Earth and Planetary Science Letters 277 (2009) 29–37

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

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

Variations in planetary convection via the effect of climate on damage

W. Landuyt *, D. Bercovici

Department of Geology and Geophysics, Yale University, New Haven, CT, USA

ARTICLE INFO

Article history:
Received 14 April 2008
Received in revised form 12 September 2008
Accepted 26 September 2008
Available online 17 November 2008

Editor: C.P. Jaupart

Keywords:
plate generation
planetary convection
damage
climate

ABSTRACT

A new model for the generation of plate tectonics suggests an important interaction between a planet's climate and its lithospheric damage behavior; and thus provides a simple explanation for the tectonic difference between Earth and Venus. We propose that high surface temperatures will lead to higher healing rates (e.g. grain growth) in the lithosphere that will act to suppress localization, plate boundary formation, and subduction. This leads to episodic or stagnant lid convection on Venus because of its hotter climate. In contrast, Earth's cooler climate promotes damage and plate boundary formation. The damage rheology presented in this paper attempts to describe the evolution of grain size by allowing for grain reduction via deformational work input and grain growth via surface tension-driven coarsening. We explore the interaction of damage and healing in two-dimensional numerical convection simulations. We also develop a simple "drip-instability" model to test the hypothesis that the competition between damage and healing controls convective and plate tectonic style by modulating episodicity at subduction zones. At small values of damage, f_A, (or large values of healing, k_A) the lithosphere remains strong enough to resist subduction on time scales of billions of years. At intermediate values of f_A and k_A the lithosphere may become mobilized and allow for short bursts of tectonic behavior followed by periods of quiescence. At large (small) values of f_A (k_A) the fineness is increased so that the viscosity of the plate boundary is reduced to allow for continuous, unimpeded subduction of lithosphere and plate-like deformation. The results suggest the feasibility of our proposed hypothesis that the interplay of climate and damage control the mode of tectonics on a planet.

1. Introduction

Although plate tectonics is a well established theory, much remains to be understood about the development of plate tectonics on Earth as well as its absence on the other terrestrial planets (Tackley, 2000a; Bercovici, 2003). Plate tectonics on Earth has been determined to have been in operation continuously for at least two billion years and may well have been in operation much earlier (Cawood et al., 2006). In contrast, stagnant lid convection is the mode of convection observed on the other terrestrial planets (Kaula and Phillips, 1981; Moresi and Solomatov, 1998; Schubert et al., 2001; O'Neill et al., 2007). It is most notable that Venus does not have plate tectonics since it is similar in many characteristics to Earth. Observations of statistically uniform impact craters over the entire surface of Venus implies uniformity in age of the Venusian lithosphere, and has been suggested to be indicative of a global resurfacing event a few hundred million years ago (Schaber et al., 1992; Strom et al., 1994). This evidence has led some to hypothesize that tectonics on Venus oscillate between stagnant lid convection and short bursts of mobile lid convection (Turcotte, 1993). Given the similarities between Earth and Venus the contrasting styles of tectonics presents a significant conundrum, specifically why does Earth exhibit plate tectonics and Venus does not? The difference in convective behavior between Earth and Venus is an important component of plate generation studies separate from considerations of plate-ness and the generation of toroidal motion (Bercovici et al., 2000; Tackley, 2000a; Bercovici, 2003). Note that because Mars, Mercury, and the Moon are considerably smaller than either Earth or Venus, and thus lost heat and became largely stagnant early in their thermal histories, we do not consider them in this comparison. An obvious difference between Earth and Venus is the existence of free surface water on Earth and its absence on Venus. This observation has led previous authors to suggest various mechanisms in which water directly facilitates the rheological weakening that permits plate formation and/or subduction initiation; for example, damage induced void generation and water ingestion leading to self-weakening (Bercovici, 1998), a reduction of the friction coefficient and hence yield stress (Moresi and Solomatov, 1998), hydrous weakening coincident with sediment loading in convergent margins leading to subduction initiation (Regenauer-Lieb et al., 2001), and deep thermal cracking and hydration of oceanic lithosphere leading to subsequent reduction in friction coefficient (Korenaga, 2007). But geophysical observations seem to suggest that Earth's lithosphere is actually dry (Evans et al., 2005), therefore the role of water in facilitating plate tectonics remains a mystery.

The formation of narrow, rapidly deforming boundaries characteristic of plate tectonics necessitates a highly non-linear rheology in order to generate significant shear localization. Incorporation of non-

* Corresponding author.
E-mail address: william.landuyt@yale.edu (W. Landuyt).

0012-821X/$ – see front matter © 2008 Elsevier B.V. All rights reserved.
doi:10.1016/j.epsl.2008.09.034

Newtonian rheologies into plate generation studies has shown an improvement in generating plate-like behaviors in comparison to Newtonian viscosity (Christensen and Harder, 1991; Weinstein and Olson, 1992; Bercovici, 1993, 1995), but typically requires viscosity exponents far greater than what would be expected from mineral physics studies (Karato and Wu, 1993). Previous studies have also implemented a yield criterion in the uppermost part of the lithosphere transitioning to temperature-dependent viscous rheology at deeper depths to incorporate a form of brittle deformation into the lithospheric rheology (Moresi and Solomatov, 1998; Tackley, 2000b). These studies were able to generate plate-like behaviors for low values of yield stress (compared to experimental work), as well as episodic behavior at intermediate yield stress values. Brittle deformation only occurs in the upper 10–15 km of the lithosphere (Kohlstedt et al., 1995), and therefore a mechanism for localization in the ductile and combined brittle–ductile region is likely necessary for mobilizing the entire lithosphere. Two-phase damage theory was developed in order to take a first-principles approach to studying the rheological weakening that leads to shear localization in the lithosphere (Bercovici et al., 2001a; Bercovici and Ricard, 2003, 2005). In the formulation of two-phase damage theory the assumption is made that some fraction of deformational work goes into the generation of internal surfaces, voids and grain size reduction, and the development of internal surfaces causes weakening in the rock. In two previous studies it was determined that grain size reducing damage was more successful at producing plate-like behaviors (Bercovici and Ricard, 2005; Landuyt et al., 2008).

Our goal here is to explain how the rheological mechanism that allows plate tectonics to form on Earth and not on Venus can fit with the observed differences between the two planets (regarding free surface water, surface temperature, atmospheric CO_2 concentration). Our hypothesis is that variations in the competition between damage and healing will allow transitions in convective behavior; these variations are associated with differences in surface and lithospheric temperatures governed by distinctions in the climatic systems of Earth and Venus. In particular, higher lithospheric temperatures due to elevated surface temperatures will act to moderate localization that is necessary for formation of plate boundaries, hence leading to episodic/stagnant lid behavior on Venus. The reason Venus has significantly higher surface temperatures is the lack of free surface water, which is necessary for climate control through its maintenance of the carbon cycle (Berner, 2004); therefore we propose that the role water plays in allowing plate tectonics is through its control on climate and not through a direct rheological weakening effect.

The interaction of climate and tectonics on Venus was used to explain the prevalence of wrinkle ridges on the planet's surface (Solomon et al., 1999). The interaction of climate, mantle convection, and melting was used for a simple model of Venus to understand coupled volcanism and climate evolution on the planet (Phillips et al., 2001). A recent study has suggested that an increase in surface temperature could shut down plate tectonics by decreasing convective stresses below the lithospheric yield stress (Lenardic et al., 2008). Our hypothesis differs by suggesting that surface temperature variations between the two planets influence the recovery and healing rate of the lithosphere, and correspondingly alters the dynamic interaction of damage and healing to suppress or mitigate localization necessary for subduction and plate boundary formation.

