The Cretaceous Normal Superchron: A Mini-Review of Its Discovery, Short Reversal Events, Paleointensity, Paleosecular Variations, Paleoenvironment, Volcanism, and Mechanism

Yutaka Yoshimura
Department of Environmental Changes, Faculty of Social and Cultural Studies, Kyushu University, Fukuoka, Japan

The Cretaceous Normal Superchron (CNS) was first defined in the 1960s to explain the Cretaceous Quiet Zone in marine magnetic anomaly profiles, which includes no or fewer geomagnetic reversals. This ~37 million years period is considered the most unique and extreme geomagnetic feature for the last 160 Myr. Superchrons may be caused by the geodynamo operating at peak efficiency with a unique heat flux at the core-mantle boundary (CMB). Previous studies suggest that the CNS is a sign of the connection between Earth’s interior and surface. During the CNS, the geomagnetic intensity may have fluctuated significantly, and the average may have changed with time, and the paleosecular variations had unique features. The warm climate around the CNS may have been caused by volcanic activity associated with active mantle convection. Such mantle convection increases heat flux at the CMB during the CNS, but geodynamo simulations predict small heat flux, which are inconsistent. This discrepancy may be resolved by the growth and collapse of a superplume or by an increase and decrease in the subduction flux.

Keywords: cretaceous normal superchron, paleointensity, paleosecular variation, paleoenvironment, large igneous province (LIP)

INTRODUCTION

The Cretaceous Normal Superchron (CNS) is an irregular stable polarity period in which no or few geomagnetic reversals occurred, lasting from 120 to 83 million years ago (Ma) (e.g., Ogg, 2020). Marine magnetic anomaly (MMA) includes the Cretaceous Quiet Zone (KQZ), which is considered evidence for the absence of geomagnetic reversals, defined as superchron. Until now, the absence of magnetic stripes in the KQZ made it challenging to use them for plate reconstructions. In 2012, two time-markers (named Q1 and Q2) were discovered by deep-tow magnetic anomaly observations in the Atlantic Ocean and the Southwest Indian Ridge (Granot et al., 2012). These possible time-markers are expected to be helpful for plate reconstructions during the CNS. Other superchrons during the Phanerozoic have also been actively discussed, of which the CNS is the most well-studied. The CNS is generally considered a consequence of the thermal effects of mantle activity on the outer core (e.g., McFadden and Merrill, 1984).
Superchrons may result from the geodynamo operating at peak efficiency with a unique heat flux at the core-mantle boundary (CMB), as suggested by geodynamo numerical simulations and paleointensities estimated from single silicate crystals (Tarduno et al., 2006).

### ITS DISCOVERY

From the 1960s, terrestrial paleomagnetic data and MMA began to reveal periods of no or fewer reversals. By summarizing published paleomagnetic measurements of igneous and sedimentary rocks at more than 35 sites in North America and elsewhere, Helsley and Steiner (1968) found that there was a period when normal magnetic polarity was dominant for at least 25 million years (Myr) in the Cretaceous. Between ~150 Ma and ~110 Ma, Larson and Chase (1972) revealed that there are reversal periods sandwiched between periods of normal polarity (KQZ and the Jurassic Quiet Zone, JQZ). In fact, during the JQZ, geomagnetic reversals were frequent and the geomagnetic intensity was weak, as shown by MMA (e.g., Tominaga et al., 2021) and the absolute paleomagnetic intensity (paleointensity) of volcanic rocks (e.g., Tauxe et al., 2013). Larson and Pitman (1972) pointed out that the CNS corresponded in time to the KQZ of previous studies (e.g., Helsley and Steiner, 1968), designating C34n as the KQZ.

