Thermal and Dynamic History of Planets
Planetary Volcanism and Crustal Evolution

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Day 1 – Fundamental concepts

Part I – Energy budget: sources of energy and their relative importance during planetary evolution

Part II – Thermal evolution of asteroids

Part III – Thermal evolution of planets

Part III – Thermal evolution of planets

3.1 Magma oceans

3.2 Long-term evolution

Part 4. – Thermal evolution of planets

Magma oceans

$^{26}Al + ^{60}Fe$

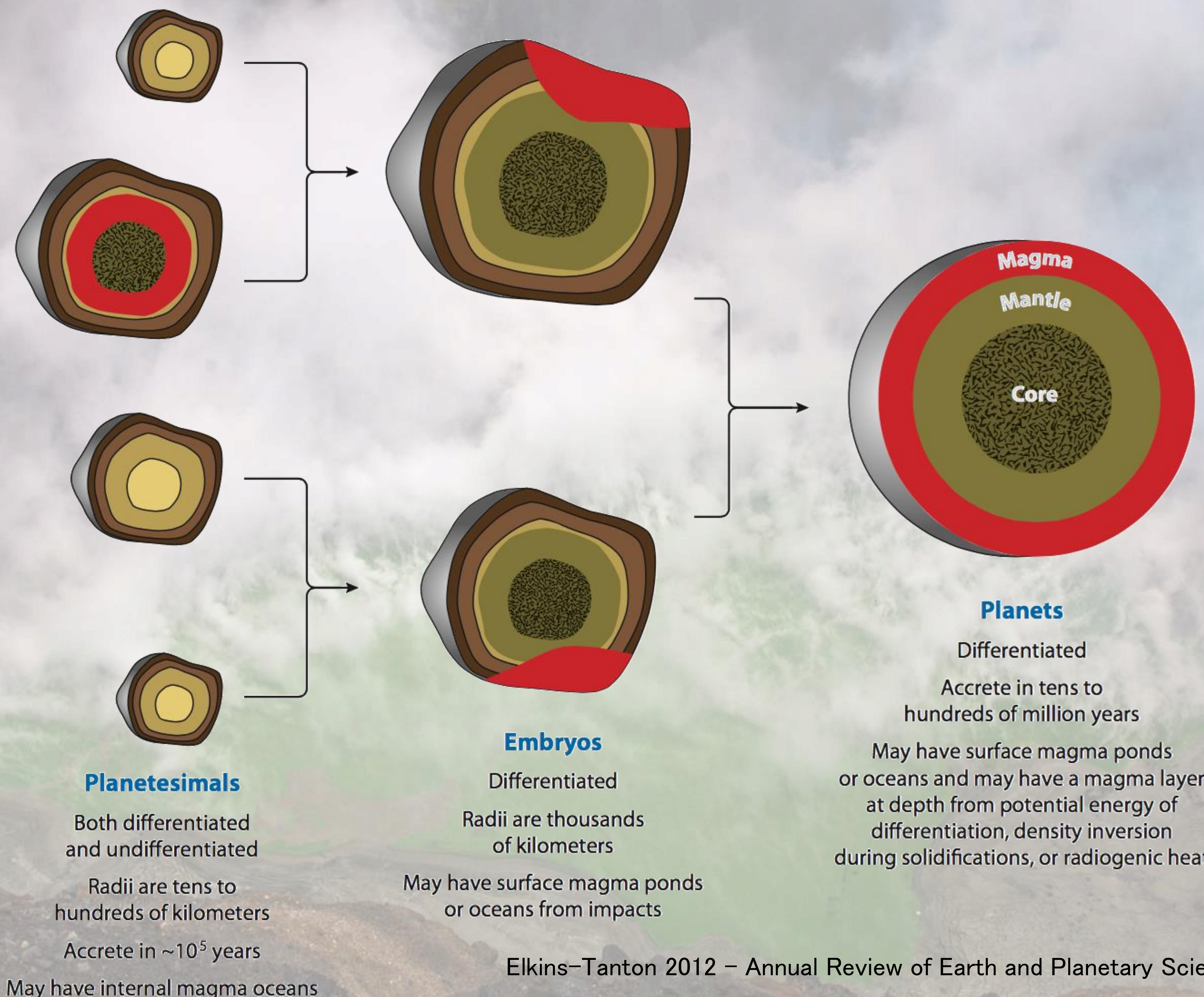
+

Accretion Energy

↓

Magma ocean are inescapable for (large planets)

3.1 – Magma oceans



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3.1 – Magma oceans

The temperature profile in a magma ocean is given by the adiabatic gradient

$$\left(\frac{\partial T}{\partial z}\right)_S = \frac{g\alpha_f T}{C_P}$$

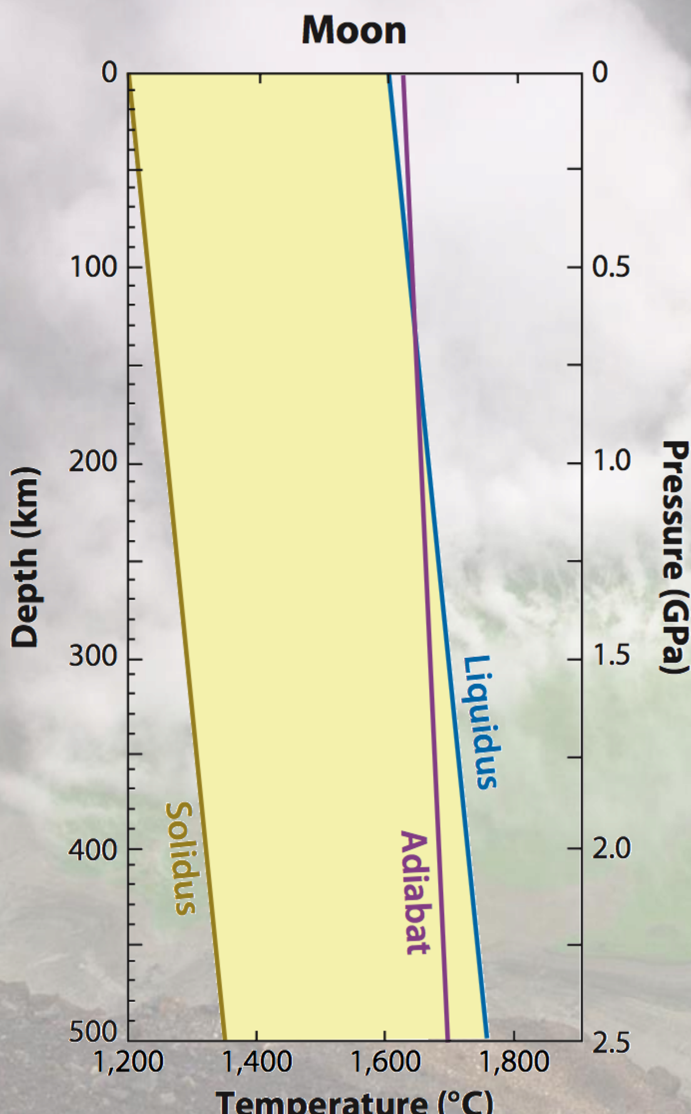
Faites glisser la croix sur la zone que vous

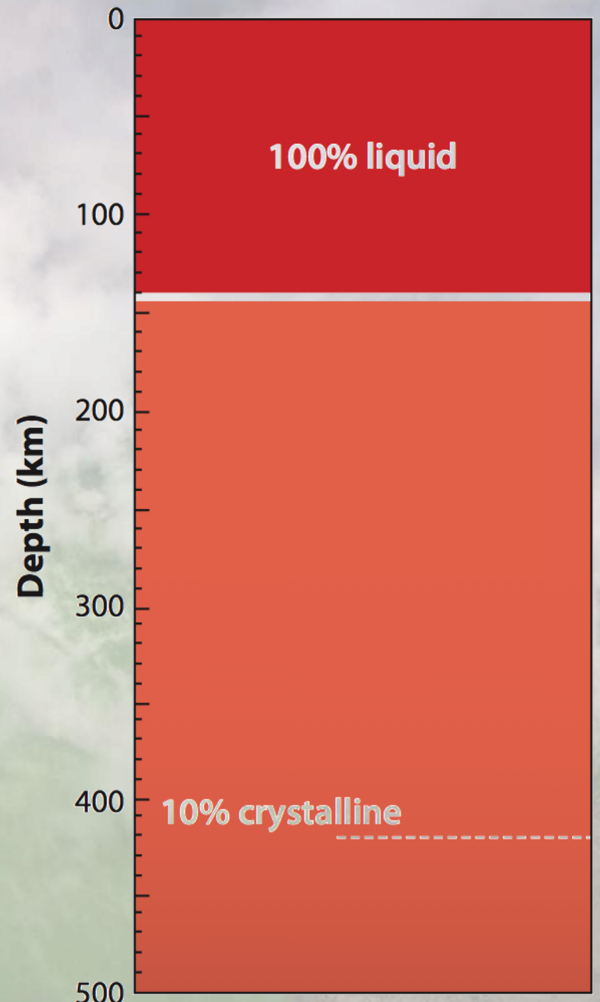
The adiabatic temperature profile ($T_s = f(P)$) is usually steeper than the solidus temperature profile.

