HELMHOLTZ ALLIANCE
PLANETARY EVOLUTION AND LIFE

Planetary Evolution and Life: Astrobiology from a Planetary Science Perspective

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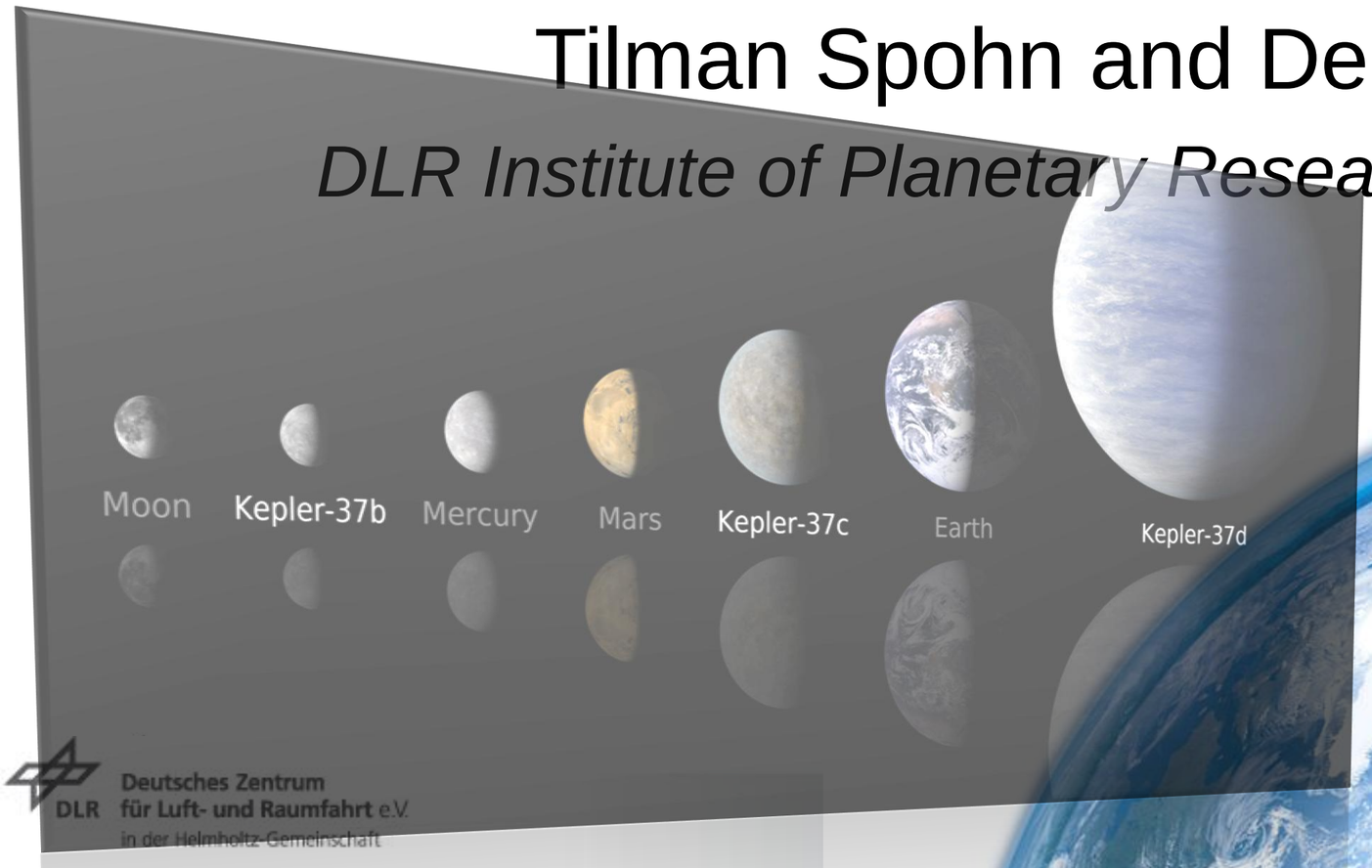
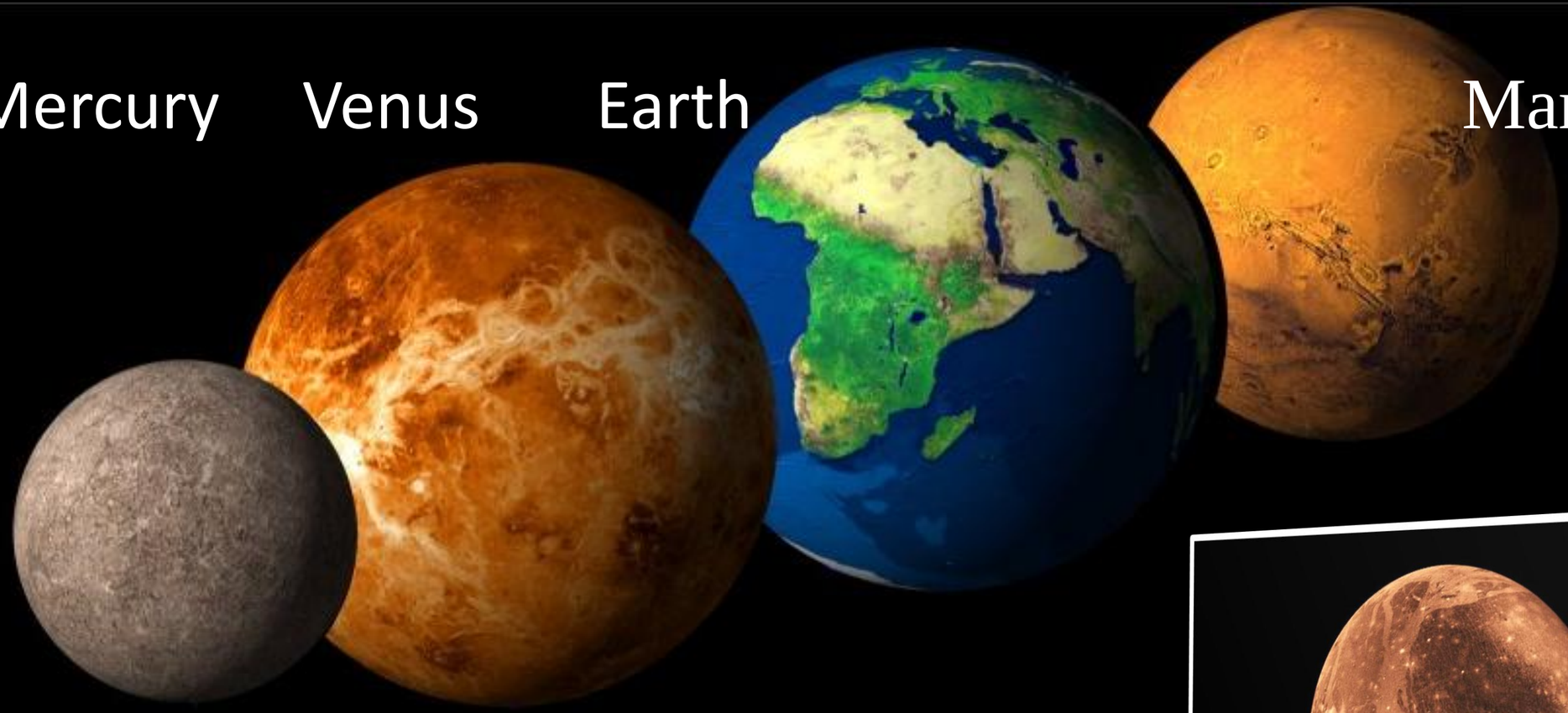
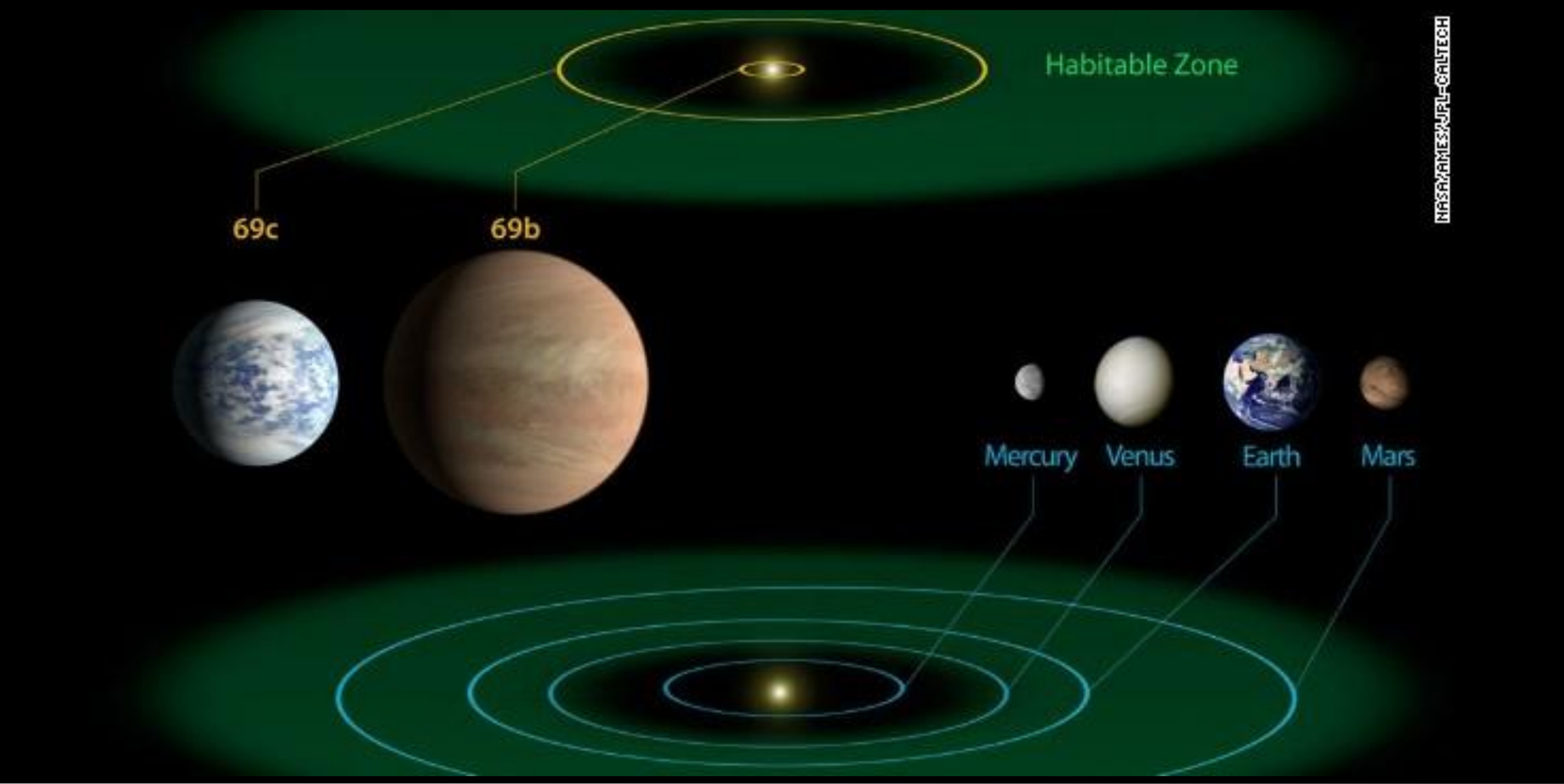


