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# Nonlinear Dynamic Study on Geomagnetic Polarity Reversal and Cretaceous Normal Superchron

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**Abstract: It is generally acknowledged that geomagnetic polarity has reversed many times in geological history and an abnormal geologic phenomenon is the Cretaceous normal superchron. However, the causes have been unknown up to now. The nonlinear theory has been applied to analyze the phenomenon in geomagnetic polarity reversal and the Cretaceous normal superchron. The Cretaceous normal superchron implies that interaction of the Earth's core-mantle and liquid movement in the outer core may be the lowest energy state and the system of Earth magnetic field maintains a sort of temporal or spatial order structure by exchanging substance and energy in the outside continuously. During 121–83 Ma, there was no impact of a celestial body that would result in a geomagnetic polarity reversal, which may be a cause for occurrence of the Cretaceous normal superchron.The randomness of geomagnetic polarity reversal has the self-reversion characteristic of chaos and the chaos theory gives a simple and clear explanation for the dynamic cause of the geomagnetic polarity reversal.**

**Key words: nonlinearity, geomagnetic polarity reversal, Cretaceous normal superchron (CNS)**

## 1 Introduction

The development of paleomagnetic studies in the second half of the last century has enabled the historical records of the Earth's magnetic field to be extended back both to archeological and nearly the whole of the geological time. So far, it has been gradually noticed that the geomagnetic field history would be linked with many global geological events and the Earth's interior evolution, such as the activity of mantle plumes, changes in the global heat flow, true polarity wander, seafloor spreading, the distribution of oil, global climate changes, the generation of oceanic plateau, seamount chains, continental flood basalts, marine magnetic anomalies, faunal extinction, mantle convection, etc. Especially, the Cretaceous normal superchron (CNS), during which the Earth's field showed no reversals, coincided well with some special changes, such as those in ocean-crust production, severe activity of the volcano, high-latitude sea surface paleotemperature and long-term sea level, wide distribution of black shale's deposition and world oil resources (Zhao, 2005; Huang et al., 2007).

In a period of the Cretaceous there occurred the Cretaceous normal superchron (CNS), a period in which the Earth's magnetic field was so uncharacteristically steady that it did not switch from normal to reversed polarity for about 40 million years (121–83 Ma). The onset time of the CNS coincides very closely with the Cretaceous pulse of rapid spreading and volcanism. Some researchers argue that, during the mid-Cretaceous when magnetic reversal frequency dropped to zero, true polar wander rates were also higher (e.g., Prevot et al., 2000), and remagnetization of rock formations was more widespread in many regions of the world (Vander Voo, 1995). These remarkable geological and geophysical signals in the mid-Cretaceous have excited great interest in the geoscientific community, leading many to suggest a connection between all of these phenomena and the deep-mantle convection.

## 2 Phenomenon of the Earth's Magnetic Field and Cause for Geomagnetic Polarity Reversal

The Earth's magnetic field is attributed to the electrically conducing outer core, which acts as a dynamo. The liquid outer core is primarily composed of iron, which is an excellent electrical conductor at core conditions. Electrical currents in the core generate a magnetic field. Buoyancy forces in the core, due to either temperature or composition, drive a fluid to flow. The flowing electrical conductor in the magnetic field induces an electric field. This is a self-

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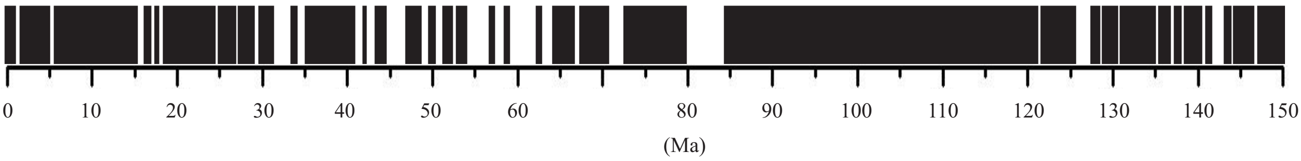


Fig. 1. Temporal geomagnetic polarity during 0–150 Ma. Observed polarity of the Earth's magnetic field for the last 150 Ma. The solid bands are the normal (present) polarity and the open bands are reversed polarity. The last polarity reversal occurred 720,000 years ago.

excited dynamo.

