Comparative planetary interiors and the effects on habitability

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in collaboration with
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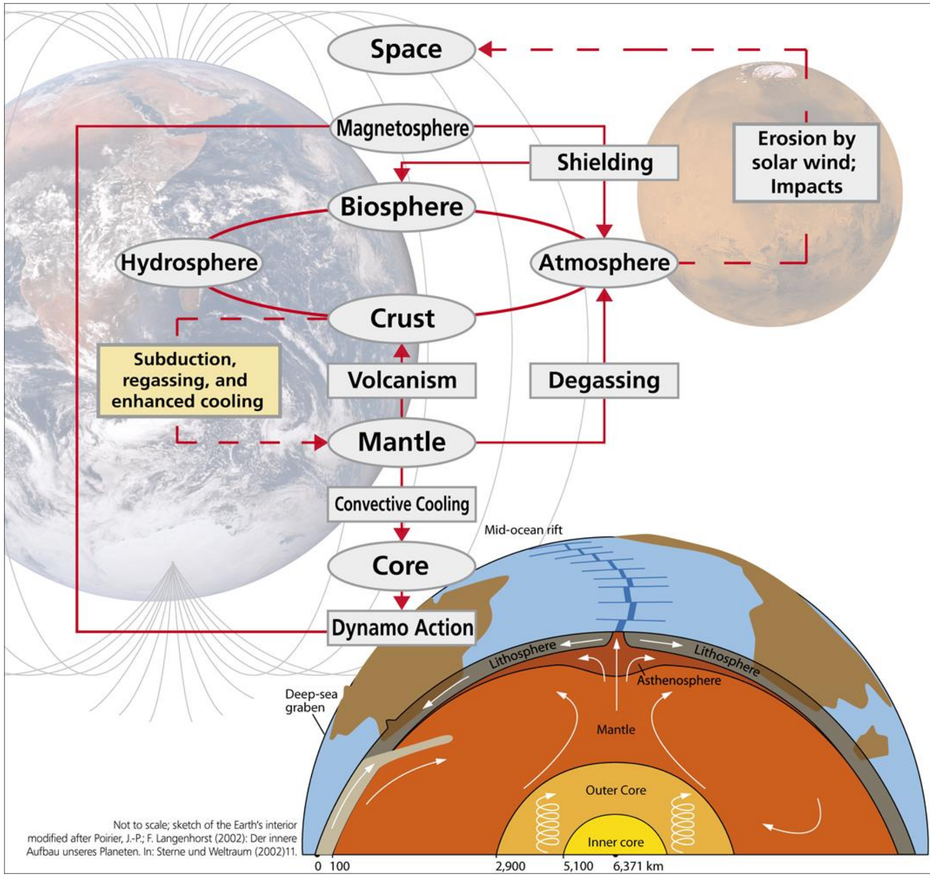
PLATO Mission Conference 2017

Outline

- How does the planetary interior infuence the habiltabilty?
  - General concept
  - Difference between plate tectonic and stagnant lid planets

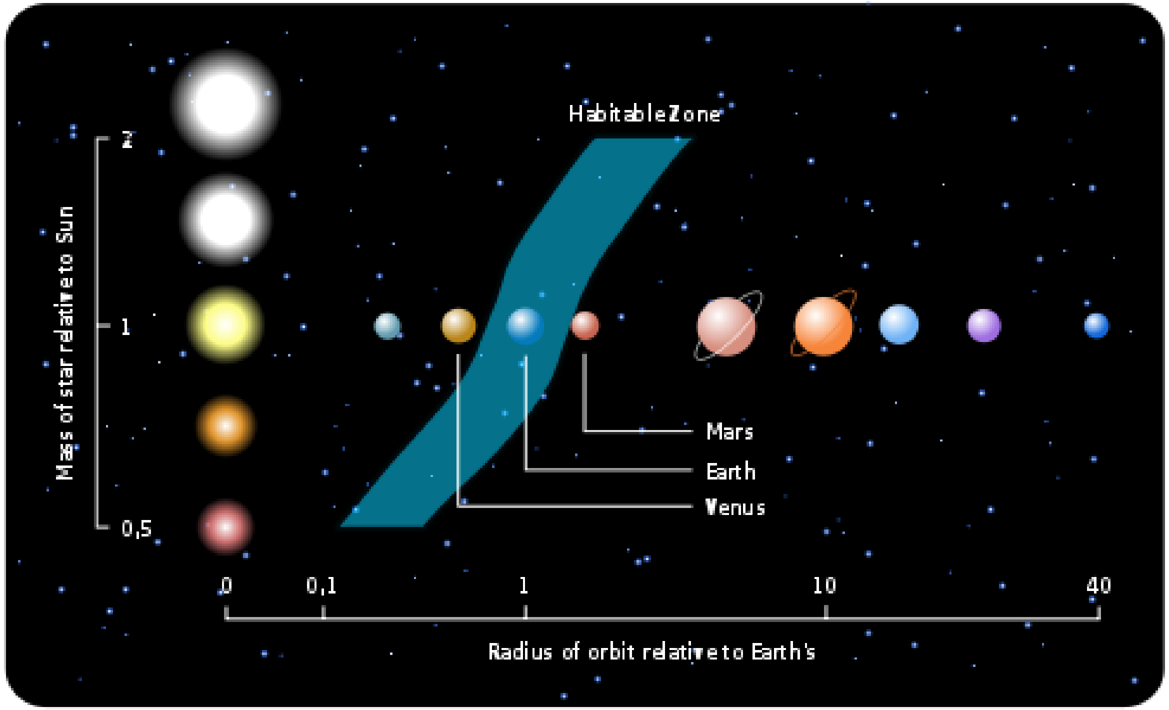
- Would an Earth-like planet be habitable without plate tectonics?
  - Coupling the interior with atmosphere models

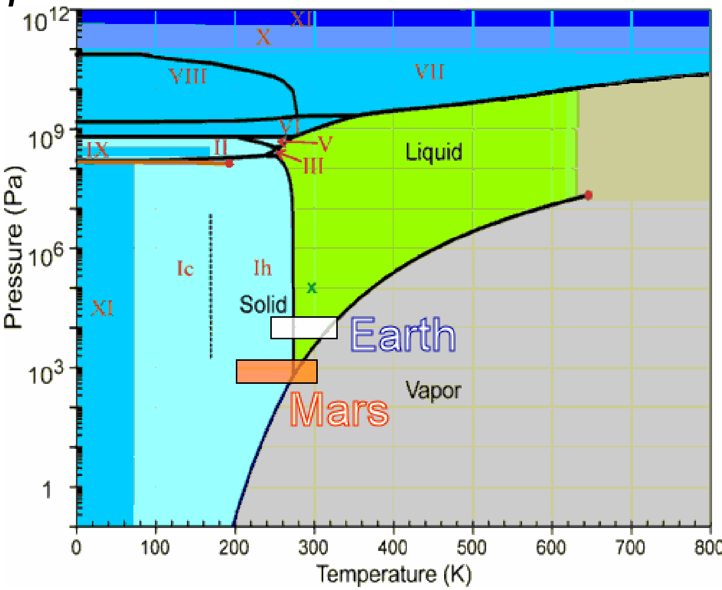


Habitability and Habitable zone

Potential of an enviroment to support life
(presence of liquid water at the surface)