DLR Deutsches Zentrum für Luft- und Raumfahrt e.V. in der Helmholtz-Gemeinschaft

Mercury Venus Earth Mars

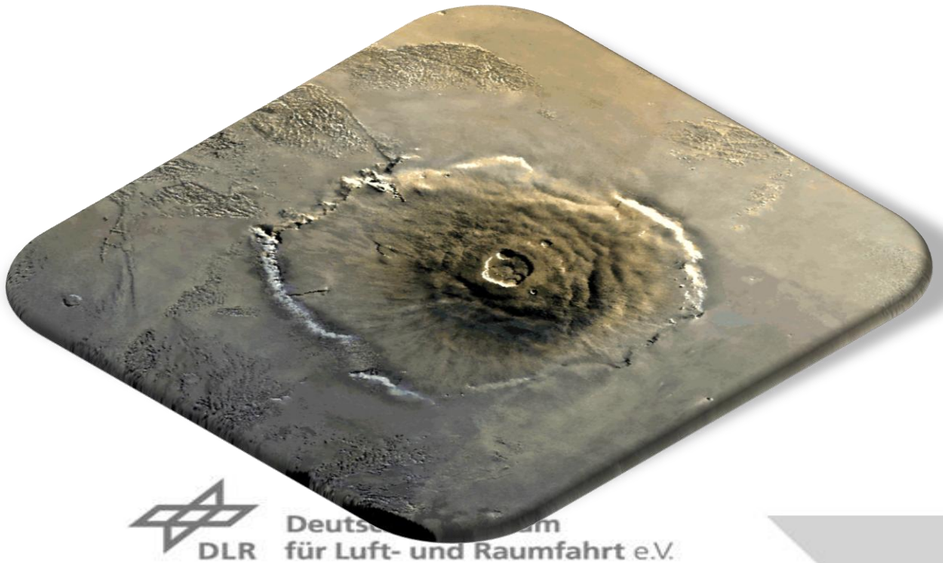


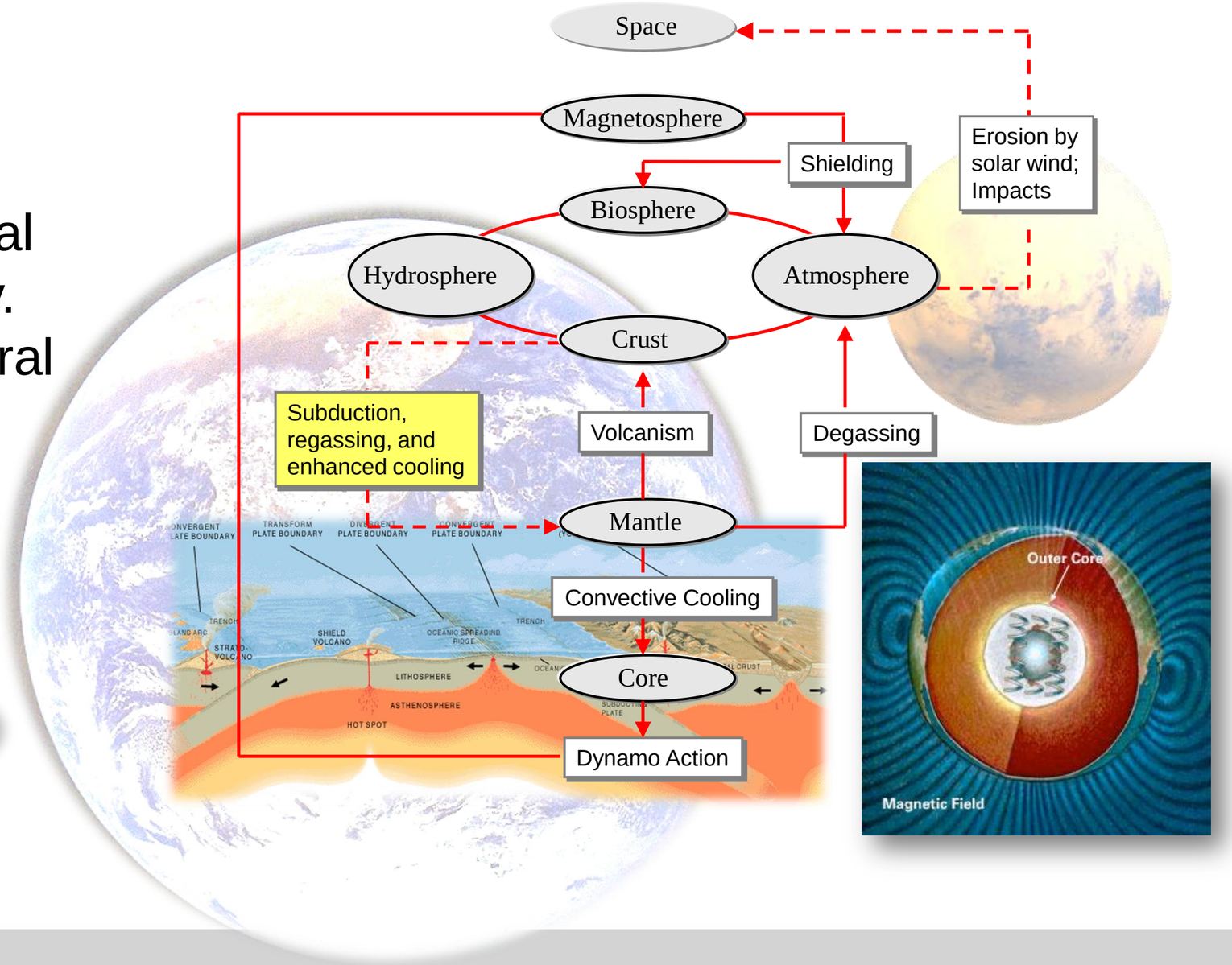
Four Planets, four individuals!
Many more Moons and „earthlike“ Exoplanets


Habitable Zone
69c
69b
Mercury
Venus
Earth
Mars
NASA/AMES/JPL-CALTECH

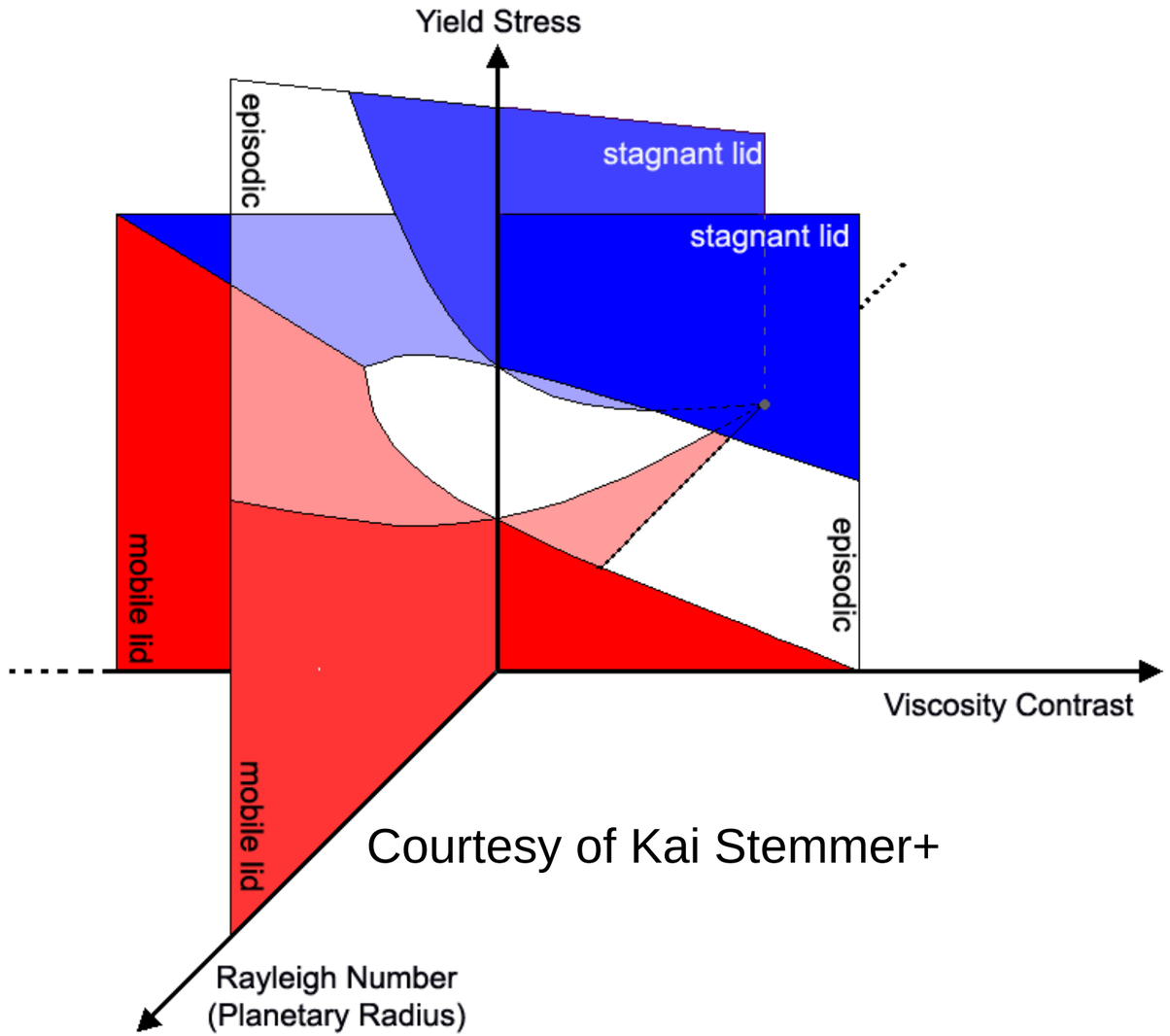
Planets are Heat Engines

..that convert thermal into gravitational, deformational and magnetic field energy. But the engine is an integral part of a complex system!

