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# Constraints on plate tectonics initiation from scaling laws for single-cell convection

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ABSTRACT

The Earth is the only planet known to have plate tectonics, while other planets are covered with a stagnant lid. On the Earth, the initiation of subduction, which is thought to be the fundamental process for plate tectonics initiation, is caused not only by the negative buoyancy of the lithosphere but also by the forces from plate motions. However, for planets which do not have plate tectonics, the very first episode of lithospheric failure has to be caused by forces other than plate motions. Sublithospheric convection has been proposed as a possible mechanism that provides lithospheric instability through inducing stresses in the lithosphere, and lithospheric failure can occur when the yield stress is below a critical value. We test the applicability of scaling laws for the critical yield stress obtained in single-cell convection simulations to strongly time-dependent multi-cell systems. We show that with an appropriate choice of characteristic aspect ratio for the convective system, the scaling laws from single-cell simulations can be used to evaluate the conditions on the terrestrial planets in the inner Solar System for plate tectonics to exist. In agreement with previous studies, the estimated values for critical yield stress and coefficient of friction are much lower than the expected values for the Earth's lithosphere.


## 1. Introduction

The diversity of terrestrial planets both inside and outside the Solar System is manifested in their composition, interior structures, surface expression, and evolution. The terrestrial planets in the inner Solar System have similar bulk compositions, yet they have very different surface features. The Earth has extensive convergent plate margins with a total length of $>5.5 \times 10^4$ km, and mid-ocean ridges of about $6 \times 10^4$ km (Stern, 2002). Venus lacks the global-scale plate boundaries observed on Earth; its surface appears to be more or less uniform and has been stable for the past few hundred Myr (e.g., Schubert et al., 1997; McKinnon et al., 1997). The landscape of Mars is characterized by hemispheric dichotomy and the lithospheric load in the Tharsis region (e.g., Zuber, 2001). On Mercury, tectonic features are generally contractional (e.g., Watters et al., 2009; Byrne et al., 2014). The variations in surface expression indicates that these planets may have diverse interior dynamics. Mantle convection can occur in mobile lid regime, transitional regime with some episodic failure, and stagnant lid regime (e.g., Solomatov, 1995; Moresi and Solomatov, 1998; Stein and Hansen, 2008). Plate tectonics is currently understood as a mode of convection that operates on the Earth, making it distinct from all other known planets where mantle convection, if existing, is likely to be in the stagnant lid regime. The convective style of planetary mantles determines the efficiency of heat transport, which has important implications for planetary evolution. The efficiency of heat transfer controls the presence of the magnetic field, because efficient cooling of the planet is necessary to drive convection in the core. Since plate tectonics provides an efficient cooling mechanism for the core, it is linked to the existence of core magnetism (Nimmo and Stevenson, 2000; Nimmo, 2002). Furthermore, plate tectonics processes such as volcanic degassing and subduction also regulate atmospheric composition (e.g., Zindler and Hart, 1986).

The topics of mode of heat transport, core dynamo, and planetary atmosphere not only concern planetary geology, but also planet habitability (e.g., Franck et al., 2000; Gonzalez et al., 2001; Lammer et al., 2009; Brack et al., 2010). The atmospheric composition and the protection by core magnetic field against solar wind are crucial for the existence of life. Therefore the question of whether a planet can have plate tectonics is also of large interest to geobiology and astrobiology.

The discovery of extrasolar planets whose masses are a few times that of the Earth gives rise to the possibility of finding more Earth-like planets. Various theories for lithospheric failure and

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planetary properties have been proposed to explore the conditions necessary for a planet to have plate tectonics (Fowler and O'Brien, 2003; Solomatov, 2004; O'Neill and Lenardic, 2007; Valencia and O'Connell, 2009; Korenaga, 2010; Karato, 2011; Foley et al., 2012). From the comparisons between the Earth and other terrestrial planets, "A reasonable conclusion is that the Earth is the remarkable planet in terms of tectonics and volcanism, not Venus", as Don Turcotte noted (Turcotte, 1996). It raises the query of why the Earth is so unique as to have plate tectonics.

Researchers gathered evidence for the beginning of plate tectonics on the Earth from various geologic indicators such as magnetic anomalies, ophiolites, metamorphic rocks, and isotopic signatures in igneous rocks (e.g., Stern and Bloomer, 1992; Stern, 2007; Shirey et al., 2008). However with an active surface, evidence is continuously destroyed so there is less data for deeper time. The rock records may also have multiple interpretations for their formation (e.g., Casey and Dewey, 1984; Pearce et al., 1992). Many came up with models of how plate tectonics and subduction could have started, yet most of them require existing boundaries and/or weak zones (e.g., McKenzie, 1977; Turcotte, 1977; Mueller and Phillips, 1991; Kemp and Stevenson, 1996; Toth and Gurnis, 1998; Stern, 2004; Nikolaeva et al., 2010; Lu et al., 2015; Gerya et al., 2015).

Studies of driving plate forces show that they mostly come from slab pull; and in addition to vertical buoyancy forces, horizontal compressive forces from already occurring plate movements are needed for subduction initiation (e.g., McKenzie, 1977; Mueller and Phillips, 1991; Lithgow-Bertelloni and Richards, 1995). Therefore the key to the initiation of plate tectonics may be in the very first episode of subduction.