→ This has a fundamental implication on the magma ocean structure

3.1 – Magma oceans

Example in the case of the Moon





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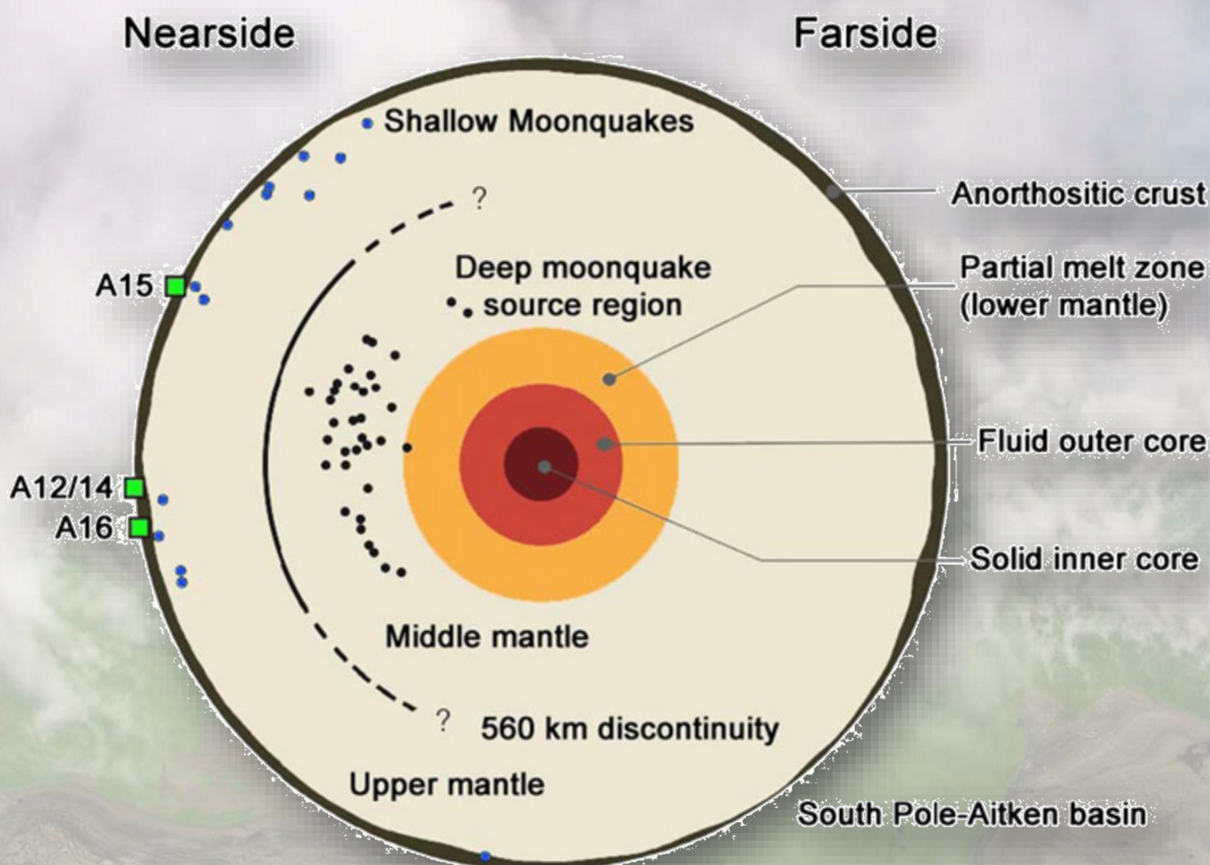
The anorthositic crust of the Moon

Geophysical data (including Apollo seismic experiments) + Apollo samples indicate that the upper crust of the moon is dominated by **plagioclase**



Khan et al. 2013 – Tectonophysics

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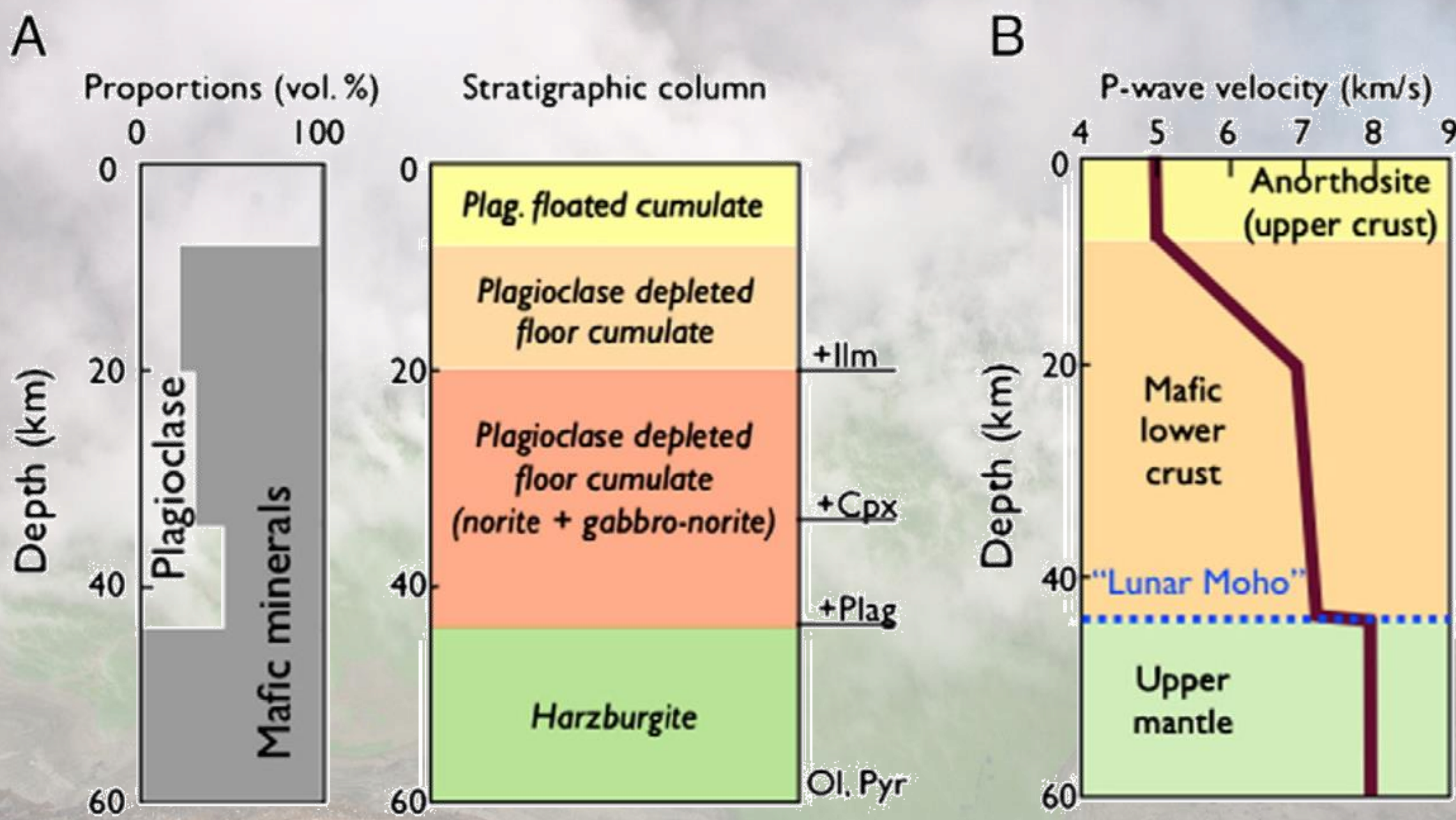

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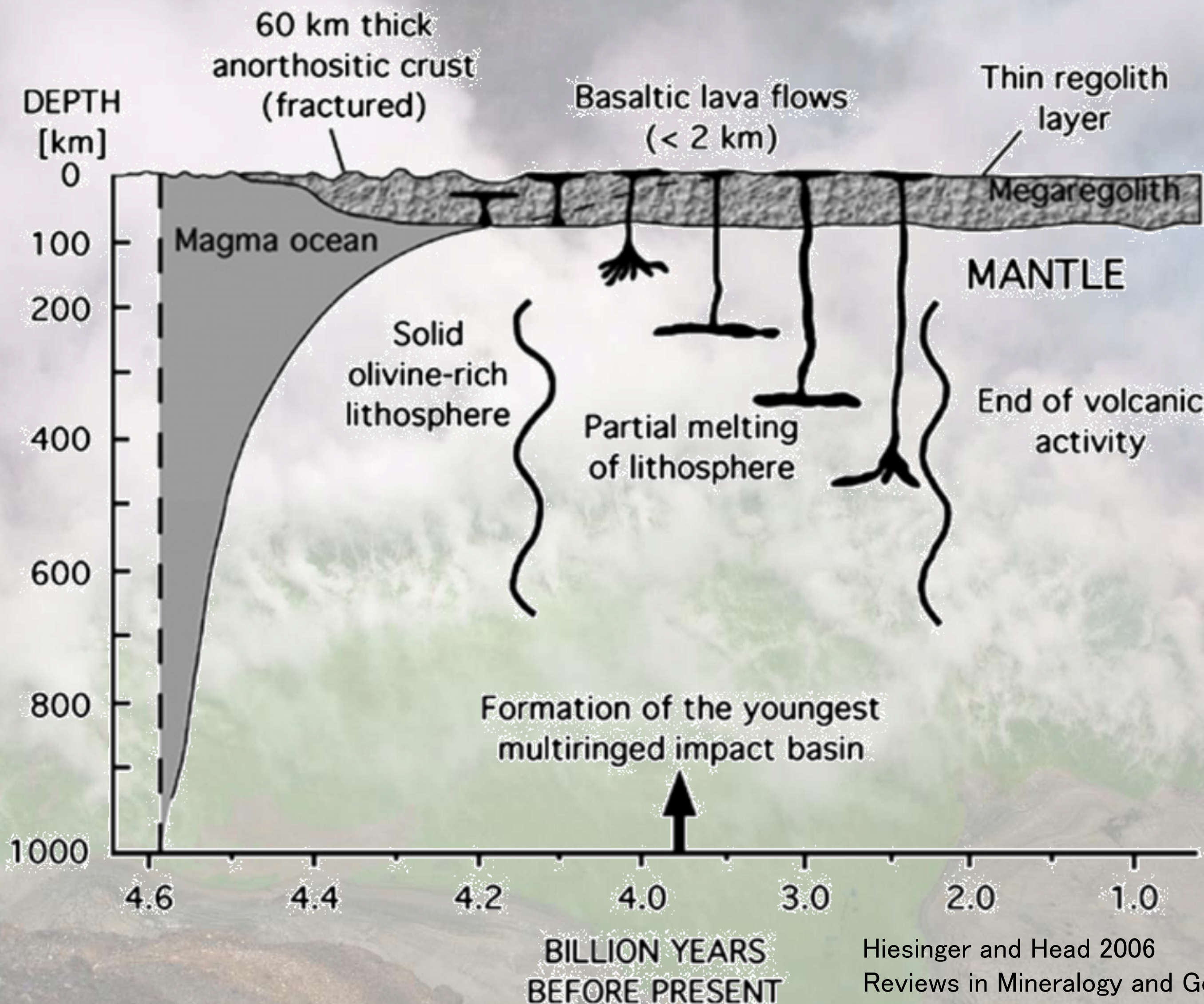
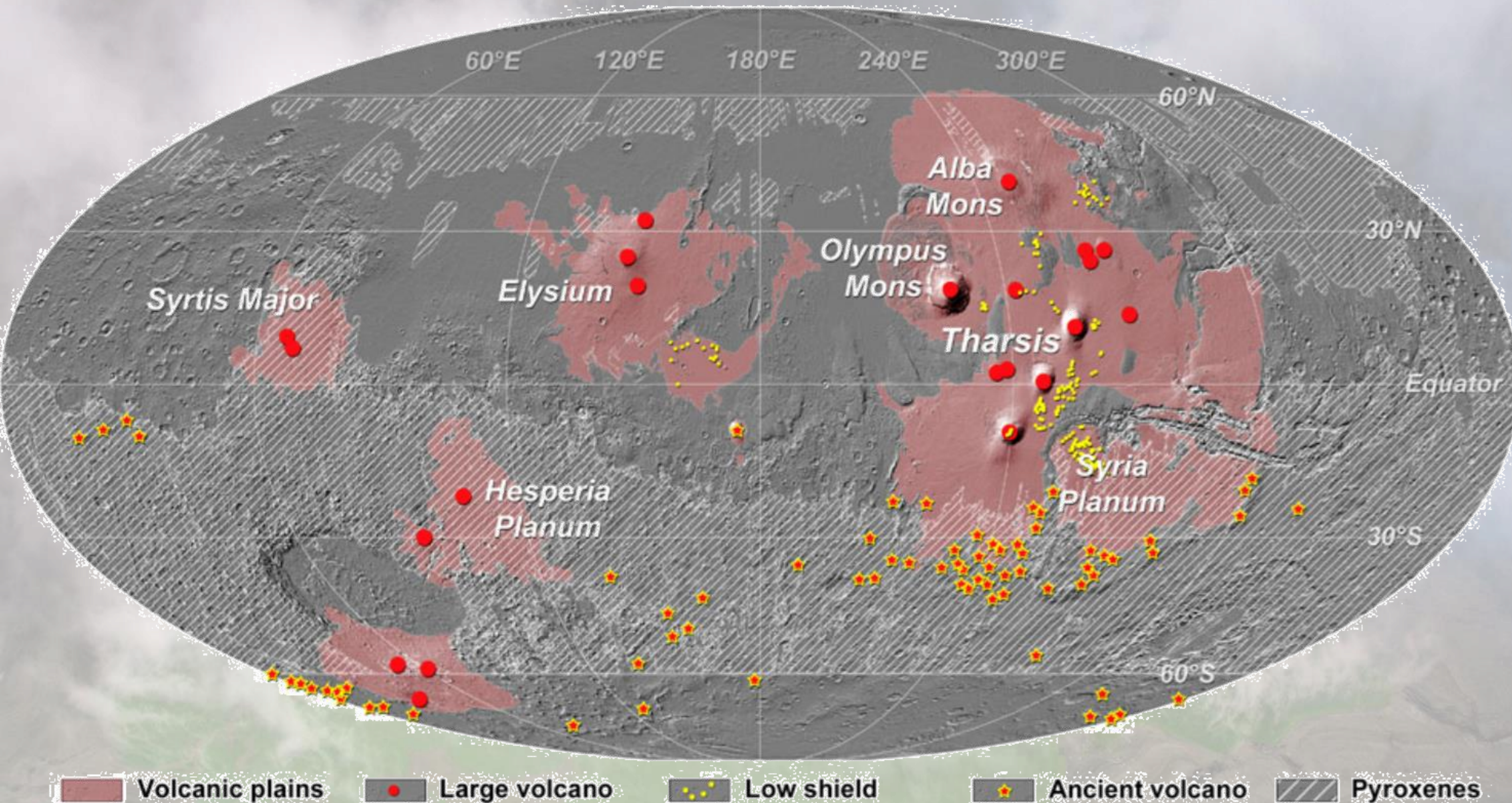