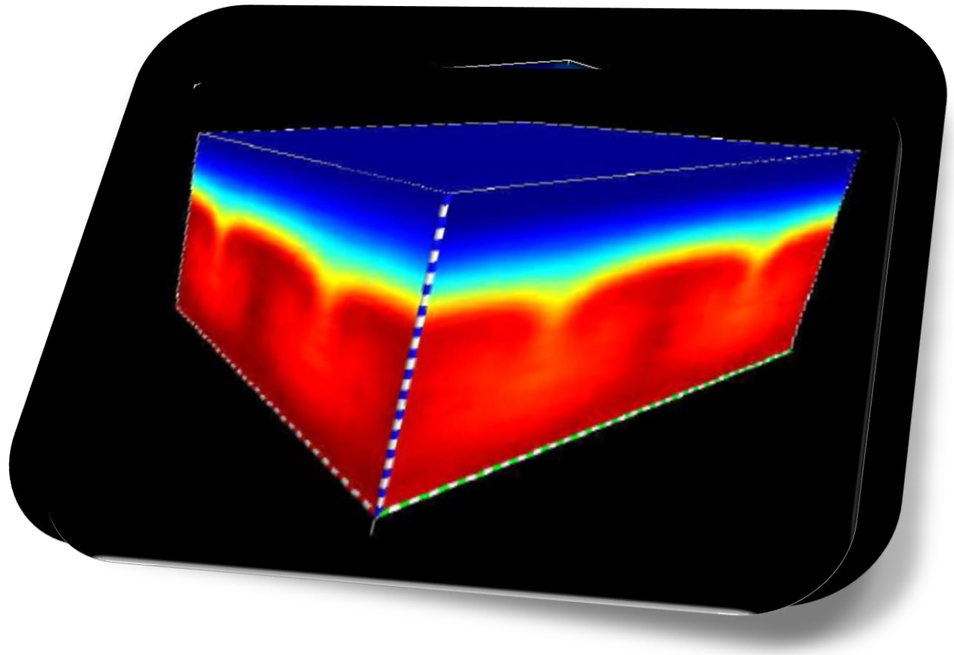




Forms of Mantle Convection



Courtesy of Kai Stemmer+

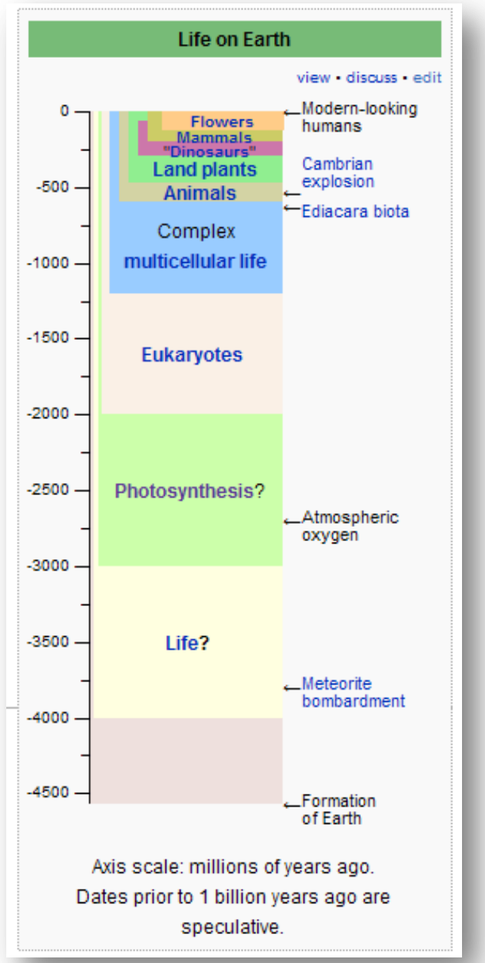


Stein and Hansen 2008

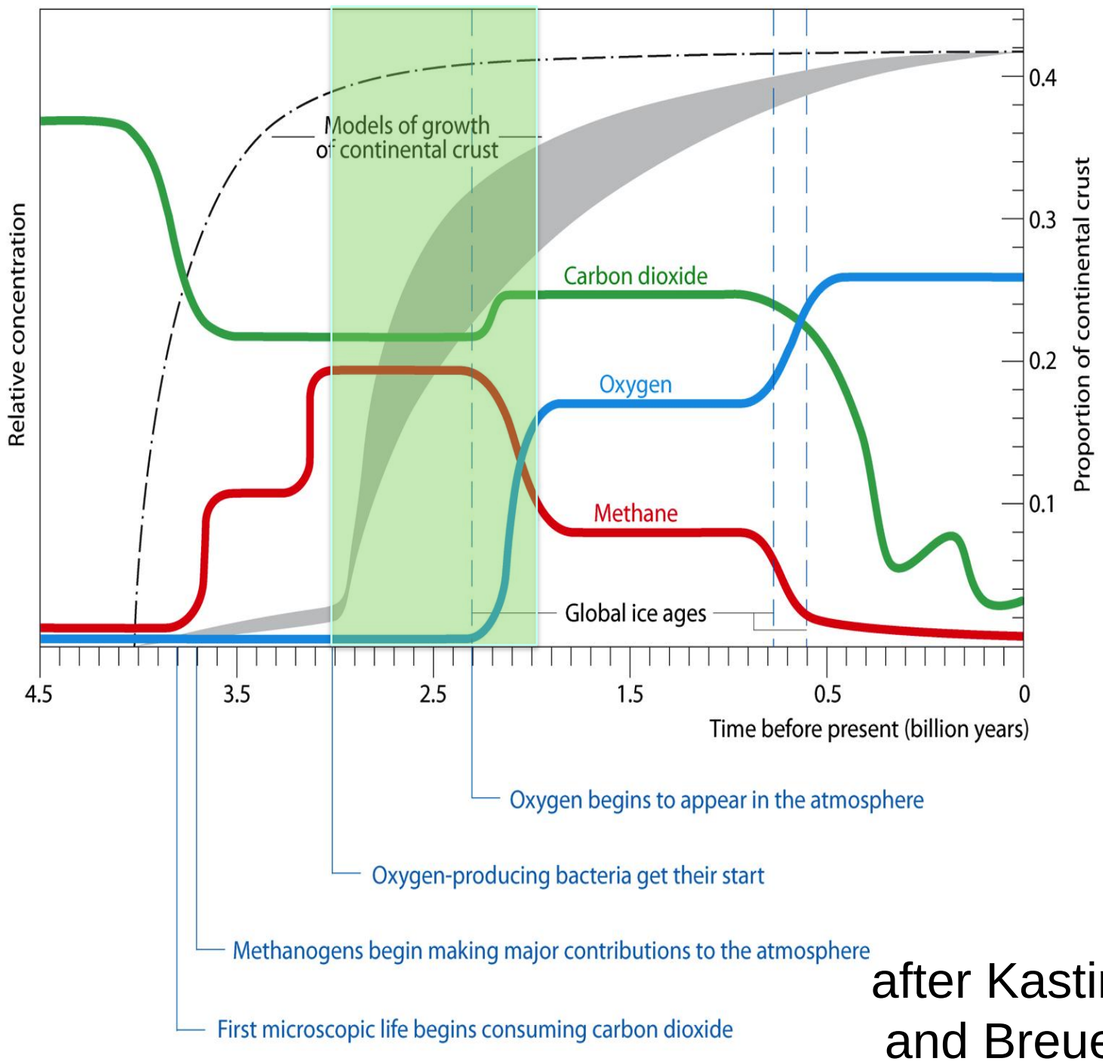
Habitability and Plate Tectonics

- Many believe that (complex, evolved) life requires plate tectonics to operate
- Plate tectonics recycles near surface rock and volatiles with the planet's interior through subduction. This helps to
  - cool the deep interior and to generate a magnetic field in the core
  - replenish depleted surface rock as the base for the nutrition chain
  - stabilize the atmosphere temperature in the long-term Carbon-Silicate-Cycle
- Origin of life hypotheses (for Earth) invoke mid-oceanic ridges or continental shelves, zones of local disequilibrium associated with plate tectonics

Feedback of Life on Planetary Evolution?

