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Earth System Dynamics Discussions

ESD Ideas: Cenozoic Ice Volume as a Driver of Geomagnetic Events

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Abstract. This study investigates the relationship between Cenozoic ice volume changes and geomagnetic events, including reversals and incomplete reversals, revealing that high frequencies of these events responded to ice volume increases over the past 49 million years. Geomagnetic events forming chrons or wiggles shorter than 0.1 Myr are particularly sensitive to ice volume changes. The findings suggest that future global warming could suppress geomagnetic activity, highlighting the impact of climate-driven ice volume changes on Earth's magnetic field dynamics.

1 Introduction

Changes in Earth's geomagnetic field, including reversals, are linked to alterations in the outer liquid core (Gubbins, 2008). Global ice volume variations, primarily driven by Antarctic and Greenland ice sheets, influence Earth's rotation through the conservation of angular momentum. Significant ice sheet growth, which can enhance mantle and crust rotation, affects the core's energy and may accelerate Earth's rotational rate; for example, a 100-meter sea level drop could amplify this effect, potentially triggering geomagnetic events such as reversals (Doake, 1977). Over million-year scales, significant ice volume events, such as the Ice Sheet Initiation during the Eocene-Oligocene transition and the expansion of the East Antarctic Ice Sheet, have shaped global climate (Zachos et al., 2001). Ice volume and geomagnetic reversal sequences from the Cenozoic provide valuable datasets (Cande and Kent, 1992; Cande and Kent, 1995; Lear et al., 2000) to explore the correlation between ice volume changes and geomagnetic reversals.

As new seafloor forms and cools at mid-ocean ridges, it captures records of Earth's magnetic field. Polarity chrons, which represent intervals between magnetic reversals, serve as the basis for the Geomagnetic Polarity Time Scale (Cande and Kent, 1992). To distinguish these chrons from shorter-duration anomalies, a 0.03 Myr threshold is arbitrarily applied. Anomalies shorter than this threshold, referred to as cryptochrons, correspond to brief intervals between reversals or incomplete reversals. Incomplete reversals are primarily associated with fluctuations in magnetic intensity and direction. Both reversals and incomplete reversals are collectively defined as geomagnetic events.

On orbital timescales, ice age cycles are closely linked to the 0.1 Myr Milankovitch eccentricity cycle, which induces sea level fluctuations of approximately 100 meters and may contribute to the occurrence of geomagnetic events (Grant et al., 2014; Fuller, 2006; Thouveny et al., 2008; Worm, 1997; Yokoyama et al., 2010). We hypothesize that while two successive glacial periods may not invariably generate two distinct geomagnetic events, there is a probabilistic likelihood of such

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Earth System Dynamics
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Discussions

occurrences, potentially giving rise to polarity chrons or cryptochrons shorter than 0.1 Myr; within the context of increased ice volume during the Cenozoic, the prevalence of short-duration geomagnetic anomalies is likely amplified, leading to a heightened frequency of geomagnetic events.

