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Mantle convection with continental drift and heat source around the mantle transition zone

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ABSTRACT

Geological studies have suggested that a significant amount of crustal material has been lost from the surface due to delamination, continental collision, and subduction at oceanic–continental convergent margins. If so, then the subducted crustal materials are expected to be trapped in the mid-mantle due to the density difference from peridotitic materials induced by the phase transition from coesite to stishovite. In order to study the effect of the subducted granitic materials floating around the mantle transition zone, we conducted two-dimensional numerical experiments of mantle convection incorporating a continental drift with a heat source placed around the bottom of the mantle transition zone. The simulations deal with a time-dependent convection of fluid under the extended Boussinesq approximation in a model of a two-dimensional rectangular box with a height of 2900 km and a width of 11,600 km, where a continent with a length of 2900 km and heat source below the continent are imposed. We found that the addition of heat source in the mantle transition zone considerably enhances the onset of upwelling plumes in the upper mantle, which further reduces the time scale of continental drift. The heat source also causes massive mechanical mixing, especially in the upper mantle. The results suggest that the heat source floating around the mantle transition zone can be a possible candidate for inducing the supercontinent cycle.

1. Introduction

The heat source in the mantle is considered to be non-uniformly distributed owing to chemical differentiation at the Earth's surface and, hence, its heterogeneous distribution may affect the style of the convection. Numerical simulations including a chemically distinct heat source have been carried out by introducing basaltic heat sources accumulating on the core mantle boundary (CMB), and have shown that upward flow is formed from basal basaltic regions (Ogawa, 2007; Nakagawa and Tackley, 2010). Here we consider a case where the heat source is concentrated around the mantle transition zone and the upper part of the lower mantle. The candidate heat source materials are granitic. Since incompatible radioactive elements are highly concentrated in granitic rocks (Turcotte and Schubert, 2001), they can be strong heat sources if subducted into the deep mantle.

Recent studies propose that a considerable amount of continental material is sinking from the Earth's surface (Von Huene and Scholl, 1991; Yamamoto et al., 2009b) and floating in the middle of the mantle (Kawai et al., 2013). Geological studies have suggested that a significant amount of granitic crust has been lost from the Earth's surface due to crustal delamination (~1.1 km^3/year) (Clift et al., 2009), continental collision (~0.4–0.7 km^3/year) (Clift et al., 2009; Stern and Scholl, 2010), and subduction at ocean–continent convergent margins (~2.5–3.0 km^3/year) (Clift et al., 2009; Stern and Scholl, 2010). For subduction at ocean–continent convergent margins, continental materials are thought to subduct through the "subduction channels" developing at the interfaces between the subducting (oceanic) and overriding plates (Von Huene and Scholl, 1991; Santosh et al., 2009; Yamamoto et al., 2009a,b; Stern, 2011). On the other hand, studies on the elastic properties show that granite is denser than the ambient mantle rock around the transition zone and the upper part of the lower mantle, typically in a depth range from 270 km to 800 km in depth for Archean granite called tonalite-trondhjemite-granite (TTG) (Irifune et al., 1994; Kawai et al., 2009; Kawai and Tsuchiya, 2012), owing to the phase transition from coesite to stishovite at around 270 km in depth. Indeed, the supply rate of continental materials through subduction channels by viscous drag to 270 km in depth at the current subduction zone is estimated to be 2.2 km^3/year (Ichikawa et al., in press). Therefore, continental materials are most likely to be stratified around 660 km in depth because it is buoyant below 800 km (Kawai and Tsuchiya, 2012). Hence, strong heat source materials are most likely to accumulate in the mantle transition zone, at least, beneath convergent margins.