- Distance to the star
- Presence and composition of atmosphere





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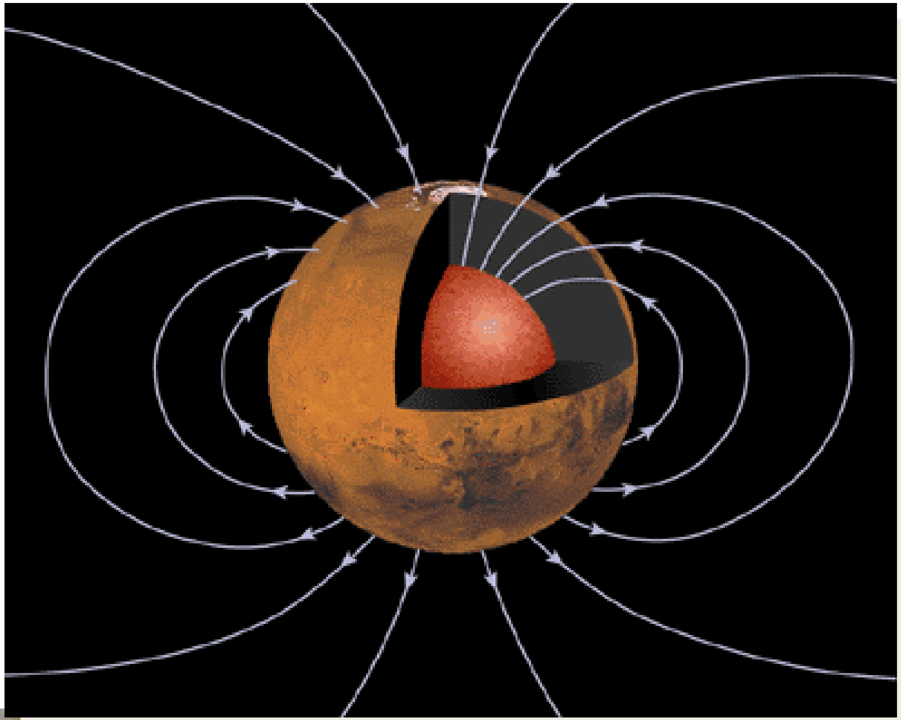
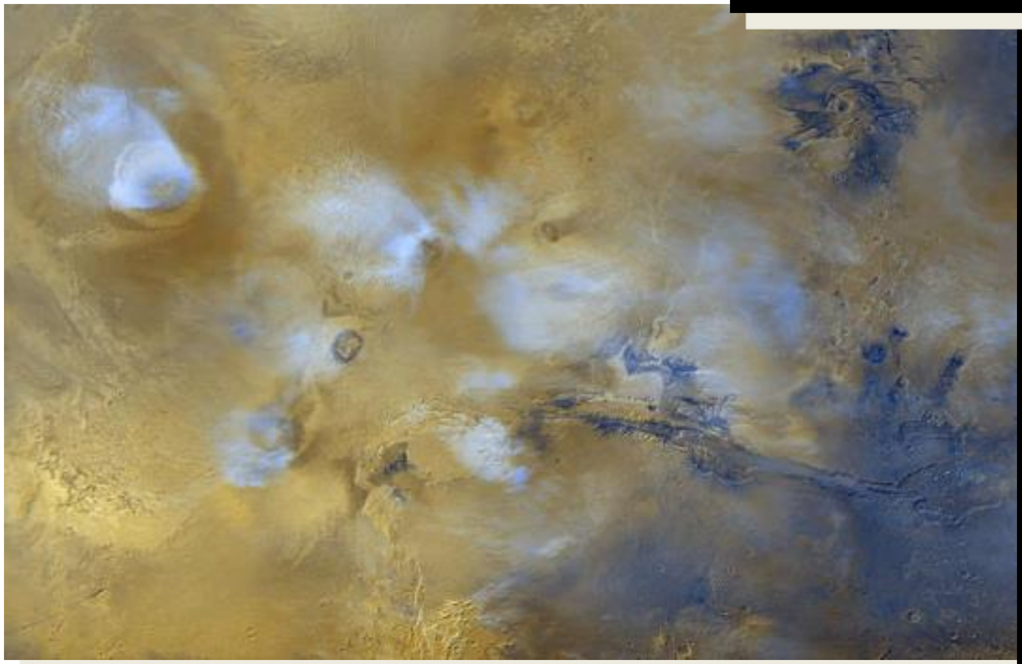
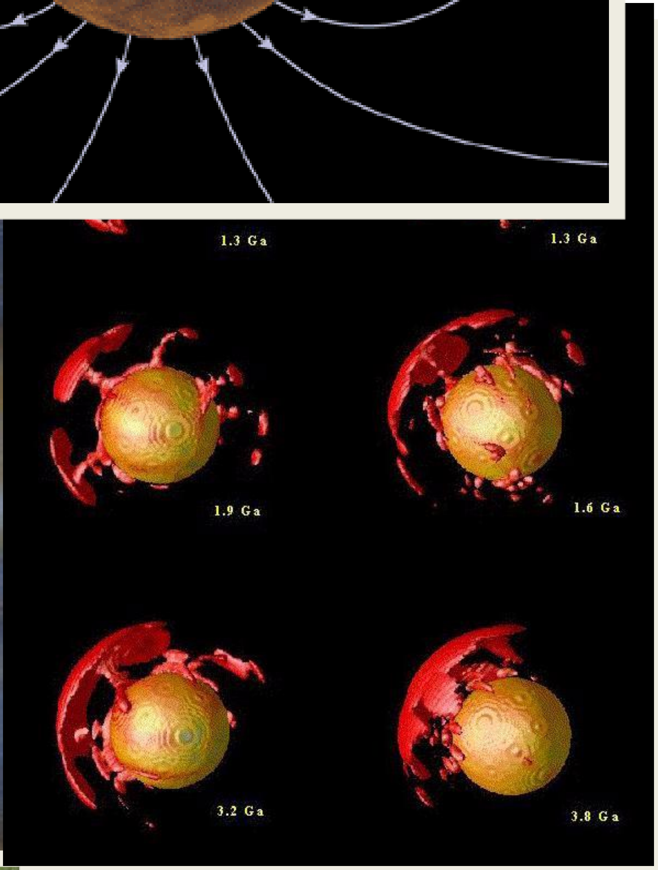
Planetary Interior Dynamics

- Volcanic and tectonic history
- Magnetic field
- Atmosphere evolution



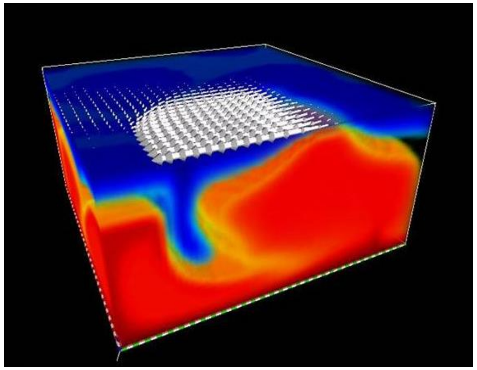


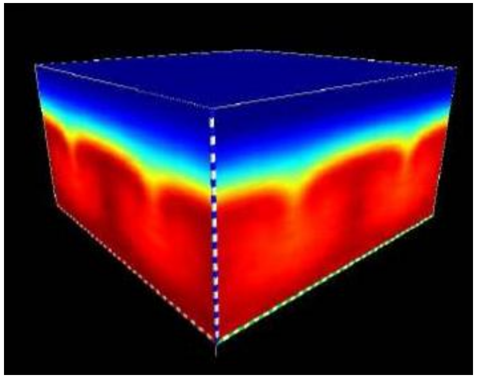


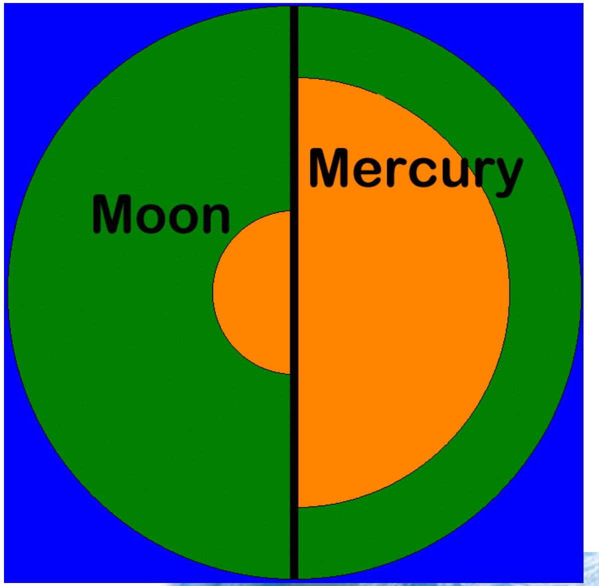
What influences the thermal, magnetic and atmosphere evolution?

