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Invited Review

Some remarks on the models of plate tectonics on terrestrial planets: From the view-point of mineral physics

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ABSTRACT

Some mineral physics-related issues are reviewed that are closely related to the operation of plate tectonics on terrestrial planets with different mass. Plate tectonic style of convection would occur when the surface layer has only modest strength relative to the stress generated by mantle convection so that it can deform and subduct into the mantle. Both the stress on the lithosphere generated by mantle convection and the resistance of the lithosphere for subduction depend on the relevant materials properties. A review is presented on the scaling relationships between relevant physical properties and planet mass and on the strength of the lithosphere. It is shown that if physically plausible scaling is made both for the relevant materials properties and the macroscopic energy balance, a large Earth-like planet may not necessarily have plate tectonics. In addition to the internal processes, the surface conditions such as the surface temperature may also play an important role via its effects on the thickness of thermal or chemical lithosphere, making it difficult for plate tectonics to operate on small planets. Therefore, in this model, plate tectonics would operate on planets with modest size like Earth, but the validity of this conclusion hinges on the characterization of (i) the influence of pressure-dependent properties on the vigor of convection and of (ii) the resistance for subduction. In particular, the processes determining the resistance for subduction have an important influence on the operation of plate tectonics. Key issues are highlighted that require further studies including the influence of depth-dependent properties on convection and the formulation of the resistance of the lithosphere for subduction.

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1. Introduction

Plate tectonics is a mode of mantle convection that occurs when the surface layer (the lithosphere) is relatively weak allowing its subduction back into the mantle. However plate tectonics is known to operate only on Earth (and perhaps early Mars (Connerney et al., 1999)) but not on other planets such as Venus and therefore it is important to understand why this is the case. An answer to this question will help us to assess the plausibility of operation of plate tectonic on other planets including super-Earths.

In the mid 1990s a theoretical framework was developed to classify the mode of mantle convection incorporating the influence of temperature sensitive rheological properties (e.g., Moresi and Solomatov, 1998; Solomatov and Moresi, 1996, 1997; Tackley, 1998). These studies showed that the style of convection is determined by the competition between convection-induced stress and the strength of the surface layer (the lithosphere): plate tectonic operates when convective stress acting on the lithosphere is larger than the strength of the lithosphere, otherwise stagnant-lid mode of convection occurs. Such an approach is used in many recent literatures where the possibility of plate tectonics (and processes of thermal evolution) on other terrestrial planets is examined including those on "super-Earths" (e.g., Foley et al., 2012; Korenaga, 2010; O'Neill et al., 2007; Papuc and Davies, 2008; Valencia et al., 2007; van Heck and Tackley, 2011). In these studies, the scaling of these two factors with the planetary mass (and, sometimes, the surface conditions) is examined to discuss either plate tectonics is plausible on super-Earths or not. In most of these studies, they conclude that plate tectonics is equally or more likely in a large planet (super-Earth) if proper surface conditions are met.

Both of these factors (the driving force and the resistance of the lithosphere for subduction) are sensitive to a number of physical properties of planetary materials and to macroscopic parameters such as the planetary mass, the mode of heating and the surface conditions (surface temperature, presence of the oceans). The main goal of such a study is to evaluate these forces (stresses) as a function of some major features of a planet (i.e., its size (mass)) to examine under which conditions plate tectonics might operate on a terrestrial planet. However such an exercise is challenging for two reasons. First, when one considers planets that are much bigger than Earth, pressure inside of them could become on the order of 1 TPa (1000 GPa), several times larger than the (zero-pressure) bulk moduli of typical planetary materials (temperature is also high, ~5000 K or more). Under these conditions, many physical properties could change dramatically. It is challenging to take into account of these factors properly. Second, the parameterization of the resistance of the lithosphere against deformation is not trivial. A standard model on rheological properties such as a model by Kohlstedt et al. (1995) predicts a high strength of the lithosphere (~500 MPa or higher) that would not allow plate tectonics to operate on Earth. One needs to go beyond such a standard model, but going beyond it is complicated and many different models have been proposed including models dealing with the localized deformation associated with subduction. For reviews on the strength of the lithosphere in relation to subduction, a reader may refer to papers by Burov (2011) and Cloetingh et al. (1989).

