VI Astrobion – September 2026

Long-term Planetary Tectonics

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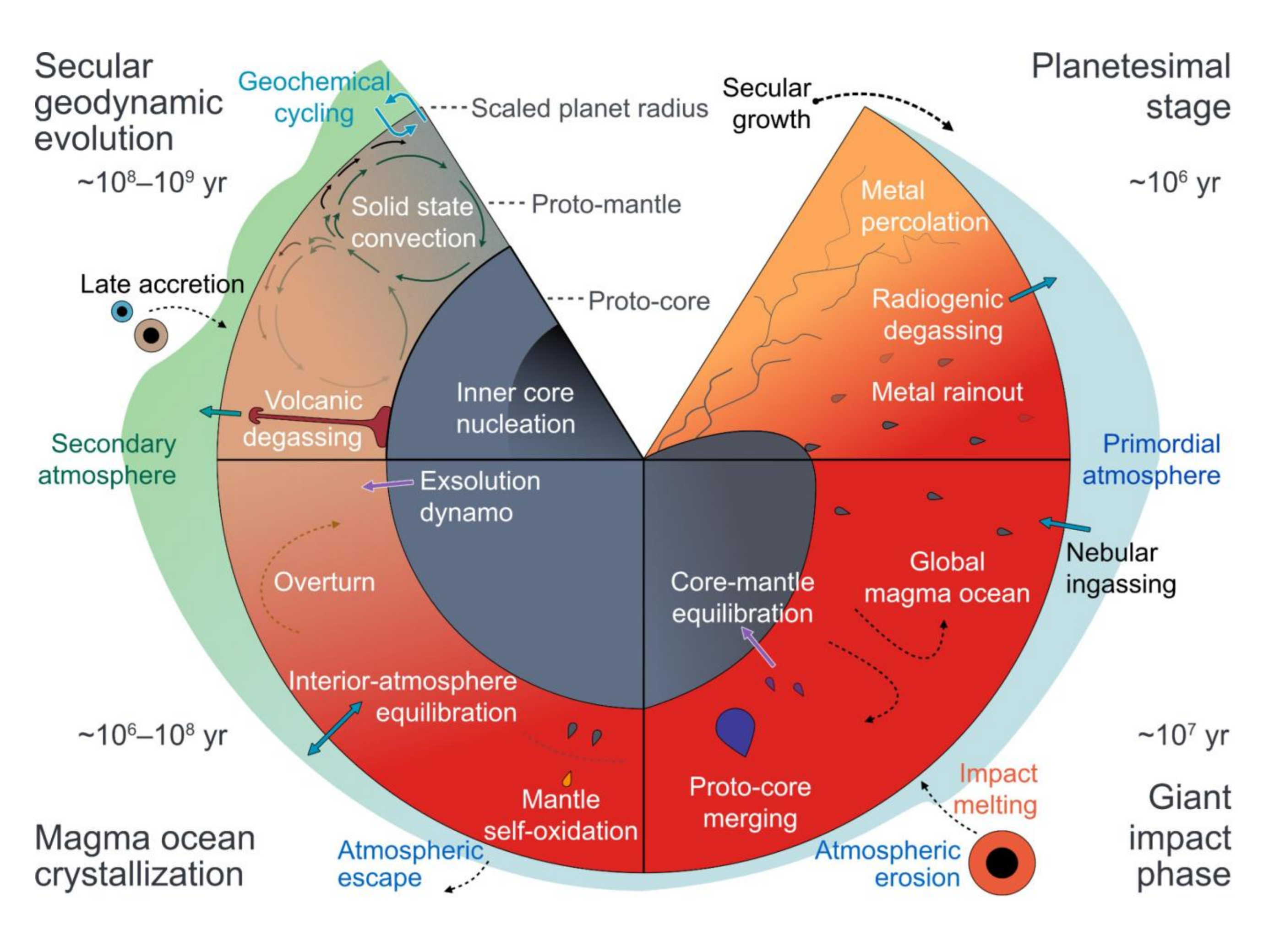
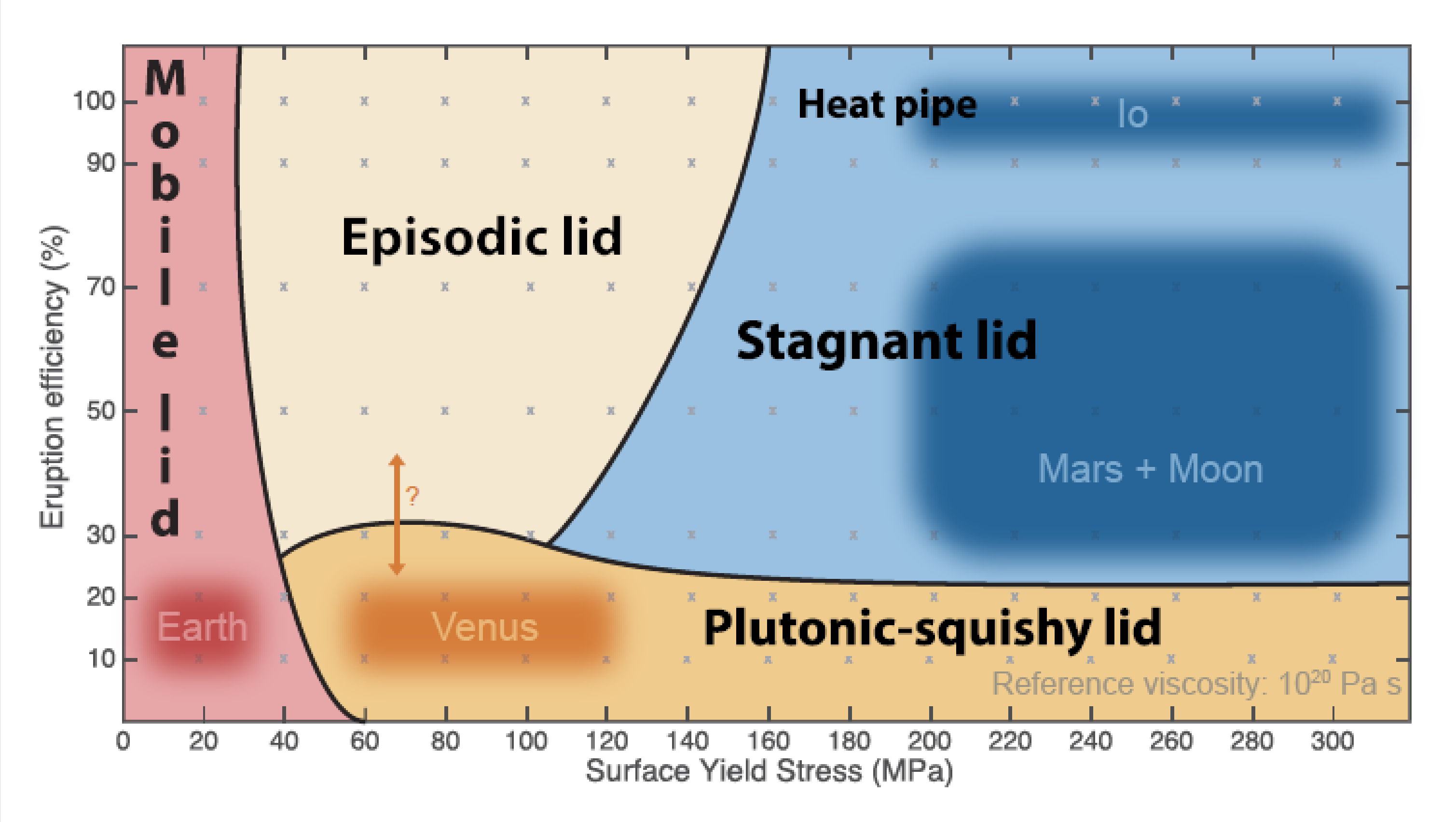
Atmosphere-Interior Evolution



Lichtenberg et al. (2022) Protostars and Planets VII

Post-MO tectonics



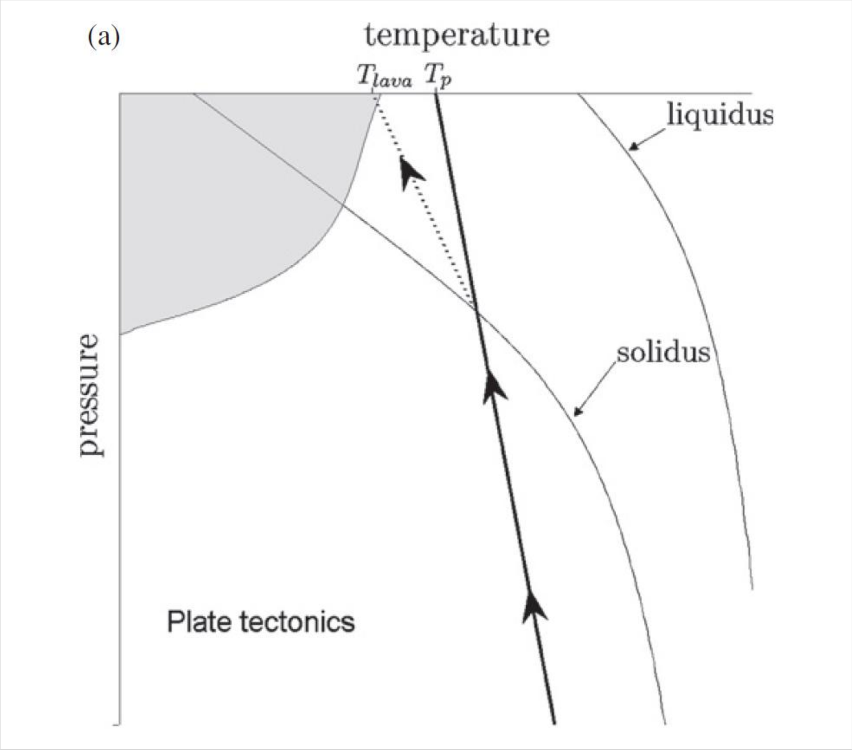
Lichtenberg et al. (2023) PPVII

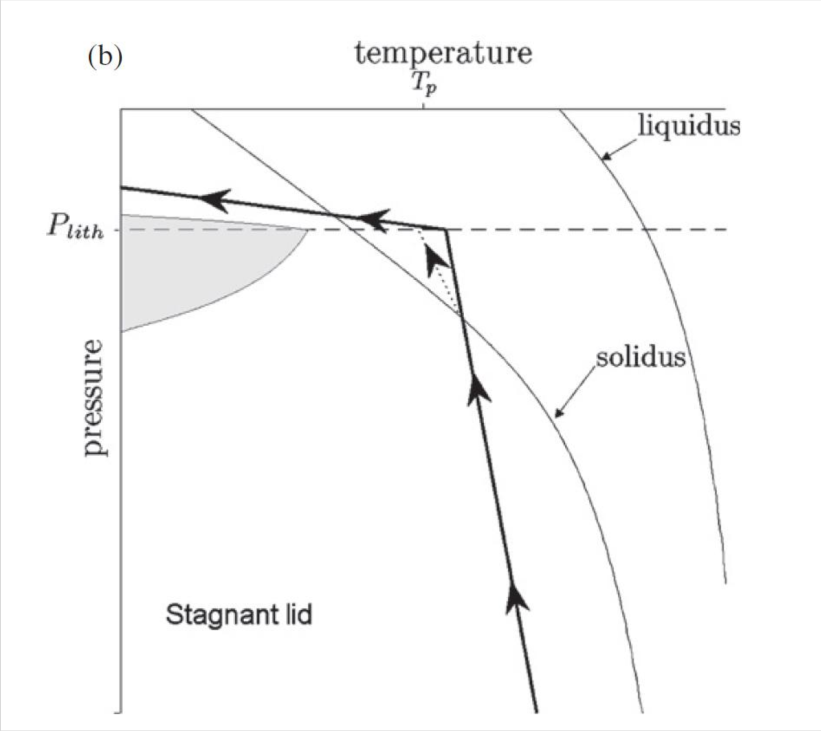
After the magma ocean phase, a rocky planet can settle into a number of different tectonic styles that all have different effects on the subsequent evolution of the surface environments.

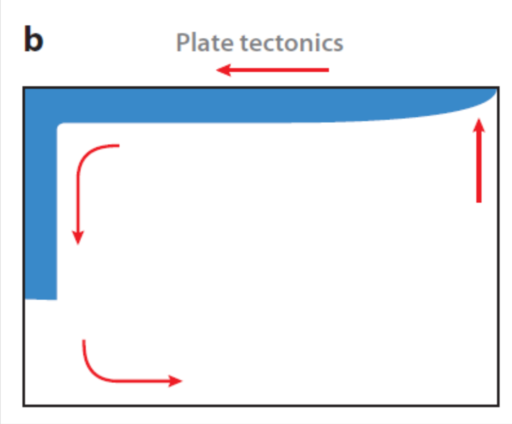
Transitions between tectonic styles may be possible throughout a planet's evolution.

Earth is currently in a mobile-lid (plate tectonic) regime, but may not always be!

Plate tectonics vs. Stagnant lid

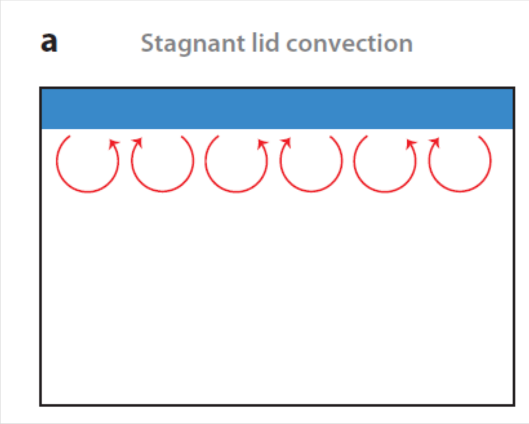




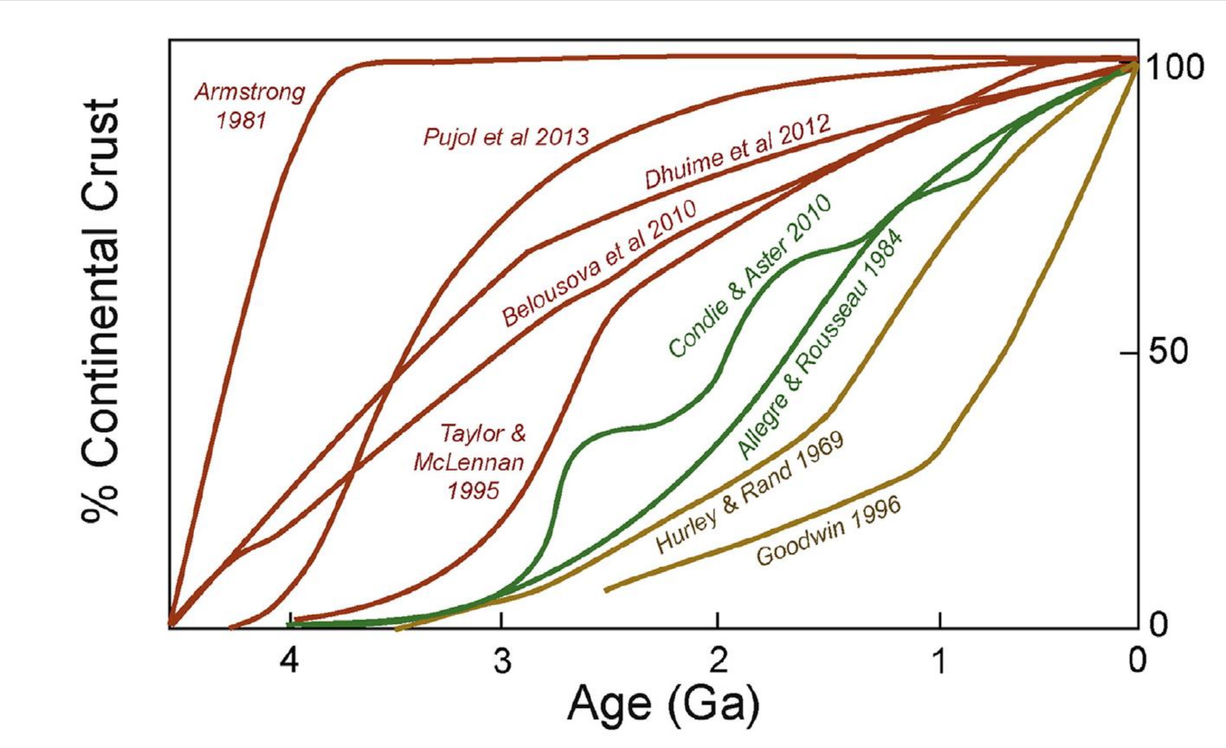


Stagnant lid tectonics may suppress melt production and limit outgassing.

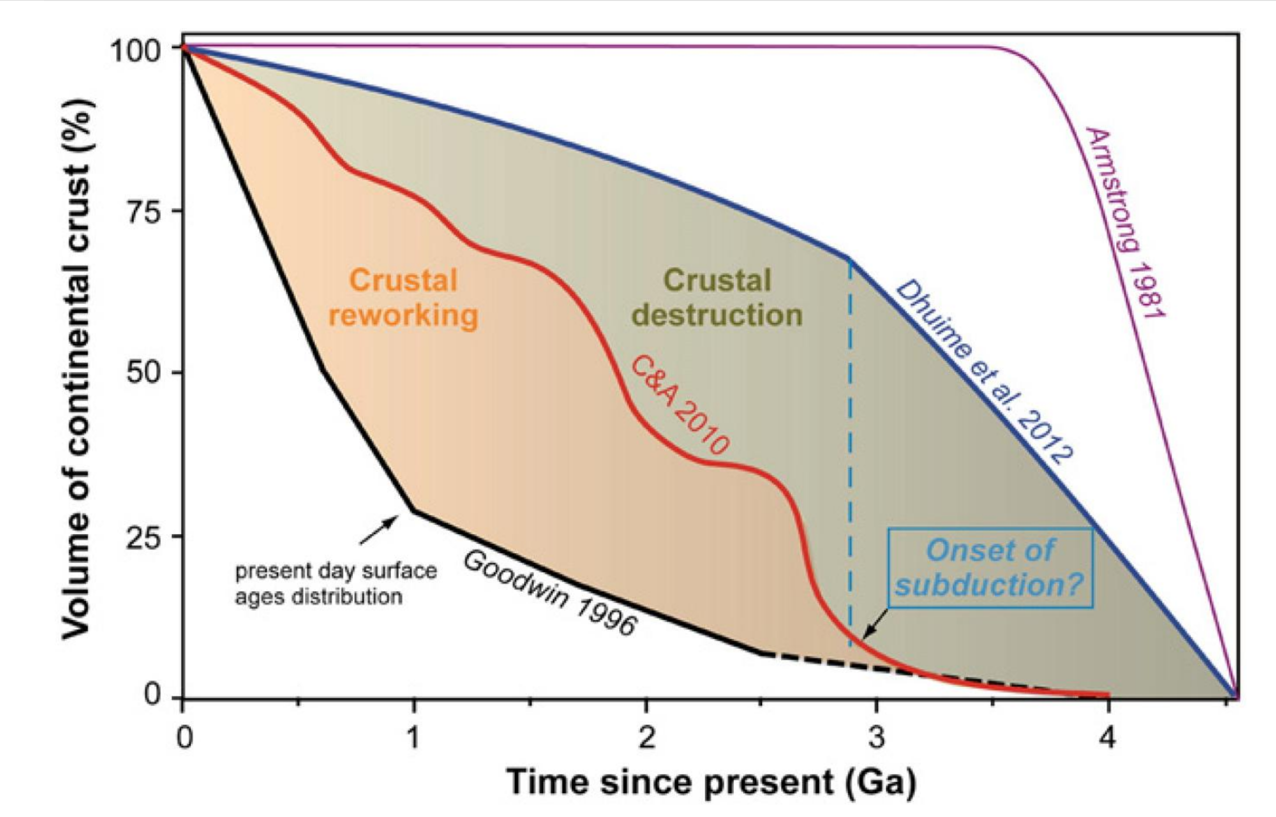
Return fluxes of material are slower and less efficient for stagnant lid.