- Tectonic mode
  (plate tectonics – stagnant lid convection)

- Mass, Size, Interior structure and composition







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One-Plate-Planet

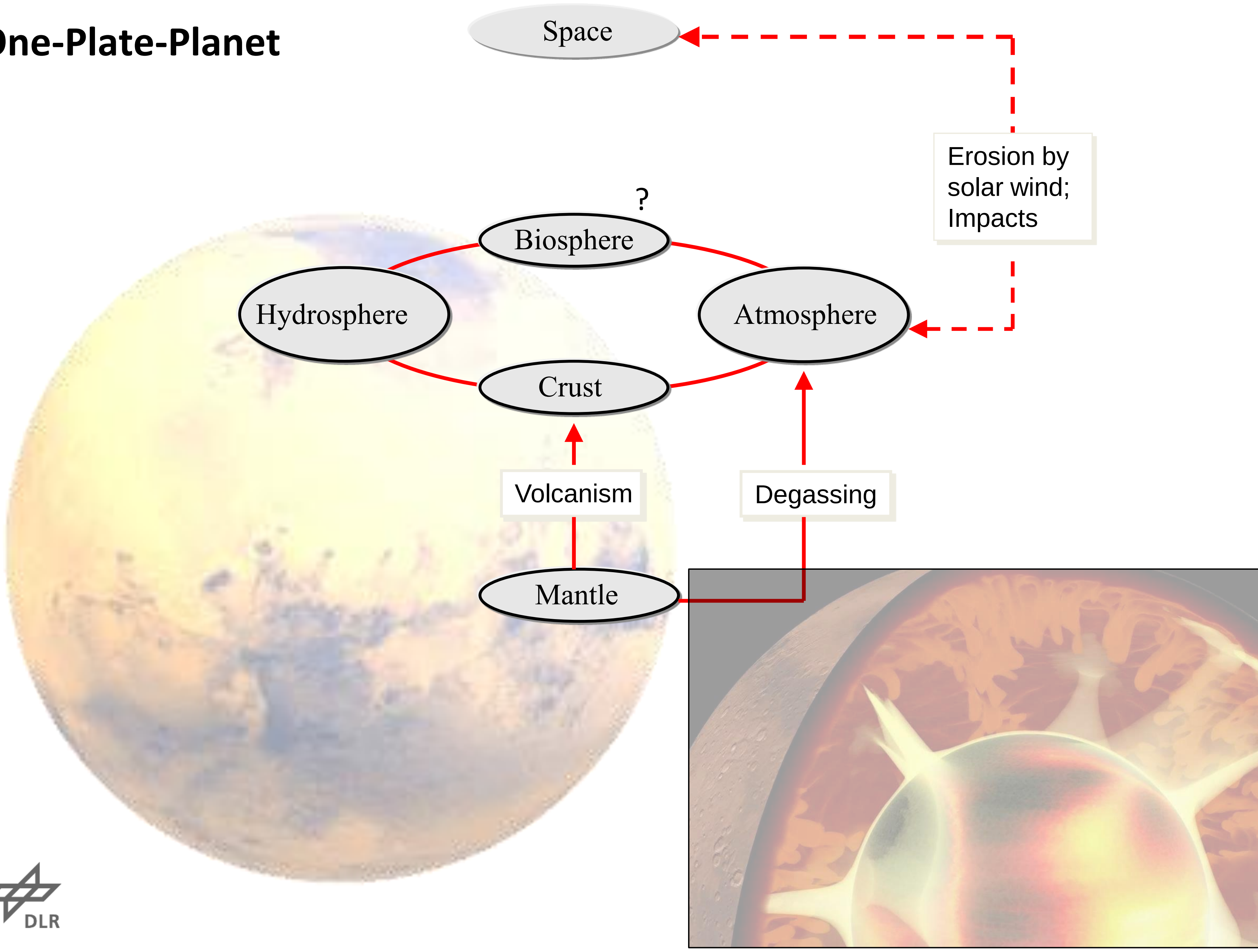
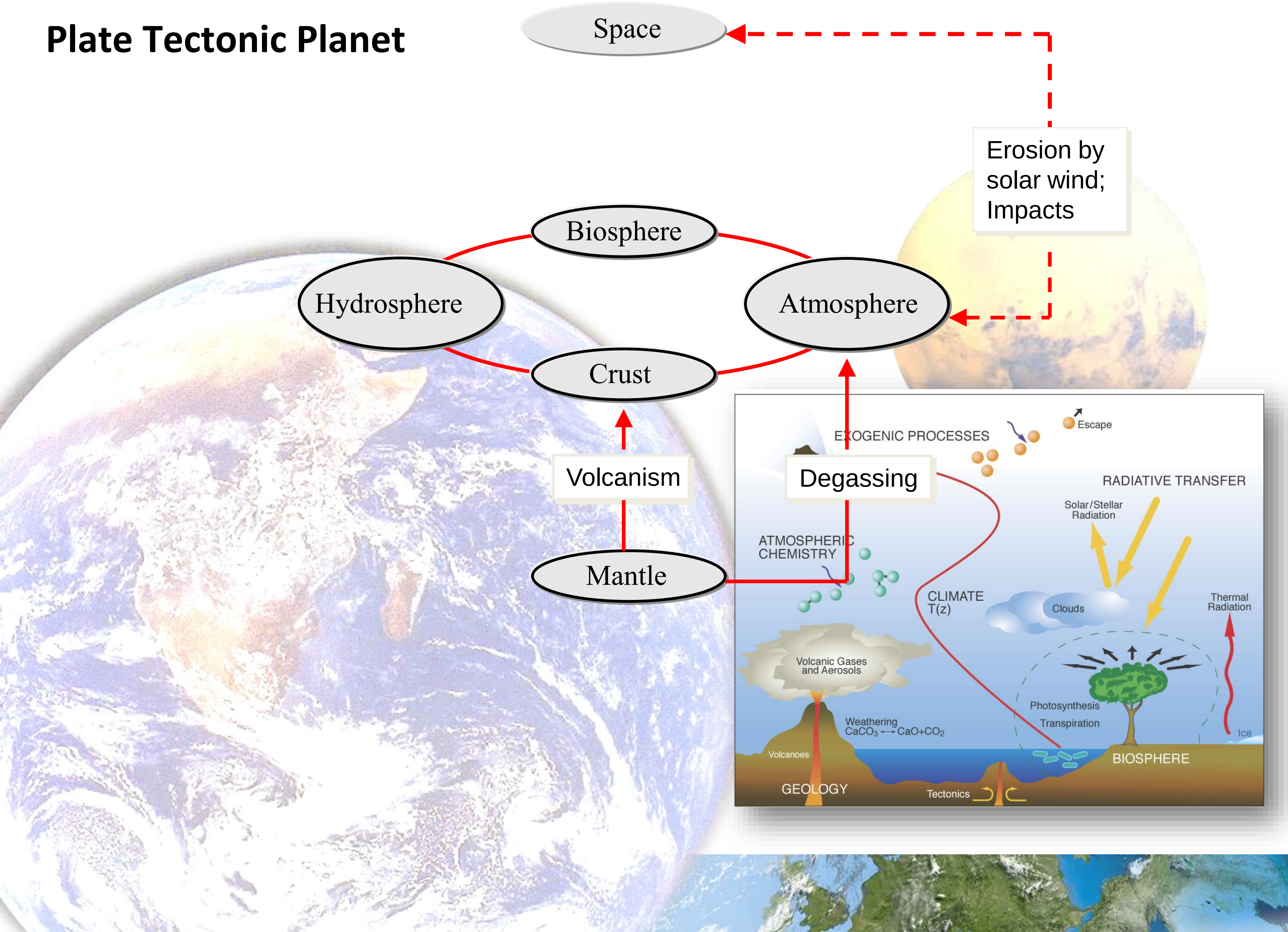


