Evolution of Earth, Venus, and Mars (interior structure)

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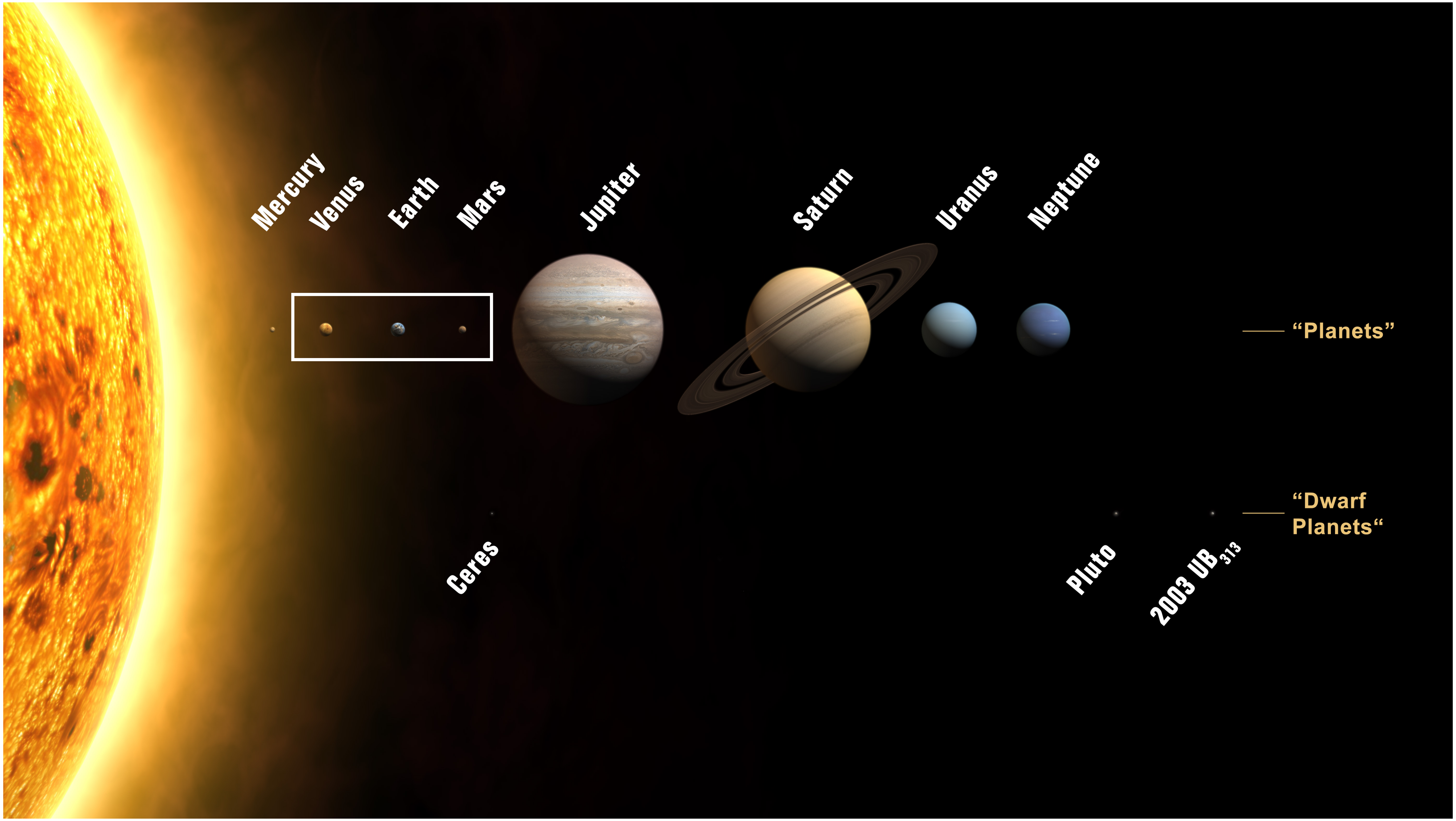
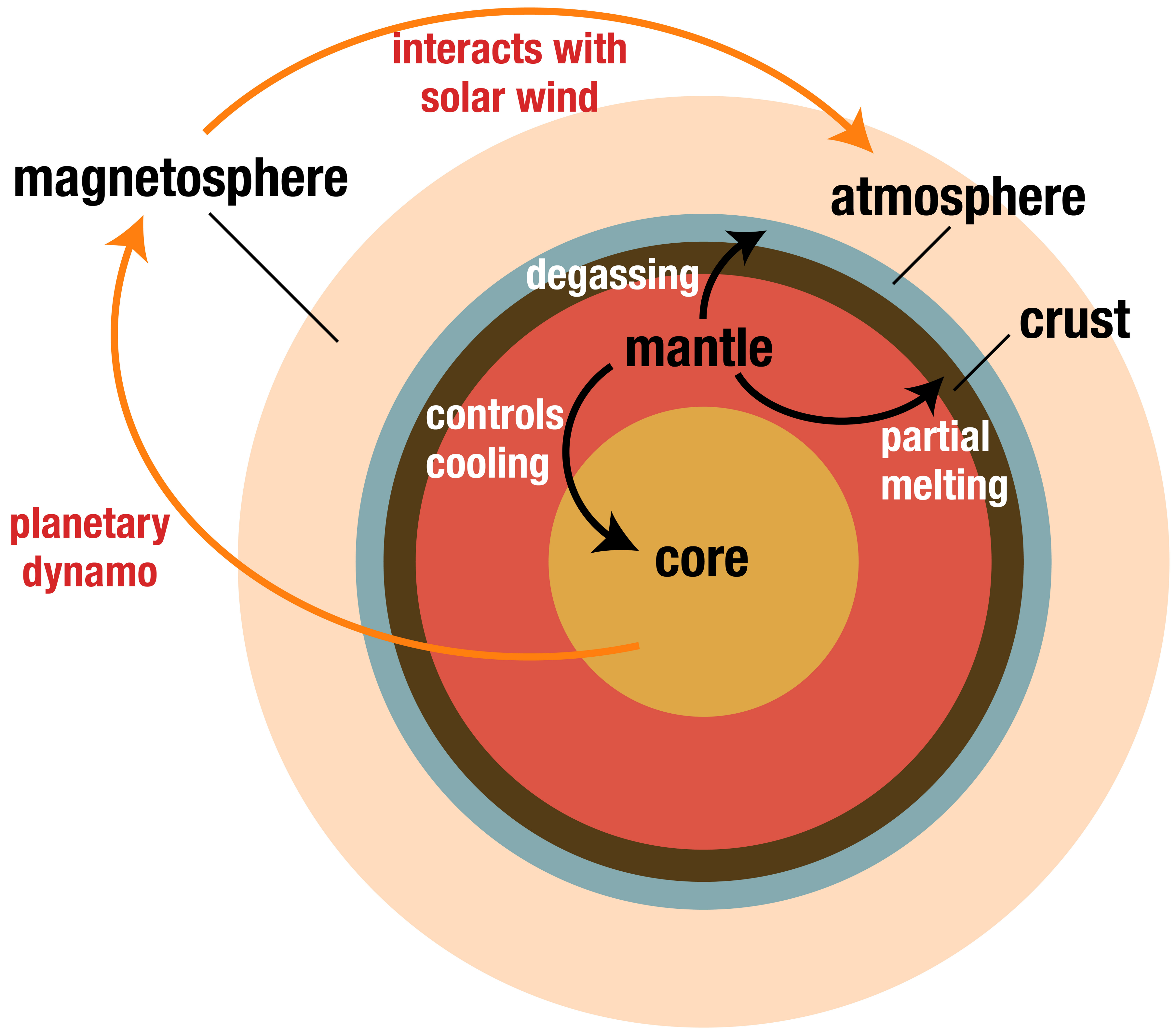
July 15, 2019 @ Sagan Summer Workshop

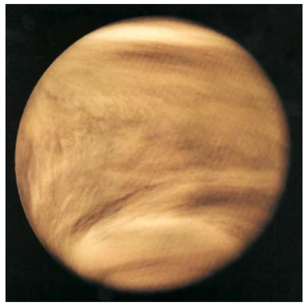
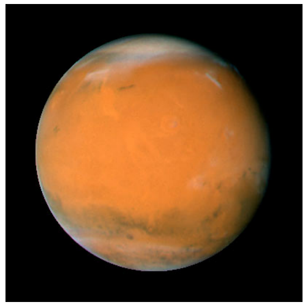
Planets in our solar system



https://apod.nasa.gov/apod/image/0608/planets_iau_big.jpg

Structure of terrestrial planets



	present-day Earth	Earth*	Venus	Mars
Atmospheric composition				
N_2	78.1	1	1.8	2.7
O_2	20.9	-	-	-
Ar	0.9	0.01	0.02	1.6
CO_2	0.035	99	98.1	95.3
Atmospheric pressure	1 atm	~80 atm	90 atm	0.006 atm
average surface temperature	15°C	~200°C	450°C	-30°C

*** Present-day Earth composition - (life-origin O_2) + (CO_2 in sedimentary rocks)**

Plate tectonics enables long-term carbon cycle

Silicate-carbonate subcycle:

chemical weathering and
marine carbonate sedimentation

$$CO_2 + CaSiO_3 \rightarrow CaCO_3 + SiO_2$$

decarbonation by volcanism, metamorphism,...

$$CaCO_3 + SiO_2 \rightarrow CO_2 + CaSiO_3$$

Organic subcycle:

net photosynthesis by organic C burial

$$CO_2 + H_2O \rightarrow CH_2O + O_2$$

“georespiration”

$$CH_2O + O_2 \rightarrow CO_2 + H_2O$$

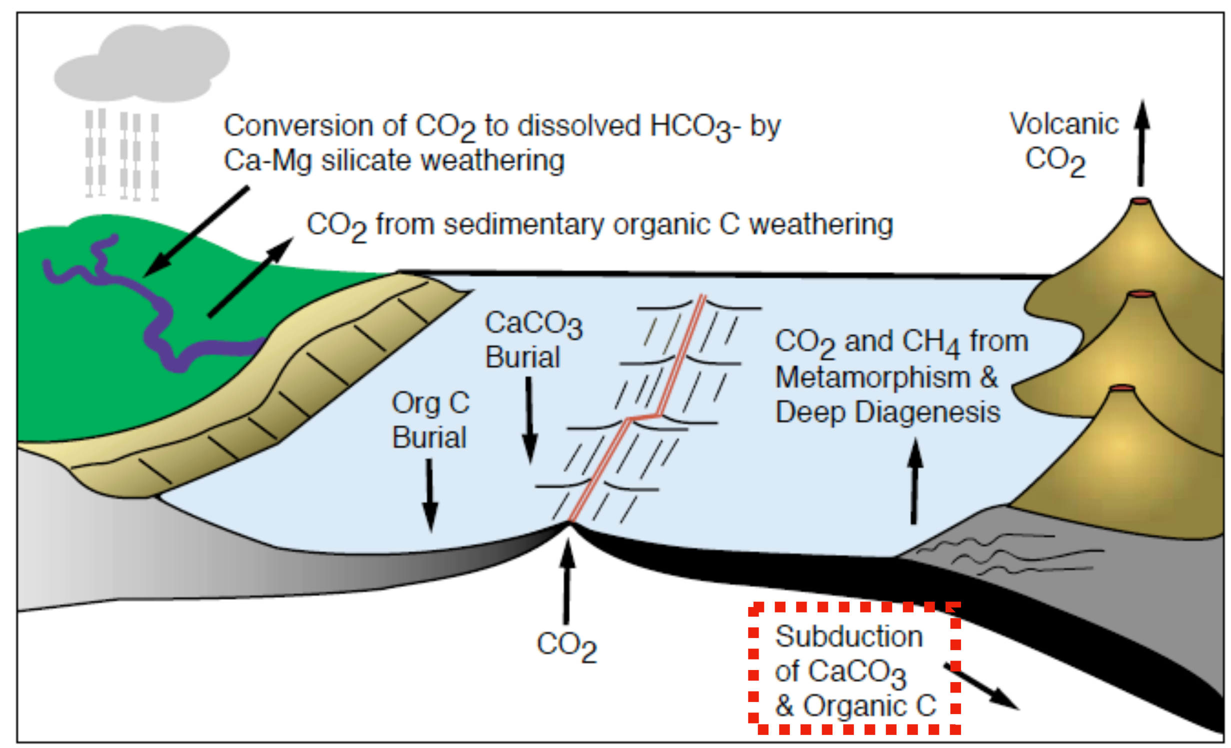


Figure 1. An idealized and simplified representation of the surficial aspects of the long-term carbon cycle. Note the exchange of carbon between rocks, on the one hand, and the oceans and atmosphere, on the other; this is the distinguishing characteristic of the long-term cycle.

[Berner, GSA Today, 1999]

Two modes of mantle convection

Stagnant lid convection (Venus and Mars)

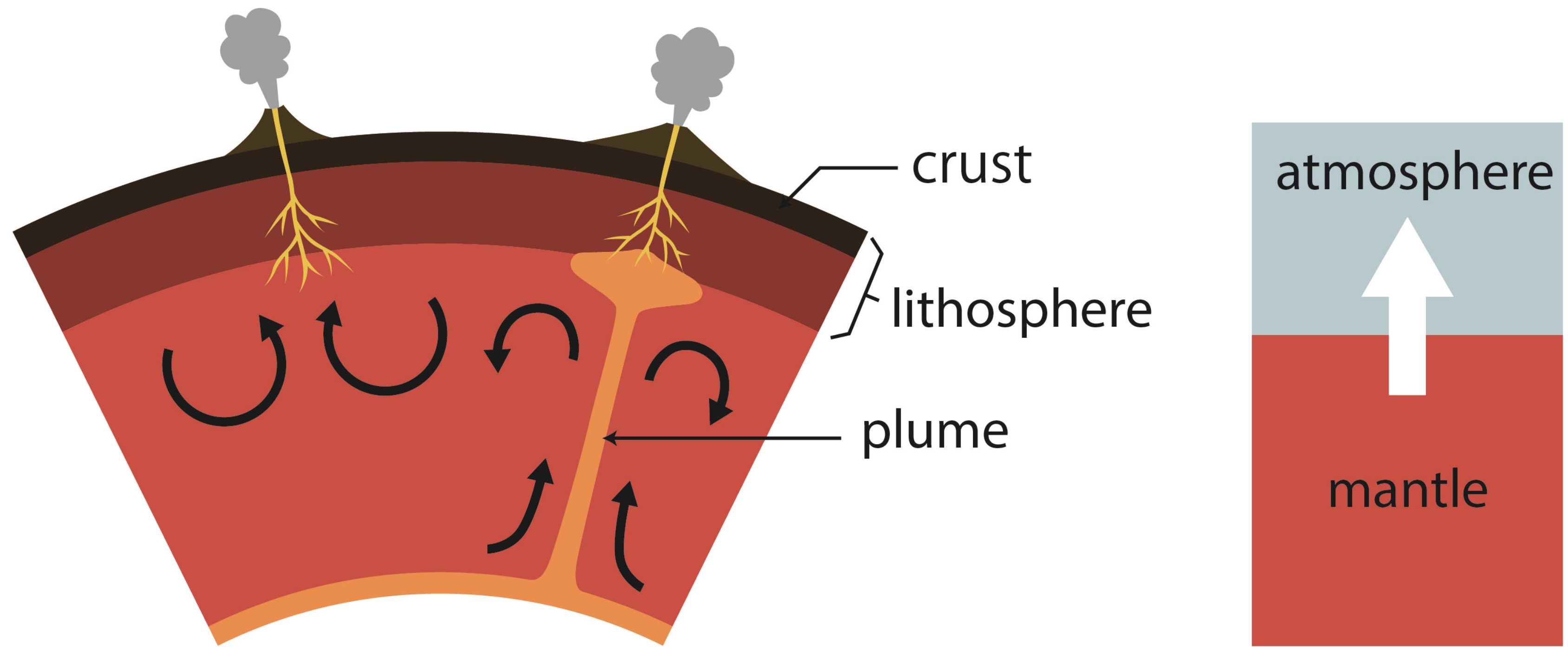
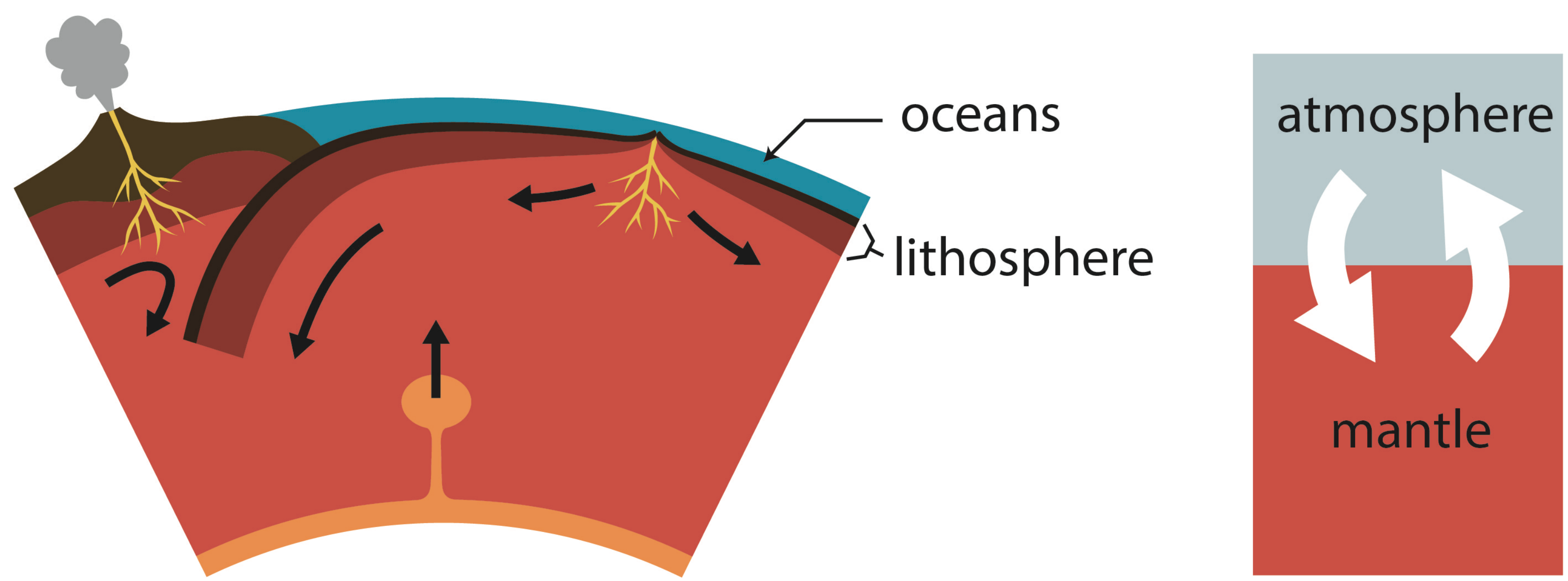


