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On the thermo-chemical origin of the stratified region at the top of the Earth's core

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ABSTRACT

I developed a combined model of the thermal and chemical evolution of the Earth's core and investigated its influence on a thermochemically stable region beneath the core-mantle boundary (CMB). The chemical effects of the growing stable region are caused by the equilibrium chemical reaction between silicate and the metallic core. The thermal effects can be characterized by the growth of the sub-isentropic shell, which may have a rapid growth rate compared to that of the chemically stable region. When the present-day CMB heat flow was varied, the origin of the stable region changed from chemical to thermochemical to purely thermal because the rapid growth of the sub-isentropic shell can replace the chemically stable region. Physically reasonable values of the present-day CMB heat flow that can maintain the geodynamo action over 4 billion years should be between 8 and 11 TW. To constrain the thickness of the thermochemically stable region beneath the CMB, the chemical diffusivity is important and should be ~O (10^{-8}) m^2/s to obtain a thickness of the thermochemically stable region beneath the CMB consistent with that inferred from geomagnetic secular variations (140 km). However, the strength of the stable region found in this study is too high to be consistent with the constraint on the stability of the stable region inferred from geomagnetic secular variations.

1. Introduction

Seismological analyses on the outermost outer core structure have recently established the presence of velocity anomalies beneath the core–mantle boundary (CMB). The velocity in this region is slightly lower than that in the preliminary reference Earth model (PREM). Within this approximately 300 km thick beneath the CMB (Tanaka, 2007; Helffrich and Kaneshima, 2010), a stable region is believed to exist. Other estimates of the thickness of this region from geomagnetic secular variations exist within the range of 60–140 km (Gubbins, 2007; Buffett, 2014). The origin of this stable region—thermal, chemical or thermochemical—remains under debate. The chemical and/or thermal origin of the stable stratification beneath the CMB has been investigated in several thermal and chemical evolution models of the Earth's core (Labrosse et al., 1997; Lister and Buffett, 1998; Buffett and Seagle, 2010; Gubbins and Davies, 2013; Helffrich, 2014; Labrosse, 2015).

The thermally stable region is modeled as a sub-isentropic region that appears when the heat flow across the CMB drops below the isentropic heat flow (e.g., Labrosse et al., 1997). This region is several hundred kilometers thick on a geological timescale (Labrosse et al., 1997; Lister and Buffett, 1998). Given the high thermal conductivity of the Earth's core (e.g., Pozzo et al., 2012; de Koker et al., 2012; Gomi et al., 2013; Ohta et al., 2016), the thermally stable region may be up to 1000 km thick (Pozzo et al., 2012; Labrosse, 2015). Numerical geodynamo simulations (Nakagawa, 2011, 2015) have suggested that a thermal origin for the sub-CMB stable region would weaken the magnetic field strength by inducing a filtering effect (Nakagawa, 2011). This has also been found in other geodynamo simulations using a co-density stratification model (Christensen and Wicht, 2008). However, the generation of the magnetic field by dynamo actions when a stable region is located beneath the CMB seems to be suppressed by stable stratification that is thicker than 500 km (Nakagawa, 2015). This argument is valid only if the CMB heat flow occurs under sub-isentropic conditions. When the CMB heat flow is sufficiently higher than the isentropic heat flow (i.e., super-isentropic conditions), the origin of the stable region observed from seismological and geomagnetic analyses might be purely chemical. To address the formation of the stratification beneath the CMB, including both thermal and chemical effects, in this study, the simultaneous thermal and chemical evolution of the Earth's core is modeled, instead of a 'co-density' approach utilizing combined

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variables for the temperature and chemical composition (Braginsky and Roberts, 1995).

Chemical effects include the reaction products of core–mantle chemical coupling; for example, the partitioning of oxygen and/or silicon into the metallic core (Asahara et al., 2007; Ozawa et al., 2008; Frost et al., 2010; Ricolleau et al., 2011; Tsuno et al., 2013) forms a 70 to 100 km thick chemically stable, low-velocity layer beneath the CMB (Buffett and Seagle, 2010; Gubbins and Davies, 2013). However, a recent high-pressure and -temperature (P-T) experiment suggested that oxygen and silicon may be dissolved as a mutually exclusive relationship (Hirose et al., 2017).

As noted above, previous investigations assumed either a thermal or chemical mechanism without considering the contributions of both effects simultaneously. Lister and Buffett (1998) investigated the thermochemical effects simultaneously, but their conclusions related to the thermal effect only, suggesting that a stable layer could form below the CMB as a result of sub-adiabatic heat flow across the stable layer. Core–mantle chemical reactions were excluded because the experimental data on the partitioning of light elements (e.g., Si and O) into the metallic core were unavailable. Such partitioning can be thermodynamically quantified via high P–T experiments (Frost et al., 2010; Ricolleau et al., 2011; Tsuno et al., 2013; Hirose et al., 2017). Using a model of the partitioning of light elements as the boundary condition, the chemical evolution of the Earth's core can be computed, indicating a chemically stable region thickness of several 10 s–100 s km (Buffett and Seagle, 2010; Gubbins and Davies, 2013). In this study, I attempt to develop a combined model of the thermal and chemical evolution of the Earth's core that includes both thermal and chemical origins for the stable region beneath the CMB and compute the thermal, chemical and magnetic evolution of Earth's core using the developed model by applying a high thermal conductivity in the core. From the results, I reveal the physics behind the formation of the stable region below the CMB and discuss their implications for the evolution and dynamics of the Earth's core over geologic timescales.