To test our hypothesis that surface temperature controls efficacy of damage and shear localization we consider the incorporation of two-phase damage physics into a coupled plate–mantle model that is convectively driven by exploring the transitions in convective behavior as a function of damage parameters. The steady-state convective behaviors for the coupled plate–mantle model were mapped in Landuyt et al. (2008), and that study is extended to determine how damage physics might explain the transition from episodic tectonics to stable plate-like convection. In this paper we consider only fineness inducing (grain size reducing) damage for two reasons: this was generally found to be more successful at generating plate-like flows than void-generating damage, and fineness-generating damage is more likely to be sensitive to variations in lithospheric temperature than void-generating damage. Our results indicate that the effect of grain size on rheology in a damage theory formulation induces transitions in convective style that can explain the differences in tectonics between Earth and Venus. We also analyze the results from our convection experiments by looking at a simple physical model for lithospheric foundering to clearly understand the subduction zone force balance of the different modes of convection. Finally, a discussion of our model for the role of free surface water in controlling climate and plate tectonics is presented that may explain why Earth exhibits stable plate-like behavior while Venus exhibits episodic behavior, even though they share many similarities.

2. Model formulation

The focus of this paper is to explain the tectonic difference between Earth and Venus by implementing a grain size reducing damage rheology in the lithosphere of the convecting system. We therefore employ a lithosphere–mantle coupling model where a Newtonian mantle is overlain by a lithospheric layer with two-phase damage rheology (Landuyt et al., 2008); this model is similar to the formulation of Weinstein and Olson (1992). The lithospheric layer is of constant thickness h and is much smaller than the thickness of the underlying mantle d, ($h \ll d$). The mass, momentum, and damage evolution equations in the lithosphere are vertically integrated and thin-sheet approximations are made, hence all variations in the lithosphere are in the horizontal direction. We consider simple Rayleigh–Benard convection to take advantage of the inherent symmetries of this mode of convection. While our model of mantle convection has certain simplicities, we are still able to understand the important coupling between damage theory and planetary convective style.

The two-phase damage equations originate from a series of papers (Ricard et al., 2001; Bercovici et al., 2001a,b; Ricard and Bercovici, 2003; Bercovici and Ricard, 2003, 2005). In our previous results with only fineness generating damage there was some porosity (void fraction) evolution, but the values of porosity were quite small and had little effect on the convective dynamics. Therefore we neglect the effect of porosity/void generating damage in this study (c.f. Landuyt et al., 2008). Following previous formulations for the matrix rheology the lithospheric viscosity is given by

$$\mu_l = \mu_p \left(\frac{A_{\mathrm{ref}}}{A}\right)^m \tag{1}$$

where μ_p is the reference lithospheric viscosity. The variable A is called fineness (Bercovici and Ricard, 2005), and is essentially the inverse grain size of the rock ($[A] = \mathrm{m}^{-1}$). The viscosity exponent m is a dimensionless positive constant, and here we consider $m = 2$ consistent with a grain size sensitive deformation mechanism (e.g. diffusion creep, grain boundary sliding) (Karato and Wu, 1993; Hirth and Kohlstedt, 2003). The evolution equation for fineness is

$$\frac{DA}{Dt} = \frac{f_A}{\gamma}\Psi - k_A A^p \tag{2}$$

where f_A is the fraction of deformational work which goes into increasing fineness (or reducing grain size), γ is the surface tension, k_A is the healing rate ($[k_A] = \mathrm{m}^{p-1}/\mathrm{s}$), and

$$\Psi = \nabla \mathbf{v} : \underline{\tau}, \tag{3}$$

is the rate of deformational work, where $\mathbf{v}$ is the lithospheric velocity, and $\underline{\tau}$ is the lithospheric stress tensor. The healing rate k_A is a function of temperature (Karato, 1989), but we assume that k_A is to leading order a function only of the mean lithospheric temperature. We choose the healing exponent p to be three in order to reproduce classical surface tension driven grain growth whereby the grain size increases with the square root of time (e.g. Karato, 1989; Evans et al., 2001). The first term in Eq. (2) allows for the reduction of grain size via the input of deformational work, hence the surface energy in the system is increased. Grain size reduction is assumed to occur through a combination of mechanisms, such as dynamic recrystallization and cataclasis. While recent work comparing theory to experiments has suggested that grain size evolution follows a relationship governed by work input (Austin and Evans, 2007), a complete quantitative description for the evolution of grain size (or grain size distribution) undergoing both grain size reduction and grain growth is still in its infancy (Ricard and Bercovici, in press). The medium is assumed to have a grain size sensitive viscosity, which can be accomplished by having a statistical average of creep mechanisms over grain size distribution (e.g. large grains undergo dislocation creep and small grains undergo diffusion creep) (Ricard and Bercovici, in press). Field and experimental work on shear localization has shown that a rock with a given grain size distribution can partially deform by dislocation creep but have the rheology controlled by the weaker diffusion creep (and hence grain size sensitive) portion (Jin et al., 1998). This observation coupled with the ubiquity of mylonites in shear zones observed on Earth (White et al., 1980; Jaroslow et al., 1996; Warren and Hirth, 2006) suggests that grain size sensitive creep plays an important role in weakening the shallow portions of the Earth.

3. Numerical results

We examine a series of numerical results to understand how changes in damage parameters affect the behavior of our mantle convection model. Our results focus on understanding changes associated with variations in the fraction of deformational work partitioned into damage, f_A, and healing rate, k_A. In previous work it was shown that the magnitude of fineness is predominantly sensitive to the ratio of f_A/k_A (Landuyt et al., 2008), hence increasing f_A relative to k_A will increase fineness (or decrease grain size) and subsequently reduce viscosity. The calculations were run with Rayleigh number $Ra=\rho g\alpha\Delta Td^3/(\kappa\mu)$ equal to 10^6 (where ρ is density, g is gravitational acceleration, d is the convecting layer depth, α is thermal expansivity, ΔT is the temperature drop across the mantle, κ is the thermal diffusivity, and μ is the mantle viscosity). The aspect ratio of the box (width/height) is two, and the lithospheric viscosity is four orders of magnitude greater than the Newtonian mantle viscosity. The equations were non-dimensionalized with the thermal diffusion time scale, mantle depth for length scale, mantle viscosity to construct pressure and stress scale, and the mantle temperature drop for the temperature scale. In this case, $\hat{k}_A$ is the non-dimensional healing rate. All simulations were initiated with a constant value of fineness in the lithosphere equal to one. We employ a combined spectral and Propagator Matrix method to solve the mass and momentum equations, and a combined spectral and finite difference method to solve the thermal equation (Landuyt et al., 2008). The calculations were performed on a spatial grid of 128 points in the horizontal direction and 64 points in the vertical direction, and this resolution was able to reproduce the results from test simulations at higher resolutions but at significantly reduced computational times. As stated previously the simplicity of our model allows for easier identification of plate-like behaviors generated from our complex damage rheology.