Plate tectonics (Earth)

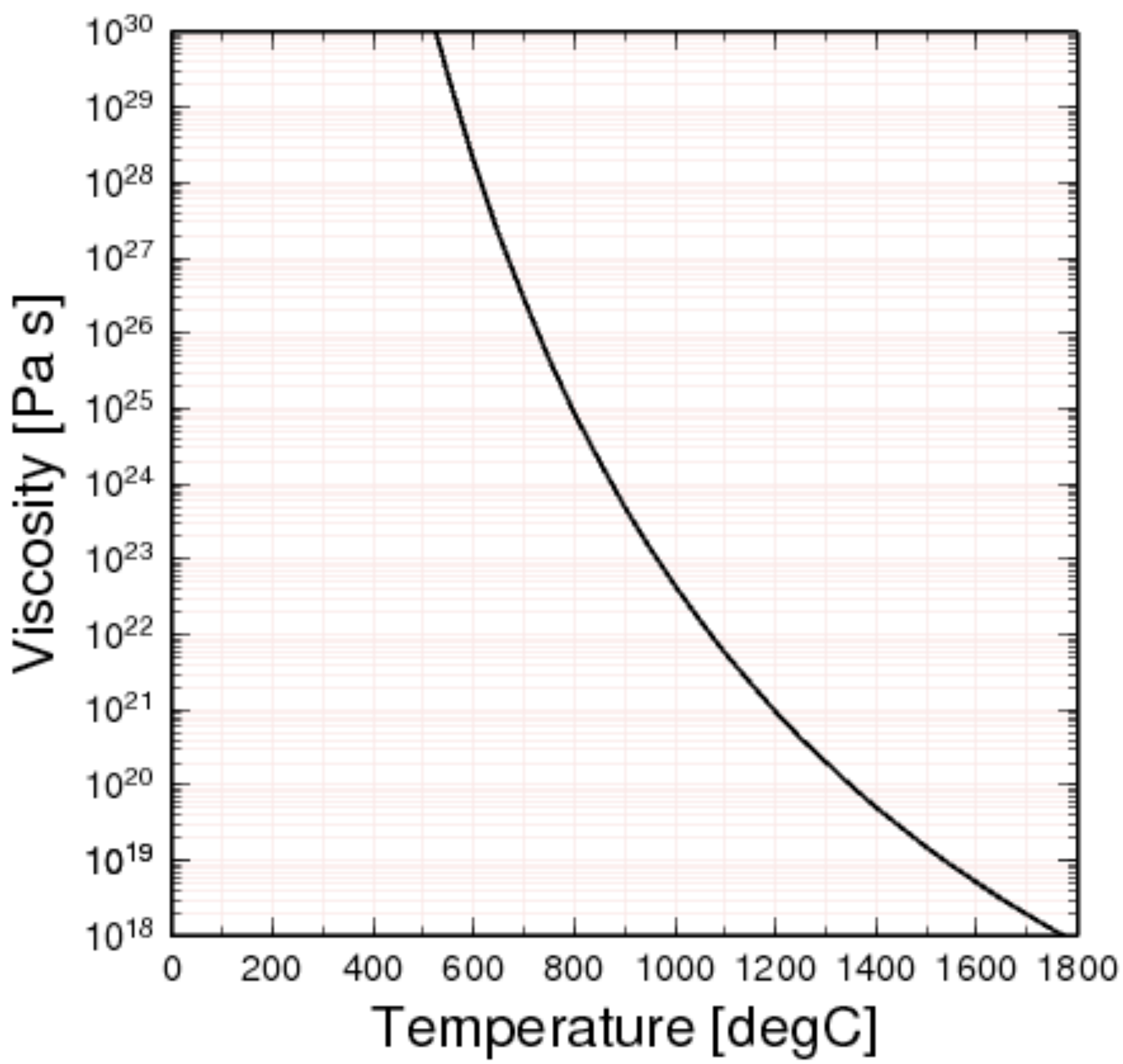


[Korenaga, 2014]

Stagnant lid convection

the most "natural" mode of convection for silicate mantle

Viscosity of silicate rocks follows the Arrhenius form: $\exp\left(\frac{E}{RT}\right)$



$Ra_i = 10^6$

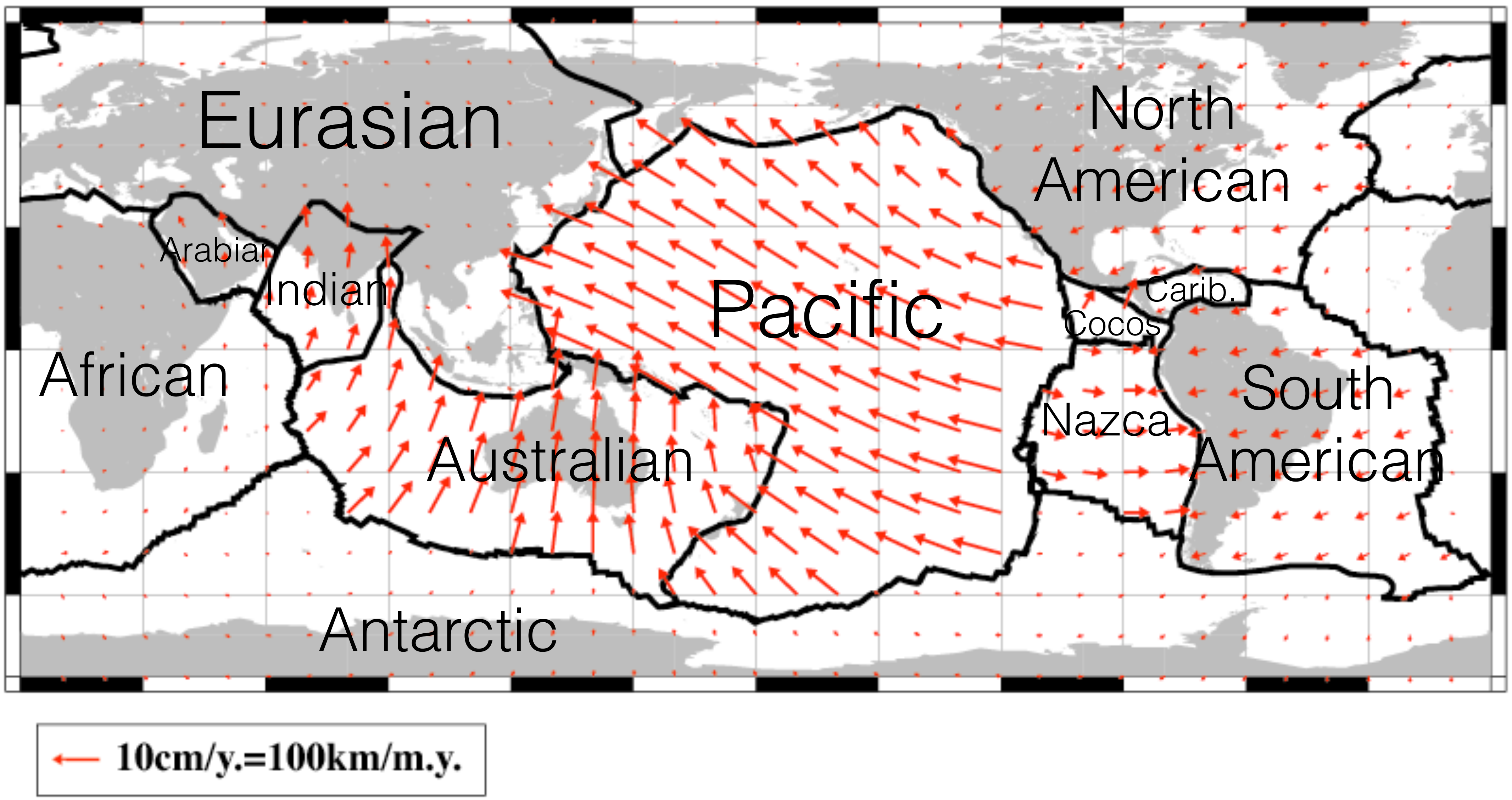
E

0 kJ/mol (isoviscous convection)

300 kJ/mol (stagnant lid convection)

Earth has plate tectonics

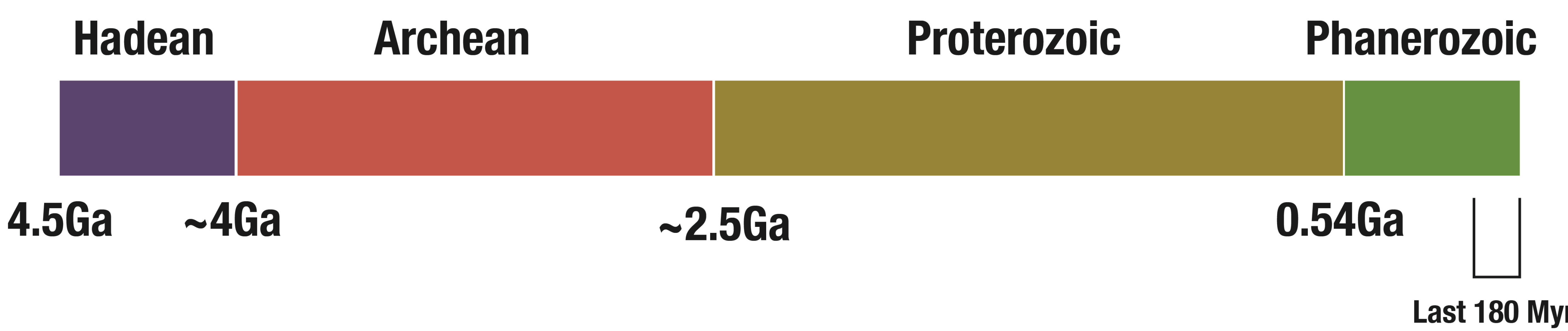
Present-day surface velocity field



Note: Smaller plates are missing in this map
(Juan de Fuca, Philippine Sea, Scotia).
The number and size of plates are time-dependent
(e.g., Cocos and Nazca used to be one plate called Farallon).

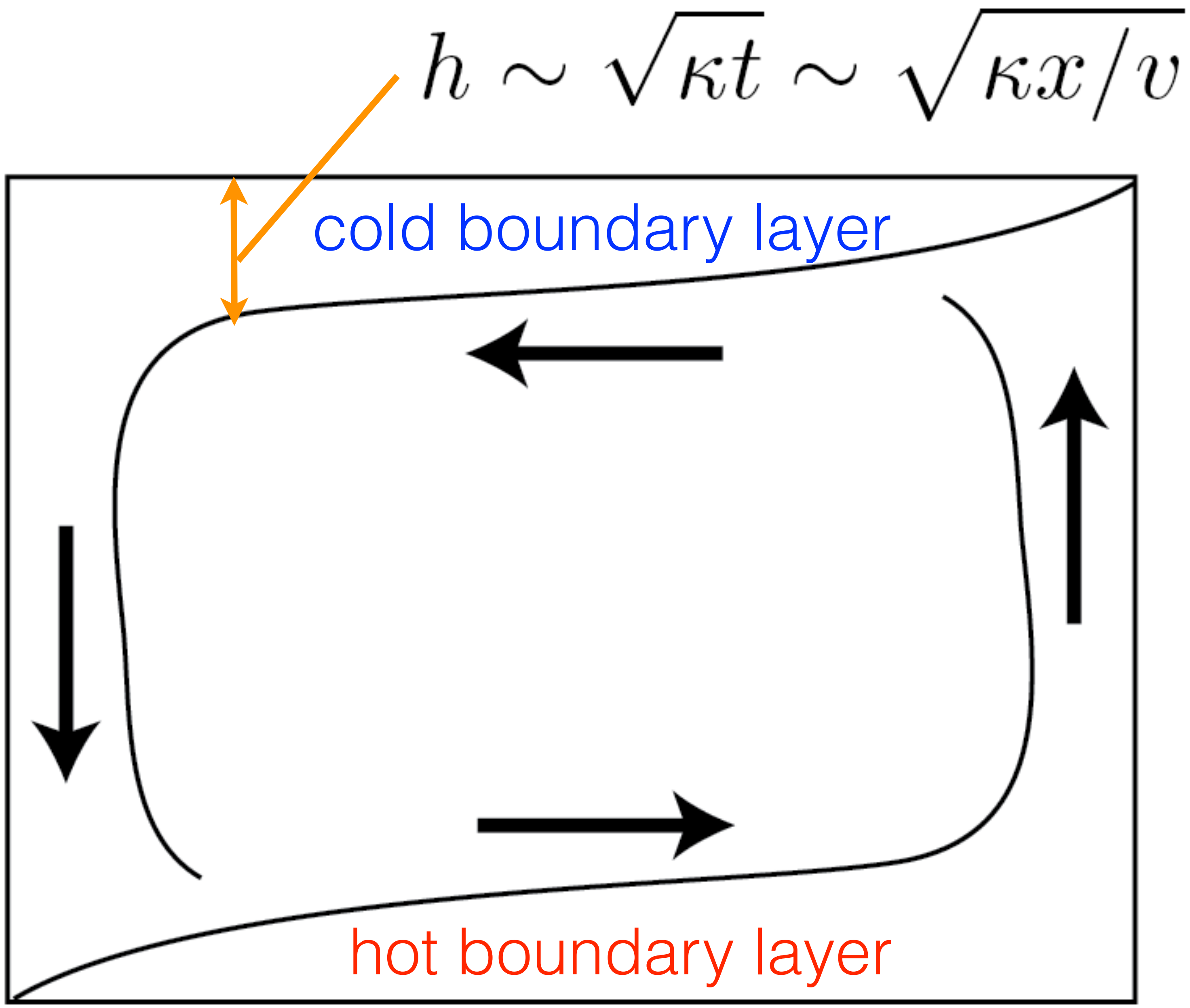
Three major questions about plate tectonics

- Why does it happen?
- How has it evolved?
- When did it start?



Basics of mantle convection

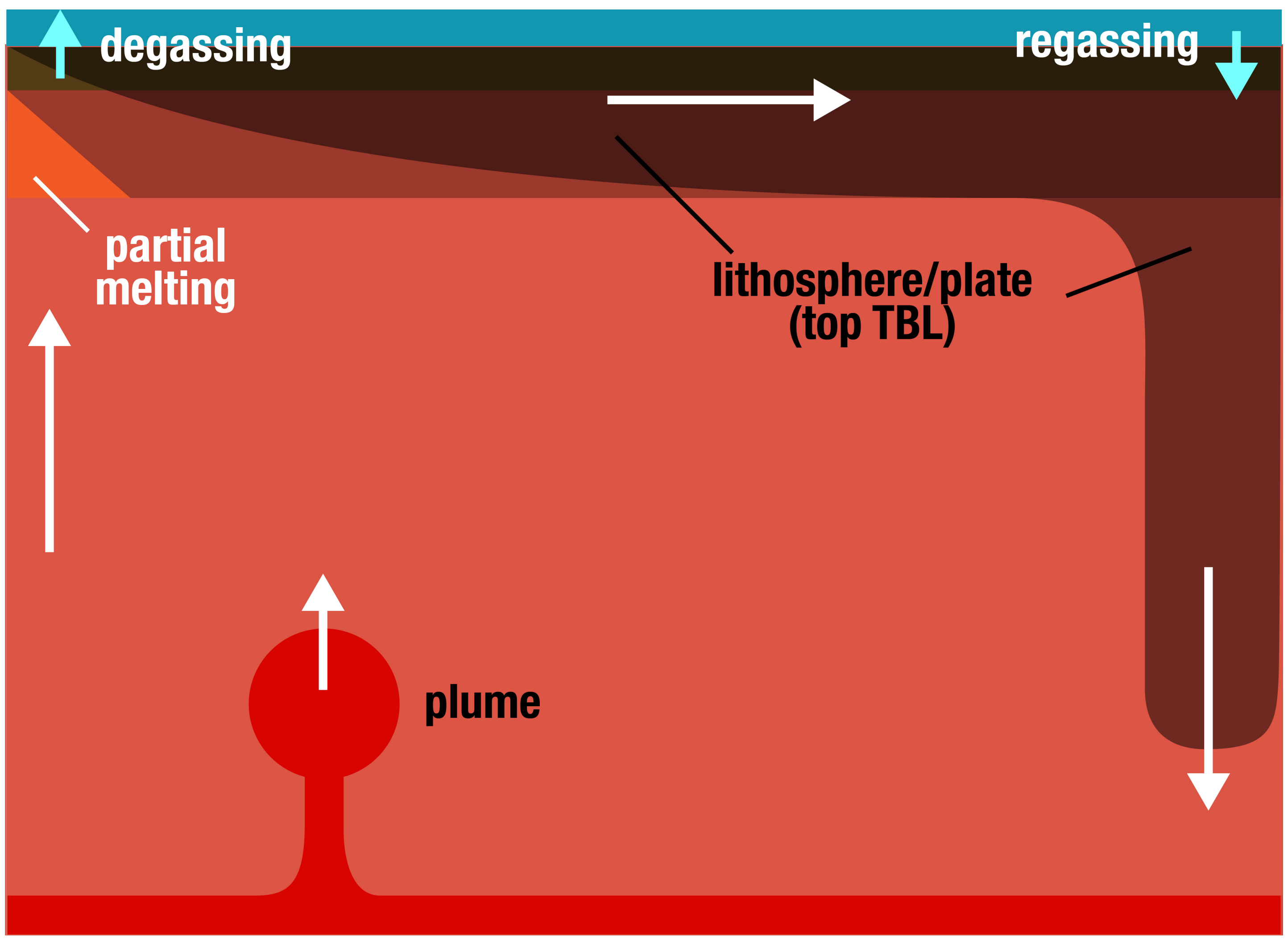
(1) simple Rayleigh-Benard convection



- convection = **con**duction +ad**vection**
- Boundary layers grow by conduction
- Faster convection leads to thinner boundary layers

