ON THE HABITABILITY OF A STAGNANT-LID EARTH N. Tosi[1,2,*], M. Godolt[1,2], B. Stracke[2], T. Ruedas[3,2], J. L. Grenfell[2], D. Höning[2], A. Nikolaou[2], A.-C. Plesa[2], D. Breuer[2] and T. Spohn[2], [1]Technische Universität Berlin, Germany; [2]German Aerospace Center (DLR), Berlin, Germany: [3]Insitute of Planetology, University of Münster, Germany. *Contact: nicola.tosi@tu-berlin.de

Introduction: Plate tectonics is considered fundamental for the habitability of the Earth and possibly a prerequisite for the habitability of other planets. Yet whether plate tectonics is a recurrent feature of terrestrial bodies orbiting other stars or unique to the Earth is unknown. The stagnant-lid, which characterises the terrestrial bodies of the Solar System other than the Earth, may rather be the most common tectonic mode through which such bodies operate. In order to understand to what extent a stagnant-lid planet can be habitable (i.e., host liquid water at its surface), we model the thermal history of the mantle, the accompanying outgassing evolution of water (H_2O) and carbon dioxide (CO_2), and the resulting climate of a hypothetical planet with the same mass, radius, and composition as the Earth, but lacking plate tectonics.

Methods: We employ a 1-D model of parametrized convection to simulate the thermal evolution of the interior over 4.5 Gyr including melt generation, crust production, and volatile extraction [e.g., 1]. We use a fractional melting model for the extraction of H_2O from the mantle and its enrichment in the crust, while the extraction of CO_2 is calculated on the base of a model of redox melting [2]. H_2O and CO_2 outgassed from the interior are used to build up a secondary atmosphere over time. We calculate the atmospheric pressure based on the solubility of H_2O and CO_2 in basaltic magmas at the evolving pressure conditions of the surface [3]. We then employ a 1-D radiative-convective, cloud-free stationary atmospheric model [e.g., 5] to calculate the resulting atmospheric temperature, pressure and water content, as well as the boundaries of the habitable zone (HZ) accounting for the evolution of the Sun luminosity.

Results: Fig. 1a shows the evolution of the mantle temperature for several models with different initial mantle temperatures ($T_{m,0}$) and water concentrations ($X_{m,0}^{H_2O}$). The thermal history is characterised by an initial heating phase after which the mantle cools at a roughly constant rate. The evolution is largely controlled by the initial water concentration of the mantle: the higher the latter, the lower is the mantle viscosity and the more efficient is the convective heat loss.

Since the solidus strongly depends on the hydration state of the mantle, the initial H_2O concentration has a large influence on the production of partial melt and on the formation of crust. The initial phase of mantle heating leads to the production of a large volume of partial melt, which causes the crust to grow the more rapidly