Our main focus is on understanding transitions in time-dependent behavior of convection within our model. In particular, maintaining a constant healing rate with different values of damage fraction f_A leads to substantially different convective behaviors (Fig. 1). For example, at $f_A=5\cdot 10^{-4}$ (Fig. 1, green curves) the system displays stagnant lid convection as evident in the very small surface velocities exhibited throughout the entire numerical simulation. While both the values of fineness and surface velocity are weakly periodic (Fig. 1), we identify this behavior as stagnant lid due to the amplitude of variations and absolute magnitude being relatively small throughout the calculation. At intermediate values $f_A=10^{-2}$ (Fig. 1, red curves) the model undergoes a transition to episodic plate mobility. The episodic plate mobility regime is identified with cases wherein the surface velocity undergoes amplitude variations over at least one order of magnitude, hence the system oscillates between what we refer to as stagnant-lid convection and a mobile-plate regime. Further increases in f_A to $5\cdot 10^{-2}$(Fig. 1, black curves) result in a transition in convective behavior to stable plate like flow. This regime is characterized by plate like surface velocities (i.e., concentrated deformation and high plate velocity) that reach steady-state after an initial set of transient oscillations. In the stable plate like regime the increased fineness values at the subduction zone maintain a viscosity reduction that allows for continuous and uninhibited lithospheric subduction. The amplitude of oscillation in the episodic regime remains large for all time, while the stable plate-like regime eventually settles to a steady velocity (Fig. 1a). Increasing damage fraction relative to healing leads to significant changes in plate velocity and convective behavior (Fig. 1a), hence the ratio of damage to healing acts to control the mode of convection. The transition in convective behavior described above can also be accomplished by choosing a suitably large value of f_A and decreasing $\hat{k}_A$(also see Landuyt et al., 2008). The transition in convective behavior is rather insensitive to the absolute magnitudes of f_A and $\hat{k}_A$ (Fig. 2), though at values of f_A on the order of 10^{-7} or less the system remains in stagnant-lid behavior for the entire

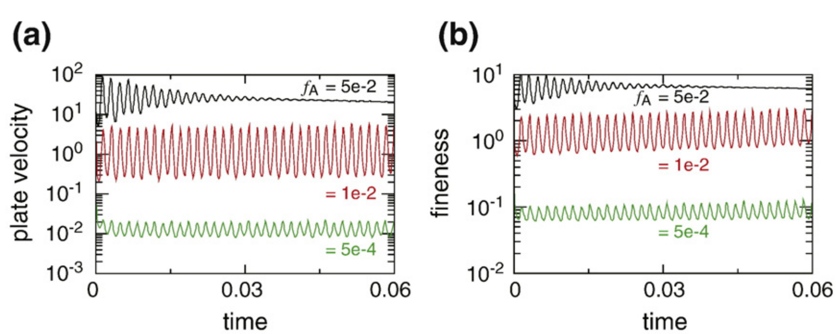

Fig. 1. The transition in convective behavior exhibited by the model as a function of increasing the fraction of deformational work partitioned into damage. Plot (a) displays the plate velocity time series, and plot (b) displays the maximum fineness time series for three different f_A,$\hat{k}_A$ pairs (both (a) and (b) are log-linear). By increasing f_A ($\hat{k}_A=2.5\cdot 10^5$) the system transitions from an initially stagnant lid regime ($f_A=5\cdot 10^{-4}$, green curves) to episodic behavior ($f_A=10^{-2}$, red curves), eventually transitioning to stable plate like behavior ($f_A=5\cdot 10^{-4}$, black curves). The time scale is non-dimensionalized by the diffusion time scale (d^2/κ, where $d\approx 3\cdot 10^6$ m and $\kappa\approx 10^{-6}$ m^2 s^{-1}) which gives the period for plate mobility in the episodic regime to be approximately 500 Myr. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

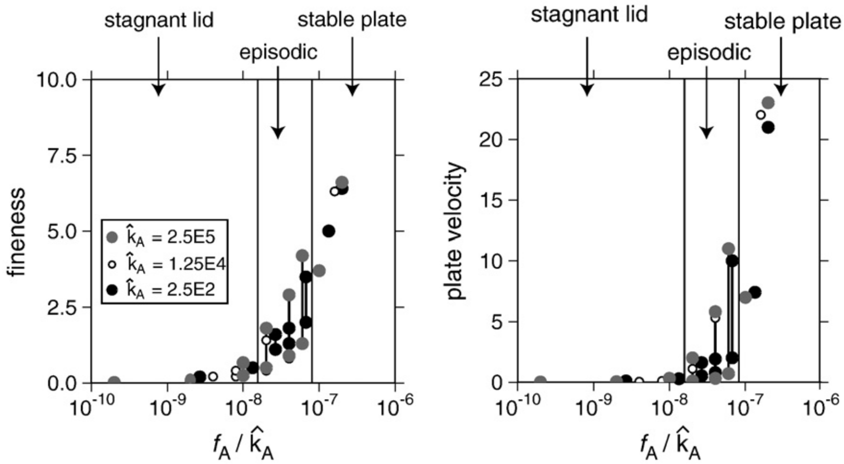

Fig. 2. Convective behavior regimes in terms of surface velocity and fineness results from a series of numerical experiments with damage rheology in the lithosphere. At low values of f_A relative to healing the system is in a stagnant lid regime, and as damage is increased the system transitions to episodic behavior and eventually stable plate like behavior. The results also show the transition in convective behavior occurs over a large range of magnitudes of damage and healing (see inset box values of $\hat{k}_A$).

numerical run. The range of $f_A/\hat{k}_A$ for which episodic behavior is exhibited is rather narrow, being less than an order of magnitude in total width.

The cycle of lithospheric mobility in the episodic convection regime is displayed in Fig. 3. At times a and b (Fig. 3) the lithospheric velocity is relatively low and the thermal boundary layer does not have any significant downwelling component. Eventually the thermal load from mass injection into the nascent subduction zone becomes large enough to overcome the viscous resistance of the lithosphere to subduction. Time c (Fig. 3) displays the rapid rise in fineness associated with the large deformational work input from subduction of the lithosphere and the corresponding increase in surface velocity; in this case, the thermal boundary layer has been substantially thinned due to the mass loss through subduction. Soon after this burst of tectonic activity the lithospheric velocity substantially decreases (time d, Fig. 3) and the fineness field evolution in the subduction zone is dominated by grain growth. The healing time scale though is longer than the time it takes for the subduction zone to develop significant negative buoyancy, hence the location of this zone of weakness and all subsequent subduction bursts occur in roughly the same region.

The transitions in convective behavior detailed above were made with the assumption that the lithospheric viscosity is four orders of magnitude larger than the underlying mantle viscosity (i.e., $\mu_R = 10^4$). While this choice for μ_R is reasonable for Earth, the μ_R for Venus remains unknown. The nature of the Venusian lithosphere possibly ranges from a thin lithosphere similar to Earth's (Sandwell and Schubert, 1992; Nimmo and McKenzie, 1998) to a significantly thicker, practically immobile lid (Kaula, 1984; Solomatov and Moresi, 1995), though the aforementioned studies suggest that it is either the same or greater than that of the Earth's lithosphere. Convection simulations run with μ_R greater than 10^4 would likely cause the transition from episodic to stable plate-like behavior to occur at a greater value of f_A/k_A since more damage would be required to mobilize an even stronger lithosphere. While small values of f_A ($<10^{-7}$) will not produce stable plate like behavior, this behavior is present for a substantial range of f_A (10^{-5} 10^0). This result implies robustness of stable plate like behavior over a wide range of f_A, which is the least constrained component of the damage model. The efficacy of $f_A = 10^{-5}$ at inducing plate like behavior is a function of the surface tension value (we assume a reasonable $\gamma \approx 1$ N/m), whereas a larger surface tension would necessitate a larger f_A to facilitate plate like