Continental crust growth

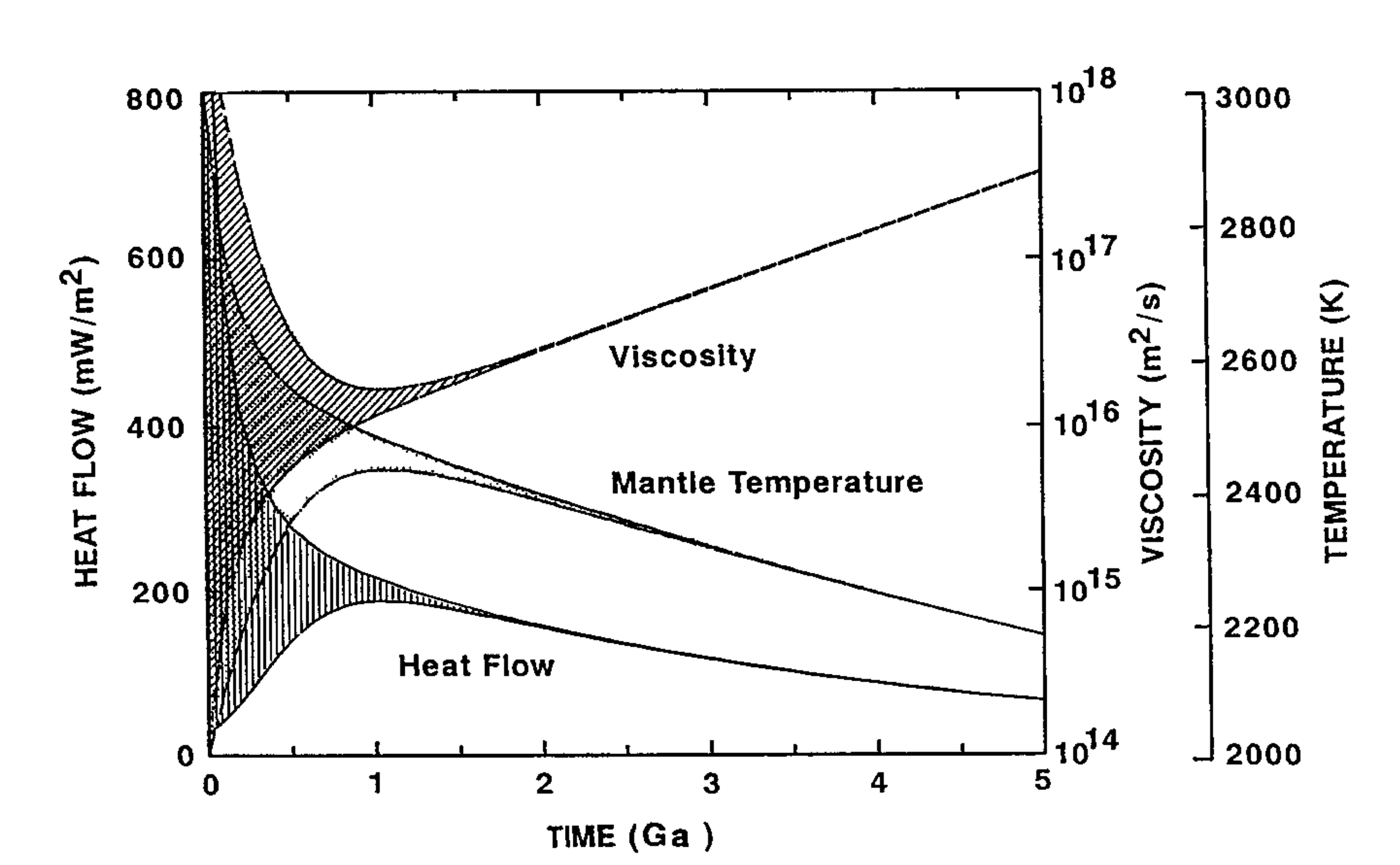


Hawkesworth et al. (2018)



Hawkesworth et al. (2013)

Thermal Evolution



Tajika & Matsui (1992)

Deep volatile cycles

Outgassing and subduction are driven by internal heating. As a planet cools off, rates of both should decrease.

- Gas production
  - Volcanic outgassing
  - Metamorphic devolatilization
  - Serpentinization
  - Reverse weathering
- Recycling of volatiles into mantle
  - Subduction of oceanic plates ← Plate tectonics
  - Plate delamination?
  - Plume/Drip magmatism? ← Stagnant lid recycling?

Diversity of volcanic centers on Earth

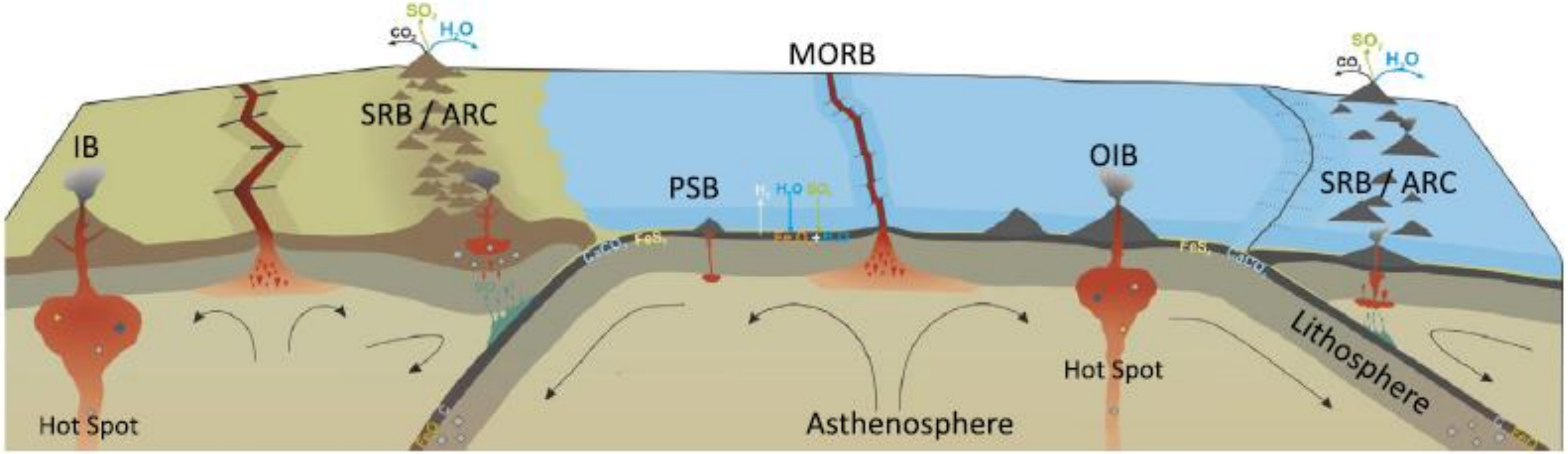
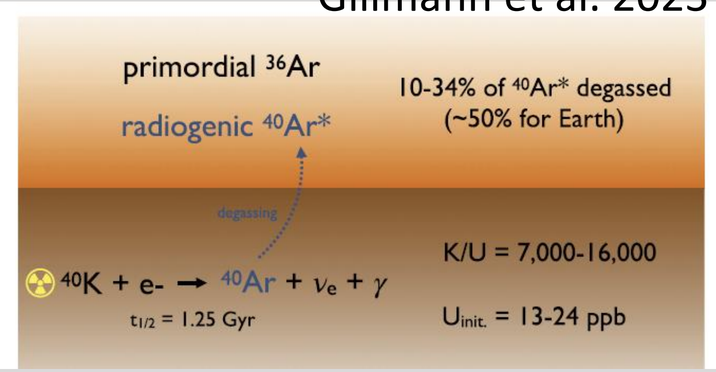


Fig. 12 Geodynamics of magmatism on Earth. MORB stands for Mid-Ocean-Ridge basalts, OIB for Oceanic-Island basalts, SRB/ARC stands for Arc-related basalts that are formed during subduction, PSB stands for Petit-spot basalts and IB means intraplate basalts. OIB and IB are related to hotspot upwellings, which sample lower mantle material, while MORB, Petit-spots and SRB sample material from the upper mantle (sometimes called the asthenosphere)

Gaillard et al. (2021)

Past outgassing rates



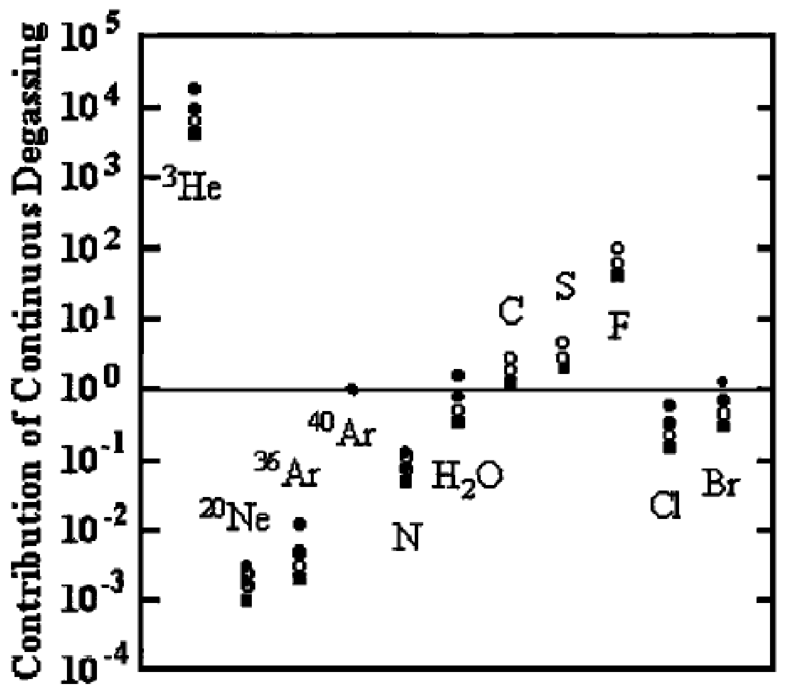
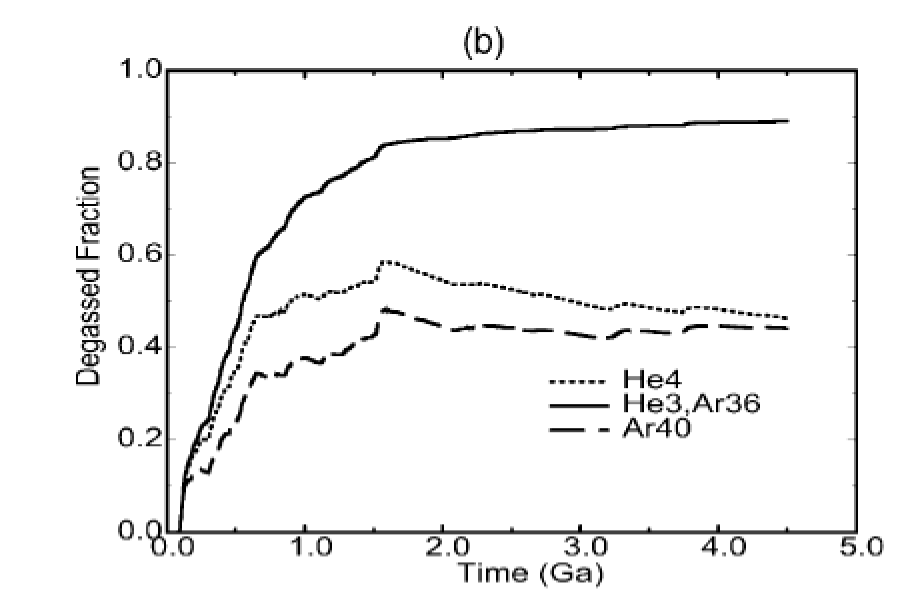


Figure 1. Contribution of continuous degassing to the present surface abundances of various volatile elements estimated by Method 1 (filled square), Method 2 (open circle), and Method 3 (filled circle).

Tajika (1998)

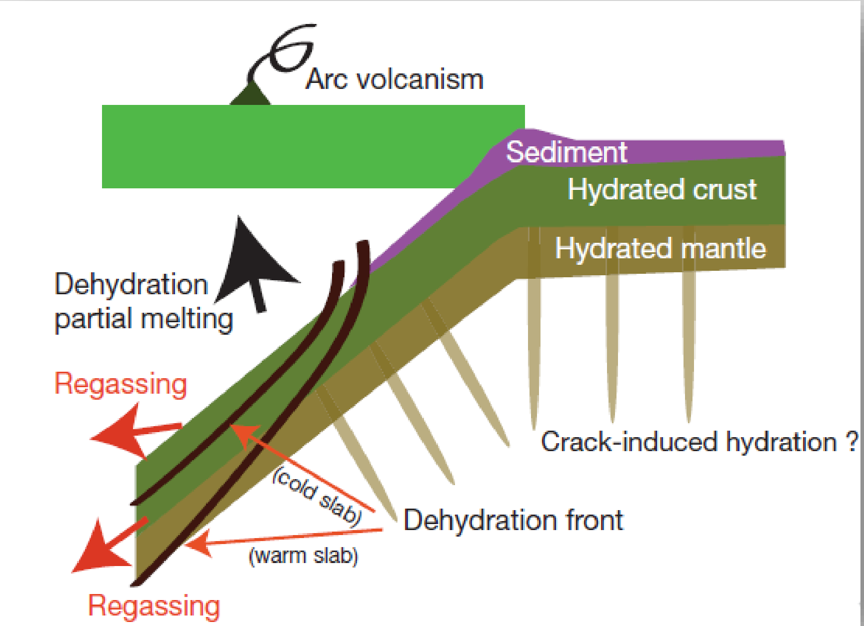
The atmospheric abundances of several elements cannot be explained with current outgassing rates, implying higher outgassing rates in the past.

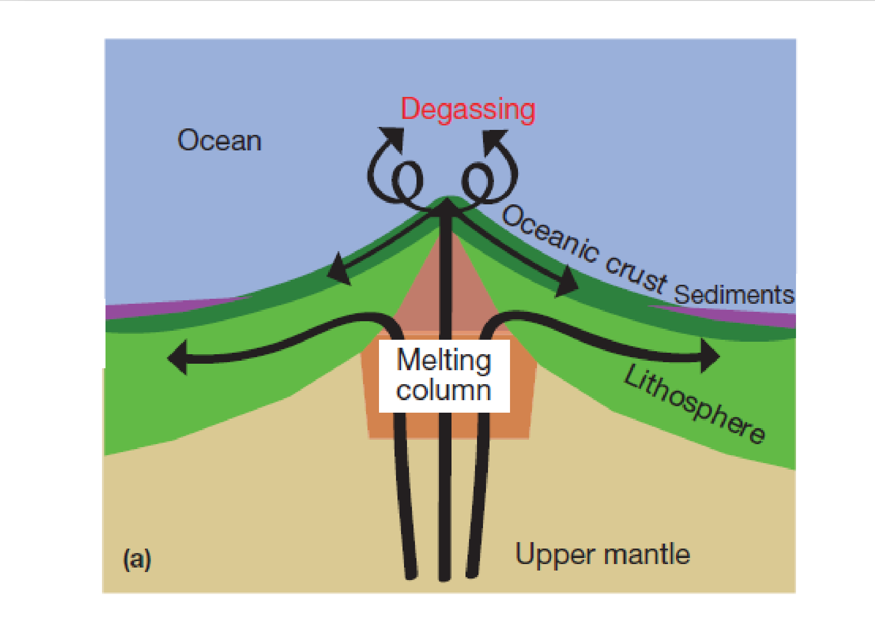
Only ~50% of He^4 and Ar^{40} seem to have been outgassed from the mantle, which constrains past mantle convection and outgassing rates.



Xie & Tackley (2004)

Deep Water Cycle



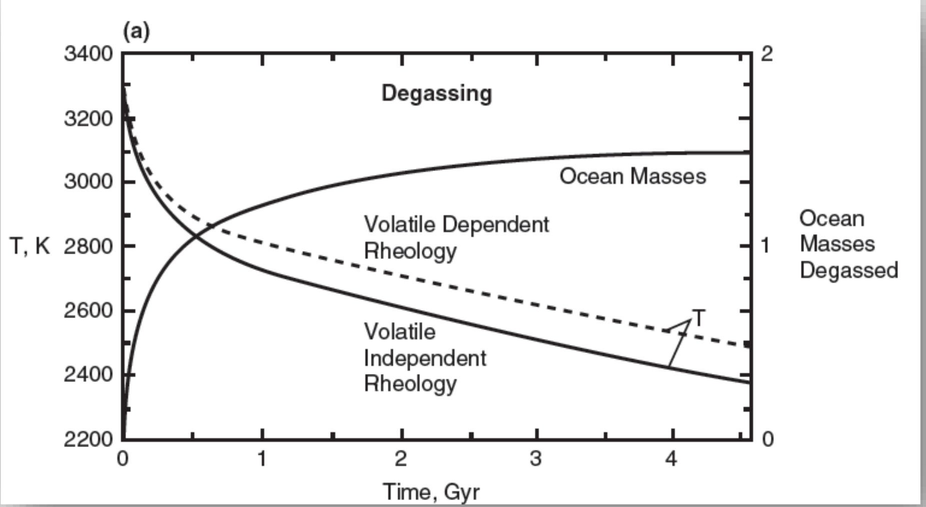


Karato (2015) TGC

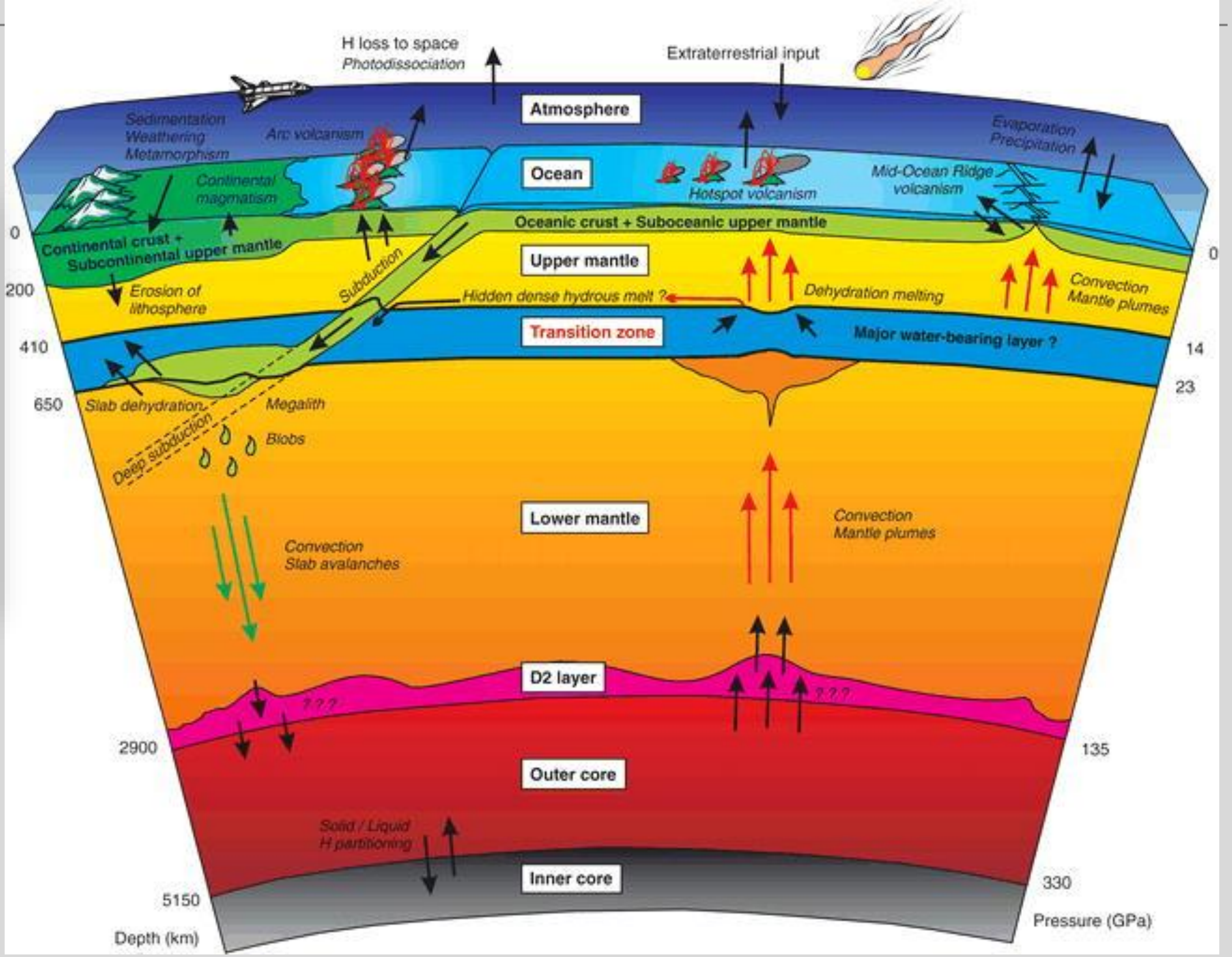
Water is transported into the mantle through subduction of hydrated minerals and sediments in a process called regassing or ingassing.

Water escapes from the mantle through volcanic eruptions at mid-ocean ridges in a process called degassing or outgassing.

