Thermal and Dynamic History of Planets
Planetary Volcanism and Crustal Evolution

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Day 2 – The thermal evolution of Mars

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

Part II – Petrological constraints on the thermal evolution of the mantle

<u>Part III – Outstanding questions</u>

Continental crust on Mars
Pieces of evidence and implications

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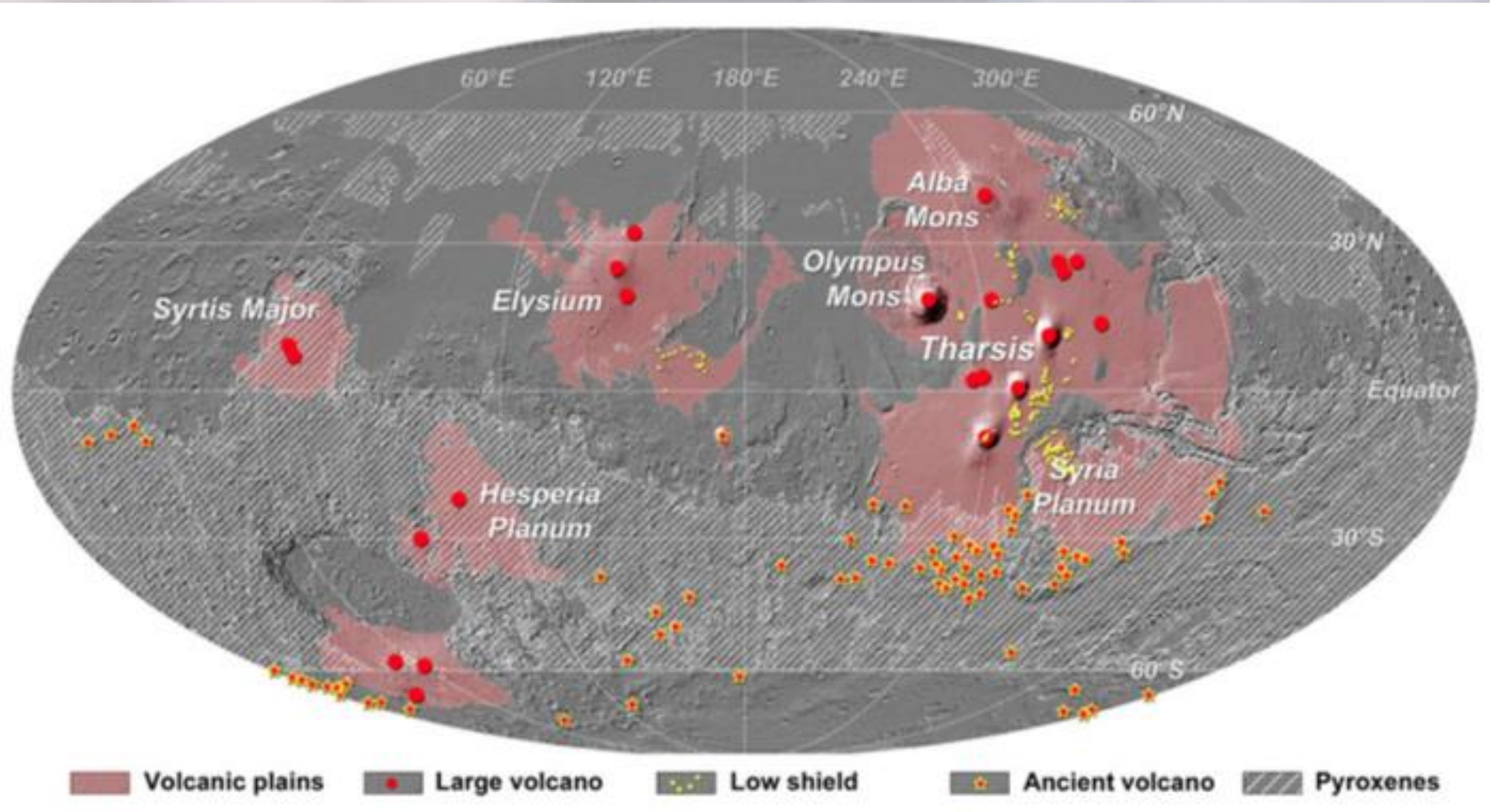
In situ evidence for continental crust on early Mars

V. Sautter[1*], M. J. Toplis[2], R. C. Wiens[3], A. Cousin[2], C. Fabre[4], O. Gasnault[2], S. Maurice[2], O. Forni[2], J. Lasue[2], A. Ollila[5], J. C. Bridges[6], N. Mangold[7], S. Le Mouélic[8], M. Fisk[9], P.-Y. Meslin[2], P. Beck[9], P. Pinet[2], L. Le Deit[7], W. Rapin[2], E. M. Stolper[10], H. Newsom[11], D. Dyar[12], N. Lanza[3], D. Vaniman[13], S. Clegg[3] and J. J. Wray[14]

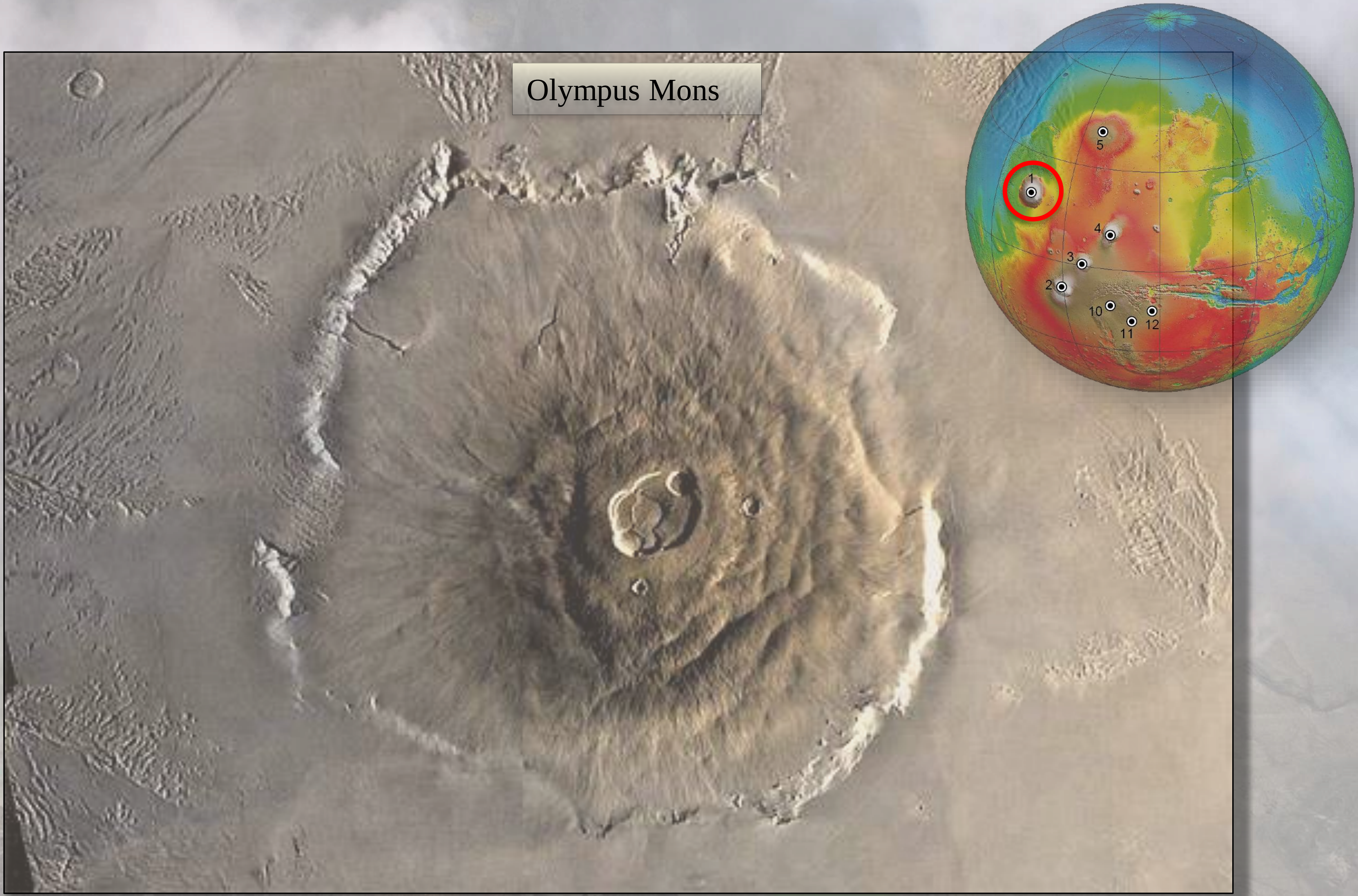
Why was this finding important with respect to our previous knowledge of Mars surface ?

4 billions of years of basaltic volcanism

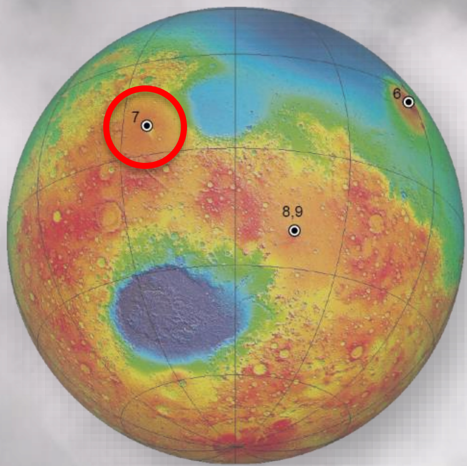


Grott et al. 2013, Space Science Reviews

4 billions of years of basaltic volcanism



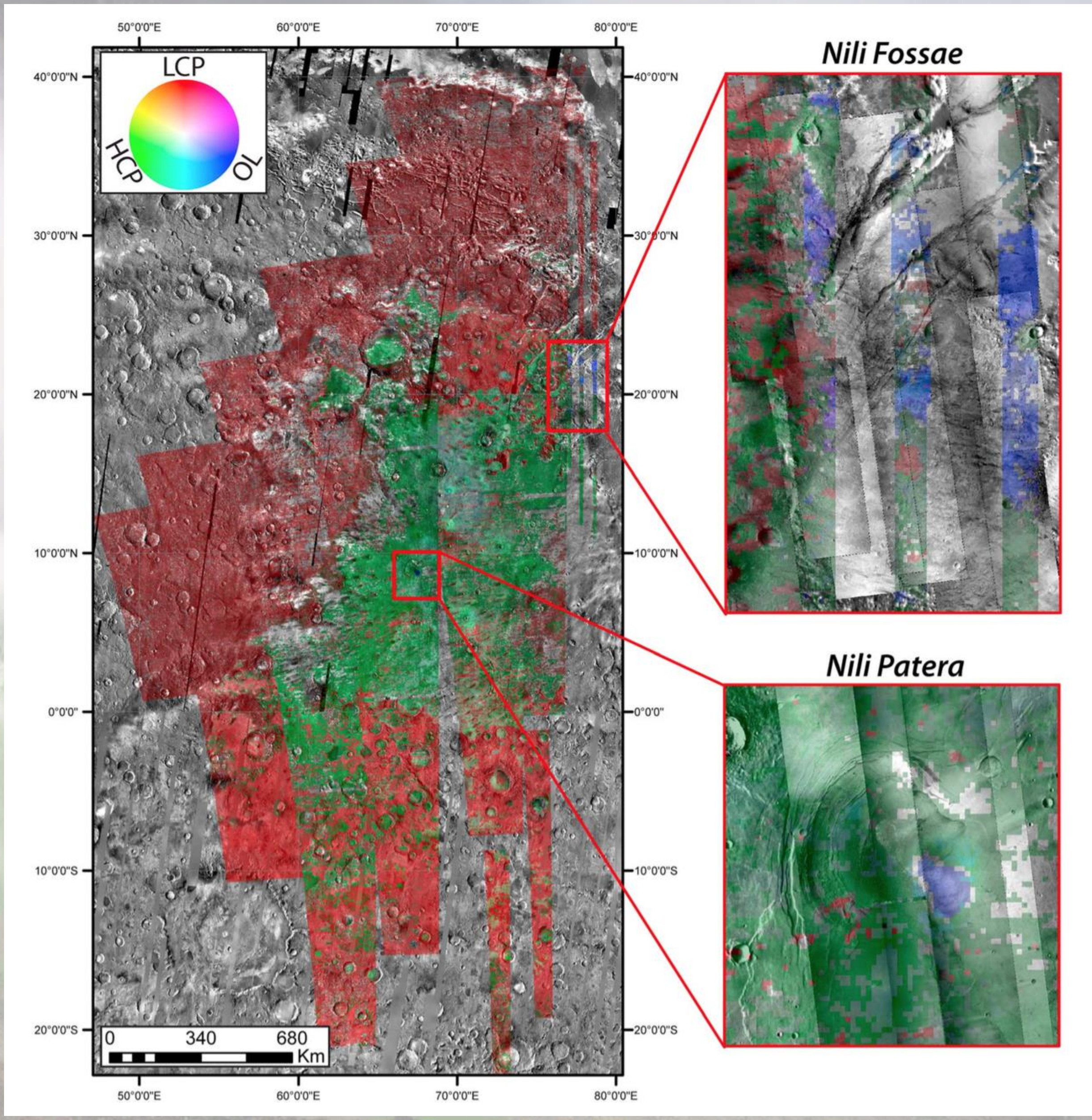
4 billions of years of basaltic volcanism