2 Cenozoic ice volume and the geomagnetic events

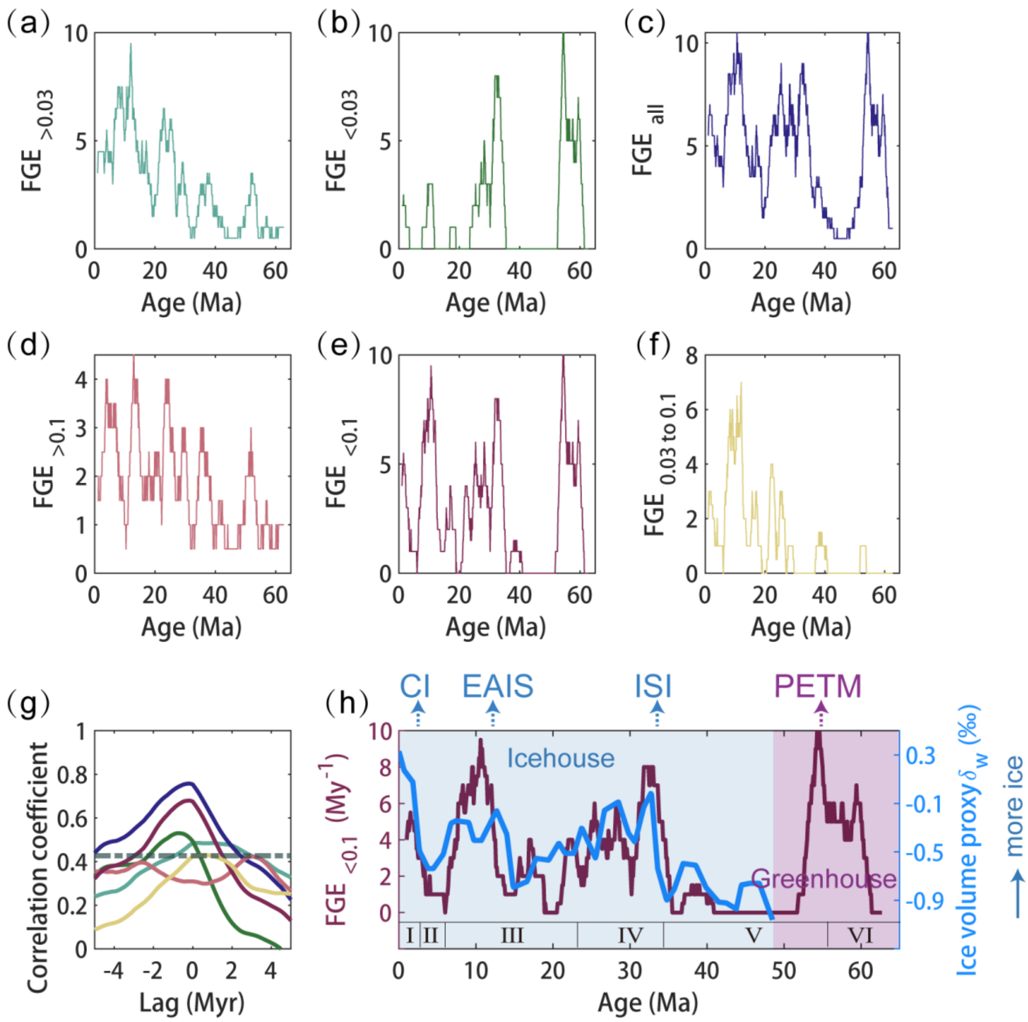

Figure 1: Variations of FGEs and the link with Cenozoic ice volume. (a) $FGE_{>0.03}$, (b) $FGE_{<0.03}$, (c) FGE_{all} (d) $FGE_{>0.1}$, (e) $FGE_{<0.1}$, and (f) $FGE_{0.03\ to\ 0.1}$. (g) Cross correlation between Cenozoic ice volume signal proxy changes δ_w and FGEs. The confidence bound is 0.43 (dashed line). (h) Variations of ice volume signal proxy δ_w (Lear et al., 2000) (blue) and $FGE_{<0.1}$ (red). PETM: Paleocene Eocene Thermal Maximum, ISI: Ice Sheet Initiation, EAIS: East Antarctic Ice Sheet growth, CI: Continental Ice growth. Ⅰ:Pleistocene, Ⅱ:Pliocene, Ⅲ: Miocene, Ⅳ: Oligocene, Ⅴ: Eocene, Ⅵ: Paleocene. The blue shaded areas represent icehouse periods, while the red shaded areas indicate greenhouse periods. The Eocene epoch serves as a transitional phase between these two climate states.

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Earth System Dynamics Discussions

By isolating the ice volume signal from benthic foraminiferal oxygen isotope values and correcting for temperature effects using magnesium/calcium ratios in foraminiferal calcite, Lear et al. (2000) established a robust ice volume proxy (δw) for the Cenozoic Era, providing the most extended continuous record of ice volume variations (49 Ma). Datasets on geomagnetic reversals and incomplete reversals over the Cenozoic Era are publicly available (Cande and Kent, 1992; Gee and Kent, 2007). The frequency of geomagnetic events (FGE) was determined using a moving window approach with a 2 Myr window width and 1 Myr increments. Six FGE groups were categorized based on cutoff durations of 0.03 Myr and 0.1 Myr (Fig. 1a–f). For example, the calculation of $FGE_{> 0.03}$ involved identifying chrons longer than 0.03 Myr, which consist of a series of geomagnetic events, and then applying the moving window method to compute the FGE within each window. This method was similarly applied to all other FGE calculations.

