Earth's magnetic field generated at D" layer

Yozo Hamano

hamano@eps.s.u-tokyo.ac.jp Dept. Earth and Planetary Sci., University of Tokyo, Japan

1 Introduction

Global seismic tomography and mantle convection modeling show the existence of horizontal variations of the physical properties in the mantle. The heterogeneities in the seismic velocities are large in the upper mantle and near the core-mantle boundary, where the D" layer is well known to be highly heterogeneous. Causes of these lateral heterogeneities are generally attributed to the temperature and/or compositional variations. Hence, the electrical conductivity heterogeneity is also expected associated with the above heterogeneities.

Although the strong lateral heterogeneity in electrical conductivity has been observed in the crust and the upper mantle, direct observation of the electrical conductivity heterogeneity of the D" layer is not possible yet. Even an average conductivity in the D" layer is still in controversial, where previous estimates of the electrical conductivity ranges from 10 S/m to 1000 S/m (Stewart et al., 1995). In order to estimate the conductivity structure in the lower mantle, we need to use the geomagnetic signals generated in the core. External signals generated by the current system in the ionosphere and magnetosphere largely attenuates through the upper mantle, and the observations of the induced field due to the external sources is not sensitive enough to detect the electrical conductivity of the lower mantle. In the present work, we utilize a newly developed method of forward modeling of 3-D earth (Hamano, 2001), which treat the induction problem in a spherical earth with a 3-D heterogeneous electrical conductivity structure. By solving the induction equations for B and E in time domain, we can calculate the temporal variation of the magnetic field on the surface caused by the current system flows in the D" layer, which is induced by the variation of the geomagnetic field in the core

2 Method and 2-layer mantle model

For the calculation, we use a simple 2-layer model of the mantle. In this model, the top layer covers the upper mantle and most part of the lower mantle, and extends from the surface to the top of the D" layer (r=6371-3731km). Thickness of the D" layer is fixed to be 250 km. Electrical conductivity of the top layer is set to 1 S/m. Published estimates of the lower mantle conductivity spans a wide range from 1 S/m to 1000 S/m. Based on the extrapolation of the result of the laboratory experiments on the electrical conductivity of mantle minerals, Shankland et al., (1993) support the lower side of the observed conductivity models. Since we are interested in the effect of the D" layer, we choose the lowermost value of 1S/m, so that the field generated in the D" layer is not severely distorted in the top layer.

At present, no consensus does exist for the electrical conductivity of the D" layer. Although the temperature dependence of the electrical conductivity does not support the high conductivity in the D" layer relative to the adjacent mantle, intrusion of the conductive core material may cause a very high conductivity (Knittel and Jeanloz, 1991; Poirier and Le Mouel, 1992) . In the present work, we calculated various models with the D" layer conductivity of 10 S/m, 50 S/m, 100 S/m, and 500 S/m.. Although much higher conductivity might be possible due to the existence of core material in the D" layer, it is not reasonable to assume the intrusion extends through the entire section of the D" layer (250 km thickness).

As for the lateral heterogeneity of the electrical conductivity in the D" layer, we use the results of the seismic mantle tomography. Most of the tomography models indicate the presence of more than +-2% of S-wave velocity heterogeneity . Compilation of the seismic tomography data sets (Yanagisawa and Hamano, 1999) indicates that standard deviation of the distribution of S-wave velocity in the D" layer slightly exceeds 1% for the existing models, suggesting feature of the heterogeneity in the D" layer of the tomography models is very similar with each other. We use the S-velocity model SAW12D obtained by Li and Romanowicz (1996) to estimate the conductivity heterogeneity in the D" layer. If the +-2% heterogeneity of S-wave velocity is fully attributed to the temperature, necessary temperature difference would be expected more than 1000 K. Possible temperature range at CMB is from 2000 to 3000K. For this variation of the temperature, Shankland et al.(1993) suggest an electrical conductivity variation of about an order of magnitude. If this S-wave velocity heterogeneity is attributed to the compositional heterogeneity, much higher difference might be expected. But, it is not clear whether the observed large scale heterogeneity reflects this compositional change. In the present work, we calculated the several cases with the conductivity contrast of +-25%, +-50%, +-75%, and +-100% correspond to the +-2% velocity contrast of the tomography model. These 4 models give the maximum/minimum conductivity ratio of 1.3, 3, 6, and 10, respectively. Although the last model is more probable, we use the other models in order to estimate the higher contrast case, because the higher contrast of the conductivity makes the numerical calculations to be unstable.