In this paper, I will discuss some of these issues with the emphasis on the role of physical properties.

2. Basic concepts

2.1. Pressure and temperature in a planet

Pressure in a planetary interior is determined (approximately) by the hydrostatic equilibrium, viz.,

$$dP = \rho g dz = \rho \frac{GM(r)}{r^2} dr \tag{1}$$

where P is pressure, g is acceleration due to gravity, z is depth, G is the gravity constant, r is the radial distance from the center of a planet and $M(r)$ is the mass in a planet within the radius r. If density is constant, this leads to

$$P = \left(\frac{4\pi}{3}\right)^{\frac{1}{3}} G\rho^{\frac{4}{3}} M^{\frac{2}{3}} \propto M^{\frac{2}{3}} \tag{2}$$

indicating that the pressure will exceed 1 TPa for a planet with 10 times Earth mass. However, pressure in a planet also depends on physical properties. Density will generally increase with the planetary mass due to compression. (Valencia et al., 2006) found $\rho \propto M^a$ with a ~ 0.2 (this means $L \propto M^{\frac{1}{3}(1-a)}$ (L: size of the planet, $\frac{1}{3}(1-a) \approx 0.27$)), so that $P \propto M^{\frac{2}{3}(1+2a)} \approx M^{0.94}$.

Processes that determine the temperature in a planet are more complicated. Firstly, temperature (distribution) in a planet evolves. In most cases, a planet is born hot and with time it cools down. However, to simplify this, I will consider a "steady-state" situation where the heat generation and heat transfer are balanced. Strictly speaking no planet would show steady-state, but considering steady-state thermal structure makes sense, because thermal evolution of a terrestrial planet includes relatively quick initial stage followed by slow evolution (Papuc and Davies, 2008). For example, the change in the mantle temperature during the last 3 Gyrs is ~200 K or less (less than 10%; e.g., Richter, 1985). Secondly, given a simplifying assumption of steady-state temperature with vigorous convection, temperature profile in the planetary mantle is made of two regions. In regions where material move horizontally, temperature-depth profile follows the conductive profile, whereas in regions where vertical material motion is large, temperature is nearly adiabatic. To simplify the analysis, I will treat these two regions separately. For the "hot mantle", I will assume a representative temperature profile following the adiabatic gradient with a characteristic temperature at the top of that layer, T_o ("potential temperature") (Fig. 1).

The adiabatic temperature gradient is given by, $\left(\frac{\partial \log T}{\partial \log \rho}\right)_{ad} = \gamma$ (e.g., Poirier, 2000) where γ is the Grüneisen parameter ($\gamma = \gamma_o \left(\frac{\rho_o}{\rho}\right)^q$ with q ~ 1 for solids; (Anderson, 1996)). Integrating this relation, one has

$$\frac{T_{ad}}{T_o} = \exp\left[\frac{\gamma_o}{q}\left\{1 - \left(\frac{\rho_o}{\rho}\right)^q\right\}\right] \tag{3}$$

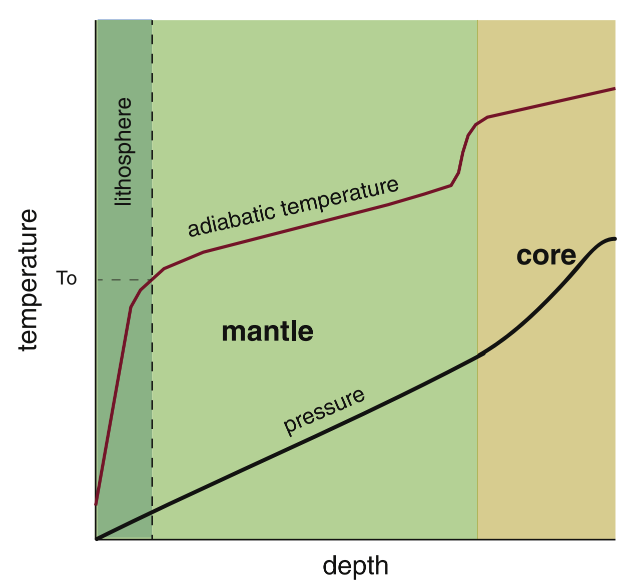

Fig. 1. A temperature and pressure distribution in a planet.