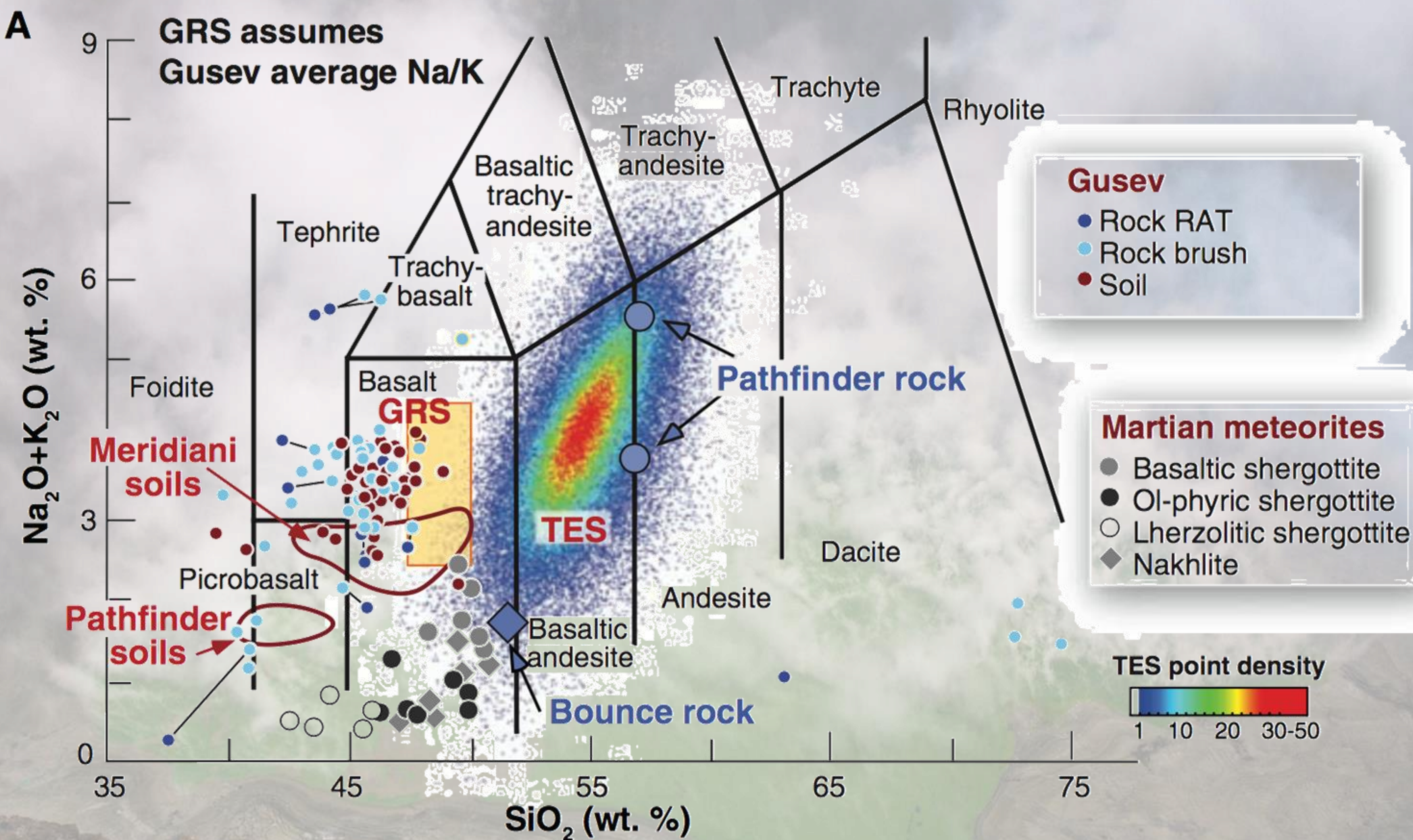
Surface mineralogy

Mafic minerals: pyroxenes
HCP = High-Calcium Pyroxene
LCP = Low-Calcium-Pyroxene
OL = Olivine

Deconvolution of visible/near IR spectroscopic images of the surface of the Syrtis Major volcano.
Clenet et al. 2013

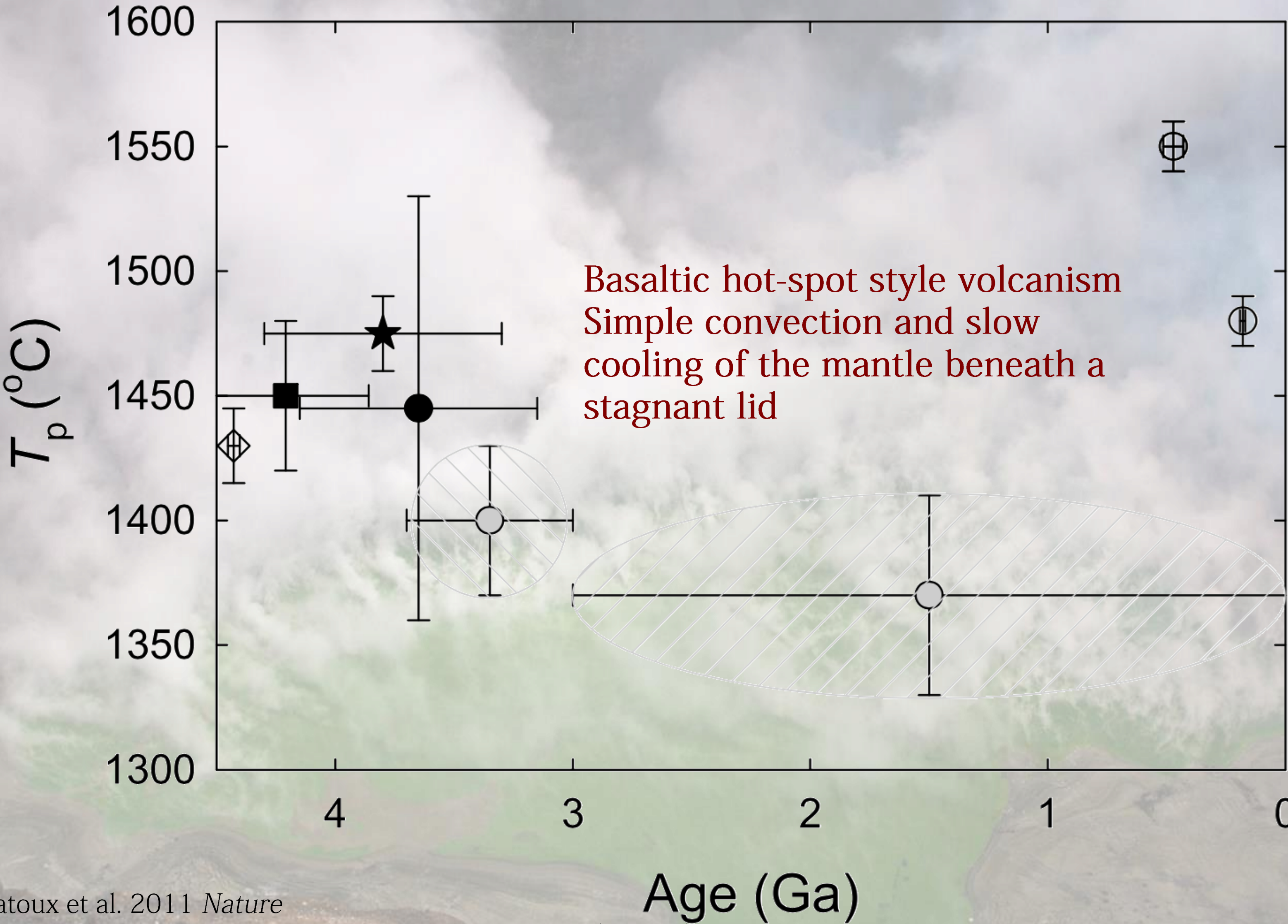


4 billions of years of basaltic volcanism



McSween et al. 2009, Science

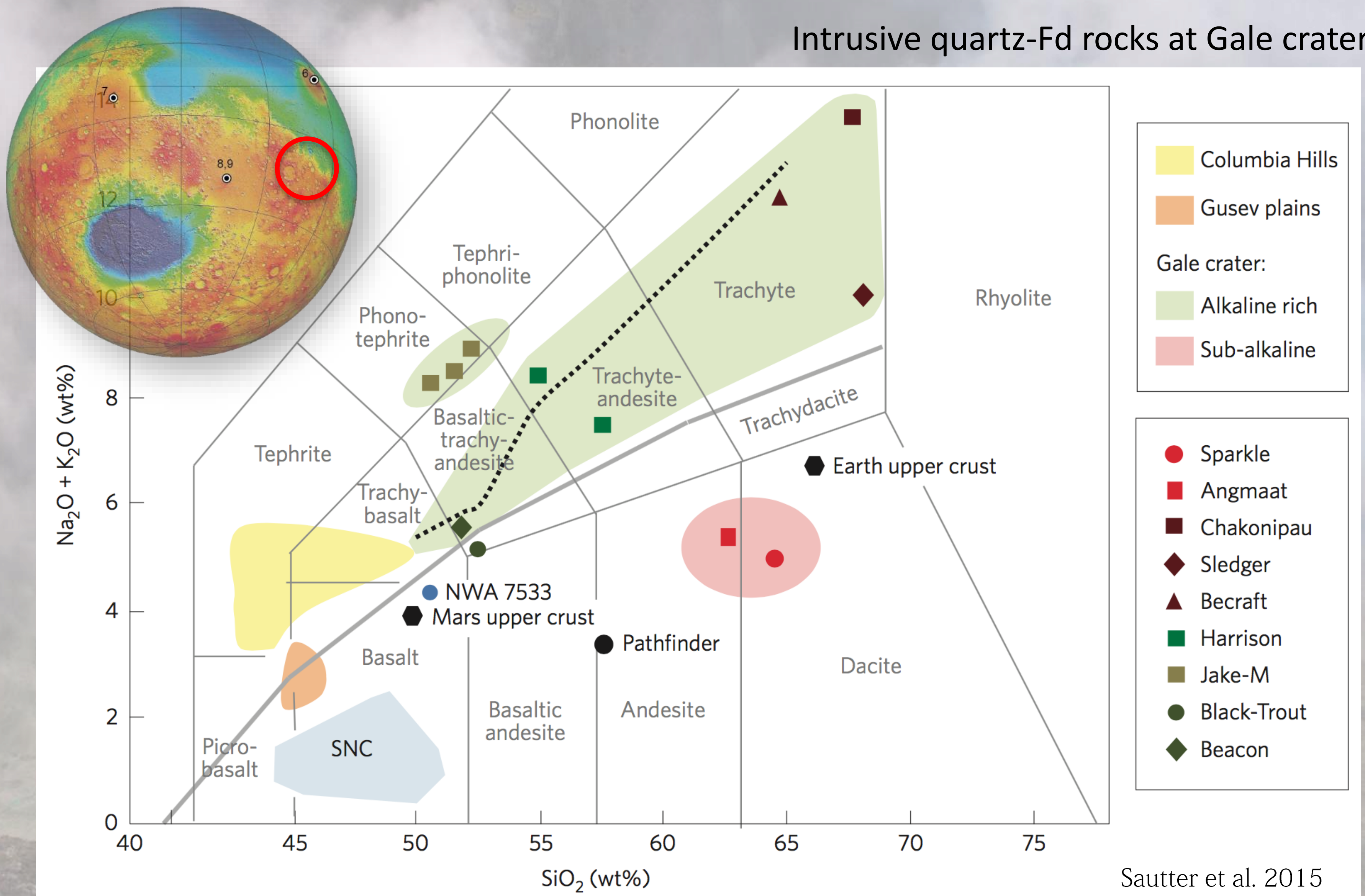
4 billions of years of basaltic volcanism



Baratoux et al. 2011 *Nature*
Baratoux et al. 2013 *Journal of Geophysical Research (Planets)*
Filiberto et al. 2015 *Journal of Geophysical Research (Planets)*