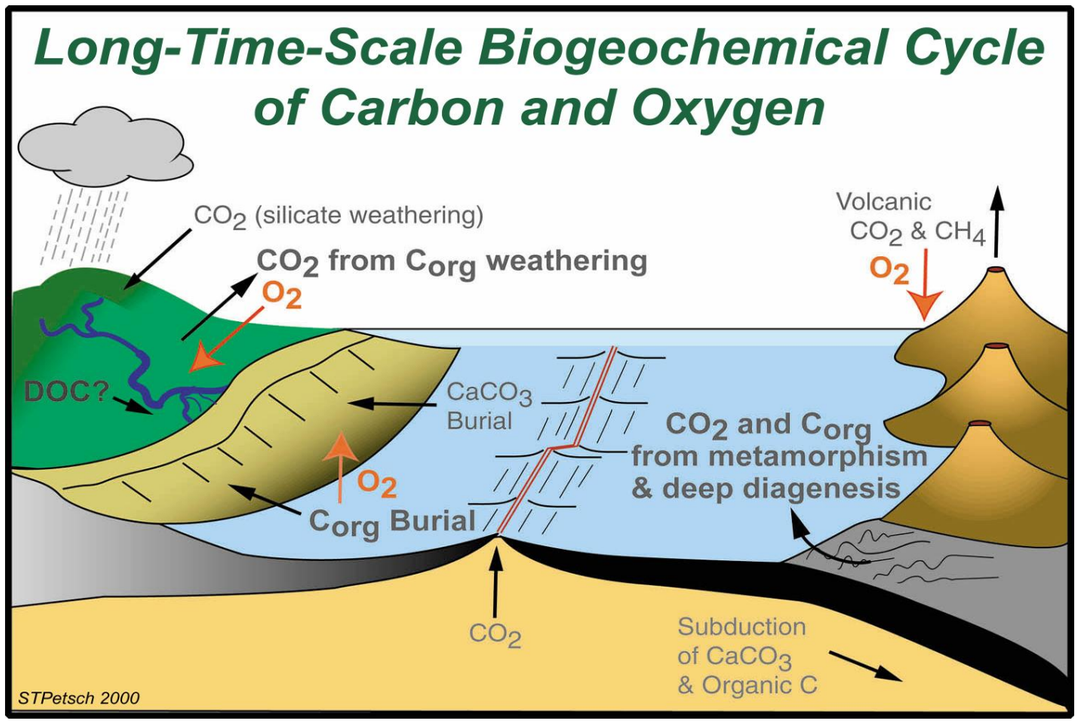


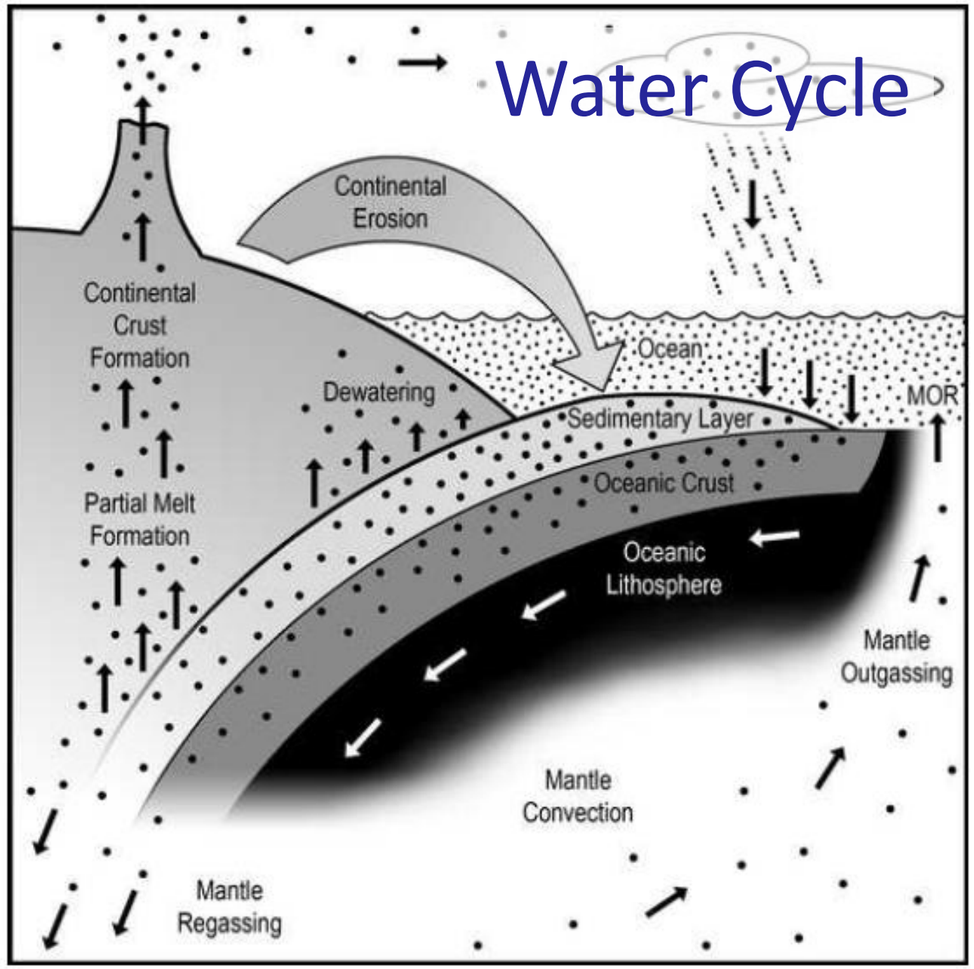
Photosynthesis established



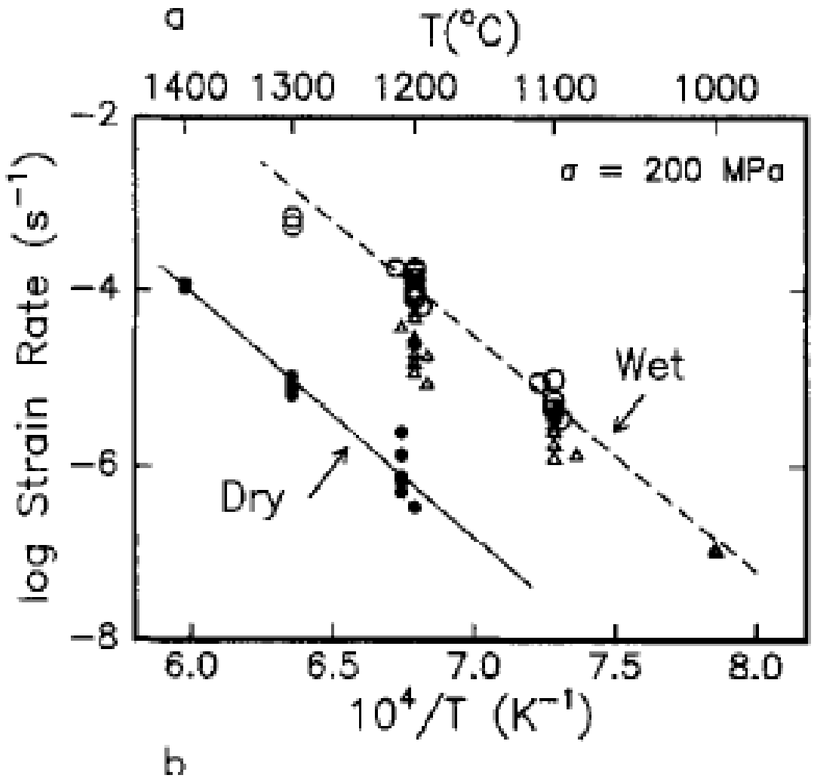
after Kasting & Catling 2003 and Breuer & Spohn 1995)

