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ON THE LIKELIHOOD OF PLATE TECTONICS ON SUPER-EARTHS: DOES SIZE MATTER?

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ABSTRACT

The operation of plate tectonics on Earth is essential to modulate its atmospheric composition over geological time and is thus commonly believed to be vital for planetary habitability at large. It has been suggested that plate tectonics is very likely for super-Earths, with or without surface water, because a planet with a larger mass tends to have sufficient convective stress to escape from the mode of stagnant-lid convection. Here, this suggestion is revisited on the basis of the recently developed scaling laws of plate-tectonic convection, which indicate that the planetary size plays a rather minor role and that the likelihood of plate tectonics is controlled largely by the presence of surface water.

Key words: Earth – planetary systems – planets and satellites: general

1. INTRODUCTION

The recent discovery of extrasolar terrestrial planets (super-Earths; Rivera et al. 2005; Beaulieu et al. 2006; Lovis et al. 2006; Udry et al. 2007; Leger et al. 2009; Charbonneau et al. 2009) has turned the possibility of finding Earth-like planets into reality, and the prospects of planned future missions such as *Kepler* appear promising (e.g., Selsis et al. 2007; Spiegel et al. 2009; von Bloh et al. 2009). One of the key questions is the likelihood of plate tectonics on such super-Earths, because this particular mode of mantle convection is essential to modulate the atmospheric composition over geological time (Berner 2004) and is thus generally believed to be vital for planetary habitability.

A planetary mantle made of silicate rocks can convect in two distinctly different ways. The most "natural" mode of convection is stagnant-lid convection, in which a rigid spherical shell covers the entire planetary surface and convection takes place only beneath this rigid lid (Solomatov 1995). The viscosity of silicate rocks is known to be strongly sensitive to temperature, and for a typical temperature difference of ∼1000 K between the hot interior and the cold surface, viscosity can easily vary by more than 10 orders of magnitude (Karato & Wu 1993). The top thermal boundary layer becoming an undeformable, stagnant lid is a corollary of temperature-dependent viscosity, and most of terrestrial planets in the solar system (i.e., Mercury, Venus, and Mars) are indeed thought to exhibit this mode of convection (Schubert et al. 2001). Earth is an exception, exhibiting plate-tectonic convection, in which the supposedly rigid surface is somehow broken up to a dozen pieces or so. Many of these broken pieces (called "plates") are continuously recycled back into the interior, so unlike stagnant-lid convection, the surface conditions are deeply connected to, and also modulated by, the dynamics of the solid interior. For plate tectonics to take place, of course, some weakening mechanism must exist to offset the temperature-dependent viscosity. A popular explanation is that the strength of the thermal boundary layer may be limited considerably by water-assisted brittle deformation (Moresi & Solomatov 1998), though this issue has not been settled yet (Bercovici 2003). Nevertheless, a mechanism based on the presence of surface water has the advantage of being able to readily explain the absence of plate tectonics on other terrestrial planets in the solar system.

Concerning the mode of mantle convection in super-Earths, an intriguing suggestion was made that the operation of plate tectonics is very likely for such planets regardless of the surface condition (Valencia et al. 2007); even if they are dry like Venus, planets more massive than Earth are likely to have greater convective stress, which may be sufficient to break a rigid lid and escape from the mode of stagnant-lid convection. This suggestion has since been controversial because some contradictory simulation results have been presented (O'Neill & Lenardic 2007; Valencia & O'Connell 2009). Also note that existing debates on this matter assume the same weakening mechanism based on brittle deformation, so an entirely different consideration may need to be made in case of other weakening mechanisms (e.g., Landuyt et al. 2008). The mechanism based on brittle deformation, however, can be fully consistent with our understanding of rock mechanics (Korenaga 2007) and is perhaps the most widely adopted mechanism in the numerical studies of plate-tectonic convection. Therefore, even by limiting ourselves to this particular mechanism, our discussion may not suffer from the substantial loss of generality. In this case, we can draw some definitive conclusions on the likelihood of plate tectonics on super-Earths, on the basis of the recently developed scaling laws of plate-tectonic convection (Korenaga 2010).