Basics of mantle convection

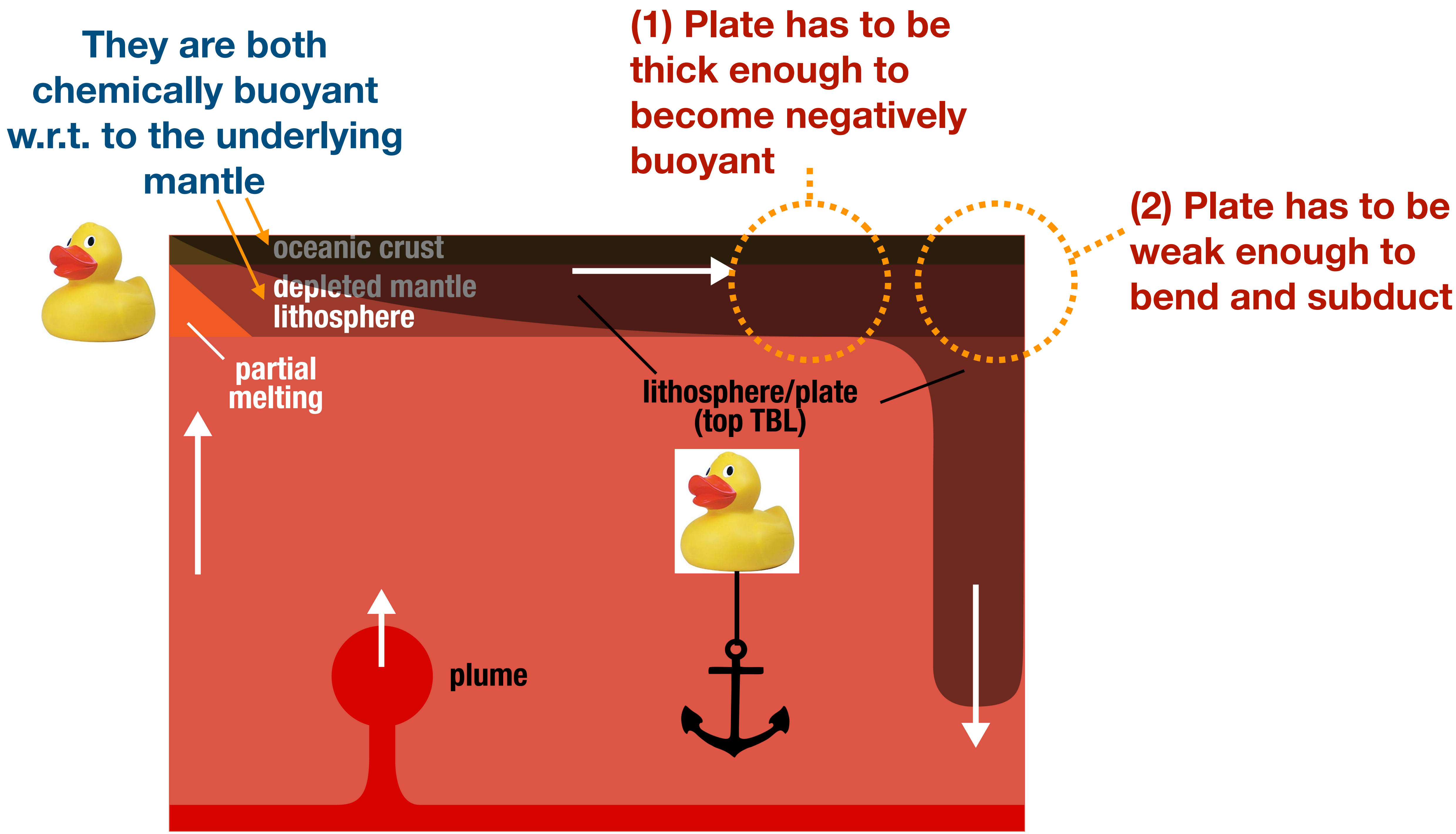
(2) R-B convection vs. mantle convection



- **Driven primarily by cooling from above**: Q_surface = Q_bottom + (radiogenic heating) + (secular cooling)
- **Variable viscosity** (stiff lithosphere)
- **Chemical differentiation** by partial melting
- **Open system behavior** (deep water cycle)

Basics of mantle convection

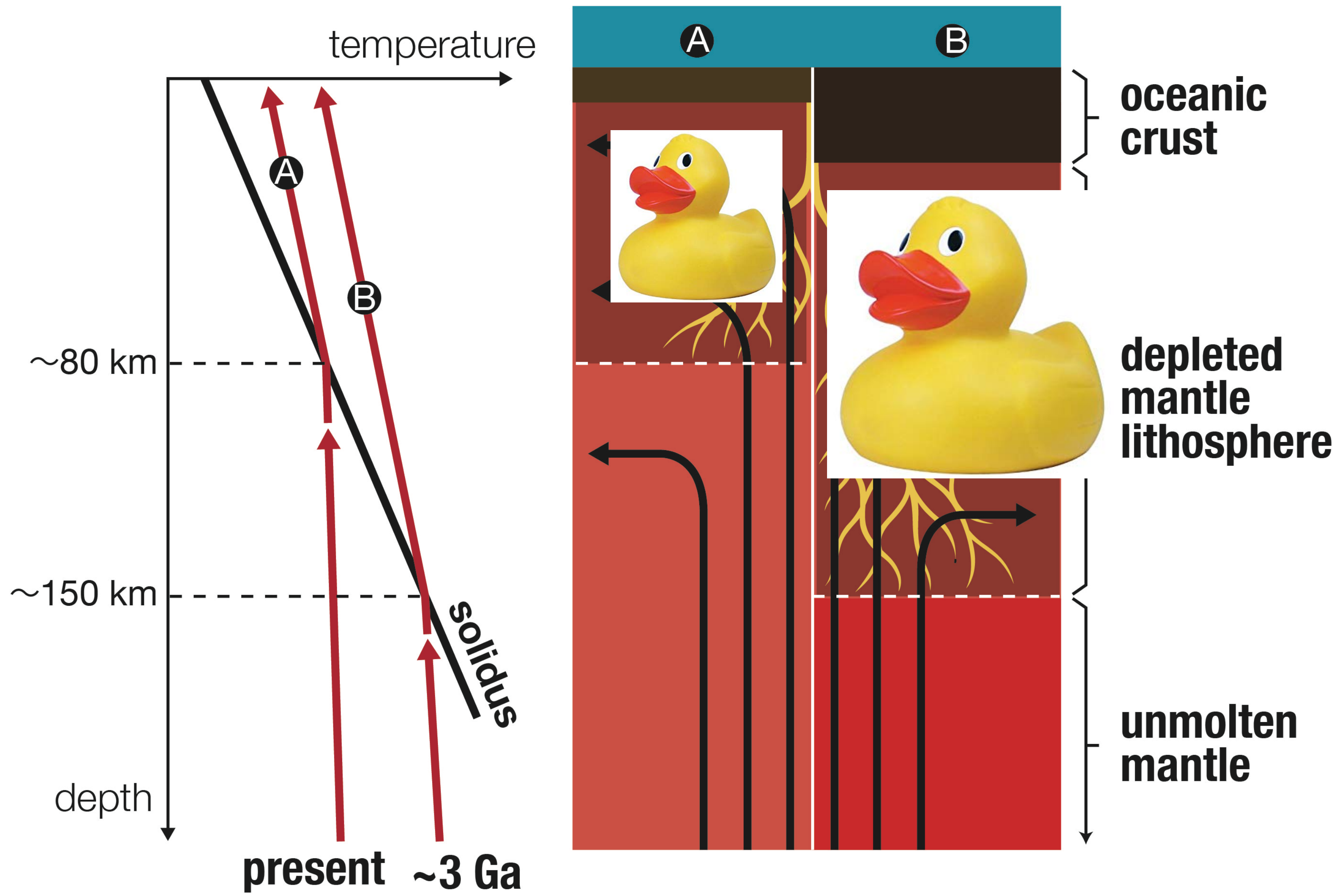
(3) two conditions for plate tectonics



Chemical buoyancy problem

- **A hotter mantle** in the past suffers from **greater chemical buoyancy**, requiring **a thicker plate** to become ready to sink.

- Thicker plate is possible with **slow plate tectonics,** but they are **more difficult to bend**.



[Korenaga, 2014]

Viscosity contrast problem

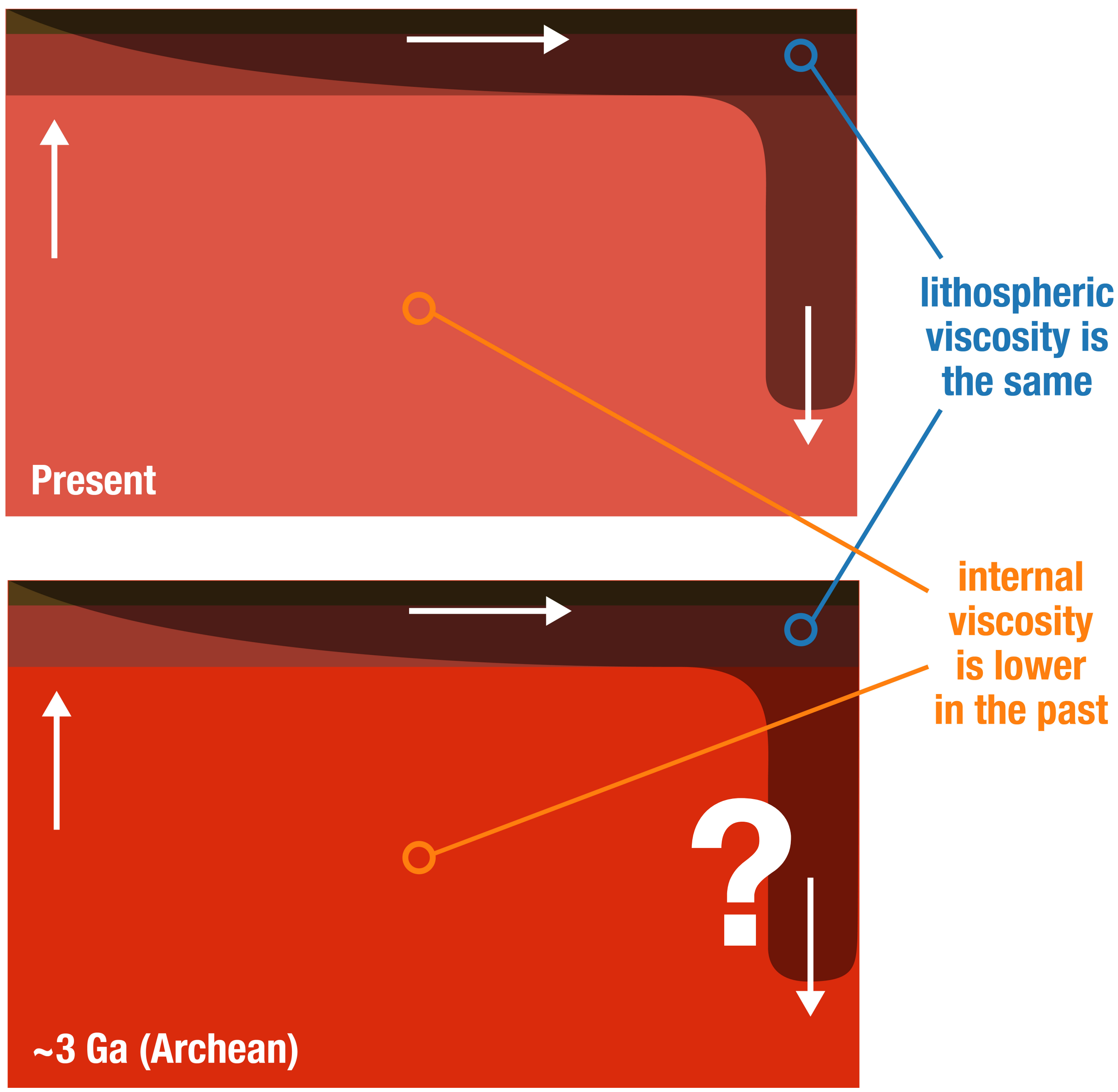
Viscosity contrast criterion for plate tectonics (under Earth conditions)

$$\frac{\eta_L}{\eta_i} < 10^3 - 10^4$$

[Korenaga, 2010]

Viscosity contrast is expected to be greater in the past

$$\left(\frac{\eta_L}{\eta_i}\right)_{\text{present}} < \left(\frac{\eta_L}{\eta_i}\right)_{\text{past}}$$



How strong is lithosphere?

(1) viscosity & yield stress

strain rate
[s^{-1}]

$$\sigma = \eta \dot{\epsilon}$$

stress
[Pa]

viscosity
[Pa s]

water
10^{-3} Pa s

peanut butter
10^{2} Pa s

mantle rocks
>10^{18} Pa s

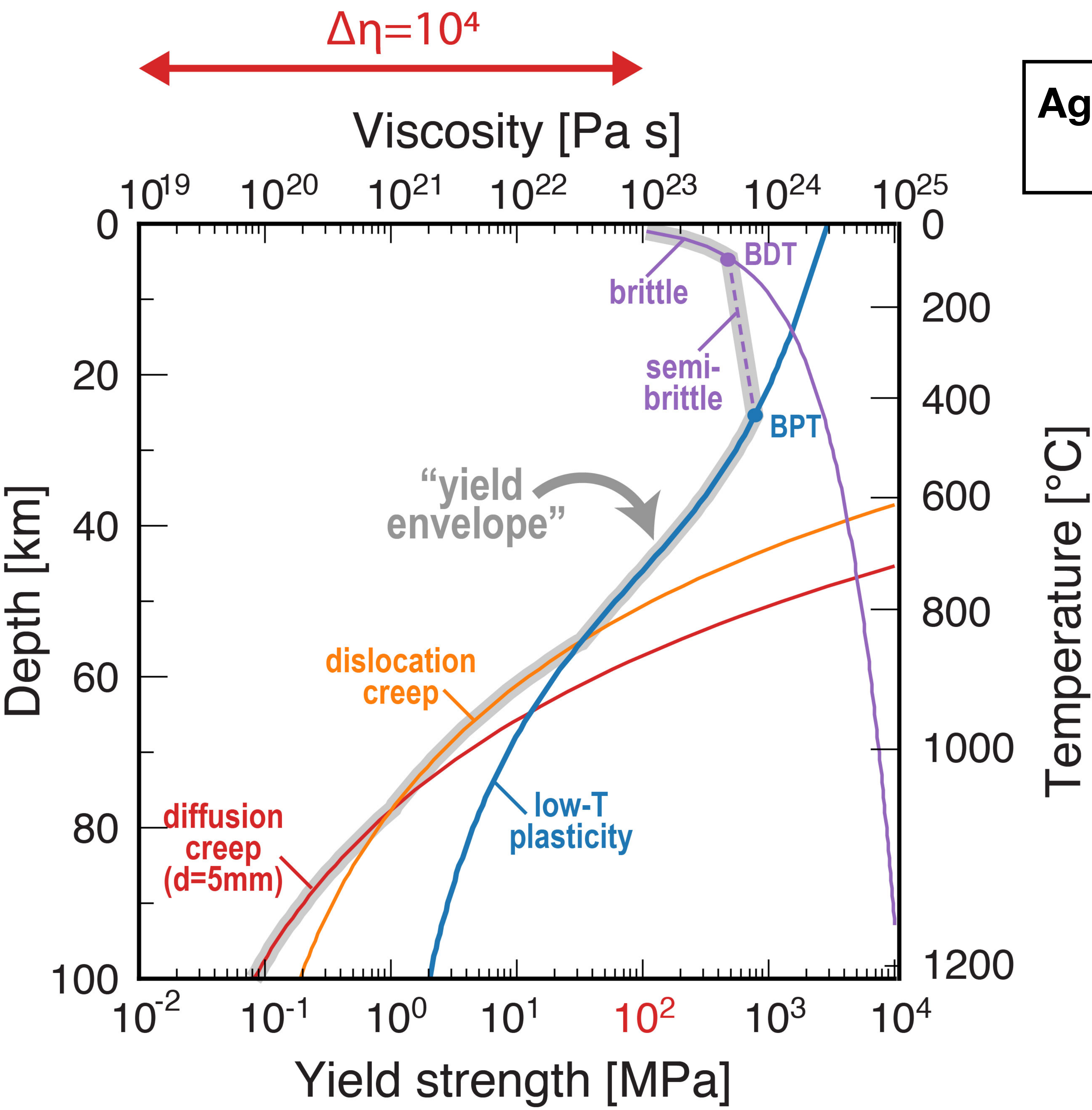
- **Two common choices:**

  1. Viscosity

  2. Yield stress (with the **geological strain rate** of **10^{-15} s^{-1}**)

How strong is lithosphere?