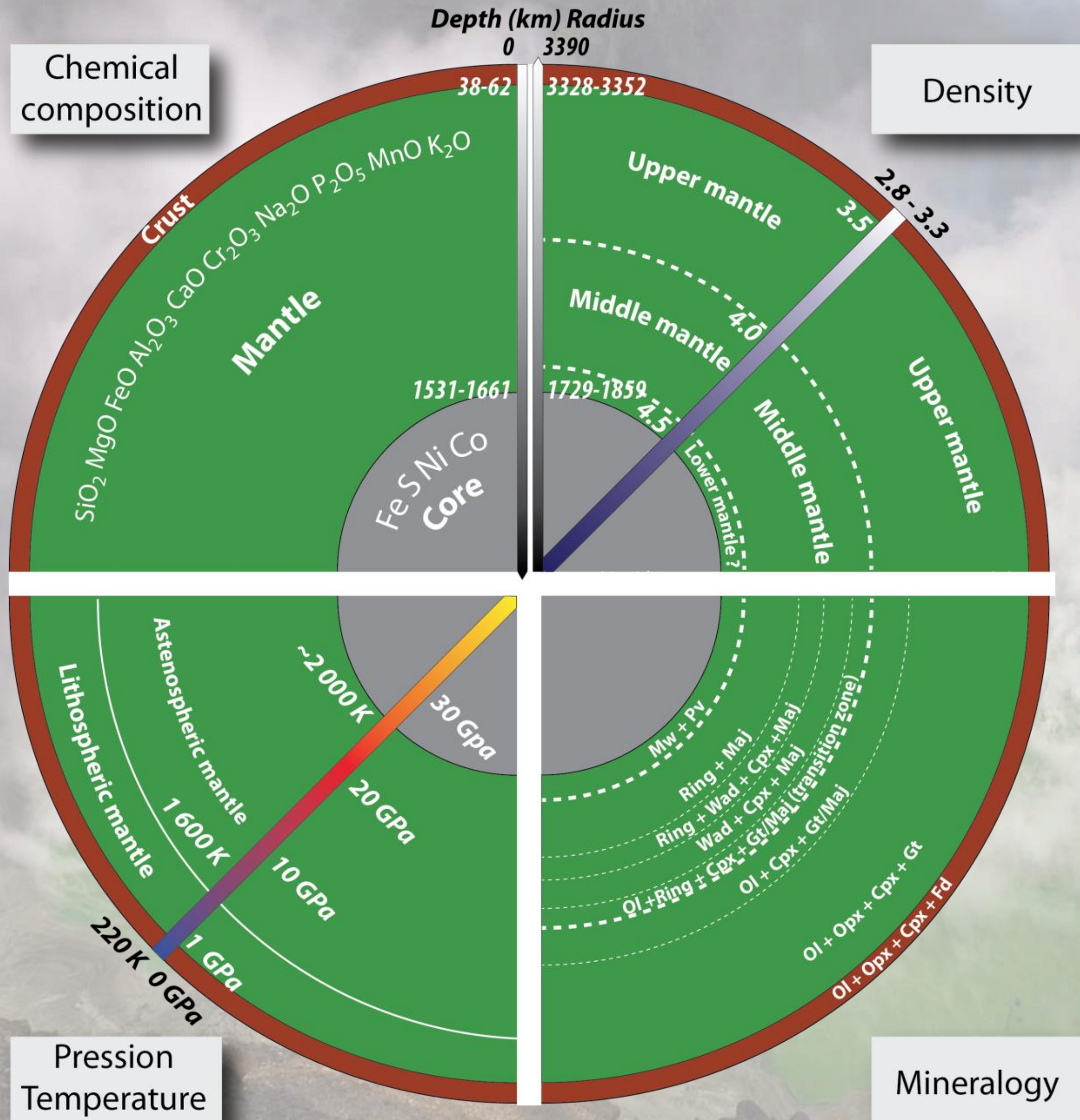
… and now igneous diversity at Gale crater !

Intrusive quartz-Fd rocks at Gale crater



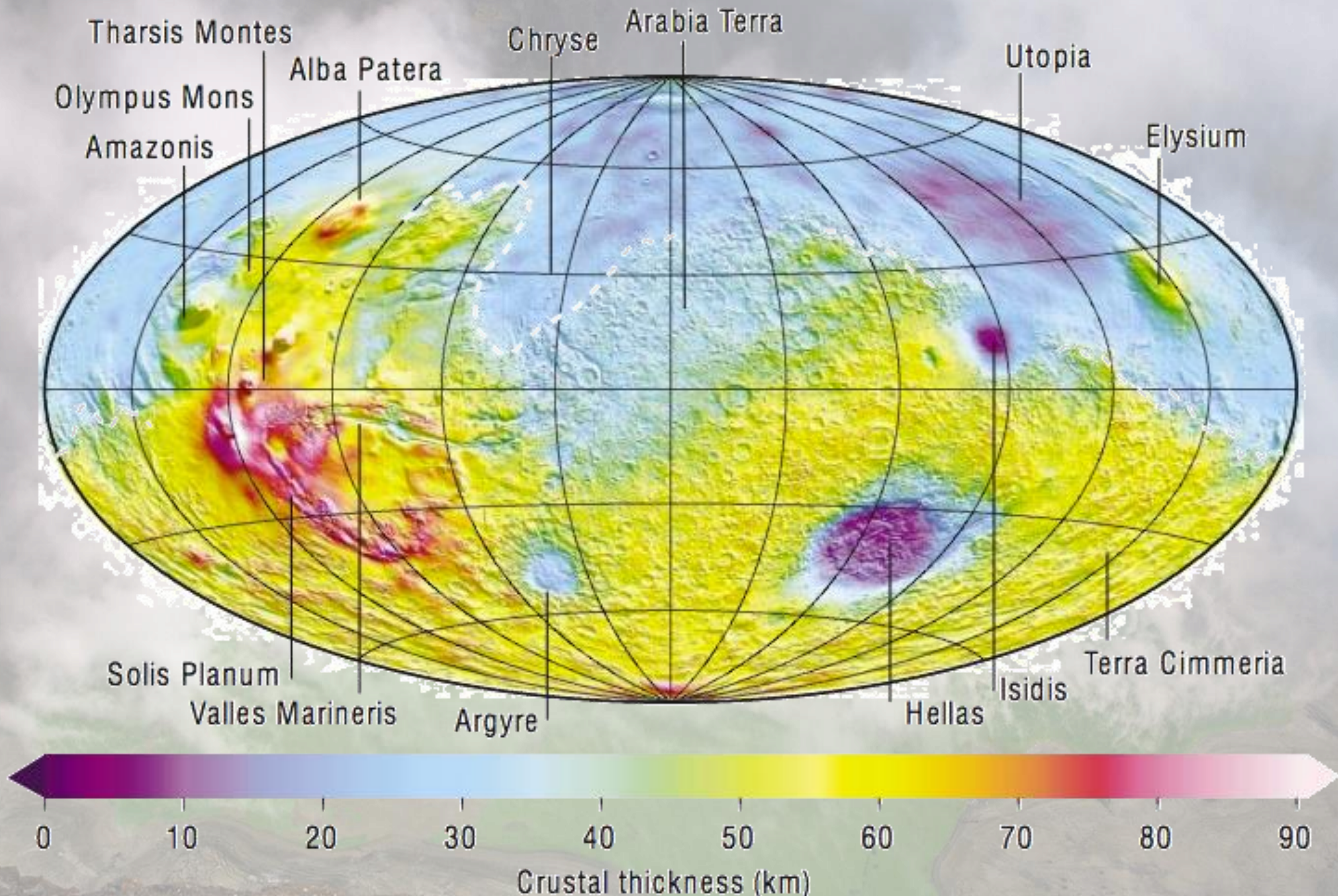
Sautter et al. 2015

What do we know about Mars interior ?



Mangold, N. Baratoux, D., Encrenaz, T., Witasse, O., Sotin. C. Mars: a terrestrial planet. Astronomy and Astrophysics Reviews (in prep)

What do we know about Mars interior ?



The density and thickness of the Martian crust

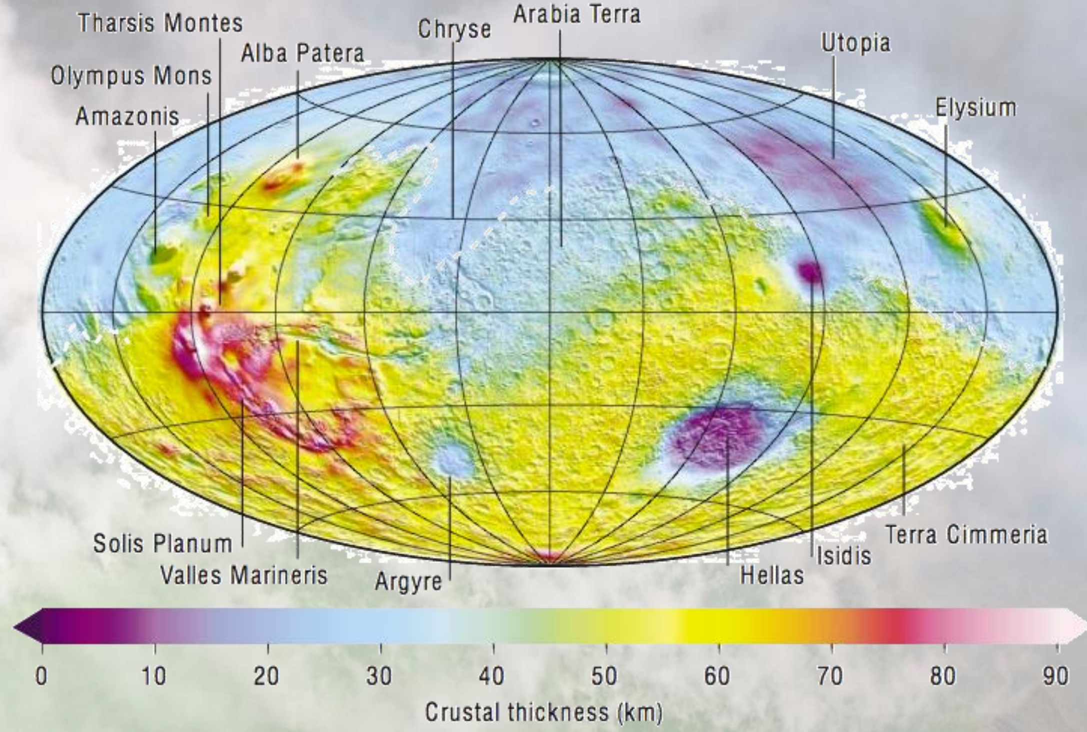
Crustal thickness maps from gravity and topography

<u>Main hypotheses :</u>

Crust is dominated by basalts

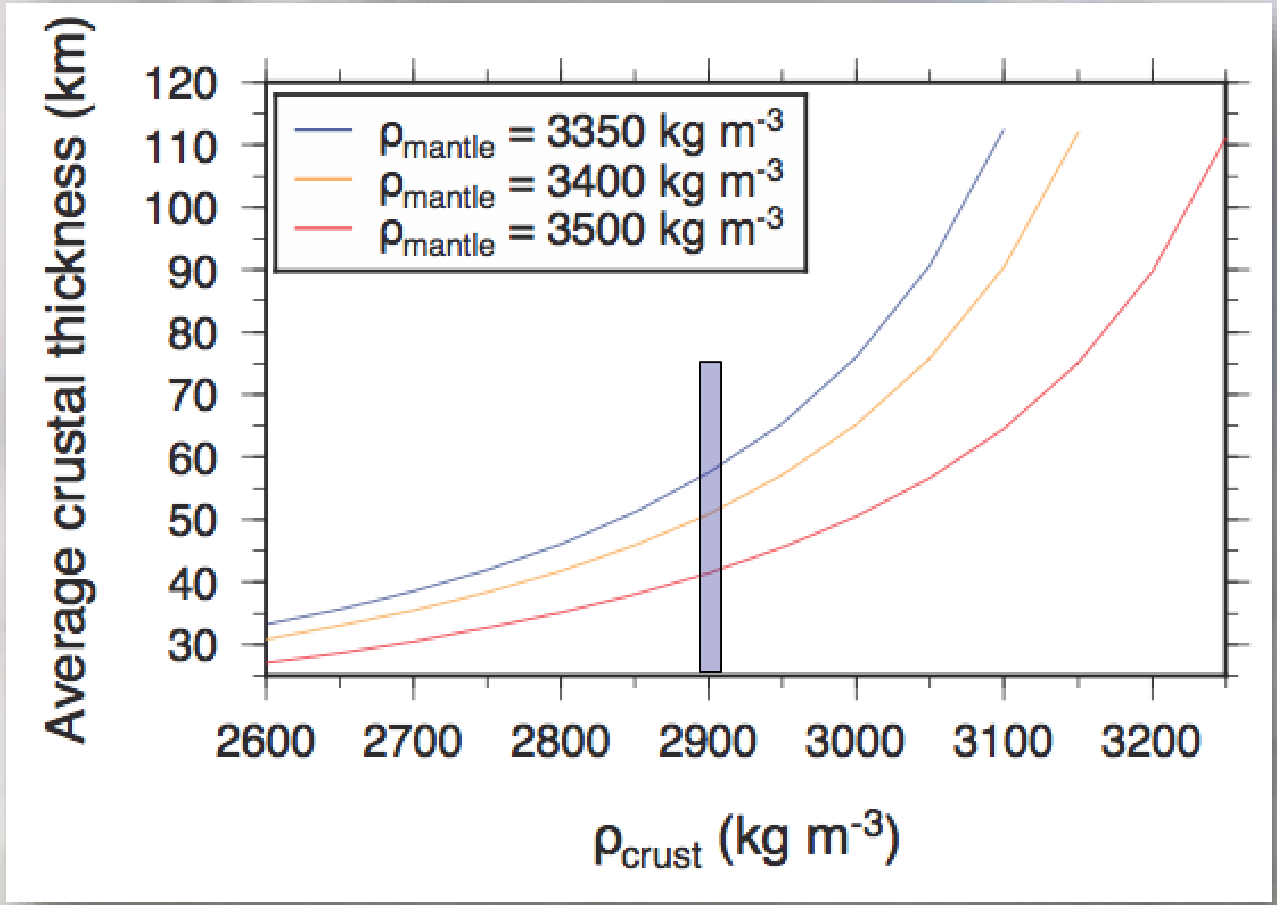
Density if 2900 kg/m^3

Calculations made 10 years ago…before most of the mineralogical observations



Zuber et al., 2000, Neumann et al., 2004

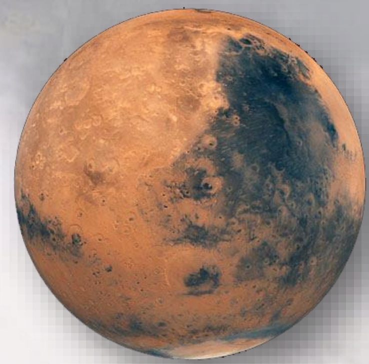
A trade-off between crustal density and thickness



Baratoux et al., 2014, Journal of Geophysical Research (Planets)

What is the composition/structure of the crust ?