Cross-correlation analysis was used to examine the relationship between FGE variations and ice volume changes. The results of the cross-correlation between FGEs and Cenozoic ice volume proxy for 49 Ma are shown in Fig. 2g. $FGE_{<0.1}$ and $FGE_{<0.03}$ correlate positively with ice volume change, with correlation coefficients of 0.68 and 0.53, respectively. The correlation between FGE_{all} and ice volume is the highest, reaching 0.76. $FGE_{>0.03}$ leads ice volume change by 1 Myr with a correlation coefficient of 0.49. $FGE_{>0.1}$ and $FGE_{0.03 \text{ to } 0.1}$ exhibit low correlation with ice volume changes. The strong correlation between FGE_{all} and ice volume suggests that increases in ice volume trigger more geomagnetic events.

FGE_{all} includes both $FGE_{>0.1}$ and $FGE_{<0.1}$; while $FG_{E>0.1}$ shows a lower correlation with ice volume, $FGE_{<0.1}$ exhibits the second-highest correlation. Therefore, the high correlation between FGE_{all} and ice volume is primarily driven by $FGE_{<0.1}$.

Fig. 2h shows the variations of $FGE_{<0.1}$ compared to ice volume changes. Both δ_w and $FGE_{<0.1}$ increase sharply from 36-35 Ma and peak at 33 Ma (Lear et al., 2000). The δ_w then gradually decreases to its minimum by 20-15 Ma. From 15 to 5 Ma, as the East Antarctic Ice Sheet (EAIS) expands (Lear et al., 2000), $FGE_{<0.1}$ rises to a maximum at 10 Ma and falls to a minimum at 5 Ma. The expansion of ice sheets in West Antarctica and the Arctic, beginning around 5 Ma, and the onset of Northern Hemisphere glaciation in Greenland, Eurasia, Northeast Asia, and North America around 3.2 Ma led to a significant increase in global ice volume over the past 5 Ma (Zachos et al., 2001). Both ice volume proxy values and $FGE_{<0.1}$ show rising trends, indicating a significant correlation between the two from 49 Ma to the present. This confirms our hypothesis.

3 Implications

Chrons and cryptochrons also occurred during ice-free greenhouse intervals, such as the Paleogene, with a potential link between geomagnetic reversals and catastrophic climate events like the Paleocene-Eocene Thermal Maximum (PETM) (Lee and Kodama, 2009). During the PETM, disruptions in the atmosphere, hydrosphere, and climate systems altered the distribution of surface water, potentially impacting Earth's rotation rate and triggering geomagnetic events. Fig. 2h illustrates an increased frequency of geomagnetic events during the Paleogene, particularly around the PETM. The occurrence of high-

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frequency geomagnetic events in both extreme greenhouse and icehouse climates is not contradictory; both result from climate-driven redistribution of surface water, which influences the rotation of Earth's mantle and crust relative to its core.

The Eocene, marking the transition from an extreme greenhouse to an icehouse climate, experienced the fewest geomagnetic events. Both colder and warmer climate conditions likely contributed to an increase in geomagnetic activity. The temperature in the Eocene was 7-12 ℃ higher than present (Zachos et al., 2001), and atmospheric CO_2 levels ranged from 250 to 2700 ppm (Zachos et al., 2008). In comparison, predicted temperature anomalies due to human activities could reach 12 ℃ by 2300 AD (Stocker et al., 2014), and atmospheric CO_2 could rise to 1800 ppm (Zachos et al., 2001). If the current trend of global warming continues, leading to the predicted temperature and CO_2 levels by 2300 AD, accelerated ice sheet melting is expected. Our results suggest that such accelerated melting would decrease the occurrence of geomagnetic events. This analysis provides new insights into the relationship between ice sheet melting under future climate warming and the increase in geomagnetic events.

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Competing interests. The authors declare no competing interests

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Earth System Dynamics Discussions

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