2. SCALING LAWS OF PLATE TECTONICS

The temperature-dependent viscosity appropriate for silicate materials may be expressed as (Karato & Wu 1993)

$$\eta_T(T_p) = \eta_r \exp\left(\frac{E}{RT_p} - \frac{E}{RT_r}\right), \quad (1)$$

where T_p is the mantle potential temperature (i.e., temperature corrected for the effect of adiabatic compression with increasing depth), η_r is the reference viscosity at $T_p = T_r$, and E is the activation energy. For Earth, reference viscosity is commonly assumed to be $\sim 10^{19}$ Pa s at the present-day potential temperature of ∼1350 °C, and a typical value of effective activation energy is 300 kJ mol^{-1} regardless of deformation mechanism (Korenaga 2006). With this Arrhenius type of temperature dependency, mantle viscosity exceeds 10^{30} Pa s for $T_p < \sim 500$ °C, thus the formation of stagnant lid seems unavoidable. The coldest part of the top thermal boundary layer can also deform by brittle failure, however, and in this case, "effective" viscosity may be considerably lowered so that the maximum deviatoric stress does not exceed the following yield stress criterion (Moresi & Solomatov 1998),

$$\tau_y = c_0 + \mu \rho g z, \quad (2)$$

where c_0 is the cohesive strength, μ is the (effective) friction coefficient, ρ is the density, g is the gravitational acceleration, and z is the depth. Experimental data on rock friction indicate that the cohesive strength is negligibly small compared to the depth-dependent part (Byerlee 1978), so it is safe to approximate as $c_0 \approx 0$. Temperature-dependent viscosity modulated by brittle failure can thus be specified by activation energy E and friction coefficient μ, or equivalently, by the following non-dimensional parameters,

$$\theta = \frac{E \Delta T_p}{R(T_s + \Delta T_p)^2}, \quad (3)$$

where T_s is the surface temperature and ΔT_p denotes the potential temperature difference between the surface and the interior, and

$$\gamma = \frac{\mu}{\alpha \Delta T_p}, \quad (4)$$

where α is the thermal expansivity. The parameter θ is known as the Frank-Kamenetskii parameter, and $\theta \sim 20$ for Earth's mantle. The parameter γ is proportional to the ratio of the frictional stress scale ($\mu \rho g h$, where h is the thickness of the top thermal boundary layer) over the convective stress scale ($\alpha \rho g \Delta T_p D$, where D is the mantle depth).

Most of previous studies on plate-tectonic convection with this type of rheology are characterized by relatively low θ values (up to ~8; e.g., Moresi & Solomatov 1998; O'Neill & Lenardic 2007), so it has been difficult to apply their results to Earth-like conditions. It is only recently that an extensive series of numerical simulations were conducted with Earth-like θ values (Korenaga 2010), and the systematics of the numerical results indicates that the Nusselt number scales with the internal Rayleigh number as

$$Nu = 2 \left(\frac{Ra_i}{Ra_c} \right)^{1/3} \Delta \eta_L^{-1/3}, \quad (5)$$

where Ra_c is the critical Rayleigh number (10^3) and $\Delta \eta_L$ is the effective viscosity contrast across the top thermal boundary layer. The Nusselt number is surface heat flux normalized by reference conductive heat flux, and the Rayleigh number measures the potential vigor of convection (e.g., Tritton 1988). When viscosity is variable in the convection system, there are more than one way of defining the Rayleigh number, and the internal Rayleigh number here is defined with internal viscosity η_i (corresponding to the temperature of $T_s + \Delta T_p$) as

$$Ra_i = \frac{\alpha \rho g \Delta T_p D^3}{\kappa \eta_i}, \quad (6)$$

where κ is the thermal diffusivity. The temperature dependency of viscosity is given by Equation (1), and the effective viscosity contrast across the top thermal boundary layer is found to be parameterized as

$$\Delta \eta_L(\gamma, \theta) \approx \exp(0.327 \gamma^{0.647} \theta). \quad (7)$$