(2) yield envelope

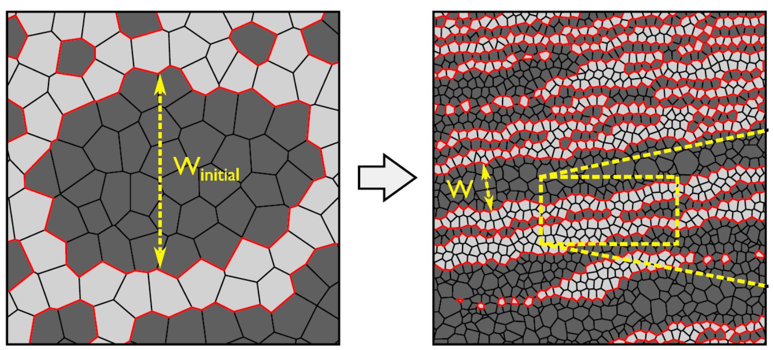


Age of lithosphere = 60 Ma

How strong is lithosphere?

(3) weakening mechanisms

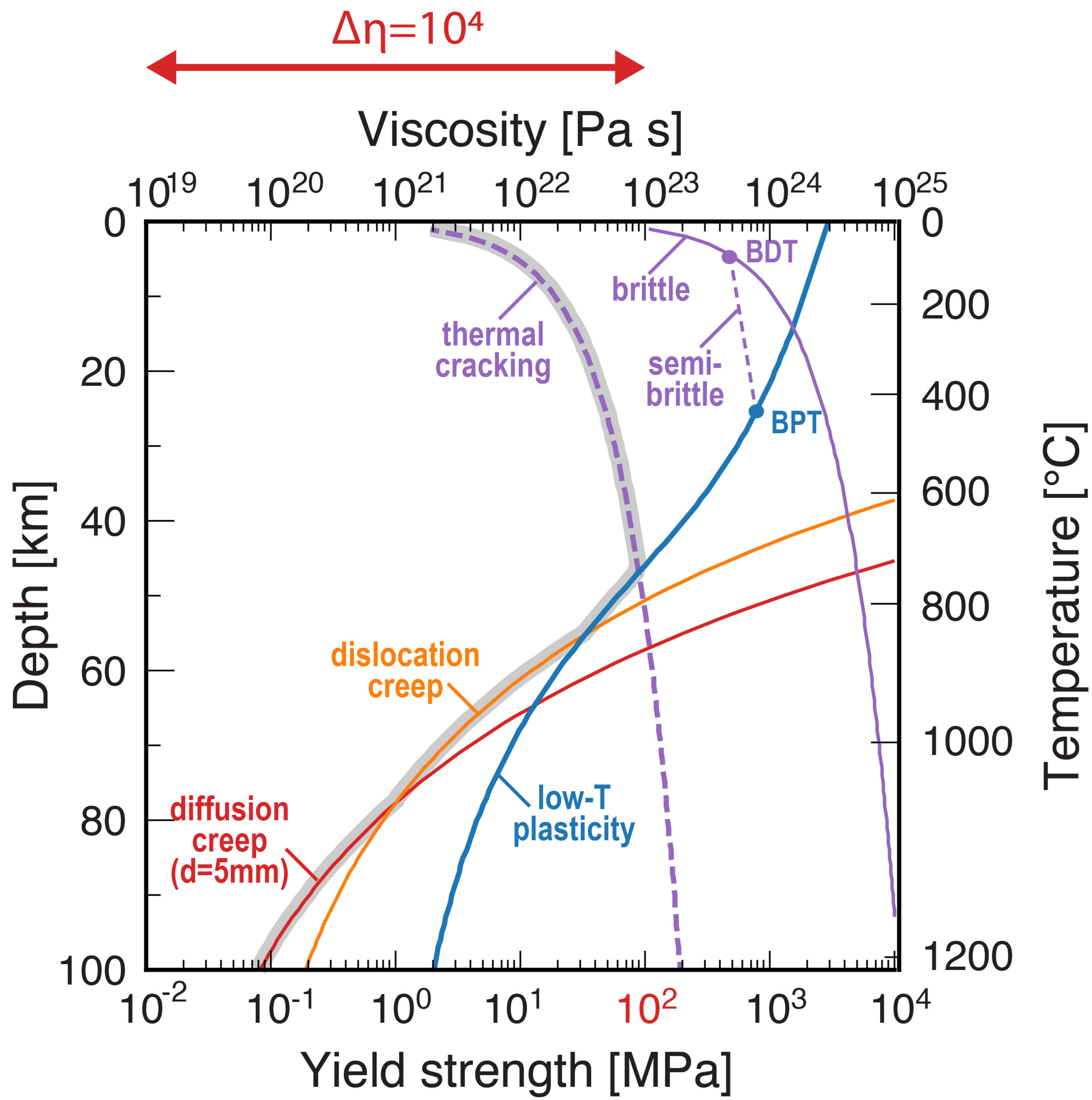
- **Grain-size reduction** (affects diffusion creep)



[Cross & Skemer, 2017]

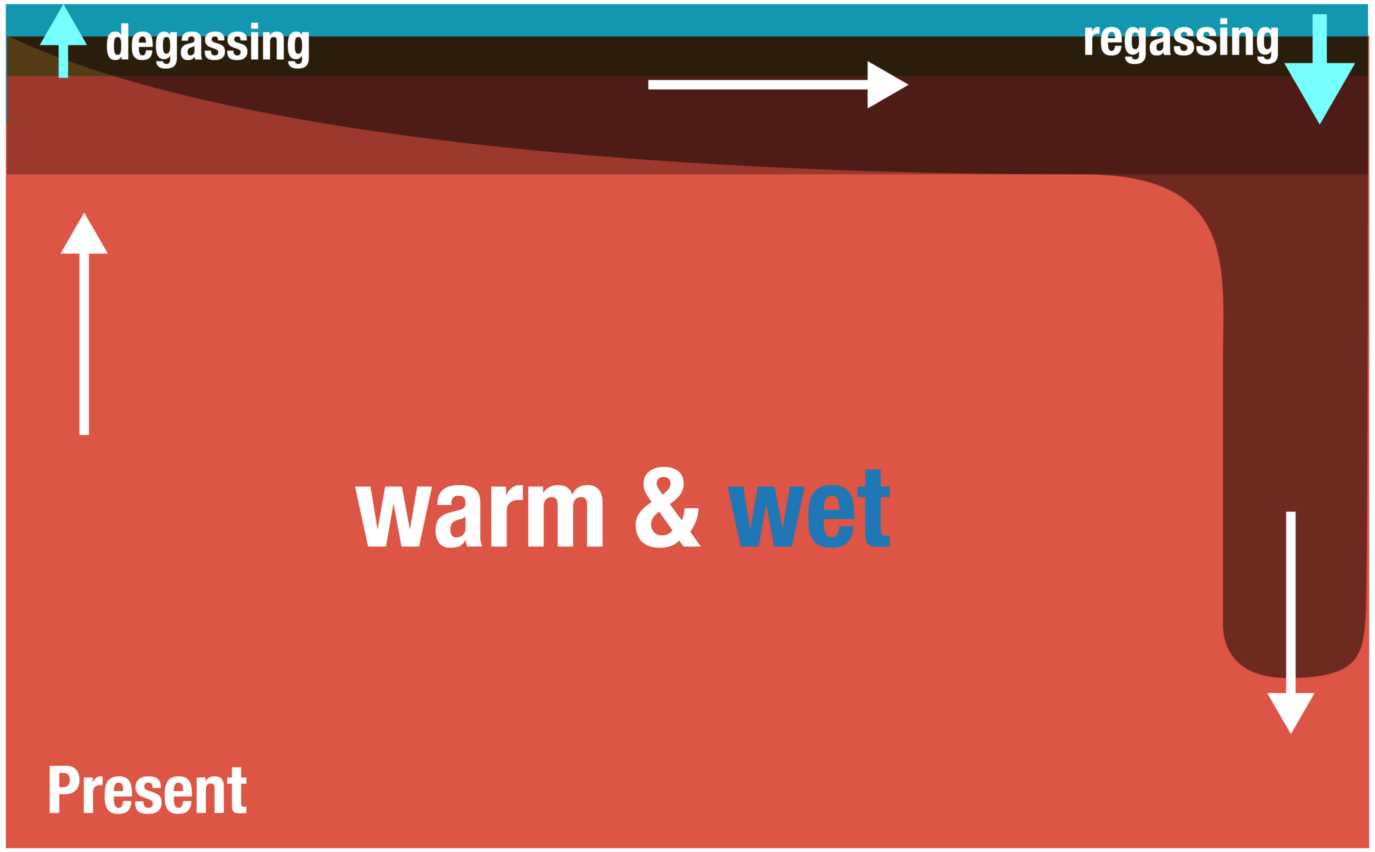
- **Thermal cracking** (affects brittle deformation)

[Korenaga, 2007]

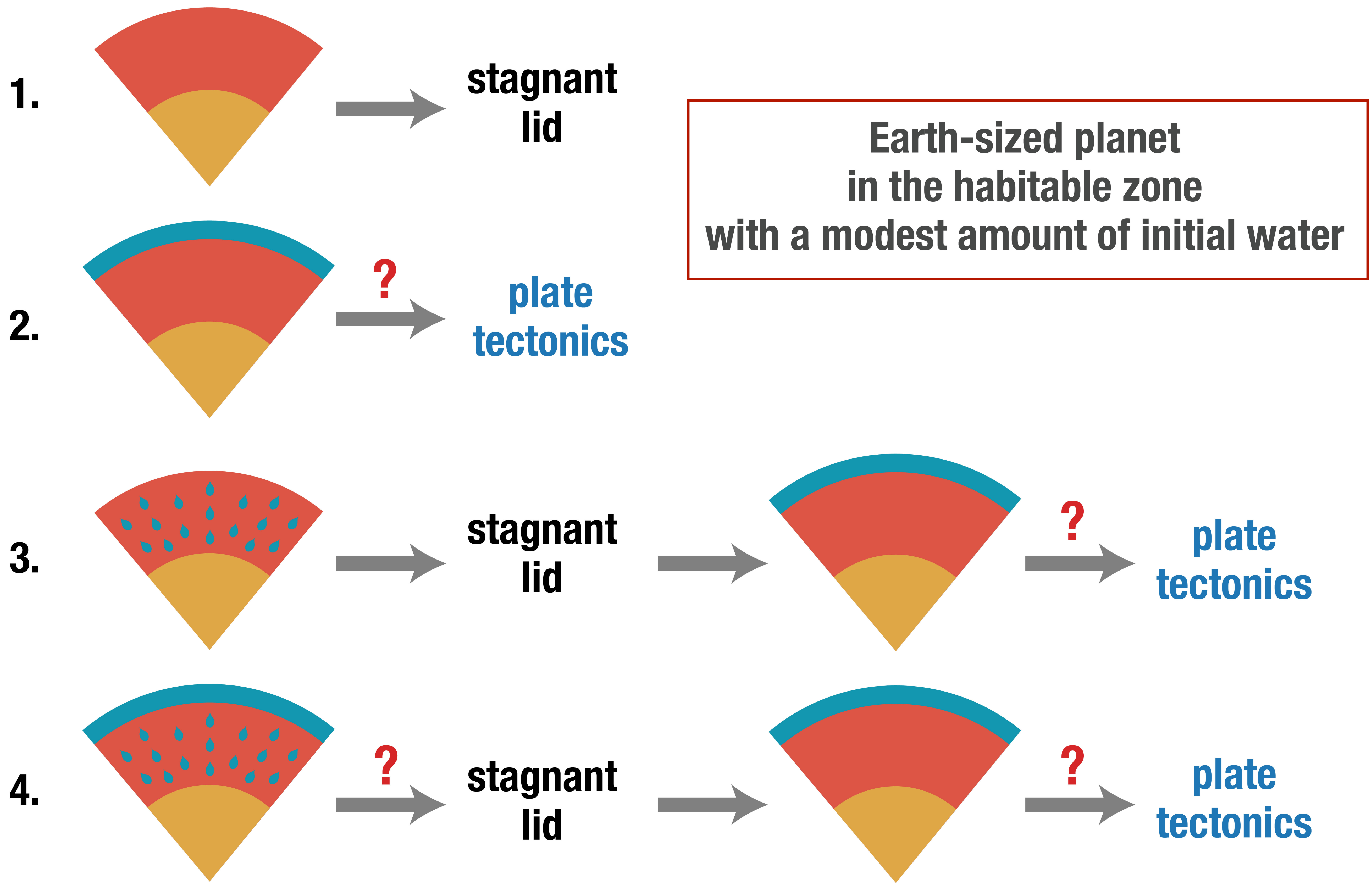


The operation of plate tectonics hinges on deep water cycle

- If the mantle was drier in the past, viscosity contrast wouldn't be higher in the past.
- This requires regassing is more efficient than degassing, which seems likely (more on later).



Where to have water is important



Three major questions about plate tectonics

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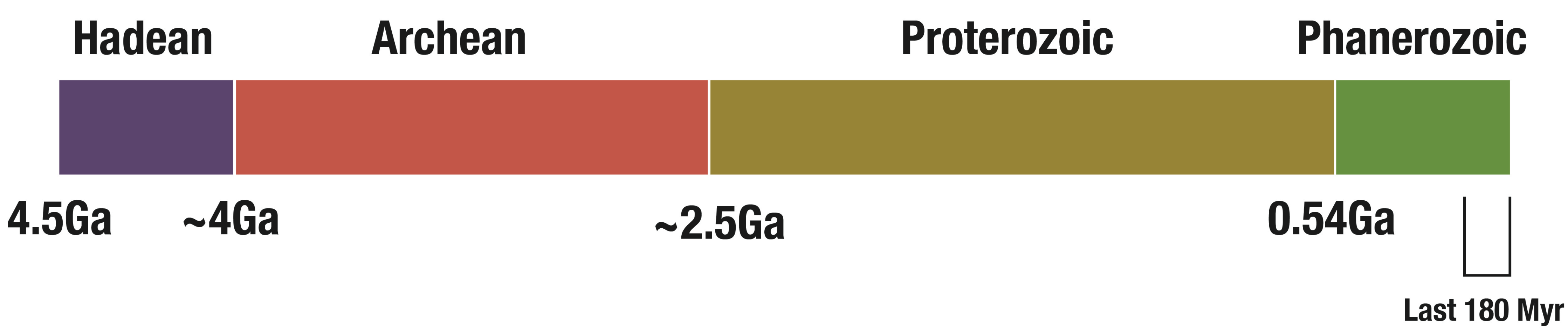


Why does it happen?

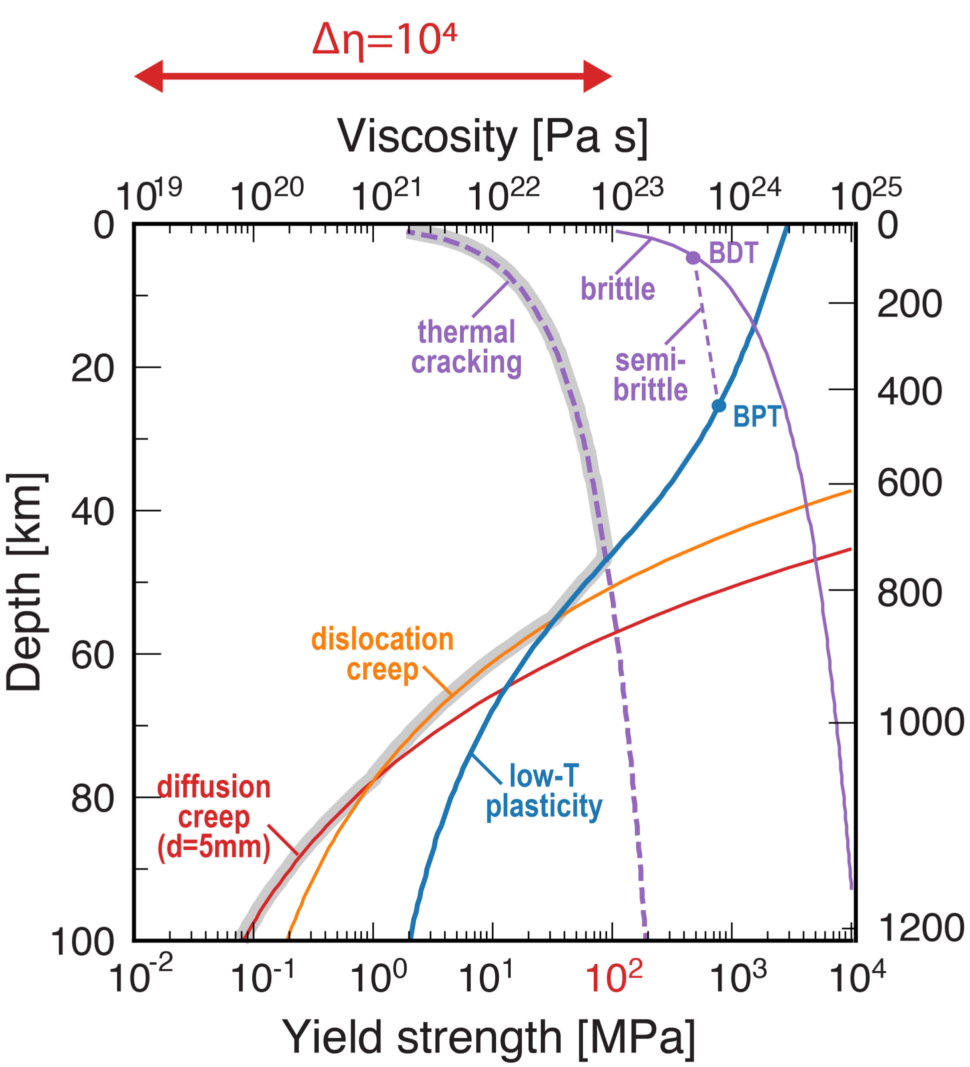
How has it evolved?

