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INEVITABILITY OF PLATE TECTONICS ON SUPER-EARTHS

DIANA VALENCIA[1] AND RICHARD J. O'CONNELL
Department of Earth and Planetary Sciences, Harvard University, Cambridge, MA; valenc@fas.harvard.edu, oconnell@geophysics.harvard.edu
AND
DIMITAR D. SASSELOV
Harvard-Smithsonian Center for Astrophysics, Cambridge, MA; dsasselov@cfa.harvard.edu
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ABSTRACT

The recent discovery of super-Earths (masses ≤10 $M_\oplus$) has initiated a discussion about conditions for habitable worlds. Among these is the mode of convection, which influences a planet's thermal evolution and surface conditions. On Earth, plate tectonics has been proposed as a necessary condition for life. Here we show that super-Earths will also have plate tectonics. We demonstrate that as planetary mass increases, the shear stress available to overcome resistance to plate motion increases while the plate thickness decreases, thereby enhancing plate weakness. These effects contribute favorably to the subduction of the lithosphere, an essential component of plate tectonics. Moreover, uncertainties in achieving plate tectonics in the 1 $M_\oplus$ regime disappear as mass increases: super-Earths, even if dry, will exhibit plate tectonic behavior.

Subject headings: Earth — planetary systems — planets and satellites: general

1. INTRODUCTION

Until recently, Earth was the largest terrestrial object known to exist. However, five super-Earth planets (a class defined as having a mass between 1 and 10 $M_\oplus$ [earth masses]) have been detected in the last few years (Rivera et al. 2005; Beaulieu et al. 2006; Lovis et al. 2006; Udry et al. 2007). The five planets have masses in the 5–10 $M_\oplus$ range, but we do not have information on their sizes and cannot be sure if these are really rocky terrestrial planets. However, their discovery provides some evidence that super-Earths might be common, and it is only a matter of chance that our solar system has none. Some of these planets might be in the "habitable zone," where the radiation from the star allows for the presence of liquid water, but only their thermal and chemical evolution will determine if they are, in fact, habitable. In turn, their thermal evolution and surface conditions depend on and affect their tectonic regime. Currently, Earth is the only planet where plate tectonics is active. Furthermore, this mode of convection has dominated our planet's geological history, is associated with geochemical cycles, and thus has been proposed as a required mechanism for life on Earth (Walker et al. 1981). Here we address whether or not super-Earths are likely to have plate tectonics or be in a stagnant lid convection like Mercury and Mars.

2. ANALYSIS

Plate tectonics is a complicated process that primarily requires lithospheric failure, deformation, and subduction. For this, convective stresses of the system have to be large enough to overcome lithospheric resistance to deformation and the plate has to reach negative buoyancy to drive subduction. The convective stresses are a function of the underlying flow field and the viscosity of the fluid, whereas the plate's strength depends on the elastic thickness and mechanical properties. Our contribution is based on identifying how the lithospheric or plate thickness (δ) and convective stresses (τ, σ) depend on planetary mass (M). We use detailed models of the internal structure of massive terrestrial planets (Valencia et al. 2006, 2007) and parameterized convection models to show that the condition for deformation and subsequent subduction is easily met by planets more massive than Earth. A second condition necessary for subduction is that the plate cools enough to develop negative buoyancy at subduction zones (Sleep 1992; Davies 1993). It is unclear as to how important this requirement is with recent elaborated petrological models (Hynes 2005; Afonso et al. 2007) suggesting that on Earth, the plate's mean density is never larger than the underlying mantle's. Nonetheless, we discuss the conditions for the development of negative buoyancy on super-Earths.

2.1. *Parametric Convection*

The thickness of the lithosphere or boundary layer (δ) depends on the Rayleigh number (Ra)—a parameter governing convection. A variety of models of boundary layer convection (O'Connell & Hager 1980; Turcotte & Schubert 2002, pp. 226–291) lead to $\delta \sim D\,(\mathrm{Ra}/\mathrm{Ra}_c)^s$, with $s = -\frac{1}{4}$ and Ra_c the critical Rayleigh number above which a fluid starts convecting. This results in δ being independent of the depth D of the convecting layer.