Note that one can easily calculate average plate thickness using the heat-flow scaling law (Equation (5)) as

$$h \sim \frac{D}{Nu}. \quad (8)$$

Furthermore, the transition from plate-tectonic convection to stagnant-lid convection is found to take place if the viscosity contrast exceeds a threshold, which obeys the following scaling:

$$\Delta \eta_{L,\mathrm{crit}} \approx 0.25 Ra_i^{1/2}. \quad (9)$$

That is, the higher the Rayleigh number is, the more easily place tectonics can take place. The stress due to the negative buoyancy of a subducting plate can be shown to be proportional to the internal Rayleigh number (Korenaga 2010), and the above threshold indicates that the system with a higher Rayleigh number can overcome a greater viscosity contrast (i.e., greater activation energy and/or greater friction coefficient; see Equation (7)) because of its higher convective stress. The above scaling laws are based on over 300 cases of thermal convection with pseudoplastic rheology in the two-dimensional Cartesian geometry, all of which were run for sufficiently long time (up to six diffusion times) to accurately measure convection diagnostics at statistically steady state. A large number of plate-tectonic cases were obtained with a wide range of rheological parameters ($\sim 10 < \theta < \sim 30$ and $0.1 \leqslant \gamma \leqslant 1$, corresponding to $\Delta \eta_L$ of up to $\sim 10^4$) and the internal Rayleigh number (from $\sim 10^5$ to 10^{10}).

The internal Rayleigh number for a super-Earth with mass M may be calculated as

$$Ra_i = Ra_{i,\oplus} \left(\frac{\Delta T_p}{\Delta T_{p,\oplus}} \right) \left(\frac{\eta(T_{p,\oplus})}{\eta(T_p)} \right) \left(\frac{M}{M_\oplus} \right)^{1.54}, \quad (10)$$

for which density, gravity, and mantle depth are assumed to be scaled with M as estimated by Valencia et al. (2006). With $\Delta T_{p,\oplus}$ of 1350 °C and $\eta(T_{p,\oplus})$ of 10^{19} Pa s (Korenaga 2010), $Ra_{i,\oplus}$ is $\sim 2.6 \times 10^9$. A few illustrative examples are shown in Figure 1. The ratio of the effective viscosity contrast over the critical value is calculated as a function of planetary mass for different combinations of the friction coefficient, the activation energy, and the potential temperature difference. The ratio should be smaller than unity for plate tectonics to be dynamically feasible. The friction coefficients for silicate rocks are generally in the range of 0.6–0.8 (Byerlee 1978), but the case with the (effective) friction coefficient as low as 0.03 can be justified by high pore fluid pressure, which may be achievable in the presence of surface water (Korenaga 2007). Such a low effective friction coefficient is essential for the operation of plate tectonics. Note that high pore fluid pressure does not directly reduce the friction coefficient but instead reduces the shear strength of a saturated rock, because the shear strength is equal to the friction coefficient times the difference between the normal compressive stress and pore pressure. The addition of water (or any other fluid phase) can thus facilitate slip nucleation, and this effect is commonly expressed in terms of the effective friction coefficient. In addition to high pore fluid pressure, there are other mechanisms that could reduce the friction coefficient, but they are not relevant to the onset of plate tectonics (see the discussion). By raising the friction coefficient to the standard value of 0.7, the viscosity ratio increases by many orders of magnitude, compared to which the mass effect is marginal; increasing the mass by one order of magnitude

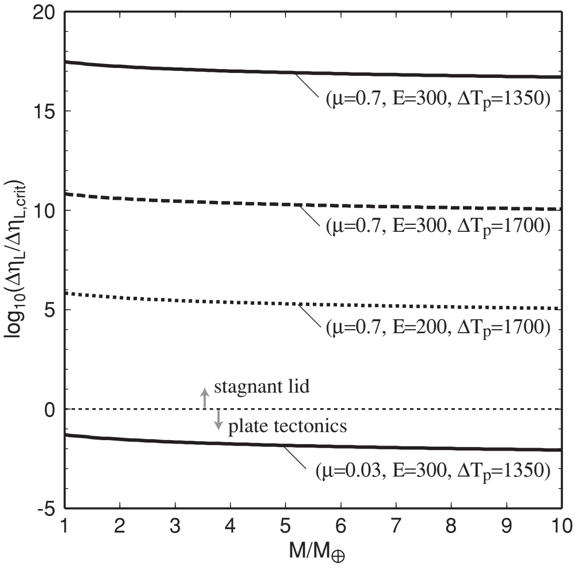

Figure 1. Effective viscosity contrast across the thermal boundary layer normalized by the critical value for the operation of plate tectonics is shown as a function of planetary mass. For plate tectonics to take place, the ratio $\Delta\eta_L/\Delta\eta_{L,\mathrm{crit}}$ must be smaller than unity. Four cases are shown for different combinations of the effective friction coefficient μ, the activation energy of temperature-dependent viscosity E (in kJ mol^{-1}), and the potential temperature difference for the planetary interior ΔT_p (in K). Note that the heat-flow scaling of Equation (5) is valid only when $\Delta\eta_L < \Delta\eta_{L,\mathrm{crit}}$.