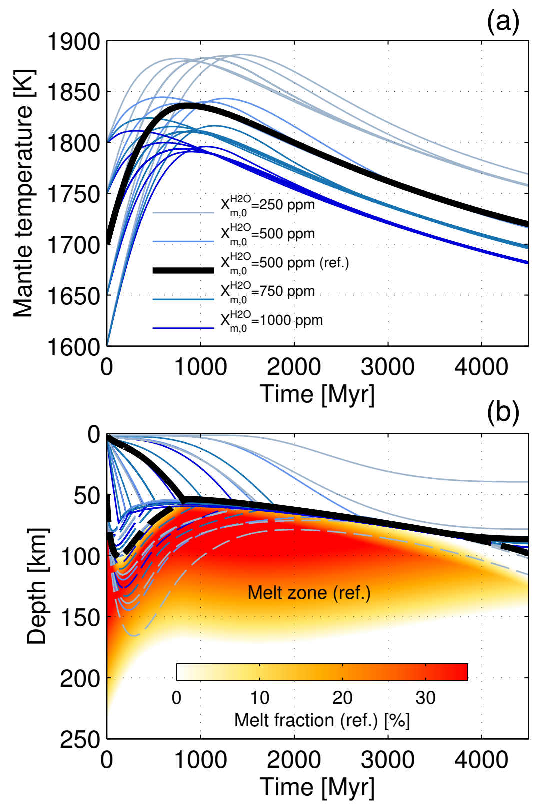

Figure 1: Evolution of the interior for different initial mantle temperatures between 1600 and 1800 K, initial water concentrations ($X_{m,0}^{H_2O}$) between 250 and 1000 ppm, and an oxygen fugacity corresponding to the iron-wüstite buffer. (a) Mantle temperature and (b) thickness of the crust (solid lines), of the stagnant-lid (dashed lines), and distribution of the melt zone and melt fraction. Line colors indicate different values of $X_{m,0}^{H_2O}$. Black lines refer to a reference model (ref.) with $T_{m,0} = 1700$ K and $X_{m,0}^{H_2O} = 500$ ppm.

the higher $X_{m,0}^{H_2O}$ is. In most cases, the crust (solid lines in Fig. 1b) stops growing when it becomes as thick as the stagnant-lid (dashed lines in Fig. 1b). When this happens, crustal recycling starts and continues nearly until the end of the evolution.

For a subset of the models shown in Fig. 1, Fig. 2 shows the outgassing evolution of H_2O and CO_2. The possibility that the two volatiles are released into the atmosphere depends on whether their concentration in surface melts is higher than their saturation concentration at the evolving pressure conditions of the atmosphere. Even for initial water concentrations in excess of 1000 ppm, the high solubility of H_2O in surface magmas [4] limits the maximal partial pressure of atmospheric H_2O to a few tens of bars (Fig. 2a). The rel-

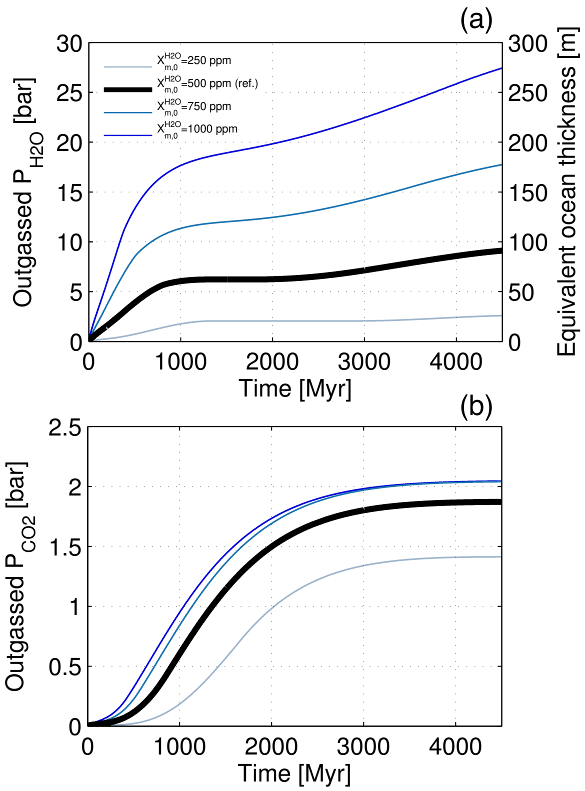

Figure 2: (a) Outgassing evolution of H_2O and (b) CO_2 for models with initial water concentrations between 250 and 1000 ppm, an initial mantle temperature of 1700 K, and an oxygen fugacity at the IW buffer.

atively low solubility of CO_2 [4] causes instead most of the carbon contained in surface melts to be released. CO_2 is then outgassed throughout the evolution (Fig. 2b) with its partial pressure that is controlled by the oxygen fugacity of the mantle. For the simulations of Fig. 2, the oxygen fugacity was set at the iron-wüstite (IW) buffer. An increase (or decrease) by one $\log_{10}$-unit with respect to the IW buffer causes the partial pressure of outgassed CO_2 to increase (or decrease) by about one order of magnitude [2] (not shown in the figure).