Deep Water Cycle

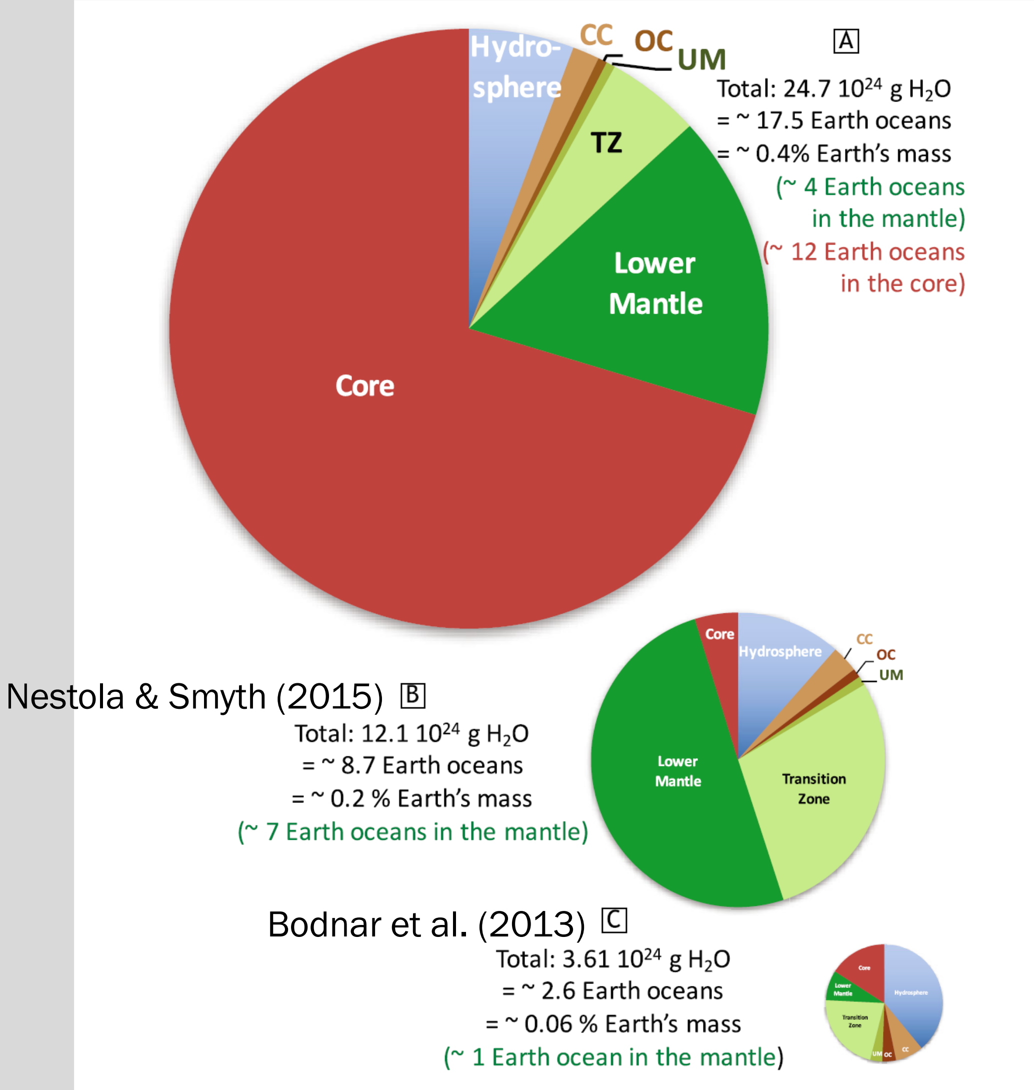


Thermal evolution + volatile recycling



McGovern & Schubert (1989), Schubert et al. (2001)

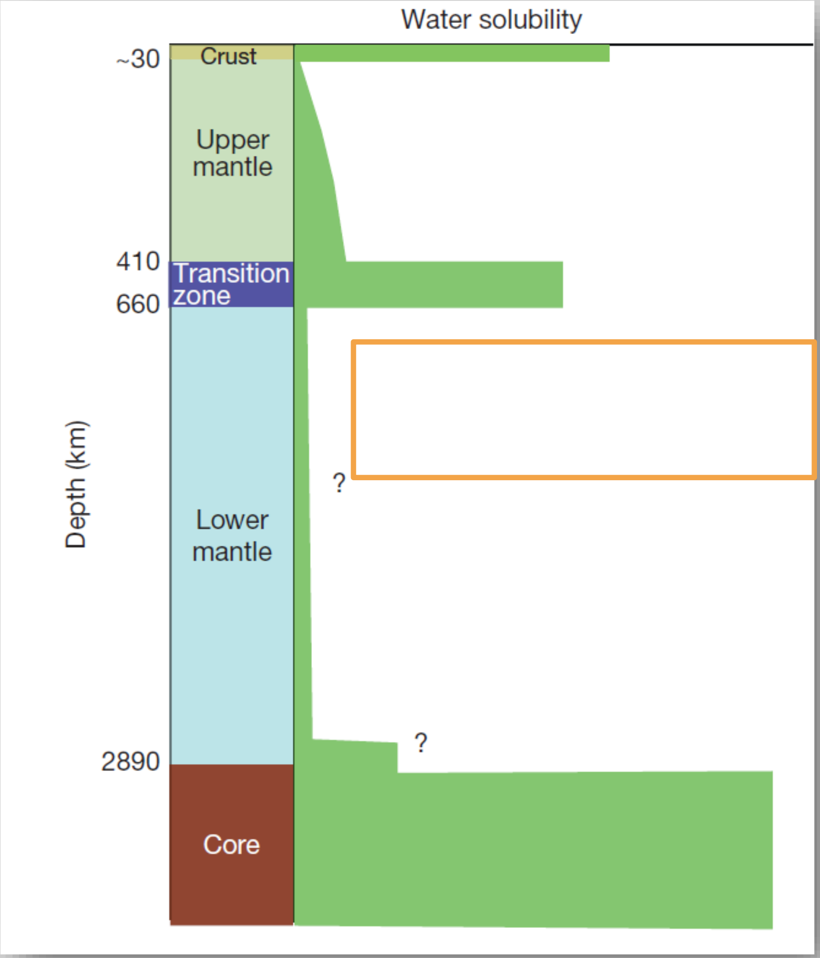
Water in Earth's Mantle



Peslier et al. (2017)

Reference	H_2O in mantle (OM)
Korenaga et al. 2017	0.56 – 1.3
Hirschmann (2018)	0.9 ± 0.2
Peslier et al. (2017)	1.1 - 7.4

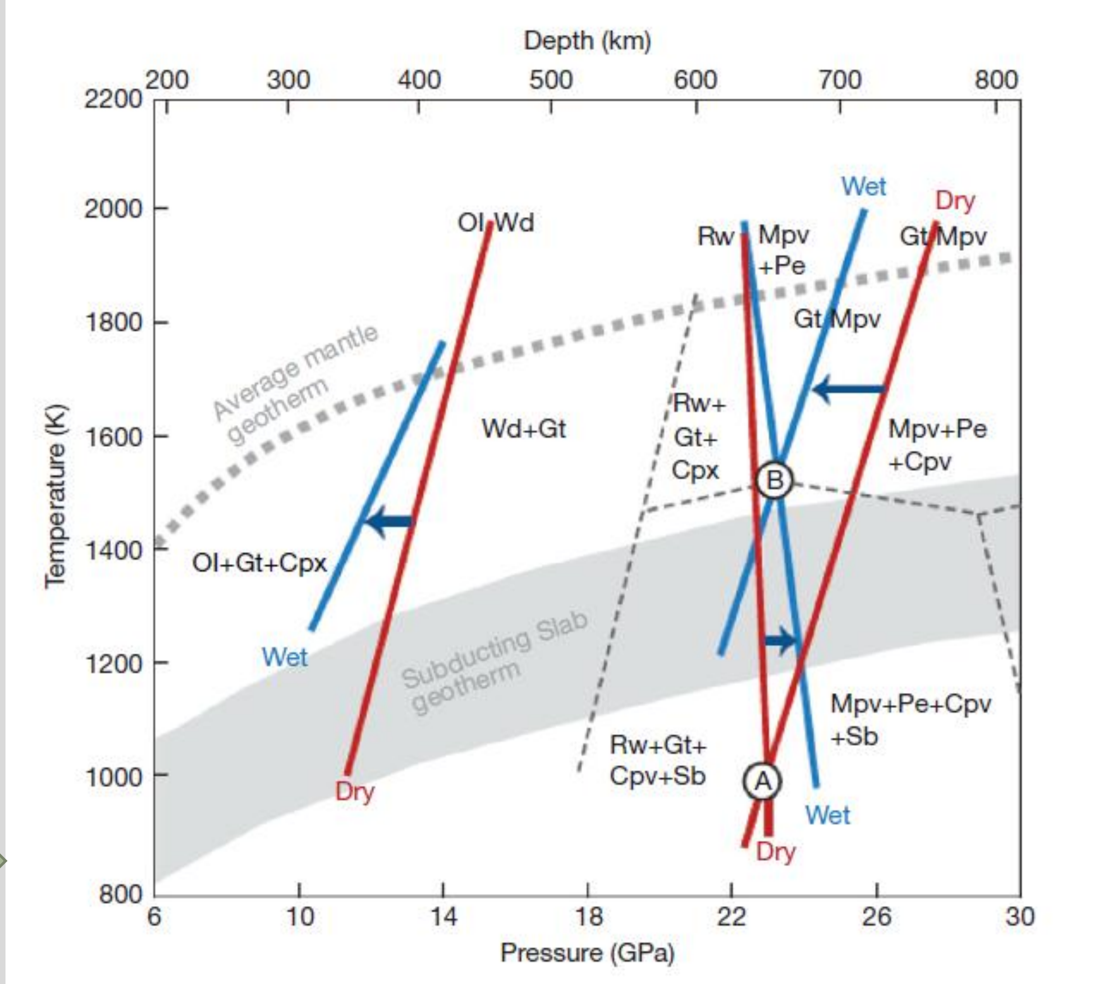
Water in the Mantle



Karato (2015) TGC

Water is not evenly distributed throughout the mantle because different minerals have different solubilities

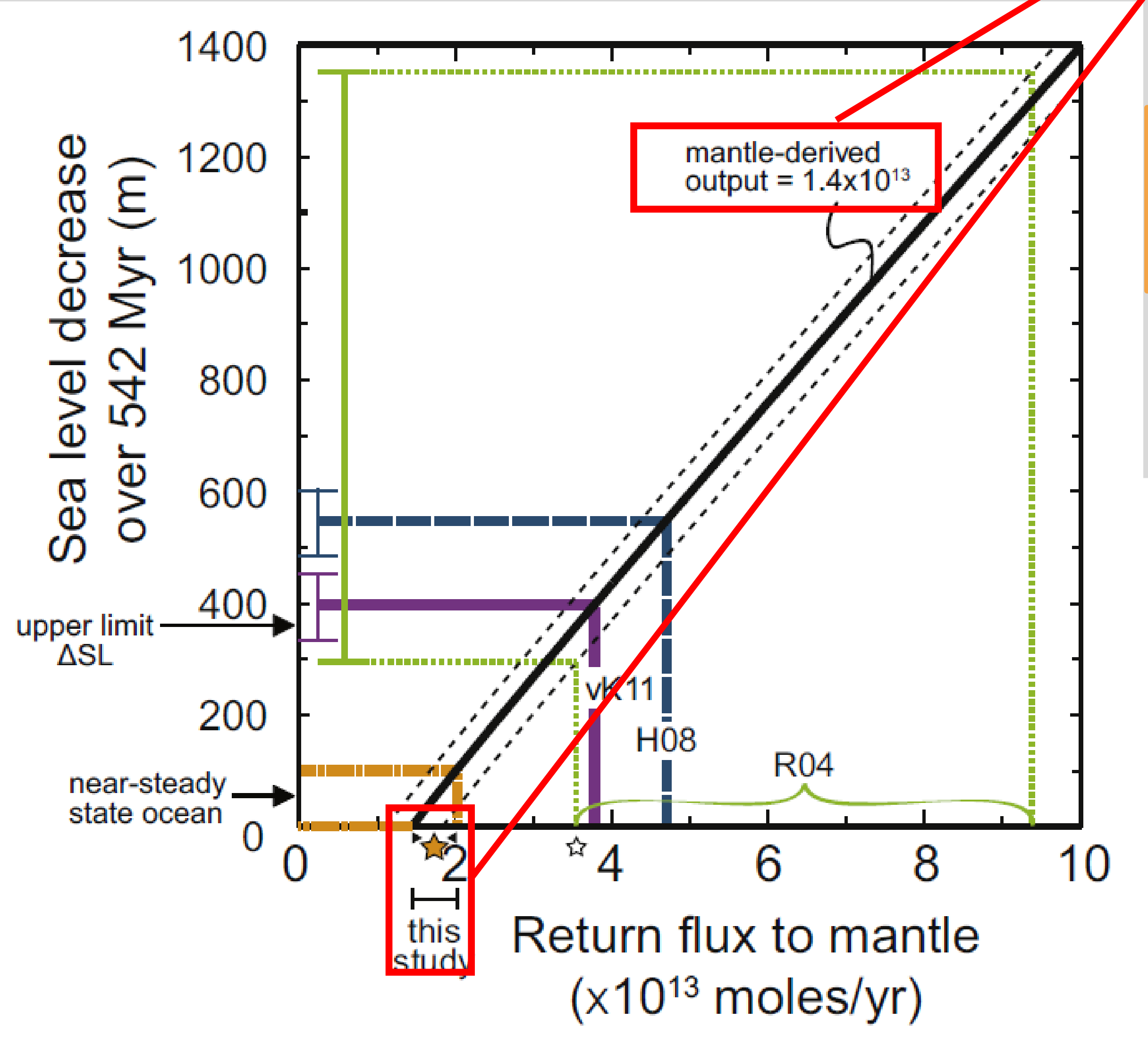
Water can influence the mineralogy of the mantle, and the depth at which mineral phase transitions occur



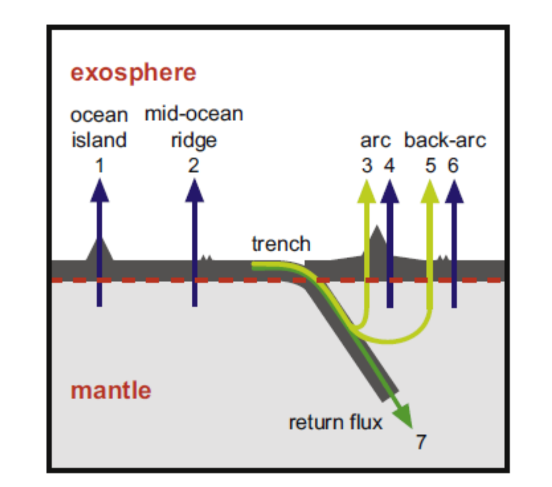
Litasov

Water flux estimates

Outgassing ~ ingassing
~ 2.5x10^{11} kg/yr



In the absence of return flux, it would take ~5.5 Gyr to outgas 1 OM at this rate

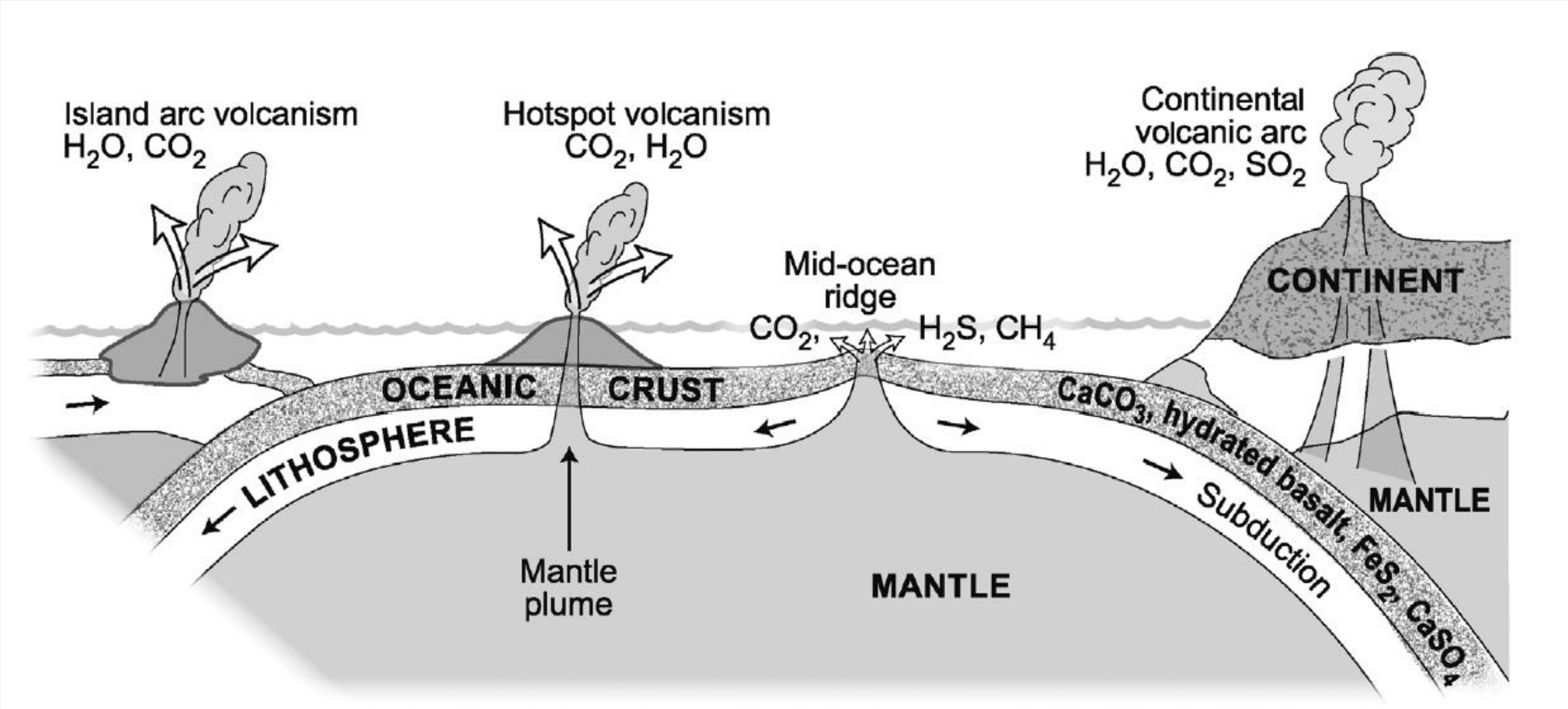


	($\times 10^{13}$ mol/yr)
Ocean island flux	0.52
Mid-ocean ridge flux	0.75
Total arc flux	3.2
Slab-derived arc flux	3.1
Total back-arc flux	0.44
Slab-derived back-arc flux	0.38
Trench input flux	6.0
Total mantle-derived output flux = (OIB + MORB + mantle-derived arc + mantle-derived back-arc)	1.4

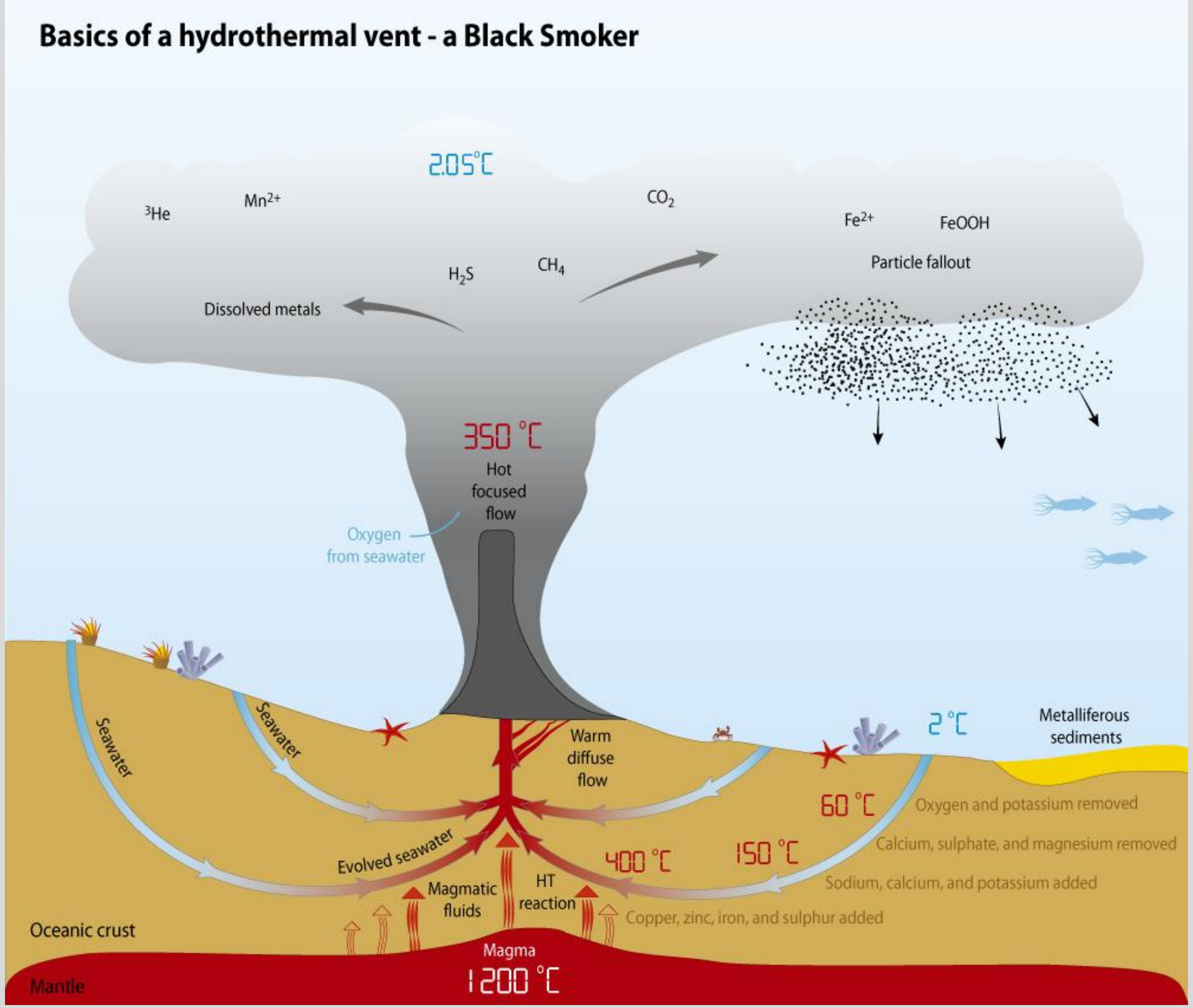
Outgassing flux estimates based on measured volatile concentrations in samples and estimates of total eruption rates.

