Planetary Tectonics and Interior Dynamics

Introduction: The history of volcanism and outgassing on a rocky planet shapes the evolution of its atmosphere and surface environment, and is thus critical for its habitability. Thus detailed models of planetary thermal evolution, for a range planet sizes, compositions, and tectonic styles (i.e. plate tectonics, stagnant lid, or other intermediate forms of surface tectonics) are critical for assessing the potential habitability of exoplanets. While much focus is placed on Earth and its evolution, and the role of plate tectonics, stagnant lid planets like Venus and Mars are likely to be common among the population of rocky exoplanets, given that Earth is the only rocky planet or moon in the solar system known to exhibit plate tectonics today [1,2]. Although plate tectonics has often been thought to be important, and possibly even necessary, for habitability, recent work shows that stagnant lid planets can potentially be habitable as well [3]. In particular, the same processes that regulate climate on Earth, the feedbacks between volcanism and weathering that compose the carbonate-silicate cycle, can operate on stagnant lid planets. CO₂ outgassing is maintained by mantle volcanism and metamorphic decarbonation of crust as it is buried by lava flows, and volcanism provides a source of fresh rock for weathering. Habitability of stagnant lid planets is therefore controlled by the evolution of mantle volcanism over time, and how long this volcanism lasts as the planet cools; the thermal evolution of the mantle is therefore critical. Unlike plate tectonic planets, on a stagnant lid planet the crust produced by volcanism grows in thickness over time, as there is no recycling via subduction. As the crust grows, it can significantly influence convection in the underlying mantle, and thus also impact the planet’s thermal and magmatic evolution. However, a detailed understanding of how stagnant lid convection, in particular the convective heat flux, is influenced by the presence of a thick crust is lacking.

The goal of this research is thus to develop scaling laws for the heat flux for stagnant lid convection with a crust, as a function of Rayleigh number, crust thickness, crust buoyancy, and the Frank-Kamenetskii parameter, which describes how strongly temperature dependent the viscosity of the mantle is. Currently, models of the thermal evolution of stagnant lid planets rely on scaling laws that are developed without a crust [3,4,5,6]. Thermal evolution models then typically make simplifying assumptions such as assuming that the convective heat flux is the same with a crust as without [3,5,6], or apply stagnant lid convection scaling laws to just the region beneath the crust [4]. However, whether these treatments capture the dynamics of stagnant lid convection with a thick crust is not clear. New scaling laws that explicitly include the effect of the crust on convective heat flux as determined from fully dynamic convection models are needed. These new scaling laws will then allow for improved thermal evolution models of stagnant lid planets, to better track features such as the history of volcanism and volatile cycling, and thus better assess the prospects for habitability of rocky exoplanets.

![Figure 1. Nusselt number as a function of average crust thickness for models with specified Rayleigh number and Frank-Kamenetskii parameter. Both Nusselt number and average crust thickness are time averages after the models have reached statistical steady-state. We find two clear limiting behaviors: A “thin crust limit,” and a “thick crust limit.”](image-url)
that the transition between these two regimes occurs when the crustal thickness is approximately equal to the lithosphere thickness convection would produce without a crust. In the thin crust limit, the convective heat flux, or Nusselt number, is approximately independent of the crust thickness (Figure 1). In the thick crust limit, increasing crust thickness leads to a thicker lithosphere, and hence lower Nusselt number. We determine scaling laws for the Nusselt number in both limits. In the thin crust limit, previously developed scaling laws that do not include a crust still hold, as the crust does not significantly influence the heat flux. In the thick crust limit, the heat flux is governed by the thickness of the lithosphere, which is composed of the crust and a thermal boundary layer beneath the crust. This thermal boundary layer thus results in a layer of sub-crustal mantle lithosphere. The thickness of the sub-crustal mantle lithosphere is found from a boundary layer stability analysis. The scaling laws fit the model results well over a wide range of Rayleigh number, crustal thickness, and Frank-Kamenetskii parameter for viscosity, and over both the thin and thick crust limits (Figure 2). Using these scaling laws in thermal evolution models shows that a thick crust, > 125 km thick, suppresses mantle heat flux during the first few billion years of evolution of an Earth-like stagnant lid planet. This causes the mantle to heat up during the first 1-2 billion years of planetary evolution, therefore producing a warm thermal transient in the mantle that lasts for several more billions of years.

**Figure 2.** Scaling law for Nusselt number in the thick crust limit, against the observed average Nusselt number from the numerical models (A). Predictions deviate from the model results at low crust thickness, when the crust does not significantly influence convection and Nusselt number is given by standard thermal convection scaling laws. The scaling law for Nusselt number, which fits the numerical model results well, is obtained by combining thick and thin crust limits against the observed Nusselt number from the numerical model results (B).

On Earth basaltic crust transforms to dense eclogite at ~ 50 km depth, meaning the lower crust is compositionally dense compared to the underlying mantle, and will tend to founder. This same process could occur on stagnant lid planets as well, as long as they have similar bulk compositions to Earth. On a stagnant lid planet, there will be a competition between the negative buoyancy of the lower crust that drives foundering, and the high viscosity of the stagnant lid that resists foundering. We therefore run additional models with a negatively buoyant crust to constrain how much crust is able to founder into the mantle, versus remaining locked in the high viscosity stagnant lid.

Preliminary results indicate that there is a critical depth in the lid where dense crust is able to founder, and above this depth crust remains locked in place. This critical depth depends on Frank-Kamenetskii parameter and Rayleigh number. Scaling laws will be developed for the amount of negatively buoyant crust that is able to founder, and the resulting heat flux and lithospheric thickness that results from crustal foundering. Combined with the results for buoyant crusts, complete scaling laws capturing convective heat flux for stagnant lid convection with both buoyant and negatively buoyant crusts will be developed, and used to improve our understanding of the thermal evolution of rocky planets.

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**References:**