When did the crust form ?

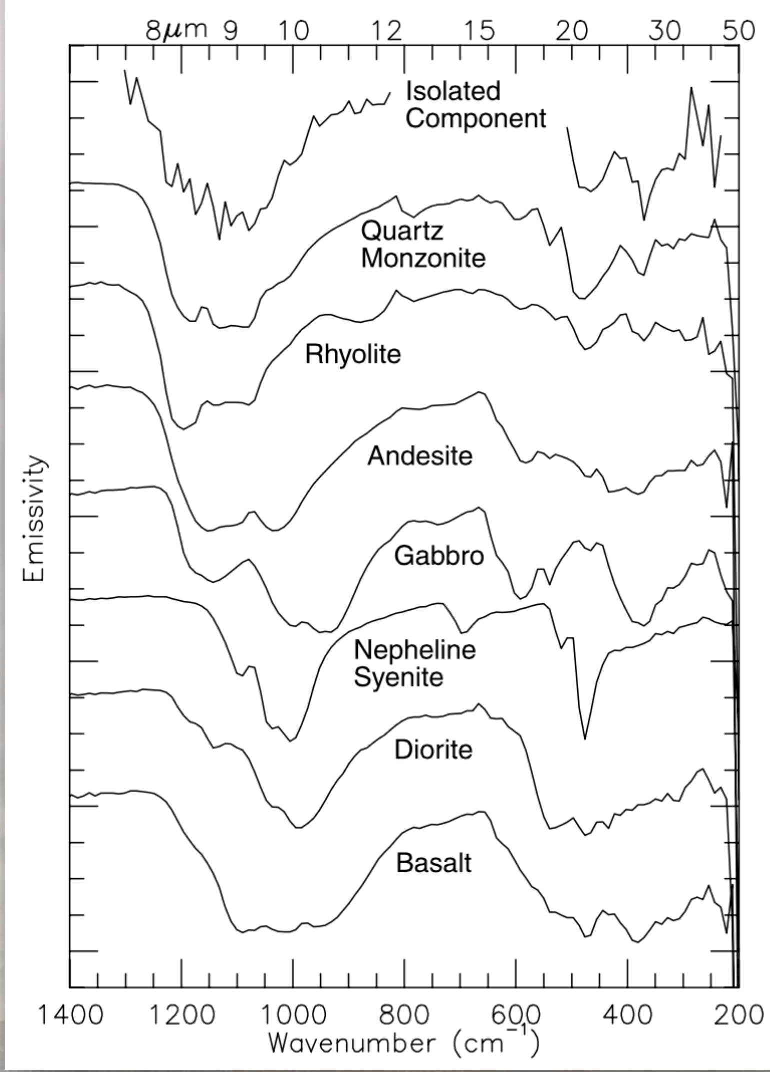


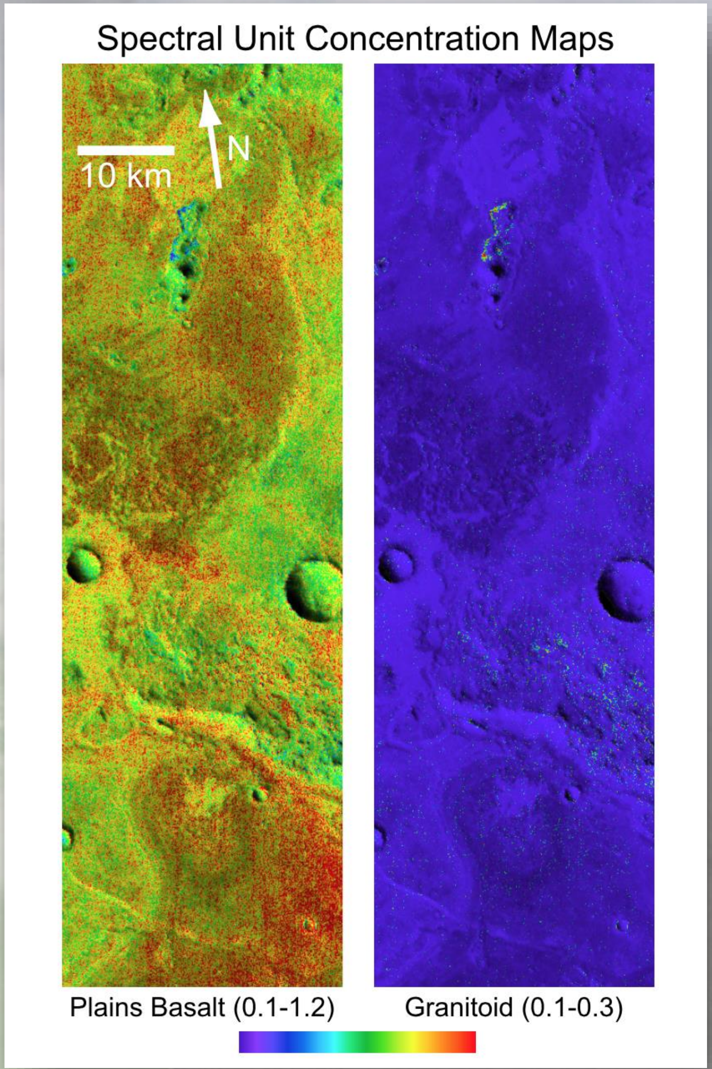
Was it really the first evidence for continental crust on early Mars ?

Can we extrapolate this "local" story to the entire crust ?

Quartzo-feldspathic material have been identified 10 years ago

Central peak, impact crater (Syrtis Major)

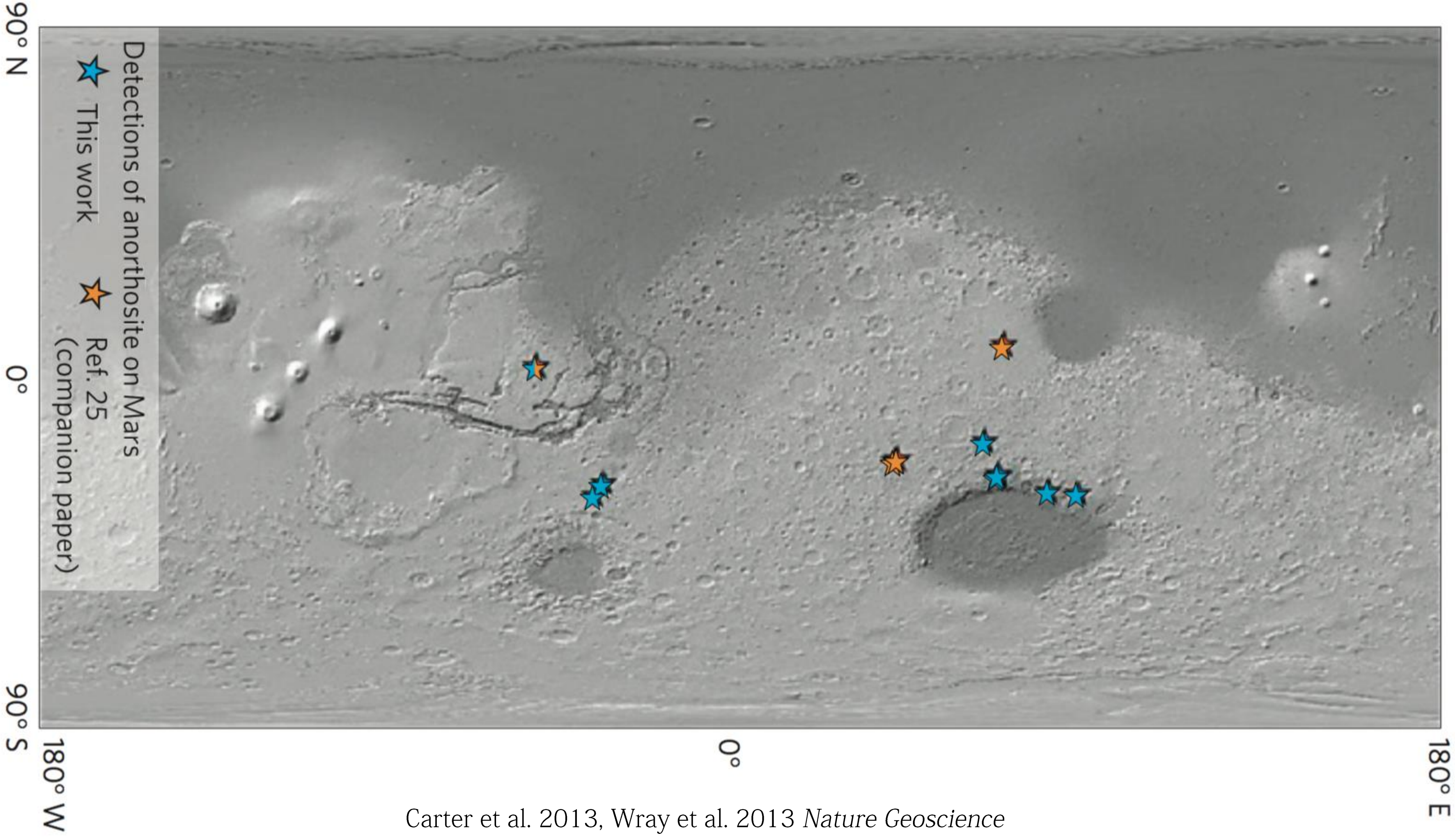




Bandfield et al. 2004 Journal of Geophysical Research Letters

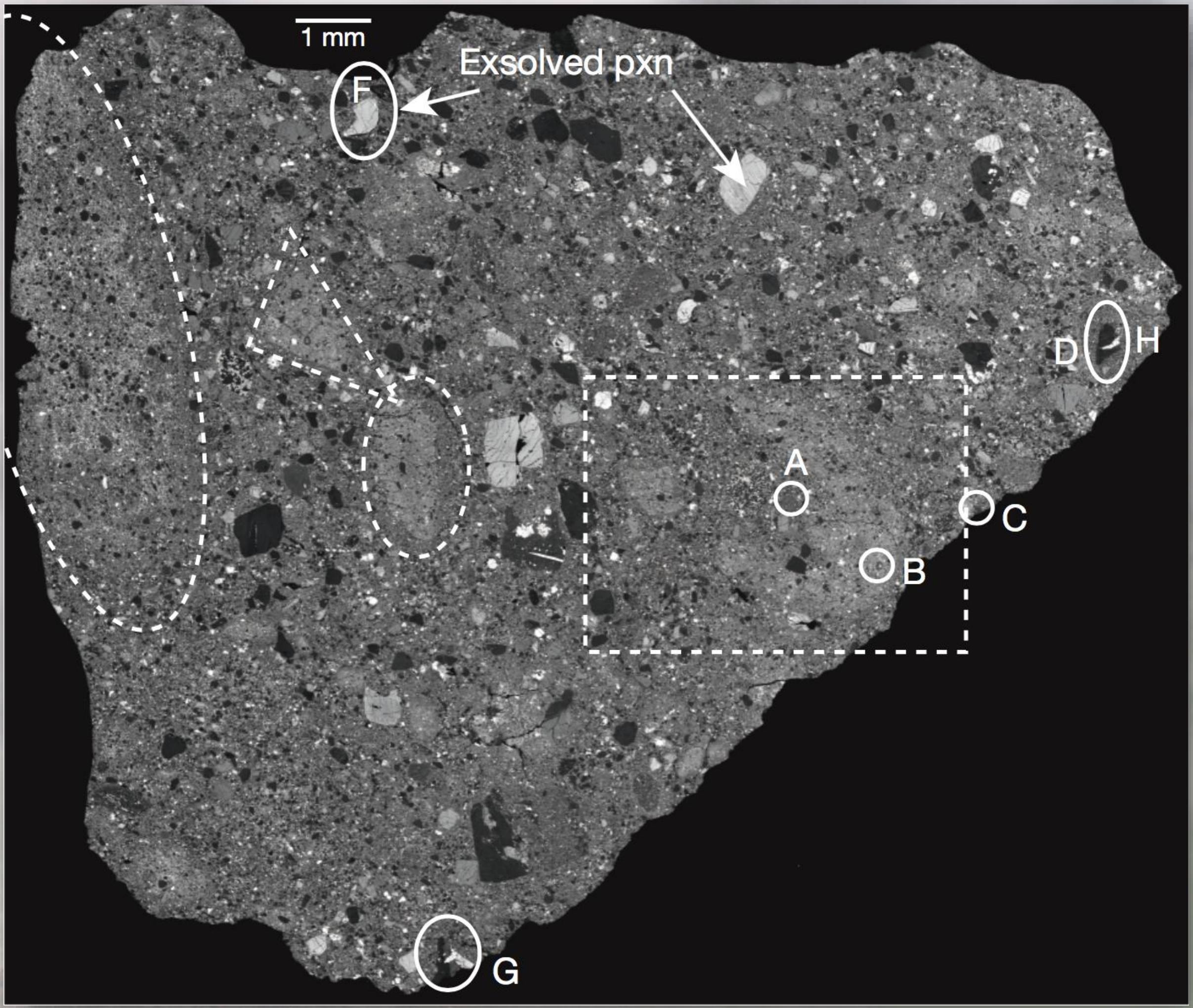
Bandfield 2006 Geophysical Research Letters

