Dennis Höning

The Influence of the Biosphere on Continental Coverage and Mantle Hydration as Feedback Cycles in the Thermal Evolution of Earth

2016

Planetologie

Der Einfluss der Biosphäre auf Kontinentalfläche und Mantel-Wassergehalt als Feedback-Schleifen in der Thermischen Evolution der Erde

Inaugural-Dissertation
Zur Erlangung des Doktorgrades der Naturwissenschaften
im Fachbereich Geowissenschaften
der Mathematisch-Naturwissenschaftlichen Fakultät
der Westfälischen Wilhelms-Universität Münster

vorgelegt von
Dennis Höning
aus Hannover

- 2016 -

Dekan:	Prof. Dr. Hans Kerp
Erstgutachter:	Prof. Dr. Tilman Spohn
Zweitgutachter:	Prof. Dr. Harro Schmeling
Tag der mündlichen Prüfung:	18.10.2016
Tag der Promotion:	18.10.2016

List of Publications

The following publications are part of this cumulative thesis:

- Höning, D., Hansen-Goos, H., Airo, A., Spohn, T., 2014. Biotic vs. abiotic Earth: A model for mantle hydration and continental coverage. Planetary and Space Science 98, 5-13.

- Höning, D., Spohn, T., 2016. Continental growth and mantle hydration as intertwined feedback cycles in the thermal evolution of Earth. Physics of the Earth and Planetary Interiors 255, 27-49.

Abstract

This thesis explores the impact of the biosphere on the interior evolution of Earth, with a focus on the growth of continents and the hydration of the mantle. A link exists through the biological enhancement of continental weathering and erosion, resulting in larger rates at which sediments are subducted. These sediments are modeled to carry water partly bound in stable phases and partly stored in pores. In addition, due to the low permeability of the upper, clay-rich part of the sedimentary layer, subducted sediments are modeled with various efficiencies to partially suppress dewatering at shallow depth. Both effects cause an increase in the rate at which water reaches mantle depth for an increasing rate of sediment subduction. Thereby, continental production and mantle water regassing are enhanced.

To investigate the effect of modified rates of continental weathering and erosion on Earth's evolution, continental growth and mantle hydration are described as a coupled system of positive and negative feedback loops. These loops also include the viscosity-reducing effect of water in the mantle and the dependence of the total length of subduction zones on the surface area of continental crust. The results are plotted in phase planes spanned by mantle water concentration and continental coverage. For a reasonable set of model parameters, the positive feedback loops are sufficiently strong to cause the emergence of multiple fixed points in this phase plane. While the fixed points at small and large values of continental coverage are stable, the intermediate fixed point is unstable with respect to continental coverage. The location of the intermediate fixed point at present day values is supported by the movement of the fixed points in the phase plane with mantle cooling, and their comparison with geological constraints: In contrast to the intermediate fixed point, both stable fixed points are located at larger values of continental coverage for a hotter mantle. However, larger continents are commonly ruled out as a part of Earth's history.

To study Earth's evolution in this system, a parameterized model of mantle convection has been coupled to the box-model via the dependence of the mantle viscosity on temperature. Initial conditions are derived from a Monte-Carlo scheme. Evolution trajectories that fit the observation of the present day continental coverage feature a rapid growth of continental crust in early stages of the evolution with only one fixed point existing in the phase plane. This fixed point is stable and located at large values of continental coverage. Since the formation of the unstable fixed point at least 1.5 billion years before present, continental crust coverage has been in steady state accompanied by a slightly increasing mantle water concentration.

A reduced rate of continental weathering and erosion associated with an abiotic Earth moves the intermediate fixed point to larger values of continental coverage. This enlarges the zone of attraction of the stable fixed point with small continental coverage and a dry mantle. The evolution curves show decreasing continental coverage and mantle water concentration since the formation of the unstable fixed point. Thereby, the trajectories approach the stable fixed point with small continental coverage and a dry mantle.

The results suggest that the effect of the biological enhancement of weathering and erosion on Earth's evolution is not linear. Rather, the biosphere could prevent a runaway process with the trajectories approaching small continents and a dry mantle. It could thus play an important role at keeping Earth in its state characterized by rapid mantle convection, extended subduction zones and continental shelves, and large continents that are emerged above sea-level.

Kurzbeschreibung

Diese Arbeit befasst sich mit dem Einfluss der Biosphäre auf die Entwicklung des Erdinneren. Hierbei liegt der Fokus auf dem Wachstum von Kontinenten und der Entwicklung des Wassergehalts im Erdmantel. Ein Link ergibt sich aus der biologischen Beschleunigung von Verwitterung und Erosion kontinentaler Kruste, was zu einer erhöhten Subduktionsrate von Sedimenten führt. Zwei Effekte dieser Sedimente werden hier modelliert: Zum einen tragen sie Wasser, zum Teil in stabilen Phasen gebunden und zum Teil als Porenwasser. Zum anderen unterdrücken Sedimente niedriger Permeabilität teilweise das Entwässern unterliegender Sedimente und ozeanischer Kruste in geringer Tiefe. Eine biologisch erhöhte Subduktionsrate von Sedimenten führt demnach zu einer größeren Rate, mit welcher Wasser in Tiefen des oberen Erdmantels transportiert wird. Hierdurch werden die Produktion kontinentaler Kruste und die Rückführung von Wasser in den Erdmantel verstärkt.

Um den Effekt einer modifizierten Verwitterungsrate auf die Entwicklung der Erde zu untersuchen, werden Kontinentalfläche und Mantel-Wassergehalt als ein gekoppeltes System aus positiven und negativen Feedback-Schleifen beschrieben. Diese Schleifen beinhalten unter anderem den verringernden Einfluss von Wasser auf die Mantel-Viskosität und den Einfluss der Kontinentalbedeckung auf die Länge der Subduktionszonen. Die Ergebnisse werden in Phasenebenen, die aus Kontinentalfläche und Mantel-Wassergehalt aufgespannt werden, dargestellt. Für viele Parameterkombinationen sind die positiven Feedbacks so stark, dass drei Fixpunkte in der Phasenebene existieren. Die beiden Fixpunkte bei hoher und niedriger Kontinentalfläche sind stabil, während der mittlere Fixpunkt instabil bezüglich der Kontinentalfläche ist. Die Lage des mittleren Fixpunkts an heutigen Werten wird durch die Bewegung der Fixpunkte in der Phasenebene unterstützt: Im Gegensatz zum mittleren Fixpunkt liegen beide stabilen Fixpunkte für einen heißeren Mantel bei größeren Werten der Kontinentalfläche. Jedoch werden größere Kontinente gewöhnlicherweise für die Geschichte der Erde ausgeschlossen.

Um die Entwicklung der Erde in diesem System zu untersuchen, wird das Box-Modell mit einem parametrisierten Modell der Mantelkonvektion über die Temperatur-Abhängigkeit der Viskosität verknüpft. Für die Wahl der Anfangsbedingungen wird ein Monte-Carlo-Verfahren genutzt. Evolutionstrajektorien, die das Kriterium der heutigen beobachteten Kontinentalfläche erfüllen, zeigen ein schnelles Kontinentalwachstum in frühen Phasen der Evolution. In diesem Zeitraum existiert nur ein Fixpunkt in der Phasenebene. Dieser ist stabil und befindet sich bei großen Werten der Kontinentalfläche. Der instabile Fixpunkt entsteht spätestens 1.5 Milliarden Jahre vor der Gegenwart. Nach der Bildung dieses

Fixpunkts ist die Kontinentalfläche stationär und die Mantel-Wasser-Konzentration steigt leicht an.

Eine verringerte Verwitterungs- und Erosionsrate, wie sie für eine abiotische Erde vermutet werden würde, verschiebt den mittleren Fixpunkt zu größeren Werten der Kontinentalfläche. Dadurch vergrößert sich der Anziehungsbereich jenes stabilen Fixpunkts mit kleiner Kontinentalfläche und trockenem Mantel. Sobald sich der instabile Fixpunkt gebildet hat, zeigen Evolutionskurven eine Verringerung der Kontinentalfläche und des Mantel-Wassergehalts, und laufen gegen den stabilen Fixpunkt mit kleiner Kontinentalfläche und trockenem Mantel.

Die Ergebnisse deuten darauf hin, dass der Einfluss einer biologischen Erhöhung der Subduktionsrate von Sedimenten auf die Evolution der Erde nicht linear ist. Vielmehr könnte die Biosphäre einen selbstverstärkenden Prozess verhindern, durch welchen die Erde einen Zustand kleiner Kontinente und einen trockenem Mantel anstreben würde. Die Biosphäre könnte demnach eine wichtige Rolle dabei spielen, die Erde in ihrem Zustand starker Mantelkonvektion, langen Subduktionszonen und Schelf-Regionen und einer großen Kontinentalfläche oberhalb des Meeresspiegels zu halten.

Table of Contents

* Removed from this online version. An up-to-date CV is available at http://www.dhoening.de/dennis_hoening_cv.pdf

1. Introduction

1.1 The Search for Life on Other Planets

The last decade yielded strong progress in the detection of extrasolar planets. Powerful space telescopes like CoRoT and Kepler allow precise measurements of stellar light curves, revealing the radii of transiting planets. Combined with the radial velocity method revealing the minimum mass of the planet, the planetary density, composition, and possible interior structure can be investigated. But would a planet with a size, mass, and received heat flux comparable to the Earth's work in a similar way? The diversity of planets even in our solar system indicates the contrary. One fundamental difference between Earth and Venus or Mars is the operation of plate tectonics. While Earth's surface is continuously recycled at convergent plate boundaries, the Martian mantle convects underneath a stagnant lid, and the tectonic mode of Venus is presumably episodic, if not stagnant lid as well. The other fundamental difference is the emergence of life, shaping Earth in various ways. Although the origin of life is not yet fully understood, hydrothermal vents could have played an important role (Corliss et al., 1981). As hydrothermal vents require the presence of large thermal gradients, mid-ocean ridges and thus plate tectonics could have been crucial. As it will be discussed in below, plate tectonics plays an important role in keeping Earth habitable by stabilizing its surface temperature (e.g., Kasting and Catling, 2003), and thus enabling the evolution of life on long time scales. However, it is still unknown whether or not Earth is the only planet that harbors life. If life originates and evolves on other planets, particularly on planets beyond our solar system – how could it be detected?

Answering this question is challenging, not the least because there is no unique definition of life, even when restricted to life on Earth. Most definitions include nonliving objects (crystals are able to reproduce, fire spreads by consuming chemical energy, computer viruses reproduce and pass on information) or exclude some living organisms. In general, life can be seen as a chemical system with specific attributes (e.g., Cleland and Chyba, 2007, and references therein). Basic attributes are structural organization (organisms are composed of one or more cells), reproduction including transmission of information (by RNA or DNA), and adaption to changing environments through Darwinian evolution. Life on Earth is based on organic molecules and needs liquid water as a solvent. From a thermodynamic point of view, life is a system that operates and is kept far from equilibrium by consuming free energy and producing large amounts of entropy.

The basic requirements for the emergence and evolution of life can be used when searching for life on other planets. Carbon as a building block for life could exist on all terrestrial bodies. Energy can be harvested from the sun, which favors planetary bodies close to their star, but also other sources are possible; secular cooling and radioactive decay within the interior provide large heat fluxes and thermal gradients particularly in massive planetary bodies, and tidal forces are strong in planetary bodies subject to time-dependent gravitational interactions with others (e.g. the Laplace resonance within the Jovian system). Liquid water can exist in a certain pressure-temperature regime and therefore within a certain distance from the host star at the planetary surface (in the case of Earth) or within the interior underneath an icy shell (in the case of icy moons). However, going to extrasolar planets, detection of life is only possible remotely. Thus, all preconditions for life are required near the surface. This limits the amount of eligible planets, particularly because the temperature range that allows water to be liquid on the surface is relatively small. The distance from the star at which liquid water would be stable on the planetary surface is called the “habitable zone”, and depends on the luminosity of the star (Hart, 1979), the atmospheric composition of the planet (Kasting et al., 1993; von Paris et al., 2011), clouds in the atmosphere (Kitzmann et al., 2010), and additional factors. Terrestrial planets discovered within the habitable zone are presumably the most promising objects for a possible future detection of life beyond our solar system.

However, life – as a process, or a system – cannot be easily detected as such. On Earth fossils can prove the former existence of organisms and thus act as biomarkers. But this does not work for extrasolar planets. In general, chemical, physical and morphological alterations to the environment that have been made by biological activity (so called biosignatures) are being observed. Signatures that are unlikely to be formed under abiotic conditions are good indicators for past or present life. For example, the atmospheric composition can act as a biosignature, if it is far from equilibrium. If large amounts of oxygen or ozone coexisting with a gas that is consumed by oxygen (e.g., methane) are detected in a planetary atmosphere, oxygen must be replenished continuously, and oxygenic photosynthesis is the most efficient way (Lovelock, 1965). However, life alters its environment in many other ways as well. Studying the interplay between the biosphere and Earth’s evolution can provide important hints on how life shapes its planet in general, and thus can help to search for life on other planetary bodies.

