A status report of MUD “Global Event” group: A dynamic interaction between Earth’s interior and surface environments in the mid Cretaceous

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1. Introduction

Mid Cretaceous has been recognized as “Greenhouse Earth”. Both marine and terrestrial records strongly suggested that the climate in this period was substantially warmer than today, with the sea surface temperature being up to 20ºC even in the Arctic region [*Jenkyns et al*., 2004]. It has been suggested that the warm climate was attributed to an enhanced rates of crustal production [e.g., *Eldholm and Coffin*, 2000], leading to an enhanced greenhouse effect with the atmospheric CO_2 level of 3-5 times higher than that of the present [*Tajika*, 1998]. Hence, it was a period when the Earth’s surface environments tightly coupled with the activity of Earth’s interior.

The paleomagnetic record of the Earth’s magnetic field shows that the dipole field reversed its polarity several hundred times during the past 150 Myr. The geomagnetic reversal occurs randomly, but in the mid Cretaceous, from 120 Ma normal geomagnetic polarity duration lasted for about 40 Myr. This is known as Cretaceous superchron. The geomagnetic field is produced and maintained by the convective motion in the Earth’s outer core; hence this suggests the core was at a peculiar state during the superchron. This coincidence of the time of anomalous activity at the surface and the core points out the role of the Earth’s mantle, which lies and connects between the two. Mantle occupies large volume and mass of the Earth, so it has a potential to control the behavior of the other parts of the Earth. To understand the mechanisms of coupling, we should investigate the activity of Earth’s interior, especially for lower mantle and core as well as surface environments with sufficient age control.

In the “Global Event” group of multi-disciplinary (MUD) investigation in IFREE, many scientists in a variety of fields including geochemistry, geodynamics, petrology, seismology, paleomagnetism, and paleoceanography have been studying and discussing the interaction between Earth’s interior and surface environment during the Cretaceous. In this report, we describe the progresses achieved by the group in 2004 and propose the directions of scientific activity of this group in 2005.

2. LIPs as a causal mechanism for Cretaceous Oceanic Anoxic Event 2

The mid Cretaceous marks episodic depositions of black shales in the ocean. The black shales are dark-colored muddy sedimentary rocks unusually enriched in organic carbon [*Ohkouchi et al*., 1997]. The depositional events of black shales were referred to as “oceanic anoxic events” (OAEs). So far two major OAEs have been proposed in the mid Cretaceous; early Aptian (ca. 120 Ma; OAE-1a) and Cenomanian-Turonian boundary (ca. 93 Ma; OAE-2). During these OAEs, carbon isotopic compositions for both marine carbonate and organic matter demonstrate substantial (up to 6‰) increases [e.g. *Gale et al*., 1993], suggesting a preferential removal of ^{13}C-depleted (-30 to -25‰) organic carbon from the atmosphere-ocean reservoir during these periods. A significant decrease in atmospheric CO_2 concentration during the OAE-2 was suggested by substantial drop in the isotopic fractionation associated with photosynthesis [*Freeman and Hayes*, 1992]. This decline is also documented indirectly by oxygen isotopic composition of marine carbonate, which indicated an 8ºC to 13ºC cooling of sea surface temperature in high latitudes in the early Turonian [*Jenkyns et al*., 1994].

Recently, we obtained a ultra-high-resolution carbon isotopic record of sedimentary organic matter from Livello Bonarelli black shale outcropped in Apennine, central Italy, a representative black shale in the OAE-2. As shown in Figure 1, we found a sharp, negative isotopic shift (~3‰) within about 15 kyr at the beginning of the event [*Kuroda*, 2005]. Furthermore, at the same stratigraphic level, we found that the lead isotopic compositions of sedimentary aluminosilicates exhibited significant shifts toward characteristic values of large igneous provinces (LIPs) [*Kuroda*, 2005]. These results are first evidence directly indicating that massive volcanism coincident with the onset of the OAE. The carbon cycle in the atmosphere-ocean pool was perturbed by massive volcanic degassing of carbon dioxide, and supply of volcanogenic aluminosilicates derived from LIPs was enhanced. In 2005, to confirm and strengthen above results, we plan to perform further analyses of the lead isotopic compositions of aluminosilicates from the OAE-2 black shales as well as Madagascal LIP, a LIP potentially caused for OAE-2.