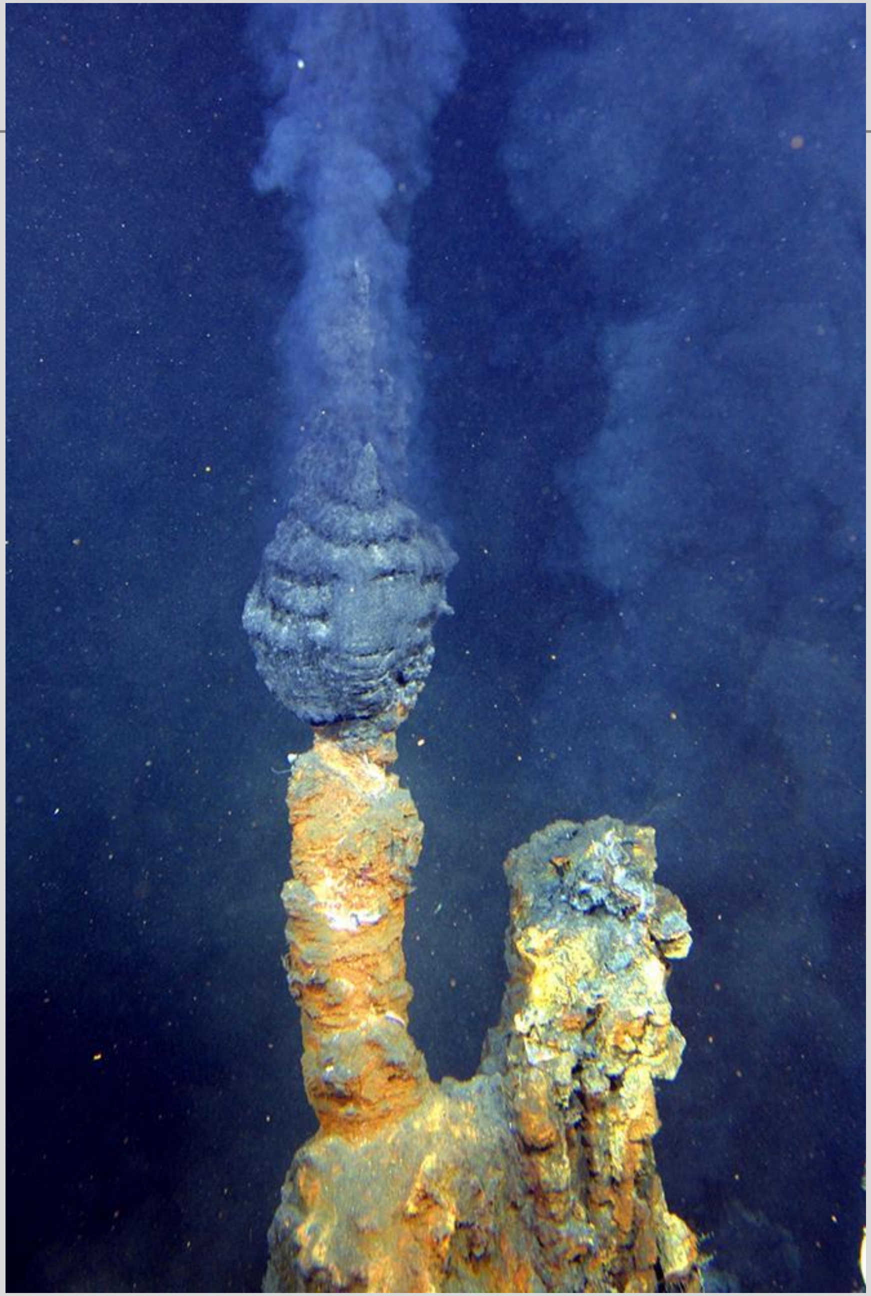
Parai & Mukhopadhyay (2012)

Volcanic outgassing - settings

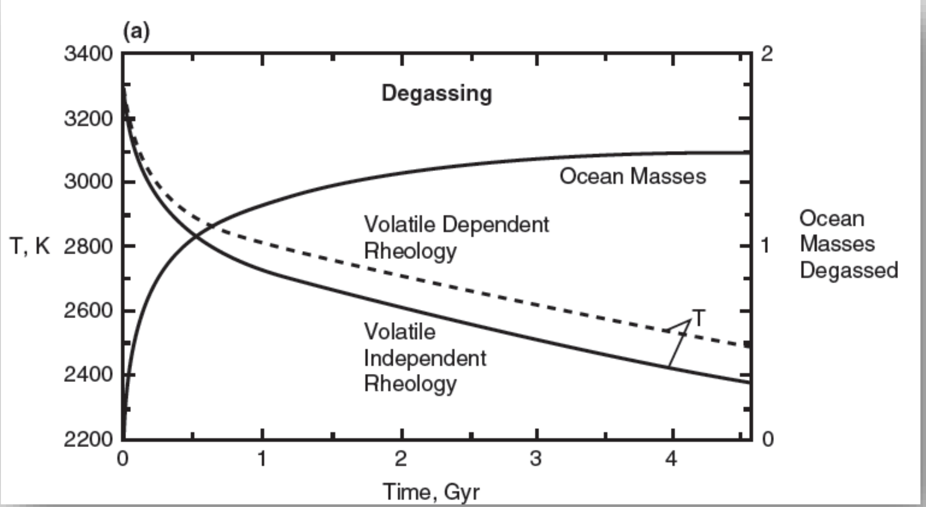


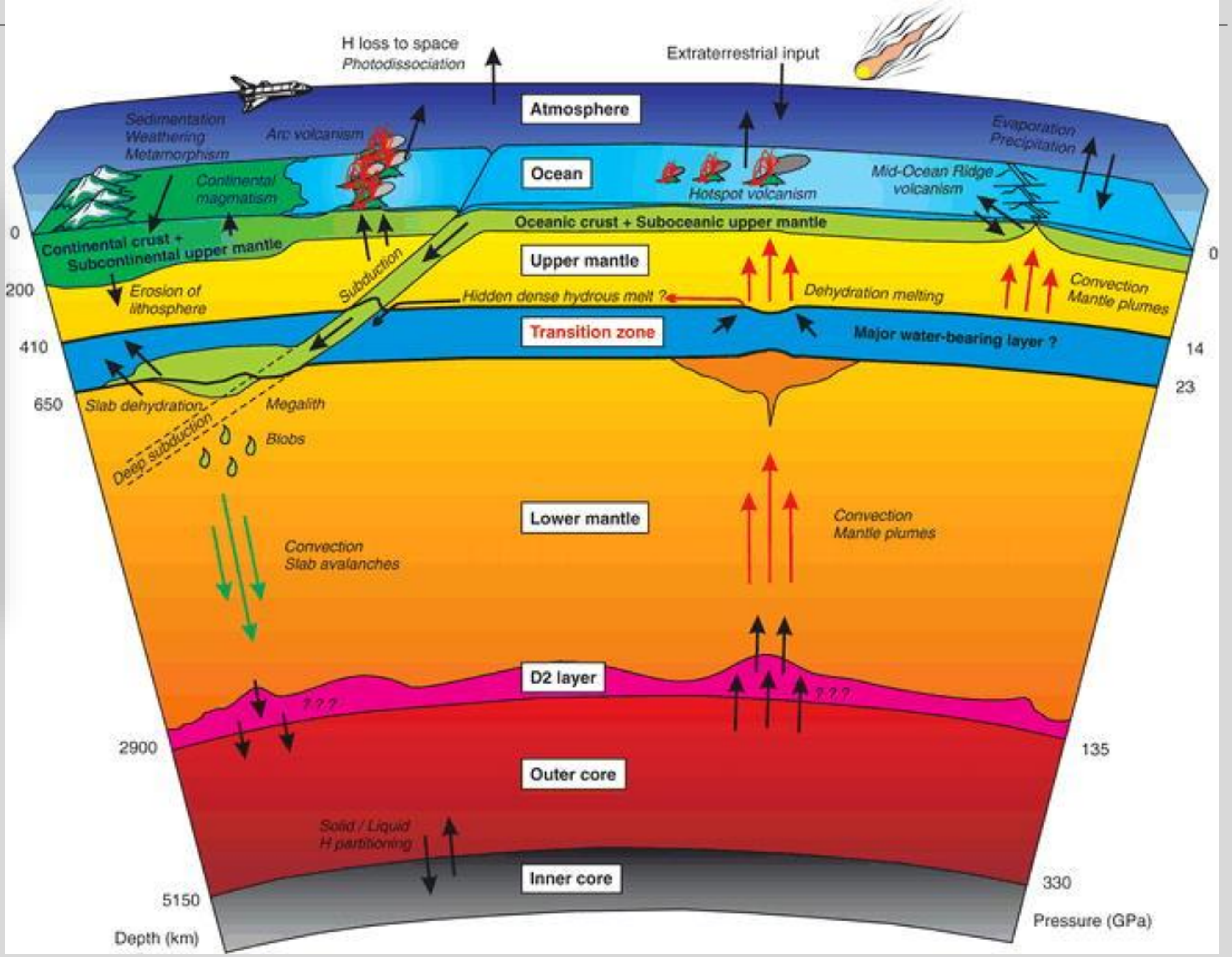
Hydrothermal vents





Deep Water Cycle

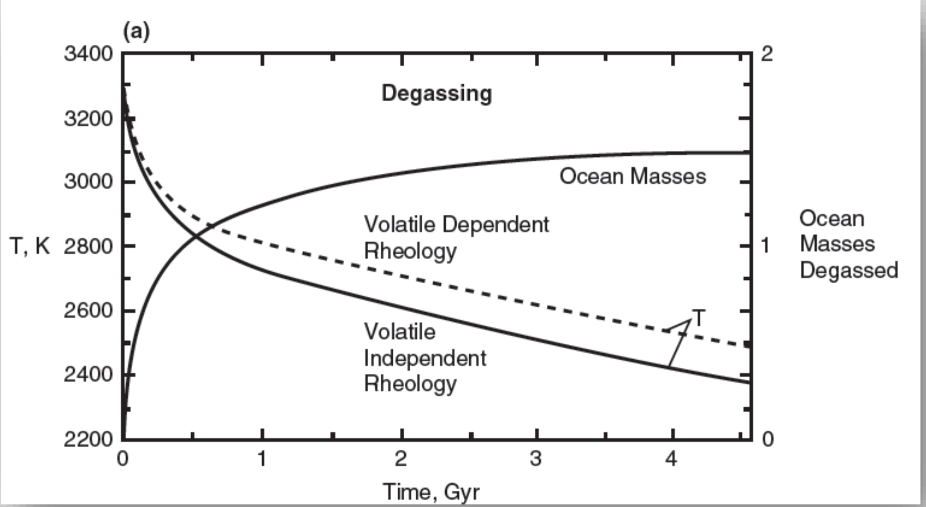




Thermal evolution + volatile recycling

McGovern & Schubert (1989), Schubert et al. (2001)

Deep Water Cycle



$$\rho c \frac{\partial \langle T \rangle}{\partial t} = -A_p q_m + \mathrm{Q}$$

$$Ra = \frac{\alpha g (T_m - T_s) l^3}{\nu \kappa}$$

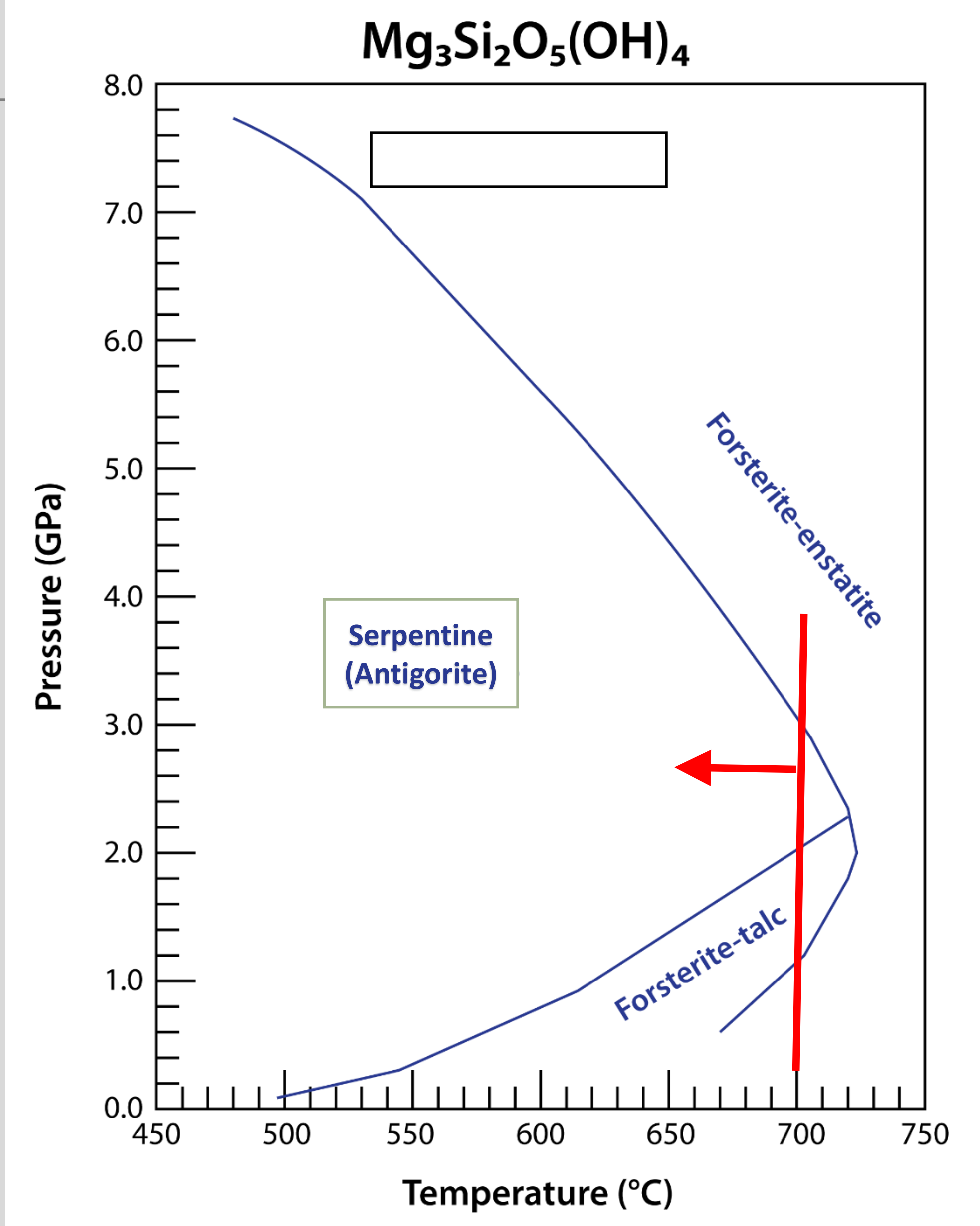
$$q_m = \frac{k(T_m - T_s)}{l} \left(\frac{Ra}{Ra_{cr}} \right)^{\beta}$$

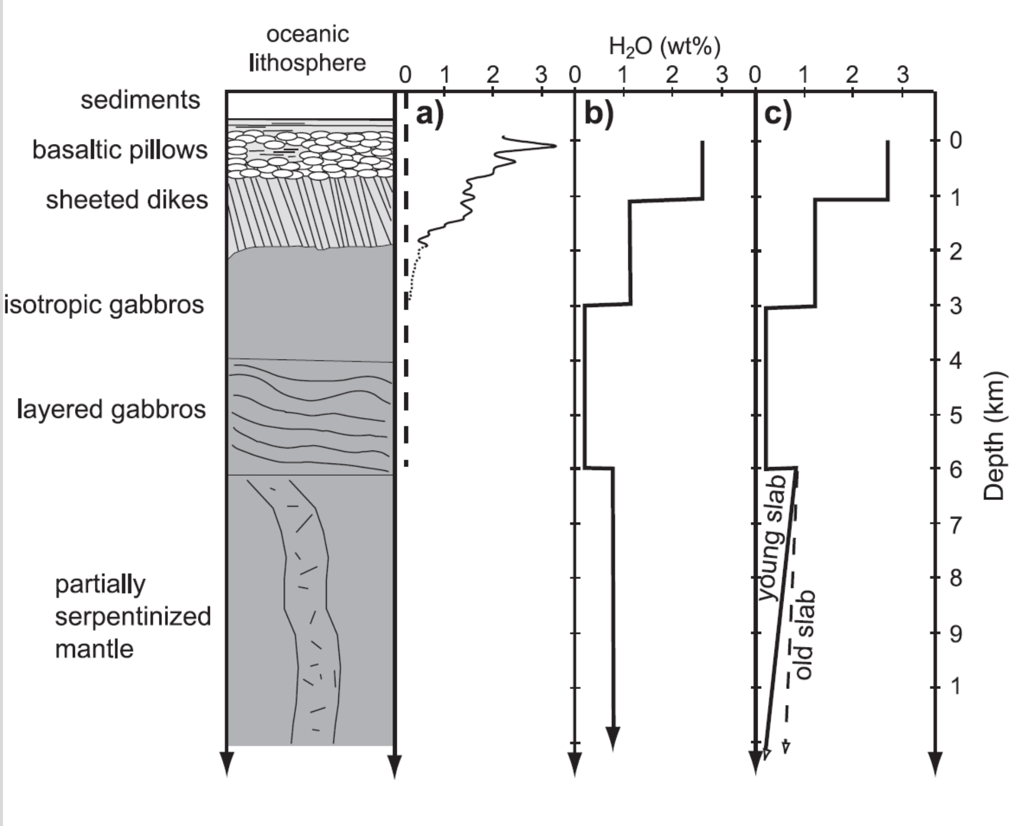
Thermal evolution + volatile recycling

$$\frac{\partial M_{H_2O,m}}{\partial t} = r_{ingas} - r_{outgas}$$

McGovern & Schubert (1989), Schubert et al. (2001)

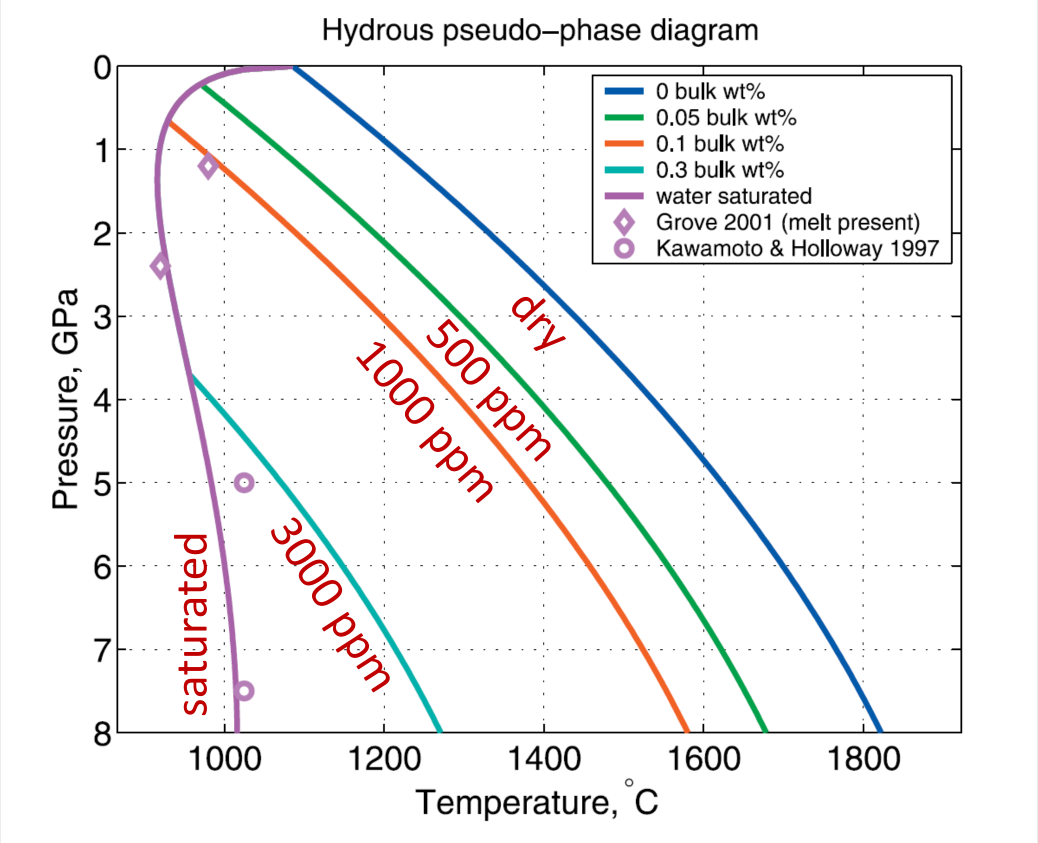
Water in subducted crust





Rupke et al. (2004)