### POSSIBLE SHORT EVENTS

Here, I introduce a short reversal event that may exist during the CNS. Ryan et al. (1978) summarized three events or clusters of brief reversed polarity during the CNS that have been reported from drill cores, particularly in deep-sea sediments: (1) Late Aptian Chron M"-1r", referred to as the ISEA event (Tarduno, 1990); (2) the Chron M"-2r" event group during the mid-Albian; and, (3) the Chron M"-3r" event group in the late Albian. The details of these short events are enigmatic because they have not been resolved in surveys of coeval MMA (Ogg, 2020). The paleomagnetic directions of possible ISEA event have also been found from Chinese lavas (Rao and Rao, 1996; Zhu et al., 2004a; Shi et al., 2004). The name of the ISEA event comes from the name of a section of the Umbria Apennines in northern Italy (VandenBerg et al., 1978). Furthermore, a recent study reports multiple geomagnetic reversals during the CNS (Zhang et al., 2021). Using paleomagnetic direction and U-Pb ages, they conclude that samples from two sections of Laos, and other magnetostratigraphy from previous studies indicate that there are at least five global and two single reversals during the CNS. However, no reversals such as the ISEA event have been found from deep-tow observations of MMA around the Atlantic Ocean (Granot et al., 2012). The altitude from the seaﬂoor of deep-tow observations and the slow rate of seaﬂoor spreading around the Atlantic Ocean may prevent the detection of such events shorter than 0.1 Myr (Granot et al., 2012).

Even if we consider potential short geomagnetic reversal events, the geomagnetic reversal frequency during the CNS is likely to be significantly lower than in other periods (Figure 1A). For example, if 6 to 14 reversals occurred during the CNS (37.3 Myr, Ogg, 2020), a simple calculation gives a reversal frequency range of 0.16–0.37/Myr for the period. In Constable (2000), the reversal frequency appears to be mainly above 1/Myr for all ages except the CNS. Considering them, perhaps we should
call the KQZ period the “Cretaceous Reversal Minimum” rather than the CNS.

**PALEOINTENSITY AVERAGE AND VARIATION**

It has been investigated whether the paleointensity during the CNS is strong or weak because a strong geomagnetic intensity may have suppressed geomagnetic reversals (Cox, 1968). However, while the geomagnetic reversal frequency during the CNS is relatively well understood from the geomagnetic polarity time scale (e.g., Constable, 2000), the paleointensity during the CNS remains ambiguous.

I summarize previous paleointensities during the CNS of submarine basaltic glass (SBG) (Pick and Tauxe, 1993; Selkin and Tauxe, 2000; Riisager et al., 2001; Kono, 1999; Zhu et al., 2002; Zhu et al., 2004a, 2004b; Zhao et al., 2004; Shi et al., 2005; Shcherbakova et al., 2007; Shcherbakova et al., 2008; Zhu et al., 2008; Qin et al., 2011; Shcherbakova et al., 2012; Zhu et al., 2004a, 2004b; Zhao et al., 2004; Shi et al., 2005; Shcherbakova et al., 2007; Shcherbakova et al., 2008; Zhu et al., 2008; Qin et al., 2011; Shcherbakova et al., 2012; Zhu et al., 2004a, 2004b; Zhao et al., 2004; Shi et al., 2005; Shcherbakova et al., 2007; Shcherbakova et al., 2008; Shcherbakova et al., 2009), and gabbro (Granot et al., 2007). Virtual (axial) dipole moments (V(A)DMs) in the CNS have been reported from 1.1 to 19.9 × 10^22 Am^2 (Tauxe et al., 2013). However, this average value is weaker than the estimated from two-flux heterogeneity of the power law of the CNS (Driscoll and Olson, 2011). If the strong average of the CNS is strong or weak because a strong geomagnetic intensity during the CNS varied with time. Besides, Granot et al. (2007) found quasi-cyclic paleointensity variations around 5.4 ± 2.0 × 10^22 Am^2. This paleointensity variability is consistent with the temporal changes in the amplitude of MMA based on more reliable research results (Tarduno et al., 2002; Biggin et al., 2008; Doubrovine et al., 2019).