Life has been present on Earth at least during the last 3.5 billion years, despite an increasing solar heat flux and a decreasing internal heat production over time. This does not only presuppose a strong ability of organisms to adapt to a changing environment. Furthermore, it suggests that the biosphere modifies Earth’s reservoirs to keep the planet habitable and in a state that favors the evolution of life. Earth co-evolves with its biosphere, and feedback cycles emerge between its reservoirs and the biosphere. These feedback cycles are often discussed for the biosphere and the climate (e.g., Lenton and von Bloh, 2001), in contrast, effects of interior evolution on habitability and biological evolution are usually only discussed in this specific direction of interest (e.g., Noack et al., 2014). However, the strongly interconnected evolutions between Earth’s biosphere, crust, and mantle imply an interplay between the biosphere and Earth's interior, in the past and at present day.

1.2 Co-Evolution of Life and Planet Earth

I start by briefly reviewing Earth's evolution and the co-evolution of its biosphere. Details can be found in e.g., Lunine (2013) or Southam et al. (2015). When Earth was formed approximately 4.6 billion years ago (Stevenson, 1983), potential energy was converted into thermal energy by accretion and differentiation. The moon-forming event 4.4 billion years ago and large bombardments by comets further heated up Earth's crust. Volcanism was widespread, and the atmosphere dominated by CO_2. Any potential surface water ocean would have been evaporated, and any potential life extinct (Sleep et al., 1989). This time period is called the Hadean eon and lasted from approximately 4.0 to 3.8 billion years b.p. The transition to the Archean eon was characterized by the oldest whole rock samples found on Earth, also including continental-type granitic rocks. The surface cooled down, stable oceans could form, and Earth became habitable. The time at which life appeared on Earth (whether it originated on Earth or was brought by impacts) is a controversial issue. Microfossils are dated back to 2.55 billion years b.p., but rocks show strong evidences for microbial activity going back to 3.5 billion years b.p. (see review by Buick, 2007). Isotopic measurements of carbonaceous inclusions within grains of apatite from 3.8 billion years old banded iron formations indicate biologic activity even earlier (Mojzsis et al., 1996). At that time, the atmosphere was mainly composed of nitrogen and carbon dioxide produced by volcanism (e.g., Kasting, 1993).

Earth's evolution has been affected strongly by the solar activity increasing with time. With ongoing hydrogen fusion in the sun's core, its density increases. The energy of compression is converted into thermal energy, and the temperature in the sun's core increases. As the fusion rate depends on temperature, the luminosity of the sun increases with its evolution, and so does the solar heat flux that reaches Earth's surface (Sagan and Mullen, 1972). Simple scaling of the mean surface temperature with the solar heat flux provides a mean surface temperature below the freezing point of water during the Archean (Kasting, 1989), which is inconsistent with samples of metamorphosed sedimentary rocks and the appearance of widespread life (Kasting and Catling, 2003; Lunine, 2013). This so-called "faint young sun paradox" can be solved by accounting for greenhouse gases in Earth's atmosphere during evolution. The amount of greenhouse gases in the present day atmosphere is comparatively small (with respect to Venus, for instance). Although water is a strong greenhouse gas, the water cycle in the atmosphere only operates on small time scales and is controlled by the surface temperature itself. However, larger abundances of greenhouse gases as carbon dioxide could have caused higher surface temperatures in the past and could solve the faint young sun paradox (Kasting and Ackerman, 1986; Kasting and Catling, 2003). Furthermore, methanogens could have played a role in shifting Earth's surface temperature to moderate values through the production of CH_4, which acts as a strong greenhouse gas in the atmosphere as well (e.g., Kasting and Catling, 2003). Note that this indicates that the biosphere has fed back on the habitability of Earth even in early evolution.

A key event in biological evolution has been the emergence of oxygenic photosynthesis by cyanobacteria at least 2.7 billion years ago (Brocks et al., 1999). The biosphere acquired the ability to convert a great amount of solar energy into chemical energy. The atmosphere increased its O_2 level approximately 400 million years later (Kasting and Catling, 2003; Holland, 2006). Aerobic respiration enabled life to generate large amounts of energy. The biological production of O_2 fed back to the atmosphere as it built up the ozone layer (by photolysis of oxygen). The ozone layer in turn absorbs ultraviolet light and thus plays an important role in protecting the biosphere. The dramatic rise of O_2 in the atmosphere after a delay of approximately 400 million years (Kasting, 2001) has been argued to be a possible result of a feedback mechanism including methane, oxygen and ozone (Goldblatt et al., 2006). In this model, with increasing oxygen production and the rise of an ozone layer, the shielding from ultraviolet light slowed down the rate at which oxygen reacts with methane. A runaway process occurred and the atmospheric oxygen level rapidly approached another stable state. This indicates that the biosphere does not only shape Earth in moving one particular stable state; it rather causes Earth's system to approach a different one. Based on processes including Earth's interior, a similar effect of Earth's biosphere will be discussed further below (Section 2).

With the ability to effectively use solar energy through oxygenic photosynthesis, life strongly benefited from the growth of continental crust. In addition to emerged continents, continental shelf regions promote a flourishing biosphere, since sunlight penetrates shallow water where it can be converted into chemical energy via photosynthesis. Continental shelf regions are the main areas of phytoplankton primary production (see e.g., Behrenfeld and Falkowski, 1997), and thus fundamental to the marine food chain. Continental crust differs from oceanic crust by having a felsic instead of mafic composition. Felsic rocks (mainly granites) have higher silica and smaller iron and magnesium contents compared to mafic rocks (mainly basalts), and are therefore less dense. While oceanic crust is formed at mid-ocean ridges and hot spots by partial melting of mantle material, the formation of continental crust is more complex. In subduction zones, the dehydration of oceanic crust, sediments, and forearc serpentinites releases water, thereby reducing the melting temperature of the subducting oceanic crust and mantle material. Partial melt with an andesitic composition is generated and migrates upwards due to its smaller density with respect to the surrounding mantle matrix. The formation of granites requires additional re-melting processes. Although the exact processes are poorly understood, there is a consensus that water is required to form new continental crust (Campbell and Taylor, 1983). The evolution of continental crust is a controversial issue: Some studies favor a rapid, early growth (around 4 billion years b.p.) and a balance of production and erosion rates thereafter (Armstrong and Harmon, 1981; Armstrong, 1991). Other studies argue for an early slow phase, followed by more rapid growth during the Archean-Proterozoic transition 2.5 billion years ago, followed by a slower growth rate afterwards (Taylor and McLennan 1985; 1995). Belousova et al. (2010) argue for a steady, more gradual growth and suggest that most of the continental crust have been formed by 2.5 billion years before present, followed by a smaller net growth rate since then. In any case, the geochemistry of the continental crust changed during the Archean-Proterozoic transition (e.g., Lunine, 2013). In contrast to recent rocks, higher abundances of sodium than potassium and a composition closer to that of the mantle can be observed in Archean rocks. Archean sediments exhibit a large variability, indicating variable conditions during their formation. The nature of Archean continents is not fully understood, at least because it is not clear when modern plate tectonics has been initiated. Without plate tectonics, large mantle heat flows in the Archean leading to widespread volcanism could have caused re-melting and differentiation of basalt, eventually producing Archean continents (e.g. Kröner, 1985). It has further been argued that a hot mantle could have caused melting of oceanic crust in subduction zones, whereas the more recent production of continents implies melting of mantle wedge material above the slab (e.g., Smithies et al., 2003). For the present day, most studies indicate a small or zero net growth rate of continental crust (Ashwal, 1989).

Depending on the thermal profile of the subduction zone and on the water-carrying minerals, water can be subducted beyond the source region of partial melt, where nominally anhydrous minerals act as an important water reservoir (e.g., Bell and Rossman, 1992). Outgassing of water occurs at mid-ocean ridges and other volcanic units. Within the atmosphere and rivers, water is transported into the oceans and subducted back into Earth's mantle within the hydrated oceanic crust and sediments. As water in the Earth's mantle lowers its viscosity (Blacic, 1972; Karato et al., 1986), the speed of convection increases. As both mantle water outgassing and regassing are enhanced, the deep water cycle describes a feedback cycle operating in the Earth's mantle (McGovern and Schubert, 1989).

Models of continental growth may be used in combination with models of mantle cooling and the record of continental freeboard to constrain the evolution of surface oceans (e.g., Harrison, 1999; Flament et al., 2008; 2011). Most studies assume a constant or decreasing surface ocean reservoir since the Archean (e.g., Kasting and Holm, 1992; Harrison, 1999). Assuming a constant planetary water inventory, this would imply that the Archean mantle was not wetter than today. Flament et al. (2013) point out that the increase in the $^{87}Sr/^{86}Sr$ of marine carbonates in the Archean, commonly used as an argument for delayed continental growth, can also be explained with the emergence of continents above sea-level.

For constant continental volume, the emergence of continents can be explained by, e.g., a decreasing surface water reservoir. For a constant planetary water inventory, this would go along with an increasing mantle water reservoir. At present day, the mantle water concentration is argued to be close to a steady state (Kasting and Holm, 1992).

1.3 Self-Regulation of Earth's System and Biological Contribution

The continuously increasing solar heat flux has strongly affected Earth's climate. A positive feedback cycle that operates on short time scales involves the surface temperature and water vapor: An increasing surface temperature raises the water vapor concentration in the atmosphere. This acts as a strong greenhouse gas, and the surface temperature increases further (for a review on climate feedback cycles, see e.g. Catling and Kasting, 2007). Without additional stabilizing mechanisms operating on short time scales, a runaway greenhouse effect would be triggered. However, a negative feedback loop is caused by the temperature-dependence of the outgoing infrared flux; with increasing temperature, Earth's surface cools more efficiently.

Additional positive feedback loops operate on long time-scales: An increasing surface temperature causes melting of polar caps. This reduces Earth's albedo and causes the surface temperature to rise further, triggering a runaway mechanism (e.g. Lenton, 2013). A key negative feedback loop on long time scales that counteracts the increasing solar heat flux is the long-term carbonate-silicate cycle (Kasting and Catling, 2003; Catling and Kasting, 2007); CO_2 in the atmosphere is dissolved in rainwater to form carbonic acid, which in turn reacts with silicate rocks. The weathering products (e.g., calcium and bicarbonate ions) are transported into oceans by rivers where calcium carbonates are precipitated. Carbonate sediments are transported with the oceanic plate and eventually subducted into the mantle. At the high pressures and temperatures of the upper mantle, metamorphic reactions release CO_2, which enters the atmosphere via volcanism. The long-term carbon cycle changes over time with decreasing volcanic activity and CO_2 outgassing and an increase in the emerged area of continents exposed to weathering. The amount of CO_2 in the atmosphere is reduced, which sustains a low surface temperature. But more importantly, the long-term carbon cycle acts as a negative feedback cycle. On one hand, weathering requires liquid water. Therefore, a frozen surface would lead to an accumulation of carbon dioxide in the atmosphere. The surface temperature would increase and the ice cover would melt. This process is argued to be a major reason for the end of Earth's ice ages (e.g., Kasting and Catling, 2003). On the other hand, the silicate-weathering rate is temperature dependent, and thus, the rate at which CO_2 is removed from the atmosphere increases with the surface temperature. With a smaller CO_2 concentration in the atmosphere the surface temperature decreases. These stabilizing mechanisms can explain why liquid water could be stable on Earth's surface for at least 3.5 billion years despite an increase in the solar heat flux (Walker et al., 1981; Kasting, 1989; Kasting and Catling, 2003).

Although the long-term carbon cycle can basically work without the contribution of life, the biosphere strengthens the negative feedback. First, life enhances silicate weathering in various ways. Particularly the production of acids by, e.g., microbes and fungi attacking silicate minerals plays an important role (e.g., Boyle and Voigt, 1973; Schwartzman and Volk, 1989; Berner, 1992; Hoffland et al., 2004; Uroz et al., 2009). In addition, the biota increases the residence time of water and thereby the time for reaction between minerals and water (e.g., Drever, 1994). Lichens, for example, that cover bare rocks provide a continuous humid environment. On long time scales, the dissolution of rock should enhance the rate of surface erosion and thereby the rate at which sediments are subducted. Additional effects of the biosphere directly enhance erosion, such as land plants that break rocks with their roots.

Second, organisms store weathering products in shells of which some are buried in sediments on the seafloor. These sediments are eventually subducted into the mantle. Note the temperature-dependence of bioactivity, so that the biological contributions to weathering and sedimentation increase with temperature. Altogether, the long-term carbon cycle works more efficiently with the contribution of an active biosphere, and the biotic enhancement of the negative feedback extends the lifespan of the biosphere (see Lenton, 2002).