The exponential relationship between δ and Ra has been extensively addressed as different flow details, geometries, turbulence, and other complicating effects are taken into account. In particular, Conrad & Hager (1999b) suggested that $s \sim 0$ where viscous dissipation within the bending subducting slab is larger than the dissipation within the shearing mantle, which is the case for thick strong plates (Conrad & Hager 1999a). However, since we show below that the plates for super-Earths are thin, the case where $s \sim 0$ can be ruled out. Other values of s will not change the qualitative results obtained here.

The deviatoric horizontal normal stress (σ) responsible for causing failure on the plate is (to first order) balanced by the shear stress (τ) applied over the base of the plate. Thus, by a simple force balance $\sigma = \tau L/\delta$, where L is the plate length, calculated from the time it takes for the plate to cool conductively and grow to a thickness δ, $L \sim \delta^2 u/\kappa$, where u is the convective velocity. The shear stress depends on the viscosity η and the velocity field of the fluid. In the most simple case, this dependence will be linear so that the stress under the plate

[1] Corresponding author.

TABLE 1
CONVECTIVE PARAMETERS' POWER-LAW DEPENDENCE ON MASS

Parameter	Earth	$\eta = \eta(T)$	Isoviscous
Plate thickness (δ)	43 km	−0.45	−0.29
Drop in temperature (ΔT)	1277°C	0.02	0.18
Plate velocity (u)	3 cm yr^{-1}	1.19	0.87
Shear stress (τ)	0.3 MPa	0.27	0.58
Normal stress (σ)	10 MPa	1.00	1.16
Plate length (L)	1800 km	0.28	0.29
Convective time (t)	70 myr	−0.91	−0.58

NOTES.—The second column displays Earth's convective parameters. The only assumed value is the plate velocity. The third and fourth columns show the values for the exponent β in the power-law relationship—i.e., $\delta = \delta_{\oplus}(M/M_{\oplus})^{\beta}$—for a bulk silicate Earth composition with a T-dependent viscosity and isoviscous cases, respectively.

is $\tau \sim \eta u/D$. The faster the flow, the larger the stress. In general, these are competing effects: viscosity decreases while velocities increase with higher temperatures (T). The relationship for velocity is $u \sim \kappa/D\mathrm{Ra}^{1/2}$ (Turcotte & Schubert 2002, pp. 226–291). A super-Earth can be expected to have larger velocities due to larger Rayleigh numbers. Thus, we need to investigate the extent to which the viscosity effect reduces the stress to predict whether or not plate failure will occur. We do so by considering two cases for viscosity: an isoviscous case ($\eta = \eta_0 = 10^{21}$ Pa s—Earth's nominal value) and a T-dependent viscosity case [$\eta = \eta_0(T/T_0)^{-30}$; Davies 1980].

2.2. *Structure and Convection*

We calculate the internal structure of terrestrial planets with masses in the range of 1–10 $M_{\oplus}$ (Valencia et al. 2006) and determine the mantle thickness, density, and gravity of each planet. We find that a power-law relationship can adequately express the dependence of these parameters on M. For planetary mantles, the Rayleigh number depends on the mantle density [$\rho = \rho_{\oplus}(M/M_{\oplus})^{0.20}$], gravity [$g = g_{\oplus}(M/M_{\oplus})^{1/2}$], mantle thickness [$D = D_{\oplus}(M/M_{\oplus})^{0.28}$], and heat flux ($q$), which all depend on the mass of the planet. Ra also depends on material properties: thermal expansivity (α), thermal diffusivity (κ), thermal conductivity (k), and viscosity (η). The latter is a strong function of T. Therefore, the Rayleigh number $\mathrm{Ra} = \alpha\rho g D^4 q/\kappa k \eta$ depends indirectly on M and T. It increases for super-Earths as the size of their mantle and interior heat increases. To account for the heat flux as a function of M, we scale radioactive heat production and indirectly consider secular cooling. It is straightforward to scale the radioactive production with M for similar bulk compositions. Secular cooling, on the other hand, can only be completely assessed by considering the full thermal evolution. More massive planets would have larger initial gravitational energy budgets to dissipate over time; we assume for simplicity that the heat to be lost to secular cooling is proportional to M. Convective velocities also scale roughly with M ($u \sim M^{1.19}$; see Table 1), so that the proportional rate of cooling should be roughly independent of M. Even though the relative contributions of radioactive heating and secular cooling to the total heat flow will depend on the evolution of the planet, we assume that heat flow scales proportionately with M, especially because we expect the radioactive production to be dominant. The internal structure model allows us to calculate Ra, δ, and T beneath the plate for planets between 1 and 10 $M_{\oplus}$. Convergence of these parameters determines the structure and final radius of each super-Earth planet.

