Earth and Planetary Science Letters 361 (2013) 391–401

Contents lists available at SciVerse ScienceDirect

Earth and Planetary Science Letters

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

Implication of the lopsided growth for the viscosity of Earth's inner core

Hugau Mizzon, Marc Monnereau *

IRAP, University of Toulouse, CNRS, Toulouse, France

ARTICLE INFO

Article history:
Received 22 March 2012
Received in revised form
29 October 2012
Accepted 2 November 2012
Editor: T. Spohn
Available online 20 December 2012

Keywords:
Earth's inner core
numerical modeling
thermal convection
translation

ABSTRACT

A particular mode of convection, called translation, has recently been put forward as an important mode of inner core dynamics because this mechanism is able to explain the observed east–west asymmetry of P-wave velocity and attenuation (Monnereau et al., 2010). Translation is a particular solution to Navier–Stokes equation with permeable boundary conditions, but depending on the viscosity of the solid core, modes with higher spherical harmonics degree can develop. At low viscosity, these modes can be dominant and dissipate the degree $l=1$ of thermal heterogeneities. Hence, a viscosity threshold may be expected below which translation cannot take place, thereby constraining the viscosity of iron at inner core conditions.

Using a hybrid finite-difference spherical harmonics Navier–Stokes solver, we investigate here the interplay between translation and convection in a 3D spherical model with permeable boundary conditions. Our numerical simulations show the dominance of pure translation for viscosities of the inner core higher than 4×10^{18} Pa s. Translation is almost completely hampered by convective motions for viscosities lower than 10^{17} Pa s and the phase change becomes an almost impermeable boundary. Between these values, a well developed circulation at the harmonic degree $l=1$ persists, but composed of localized cold downwellings, a passive upward flow taking place on the opposite side (the melting side). Such a convective structure remains compatible with the seismic asymmetry.

1. Introduction

The image of the inner core growing slowly at the center of the Earth by gradual cooling and solidification of the surrounding liquid outer core is being replaced by the more vigorous image of a "deep foundry" (Buffett, 2011), where melting and crystallization rates exceed by many times the net growth rate (Monnereau et al., 2010; Alboussiere et al., 2010; Gubbins et al., 2011)

During 70 yr, the analysis of compressive waves (P-waves) and free oscillations excited after large earthquakes have been depicting a more and more complex structure of the inner core. The latter appears anisotropic, with a fast axis parallel to Earth's spin axis. It is also asymmetric: within the outermost 100 km, velocity and attenuation of P-waves increase from the hemisphere facing America (west) to the one facing Asia (east) (Tanaka and Hamaguchi, 1997); anisotropy also seems stronger in the Western hemisphere than in the Eastern one (Deuss et al., 2010).

In the 1980's and 1990's, anisotropy was thought to be the prominent feature. This is commonly attributed to the preferred orientation of iron crystals, possibly acquired during solidification but most probably resulting from creep flow. Thermal convection, developing a flow characterized by a spherical harmonic degree $l=1$ (a clementine shape), orientated along the spin axis of the Earth, was one of the first candidates to account for anisotropy (Jeanloz and Wenk, 1988). In this model and the following ones (Weber and Machetel, 1992; Buffett, 2009), the nature of the inner core boundary (i.e. a phase change) was not considered, a classical impermeable boundary condition being preferred. With permeable boundary conditions – a phase change does not prevent material transfer – an expression of convection at the first harmonic degree is a constant velocity field across the inner core, that obviously does not produce any deformation, but implies melting on one side and crystallization on the opposite side. This peculiar situation, called translation of the inner core, has recently been put forward to explain the hemispherical asymmetry of velocity and attenuation (Monnereau et al., 2010).

If the inner core grows in a superadiabatic regime, which is the condition for the onset of convection, an unstable thermal stratification develops, so that any infinitesimal thermal heterogeneity of harmonic degree $l=1$ (i.e. one side colder than the other one) will be amplified. Such a heterogeneity will induce a displacement of the inner core to maintain its center of mass – shifted toward the denser/colder hemisphere – at the center of the Earth. The inner core acquires a positive topography on the hotter and lighter side and a negative one on the opposite side. This topography is thermodynamically unstable: the side

* Corresponding author.
E-mail address: marc.monnereau@irap.omp.eu (M. Monnereau).

0012-821X/$ - see front matter © 2012 Elsevier B.V. All rights reserved.
http://dx.doi.org/10.1016/j.epsl.2012.11.005

emerging above the phase change melts, bringing hotter material up to the surface, while the sinking side allows crystallization. The phase change acts to remove the topography, which is continuously rebuilt by isostatic equilibrium. This feedback results in a permanent drift from the crystallizing side to the melting side, the drift velocity being controlled by the ability of the outer core to restore the adiabatic condition at the surface of the inner core.

Translation provides an attractive conceptual framework to understand the hemispherical asymmetry of seismic properties, in particular the positive correlation between P-wave velocity and attenuation. To our knowledge, only multiple scattering of P-waves in iron aggregates has consistently explained this striking correlation by introducing a variation of grain size from one hemisphere to the other (Monnereau et al., 2010; Calvet and Margerin, 2012). If they do not experience deformation, iron crystals grow as they transit from one hemisphere to the other. Larger crystals constituting a faster and more attenuating medium, a translation velocity of some cm/yr (about 10 times the growth rate) is enough to account for the seismic asymmetry, with grains of a few hundred meters on the crystallizing side (west) growing up to a few kilometers before melting on the east side, and a drift direction located in the equatorial plane.