In the present calculation, the coefficients of the spherical harmonic coefficients of the S-wave tomography model is multiplied by the scale factors given above, and used for the calculation. In our approach, the coefficient of the spherical harmonic expansion is directly used for the calculation of the induction effect. For the calculation of the response function of the present earth model, we solved the magnetic induction equations for B and E, simultaneously, since the two modes (toroidal and poloidal) are mutually coupled. The time integration starts when the given core field is suddenly applied at t=0. Time derivative of the induced field generated by this abrupt change of the core field gives the impulse response function of the induced field. Although SAW12D model is given up to 12 degrees, we calculated the response functions up to degree 10. In order to check the termination effect, we calculated the coefficients up to degree 12 for some models. But,no appreciable difference was observed in the calculated response functions.

3 Results

3.1 Response to the poloidal field in the core

As a poloidal core field, we choose an axial dipole field p10, since, at the earth's surface, the axial dipole field dominates and its variations in the longer time scale also dominates over the other components of the geomagnetic field. At CMB, we assume that the axial dipole field is abruptly applied to the boundary, and the response function of all the components of the toroidal and poloidal field up to degree 10 were calculated by the time integration of the diffusion equations.

At the earth's surface, the toroidal field disappears, and only the poloidal field exists. The time variation of the poloidal field is transient one, and is generated by the electric current flows within the D" layer induced by the abrupt change of the core field. Time duration of the responses depends on the average conductivity of the D" layer. At the earth's surface, the response functions to the abrupt change of the poloidal core field have a spindle shape, and consist of the initial rapidly increasing phase (or decreasing one, depends on the sign of the induced field) to the maximum (or minimum) values and the later gradual decreasing phase (or increase) to zero. Typical rise times to the maximum (or minimum) values are 17 days, 33 days, 50 days, and 170 days, for the D" layer conductivity of 10 S/m, 50 S/m, 100 S/m and 500 S/m, respectively. The rise time is slightly diminished for the higher degree of the coefficients. Surface induced field is dominated with the low degree components, suggesting the random excitation of the induced field in the D" layer. Within each degree, h21, h22, g30, h32, g41,h42.g44.h52,and h54 components are large compared to other components.

Amplitude of the response functions depend on the conductivity of the D" layer. For one of the dominant phase of h21, the amplitudes are 0.00025, 0.0007, 0.00087, 0.00108, for the conductivities of 10 S/m, 50 S/m, 100 S/m and 500 S/m, respectively, where the values are normalized to the magnitude of g10 at CMB. It is to be noted that the time variation of the g10 component at the earth's surface has a shape of ramp function, and the final value is 0.128 due to the geometrical attenuation. The increase of the amplitude of the response functions with the increase of the D" layer conductivity is attributed to the increase of the current flow in the D" layer corresponds to the higher conductivity. This characteristics of the response functions to the poloidal induction of the core field is different in the next toroidal induction case.

3.2 Response to the toroidal field in the core

For the toroidal field in the core, we first choose t20 component, since the component is considered to be a dominant toroidal field corresponds to the dominance of the axial dipole component in the poloidal field. For the response function of the poloidal field, t20 component are abruptly applied in the core at t=0, and time integration started. The computation procedure is the same as the poloidal case.

Response of the poloidal fields in this case is quite different compared to the poloidal induction. Time variation of the response functions of the poloidal components has a shape of a ramp function, where each component monotonously changes from the zero starting value to the final value. Hence, the permanent poloidal field remains correspond to the existence of the toroidal field in the core. This situation is easily understand as follows.

As evident from the Maxwell equations, the toroidal magnetic field is accompanied with the poloidal electric field, and the radial component of the electric current exist. The existence of the toroidal magnetic field at CMB means the electric current flows into the lowermost part of the mantle. This current flows the conductive part of the mantle, and returns to the core. If the conductive part of the mantle is laterally homogeneous, this current system does not generate the poloidal magnetic field. However, if the lowermost part of the mantle, i.e. the D" layer, is laterally heterogeneous, the horizontal current concentrate to the relatively conductive part within the D" layer, and this current flow arises the poloidal field which can be observed at the earth's surface.

In the present case, t20 field in the core, the permanently generated poloidal field is dominated with the higher degree components. At the top of the D" layer, degree 1 and degree 2 components are not effectively generated and the components higher than degree 3 are more or less randomly generated. At the earth's surface, the mean square field strength, which is proportional to the magnetic energy of each degree, monotonously decreases with the increase of the degree. Contrary to the poloidal induction case, the dependence of the power of the generated field on the electrical conductivity of the D" layer is weak. For the range of the conductivity between 50 S/m and 500 S/m, the difference of the generated field is negligible, though the power is reduced by factor 2 for the conductivity of 10 S/m. On the other hand, the dependence on the conductivity contrast is relatively large. Mean square field strength for degree 3 is 7x10^{-7}, 2.5x10^{-7}, 1.3x10^{-7}, 0.3x10^{-7}, for the conductivity contrast of 100%, 75%,50%,and 25%, respectively. The values are normalized to the toroidal field. Hence, degree 3 poloidal field of 1/1000 of the toroidal core field is generated at the surface in the case of 100% contrast. This amplitude is reduced by a factor of 5 for the 25% contrast case.