However, the self-regulation of Earth's surface temperature is, for instance, limited by hydrogen escape (upper limit of solar luminosity), and by a formation of reflective CO_2-clouds (lower limit) (Kasting et al., 1993). Lovelock and Whitfield (1982) point out that a decrease of the CO_2 concentration in the atmosphere could limit the life span of the biosphere, because photosynthesis only works above a critical value of the CO_2 concentration. As the weathering rate increases with bioactivity, Caldeira and Kasting (1992) propose that the critical solar luminosity for the self-regulation of Earth's climate is approximately 1.05 of its present day value, corresponding to around 0.9 Gyr from the present day. At larger values of solar luminosity, Earth's surface temperature would rapidly increase, eventually removing the surface water through photodissociation and hydrogen escape. The emergence of such tipping points (states at which small disturbances would cause the system to evolve into another state) is typical for systems that contain positive feedback loops (see Lenton, 2013, for a review on tipping points in environmental systems). If the system exceeds a tipping point it collapses and evolves towards another stable state. If life moves the tipping point, it could be crucial in keeping Earth's surface temperature at moderate values, which in turn permits a widespread biosphere.

Margulis and Lovelock (1974) first discussed the self-regulation of Earth's climate at habitable conditions with the contribution of life itself, and proposed the Gaia-theory. Earth and its biosphere are treated as one complex system that evolves in a way that habitable conditions are sustained. As a hypothetical example, Lovelock (1983) developed a model called "Daisyworld", where the surface temperature of a planet is regulated via the temperature-dependent growth of black and white daisies, and via their effect on the planetary albedo. A main issue in the Gaia-theory is the intended feedback of the biosphere on Earth's evolution. How does life "know" what keeps Earth habitable, and why should it contribute? Studies focus on exploring how self-regulation could arise from natural selection (e.g. Lenton, 1998). A concept is used where individual organisms change their environment in various ways. Organisms that benefit from the environmental change will grow, whereas others will die out. On long-term evolution, organisms should dominate that change their environment in a way where they grow at an optimum rate.

1.4 Effects of Life on Planetary Interior Evolution

Life is known to have strongly impacted the evolutions of Earth's oceans, crust and atmosphere (e.g., Kasting and Siefert, 2002; Holland, 2006; Sleep et al., 2012). Moreover, plate tectonics allows possible effects of surface life on interior evolution. Through recycling of oceanic crust and sediments, the biosphere is argued to have modified chemical fluxes into the mantle, leaving a biological record (Sleep et al., 2012). This is particularly true after photosynthesis developed, as photosynthetic life harvests large amounts of solar energy and converts it into chemical energy. Rosing et al. (2006) point out that the rate at which solar energy is captured by photosynthetic life exceeds the present day heat flow from Earth's interior by far. Part of this energy could be transferred within geochemical cycles by weathering processes and impact Earth's interior by subduction of sediments and altered oceanic crust. The authors hypothesize that the formation of continental crust has been a major consequence of the conversion of solar energy by biological forcing that is channeled into geochemical cycles. As discussed earlier, continents are formed in subduction zones with the presence of water. Biological processes that alter the oceanic crust and the sediments in a way that the water transportation rate to depth is enhanced contribute indirectly to the formation of continental crust. Dyke et al. (2011) argue that the free energy generated by surface life and put into geochemical cycles alters the boundary conditions for interior geological processes. Their model account for the thinning of continental crust due to biologically enhanced surface weathering processes, resulting in larger mantle heat flows eventually enhancing oceanic crust recycling and outgassing of CO_2 into the atmosphere. However, the model neglects any effects of weathering products on subduction zone processes, which could cause nonlinear overall effects of enhanced weathering rates that are difficult to predict.

Assuming that free energy produced by surface life via photosynthesis is channeled into geochemical cycles that include Earth's interior, the main mechanism on Earth is subduction. Of all components in the subducting slab, the sedimentary layer, mainly originating from weathered and eroded continental crust, is the main reservoir that is directly affected by surface life. A biologically modified rate, structure and composition of subducted sediments could then impact metamorphic reactions in subduction zones. The surface energy of these sediments is provided by geochemical cycles operating on Earth's surface, including biological activity. Various possible effects of subducted sediments on subduction zones processes and continental production have been proposed. For example, Manning (1996) argues that the presence of sediments along the slab-mantle interface increases the aqueous silica concentration, eventually affecting the production and overall composition of continental crust. Rosing et al. (2006) point out that clay minerals produced during weathering can act as alkali exchange media, and Theissen and Rüpke (2010) discuss the blanketing effect of a sedimentary layer on crustal heat flow and metamorphic reactions due to its low thermal conductivity. Although overlying sediments at mid-ocean ridges would result in larger crustal temperatures, a sedimentary layer in subduction zones could isolate the crust from the hot mantle.

Water-related effects of sediments in subduction zones are of particular importance, as they can cause strong positive feedbacks, which will be discussed further below. Two mechanisms and their overall effect on Earth's system and interior evolution are here discussed in detail. First, subducted sediments carry water, partly bound in stable phases (Jarrard, 2003). Significant quantities of pore- and structural water are expelled at shallow depth but some of the water will reach the upper mantle stored in e.g. clay-rich sediments (Hacker, 2008) and hydrous minerals formed by low-temperature metamorphic reactions during subduction (Jarrard, 2003; Stern, 2002). Ono (1998) points out that sediments play an important role in transporting water into the mantle particularly in hot subduction zones. Second, the upper part of the sedimentary layer is clay-rich and has a low permeability. The permeability further decreases with increasing lithostatic pressure and compaction such that the sedimentary layer acts as an increasingly effective barrier to shallow dewatering (Shipley and Moore, 1986; Moore, 1987).

At greater depth, the remaining water could then be used by low-grade metamorphic reactions. Additionally, it could react with peridotite in the forearc mantle to form serpentinites (Scambelluri and Tonarini, 2012; Hyndman and Peacock, 2003; Hattori and Guillot, 2003; Guillot and Hattori, 2013) that are dragged downward with the convection current. Lafay et al. (2013) argue that water can be transported to greater depth via a "trap-and-release system". Altogether, subduction of water is strongly affected by subducted sediments and mantle wedge serpentinites, eventually affecting partial melting and continental crust production (e.g., Deschamps et al., 2012; 2013).

With Earth's biosphere enhancing continental weathering and erosion, it increases the loss rate of continental crust. However, these processes also enhance the subduction rate of sediments, and ultimately the production of continental crust and the regassing of water into Earth's mantle. The combined effect strongly depends on the interconnection between the continental and the mantle water cycle. The investigation of evolving feedback cycles is essential to understand how surface life feeds back on planetary evolution including the interior.

2. Summary and Discussion of the Publications

The goal of this thesis was to identify and to investigate possible effects of the surface biosphere on the interior evolution of Earth. To this aim, it is assumed the biosphere increases the rate of surface erosion per surface area of continental crust by increasing the weathering rate. This results in a larger rate at which sediments are subducted. With sediments influencing the water transport in subduction zones, the biosphere indirectly impacts the formation of continental crust and the regassing of water into Earth's mantle. To investigate the overall effect on Earth's evolution, the combined surface area of continental crust (also termed as continental coverage) and the concentration of water in Earth's mantle are described as a coupled system of feedback loops in the thermal evolution of Earth.

This section serves as a combined summary and discussion of both publications, which can be found as appendices. It further includes the discussion of some aspects in a broader context and the presentation of results in a more profound way. I start with introducing the model in Section 2.1, and discuss the results in phase planes spanned by mantle water concentration and continental coverage in Section 2.2. I show how multiple fixed points can exist in this phase plane as a consequence of subducting sediments increasingly impacting the feedback cycles. As the mantle cools, fixed points appear and move in the phase plane. Based on the moving of the fixed points, I show in Section 2.3 how the fixed point that is representative of present day Earth can be identified. In a steady state model, I discuss the effect of Earth's biosphere on the system as a shift of the fixed points due to varying the rates of surface erosion and sedimentation. In Section 2.4, I present possible evolution paths of Earth to constrain the initial conditions of the model. To simulate the evolution of an abiotic Earth, the model uses the obtained initial conditions but reduced rates of surface erosion and sedimentation.

2.1 Continental Growth and Mantle Hydration as Intertwined Feedback Cycles

This section serves as a basic outline of the model, which is illustrated in Fig. 1. Mathematical details can be found in Höning and Spohn (2016), which is based on Höning et al. (2014). The model interconnects the feedback cycles of mantle water concentration (Fig. 1, blue branch) and continental coverage (Fig. 1, red branch). The cycles are coupled through the subduction of water to mantle depth. A part of this water is released in the source region of partial melt, while the rest is subducted further and eventually regassed into the mantle. To limit the complexity of the model, a constant ratio is assumed. The production rate of continental crust is set proportional to the rate at which water is released in the source

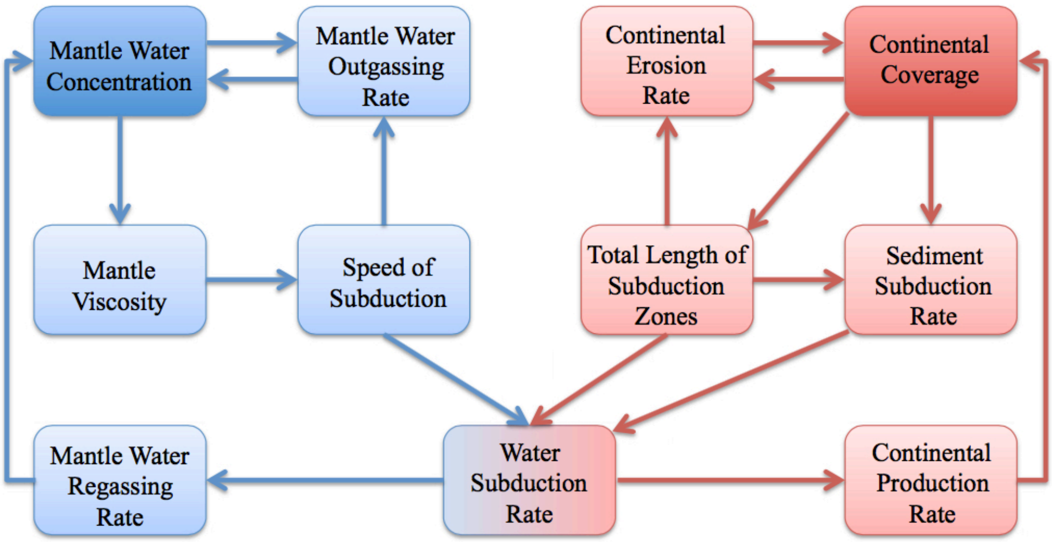

Fig. 1: Flowchart representing the intertwined feedback cycles of continental growth and mantle hydration, after Höning and Spohn (2016). The arrows represent effects. Feedback cycles related to the evolutions of mantle water concentration and continental coverage are colored blue and red, respectively. The interconnection of both feedback cycles occurs through the subduction of water.

region of partial melt. The difference between mantle water regassing and outgassing over time determines the evolution of water in the mantle, and the difference between continental production and erosion over time determines the net growth rate of continental crust.

The mantle viscosity is a key parameter of the blue branch in Fig. 1. It is calculated dependent on temperature and water concentration based on a model for dislocation creep following Karato and Jung (2003). Note that this assumption presupposes that dislocation creep dominates over diffusion creep at pressures in the upper mantle, as indicated by laboratory experiments by e.g., Mei and Kohlstedt (2000). Unfortunately, the actual present day concentration of water in Earth's mantle is not well established. However, the model uses a relative mantle viscosity, for which the reference mantle viscosity is derived from an assumed present day mantle temperature and mantle water concentration.

The mantle viscosity strongly decreases with increasing mantle temperature and mantle water concentration (see, e.g., Fig. 3 of Höning and Spohn, 2016), thereby enhancing the convection strength. The effect on the rate of convection is derived using boundary layer theory (e.g., Turcotte and Schubert, 2002). The subduction rate is set proportional to the convection rate. As a wet mantle causes rapid convection and subduction, the rate of mantle water regassing is enhanced. This establishes a positive feedback, with an accelerating increase in the mantle water concentration.

However, a negative feedback stabilizes the system: To determine the mantle water outgassing rate, a rising mantle plume with a certain speed, thickness and water concentration underneath a generic mid-ocean ridge is considered. The speed and thickness are again scaled with the mantle viscosity using boundary layer theory. Altogether, the mantle water outgassing rate increases with the mantle water concentration to a larger extent than the mantle water regassing rate does (see also Fig. 3 of Höning and Spohn, 2016). This indicates that Earth's state concerning mantle water concentration is stable; small disturbances would cause the mantle water concentration to evolve back into this state.