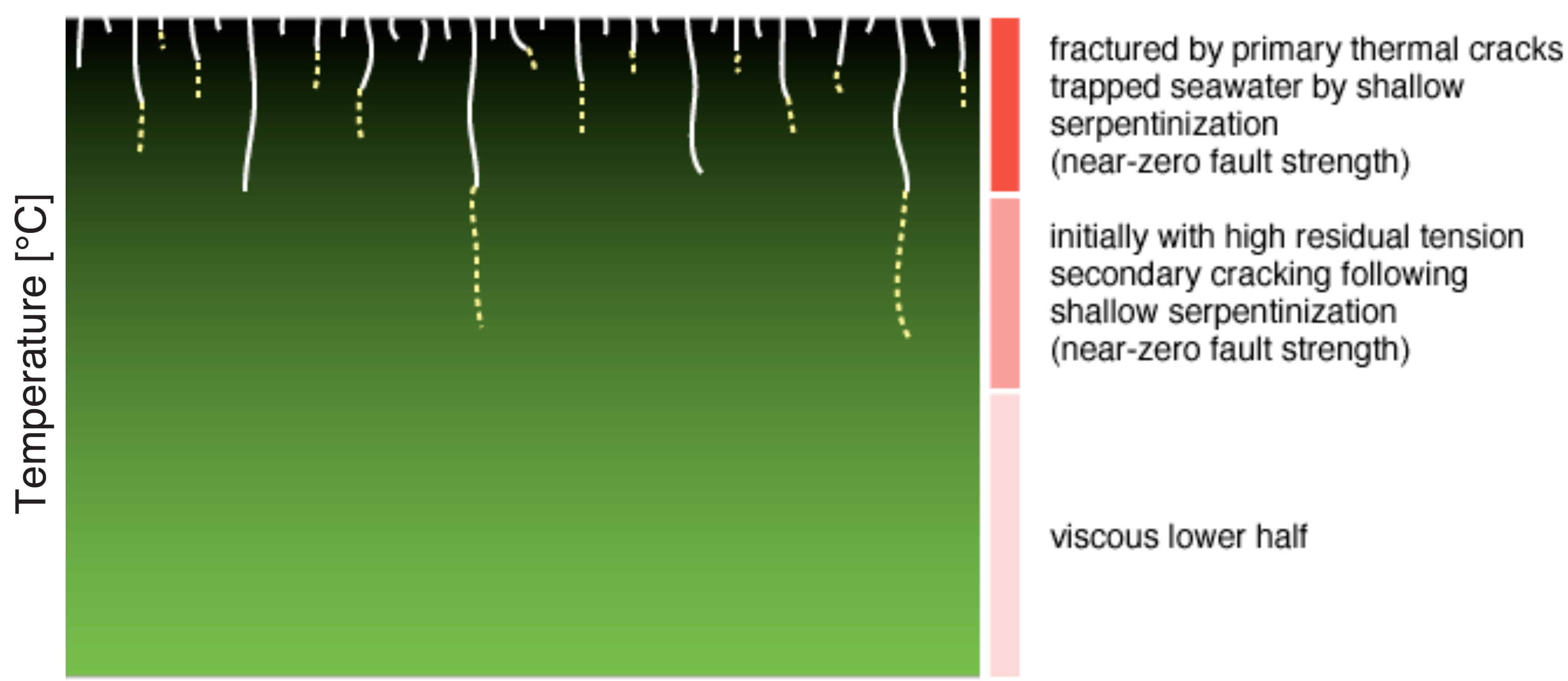
When did it start?

Thermal cracking?

… so far only indirect evidence [Korenaga 2017]

- apparent thermal expansivity from seafloor subsidence
- reduction in seismic velocity
- intermediate-depth earthquakes



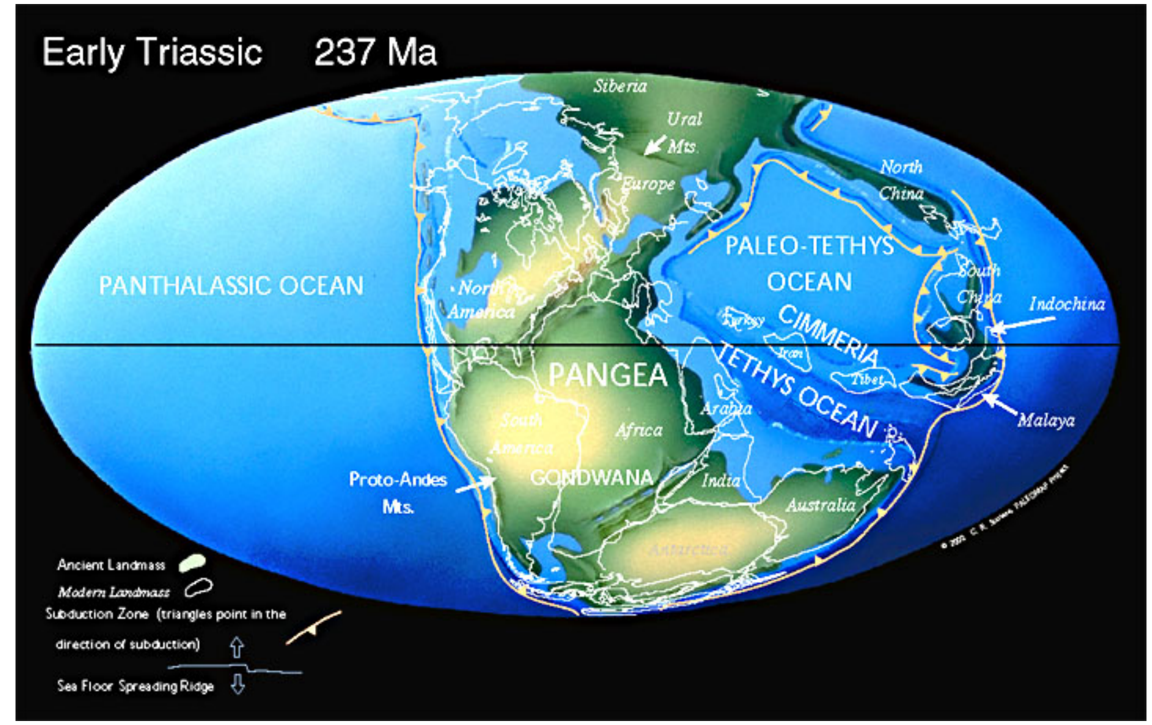


[Korenaga, JGR, 2007]

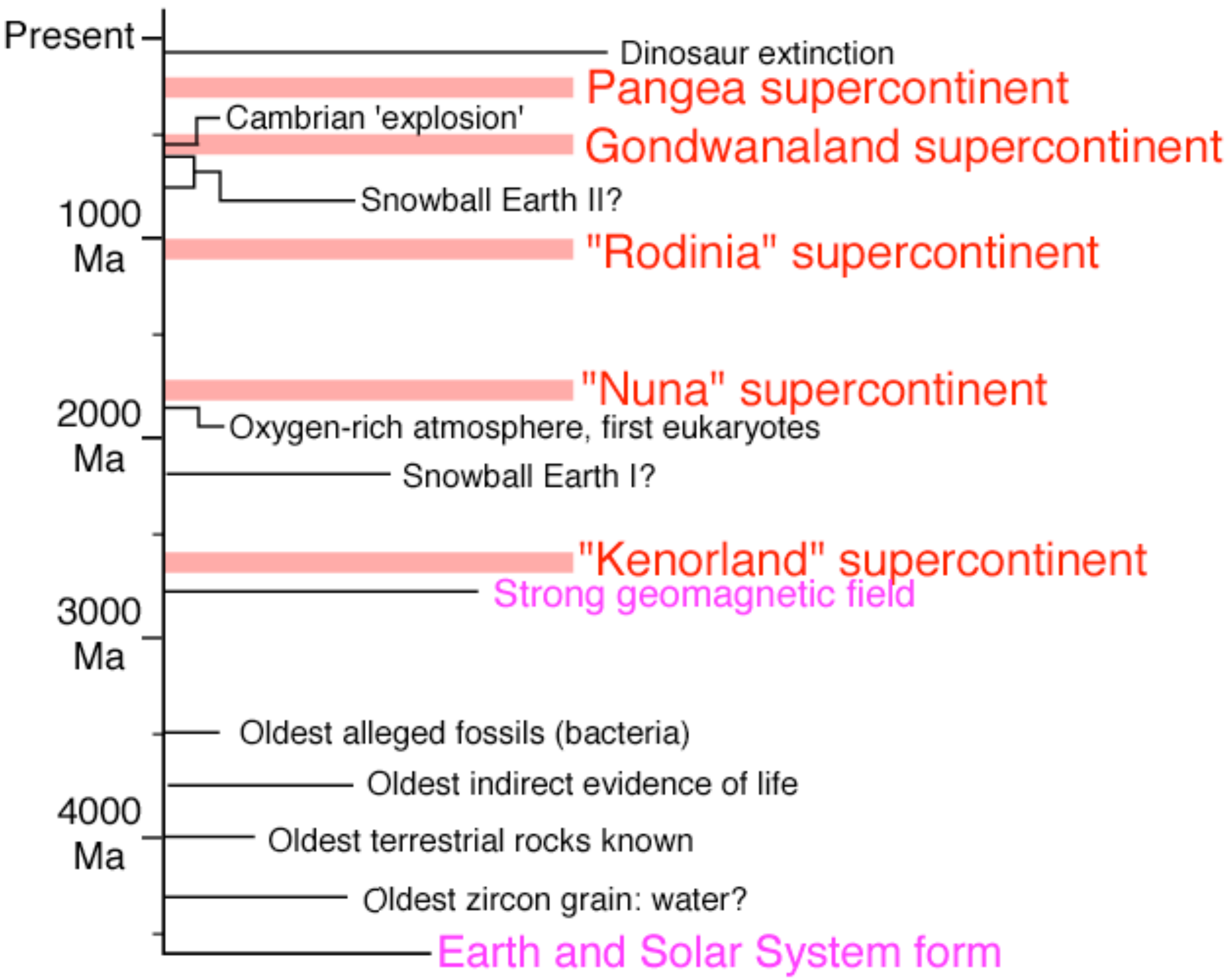
Why does it happen?

How has it evolved?

When did it start?



http://scotese.com



Formation of supercontinent

=

Closure of ocean basins

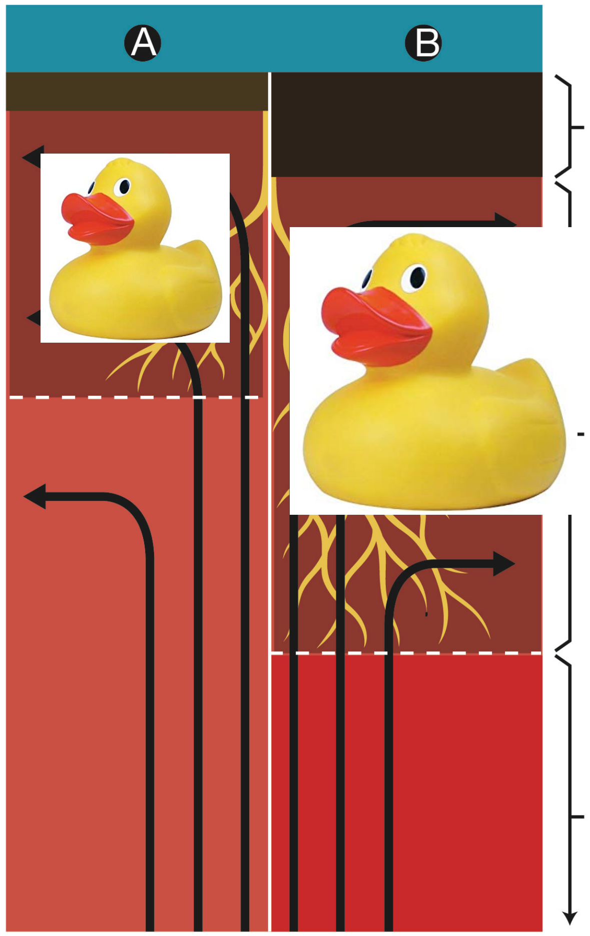
=

Initiation of subduction

Why does it happen?

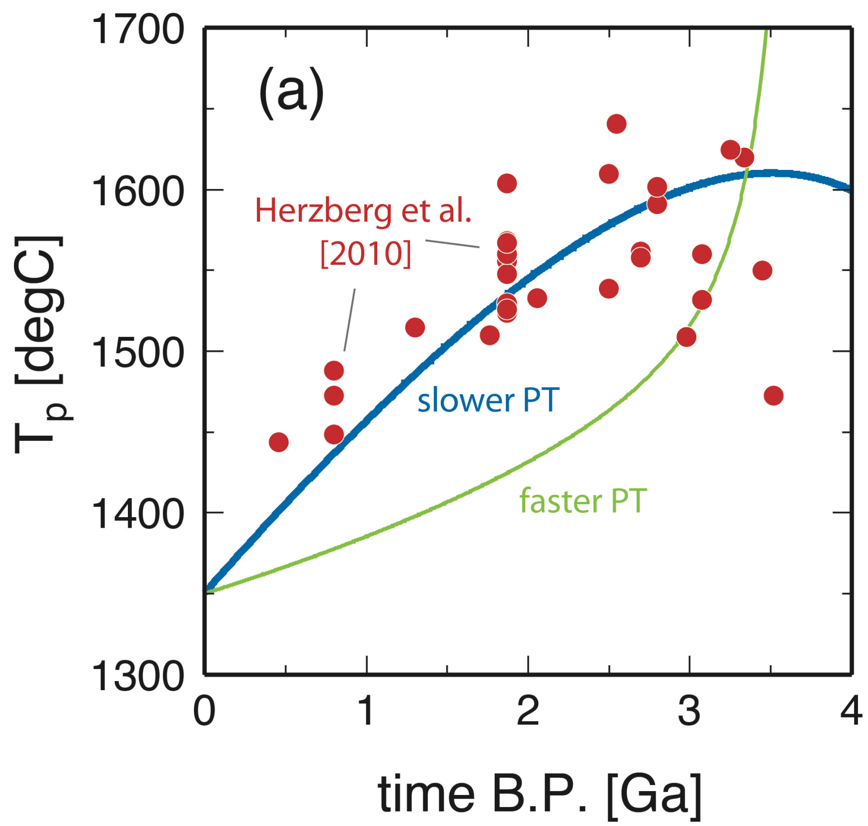
How has it evolved?

When did it start?



Chemical buoyancy criterion requires **thicker plates** and **slower plate tectonics in the past**, which is consistent with a wide variety of geochemical and geological data.

- Geochemical budget of heat-producing elements [McDonough & Sun 1995; Lubetskaya & Korenaga 2007]
- Passive margin lifespans [Bradley 2008]
- Cooling history of upper mantle [Herzberg et al., 2010; Servali & Korenaga, 2018]
- Continental reconstruction [Condie et al., 2015; Pehrsson et al., 2016]
- Atmospheric xenon budget [Padhi et al., 2012]
- Archean seawater chemistry [Korenaga et al., 2017]

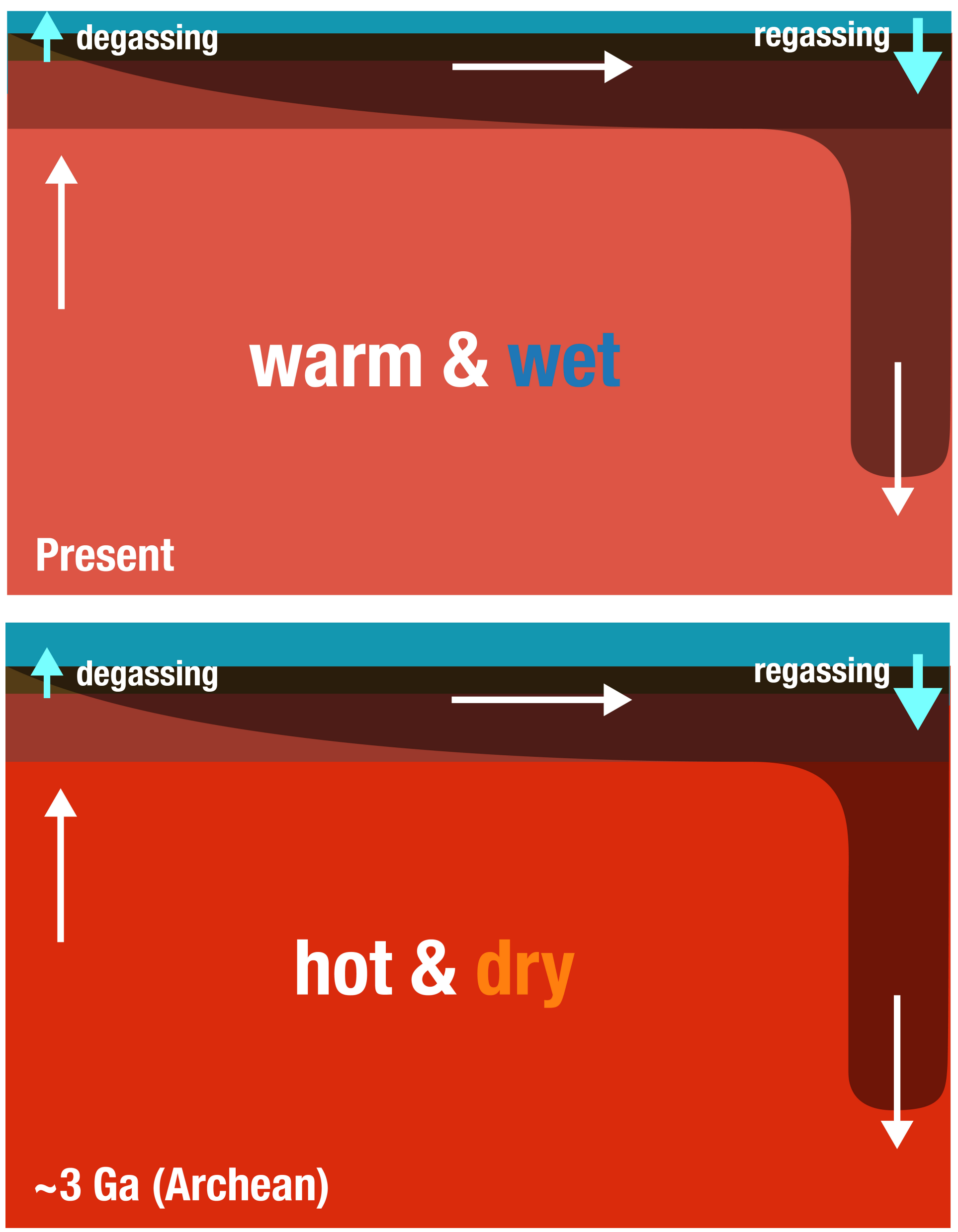


[Korenaga et al., PTRSA, 2017]

Why does it happen?