3. The rhythm generated by mantle transition zone

The intermittent activity of mantle plumes is one of the plausible substances that produce the rhythm relating to these phenomena [e.g., *Larson*, 1991]. The subject is how we can reproduce mantle plumes activity that has intermittency of hundreds million years with large fluctuation of heat transport. The thickness of boundary layer for mantle convection is about hundred kilometers, and it may not be sufficient for generating such long-term and large-amplitude intermittency. Here we focus on the phase transition of mantle minerals at 660 km depth, which works as a barrier against the vertical flow, and seek the intrinsic intermittency of mantle convection. In order to clarify the origin of the correlation between the variations of the surface volcanism and the core, we performed numerical simulation of mantle convection in a 3-D spherical shell, where systematic parameter studies were made in the space of the Rayleigh number (*Ra*) and the Clapeyron slope (*dP/dT*) of the phase transition at 660 km depth [*Yamagishi et al*., in this volume]. In the studied parameter range (Ra: $7x10^4$ ~ $7x10^6$, *dP/dT*: 0 ~ -16MPa/K), we find three convection regimes. At low *Ra* and low |*dP/dT*|, the whole-layer convection mode is observed, and at high *Ra* and high |*dP/dT*|, the convection is in two-layer mode. At transitional values of *Ra* and |*dP/dT*|, the convection mode vacillates between the whole-layer and the two-layer regimes. In this intermittent convection regime, especially for the conditions close to two-layer mode, there exist horizontally large-scale stagnant structures in the mantle transition zone, and they collapse into the lower mantle periodically. This causes the fluctuations of surface and core-mantle boundary (CMB) heat flows, moreover the surface and CMB heat flows vary coherently (Fig. 2). The surface heat flow can be translated into volcanic activity, and high heat flow means high production rate of the crust. The cycle of the heat flow variation at both top and bottom of the mantle is characterized by the rapid increase within several tens of million years, and gradual decrease after the peak. This feature is very similar to the curve of reconstructed crustal production rate that has the maximum in mid-Cretaceous. Lateral heterogeneity of the heat flow is also high around the peak. In the typical case for *Ra*=$7x10^6$, the period of the fluctuation is around 200 Myr, which is comparable with the geological evidences mentioned above. The time lag of the peaks of heat flows between the top and bottom is within several million years in these simulations. The coherency of the surface and the CMB heat flow suggests that the CMB heat flow is considered to be high during the Cretaceous superchron, and that it has been gradually decreased to the present value.

The total heat flow and the spatial pattern of heat flux at the CMB may control the convective motion and magnetic field generation in the fluid outer core. Recent geodynamo simulations indicate that the increase of the total heat flow through the CMB changes the geodynamo from stable dipolar dynamos to unstable multipolar dynamos [*Kutzner and Christensen*, 2002], and axially symmetric and equatorial symmetric pattern in heat flux realize stable dipolar dynamo [*Glatzmaier et al*., 1999]. The above interpretation from the mantle simulation is in opposite sense from that based on the geodynamo simulation. Therefore, we are planning to carry out both mantle and geodynamo simulations with more earth-like settings. In the previous dynamo models, the Ekman number, which is the ratio of the viscous force to the Coriolis force, were taken to be much higher than the Earth for the sake of numerical stability. At the lower Ekman number, different dynamo regime may arise, where the increase of *Ra* stabilizes the dynamo action. The simulations with the heterogeneous boundary conditions at the top of the core (that is, the bottom of the mantle) are not studied enough. By using the Earth Simulator, we put the patterns of bottom heat flux from mantle simulations as the boundary conditions for core simulations, and study the reaction of core convection. On the side of mantle simulation, we will take additional effects into account for the calculation. One is the viscosity variation in the mantle, such as higher viscosity for the lower mantle and temperature-dependence of viscosity. Moreover, we check the role of the other two phase transitions proposed for mantle, 410 km with positive Clapeyron slope, and near the bottom of the lower-mantle (post-perovskike), separately and simultaneously with 660 km phase transition. With these simulations, we can make up clearer image for the interacting two convective systems, mantle and core.