Detection of anorthosite from visible/NIR spectroscopy



Carter et al. 2013, Wray et al. 2013 *Nature Geoscience*

NWA 7533 – Evidence for early crustal differentiation



Humayun et al. 2013, Nature

"NWA 7533 contains numerous evolved igneous clasts that contain zircons. These evolved lithologies (monzonitic or mugearitic magmas) probably formed by re-melting of the primary Martian crust either at depth in the presence of volatiles or by differentiation of large impact melt sheets."

↓

evidence for early crustal differentiation

Age (zircons) : 4.428 (+/- 25) million years

The density and thickness of the Martian crust

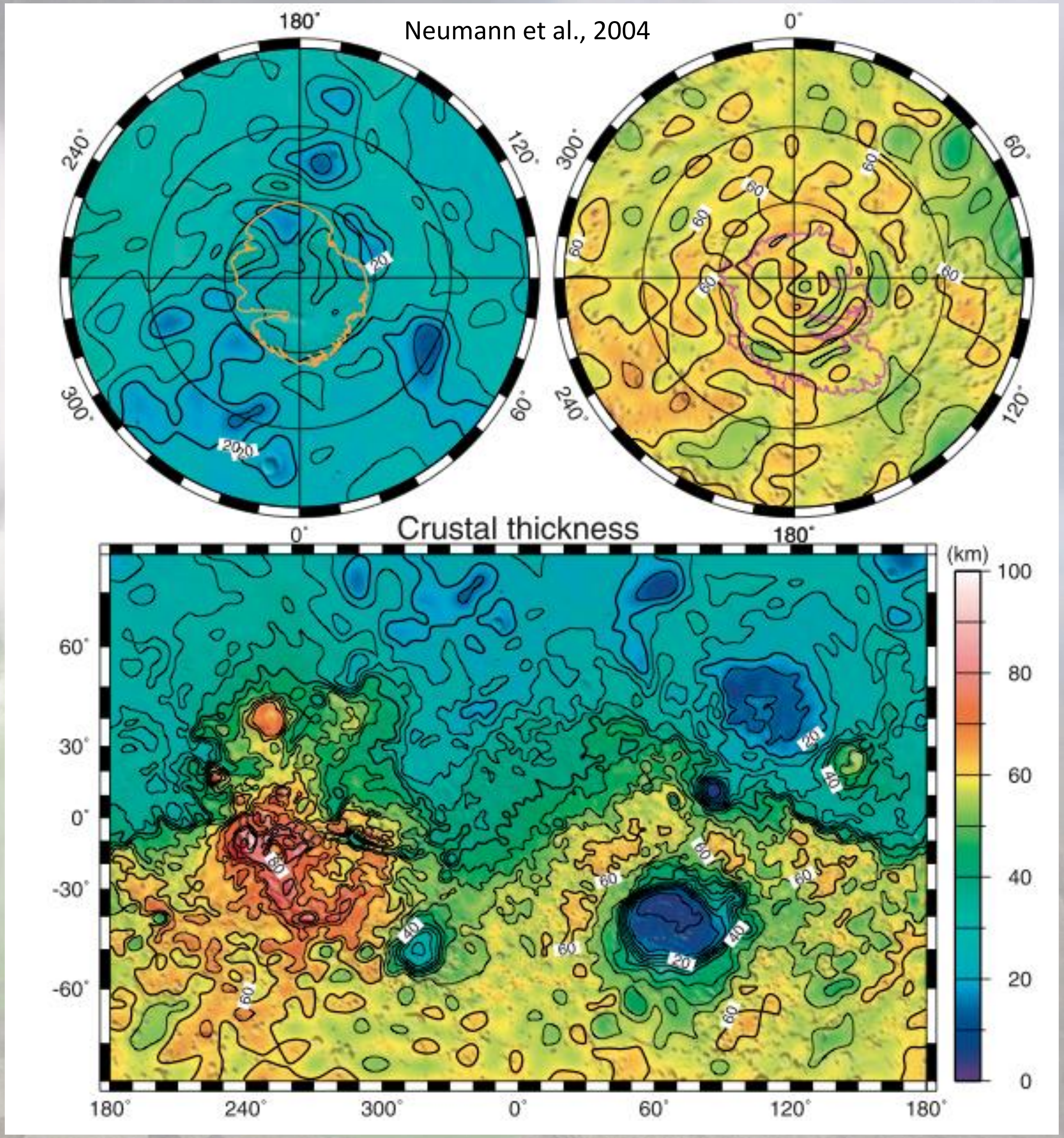
Crustal thickness maps from gravity and topography

<u>Main hypotheses :</u>

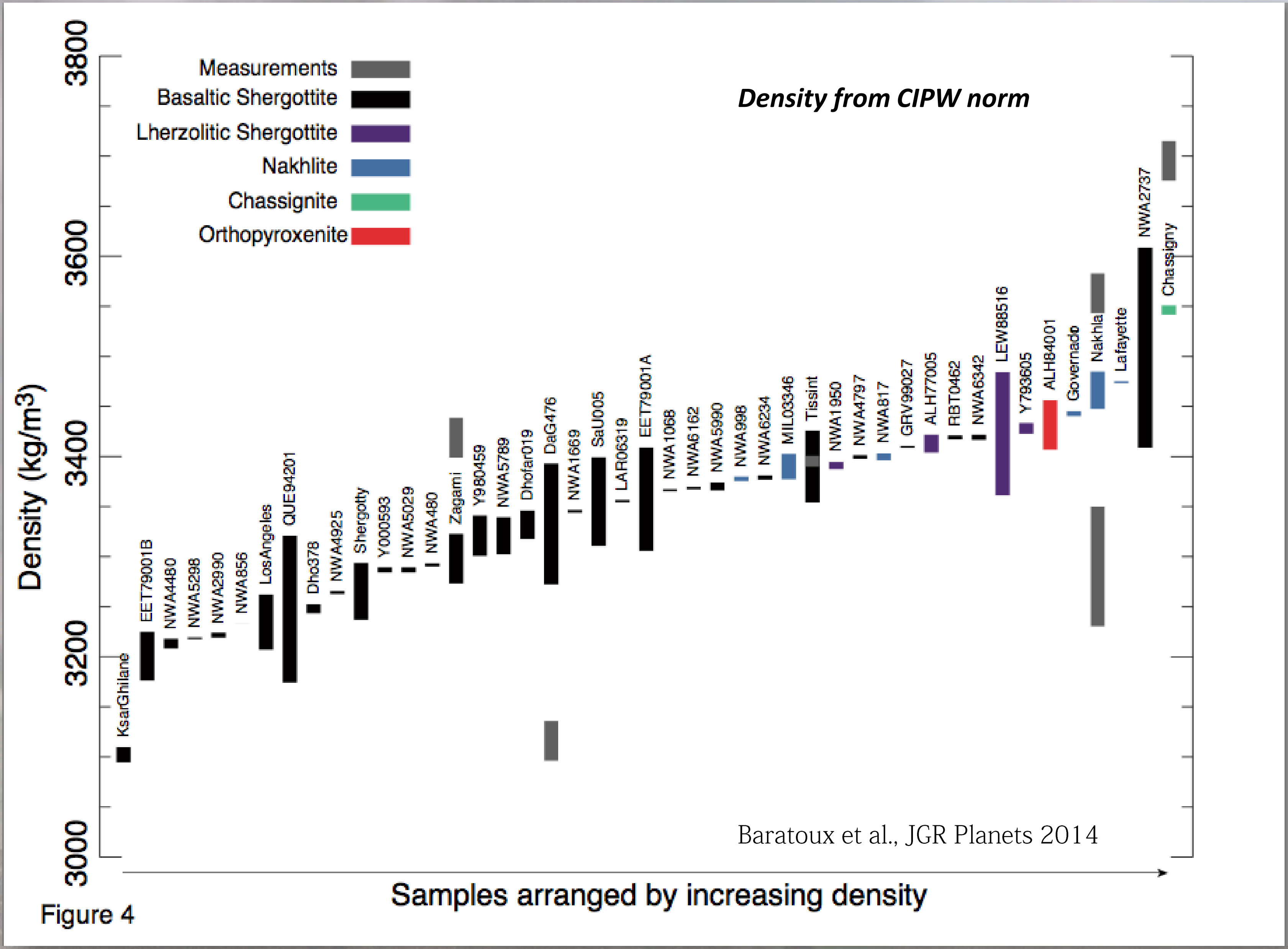
Crust is dominated by basalts

Density = 2900 kg/m^3
(2600 – 3000 kg/m^3)
Average thickness ~ 50 km

Calculations made 10 years ago…before most of the mineralogical observations



Martian meteorites are dense

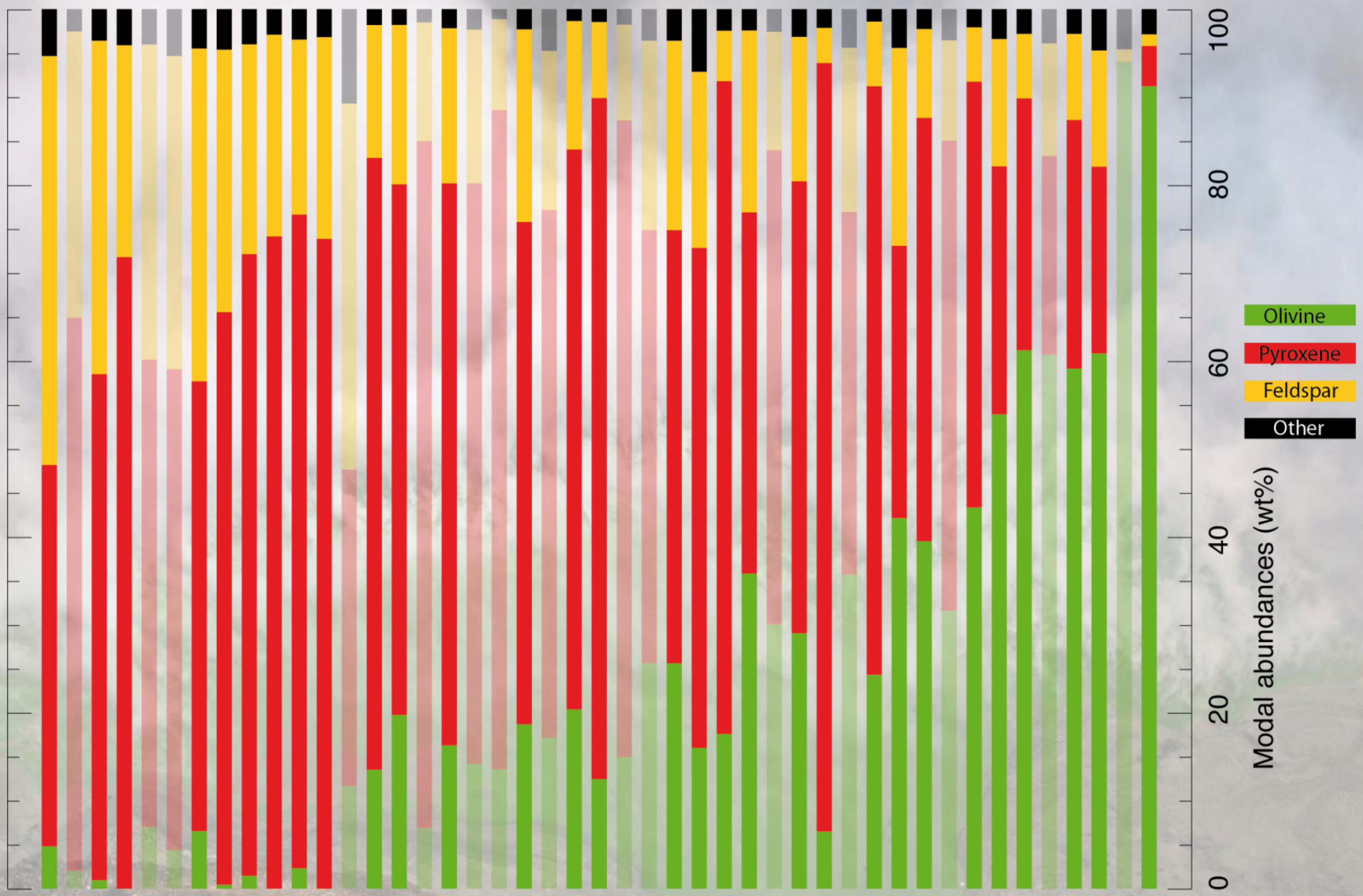


Martian Basalts are dense

> 3200 kg/m^3

Martian meteorites are dense

Meteorite chemistry => CIPW norm => Density



Baratoux et al., 2014, Journal of Geophysical Research (Planets)