How has it evolved?

When did it start?



Viscosity contrast criterion requires **net water influx**, which is also consistent with **deep water cycle**.

- from **present-day fluxes**: **~6-11 x 10^{14} g/yr** [Ito et al., 1983; Jarrard 2003]
- from **numerical modeling**: **7 x 10^{14}** (present) to **4 x 10^{14} g/yr** (Archean) [Magni et al. 2014]
- from **the constancy of continental freeboard**: **3-4.5 x 10^{14} g/yr** for the last 2.5 Gyr [Korenaga et al., 2017]

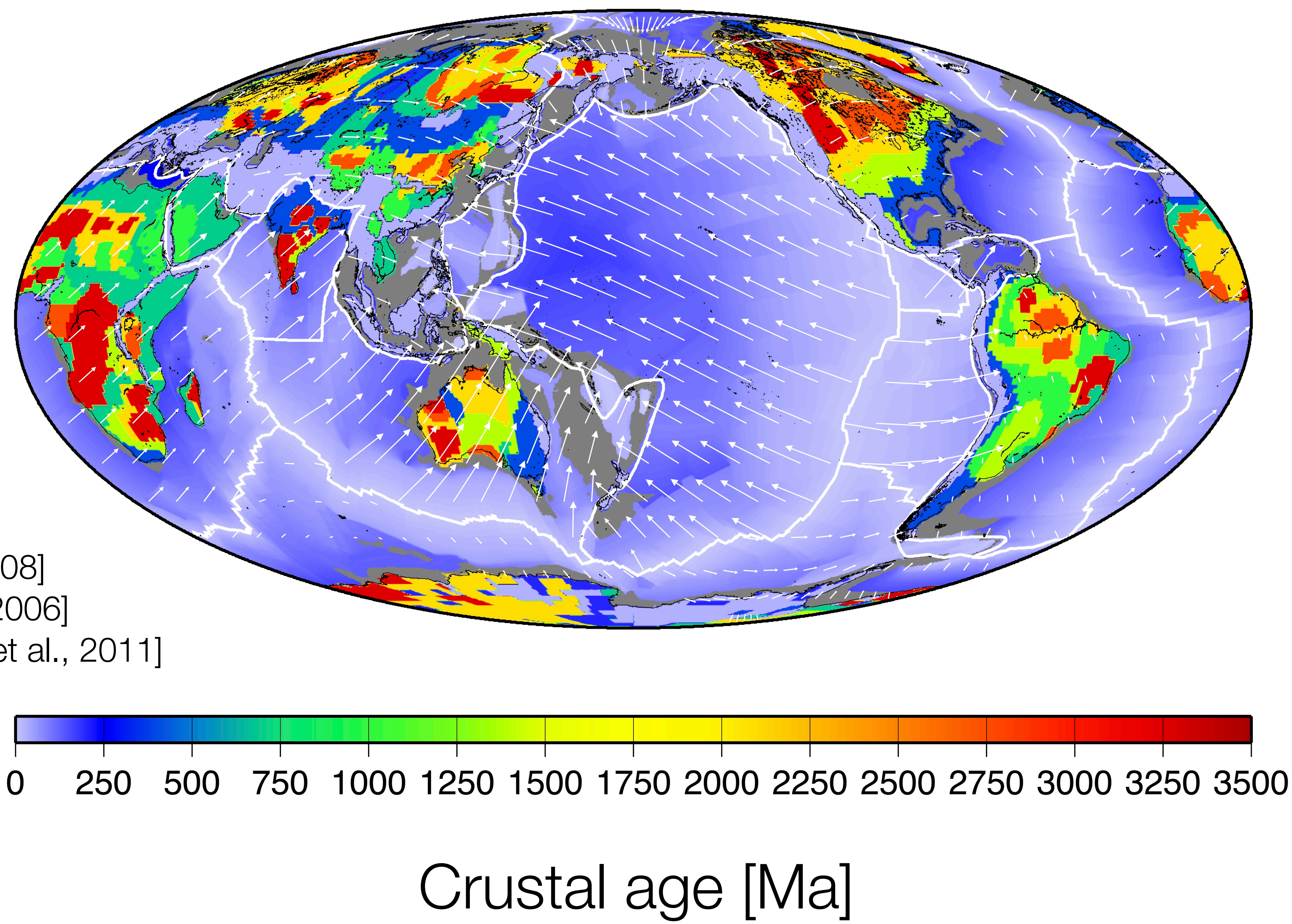
(*) With the influx of 3 x 10^{14} g/yr, the present-day oceans can be drained within 4.5 Gyr.

Why does it happen?

How has it evolved?

When did it start?

How about beyond 3 Ga?



oceanic crust [Müller et al., 2008]
continental crust [Artemieva, 2006]
absolute plate motion [Argus et al., 2011]

Historical perspectives on continental growth studies

1980 **1990** **2000** **2010** **2020**

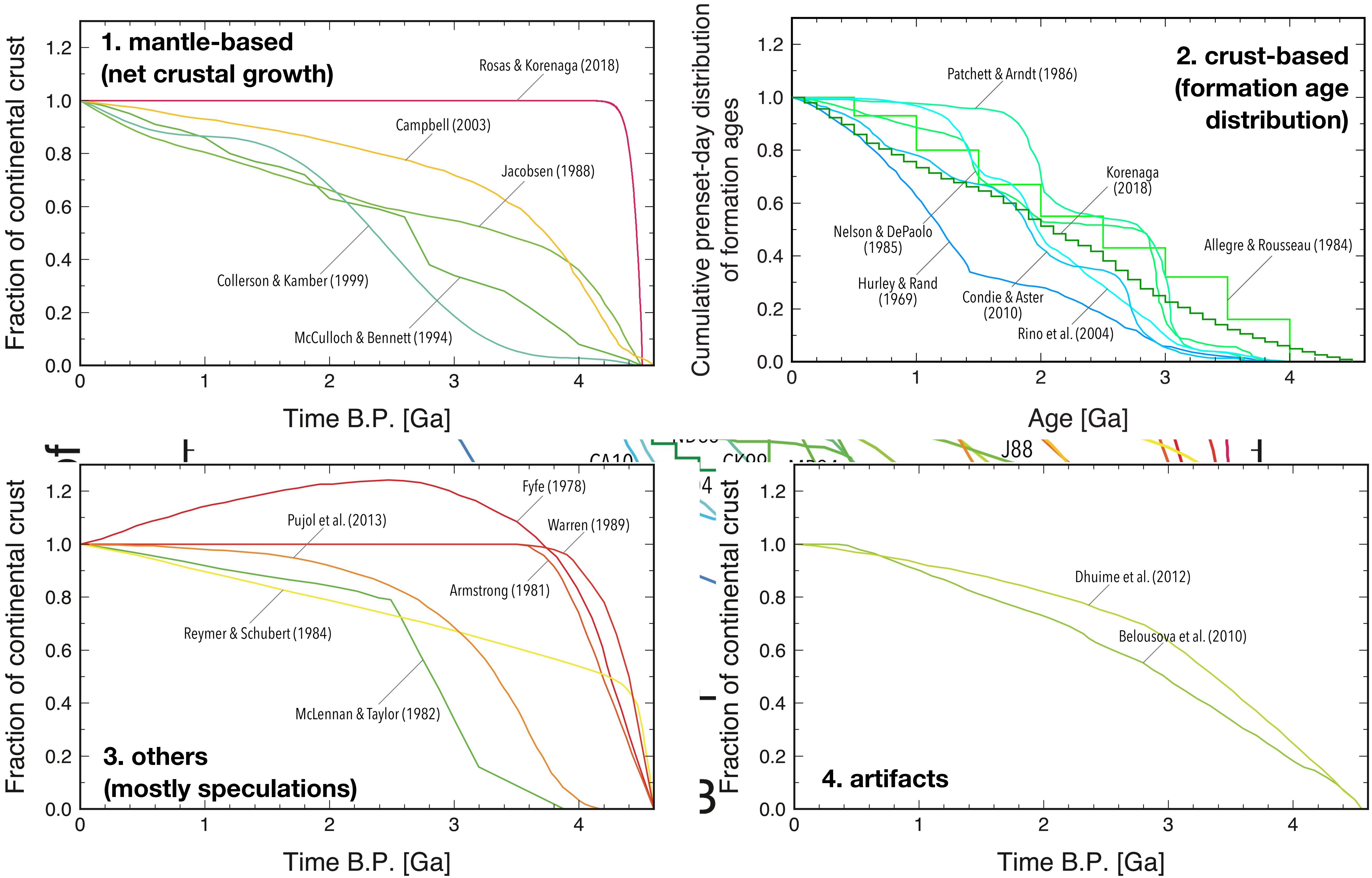
Classical Era **Dark Ages** **Renaissance?**

Jacobsen (1988)
Patchett & Arndt (1986)
Nelson & DePaolo (1985)
Allegre & Rousseau (1984)
Armstrong (1981)

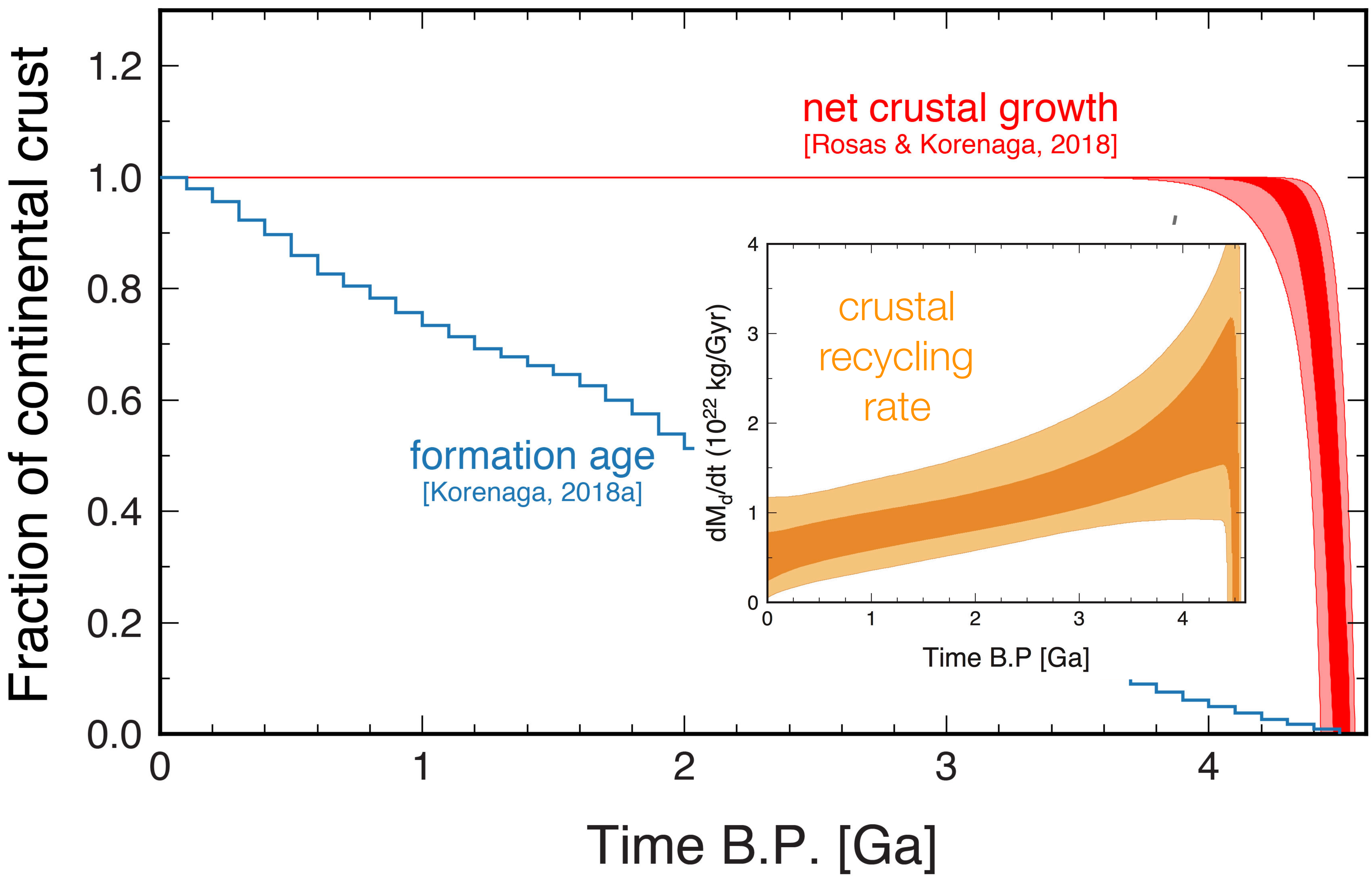
Darkest Hours (2010-2017)




Models of continental growth



Latest mantle- and crust-based models



[Korenaga, PTRSA, 2018]

Relation between net crustal growth and the present-day distribution of formation ages

formation age (τ) distribution at time t

$$\int_0^t m(t,\tau)\, d\tau = M_c(t)$$

crustal mass at time t

new crust generation rate

crustal recycling rate

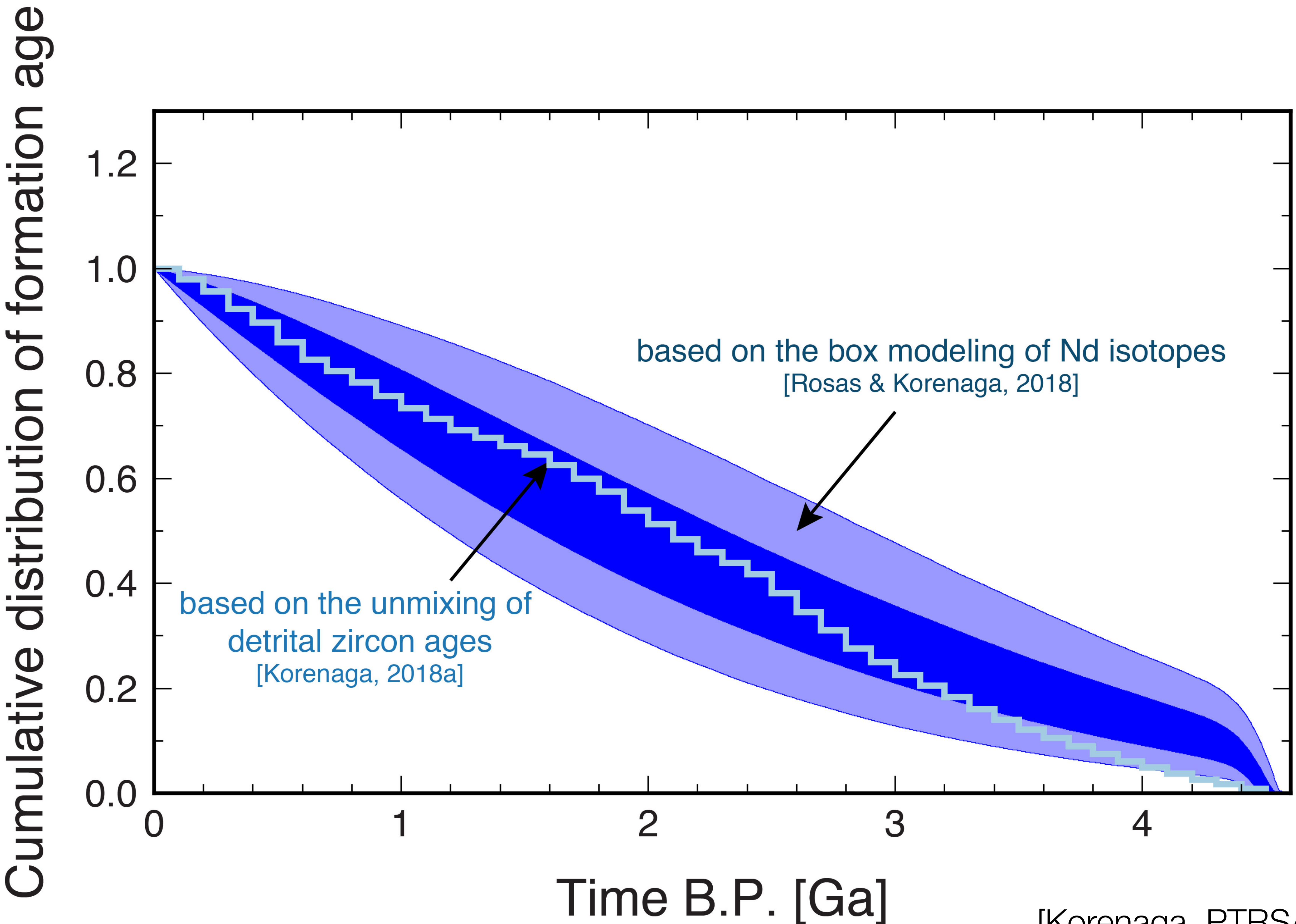
$$\frac{\partial m(t,\tau)}{\partial t} = \dot{M}_u(t)\,\delta(t-\tau) - \frac{\dot{M}_d(t)}{M_c(t)} m(t,\tau)$$

