Icarus 234 (2014) 174–193

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

The tectonic mode of rocky planets: Part 1 – Driving factors, models & parameters

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ARTICLE INFO

Article history:
Received 2 August 2013
Revised 26 January 2014
Accepted 28 January 2014
Available online 8 February 2014

Keywords:
Earth
Extra-solar planets
Terrestrial Planets
Planetary Dynamics
Geophysics

ABSTRACT

A recent debate as to whether plate tectonics should occur on super-Earths raises two questions: (1) how can this disagreement between previous models be disentangled, and (2) what controls the propensity of plate tectonics on Earth and other planets?

To tackle these questions, we use a 1D thermal evolution model to study the ratio of driving to resistive forces of plate tectonics for a variety of initial conditions, two intrinsically different plate tectonics models, and for a large range of model parameters. This wide approach allows us to crystallize some fundamental factors driving plate tectonics.

We find that the way plate tectonics reacts to changes of interior temperature is key for understanding how plate tectonics depends on a planet's mass (and composition) and derive a new approach to better constrain appropriate scaling parameters for 1D models (i.e., for heat flux (β), convective velocity (γ), and aspect ratio (ε)). This allows us to track back the discrepancy between various groups to different 1D scaling parameters (β, γ, ε), or to different yield stress scalings, interior temperatures, or initial conditions in 2D models. Our results also show that planet structure, composition, and initial conditions significantly affect plate tectonics.

By re-analyzing previous 2D plate tectonics models and setting them in relation to our results, we suggest that: (1) increasing interior temperatures and planet mass make plate tectonics less likely; (2) plate tectonics is more likely with increasing mantle viscosity (if vigorously convecting) and not generally with increasing Rayleigh number *Ra*.

Moreover, our results demonstrate that trying to understand distant worlds teaches us how some present assumptions used to describe the dynamics of the Earth (e.g., $\beta = 1/3$, $\gamma = 2/3$, $\varepsilon = 0$, or plate tectonics more likely with increasing *Ra*) might not be appropriate – implying that we have to partially revise our current understanding of the Earth's evolution and rock cycle.

1. Introduction

The tectonic modes of a planet are represented with two end-member cases: stagnant lid convection or plate tectonics. A single lid on top of the convecting mantle thermally insulates the interior of the planet in stagnant lid convection, whereas in the case of plate tectonics, the lithosphere consists of several plates that can subduct and are recycled into the mantle.

The tectonic mode of a rocky planet not only influences the efficiency of interior cooling, it further strongly impacts volcanic outgassing and recycling of carbon and water. It thus modifies the chemical composition of atmospheres and also affects climate and surface habitability on Earth and other planets. Moreover, biosignatures (gases produced by life that accumulate in a planet's atmosphere, e.g., Seager et al., 2013) have been suggested as good indicators to spectroscopically infer life on alien worlds. However, geological outgassing can mimic gaseous signatures of life, and hence it is necessary to better constrain the amount and composition of outgassed gases on rocky planets, to be able to distinguish true signs of life from false-positives.

To understand outgassing and habitability, we therefore have to know the tectonic mode of rocky planets, in especially of rocky super-Earths (rocky planets with masses between 1 and 10 Earth masses ($M = 1$–10)), which are common in our Galaxy (e.g., Dressing and Charbonneau, 2013) and are a current and future major target of exoplanet research. The link between tectonic

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http://dx.doi.org/10.1016/j.icarus.2014.01.042
0019-1035/

mode, outgassing and habitability is one reason why both the geophysics and the exoplanet community should investigate if there are ways to quantify how common plate tectonics and volcanism are in the Galaxy.

Various numerical studies seem to fundamentally disagree how plate tectonics is affected by planet mass: in comparison to Earth, Foley et al. (2012), Tackley et al. (2013), Valencia et al. (2007), Valencia and O'Connell (2009), and Van Heck and Tackley (2011) find plate tectonics more likely, O'Neill and Lenardic (2007), O'Neill et al. (2007) and Stein et al. (2011, 2013) less likely, and Noack and Breuer (2013) more or less likely on Earth-like super-Earths. So far, it is not clear why these models differ in their general conclusion although Lenardic and Crowley (2012) suggest that tectonic mode solutions are possibly non-unique for the same set of model parameters and depend on different evolutionary paths.

In contrast, we show with a 1D parameterized thermal evolution model that the distinct results can be simply traced back to divergent model assumptions: such as differences in 1D parameterized scaling parameters, and for 2D convection models to differences in boundary conditions, interior temperatures, or the scaling of yield stresses and thermal and transport properties with planetary mass.

In the following paragraphs, a short review is given of how 2D and 3D mantle as well as 1D parameterized convection models simulate plate tectonics, about the chosen values for important 1D scaling parameters, as well as how parameterized models relate to 2D or 3D convection models. This is necessary to understand how model assumptions and parameters control the propensity of plate tectonics, and how we can relate results obtained with 1D parameterized models to 2D or 3D mantle convection models.