Hiesinger and Head 2006
Reviews in Mineralogy and Geochemistry

The surface of Mars – basalts

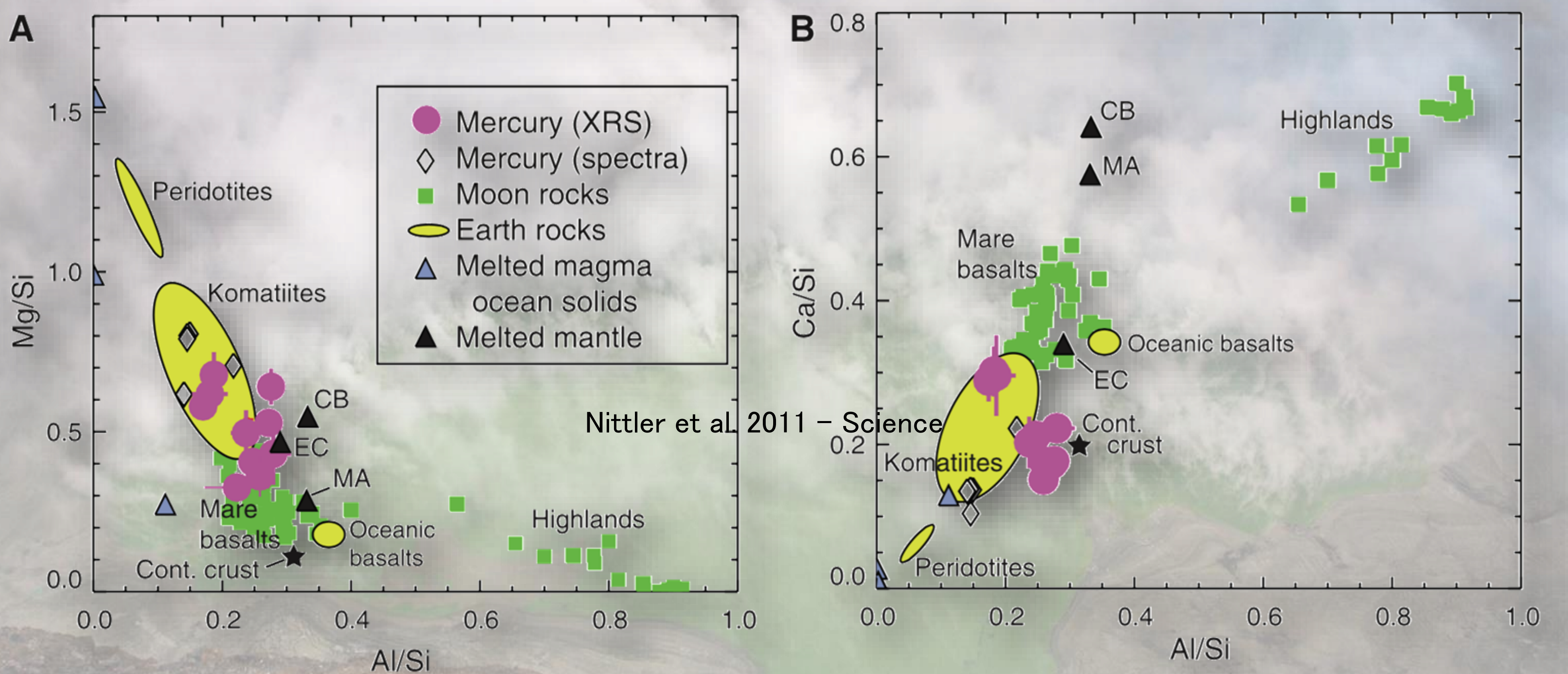


Where is the floatation crust ?

Is there any remnants of the magma ocean ?

The surface of Mercury

X-ray spectrometry during solar flares



Nittler et al. 2011 – Science

The surface of Mercury

Confirmation from gamma-ray spectrometer

Aluminum abundance on the surface of Mercury: Application of a new background-reduction technique for the analysis of gamma-ray spectroscopy data

Patrick N. Peplowski,[1] Edgar A. Rhodes,[1] David K. Hamara,[2] David J. Lawrence,[1] Larry G. Evans,[3] Larry R. Nittler,[4] and Sean C. Solomon[4,5]

Received 2 July 2012; revised 24 September 2012; accepted 7 October 2012; published 7 December 2012.

[1] A new technique has been developed for characterizing gamma-ray emission from a planetary surface in the presence of large background signals generated in a spacecraft. This technique is applied to the analysis of Al gamma rays measured by the MESSENGER Gamma-Ray Spectrometer to determine the abundance of Al on the surface of Mercury. The result ($Al/Si = 0.29^{+0.05}_{-0.13}$) is consistent with Al/Si ratios derived from the MESSENGER X-Ray Spectrometer and confirms the finding of low Al abundances. The measured abundance rules out a global, lunar-like feldspar-rich crust and is consistent with previously suggested analogs for surface material on Mercury, including terrestrial komatiites, low-iron basalts, partial melts of CB chondrites, and partial melts of enstatite chondrites. Additional applications of this technique include the measurement of other elements on Mercury's surface as well as the analysis of data from other planetary gamma-ray spectrometer experiments.

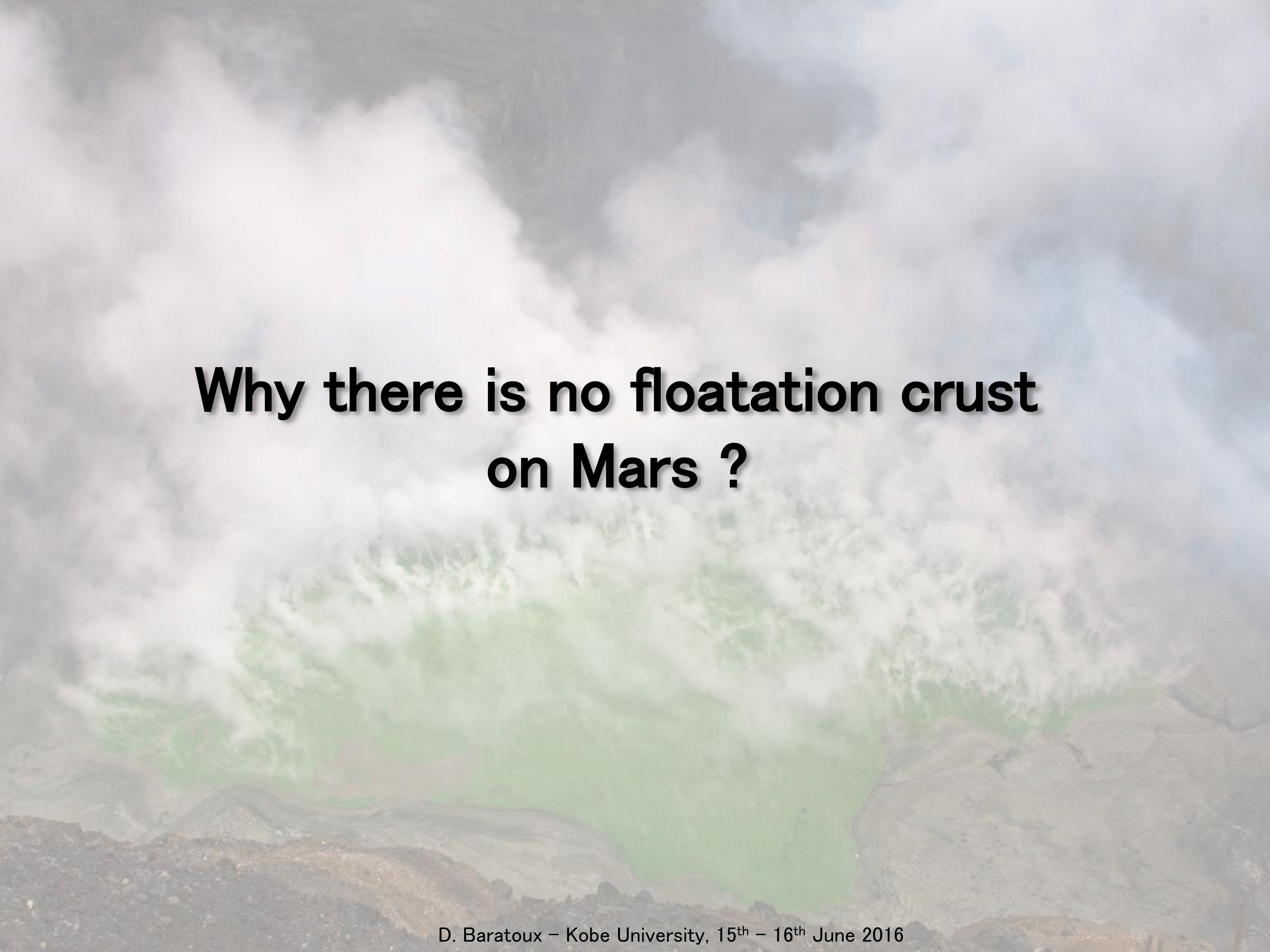
Citation: Peplowski, P. N., E. A. Rhodes, D. K. Hamara, D. J. Lawrence, L. G. Evans, L. R. Nittler, and S. C. Solomon (2012), Aluminum abundance on the surface of Mercury: Application of a new background-reduction technique for the analysis of gamma-ray spectroscopy data, *J. Geophys. Res.*, *117*, E00L10, doi:10.1029/2012JE004181.

