GEOPHYSICAL RESEARCH LETTERS, VOL. 34, L19204, doi:10.1029/2007GL030598, 2007

Geological consequences of super-sized Earths

C. O'Neill[1] and A. Lenardic[2]

Received 6 May 2007; revised 20 July 2007; accepted 22 August 2007; published 11 October 2007.

[1] The discovery of terrestrial-scale extrasolar planets, and their calculated abundance in the galaxy, has prompted speculation on their surface conditions and thermal structure. Both are dependent on the tectonic regime of a planet, which is itself a function of the balance between driving forces, and the resistive strength of the lithosphere. Here we use mantle convection simulations to show that simply increasing planetary radius acts to decrease the ratio of driving to resisting stresses, and thus super-sized Earths are likely to be in an episodic or stagnant lid regime. This effect is robust when associated increases in gravity are included, as the more dominant effect is increased fault strength rather than greater buoyancy forces. The thermo-tectonic evolution of large terrestrial planets is more complex than often assumed, and this has implications for the surface and conditions habitability of such worlds. **Citation:** O'Neill, C., and A. Lenardic (2007), Geological consequences of super-sized Earths, *Geophys. Res. Lett.*, *34*, L19204, doi:10.1029/2007GL030598.

1. Introduction

[2] The recent discovery of small (<5.5 Earth masses (M_e)) planets around M-sized stars has prompted speculation on their composition and surface conditions [*Beaulieau et al.*, 2006; *Boss*, 2006]. In particular, the presence of free water on the surface is important for possible exo-biology. Simulations have shown that for a wide range of solar-system configurations, the formation of planets with masses between 1–10 Me, and a high water content - waterworlds - is expected to be quite common [*Franck et al.*, 2003; *Ida and Lin*, 2005; *Valencia et al.*, 2006; *Leger et al.*, 2004].

[3] The surface conditions of such bodies are a strong function of the volcanic and tectonic history of the planet. Earth, the largest observed terrestrial body to date, is also the only body to possess plate tectonics, and "active-lid" surface regime. All other terrestrial bodies in the solar-system are currently in the "stagnant-lid" regime and exhibit little or no surface motion. The clement surface conditions (including the presence of liquid water) on Earth compared with the stagnant lid bodies, is often associated with its current tectonic regime [*Kastings*, 1996]. Speculation into the nature of "Super-Earths" - terrestrial bodies of primarily silicate-metal composition, of the order of 1–10 M_e, have nearly always assumed that such planets operate under an active-lid regime, akin to plate tectonics [e.g., *Valencia et al.*, 2006].

[1]GEMOC ARC National Key Centre, Department of Earth and Planetary Science, Macquarie University, Sydney, New South Wales, Australia.

[2]Department of Earth Science, Rice University, Houston, Texas, USA.

0094-8276/07/2007GL030598

[4] Here we outline some theoretical problems with this assumption, particularly concerning the application of stress scalings to larger planets. We show that, all things being equal, such planets are expected to be in a stagnant-lid regime as planetary radius increases. The stress state of large planetary bodies is likely to be an extremely complicated phenomenon, but these results indicate the surface tectonic regime, and consequently the atmospheric and hydrological conditions on Super-Earths are likely to be quite different than previously suggested, and this may impinge on the probability of life on such worlds.

2. Model Setup

[5] Since there are any number of ways to imagine silicate-metal planet configurations, for simplicity we will stick to a directly scaled-up version of Earth, with similar core-mantle volume ratios. The consequences of directly scaling planetary radii can be summarized as: 1) Increased depth of the convecting mantle, thus higher Rayleigh numbers and convective velocities, 2) Higher gravity, which also increases Rayleigh number, but the increased pressure which ensues also results in very high fault strength for comparable depths on Earth, 3)Variation in convective stress. The convective stress (τ) is given by

$$\tau \sim \eta \, \mathrm{v}/\delta \tag{1}$$

[6] Here η is the viscosity, and δ the relevant depth scale [e.g., *Turcotte and Schubert*, 1982]. While velocity increases with increasing Rayleigh number, the increase in mantle depth (and thus depth scale) acts to mitigate the increase in stress. Direct comparison is not possible between stresses on different planets as planetary radii are involved in the scaling process. Rather, here we non-dimensionalize the problem to allow comparison between different mantle thicknesses, using the relationship between dimensional (τ) and non-dimensional (τ') stresses given by:

$$\tau = \left(\eta_0 \kappa / \mathrm{d}^2\right) \tau' \tag{2}$$

[7] Here η_0 is a reference viscosity, κ the thermal diffusivity, and d the mantle depth.