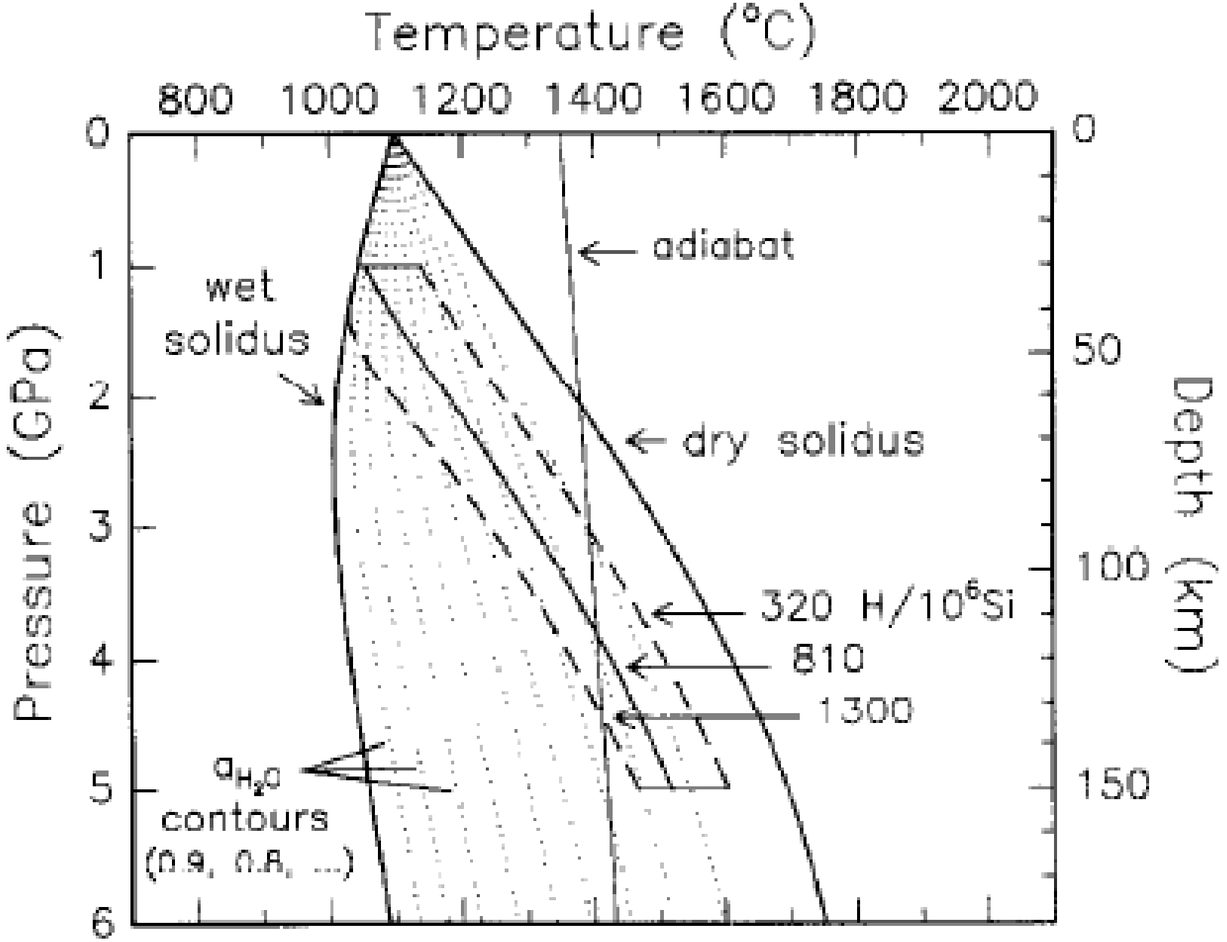
Feedback of Life on Planetary Evolution





Mantle Water and its Effects on Rheology and Melting Temperature

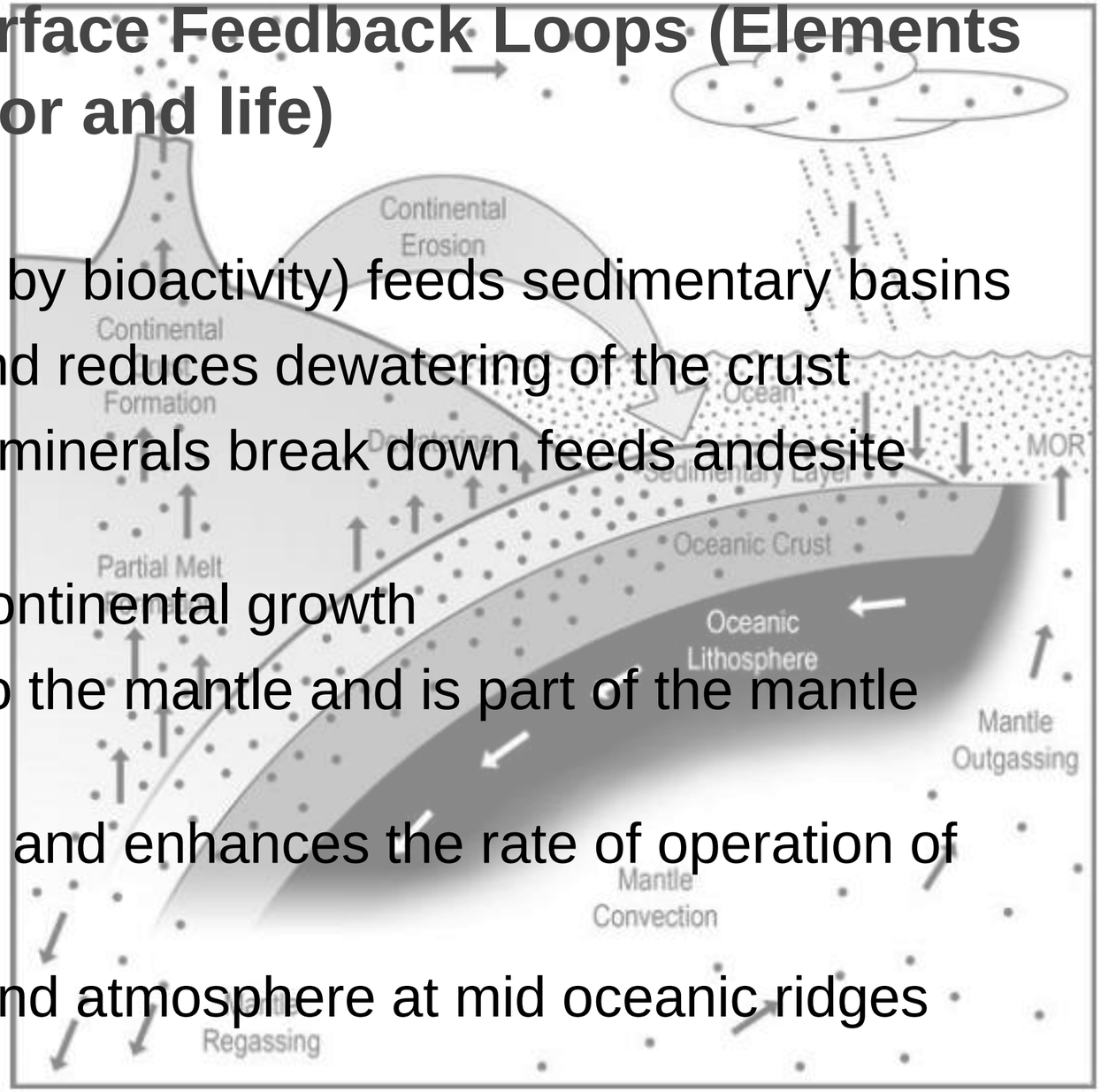


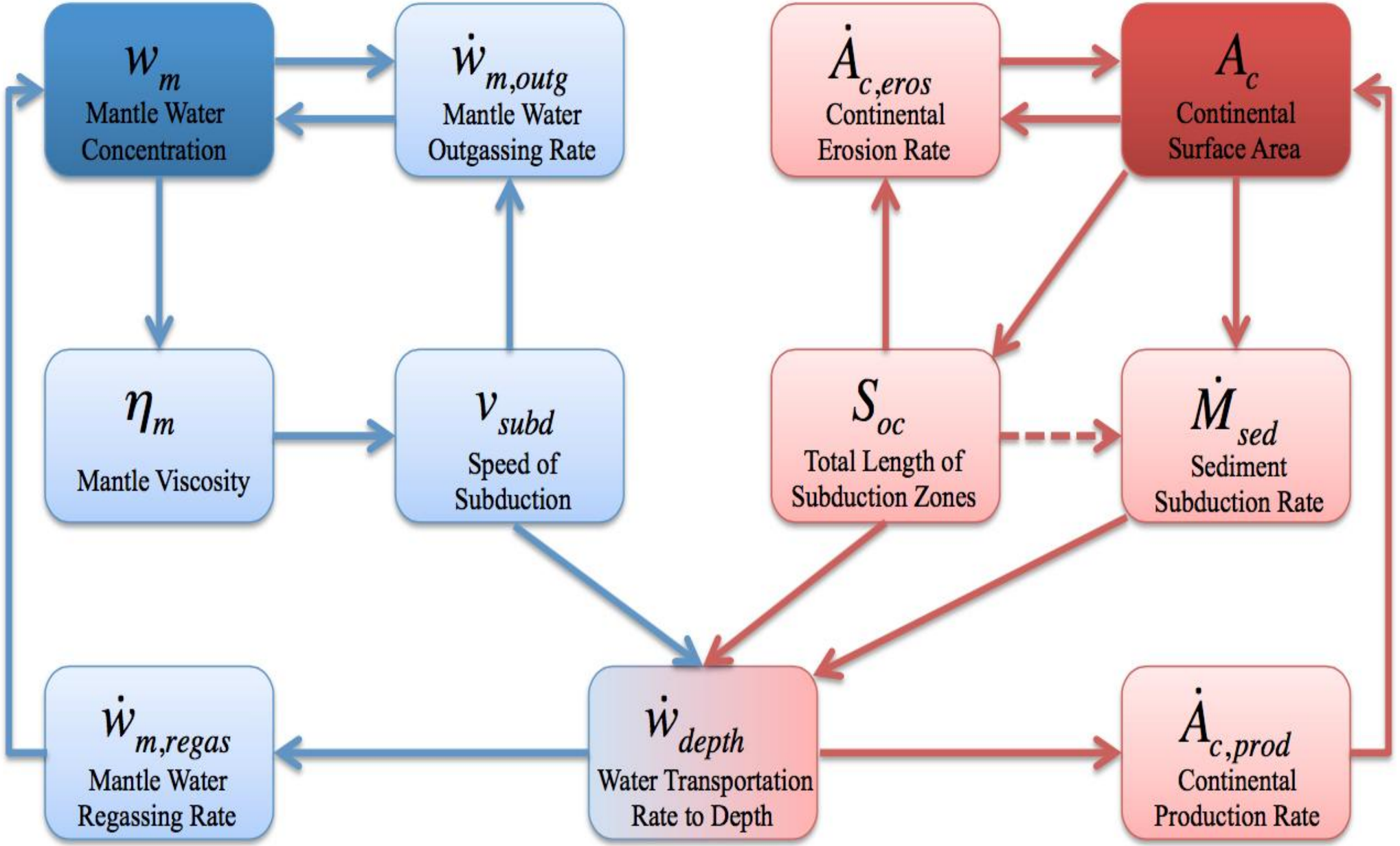


Hirth and Kohlstedt 1996

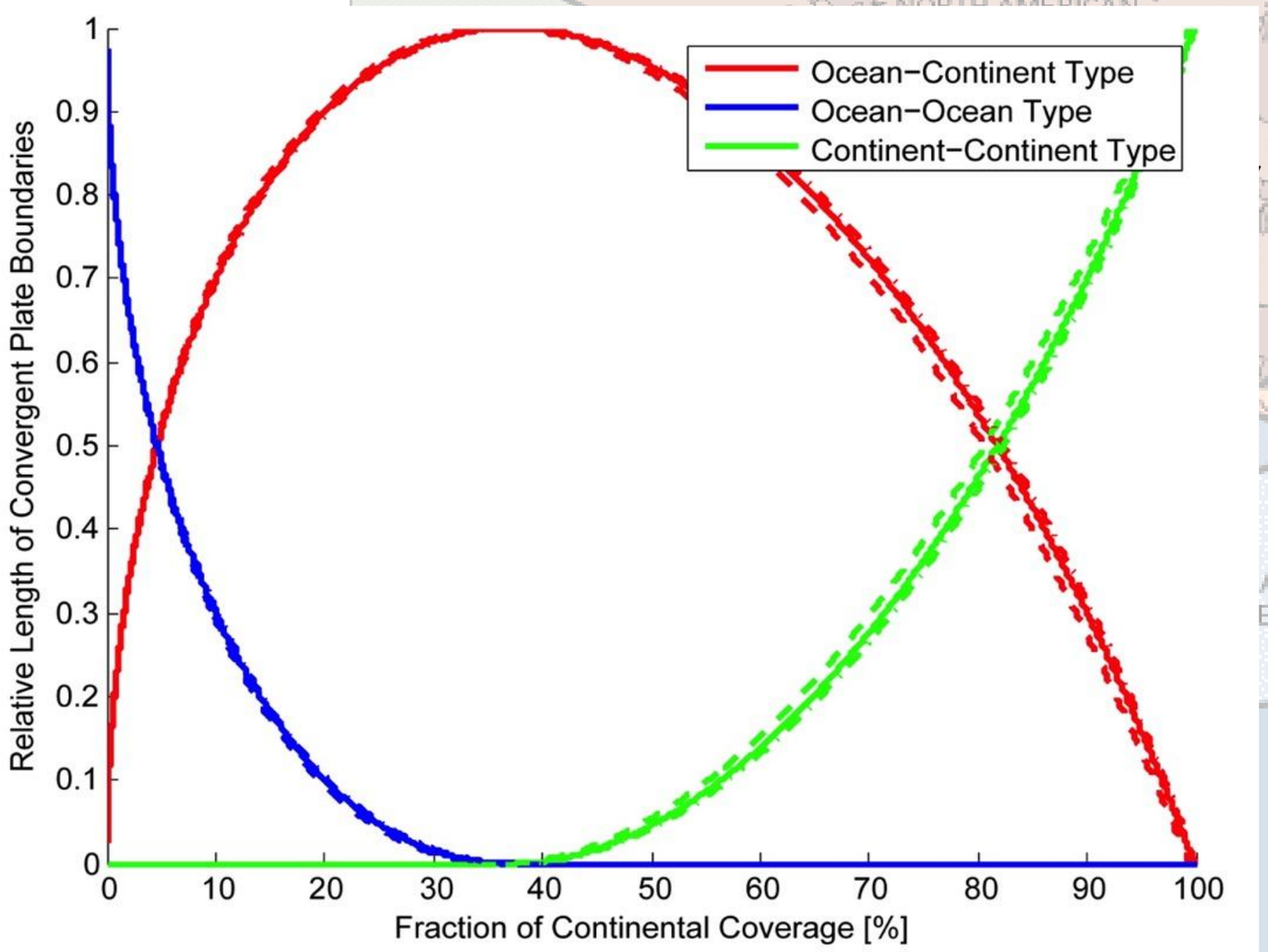
Mantle Water - Continent Surface Feedback Loops (Elements of a feedback between interior and life)

- Continental Erosion (enhanced by bioactivity) feeds sedimentary basins
- Sediment layer carries water and reduces dewatering of the crust
- Water released when hydrous minerals break down feeds andesite source region
- Andesitic volcanism provides continental growth
- Remaining water is injected into the mantle and is part of the mantle water budget
- Water reduces mantle viscosity and enhances the rate of operation of the tectonic engine
- Water is released to the crust and atmosphere at mid oceanic ridges




w_m
Mantle Water Concentration
$\dot{w}_{m,outg}$
Mantle Water Outgassing Rate
$\dot{A}_{c,eros}$
Continental Erosion Rate
A_c
Continental Surface Area
η_m
Mantle Viscosity
v_{subd}
Speed of Subduction
S_{oc}
Total Length of Subduction Zones
$\dot{M}_{sed}$
Sediment Subduction Rate
$\dot{w}_{m,regas}$
Mantle Water Regassing Rate
$\dot{w}_{depth}$
Water Transportation Rate to Depth
$\dot{A}_{c,prod}$
Continental Production Rate