The evolution of continental crust coverage (Fig. 1, red branch) includes further feedback loops. To limit the complexity of the model, a constant height of continental crust is assumed, so that a net growth of the continental crust volume results in an increase in continental coverage. Erosion of continental crust is divided into surface erosion and subduction erosion, which are the main mechanisms to erode continental crust (e.g., Stern, 2011). As the height of continental crust is kept constant, both types of erosion cause a loss of the surface area of continental crust. However, if the model would account for the topography, surface erosion would on one hand reduce the continental area by eroding regions of thin continental crust, but on the other hand reduce the height in regions of thick continental crust. Therefore, the present model likely overestimates the effect of surface erosion in reducing the area of continental crust. The effect of this simplification on the results will be discussed in Section 2.2.

The rate of surface erosion is set proportional to the total surface area of continental crust. Subduction erosion, on the other hand, takes place where oceanic crust is subducted underneath continental crust. Therefore, the rate of subduction erosion is set proportional to the total length of ocean-continent subduction zones. Although the rate of subduction erosion in general further depends on other factors as the speed of subduction and the sediment thickness, it is independent of these factors for a rapid subduction and for a small sediment thickness (Stern, 2011). As the mantle has been significantly hotter than today during large periods of the evolution, causing rapid subduction and a thin sediment cover, these additional factors are neglected in the model.

The total length of ocean-continent subduction zones is modeled as a function of the continental surface area. In doing so, the total length of convergent plate boundaries is kept constant. However, ocean-ocean subduction zones should dominate over ocean-continent subduction zones for much smaller continental coverage than at present day. For a (putative) much larger continental coverage, continent-continent convergence zones should dominate. In the model, the total length of ocean-continent subduction zones is set proportional to the total length of ocean-continent margins. This length is calculated using stochastic geometry (Schneider and Weil, 2008), assuming randomly distributed spherical caps as continents, which may overlap. The total length of ocean-continent margins shows a maximum at a continental coverage of approximately 40% (see Fig. 4 of Höning and Spohn, 2016). This is roughly the value of present day Earth (including the continental shelves). At this maximum, all convergence zones are assigned to an ocean-continent type. For smaller values of continental coverage, the total length of ocean-continent subduction zones decreases and the remaining length of convergence zones is assigned to an ocean-ocean type. For larger continental coverage, the total length of ocean-continent subduction zones decreases, too. However, in this case, the remaining length of convergence zones is assigned to a continent-continent type.

In general, continental erosion acts as a negative feedback. This is because increasing values of continental coverage enhance continental erosion, which in turn counteracts the increasing continental coverage. However, the strength of this negative feedback depends on the ratio between surface erosion and subduction erosion, and on the actual value of continental coverage. The rate of surface erosion linearly increases with continental coverage. In contrast, subduction erosion is particularly efficient for continental coverage of approximately 40%, which is the value for which the total length of ocean-continent subduction zones has its maximum. Assuming that surface erosion and subduction erosion contribute with similar shares to the present day total erosion rate (consistent with Stern, 2011), a particularly strong negative feedback for values of continental coverage below 40% results. In this range, both surface erosion and subduction erosion increase with continental coverage. At values of continental coverage above 40%, a decreasing rate of subduction erosion counteracts an increasing rate of surface erosion. Therefore, the negative feedback is comparatively weak here.

Further, the shares between the three types of convergence zones are important as no water subduction occurs at continent-continent convergence zones. At values of continental coverage larger than 40%, increasing the continental coverage reduces the total length of subduction zones, thereby establishing a negative feedback. In the extreme case of 100% continental coverage, subduction zones vanish and the rate of continental production is zero.

The box model of continental coverage (Fig. 1, red branch) also includes positive feedbacks. Surface erosion of continental crust produces sediments that are eventually subducted into Earth's mantle (e.g., Plank and Langmuir, 1998). Subducted sediments are modeled to carry water partly bound in stable mineral phases and partly stored in pores. In addition, due to the low permeability of the upper, clay-rich part of the sedimentary layer, subducted sediments are modeled with various efficiencies to partially suppress dewatering of pore- and loosely bound water at shallow depth (see the preceding Section 1.4 for details). The rate at which free- and loosely bound water of the oceanic crust and sediments is expelled through the overlying sedimentary layer is calculated using Darcy's law (for mathematical details, see Höning and Spohn 2016, Section 7). The thickness of the sedimentary layer increases with the rate of surface erosion and decreases with the speed of subduction and with the total length of convergence zones that margin continental crust. The representative permeability of the sedimentary layer is calculated as a function of pressure using a cubic law following Kwon et al.

(2004). Overall, a positive feedback cycle emerges as large continents result in a large rate at which sediments are subducted, which in turn enhances continental crust production and mantle water regassing.

Unfortunately, the strengths of the individual feedbacks in the evolution of continental crust are difficult to quantify, as they depend on poorly known parameters. However, a reasonable set of parameter values (Höning and Spohn 2016, reference model) has the strength of the positive feedbacks exceeding the strength of the negative feedbacks within a certain range of continental coverage. This implies that the Earth's system possesses multiple steady states. These features are known to arise from positive feedbacks in non-linear systems such as the climate (discussed in Section 1.3, see also Lenton, 2013). However, it has been discussed for a system concerning continental coverage and mantle water concentration for the first time as a part of this thesis (Höning et al., 2014; Höning and Spohn, 2016).

To investigate the feedback cycles over Earth's history, a thermal evolution model based on parameterized mantle convection has been coupled to the box model via the temperature-dependence of the mantle viscosity. Parameterized thermal evolution models of the Earth and other planetary bodies are described in, e.g., Schubert et al. (2001) or Davies (2007). The model uses boundary layer theory and parameterization of the convective heat transport. The evolution of the mantle temperature is based on the conservation of energy, and the thicknesses of the thermal boundary layers are derived using a local instability criterion (e.g., Stevenson et al., 1983). The temperature profile in the convecting mantle is assumed to be adiabatic. For details, see Höning and Spohn (2016, Section 3.1). Initial conditions (mantle temperature, mantle water concentration, and onset time of continental production and mantle water regassing through subduction) for the evolution are derived from a Monte-Carlo scheme.

Earth's biosphere is assumed to contribute to the present day rate of continental weathering. An abiotic Earth (that is a version of the Earth without a biosphere) would thus feature smaller rates of surface erosion. On the one hand, this would reduce the loss rate of continental crust, but on the other hand it would also reduce its gain rate because of the smaller rate at which sediments are subducted, resulting in a smaller rate of water subduction. The combined effect depends on the coupling between the individual feedback cycles and is investigated in the next sections.

2.2 Phase Planes and Fixed Points

The results are plotted in phase planes spanned by mantle water concentration and continental coverage. Each phase plane is valid for a certain set of model parameters and for a certain mantle temperature. As discussed in Section 1.2, the

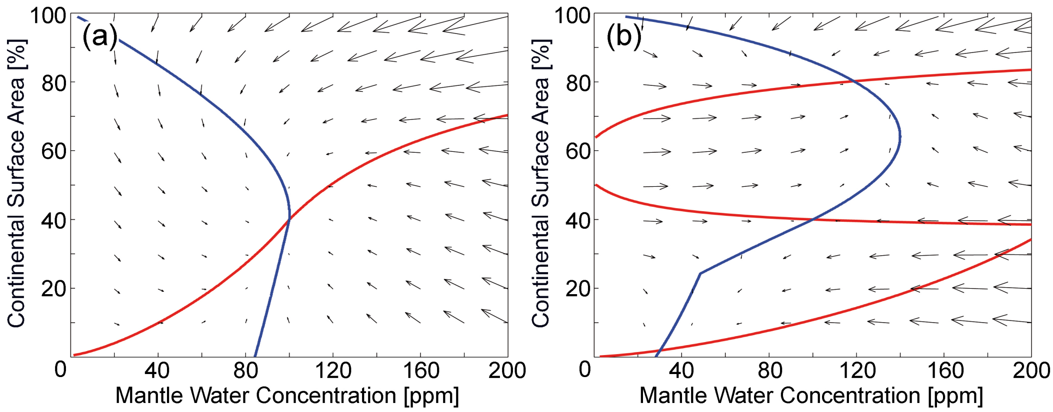

Fig. 2: Phase planes for the present day mantle temperature spanned by mantle water concentration and continental surface area. The blue and the red lines connect steady state values of mantle water concentration and continental surface area, respectively, and crossing points represent fixed points. Arrows indicate the direction of an evolving trajectory and their length is proportional to the rate of convergence. (a) Model with weak positive feedbacks (water with 90% bound within the subducting oceanic crust and with 10% within subducting sediments, other parameter values as in Höning an Spohn, 2016, Section 9.3.3). Only one fixed point exists in the phase plane. This fixed point is stable. (b) Reference model of Höning and Spohn (2016, Section 9.1). Sediments are also modeled to carry water partly bound in stable phases and to partially suppress shallow dewatering here. Positive feedbacks are sufficiently strong to cause the existence of three fixed points, of which the intermediate fixed point is unstable and located at present day values.

observed present day net rates of change of continental coverage and water concentration are small. Therefore, the model is scaled such that for the present day values of mantle temperature, continental coverage, and mantle water concentration, the latter two parameters are in steady state. As a consequence, the phase plane possesses a fixed point at these values. However, phase planes can significantly differ from each other concerning the possible existence of multiple fixed points, depending on the strengths of the individual feedbacks.

In general, the phase plane can either possess one or three fixed points. I start with discussing a phase plane for the present day mantle temperature that possesses only one fixed point, as derived from a model with weak positive feedbacks (Fig. 2a). Water is modeled to be bound within the subducting oceanic crust with 90% and within subducting sediments with 10%. The effect of the sedimentary layer in partially suppressing dewatering at shallow depth is neglected at this point.

The red line in the phase plane connects steady state values of continental coverage for different values of mantle water concentration. This line has a positive slope, because the speed of subduction and thus the rate of continental production increase with the mantle water concentration. Continental erosion, in contrast, is independent of the mantle water concentration.

The blue line connects steady state values of mantle water concentration for different values of continental coverage. Below 40% continental coverage, the steady state value of mantle water concentration increases with continental coverage. This is because the subduction rate of sediments increases with continental coverage, thereby enhancing the subduction rate of water. At values above 40%, however, the steady state value of mantle water concentration decreases with increasing continental coverage. This is due to the formation of continent-continent type convergence zones, which reduces the global rate of water subduction. For a continental coverage of 100%, subduction zones vanish and no mantle water regassing occurs. Therefore, the steady state value of mantle water concentration is zero here.

The crossing point of the steady state lines represents the fixed point of the system. Arrows indicate the direction of the evolution for certain points in the phase plane, and their lengths are proportional to the speed of convergence. The arrows point towards the fixed point, indicating that the fixed point is stable. Evolution trajectories in its vicinity would approach this fixed point. This is a reasonable result, because the strength of the negative, stabilizing feedbacks exceeds the strength of the positive feedbacks in this scenario.

Enhancing the strengths of the positive feedbacks or reducing the strengths of the negative feedbacks will reduce the stability of the fixed point. Ultimately, this leads to local bifurcation; the stable fixed point converts into an unstable fixed point, while two more fixed points form that are stable and located at smaller and larger values of continental coverage.

Fig. 2b shows the reference model of Höning and Spohn (2016, Section 9.1). This model additionally accounts for the effect of sediments in partially suppressing shallow dewatering due to their low permeability. This effect enhances the role of sediments in continental crust production and thus enhances the positive feedback. As a result, three fixed points exist in the phase plane. The intermediate fixed point is stable with respect to mantle water concentration but unstable with respect to continental coverage. Geometrically, it is a saddle point. The upper and the lower fixed points are stable.

Does the Earth's phase plane possess one fixed point as in Fig. 2a or three fixed points as in Fig. 2b? Answering this question is crucial as Earth's evolution strongly depends on the appearance and movement of the fixed points over time. After all, the effect of the biosphere on Earth's evolution depends on the possible existence of multiple fixed points in the phase plane.

Although their overall effect is difficult to quantify, subducted sediments have been assigned a large variety of effects (discussed in the previous Section 1.4) that eventually reinforce positive feedbacks in the continental and mantle water cycles. This reduces the stability of the fixed point, thereby enhancing the propensity of bifurcation. Note that for weaker negative feedbacks, bifurcation would also occur for weak positive feedbacks. As discussed in the preceding Section 2.1, the present model likely overestimates the effect of surface erosion on the loss rate of continental crust coverage. Therefore, one could reduce the rate of surface erosion with respect to subduction erosion in the model. This would weaken the negative feedback because large continents would be eroded less efficiently. As a consequence, the stability of the fixed point would be reduced. In the extreme case of modeling subduction erosion as the only mechanism to erode continental crust, bifurcation would occur for fractions of water carried by sediments of less than 1% (not shown here). Altogether, the existence of three fixed points in the phase plane is plausible.

However, the positions of the individual fixed points in the phase plane depend both on poorly known parameters and on individual mechanisms the model accounts for. If three fixed points exist in the phase plane, the question rises of which fixed point would be representative of the present day Earth. In Fig. 2b, the intermediate, unstable fixed point is located at present day values concerning continental coverage and mantle water concentration. Alternatively, the upper, stable fixed point could be located at present day values; such a scenario is presented in Höning et al. (2014), for which subduction erosion was neglected and sediments were not modeled to carry water. However, with an increasing role of subduction erosion with respect to surface erosion, the total erosion rate for large continental coverage is reduced. As a result, the upper branch of the steady state continental coverage curve moves to larger values, and the location of the upper stable fixed point at present day values would require increasingly unrealistic parameter combinations. In the next section, I present a concept of how the question of which fixed point is representative of present day Earth can be addressed.

