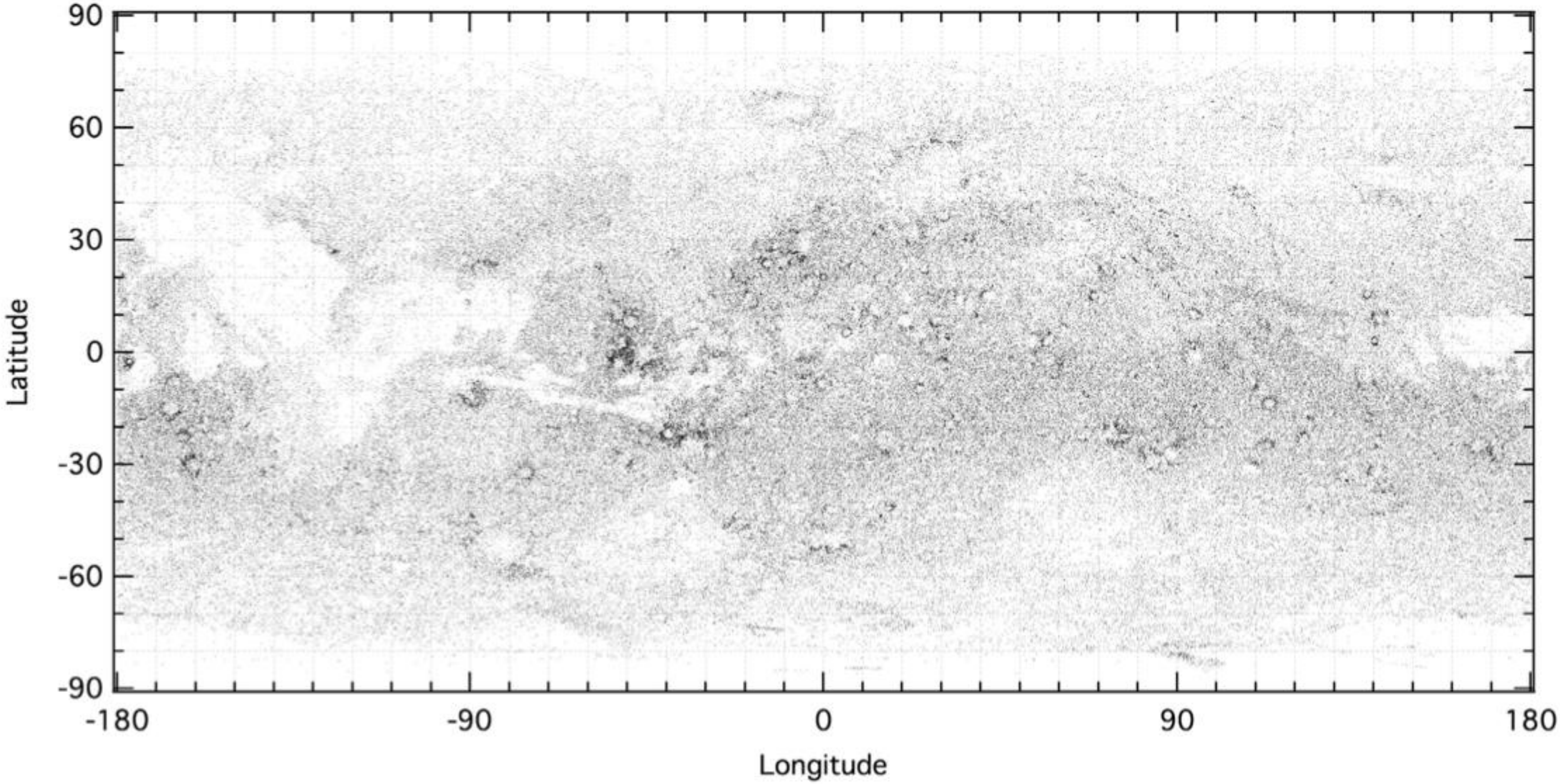


Geological maps



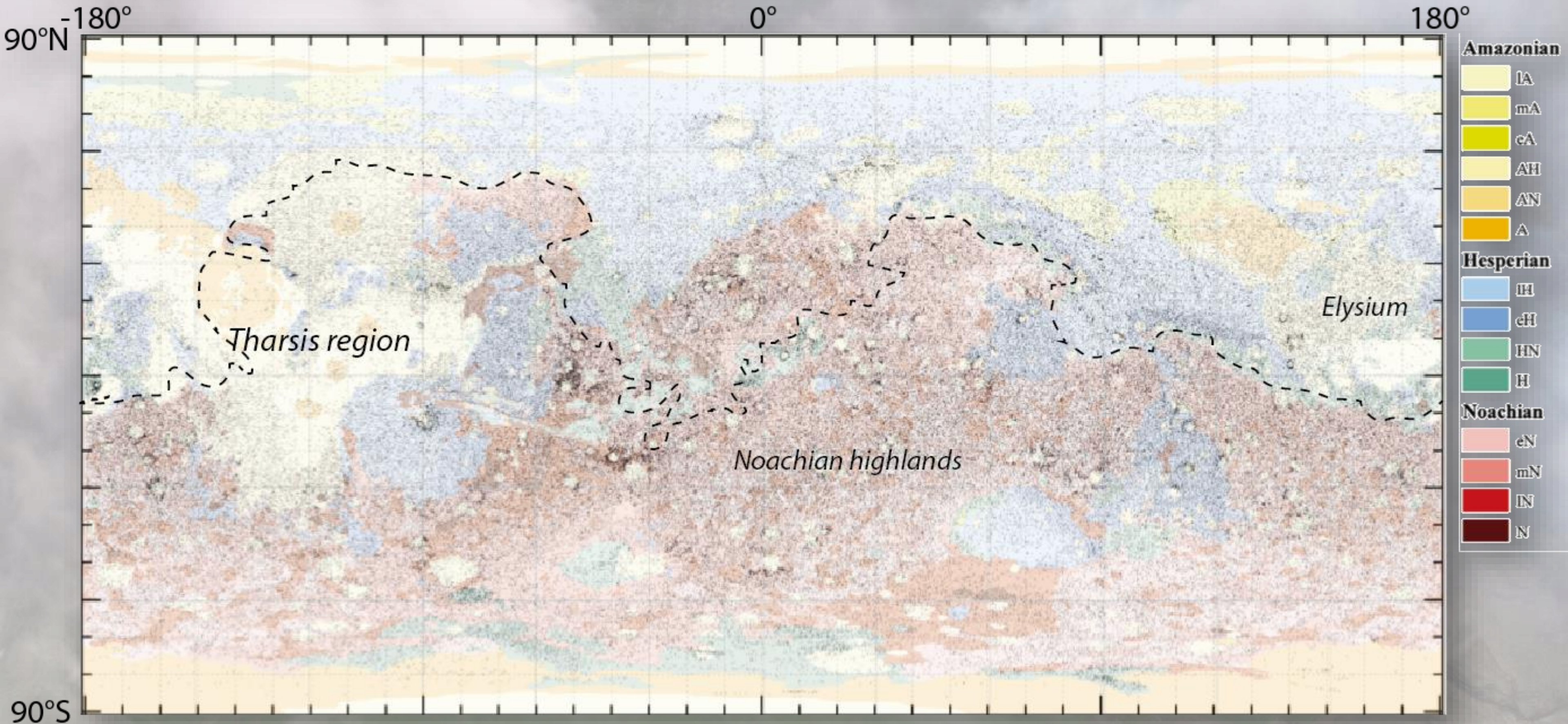
Tanaka et al., 2014, Planetary and Space Science

Ages from crater counts

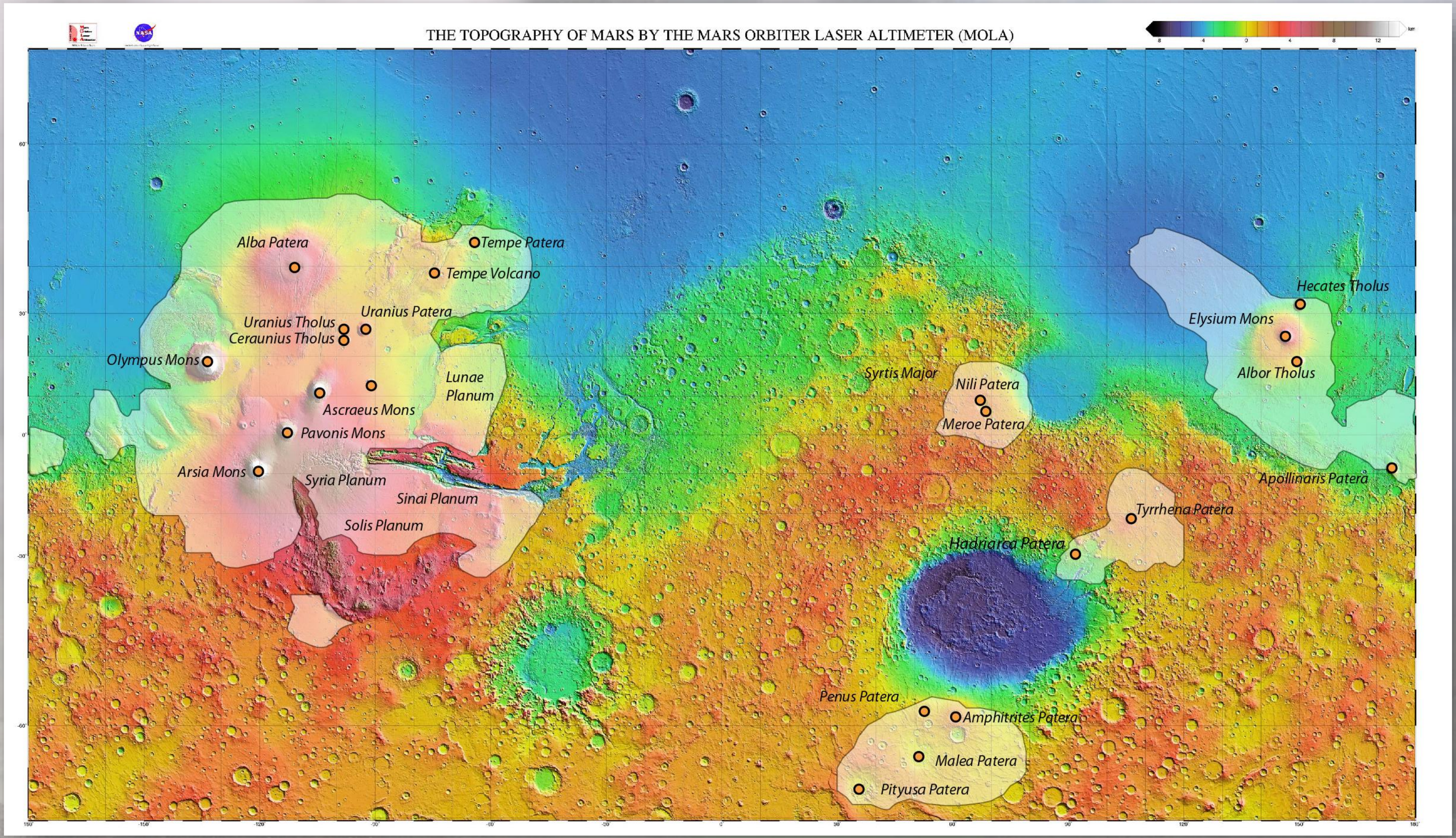


Robbins and Hynek, 2012, Journal of Geophysical Research

Geological map of Mars and crater density

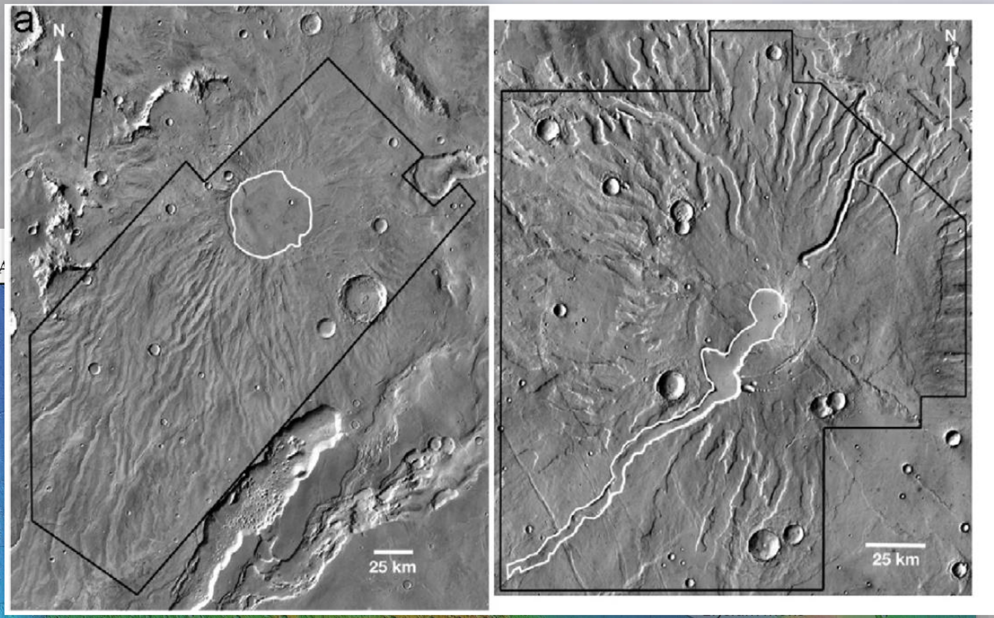


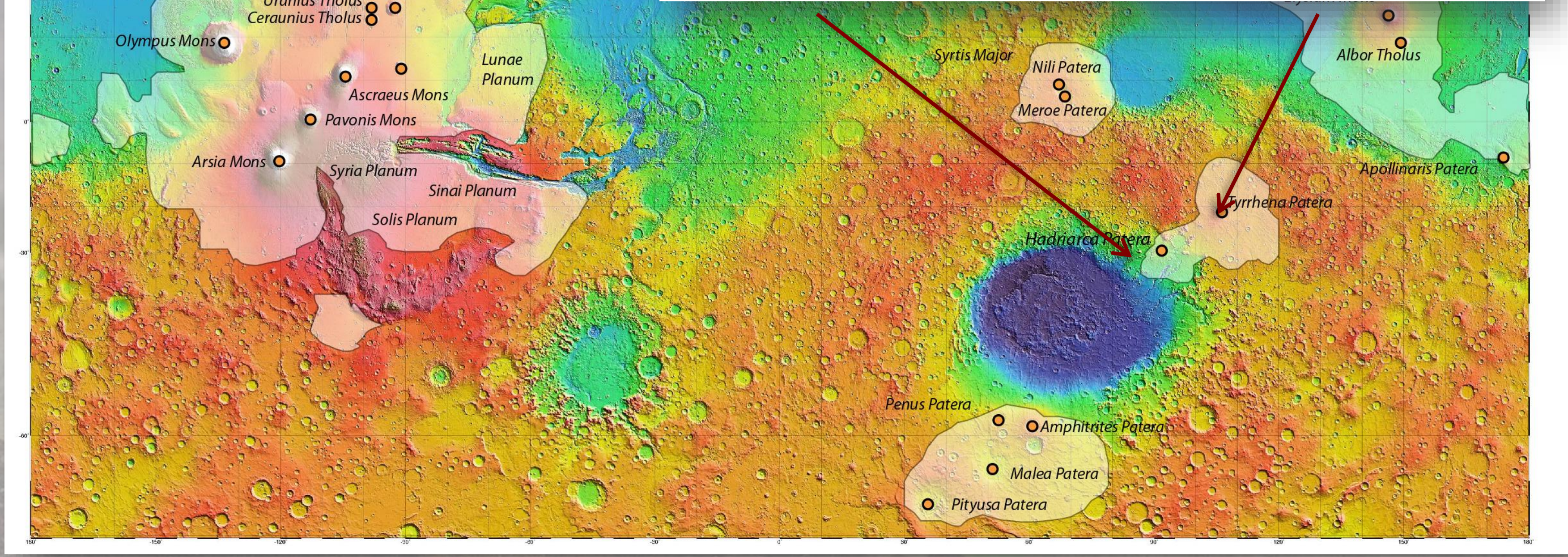
Volcanic provinces



Volcanic provinces

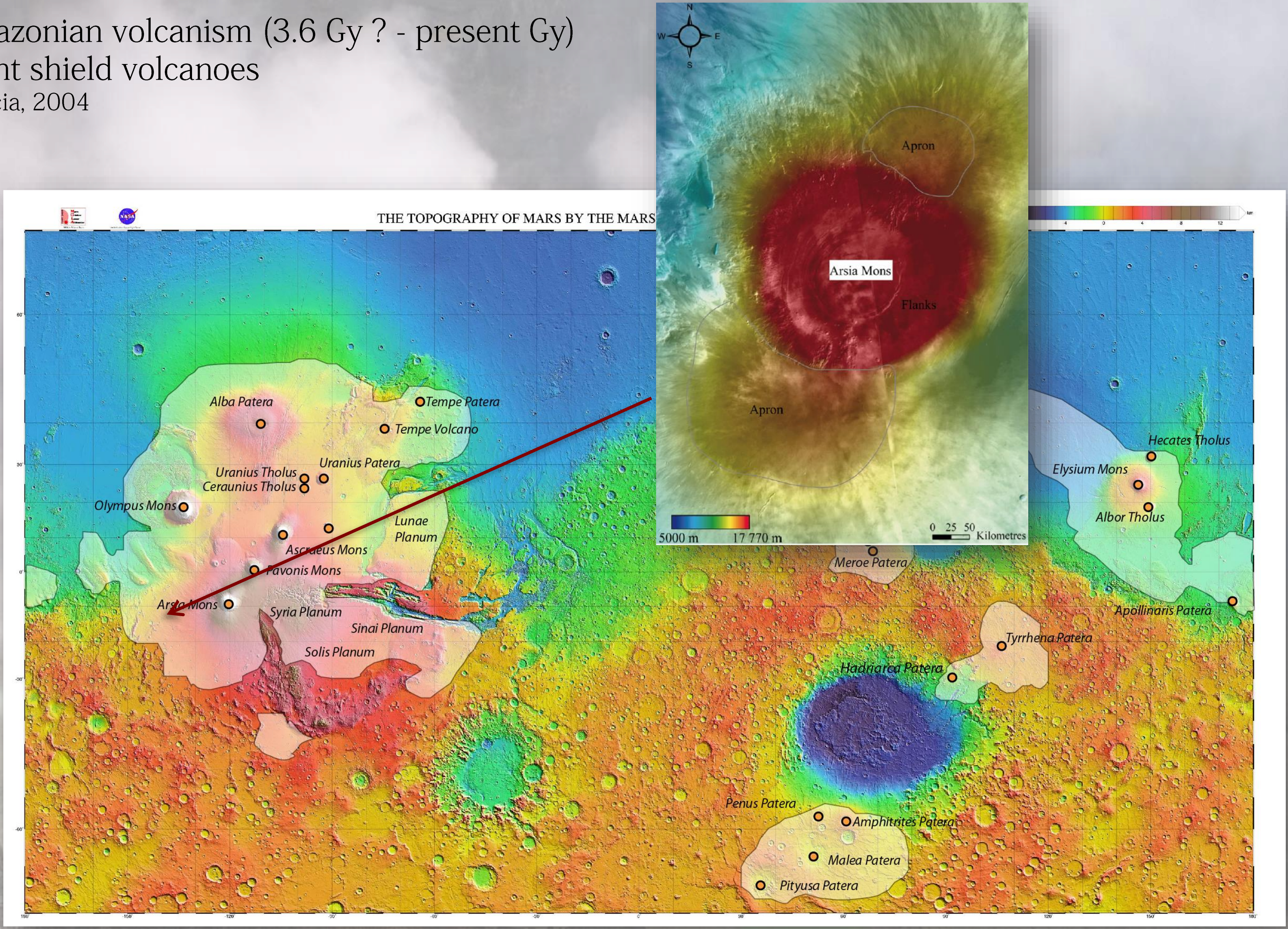
Hesperian volcanism (3.9 – 3.0 Gy)
Partially eroded shield volcanoes
Circum-Hellas Volcanic Province
Williams et al., 2008





