Earth and Planetary Science Letters 361 (2013) 448–459

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

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

The influence of mantle internal heating on lithospheric mobility: Implications for super-Earths

C. Stein [a,*], J.P. Lowman [b,c], U. Hansen [a]

[a] Institut für Geophysik, Westfälische Wilhelms-Universität Münster, Corrensstr. 24, Münster, Germany
[b] Department of Physical and Environmental Sciences, University of Toronto Scarborough, 1265 Military Trail, Toronto, ON, Canada M1C 1A4
[c] Department of Physics, University of Toronto, 60 St. George St., Toronto, ON, Canada M5S 1A7

ARTICLE INFO

Article history:
Received 20 September 2011
Received in revised form
4 November 2012
Accepted 5 November 2012
Editor: T. Spohn
Available online 7 December 2012

Keywords:
mantle convection
internal heating
stagnant-lid convection
super-Earths

ABSTRACT

Super-Earths, a recently discovered class of exoplanets, have been inferred to be of a similar rock and metal composition to the Earth. As a result, the possibility that they are characterised by the presence of plate tectonics has been widely debated. However, as the super-Earths have higher masses than Earth, it is assumed that they will also have higher Rayleigh numbers and non-dimensional heating rates. Accordingly, we conduct a systematic 2D study to investigate the influence of these parameters on the surface behaviour of mantle convection. The main focus of our work considers the response of surface motion to the mantle's internal heating. However, we also include an analysis of other parameters scaling with planet mass, such as viscosity.

In agreement with the findings of Valencia and O'Connell (2009) and van Heck and Tackley (2011) we find plate-like surface mobilisation for increased Rayleigh numbers. But increasing the internal heating leads to the formation of a strong stagnant-lid because the mantle heating effects thermally activated viscosity. Additionally, viscosity is affected by the increased pressures and temperatures of super-Earths. In total, our findings indicate that surface mobility will likely be reduced on super-sized Earths.

Our numerical models show that the interior temperature of the convecting system is of vital importance. In planets with a hotter interior plate tectonics is less likely.

1. Introduction

The Earth is the only planet in our solar system featuring plate tectonics, however, the number of terrestrial planet candidates for plate tectonics appears to be steadily increasing. As a result of advancements in astronomical observations (including transit surveys by the space missions CoRoT, Kepler and Gaia and the implementation of improved techniques for determining radial velocity using ground-based telescopes), the list of recently detected extrasolar planets orbiting their parent star continues to increase. Mostly, these newly discovered exoplanets have masses comparable to Jupiter's. However, due to improvements in the mass detection limit, the number of planets confirmed to have masses close to that of the Earth is also increasing. Very recently, Doppler spectroscopy was used to detect GJ581e (Mayor et al., 2009), an exoplanet with a mass of only 1.9 Earth masses ($M_\oplus$). Members of this new class of relatively small extrasolar planets, with masses of $1-10\,M_\oplus$, are considered to be rocky in nature (Rivera et al., 2005; Valencia et al., 2006; Mayor et al., 2009). These 'super-Earths' have therefore attracted considerable interest (cf. Haghighipour, 2011) because they might have a surface behaviour resembling the Earth's (e.g., Valencia et al., 2007b).

The interior structure of a super-Earth has been inferred from various mass-radius relationship analyses that assume equations of state (EOS) based on knowledge of the Earth's structure (Valencia et al., 2006; Sotin et al., 2007; Seager et al., 2007). However, some uncertainties exist when extrapolating the EOS in the range of pressures and temperatures required in super-sized planets (Seager et al., 2007). Moreover, the size of a planet affects the parameters determining the vigour and mode of mantle convection. Hence, when compared with the Earth, the surface expression of mantle convection in a super-Earth might be affected in such a way that a change occurs in lithosphere mobilisation, from plate-like surface behaviour to a stagnant-lid mode.

Crucial to the question which tectonic regime prevails is the balance of forces acting on the plates. On the one hand there is resistance of the plates to deformation (e.g., the thickness and viscosity of the plate) and on the other hand there is convective

* Corresponding author.
E-mail address: stein@earth.uni-muenster.de (C. Stein).

0012-821X/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.epsl.2012.11.011

traction at the base of the lithosphere (cf. Valencia et al., 2007b; O'Neill and Lenardic, 2007; van Heck and Tackley, 2011). The shear stresses acting on the base of the plate are strongly related to the tectonic regime. Thus internal heating plays an essential role but also other aspects such as variable viscosity or the presence of water affect the tectonic regime and therefore the balance of resistive to convective stresses (Moresi and Solomatov, 1998).