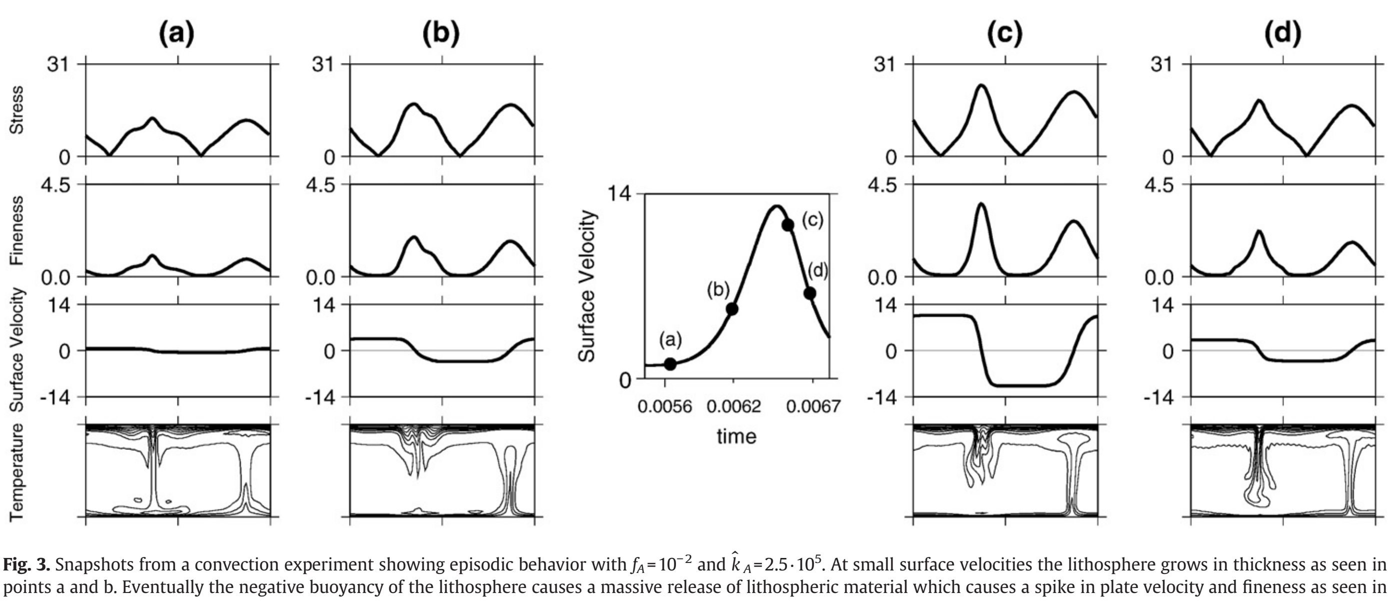

Fig. 3. Snapshots from a convection experiment showing episodic behavior with $f_A = 10^{-2}$ and $\hat{k}_A = 2.5 \cdot 10^5$. At small surface velocities the lithosphere grows in thickness as seen in points a and b. Eventually the negative buoyancy of the lithosphere causes a massive release of lithospheric material which causes a spike in plate velocity and fineness as seen in frame c. After the foundering of lithosphere the surface velocity decreases and the fineness evolution is dominated by healing (frame d).

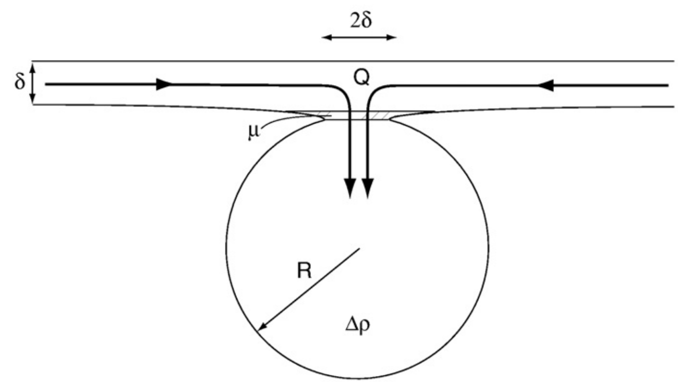

Fig. 4. The drip instability model employed in this study. The view is side-on, and the cylinder extends uniformly a distance L into the page.

behavior. Results from the convection simulations show that variations in $f_A/\hat{k}_A$ of around one order of magnitude allow for the spectrum of convective styles to be exhibited, therefore it seems plausible that variations in the damage parameters offer an explanation for the differences in convective style between Earth and Venus.

4. A simple drip instability model

To understand transitions in convective behavior we consider a simple conceptual model of a drip instability (see Fig. 4). Our hypothesis is that the style of convection (stagnant, episodic, or stable-plate) results from the interplay of damage and healing as it occurs specifically at subduction zones. Hence we test how the drip instability is modulated by damage and healing. The drip instability is represented by a cold, negatively buoyant cylinder viscously detaching from the overlying lithospheric layer. The cylinder becomes heavier and more unstable as it acquires mass from the lithospheric convergent zone. Deformation is focused in a detachment region, which connects the cylinder and lithospheric layer and is thus where damage and healing is concentrated. When the detachment region weakens to a critical level (defined below) the cylinder breaks away and is no longer considered in the model. Subsequently a new cylinder is formed and the process repeats itself. In the model, a very long repeat cycle is indicative of stagnant lid behavior. A very high frequency cycle is representative of continuous subduction, while an intermediate cycle implies episodic behavior.

Conservation of mass in the cylinder requires that

$$\frac{dV}{dt} = Q, \; V = \pi R^2 L \tag{4}$$

where V is the volume of the cylinder, R is the cylinder radius, L is the length of the cylinder, and Q is the constant slab volume flux. The stress on the detachment region (σ) is given by the negative buoyancy of the cylinder acting over the area of the detachment region,

$$\sigma = \frac{\pi R^2 L \Delta\rho g}{2\delta L} = \frac{\pi R^2 \Delta\rho g}{2\delta}. \tag{5}$$

The other evolution equation to consider is the change in fineness (which controls viscosity) in the fault, as defined in Eq. (2). Since the deformational work (Ψ) in the fault is given by Eq. (3), Ψ is given by σ^2/μ, where $\mu = \mu_p A^{-m}$ and is σ is given by Eq. (5). Thus, the evolution of fineness in the fault goes as

$$\frac{dA}{dt} = \frac{f_A}{\gamma}\frac{A^m}{\mu_p}\left(\frac{\pi R^2 \Delta\rho g}{2\delta}\right)^2 - k_A A^p. \tag{6}$$

We non-dimensionalize the above equations with the spatial length scale $R = (\mu_p Q/L\Delta\rho g)^{1/3} R'$, the inverse grain size with $A = A_o A'$, and the time scale by $t = (\mu_p/\Delta\rho g)^{2/3}(Q/L)^{-1/3}\; t' = \tau_{cyl} t'$. This non-dimensionalization results in the following set of equations where all primes designating non-dimensional quantities have been dropped

$$\frac{dR}{dt} = \frac{1}{2\pi R} \tag{7}$$

$$\frac{dA}{dt} = f_A D A^m R^4 - \hat{k}_A A^p \tag{8}$$

where $D = (\mu_p/(\gamma A_o))(\pi^2 Q/4\delta^2 L)$ is the damage number, and $\hat{k}_A = k_A A_o^{p-1} (\mu_p/\Delta\rho g)^{2/3} (Q/L)^{-1/3}$ is the non-dimensional healing rate.

Initially the cylinder inflates due to the constant mass flux into it. As the cylinder begins to grow, the stress on the detachment region from the negative buoyancy of the cylinder increases and this region is damaged and weakened. When the stiffness of the detachment region, defined to be the region's viscosity multiplied by its width (Ribe, 1992; Weinstein and Olson, 1992), is reduced to a critical value (arbitrarily defined to be 10 percent of the undamaged region's stiffness) the cylinder breaks away from the lithospheric layer and no longer remains part of the system. The cylinder's radius is then reset to its initial value (which is determined by the width of the detachment region, or $R_o = \delta$). The value of fineness in the detachment region is not reset because the history of deformation is retained. However the new cylinder has a small negative buoyancy, hence deformation on the detachment region is small and initially undergoes significant healing. The detachment region subsequently weakens as the cylinder grows until separation occurs again.