Volcanic provinces

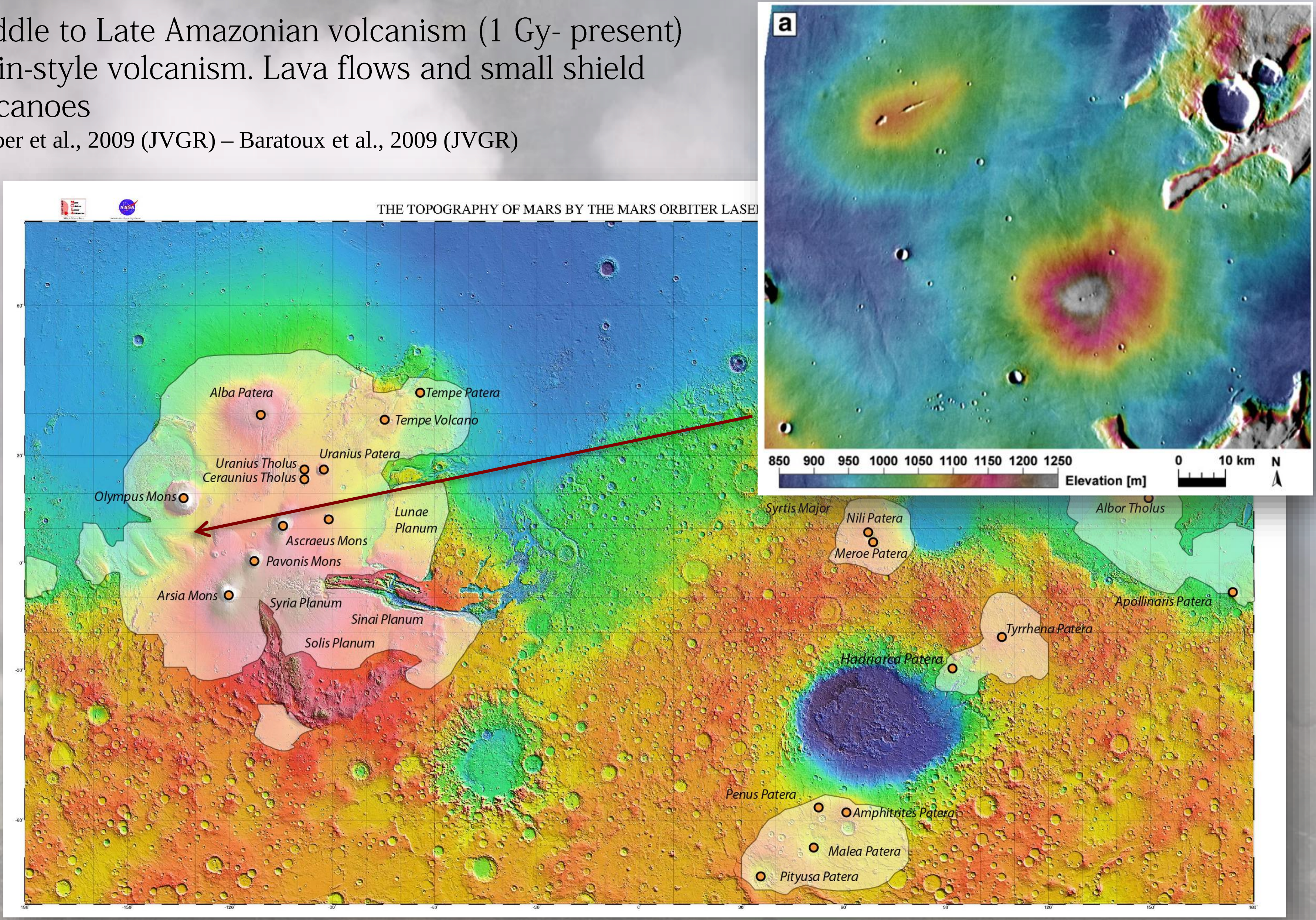
Amazonian volcanism (3.6 Gy ? - present Gy)
Giant shield volcanoes
Plescia, 2004



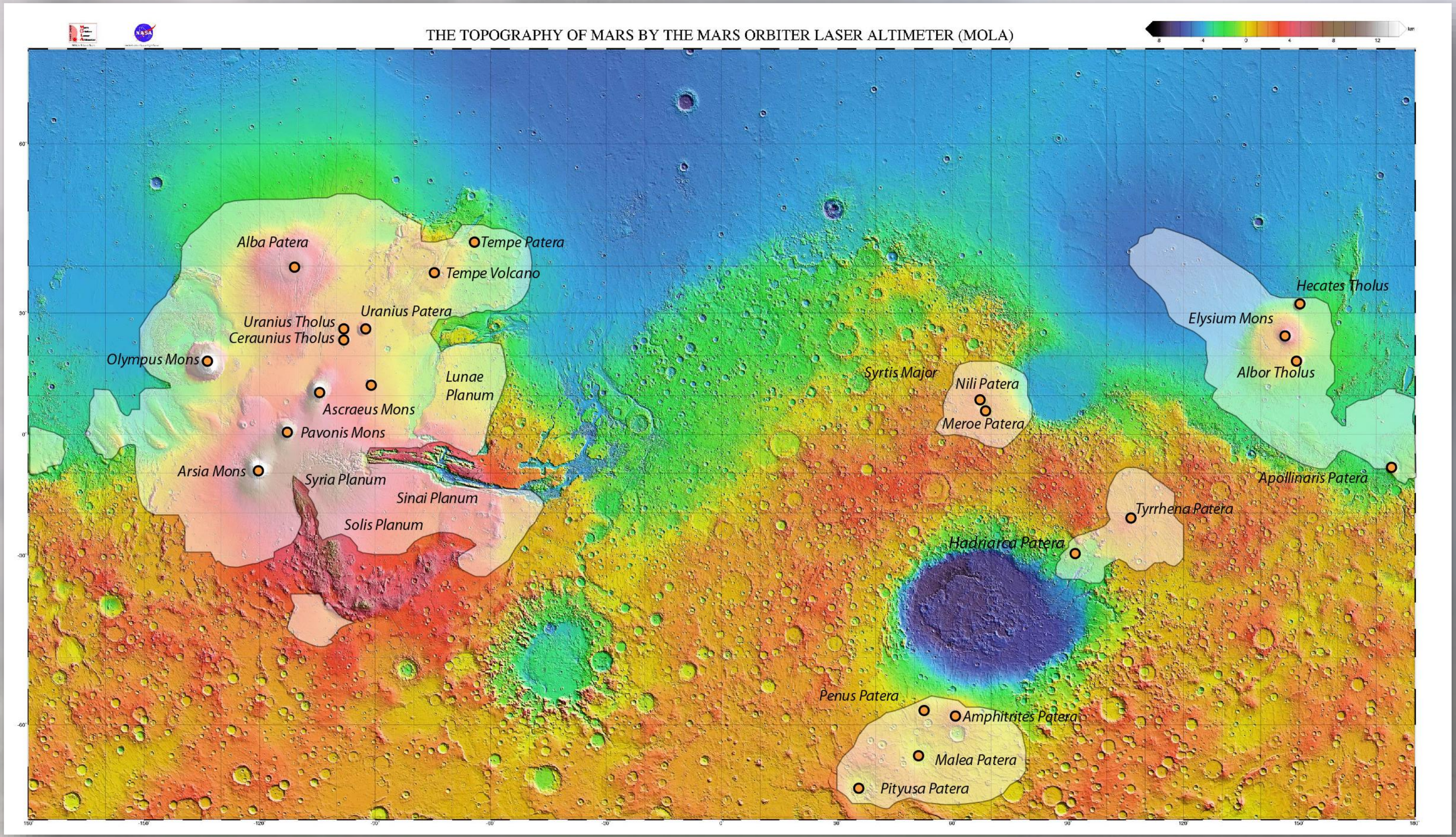
Volcanic provinces

Middle to Late Amazonian volcanism (1 Gy- present)
Plain-style volcanism. Lava flows and small shield volcanoes

Hauber et al., 2009 (JVGR) – Baratoux et al., 2009 (JVGR)



What is the Noachian crust ?



- Eroded volcanoes ?
- Cumulates (magmatic chambers) exposed by erosion ?

- A primary crust formed in the context of a magma ocean ? (like for the moon)

One crust or several crusts ?

Multiple crustal extraction events

Primary crust

Secondary crust

Tertiary crust

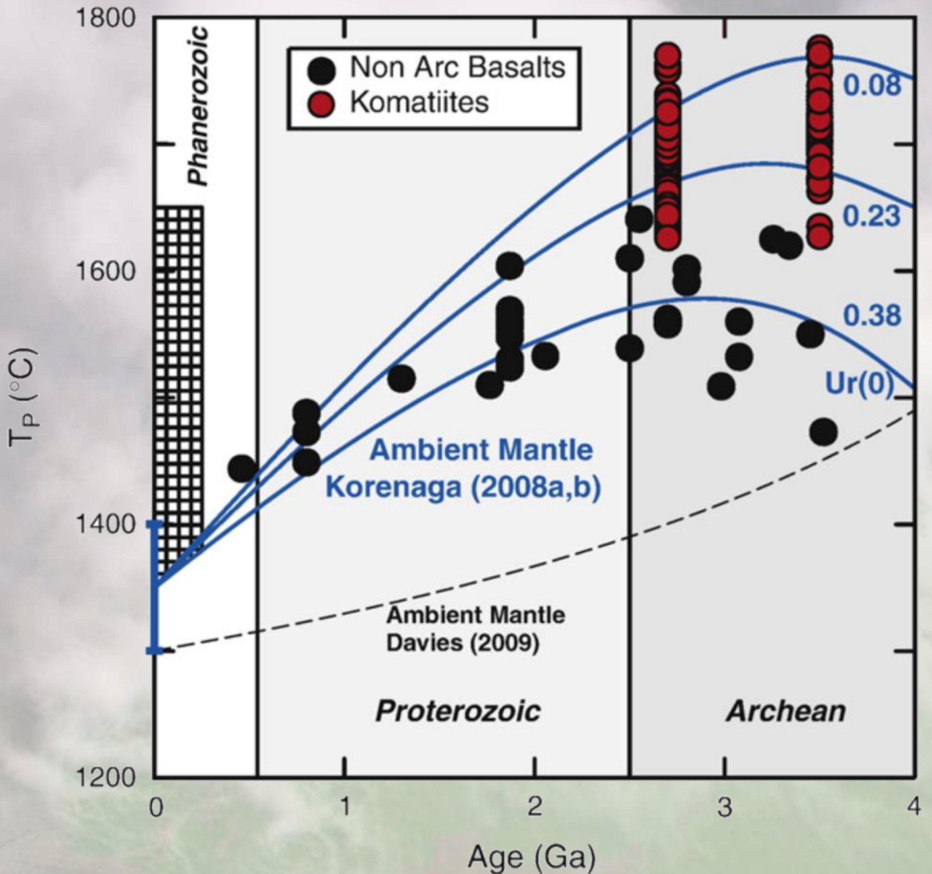
How/when did the Martian crust form ?

	Earth	Moon	Mars
Primary Crust – Magma ocean Crystallization (cumulates)	No sample	Anorthositic crust	Highlands ? (Not a plagioclase-floatation crust)
Secondary crust – volcanism, partial melting of the mantle	Basaltic volcanism, oceanic crust, LIP	Mare (basaltic) volcanism	Tharsis, Elysium, Hesperia Planum, etc…
Tertiary crust – differentiated crust, re-melting of the crust	Continental crust	Almost non-existant	May be ?

Formation of primary crust should precede the formation of secondary and tertiary crusts, but the formation of secondary and tertiary crusts may occur simultaneously

The surface of Mars would correspond to a secondary crust

Petrologic expression of thermal evolution of the interior



Herzberg et al., 2010, EPSL

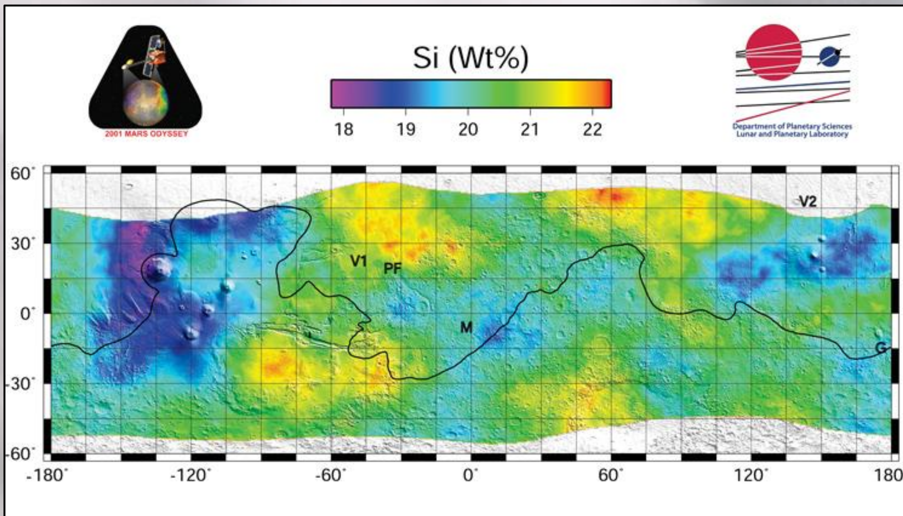
Magmatism & Voclanism

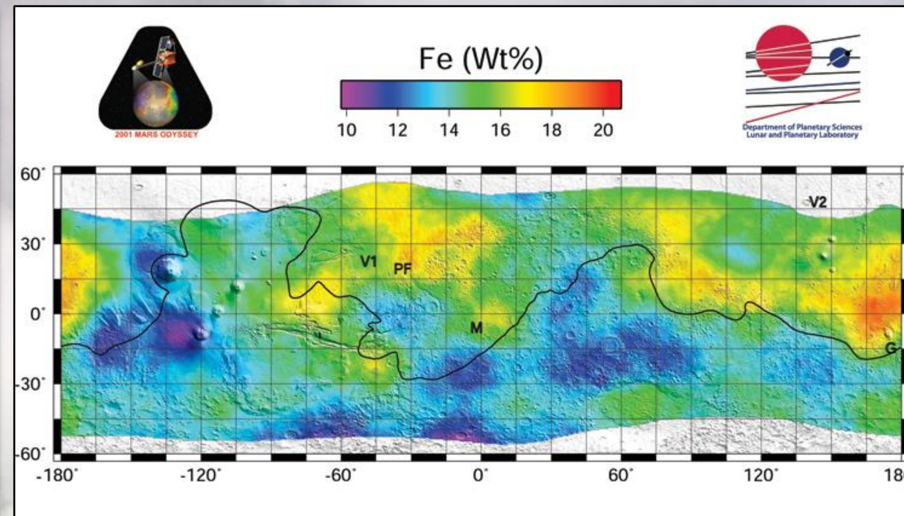
Expression of the thermal state of the mantle

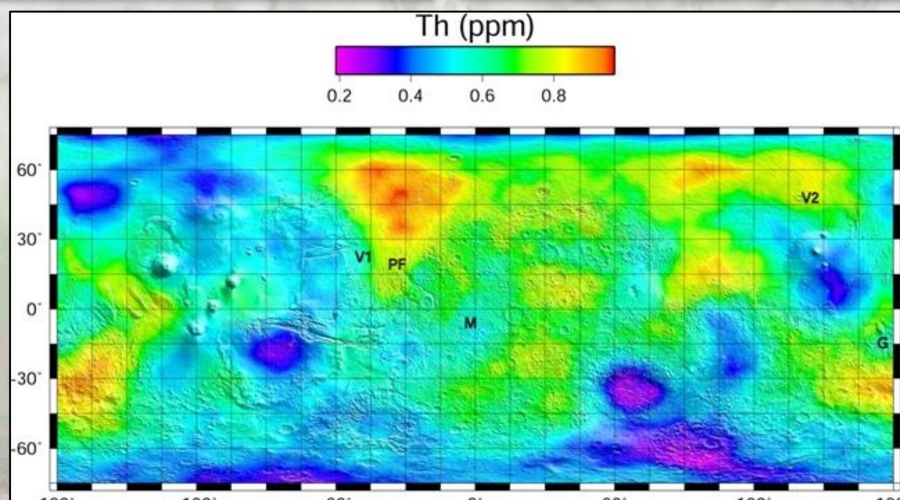
Comparison with numerical models of the thermal evolution of the Earth

A scenario for the thermal evolution of Mars compatible with the volcanic activity at the surface was missing !