Many volcanic rocks at the surface of the Earth can be magnetized because of the presence of minerals such as magnetite. When these volcanic rocks were cooled through the Curie temperature, they acquired a permanent magnetism from the Earth's field at the time of cooling. Paleomagnetic studies of remanent magnetism have provided a variety of remarkable conclusions (Ji et al., 2007). These studies have traced the movement of the rocks due to plate tectonics and continental drift over periods of hundreds of millions of years. They have shown that the magnetic field at the surface of the Earth has been primarily a dipole, as it is today, and has remained nearly aligned to the Earth's axis of rotation. These studies have also shown that the Earth's magnetic pole becomes the south magnetic pole and vice versa. The observed polarities of the Earth's magnetic field for the last 150 Ma are given in Fig. 1. Measurements indicate that for the last 720,000 years the magnetic field has been in its present (normal) orientation, while between 0.72 and 2.5 Ma B.P. there was a period during which the orientation of the field was predominantly reversed. Clearly, a characteristic of the core dynamo is that it is subject to spontaneous reversals.

For at least the last 160 million years, as known from evidence preserved in the geological record, the Earth's magnetic field has reversed many times in the past, the mean time between reversals being roughly 200,000 years with individual reversal events taking only two thousand years (Clement, 2003). Past field reversals are recorded in the "frozen" magnetic domains in layered basalts on land and on the spreading ocean floors, since the sea floor spreads at a fairly constant rate, this resulting in broad "stripes" of sea floor, from which the past magnetic field direction can be read. It is believed that the last occurred some 780,000 years ago (referred to as the Brunhes-Matuyama reversal), giving rise to the speculation that we are overdue for a reversal. A list of dates of past geomagnetic polarity reversals is known as the geomagnetic polarity time scale. The polarity time scale is broken down into times of dominantly normal polarity and dominantly reversed polarity. These time units are called chrons. Since the last 330 Ma, a vast majority of polarity chron durations generally lies in the range of 0.1 to 1.0 Ma intervals and there are only a few with the duration greater than 2 Ma (Opdyke and Channell, 1996). Merrill et al. (1996) concluded that for the Cande and Kent (1992) time scale, the stabilities for both normal and reversed polarities are statistically the same (or non-stationarity). This is in contrast to earlier conclusions that normal and reverse polarity states had significantly different stabilities, based on earlier times cales (e.g., Philips, 1977). The rate of reversal has varied with time, with a steady decrease from 165 to 120 Ma and a steady increase from 83 Ma to the present (averaged over the past 20 Ma the dipole field has reversed almost five times per million years). The random type of reversal pattern cannot be explained by the physical characteristics of either the liquid or solid part of the core, but might be related to what goes on in the mantle. The fact that the Earth's magnetic field has reversed its polarity many hundreds of times is one of the most significant discoveries in paleomagnetism.

We can imagine the process of a polarity reversal. At the beginning of a reversal the reversed polarity appears firstly in a limited area of the Earth's surface, when most parts of the globe are still in normal polarity. Then the RP area expands, and is associated with intensified reversed field in it. At the same time, new RP areas might appear. If the variation continues in the same way, the whole magnetic field will eventually change its polarity. On the other hand, if the magnetic field varies in the opposite way, an "aborted reversal" will be seen, as demonstrated by Glatzmair and Roberts in their numerical simulation. Paleomagnetic data show that polarity reversals are sometimes global phenomena, and sometimes only local phenomena. The most recent global-scale polarity transition occurred at about 780 ka. After that many events of polarity reversal have been recorded, but no one developed at the global scale. The above-mentioned discussion suggests that reversed polarity would not be usually observed simultaneously in the whole globe. It is also suggested that there might exist several magnetic poles during a polarity transition.

