

# SUPERDIPOLE GEOMAGNETIC FIELD IN THE PAST

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**Abstract:** According to the model of the Earth's cooling, before the solid core origin, there was a sub-adiabatic layer at the core-mantle boundary several hundred kilometers thick. In this layer magnetic field generation was suppressed. Removing the field generation region from the Earth's surface led to an effective weakening of the small-scale component of the magnetic field. After the solid core appeared, convection extended throughout the whole bulk of the core with the possible exception of the F-layer at the core-mantle boundary, which is no more than 100 km thick. As a result the non-dipole counterpart of the magnetic field should be stronger at the Earth's surface. The decrease of the ratio of the dipole to non-dipole field with the origin of the solid core was an order of magnitude or more.

**Keywords:** geodynamo, core-mantle boundary, Earth's cooling, inner core

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## Introduction

The Earth's magnetic field is generated in the liquid metallic core [Aubert, 2023]. Currently the magnetic field is described by the dipole field comprising 90% of the magnetic field energy. The rest 10% of the energy is accounted to the multipole component [Lowes, 1974]. The ratio of these two counterparts determines the dipolarity of the magnetic field:

$$Dip = \frac{(g_1^0)^2}{(g_1^1)^2 + (h_1^1)^2 + R},$$

$$R = \sum_{n=2}^{\infty} \left(\frac{a}{r_b}\right)^{2n-2} \sum_{m=0}^n (n+1) ((g_n^m)^2 + (h_n^m)^2),$$

where  $a$  is Earth's radius,  $r_b$  the core radius, and  $g_n^m$ ,  $h_n^m$  are the Gauss coefficients [Christensen et al., 2010]. For the present time  $Dip \sim 1.5$ .

It is believed that magnetic field was dipole in the past as well. However the degree of dipolarity is not well-known.

The age of the geomagnetic field, which is at least 3.5 billion years [Nichols et al., 2024], is comparable with the age of the Earth 4.6 Gy. So far since the moment of separation of the Earth into the metallic core and non-conductive mantle, the Earth's counterparts, including the Earth's core and mantle, have evolved, it can be expected that intensity and spectra of the magnetic field could change as well.

The most important factors, influencing the generation of the magnetic field in the core, are the geometry of the core, which changed as the solid core in the center of the Earth grew, and the change in the amount of energy  $Q_J$ , available to the magnetic field generation.

What is less trivial, that for an observer at the Earth's surface the distance to the region of magnetic field generation is also important. The greater the distance, the greater the dipolarity of the magnetic field. The distance is the sum of the thickness of the mantle <sup>1</sup>

<sup>1</sup> Usually, thickness of the mantle is constant in the models.

## RESEARCH ARTICLE

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and the depth of the magnetic field location inside the liquid core. The latter is determined by the shape of the flow and can be quite large, of order of several hundred kilometers. Such a large depth can change morphology of the magnetic field dramatically, see review of the modern results in [Christensen, 2018].

Provided of appearance of sub-adiabatic layer at the core-mantle boundary (CMB), where the radial component of the velocity is small, generation of the magnetic field takes place deeply inside of the liquid core. The existence of such layer was predicted in [Gubbins *et al.*, 1982] and is confirmed by the models of the core cooling [Reshetnyak, 2019].

Influence of sub-adiabatic layer on the magnetic field generation is of great importance before the inner core origin. After that compositional convection mechanism forces flow in the whole bulk of the core except the thin slurry F-layer at CMB [Braginsky, 1963], [Gubbins and Davies, 2013]. Its thickness is much smaller than the thickness of the sub-adiabatic (thermal) layer and is of order 10–100 kilometers or less.

Below we consider scenario of the joint cooling of the core and mantle of the Earth and show that before the appearance of the solid core, the sub-adiabatic layer prevented dynamo in the upper layer of the liquid core. As a result, observers at the Earth's surface registered magnetic field with an increased dipolarity. Such a magnetic field is denoted as the super-dipole.