present-day cumulative distribution of formation ages

formation age (τ) distribution at present

$$F(\tau) = \frac{1}{M_c(t_p)} \int_0^\tau m(t_p,\xi)\, d\xi$$

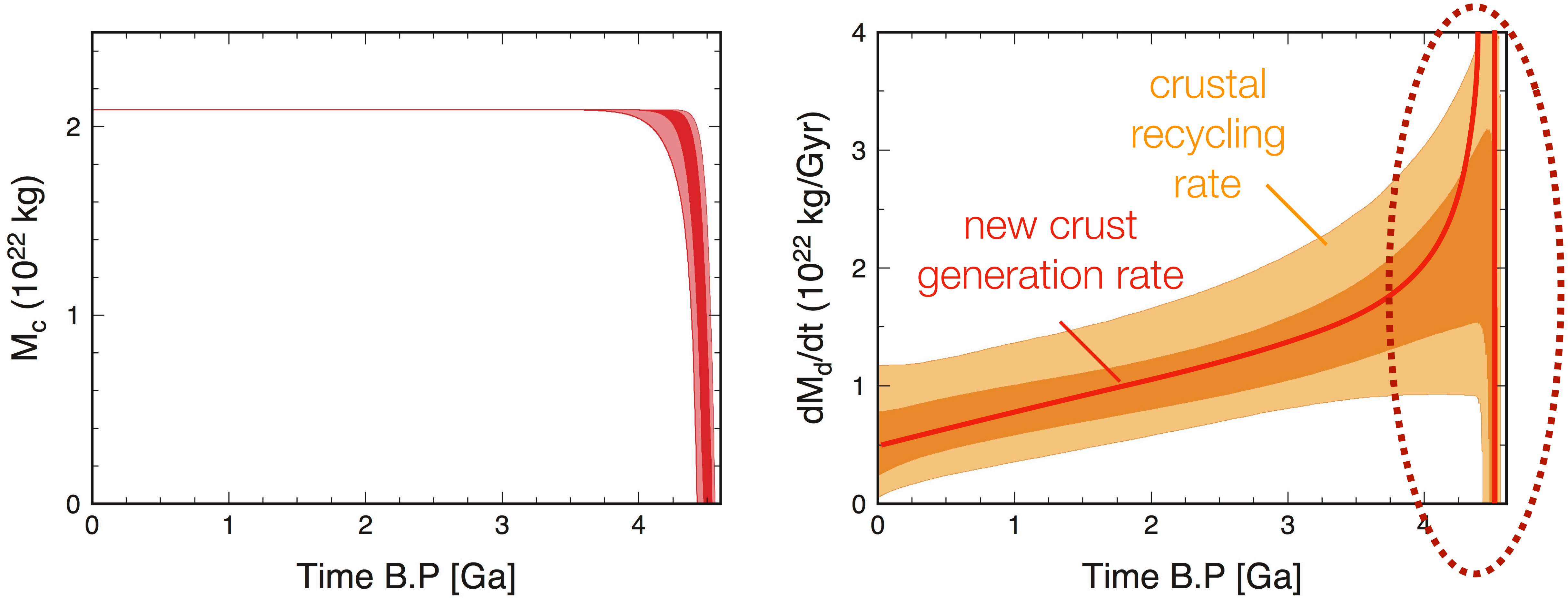
Two ways to the present-day distribution of crust formation ages



[Korenaga, PTRSA, 2018]

Implications of new growth model

[cf. oceanic crust generation rate: ~7 x 10^{22} kg/Gyr
present-day recycling rate: 0.7-0.9 x 10^{22} kg/Gyr]



[Korenaga, PTRSA, 2018]

- Rapid crustal growth and efficient recycling in the early Earth
- Persistent crustal generation and recycling through Earth history

Insights from magma ocean solidification modeling

JGR Solid Earth

RESEARCH ARTICLE

10.1029/2018JB016932

This article is a companion to Miyazaki and Korenaga (2019), https://doi.org/10.1029/2018JB016928.

On the Timescale of Magma Ocean Solidification and Its Chemical Consequences: 1. Thermodynamic Database for Liquid at High Pressures

Yoshinori Miyazaki[1] and Jun Korenaga[1]

JGR Solid Earth

RESEARCH ARTICLE

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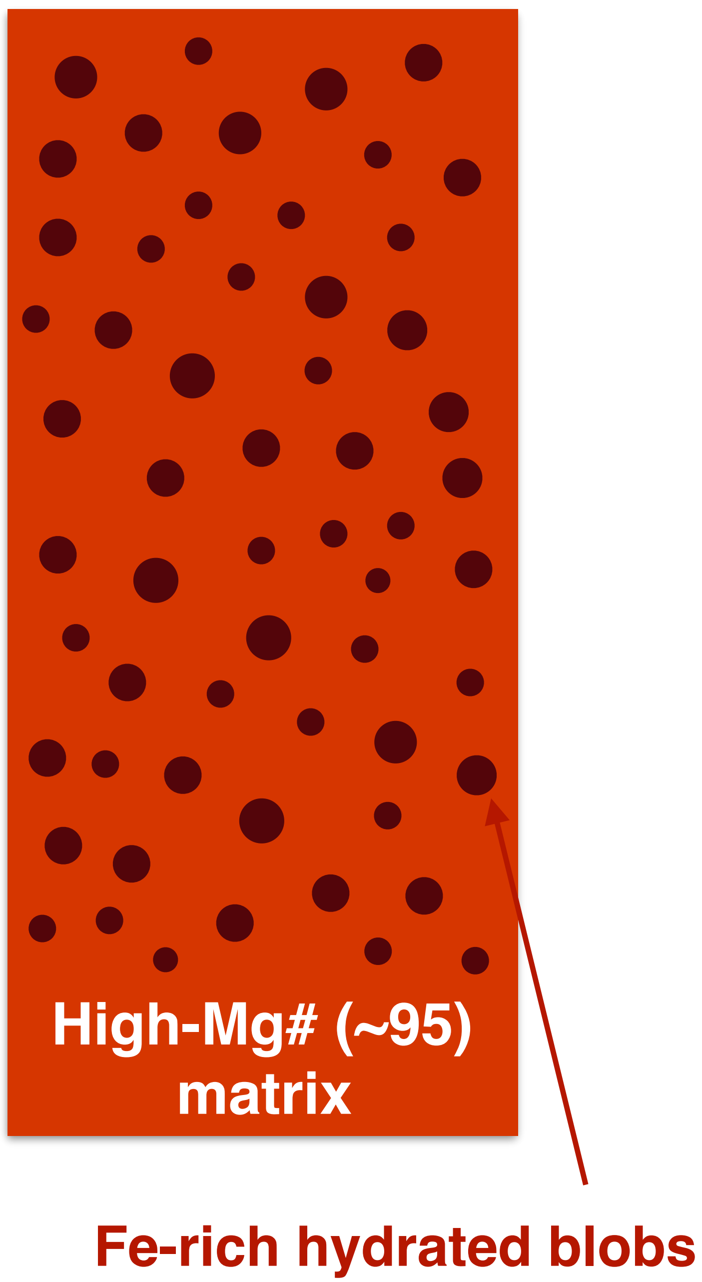
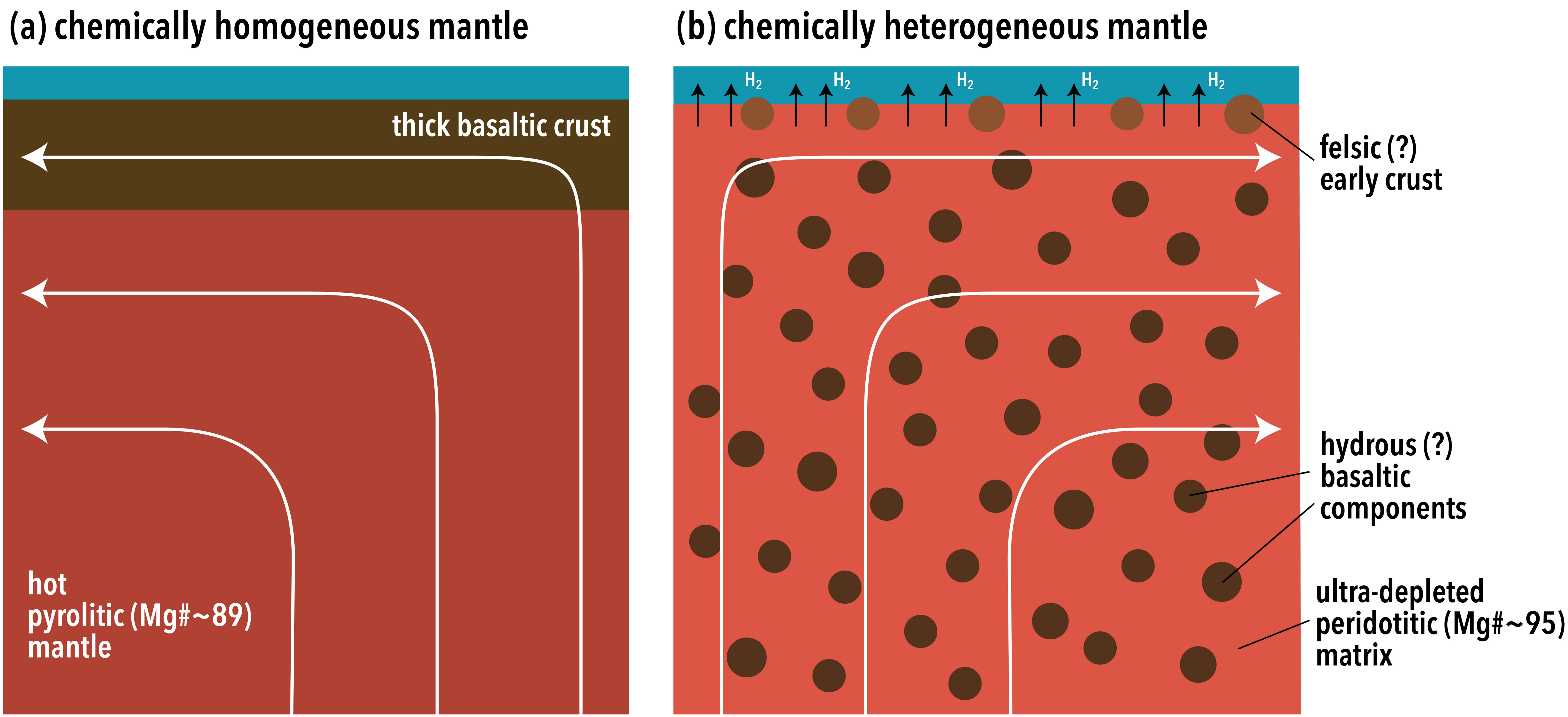
On the Timescale of Magma Ocean Solidification and Its Chemical Consequences: 2. Compositional Differentiation Under Crystal Accumulation and Matrix Compaction

Yoshinori Miyazaki[1] and Jun Korenaga[1]

[Miyazaki and Korenaga, 2019a,b]



Early Earth dynamics with a chemically heterogeneous mantle?



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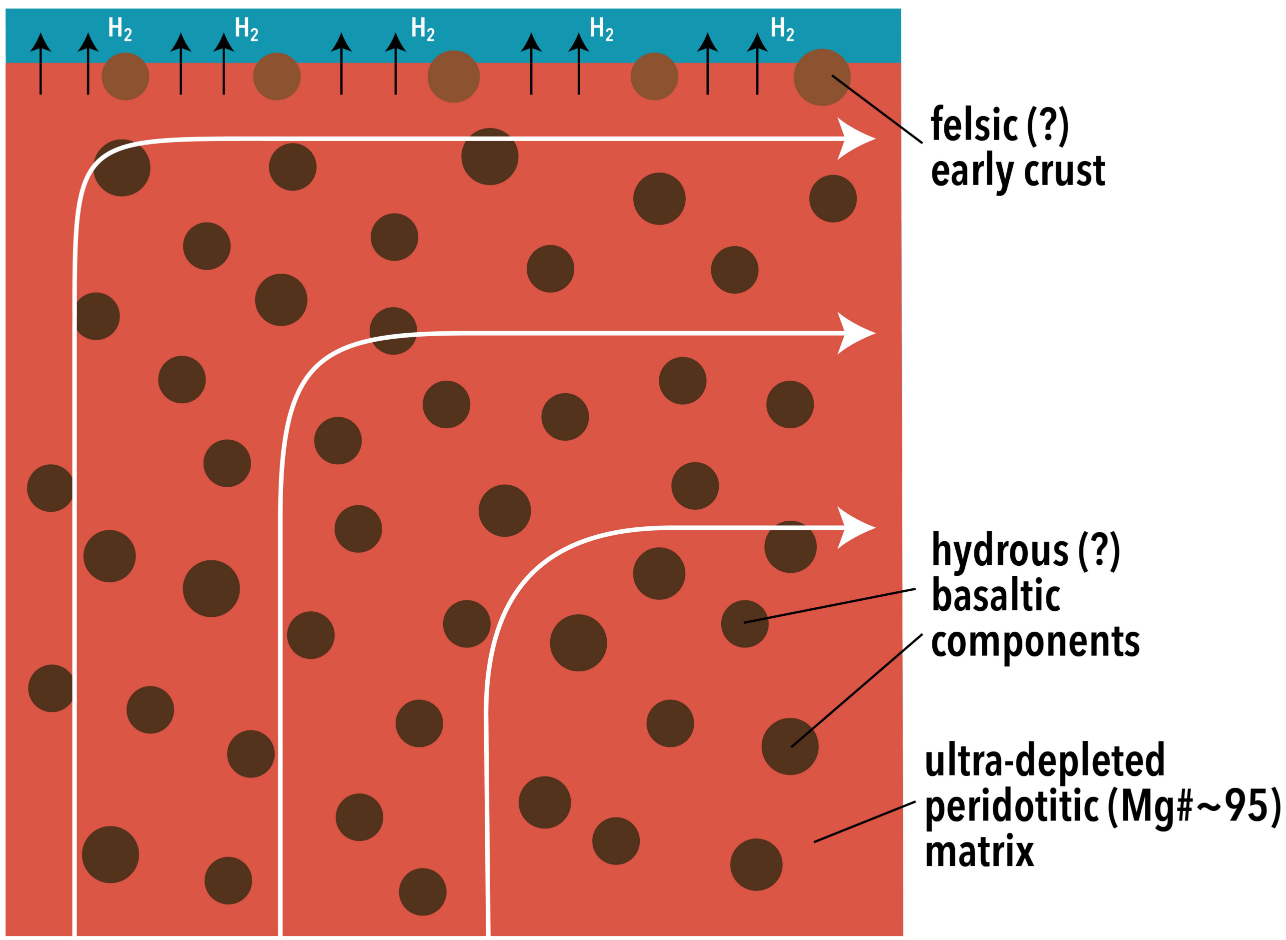
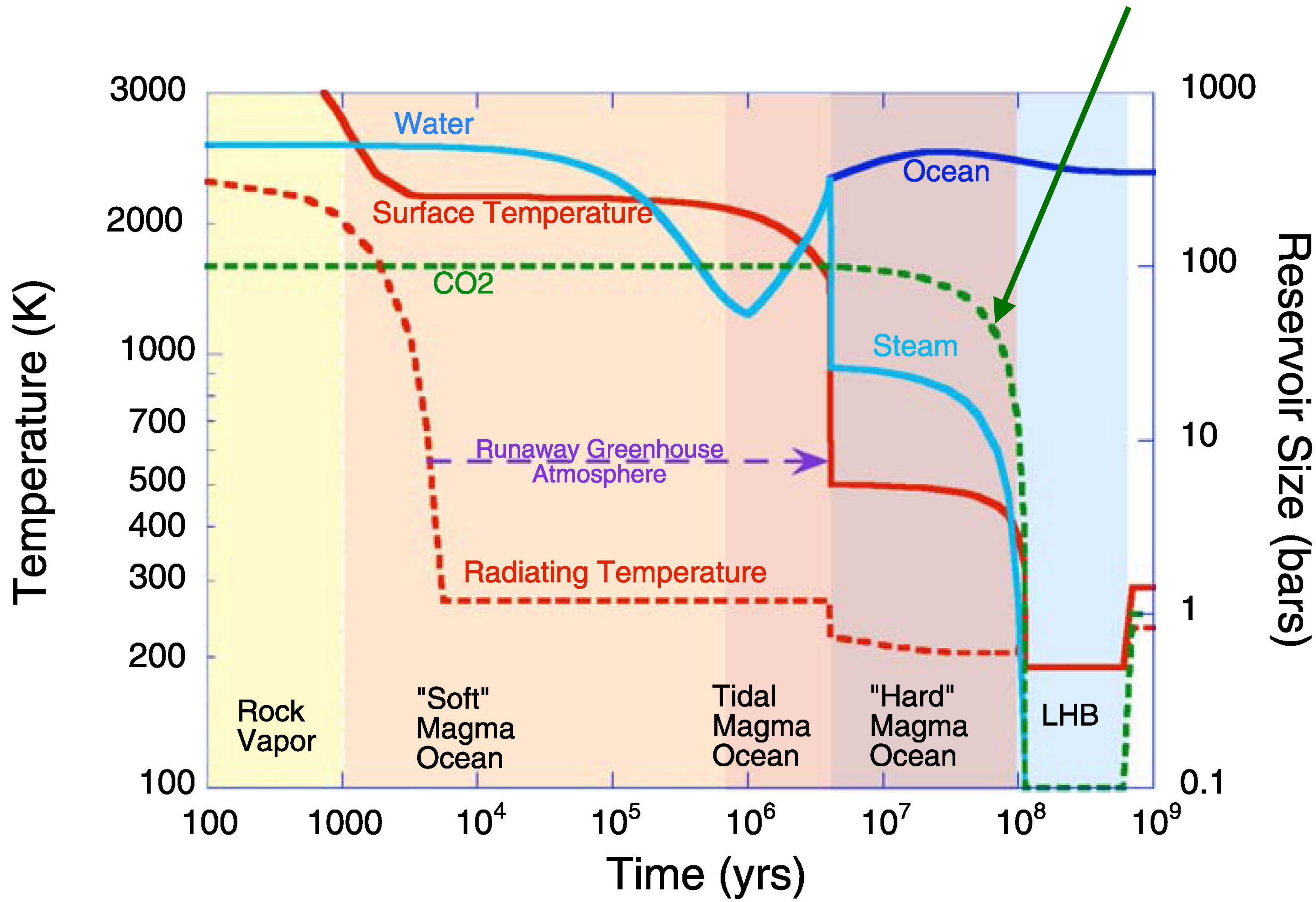