The change in magnetic reversal frequency is on a time scale of 50 Ma, which is consistent with the time scale of mantle convection. This might imply that although an individual reversal possibly has its intrinsic geodynamo origin in fluid motions and electric currents in the earth's core, the changes in magnetic reversal frequency are probably correlated with mantle convection. In other words, changes in energy in the outer core become available to generate turbulence in the fluid motion in the mantle. Larson et al. noted that there is an inverse correlation among magnetic reversal frequency mantle plume activities. They pointed out that this inverse correlation is especially obvious during the CNS, when mantle plume activity was at a maximum. It has been recognized for more than a decade that the core-mantle boundary region, especially the heterogeneous D" layer at the base of the mantle, is a plausible site for mantle plume generation. Because of the high temperature of the D" layer its viscosity is expected to be much smaller than that in the overlying mantle. Mantle plumes erupt from the D" layer wherever thermal buoyancy overcomes the viscosity of the overlying mantle, and lateral flow is added to the layer, which is thinned by the amount of material necessary to fuel the rising plumes. The thinning of D" can lead to an increase in the rate of heat conduction across the core-mantle boundary. The core will respond by convecting more vigorously to restore the abnormal heat loss through its top surface. At last, the increased convection in the outer core will be balanced by an increased rate of freezing at the inner-outer core boundary. It seems that the increase in convection in the outer core can decrease in magnetic reversal frequency. When the convection in the outer core reaches the crucial value, the geomagnetic polarity will keep stable.

The mantle convection might modulate the geodynamo process and geomagnetic secular variation through changes in the topography and heat flux at the CMB. Consequently, the heat structure of the lower mantle would control the way of magnetic reversal frequency. The disturbance of heat in the lower mantle is possibly related to the instability of the heat boundary in the D" layer, and can control the convection in the outer core. This will result in stable or quick variations in reversal frequency.

The mechanism responsible for geomagnetic reversals is not well understood. Most scientists now agree that the Earth's magnetic field arises from convection currents in the liquid outer part of the core, which is a good conductor of electricity. These currents constitute an amplifying, self-sustaining geodynamo. Researchers use the term "geodynamo" to refer to the idea that the geomagnetic field is generated in the center of the Earth. Some scientists have produced models for the core of the Earth wherein the magnetic field is only quasi-stable and the poles can spontaneously migrate from one orientation to the other over the course of a few hundred to a few thousand years. Other scientists propose that the geodynamo first turns itself off, either spontaneously or through some external action like a comet impact, and then restarts itself with the north pole pointing either up or down. The longevity of the Earth's magnetic field, which appears to have existed at least 3 billion years before present (McElhinny and Senanayake, 1980), requires that the geodynamo has to be sustained by core convection, or the field would die away on a time scale of the order of 104 years due to thermal dissipation (Merrill, 1995 ). Long-term variations in the behavior of the Earth's magnetic field should thus reflect variations in core convection. It is expected, and geodynamo simulations confirm (e.g., Glatzmaier et al., 1999; Coe et al., 2000) that the amount and pattern of heat that the mantle allows to flow out of the core would affect both the intensity and stability of the field by controlling the vigor and pattern of convection. The heat flux out of the core depends in turn on the temperature distribution in the lower mantle. Together, these concepts imply that the changes in temperature accompanying lower-mantle dynamics will affect the geomagnetic field, and that therefore observed long-term changes in geomagnetic field may be related to changes in mantle convection.

It is now considered that the Earth's magnetic field is generated by the geodynamo in the outer core of the Earth, and is affected by the evolution of the CMB, the D" layer, and the core-mantle coupling. Meanwhile, fluid motion in the outer core can affect the mantle convection, and then the plate motion and the eruption of ocean basalts. Therefore, the geomagnetic field links not only with the fluid motion in the outer core, but also with many geological events (such as mantle convection, mantle plume activity, global heat flux, true polar wander, climatic changes, seamount chains, continental basalts and the faunal extinction). Of course, it is difficult to clarify the mechanism of this correlation.

There has been much discussion in recent years about the impacts of extraterrestrial bodies on the Earth and their possible connection with geomagnetic reversals and mass extinction. Glass and Heezen pointed out that the great field tektites covering Australia, Indonesia and a large part of the Indian Ocean fell about 0.7 Ma ago, at about the time of the last magnetic reversal. They proposed that the fall of the body from which the tektites were formed killed the now extinct radiolarian and gave a jolt to the Earth, disturbing motions in the core and causing the dynamo to reverse, and even affected the reversal frequency.