Plate Tectonic Planet



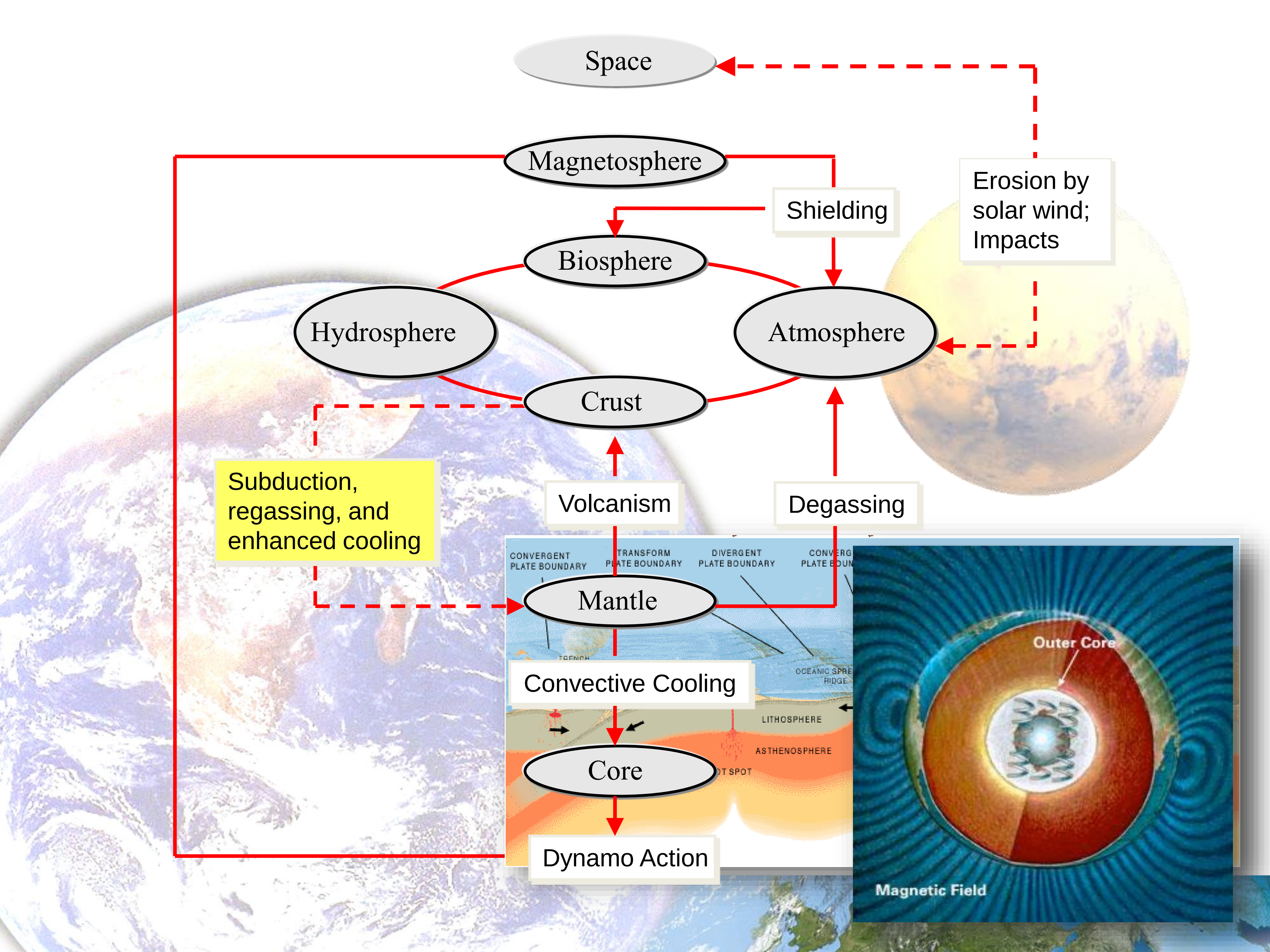

Space
Magnetosphere
Shielding
Erosion by
solar wind;
Impacts
Biosphere
Hydrosphere
Atmosphere
Crust
Subduction,
regassing, and
enhanced cooling
Volcanism
Degassing
CONVERGENT
PLATE BOUNDARY
TRANSFORM
PLATE BOUNDARY
DIVERGENT
PLATE BOUNDARY
Mantle
Convective Cooling
LITHOSPHERE
ASTHENOSPHERE
Core
Dynamo Action
Outer Core
Magnetic Field

Plate tectonics and habitability

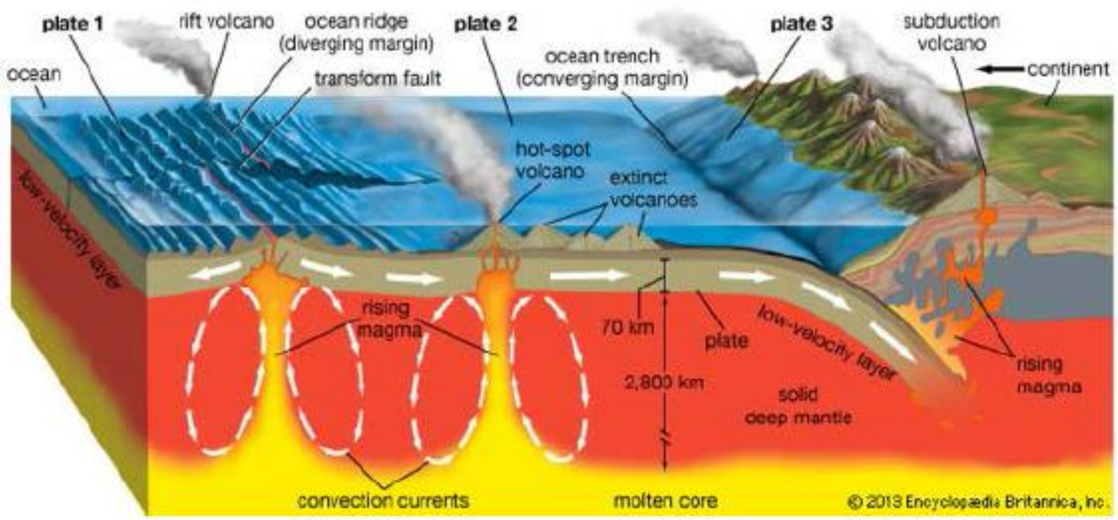
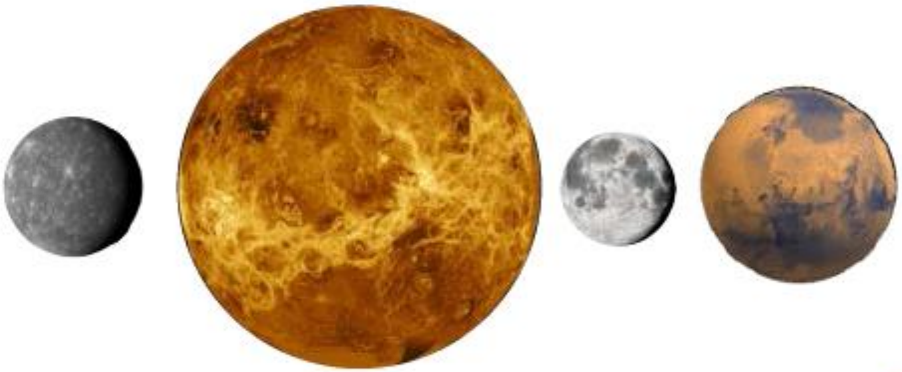


Plate tectonics recycles near-surface rocks and volatiles with the planet's interior through subduction. This helps

- to create **geologic diversity**, e.g., granitic cratons that will form continents and continental shelfs and mid oceanic ridges with their black smokers
- to replenish depleted surface rock as the base for the **nutrition chain**
- to stabilize the **atmosphere temperature** and create clement conditions through the carbonate-silicate cycle
- to cool the deep interior and to generate a **magnetic field** in the core

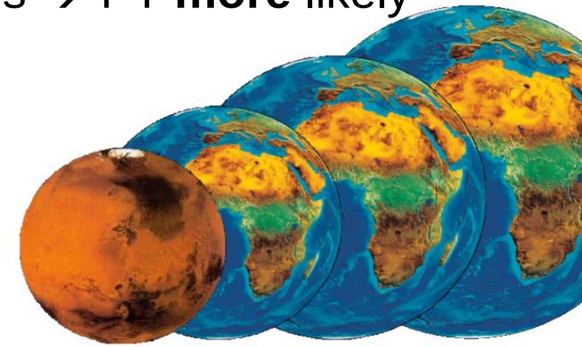
Stagnant lid vs Plate tectonics



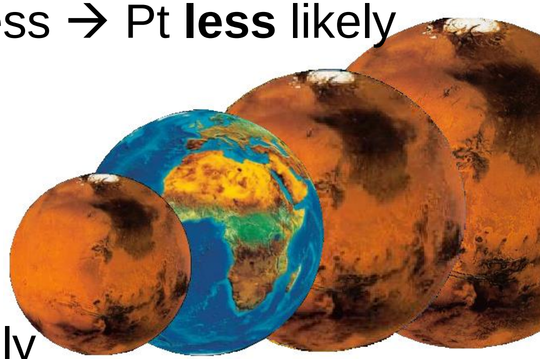
- The strong dependence of rock viscosity on temperature naturally leads to the formation of a stagnant lid
- The ultimate reasons why plate tectonics occurs only on Earth are unknown, let alone on extrasolar bodies, whether of larger or similar size

The big debate: Plate tectonics on exoplatents

- Increase in mass results in stronger lithospheric stresses → PT **more** likely
  - Valencia et al. (2007)
  - Valencia and O‘Connell (2009)
  - Van Heck and Tackley (2011)
  - Foley et al (2012)