GRS Data – Global Maps of SiO_2, FeO and Thorium

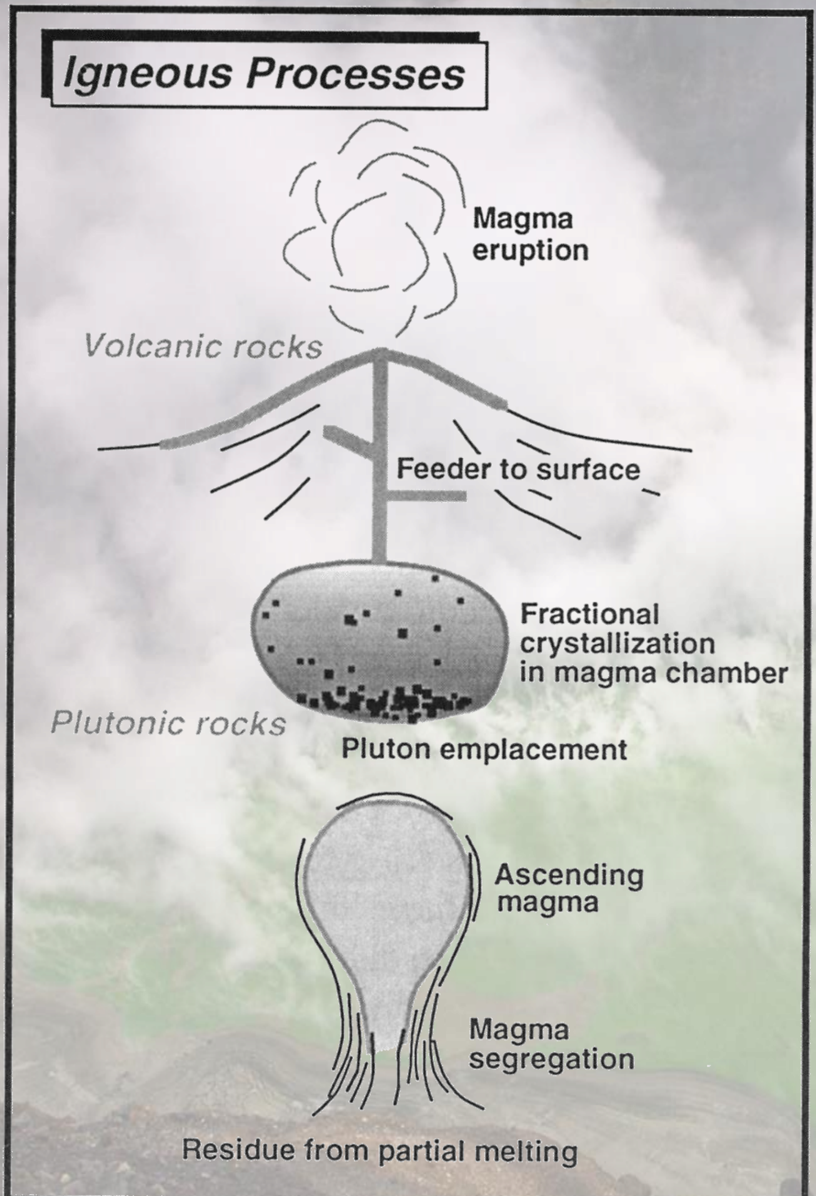






Boynton et al., 2007

Petrogenesis of Martian Volcanic Rocks



Eruption of magmas
Liquid + Phenocrists

Few kilometers below the surface
Magmatic chambers
Fractional Crystallization

Transport

At greater depth in the mantle:
Zone of partial melting

McSween, Meteorites and their parent bodies

Batch melting experiments on pMELTS

Mantle source – dry primitve martian mantle of Dreibus and Wanke

Title: DW85Mg75-195
Initial Composition: SiO2 44,400
Initial Composition: TiO2 0,1400
Initial Composition: Al2O3 3,02
Initial Composition: Cr2O3 0,760
Initial Composition: FeO 17,9
Initial Composition: MnO 0,4600
Initial Composition: MgO 30,2
Initial Composition: CaO 2,45
Initial Composition: Na2O 0,50
Initial Composition: K2O 0,0350
Initial Composition: P2O5 0,1600
Initial Temperature: 1600,00
Final Temperature: 800,00
Initial Pressure: 19500,00
Final Pressure: 19500,00
Increment Temperature: 1,00
Increment Pressure: 0,00
dp/dt: 0,00
log fo2 Path: -3FMQ

→ pMELTS simulation from 1600° C to 800° C

↓

Composition of the liquid
Mineral assemblage and mineral chemistry
Physical properties (density, viscosity)

What are MELTS and pMELTS ?

A family of thermodynamic calculators with the ability to simulate the evolution of silicate melts and solids as a function of pressure and temperature, under thermodynamic equilibrium

http://melts.ofm-research.org

Inputs (what you need to know)

Composition
fO_2 / fO_2 buffer
P, T path

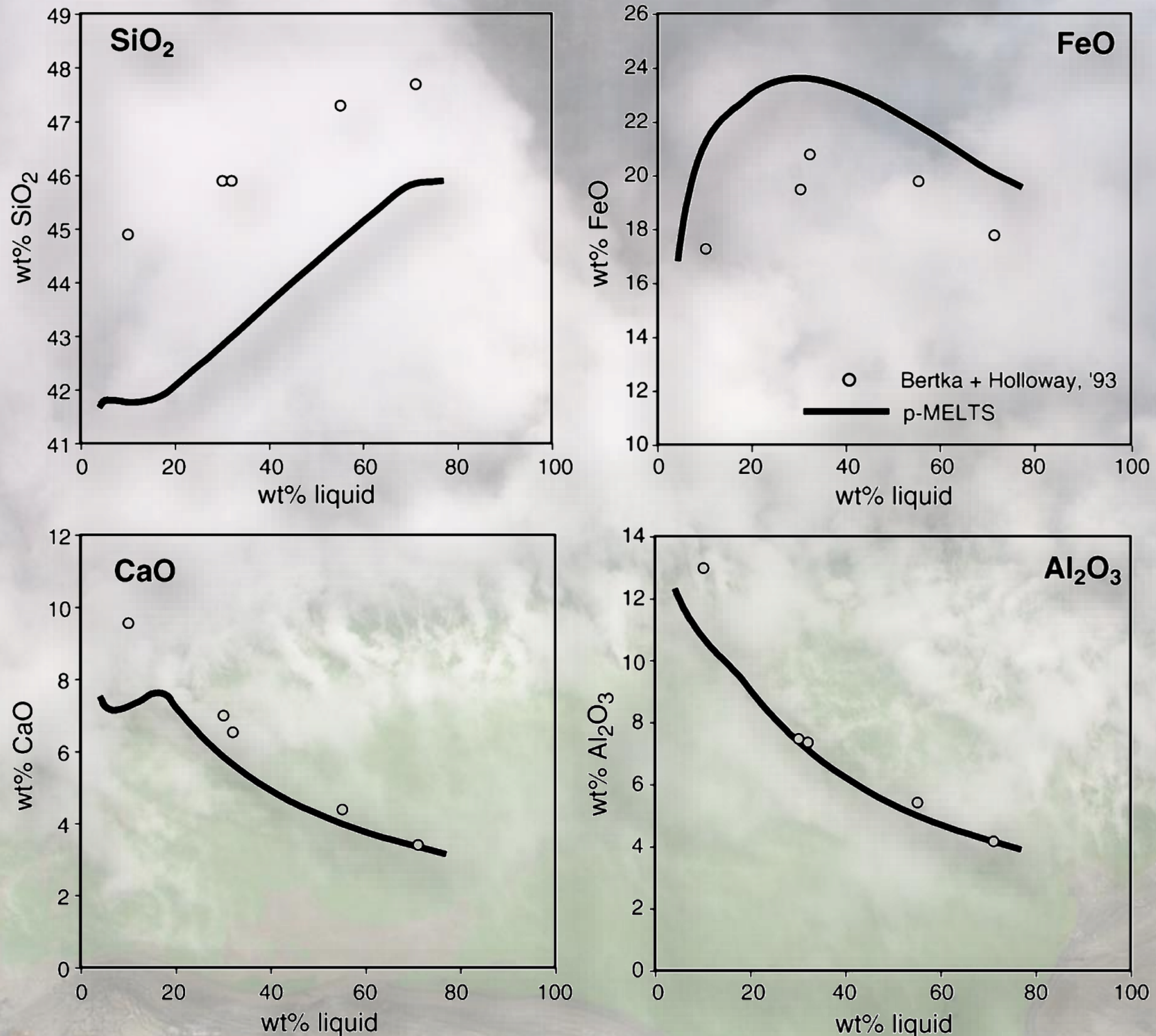
→

Outputs (what you get)

Chemical composition of the liquid
Mineral assemblage and mineral chemistry
Thermodynamical properties

Comparing Pmelts / Experimental Data

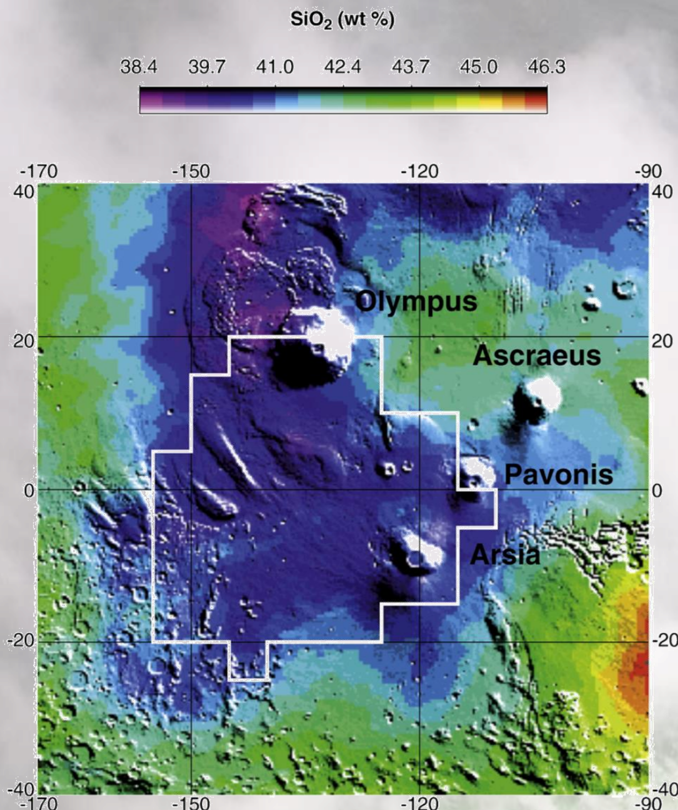
How does pMELTS reproduce the real world ?

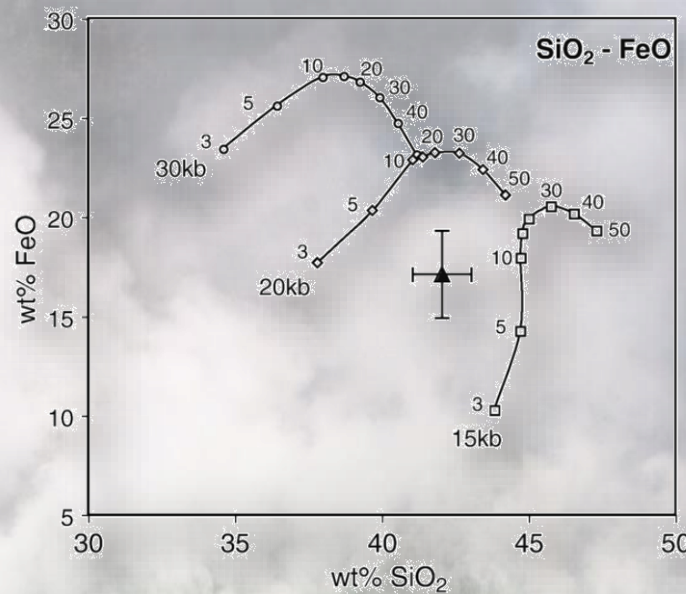


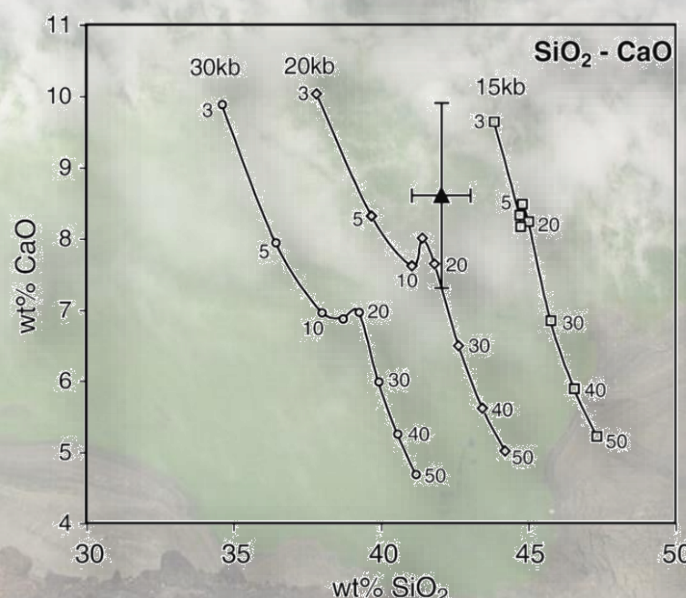
Maary et al., 2009
Journal of Volcanology and Geothermal Research

Correct for the trends
Offset between experimental data and experimental modeling (easily corrected)

Conditions of Formation of Volcanic Rocks at the Tharsis Dome







Comparison between major element abundances in volcanic rocks and partial melts of the martian mantle.

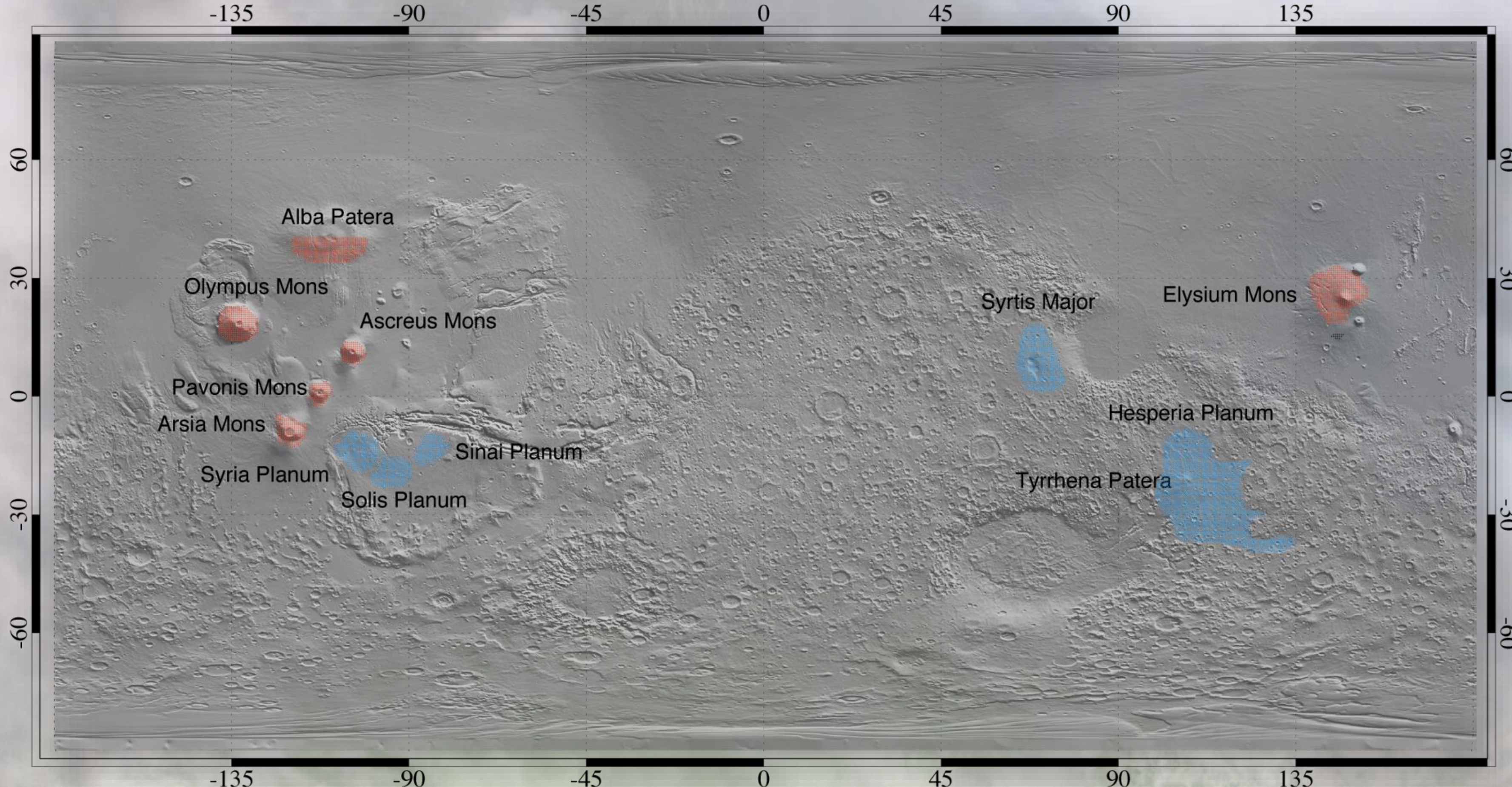
Maary et al., 2009
Journal of Volcanology and Geothermal Research