The anorthositic crust on the Moon is considered to be the best evidence for the existence of magma oceans

But…

Mercury, Mars (and in fact, no other rocky planet) have a flotation crust !

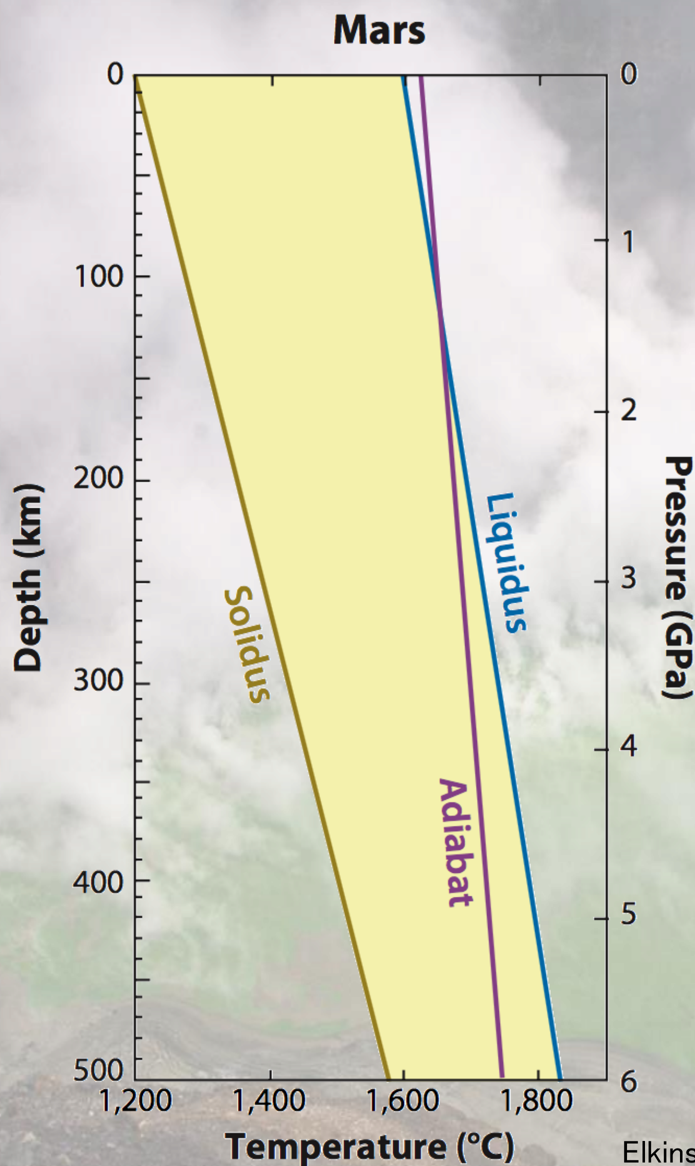
So…why there is no floatation crust on Mars or Mercury ?

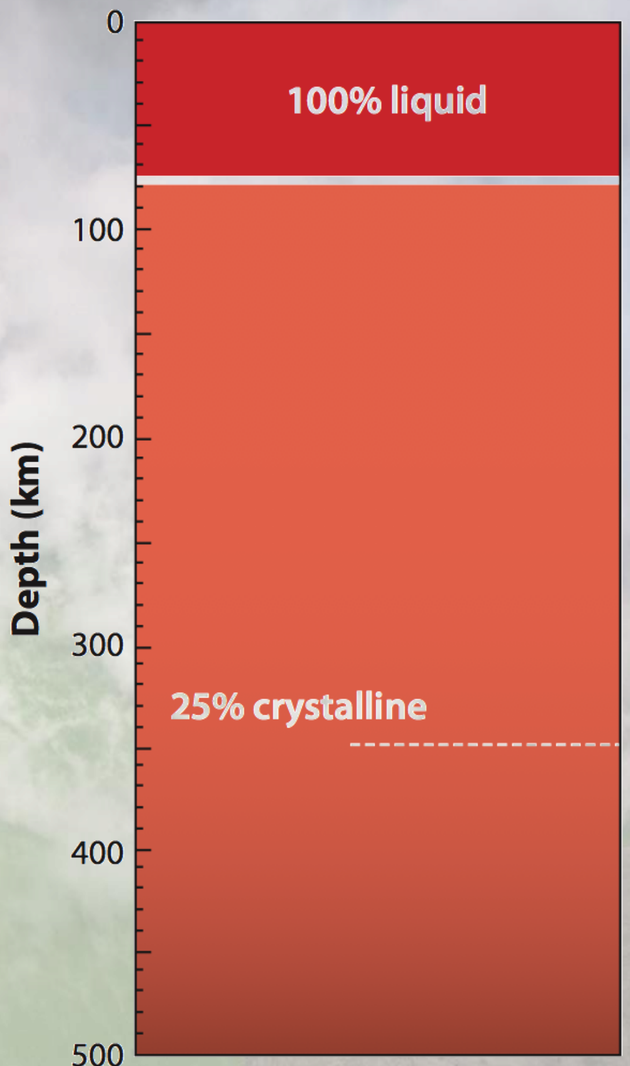


Why there is no floatation crust on Mars ?