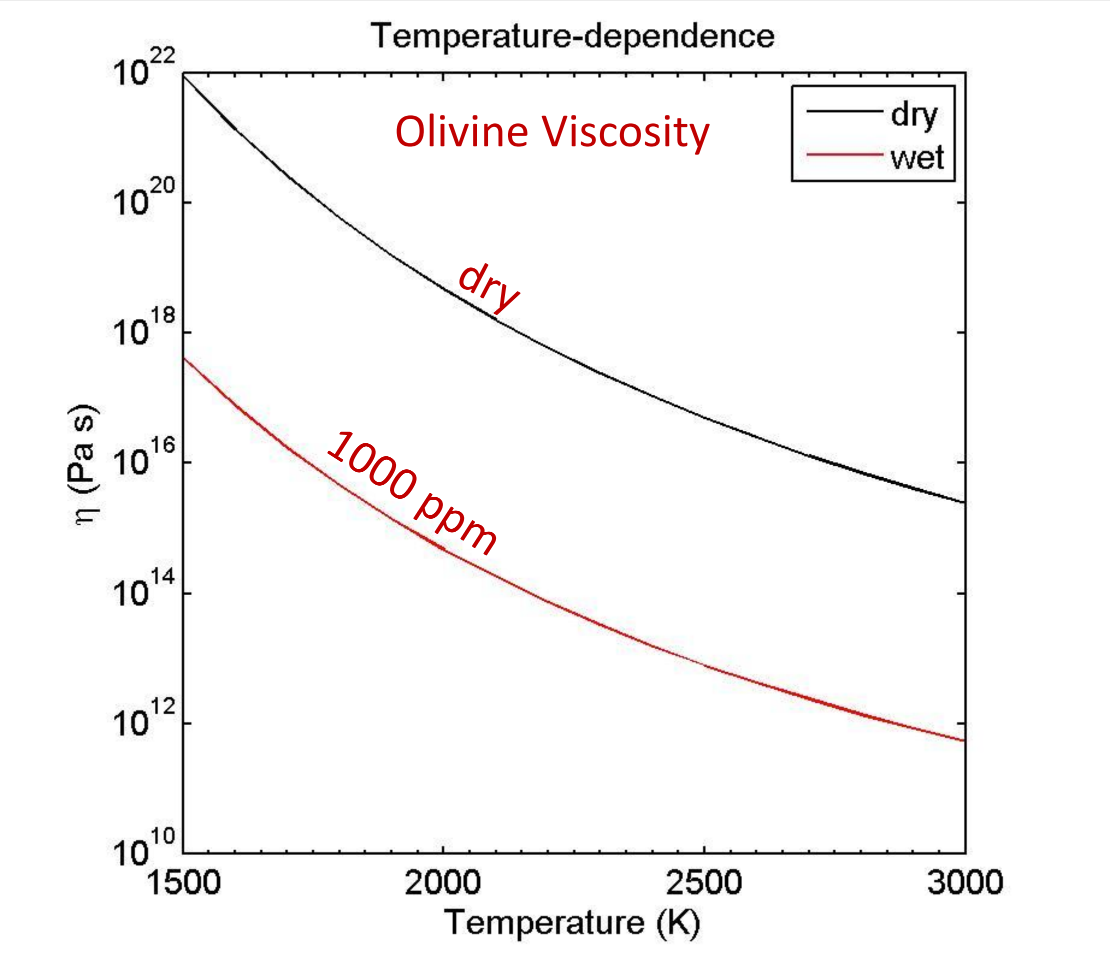
Melting point depression



Katz et al. (2003)

Water behaves incompatibly and lowers the activity of the melt, isobarically shifting the melting point to lower temperatures.

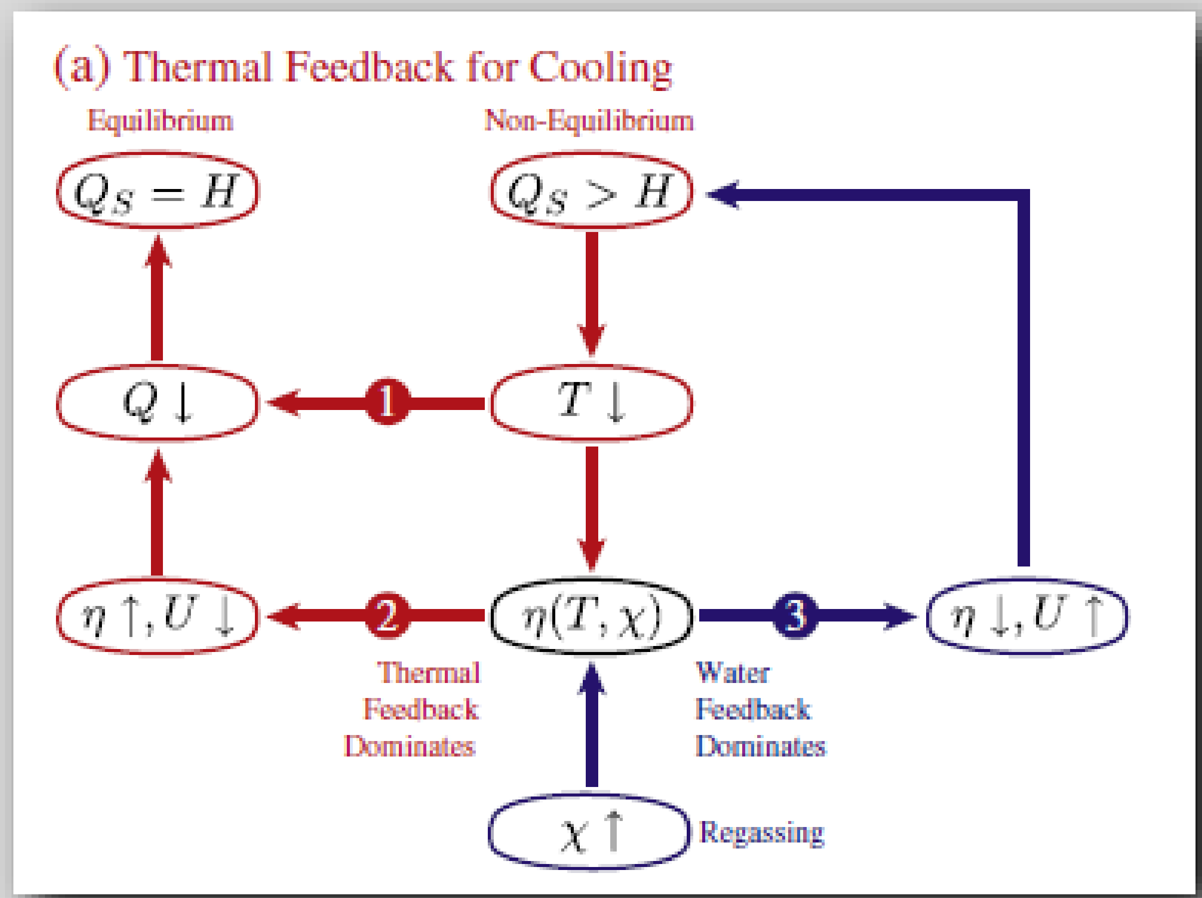
Viscosity depression



Hirth & Kohlstedt (2003)

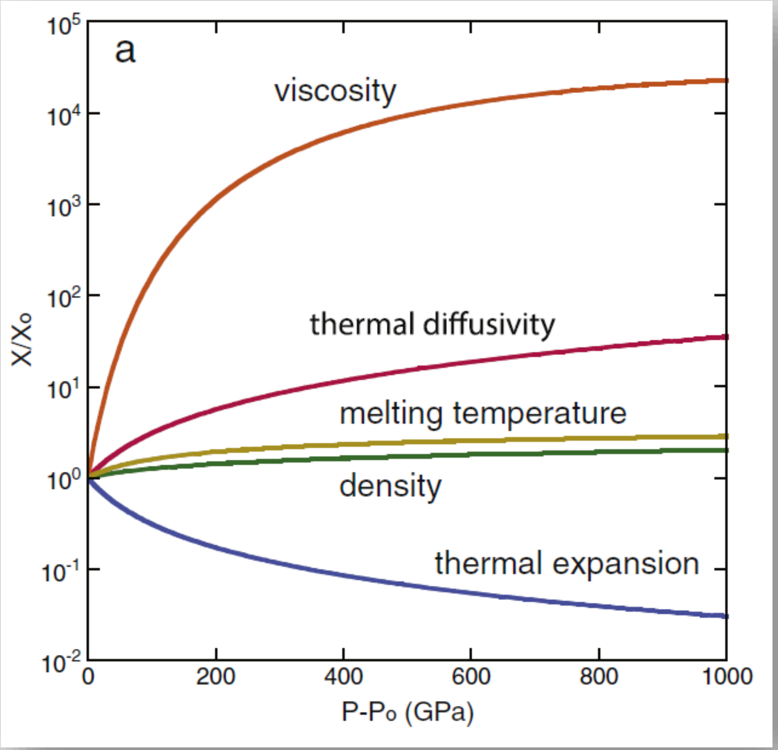
Water lowers mantle viscosity, influencing mantle thermal evolution.

Temperature – Viscosity Feedback



Crowley et al. 2011

Super-Earth properties



Karato (2015) TGC

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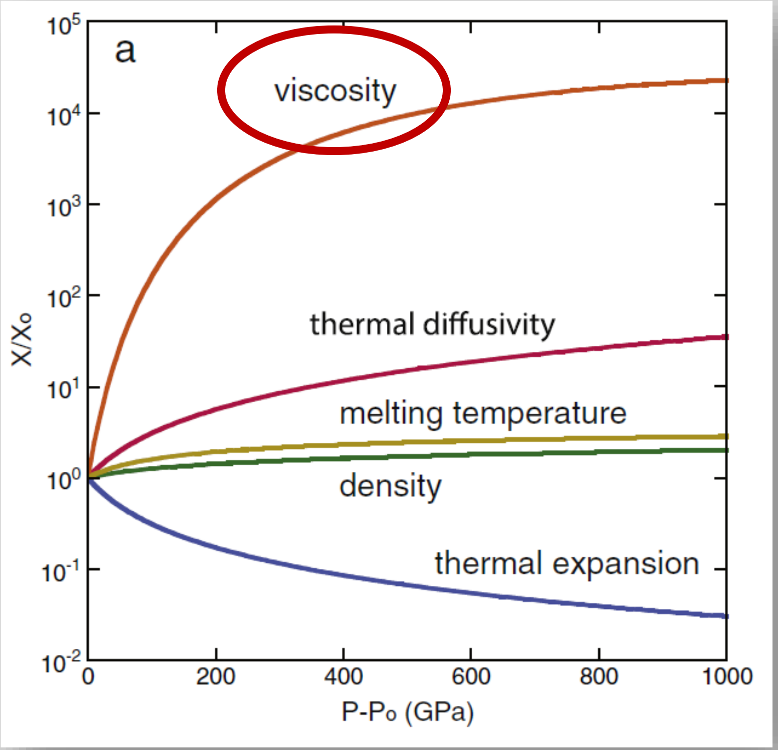


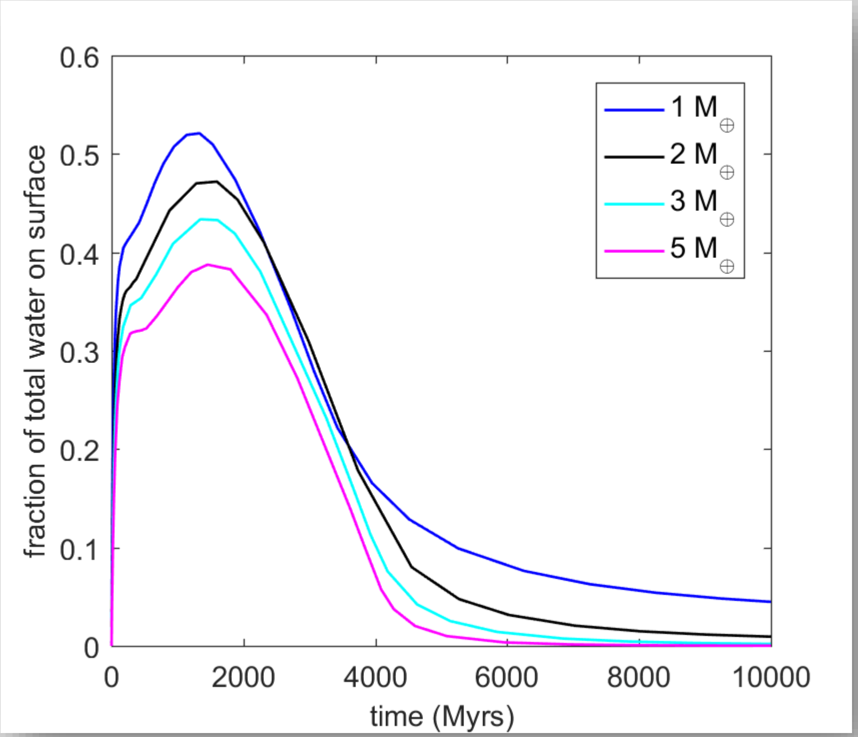
Karato (2015) TGC

$$\eta = \eta_0 f_{H_2O}^{-r} \exp\left(\frac{E_A + PV_A}{RT}\right)$$

Viscosity has a strong effect on the rate of mantle convection, and will therefore effect planet evolution.

Surface Water Abundance

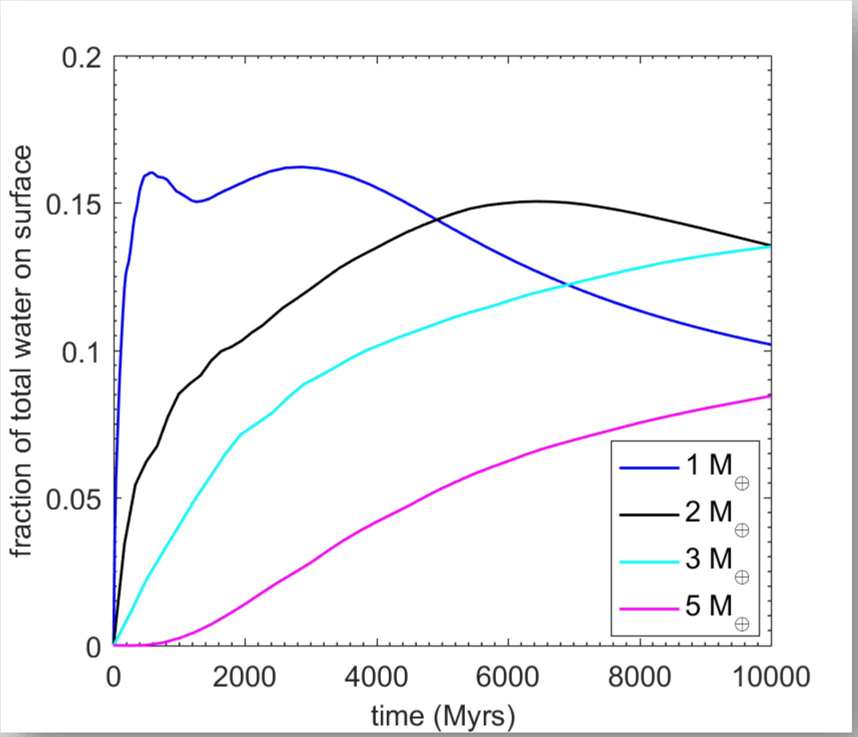
low pressure



Schaefer & Sasselov (2015)

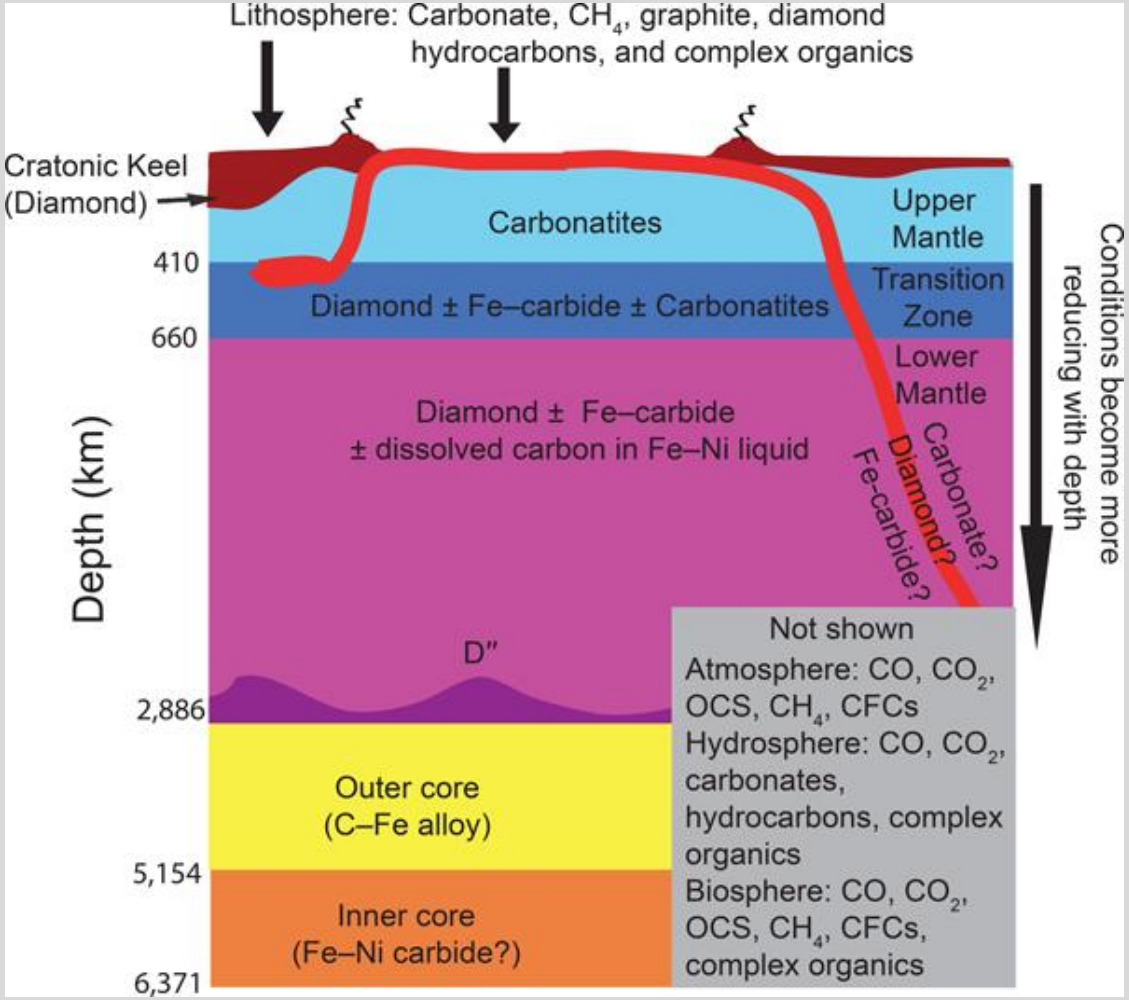
When pressure effect on viscosity is small, planets form oceans early and lose them to the mantle as they age.

high pressure



When pressure effect on viscosity is large, oceans are smaller on all planets and delayed on larger planets.