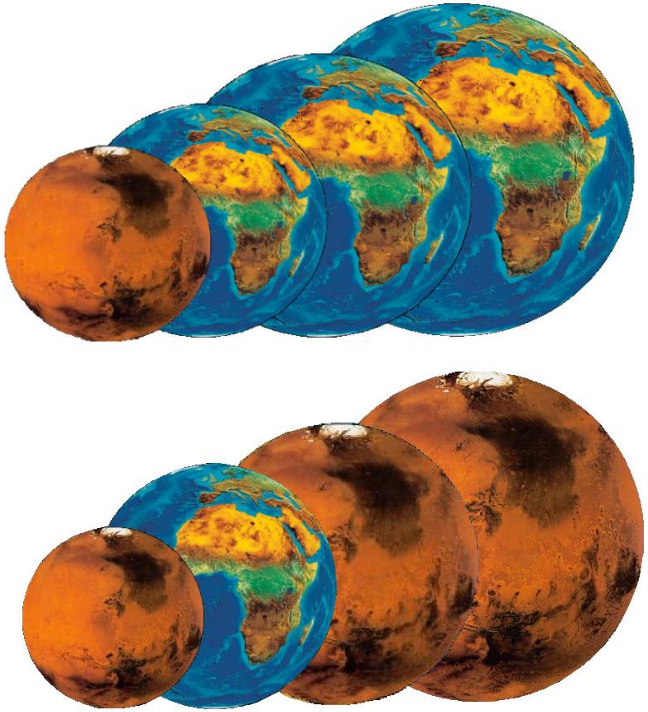
- Increase in mass results in stronger increase of yield stress → Pt **less** likely
  - O‘Neill and Lenardic (2007)
  - O‘Neill et al. (2007)
  - Stein et al. (2004)



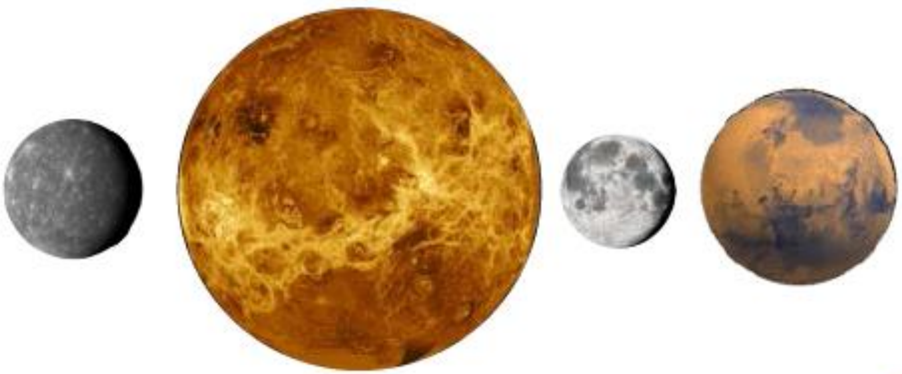
- Increase in internal heating rate → Pt **equally or less** likely
  - Van Heck and Tackley (2011)
  - Stein et al. (2013)
  - Foley et al (2012)
  - Stamenkovic and Breuer (2014)

The big debate: Plate tectonics on exoplatents

- History dependent (e.g. initial conditions)
  - Lenardic and Crowley (2012)
  - Weller and Lenardic (2012)
  - Noack and Breuer (2013)
  - Stamenkovic et al. (2014)
  - Weller et al. (2015)
  - Wong and Solomatov (2016)
  - O'Neill et al. (2016)

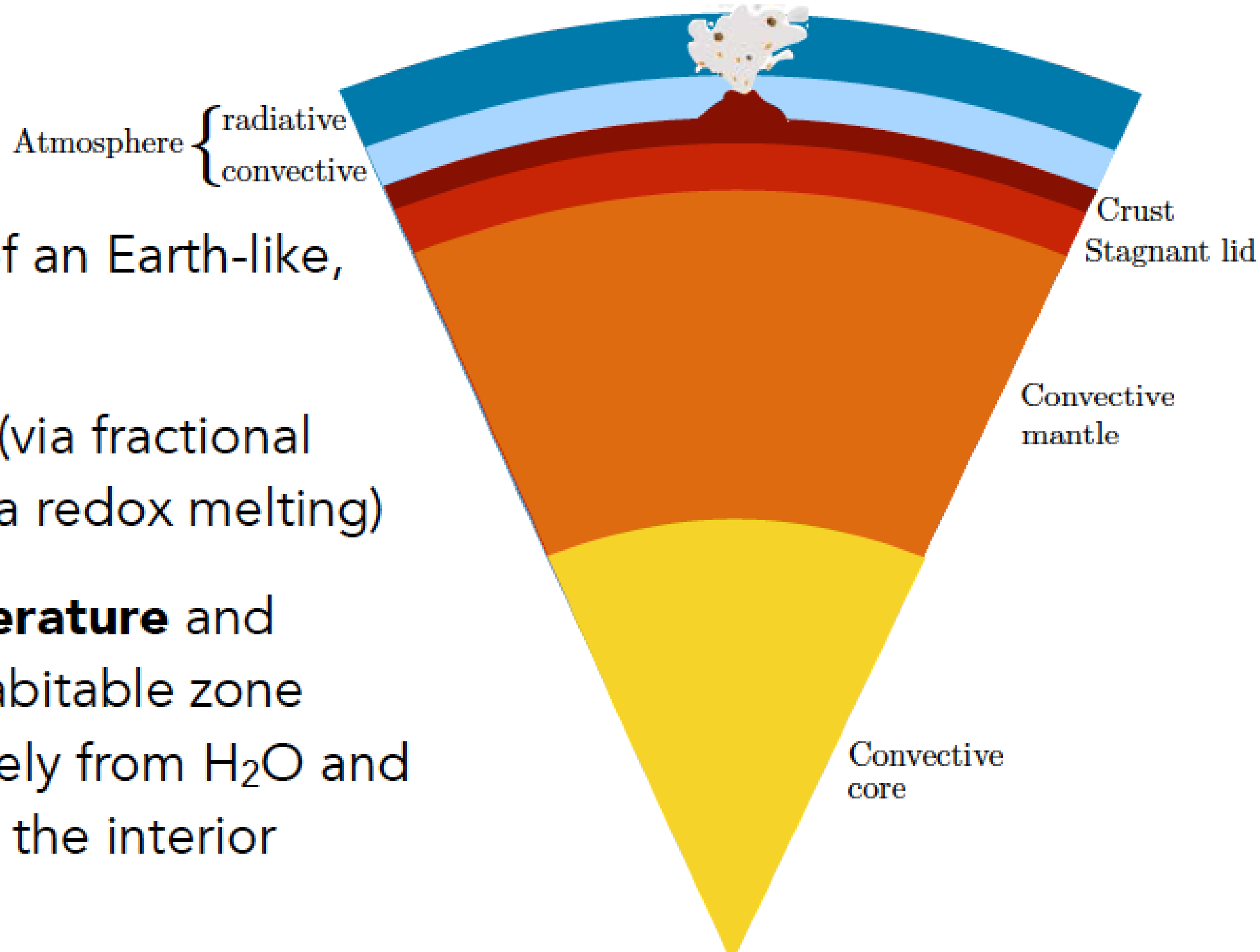


Stagnant lid vs Plate tectonics



- The strong dependence of rock viscosity on temperature naturally leads to the formation of a stagnant lid
- The ultimate reasons why plate tectonics occurs only on Earth are unknown, let alone on extrasolar bodies, whether of larger or similar size
- Would an Earth-like planet without plate tectonics be habitable, i.e. have liquid water at the surface?

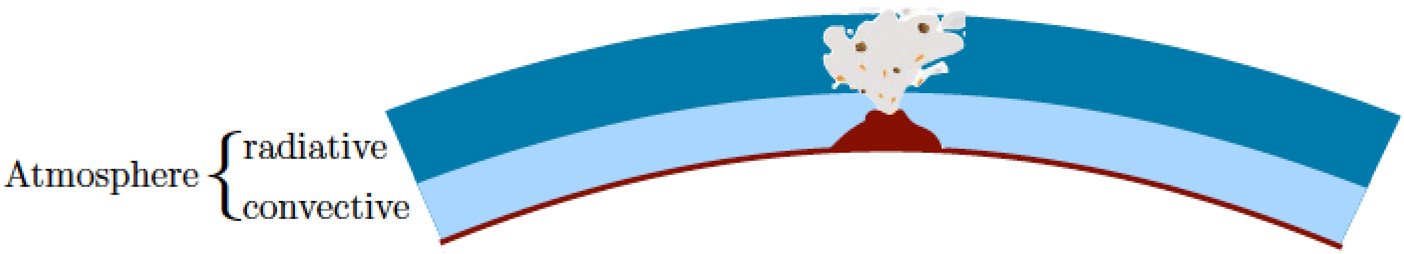
Interior + atmosphere modelling



- **Interior evolution** of an Earth-like, stagnant lid planet
- **Outgassing** of H_2O (via fractional melting) and CO_2 (via redox melting)
- **Atmospheric temperature** and boundaries of the habitable zone determined exclusively from H_2O and CO_2 outgassed from the interior