1.1. Plate tectonics, 2D and 3D convection models

2D and 3D convection models (e.g., Stein et al., 2004; Tackley, 2000; Trompert and Hansen, 1998) introduce plate tectonics by using a viscoplastic rheology. The latter reduces the effective viscosity of the lithosphere locally at a given radius R whenever $\tau_D(R) > \tau_y(R)$ with τ_D driving stresses caused by convection and τ_y resistive yield stresses – initiating subduction-like behavior (e.g., O'Neill and Lenardic, 2007; O'Neill et al., 2007; Stein et al., 2011, 2013; Tackley et al., 2013; Van Heck and Tackley, 2011). This approach is based on the assumption that the lithosphere locally weakens whenever driving stresses caused by convection overcome resistive yield stresses (e.g., Moresi and Solomatov, 1998). The yield stress is depth dependent and can be complex (e.g., Kohlstedt et al., 1995). But experimental data suggest that the cohesive strength is negligible under lithospheric conditions (Byerlee, 1978) and that as a first approximation $\tau_y(R)$ at radius R increases linearly with pressure (Byerlee, 1968):

$$\tau_y(R) = g\rho_{up}C_{fric}(R_p - R) \tag{1}$$

Here g is the surface gravity, R_p is the planet radius, and ρ_{up} is the average upper mantle density (Table 2). C_{fric} is the friction coefficient of lithospheric rocks, and dry rock experiments suggest values of $C_{fric} \sim 0.6$–0.9 (Byerlee, 1968). However, experiments with hydrated serpentinites (Escartin et al., 2001) suggest that C_{fric} could be smaller and in the order of $\sim$0.15–0.45 if water can penetrate the lithosphere.

Although the here-described method is commonly used, it should be noted that its validity has been questioned; as for instance it has no 'memory' on pervious weakening zones (e.g., Bercovici, 2003). Moreover, it is crucial to emphasize that any model that solely studies plate yielding, as the one used here, describes a necessary but maybe not sufficient criterion for plate tectonics. Nonetheless, it is a first step to understand general features of the driving factors for plate tectonics.

1.2. Plate tectonics and parameterized 1D models

In general computer simulations of planetary interiors are divided in parameterized 1D models and their 2D or 3D counterparts. 2D and 3D models are costly and use often, due to numerical reasons, unrealistic parameter values that do not represent the specific conditions of a convecting planet (too high viscosities, too small yield stresses, or too low interior temperatures). 1D parameterized models offer an alternative way to explore a more realistic and wider parameter space for super-Earths (e.g., Foley et al., 2012; Kite et al., 2009; Korenaga, 2010b; O'Rourke and Korenaga, 2012; Papuc and Davies, 2008; Stamenković et al., 2012; Valencia et al., 2007; Valencia and O'Connell, 2009).

The 1D parameterized models are based on scaling laws derived from 2D and 3D convection models and on assumptions about how plate tectonics is initiated or maintained. Thus, it is important to define how 1D models differ in modeling the initiation and maintenance of plate tectonics. To model initiation, we assume planets in a stagnant lid regime (e.g., Korenaga, 2010b; O'Rourke and Korenaga, 2012), and compute their ability to start plate tectonics. To investigate maintenance, we assume planets in a plate tectonics mode and investigate their ability to maintain plate tectonics (e.g., Valencia et al., 2007; Valencia and O'Connell, 2009). The different concepts are illustrated in Fig. 1, where the thermal lithosphere is given by $(\delta_u + L)$ in the initiation scenario, with δ_u the upper thermal boundary layer (see Eq. (4), Fig. 1b) and L the stagnant lid thickness (see Stamenković et al., 2012). In the maintenance scenario, the thermal lithosphere consists only of the upper thermal boundary layer, analogous to the plate definition

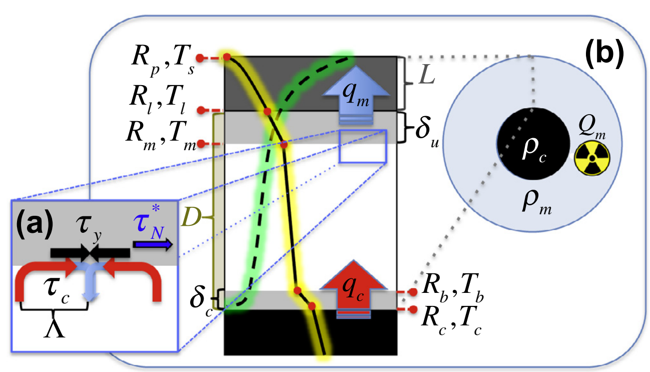

Fig. 1. Sketch showing the plate tectonics, planet structure and thermal boundary layer model. (a) Stresses relevant to plate tectonics: for plate tectonics to occur, driving stresses τ_D must exceed resistive yield stresses τ_y. For the F model, the convective shear stress at the base of the thermal lithosphere corresponds to the driving stress, $\tau_D = \tau_c$. For the S model, τ_c causes a "characteristic" stress inside the thermal lithosphere $\tau_D = \tau_N^* = \tau_c \cdot \Lambda \cdot (L + \delta_u)^{-1}$ driving plate tectonics. Here $(L + \delta_u)$ is the thickness of the thermal lithosphere, and Λ is the length of the convective cell from a rising hot plume to a sinking cold plume (or half the distance between two sinking plumes for purely internally heated systems). (b) Structure: the depth profile of temperature (solid yellow line) and viscosity (dashed green line) for temperature-dependent viscosity are shown. In the case of stagnant lid planets (initiation case) the thermal lithosphere is composed of the stagnant lid of thickness L and the upper thermal boundary layer of thickness δ_u (needed to parameterize the heat flux out of the convecting mantle q_m). For plate tectonics planets (maintenance case), no stagnant lid is present and hence $L = 0$. The temperature is adiabatic in between the thermal lithosphere (R_m) and R_b. The whole mantle (with thickness $(R_p - R_c)$) is heated by decaying radiogenic heat sources $Q_m(t)$ and from the core by the core–mantle heat flow q_c. In the core (black region), we assume adiabatic temperatures. Earth properties for mantle and core are listed in Table 2. Earth-like composition and structure as well as $T_s = 290$ K for super-Earths are initially assumed. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)