As for the spatial distribution of the generated field, we synthesized the vertical component of the geomagnetic field, Bz, from the calculated surface gauss coefficients up to degree 10. Comparison of the synthesized field with the field calculated from the IGRF field averaged for the period of 1900 - 2000 by using the IGRF gauss coefficients from degree 3 to degree 10, indicates that main feature of the IGRF field is explained by the field generated in the D" layer. This suggests that the higher degree components of the geomagnetic field (higher than degree 2) of the present geomagnetic field are generated at the D" layer due to the existence of the toroidal field in the core, and not the poloidal field in the core. The necessary strength of the toroidal field in the core is estimated to be about 10 mT for the 50 % contrast case. If the conductivity contrast is 100%, the necessary toroidal field can be reduced to 3 mT, and about 20 mT is required for the 25% contrast case. The magnitude of this toroidal field is about an order of magnitude larger than that of the poloidal field

4 Discussion

Since the magnetic field due to t20 field in the core is similar to the present geomagnetic field, we calculated the field generated by t10, t30, t40, t50, t60, t70, and t80 components in the core. The field generated by these zonal toroidal field show similar features with the field generated by t20, where the field generated by the even degree toroidal field is rather similar to the field generated by t20, and the field generated by the odd degree toroidal field is quite different. This may suggest the dominance of the even-degree toroidal field in the core.

The efficiency of generation of the poloidal field increases for the higher degree toroidal field. In the case of t80 toroidal field, generated power of the poloidal field is about an order of magnitude larger than that of t20 induction. Hence, the required strength of t80 toroidal field is 2.5 mT for the 50% contrast case. This toroidal field is typical of the toroidal field strength in the core obtained by balancing the Lorentz and Coriolis forces. Stewart et al.(1995) estimated the toroidal field strength of 3.5 mT from the observed elctromagnetic torque between the mantle and the core. It is also to be noted that the higher degree toroidal field more efficiently generates the degree 1 and degree 2 components of the poloidal field, although the generated degree 1 and 2 components are not sufficient to explain the present geomagneic field.

Since each component of the toroidal field generate the surface poloidal field similar to the present geomagnetic field, we combined all the field generated by the zonal toroidal field of degree 1 to 8, and fitted to the IGRF geomagnetic field by the least squares method. Result of the least squares fit gives a field pattern very similar to the present geomagnetic field with the spherical harmonic components higher than degree 2. Moreover, this fitting procedure gives the estimate of the toroidal field in the core . The latitudinal dependence of the toroidal field in the core has two peaks in each hemisphere, and the highest strength of the zonal toroidal field is attained at around 70-80N, which is roughly correspond to the intersection of the cylinder surrounding the inner core. The corresponding peak at high latitude in the southern hemisphere is obscure, suggesting the highly biased distribution of the toroidal field at high latitudes. The middle latitude peaks at aroun 30N and 30S is rather comparable in the northern and the southern hemisphere.

5 Reference

Hamano, Y., Electromagnetic tomography: method in time domain, *this issue*, 2001.

Knittel, E., and R. Jeanloz, Earth's core-mantle boundary: Results of experimants at high pressure and temperature, *Science*, **251**, 1438–1443, 1991.

Li, X. -D., and B. Romanowicz, Global mantle shear velocity model developed using nonlinear asymptotic coupling theory, *J. Geophys. Res.*, **101**, 22,245–22,272, 1996.

Poirier, J.-P., and , J. L. Le Mouel, Does infiltration of core material into the lower mantle affect the observed geomagnetic field, *Phys. Earth Planet. Int.*, **73**, 29–37, 1992.

Shankland, T. J., J. Peyronneau, and J. -P. Poirier, Electrical conductivity of the Earth's lower mantel, *Nature*, **366**, 453–455, 1993.

Stewart, D. N., F. H. Busse, K. A. Whaler, and D. Gubbins, Geomagnetism, Earth rotation and the electrical conductivity of the lower mantle, *Phys. Earth Planet. Int.*, **92**, 199–214, 1995.

Yanagisawa, T., and Y. Hamano, "Skewness" of S-wave velocity in the mantle, *Geophys. Res. Letters*, **26**, 791–794, 1999.