Total Length of Ocean-Continent Subduction Zones



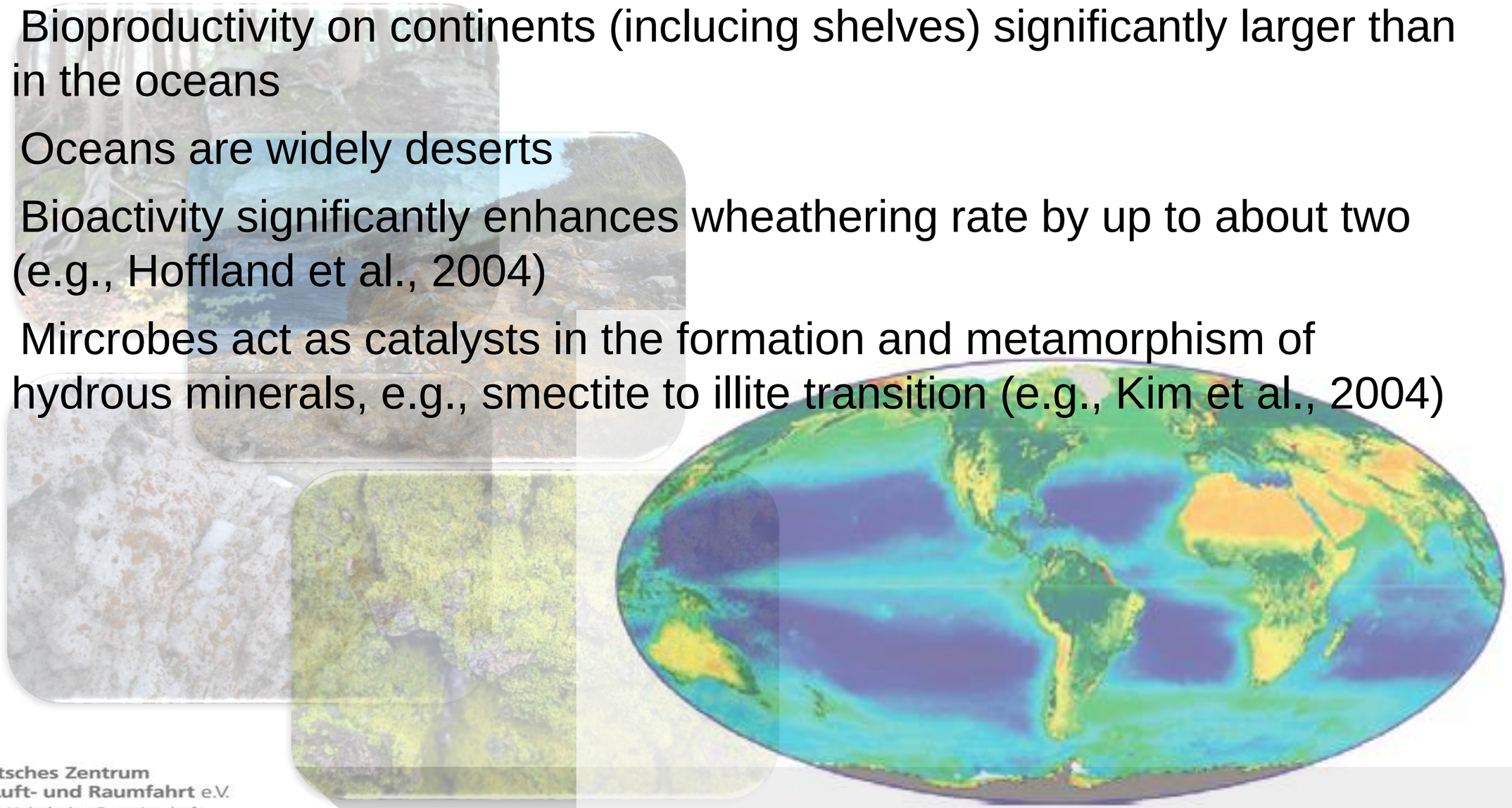
Model continents as randomly distributed spherical caps. Total length of plate margins is taken constant

Growth of continents results in extension of ocean-continent subduction zones at the expense of ocean-ocean subduction zones.

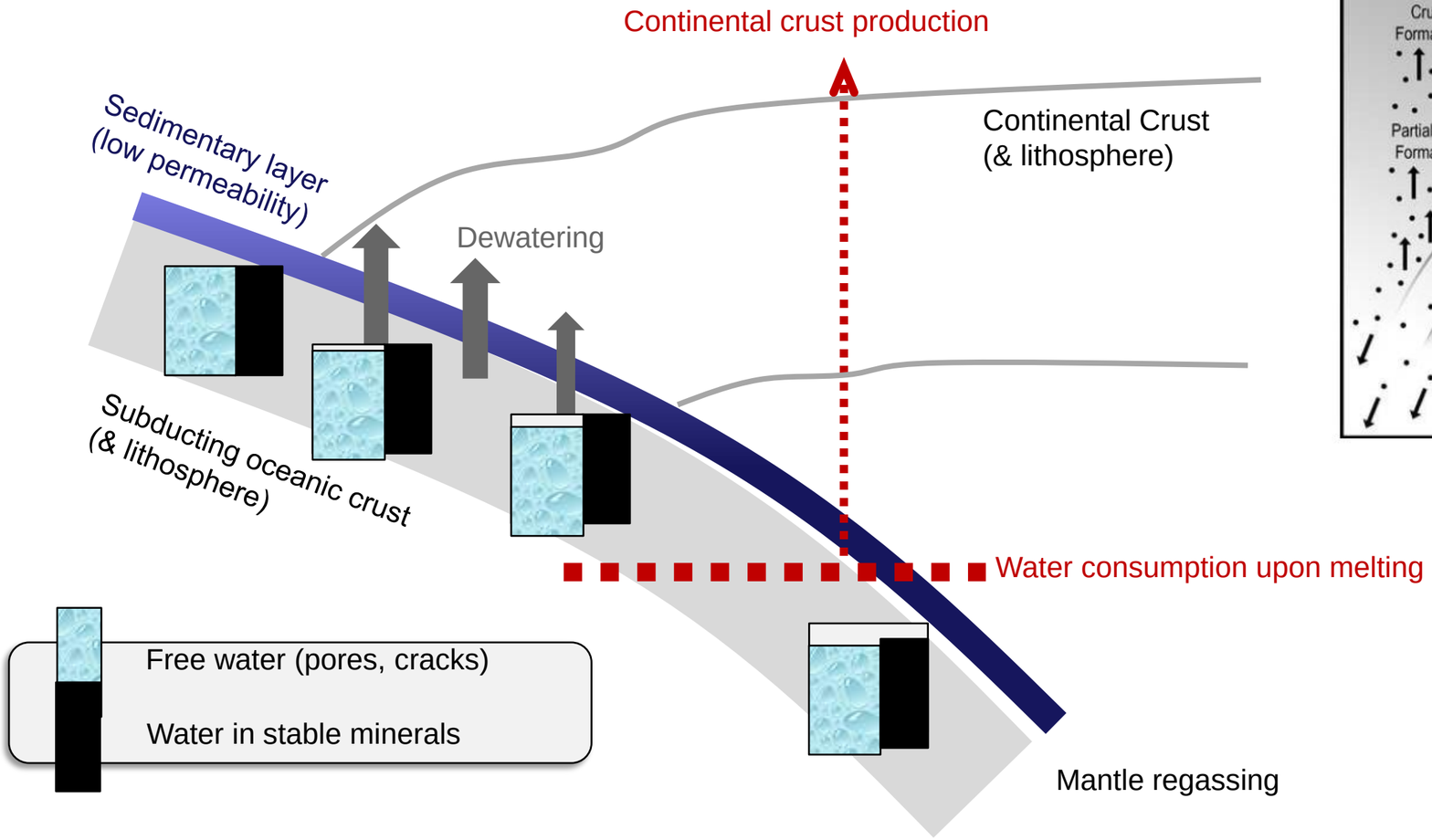
Ocean-continent subduction zones have sediment layers with thicknesses proportional to the continental surface area

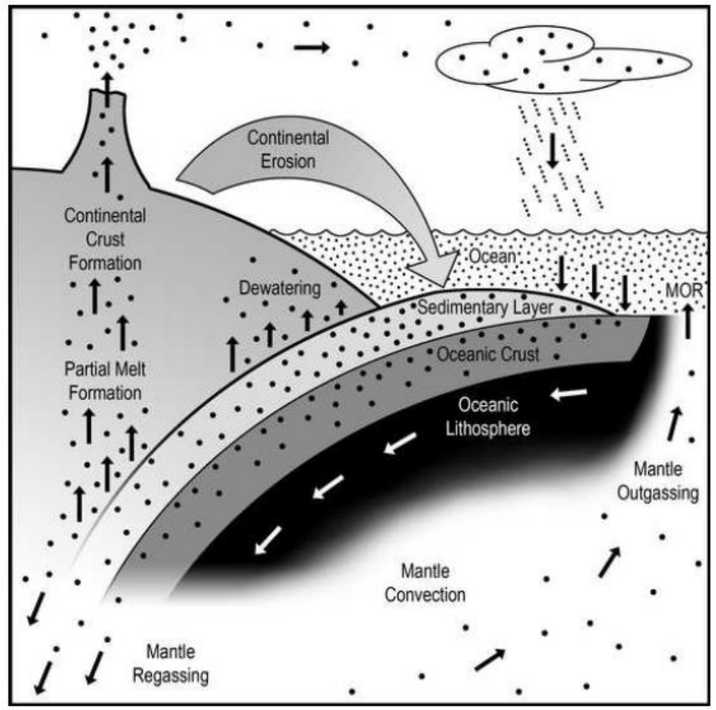
Coupling to the Biosphere

- Bioproductivity on continents (inclucing shelves) significantly larger than in the oceans
- Oceans are widely deserts
- Bioactivity significantly enhances wheathering rate by up to about two (e.g., Hoffland et al., 2004)
- Mircrobes act as catalysts in the formation and metamorphism of hydrous minerals, e.g., smectite to illite transition (e.g., Kim et al., 2004)