**PALEOENVIRONMENT**

The mid-Cretaceous had a warm climate, with carbon dioxide concentrations of ~1,000 ppm, more than twice the present-day level (Foster et al., 2017). The sea level of 160–85 Ma was the highest (>150 m) during the Phanerozoic (van der Meer et al., 2017). There was a temperate rainforest in Antarctica during the Turonian-Santonian period (92–85 Ma) (Klages et al., 2020). Why did the warm climate of the mid-Cretaceous occur? Lee et al. (2013) proposed the hypothesis that the Cretaceous to Paleogene was a period when the continental arc was dominant and that the mid-Cretaceous greenhouse Earth was caused by the release of carbon dioxide into the atmosphere due to the interaction of ancient carbonates and magma in the continents. Brune et al. (2017) proposed that the length of the Cretaceous continental rift may have been a driving force for carbon dioxide release and warming, based on reconstructions of the length of the continental rift over the past 200 Myr and numerical carbon cycle models. Both hypotheses may have contributed to the warming of the mid-Cretaceous. On the other
hand, Lee et al. (2013) explained that Large Igneous Provinces (LIPs) would have to erupt every 1 Myr for LIPs to cause the Cretaceous global warming, which is based on the response time of CO₂ withdrawal from the exogenic system (<1 Myr) and the typical duration of LIPs (<2 Myr). However, it has recently been found that there were some LIPs with long eruption durations that lasted for tens of millions of years during the CNS (Dockman et al., 2018; Jiang et al., 2021). In addition, Johansson et al. (2018) suggested that there is a link between the timing of LIPs eruptions around 90–50 Ma and the increase in atmospheric CO₂. Therefore, it is possible that the activities of LIPs had an influence on the warm climate during the mid-Cretaceous.

LARGE IGNEOUS PROVINCES

LIPs are massive volcanic complex formed by the eruption or intrusion of giant, mainly mafic magmas, which was not formed by the spreading or subduction of the ocean floor (Coffin and Eldholm, 1994). On the continent, it is often called a continental flood basalt, and on the ocean floor, it is called an oceanic plateau. At the time of the CNS, the eruption of LIPs was frequent (Figures 2A,B). This has been termed the “pulse” during the mid-Cretaceous by Larson (1995), and discussions of its relevance to the effects on the geomagnetic field through the CMB, as indicated by the occurrence of the CNS, have been continued (Courtillot and Olson, 2007; Biggin et al., 2012; Olson and Amit, 2015). Based on geochronological data, the LIPs known to have erupted during the CNS period include the Ontong-Java Plateau (Mahoney et al., 1993; Timm et al., 2011), the Kerguelen Plateau (Duncan, 2002; Jiang et al., 2021), Rajmahal, Bengal, Sylhet Traps (Coffin et al., 2002; Kent et al., 2002; Ray et al., 2005), the High Arctic LIP (Dockman et al., 2018), the Caribbean LIP (Serrano et al., 2011), Madagascaran flood basalts (Storey et al., 1995; Cucinello et al., 2021), the Agulhas Plateau, the Northeast Georgia and Maud Rise (Parsiegla et al., 2008), and the Hess Rise (Pringle and Dalrymple, 1993). It is interesting to note that volcanism in China (Zhu et al., 2008), production of granite (Yokoyama et al., 2016), and kimberlites (Griffin et al., 2014) were active during the CNS. Besides, seamount volcanism was active in...
the Western Pacific during the Cretaceous of 115–60 Ma (Koppers et al., 2003). What they show is the fact that mantle convection was unusually active during the CNS. East et al. (2020) proposed that high subduction fluxes before the CNS caused the mantle return flow, which increased the activity of LIPs.

**DISCUSSION OF THE CAUSE OF THE CNS**

The cause of the CNS is an open question in earth science. The influence of mantle convection has long been considered as a cause of the CNS (McFadden and Merrill, 1984; Larson, 1991; Larson and Olson, 1991; Larson, 1995; Glatzmaier et al., 1999; Courtillot and Olson, 2007; Olson et al., 2010; Amit and Olson, 2015; Olson and Amit, 2015). During the CNS, there was a lot of volcanic activity and seafloor production. These activities imply vigorous mantle convection, which could have affected the outer core. The numerical geodynamo simulation predicts a minimum heat flux at the CMB during the CNS (Olson et al., 2010), while the mantle convection simulation predicts a maximum heat flux (Zhang and Zhong, 2011). This is a contradiction.