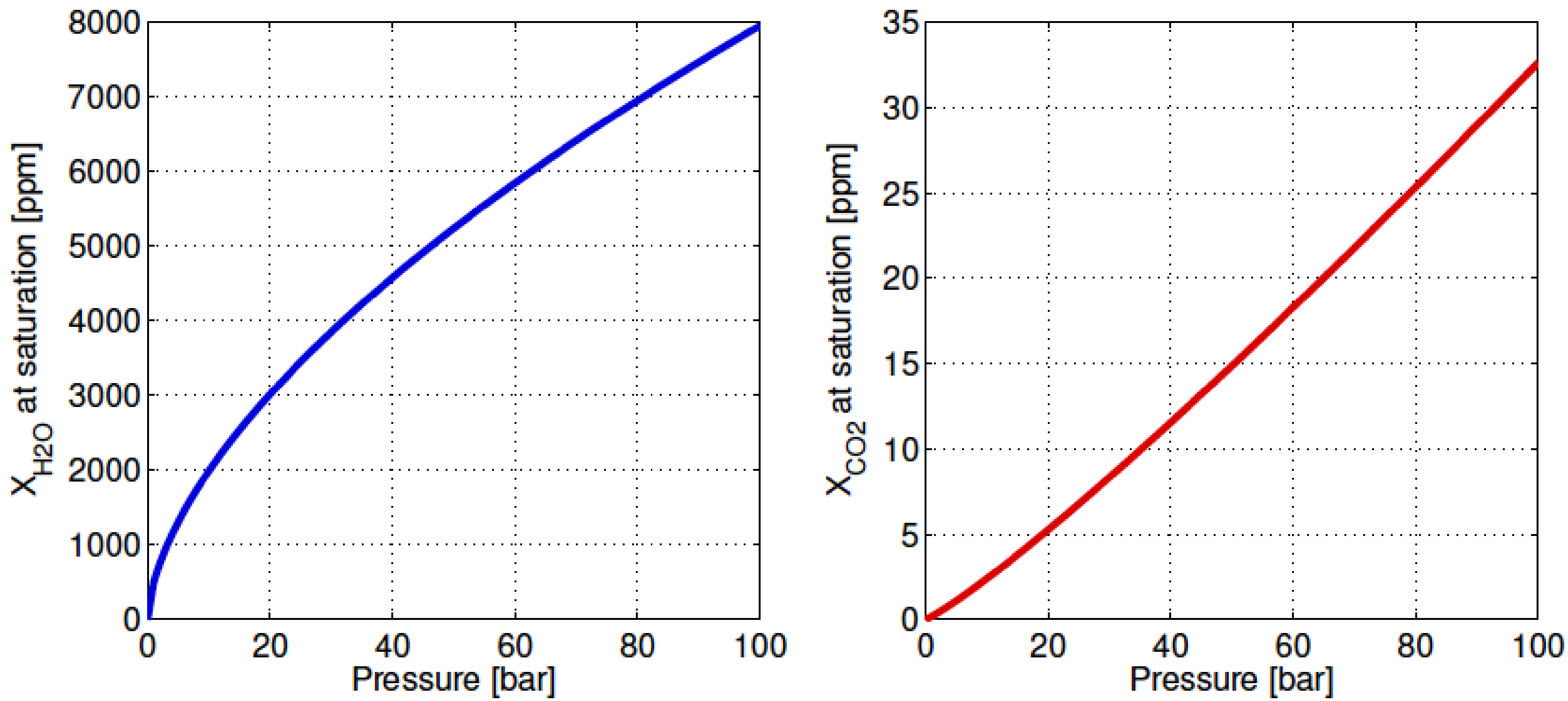
Tosi et al., 2016

Atmospheric model



- **1-D model of radiative-convective equilibrium** based on *Kasting et al.*, (1984; 1988), *Segura et al.* (2003), *von Paris et al.* (2008; 2010; 2015)
- **Model features:**
  - cloud-free
  - steady-state temperature and pressure calculation
  - H_2O profile derived from temperature and relative humidity profiles
  - energy transport via moist convection and radiative transfer
  - linear increase of Sun's luminosity with time (*Gough*, 1981)
  - no primordial H-He atmosphere, no atmosphere from magma ocean, only H_2O and CO_2 degassing from the interior

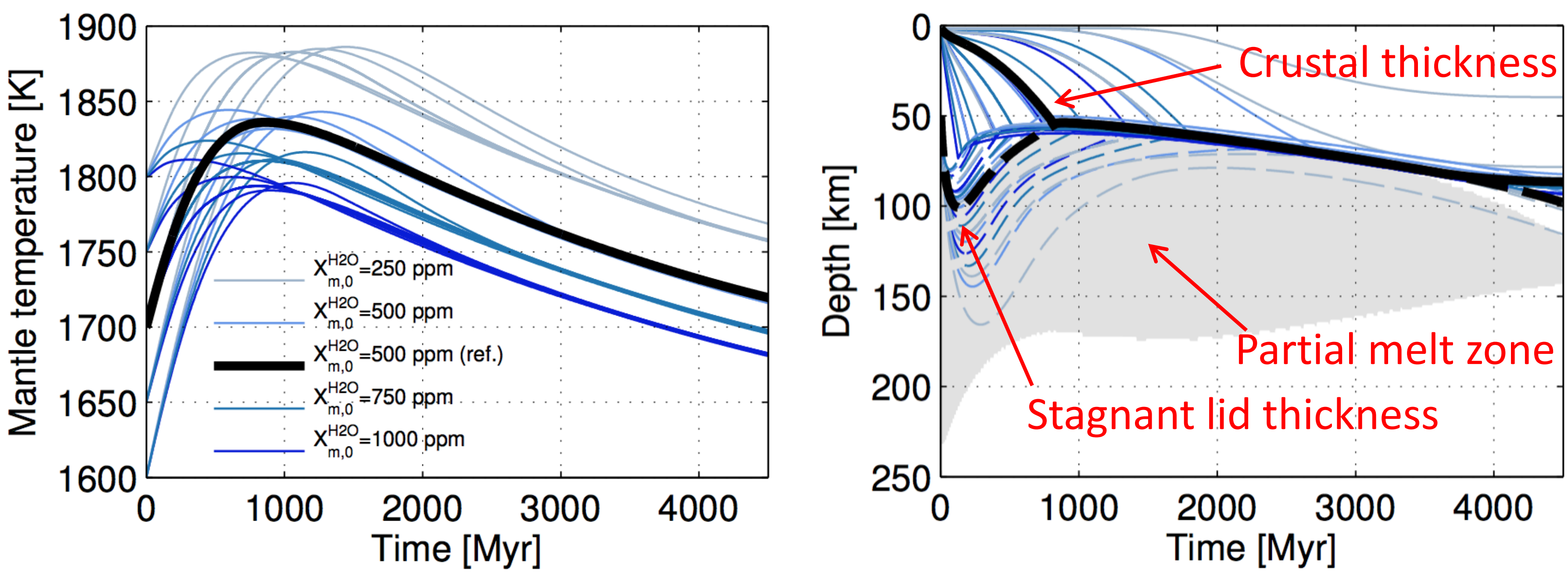
H_2O and CO_2 solubility in basaltic magmas



Newman & Lowenstern (2002)

- Outgassing of H_2O and CO_2 into the atmosphere ultimately depends on their solubilities in surface (basaltic) melts
- H_2O solubility is more than a factor 100 larger than CO_2 solubility $\Longrightarrow$ as the atmospheric pressure grows, H_2O tends to be retained in the melt, while CO_2 outgassed