Many of the relevant parameters scale directly with the planet's size but often only single aspects have been considered in previous studies, and these were shown to partly have an opposing effect on lithospheric mobility. Consequently, controversial results have been presented (Valencia et al., 2006, 2007b; O'Neill and Lenardic, 2007; Valencia and O'Connell, 2009; Korenaga, 2010; van Heck and Tackley, 2011). O'Neill and Lenardic (2007) have numerically shown that an increased radius leads to a stagnant-lid mode of convection as the resistive strength of the lithosphere increases more strongly than the convective stresses. Their result is based on scaling of the yield stress. Assuming Earth's dimensional yield stress, they scale the non-dimensional yield stress to higher masses. As a consequence the convective stresses are no longer sufficient to overcome the high non-dimensional yield stress and thus the resistive strength prevails as dominant. Considering scaling laws, Valencia et al. (2006, 2007a,b) and Valencia and O'Connell (2009) reason that increased masses will result in higher Rayleigh numbers (therefore higher convective stresses) and argue for lithosphere mobilisation on super-Earths. Based on simple relationships for plate thickness and convective stresses Valencia et al. (2007b) and Valencia and O'Connell (2009) scale these to larger mass planets and find that plate thickness (resistive strength) is reduced and thus easily overcome by the increased convective stresses. A potential problem with their result is that their parameterisations are derived from the boundary-layer theory which holds for the plate tectonic regime but differs in the stagnant-lid regime as viscosity changes (Moresi and Solomatov, 1998). Similarly, Korenaga (2010) adopts the scaling laws of the plate tectonic regime in strongly temperature-dependent viscosity with brittle failure. He argues that the resistive force of the plate not only increases with planet size (as assumed by O'Neill and Lenardic, 2007) but also scales with the thickness of the plate. Thus, increasing a planet's mass (i.e., increasing the Rayleigh number) decreases plate thickness, which had not been considered in O'Neill and Lenardic (2007). Further Korenaga (2010) discusses the effect of water which more strongly controls the likelihood of plate tectonics than the planet's size and states that the high-convective stresses (as also found by Valencia et al., 2007b) will only lead to plate motion on a wet planet. Finally, van Heck and Tackley (2011) combine analytical scalings and numerical models by directly comparing both their results. Also, they do not scale either Rayleigh number or yield stress with planet size but change both parameters simultaneously. In particular, they considered the scaling of the ratio of convective to yield stress with mass in purely internally heated and purely basally heated convection. For basally heated convection with a friction coefficient (depth-dependent yield stress) they emphasise Korenaga's (2010) result that planet size does not matter for a constant density scaling. Apart from this, their finding that convective stresses outweigh resistive forces agrees with Valencia et al. (2007b) and Valencia and O'Connell (2009). Additionally, van Heck and Tackley (2011) observe that plate tectonics is more likely in purely basally heated convection than in purely internally heated convection.

As pointed out by van Heck and Tackley (2011) the likelihood of plate tectonics on more massive planets depends on the heating mode. While the authors compared the two end-member cases of purely internal heating and purely basal heating, a combination of both heating modes seems more likely. In so-called mixed-heated convection both internal heat sources, owing to the decay of radioactive elements, as well as basal heating from the core play a role. In the past, not only a difference between purely basally heated and purely internally heated convection has been reported by van Heck and Tackley (2011). Also, the prediction of plate tectonics on super-Earths by Valencia and O'Connell (2009) and van Heck and Tackley (2011), obtained in purely internally heated systems, seems to contradict the observation of Stein et al. (2004) who investigated a numerical mantle convection model featuring mixed-mode heating and found that stagnant-lid convection occurs for systems with higher internal heating rates.

Given this background, we focus on the effect of the mantle internal heating with regard to lithospheric mobility. We compare purely internal heating results (cf. Valencia and O'Connell, 2009; van Heck and Tackley, 2011) with those obtained in mixed-mode heating convection. In addition, we are interested in the combination of different parameters. For example, we are interested in the combination of high Rayleigh numbers and strong internal heating (cf. van Heck and Tackley, 2011). Both increase with mantle depth but have an opposing effect on the surface behaviour. Fig. 1a and b show schematic regime diagrams of the Rayleigh number and heating rates versus yield stress, respectively, showing that high Rayleigh numbers promote surface mobility while strong internal heating leads to a transition from plate mobilisation to stagnant-lid convection (Stein et al., 2004). Thus, while high Rayleigh numbers favour surface mobility, it remains undetermined whether this still applies at high internal heating.

Additionally, Fig. 1c and d show schematic regime diagrams of the pressure-dependent and temperature-dependent viscosity contrast versus yield stress, respectively. Like high Rayleigh numbers, a strong pressure dependence of the viscosity enables plate tectonics, whereas the viscous resistance of the plates (i.e., plate viscosity) is higher for a strong temperature dependence hindering plate tectonics (Stein et al., 2004). Thus, all convection and rheological parameters that will likely change with planet mass affect surface mobility. For super-Earths the interplay of these parameters is important.

As the mode of heating was shown (Stein et al., 2004; van Heck and Tackley, 2011) to be of great importance we arrange our study in terms of the internal heating. First we analyse the general effect of the individual non-dimensional convection and rheology parameters on the lithospheric mobility. We start by studying the effect of an increasing internal heating rate. Then we systematically add a further complexity to the system and study the surface behaviour resulting from this new parameter with respect to the heating rate. Implementing this approach we first identify the physical mechanisms that cause transitions between mobile-lid and stagnant-lid convection. Finally, we discuss parameter values for super-Earths and present calculations featuring these parameter values.

2. Method

To reduce the dependence of our findings on modelling methods we employ two distinct model approaches. Each solves for thermally driven convection in an incompressible Boussinesq fluid with infinite Prandtl number and variable viscosity. The 2D Cartesian geometry experiments were carried out in a square box employing free-slip, impermeable boundaries and reflective side-wall conditions for the temperature. The material is cooled from the top ($T=0$) and heated ($T=1$) at the bottom. The non-dimensional equations describing thermal convection with internal