Carbon in the mantle

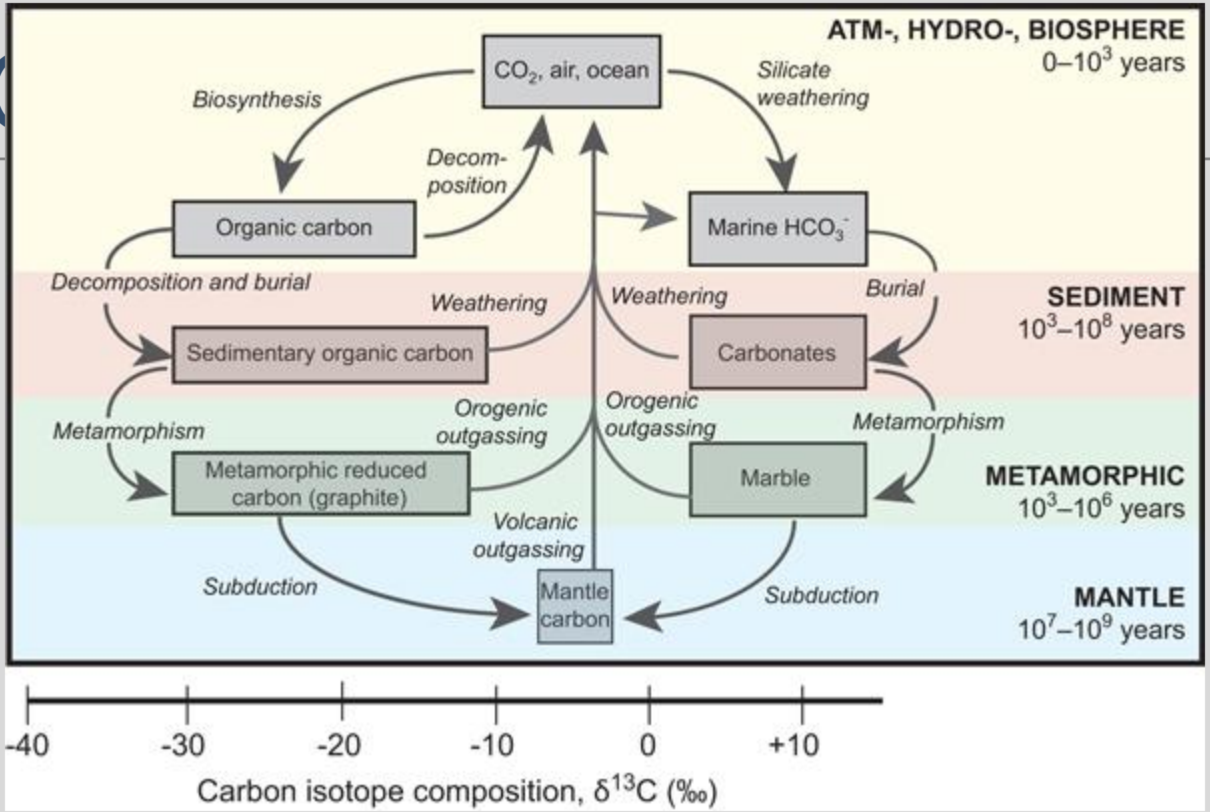


Mikhail & Füri (2019)

Unlike water, carbon is mostly found in accessory phases in the mantle, because of low solubility in solid silicates.

The most abundant carbon phase in the mantle is likely diamonds.

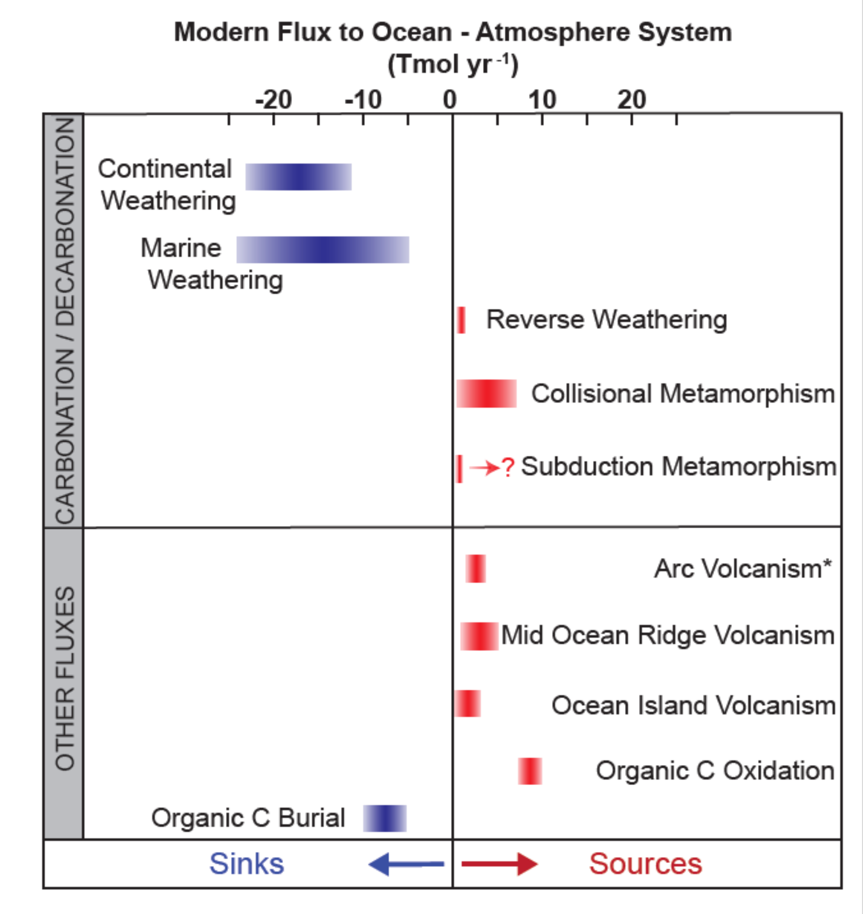
Carbon also affects melting and viscosity in the mantle, although to a lesser degree than water.



Suarez et al. (2019)

Carbon cycles on very short timescales in the surface reservoirs. Exchange with the mantle occurs on much longer timescales.

Estimates of carbon fluxes based on observed processes on Earth. Total net carbon flux into the atmosphere ranges from -45 to +11 Tmol CO_2/yr.



Stewart et al. (2019) AmMin

Carbon Cycle

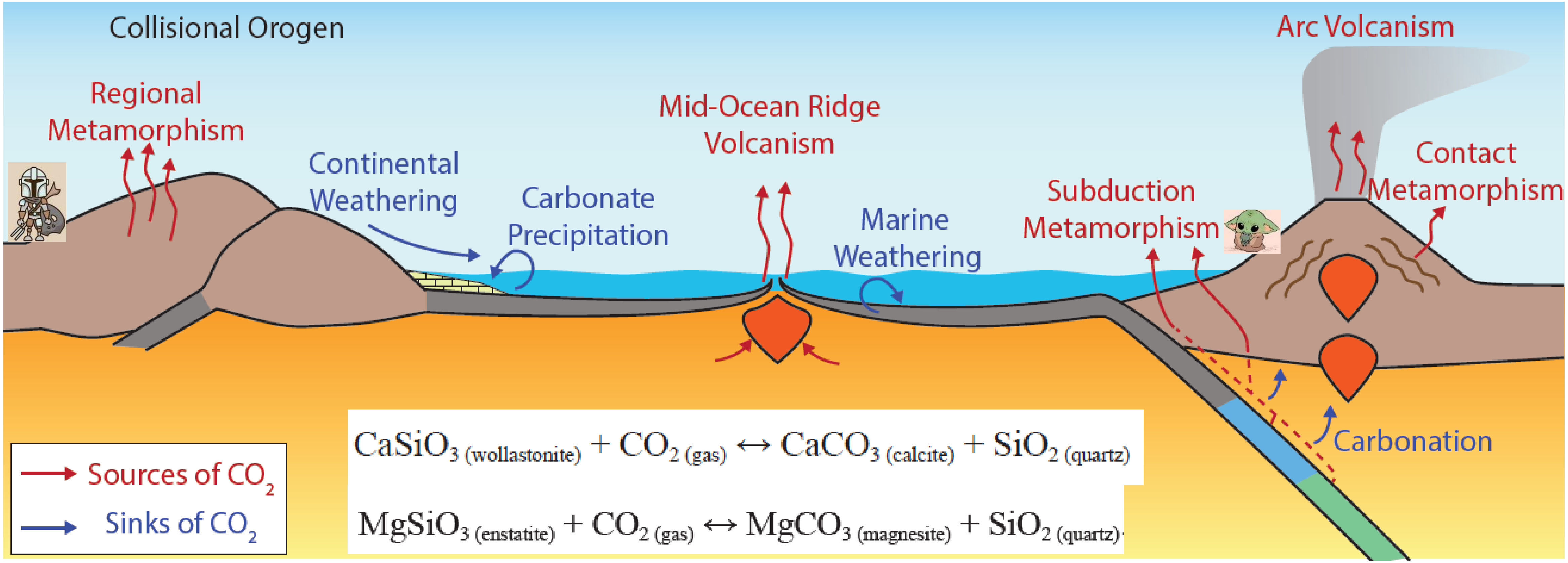
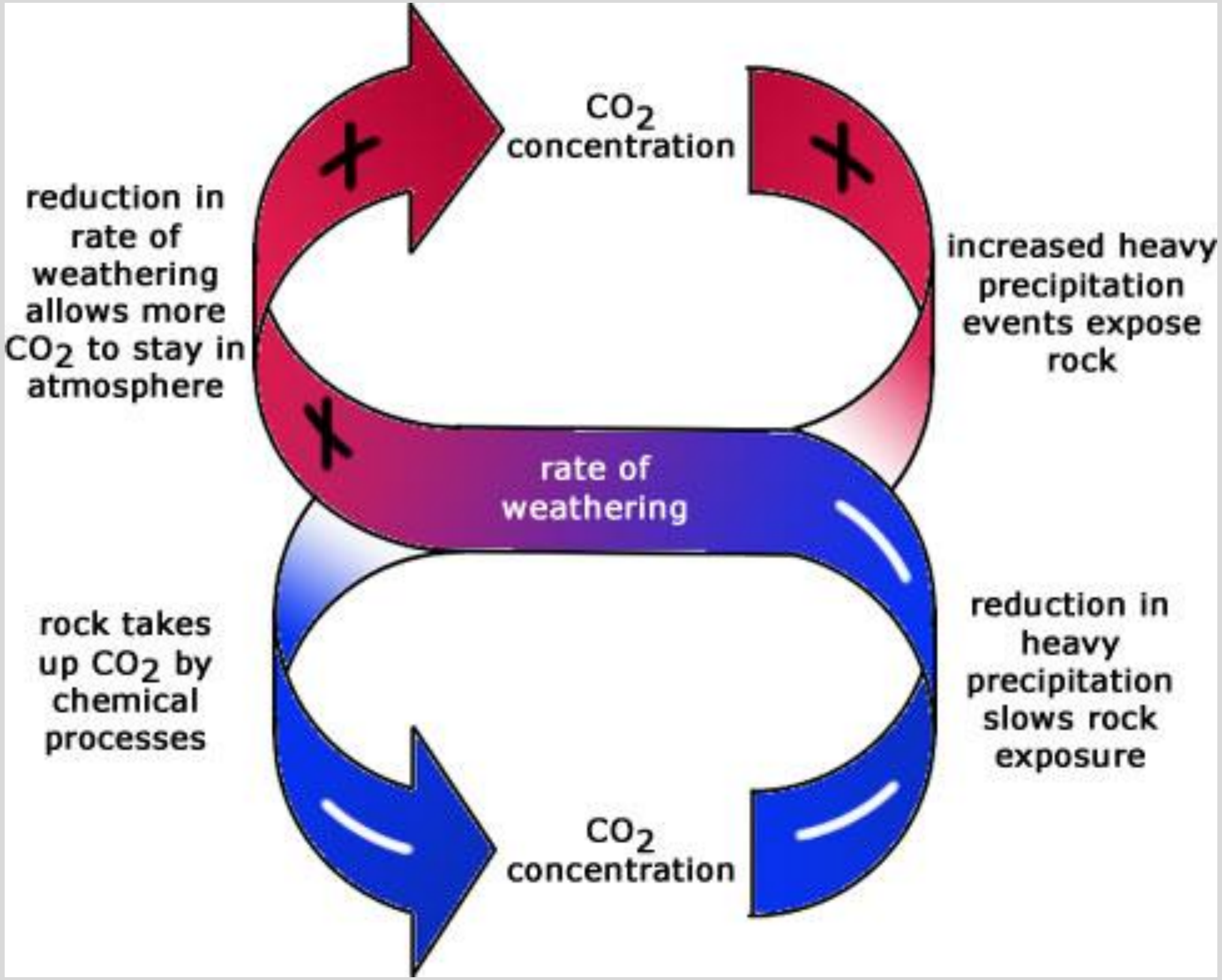


Figure 1. Schematic cross section showing the tectonic context of major carbonation/decarbonation processes. Sources of atmospheric CO_2 are indicated in red, whereas sinks are in blue.

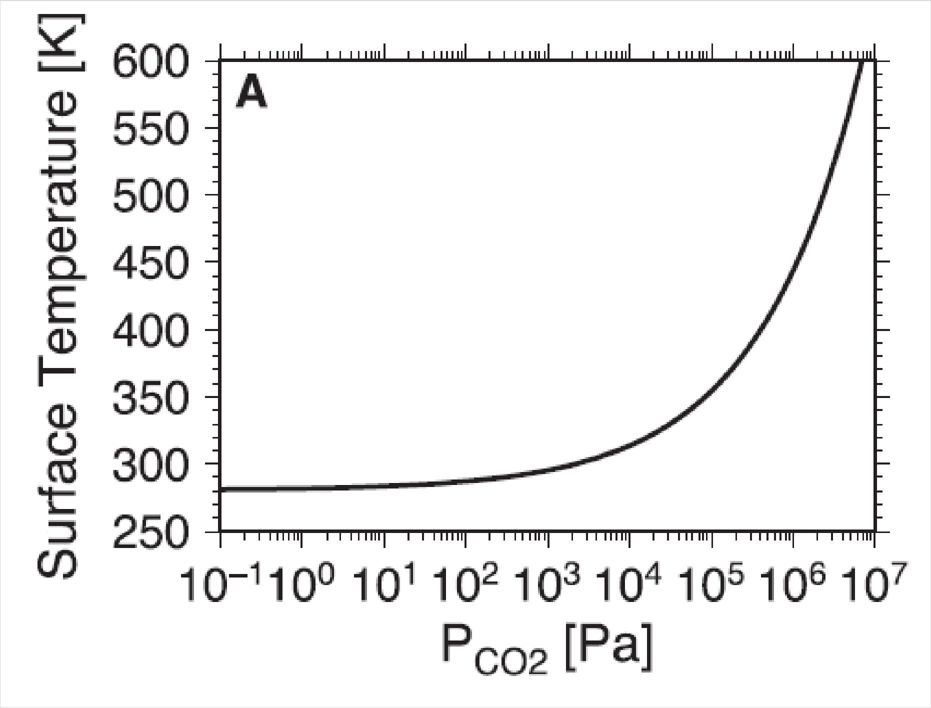
Stewart et al. (2019) AmMin

Carbon Cycle and climate



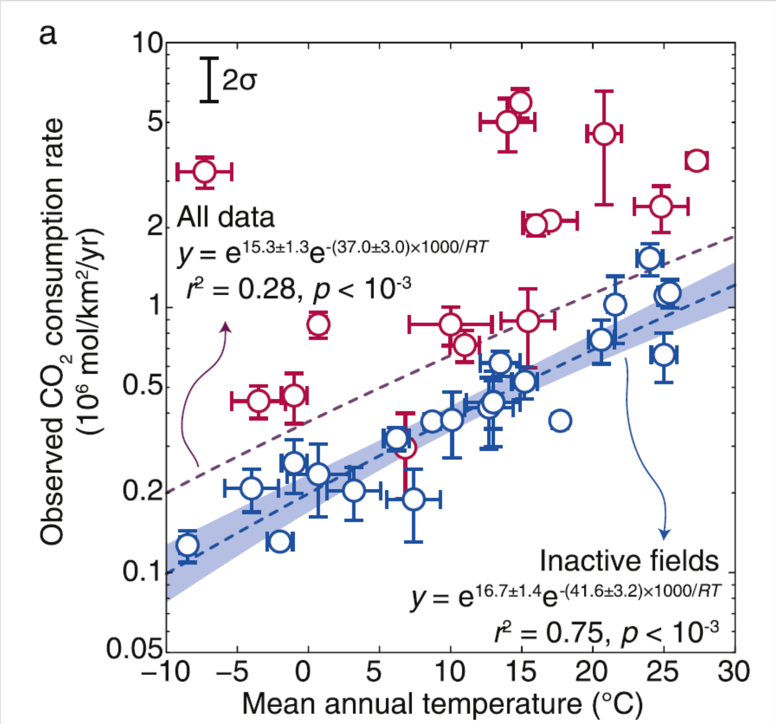
The carbon cycle creates a negative feedback cycle that can stabilize climate.

Foley (2015)



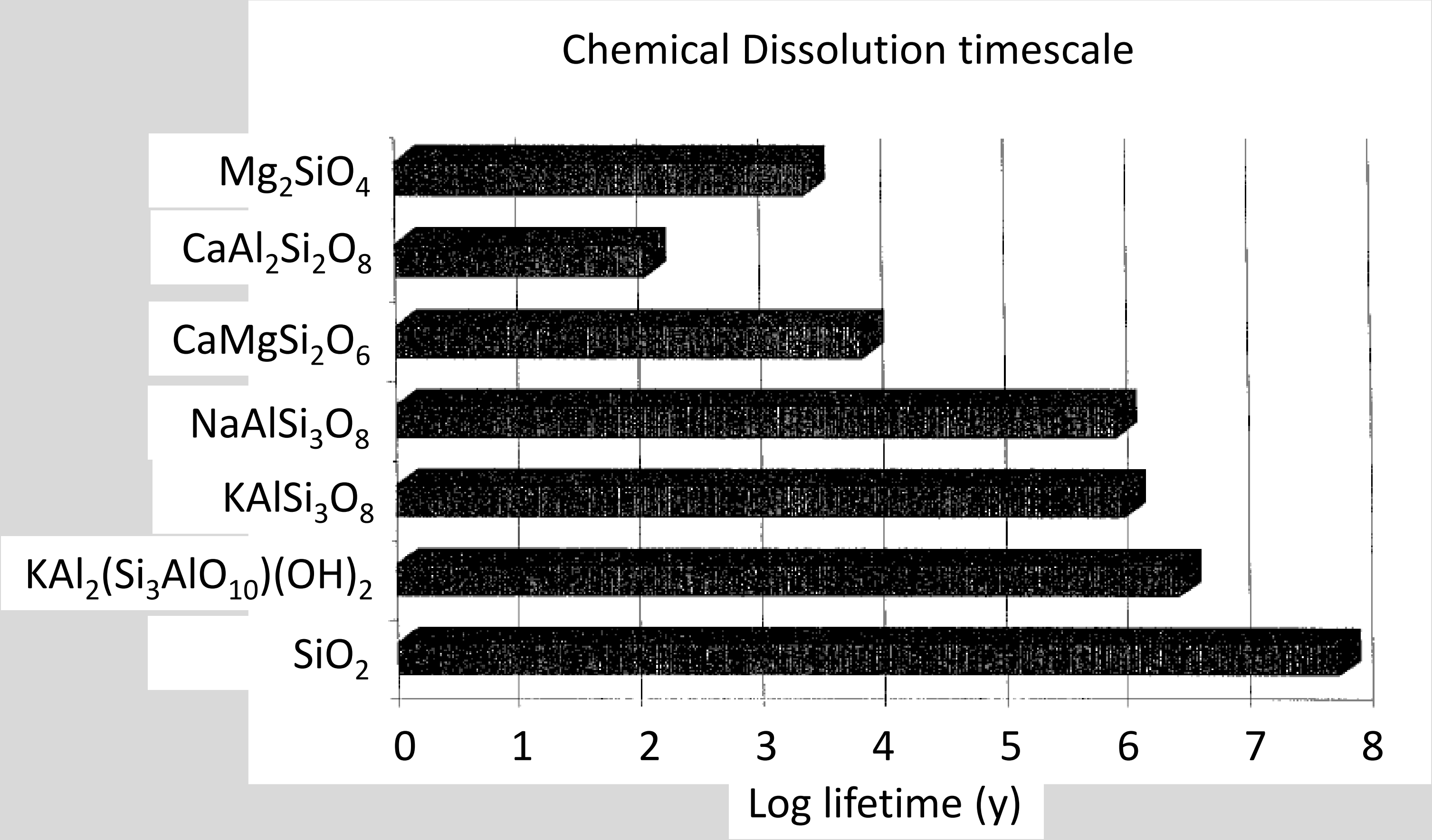
Chemical weathering rates

T-dependence of basalt weathering

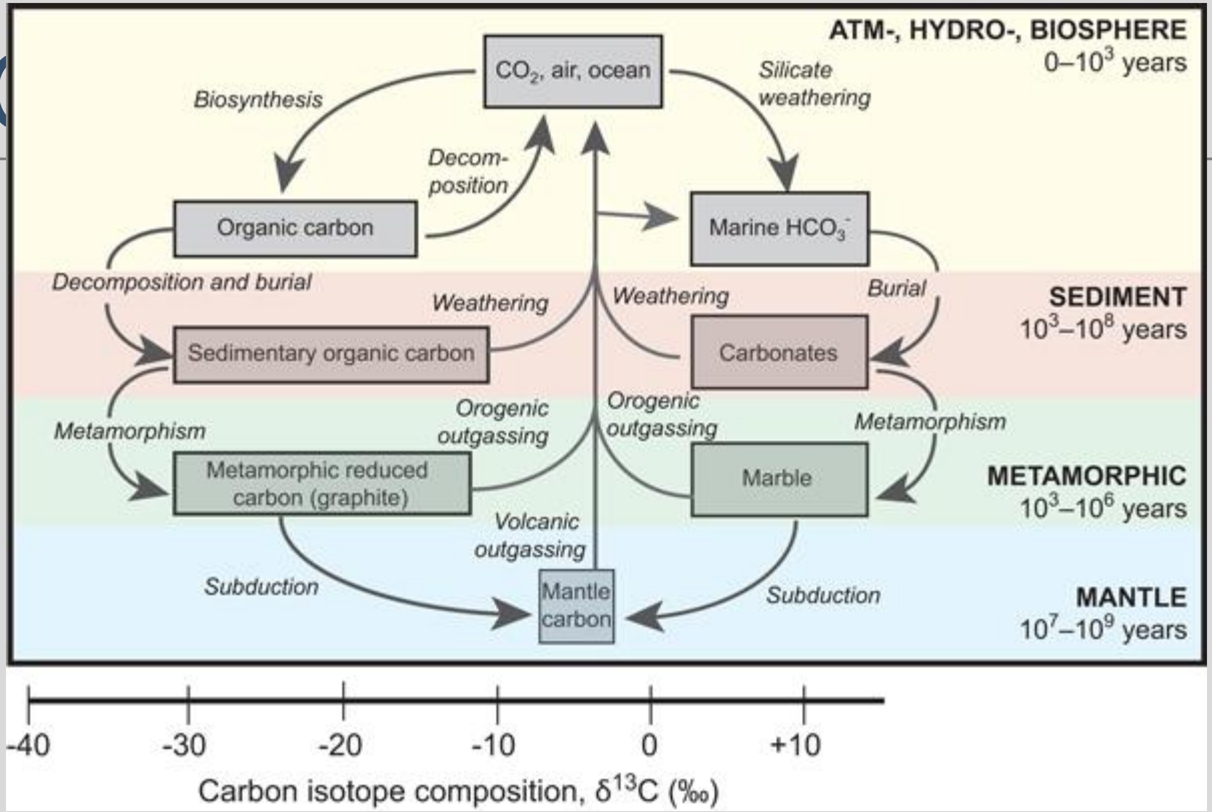


Li et al. (2016)