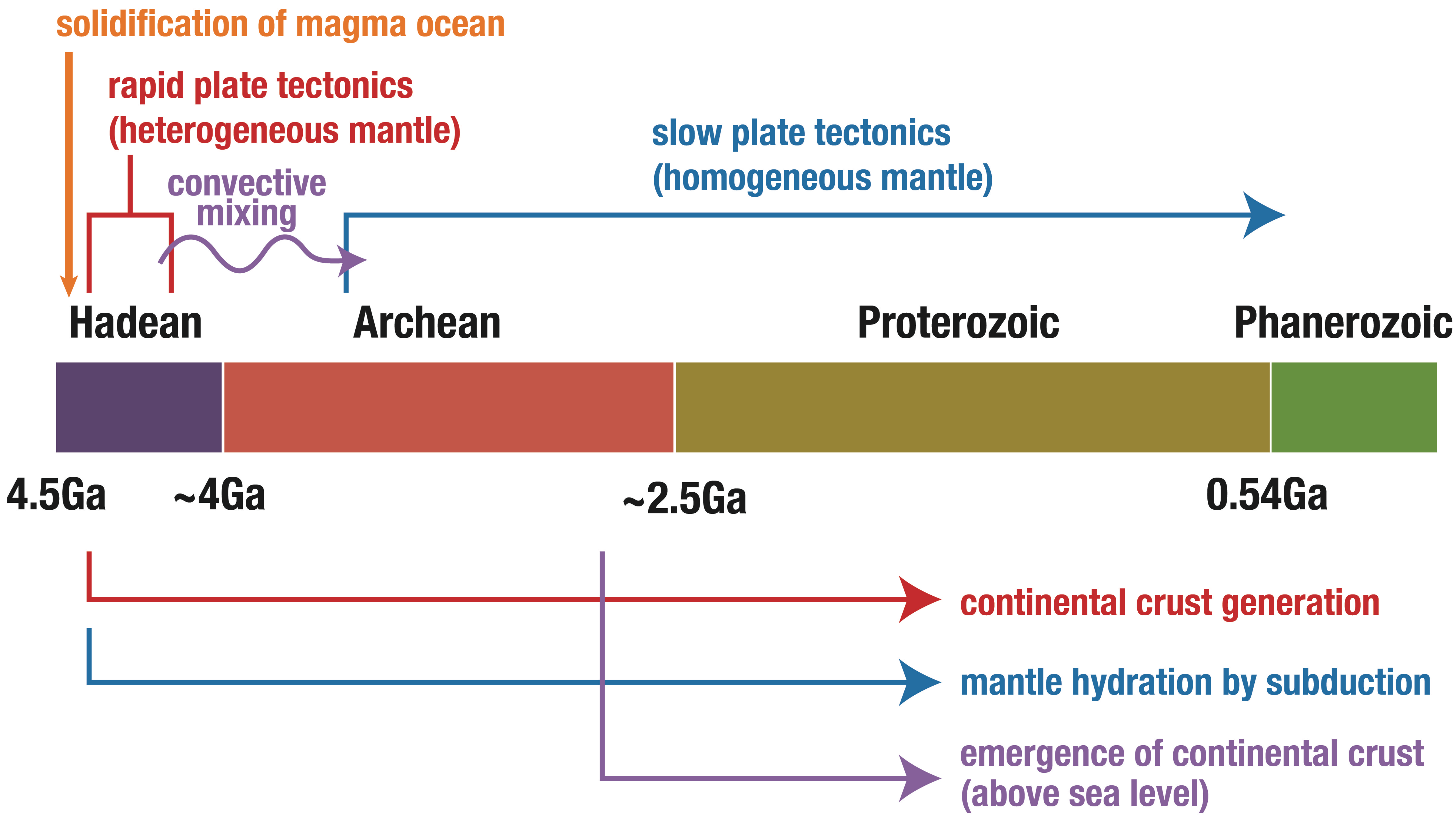
- Abundant exposure of peridotite at seafloor becomes possible (H_2 generation and CO_2 sequestration)
- Melting of hydrous basaltic components may generate felsic early crust.
- The lack of uniformly thick (buoyant) crust facilitates rapid subduction.
- Efficient core cooling (and thus early geodynamo) becomes possible?

Rapid plate tectonics (in the very early Earth) enables efficient sequestration of CO_2?

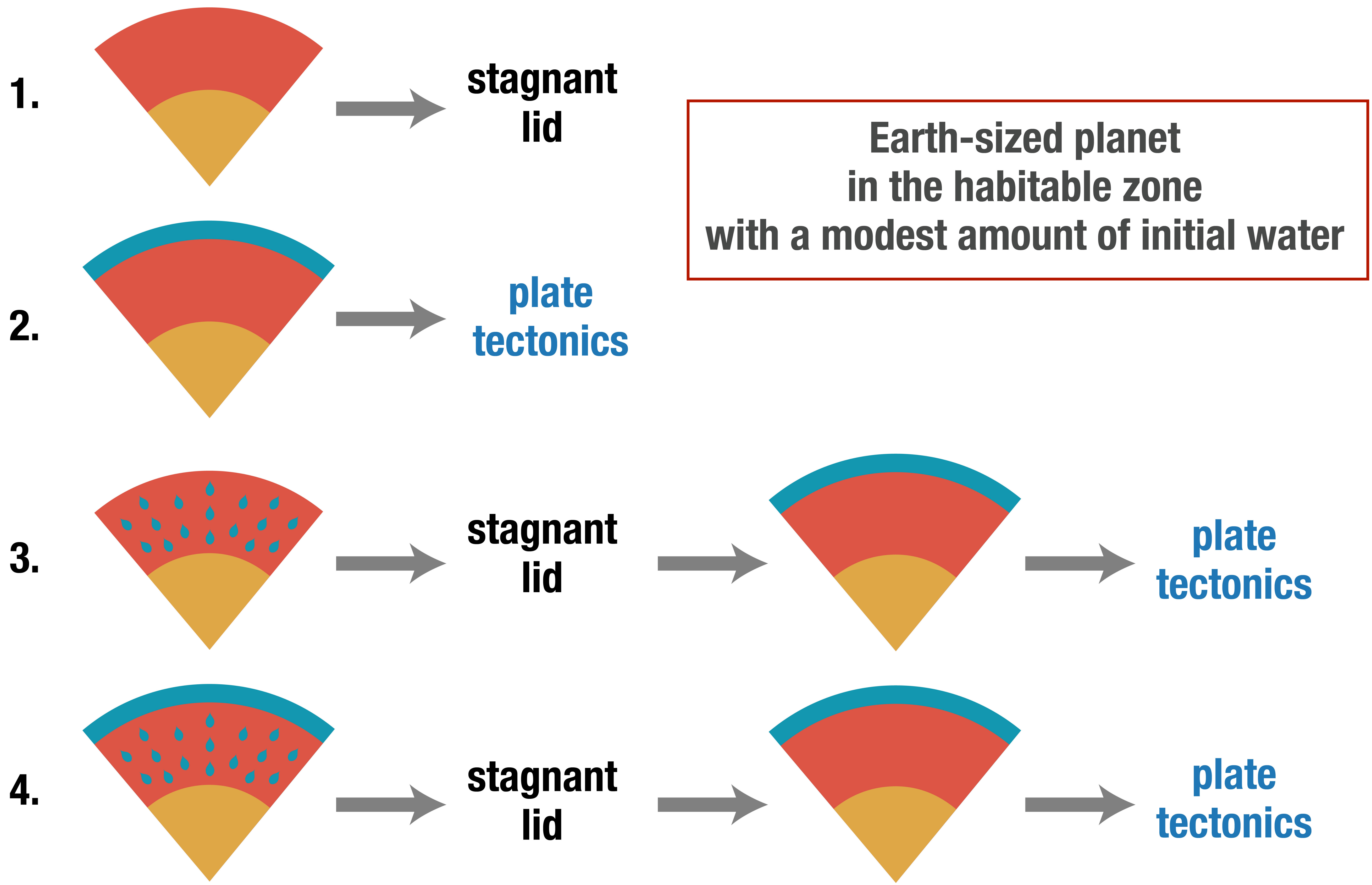


[Zahnle et al., *Space Sci. Rev.*, 2007]

Likely evolution of plate tectonics on Earth



On evolutionary paths of terrestrial planets



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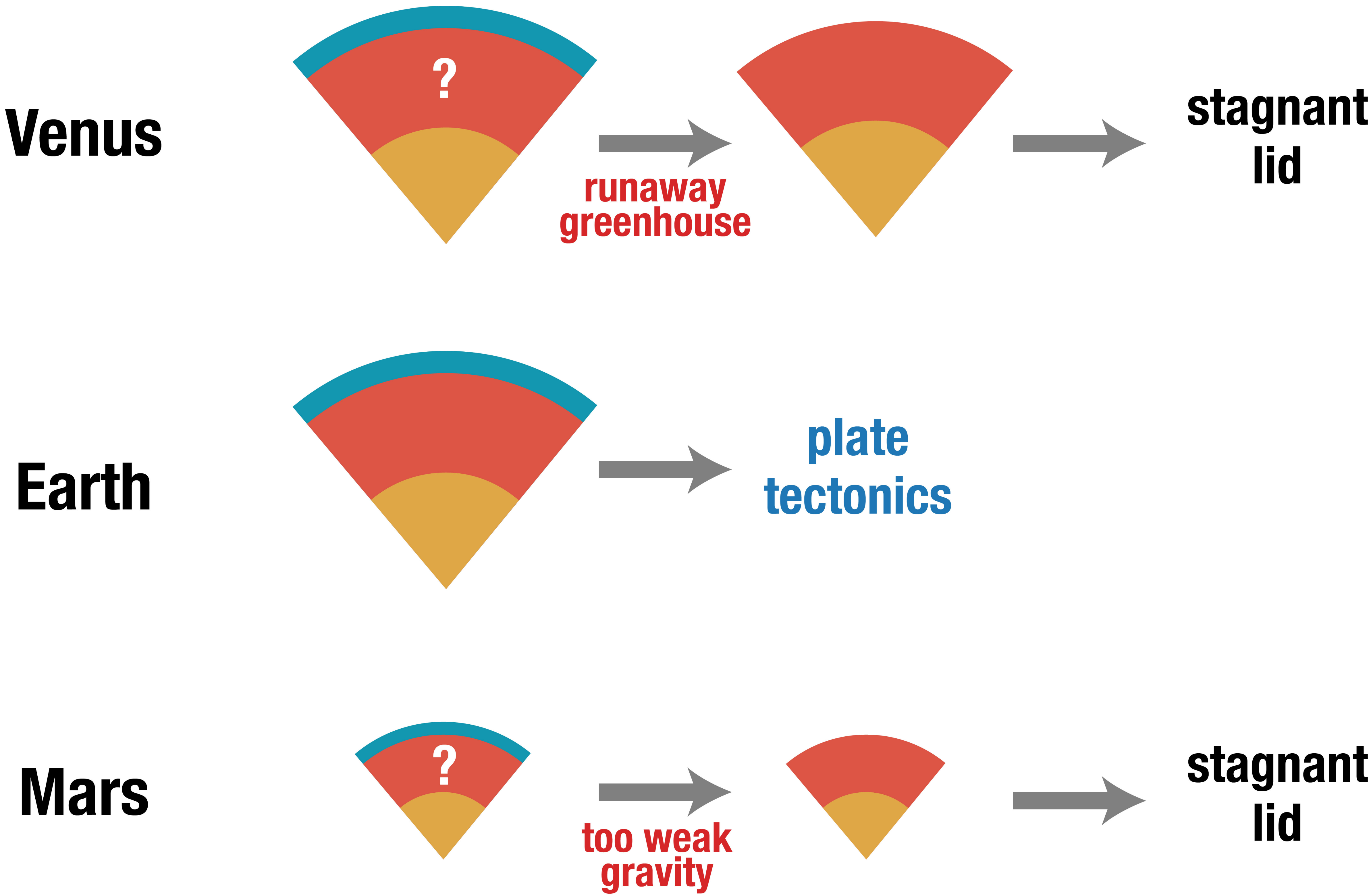
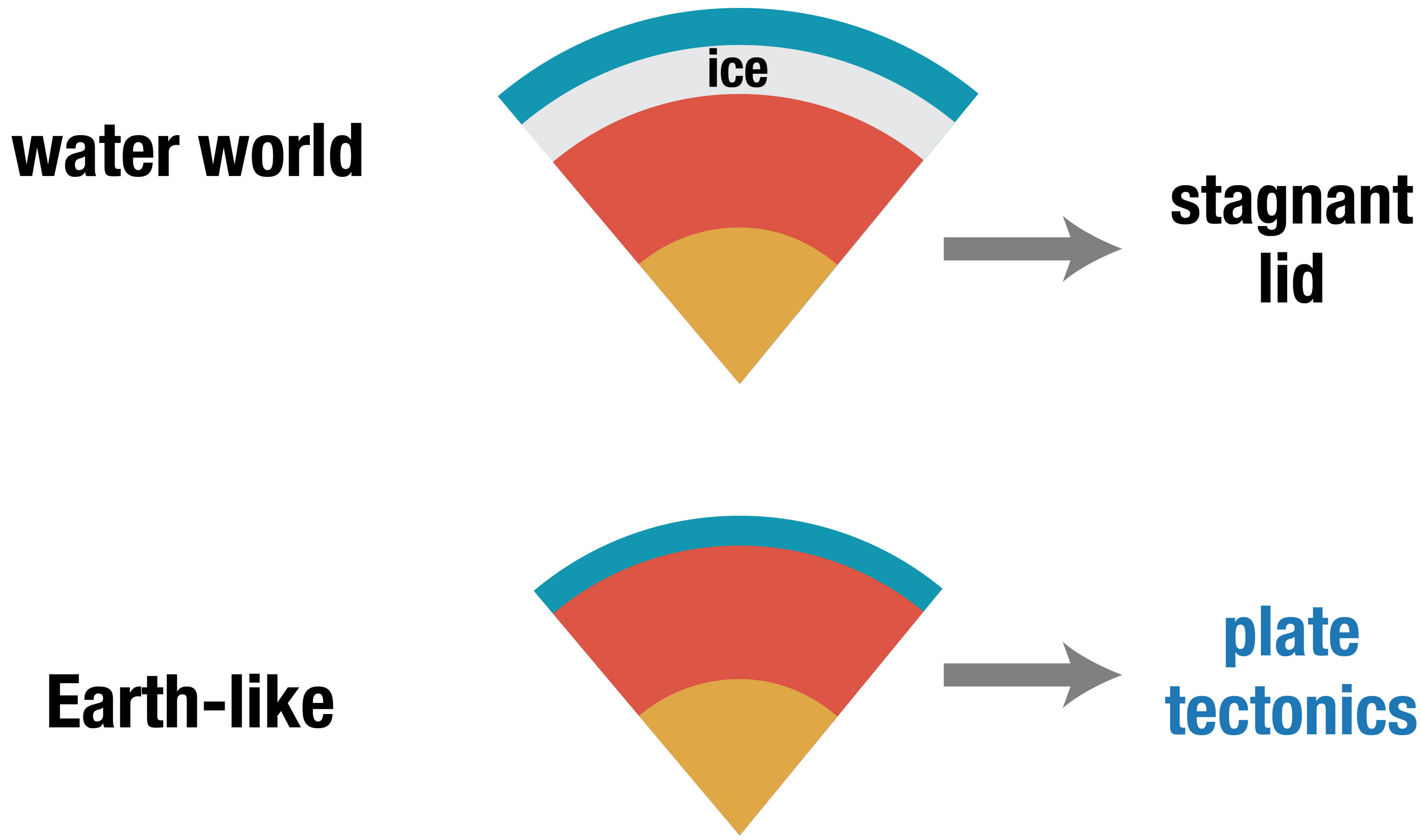


Exoplanetary considerations



Conclusions

- Plate tectonics has probably been operating on Earth since its beginning, soon after the solidification of magma ocean.
- Its operation hinges on a delicate balance of different kinds of water effects. It is not so easy to keep plate tectonics.
- Right heliocentric distance, right amount of initial water (preferably on surface), and right size are all important, if we want to have an Earth-like planet.
- Two key issues for a general theory of planetary evolution are (1) conditions for plate tectonics, and (2) the effects of plate tectonics on surface environment.

References

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