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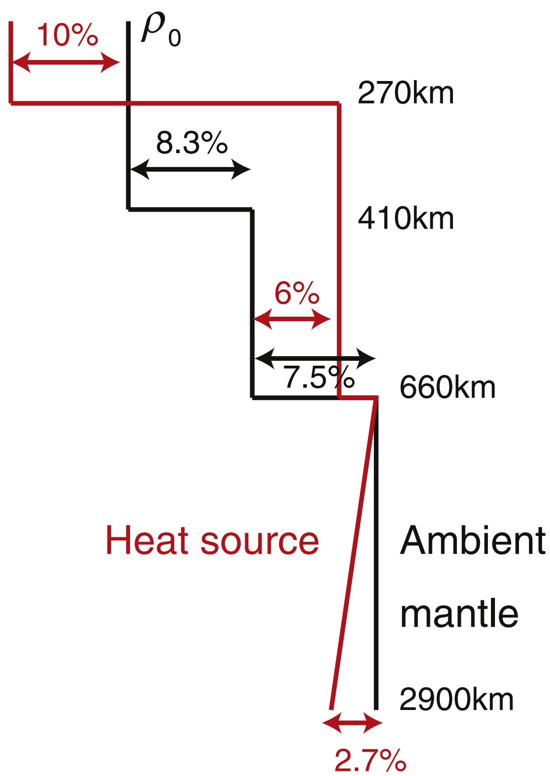

Fig. 1. Density difference arising from phase transitions. The black and the red lines denote the densities of the ambient mantle and the heat source material, respectively. The reference density, $\rho_0 = 3300$ kg/m^3, is the density of the ambient mantle at the surface.

It is therefore most likely that distinct heat sources in the mid-mantle strongly affect the convection patterns in the mantle. However, almost no earlier numerical studies have considered their possible effects so far. Some numerical studies including the piles of basaltic materials have been carried out, and have suggested that positions of upwelling plumes coincide with these of piles (Ogawa, 2007; Nakagawa and Tackley, 2010). Senshu et al. (2009) have suggested that plumes initiated from granitic piles on CMB are related to the origin of the superplume–supercontinent cycle. On the other hand, the granitic heat sources in the mid-mantle are expected to rapidly interact with the surface motions since they are located much closer to the Earth's surface than the basal piles. In other words, the granitic materials in the mantle transition zone are expected to actively control the convecting flows in the mantle, rather than to be passively advected by the ambient flows (Korenaga, 2004).

Heat sources in the mid-mantle are most likely to significantly affect the course of the accretion and dispersal of the supercontinents which occurred several times during the Earth's history. The cyclic behavior, commonly termed “supercontinent cycle” or the “Wilson cycle” (Wilson, 1966), includes, for example, the formation of Pangea (about 330 Ma) and its breakup (starting about 175 Ma) (Veevers, 2004), the formation of Rodinia (about 900 Ma) and its breakup (during 825 and 750 Ma) (Li et al., 2008), and the formation and breakup of far earlier supercontinents (see Nance et al., 2013 for a review). Owing to the recent progress in three-dimensional models of mantle convection, several studies have been carried out which implemented mobile continents with plate tectonics (Yoshida, 2010; Rolf and Tackley, 2011; Yoshida and Santosh, 2011; Coltice et al., 2012). These breakups of supercontinents are most likely to be caused by the impingement of ascending plumes beneath them (Storey, 1995). Various ideas for the impingement have been proposed as follows: thermal insulating effect of the supercontinent (Anderson, 1982; Gurnis, 1988; Yoshida et al., 1999; Evans, 2003; Coltice et al., 2007; Coltice et al., 2009; Yoshida, 2010) and formation of upwelling plume in response to circum-continental subduction (Zhong et al., 2007; Li and Zhong, 2009). On the other

Table 1
Meanings and values of the symbols used in this study.