2.3 Movement of the Fixed Points and the Impact of Bioactivity

In this section, the movements of the fixed points in the phase plane with mantle cooling are investigated. These movements can additionally constrain whether one or three fixed points exist in the phase plane, and help to identify the fixed point that is representative of present day Earth. To this aim, the movements of the fixed points, for which the respective present day phase planes are presented in Fig. 2, are illustrated as dots in Fig. 3. I start with discussing the scenario of only one fixed point existing in the present day phase plane (Fig. 3a). This fixed point is stable and moves as the mantle temperature decreases from hot (red) to cold (blue). The reference mantle temperature for the present day, for which the phase plane is plotted in Fig. 2a, is colored green. Although strongly dependent on initial conditions and on details of the thermal evolution model, this temperature range is representative of thermal evolutions of the model neglecting the first 1 billion year.

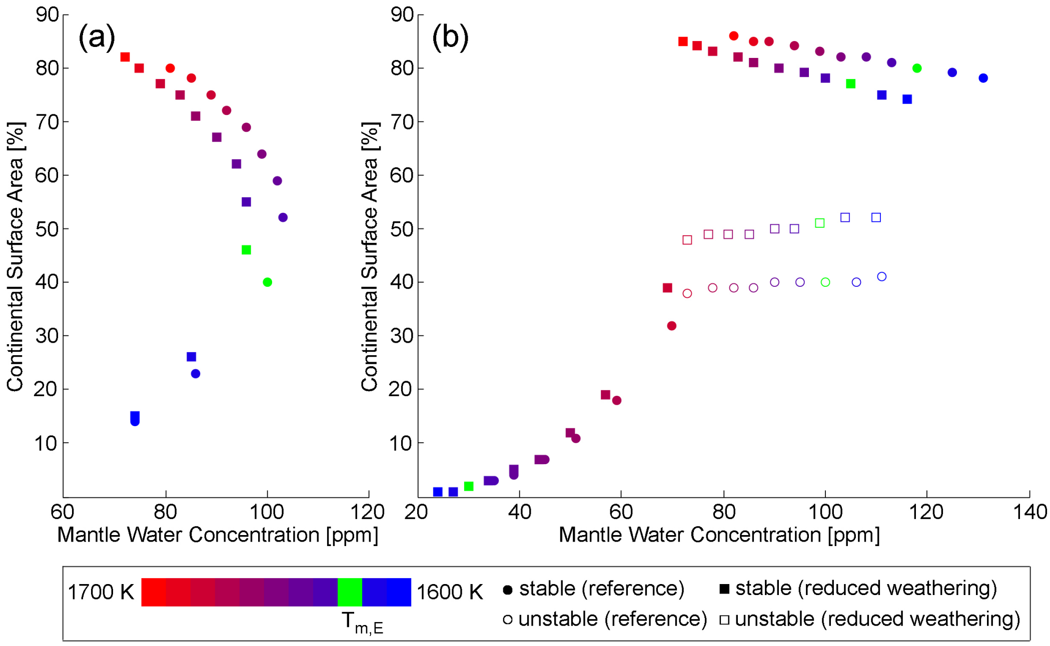

Fig. 3: Fixed points (filled: stable, empty: unstable) in phase planes spanned by continental coverage and mantle water concentration. Dots represent fixed points using the reference rate of surface erosion, and squares represent fixed points for the rates reduced by 20% (abiotic scenario). Colors represent fixed points for mantle temperatures varying from 1700K (red) to 1600K (blue), while the reference mantle temperature for the present day of 1620K is colored green. (a) Positive feedbacks are too weak to cause bifurcation and only one fixed point (which is stable) exists for a given mantle temperature. For model details see caption of Fig. 2a. (b) Positive feedbacks are sufficiently strong to cause the existence of three fixed points for the present day mantle temperature. For model details see caption of Fig. 2b.

In the scenario of only one fixed point (Fig. 3a), the fixed point moves to smaller values of continental coverage as the mantle cools. This is because continental production is mainly determined by the speed of subduction increasing with mantle temperature, with only a weak contribution of subducted sediments. Note that rapid subduction caused by a hot mantle, however, does not necessarily imply a large steady state mantle water concentration. This is a result of rapid subduction also causing large steady state continental coverage, which in turn reduces the total length of subduction zones. As a consequence, the rate of mantle water regassing is reduced. The steady state mantle water concentration is highest for a mantle temperature that causes steady state continental coverage of approximately 50%. Note that this value is larger than the value of continental coverage for which the total length ocean-continent subduction zones has its maximum (that is approximately 40%). This is because the speed of subduction and thus the mantle water regassing rate increase with the mantle temperature to a larger extend than the mantle water outgassing rate does (see Fig. 3 of Höning and Spohn, 2016).

As discussed above, Earth's biosphere is assumed to enhance continental weathering, resulting in larger rates of surface erosion. To study the role of the biosphere on the system, squares represent fixed points for models for which the rate of surface erosion is reduced by 20% (abiotic scenario). Note that this value is chosen arbitrarily to qualitatively observe how bioactivity shifts the fixed point. The different locations between the squares and the dots in Fig. 3a illustrate that the biosphere shifts the fixed point to slightly smaller values of continental coverage. This is because the enhancement of the loss rate of continental crust caused by an increased surface erosion rate exceeds the enhancement of continental production caused by an increased water subduction rate within the sediments. The smaller steady state continental coverage, however, keeps a large total length of subduction zones, and thereby a large steady state mantle water concentration. In addition, sediments still contribute to mantle water regassing, albeit to a small extent. As only one fixed point exists in the phase plane, evolution trajectories would approach this fixed point. Thus, the difference in evolution between the biotic and the abiotic scenario strongly depends on the actual value of the biological enhancement of continental weathering and erosion, which is difficult to quantify.

The different colors of the dots for different mantle temperatures in Fig. 3a show that the fixed point moves due to mantle cooling from large continental coverage down towards present day values. Therefore, one could expect that approaching trajectories would decrease in continental coverage with time, too (see also Höning and Spohn, 2016, Section 9.3.5). This would imply larger continental coverage in Earth's history. However, such a scenario is commonly ruled out for the Earth (e.g., Schubert and Reymer, 1985). Therefore, a phase plane possessing only one fixed point as in Figs. 2a and 3a is presumably not representative of present day Earth.

Fig. 3b shows the movements of the stable fixed points (filled) and of the unstable fixed point (empty) for a scenario with three fixed points (reference model of Höning and Spohn, 2016, Section 9.1). The green dots again represent the fixed points for the present day mantle temperature. The respective present day phase plane is plotted in Fig. 2b. With ongoing mantle cooling, the stable fixed points, particularly the lower one, move to smaller values of continental coverage. Analogue to the scenario of only one fixed point, a location of this fixed point at values observed for the present day would likely imply larger continental coverage in Earth's history. Therefore, these fixed points are presumably not representative of present day Earth. In contrast, the intermediate, unstable fixed point remains close to its initial value of continental coverage as the mantle cools, so that constant continental coverage for Earth's recent past is possible. Although this fixed point is unstable, the rates of change in the vicinity of this fixed point are small (see arrows in Fig. 2b). Altogether, the movements of the fixed points with mantle cooling support the proposed existence of multiple fixed points in the phase plane and the position of the intermediate, unstable fixed point at values observed for the present day.

In the proposed scenario of three fixed points, the position of the intermediate fixed point in the phase plane is particularly important as it determines the zones of attraction of the stable fixed points. To prevent a trajectory from evolving towards the lower stable fixed point, a formation of the unstable fixed point at small values of continental coverage is beneficial. This is valid not only for the scenario of the intermediate fixed point located at values observed for the present day, but also for a scenario where the upper stable fixed point is located at these values (as in Höning et al., 2014).

A main result in Höning et al. (2014) was that a reduced rate of continental weathering and erosion as expected for an abiotic Earth moves the unstable fixed point to larger vales of continental coverage. As a consequence, the zone of attraction of the lower stable fixed point enlarges so that it becomes more likely for the planet to approach this state. The different locations of the dots and squares in Fig. 3b illustrate this feature independently of the mantle temperature.

For the proposed position of the unstable fixed point at values observed for the present day, the present day rates of continental weathering and erosion are of particular importance, since smaller rates would inevitably cause Earth to approach a state with small continental coverage and a dry mantle. In the next section, I will discuss this scenario in more detail and compare the evolutions of Earth and its abiotic analogue.

2.4 Earth's Evolution and Evolution of an Abiotic Earth

As discussed above, the existence of only one fixed point in the phase plane would cause evolution trajectories to follow the movement of this fixed point. However, for the proposed emergence and movement of multiple fixed points in the phase plane (Figs. 2b and 3b), Earth's evolution gets more complicated. To address this issue, the box model is coupled to a parameterized thermal evolution model based on boundary layer theory via the mantle viscosity. Initial conditions (mantle temperature, mantle water concentration, and the onset time of continental crust production and mantle water regassing through subduction) are derived from a Monte-Carlo simulation. All parameter combinations that end up with the present day continental crust coverage of 40% are treated as successful and plotted as trajectories in Fig. 4.

Phase planes are shown at five points in time of the evolution. Note that the phase planes are strictly valid for individual values of the mantle temperature rather than time. The mapping of temperature onto time occurs via one sample trajectory (green). The time it takes to reach a given temperature differs between models with different initial conditions, particularly in early stages of the evolution. Therefore, the points in time where the phase planes are plotted are strictly valid for the green sample trajectory only. However, the differences in temperature between the trajectories at any given time (at least beyond 1 Gyr) are small (see Höning and Spohn, 2016, Fig. 8c). Therefore, the error in associating phase

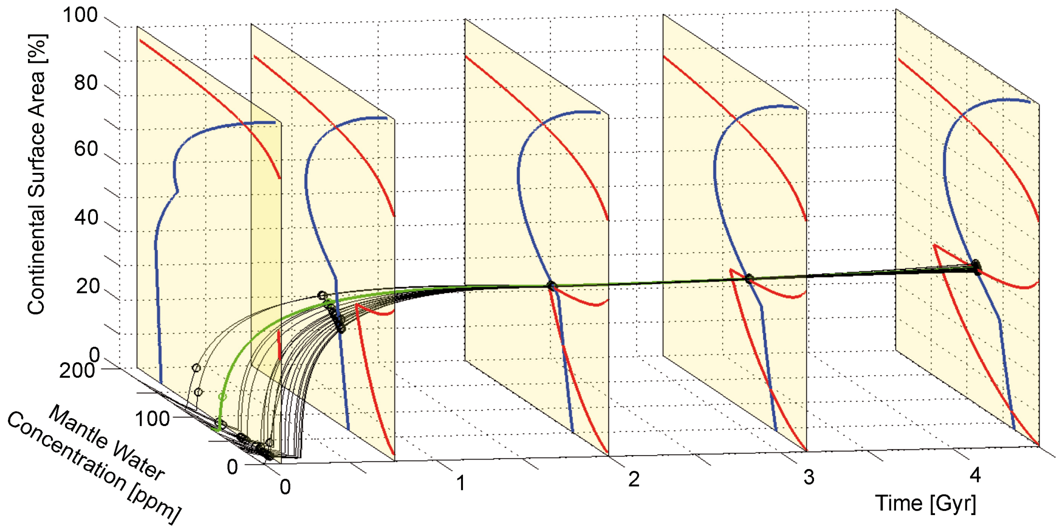

Fig. 4: Reference model of Höning and Spohn (2016). Evolution trajectories (green and black) of continental coverage and mantle water concentration with time and phase planes for mantle temperatures of 1800K (corresponding to 0.10 Gyr of the green trajectory), 1700K (0.76 Gyr), 1675K (2.00 Gyr), 1660K (3.15 Gyr), and 1641K (4.50 Gyr). The blue and red lines connect steady state values of mantle water concentration and continental coverage, respectively, and circles indicate points where trajectories intersect the phase planes.

planes with time can be accepted. Note further that the mantle temperatures reached at 4.5 Gyr by the evolution models do not exactly match the reference mantle temperature for the present day. Therefore, the phase plane in Fig. 4 at 4.5 Gyr differs from the phase plane in Fig. 2b to some extent.

In the simulations that satisfy the present day continental coverage, continents grow rapidly after the onset of continental production. At this time, only one fixed point exists, which is stable and located at large continental coverage thereby attracting the evolution trajectories. The unstable fixed point forms approximately after 2 billion years and does not change its location to a large extent afterwards (see also Fig. 3b). The successful trajectories have evolved into the vicinity of this fixed point and small net rates of change allow the trajectories to remain there.