Magma ocean evolution

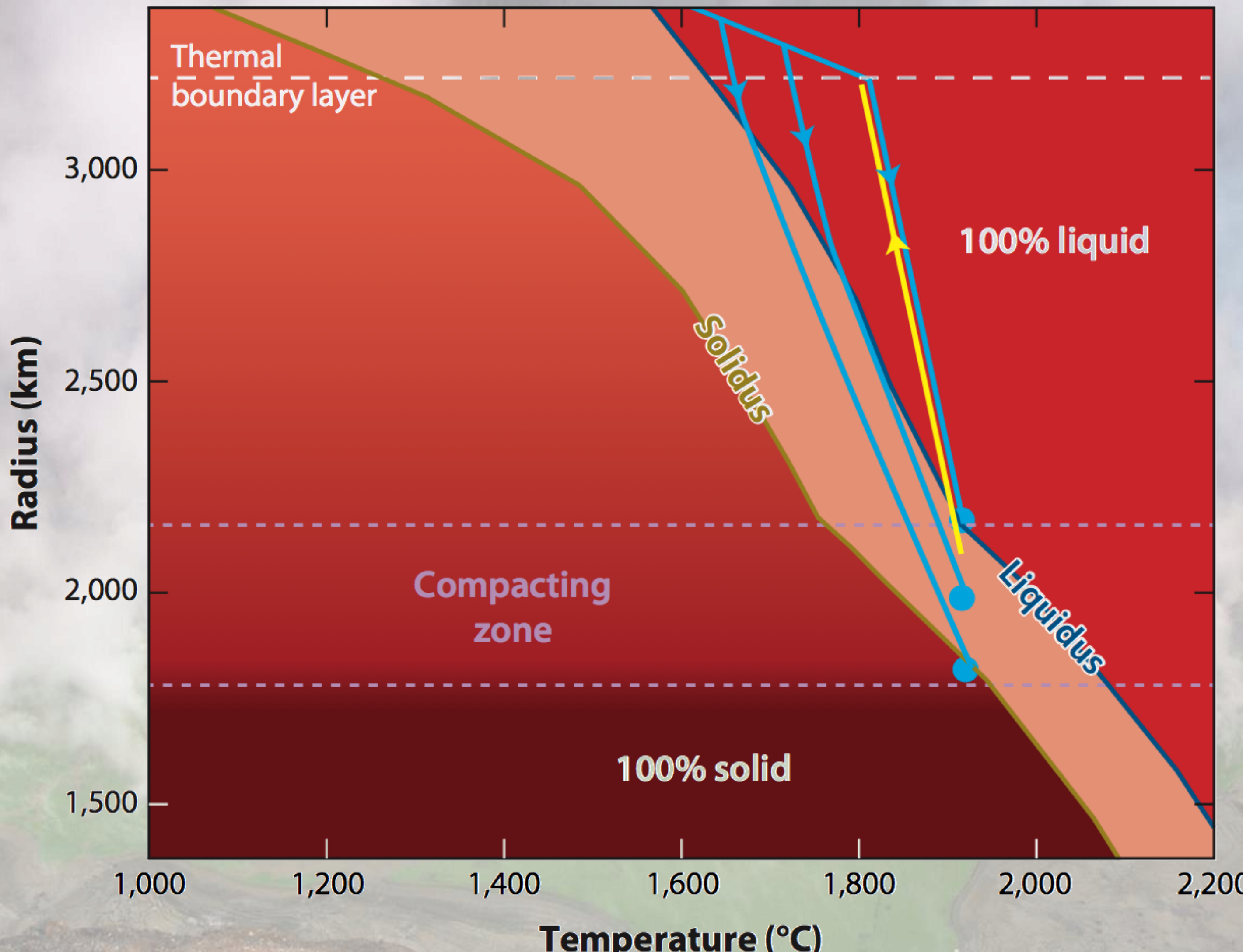
The case of Mars





Elkins–Tanton 2012 – Annual Review of Earth and Planetary Science

Magma ocean evolution
The case of Mars



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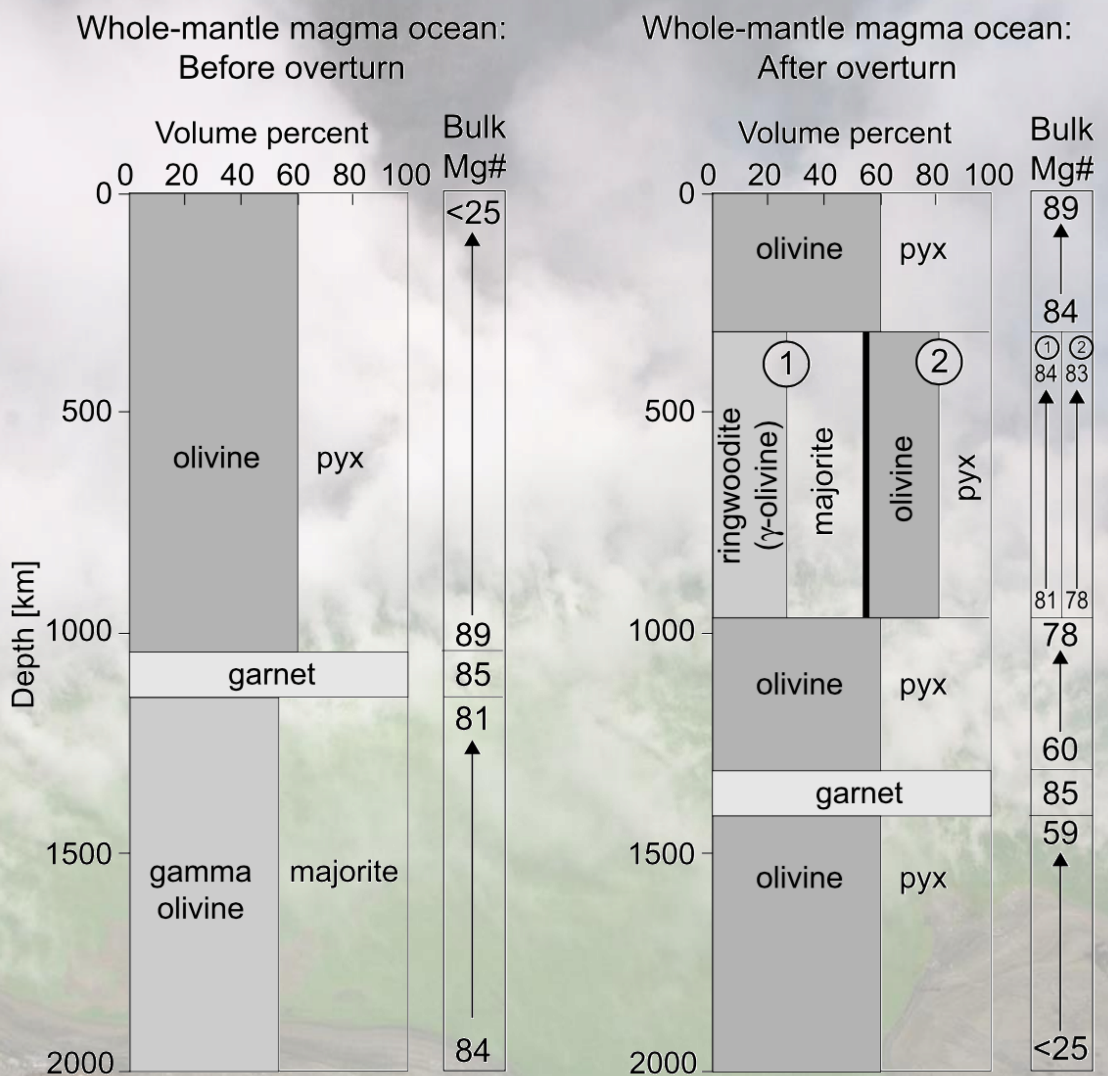
Why there is no floatation crust on Mars ?