Chemistry (Si, Fe, Ca) consistent with primary melts of the martian mantle (DW85, iron-rich)

5% - 10% partial melting at 17kbar

Pressure is also consistent with independant estimates of the thickness of the lithosphere (from gravity/topography)

Selection of 12 volcanic provinces



Selection of 12 volcanic provinces

Homogeneous composition

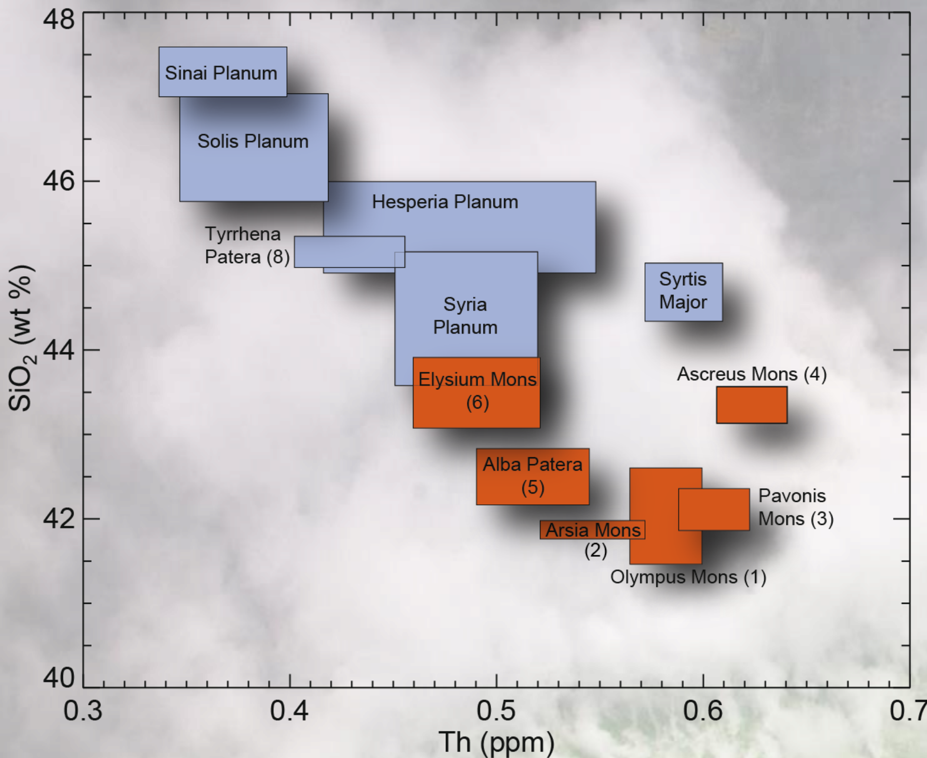
Morphological evidences for volcanic landforms

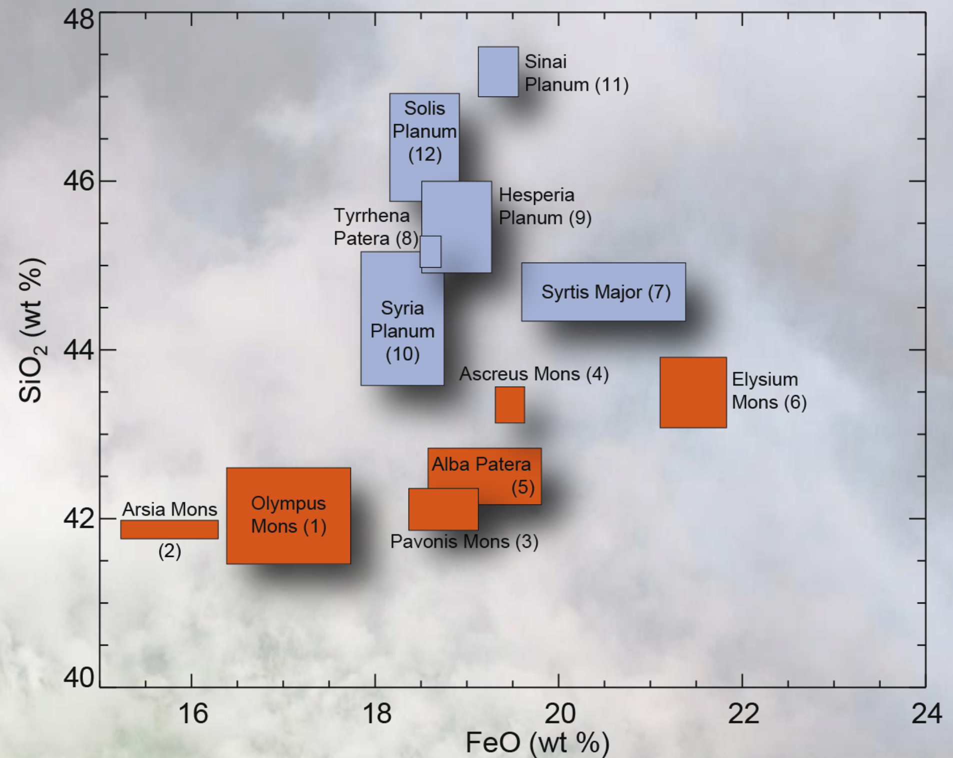
6 young volcanic provinces (Amazonian)

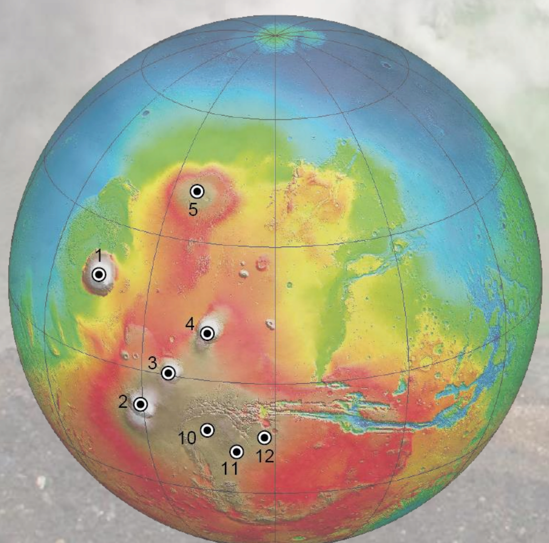
6 old volcanic provinces (Hesperian)

Baratoux et al. 2011, Nature

SiO_2, FeO and Thorium for 12 volcanic provinces

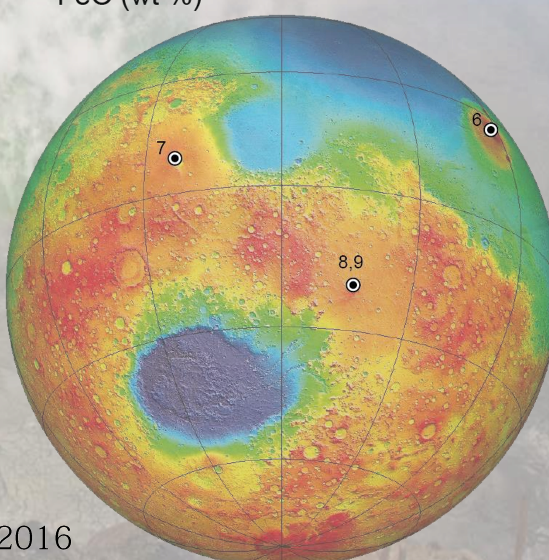






What are the meaning of these trends ?

Baratoux et al. (2011) - Nature

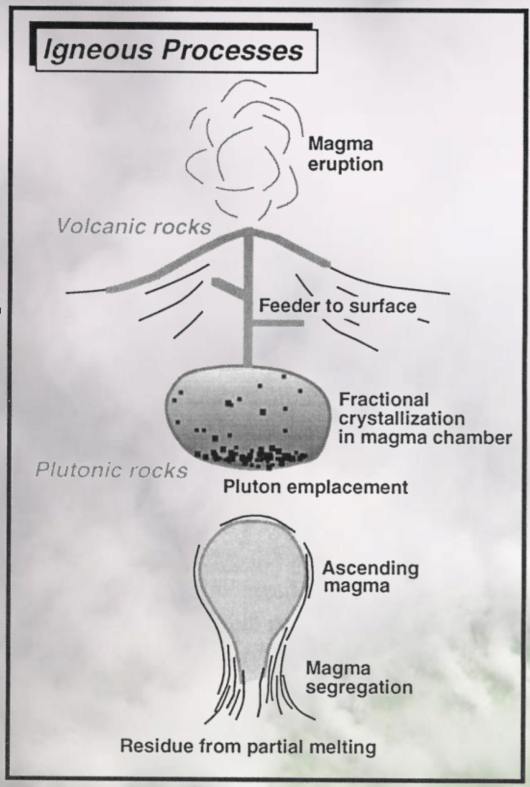


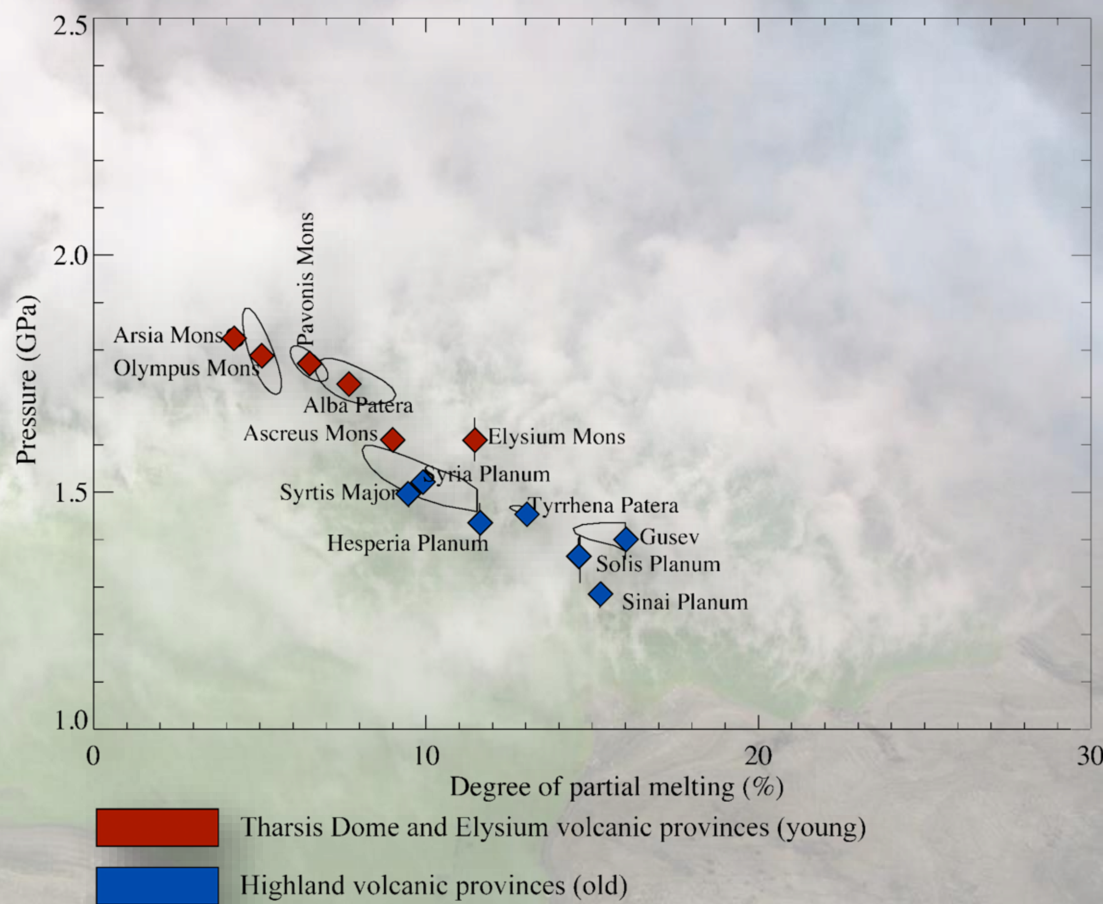
Conditions of partial melting from chemical composition

P / F from SiO_2, FeO, et Th abundances (wt%)

DW85 mantle (Dreibus & Wanke, 1985) – constrained from martian meteorites
Batch melting model (pMELTS)

McSween, Meteorites and their parent bodies





$SiO_2 = f(P,F, DW85)$

$FeO = f(P,F, DW85)$

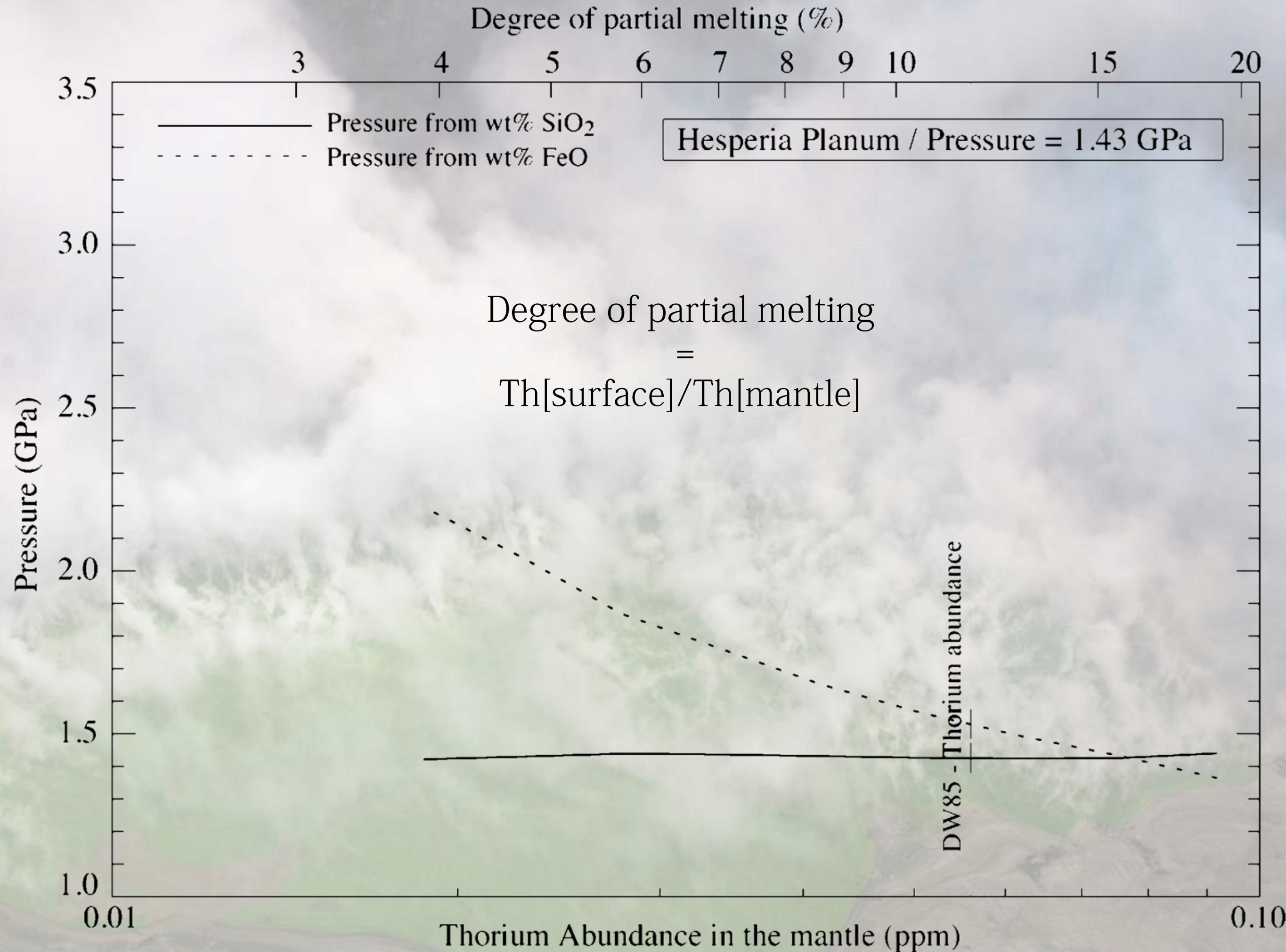
P: Pressure
F: Degree of partial melting

Baratoux et al. (2011) - Nature

Independent check for the degree of partial melting from Thorium

Determination of conditions of partial melting from Si, Fe and Th

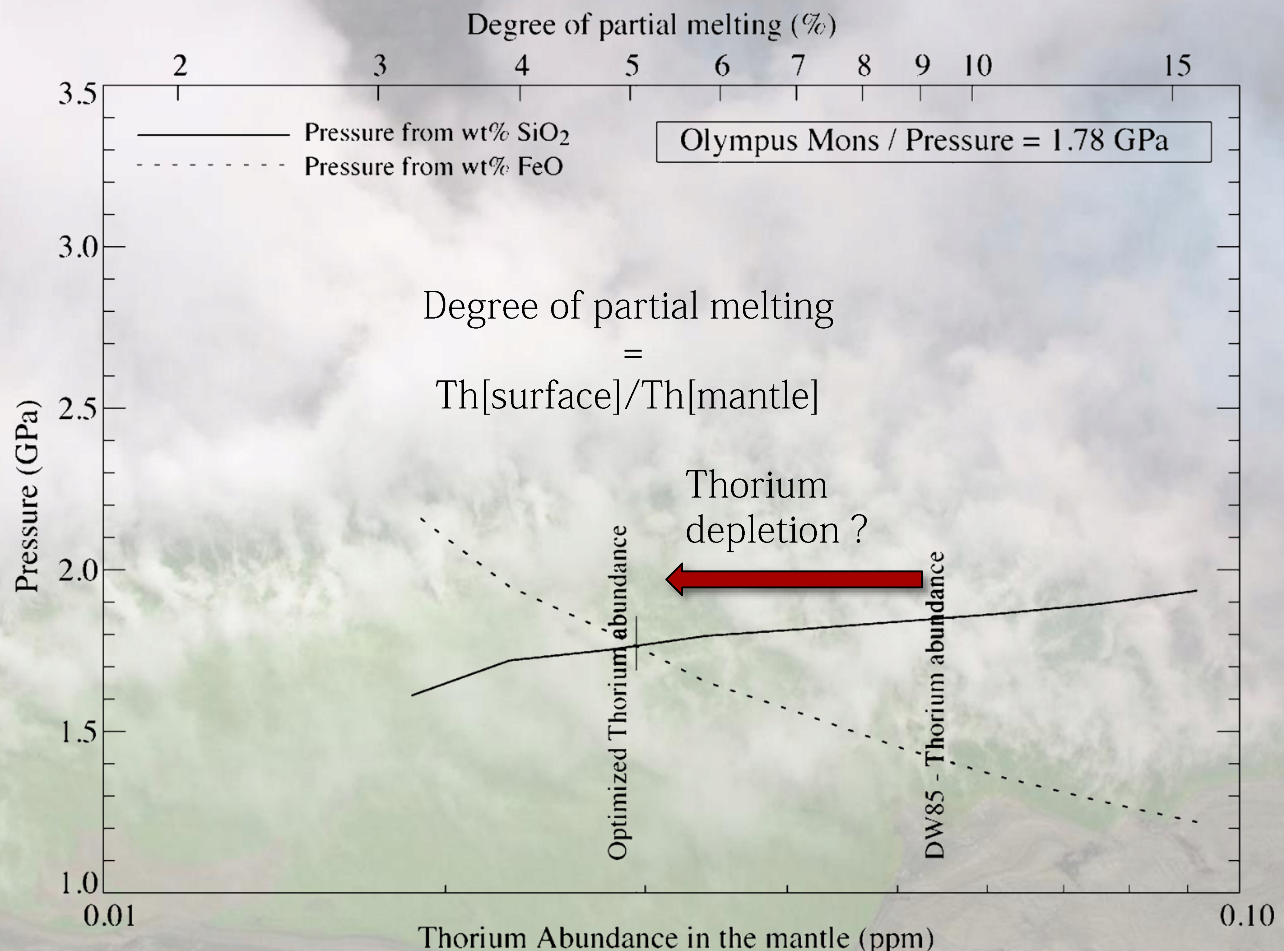
Thorium is incompatible.
Its concentration in the melt is inversely proportional to the degree of partial melting.