In Fig. 5, the evolution trajectories of Fig. 4 are plotted (a) in the phase plane for the present day reference mantle temperature and (b) as functions of time. Note that the continental surface area is approximately in steady state since the last 2 billion years, accompanied by a slightly increasing mantle water concentration. This is a result of the movement of the intermediate fixed point (see Fig. 3b). As discussed in Section 1.2, an increasing mantle water reservoir would go along with a decreasing surface water reservoir (for a constant planetary water inventory). This could result in the emergence of continents above sea-level, which presumably has occurred in the Archean (Flament et al., 2013).

The evolution of an abiotic Earth is simulated by taking the same parameter values and initial conditions, but reducing the rate of surface erosion by 20%

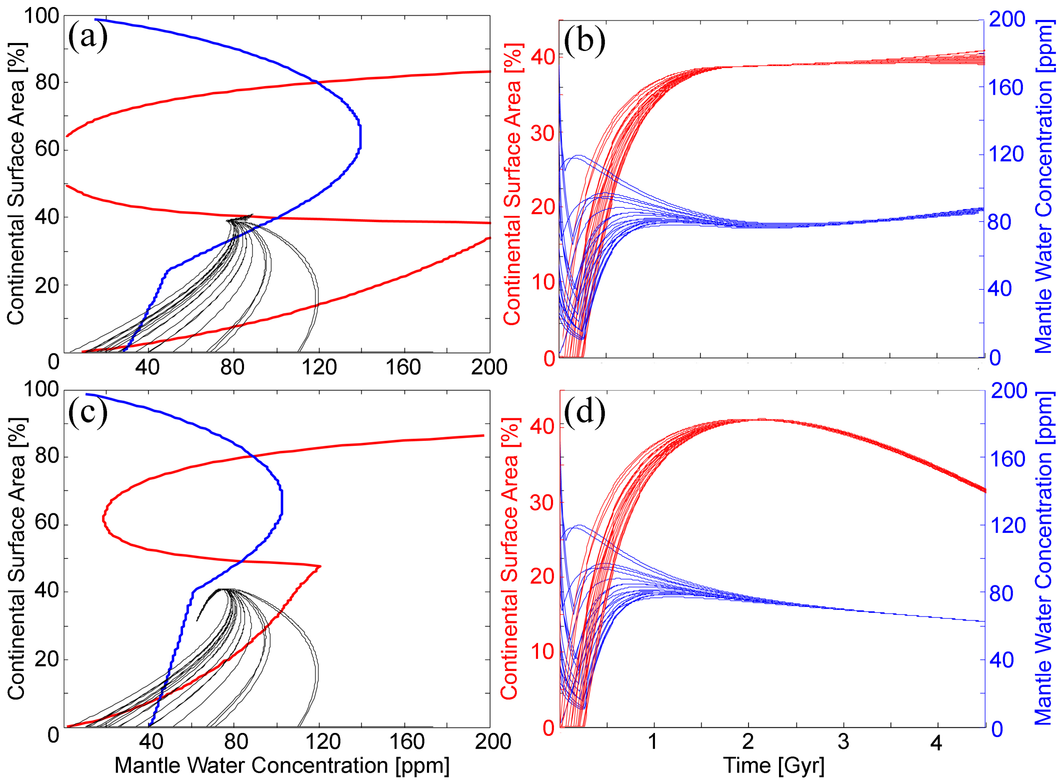

Fig. 5: (a) and (b): Reference model of Höning and Spohn (2016); (c) and (d): same model but using a rate of surface erosion reduced by 20% as associated with an abiotic Earth (see Höning and Spohn, 2016, Section 10.3). (a) and (c) show phase planes spanned by mantle water concentration and continental coverage for the present day reference mantle temperature where blue and red lines connect steady state values of mantle water concentration and continental coverage, respectively. Black lines represent evolution trajectories up to the present day. (b) and (d) show the evolution trajectories of mantle water concentration (blue) and continental surface area (red) as functions of time.

(Figs. 5c+d). The evolution of the first 2 billion years is similar to the biotic scenario, with the trajectories approaching the stable fixed point with large continental coverage. In the following, the unstable fixed point forms, but at larger values of continental coverage compared to the biotic scenario (see also Fig. 3b). The trajectories have evolved into the (emerging) zone of attraction of the fixed point with small continental coverage and a dry mantle. As a result, both parameter values decrease, and the model ends up with 30% (instead of 40% in the biotic model) of continental crust coverage and a water concentration in the mantle of 60 ppm (instead of 85 ppm). Note again that a decreasing mantle water concentration would go along with an increasing water reservoir on Earth's surface. Therefore, the area of continents that are emerged above sea-level would be expected to be much smaller. Note further that the biological enhancement of surface erosion (caused by an increased weathering rate) used in the model is not well constrained quantitatively. However, the actual value is not of great importance here since any trajectory in the zone of attraction of the lower stable fixed point would approach it, independently of the exact location of the unstable fixed point.

In other words, with the formation of the unstable fixed point, the system develops bistability, and large rates of continental weathering and surface erosion are required to keep Earth at its state of continental coverage and mantle water concentration. The unstable fixed point forms as the mantle cools below a critical temperature. In the reference model, this temperature is approximately 60 K above its present day value. The corresponding age of the planet depends on its thermal evolution. The reference model of Höning and Spohn (2016) uses a thermal evolution model based on parameterized mantle convection with a local boundary layer stability criterion and $\beta = 1/3$ as the exponent in the scaling of the Nusselt-Number (a measure of the convective heat transport) with the Rayleigh-Number (a measure of the strength of convection). This parameterization causes rapid early cooling and less cooling afterwards and the unstable fixed point forms approximately 2.5 billion years before present. However, a model with $\beta = 0.2$ (see Höning and Spohn, 2016, Section 9.2) results in a reduced cooling in the early evolution and in a stronger cooling in the recent past. In this model, the unstable fixed point forms roughly 1 billion year before present.

These ages can be compared with the evolution of Earth's biosphere, particularly concerning the biological enhancement of weathering. Despite the contribution of microbes to weathering (e.g., Uroz et al., 2009), the global rates are believed to have significantly increased with the emergence of land plants and fungi 0.5-1.0 billion years ago (Kenrick and Crane, 1997; Heckman et al., 2001). This evolution could have been crucial to keep Earth at its state concerning continental coverage and mantle water concentration. Theories claiming that an unusually rapid evolution of Earth's early biosphere has been crucial to regulate Earth's system and to keep Earth habitable (Chopra and Lineweaver, 2016) could be expanded: Later steps of the evolution of the biosphere could also have been important, if Earth's system developed bistability in the more recent past.

Although the rates of change in the vicinity of the unstable fixed point are small, additional self-regulating mechanisms may be required in order for disturbances not to cause Earth to evolve away from this fixed point. In Höning and Spohn (2016, Section 10.5), we discussed some possible mechanisms. One mechanism includes the total area of continental crust determining the total length of continental margins. This length has a maximum at the present day continental coverage of 40% (see Höning et al., 2014; Höning and Spohn, 2016, Section 4), thereby maximizing the total length of continental shelves. These, in turn, are great habitats for early and evolved life. Therefore, large continental shelves cause large rates of organic carbon fixation and deposition. This eventually causes large rates of carbon subduction. As noted above, the subduction of carbon has been argued to control partial melting (Dasgupta and Hirschmann, 2010). Therefore, large continental shelves could enhance the rate of magmatism and thereby continental crust production. Overall, additional negative feedback cycles could be taken into account, which could convert an intrinsically unstable fixed point into a fixed point that is locally stable.

3. Summary, Conclusions, and Outlook

Models investigating the co-evolution of Earth and its biosphere typically focus on surface reservoirs such as the atmosphere, oceans, and crust (e.g., Kasting and Siefert, 2002; Holland, 2006). Positive feedback loops can cause the emergence of tipping points and multiple steady states in environmental systems (e.g., Lenton, 2013), while stabilizing effects keep Earth habitable (e.g., Catling and Kasting, 2007). The role of life in regulating Earth's system is closely related to the Gaia-hypothesis (Margulis and Lovelock, 1974). However, models of Earth's interior models have not been included so far. Models of mantle convection commonly neglect effects attributed to surface life, although the energy and entropy budgets of Earth's system and its interior are certainly affected by bioactivity (e.g., Rosing et al., 2006; Kleidon, 2010; Dyke et al., 2011).

The goal of this thesis was to identify mechanisms of how surface life can affect Earth's interior and to investigate the impact of the biosphere during Earth's evolution. To this aim, continental growth and mantle hydration have been described as a coupled system of feedback loops. It has been shown that these feedback loops can cause the emergence of multiple fixed points in a phase plane spanned by continental coverage and mantle water concentration. Effects of sediments in subduction zones reinforcing positive feedbacks could be particularly crucial. Sets of reasonable, albeit not well constrained parameters result in two stable fixed points that are not representative of the present day Earth (one corresponding to small continents and a dry mantle, the other to large continents and a wet mantle). Instead, an intermediate, unstable fixed point is located at present day values.

It has been shown that cooling of the mantle causes a movement of the stable fixed points to smaller values of continental coverage. In contrast, the intermediate, unstable fixed point remains close to its initial value of continental coverage. This supports the finding of the intermediate fixed point as a representative of present day Earth, because larger continental coverage is commonly ruled out for Earth's history (e.g., Schubert and Reymer, 1985). The models can produce plausible evolution curves with early rapid continental growth followed by a steady state. These growth curves are in qualitative agreement with geochemical studies by, e.g., Armstrong and Harmon (1981) and Armstrong (1991).

The model shows a slightly increasing mantle water concentration since the Archean. For a constant total water inventory, this would go along with a decreasing surface water reservoir. This can result in the emergence of continents above sea-level, even for constant volume of continental crust. As Flament et al. (2013) point out, the increase in the $^{87}Sr/^{86}Sr$ of marine carbonates in the Archean could be explained with the emergence of continents, and do not require a pulse of continental growth. Altogether, the model is consistent with geological constraints.

An abiotic Earth would be assumed to feature smaller rates of continental weathering and surface erosion. This would cause a shift of the intermediate fixed point to larger values of continental coverage, thereby enlarging the zone of attraction of the lower stable fixed point. It would thus become increasingly likely for the planet to approach the fixed point with small continental coverage and a dry mantle. Evolution models using the same initial conditions as for the biotic model but a reduced rate of continental weathering and erosion feature smaller continental crust coverage and a drier and hotter mantle for the present day. This would imply a significantly smaller area of continents that are emerged above sea-level compared to the biotic model. Additional self-regulating effects including Earth's biosphere could keep Earth at the intrinsically unstable fixed point and permit both, disturbances during evolution, and a greater range of initial conditions, to match present day observations.

The existence of multiple fixed points has implications on the surface area of continental crust and on the concentration of water in the mantle that could be expected on other planets with plate tectonics. Without self-regulating mechanisms, such as possibly the role of life on Earth, the state of the planet would be expected to strongly depend on initial conditions and could feature a large range of values between these fixed points at present day. In particular, clusters of possible present day states around the upper stable fixed point and around small values of continental coverage accompanied by a dry mantle have been found (see Höning and Spohn 2016, Section 10.5). Assuming a constant planetary water inventory, a planet with a mantle wetter than that of present day Earth, accompanied by a larger continental surface area would feature small surface oceans and a rather dry climate. The other extreme – a dry mantle and small continental coverage – would rather be an ocean-planet. However, a balance between oceans and continents as in the case of Earth is presumably the scenario most beneficial for life, particularly as it results in large continental shelves, being preferred areas of biomass production.

Future work throughout multiple disciplines is required to better constrain these conclusions. The quantification of roles of subducting sediments in water transport and continental production (discussed in, e.g., Manning, 1996; Ono, 1998; Rosing, 2006; Hacker, 2008; Dasgupta and Hirschmann, 2010) should be of particular interest. It would help to better constrain the strength of the positive feedbacks, which – as have been shown in this thesis – can cause bifurcation in the system. Numerical models should account for the formation of forearc serpentinites by water release above the source region of partial melt, which are dragged further down by induced convection (e.g., Scambelluri and Tonarini, 2012; Guillot and Hattori, 2013; Lafay et al., 2013; Deschamps et al., 2013). Moreover, the role of interbedded and overlying sediments of low permeability in partially suppressing dewatering at shallow depth should be taken into account. 2D and 3D models of subduction zones and of mantle convection are necessary to better constrain these effects; for the present day, since dehydration and melting also depend on local temperatures, and over Earth's history, since simple boundary layer theory may overestimate the dependence of the plate speed on mantle viscosity. Furthermore, a possible correlation between the rate of sediment subduction and volcanic activity at present day subduction zones should be investigated.