### Model of the Earth Cooling

We will take as the basis the model of the joint cooling of the mantle and the core of the Earth [Reshetnyak, 2022]. Cooling of the Earth occurs due to the heat flux  $Q_s$  at the surface of the Earth into the surrounding space. The modern value  $Q_s$  is known from observations and is equal to 49 TW. Note, that in the past  $Q_s$  was in order of magnitudes larger than now.

Time  $t$  in the model starts from the moment of separation of the Earth into the mantle and liquid core (approximately 50–100 million years after the end of accretion). The equations of the model are integrated over 6 billion years. The present time  $t$  corresponds to  $t = 4.5$  Gy.

The joint model of cooling let us skip usage of the prescribed heat flux at CMB  $Q_b$ , which is uncertain, and can be calculated in the model directly. The heat flux  $Q_b$  determines cooling of the liquid core. During cooling the solid core begins to grow in the center of the liquid core. Currently, according to seismologists' observations, its radius is  $c = 1200$  km. The age of the core is not known from observations and varies in the models in the range 1–2 Gy [Labrosse *et al.*, 2001].

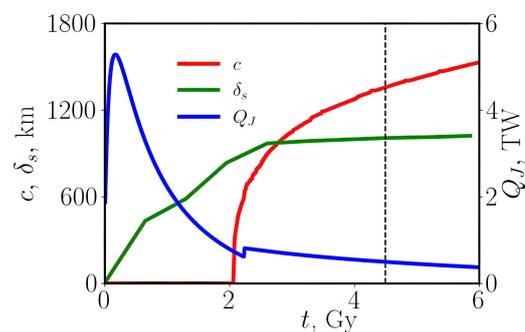
If  $Q_b$  is less than that associated with the adiabatic temperature distribution in the liquid core, the sub-adiabatic thermal layer is formed at CMB. In this layer, as in the solid core, the evolution of the temperature is described by the solution of the heat conduction equation.

For the analysis it is convenient to formulate the inverse problem, the solution of which satisfies the modern values of  $c$  and  $Q_s$ . In addition, the condition of a sufficient amount of energy  $Q_f$ , available for generation of the modern magnetic field, 0.5 TW is introduced [Roberts *et al.*, 2003]. The equations, the values of the model parameters and details of the Monte-Carlo approach for the inverse problem solution are available in [Reshetnyak, 2022]. The multi-processors C++ code is developed for UNIX workstation using MPI library.

The main point of the current simulations is the higher value of the thermal conductivity  $k = 150$  W/(m · K) of the liquid core [Gubbins *et al.*, 2015] which is 3 times larger than in [Reshetnyak, 2022]. Provided that the heat flux at CMB is ruled by the process in the mantle and slightly depends on the processes in the core, increase of  $k$  leads to the origin of the sub-adiabatic layer at CMB in the core. In other words mantle can not provide enough cooling for the convection in the whole volume of the core.

The inner core in the model appeared 2.5 billion years ago, see Figure 1. By this time, a sub-adiabatic layer of thickness  $\delta_s \sim 800$  km already existed in the core. Note, that before the inner core origin there was enough energy  $Q_f > 0.5$  TW to generate a magnetic field. If for the models with the liquid core cooling alone possibility of magnetic field generation

only by the mechanism of thermal convection (before the appearance of a solid core) is the subject of discussion [Olson, 2013], then in the models with the joint cooling of the mantle and core it turns out that  $Q_b$ ,  $Q_J$  are sufficient to maintain the dynamo process. The reason is existence of the more developed convection in the mantle in the joint models at the early stages of the planet evolution [Abe, 1993]. At that time, the mantle temperature was somewhat higher than now, and the viscosity of the substance of the mantle, which depends on the temperature in an exponential law, was lower. As a result  $Q_J$  was large enough to provide magnetic field generation, see Figure 1. The origin of the inner core only slightly increased  $Q_J$ , what makes it difficult to identify the inner core origin using paleomagnetic data. Compared to the joint models only 10–20% increase of  $Q_b$  for 4.5 Gy was introduced in the models for the liquid core cooling alone [Labrosse *et al.*, 1997], as a result  $Q_J$  was quite small and existence of the magnetic field generation before the inner core origin was under consideration.



