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The effects of internal heating and large scale climate variations on tectonic bi-stability in terrestrial planets

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ABSTRACT

We use 3D mantle convection and planetary tectonics models to explore the links between tectonic regimes and the level of internal heating within the mantle of a planet (a proxy for thermal age), planetary surface temperature, and lithosphere strength. At both high and low values of internal heating, for moderate to high lithospheric yield strength, hot and cold stagnant-lid (single plate planet) states prevail. For intermediate values of internal heating, multiple stable tectonic states can exist. In these regions of parameter space, the specific evolutionary path of the system has a dominant role in determining its tectonic state. For low to moderate lithospheric yield strength, mobile-lid behavior (a plate tectonic-like mode of convection) is attainable for high degrees of internal heating (i.e., early in a planet's thermal evolution). However, this state is sensitive to climate driven changes in surface temperatures. Relatively small increases in surface temperature can be sufficient to usher in a transition from a mobile- to a stagnant-lid regime. Once a stagnant-lid mode is initiated, a return to mobile-lid is not attainable by a reduction of surface temperatures alone. For lower levels of internal heating, the tectonic regime becomes less sensitive to surface temperature changes. Collectively our results indicate that terrestrial planets can alternate between multiple tectonic states over giga-year timescales. Within parameter space regions that allow for bi-stable behavior, any model-based prediction as to the current mode of tectonics is inherently non-unique in the absence of constraints on the geologic and climatic histories of a planet.

1. Introduction

The Earth is the only planetary body in our solar system with currently active plate tectonics. Plate tectonics is characterized by horizontal motion of strong surface plates. Surface motion is accommodated by localized rock failure along relatively narrow plate boundary zones. For the thermal state of the planet, the critical aspect of plate tectonics is that the cold surface plates participate in mantle overturn and cool the hot interior. For this reason, plate tectonics is considered an example of mobile-lid mantle convection (also referred to as active-lid convection). A more common regime throughout our solar system is stagnant-lid mantle convection (i.e., single plate planet). This regime is not associated with significant horizontal surface motions and the outer rock layer does not participate in mantle overturn and interior cooling. There is also the possibility of a transitional tectonic regime associated with episodic behavior. The episodic regime is characterized by periods of quiescence (akin to stagnant-lid) punctuated with rapid episodes of surface overturn (Moresi and Solomatov, 1998). The three modes of convection and surface tectonics described can potentially operate on a single planetary body at different times in its evolution (O'Neill et al., 2007; Weller and Lenardic, 2012; Crowley and O'Connell, 2012).

As the Earth cools and internal energy sources are tapped, plate tectonics will begin to wane and eventually cease entirely; the Earth will move from a mobile-lid into a stagnant-lid regime. While the end state is agreed upon, the timing is not. The initiation time of plate tectonics is also not agreed upon. Indeed, the nature of early Earth tectonics remains hotly debated, with implications that extend to the current state of the planet (e.g., Davies, 1993; Calvert et al., 1995; Condie and Kroner, 2008; O'Neill et al., 2007; Stern, 2008; Moyen and van Hunen, 2012; Debaille et al., 2013).

Uncertainty about the initiation of plate tectonics on the Earth has been extended into the realm of the extra-solar terrestrial planets, in particular those significantly larger than the Earth (so-called "super-Earths"). Some groups have argued that a

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stagnant-lid regime should be favored (O'Neill and Lenardic, 2007; Stein et al., 2011, 2013) while others argue that these planets will be in a mobile-lid mode of convection and tectonics (Valencia et al., 2007; Valencia and O'Connell, 2009; van Heck and Tackley, 2011; Tackley et al., 2013).

Part of the difficulty in using mantle convection models to predict tectonic state relates to uncertainties in the degree to which variations in internal heating and convective vigor can affect the surface stress levels a planet experiences. Scaling theories, based upon the simple example of a bottom-heated system, predict increased convective stresses with increasing convective vigor (i.e. mantle Rayleigh number). This effect translates to higher lithospheric stresses for larger planets and a greater potential for plate tectonics (Valencia et al., 2007). However, increases in the internal heating rate of the mantle have also been shown to favor a stagnant-lid regime for a given planetary size (O'Neill et al., 2007; O'Neill and Lenardic, 2007; Stein et al., 2013). In a similar vein, it has been argued that an increase in the long-term surface temperature of a planet can extend into the planetary interior and that the associated heating effect can initiate a transition from active- to stagnant-lid tectonics (Lenardic et al., 2008; Landuyt and Bercovici, 2009; Lenardic and Crowley, 2012; Foley et al., 2012).

Recent studies examining transitions in the mode of planetary tectonics can be divided into two categories. The first set contain those interested in how variations in specific material and thermal parameters can affect the tectonic regime expressed (e.g., Moresi and Solomatov, 1998; O'Neill et al., 2007; Lenardic et al., 2008; Landuyt and Bercovici, 2009; Lenardic and Crowley, 2012; Foley et al., 2012). The second set consists of those interested in how the inherently non-linear behavior of the convecting system, and differing evolutionary conditions, can allow for the potential of multiple stable tectonic states for equivalent material and thermal parameters (Crowley and O'Connell, 2012; Weller and Lenardic, 2012; Lenardic and Crowley, 2012).

