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Collapse of passive margins by lithospheric damage and plunging grain size

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ABSTRACT

The collapse of passive margins has been proposed as a possible mechanism for the spontaneous initiation of subduction. In order for a new trench to form at the junction between oceanic and continental plates, the cold and stiff oceanic lithosphere must be weakened sufficiently to deform at tectonic rates. Such rates are especially hard to attain in the cold ductile portion of the lithosphere, at which the mantle lithosphere reaches peak strength. The amount of weakening required for the lithosphere to deform in this tectonic setting is dictated by the available stress. Stress in a cooling passive margin increases with time (e.g., due to ridge push), and is augmented by stresses present in the lithosphere at the onset of rifting (e.g., due to drag from underlying mantle flow). Increasing stress has the potential to weaken the ductile portion of the lithosphere by dislocation creep, or by decreasing grain size in conjunction with a grain-size sensitive rheology like diffusion creep. While the increasing stress acts to weaken the lithosphere, the decreasing temperature acts to stiffen it, and the dominance of one effect or the other determines whether the margin might weaken and collapse. Here, we present a model of the thermal and mechanical evolution of a passive margin, wherein we predict formation of a weak shear zone that spans a significant depth-range of the ductile portion of the lithosphere. Stiffening due to cooling is offset by weakening due to grain size reduction, driven by the combination of imposed stresses and grain damage. Weakening via grain damage is modest when ridge push is the only source of stress in the lithosphere, making the collapse of a passive margin unlikely in this scenario. However, adding even a small stress-contribution from mantle drag results in damage and weakening of a significantly larger portion of the lithosphere. We posit that rapid grain size reduction in the ductile portion of the lithosphere can enable, or at least significantly facilitate, the collapse of a passive margin and initiate a new subduction zone. We use this model to estimate the conditions for passive margin collapse for modern and ancient Earth, as well as for Venus.

1. Introduction

Knowing how and why plate tectonics exists is critical for understanding Earth's surface and interior evolution, as well as that of other planets. The main driving force for plate motion appears to come from the negative buoyancy of subducting slabs, as evident in the correlation between the fraction of subduction zone boundary per plate, and the plate's velocity (Forsyth and Uyeda, 1975). However, the origin of subduction, and specifically the mechanism for its initiation remain enigmatic, because as the lithosphere becomes colder, denser and more likely to sink, it also stiffens and requires more force to deform and founder into the mantle (Cloetingh et al., 1989; Solomatov, 1995).

A large proportion of subduction zones that are active today initiated during the Cenozoic, which indicates that subduction initiation is a commonly occurring process on modern Earth (Stern, 2004). Moreover, it is reasonable to assume that spontaneous subduction occurred at some point in the Earth's history, as part of the initiation of global plate tectonics. It is worth noting that there exist models for the onset of plate tectonics through other means, such as the lithospheric collapse at an active transform plate boundary (Casey and Dewey, 1984; Stern, 2004), formation of new plate boundaries by accumulation of lithospheric damage from proto-subduction (Bercovici and Ricard, 2014), or the plume-induced subduction initiation (Gerya et al., 2015). We expect that as the physical conditions on an evolving Earth change (e.g., its mantle and surface temperature, continental cover, convective lengthscale, etc.), so does its style of plate tectonics, sub-

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duction and subduction initiation. Whether it is possible to spontaneously form a new trench at modern Earth conditions, or if modern subduction relies on the tectonic features inherited from 1–3 billions of years of ongoing plate tectonics, is currently not know.

The coincidence of many currently active subduction zones with the continental margins prompts the hypothesis that spontaneous subduction initiation is caused by the collapse of passive margins (e.g., Stern, 2004), which is also invoked as the mechanism for ocean closure in the Wilson cycle (Wilson, 1968).

As new oceanic lithosphere forms after continental rifting, it cools and the stress at its bounding passive margin increases due to ridge push (Dahlen, 1981), thermal contraction (Korenaga, 2007), tensile stresses at the junction between the oceanic lithosphere and the continent (Kemp and Stevenson, 1996), flexure under sedimentary loads (Cloetingh et al., 1989; Regenauer-Lieb et al., 2001), and possibly the stress due to drag from underlying mantle flow (Gurnis, 1988; Lenardic et al., 2011). Imposed and/or increasing stress has the potential to weaken the ductile portion of the lithosphere by dislocation creep, or by decreasing grain size in conjunction with a grain-size sensitive rheology like diffusion creep. The nonlinear coupling of viscosity to stress or to grain size can induce a self-weakening feedback (Montési and Hirth, 2003; Bercovici and Ricard, 2005; Rozel et al., 2011; Bercovici and Ricard, 2012), which manifests itself as a localized shear zone. However, this weakening is opposed by the thermally induced stiffening during lithospheric cooling, and the dominance of one effect or the other determines whether or not the margin might weaken and collapse, possibly allowing for the plate to subduct and form a new trench.