**Figure 1.** Evolution of the inner core radius  $c$ , thickness of sub-adiabatic layer  $\delta_s$  and energy available for magnetic field generation  $Q_J$ .

Note, that the joint cooling model predicts the older inner core due to the larger  $Q_b$  at the early times. But the sub-adiabatic layer masks this effect. As a result, it takes 2 Gy after the end of accretion for the inner core to appear.

### Consequences for the Geodynamo

Generation of the large-scale magnetic field is possible in the certain range of amplitudes of convection energy sources ( $E_{\min}$ ,  $E_{\max}$ ) [Christensen and Aubert, 2006]. Qualitatively, the result does not depend on whether convection is purely thermal or combined thermal and compositional. The latter is associated with the flux of the light fraction, released during the growth of the solid core. The lower limit of this range  $E_{\min}$  is determined by the minimum energy required to maintain the dynamo process. In the vicinity of  $E_{\min}$  magnetic field is the strong non-reversing dipole.

The upper limit  $E_{\max}$  is associated with implementation of the required balance of forces, at which generation of the large-scale magnetic field is possible. When the source energy exceeds the  $E_{\max}$  value, the magnetic field becomes small-scale, the magnetic dipole often changes sign, its amplitude decreases by an order of magnitude or more. The total magnetic energy in the core is comparable to the former case.

According to paleomagnetic observations, there is no reason to believe that ancient magnetic dipole field was weaker than the modern one significantly [Smirnov *et al.*, 2016]. From that follows that the energy sources did not change significantly during the evolution. On the other hand, the appearance of the sub-adiabatic layer imposes additional restrictions on the generation of the magnetic field, changing its structure at the surface of the planet [Gastine *et al.*, 2020]. The presence of the negative temperature gradient in the layer leads to the suppression of the radial velocity component, making dynamo impossible. Although some radial velocity perturbations penetrate into the sub-adiabatic layer, overall convection becomes less intensive and magnetic field generation is effectively shifts deeper in the liquid core.

The removal of the active generation region from the observer at the Earth's surface leads to an effective dipolarization of the magnetic field due to the faster weakening of the small-scale field compared to the dipole component. The field becomes superdipole.

To be more specific consider some results of the numerical modeling. The degree of stratification in the sub-adiabatic layer can be measured by the squared value Brunt–Väisälä frequency  $N$ :

$$N^2 = \alpha g \left( \frac{\partial T}{\partial r} - \frac{\partial T}{\partial r} \Big|_s \right),$$

where  $\alpha$  is coefficient of volume expansion,  $g$  is the gravity,  $T$  is temperature, and  $s$  denotes isentropic profile of  $T$  over radius  $r$ . Positive  $N^2$  corresponds to unstable flow, and negative – to thermal stratification, [see, e.g., Rogister and Valette, 2009].

In the general case with  $N^2 < 0$  only in the layer (near CMB), it is important to know not only the boundary layer thickness  $\delta_s$  (where  $N^2$  changes sign), but the distance of penetration  $D_p$  of a convective eddy of size  $L_s$  into the layer:

$$D_p = \left( \frac{N}{\Omega} \right)^{-1} L_s,$$

where  $\Omega$  is the rotation rate of the Earth [Takehiro and Lister, 2001]. The larger  $N$  (the stronger stratification) the smaller is  $D_p$ . On contrary, increase of  $\Omega$  leads to intensification of columnar convection, and as a result to the larger amplitude of convective eddy at the boundary of stratified layer ( $D_p$  increases). The idea is that even for the large  $\delta_s$  effect of penetration of the intensive convection into the sub-adiabatic layer can be important.

Numerical experiments [Gastine et al., 2020] reveal that already layers with  $\delta_s \sim 200\text{--}300\text{ km}$  and accepted in dynamo community values of  $\Omega$  increase dipolarity of the magnetic field at the surface of the Earth in order of magnitude. The authors also indicate that known patches of the inverse polarity of the magnetic field at the high latitudes disappear as well. The latter increases the axi-symmetric counterpart of the magnetic field. The other interesting effect is that the layer amplifies the anti-symmetric modes in respect to the equator plane.