1. Al has been sequestered in the garnet layer

2. Water abundance inhibits the crystallization of plagioclase

3. The crystallized magma ocean is unstable, and the overturn produces a secondary crust.

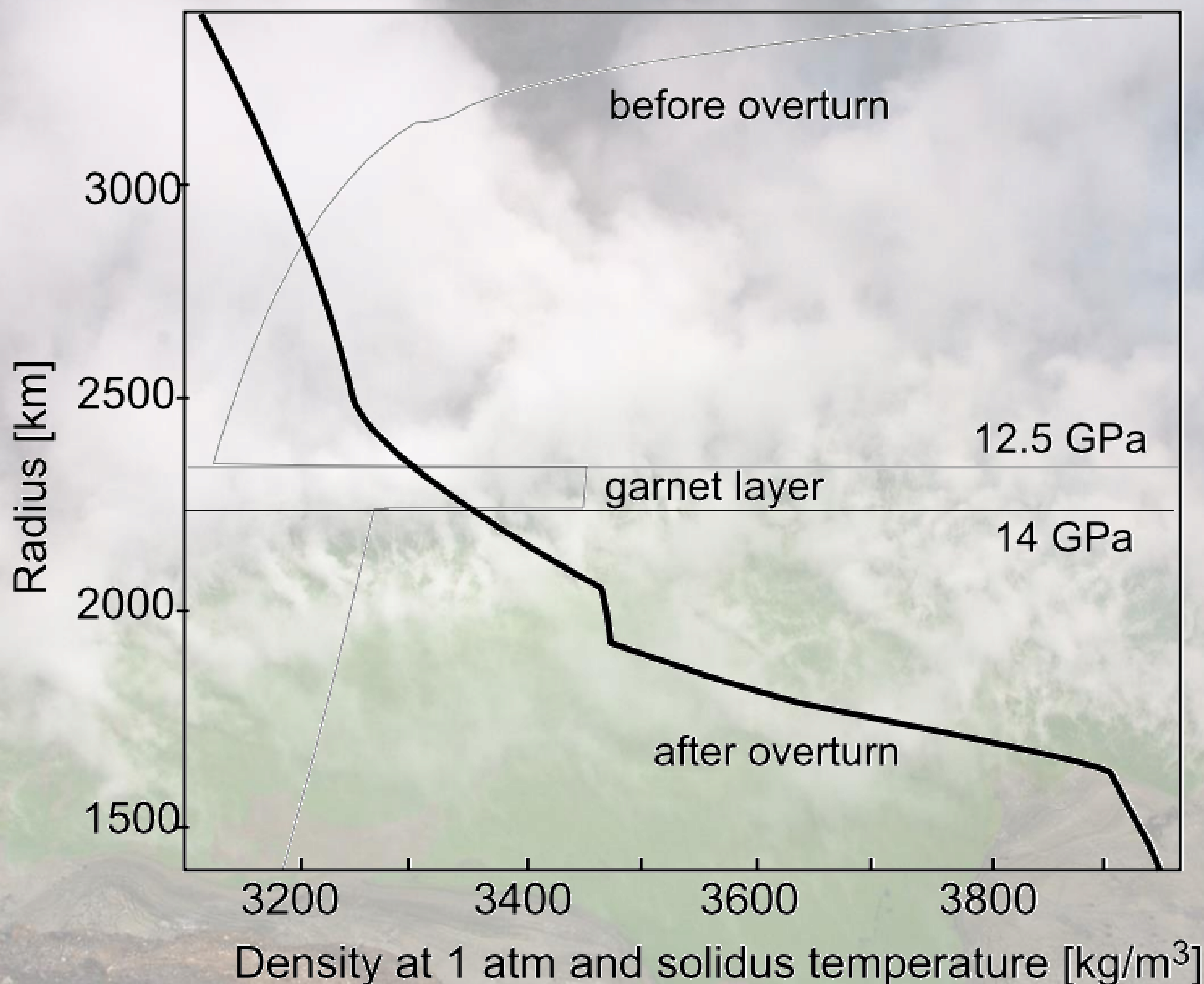
Magma ocean evolution
The case of Mars



Elkins–Tanton 2005 – JGR–Planets

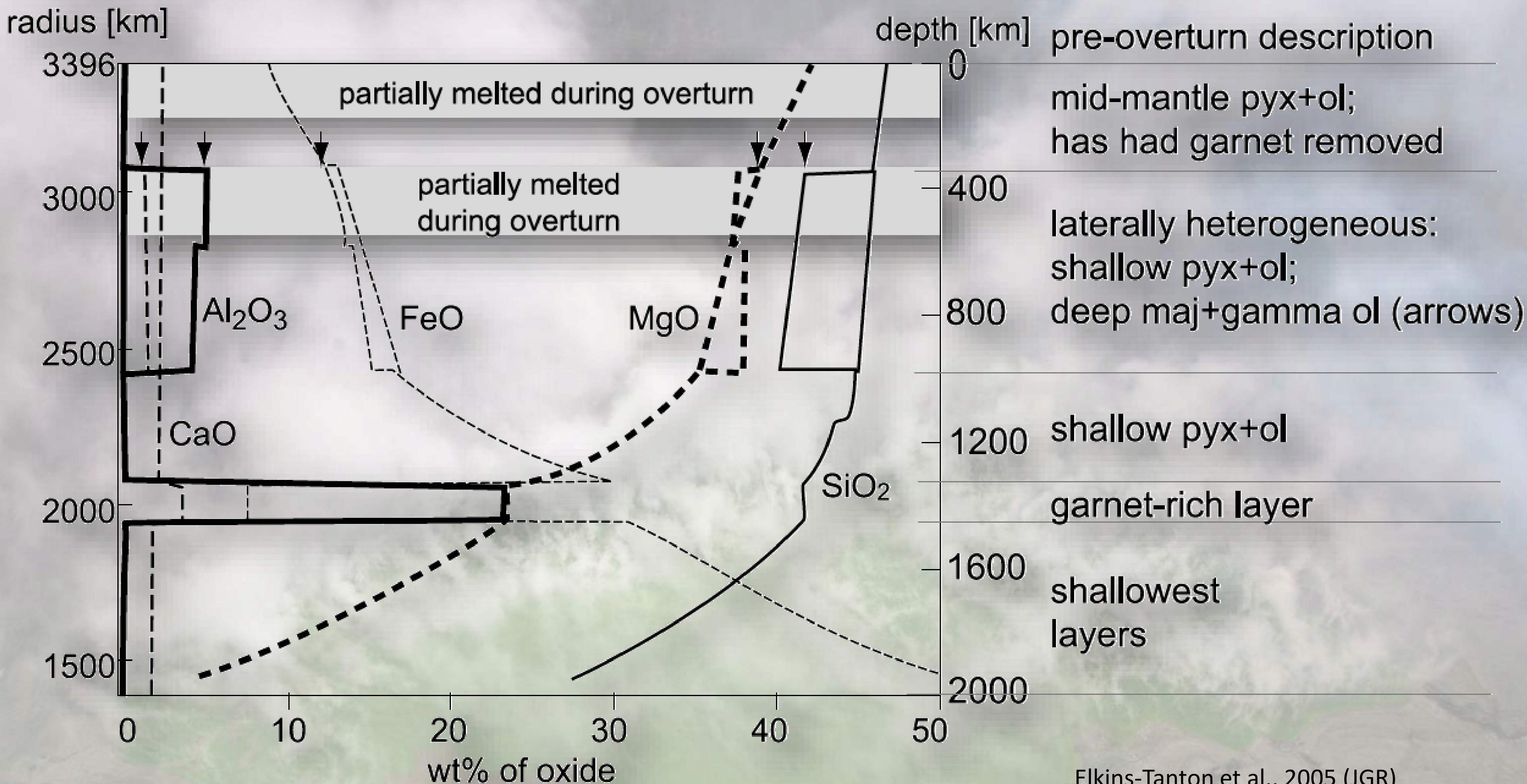
Magma ocean evolution

The case of Mars



Elkins-Tanton 2005 - JGR-Planets

A primary crust formed during mantle overturn



Elkins-Tanton et al., 2005 (JGR)

A wide range of possible scenario depending on the magma ocean depth that are not necessarily incompatible with the Noachian crust composition

Magma ocean evolution
The case of Mars

Magma ocean crystallization

Overturn – adiabatic decompression

Melting

Production of an olivine–pyroxene “primary crust”

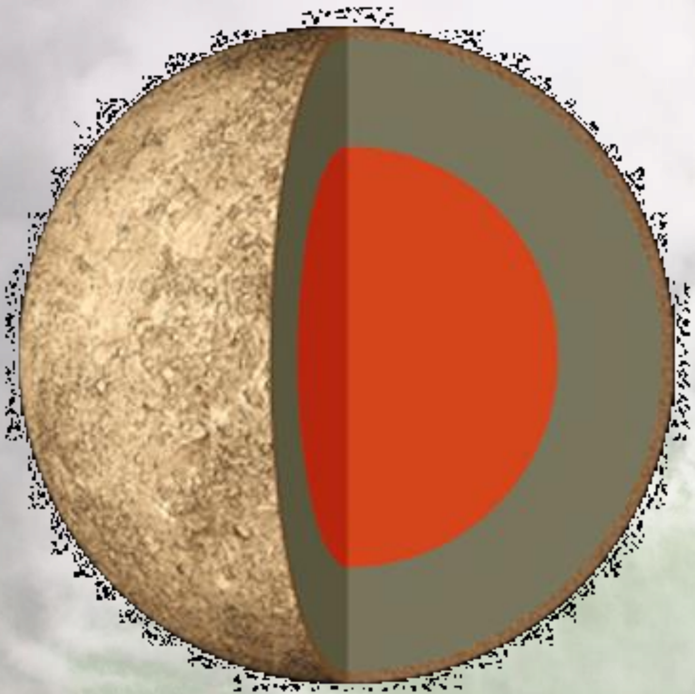
Why there is no floatation crust on Mercury ?

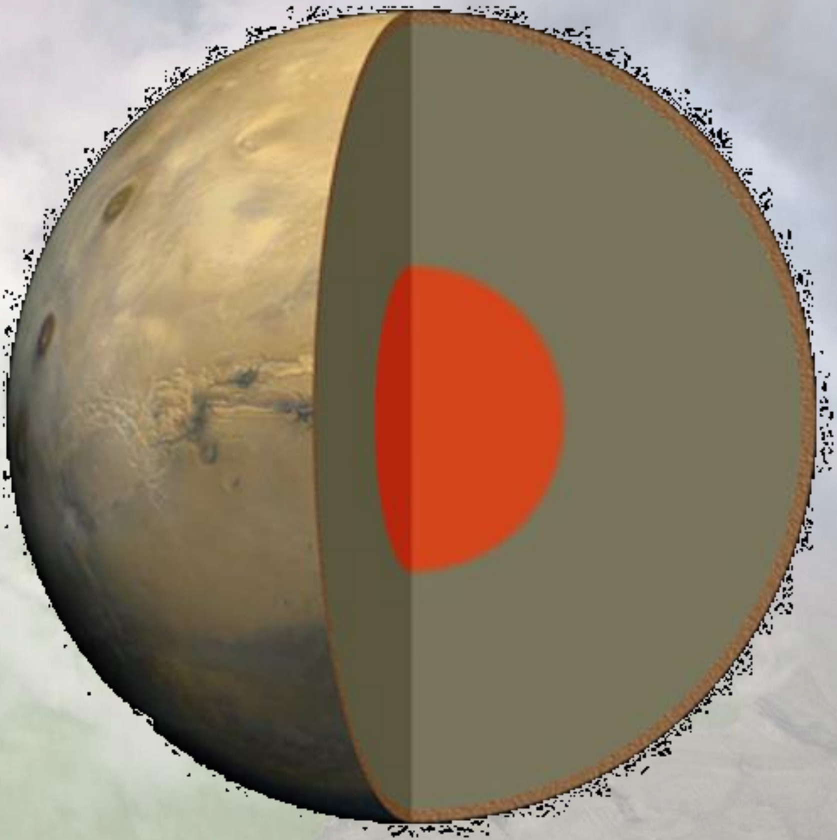
1. Al has been sequestered in the garnet layer ?

2. Water abundance inhibits the crystallization of plagioclase ?

3. The crystallized magma ocean is unstable, and the overturn produces a secondary crust.

Internal structure of Mercury vs Mars





Mercury has a large core, shallow mantle, and surface is poor in Fe

Why there is no floatation crust on Mercury ?

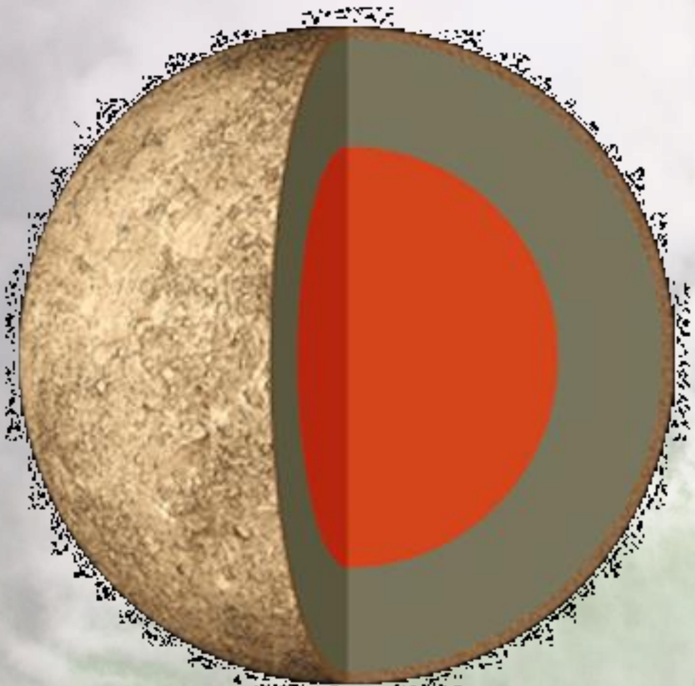
1. Al has been sequestered in the garnet layer ?
No – mantle is not deep enough

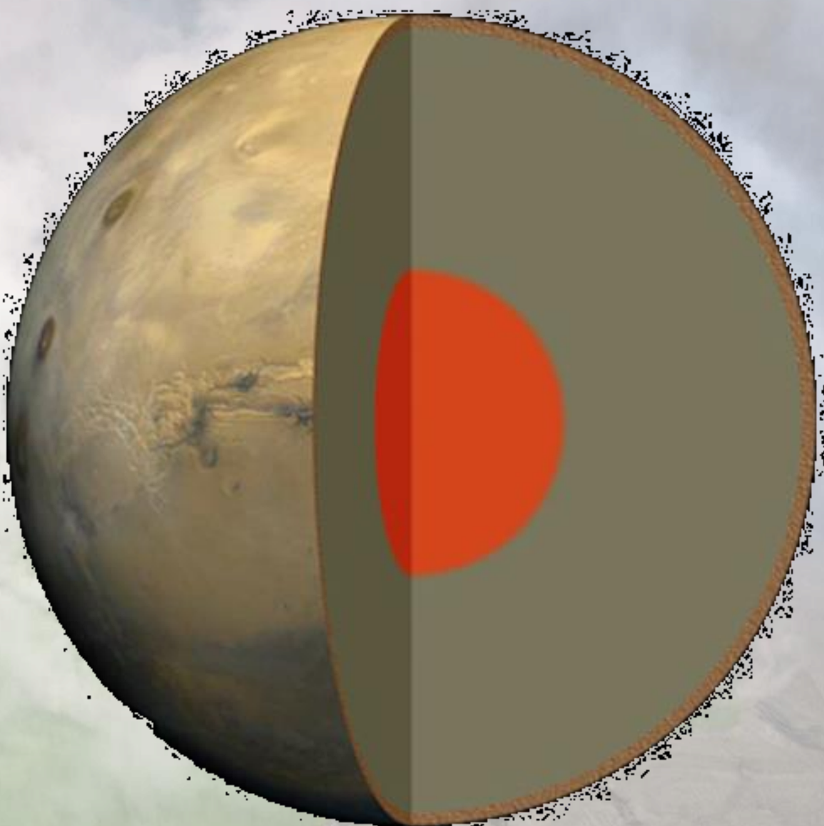
2. Water abundance inhibits the crystallization of plagioclase ?
Mercury is not rich in volatiles