[8] An example of the behaviour of quantitatively larger systems is shown in Figure 1. In this example, a scale factor of 1 is equivalent to an Earth-radius model. Increasing scale factors represent successively increasing radius. We assume a constant yield stress for each planet, and scale them to the non-dimensional state appropriately [*Moresi and Solomatov*, 1998]. We also explore the effect of pressure dependent Byerlee-style frictional laws later. The code used for these simulations has been previously outlined in *Moresi and Solomatov* [1998]. The viscosity in these examples is extremely temperature dependent and varies over six orders of magnitude, and increases by a factor of 30 with depth.

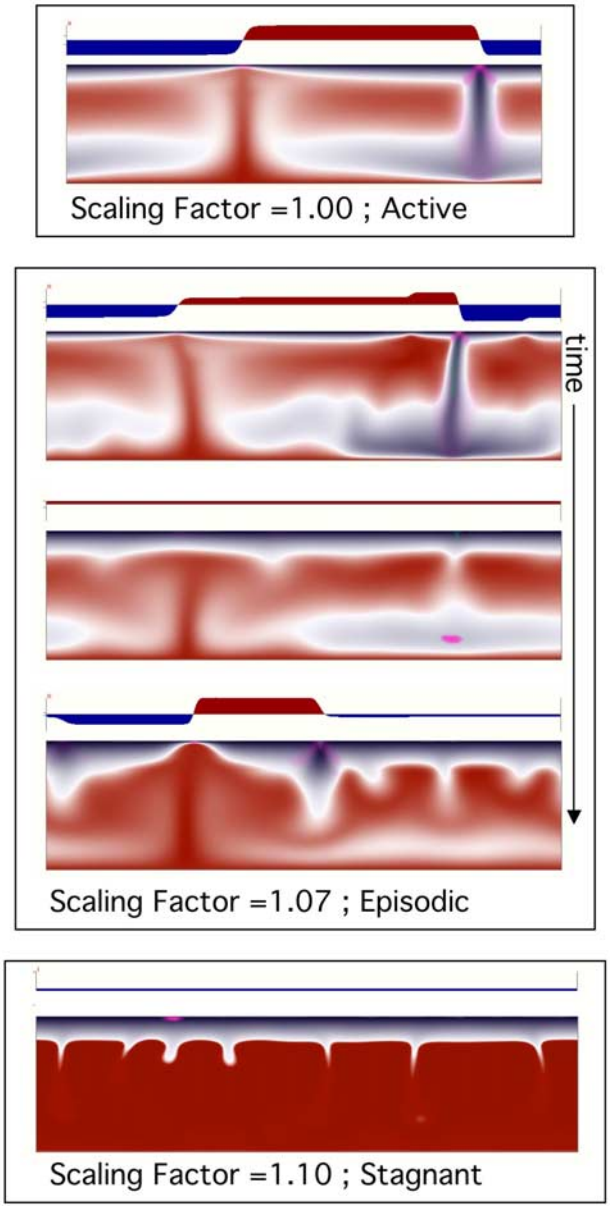

Figure 1. Variation in planetary dynamics for increasing scale factor (or, equivalently, planetary radius). Surface yield stress is 44.6 MPa (scaled to Earth), basal Rayleigh number is 10^7, other parameters described in model setup. For an Earth-sized planet (Scaling factor = 1), the tectonic regime is mobile lid, of which plate tectonics is an example. For larger planetary radii, the tectonic regime first changes to episodic (middle), and then stagnant (bottom), for increased scaling factor and thus planetary radius.

The ratio of internal heating to basal heating is 64–36% for the reference active-lid state. The modelling domain was 4 × 1 with wrap-around side boundary conditions, free slip and constant-T top and basal conditions, and a resolution of 256 × 64 grid cells.

3. Results

[9] In Figure 1, for parameters appropriate to Earth, the mantle is in a steady-state "active-lid" regime akin to plate tectonics, involving long-lived subduction zones, and smooth step-like plate velocities. As the planetary scaling factor increases in Figure 1, the planet enters an episodic regime, characterized by rapid pulses of subduction interspersed by long periods of quiescence. This style of convection was explored in detail by *Moresi and Solomatov* [1998]. If the scaling factor is increased even more, the planet enters a stagnant lid regime. The transition is in consequence to the relationship between the yield stress - which is constant when dimensionalized to each planet's natural state using equation (2), and the convective driving stresses. The effective driving stress decreases relative to the yield stress as the scaling factor, and hence planetary radius, increase. At face value, all other factors the same, this implies due to the interaction of driving and resisting stresses, larger planetary masses than Earth should be in the episodic or stagnant lid regime.