Results are consistent for old volcanism

Determination of conditions of partial melting from Si, Fe and Th

Thorium is incompatible.
Its concentration in the melt is inversely proportional to the degree of partial melting.

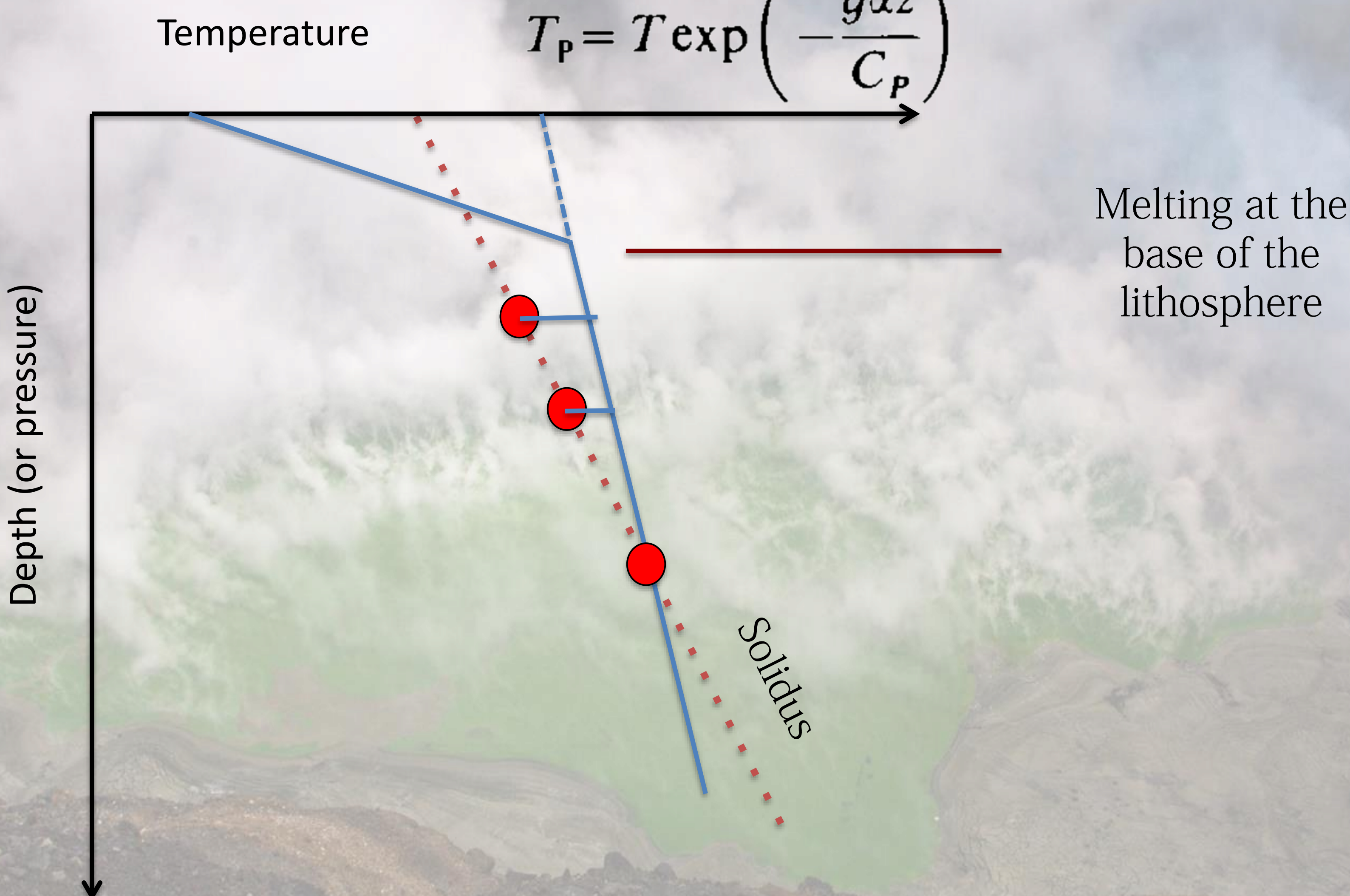


Implies a depleted mantle for young volcanismm

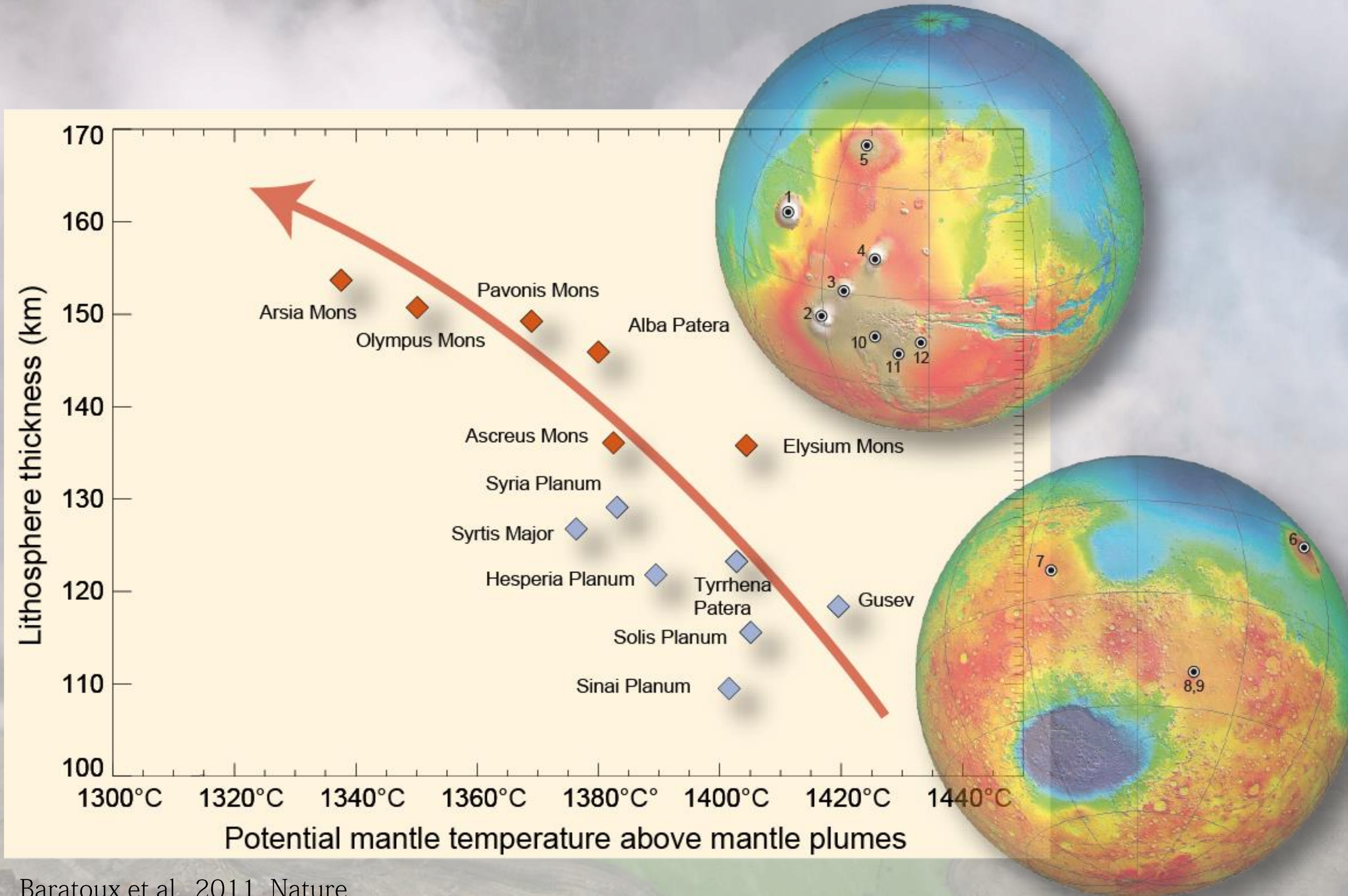
P, T => T_{pot} and T_L

Potential mantle temperature and lithosphere thickness

$$T_P = T \exp\left(-\frac{g\alpha z}{C_P}\right)$$

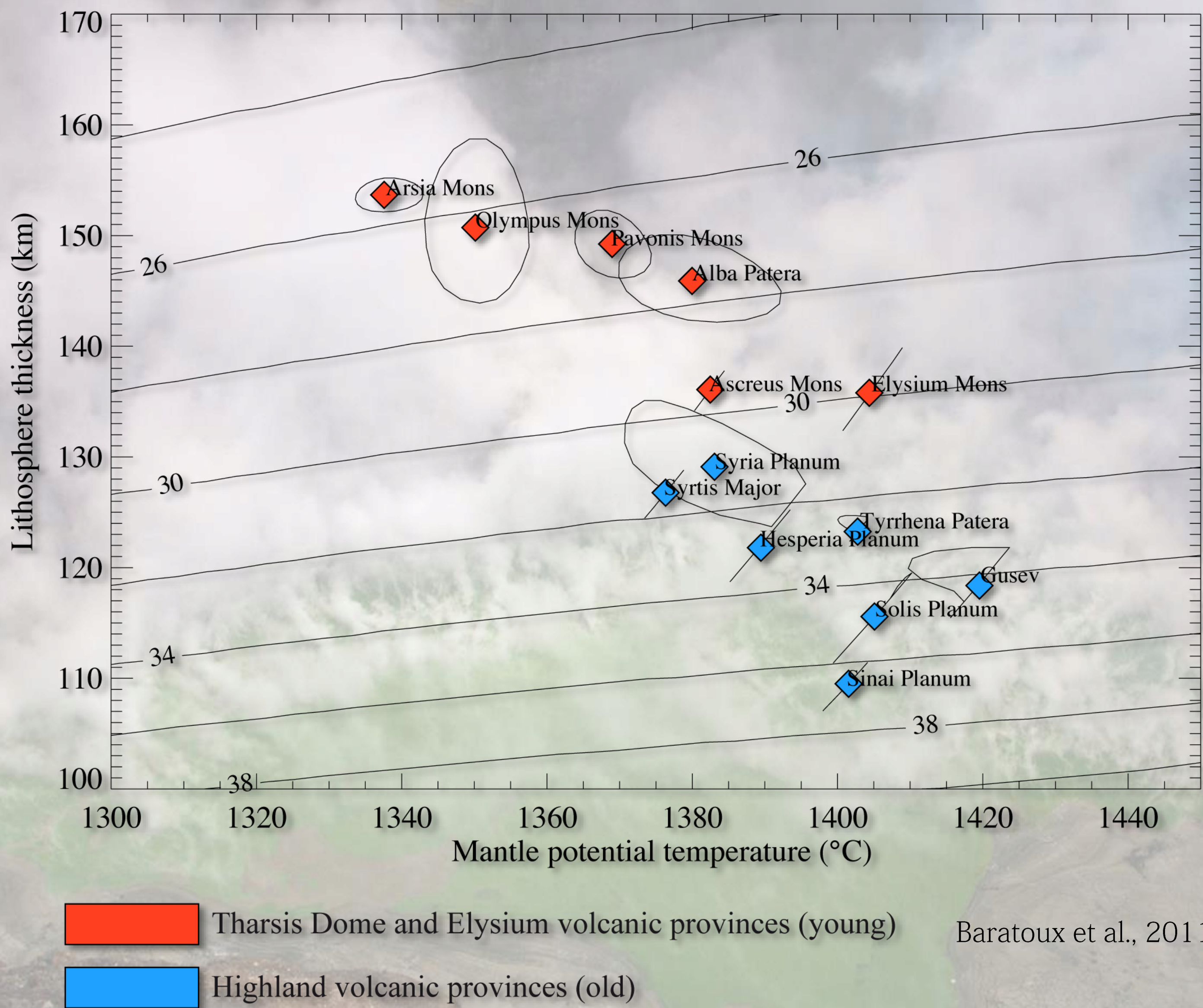


The petrological expression of Mars cooling history



Baratoux et al., 2011, Nature

The petrologic expression of Mars cooling history



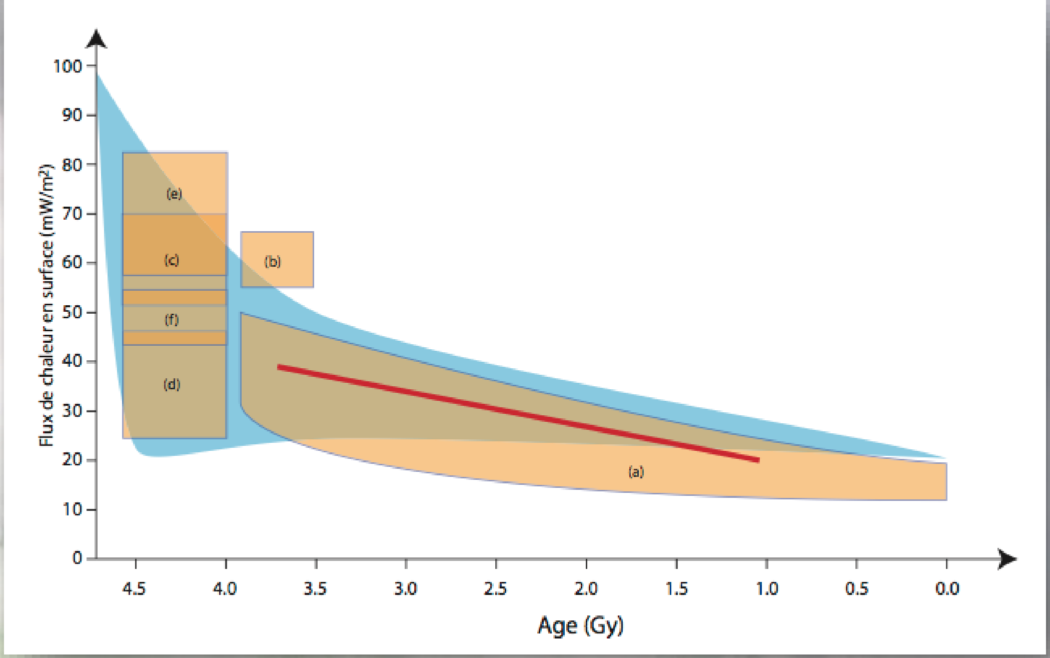
Baratoux et al., 2011 Nature

Martian mantle cooling rate

✓ Our results are compatibles with:

✓ Numerical modeling of mantle convection (Hauck and Philipps, 2002, Schumacher and Dreuer, 2005, Fraeman and Korenaga, 2010)

Thermal evolution from lithosphere elastic thicknesses constrained by gravity/topography data (Mc Govern et al., 2002, Belleguic et al., 2005, etc …).