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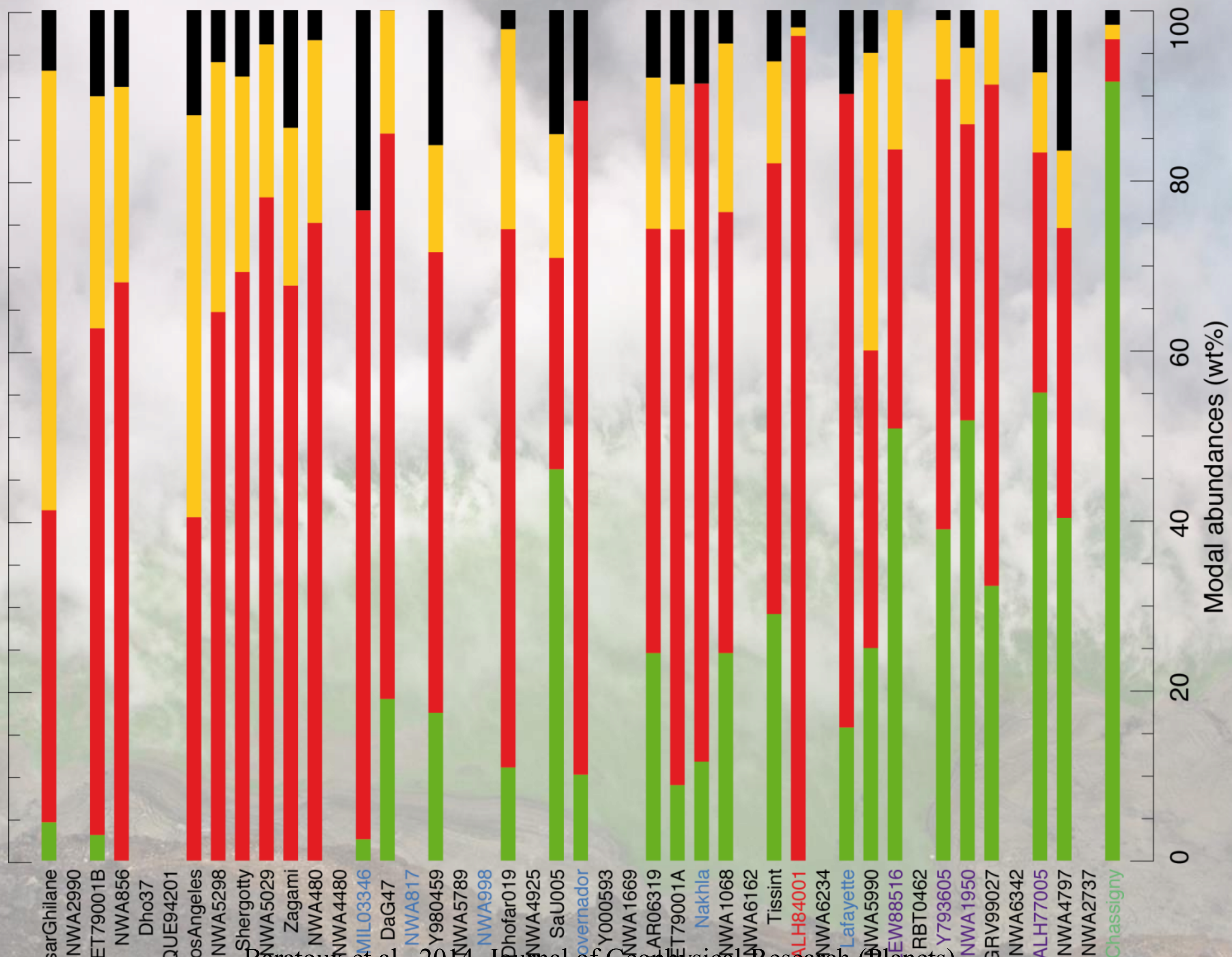
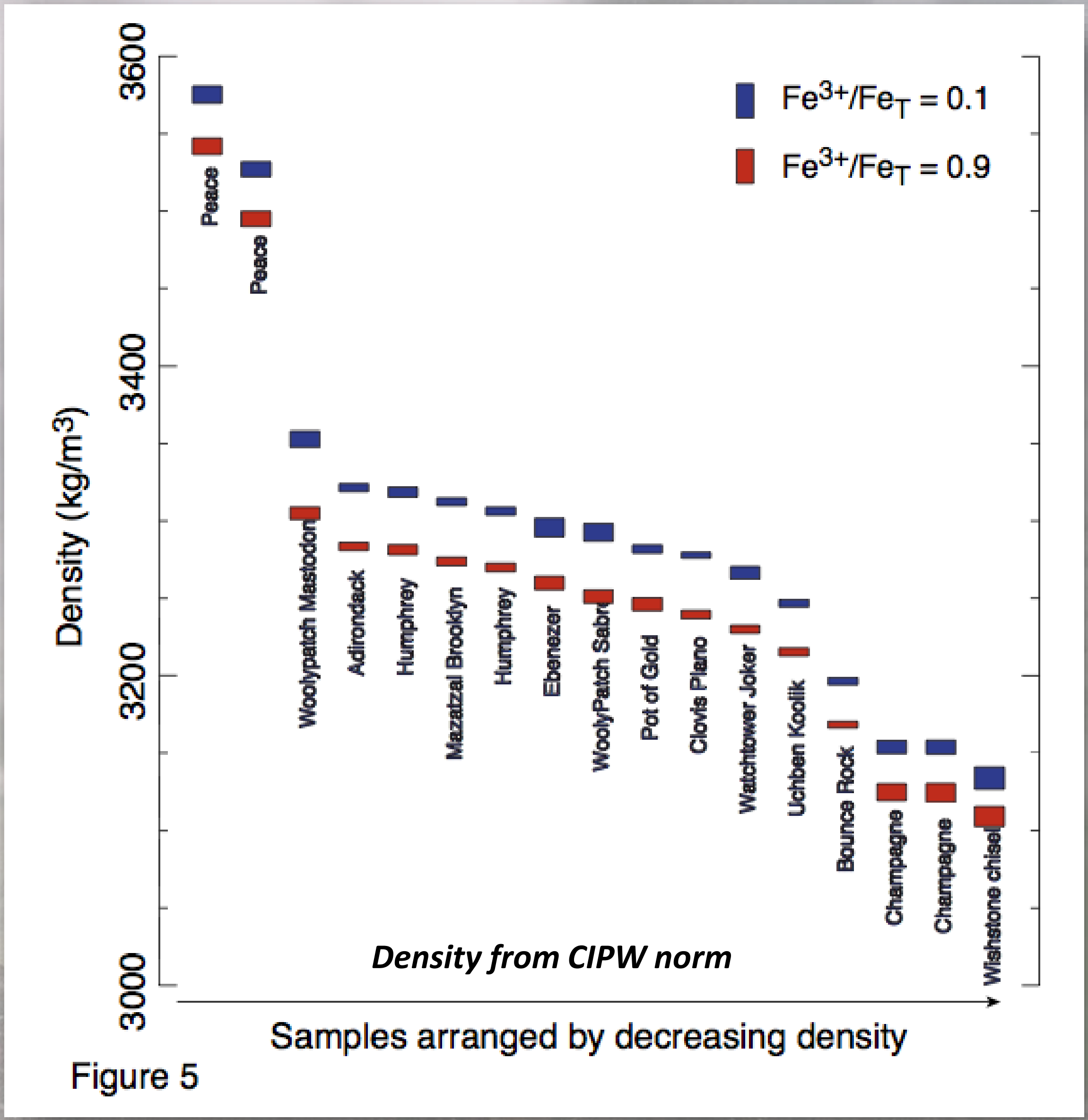


Baratoux et al., 2014, Journal of Geophysical Research (Planets)