[10] To test how robust this conclusion is, we have run a large parameter suite of simulations testing a range of scaling factors and yield strengths. The results are shown in Figure 2. For most scaling factors, simply increasing yield strength will result in a transition from an active-lid regime, through the episodic regime, to a stagnant lid regime. The transitions are due to the increase in relative strength of the plates relative to the driving stresses, and in the stagnant extreme, the system stresses are insufficient to overcome the large yield stress imposed. These transitions are quite well understood and have been studied in detail before [*Moresi and Solomatov*, 1998]. More interestingly, there is a systematic transition from active-lid to stagnant lid with increasing scaling factor. An episodic regime may exist between the mobile and the stagnant regimes, but its stability depends strongly on the yield parameters. For strong lithospheric strengths, the system may shift from active to stagnant behaviour for a marginally larger planet than Earth. For a range of weaker lithospheres, the active lid regime is dominant for longer, an episodic regime more apparent, and the stagnation of the lithosphere delayed until quite large planet sizes (scaling factor ~1.10).

[11] As noted the interplay between resisting and driving stresses is quite complex for a planet and we have highlighted the dominant effect in the absence of any complexities. Two potential factors of equal importance are pressure-dependent yield stress, and the effect of gravity, and hence higher pressures, on larger planets. Figure 3 summarizes the results of simulations which include variations in gravity with planetary radius, and also pressure-dependent fault strength. The effective yield strength is given by the relation $\tau_y = C_0 + \mu P$. Here P is the pressure, and the coefficient of friction μ in all cases is 0.2. The cohesion term C_0 varies to give the surface yield stresses on the y-axis is Figure 3. The basal Rayleigh number of 7×10^7 (for a scaling factor of 1), other parameters as listed in the model setup.

[12] As shown in Figure 3, the effect of these factors acts to strengthen the main conclusions of this study. In a system with a pressure-dependent Byerlee-style yield stress, and higher gravity, the dominant effect with increasing planetary radius is a drastic increase in the fault strength, due to the high pressures at depth along the fault. Thus while we demonstrated the transition in which the effective yield stress of the planet was for all cases similar, for more complex rheologies, this acts to enhance the transition into

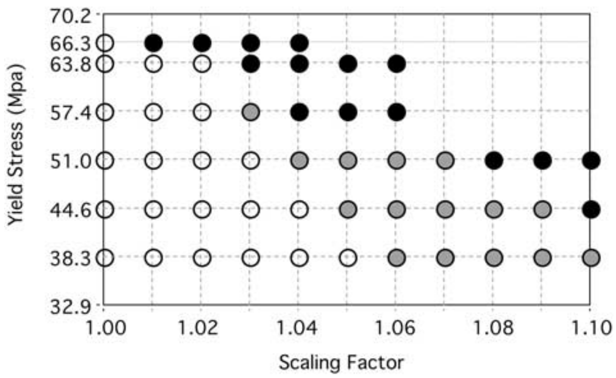

Figure 2. Simulated tectonic regime for different yield stress values and scaling factors. Unfilled circles represent mobile lid convection, light grey episodic convection, and black circles stagnant lid convection. The trend for planets to transition into stagnant lid convection for increasing planetary radius (and scaling factor) is robust over a large range of yield strengths applicable to Earth.

stagnant lid convection for greater planetary radius. Higher gravity likewise enhances the buoyancy forces in the system, but these feed into surface stresses primarily by the coupling implied by equation (1), and thus this effect is offset by the decreasing velocity gradients for larger mantle thicknesses. Of the two effects, the increase in fault strength drastically outweighs the change in convective stress and thus our fundamental conclusion, that super-sized Earths should enter a stagnant lid regime, is unchanged.

4. Discussion and Conclusions

[13] Clearly, the tectonics of large terrestrial planets is a complex subject, and even Earth is incompletely understood. There are a lot of permutations of the parameter range we have explored that need to be thoroughly investigated. Some potential complexities which we have not considered in our models here include depth-dependent properties, such as thermal expansivity [*Hansen et al.*, 1993], phase transitions [*Murakami et al.*, 2004; *Nakagawa and Tackley*, 2004], new phases [*Umemoto et al.*, 2006], conductivity, and compressible convection formulations [*Dubuffet et al.*, 1999], all of which will be increasingly important for larger planets. This paper primarily considers the basic variation in convective stress with increasing depth, and the effects on the lid. Other considerations may affect the planform and style of convection but have a lesser impact on surface convective stresses. For instance, *O'Neill et al.* [2007] consider the impact of phase transitions on surface stresses, and found no systematic variations with Clayperon slope, and thus phase transitions are unlikely to qualitatively change our primary result. These complexities should be examined in more detail in future work.