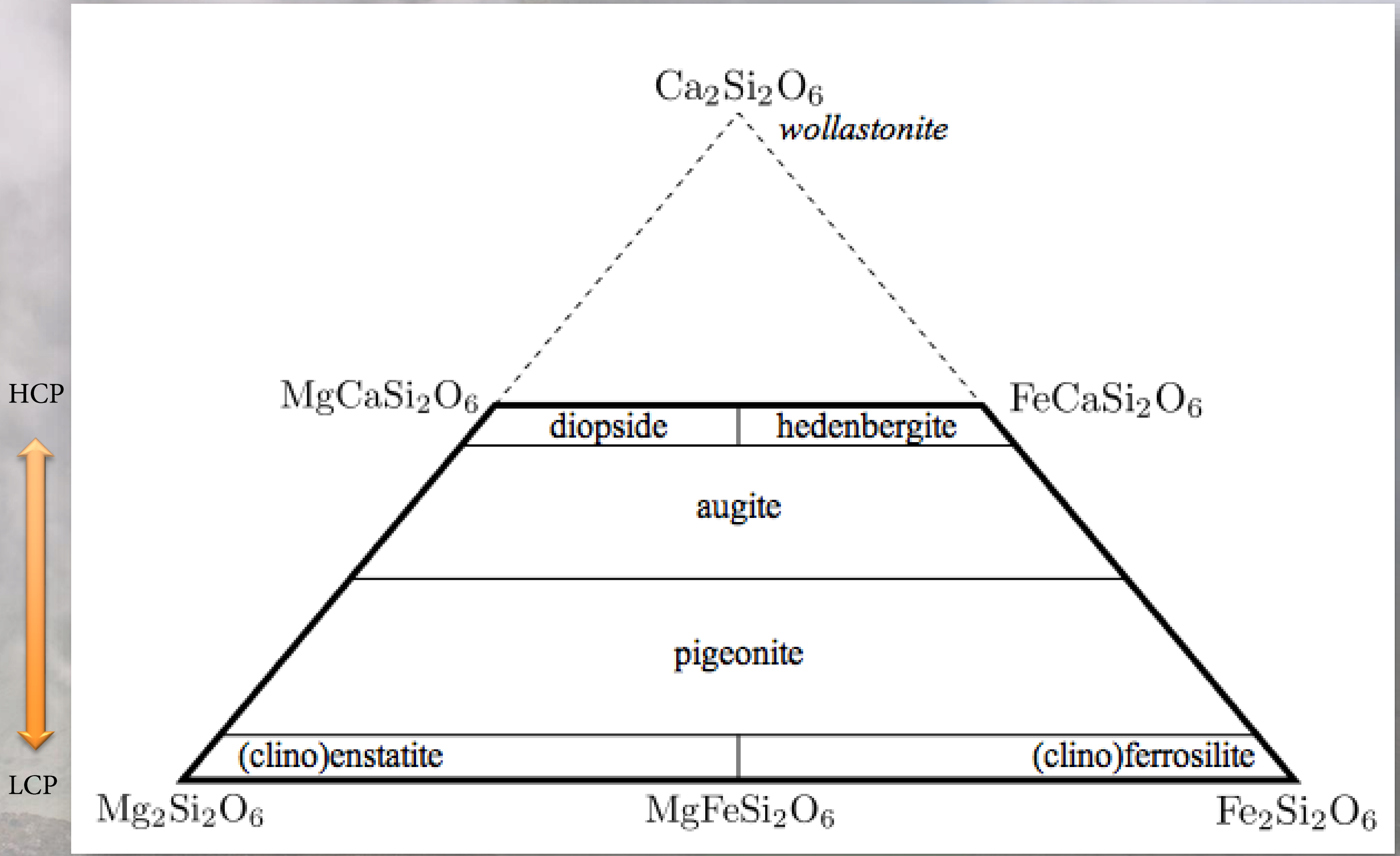
→ Martian cooling rate : 30 – 40 K / Gy
Terrestrial cooling rate : 50 – 100 K / Gy

Large uncertainty on the thermal state of the mantle in the Noachian

Geochemical expression of planetary cooling

Is there a mineralogical expression of planetary cooling ?

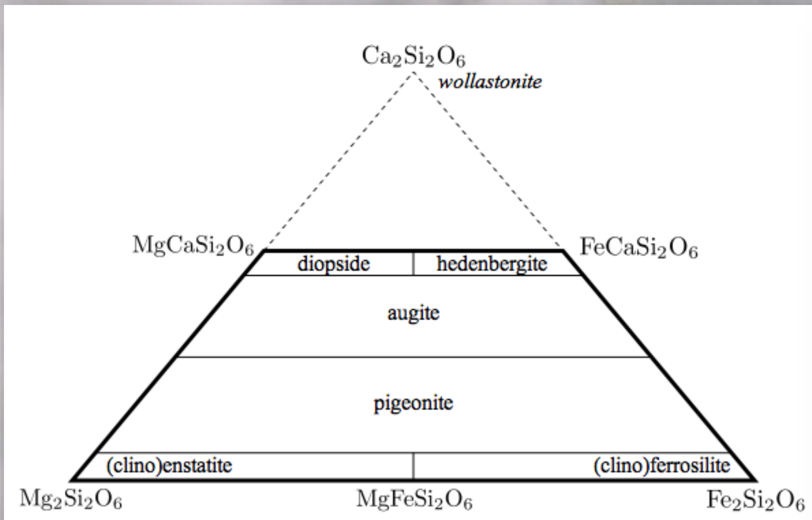
Pyroxenes – Vis/NIR spectroscopy can map pyroxene composition

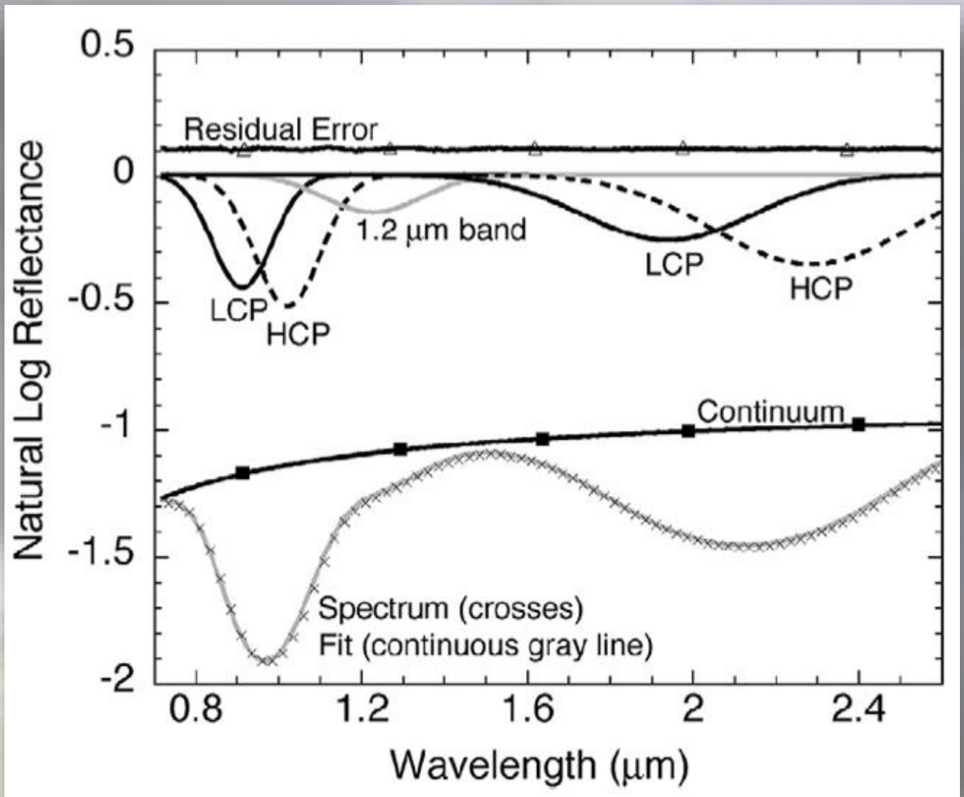


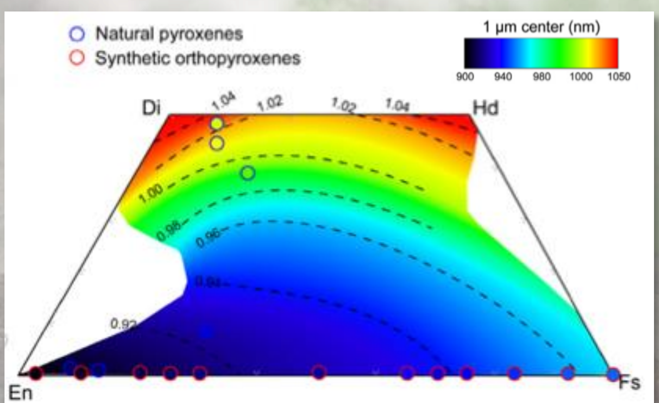
Pyroxenes – Vis/NIR spectroscopy can map pyroxene composition

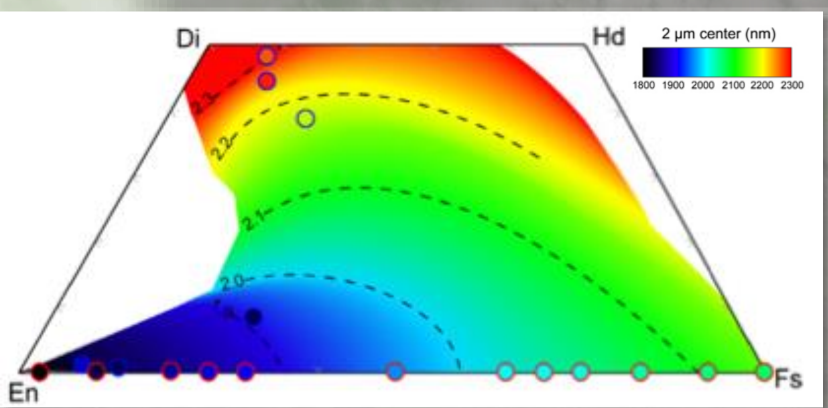
HCP

LCP



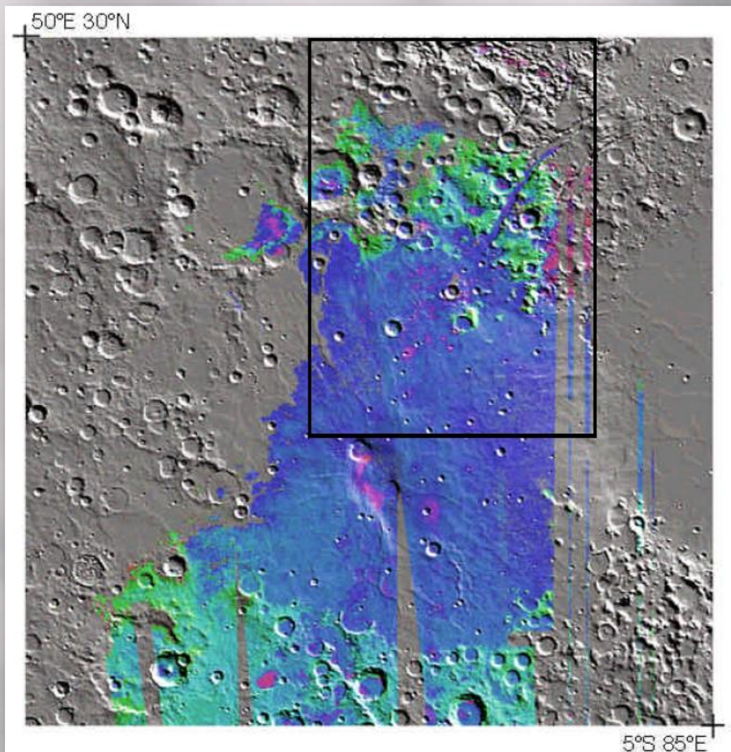




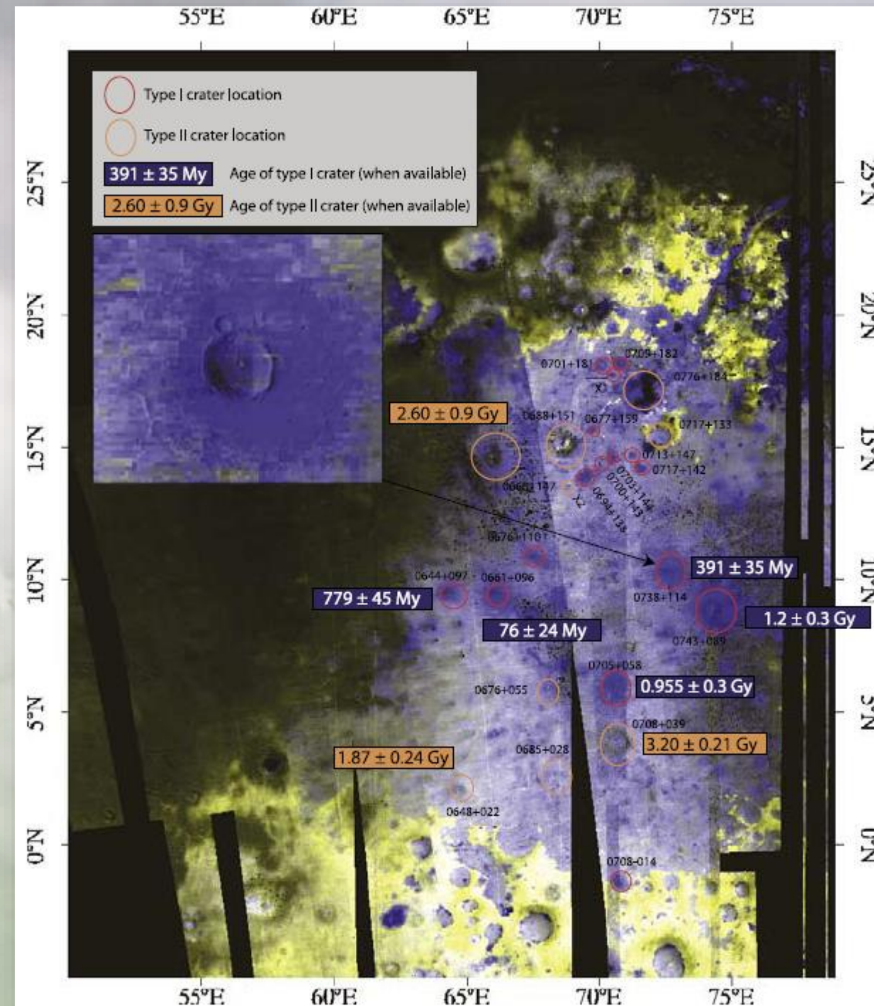


Clenet et al., 2011

A transition in pyroxene composition at the H/N boundary



Mustard et al., 2005 (LPSC)



Baratoux et al., 2007 (JGR-planets)

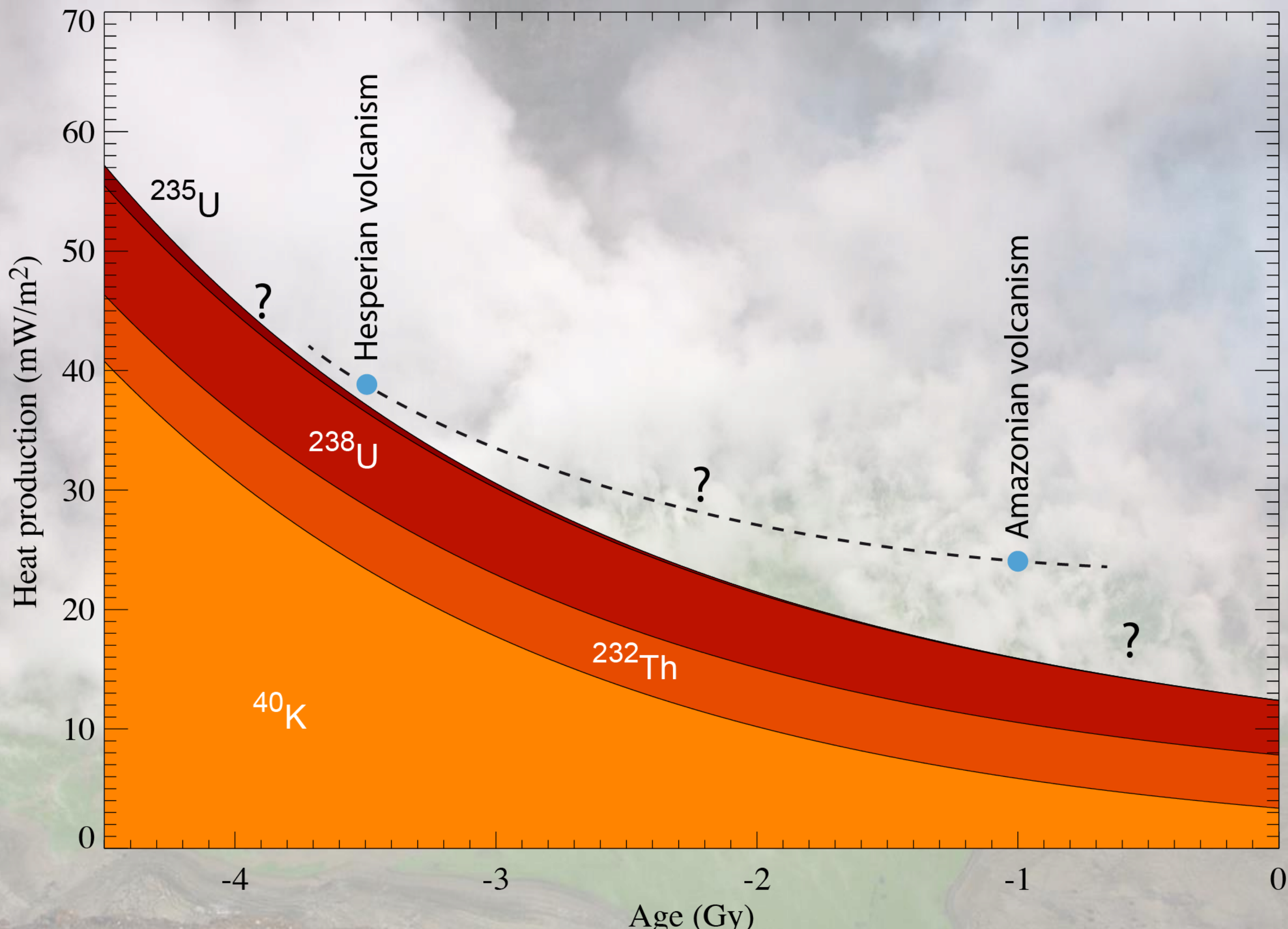
The mineralogy of the Noachian crust appears to be different