Translation was also proposed to be responsible for the formation of a dense layer at the bottom of the outer core, since the high rate of melting and crystallization would release a liquid depleted in light elements at the surface of the inner core (Alboussiere et al., 2010). This would explain the anomalously low gradient of P-wave velocity in the lowermost 200 km of the outer core (Poupinet et al., 1983).

Clearly, translation cannot account for anisotropy. Translation is one particular solution to Navier–Stokes equation with permeable boundary conditions. Other modes of higher spherical harmonic degrees can develop. The development of these modes depends on the Rayleigh number, that controls the vigor of the convection, and thus mainly on the viscosity of the solid portion of the core. At high Rayleigh number (low viscosity), these modes can be dominant and dissipate the degree $l=1$ of the thermal heterogeneities: the source of the translation. Thus a viscosity threshold may be expected below which translation would not take place. This may constrain the viscosity of iron at the conditions of the inner core, based on seismological observation. In this paper, we present dynamic models of the inner core taking into account the phase change boundary and study the development of the different modes of convection.

2. Model setup

The inner core dynamics is a moving boundary problem that can be treated in all its complexity (Deguen and Cardin, 2011). For the sake of simplicity, we may neglect the variation of the radius with time, and focus on the present time dynamics. This assumption is plainly justified since the translation velocity required to account for seismic properties of the inner core, but also for the formation of a dense layer above the ICB, should exceed the inner core growth rate by one or two orders of magnitude (Monnereau et al., 2010; Alboussiere et al., 2010).

2.1. Energy equation

The energy equation is thus written in terms of the temperature relative to the adiabat anchored at the ICB ($\Theta = T - T_S$), in which the decrease of the ICB temperature with time plays the role of an internal heating:

$$\rho_s C_p \frac{D\Theta}{Dt} + \alpha \rho_s g \Theta v_r = k \Delta \Theta + \tau : \nabla \mathbf{v} + \Phi. \tag{1}$$

ρ_s is the density of solid iron, C_p the specific heat, α the thermal expansion coefficient, g the gravity, v_r the radial velocity, τ the deviatoric stress tensor, $\mathbf{v}$ is the velocity vector and k the conductivity. Φ, the effective internal heating, results from a competition between the heat lost by conduction along the adiabat and the secular cooling of the core:

$$\Phi = k \Delta T_S - \rho_s C_p \frac{dT_S}{dt}. \tag{2}$$

The surface is assumed isothermal, $\Theta = 0$. This is equivalent to neglecting the small temperature perturbation corresponding to the ICB topography ($\sim 10^{-3}$ K) compared to the one involved in the dynamics (~ 1 K).

2.2. Momentum equations

As for the mantle, inertial forces can be neglected because of the high viscosity of solid iron at the inner core temperature and pressure conditions, which is at least 10^{16} Pa s (Yoshida et al., 1996). Conservation of momentum just expresses the balance between buoyancy and viscous forces. It is time independent.

$$\nabla \cdot \sigma = -\delta \rho \mathbf{g}. \tag{3}$$

σ is the stress tensor, $\mathbf{g}$ the gravity and $\delta\rho$ the deviation from the density reference profile. Here, pressure dependence of the density has been neglected, so that the mass conservation reduces to $\nabla \cdot \mathbf{v} = 0$. The permeable surface condition is introduced. It describes the balance between the radial stress and buoyancy forces induced by topography:

$$\sigma_{rr}|_{R_{ic}} = (\rho_l - \rho_s) g_{icb} h, \tag{4}$$

where σ_{rr} is the radial stress, R_{ic} the inner core radius, ρ_l the density of liquid iron, g_{icb} the gravity at the surface of the inner core and h the topography. In addition, the surface is considered as tangential stress free:

$$\sigma_{r\theta,\phi}|_{R_{ic}} = 0. \tag{5}$$

2.3. Surface heat exchange with the outer core

The topography is thermodynamically unstable and eroded at a rate depending on the vigor of convection within the outer core. In the mantle, the position of mineral phase transitions is mainly related to the ambient temperature, latent heat exchanges having almost no effect. For instance, a transition with a positive Clapeyron slope like olivine to spinel occurs deeper in ascending (hot) currents than in dipping slabs. The reverse situation happens for the ICB. The turbulent flow in the liquid maintains the temperature above the surface close to the adiabat so that the topography only depends on the temperature variations induced by the latent heat effects and not on temperature anomalies within the inner core. Topography is thus positive where material exits the inner core because of the cooling induced by the latent heat consumption. Local thermodynamical equilibrium is achieved when the rate at which the inner core consumes or releases latent heat equals the rate at which the outer core brings or takes the energy to maintain the adiabatic temperature. This can be written as (Alboussiere et al., 2010; Deguen, 2012)

$$v_r|_{R_{ic}} = \frac{h}{\tau_\phi}, \tag{6}$$