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Compositional constraints on the lifetime of habitable climates on rocky exoplanets

Bradford Foley[1] and Cayman Unterborn[2]

[1]Pennsylvania State University, Department of Geosciences, University Park, United States of America (bjf5382@psu.edu)
[2]Southwest Research Institute, San Antonio, United States of America (kmanunterborn@gmail.com)

An essential factor for the habitability of rocky exoplanets over geologic timescales is climate regulation via the carbonate-silicate cycle. Without such regulation, uninhabitably hot or cold climates could form, even for planets lying within their host star's habitable zone. While often associated with plate tectonics, recent work has shown that the carbonate-silicate cycle can operate on planets in a stagnant-lid regime of tectonics, as long as volcanism is active. Volcanism drives release of CO_2 to the atmosphere, without which climate could cool into a globally frozen state, and the creation of fresh rock for weathering, without which a CO_2-rich hothouse climate could form. A key factor dictating how long volcanism can last on a rocky planet is the budget of heat producing elements (U, Th, and K) it acquires during formation. While not directly measurable for exoplanets, estimates on the range of heat producing elements (HPEs) can be made from stellar composition observations. We estimate a probability distribution of HPE abundances in rocky exoplanets based on the Hypatia catalog database of stellar U, Th, and K abundances, where Eu is used as a proxy for the difficult to measure U.

We then constrain how long volcanism, and hence habitable climates, can last on rocky exoplanets in a stagnant-lid regime using a simple thermal evolution model where initial HPE abundances in the mantle are randomly drawn from the distributions constructed from the Hypatia catalog. We further explore the influence of planet size and factors such as the initial mantle temperature and mantle reference viscosity in our models. Our models are conservative, meant to estimate the earliest time that volcanism could cease on rocky exoplanets. We find volcanism lasts for ~2 Gyrs, with 95% confidence intervals of 0.6-3.8 Gyrs for an Earth-sized planet, increasing modestly to ~3.5 Gyrs (95% confidence intervals of 1.4-5.8 Gyrs) for a six Earth mass planet. The variation in volcanism lifetime is largely determined by the K abundance of the planet, as K is a potent HPE and highly variable in stars. The likelihood of acquiring high enough abundances of the long half-life HPEs, Th or ^{238}U, to power long-lived volcanism through these heat sources is low. In most cases even Th and ^{238}U abundances at the high end of our observationally constrained probability distributions are not sufficient to power volcanism on their own, such that planets will see volcanism cease once K concentrations have decayed. Only with a high reference viscosity can Th or ^{238}U potentially drive long-lived volcanism, as in this case volcanism can be sustained for a lower total radiogenic heat production rate.