2. Model description

2.1. Basic concept

The thermal and chemical effects on the thermochemical evolution system in the stable region of Earth's core were conceptualized by Lister and Buffett (1998) and Buffett and Seagle (2010), which is assumed as thermo-chemically diffusive zone. A schematic image of the stable region beneath the CMB is shown in Fig. 1. I suppose that the chemically stable region starts growing before the thermally stable region. Indeed, the thermally stable region begins forming only when the heat flow achieves sub-isentropic conditions (Fig. 1). Therefore, I individually compute the growth of the interface between the stable and well-mixed regions caused by thermal and chemical effects. Thermochemical equilibrium is also assumed at the CMB. However, the relevance of this assumption remains under debate because other mechanisms of compositional convection caused by core-mantle chemical coupling, such as the dissolution of light elements (e.g., Mg (O'Rourke and Stevenson, 2016; Badro et al., 2016) and Si (Hirose et al., 2017)), have been proposed.

The element exchange across the CMB obeys chemical equilibrium thermodynamics (Frost et al., 2010; Ricolleau et al., 2011). Although the metal–silicate partitioning of light elements in the Earth's core should involve various species (e.g., Si, C, O, S, and H) (Poirier, 1994; Okuchi, 1997; Tsuno et al., 2013), here, I assume that oxygen alone partitions between the metallic core and the silicate mantle because oxygen diffuses much faster than other light elements, such as Si (Pozzo et al., 2013; Ichikawa and Tsuchiya, 2015; Helffrich, 2014), and a mutually exclusive relationship has been reported between oxygen and silicon (Hirose et al., 2017). Buffett and Seagle (2010) present a simplified computation of the thermal evolution and consequent growth of the inner core. For a more realistic treatment of the onset and growth rate of the inner core, I simultaneously integrate both chemical and thermal evolution equations in the well-mixed region.

As discussed in the next section, in the stable region, I again assume to be thermo-chemically diffusive region, however, thermal and chemical diffusions is difficult to be simultaneously solved in terms of numerical solution because the timescales for thermal and chemical diffusion are very different. Indeed, thermal diffusion is approximately three to four orders of magnitude faster than chemical diffusion. In addition, the chemical diffusion equation includes non-linear effects due to the baro-diffusion term, meaning that a numerical procedure for solving the chemical equation should be applied in an explicit scheme instead of implicit scheme. Here, the chemical composition in the stable region is obtained by numerical solution of the chemical diffusion equation, whereas the temperature profile in the stable region is approximated as an analytical solution of a one-dimensional (1-D) heat conduction equation applying with boundary conditions at the CMB (heat flux)

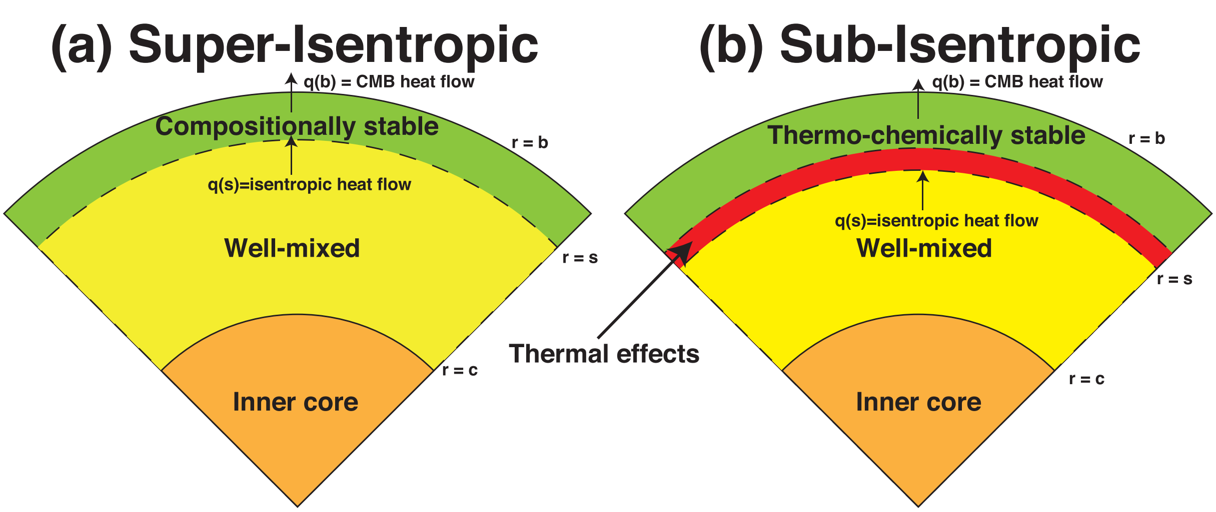

Fig. 1. Schematic illustration of the stable region forming beneath the CMB: (a) super-isentropic condition (purely chemical region) and (b) sub-isentropic condition (thermochemical region). To find the thermochemically stable region, I consider both thermal and chemical contributions to the growth rate of the interface displacement.

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