Thermal and crustal evolution

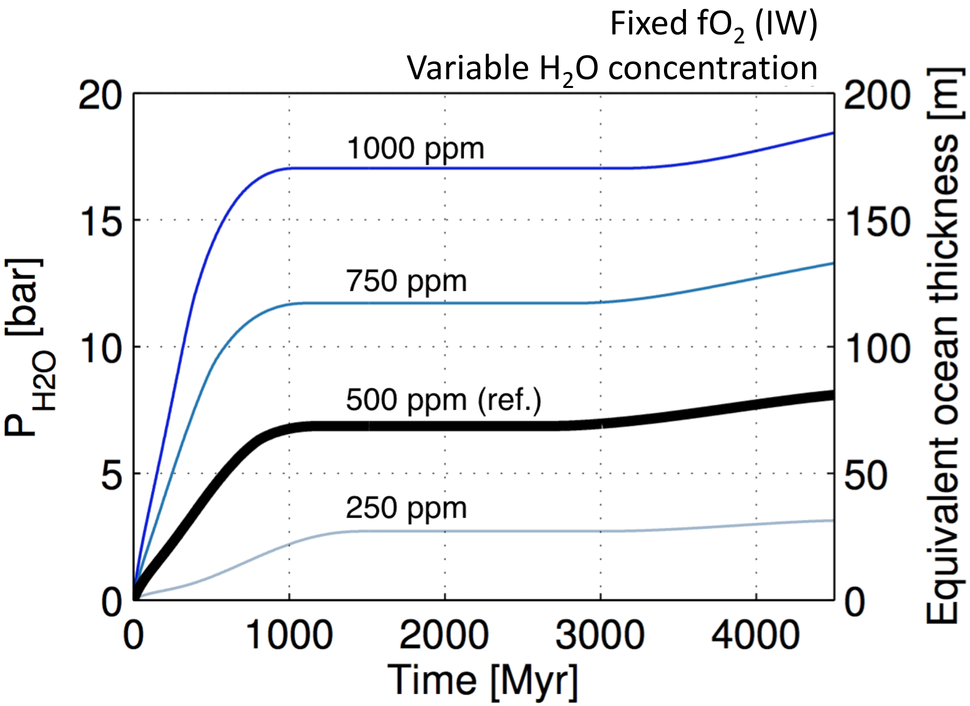


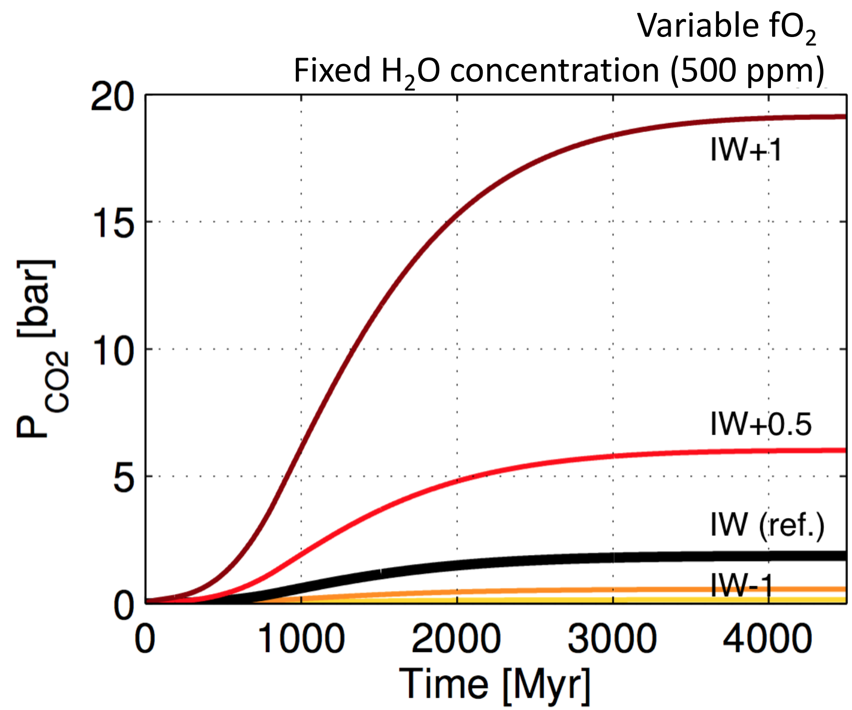
Tosi et al., A&A (2017)

- Initial heating phase between 500 and 1500 Myr followed by secular cooling
- Rapid crust production followed by delamination with the crust quickly becoming as thick as the stagnant lid

Crustal Recycling by Delamination

Outgassing evolution of H_2O and CO_2

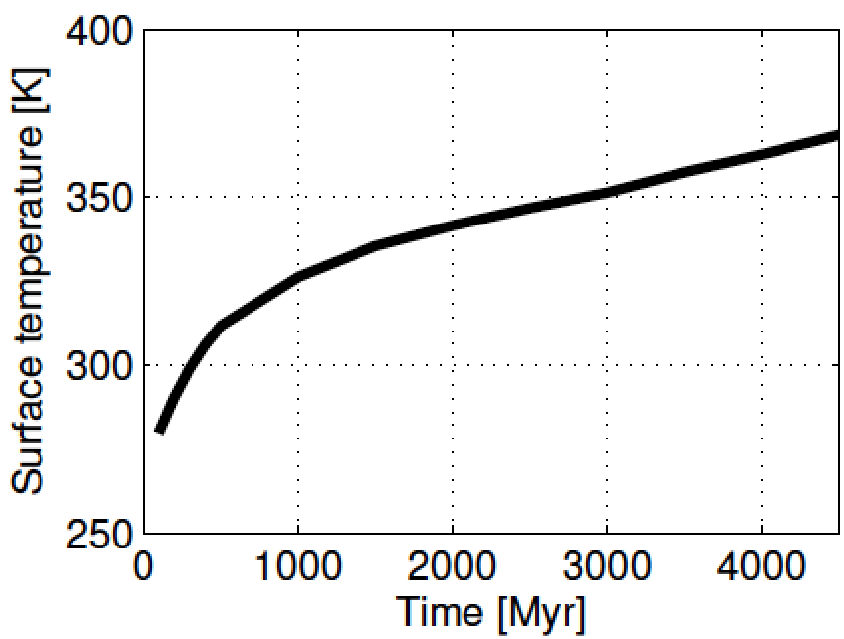


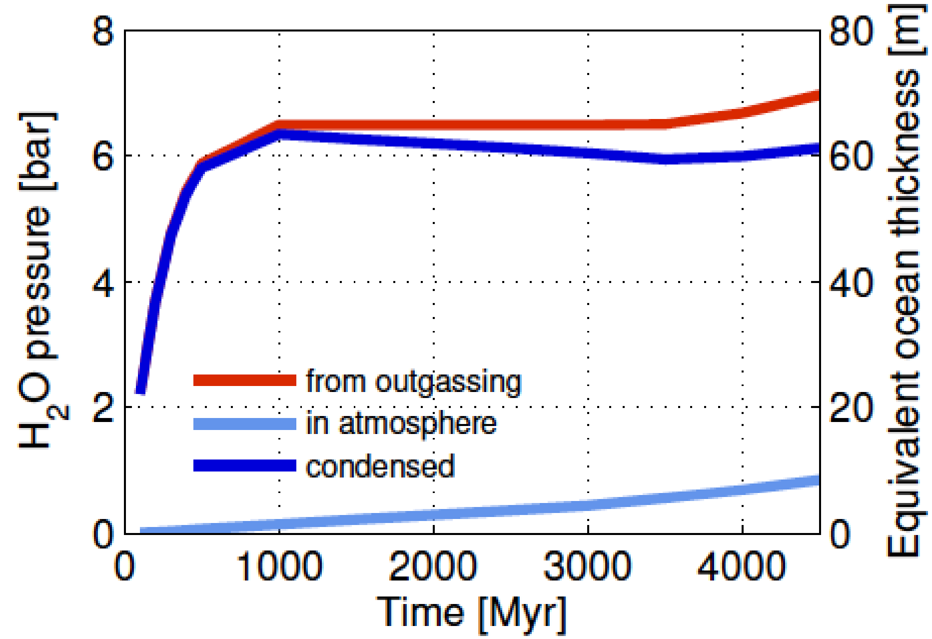


Tosi et al., A&A (2017)

- Outgassing of H_2O limited by its high solubility in basalt
- ~20 bar H_2O outgassed from the interior for H_2O concentrations up to 1000 ppm
- Low solubility of CO_2 allows all CO_2 in the melt to be outgassed throughout the evolution
- ~2 bar CO_2 outgassed from the interior for fO_2 at IW, ~20 bar for fO_2 at IW+1, …