Changes in the CMB heat flux due to growth and collapse of the superplume were proposed as the cause of the CNS, which can resolve the above contradiction (Olson and Amit, 2015) (Figure 2C). When superplumes (they referred it as Large low-shear-velocity provinces, LLSVP) grow, the D″ layer is pulled down by superplumes and becomes thinner. Conversely, when superplumes collapse, the original shortage returns to the D″ layer and thickens it. The thicker the D″ layer, the harder it is for slabs to affect the outer core thermally, which reduces geomagnetic reversals. On the other hand, as it becomes thinner, the outer core becomes more strongly influenced by the slabs, and geomagnetic reversals increase. The change in the thickness of the D″ layer is predicted by viscous fluids experiments (Olson and Kincaid, 1991) and numerical thermochemical convection simulation (Li et al., 2018). When a superplume collapses, a hot plume is thought to be generated from its edge (Steinberger and Torsvik, 2012). Olson and Amit (2015) argued that it was a reasonable scenario because the time-lag (30–60 Myr) that the hot plume reaches the lithosphere and erupts LIPs is consistent with the time lag between the geomagnetic reversal frequency and the frequency of LIPs. Such correlation was also pointed out by Biggin et al. (2012). However, can the shape of the superplume (LLSVP) and D″ layer variable with time? Whether the shape of LLSVP is vertically variable or remains stable is still inconclusive (Garnero et al., 2016).

Another candidate for the cause of the CNS is the change in subduction rates (Figure 2D). Hounslow et al. (2018) found a 120 Myr time lag between the subduction flux and the geomagnetic reversal frequency. This time lag is intermediate between the seismologically expected long time lag for the subducted slab to reach the CMB from the surface (~150–300 Ma) and the short time lag predicted by numerical mantle convection models (~30–60 Ma), which may be real value. More recently, Williams et al. (2021) found that the two peaks of oceanic heat flow were roughly consistent with the onset of two superchrons (CNS and the Permian-Carboniferous Reversed Superchron), respectively. These results are consistent with Hounslow et al. (2018). In summary, the subduction flux may control the reversal frequency. This means that the occurrence of the CNS may be due to low subduction flux.

Why do subduction fluxes vary so widely and periodically on a scale of tens of millions of years? Based on the relationship between the subduction zone lengths and the convergence rates (Ruff and Kanamori, 1980), the long subduction zone would have accelerated the plate spreading rate since 180 Ma. Or, as an exotic idea, a true polar wander (TPW) might change the regime of mantle convection and affect its convection speed. In addition, when the spreading rate of the mid-ocean ridge becomes high like around the CNS, the density and temperature of the subducting plate are lower and hotter than in other periods. In the future, we will also have to consider the effect of this hot and low-density plate subduction on mantle convection. I think it is more likely that a relatively hot slab would reach the CMB but not cool it, which decreases the heat flux average at the CMB, which may also cause the CNS. The slab effect on the CMB must be tested by the slab-sinking model.

**SUMMARY**

The small CMB heat flux would cause the CNS. The mantle convection was active during the CNS and may have affected the geomagnetic field and the Earth’s environment. Future studies need to elucidate the effects of active mantle convection on the CMB.

**AUTHOR CONTRIBUTIONS**

YY designed the research and prepared the manuscript.

**FUNDING**

This work was supported by R3QR Program (Qdai-jump Research Program) 01265, “Wakaba Challenge” of Kyushu University.