Rocks observed in-situ at Gusev or Meridiani (Mars Exploration Rovers) are dense



Baratoux et al., JGR Planets 2014

Surface chemistry suggests a high-density crust

Surface chemistry => CIPW norm => density

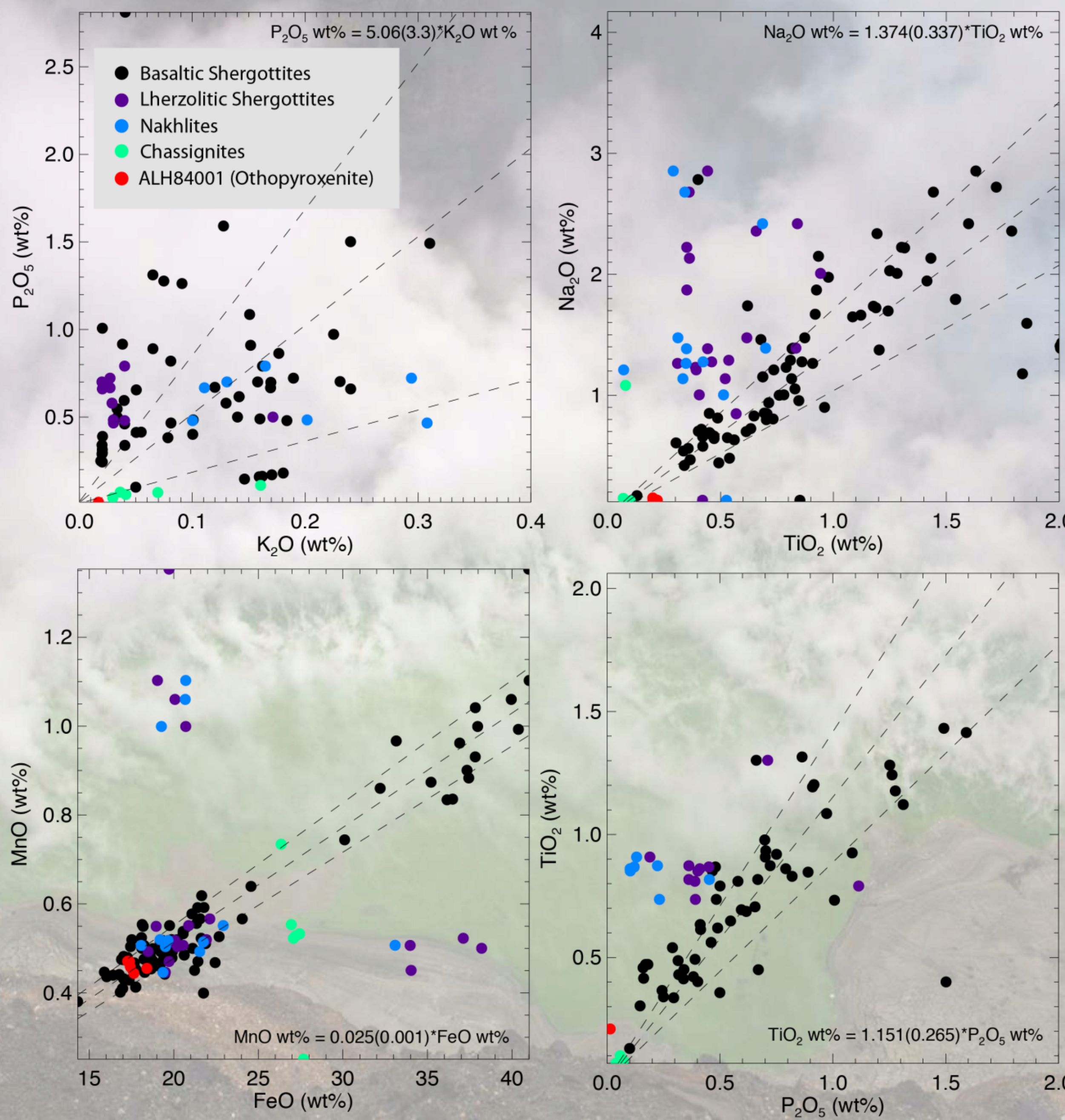
SiO_2, CaO, Al_2O_3, FeO GRS Maps

<u>Missing elements</u>

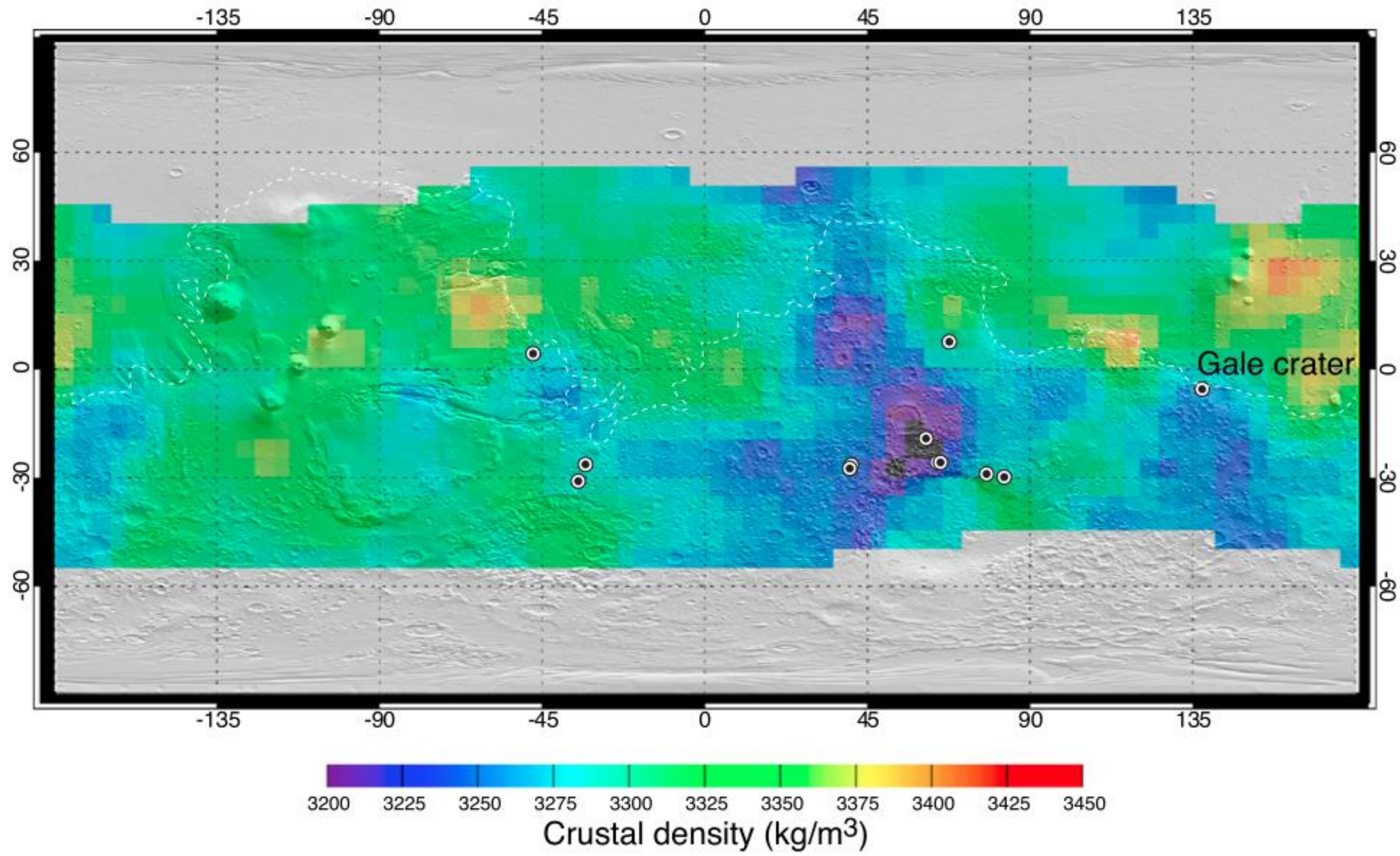
K_2O, P_2O_5, Na_2O, TiO_2

and MgO !

Surface chemistry suggests a high-density crust



Surface chemistry suggests a high-density of upper crust



Density from GRS surface chemistry
Minor elements from ratios in martian shergottites
+ CIPW norm

Baratoux et al., JGR Planets 2014

Surface chemistry suggests a high-density of upper crust

Density from GRS surface chemistry

Minor elements from ratios in martian shergottites

\+ *CIPW norm*

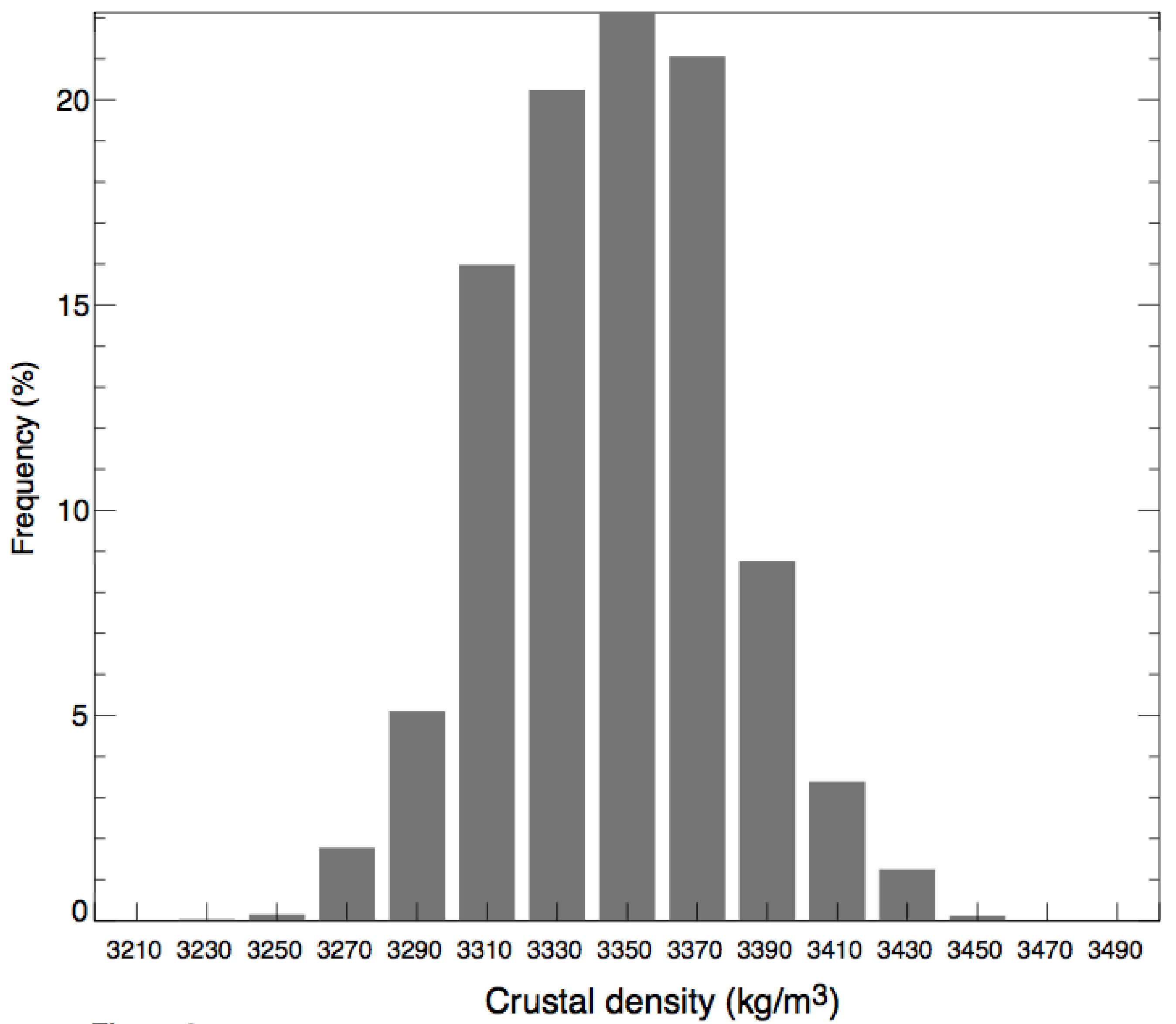
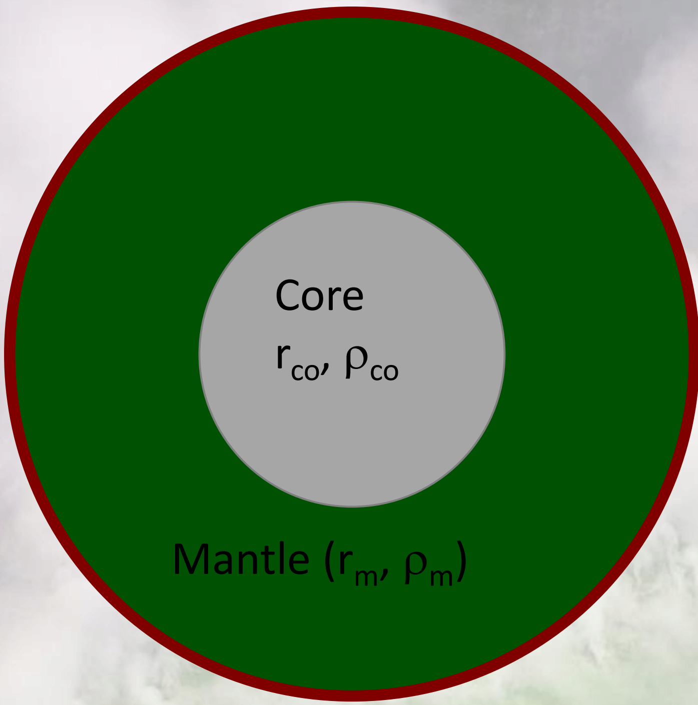


Figure 9

Baratoux et al., JGR Planets 2014

Is a high-density crust compatible with the mass or Mars and Moment of inertial factor ?



Crust (R, ρ_{cr})

Depth-dependent mantle density

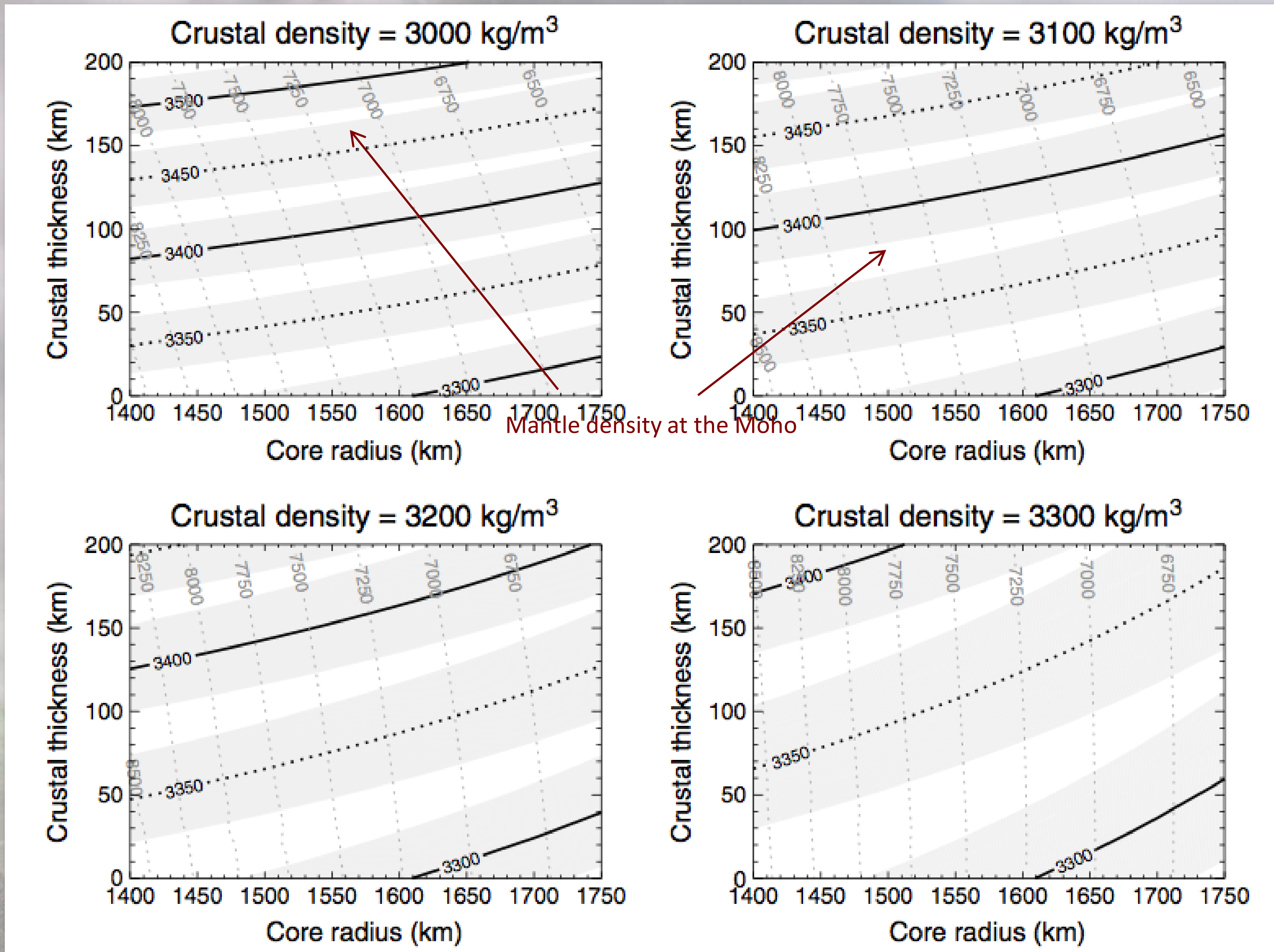
$$\rho_m(r) = \alpha r + \beta$$

***2** equations, **5** unknowns*
($r_m, \rho_m, r_{co}, \rho_{co}, \rho_{cr}$)

$$\rho = \rho_{cr} + \rho_{co}\left(\frac{r_{co}}{R}\right)^3 + \left(\frac{r_m}{R}\right)^3(\beta - \rho_{cr}) + \frac{3\alpha}{4R^3}\left(r_m^4 - r_{co}^4\right) - \beta\left(\frac{r_{co}}{R}\right)^3$$