Ocean-Continent Subduction Zone

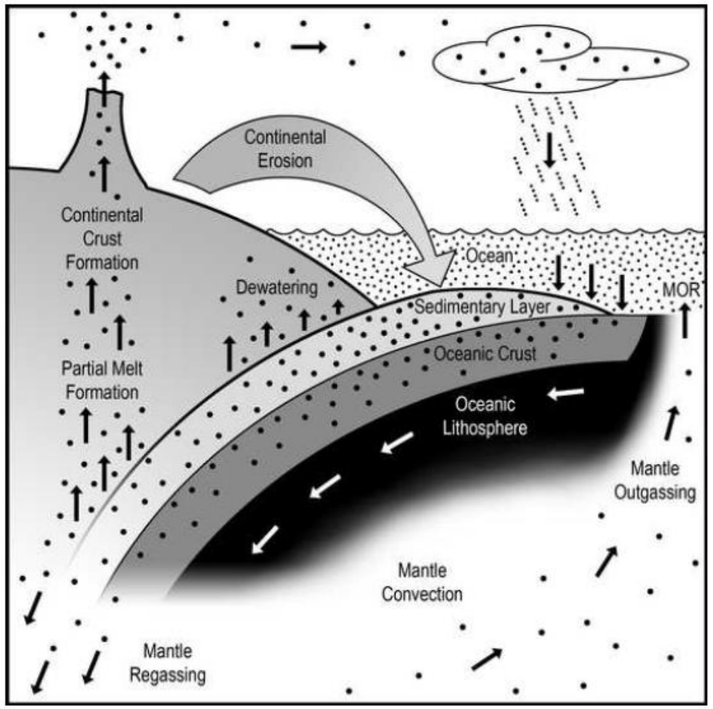




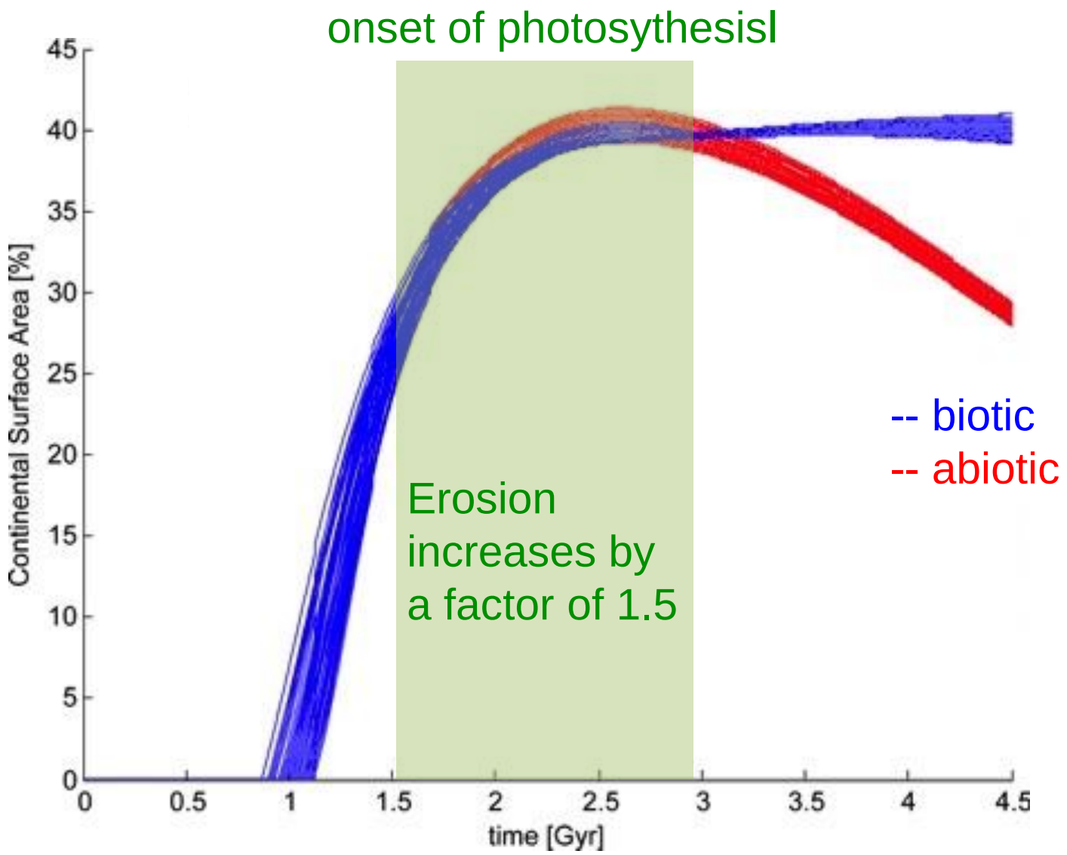
Höning et al., 2014

Evolution Calculation

- The subduction zone and continental growth model is coupled to a parameterized thermal model of the Earth with viscosity depending on temperature and mantle water concentration.
- The subduction zone model feeds the evolution model with the rate of water inserted into the mantle. The evolution model feeds the subduction model with the mantle convection speed assumed to equal the plate speed.
- The evolution model also calculates the dewatering rate of the mantle at mid-oceanic ridges.
- Little constrained parameters are chosen using a Monte Carlo scheme



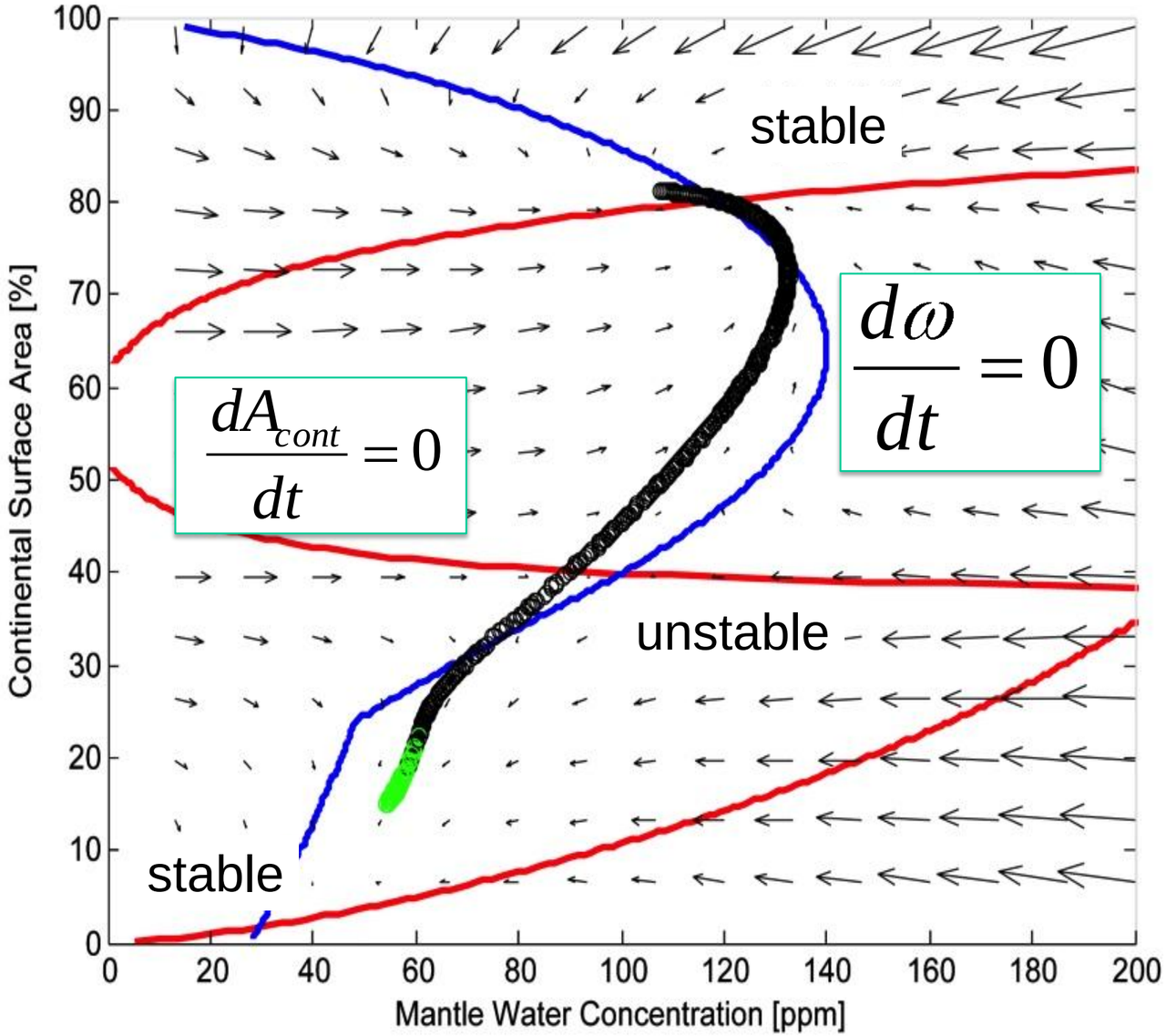
Continental Coverage and Erosion



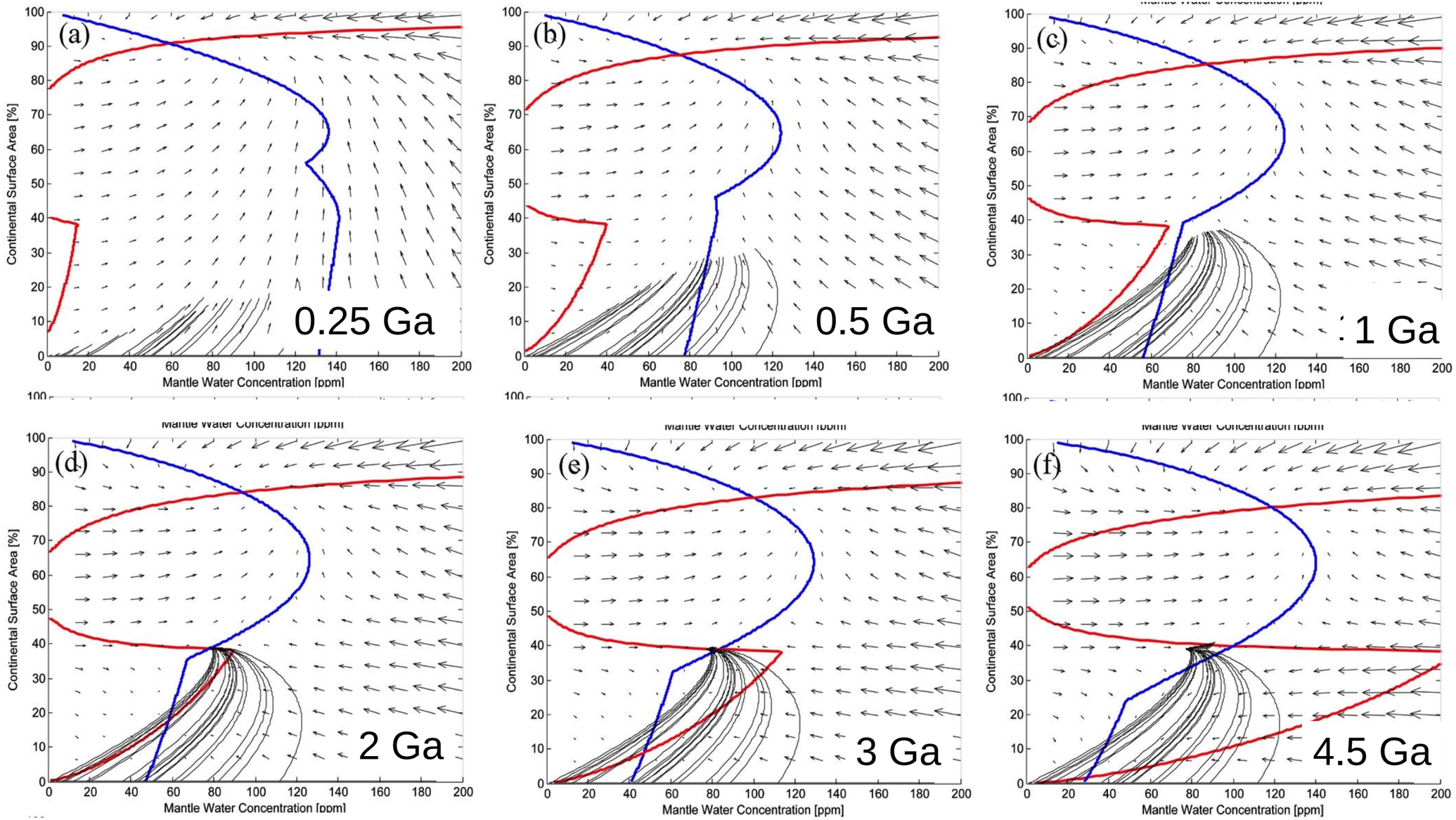
Feedback to
continental growth

Phase Plane

The model can be gauged to represent the present Earth.
Parameters are chosen such that with the present weathering rate, the present mantle water content and continental surface area is recovered.
Evolution calculations are needed to see where the system evolves to



