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Supply rate of continental materials to the deep mantle through subduction channels

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ABSTRACT

Geological studies have revealed that continental materials subduct from the Earth's surface via the following three mechanisms: tectonic erosion, sediment subduction, and direct subduction of immature oceanic arcs. Then, the continental materials are transported through subduction channels that are located between subducting slabs and mantle wedges. However, the depth that a subduction channel reaches and the magnitude of the flux of subducted materials at that depth are not clear. Here, in order to estimate the supply rate of continental materials to the deep mantle, we have conducted a numerical simulation of a subduction channel based on the finite difference method. We have found that a sustainable thickness of the channel in the deep mantle is ~2–3 km and its corresponding flux of continental materials integrated over the length of the current subduction zones is 2.2 km^3/yr. These results indicate that almost all of the continental material that is subducted through the channel is capable of reaching the depth of the mantle transition zone. The total amount of continental materials conveyed to the deep mantle over 4 Gyr is estimated to be about 10^{10} km^3, which is greater than the volume of the present continental crust at the surface of the Earth.

1. Introduction

Earth is the only planet with granite and continents (Campbell and Taylor, 1983). Continental materials contain a large amount of incompatible and radiogenic elements, which may affect terrestrial thermal history and chemical evolution, as well as the Earth's surface environment. Continental growth is, therefore, essential for understanding the Earth's evolution.

It has been believed that continental crust monotonically increases due to its buoyancy during magmatism (McCulloch and Bennett, 1994). On the other hand, the growth rate of the crust is considered to be highly dependent on the vigor of mantle convection. Although a large amount of the continental crust should have been produced during the Archean because of the high potential temperature in the mantle (Armstrong, 1991; Belousova et al., 2010), the amount of existing Archean granite is relatively small and a considerable amount could be missing. Moreover, recent geological studies have suggested that a significant amount of granitic crust has been lost from the surface due to crustal delamination (~1.1 km^3/yr) (Clift et al., 2009) and continental collision (~0.4–0.7 km^3/yr) (Clift et al., 2009; Stern and Scholl, 2010) along with losses at the ocean-continent subduction zone (~2.5–3 km^3/yr) (Clift et al., 2009; Stern and Scholl, 2010). Meanwhile, the addition of continental crust is estimated to be 3.2–5.0 km^3/yr (Clift et al., 2009) or ~3.2 km^3/yr (Stern and Scholl, 2010), which is mainly controlled by arc magmatism and oceanic plateaus. Therefore losses and additions of the continental crust are estimated to be nearly balanced.

At the ocean-continent subduction zone, where the losses of the granitic crust are greatest, the following three mechanisms for the subduction of continental materials are suggested (see Yamamoto et al. (2009b) for review): tectonic erosion (Von Huene and Scholl, 1991), sediment-trapped subduction, and direct subduction of immature oceanic arcs on oceanic micro plates, which are found, for example, in the western Pacific (Yamamoto et al., 2009a). In these processes, the subducting granitic materials are conveyed through subduction channels that have a thickness at the Earth's surface of less than 2–3 km (Clift and Vannucchi, 2004; Collot et al., 2011; Moore et al., 2007). These processes also control the trace-element and isotopic composition of the mantle. The following two suggestions given by several geochemical studies coincide with the subduction of continental material: recycling of continental materials which have been subducted into the deep mantle (e.g. Hofmann, 1997) and the reservoir of continental materials in the mantle which has been effectively isolated for 2–3 Gyr (Murphy et al., 2002). Hence, in order to understand continental growth and chemical evolution of the mantle, it is important to consider how continental materials have sunk into the mantle and how much they have subducted.

On the other hand, studies on the elastic properties of continental materials such as Archean granite have found a gravitationally stable region ranging from 270 to 800 km in depth (Irifune et al., 1994; Kawai and Tsuchiya, 2009; Kawai et al., 2009, 2013). This implies the possibility of a reservoir of continental material in the mantle transition zone (Kawai et al., 2009, 2010, 2013). Therefore, it is

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essential to consider how buoyant continental materials are carried to 270 km depth where coesite undergoes a phase transition to stishovite and continental materials become denser than the surrounding mantle.

Previous studies on the subduction of continental materials have conducted 2-D or 3-D mantle convection simulations (e.g. Afonso and Zlotnik, 2011; Babeyko and Sobolev, 2008; Currie et al., 2007; Gerya et al., 2008; Li et al., 2011; Sobolev and Babeyko, 2005) largely focusing on the formation and exhumation of high- to ultrahigh-pressure (HP–UHP) metamorphic rocks in the continental subduction or collision zones. In the 2-D or 3-D studies, detachment of the subduction channel at about 100 km is often observed (e.g. Gerya, 2011). Meanwhile, Currie et al. (2007) suggested that the detachment of the channel occurs if its thickness is larger than ~350 m by using 2-D calculations. However, numerical resolutions of these simulations (at least ~1 km) make it difficult to reproduce the flow of the subduction channel, in which the flow field can drastically vary by several hundred meters due to the high viscosity contrast between continental materials and the mantle materials (~10^3).

In this study, we performed a numerical simulation of a subduction channel by creating a 1-D model with non-Newtonian rheology and high resolution (10 m) so that it can accurately capture the flow inside the channel and estimate the supply rate of continental materials transported to the deep mantle.