## 3 Causes for the Cretaceous Normal Superchron and Its Nonlinear Analysis

During the 40-Ma period from 83 to 121 Ma there were no reversals at all. The long period of normal magnetism from 83 to 121 Ma is known as the Cretaceous normal superchron, or the CNS (Helsley and Steiner, 1969). The Earth's magnetic field has two states, one in which the field reverses at a rate of 2–4 times/Ma, and the other in which the field does not reverse at all. Superchrons are so long that they clearly do not represent an ordinary polarity change, but imply a fundamental transition in the dynamo processes (Eide and Torsvik, 1996; Merrill et al., 1996). Courtillot and Besse (1987) argued that superchrons represent a low-energy state with infrequent instabilities and correspond to an inactive period in the D″ layer.

The geological events in the Cretaceous have attracted us for a long time, especially the CNS, because many global occurred. The rate of production of ocean crust over the CNS is two times that in the last 80 Ma; black shales were found only in the CNS; the paleotemperature and paleo-sea level in the CNS were much higher than that out of it; world oil resources are remarkably higher in the CNS. At present, it is widely accepted that magnetic polarity reversals are linked with these global geological events through the Earth's interior activity and coupling between layers, though it is difficult to demonstrate the mechanism of this correlation. It should be noted that most of the global geological events mentioned above are observed from the ocean. What happened in continent in the CNS? It is generally believed that structure transition from compression to extension, in eastern China, occurred at about 135 Ma, which coincides with the CNS. Also, an important period for oil formed in the Songliao Basin links with the CNS. Thus, we suggest that the Earth's interior activity was in an anomalous state during the CNS. It is this anomalous activity that causes occurrence of the CNS and many global geological events.

Two views about the reversal rates preceding the CNS were discussed by scientists, which have quite different implications for the Earth's history and associated events and processes. In one view, McFadden and Merrill (1984, 2000) envision a long-term influence of mantle convection on the geodynamo, which led to a progressive decrease of reversal rate from ~4.5 times per million years at about 160 Ma to zero at ~120 Ma, and then a steady increase from ~83 Ma to the present value of almost five times per million years (averaged over the past 20 Ma). In this case, the CNS would be a natural product of such a decrease of reversal rate when it reached zero at ~120 Ma. The other view, supported by Gallet and Hulot (1997) and Hulot and Gallet (2003), suggests that there was a nearly stationary reversal rate process up to or very close to the CNS, raising the possibility that the CNS might represent a sudden non-linear transition between a reversing and a non-reversing state of the geodynamo. In their analysis, the only possibility of identifiable precursory behavior in the polarity time scale that might signal the onset of the CNS (Hulot and Gallet, 2003) is the longest of all pre-CNS chrons, ~3 Ma before the onset of the superchron. These competing interpretations are inherently testable by analysis of complementary paleomagnetic data, such as paleosecular variation of directions and paleointensity, both near the beginning and the end of the CNS. For instance, sharp changes in time-averaged field characteristics would indicate a sudden non-linear transition between reversing and non-reversing states.

A random fluctuation of the non-dipole field could seed a reversal when the axial dipole field decreases to a low enough value relative to the non-dipole field (Cox, 1968). Many attempts have been made since then to quantify such models and address possible correlations between reversal frequency and field intensity. Roberts and Stix (1972) showed that dynamo fields are made up of two families, the primary (dipole) family and the secondary (quadrupole or nondipole) family, respectively. Under certain symmetric conditions in the core, these families are non-interacting. However, if the symmetric conditions are violated, the two dynamo families will interact. Merrill and McFadden (1988) have developed a class of models (called M2 models) to explain reversals of the geomagnetic field. They suggested that a reversal would occur when some instability increases the coupling between the primary and secondary families. They predicted that the relative contribution of the secondary family to the magnetic field should have been smaller when the reversal rate is lower than when it is high. In particular, the relative contribution of the secondary family was lower during the Cretaceous normal superchron than other times during the past 180 Ma.