4.1. Results

To facilitate comparison between the convection experiments and the drip instability (or cylinder) model, we run multiple cases with similar values of damage parameters (i.e. f_A, $\hat{k}_A$, and D). The above equations are solved with a fifth-order, adaptive time-step Runge–Kutta solver. The constant Q/L is estimated by assuming a plate velocity of 1 cm/yr and the lithospheric thickness (δ) of 100 km, hence $Q/L \approx 10^{-5}$ m^2 s^{-1}. We also assume that $\mu \approx 10^{25}$ Pa s (Beaumont, 1976), $\Delta\rho g \approx 500$–1000 Pa m^{-1}, and $A_o \approx 10^2$–10^3 m^{-1}. The ratio of the time scale for the cylinder model (τ_{cyl}) to that for the convection experiments ($\tau_{conv} = d^2/\kappa$) is given by

$$\frac{\tau_{cyl}}{\tau_{conv}} = \frac{\left(\mu_p/\Delta\rho g\right)^{2/3}(Q/L)^{-1/3}}{d^2/\kappa} = 10^{-2}\text{–}10^{-3} \tag{9}$$

where κ is the thermal diffusivity (10^{-6} m^2 s^{-1}) and d is the depth of the convecting system (1–$3 \cdot 10^6$m). Given the above estimations this implies that $\hat{k}_{A_{cyl}} = (\tau_{cyl}/\tau_{conv})\hat{k}_{A_{conv}}$ and $D_{cyl} = (\tau_{conv}/\tau_{cyl})D_{conv}$. The values of $\hat{k}_{A_{conv}}$ vary throughout the convection experiments, but the value of D_{conv} is held constant at 10^4. The ratio τ_{conv}/τ_{cyl} is 300 based on the range of parameters listed above and to maintain a similar maximum value of fineness between the convection and cylinder model experiments. The values of healing rate and time scale presented for the cylinder model are adjusted to the diffusive time scale (i.e., $\hat{k}_{A_{conv}}$).

The time series behavior of the fineness curves for the falling cylinder model reveals variations which are similar to the results from the stagnant lid, episodic, and stable plate like behavior of the convection simulations (Fig. 5). At large healing rates ($\hat{k}_A = 10^5$ black curve) the fineness remains very low for a substantial portion of the numerical run, and only grows to a modest level when the cylinder radius becomes large. The average value of fineness for the largest healing rate though remains very small, and the stiffness of the detachment region leads to a stagnation of the cylinder (i.e., failure to subduct) on long time scales (of order a few billion years). At an intermediate healing rate ($\hat{k}_A = 10^3$ red curve) the system transitions into episodic behavior where the model's variables (R and A) undergo periodic oscillations on the order of a few hundred million years. For

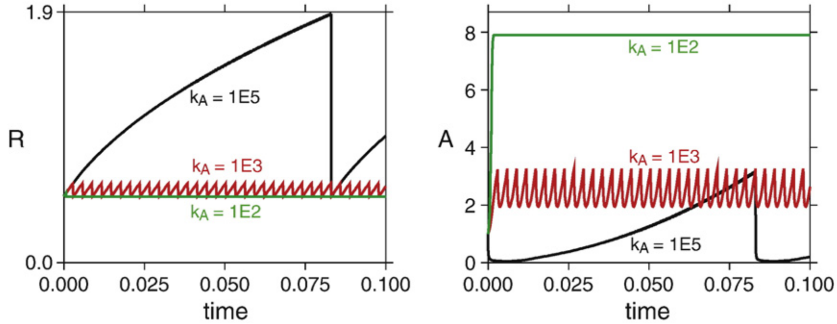

Fig. 5. Results from the drip instability model demonstrating long term stagnation of the cylinder ($\hat{k}_A=10^5$ black curves), episodic detachment $\hat{k}_A=10^3$ (red curves), and continuous detachment/delamination ($\hat{k}_A=10^2$ green curves). The parameters displayed are cylinder radius R and fineness value in the detachment region A. The value of damage fraction is $f_A=5\cdot10^{-5}$ and the three different healing rates (k_A) are identified in the legend. The time scale and healing rate values presented have all been adjusted to the diffusive scale used in the convection experiments. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

this set of parameters the cylinder must grow to provide enough negative buoyancy to weaken the detachment region via damage and thereby overcome the resistance to delamination. After the cylinder is released the fineness in the detachment region decreases (i.e., the damaged medium heals) until the weight of the cylinder damages the detachment region at a greater rate than it is being healed. This series of oscillations continues indefinitely as long as there is a mass source to feed the cylinder. Finally, the smallest value of healing rate ($\hat{k}_A=10^2$ green curve) induces substantially different behavior. The fineness in the detachment region rapidly increases to its steady-state value and remains unchanged throughout the calculation. In this mode the fineness reaches a critical value and the detachment region remains sufficiently and permanently weak to allow for steady, unimpeded detachment. The cylinder radius also remains unchanged from its starting value, implying that the system is undergoing continuous and steady delamination/detachment events, which is similar to subduction in the stable plate like behavior of convection simulations. Although the cylinder model has many simplifications, it is able to demonstrate a transition in delamination/detachment modes that is similar to the transition in convective behavior from episodic to stable plate like demonstrated by the full numerical convection experiments with a damageable lithosphere.

Comparing the results of the cylinder model and the convection experiments over a range of damage and healing rates we find similar transitions in fineness evolution for both models (Fig. 6). In order to capture the transition in convective behavior we define a new variable called the fineness rate, this variable is the product of the range of fineness values and the frequency of oscillation i.e., $(A_{max}-A_{min})\cdot\nu$, where ν= frequency of oscillation. At small and intermediate $f_A/\hat{k}_A$ the values of fineness from the cylinder model oscillate between A_{max} and A_{min} (see Fig. 5), but at the lower end values ($f_A/\hat{k}_A<10^{-8.5}$) the period of oscillation is long enough (hence fineness rate is small) that we associate this result with stagnant lid behavior similar to that in the convection experiments. The peak in fineness rate for both the convection experiments and the cylinder model occurs for $f_A/\hat{k}$ between 10^{-8} and 10^{-7} (Fig. 6); the increase in fineness rate seen by increasing $f_A/\hat{k}_A$ is predominantly due to an increasing frequency of oscillation, ν (see Fig. 5). At larger $f_A/\hat{k}$ ($>10^{-7}$), both the cylinder model and convection data exhibit no range of fineness (i.e., $A_{max}=A_{min}$) and hence negligible fineness rate, we associate this with the stable plate like regime since subduction occurs unimpeded and continuously due to the large fineness and hence low viscosity. The results from the cylinder model further suggest that the transition in convective behavior and the frequency of subduction demonstrated by the convection simulations are controlled by the interaction of damage and healing in initiating subduction.

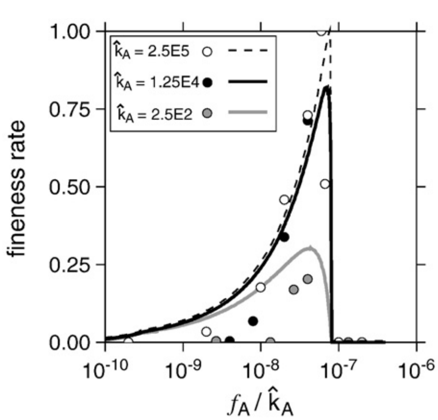

Fig. 6. A comparison of fineness rate for the convection experiments and the cylinder model. The plot compares the fineness rate results as a function of $f_A/\hat{k}_A$ for the cylinder model (colored lines) and the convection simulations (colored dots). The values of fineness rate for both the convection experiments and the cylinder model have each been normalized by their respective maximum value of fineness rate at $\hat{k}_A=2.5\cdot10^5$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