Additional effects that are not included in the present model could impact the feedbacks in the continental and mantle water cycles. In particular, the insulating effect of continental crust on the temperature distribution in the mantle underneath and on the surface heat flow (e.g., Gurnis, 1988; Lenardic et al., 2005; 2011) could establish a positive feedback since it could cause large-scale melting (Coltice et al., 2007; 2009) and thereby possibly the production of continental crust. Positive feedbacks can further be established by continents that favor the initiation of subduction (Rey et al., 2014). With additional positive feedbacks, the propensity of multiple fixed points in the phase plane increases.

Another important topic is the quantification of the overall biologically enhancement of weathering and erosion (Schwartzman and Volk, 1989) over Earth's history, which likely changed with the emergence of e.g. bacteria (Uroz et al., 2009), fungi (Hoffland et al., 2004), and land plants (Drever, 1994). This would result in shifts of the unstable fixed point in the phase plane over time. In addition, accounting for effects of e.g., the surface temperature, atmosphere, or topography (which has an impact on the flow of water and on the overall fraction of emerged continents, see Flament et al., 2008) on the global weathering and erosion rates would allow a more accurate investigation of Earth's evolution in the phase plane. Finally, an application of the model to other planets with plate tectonics would not only require an expansion concerning physical parameters of the planetary interior (e.g., the size, mass, composition, or thermal evolution of the planet) but further an estimation of differences in the weathering rate related to, for example, a different climate.

Other effects of surface life than the enhancement of the rates of continental weathering and erosion have the potential to impact the interior evolution of Earth and should be investigated in more detail. We discussed one potential link in Höning et al. (2014): Microbial activity can promote the conversion of the soft, swollen clay mineral smectite to illite, which is much stronger and denser (e.g., Kim et al., 2004). Thereby, the permeability of the clay layers decrease (e.g., Nadeau, 2011). In a subduction zone, this reduces the rate at which free- and loosely bound water is expelled through the clay-rich sedimentary layer. More water could be transported to mantle depth, thereby impacting the cycles discussed in this thesis. However, more work is needed to model these and other effects in detail.

Altogether, the contribution of life to the self-regulation of Earth's system is presumably not limited to the climate but further includes Earth's interior dynamics and geological state. Note that Earth's present day state concerning continental coverage and mantle water concentration allows an efficient carbonate-silicate cycle that keeps Earth's surface temperature in a habitable range. Large continents that are emerged above sea-level, promoted by rapid continental production and efficient mantle water recycling, and extended subduction zones, facilitate efficient removal of CO_2 from the atmosphere. In addition, a wet mantle causes rapid subduction of carbonate sediments. Future work is required to include possible feedbacks of the long-term carbonate silicate cycle in the present model.

Note further that the present day state of Earth, which could be stabilized by self-regulating mechanisms including bioactivity, is characterized by large energy fluxes; plate tectonics in general imply a large mantle heat flow, particularly with a large total length of subduction zones. The viscosity-reducing effect of water in the mantle maintains vigorous mantle convection, also promoting a large mantle heat flow. Moreover, a large area of emerged continents and large continental shelves enable the biosphere to harvest solar energy to a large extent and convert it into chemical energy, thereby enhancing the rates of carbon fixation and deposition and the rate of sediment subduction.

One could speculate that such self-regulating mechanisms including bioactivity are not limited to Earth. Life in general could shape its planet in a way to permit large energy fluxes and consumption by the biosphere, which in turn is required to keep the internal entropy small (Lovelock, 1965). In case of Earth, the combination of large areas of shallow water, distributed continents with a total coverage of approximately 40%, volcanism and plate tectonics could then indicate the presence of an active biosphere. An atmosphere far from thermodynamic equilibrium, which is generally argued to act as a biosignature (Hitchcock and Lovelock, 1967), would be a consequence.

References

Armstrong, R.L., Harmon, R.S., 1981. Radiogenic Isotopes – the case for crustal recycling on a near-steady-state no-continental-growth Earth. Phil. Trans. R. Soc. 301(1461), 443-472.

Armstrong, R.L., 1991. The persistent myth of crustal growth. Austr. J. Earth Sci. 38, 613-630.

Ashwal, L.D., 1989. Introduction. In: Growth of the continental crust. Tectonophysics 161(3-4), 143-145.

Behrenfeld, M.J., Falkowski, P.G., 1997. Photosynthetic rates derived from satellite-based chlorophyll concentration. Limnology and Oceanography 42(1), 1-20.

Bell, D.R., Rossman, G.R., 1992. Water in Earth’s mantle. The role of nominally anhydrous minerals. Science 255(5050), 1391-1397.

Belousova, E.A., Kostitsyn, Y.A., Griffin, W.L., Begg, G.C., O’Reilly, S.Y., Pearson, N.J., 2010. The growth of the continental crust: constraints from zircon Hf-isotope data. Lithos 119, 457-466.

Berner, R.A., 1992. Weathering, plants, and the long-term carbon cycle. Geochimica et Cosmochimica Acta 56(8), 3225-3231.

Blacic, J.D., 1972. Effect of water on the experimental deformation of olivine. In: Heard, H.C., et al. (Eds.), Flow and Fracture of Rocks, Geophysical Monograph Series 16. AGU, Washington D.C., 109-115.

Boyle, J.R., Voigt, G.K., 1973. Biological weathering of silicate minerals. Plant and soil 38(1), 191-201.

Brocks, J.J., Logan, G.A., Buick, R., Summons, R.E., 1999. Archean molecular fossils and the early rose of eukaryotes. Science 285(5430), 1033-1036.

Buick, R., 2007. The earliest records of life on Earth. In: Planets and life: The emerging science of astrobiology. Sullivan, W.T., Baross, J.A. (Eds.). Cambridge University Press.

Caldeira, K., Kasting, J.F., 1992. The life span of the biosphere revisited. Nature 360, 721-723.

Campbell, I.H., Taylor, S.R., 1983. No water, no granites – no ocean, no continents. Geophys. Res. Lett. 10(11), 1061-1064.

Catling, D., Kasting, J.F., 2007. Planetary atmospheres and life. In: Planets and Life: The Emerging Science of Astrobiology. Sullivan, W.T., Baross, J.A. (Eds.). Cambridge University Press.

Chopra, A., Lineweaver, C.H., 2016. The case for a gaian bottleneck: the biology of habitability. Astrobiology 16(1), 7-21. doi:10.1089/ast.2015.1387

Cleland, C.E., Chyba, C.F., 2007. Does life have a definition? In: Sullivan, W.T. and Baross, J.A. (Eds.), Planets and Life: The emerging science of astrobiology, 119-131.

Coltice, N., Phillips, B.R., Bertrand, H., Ricard, Y., Rey, P., 2007. Global warming of the mantle at the origin of flood basalts over supercontinents. Geology 35(5), 391-394.

Coltice, N., Bertrand, H., Rey, P., Jourdan, F., Phillips, B.R., Ricard, Y., 2009. Global warming of the mantle beneath continents back to the Archaean. Gondwana Res. 15, 254-266.

Corliss, J.B., Baross, J.A., Hoffman, S.E., 1981. An hypothesis concerning the relationship between submarine hot springs and the origin of life on Earth. Oceanologica Acta, Proceedings 26th International Geological Congress, Geology of oceans symposium, 59-69.

Dasgupta, R., Hirschmann, M.M., 2010. The deep carbon cycle and melting in Earth's interior. Earth Planetary Science Letters 298, 1-13.

Davies, G.F., 2007. In: Stevenson, D. (Ed.), Thermal evolution of the mantle. Treatise on Geophys. 9, Evolution of the Earth, Elsevier, Amsterdam, 197-216.

Deschamps, F., Godard, M., Guillot, S., Chauvel, C., Andreani, M., Hattori, K., Wunder, B., France, L., 2012. Behavior of fluid-mobile elements in serpentinites from abyssal to subduction environments: Examples from Cuba and Cominican Republic. Chemical Geology 312-313, 93-117.

Deschamps, F., Godard, M., Guillot, S., Hattori, K., 2013. Geochemistry of subduction zone serpentinites: A review. Lithos 178, 96-127.

Drever, J.I., 1994. The effect of land plants on weathering rates of silicate minerals. Geochim. Cosmochim. Acta 58(10), 2325-2332.

Dyke, J.G., Gans, F., Kleidon, A., 2011. Towards understanding how surface life can affect interior geological processes: a non-equilibrium thermodynamics approach. Earth Syst. Dynam. 2, 139-160.

Flament, N., Coltice, N., Rey, P.F., 2008. A case for late-Archean continental emergence from thermal evolution models and hypsometry. Earth Planet. Sci. Lett. 275, 326-336.

Flament, N., Rey, P.F., Coltice, N., Dromart, G., Olivier, N., 2011. Lower crustal flow kept Archean continental flood basalts at sea level. Geology 39(12), 1159-1162. doi:10.1130/G32231.1

Flament, N., Coltice, N., Rey, P.F., 2013. The evolution of the 87Sr/86Sr of marine carbonates does not constrain continental growth. Precambrian Research 229, 177-188. doi:10.1017/j.precamres.2011.10.009

Goldblatt, C., Lenton, T.M., Watson, A.J., 2006. Bistability of atmospheric oxygen and the Great Oxidation. Nature 443, 683-686.

Guillot, S., Hattori, K., 2013. Serpentinites: Essential Roles in Geodynamics, Arc Volcanism, Sustainable Development, and the Origin of Life. Elements 9, 95-98.

Gurnis, M., 1988. Large-scale mantle convection and the aggregation and dispersal of supercontinents. Nature 332, 695-699.

Hacker, B.R., 2008. H_2O subduction beyond arcs. Geochem. Geophys. Geosys. 9(2), 2008. doi:10.1029/2007GC001707

Harrison, C.G.A., 1999. Constraints on ocean volume change since the Archean. Geophys. Res. Lett. 26(13), 1913-1916.

Hart, M.H., 1979. Habitable zones about main sequence stars. Icarus 37(1), 351-357.

Hattori, K., Guillot, S., 2003. Volcanic fronts form as a consequence of serpentinites dehydration in the forearc mantle wedge. Geology 31(6), 525-528.

Heckman, D.S., Geiser, D.M., Eidell, B.R., Stauffer, R.L., Kardos, N.L., Hedges, S.B., 2001. Molecular evidence for the early colonization of land by fungi and plants. Science 293, 1129-1133. doi:10.1126/science.1061457

Hitchcock, D.R., Lovelock, J.E., 1967. Life detection by atmospheric analysis. Icarus 7, 149-159.

Hoffland, E., Kuyper, T.W., Wallander, H., Plassard, C., Gorbushina, A.A., Haselwandter, K., Holström, S., Lendeweert, R., Lundström, U.S., Rosling, A., Sen, R., Smits, M.M., van Hees, P.A.W., van Breemen, N., 2004. The role of fungi in weathering. Front Ecol. Environ. 2(5), 258-264.

Holland, H.D., 2006. The oxygenation of the atmosphere and oceans. Philos. Trans. R. Soc. 361, 903-915.

Höning, D., Hansen-Goos, H., Airo, A., Spohn, T., 2014. Biotic vs. abiotic Earth: A model for mantle hydration and continental coverage. Planetary and Space Science 98, 5-13.

Höning, D., Spohn, T., 2016. Continental growth and mantle hydration as intertwined feedback cycles in the thermal evolution of Earth. Physics of the Earth and Planetary Interiors 255, 27-49.

Hyndman, R.D., Peacock, S.M., 2003. Serpentinization of the forearc mantle. Earth Planet. Sc. Lett. 212, 417-432.

Jarrard, R.D., 2003. Subduction fluxes of water, carbon dioxide, chlorine, and potassium. Geochem. Geophys. Geosys. 4(5), doi:10.1029/2002GC000392

Karato, S.-I. Paterson, M.S., FitzGerald, J.D., 1986. Rheology of synthetic olivine aggregates: Influence of grain size and water. J. Geophys. Res. 91(B8), 8151-8176.

Karato, S.-I., Jung, H., 2003. Effects of pressure on high-temperature dislocation creep in olivine. Philos. Mag. 83(3), 401-414.

Kasting, J.F., Ackerman, T.P., 1986. Climatic consequences of very high carbon dioxide in the Earth's early atmosphere. Science 234(4782), 1383-1385.

Kasting, J.F., 1989. Long-term stability of the Earth's climate. Palaeogeography, Palaeoclimatology, Palaeoecology (Global and Planetary Change Section) 75, 83-95.

Kasting, J.F., Holm, N.G., 1992. What determines the volume of the oceans? Earth Planet. Sci. Lett. 109, 507-515.

Kasting, J.F., 1993. Earth's early atmosphere. Science 259(5097), 920-926.

Kasting, J.F., Whitmire, D.P., Reynolds, R.T., 1993. Habitable zones around main sequence stars. Icarus 101, 108-128.

Kasting, J.F., 2001. The rise of atmospheric oxygen. Science 293(5531), 819-820.

Kasting, J.F., Siefert, J.L., 2002. Life and the Evolution of Earth's atmosphere. Science 296, 1066-1068.

Kasting, J.F., Catling, D., 2003. Evolution of a habitable planet. Annu. Rev. Astron. Astrophys. 41, 429-63.