There have been many models to suggest a connection between all these phenomena and deep-mantle convection because the CNS is closely associated in time with a marked increase in seafloor spreading and production of oceanic plateaus, seamount chains, and continental flood basalts. Wilson (1963, 1965) introduced the idea of stationary mantle "hot spots" across which lithospheric plates drift in order to explain the age progression of the Hawaiian volcanic chain. Morgan (1971) suggested that such hot spots were the surface expression of narrow plumes originating deep in the mantle. Jones (1977) placed the source in the D″ layer at the base of the mantle and suggested that the thermal boundary layer becomes unstable and breaks down by the formation of blobs or plumes. According to Jonesp's model, there would be a relatively rapid decrease in mean polarity length following the Cretaceous normal superchron with a subsequently longer period of time in which the mean polarity lengths increase. This is not what is observed—a decrease in the length of polarity intervals since the Cretaceous appears to have continued up to ～12 Ma ago. Loper and McCartney (1986) have developed these ideas further. They assume that the rate of reversals is related to the rate of energy supply to the geodynamo, which is controlled by the D″ layer. When the layer is thick, the energy supply is low so that the dynamo is in a quiet state with fewer reversals. On the other hand, when the layer is thin, the energy supply is greater so that the dynamo is in a more disturbed state with frequent reversals. It is interesting to note that Sheridan (1983) has developed a model based on similar ideas and suggested a correlation just opposite: reversal frequency is low during periods of plume eruption and high when plumes are absent.

Many plume-related models have been developed to explain the large crustal-production events in the mid-Cretaceous, including plume heads (Larson, 1977; Richards et al., 1989) and the initiation of rifting (White and McKenzie, 1989). Other researchers have investigated alternatives to the plume model with emphasis on the role of lithospheric processes in the history of the dynamic mantle over time (Humphreys et al., 2000). Larson (1991) noted that the formation of oceanic crust (seamount chains etc.) showed a 50%–75% increase between 120 and 80 Ma ago and this increase, which was concentrated in the Pacific Ocean, coincides almost exactly with the CNS. He proposed a Cretaceous superplume under the Pacific basin for the cause of the CNS, and showed the superplume's correlation with the ocean-crust production, long-term eustatic seal level, high-latitude sea-surface paleotemperatures and times of black shale production and world oil resources (Larson and Olson, 1991). He further argued that the mid-Cretaceous superplume is only the most recent of a longer history of non-periodic releases of heat from the core-mantle boundary and that it should be possible to recognize other superplume episodes by identifying other intervals of long magnetic polarity, such as the Permo-Carboniferous Kiaman reverse superchron. Larson and Kincaid (1996) suggested that cold slab penetration into the lower mantle caused a thermal boundary layer normally at 670 km to be rapidly advected upward as the slab descended through the lower mantle, driving up the heat flux across the core-mantle boundary and stabilizing the magnetic reversal process.

It is speculated by Muller (2002) that when a massive asteroid or comet slammed into the Earth's surface at an oblique angle, the lower mantle would jerk sideways, shearing off whole mountains of sediment. As the sediments slide up, a downward-sinking mass of cool iron could completely disrupt large convection cells. Although variously oriented local fields within the core would remain strong, at the surface the Earth's dipole magnetic field would collapse. And then, over thousands of years, as the large convective cells in the core gradually reestablish themselves, the dipole field at the surface would turn itself back on, with a fifty-fifty chance of opposite polarity.

According to numerical simulations, a stable (non-reversing) geodynamo may be more efficient at generating stronger dipole fields, and that this condition can arise from a favorable pattern of laterally varying heat flux across the core-mantle boundary. Thus it is important both for understanding how the geodynamo works and for inferring past lower-mantle conditions to find out whether or not the average field strength really was unusually high during the CNS. An alternative conjecture for occurrence of the CNS is that the geomagnetic field can switch abruptly into and out of a non-reversing state, simply by virtue of the highly nonlinear geodynamo processes operating in the core. This hypothesis can be tested by seeing whether there is an identifiable temporal trend in paleointensity or dispersion leading up to the beginning or end of the CNS.

Rikiake (1958) proposed the symmetric two-disk dynamo, which is composed of two symmetric disk dynamos in which the current produced by one dynamo energizes the other. This dynamo is subject to random reversals of the magnetic field and behaved in a chaotic manner.

The models of Rikiake's dynamo are clearly gross simplifications of the complex fluid flows that occur in the Earth's core. Nevertheless, the models produce patterns of random reversals that are remarkable similar to the reversals of the Earth's magnetic field. Again this can be taken as evidence that the dynamo action in the core is chaotic. It is certainly desirable to consider higher-order systems that better simulate the "turbulent" interactions between electrical currents and flows of the electrically conducting fluid (Turcotte, 1997).