Atmospheric evolution at 1 AU



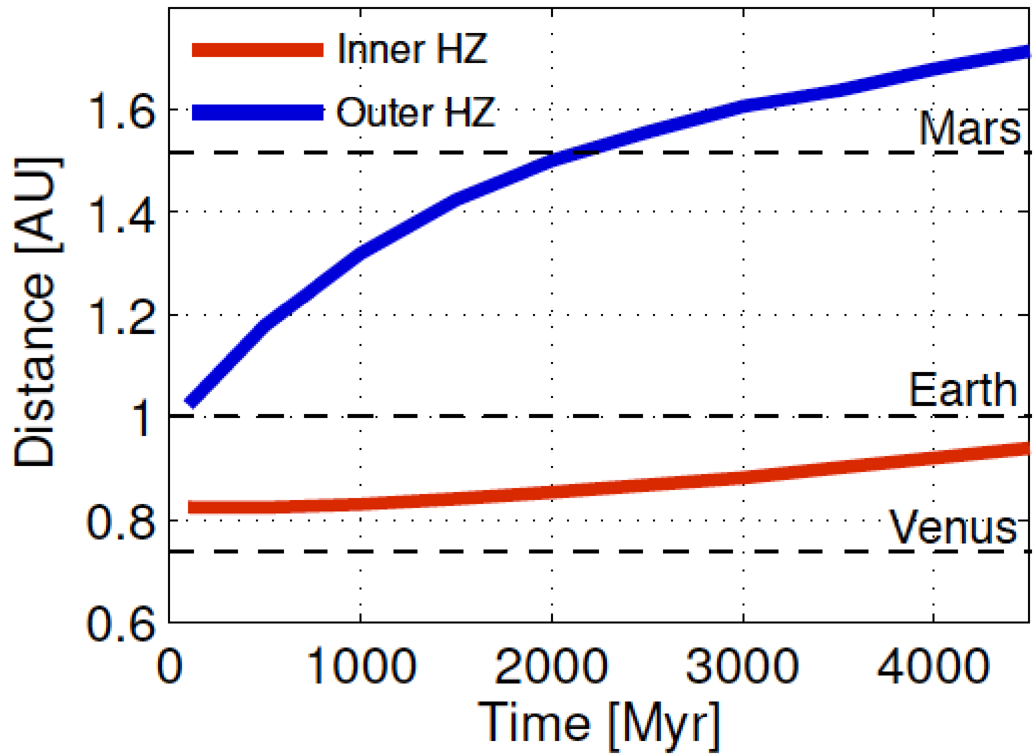


Reference model: $T_m^0 = 1700$ K, $X_{H_2O}^0 = 500$ ppm, $\Delta IW = 0$

- Surface temperature rises due to linear brightening of the Sun and increase in greenhouse gases from the interior
- Water vapour in the atmosphere increases with surface temperature
- A liquid water reservoir of ~2% of an Earth ocean can build up

Tosi et al., 2017

Habitable zone evolution

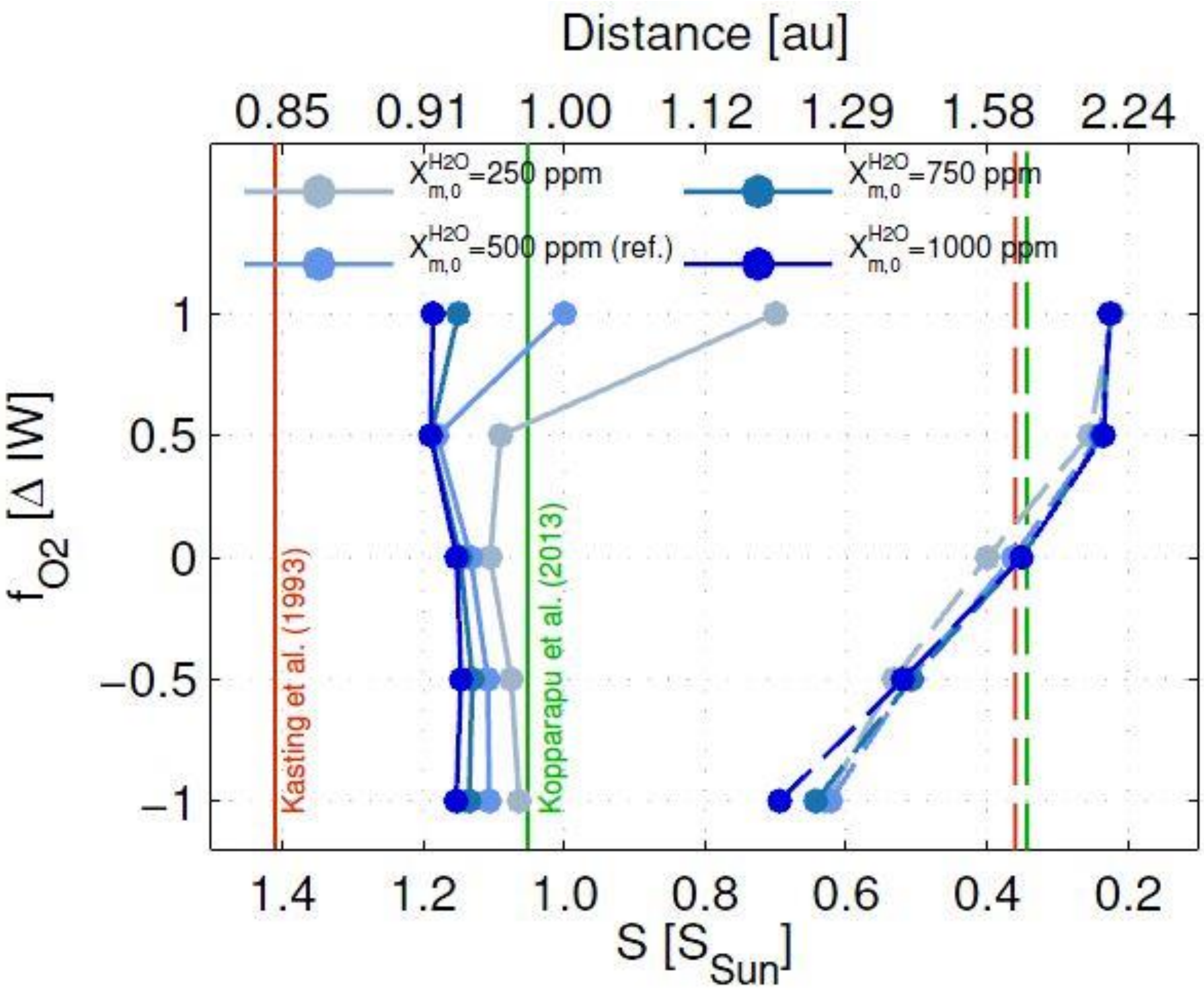


Tosi et al., 2017

Reference model: $T_m^0 = 1700$ K, $X_{H_2O}^0 = 500$ ppm, $\Delta IW = 0$

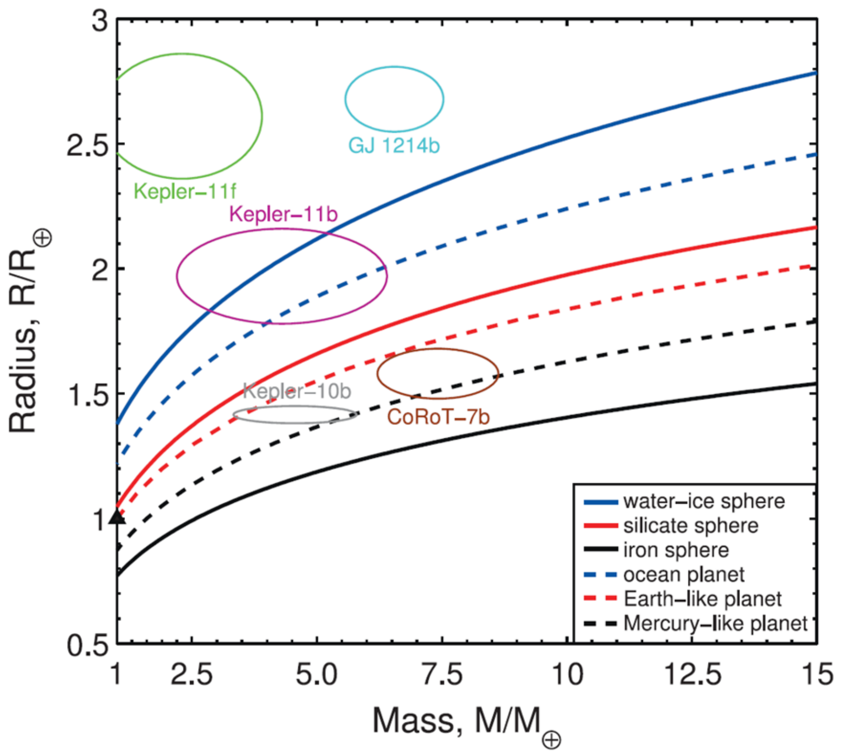
- Inner HZ controlled mainly by increasing solar luminosity
- Outer HZ controlled by outgassed CO_2 and increasing solar luminosity
- A stagnant lid Earth could be habitable today at Mars' orbit, but not at Venus' orbit

Present-day habitable zone



Habitable zone varies with time and depends on

- Initial volatile content (oxygen fugacity)
- Tectonic style
- Mass and size of the planet
- Interior structure
- Atmosphere loss processes
  - Solar activity
  - Weathering rates



Conclusion

- The Earth has a fine-tuned balance between volatiles in the interior, the atmosphere and hydrosphere
- But a stagnant lid Earth can be also habitable although surface conditions are less stable
- We need to consider also weathering and atmopshere loss processes as well as different planetary masses and sizes