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# Degassing, weathering, decarbonation: What determines the atmospheric $CO_2$ content on stagnant lid planets?

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## Abstract

The habitability of stagnant lid planets is greatly affected by their atmospheric $CO_2$ partial pressure. $CO_2$ degassing on stagnant lid planets is lower compared to plate tectonics planets, because melting takes place at a larger depth. However, since stagnant lid planets lack subduction zones, degassed $CO_2$ cannot be recycled back into the mantle. Freshly produced basaltic crust can be carbonated, but buried and sinking crust will be subject to metamorphic decarbonation. We show that the expected atmospheric $CO_2$ partial pressure on Earth-sized stagnant lid planets crucially depends on the assumed dependence of weathering on temperature or atmospheric $CO_2$, the initial mantle temperature, and the oxidation state of the mantle.

## 1. Introduction

Most planets within our solar system do not possess plate tectonics, and most exoplanets are also expected to have their mantle convecting beneath a stagnant lid. The influence of the tectonic mode on the atmospheric $CO_2$ partial pressure is not clear: On the one hand, $CO_2$ degassing is low for stagnant lid planets because partial melting takes place beneath the stagnant lid at large pressures. On the other hand, it is not feasible for a stagnant lid planet to recycle degassed $CO_2$ back into the mantle. However, if liquid water is present on the surface of a stagnant lid planet, weathering of freshly produced crust can take place. Carbonated crust can then be buried by new volcanic eruptions until increasing temperatures with depth cause metamorphic decarbonation and the supply of $CO_2$ back to the atmosphere. We study the combined effect of degassing, weathering and decarbonation on stagnant lid planets and explore the most crucial parameters that determine the atmospheric $CO_2$ content on stagnant lid planets.

## 2. Model

We employ a 1D thermal evolution model of a stagnant lid planet based on a parameterization of heat transport by convection [1]. We track carbon reservoirs in the mantle, crust, and atmosphere. $CO_2$ is degassed from the mantle into the atmosphere, weathering is the flux of $CO_2$ from the atmosphere to the crust, and decarbonation releases $CO_2$ from the crust to the atmosphere. Modelling degassing, we employ a model of redox melting [1] assuming that the concentration of $CO_2$ in the melt depends on the oxidation state of the mantle. We test weathering scalings using both a direct dependence on the atmospheric $CO_2$ concentration [2] and a dependence on the surface temperature [3]. Modelling metamorphic decarbonation, we follow [4] and assume that decarbonation occurs at a temperature that increases linearly with depth.

## 3. Results

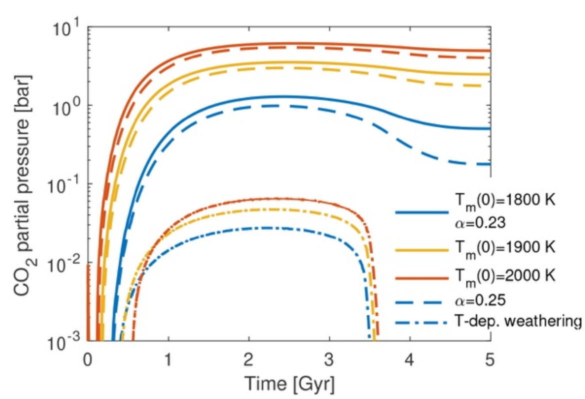


Fig. 1: Atmospheric $CO_2$ evolution for initial mantle temperatures of 1800 K (blue), 1900 K (yellow), and 2000 K (red) using a $CO_2$-dependent weathering model (solid and dashed lines) and a temperature-dependent weathering model (dashed-dotted lines).

In Fig. 1, we show the evolution of the atmospheric $CO_2$ partial pressure for different initial mantle temperatures and seafloor-weathering scalings. If a $CO_2$-dependent weathering model is used, $CO_2$ accumulates in the atmosphere and can reach several bars. The initial mantle temperature plays a crucial role because a hot initial mantle leads to rapid early degassing. Since any $CO_2$ that is degassed cannot be recycled back into the mantle, the initial mantle temperature determines the entire evolution of the atmospheric $CO_2$ partial pressure. In contrast, a temperature-dependent weathering model does not allow $CO_2$ to accumulate in the atmosphere in substantial quantities. Here, after 3-4 billion years, the mantle has cooled down to an extent that the rates of degassing and decarbonation are not sufficient to compensate weathering, and the atmospheric $CO_2$ partial pressure approaches zero.

We further find that the oxidation state of the mantle has a large impact on the atmospheric $CO_2$ partial pressure, in particular if a $CO_2$-dependent weathering model is used. Increasing the oxygen fugacity of the mantle from the iron-wüstite buffer (IW) to IW+1 can result in an increase of the atmospheric $CO_2$ partial pressure at 4.5 billion years of more than one order of magnitude.

## 4. Summary and Conclusions

We couple a thermal evolution model of a stagnant lid planet based on a parameterization of the convective mantle heat flow with models of degassing, weathering and decarbonation in order to identify factors that determine the evolution of the atmospheric $CO_2$ content on stagnant lid planets. We find:

- The model used for weathering crucially affects the atmospheric $CO_2$ partial pressure: While a $CO_2$-dependent weathering model results in an accumulation of $CO_2$ in the atmosphere and in a partial pressure in the order of a few bars, atmospheric $CO_2$ approaches zero if a temperature-dependent weathering model is used instead.

- The initial mantle temperature is important for the $CO_2$ partial pressure. A hot initial mantle results in rapid early outgassing of $CO_2$, which cannot be recycled back into the mantle, resulting in large decarbonation rates throughout the evolution.

- The oxidation state of the mantle determines the concentration of $CO_2$ in the melt, which has a substantial effect on the atmospheric $CO_2$ partial pressure.

- The decreasing atmospheric $CO_2$ partial pressure with mantle cooling in the late evolution may partially compensate for the temperature increase caused by increasing solar luminosity with time, thereby keeping the planet habitable in the long-term.

## References

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