**ACKNOWLEDGMENTS**

I appreciate Masakazu Fujii, Roi Granot, Chie Kato, Joseph Kirschvink, Hironao Matsumoto, Kyoko Okino, Masahiko Sato, and Toshitsugu Yamazaki for discussion. I thank Catherine Constable and Lisa Tauxe for providing data. I also thank Adam Sproson for English language editing. The manuscript was greatly improved by constructive comments from Peter Driscoll and the Associate Editor Yohan Guyodo.
Tauxe, L. (2006). Long-term Trends in Paleointensity: the Contribution of DSDP/ODP Submarine Basaltic Glass Collections. *Phys. Earth Planet. Interiors* 156 (3-4), 223–241. doi:10.1016/j.pepi.2005.03.022

Tauxe, L., and Staudigel, H. (2004). Strength of the Geomagnetic Field in the Cretaceous Normal Superchron. *Rev. Geophys.* 42 (4), 473–495. doi:10.1029/2004rg000189

Tauxe, L., Gee, J. S., Steiner, M. B., and Staudigel, H. (2013). Paleointensity Results from the Jurassic: New Constraints from Submarine Basaltic Glasses of DSDP Site 801C. *Geochem. Geophys. Geosyst.* 14 (10), 4718–4733. doi:10.1002/2012gc000635

Tauxe, L., and Yamazaki, T. (2015). “Paleointensities,” in *Treatise on Geophysics*. 2nd ed. (Elsevier), Vol. 5, 461–509. doi:10.1016/b978-0-444-53802-4.00107-x

Thomas, D. N., Biggin, A. J., and Schmidt, P. W. (2000). A Palaeomagnetic Study of Jurassic Intrusives from Southern New South Wales: Further Evidence for a Pre-cenozoic Dipole Low. *Geophys. J. Int.* 140 (3), 621–635. doi:10.1046/j.1365-246x.2000.00049.x

Timm, C., Hoernle, K., Werner, R., Hauff, F., van den Bogaard, P., Michael, P., et al. (2011). Age and Geochemistry of the Oceanic Manakhi Plateau, SW Pacific: New Evidence for a Plume Origin. *Earth Planet. Sci. Lett.* 304 (1-2), 135–146. doi:10.1016/j.epsl.2011.01.025

Tominaga, M., Tivey, M. A., and Sager, W. W. (2021). A New Middle to Late Jurassic Geomagnetic Polarity Time Scale (GPTS) From a Multiscale Marine Magnetic Anomaly Survey of the Pacific Jurassic Quiet Zone. *Journal of Geophysical Research: Solid Earth* 126 (3), e2020JB021136. doi:10.1029/2020JB021136

Tsunakawa, H., Wakabayashi, K. I., Mochizuki, N., Yamamoto, Y., Ishizaka, K., Hirata, T., et al. (2009). Paleointensity Study of the Middle Cretaceous Iritono Granite in Northeast Japan: Implication for High Field Intensity of the Jurassic Quiet Zone. *Mem. Natl. Mus. Nat. Sci.* 246x.2000.00049.x

Van der Meer, D. G., van den Berg van Saparoea, A. P. H., Van Hinsbergen, D. J. J., Willett, K. S., and Torsvik, T. H. (2013). New Evidence for a Plume Origin. *Earth Planet. Sci. Lett.* 413, 223–242. doi:10.1016/j.epsl.2015.01.015

Van der Meer, D. G., van den Berg van Saparoea, A. P. H., Van Hinsbergen, D. J. J., Van de Weg, R. M. B., Godderis, Y., Le Hir, G., et al. (2017). Reconstructing First-Order Changes in Sea Level during the Phanerozoic and Neoproterozoic Using Strontium Isotopes. *Gondwana Res.* 44, 22–34. doi:10.1016/j.gr.2016.11.002

VandenBerg, J., Klooijtjik, C. T., and Wonders, A. H. A. (1978). Late Mesozoic and Cenozoic Movements of the Italian Peninsula: Further Paleomagnetic Data from the Umbrian Sequence. *Geol. Soc. America Bull.* 89 (1), 133–150. doi:10.1130/0012-821x(1978)89<133:macmom>2.0.co;2

Williams, S., Wright, N. M., Cannon, J., Flament, N., and Müller, N., et al. (2021). Reconstructing Seafloor Age Distributions in Lost Ocean Basins. *Geosci. Front.* 12 (2), 769–780. doi:10.1007/s11609-020-00604-x