3. The crystallized magma ocean is unstable, and the overturn produces a secondary crust.
Yes, possible, too.

4. But there is also another possible explanation.

Internal structure of Mercury vs Mars





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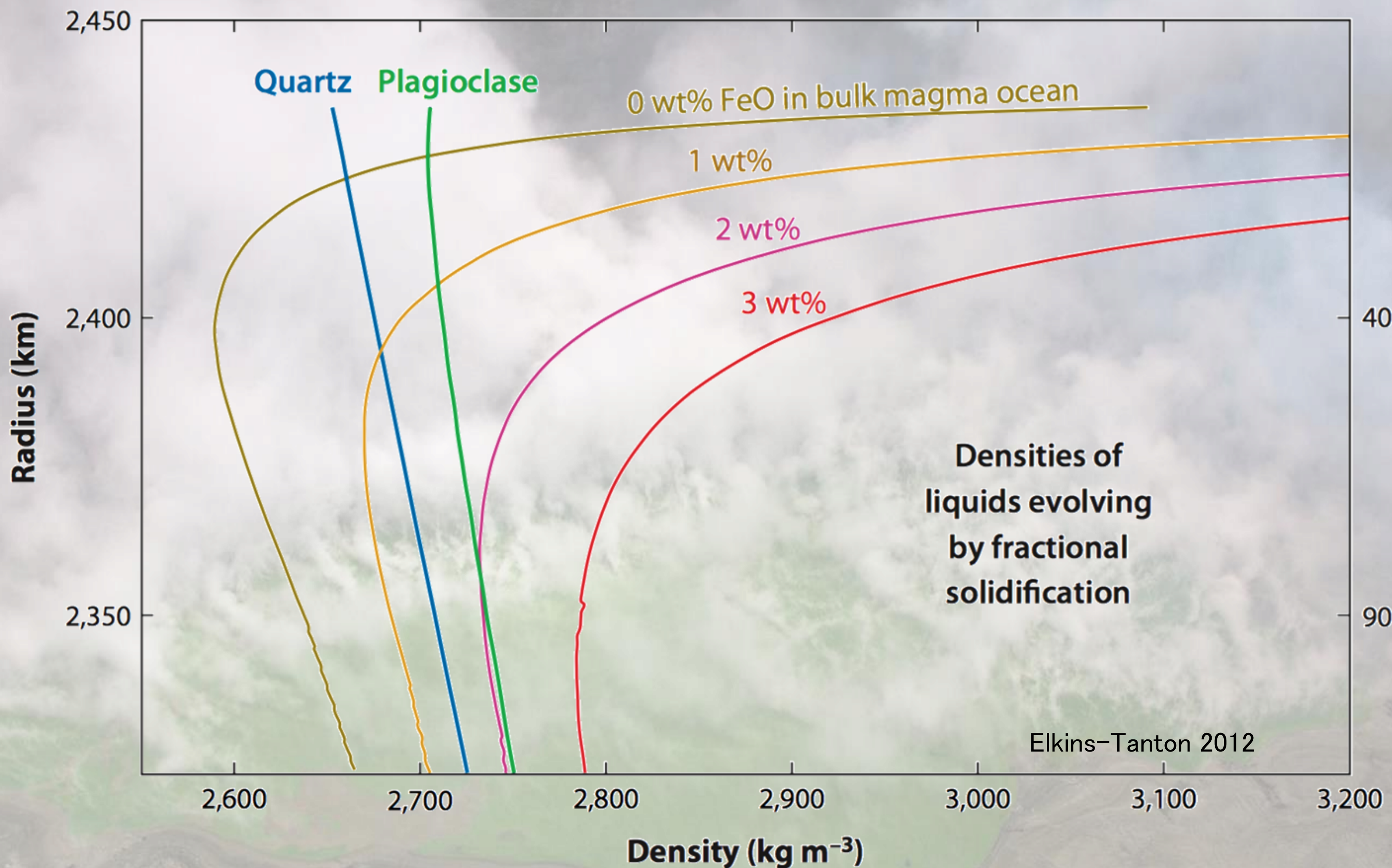
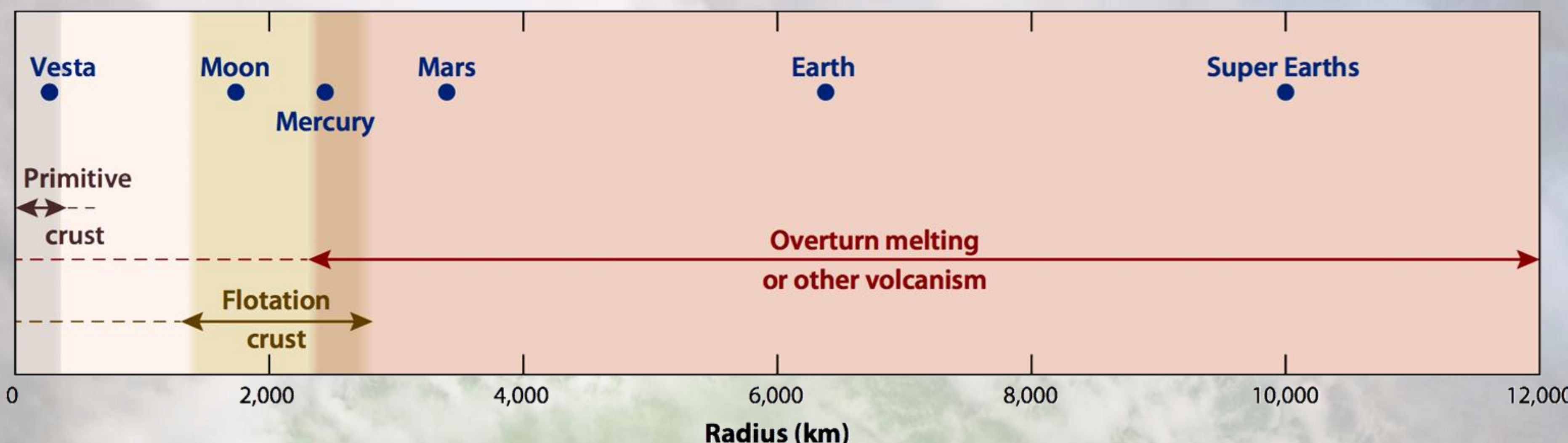


Plagioclase cannot float in a Mercury magma ocean

Magma oceans as a function of planet size



Elkins-Tanton 2012 – Annual Review of Earth and Planetary Science

Part 4. – Long-term thermal evolution

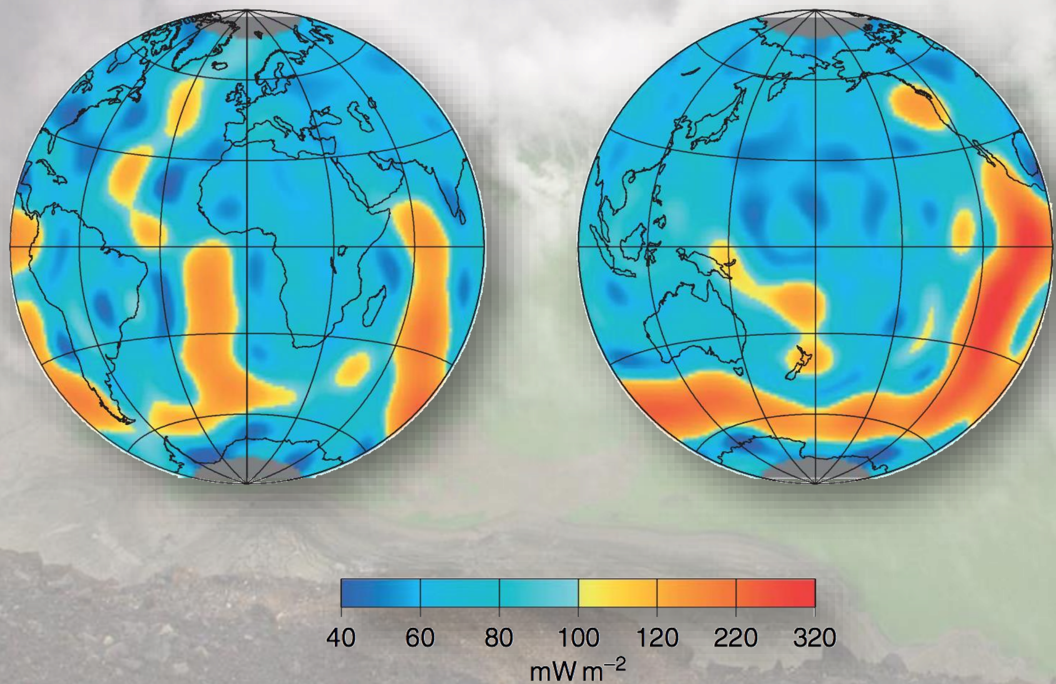
Our planet is cooling

$$^{232}\mathrm{Th} \rightarrow {}^{208}\mathrm{Pb} + 6\,{}^{4}\mathrm{He} + 4\mathrm{e}^{-} + 4\bar{\nu}_e + 42.7\ \mathrm{MeV}$$

$$^{40}\mathrm{K} \rightarrow {}^{40}\mathrm{Ca} + \mathrm{e}^{-} + \bar{\nu}_e + 1.31\ \mathrm{MeV}$$

$$^{40}\mathrm{K} + \mathrm{e}^{-} \rightarrow {}^{40}\mathrm{Ar} + \nu_e + 1.51\ \mathrm{MeV}$$

$$^{238}\mathrm{U} \rightarrow {}^{206}\mathrm{Pb} + 8\,{}^{4}\mathrm{He} + 6\mathrm{e}^{-} + 6\bar{\nu}_e + 51.7\ \mathrm{MeV}$$



Heat production : 20 TW

Heat loss: 40 TW

The Earth is cooling

The Urey ratio

Internal heat production within the entire Earth divided by total surface heat flux.

Ur > 1: The Earth is heating up !