For the reference model shown in Figs. 1 and 2, we show in Fig. 3 the evolution of the surface temperature and of the HZ. The former increases over time both because of the increase of CO_2 and H_2O and because of the increase in the Sun luminosity. The obtained surface temperatures and pressures allow most of the outgassed H_2O to be in its liquid phase throughout the evolution, except for the first few hundred Myrs (Fig. 3a). For the reference model, a liquid water reservoir of 9 bar ($\sim$ 3% of an Earth ocean) is obtained after 4.5 Gyr. Fig. 3b shows the orbital distances at which a planet would receive the insolation needed to reach the boundaries of the HZ. Considering the evolution of the solar luminosity leads to an increase in orbital distance of the inner and outer HZ. At 1 AU, a stagnant-lid planet would lie within the HZ throughout its history.

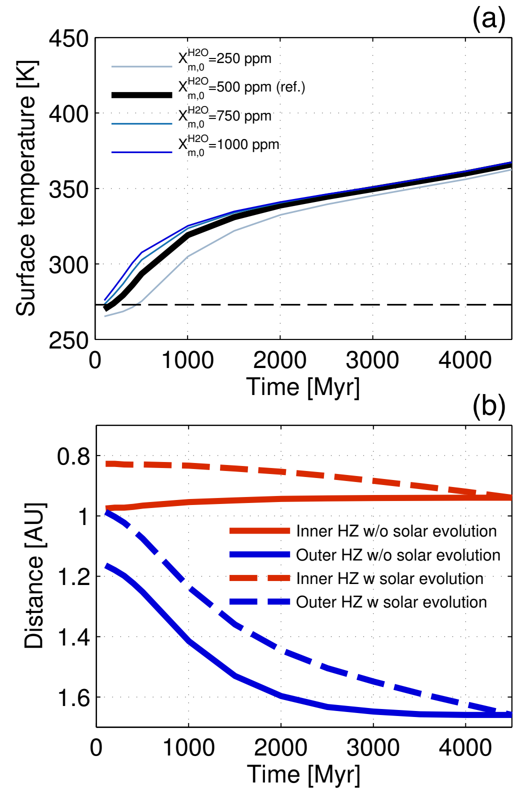

Figure 3: (a) Evolution of the surface temperature for the same models of Fig. 2. The dashed line indicates the freezing point of water (273 K). (b) Evolution of the inner (red) and outer (blue) boundaries of the habitable zone (HZ) for the reference model (ref.) taking into account the evolution of the Sun's luminosity (dashed lines) and neglecting it (solid lines).

Conclusions: We have modeled the thermal and outgassing evolution and the resulting climate of an Earth-like planet lacking plate tectonics. Outgassing of H_2O is limited to few tens of bars by the increasing atmospheric pressure and high solubility of water in surface magmas, which places de facto an upper bound on the amount of water that can be delivered to the atmosphere from the interior. The low solubility of CO_2 causes instead most of the carbon extracted from the mantle to be outgassed. The partial pressure of atmospheric CO_2 is largely controlled by the redox state of the mantle, with values that range from a few bars (Fig. 2b) for an oxygen fugacity at the IW buffer to tens of bars if more oxidizing conditions are assumed for the mantle. At 1 AU and for most cases, liquid water on the surface is possible, hence the planets considered would be regarded as habitable although the atmospheric temperature may be well above the limits for terrestrial life.

References: [1] Morschhauser A. et al. (2011) *Icarus*, 212, 541–558. [2] Grott et al. (2011) *EPSL*, 308, 391–400. [3] von Paris et al. (2010) *A&A*, 522, A23. [4] Newman & Lowenstern (2002) *Comput. Geosci.*, 28, 597–604.