Here, we present a model of the thermal and mechanical evolution of a passive margin, wherein we predict formation of a weak shear zone that spans a significant depth-range of the nominally cold and strong ductile portion of the lithosphere. The rates of cooling, grain growth and grain damage determine the rheological response and weakening of the margin through time. We posit that grain size reduction by two-phase grain-damage in the ductile portion of the lithosphere can enable, or at least significantly facilitate, the collapse of a passive margin. Applying these results to the expected conditions on early and modern Earth sheds light on when in Earth's history the conditions may have been optimal for the initiation of subduction. For the thermal conditions representative of Venus, our model predicts that the rate of grain size reduction is too slow to offset thermal stiffening, precluding the formation of localized plate boundaries via the collapse of passive margins on that planet.

2. Stress and temperature evolution model

2.1. Stiffening due to cooling and how to offset it

As shown by Solomatov (1995), after Christensen (1984), cooling and thermal stiffening of the lithosphere should preclude plate tectonics and initiation of subduction. Thus, as in all problems of plate generation (Bercovici et al., 2015b), our goal is to understand what mechanisms and under which conditions offset thermal stiffening.

We limit our analysis to the depth-range of the passive margin where viscous deformation is thought to dominate, which is, for 50 Myr old sea-floor, roughly from 10 to 80 km. This relatively cold and ductile region is considered to be the strongest part of the lithosphere (e.g., Kohlstedt et al., 1995) and is therefore a bottleneck for strain localization and plate boundary formation.

We assume that lithospheric rocks have a composite rheology, whereby the deformation can be accommodated by diffusion and dislocation creep:

$$\dot{e} = A\tau^n + \frac{B}{r^m}\tau \quad (1)$$

where $\dot{e}$ and τ are the square roots of the second invariants of the strain rate and stress tensors, respectively, n and m are the stress and grain size exponents, respectively (see Table 1), and r is a quantity proportional to grain size (see Section 3). The dislocation and diffusion creep compliances A and B, respectively, are temperature-dependent and follow an Arrhenius-type relation (see Table 1). The effect of pressure across the depth of the lithosphere is assumed to be significantly less than that of temperature and is therefore not considered, for simplicity.

When the lithosphere predominantly deforms by dislocation creep, its effective viscosity is

$$\mu_{\text{disl}} = \frac{1}{2A\tau^{n-1}} \quad (2)$$

In diffusion creep, the effective viscosity is

$$\mu_{\text{diff}} = \frac{r^m}{2B} \quad (3)$$

If the lithosphere cools from the upper mantle temperature of 1500 K to the temperature of 800 K at the top of the ductile portion of the lithosphere ($\sim$ 10 km depth), the dislocation creep viscosity would increase by a factor of 10^{16} (see Table 1 for relevant rheological properties). This thermal stiffening can be offset by an increase in stress by a factor of 10^8.

For the same temperature drop (from 1500 K to 800 K), the diffusion creep viscosity would increase by a factor of 10^9 (see Table 1), which can be offset by a decrease in grain size by a factor of 10^{-3}.

Observational and experimental data, as well as theoretical models, suggest that lower temperature, or shallower depth, is associated with higher stress (see Section 2.2) and smaller grain size (Linckens et al., 2015; Mulyukova and Bercovici, 2017). Both of these effects act to lower the viscosity and counteract the effect of thermal stiffening. Moreover, an increase in stress acts to lower the viscosity both in dislocation creep, as outlined above, and in diffusion creep, due to anti-correlation between grain size and stress (see Section 3).

While the above analysis demonstrates that grain size reduction in diffusion creep, or stress increase in dislocation creep can offset thermally induced stiffening, it remains to be shown if these mechanisms are efficient enough at the conditions typical of passive margins to significantly weaken the lithosphere, and subsequently trigger subduction. In this study, we demonstrate that weakening of the lithosphere by grain damage can reduce its viscosity to values below that of the underlying upper mantle and lead to, or at least facilitate, the collapse of the passive margin.

2.2. Sources of stress

2.2.1. Ridge push

As oceanic lithosphere moves away from a spreading center it cools and undergoes internal deformation and subsidence relative to its original position at the ridge. This deformation is driven by a vertical adjustment of loads as the system evolves towards isostatic equilibrium. After isostasy is reached, there remains a deviatoric stress, known as ridge push, which compensates for the pressure head associated with the seafloor topography (see Turcotte and Schubert, 2014, pp. 281–282). Ridge push stress τ_{rp} is compressive in the horizontal direction (defined so that the horizontal normal stress $\tau_{xx} > 0$) and tensile in the vertical direction ($\tau_{zz} < 0$), where $\tau_{\text{rp}} = \tau_{xx} = -\tau_{zz}$, while shear stress-components are assumed to be zero. The ridge push stress is given by Dahlen (1981):