Studies focusing on the effects of specific parameters on the tectonic regime have explored the effects of changing lithospheric properties, e.g. yield stress (Moresi and Solomatov, 1998) and changes in the internal properties of the mantle (O'Neill et al., 2007). Two groups have suggested that changes in the long-term climate of a planet may result in tectonic transitions (Lenardic et al., 2008; Landuyt and Bercovici, 2009; Lenardic and Crowley, 2012; Foley et al., 2012). Both groups argue that much warmer surface temperatures over geologic time scales may initiate the cessation of plate tectonics. These results have potential applications to Venus, where the possibility of significant fluctuations in the long term climate (both warming and cooling) has been suggested (e.g., Solomon et al., 1999; Phillips et al., 2001). Additional work has extended this concept to warm exoplanets (Foley et al., 2012).

More recently, several studies have argued that the evolutionary pathway of a planet is the dominant factor in determining the mode of tectonics that the system expresses, as opposed to the particular material, thermal, and orbital parameters associated with the planet in its current state (Crowley and O'Connell, 2012; Weller and Lenardic, 2012; Lenardic and Crowley, 2012). Nonlinearities inherent in the tectono-convective system lead to a hysteresis of states in which multiple regimes are possible for the same planetary parameter values. The hysteresis window, defined as the range in parameter space for which multiple stable solutions exist, was found to increase with increases in the temperature-dependence of mantle viscosity and the vigor of mantle convection, as expressed by a bottom Rayleigh number (Weller and Lenardic, 2012). Both of those factors are expected to increase for larger terrestrial planets and, as a result, the parameter space region associated with multiple stable states is predicted to increase with planetary size. Within the hysteresis window, the final tectonic regime of the system (e.g. mobile or stagnant) becomes a function of a planet's specific geologic and climatic history. Given that historical constraints are sparse to non-existent for extrasolar planets, this implies that predicting the tectonic state of an extrasolar planet will become more difficult as the size of the planet increases. This stands in stark contrast to the idea that the potential for plate tectonics increases with planetary size and, as a result, plate tectonics become "inevitable" for super-Earths (Valencia et al., 2007). What is currently unclear is how the hysteresis window depends on the level of internal heating within the mantle of a terrestrial planet. This heating level can serve as a proxy for the thermal age of a planet, and thus mapping the window as a function of the heating rate can provide insights into how the potential of multiple tectonic states varies over the geologic lifetime of a planet. This idea provides the initial motivation for this paper.

In this work, we evaluate the effects of changing levels of internal heating on the tectonic regime of a planet using 3D mantle convection simulations. We also evaluate the degree of climatic driven temperature change needed to cause a transition from an active-lid mode of convection as a function of the internal heating rate. As that heating rate can serve as a proxy for the thermal age of a planet, this can give insights into how the stability of plate tectonics, to large and long-lived climate excursions, changes over a planets lifetime. We show that transitions in tectonic regimes have strong dependencies on the history of the system, the level of internal heating in the mantle, and the value of long-lived surface temperatures changes.

2. Models and methods

We explore a model of planetary convection defined by the equations of mass, momentum, and energy conservation, assuming incompressibility. The governing equations, in non-dimensional form, are given by:

$$u_{i,i} = 0 \tag{1}$$

$$-P_{,i} + \left(\eta(u_{i,j} + u_{j,i})\right)_{,j} + Ra\,T\delta_{ir} = 0 \tag{2}$$

$$T_{,t} + u_i T_{,i} = T_{,ii} + Q \tag{3}$$

where u is the velocity, P is dynamic pressure, η is the viscosity, Ra is the Rayleigh number, T is temperature, δ_{ij} is the Kroneker delta tensor, Q is the heat production rate, i and j represent spatial indices, r is a unit vector in the radial direction, t is time, and the form $X_{,y}$ represents the derivative of X with respect to y. Repeated indices imply summation.

The Rayleigh number is defined as:

$$Ra = g\rho\alpha\Delta T d^3/(\kappa\eta_{0,i}) \tag{4}$$

where α is the thermal expansivity, ρ is density, g is gravity, κ is the thermal diffusivity, η_0 is the reference viscosity, and d is layer depth. ΔT is the reference temperature drop across the system, given as: the temperature drop from the base of the convecting layer to the surface (T_s–T_b). A Rayleigh number can also be defined using the average internal viscosity of the mantle. The internal viscosity η_i depends on the internal temperature, which is not known *a priori* (it is part of the model solution). Therefore, Ra based on internal viscosity may only be calculated after the model has been run to a statistically steady state. The general form of temperature-dependant viscosity is given by:

$$\eta = \exp(-\theta T) \tag{5}$$

with:

$$\theta = A\Delta T \tag{6}$$