2. Methods

2.1. Description of model

We consider a subduction channel of continental materials between a subducted lithospheric slab and a peridotite mantle wedge (Fig. 1(a)). The continental materials in the channel are provided via mechanisms such as tectonic erosion and sediment subduction. The relatively more viscous materials on either side restrict the direction of the flow inside the channel. The materials in the channel are dragged down by the slab and are driven up by their own buoyancy.

Here, we employ a model for the slab, the subduction channel, and the mantle wedge (Fig. 1(b)). The x-direction is taken to be perpendicular to the slab. We consider a profile of the y-component of the velocity of the region between the slab-subduction channel boundary, $x = 0$ km and $x = L$. The slab dip angle, θ_d, can be incorporated into the model by taking the y-component of the gravitational acceleration. Because it is impossible to have L set to infinity in these approximations, L is set to 100 km since it is large enough to represent the flow in the subduction channel. Also, since the difference between velocity calculated using $L = 100$ km and $L = 1000$ km is less than 0.01% of the results, $L = 100$ km was determined.

We solve an equation for the mechanical balance between the buoyancy and the viscous drag on the subducting slab and calculate the velocity profile at every given depth. The y-component of the 1D-velocity profile, $u(x)$, in which the upward velocity is positive (Ref. Fig. 1), is numerically calculated by the following equations of mechanical balance,

$$\frac{d}{dx}\left(\eta\left(\frac{du}{dx}\right)\right) + \Delta\rho_{\mathrm{g}} = 0, (0<x\le D) \text{ and } \frac{d}{dx}\sigma = 0, (D<x\le L), \tag{1}$$

where, η, $\Delta\rho = \rho_g - \rho_m$ (<0), and g (<0) are viscosity, density difference between the subduction channel, ρ_g, and the mantle, ρ_m, and gravitational acceleration, respectively. The way to calculate viscosity will be described in the next paragraph. Between D and L, the mantle wedge is buoyantly neutral so that force acting on the mantle wedge is only stressed from the subduction channel. The calculations are one-dimensional in the x-direction (vertical to the slab) (Fig. 1). The derivative with respect to the y-direction (parallel to the slab) is neglected because of its small rate-of-change of velocity and geometry compared to that with respect to the x-direction.

The calculations have been conducted via the finite difference method with 10 m grid spacing. The boundary conditions at both ends are $u(0) = U$ and $u(L) = U_2$, respectively.

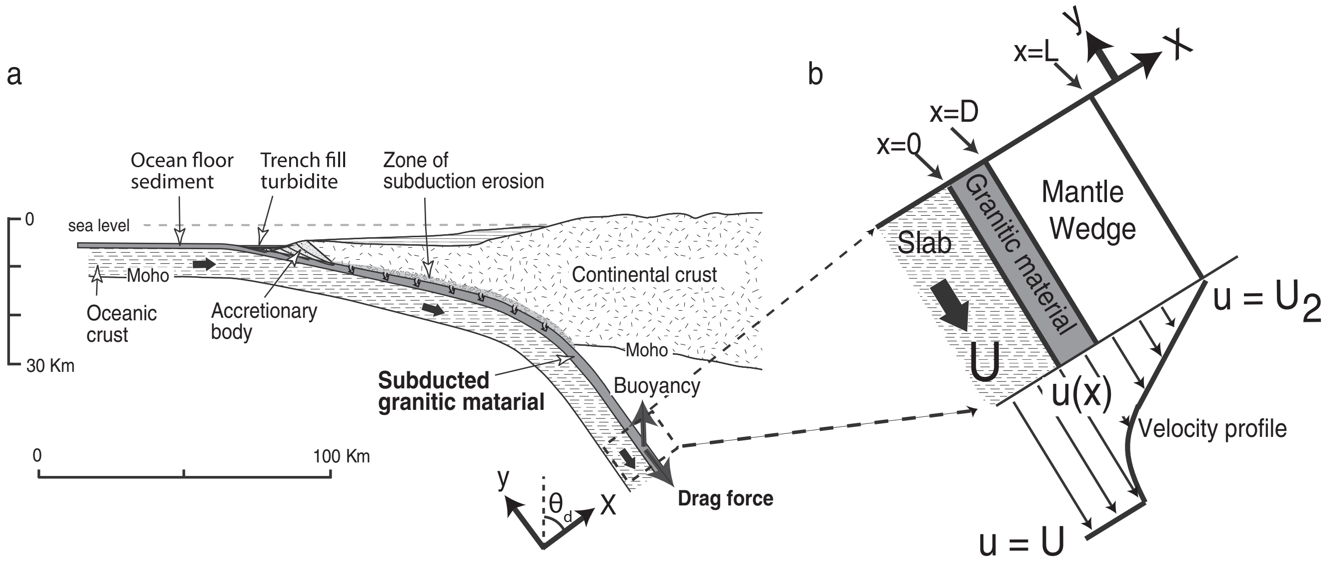

Fig. 1. Numerical setting. (a) Diagram of a subduction channel of granite accompanied by a subducting slab. The subduction channel is composed of the subducted sediments and eroded continental materials. The flow in the subduction channel is determined by a balance between drag force from the slab and its own buoyancy. The slab dip angle is θ_d. (b) Steady one-dimensional model, which corresponds to the case where the motion in the subduction channel is restricted to the y-direction. The x and y axes are perpendicular and parallel to the slab, respectively. The origin of the x axis is taken at the slab-subduction channel boundary. D is the thickness of the channel and L is the numerical domain size taken as 100 km. U and U_2 are the y component of the velocities of the subducting slab and the mantle wedge at $x = L$, respectively.