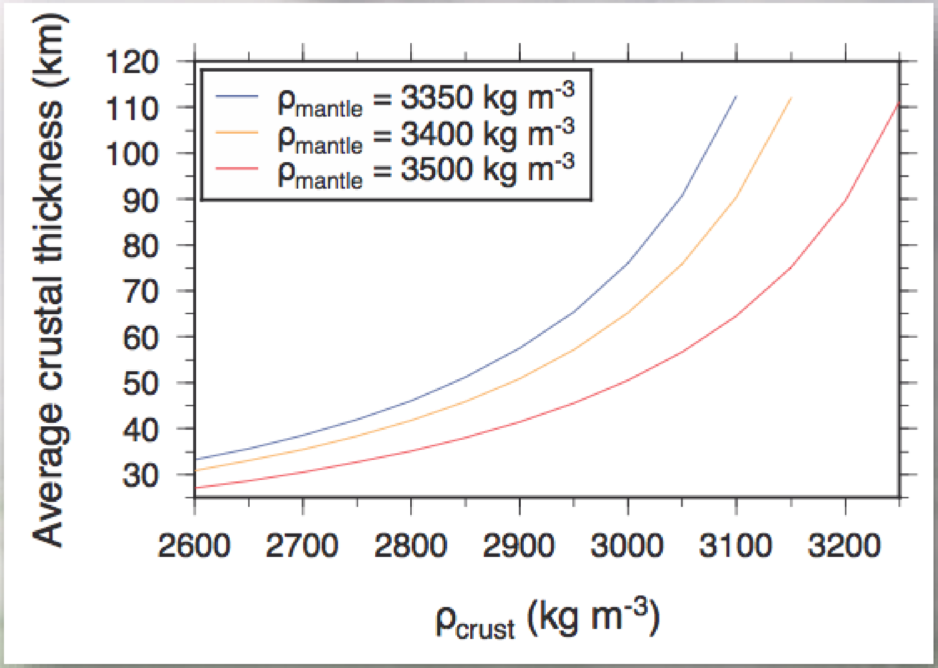
$$\frac{I}{MR^2} = \frac{2}{5}\left[\frac{\rho_{cr}}{\rho} + \left(\frac{r_{co}}{R}\right)^5\left(\frac{\rho_{co} - \beta}{\rho}\right) + \left(\frac{r_m}{R}\right)^5\left(\frac{\beta - \rho_{cr}}{\rho}\right)\right] + \frac{\alpha}{3\rho R^5}\left(r_m^6 - r_{co}^6\right)$$

Is a high-density crust compatible with the mass or Mars and Moment of inertial factor ?



Implications

If crust is dominated by basalt
=> Crust thickness should be revised (> 100 km)
crustal delamination becomes possible (basalt-to-eclogite transition),
or crustal flow (unstable crustal dichotomy) (Nimmo et al. 2005)



Baratoux et al., 2014 – JGR-Planets

Existence of a buried felsic/anorthositic (light) component

Martian Basalts are dense

- 3200 kg/m^3

Why ?

Because the Martian mantle is iron-rich

The paradox arising from low density values estimated from geophysical data (2800 - 2900 kg/m3) and the density of martian basalts may be resolved if we postulate on the existence of a buried light/differentiated crustal component.

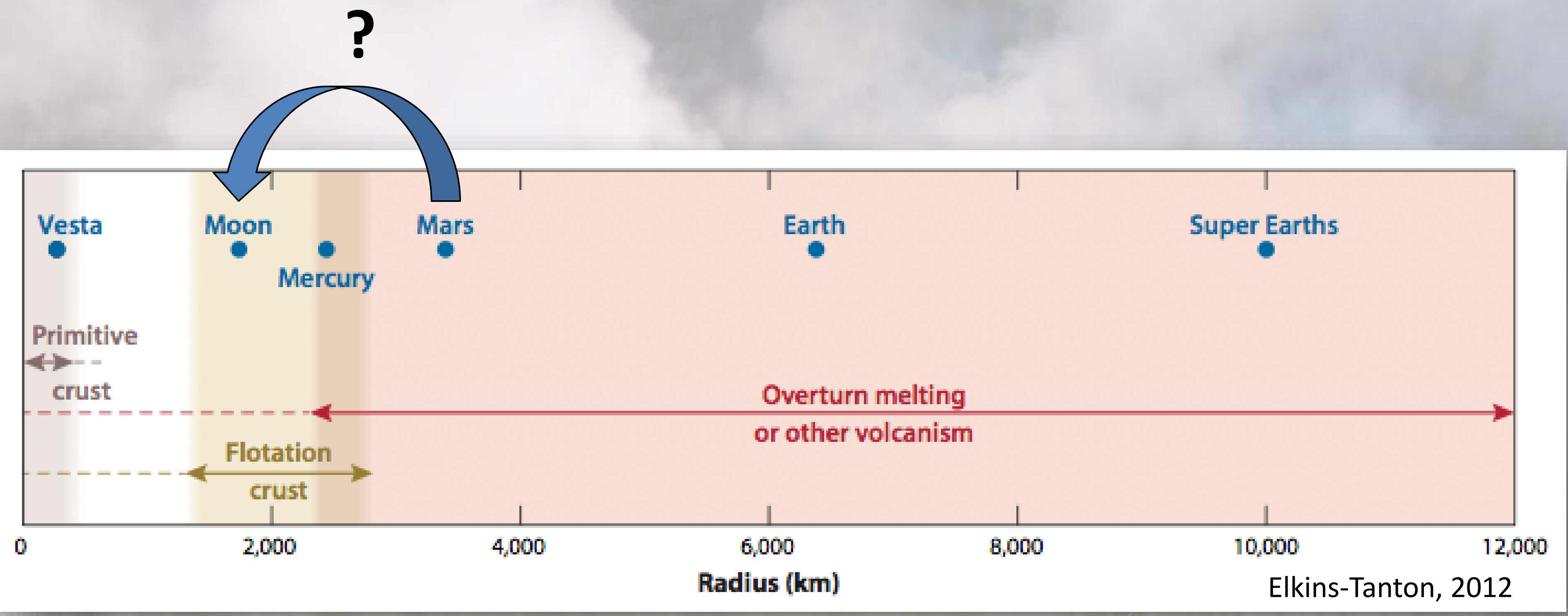
Dense upper crust / buried light "continental" crust?
Extrapolation of local observations (in-situ, spectral) to the entire crust

What is the origin of the buried felsic component ?

Wet partial melting of crustal basalts and **recycling of the residue ?**

What is the origin of the buried felsic component ?

Formation of a floatation crust (plagioclase) in a dry/shallow magma ocean ?

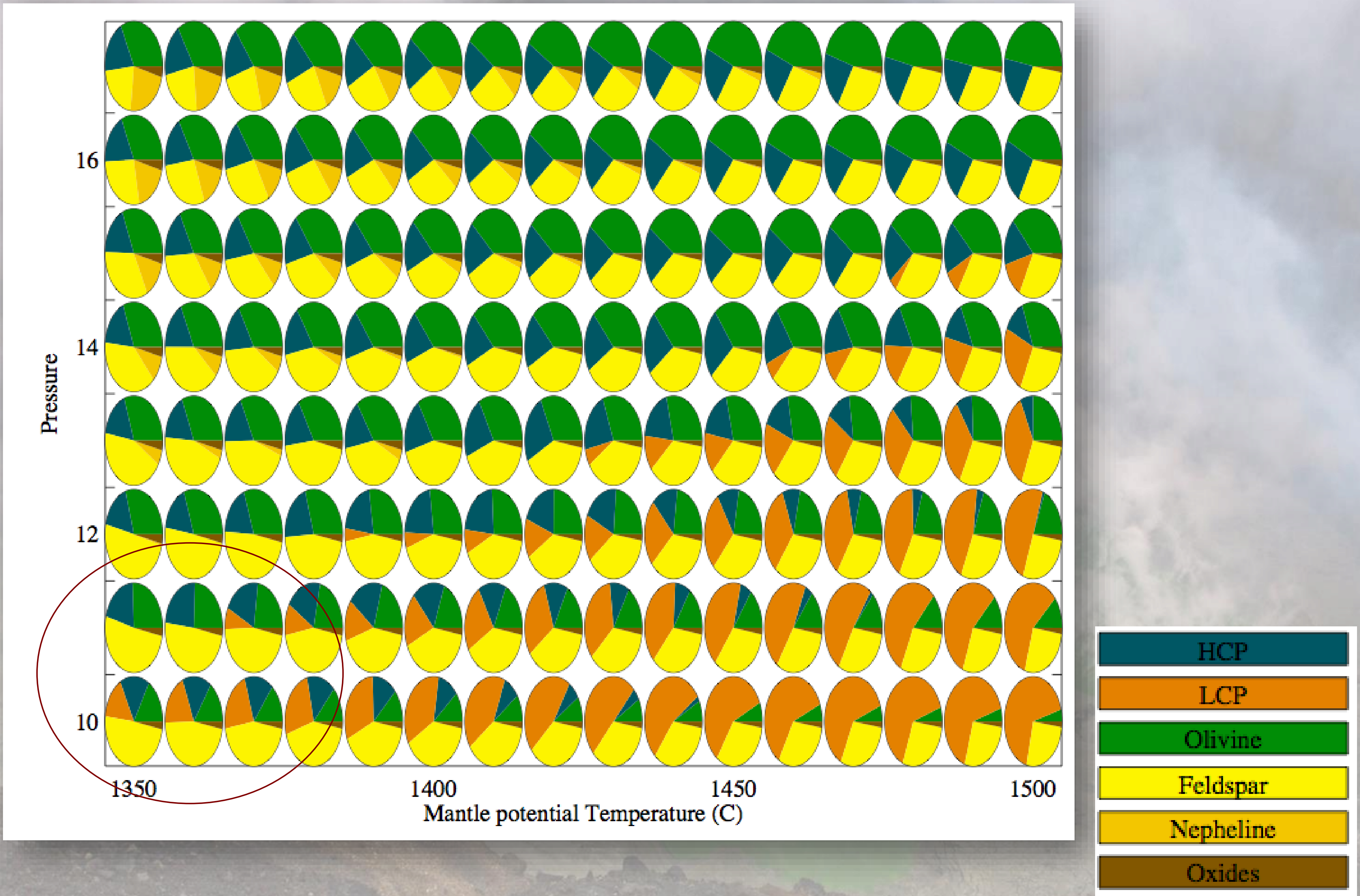


Dry shallow magma ocean allows the formation of felsdpar-rich lithologies (e.g., tonalite, anorthosite) by segregation of mafic crystals from Si-rich evolved liquids crystallizing at the surface

Morse, *Earth and Plan. Sc. Letters*, 1986

Harrison, *Ann. Rev. Earth Plan. Sc.*, 2009.

Shallow melting of the martian mantle



Conclusions

Mars mantle cools down over time : 30 K/Gy (slow in comparison to the Earth, plate tectonics is an efficient cooling mechanism)

Mars mantle is still warm – explains recent volcanism – present volcanism is possible (mantle temperature near solidus)

Thermal evolution of Mars explains surface chemical and mineralogical trends as seen from orbiting instruments

Martian basalt are dense – The crust is either dominated by basaltic rocks and is thick (> 100 km) or it is more likely composed of felsic/anorthositic components

=> extent, volume, and origin of the felsic component ?
(magma ocean ? Crustal melting ? Shallow mantle melting ?)
InSight....