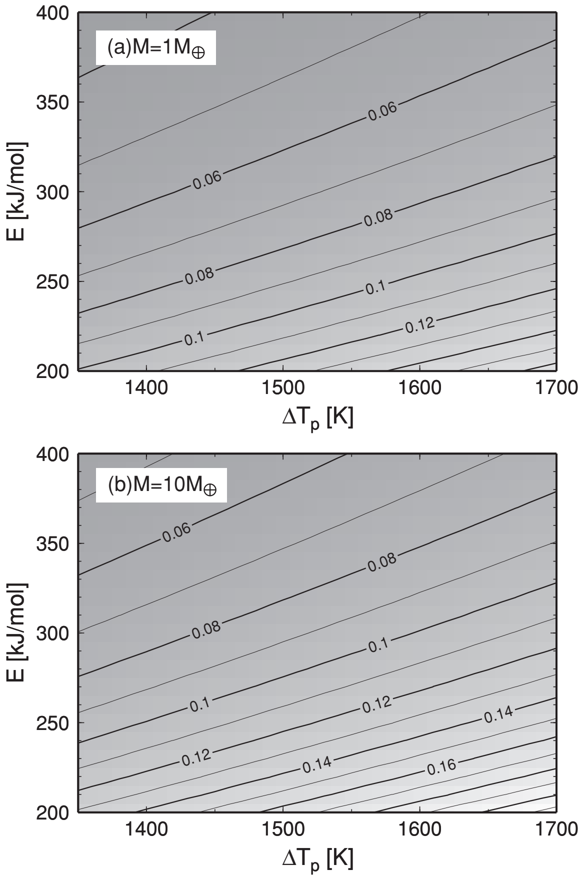

Figure 2. Maximum effective friction coefficient for the existence of plate tectonics is shown as a function of the potential temperature difference and the activation energy, for the cases of (a) $M = 1\,M_\oplus$ and (b) $M = 10\,M_\oplus$. For plate tectonics to occur, the effective friction coefficient should be smaller than the values shown.

results in a reduction in the viscosity ratio only by a factor of ~6. The potential temperature of super-Earths does not have to coincide with that of the present-day Earth (it is difficult to predict the present-day temperature of any terrestrial planet even in the simple case of stagnant-lid convection (cf. Fraeman & Korenaga 2010)), and a higher potential temperature helps to reduce the viscosity ratio by raising the Rayleigh number as well as lowering both θ and γ. Yet, raising the potential temperature to 1700 °C, which is appropriate for the situation soon after a putative magma ocean but unrealistically high for the present-day condition, is not sufficient to bring the viscosity contrast into the plate-tectonic regime. Lowering the activation energy to its likely lower bound (Korenaga & Karato 2008) has a similarly limited effect. To summarize these effects, the maximum effective friction coefficient allowed in plate-tectonic convection is shown in Figure 2 for a range of the activation energy and the potential temperature difference. Even for the case of $M = 10\,M_\oplus$, the effective friction coefficient has to be lower than ~0.1, and it requires extreme conditions to raise it to 0.2. In other words, a Venus-like dry planet is likely to stay in the mode of stagnant-lid convection even if its mass is considerably greater than Earth's.

3. DISCUSSION AND CONCLUSION

In light of the scaling of plate-tectonic convection, or more accurately, thermal convection with strongly temperature-dependent viscosity and brittle failure, it is straightforward to discuss the potential limitation of previous debates on the likelihood of plate tectonics on super-Earths. O'Neill & Lenardic (2007) argued that plate tectonics is unlikely on super-Earths because higher yield stress due to greater gravity (Equation (2)) is more important than higher convective stress expected from higher Rayleigh number, and they presented supporting numerical simulation results. The ratio of frictional stress over convective stress, however, is expected to scale with h/D (cf. Equation (4)), and the thickness of thermal boundary layer h decreases with an increasing Rayleigh number. Their numerical results are thus puzzling, and because their modeling is not fully described, it is difficult to identify the origin of this puzzling behavior. At any rate, the temperature-dependent viscosity they employed corresponds to θ of only ~7 (i.e., the viscosity contrast across the top thermal boundary layer would be only 10^3 even in the absence of brittle failure), so such model behavior is not readily applicable to the mantle dynamics of Earth and super-Earths.