3. RESULTS

Figure 1 shows the dependence of plate thickness (*blue*) and horizontal normal stress (*green*) as a function of M for the T-dependent viscosity case and Earth-like radioactive heat sources (*solid lines*). An additional case with reduced heat sources (*dashed lines*) is discussed below. The trends between these two scenarios and scaling exponents are similar, although their 1 $M_{\oplus}$ values are different.

As expected, the plate thickness decreases as the M of the planet increases. This is because a more vigorous convective interior can transport heat more efficiently to the surface and sustain a higher surface heat flux. In addition, shear stress underneath the plate increases proportionately with M (Fig. 2),

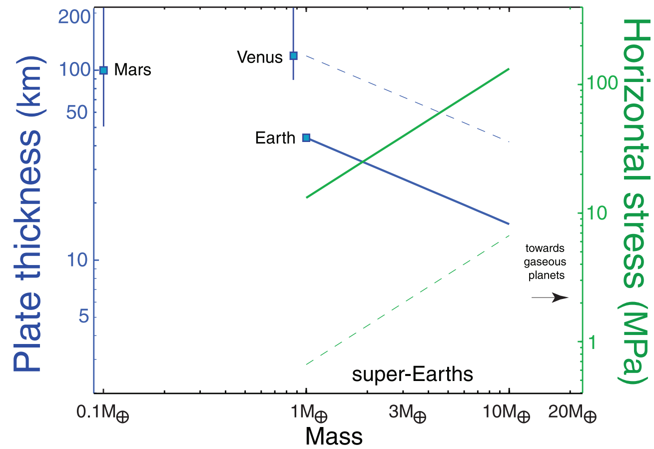

FIG. 1.—Plate thickness and stress for super-Earths. The dependence of plate thickness (*blue axis*) and horizontal normal stress (*green axis*) on mass are shown for a bulk silicate Earth composition (*solid lines*) and a reduced heat content case (*dashed lines*). Both cases have a T-dependent viscosity treatment. As mass increases, the stress available to overcome plate resistance increases, while plate thickness decreases, enhancing plate weakness. Plate thickness for Mars and Venus is shown with their uncertainty (from Zuber et al. 2000; Nimmo & McKenzie 1998). The Earth's plate thickness is a global average. Planets with masses larger than 10 $M_{\oplus}$ can start to retain gas during formation (Ida & Lin 2004).

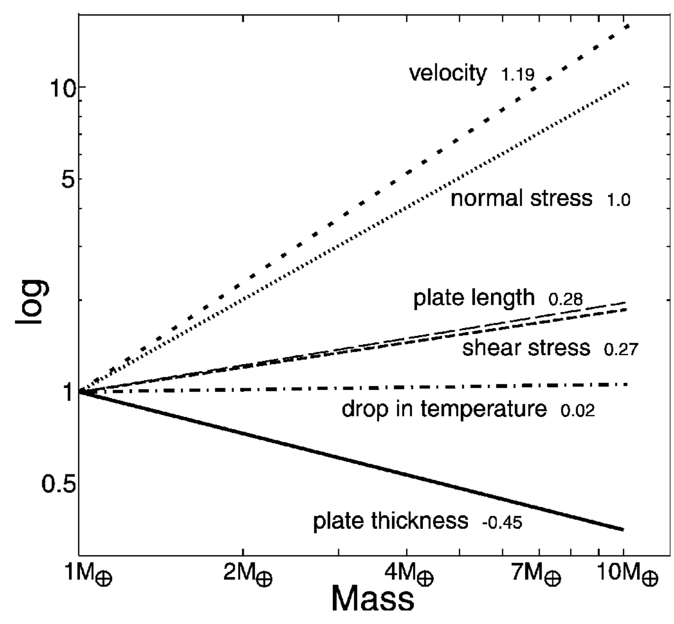

FIG. 2.—Convective parameters scaling with planetary mass. Plate thickness (*solid line*), drop in temperature within the plate (*dash-dotted line*), shear stress (*medium-dashed line*), plate length (*long-dashed line*), normal stress on plate boundaries (*dotted line*), and convective velocity (*short-dashed line*) depend on the mass of the planet. This dependence can be fitted to a power law, with corresponding exponents shown as numbers. The values are normalized for Earth; see Table 1.