Basalts cover ~3-5% of continents, but consume more than 30% of CO_2 in global silicate weathering cycle



Kump et al. (2000)



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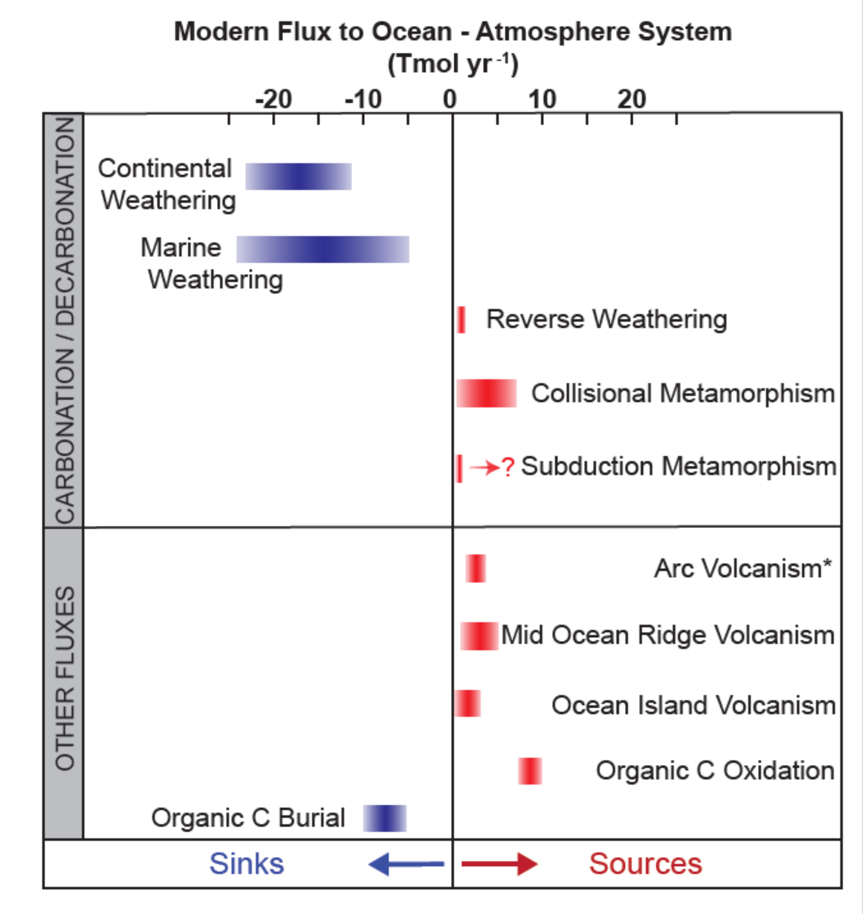


Stewart et al. (2019) AmMin

Carbon Cycle

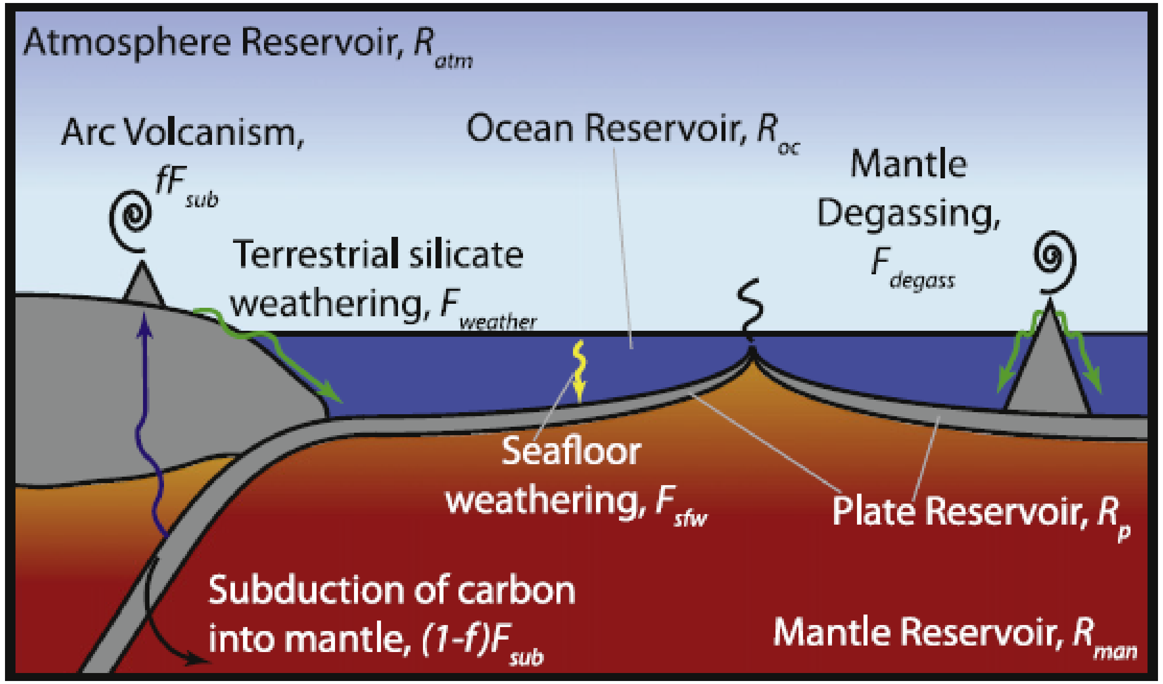


Figure 1. Schematic diagram of the global carbon cycle model used in this study.

Foley (2015)

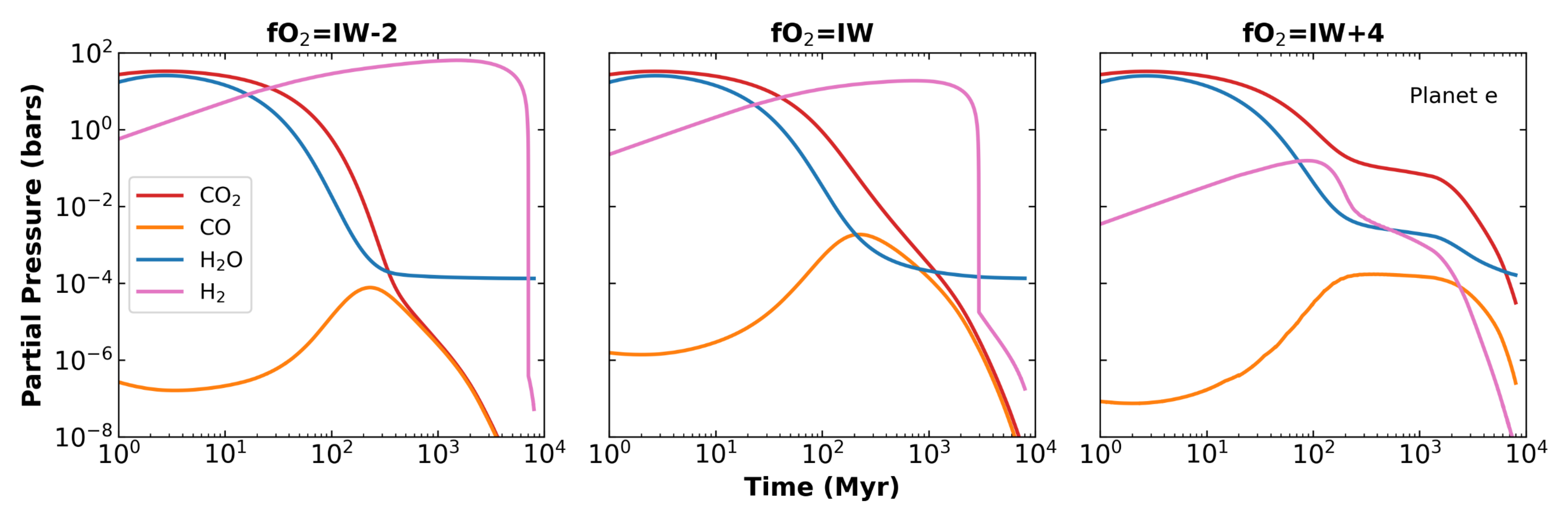
$$CaSiO_{3\,(wollastonite)} + CO_{2\,(gas)} \leftrightarrow CaCO_{3\,(calcite)} + SiO_{2\,(quartz)}$$

We incorporate the model of Foley (2015) for the deep carbon cycle into the deep water cycle model of Schaefer & Sasselov (2015).

The model includes sources from outgassing and arc volcanism. Sinks include continental and seafloor weathering, and dissolution in ocean.

Junellie Perez (JHU)

Trappist- 1e outgassing

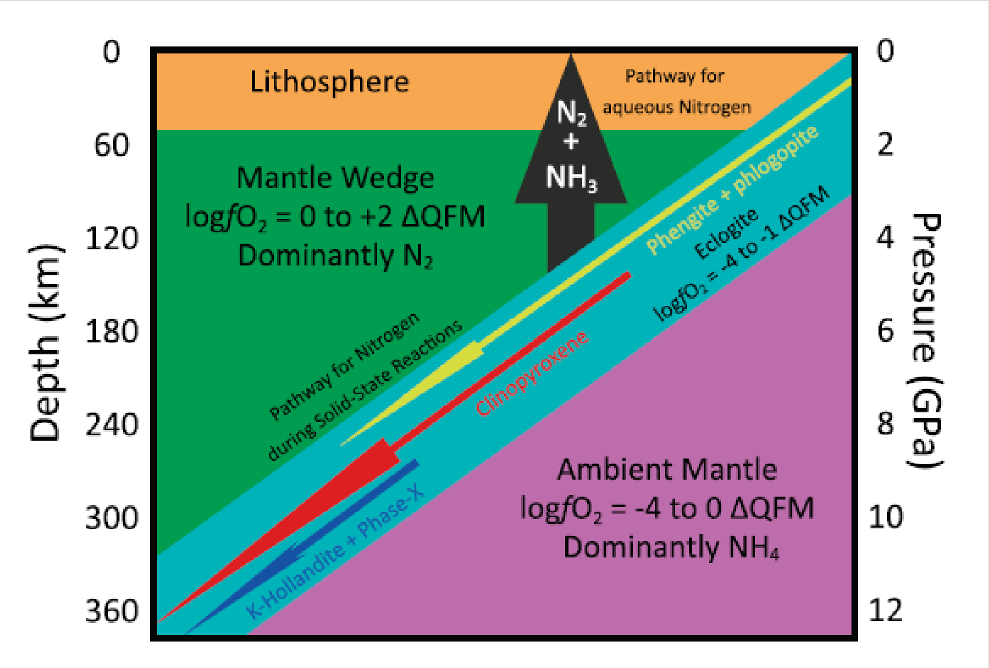


Perez et al. (2026) *JGR:Planets, in review*

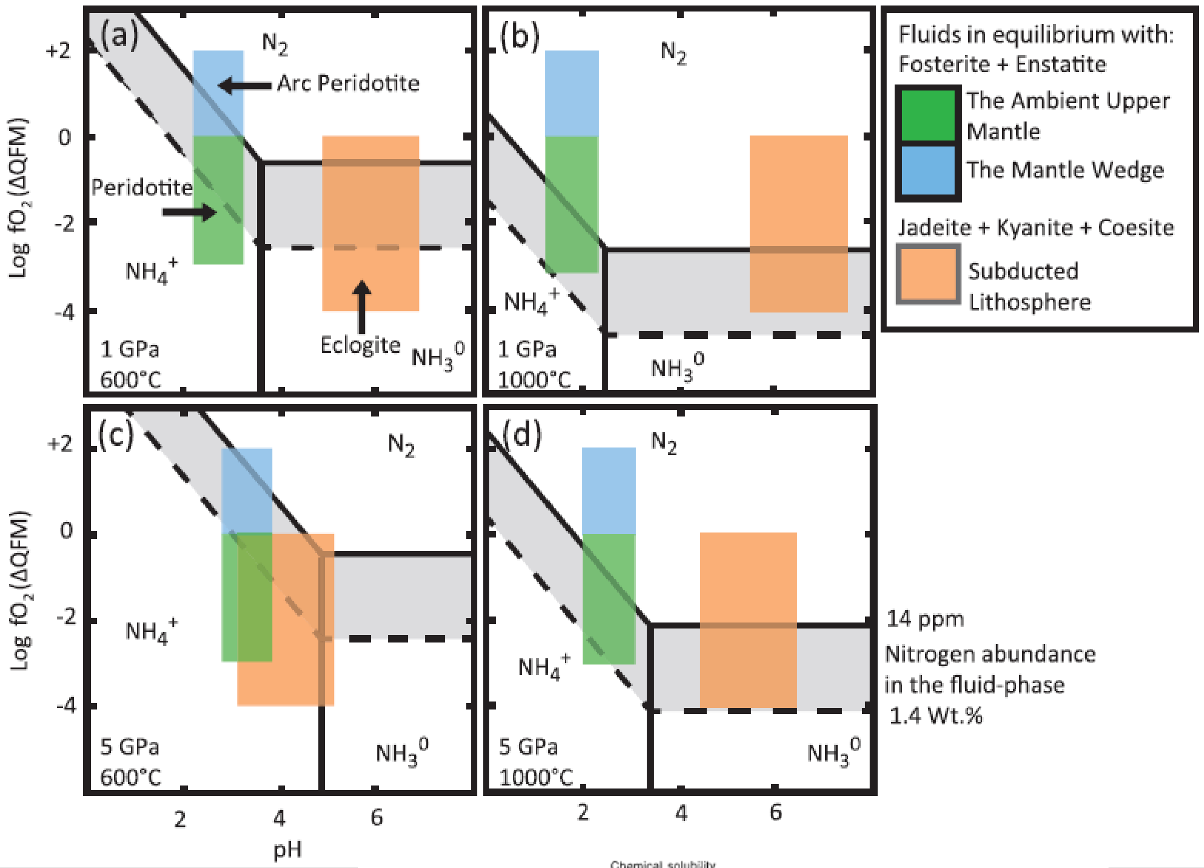
Less carbon outgassing, more reduced gases (H_2 and CO), but CO -> CO_2 through photochemistry and H_2 escapes

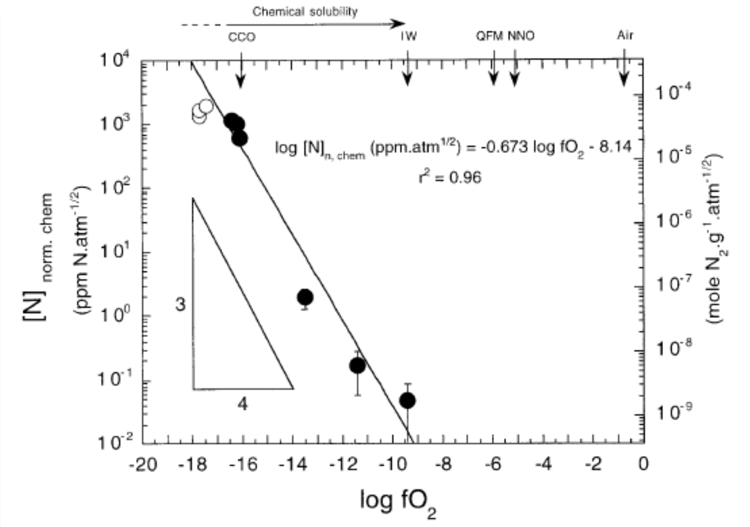
More carbon outgassing, more oxidized gases (H_2O and CO_2)

Nitrogen



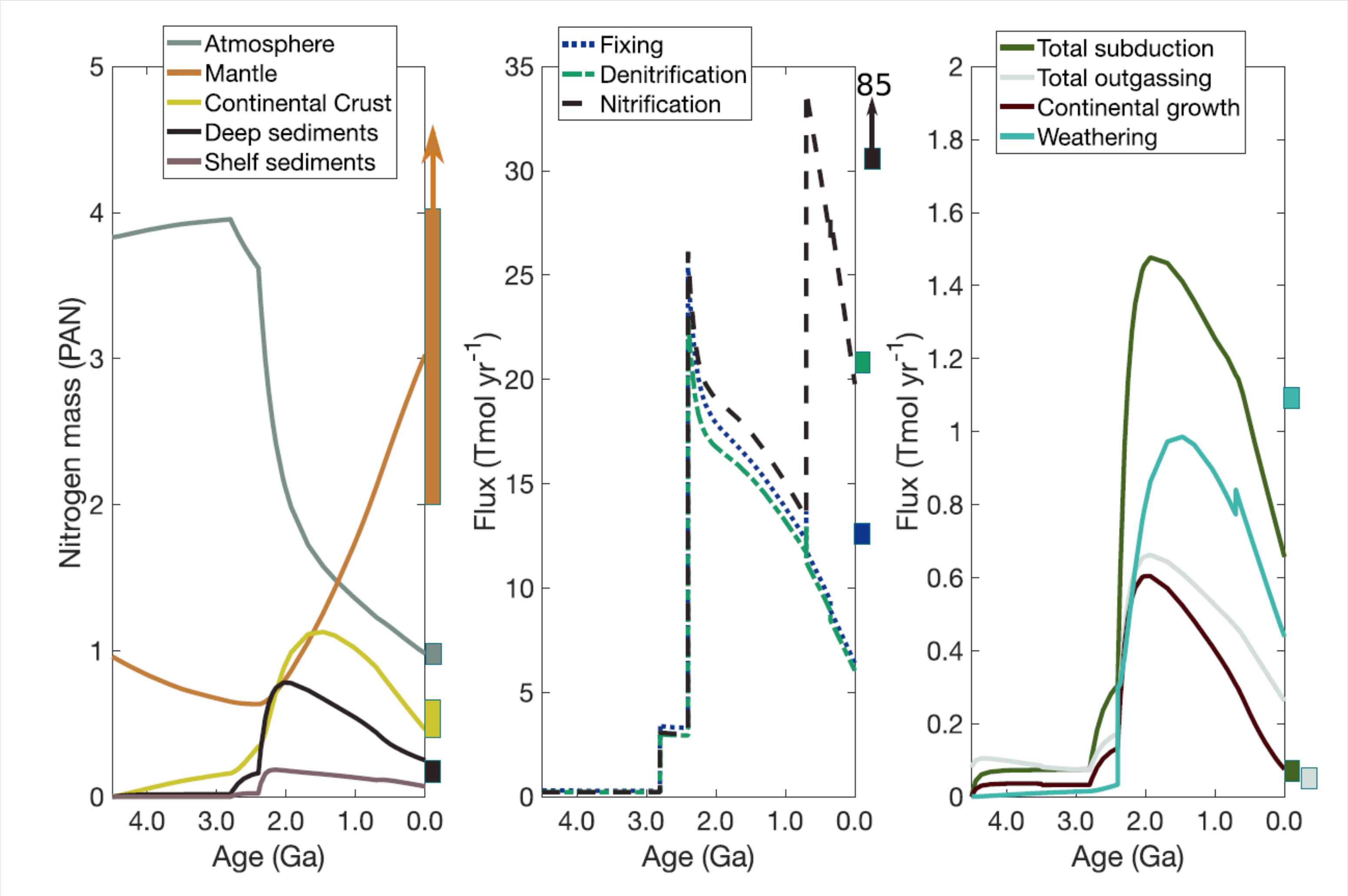
Mikhail et al. (2017)





