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# Modelling the effects of internal heating in the core and lowermost mantle on the earth's magnetic history

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**Abstract**

Recently, an incompatible-element enriched reservoir, bearing a high degree of radioactive heating, has been proposed to exist at the base of the mantle. This scenario has been discussed based on parameterized thermal and magnetic models of the core [Buffett, B.A., 2002. Estimates of heat flow in the deep mantle based on the power requirements for the geodynamo. Geophys. Res. Lett. 29(12), 7], as well as on geochemical grounds [Tolstikhin, I., Hofmann, A.W., 2005. Early crust on top of the Earth's core. Phys. Earth Plan. Int., 148, 109-130; Boyet M., Carlson, R.W., 2005. $^{142}$Nd Evidence for early (> 4.53 Ga) global differentiation of the sillicate earth. Science 309, 576-581]. A high degree of radioactivity at the base of the mantle [Buffett, B.A., 2003. The thermal state of Earth's core. Science 299, 1675-1677], or alternatively the presence of radioactivity in the core [e.g., Labrosse, S., 2003. Thermal and magnetic evolution of the Earth's core. Phys. Earth Plan. Int. 140, 127-143; Nimmo F., Price, G.D., Brodholt, J., Gubbins, D., 2004. The influence of potassium on core and geodynamo evolution. Geophys. J. Int. 156, 363-376], have been proposed as means to allow sufficient buoyancy to power the geodynamo and maintain a magnetic field throughout most of the Earth's history as palaeomagnetic records indicate [McElhinny, M.W., Senanayake, W.E., 1980. Paleomagnetic evidence for the existence of the geomagnetic field 3.5 Ga ago. J. Geophys. Res. 85, 3523-3528; Hale, C.J., D.J. Dunlop, 1984. Evidence for an early Archean geomagnetic field: a paleomagnetic study of the Komati Formation, Barberton Greenstone Belt, South Africa. Geophys. Res. Lett. 11, 97-100], while maintaining a sufficiently high temperature in the core. The present paper analyzes the consequences of internal heating in the core and the lowermost mantle on the core's magnetic history using numerical simulations of convection in the mantle coupled to an energy balance model for the core. This method allows feed-back at each time step between the cooling histories in the core and mantle through the heat flux and temperature at the core-mantle boundary (CMB). We employ a two dimensional, spherical-axisymmetric model of convection in the Earth's mantle, coupled to a heat reservoir model for the core. We calculate at each time-step the entropy available for ohmic dissipation in the core and use this result to estimate the intensity of a magnetic field generated by geodynamo action. In agreement with Nimmo et al. [Nimmo F., Price, G.D., Brodholt, J., Gubbins, D., 2004. The influence of potassium on core and geodynamo evolution. Geophys. J. Int. 156, 363-376], we find that the presence of 300 ppm potassium in the core allows for a magnetic field to have existed over the lifetime of the Earth with a reasonable final value for the temperature at the CMB. Almost all of the models with high internal heating at the base of the mantle exhibit warming of the core throughout much of the Earth's thermal history, a state that would prohibit a functioning geodynamo. In one simulation, we are driven to a scenario where the inner core has existed over the lifetime of the Earth only to gradually melt and then refreeze, with a functioning geodynamo existing for a short time. We conclude that careful tuning of the mantle viscosity, internal heating rate and initial core temperatures would be required in order to achieve a magnetic field over the lifetime of the Earth in

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the presence of a basal layer with a high degree of internal heating and therefore such a scenario must be better constrained before it could present itself as viable.


*Keywords:* Mantle; Core; Geodynamo; Thermal history; Magnetic field; Radioactivity

## 1. Introduction

The Earth's magnetic field is generated in the metallic core by dynamo action (e.g., Stevenson, 2003a). Convection of the molten iron alloy in the outer core supplies the energy for the geodynamo process. The buoyancy forces which drive convection in the outer core can be both thermal and compositional. Thermally-driven convection occurs as a result of secular cooling of the core from above. Internal heating in the core, if it exists, adds further thermal buoyancy. When the temperature at the center of the Earth drops below the liquidus for the core alloy, the inner core starts to freeze and inner core solidification proceeds as the core continues to cool. Although the latent heating and gravitational energy release associated with the solidification of the inner core are relatively modest compared with the energy of secular cooling, the compositional buoyancy associated with the release of lighter material from the metallic alloy as the inner core freezes can be a dominant contributor to the geodynamo action.

The cooling of the core and the solidification of the inner core are controlled by the amount of heat the mantle is able to remove from the core. The efficiency with which the mantle extracts heat from the core depends on the temperature drop across the CMB and the dynamical state of convection in the mantle. If the amount of heat extracted from the core is large, vigorous convection takes place in the core, and the geodynamo process can generate a magnetic field and maintain it against dissipative processes. Conversely, if the heat flux across the CMB is too low, the core adiabatic gradient cannot be sustained by the low rate of cooling and the heat transfer is done solely through conduction. In this case, the geodynamo process shuts off. The criterion for a dynamo in terrestrial planets may not differ significantly from the criterion for convection (Stevenson, 2003a), however from entropy considerations it might be concluded that the amount of heat flow across the CMB required to maintain the geodynamo must be in excess of the minimum amount required for convection. Clearly, additional energy sources in the core, such as those associated with the inner core solidification, or internal heating, increase the chances of an operating geodynamo. Thus, the age of the inner core and the heat sources present in the core are of interest for the history of magnetic field generation.

In contrast with geochemical studies which predict an inner core age in excess of 3.5 Gyrs (Brandon et al., 2003), thermal studies for the age of the inner core using parameterized models with prescribed fluxes (e.g., Labrosse et al., 2001; Buffett, 2002), parameterized models of the Earth's thermal history, (e.g., Nimmo et al., 2004), and numerical models of convection coupled with parameterized models for the core (e.g., Butler et al., 2005), have found that the inner core is unlikely to have existed over the entire lifetime of the Earth, its age being probably of order 1.5 Gyrs. The experimental work of Aurnou et al. (2003) and the numerical modeling of Aubert (2005) have also shown that rapid inner core growth, or a young inner core, is consistent with the buoyancy flux at the CMB required to drive polar vortex motions at the CMB that are similar in magnitude to those inferred from the present-day secular variation of the magnetic field (e.g., Olson and Aurnou, 1999). Labrosse et al. (2001), Nimmo et al. (2004), Butler et al. (2005) have all shown that including radioactivity in the core has only a small effect on the age of the inner core. Butler et al. (2005) showed that constraining the inner core growth such that in the final stage the size of the current Earth's inner core is achieved, the age of the inner core can even be decreased slightly by the inclusion of internal heat sources.

The dependence of the power available for the geodynamo process on the heat flow across the CMB has been addressed in a large number of papers (e.g., Buffett et al., 1996; Buffett, 2002; Labrosse and Macouin, 2003) although the exact magnitude of the heat flow at the CMB required to maintain an active dynamo remains poorly constrained. Buffett (2002), Lister (2003), Labrosse (2003) have shown in their energy balance calculations that if ohmic dissipation in the core is required to be the same before and after the appearance of the inner core and the current heat flow at the CMB is required to be reasonably high, as the estimated temperature drop across the CMB of roughly 1000 K suggests (e.g., Anderson, 2002; Boehler, 2000), then unrealistically high early temperatures for the core and mantle are predicted. For models that are integrated forward in time, this result can be restated that if a reasonable initial core tempera-