and thus, the deviatoric horizontal normal stress also increases. This means that the viscosity reduction effect on stress is very small compared to the velocity effect. This is the case because the drop in T within the plate and hence local viscosity are nearly independent of M, as indicated by our calculations for the more realistic T-dependent viscosity case (Fig. 2). For similar surface temperature, the increase in temperature at the base of the lithosphere between Earth and a super-Earth differs at most by only 5%. We think the reason for this surprising result is a very efficient negative feedback induced by viscosity. If T increases, the viscosity decreases and heat flux increases, cooling the planet and reducing T. We ignore pressure (P) effects on viscosity because we expect them to be small under thin plates and because we find that P at the base of the plate is roughly the same for all super-Earths.

Figure 2 shows the dependence of all the relevant convective parameters with planetary mass normalized to the Earth's values for the T-dependent case. The results can be adequately fitted to a power law such as $\delta = \delta_{\oplus}(M/M_{\oplus})^{\beta}$, where the exponent β shows the dependence on M. In a vigorously convective interior (high Ra), the velocities are expected to be large, and this is evident in Figure 2. The relative size of the convection cells measured as the length of the plate with respect to its radius (L/R) increases slightly, from a 0.29 ratio for a 1 $M_{\oplus}$ planet to a 0.30 ratio for a 10 $M_{\oplus}$ planet. The maximum plate age, related to the convective overturn, in a super-Earth is much less (see Table 1 for $\beta = -0.91$).

3.1. *Heat Flow*

In addition to a bulk silicate Earth composition for radioactive sources, we also consider planets with no ^{40}K content. As a result of potassium's volatile nature, Earth is depleted in this element (McDonough & Sun 1995). It is therefore possible for other planets to also have nonchondritic K concentrations. U/O and Th/O ratios can be expected to be fairly constant for planets forming around stars with a relatively recent supernova event (within 10 Gyr). K contributes less than one-third of total heat from radioactive sources at the present time on Earth. Within this context, we consider a pessimistic scenario for a super-Earth with only one-third of its chondritic heat flow (Q) and no secular cooling contribution.

This end-member case (Q/3) shows comparatively thicker plates (Fig. 1), with 117 km versus 43 km in thickness for a 1 $M_{\oplus}$ planet. In addition, the driving force is on the order of 1–6 MPa, which is lower than Earth's value of ~10 MPa. This is an extreme case where subduction would be difficult but still possible for the most massive super-Earths if other factors, such as the presence of hydrated minerals, is invoked to reduce the strength of the plate. For each planetary mass, there is a threshold in heat flow below which the convective driving force would not be sufficient to maintain subduction and plate tectonics would cease. Nonetheless, most of the super-Earths that will be detected in the next few years will likely fall in a regime above the Q/3 scenario.

3.2. *Lithospheric Buoyancy*

On Earth, the oceanic lithosphere is comprised of 7 km of basaltic crust (chemically buoyant), overlaying lithospheric mantle. We perform a simple buoyancy calculation at subduction ages by considering the thermal contraction from the ridge. We determine maximum crustal thicknesses that still allow the lithospheric mean density to be larger than the underlying mantle's. We find this value to be 13% the plate thickness at subduction zones (twice the average thickness—δ). The crustal thickness depends on the extent of melting under ridges, which depends on the P and T conditions. As shown above, T at ridges and under plates varies little with M, so that with larger gravity values, melting occurs at shallower depths in super-Earths. A simple calculation shows that the crust thins with increasing planetary M, and while it becomes a larger component of the also thinning boundary layers, its thickness stays below the threshold allowing negative buoyancy. This effect stands in contrast to the young Earth that had a higher potential T but same P profile (Nisbet & Fowler 1983; Davies 1993). To precisely assess the density of the plate, detailed petrological models like those of Hynes (2005) and Afonso et al. (2007) are needed. It is important to point out that their models do not predict negative buoyancy on Earth when the plate's density is compared to sublithospheric density, arguing that perhaps this condition is not critical for the initiation of subduction. In addition, Becker et al. (1999) showed that in compressive regions, the cold plate can thicken to a point that negative buoyancy is inevitable and subduction follows. If negative buoyancy is indeed a necessary condition, our simple calculations show that super-Earths can satisfy it.