5. Discussion

5.1. Feasibility of hypothesis

Our hypothesis is that the differences in convective style between Earth and Venus are related to surface temperature and climatic variations between the planets, since climate influences the damage parameters (f_A,$\hat{k}_A$) that control the mode of convection on a planet. The surface temperature of Venus is approximately 400 K higher than on Earth (Seiff, 1983), although the mantle temperature difference will be less owing to the temperature dependence of viscosity. The difference in mantle temperature drop between Earth and Venus can be estimated by comparing their global heat flux (Q); we assume that

$$Q_v=\beta Q_e, \tag{10}$$

where β is of order one (given the planets similar sizes, although the higher surface temperature Venus might suggest β is modestly less than one) and the subscripts e and v stand for Earth and Venus, respectively. For both planets $Q=(k\Delta T/d)Nu$, where the Nusselt number (Nu) goes as

$$Nu\sim Ra^{1/3}=\left(\frac{\rho\alpha g d^3}{\kappa}\right)^{1/3}\left(\frac{\Delta T}{\mu(T)}\right)^{1/3}, \tag{11}$$

and T is the mantle temperature. Using Eq. (11) in (10) and assuming that κ, α, g, d, and ρ are the same for the two planets we arrive at the following equation for mean lithospheric temperature difference between Earth and Venus

$$\beta\frac{\Delta T_e^{4/3}}{\exp(E/(3RT_e))} = \frac{\Delta T_v^{4/3}}{\exp(E/(3RT_v))}, \quad (12)$$

where E is the activation energy for viscosity (we assume that $E\sim300$ kJ/mol; Karato and Wu, 1993). The mantle temperature $T_{e,v}$ is $T^s_{e,v}+\Delta T_{e,v}$, where T^s is the surface temperature, and the lithospheric temperature is then $T^l_{e,v}$ $T^s_{e,v}$=$T_{e,v}+\Delta T_{e,v}/2$. Since the surface temperature for Earth and Venus and the approximate temperature drop across Earth's mantle is known we can then estimate ΔT_v. Assuming the heat flux constant β is approximately one, the difference in average lithospheric temperature $\delta T_l\,(=T^l_v-T^l_e)$ between Venus and Earth is about 200 K, similar to previous estimates (Nimmo and McKenzie, 1998). The Nusselt–Rayleigh number relationship for a planet is still controversial (e.g. Korenaga, 2003, 2006). The above relationship has been shown to be appropriate for both mobile lid convection (Gurnis, 1989; Moresi and Solomatov, 1998) and stagnant-lid convection at steady state (Davaille and Jaupart, 1993; Solomatov, 1995), therefore we employ this relationship since both planets are typically in either of these convective modes.

The evolution of grain size involves a competition between damage and healing, and each is sensitive to variations in temperature. The rate of healing during grain growth is $k_A=k_o\exp(-H/(RT))$ (Karato, 1989), where k_o is the reference healing rate, H is an activation enthalpy, R is the gas constant, and T is the temperature. Assuming that the material parameters for grain growth are the same for Earth and Venus, the ratio of Venus's healing rate (k_{A_v}) to Earth's healing rate (k_{A_e}) in the lithosphere would be

$$\frac{k_{A_v}}{k_{A_e}} = \exp\left(-\frac{H}{R}\left(\frac{T^l_e-T^l_v}{T^l_eT^l_v}\right)\right). \quad (13)$$

We choose an activation enthalpy for grain growth in pure olivine ($H=2\cdot10^5$J/mol K; Karato, 1989), although in a mantle-like mineral assemblage this activation energy is difficult to quantify (Solomatov et al., 2002; Ohuchi and Nakamura, 2006). The lithospheric healing rate for a planet with a given surface temperature $T^s>T^s_e$ is larger than Earth's healing rate (Fig. 7a). At Venusian surface temperatures the lithospheric healing rate is about two orders of magnitude larger than Earth's lithospheric healing rate. Deformational work (Ψ) is equal to τ^2/μ, and both viscosity (μ) and stress (τ) are sensitive to temperature variations. The viscosity has an Arrhenius type sensitivity to temperature as used in Eq. (12), and $\tau=\mu u/d$, where u is the convective velocity and $u\sim Ra^{2/3}$ from scaling analyses for convection. By isolating the temperature dependence of the Rayleigh number as $\sim\Delta T/\mu$ (see Eq. (11) above) we arrive at

$$\Psi\sim\mu_p\left(\frac{u}{d}\right)^2\sim c\mu_p\frac{\Delta T^{4/3}}{\mu^{4/3}} \quad (14)$$

where μ_p is the lithospheric viscosity, μ is the mantle viscosity, c is a constant, and this leads to

$$\frac{\Psi_v}{\Psi_e} = \frac{\mu_{p_v}}{\mu_{p_e}}\left(\frac{\Delta T_v}{\Delta T_e}\right)^{4/3}\left(\frac{\mu(T_e)}{\mu(T_v)}\right)^{4/3}. \quad (15)$$

For larger surface temperature, both the temperature drop across the lithosphere and viscosity decrease, thus the deformational work remains a very weak function of temperature and almost equal to the value on Earth even out to Venusian surface temperatures (Fig. 7b). The ratio of damage to healing is therefore about two to three orders of magnitude lower on Venus than on Earth (Fig. 7c). Assuming that Earth is in the stable plate-like regime of Fig. 2, a reduction in the damage to healing ratio characteristic of Venus could readily put Venus into the episodic or stagnant lid convective regime. Without specifically knowing f_A it is difficult to know in which regime Venus would reside. The above analysis though explains the differences in tectonic style of Venus and Earth in terms of variations in damage and healing brought about by differences in surface temperature between the planets. If the surface temperature on either planet were to rise significantly higher (i.e.~1000 K), then both planets would likely undergo subduction since the viscosity difference between the lithosphere and mantle would become negligible (given the Arrhenius relationship for temperature dependent viscosity) and the system would undergo isoviscous convection.

5.2. Model for plate tectonic formation

The above analysis suggests criteria for the development of plate tectonics on a planetary body. Venus is most distinct from Earth in that it lacks free surface water, has an atmosphere mainly composed of CO_2, and hence high surface temperatures. The role of water in facilitating plate tectonics by hydrating the lithosphere is a common theme in many plate generation studies (Lenardic and Kaula, 1994; Bercovici, 1998; Moresi and Solomatov, 1998); however observations suggest that the Earth's lithosphere is dry (Evans et al., 2005), hence the lithospheric hydration state of Earth and Venus are similar. It is

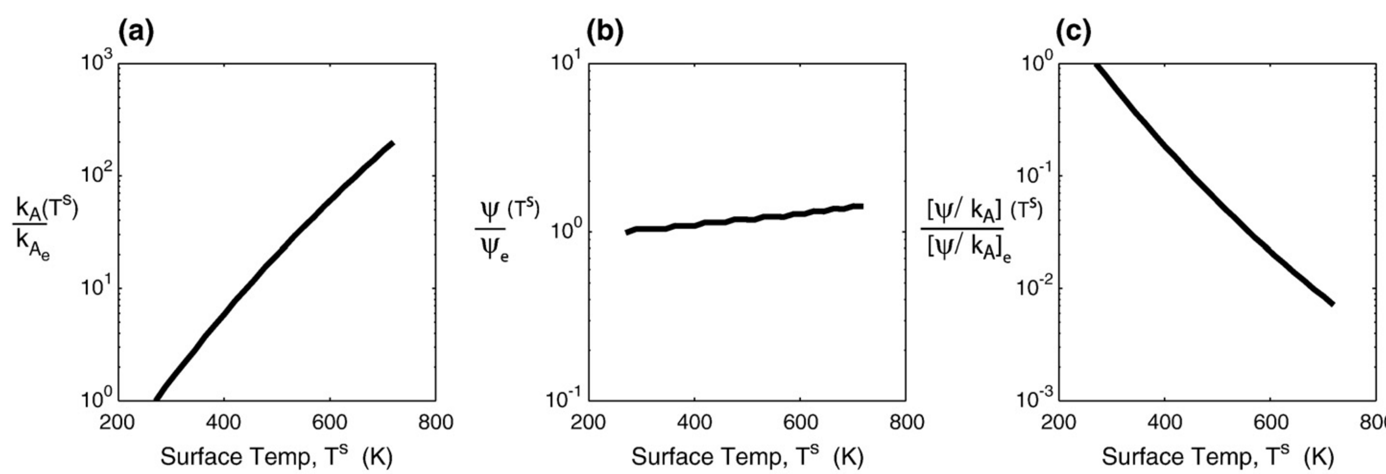

Fig. 7. The variations in lithospheric grain growth healing rate (normalized by Earth's value) as a function of surface temperature (a), the variation in deformational work (normalized by Earth's value) as a function of surface temperature (b), and the variation in damage to healing rates (normalized by Earth's value) as a function of surface temperature (c). An increase in surface temperature leads to an increase in both the lithospheric temperature and healing rate, while deformational work remains insensitive to surface temperature rise. The ratio of damage to healing therefore decreases as surface temperature increases.