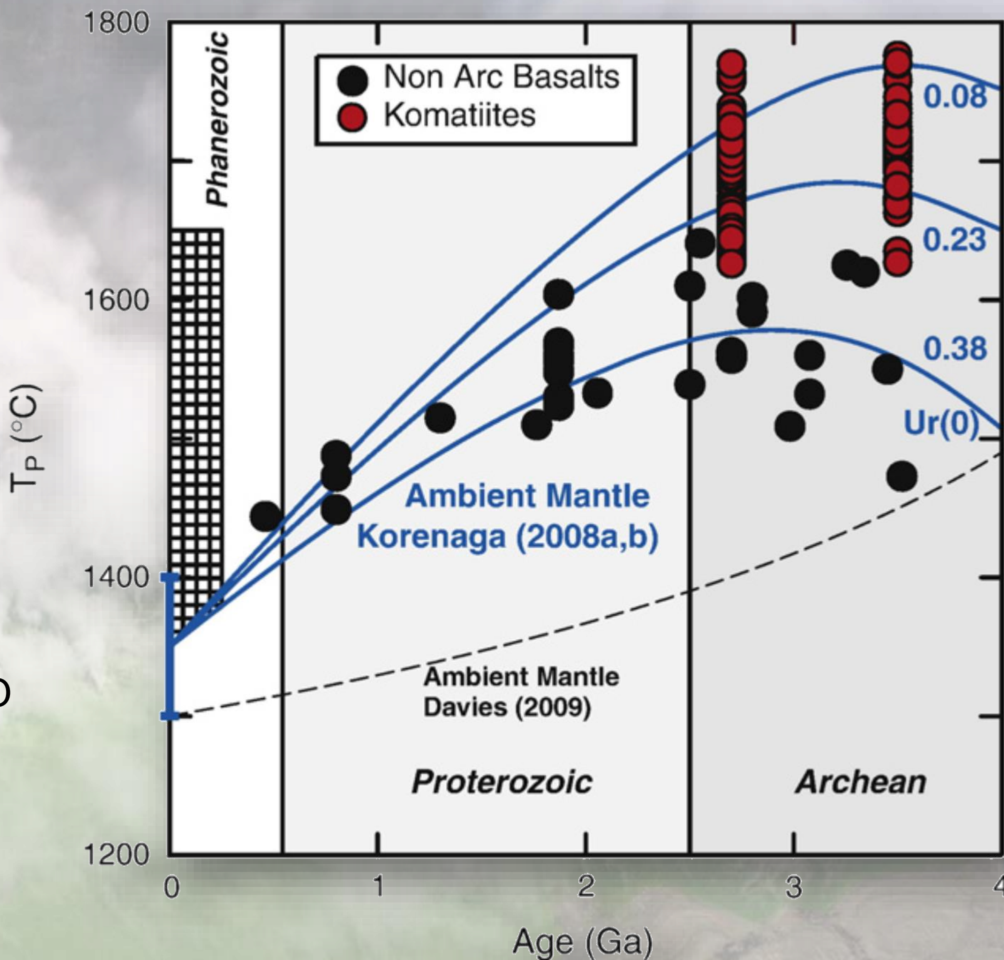
Ur < 1: The Earth is cooling down !

Present Ur value ~ 0.3

The Urey ratio

Mantle potential temperature

$T_P(°C) = 1463 + 12.74MgO - 2924/MgO$



Herzberg et al. 2010 – Earth and Planetary Science Letters

Mantle Potential Temperature

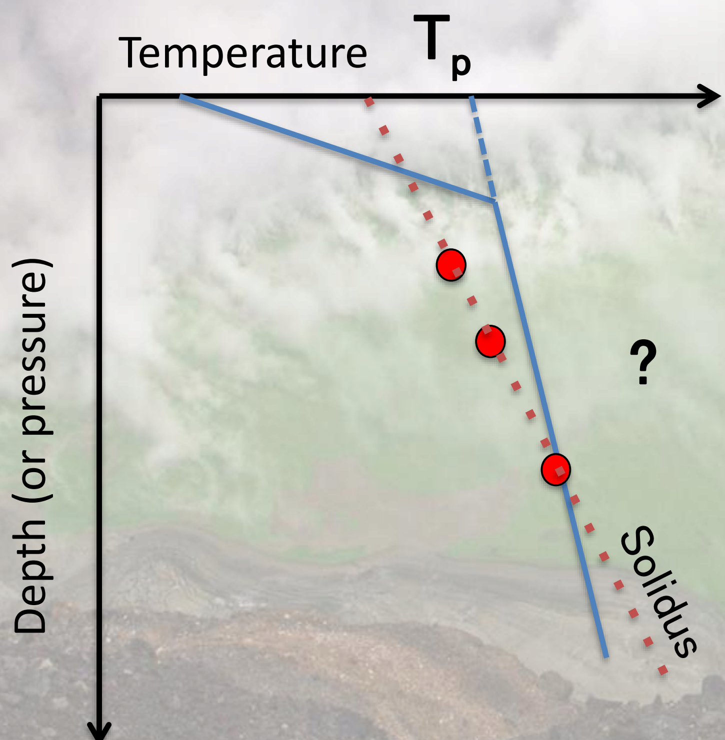
How do we measure the temperature of the interior of the Earth ?

Adiabatic temperature gradient in a convecting mantle

$$\left(\frac{\partial T}{\partial z}\right)_S = \frac{g\alpha_f T}{C_P}$$

For instance, at T = 1500 K

$$\left(\frac{\partial T}{\partial z}\right)_S \simeq 1\,^{\circ}\mathrm{C\,km^{-1}}$$



How can we compare estimates of mantle temperatures at different depths ?

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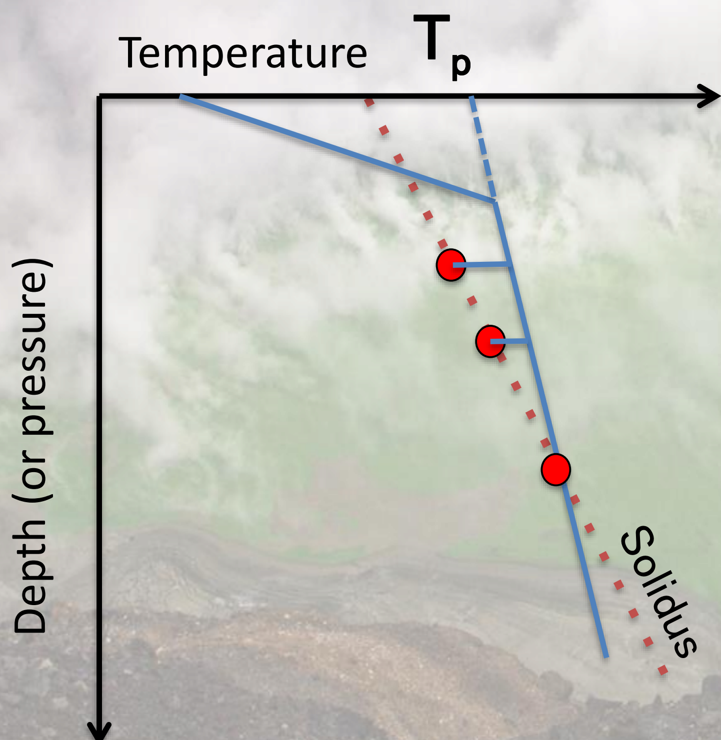

How can we compare estimates of mantle temperatures at different depths ?

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

Mantle Potential Temperature

How do we measure the temperature of the interior of the Earth ?

Geophysical approach

Thickness of the elastic lithosphere – Measurement of the depth of an isotherm

The gravitational field of a planet holds information on the surface and subsurface mass distribution and the relationship be- tween the observed gravitational signal and the topography can be inverted to infer densities and elastic parameters of the litho- sphere

Petrological approach

Conditions of partial melting of volcanic rocks exposed at the surface.

A complex problem – the surface composition of magmas depend on

- Composition of the mantle source
- Conditions of partial melting (integration of melts generated along a P-T path)
- History of magma ascent (fractional crystallization)

Numerical approach – Simulations

Numerical simulations of mantle convection

The Urey ratio

Mantle potential temperature

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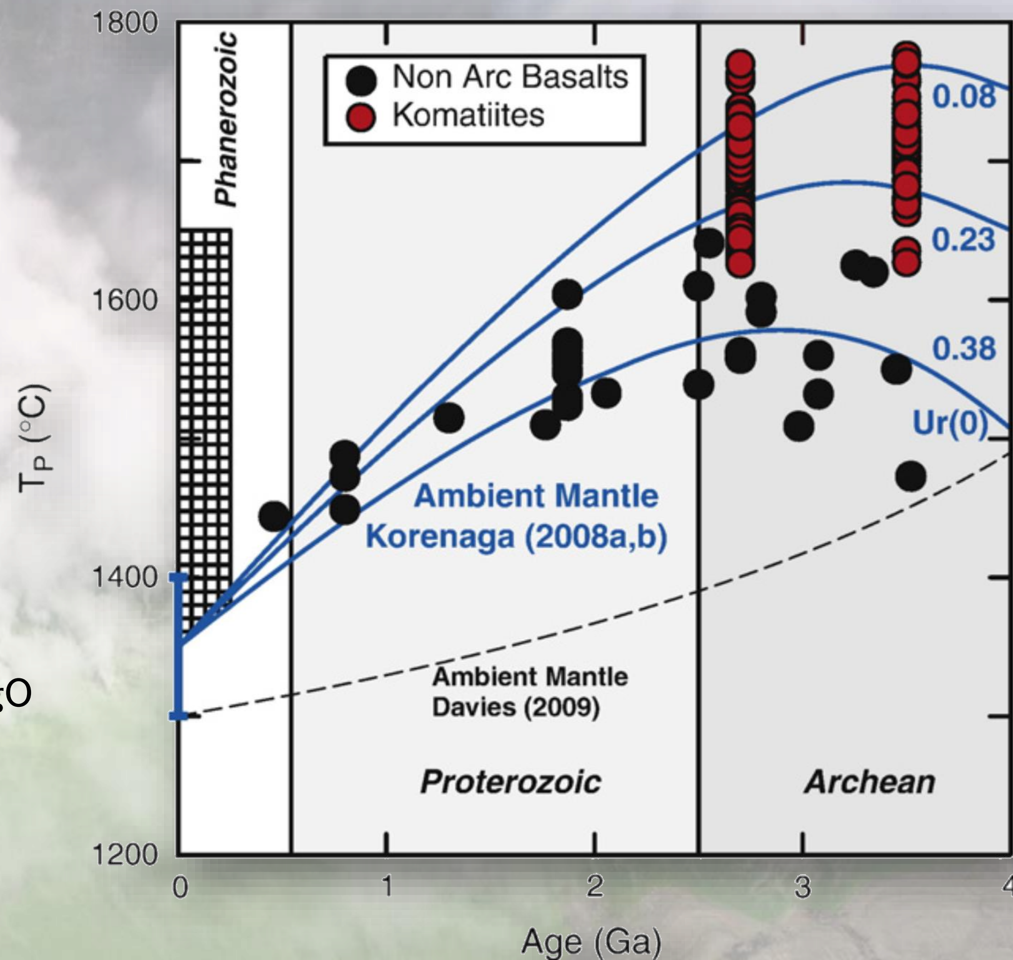

Herzberg et al. 2010 – Earth and Planetary Science Letters

Major issue – Mantle is chemically and thermally heterogeneous
How can we make sure that we measure an "ambient" mantle temperature ?

Can we decipher the thermal evolution of another planet than the Earth ?

How would this help us to understand the thermal evolution of our planet ?