-Change in pyroxene composition
-Less plagioclase

HCP = High-Calcium-Pyroxene
LCP = Low-Calcium-Pyroxene

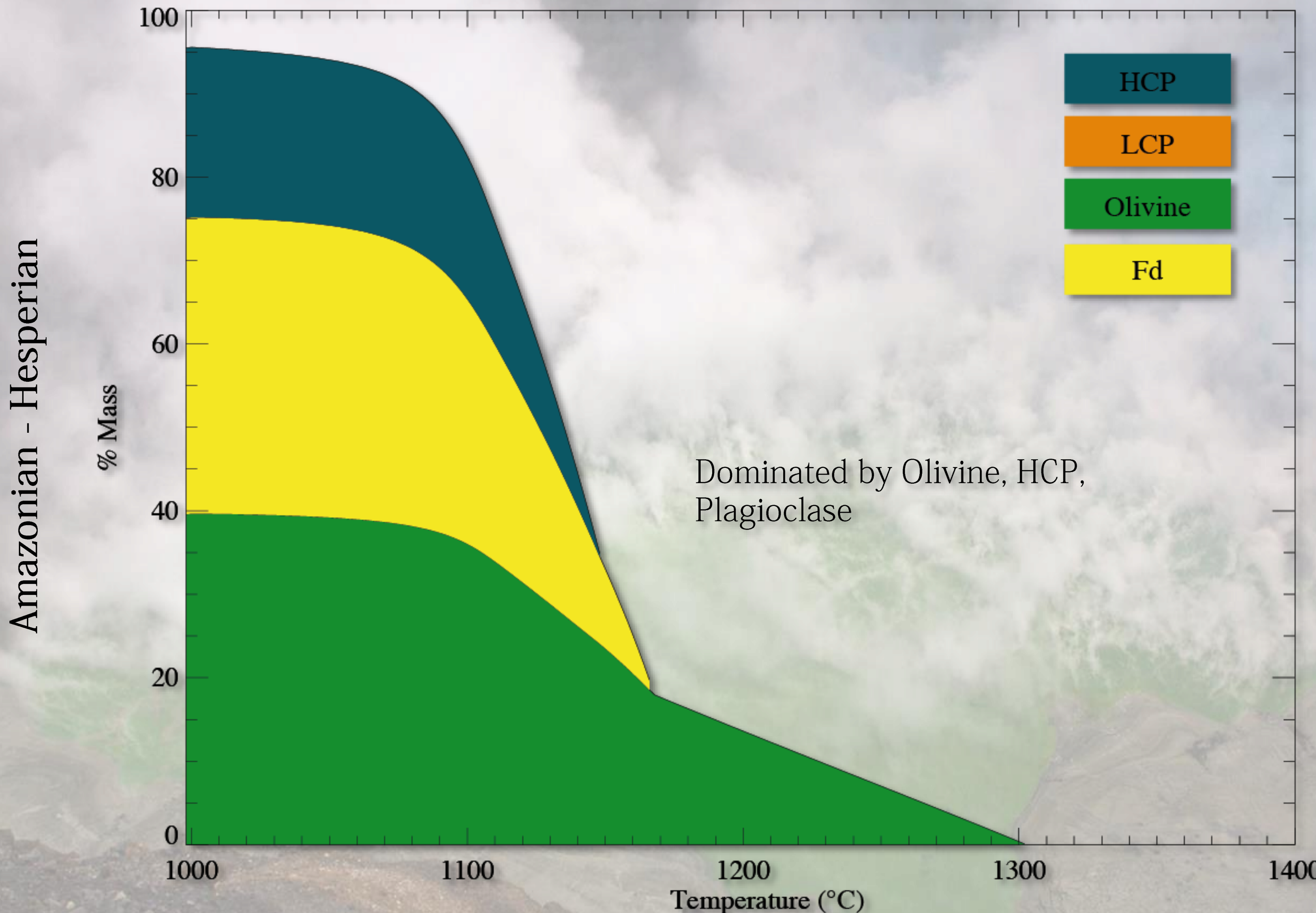
Heat producing elements as a function of time

More HPE during early Mars -> ancient mantle should be warmer



Thermal evolution of Mars

Prediction of partial melts composition and crystallization assemblages



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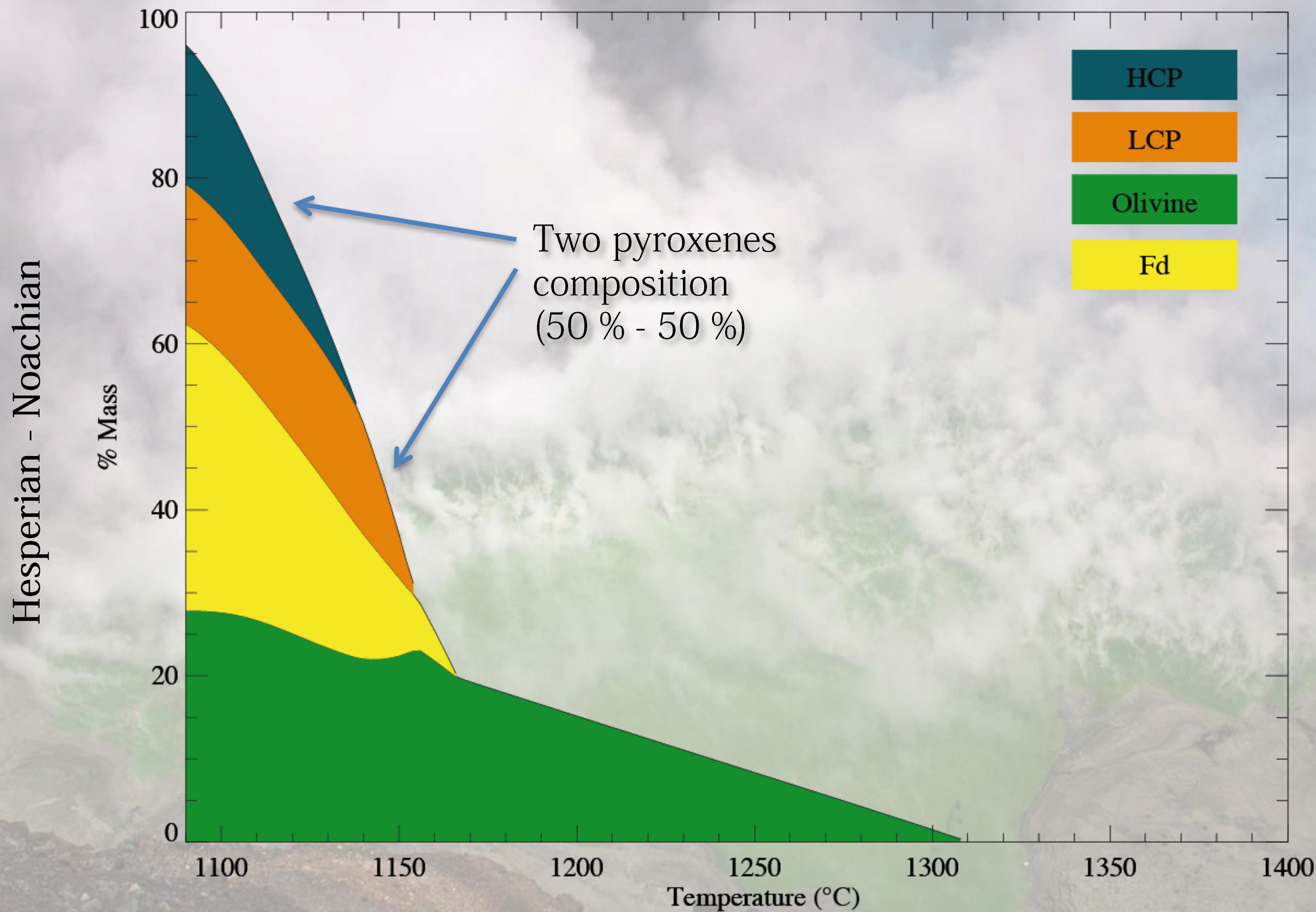

Thermal evolution of Mars

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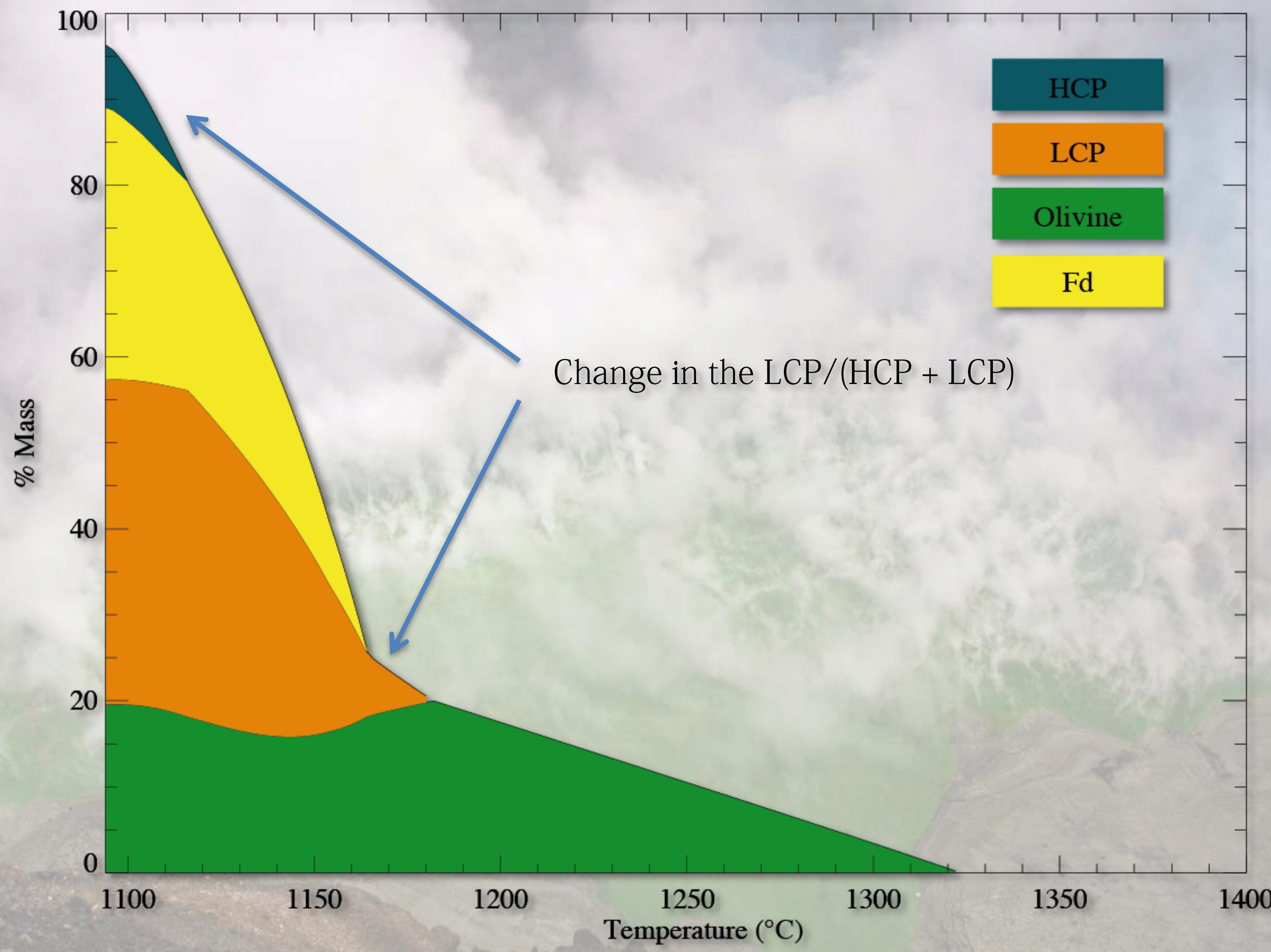
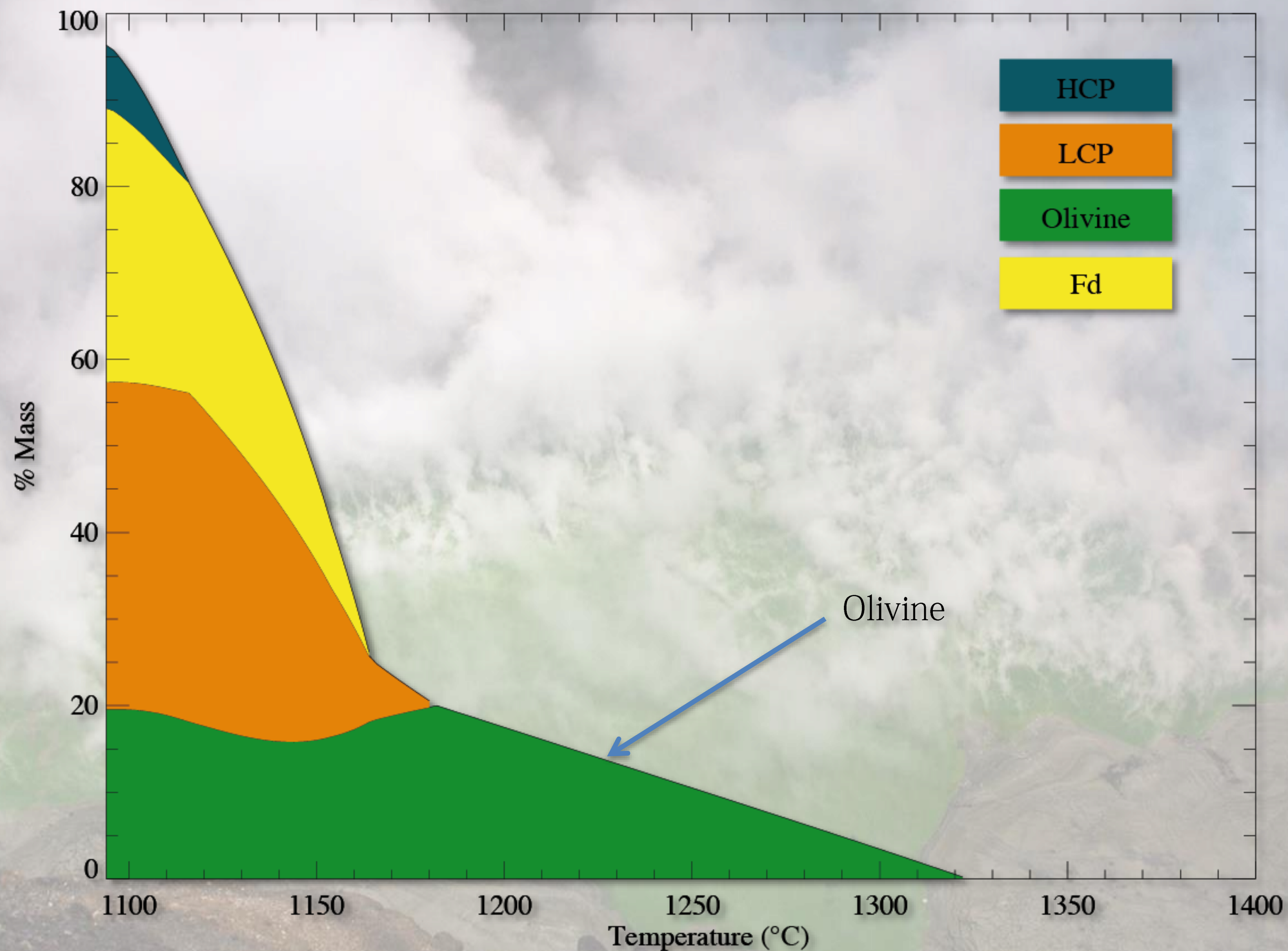
Noachian - ?



Thermal evolution of Mars

Prediction of partial melts composition and crystallization assemblages

Noachian - ?



