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PLATE TECTONICS ON EARTH-LIKE PLANETS

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Introduction

Due to new technologies the number of terrestrial exoplanets detected in the past few years increased rapidly. Some of these planets have masses up to 10 Earth masses, and may be Earth-like, i.e. they consist of an iron core and a silicate mantle. The habitability of these planets is a widely discussed topic. On Earth, plate tectonics recycles carbon, stabilizes the atmosphere, cools the interior and helps to maintain a magnetic field. It therefore may be an indicator for the habitability of a planet. We investigate the likeliness of plate tectonics on Earth-like planets to find possible constraints on the habitability depending on the mass of such a planet.

1. Methods

We use a 2D spherical mantel convection model [1] and investigate planets with Earth-like composition assuming a perovskite rheology in the mantle and using the rheological parameters of [2]. Earth-like values are scaled to more-massive planets following [3]. We examine the pressure effect on the viscosity and its influence on mantle dynamics. So far, this has been neglected in earlier studies of plate tectonics on super-Earths (e.g. [3, 4]).

We use an activation energy of $E^* = 300kJ/mol$ and new rheological parameters derived for perovskite [2] in the high-pressure regime with an activation volume $V^* = 3.14cm^3/mol$ at the surface decreasing with pressure.

Plastic yielding occurs in our model, if the convective stresses exceed the yield stress at any depth. Our yield stress is taken to be depth-dependent.

$$\sigma_{yield} = \sigma_{surf} + f_{yield}\,(p - p_W)\,\mu \qquad (1)$$

The surface yield stress is $\sigma_{surf} = 50MPa$, the friction coefficient is $\mu = 0.6$ and the rheology of the mantle is assumed to be wet, i.e. pressure p is reduced by pore water pressure p_W. The yield stress scaling factor f_{yield} is explained in Section 2.2.

We want to investigate the influence of temperature and pressure on the propensity of plate tectonics, i.e. the tendency of a planet to obtain plate tectonics compared to an Earth-size planet.

2. Results

For this study, we define an Earth-like reference planet and then vary parameters such as internal heating rate or include the pressure effect of the viscosity to investigate the effect on the propensity of plate tectonics.

2.1. Influence of mantle temperature

We simulate an Earth-size planet with temperature-dependent viscosity and vary the heating rates from eight times the present-day value $H = 8$ ($\approx 4.5Gyr$ ago) to a value of $H = 0.2$. We find that for the considered case an either hot or cold interior leads to the stagnant lid regime, whereas for intermediate temperatures the planet is in the plate tectonics regime. Our investigation suggests that the propensity of plate tectonics has a peak during the thermal evolution.

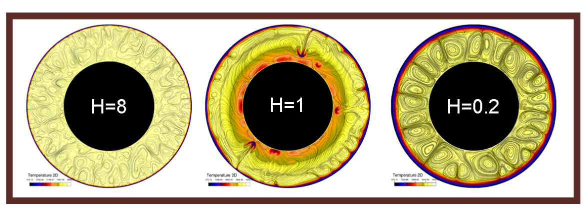

Figure 1: Influence of mantle temperature (i.e. internal heating rate) on propensity of plate tectonics.

2.2. Influence of pressure in the mantle

We want to investigate if the pressure effect on the viscosity and a possible sluggish or stagnant lower mantle can have an influence on the occurrence of plate tectonics. To determine the tendency of plate tectonics we vary the yield stress (Equation 1).

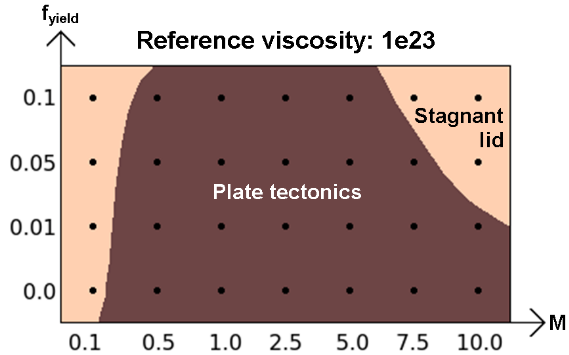

Figure 2: Occurrence of plate tectonics (dark brown area) depending on mass M and scaling factor f_{yield}.

We use a constant surface yield stress and vary the yield stress scaling factor f_{yield} (see Fig. 2), which is 1.0 for the upper mantle of Earth. The pressure in the mantle of super-Earths larger than a few Earth masses may lead to an increased viscosity in the lower mantle of the planet, which makes plate tectonics less likely. For these planets only unrealistically small yield stress scaling factors led to plate tectonics; planets much smaller than Earth are always in a stagnant lid regime. Propensity of plate tectonics hence seems to have a peak between 1 and 5 Earth masses.

3. Discussion

In our study we assume a pure perovskite mantle with new rheological parameters derived for high pressures [2], where the viscosity increases with pressure. However, the variation of viscosity with pressure is strongly debated. It might as well decrease with pressure [5, 6], which might have an effect on our results.

However, not only the lower stagnant mantle influences the propensity of plate tectonics, but the pressure effect on viscosity in the upper mantle and the mantle temperature, as well. Planets more massive than Earth are assumed to have higher interior temperatures due to accretion and radioactive heat sources. The results from Section 2.1 indicate that these planets are less likely to have plate tectonics compared to Earth independent of any pressure effects.

4. Summary and Conclusions

Our results indicate that the propensity of plate tectonics has a peak at a specific mass. For the parameters used in our studies the peak occurs between one and five Earth masses. Considering further that in general a planet is cooling and mantle temperatures decrease in time, our results show that the propensity of plate tectonics may have an additional peak during the thermal evolution.

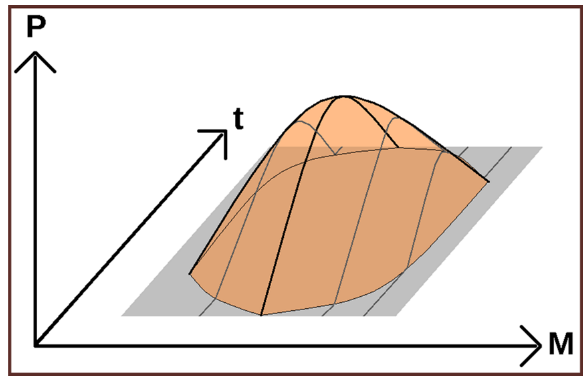

Figure 3: Propensity P of plate tectonics on Earth-like planets depends on time t (i.e. mantle temperature) and mass M of the planet.

The propensity of plate tectonics seems to be highly dependent on time (i.e. temperature) and mass of a planet. Plate tectonics hence may occur more seldom than previously thought.

Acknowledgements

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