There has been many studies on how plate tectonics could have emerged on a planet. For a planet which does not have plate tectonics, the first episode of subduction or large-scale lithospheric movement would be more accurately termed as "lithospheric failure". We thus refer to the process of plate tectonics initiation by "lithospheric failure", the term used by Fowler and O'Brien (2003). A potential mechanism for lithospheric failure is sublithospheric convection (e.g., Ogawa, 1990; Fowler and O'Brien, 2003; Solomatov, 2004). A major difficulty for this mechanism is the high strength of the lithosphere that prevents it from failing. In numerical studies the strength is often reduced with a yield stress, which is a simplification of the weakening mechanisms in the lithosphere (e.g., Fowler, 1993; Trompert and Hansen, 1998; Moresi and Solomatov, 1998; Tackley, 2000; Richards et al., 2001; Solomatov, 2004; Stein et al., 2004; O'Neill et al., 2007; Wong and Solomatov, 2015). Obtaining scaling relations of the yield stress and physical parameters can help understanding the conditions favorable for plate tectonics.

This study aims to apply scaling laws developed for lithospheric (or lid) failure in relatively simple and controlled convection systems to lid failure in more variable time-dependent convection systems typical in planetary mantles. Our goal is to assess whether conditions on terrestrial planets in the inner Solar System allow plate tectonics to exist over geologic time, as these planets have more constraints from available observational data.

## 2. Critical yield stress approach and scaling laws

One way of studying the criterion of lithospheric failure for different planets is to develop scaling relations between the yield stress of planetary lithospheres and various physical parameters. Lithospheric failure is controlled by the stresses due to the forces acting on the lithosphere, and the strength of the lithosphere expressed in terms of the yield stress. The strength of the lithosphere can be determined experimentally or from geophysical observations. Due to uncertainties in assumptions and complications in extrapolation, these observed values of lithospheric strength are not well constrained and are usually too high for lithospheric failure (e.g., Kohlstedt et al., 1995; Gurnis et al., 2004). For these reasons we obtained scaling laws using the critical yield stress approach: the yield stress is a variable that is adjusted to the point at which the lithosphere becomes unstable, while the other parameters of the convective system are held constant (Solomatov, 2004; Wong and Solomatov, 2015). This process is repeated for different sets of convective parameters.

To examine how the yield stress affects the stress distribution of the lithosphere, Wong and Solomatov (2015) carried out an analysis of the spatial variation in magnitude of stresses induced in the lithosphere by sublithospheric convection. They found that the process of subduction can be approximately described by the gravitational sliding model in which the stresses are caused by the variations of the lid relief, in particular the dipping of the lid slope that provides the instability. To find out the extent of weakening needed for the lithosphere to become unstable, they determined the depth of the region affected by the yield stress (termed the depth of the plastic zone $\delta_{pl}$, Fig. 1). The depth of the plastic zone is approximately 1/2–1/3 of the lithospheric thickness for failure to occur. Wong and Solomatov (2015) obtained the following expressions for the critical yield stress $\tau_{y,cr}$ and critical yield stress gradient $\tau'_{y,cr}$:

$$\tau_{y,cr} = -\alpha\rho_0 g \frac{dT}{dy}\lambda \frac{y_{pl}^2}{2}\frac{a}{\delta_{pl}}, \quad (1)$$

$$\tau'_{y,cr} = -\alpha\rho_0 g \frac{dT}{dy}\lambda \frac{y_{pl}^2}{2}\frac{a}{\delta_{pl}^2}, \quad (2)$$

where $\alpha$ is the thermal expansivity, $\rho_0$ is the reference density, $g$ is the gravitational acceleration, $T$ is the temperature, $\lambda$ is the lid slope, $a$ is the aspect ratio, and $y_{pl}$ is the distance from the bottom of the thermal boundary layer $\delta_0$ to the plastic depth $\delta_{pl}$ (Fig. 1). $\delta_0$ is defined by the depth that reached interior temperature $T_i$, which is found by averaging the temperature in convecting interior excluding boundary effects. As in the method for determining the lid slope in Wong and Solomatov (2015), $\delta_0$ at the edge ($x = a$) is

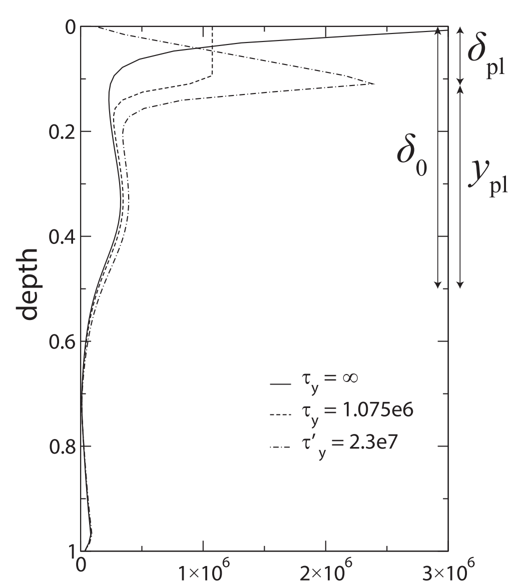


Fig. 1. Depth of plastic zone $\delta_{pl}$ and the vertical distance $y_{pl}$ from the bottom of the thermal boundary layer $\delta_0$ to $\delta_{pl}$. Profile taken at the downwelling edge of the convecting cell.