4. SUMMARY AND IMPLICATIONS

In summary, convection is more vigorous in massive terrestrial planets, making their lithospheres thinner and therefore reducing lithospheric strength. Furthermore, they achieve larger stresses owing primarily to larger velocities and therefore can more easily overcome the lithospheric resistance to deformation. Plates may reach negative buoyancy on super-Earths despite their relative younger ages. This scenario is suitable for the failure of the plate and subsequent subduction, which is a necessary step for plate tectonics. Given that Earth's convective state leads to plate tectonics, the more favorable conditions experienced by super-Earths will inevitably lead to plate tectonics. Furthermore, planets of similar mass should have the same potential to exhibit plate tectonics. Conversely, this physics can help explain why small planets like Mars, Mercury, and the Moon do not exhibit plate tectonics.

4.1. *Role of Water*

Venus is only slightly smaller than Earth and does not exhibit plate tectonics, although some authors (Turcotte 1993; Jellinek et al. 2005) have suggested it may have in the past. This observation indicates that the ~1 $M_{\oplus}$ case falls within a zone of transition between "hard" stagnant lid and mobile plate regimes. In this case, characteristics other than M may be important to the dynamics of the lithosphere. For example, the high surface temperature of Venus might lead to a weak, highly deformable boundary layer that would not support the coherent platelike behavior that characterizes oceanic plates on Earth. Moreover, plate strength is relatively large compared to the mantle driving force in the 1 $M_{\oplus}$ case; yield stresses are on the order of 1–5 GPa for olivine (the representative upper mantle mineral; Chen et al. 1998), whereas our calculations, in agreement with more detailed models (Becker & O'Connell 2001), suggest an underlying driving force of only 10 MPa. Since slip can occur on preexisting faults at stress values of a few MPa, the existence of plate tectonics in the 1 $M_{\oplus}$ regime may thus depend crucially on the conditions required to initiate subduction. The presence of water is one possible mechanism to reduce the yield strength of a plate and friction on faults. Experiments show that water reduces the yield strength of olivine by 62% when raising the temperature from 25°C to 400°C at 10 GPa, compared to a drop of 39% in dry olivine (Chen et al. 1998). Hence, the hydration level of Venus's mantle, which is 1–2 orders of magnitude lower than on Earth (Zolotov et al. 1997), may make it very difficult for convective forces within this planet to overcome plate resistance.

For larger planets, super-Earths, these issues become less relevant. A wet super-Earth will clearly have enough driving force to sustain subduction. But, more importantly, the consequences for initiating subduction associated with the hydration of a 1 $M_{\oplus}$ planet (i.e., a reduction of the yield strength by half) would be similar to a doubling of the mass of the planet (Fig. 2). That is to say, both scenarios would be as likely to initiate and maintain subduction.

4.2. *Atmospheric Observables*

The difference between a super-Earth with active plate tectonics and one with stagnant lid is in the access of upper mantle material and gases to the atmosphere. The first case allows several global geochemical cycles to operate, like the CO_2 and SO_2 ones. For example, cases in our solar system include Earth with a CO_2 cycle and possibly early Mars with a SO_2 cycle (Halevy et al. 2007). Earth has had stable modest levels of atmospheric CO_2 (between 160 and 7000 ppm; Royer et al. 2001) in the last 0.5 Gyr, whereas Venus levels stand today at 96%. A planet with plate tectonism and a carbonate rock reservoir has an efficient built-in cycle that stabilizes climate at temperatures within the liquid water regime (Kasting 1996). A super-Earth that has plate tectonics and weathering capabilities can be expected to have CO_2 atmospheric concentrations that would yield temperatures around liquid water. Therefore, evidence against the presence of plate tectonics on an exoplanet would be the detection of high values of CO_2 for the age of the star, type of star, and orbital distance. An SO_2-based atmosphere is also possible and the same reasoning would apply, since the sulfur cycle operates analogously to the carbon cycle. But obviously, more theoretical research is necessary to model the details and predict the right observable signatures.

In conclusion, we show here that as mass increases, the process of subduction, and hence plate tectonics, becomes easier. Therefore, massive super-Earths will very likely exhibit plate tectonics. In the future, with the *Terrestrial Planet Finder* by NASA and *Darwin* by ESA, it might be possible to use spectroscopy to identify atmospheric signatures suggesting plate tectonism on these objects. This class of planets offers the possibility of finding Earth analogs and, in particular, make attractive targets in the search for habitable planets.

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