The argument of Valencia et al. (2007) is physically more plausible. A higher Rayleigh number characterizing a super-Earth should correspond to greater convective stress, so the convective system is more prone to plate tectonics. This is qualitatively similar to what Equations (7) and (9) indicate. The difference is a quantitative one; an increase in convective stress is not strong enough to make plate tectonics possible on a dry planet. It is not surprising, however, to see such quantitative difference between an order-of-magnitude analysis (Valencia et al. 2007) and scaling laws built on the systematics of finite-amplitude convection (Korenaga 2010). The weakening mechanism due to brittle failure makes mantle viscosity stress-dependent, and its combination with temperature-dependent viscosity results in highly nonlinear dynamics. With greater nonlinearity, it becomes more difficult to accurately estimate a priori the stress scale or the velocity scale because these scales are to be adjusted self-consistently in a convecting system. The parameterization of the effective viscosity contrast (Equation (7)) or its threshold (Equation (9)) are reasonably reliable because they are supported by a large number of model runs with Earth-like parameters, but these relations remain empirical. A more theoretical approach to derive them has yet to be formulated, and it is a challenging problem as it must handle the emergence of self-organization in fluid dynamics with nonlinear rheology. For example, one of the important resisting forces for plate tectonics comes from the bending of subducting plates, and the energy dissipation of plate bending is sensitive to the bending curvature. The modeling results of Korenaga (2010) suggests that the bending curvature is a function of the Rayleigh number, but at the moment there exists no theory that can predict the bending curvature.

This study suggests that, if the strength of the top thermal boundary layer is limited by brittle failure, having a sufficiently low effective friction coefficient ($< \sim 0.1$) is critical for the operation of plate tectonics on super-Earths. The studies of earthquake dynamics suggest a variety of mechanisms that can reduce the friction coefficient during fault slip, such as flash heating at highly stressed frictional microcontacts and thermal pressurization of fault-zone pore fluid (e.g., Rice 2006), but these mechanisms are invariably dynamic, requiring already-ongoing slip along a pre-existing fault, which may be taken for granted only in the presence of plate tectonics. Calling for such mechanisms when discussing the mode of mantle convection (i.e., stagnant lid versus plate tectonics) would thus lead us to a chicken-and-egg problem. Other dynamic weakening mechanisms, including the thermal decomposition of a hydrous phase (Han et al. 2007), the formation of a gel-like layer in wet silica-rich fault zones (Di Toro et al. 2004), and the formation of a macroscopic melt layer along a fault (Rempel & Rice 2006), are even more secondary; they can set in only at a large enough slip or with large enough rise in fault temperature, so they suffer from the same conundrum. Therefore, according to the current understanding of rock mechanics (Scholz 2002), the hydration of the top thermal boundary layer by thermal cracking (Korenaga 2007) appears to be the only viable mechanism that could make the effective friction coefficient low enough for the onset of plate tectonics, indicating that the likelihood of plate tectonics on a given planet may be controlled largely by the presence of surface water and not much by its size. This view is also consistent with the absence of plate tectonics on Venus despite a profusion of dynamic weakening mechanisms. Once plate tectonics is initiated, the aforementioned dynamic weakening mechanisms could of course take place, and note that some of them require, either directly or indirectly, the presence of surface water.

The present-day surface condition is a complex function of how a planet has evolved through time. The presence of surface water may require in some cases a chance delivery of water from other astronomical objects (Lunine et al. 2003; Marty & Yokochi 2006), whereas abundant surface water could also have a purely endogenous origin (Fraeman & Korenaga 2010). The size insensitivity of the mode of mantle convection implies a variety of situations to be expected for super-Earths. Future observations on extrasolar terrestrial planets may provide some important clues on their evolutionary paths, or at least we need to understand how the present-day surface condition of a terrestrial planet is controlled by its long-term evolution, in order to better interpret such observations.

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