Thermal evolution of Mars

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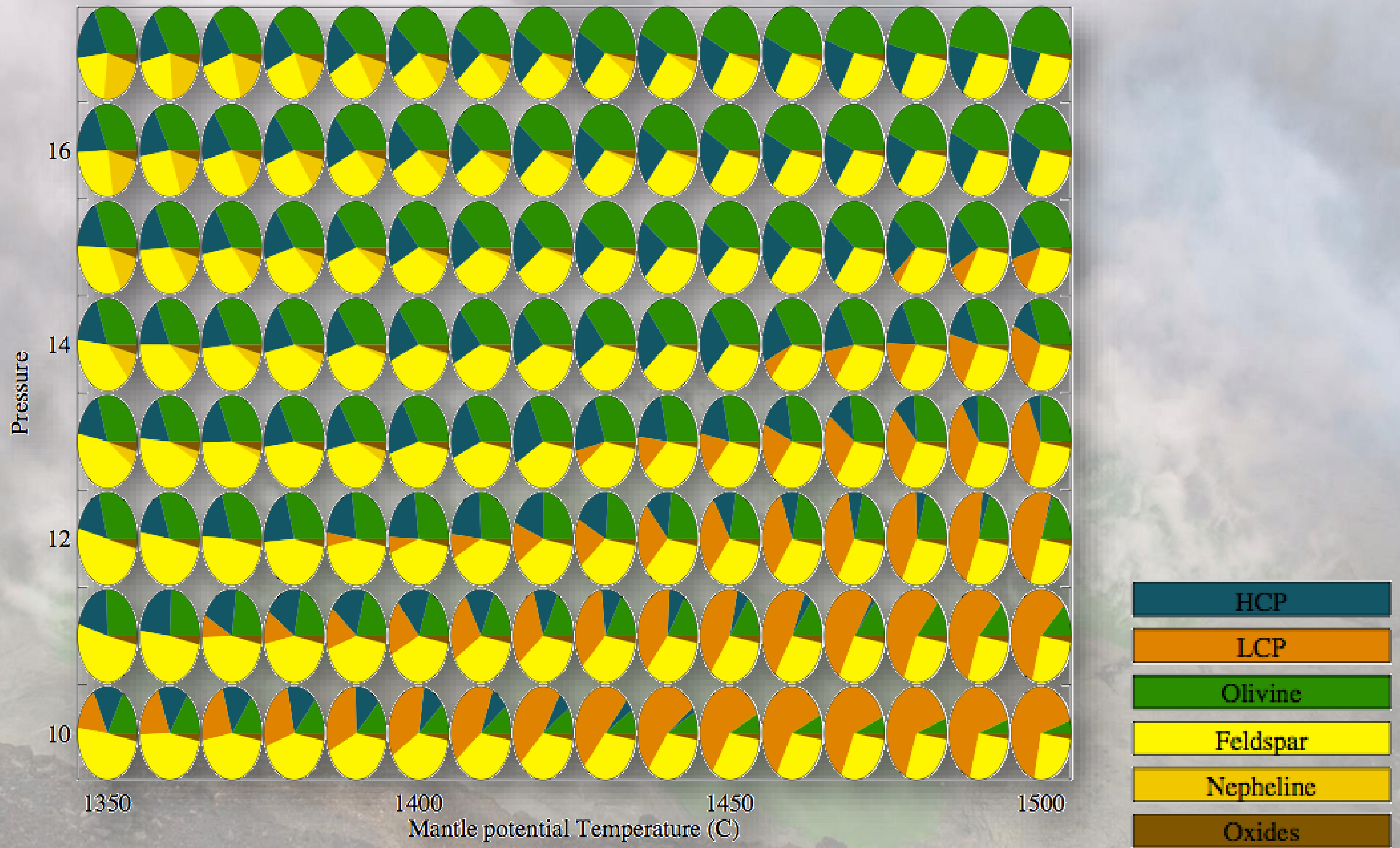
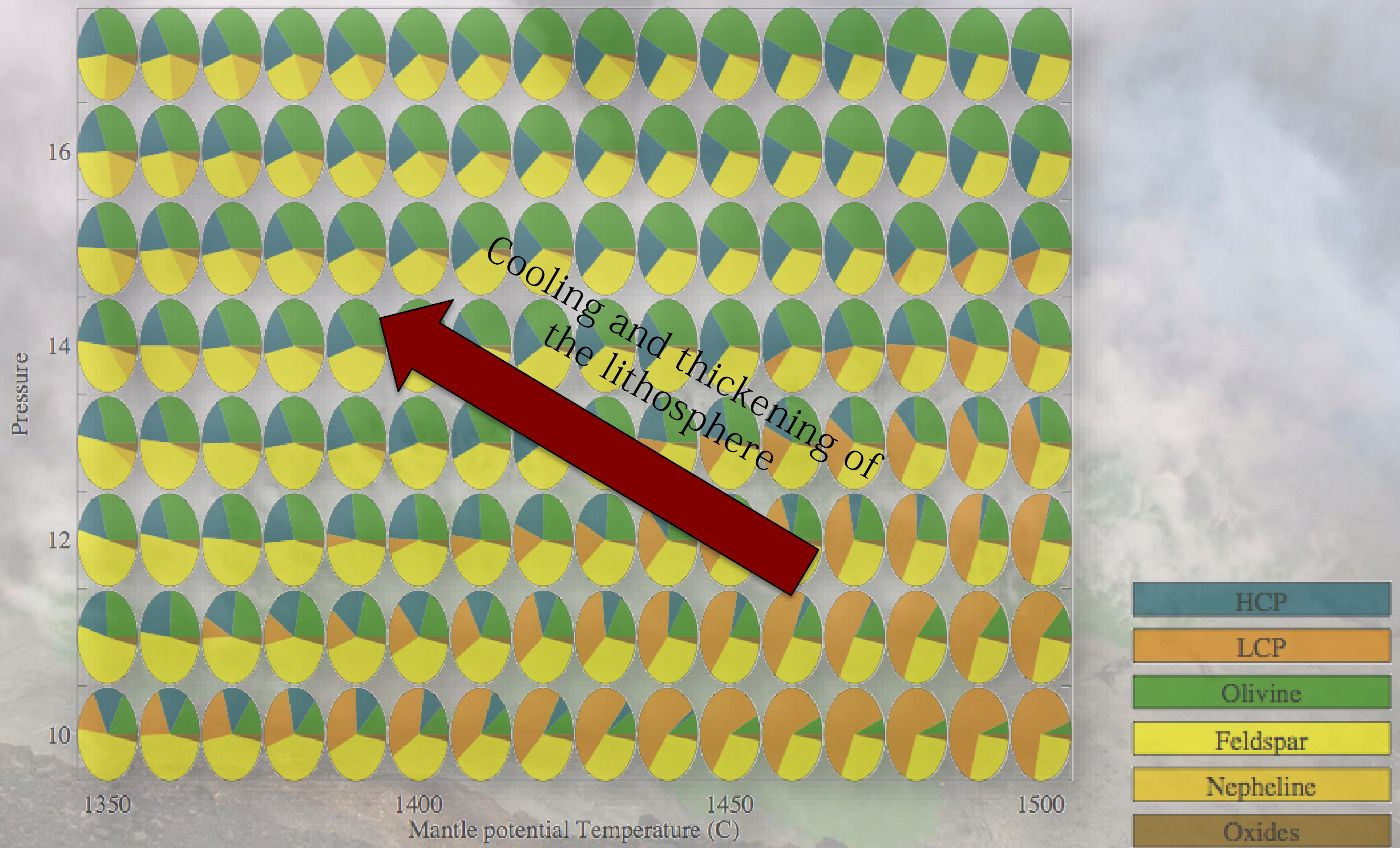


D. Baratoux - Kobe University, 15th – 16th June 2016

Thermal evolution of Mars

Prediction of partial melts composition and crystallization assemblages



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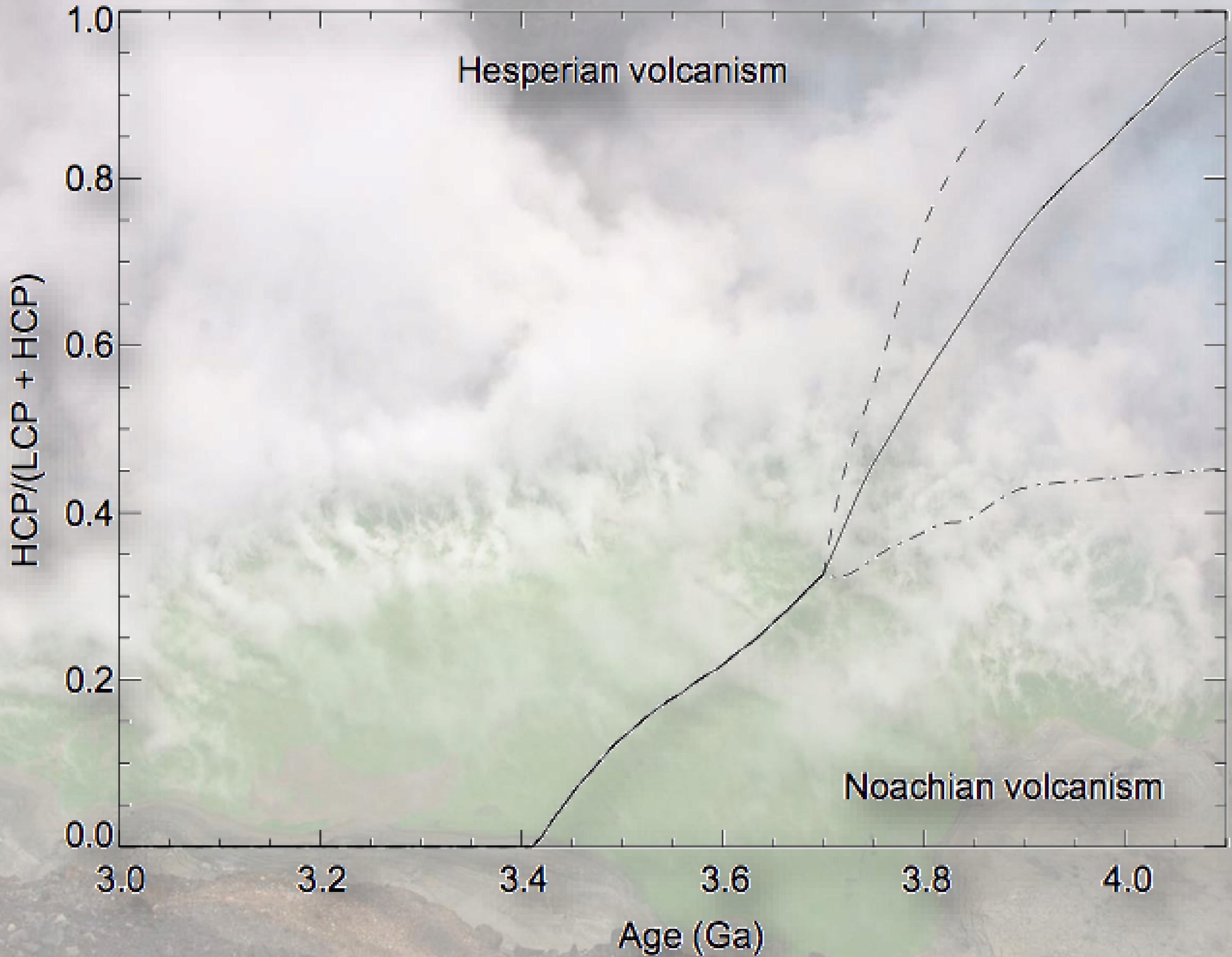
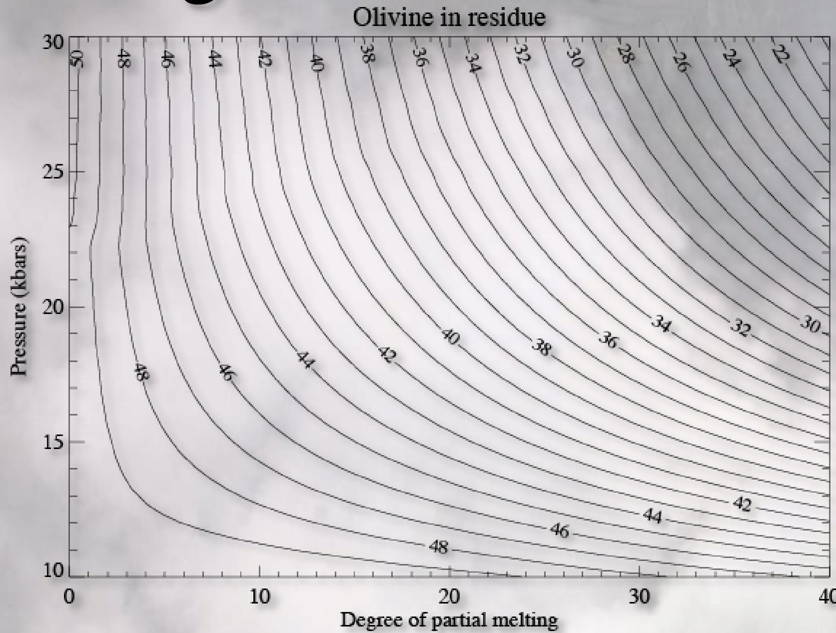
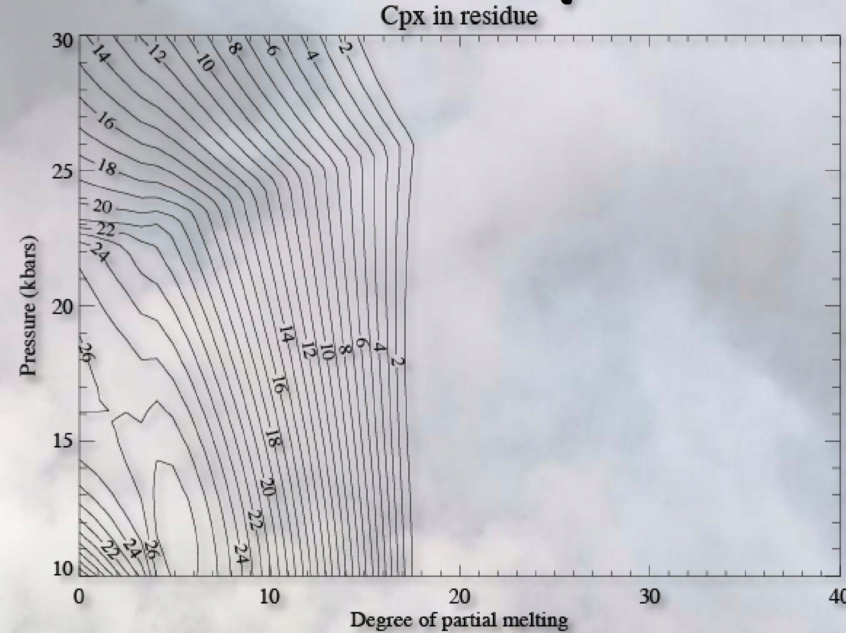
Thermal evolution of Mars

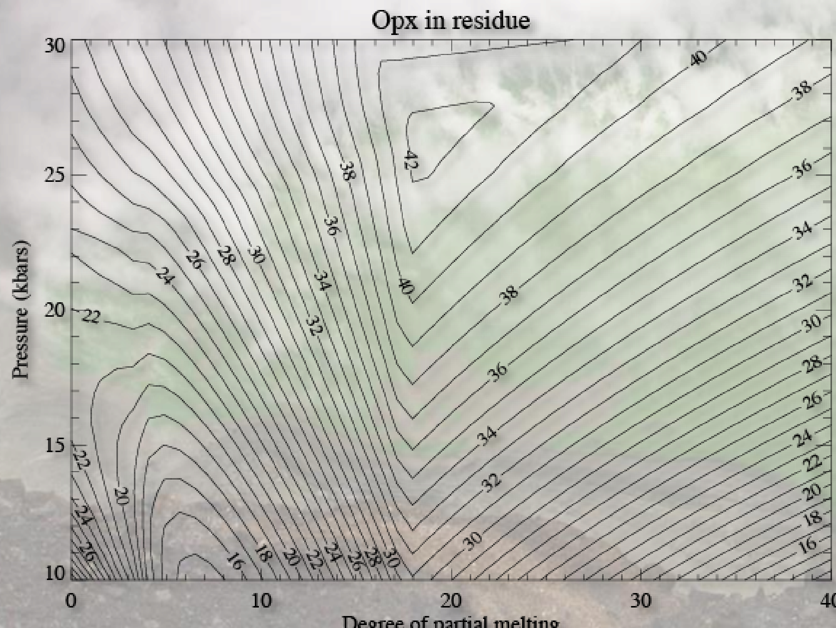
A natural evolution of the LCP/(HCP + LCP) ratio



Change in LCP/(HCP + LCP) ratio – why ?







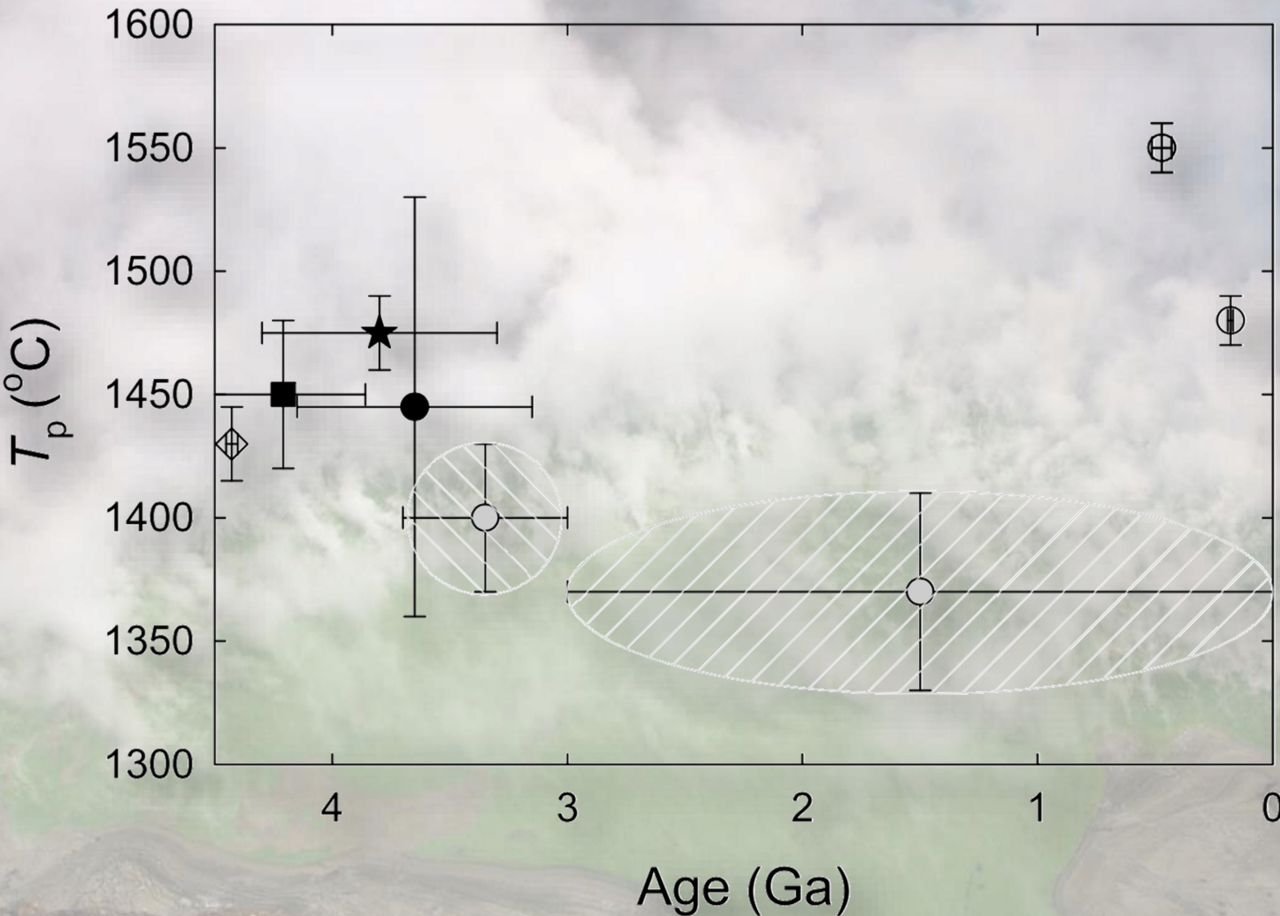
18 % partial melting > 100% of Cpx in the liquid

> Opx starts to melt

18 % partial melting achieved
for Tpot ~1420°C and P = 13 kbars

Conclusion (preliminary)

Basaltic material on Mars consistent with simple convective cooling of the mantle



Filiberto et al. 2015 – JGR Planets