[14] So far, however, the concept that super-Earths may be in a stagnant lid regime has rarely been addressed, and the primary motivation for this paper is to show that there are very sound physical reasons for believing that most giant Earths may indeed be stagnant. Stagnant-lid tectonics is a fundamentally different regime from plate tectonics, and the volcanic and atmospheric evolution of a planet are vastly different in a stagnant lid regime.

[15] Without plate tectonics as an efficient cooling mechanism for the mantle, enhanced internal temperatures may lead to increased mantle melting and heat loss via magma transport through the stagnant lid and extreme surface volcanism, as is the case with Io today [*Moore*, 2003].

[16] Furthermore, the recycling of water and CO_2 at subduction zones is a crucial regulator for atmospheric greenhouse gas contents and thus surface temperatures. Without any regulation, or sequestration of volcanic CO_2, higher temperature would result in higher atmospheric H_2O, which is then vulnerable to photo-disassociation in the upper atmospheric and loss to space by sputtering [*Bullock and Grinspoon*, 2001]. This may have been the fate of Venus' water, and may well be the ultimate fate of water on planets without plate-tectonics.

[17] Our subset of planets with demonstrated liquid-water oceans and life is limited to Earth, and plate tectonics plays a large role in both these systems. At first glance our results suggest that the stagnation of super-Earths may be common, and the chances of finding life on such bodies is diminished. The crucial point, though, is that it is not possible to separate the effects of space (i.e., size) and time in the tectono-thermal evolution of planets. A directly scaled-up version of Earth is not at the same point of its tectono-thermal evolution as Earth is, and while such a planet may be in a stagnant regime, it doesn't mean it will always be so.

[18] To summarize, increasing planetary radius acts to decrease the ratio between driving forces and resistive strength, both through simple increased depth scales, and thus increased non-dimensional yield stress, and also through increased fault strength under high gravity, which dominates other effects such as convective velocities. At

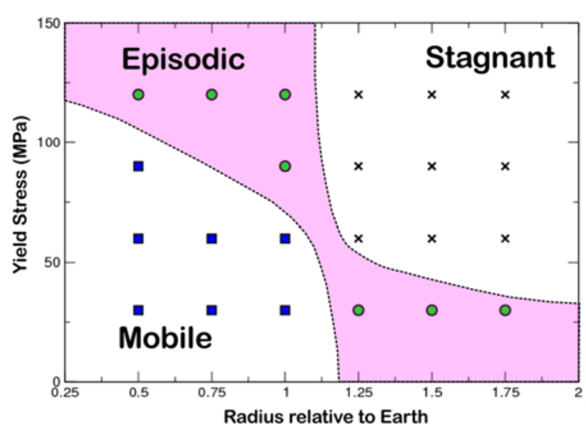

Figure 3. Convection with Byerlee-style pressure-dependent yield stress, for a basal Rayleigh number of 7×10^7 (for a scaling factor of 1), and with 64% internal heating. The coefficient of friction is 0.2 for all examples, the yield stress is varied by changing the cohesion term C_0, and is listed scaled for Earth. Gravity is varied in this example to account for larger planetary mass. Larger radius (or scaling factor) result in greater buoyancy forces, but also increased fault strength due to increased pressure. Thus planets with larger radii again tend to be in an episodic or stagnant regime, depending on the absolute yield stress.

face value these results suggest super-Earths may in fact be in an episodic or stagnant-lid regime, rather than a mobile-lid regime similar to Earth's plate tectonics. This would profoundly affect the surface conditions and habitability of such planets, both of which need to be considered in the framework of the tectono-thermal evolution of large terrestrial worlds.

[19] **Acknowledgments.** We thanks Dave Yuen and an anonymous referee for useful comments. This work is supported by a Macquarie University Research Fellowship, and is GEMOC publication 497.

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A. Lenardic, Department of Earth Science, Rice University, MS-126, Houston, TX 77030, USA.

C. O'Neill, GEMOC ARC National Key Centre, Department of Earth and Planetary Science, Macquarie University, Sydney, NSW 2109, Australia. (coneill@els.mq.edu.au)