Kenrick, P., Crane, P.R., 1997. The origin and early evolution of plants on land. Nature 389, 33-39.

Kim, J., Dong, H., Seabaugh, J., Newell, S.W., Eberl, D.D., 2004. The role of microbes in the smectite- to illite reaction. Science 303, 830-832.

Kitzmann, D., Patzer, A.B.C., von Paris, P., Godolt, M., Stracke, B., Gebauer, S., Grenfell, J.L., Rauer, H., 2010. Clouds in the atmospheres of extrasolar planets. I. Climatic effects of multi-layered clouds for Earth-like planets and implications for habitable zones. A&A 511, A66.

Kleidon, A., 2010. Life, hierarchy, and the thermodynamic machinery of planet Earth. Phys. Life Rev. 7, 428-460.

Kröner, A., 1985. Evolution of the Archean continental crust. Ann. Rev. Earth Planet. Sci. 13, 49-74.

Kwon, O., Kronenberg, A.K., Gangi, A.F., Johnson, B., Herbert, B.E., 2004. Permeability of illite-bearing shale: 1. Anisotropy and effects of clay content and loading. J. Geophys. Res. 109, B10205. doi:10.1029/2004JB003052.

Lafay, R., Deschamps, F., Schwartz, S., Guillot, S., Godard, M., Debret, B., Nicollet, C., 2013. High-pressure serpentinites, a trap-and-release system controlled by metamorphic conditions: Example from the Piedmont zone of the western Alps. Chemical Geology 343, 38-54.

Lenardic, A., Moresi, L.-N., Jellinek, A.M., Manga, M., 2005. Continental insulation, mantle cooling, and the surface area of oceans and continents. Earth and Planetary Space Science 234(3-4), 317-333. doi:10.1016/j.epsl.2005.01.038

Lenardic, A., Cooper, C.M., Moresi, K., 2011. A note on continents and the Earth's Urey ratio. Phys. of the Earth and Planet. Int. 188, 127-130. doi:10.1016/j.pepi.2011.06.008

Lenton, T.M., 1998. Gaia and natural selection. Nature 394, 439-447.

Lenton, T.M., van Bloh, W., 2001. Biotic feedback extents the life span of the biosphere. Geophys. Res. Lett. 28(9), 1715-1718.

Lenton, T.M., 2002. Testing Gaia: The effect of life on Earth's habitability and regulation. Climatic Change 52, 409-422.

Lenton, T.M., 2013. Environmental tipping points. Annu. Rev. Environ. Resourc. 38, 1-29.

Lovelock, J.E., 1965. A physical basis for life detection experiments. Nature 207(4997), 568-570.

Lovelock, J.E., Whitfield, M., 1982. Life span of the biosphere. Nature 296, 561-563.

Lovelock, J.E., 1983. Gaia as seen through the atmosphere. In: Westbroek, P., deJong, E.W. (Eds.). Biomineralization and Biological Metal Accumulation, 15-25. D. Reidel Publishing Company.

Lunine, J.I., 2013. Earth: Evolution of a habitable world (second edition). Cambridge University Press.
Manning, C.E., 1996. Effects of sediments on aqueous silica transport in subduction zones. Geophys. Monograph 96, 277-284.
Margulis, L., Lovelock, J.E., 1974. Biological modulation of the Earth's atmosphere. Icarus 21(4), 471-489.
Mei, S., Kohlstedt, D.L., 2000. Influence of water on plastic deformation of olivine aggregates, 2. Dislocation creep regime. J. Geophys. Res. 105(B9), 21,471-21,481.
McGovern, P.J., Schubert, G., 1989. Thermal evolution of the Earth: effects of volatile exchange between atmosphere and interior. Earth Planet. Sci. Lett. 96, 27-37.
Mojzsis, S.J., Arrhenius, G., McKeegan, K.D., Harrison, T.M., Nutman, A.P., Friend, C.R.L., 1996. Evidence for life on Earth before 3,800 million years aro. Nature 384, 55-59.
Moore, J.C., 1987. Expulsion of fluids from depth along a subduction-zone decollement horizon. Nature 326(23), 785-788.
Nadeau, P.H., 2011. Earth's energy "Golden Zone": a synthesis from mineralogical research. Clay Miner. 46, 1-24.
Noack, L., Godolt, M., von Paris, P., Plesa, A.-C., Stracke, B., Breuer, D., Rauer, H., 2014. Can the interior structure influence the habitability of a rocky planet? Planetary and Space Science 98, 14-29.
Ono, S., 1998. Stability limits of hydrous minerals in sediment and mid-ocean ridge basalt compositions: Implications for water transport in subduction zones. J. Geophys. Res. 103(B8), 18,253-18,267.
Plank, T., Langmuir, C.H., 1998. The chemical composition of subducting sediment and its consequences for the crust and mantle. Chem. Geol. 145, 325-394.
Rey, P.F., Coltice, N., Flament, N., 2014. Spreading continents kick-started plate tectonics. Nature 513, 405-408.
Rosing, M.T., Bird, D.K., Sleep, N.H., Glassley, W., Albarede, F., 2006. The rise of continents – an essay on the geological consequences of photosynthesis. Paleogeog. Paleoclumatol. Paleoecol. 232, 99-113.
Sagan, C., Mullen, G., 1972. Earth and Mars: Evolution of atmospheres and surface temperatures. Science 177(4043), 52-56.
Scambelluri, M., Tonarini, S., 2012. Boron isotope evidence for shallow fluid transfer across subduction zones by serpentinized mantle. Geology 40(10), 907-910.
Schneider, R., Weil, W., 2008. Probability and its implications. In: Gani, J., Heyde, C.C., Jagers, P., Kurtz, T.G. (Eds.), Stochastic and Integral Geometry. Springer, Berlin-Heidelberg.
Schubert, G., Reymer, A.P.S., 1985. Continental volume and freeboard through geological time. Nature 316, 336-339.
Schubert, G., Turcotte, D.L., Olson, P., 2001. Mantle convection in the Earth and Planets. Cambridge University Press.

Schwartzmann, D.W., Volk, T., 1989. Biotic enhancement of weathering and the habitability of Earth. Nature 340, 457-460.
Shipley, T.H., Moore, G.F., 1986. Sediment accretion, subduction, and dewatering at the base of the trench slope off Costa Rica: A seismic reflection view of the décollement. J. Geophys. Res. 91(B2), 2019-2028.
Sleep, N.H., Zahnle, K.J., Kasting, J.F., Morowitz, H.J., 1989. Annihilation of ecosystems by large asteroid impacts on the early Earth. Nature 342, 139-142.
Sleep, N.H., Bird, D.K., Pope, E., 2012. Paleontology of Earth's mantle. Annu. Rev. Earth Planet. Sci. 40, 277-300.
Smithies, R.H., Champion, D.C., Cassidy, K.F., 2003. Formation of Earth's early Archaean continental crust. Precambrian Res. 127, 89-101.
Southam, G., Westall, F., Spohn, T., 2015. Geology, life and habitability. In: Treatise on geophysics (second edition), Schubert, G. (Ed.), 473-486.
Stern, R.J., 2002. Subduction zones. Rev. Geophys. 40(4). doi:10.1029/2001RG000108
Stern, C.R:, 2011. Subduction erosion: rates, mechanisms, and its role in arc magmatism and the evolution of the continental crust and mantle. Gondwana Res. 20 (2-3), 284-308.
Stevenson, D.J., 1983. The nature of the Earth prior to the oldest known rock record – The Hadean Earth. In: Earth's earliest biosphere: Its origin and evolution. Princeton University Press, 32-40.
Stevenson, D.J., Spohn, T., Schubert, G., 1983. Magnetism and thermal evolution of the terrestrial planets. Icarus 54, 466-489.
Taylor, S.R., McLennan, S.M., 1985. In: Yardley, B.W.D. (Ed.). The continental crust: its composition and its evolution. Oxford: Blackwell.
Taylor, S.R., McLennan, S.M., 1995. The geochemical evolution of the continental crust. Rev. Geophys. 33(2), 241-265.
Theissen, S., Rüpke, L.H., 2010. Feedback of sedimentation on crustal heat flow: New insights from the Voring Basin, Norwegian Sea. Basin Research 22(6), 976-990.
Turcotte, D.L., Schubert, G., 2002. Geodynamics, second edition, Cambridge University Press, New York.
Uroz, S. Calvaruso, C., Turpault, M.-P., Frey-Klett, P., 2009. Mineral weathering by bacteria: ecology, actors and mechanisms. Trends in Microbiology 17(8), 378-387.
von Paris, P., Gebauer, S., Godolt, M., Rauer, H., Stracke, B., 2011. Atmospheric studies of habitability in the Gliese 581 system. Astronomy & Astrophysics 532, A58. doi:10.1051/0004-6361/201016058
Walker, J.C.G., Hays, P.B., Kasting, J.F., 1981. A negative feedback mechanism for the long-term stabilization of Earth's surface temperature. J. Geophys. Res. 86(C10), 9776-9782.

Appendices

Höning et al., 2014. Biotic vs. abiotic Earth: A model for mantle hydration and continental coverage

Höning, Dennis, Hansen-Goos, Hendrik, Airo, Alessandro, Spohn, Tilman, 2014. Biotic vs. abiotic Earth: A model for mantle hydration and continental coverage. Published in: Planetary and Space Science 98, 5-13.

Summary:

In the first publication that is part of this thesis we present a model that links the surface biosphere to the combined area of Earth's continental crust and the hydration state of Earth's mantle. The link is based on the assumption that the biosphere enhances continental weathering and erosion, thereby enhancing the rate at which sediments are subducted. A thick sedimentary layer of low permeability on top of a subducting oceanic slab is modeled to reduce its dewatering upon subduction at shallow depth. This leads to a greater availability of water at greater depths, thereby enhancing continental production and mantle water regassing.

The model uses the combined area of continental crust and the concentration of water in the mantle as basic variables. The mantle water outgassing rate and the rate of subduction are derived using boundary layer theory from the mantle viscosity, which is calculated depending on the water concentration. Continental crust is eroded via surface erosion, thereby producing sediments. The total length of ocean-continent subduction zones is set proportional to the total length of continental margins, which is derived from stochastic geometry assuming randomly distributed spherical caps as continents, which may overlap.

The steady state results show that strong positive feedbacks including the role of subducted sediments can cause the emergence of up to three fixed points in a phase plane spanned by mantle water concentration and continental coverage, of which the intermediate fixed point is unstable. With the assumption of a present day steady state of these parameters, the fixed point with large values of mantle water concentration and continental coverage is shifted to values observed for the present day. The results show that a reduced continental weathering and erosion rate as expected for an abiotic Earth moves the unstable fixed point to larger values of continental coverage. Thereby, it enlarges the zone of attraction of the stable fixed point with a dry mantle and small continental coverage. This would raise the propensity of trajectories with various initial conditions to approach this state

This paper is removed from this online-version. It is available at http://www.sciencedirect.com/science/article/pii/S0032063313002663

Höning and Spohn, 2016. Continental growth and mantle hydration as intertwined feedback cycles in the thermal evolution of Earth

Höning, Dennis, Spohn, Tilman, 2016. Continental growth and mantle hydration as intertwined feedback cycles in the thermal evolution of Earth. Published in: Physics of the Earth and Planetary Interiors 255, 27-49.

Summary:

In this follow-up publication, we extended the model to account for additional, important processes within the feedback cycles: Sediments are also modeled to carry water partly bound in stable phases, and subduction erosion partly replaces surface erosion. These additional mechanisms prohibit a formation of the upper stable fixed point at 40% continental coverage for a reasonable set of parameters. In contrast, with the precondition of a present day steady state continental crust coverage and mantle water concentration, the intermediate, unstable fixed point is shifted to values observed for the present day. In this case, the biologically enhanced, present day rates of continental weathering and erosion are of particular importance. Reducing these rates would inevitable cause the unstable fixed point to move to values larger than these observed for the present day. Thus, evolution trajectories would approach the stable fixed point with small continental coverage and a dry mantle.

To investigate Earth's evolution in the phase plane, a parameterized thermal evolution model has been coupled to the box model via the dependence of the mantle viscosity on temperature. Initial conditions for sample trajectories are derived from a Monte-Carlo scheme. Models are treated as successful if they result in the value of continental coverage observed for the present day. These models show an early rapid growth of continental crust and a steady state for at least the past 1.5 billion years. In the latter period, the mantle water concentration slightly increases. These evolutions are consistent with geological constraints.

For the simulation of the evolution of an abiotic Earth, we use the same parameters and initial conditions but reduced rates of continental weathering and erosion. The results show a reduced area of continental crust and in a dryer mantle for the present day. Thereby, trajectories approach the lower stable fixed point. We conclude that the biosphere could play an important role in keeping Earth in a state with a large area of continental crust, with extended subduction zones and with a wet mantle.

This paper is removed from this online-version. It is available at
http://www.sciencedirect.com/science/article/pii/S0031920116300103