Libourel et al. (2003)

Nitrogen cycling

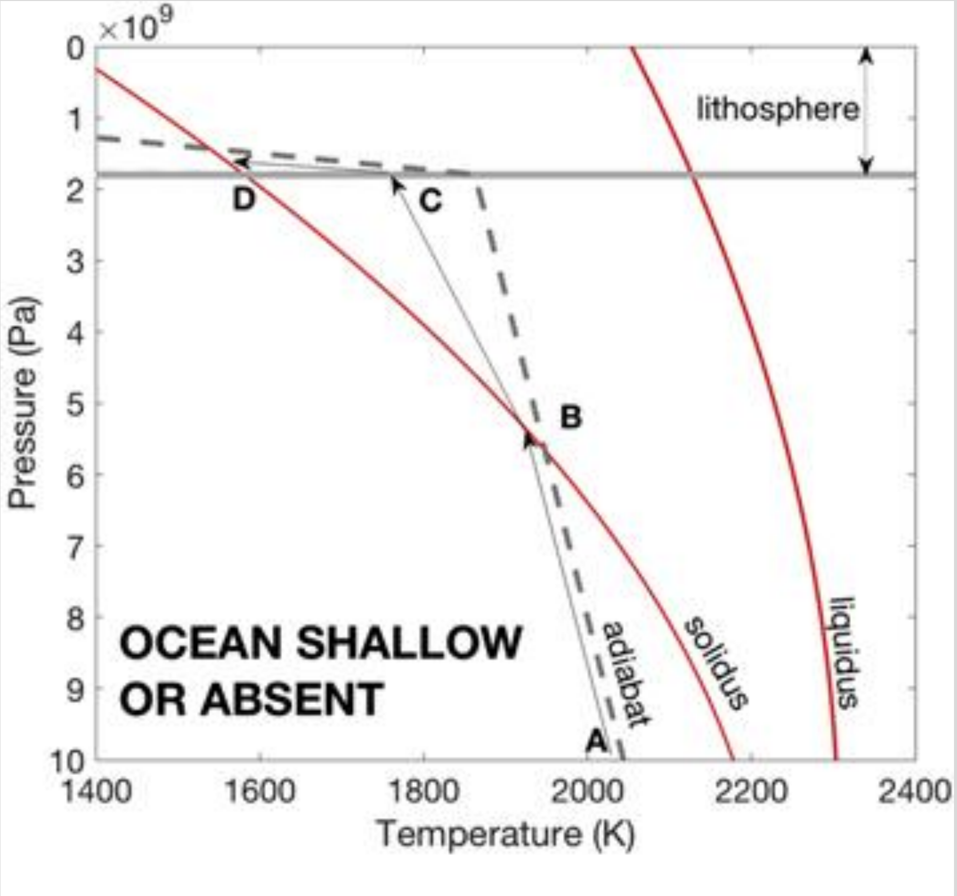


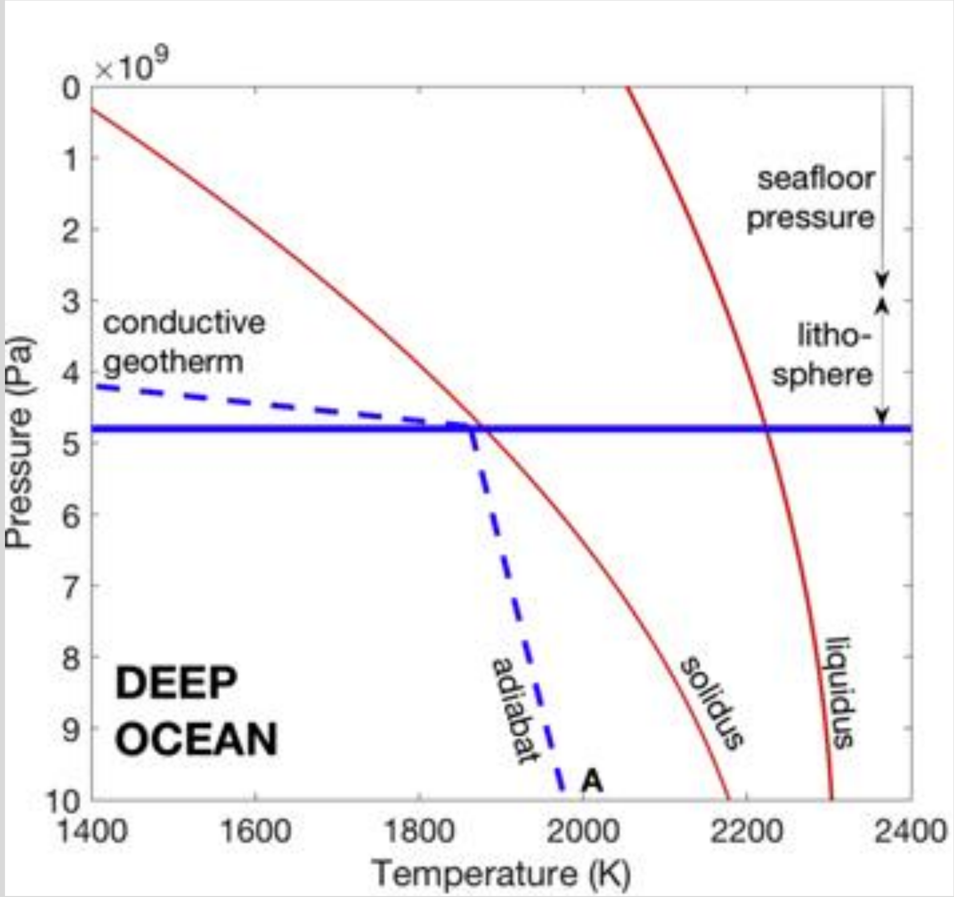
Nitrogen cycle models that try to match present-day Earth *must* include biological processes.

Nitrogen-fixation by bacteria play a strong role in present-day nitrogen cycles on the Earth.

Johnson et al. (2018)

Pressure inhibits melting (& outgassing)

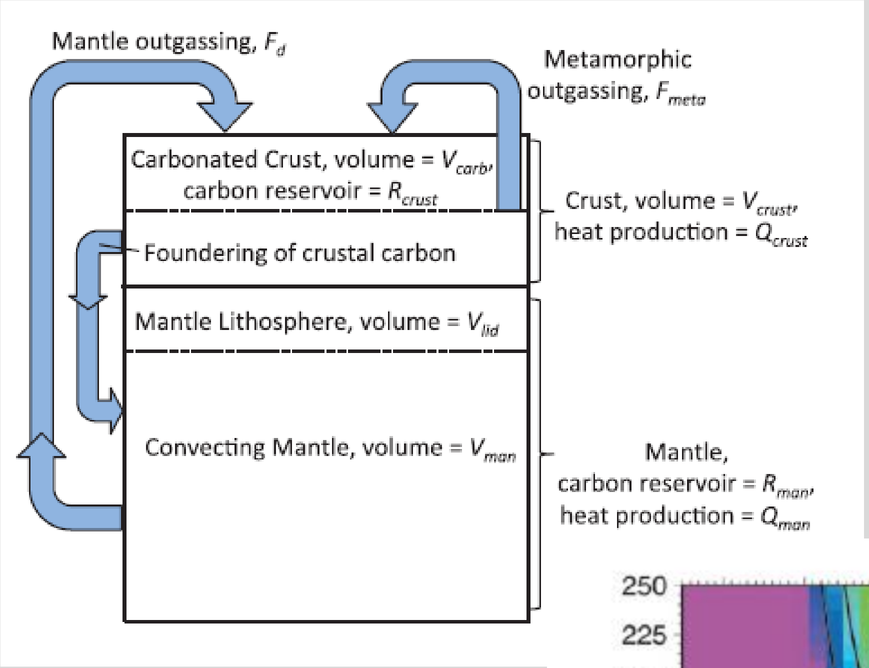




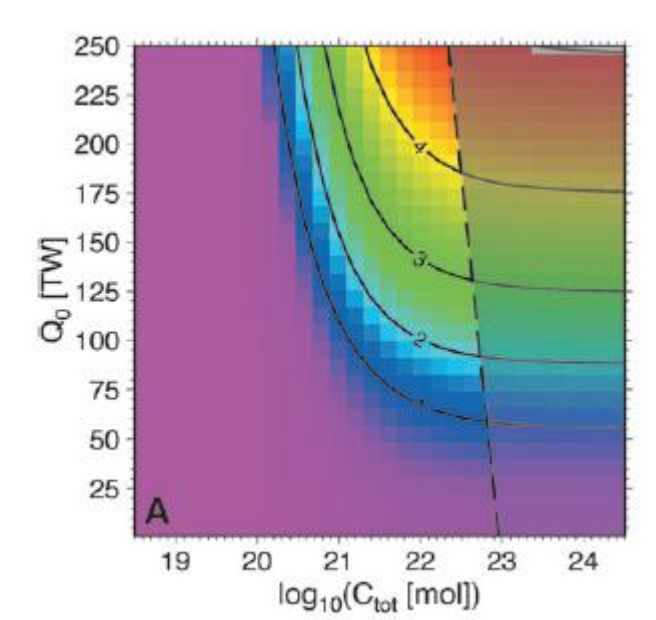
Kite & Ford (2018)

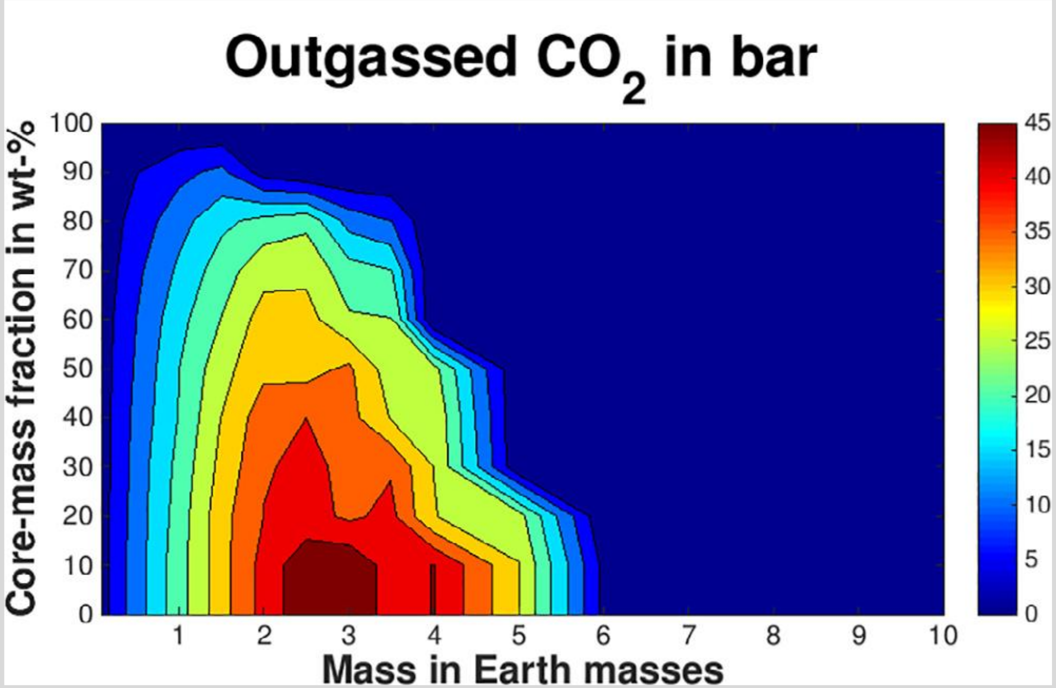
Plate tectonics vs. Stagnant lid

Noack et al. (2017)



Foley & Smye (2018)





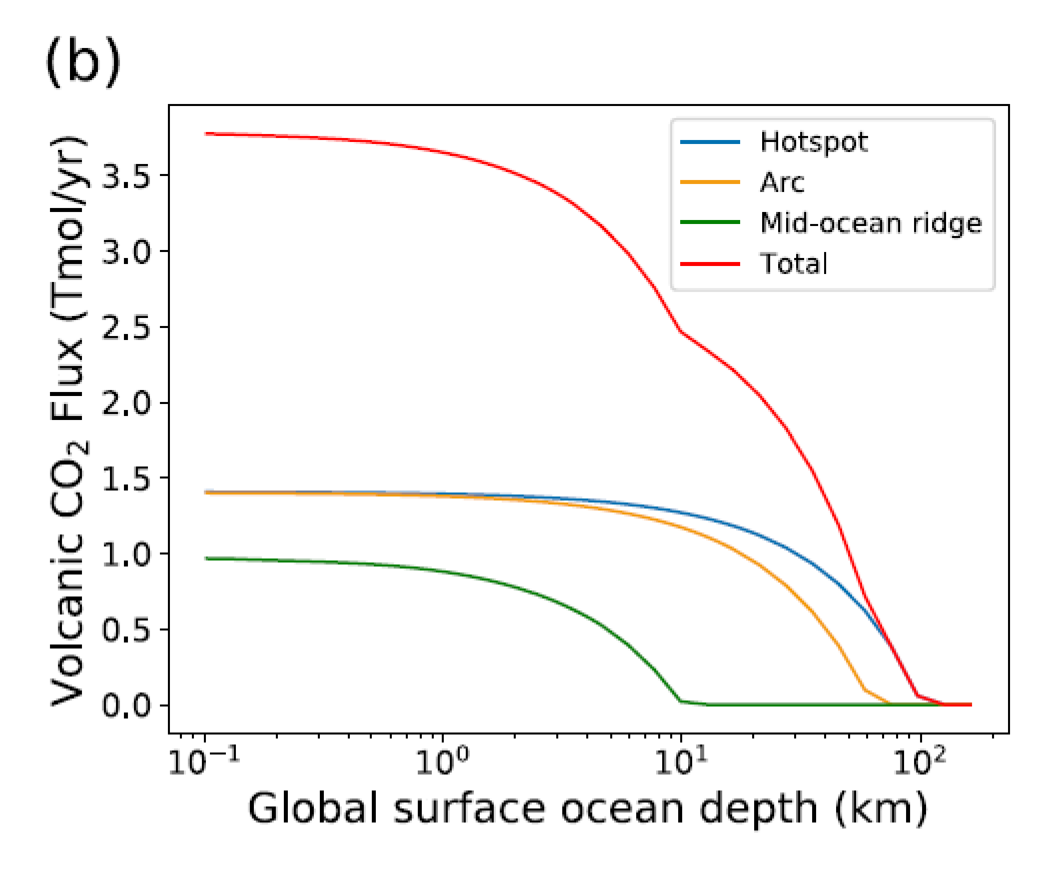
Time at which outgassing falls below present-day Earth.

Purple = no outgassing. Likely Snowball Earth.

Melting (and therefore outgassing) is suppressed by higher pressures at the base of the lid.

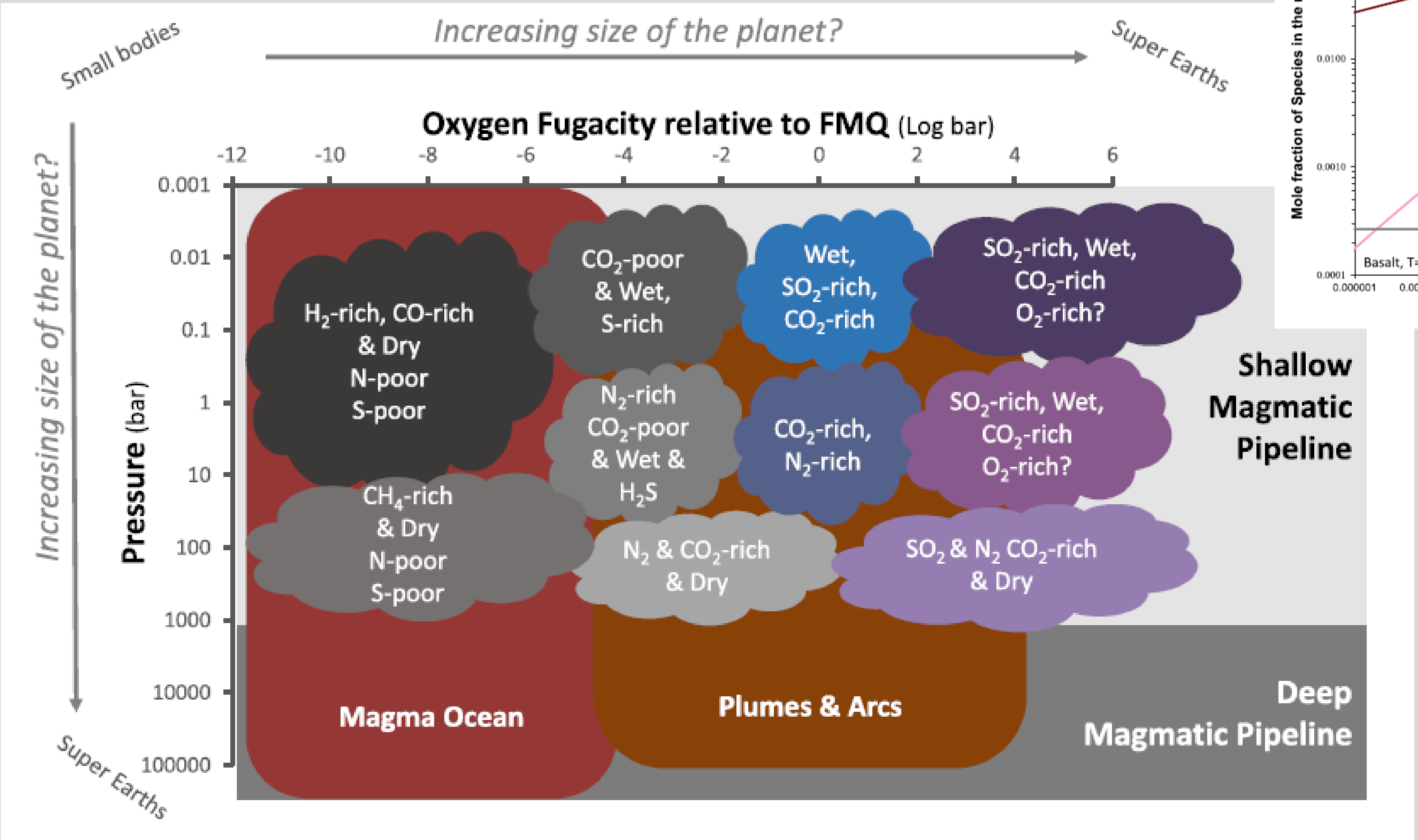
Waterworlds

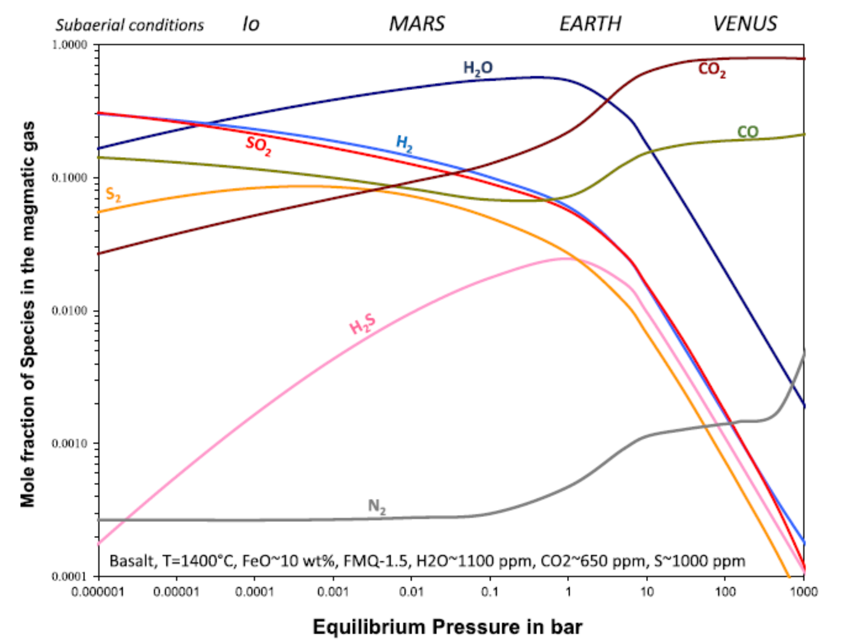
Like stagnant lid planets, the excess overburden pressure on melting centers of water worlds is likely to inhibit melt outgassing.



Krissansen-Totton et al. 2021

Pressure & Outgassing





Pressure-dependence of outgassing also affects gas speciation and amount of gas that can evolve.

High volcanic pressures imply limited (if any) outgassing).

Gaillard et al. (2021)

Takeaways

- Post-MO planets can adopt different tectonic styles: plate tectonics, stagnant lid, etc.
- Deep volatile cycles between mantle and surface control long-term abundances of volatiles at the surface through outgassing, burial and subduction

Questions?