## 4 Conclusion

The Earth's magnetic field is highly variable both on historical, archeomagnetic and geologic time scales. The geodynamo appears to have two basic states: a reversing state and a nonreversing state (Merrill et al., 1996). For the polarity data of the past 160 Ma the simplest interpretation would be that changing boundary conditions imposed by the mantle resulted in changes in reversal rate from about 160 Ma onward. Sometime in the mid-Cretaceous (soon after 121 Ma), the reversal process ceased and the Cretaceous normal superchron formed. The cessation of reversal process coincides with the peak in plume productions, which manifest themselves as LIPs, such as the Ontong Java Plateau (120 Ma), and marks a fundamental transition in the dynamo process. The dynamo process underwent another transition sometime before 83 Ma and reversal process restarted.

The Cretaceous normal superchron implies that interaction of the Earth's core-mantle and liquid movement in the outer core may be the lowest energy state and the system of the Earth magnetic field maintains a sort of temporal or spatial order structure by exchanging substance and energy in the outside continuously. for occurrence of. The randomness of geomagnetic polarity reversal has the self-reversion characteristic of chaos and the chaos theory gives a simple and clear explanation for the dynamic cause of geomagnetic polarity reversal.

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## References

Cande, S.C., and Kent, D.V., 1992. A new geomagnetic polarity time scale for the late Cretaceous and Cenozoic. *J. Geophys. Res.*, 97(12): 13917–13951.

Clementb, M., 2003. How long does it take for the Earth's magnetic to reverse? *Eos Trans. AGU*, 84(46): Fall Meet. Suppl., Abstract GP41D-08.

Coe, R.S., Hongre, L., and Glatzmaier, G.A., 2000. An examination of simulated geomagnetic reversals from a paleomagnetic perspective. *Phil. Trans. Roy. Soc. London*, Series A, 358(11): 1141–1170.

Courtillot, V., and Besse, J., 1987. Magnetic field reversals, polar wander, and core-mantle coupling. *Science*, 237: 1140–1147.

Cox, A.L., 1968. Lengths of geomagnetic polarity intervals. J Geophys Res, 73(12): 3247–3260.

Eide, E.A., and Torsvik, T.H., 1996. Paleozoic supercontinental assembly, mantle flushing, and genesis of the Kiaman Superchron. *Earth Planet. Sci. Lett*., 144(2): 389–402.

Gallet, Y., and Hulot, G., 1997. Stationary and nonstationary behaviour within the geomagnetic polarity time scale. *Geophys. Res. Lett*., 24(10): 1875–1878.

Glatzmaier, G.A., Coe, R.S., and Hongre, L., 1999. The role of the Earth's mantle in controlling the frequency of geomagnetic reversals. *Nature*, 401(4): 885–890.

Helsley, C.E., and Steiner, M.B., 1969. Evidence for long interval of normal polarity during the Cretaceous period. *Earth Planet. Sci. Lett*., 5(2): 325–332.

Huang Yongjian, Wang Chengshan, Hu Xiumian and Chen Xi, 2007. Burial Records of Reactive Iron in Cretaceous Black Shales and Oceanic Red Beds from Southern Tibet. Acta Geologica Sinica (English edition), 81(3):463–469.

Hulot, G., and Gallet, Y., 2003. Do superchrons occur without any palaeomagnetic warning? *Earth Planet. Sci. Lett*., 210: 191–201.

Humphrey, E.D., Dueker, K.G., and Schutt, D.L., 2000. Beneath Yellowstone: Evaluating plume and nonplume models using teleseismic images of the upper mantle. *GSA Today*, 10(1): 1–7.

Ji Weiqiang, Xu Wenliang, Yang Debin, Pei Fuping, Jin Ke and Liu Xiaoming, 2007. Chronology and Geochemistry of Volcanic Rocks in the Cretaceous Suifenhe Formation in Eastern Heilongjiang, China. Acta Geologica Sinica (English edition), 81(2):266–277.

Jones, G..M., 1977. Thermal interaction of the core and the mantle and long term behaviour of the geomagnetic field. *J. Geophys. Res*., 17(1): 135–140.

Larson, R.L., 1991. Latest pulse of Earth: Evidence for a mid-Cretaceous superplume. *Geology*, 19(3): 547–550.