4. Paleomagnetic reconstruction of the intensity and stability of geomagnetic field during the Cretaceous superchron

Superchrons certainly suggest a strong influence of the intermittent activity of the mantle on the geodynamo because core dynamics has no natural timescale that long. A particular dynamo regime driven by high CMB heat flow during superchrons could be reflected by average geomagnetic field strength and variance. To document the long-term nature of the Cretaceous superchron, therefore, has been a major matter of interest to paleomagnetism. However, there is a small number of published determinations of absolute paleointensity obtained by reliable double-heating techniques (several versions of the Thelliers' method) for this period, and at this stage, their dispersion prevent us from settling how the mid Cretaceous field intensity is characterized. For the beginning and the end of the superchron, the majority of the previous data [e.g., *Tanaka and Kono*, 2002] yield lower intensities than today's value by roughly a factor of 2. On the other hand, recent studies with plagioclase crystals derived from the mid Cretaceous volcanic units [e.g., *Tarduno et al*., 2001] showed approximately 1.5 times higher intensities than that of today's field.

Aiming at accumulation of reliable paleomagnetic data during the Cretaceous superchron, we have started the following two studies. The first subject is absolute paleointensity determinations with single plagioclase crystals included in volcanic rocks. This could be a promising approach to obtain the most reliable data from Mesozoic and older volcanic rocks, being accompanied by microscopic magnetic observations and TEM observations of magnetization careers. We are starting with examinations of the validity of this technique, using plagioclase samples from recent lava flows of Izu-Oshima, Fuji Volcano, etc., from which we have already obtained absolute intensities with whole rock samples. After establishment and improvement of the methodology, we can adopt it to samples with an age of the mid Cretaceous. Another target is Scaglia Formation, central Italy, described in Section 2. This sequence might have the potential for providing a continuous record of the geomagnetic field over the whole duration of the superchron. From several pilot specimens from limestone samples, we have succeeded to extract stable magnetization components which could be post-depositional remanences. Using this sedimentary sequence, we attempt to reconstruct variation in the geomagnetic field direction, to assess its stability by evaluation of variances of the directional data, and to apply the relative paleointensity method.

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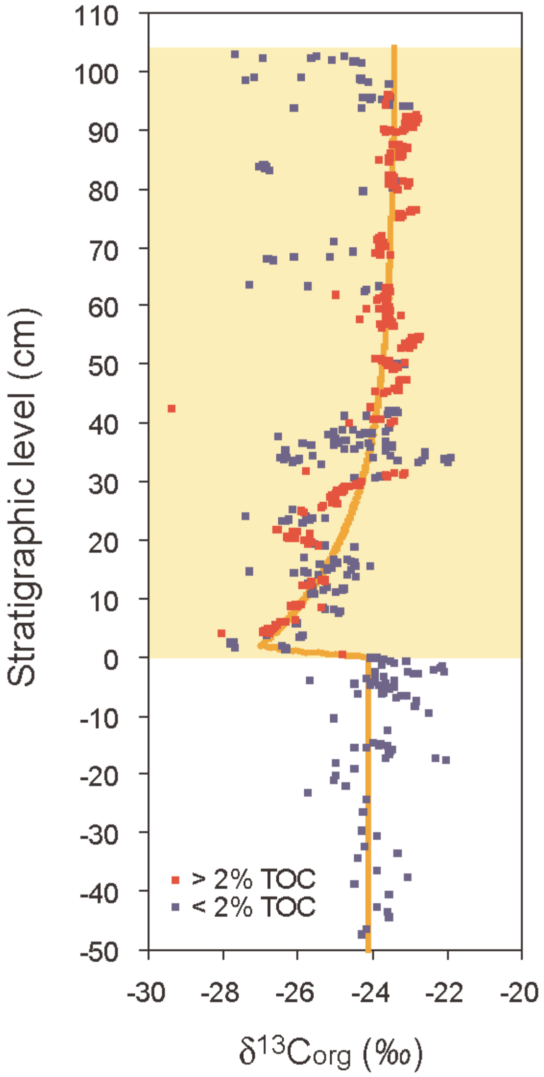

Figure 1. Stratigraphic variation of carbon isotopic composition of total organic matter in the Livello Bonarelli black shale and uppermost Cenomanian limestone. The 0 cm level corresponds to the base of the Bonarelli, and the yellow interval corresponds to the Bonarelli.