So far the features of the magnetic field corresponding to the large  $\delta_s$  contradicts to observations, the authors of [Gastine et al., 2020] come to the conclusion that the sub-adiabatic layer should be small and its effect on the magnetic field at the surface at the Earth is negligible for the present time.

This conclusion in somewhat is not surprising because the flux of the light material, releasing during the inner core growth, increases  $D_p$ . But before the inner core origin effect of the sub-adiabatic layer could be much more pronounced. Note, that accordingly to Figure 1 to the moment of the inner core origin  $\delta_s$  was 800 km. Of course the exact value  $\delta_s$  depends on the parameters of the model of the Earth's cooling, however we can not exclude such a possibility at all and should include this scenario in the more complex models.

## Discussion and Conclusions

Above we have shown that it is possible to identify the appearance of the solid core using paleomagnetic data. On the one hand, the amount of energy  $Q_f$ , available for generation of the magnetic field, did not change significantly with the appearance of the solid core. On the other hand, the appearance of a solid core leads to propagation of convection and dynamo process into the entire volume of the liquid core. For the observer it means that the magnetic field generation region is approaching to the core surface.

Note, that the above mentioned scenario of the magnetic field evolution is based only on the influence of convection near CMB on the magnetic field at the surface of the planet. The general problem is more complex. There are many other effects which can change structure and intensity of the magnetic field during evolution. Here we list some of them. The magnetic field generation in the whole volume of the liquid core is also sensitive to the inner core origin in the other way as well. Since magnetic field generation is very intense

at the inner core boundary due to the differential rotation, the maximum of the magnetic field generation effectively moves deeper into the liquid core with the inner core origin. The latter is expressed in an increase of dipolarity of the magnetic field at the surface in the same way as for the sub-adiabatic layer. It can mask detection of the inner core origin. In its turn, decrease of the thickness of the liquid core, related to the growth of the inner core, decreases the scale of the magnetic field, making it solar-like with the smaller *Dip*.

The other long-term effect is the general cooling of the Earth, which decreases intensity of convection. As was mentioned above, approach to  $E_{\min}$  leads to the strong dipole regime without reversals.

To take into account all these effects (inner core growth and penetration of convection in the sub-adiabatic layer) together with the cooling Earth's model the direct numerical simulations of dynamo equations are needed.