Larson, R.L., 1997. Superplumes and ridge interactions between Ontong Java and Manihiki Plateau and the Nova-Canton Trough. *Geology*, 25: 779–782.

Larson, R.L., and Kincaid, C., 1996. Onset of mid-Cretaceous volcanism by elevation of the 670 km thermal boundary layer. *Geology*, 24(4): 551–554.

Larson, R.L., and Olson, P., 1991. Mantle plumes control magnetic reversal frequency. *Earth Planet. Sci. Lett.*, 107(3): 437–447.

Loper, D.E., and McCartney, K., 1986. Mantle plumes and the periodicity of magnetic field reversals. *Geophys. Res. Lett*., 13 (11): 1525–1528.

McElhinny, M.W., and Senanayake, W.E., 1980. Paleomagnetic evidence for the existence of the geomagnetic field 3.5 Ga ago. *J. Geophys. Res*., 85(12): 3523–3528.

McFadden, P.L., and Merrill, R.T., 1984. Lower mantle convection and geomagnetism. *J. Geophys. Res*., 89(12): 3354–3362.

McFadden, P.L., and Merrill, R.T., 2000. Evolution of the geomagnetic reversal rate since 160 Ma: Is the process continuous? *J. Geophys. Res*., 105(22): 28455–28460.

Merrill, R.T., and McFadden, P.L., 1988. Secular variation and the origin of the geomagnetic field reversals. *J. Geophys. Res*., 93(21): 11589–11597.

Merrill, R.T., McElhinny, M.W., and McFadden, P. L., 1996. *The Magnetic Field of the Earth: Paleomagnetism, the Core, and the Deep Mantle*. San Diego: Academic Press, 541.

Morgan, W.J., 1971. Convection plumes in the lower mantle. *Nature*, 230(1): 42.

Muller, R.A., 2002. Avalanches at the core-mantle boundary. *Geophys. Res. Lett*., 29: 10.1029/2002GL015938.

Opdyke, N.D., and Channell, J.E.T., 1996. *Magnetic Stratigraphy*. San Diego: Academic Press, International Geophysics Series, 64(1): 1–341.

Phillips, J.D., 1977. Time variation and asymmetry in the statistics of geomagnetic intervals. *Geophys. J. Roy. Astr. Soc*., 43(4): 747–744

Prevot, M., Mattern, E., and Camps, P., 2000. Evidence for a 20° tilting of the Earth's rotation axis 110 million years ago. *Earth Planet. Sci. Lett.*, 179(3): 517–528.

Richards, M.A., Duncan, R.A., and Courtillot, V.E., 1989. Flood basalts and hot spot track: Plume heads and tails. *Science*, 246 (1): 103–107.

Rikiake, T., 1958. Oscillations of a system of disc dynamos. *Proc. Cambridge Phil. Soc*. 54(1): 89–105.

Robert, P.H., and Stix, M., 1972. α-effect dynamos by the Bullard-Gellman formalism. *Astron. Astrophys*., 18(3): 453–466.

Sheridan, R.E., 1983. *Phenomena of Pulsation Tectonics Related to the Breakup of the Eastern North American Continental Margin*. Initial Report of the Deep Sea Drilling Project. Washington, D.C.: Government Printing Office, 76(5): 897–909.

Turcotte, D.L., 1997. *Fractals and Chaos in Geology and Geophysics* (2nd edn.), Cambridge: Cambridge Univ. Press, 398.

Vander Voo, R., 1995. *Remagnetizations and Superchron*. Eos (American Geophysical Union Fall meeting abstract volume), F171.

White, R., and McKenzie, D., 1989. Magmatism at rift zones: The generation of volcanic continental margins and flood basalts. *J. Geophys. Res*., 94(14): 7685–7729.

Wilson, J.T., 1963. A possible origin of the Hawaiian islands. *Can. J. Phys*., 41: 863–873.

Wilson, J.T., 1965. Convection currents and continental drift: Evidence from ocean islands suggesting movement I the Earth. *Phil. Trans. Roy. Soc. A*., 258(1): 145–153.

Zhao Xixi, 2005. The Earth's magnetic field and global geologic phenomena in mid-Cretaceous. *Earth Sci. Frontiers*, 12(2): 199–216.