Yamamoto, Y., and Tsunakawa, H. (2005). Geomagnetic Field Intensity during the Last 5 Myr: LTD-DHT Shaw Paleointensities from Volcanic Rocks of the Society Islands, French Polynesia. *Geophys. J. Int.* 162 (1), 79–114. doi:10.1111/j.1365-246x.2005.02651.x

Yamazaki, T., and Yamamoto, Y. (2014). Paleointensity of the Geomagnetic Field in the Late Cretaceous and Earliest Paleogene Obtained from Drill Cores of the Louisville Seamount Trail. *Geochem. Geophys. Geosyst.* 15 (6), 2454–2466. doi:10.1002/2014gc005298

Yokoyama, K., Shigeoka, M., Otomo, Y., Tokuno, K., and Tatsunami, Y. (2016). Uraninite and Thorite Ages of Around 400 Granitoids in the Japanese Islands. *Mem. Natl. Mus. Nat. Sci.* 51, 1–24.

Yoshimura, Y., Yamazaki, T., Yamamoto, Y., Ahn, H. S., Kidane, T., and Otofuji, Y. (2020). Geomagnetic Paleointensity Around 30 Ma Estimated from Afro-Arabian Large Igneous Province. *Geochem. Geophys. Geosystems* 21 (12), e2020GC009341. doi:10.1029/2020gc009341

Zhang, D., Yan, M., Song, C., Zhang, W., Fang, X., and Li, B. (2021). Frequent Polarity Reversals in the Cretaceous Normal Superchron. *Phys. Rev. Lett.* 48 (5), e2020GL091501. doi:10.1029/2020gl091501

Zhang, N., and Zhong, S. (2011). Heat Fluxes at the Earth’s Surface and Core–Mantle Boundary since Pangaea Formation and Their Implications for the Geomagnetic Superchrons. *Earth Planet. Sci. Lett.* 306 (3-4), 205–216. doi:10.1016/j.epsl.2011.04.001

Zhao, X., Riisager, P., Riisager, J., Draeger, U., Coe, R. S., and Zheng, Z. (2004). New Paleointensity Results from Cretaceous basalt of Inner Mongolia, China. *Phys. Earth Planet. Interiors* 141 (2), 131–140. doi:10.1016/j.pepi.2003.12.003

Zhu, R., Hoffman, K. A., Nomade, S., Renne, P. R., Shi, R., Pan, Y., et al. (2004a). Geomagnetic Paleointensity and Direct Age Determination of the ISEA (M0r?) Chron. *Earth Planet. Sci. Lett.* 217 (3-4), 285–295. doi:10.1016/s0012-821x(03)00613-7

Zhu, R., Lo, C. H., Shi, R., Shi, G., Pan, Y., and Shao, J. (2004b). Paleointensities Determined from the Middle Cretaceous basalt in Liaoning Province, Northeastern China. *Phys. Earth Planet. Interiors* 142 (1-2), 49–59. doi:10.1016/j.pepi.2003.12.013

Zhu, R., Pan, Y., He, H., Qin, H., and Ren, S. (2008). Paleomagnetism and 40Ar/39Ar Age from a Cretaceous Volcanic Sequence, Inner Mongolia, China: Implications for the Field Variation during the Cretaceous Normal Superchron. *Phys. Earth Planet. Interiors* 169 (1-4), 59–75. doi:10.1016/j.pepi.2008.07.025

Zhu, R., Pan, Y., and Shi, R. (2002). New Cretaceous Paleointensity Data and the Constraints on Geodynamics. *Sci. China Ser. D-earth Sci.* 45 (10), 931–938. doi:10.1360/02yd90992

Conflict of Interest: The author declares that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher’s Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.

Copyright © 2022 Yoshimura. This is an open-access article distributed under the terms of the Creative Commons Attribution License (CC BY). The use, distribution or reproduction in other forums is permitted, provided the original author(s) and the copyright owner(s) are credited and that the original publication in this journal is cited, in accordance with accepted academic practice. No use, distribution or reproduction is permitted which does not comply with these terms.