well known that Earth's ocean is a significant reservoir for carbon, and its presence allows the formation of a carbon cycle that moderates the amount of CO_2 in the atmosphere and subsequently surface temperatures (Berner, 2004). Venus on the other hand has little to no free surface water, and correspondingly has a large amount of CO_2 in the atmosphere which leads to the significantly higher surface temperatures. The corresponding increase in surface temperature going from Earth to Venus leads to higher average lithospheric temperatures, and following the analysis described above leads to a reduction in the damage to healing ratio and hence larger grain sizes in the lithosphere. According to our analysis this effect may place Venus in an episodic or stagnant-lid mode of convection. Therefore free surface water potentially allows for plate tectonics through regulation of climate, and not necessarily through a direct rheological effect such as weakening of faults (Moresi and Solomatov, 1998). While our study shares similar views on the importance of the interaction between climate and convection as the recent study by Lenardic et al. (2008), the two models are quite different in operation. Lenardic et al. (2008) suggest that increases in surface temperature leads to a decrease in convective stress below the lithospheric yield, thereby not allowing convection to “break” the lithosphere and cause subduction. On the contrary, our model suggests that the larger surface temperature on Venus causes an increase in the healing rate that leads to a moderation or obstruction of localization necessary for plate boundary formation and subduction of the lithosphere. Moreover, the two models likely predict different tectonic responses to climate change. In our model, tectonic variations are controlled by lithospheric temperature which dictates the healing rate, hence the timescale for response to climate change is the thermal diffusion timescale for the lithosphere (~100 Myr). In the Lenardic et al. (2008) hypothesis, changing convective stresses necessitates changing the overall mantle temperature, therefore the diffusion timescale governing the response to climate change is significantly longer (~Gyr). The role of free surface water in moderating climate and surface temperature as suggested above accounts for a feasible weakening mechanism in the brittle–ductile and ductile portion of the lithosphere and also includes one of the primary differences between Earth and Venus, namely free surface water. Our model for the formation of plate tectonics allows for an explanation of this planetary dichotomy that includes free surface water but does not necessitate hydrating a lithosphere that is observed to be dry.

6. Summary and conclusion

The range of observed planetary behaviors within our solar system necessitates an explanation, especially the difference in tectonic behavior of Venus and Earth given their abundant similarities (Schubert et al., 2001). The damage rheology presented in this paper attempts to describe the evolution of grain size by allowing for grain size reduction via deformational work input and grain growth via curvature-driven coarsening (Bercovici and Ricard, 2005; Landuyt et al., 2008). While the model for grain size evolution we assume is rather simple, recent work has suggested that a theoretical approach employing conservation of energy is successful at reproducing experimental results (Austin and Evans, 2007). The idea that grain size mechanisms are responsible for controlling the strength of faults is not a new idea since reduced grain sizes and grain size sensitive creep are not uncommon in shear zones (White et al., 1980; Jaroslow et al., 1996; Kameyama et al., 1997; Jin et al., 1998; Bercovici and Karato, 2003; Warren and Hirth, 2006). Over a large range of parameters associated with grain size evolution model we employ, we find that relatively small changes in deformational work input and healing rate can account for stagnant lid, episodic and stable plate-like states. Calculations of the variation in lithospheric healing rate and deformational work input for both Earth and Venus suggest that surface temperature variations between the two planets can explain the different modes of convection exhibited.

Our proposed model of plate generation suggests an important role for surface water that is very different from previous hypotheses where water acts to directly cause rheological weakening (Tozer, 1985; Lenardic and Kaula, 1994; Korenaga, 2007). The role of water in our model causes weakening by moderating surface temperatures and subsequently allowing localization to become more efficacious. Therefore our model allows an explanation of the tectonic differences between Earth and Venus that also fits current geophysical observations (e.g. similar hydration state for both Venus and Earth's lithosphere).

Acknowledgements

We thank Yanick Ricard for helpful comments. We also thank Mark Jellinek for a thorough review and suggesting the difference in timescale responses to climatic forces between Lenardic et al. (2008) and our hypothesis. Reviews by Jun Korenaga, and two anonymous reviewers helped to clarify and improve the manuscript. Support was provided by the National Science Foundation (NSF, grant EAR-0537599).

References

Austin, N., Evans, B., 2007. Paleowattmeters: a scaling relation for dynamically recrystallized grain size. Geology 35 (4), 343–346.
Beaumont, C., 1976. The evolution of sedimentary basins on a viscoelastic lithosphere. Geophys. J.R. Astron. Soc. 55, 471–497.
Bercovici, D., 1993. A simple model of plate generation from mantle flow. Geophys. J. Int. 114, 635–650.
Bercovici, D., 1995. A source-sink model of the generation of plate tectonics from non-Newtonian mantle flow. J. Geophys. Res. 100, 2013–2030.
Bercovici, D., 1998. Generation of plate tectonics from lithosphere–mantle flow and void–volatile self-lubrication. Earth Planet. Sci. Lett. 154, 139–151.
Bercovici, D., 2003. The generation of plate tectonics from mantle convection. Earth Planet. Sci. Lett. 205, 107–121.
Bercovici, D., Karato, S., 2003. Theoretical analysis of shear localization in the lithosphere. In: Karato, S., Wenk, H. (Eds.), Reviews in Mineralogy and Geochemistry: Plastic Deformation of Minerals and Rocks, vol. 51. Min. Soc. Am., Washington, DC, pp. 387–420. Ch. 13.
Bercovici, D., Ricard, Y., 2003. Energetics of a two-phase model of lithospheric damage, shear localization and plate-boundary formation. Geophys. J. Int. 152, 581–596.
Bercovici, D., Ricard, Y., 2005. Tectonic plate generation and two-phase damage: void growth versus grain size reduction. J. Geophys. Res. 110, 1–18.
Bercovici, D., Ricard, Y., Richards, M., 2000. The relation between mantle dynamics and plate tectonics: a primer. In: Richards, M.A., Gordon, R., van der Hilst, R. (Eds.), History and Dynamics of Global Plate Motions, Geophys. Monogr. Ser., vol. 121. Am. Geophys. Union, Washington, DC, pp. 5–46.
Bercovici, D., Ricard, Y., Schubert, G., 2001a. A two-phase model of compaction and damage, 1. General theory. J. Geophys. Res. 106 (B5), 8887–8906.
Bercovici, D., Ricard, Y., Schubert, G., 2001b. A two-phase model of compaction and damage, 3. Applications to shear localization and plate boundary formation. J. Geophys. Res. 106 (B5), 8925–8940.
Berner, R.A., 2004. The Phanerozoic Carbon Cycle. Oxford University Press.
Cawood, P.A., Kroner, A., Pisarevsky, S., 2006. Precambrian plate tectonics: criteria and evidence. GSA Today 16 (7), 4–11.
Christensen, U., Harder, H., 1991. Three-dimensional convection with variable viscosity. Geophys. J. Int. 104, 213–226.
Davaille, A., Jaupart, C., 1993. Transient high-rayleigh-number thermal convection with large viscosity variations. J. Fluid Mech. 254, 141–166.
Evans, B., Renner, J., Hirth, G., 2001. A few remarks on the kinetics of static grain growth in rocks. Int. J. Earth Sci. 90, 88–103.
Evans, R., Hirth, G., Baba, K., Forsyth, D., Chave, A., Mackie, R., 2005. Geophysical evidence from the melt area for compositional controls on oceanic plates. Nature 391, 249–252.
Gurnis, M., 1989. A reassessment of the heat transport by variable viscosity convection with plates and lids. Geophys. Res. Lett. 16, 179–182.
Hirth, G., Kohlstedt, D., 2003. Rheology of the upper mantle and the mantle wedge: a views from the experimentalists. In: Eiler, J. (Ed.), Inside the Subduction Factory, Geophys. Monogr. Ser., vol. 138. Am. Geophys. Union, Washington, DC, pp. 83–105.
Jaroslow, G., Hirth, G., Dick, H., 1996. Abyssal peridotite mylonites: implications for grain-size sensitive flow and strain localization in the oceanic lithosphere. Tectonophysics 256, 17–37.
Jin, D., Karato, S., Obata, M., 1998. Mechanisms of shear localization in the continental lithosphere: inference from the deformation microstructures of peridotites from the Ivrea zone, northwestern Italy. J. Struct. Geol. 20, 195–209.
Kameyama, M., Yuen, D., Fujimoto, H., 1997. The interaction of viscous heating with grain-size dependent rheology in the formation of localized slip zones. Geophys. Res. Lett. 24, 2523–2526.
Karato, S., 1989. Grain growth kinetics in olivine aggregates. Tectonophysics 20 168, 255–273.
Karato, S., Wu, P., 1993. Rheology of the upper mantle: a synthesis. Science 260, 771–778.