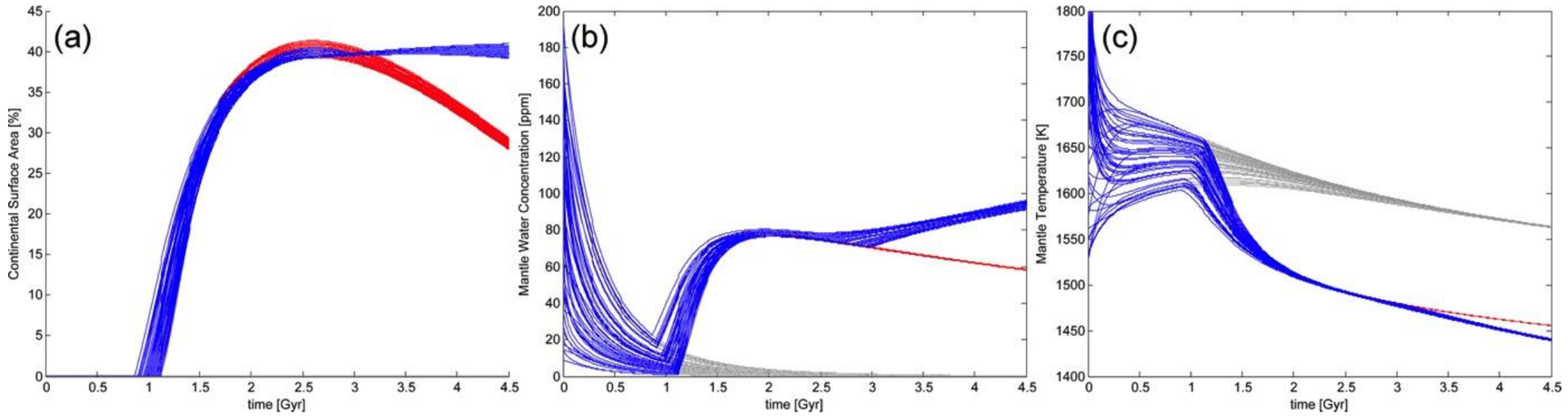
Höning et al., 2014; Höning and Spohn, 2015


(a)
0.25 Ga
(b)
0.5 Ga
(c)
1 Ga
(d)
2 Ga
(e)
3 Ga
(f)
4.5 Ga
Continental Surface Area [%]
Mantle Water Concentration [ppm]

Continental Coverage

Mantle Water Concentration

Mantle Temperature

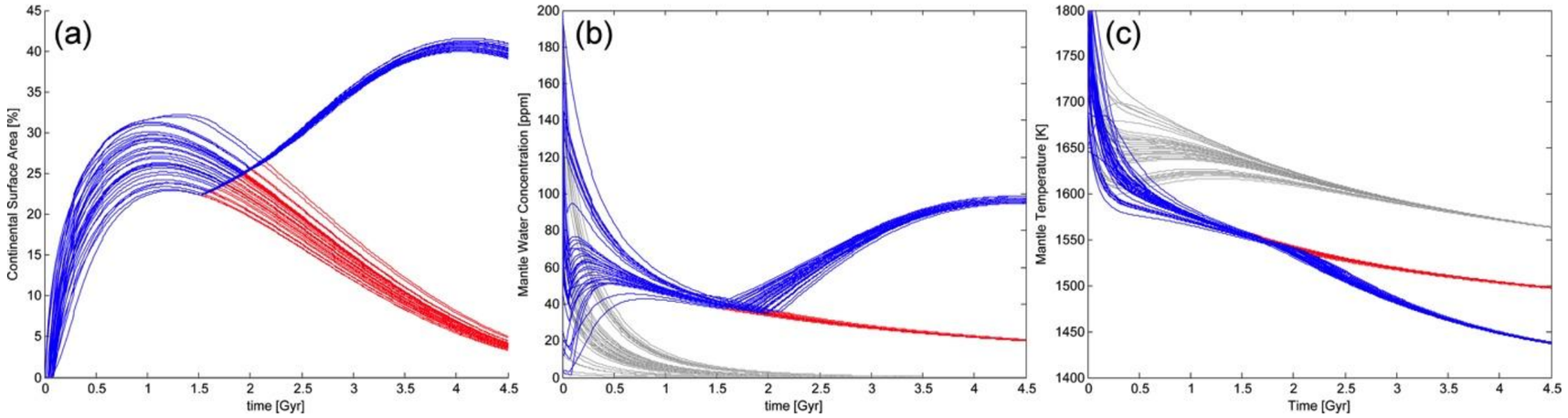


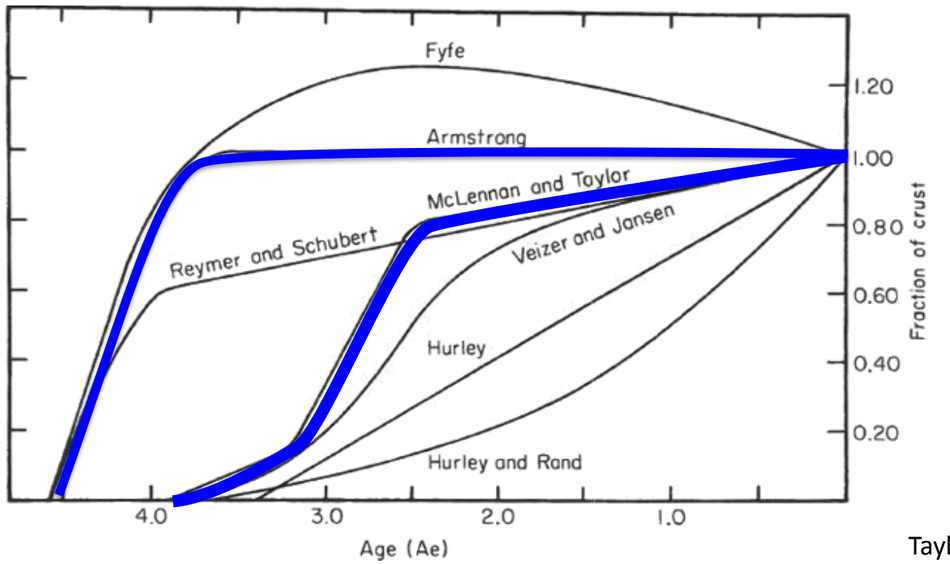
-- biotic

-- abiotic

-- no H_2O subduction

Alternative Scenario (increased effect of sediments)

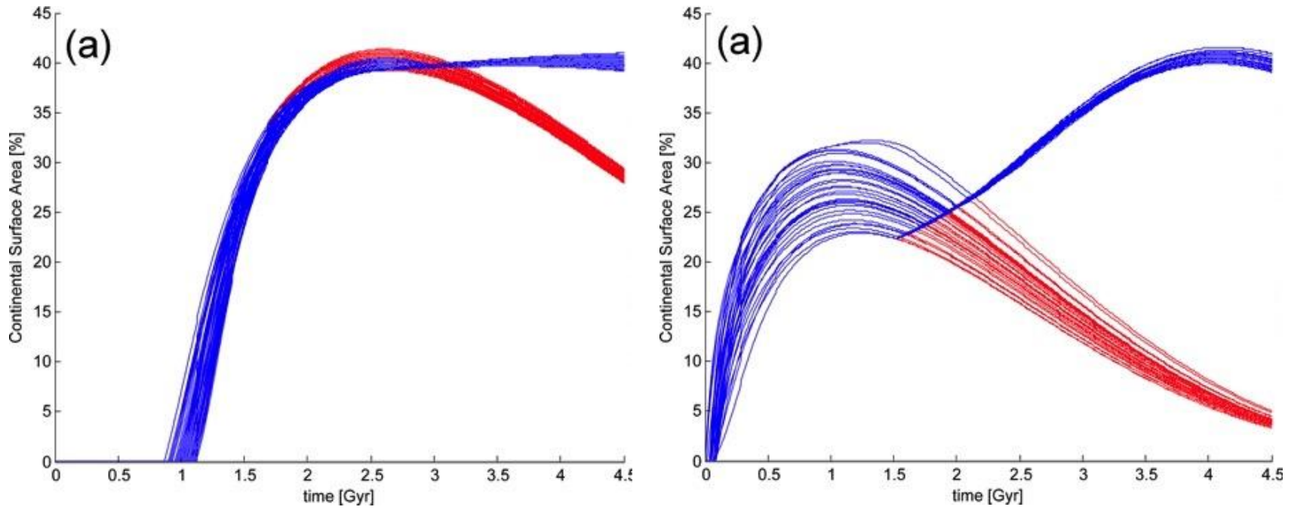




Taylor & McLennan, 1985

biotic

abiotic



Conclusions

- Thermal evolution models of the Earth have hitherto mostly neglected the effect of the water and continent cycles.
- Including the cycles sets up a non-linear system with attractors in a phase plane spanned by the continental surface coverage and mantle water concentration
- Without feedback to continental growth continents should grow and then shrink
- Coupling to continental surface area stabilizes continental coverage. Feedback would be enhanced if fractionation of heat sources were taken into account. The feedback is enhanced by bio-activity
- The p.d. continental coverage maximizes the length of the ocean-continent subduction zone
- There are up to three equilibrium points, two stable, one unstable points. Most solutions evolve to the stable point at large continental coverage and high mantle water content
- The Earth, however, appears to have evolved to the unstable point although the likelyhood is only a percent or so.
- Bioactivity should have stabilized the mantle water content and the continental coverage through enhanced erosion and sedimentation

Thank You

Acknowledgements:

I profited from input from Doris Breuer, Hendrik Hansen-Goos, and Allessandro Airo