Symbols	Meanings	Value
ρ_0	Reference density	3.3×10^3 kg/m^3
ΔT	Temperature scale	3750 K
D	Thickness of the model	2900 km
α_{top}	Thermal expansivity at the top	2×10^{-5} K^{-1}
C_p	Specific heat	1.2×10^3 J/kg K
κ_{top}	Thermal diffusivity at the top	10^6 m^2/s
g	Gravitational acceleration	9.8 m/s^2
H	Heating rate of ambient mantle	0.48×10^{-11} W/kg
H_c	Heating rate of heat source	28.9×10^{-11} W/kg

Table 2
Input parameters. Rayleigh numbers are as follows: $Ra_{top} = 5.9\times10^4$ ($\eta_{top} = 10^{24}$ Pa s) for series A, $Ra_{top} = 1.87\times10^5$ ($\eta_{top} = 3.16\times10^{23}$ Pa s) for series B, $Ra_{top} = 5.9\times10^5$ ($\eta_{top} = 10^{23}$ Pa s) for series C, $Ra_{top} = 5.9\times10^6$ ($\eta_{top} = 10^{22}$ Pa s) for D7, and $Ra_{top} = 1.87\times10^7$ ($\eta_{top} = 3.16\times10^{21}$ Pa s) for E7. $F(= c_0\rho_0H_cdl)$ indicates a total heat production rate of the heat source. Cases C7_l0.1, C7_l0.2,..., and C7_l0.9 have different horizontal scale of heat source, l, from case C7. In case C7_lX, l is taken to be $0.85XD$. Other than the value of l, the Cases C7_l0.1, C7_l0.2,..., and C7_l0.9 are not different from case C7.

Case	d/D	c_0	$F = c_0\rho_0H_cdl$ [kW/m]
A0, B0, C0	0	0.0000	0
A1, B1, C1	0.08	1.0000	545
A2, B2, C2	0.08	0.7500	409
A3, B3, C3	0.08	0.5000	273
A4, B4, C4	0.08	0.2500	136
A5, B5, C5	0.12	0.6667	545
A6, B6, C6	0.12	0.5000	409
A7, B7, C7, D7, E7	0.12	0.3333	273
C7_l0.1,C7_l0.2,...,C7_l0.9	0.12	0.3333	273
A8, B8, C8	0.12	0.1667	136
A9, B9, C9	0.16	0.5000	545
A10, B10, C10	0.16	0.3750	409
A11, B11, C11	0.16	0.2500	273
A12, B12, C12	0.16	0.1250	136
A13, B13, C13	0.32	0.2500	545
A14, B14, C14	0.32	0.1875	409
A15, B15, C15	0.32	0.1250	273
A16, B16, C16	0.32	0.0625	136
A17, B17, C17	0.48	0.1667	545
A18, B18, C18	0.48	0.1250	409
A19, B19, C19	0.48	0.0833	273
A20, B20, C20	0.48	0.0417	136
A21, B21, C21	0.08	0.1250	68
A22, B22, C22	0.12	0.0833	68
A23, B23, C23	0.16	0.0625	68
A24, B24, C24	0.32	0.0313	68
A25, B25, C25	0.48	0.0208	68

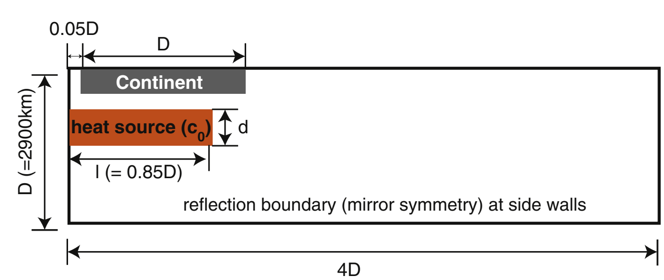

Fig. 2. The initial setting of the two-dimensional convection model. Reflection boundary conditions are imposed at both the vertical walls. The viscosity of the continent is taken to be 10^3 times higher than that of the ambient mantle. The left wall corresponds to a center plane of the supercontinent because of the imposed mirror symmetry. Between the left wall and the continent, a weak zone is put by placing the continent $0.05D$ away from the wall in order to enhance the breakup of the supercontinent.