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Climate Stability and Habitability of Earth-like Stagnant Lid Planets

Bradford Foley
Pennsylvania State University, Department of Geosciences, United States (bjf5382@psu.edu)

Plate tectonics has often been considered a requirement for long-term habitability of rocky planets, as cycling of volatiles between the surface and interior, continuous volcanism, and creation of topographic gradients through orogenic processes, help stabilize climate on Earth via the long-term carbon cycle. However, for the carbon cycle to operate and stabilize climate, all that is necessary is for weathering rates to be, in bulk, controlled by mineral dissolution reaction kinetics, rather than the supply of weatherable rock at the surface, and active CO_2 outgassing. When weathering is controlled by reaction kinetics, a feedback between weathering and climate, that regulates surface temperature, exists. However, neither requirement for climate stability directly necessitates plate tectonics. Even a stagnant lid planet experiences volcanism and outgassing, at least during it's early history, and produces fresh, weatherable surface rocks due to this volcanism. In this work I assess whether, and under what conditions, Earth-like stagnant lid planets can meet the above requirements and potentially sustain long-lived, habitable climates.

To determine the conditions necessary for habitable climates on stagnant lid planets, and how long such climates last, models of thermal evolution, crustal production, and CO_2 cycling are used. Specifically, I determine when planets can maintain rates of CO_2 degassing large enough to prevent global surface glaciation, but small enough so as not to exceed the upper limit on weathering rates provided by the supply of fresh rock, a situation which would lead to runaway atmospheric CO_2 accumulation and an inhospitably hot climate. The models show that stagnant lid planets with initial radiogenic heating rates of 100-250 TW, and with total CO_2 budgets ranging from $\sim 10^{-2} - 1$ times Earth's estimated CO_2 budget, can maintain volcanic outgassing rates suitable for habitability for $\approx 1 - 5$ Gyrs; larger CO_2 budgets result in uninhabitably hot climates, while smaller budgets result in global glaciation. High radiogenic heat production rates favor habitability by sustaining volcanism and CO_2 outgassing longer. The influence of initial atmospheric conditions are also tested, demonstrating that whether plants start hot or cold does not interfere with their ability to develop long-lived temperate climates. However, stagnant lid planets are unlikely to be able to recover from a snowball episode, especially as they age, as outgassing becomes dominated by crustal burial and metamorphism on older planets. Such outgassing would occur beneath a frozen ocean, and thus be incapable of triggering recovery from a snowball state.

Ultimately, the results provide some first order guidance for future exoplanet missions, by predicting the age at which habitability becomes unlikely for a stagnant lid planet as a function of initial radiogenic heat budget. This prediction is powerful because both planet heat budget and age can potentially be constrained from stellar observations.