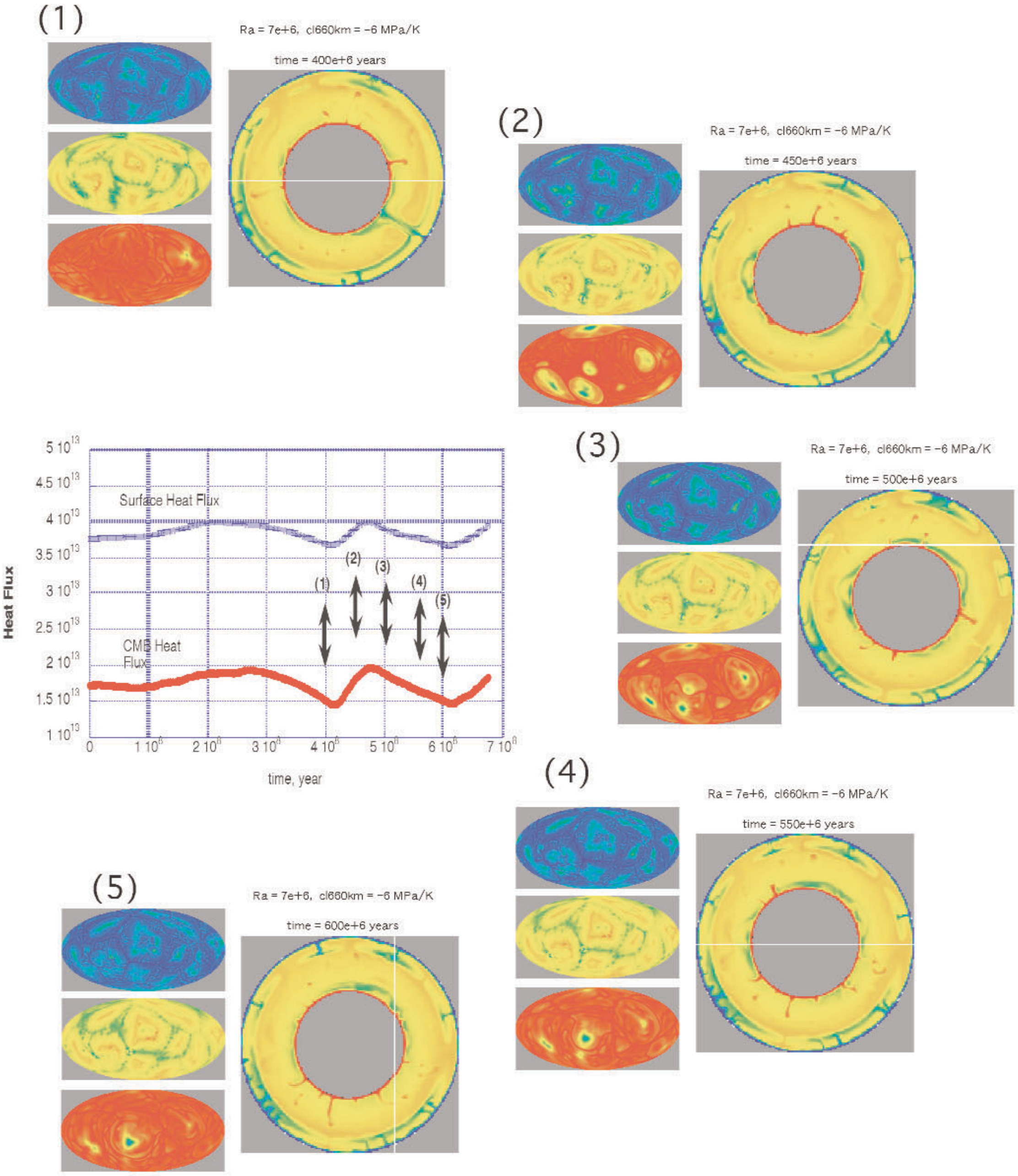

Figure 2. Variations of the temperature distribution during one cycle of the intermittent convection. Ra=7x10^6, dP/dT=-6 MPa/K. (1) t=400 million year, (2) t=450 million years, (3) t=500 million years, (4) t=550 million years, (6) t=600 million years. The graph shows the time series of the surface heat flux (blue), and CMB heat flux (red), for about 700 million years.