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## References

- Abe Y. Physical state of the very early Earth // *Lithos*. — 1993. — Vol. 30, no. 3/4. — P. 223–235. — [https://doi.org/10.1016/0024-4937\(93\)90037-d](https://doi.org/10.1016/0024-4937(93)90037-d).
- Aubert J. State and evolution of the geodynamo from numerical models reaching the physical conditions of Earth's core // *Geophys. J. Int.* — 2023. — Vol. 235, no. 1. — P. 468–487. — <https://doi.org/10.1093/gji/ggad229>.
- Braginsky S.I. Structure of the F layer and reasons for convection in the Earth's core // *Dokl. Akad. Nauk. SSSR Engl. Trans.* — 1963. — Vol. 149. — P. 1311–1314.
- Christensen U. Geodynamo models with a stable layer and heterogeneous heat flow at the top of the core // *Geophys. J. Int.* — 2018. — Vol. 215, no. 2. — P. 1338–1351. — <https://doi.org/10.1093/gji/ggy352>.
- Christensen U. and Aubert J. Scaling properties of convection-driven dynamos in rotating spherical shells and application to planetary magnetic fields // *Geophys. J. Int.* — 2006. — Vol. 166. — P. 97–114. — <https://doi.org/10.1111/j.1365-246X.2006.03009.x>.
- Christensen U., Aubert J. and Hulot G. Conditions for Earth-like geodynamo models // *Earth Planet. Sci. Lett.* — 2010. — Vol. 296, no. 3/4. — P. 487–496. — <https://doi.org/10.1016/j.epsl.2010.06.009>.
- Gastine T., Aubert J. and Fournier A. Dynamo-based limit to the extent of a stable layer atop Earth's core // *Geophys. J. Int.* — 2020. — Vol. 222, no. 2. — P. 1433–1448. — <https://doi.org/10.1093/gji/ggaa250>.
- Gubbins D., Alfè D., Davies C.J., et al. On core convection and the geodynamo: Effects of high electrical and thermal conductivity // *Phys. Earth Planet. Int.* — 2015. — Vol. 247. — P. 56–64. — <https://doi.org/10.1016/j.pepi.2015.04.002>.
- Gubbins D. and Davies C.J. The stratified layer at the core–mantle boundary caused by barodiffusion of oxygen, sulphur and silicon // *Phys. Earth Planet. Int.* — 2013. — Vol. 215. — P. 21–28. — <https://doi.org/10.1016/j.pepi.2012.11.001>.
- Gubbins D., Thomson C.J. and Whaler K.A. Stable regions in the Earth's liquid core // *Geophys. J. Roy. Astr. Soc.* — 1982. — Vol. 68, no. 1. — P. 241–251. — <https://doi.org/10.1111/j.1365-246X.1982.tb06972.x>.
- Labrosse S., Poirier J.-P. and Le Mouél J.-L. On cooling of the Earth's core // *Phys. Earth Planet. Int.* — 1997. — Vol. 99, no. 1. — P. 1–17. — [https://doi.org/10.1016/S0031-9201\(96\)03207-4](https://doi.org/10.1016/S0031-9201(96)03207-4).
- Labrosse S., Poirier J.-P. and Le Mouél J.-L. The age of the inner core // *Earth Planet. Sci. Lett.* — 2001. — Vol. 190, no. 3/4. — P. 111–123. — [https://doi.org/10.1016/S0012-821X\(01\)00387-9](https://doi.org/10.1016/S0012-821X(01)00387-9).
- Lowes F.J. Spatial power spectrum of the main geomagnetic field // *Geophys. J. R. Astr. Soc.* — 1974. — Vol. 36. — P. 717–725. — <https://doi.org/10.1111/j.1365-246x.1974.tb00622.x>.
- Nichols C.I.O., Weiss B.P., Eyster A., et al. Eoarchean records of the geomagnetic field preserved in the Isua Supracrustal Belt, southern west Greenland // *J. Geophys. Res. Solid Earth*. — 2024. — Vol. 129, no. 4. — e2023JB027706. — <https://doi.org/10.1029/2023JB027706>.
- Olson P. The new core paradox // *Science*. — 2013. — Vol. 342, no. 6157. — P. 431–432. — <https://doi.org/10.1126/science.1243477>.
- Reshetnyak M.Yu. Evolution of the inner core of the Earth: consequences for geodynamo // *Magnetohydrodynamics*. — 2019. — Vol. 55, no. 1/2. — P. 175–183.
- Reshetnyak M.Yu. Mantle cooling regulation and ancient geomagnetic field // *Russ. J. Earth Sci.* — 2022. — Vol. 22. — ES2006. — <https://doi.org/10.2205/2022ES000797>.

- Roberts P.-H., Jones C.A. and Calderwood A.R. Energy fluxes and ohmic dissipation in the Earth's core // *Earth's core and lower mantle* / ed. by C.A. Jones, A.M. Soward and K. Zhang. — Taylor, Francis, 2003. — P. 100–129. — <https://doi.org/10.1201/9780203207611.CH5>.
- Rogister Y. and Valette B. Influence of liquid core dynamics on rotation modes // *Geophys. J. Int.* — 2009. — Vol. 176. — P. 368–388. — <https://doi.org/10.1111/j.1365-246X.2008.03996.x>.
- Smirnov A.V., Tarduno J.A., Kulakov E.V., et al. Palaeointensity, core thermal conductivity and the unknown age of the inner core // *Geophys. J. Int.* — 2016. — Vol. 205, no. 2. — P. 1190–1195. — <https://doi.org/10.1093/gji/ggw080>.
- Takehiro S. and Lister J.R. Penetration of columnar convection into an outer stably stratified layer in rapidly rotating spherical fluid shells // *Earth Planet. Sci. Lett.* — 2001. — Vol. 187, no. 3/4. — P. 357–366. — [https://doi.org/10.1016/S0012-821X\(01\)00283-7](https://doi.org/10.1016/S0012-821X(01)00283-7).