Kaula, W., 1984. Tectonic contrasts between Earth and Venus. Geophys. Res. Lett. 11, 35–37.
Kaula, W., Phillips, R., 1981. Quantitative tests for plate tectonics on Venus. Geophys. Res. Lett. 8, 1187–1190.
Kohlstedt, D., Evans, B., Mackwell, S., 1995. Strength of the lithosphere: constraints imposed by laboratory experiments. J. Geophys. Res. 100 (17), 587–17,602.
Korenaga, J., 2003. Energetics of mantle convection and the fate of fossil heat. Geophys. Res. Lett., 30 (8), 1437.
Korenaga, J., 2006. Archean geodynamics and the thermal evolution of Earth. In: Benn, K., Mareschal, J.-C., Condie, K. (Eds.), Archean Geodynamics and Environments, Geophys. Monogr. Ser., vol. 164. Am. Geophys. Union, Washington, DC, pp. 7–32.
Korenaga, J., 2007. Thermal cracking and the deep hydration of oceanic lithosphere: a key to the generation of plate tectonics? J. Geophys. Res. 112, B05408. doi:10.1029/2006JB004502.
Landuyt, W., Bercovici, D., Ricard, Y., 2008. Two-phase damage theory and plate generation in a model of mantle convection. Geophys. J. Int. 174, 1065–1080.
Lenardic, A., Kaula, W., 1994. Self-lubricated mantle convection: two dimensional models. Geophys. Res. Lett. 21, 1707–1710.
Lenardic, A., Jellinek, A., Moresi, L.-N., 2008. A climate change induced transition in the tectonic style of a terrestrial planet. Earth Planet. Sci. Lett. 271, 34–42.
Moresi, L., Solomatov, V., 1998. Mantle convection with a brittle lithosphere: thoughts on the global tectonic style of the Earth and Venus. Geophys. J. Int. 133, 669–682.
Nimmo, F., McKenzie, D., 1998. Volcanism and tectonics on Venus. Ann. Rev. Earth Planet. Sci. 26, 23–51.
Ohuchi, T., Nakamura, M., 2006. Grain growth in the forsterite-diopside system. Phys. Earth. Planet. Inter. 160, 1–21.
O'Neill, C., Jellinek, A., Lenardic, A., 2007. Conditions for the onset of plate tectonics on terrestrial planets and moons. Earth Planet. Sci. Lett. 261, 20–32.
Phillips, R., Bullock, M., Hauck I., S.A., 2001. Climate and interior coupled evolution on Venus. Geophys. Res. Lett. 28 (9), 1779–1782.
Regenauer-Lieb, K., Yuen, D., Branlund, J., 2001. Initiation of subduction: criticality by addition of water. Science 294, 578–580.
Ribe, N., 1992. The dynamics of thin shells with variable viscosity and the origin of toroidal flow in the mantle. Geophys. J. Int., 110, 537–552.
Ricard, Y., Bercovici, D., 2003. Two-phase damage theory and crustal rock failure: the theoretical 'void' limit, and the prediction of experimental data. Geophys. J. Int. 155, 1057–1064.
Ricard, Y., Bercovici, D., in press. A continuum theory of grainsize evolution and damage. J. Geophys, Res.
Ricard, Y., Bercovici, D., Schubert, G., 2001. A two-phase model of compaction and damage, 2, applications to compaction, deformation, and the role of interfacial surface tension. J. Geophys, Res. 106 (B5), 8907–8924.
Sandwell, D., Schubert, G., 1992. Evidence for retrograde lithospheric subduction on Venus. Science 257, 776-770.
Schaber, G., Strom, R., Moore, H., Soberblom, L., Kirk, R., Chadwick, D., Dawson, D., Gaddis, L., Boyce, J., Russell, J., 1992. Geology and distribution of impact craters on Venus: what are they telling us? J. Geophys. Res. 97, 13257–13301.
Schubert, G., Turcotte, D., Olson, P., 2001. Mantle Convection in the Earth and Planets. Cambridge Univ. Press.
Seiff, A., 1983. Thermal structure of the atmosphere of Venus. In: Hunten, D., Colin, L., Donahue, T., Moroz, V. (Eds.), Venus. University of Arizona Press, Tucson, pp. 215–279.
Solomatov, V., 1995. Scaling of temperature dependent and stress dependent viscosity convection. Phys. Fluids 7, 266–274.
Solomatov, V., Moresi, L., 1995. Stagnant lid convection on Venus. J. Geophys. Res. 101, 4737–4753.
Solomatov, V., El-Khozondar, R., Tikare, V., 2002. Grain size in the lower mantle: constraints from numerical modeling of grain growth in two-phase systems. Phys. Earth Planet. Int. 129, 265–282.
Solomon, S., Bullock, M., Grinspoon, D., 1999. Climate change as a regulator of tectonics on Venus. Science 286, 87–90.
Strom, R., Schraber, G., Dawson, D., 1994. The global resurfacing of Venus. J. Geophys. Res. 99, 10899–10926.
Tackley, P., 2000a. Mantle convection and plate tectonics: toward and integrated physical and chemical theory. Science 288, 2002–2007.
Tackley, P., 2000b. Self-consistent generation of tectonic plates in time dependent, three-dimensional mantle convection simulations, 1. Pseudoplastic yielding. Geochem. Geophys. Geosystems (G^3) 1 2000GC000036.
Tozer, D., 1985. Heat transfer and planetary evolution. Geophys. Surv. 7, 213–246.
Turcotte, D., 1993. An episodic hypothesis for Venusian tectonics. J. Geophys. Res. 98, 17061–17068.
Warren, J., Hirth, G., 2006. Grain size sensitive deformation mechanisms in naturally deformed peridotites. Earth Planet. Sci. Lett. 248, 438–450.
Weinstein, S., Olson, P., 1992. Thermal convection with non-Newtonian plates. Geophys. J. Int. 111, 515–530.
White, S., Burrows, S., Shaw, N., Humphreys, F., 1980. On mylonites in ductile shear zones. J. Struct. Geol. 2, 155–189.