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Testing the hypothesis of orbital (eccentricity) influence on Earth's magnetic field

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Abstract

We test a recent suggestion that orbital eccentricity has influenced the geomagnetic field by performing a range of spectral analyses, including estimation of statistical confidence limits, on a 2.2-million-year paleomagnetic inclination record from the western Caroline Basin (WCB). Our analyses indicate that the claimed ~ 100 -kyr signal, while present over discrete portions of the WCB paleomagnetic record, is not statistically significant for the entire record and is not modulated by the 404-kyr eccentricity component as would be expected if the signal was influenced by orbital eccentricity. This signal also has highly variable phase compared to orbital eccentricity variations and the paleomagnetic record shows no statistically significant coherency with the orbital signal. Our results from a nearby coeval western Philippine Sea record support the present analysis. Together, these data suggest that the hypothesis of orbital energization of the geomagnetic field has yet to be convincingly demonstrated.

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1. Introduction

Despite having a chequered history, the idea that external (orbital) forcing significantly contributes to the energy budget of the Earth's magnetic field has recently made a comeback [1–3]. Early suggestions that the geomagnetic dynamo is energized by orbital precession [4] lost favour because calculations indicated that the energy

available from precession was at most 10% of that required to drive the dynamo [5]. Buoyancy-driven convection in the Earth's liquid outer core is now the most widely accepted hypothesis for field generation [6] and numerical magnetohydrodynamic models are coming closer to providing reasonable simulations of an internal, self-sustaining field [7]. Nevertheless, increased recovery of high-quality paleomagnetic records from the deep-sea has provided the long high-resolution geomagnetic time series needed to test for the presence of orbital periodicities and several suggestions of orbital influences have been made in recent years.

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Yamazaki and Oda [3] recently presented evidence from the western Caroline Basin (WCB) for a 100 000-yr (100-kyr) periodicity in inclination and intensity of the geomagnetic field, which they interpret to indicate modulation of the geomagnetic field by orbital eccentricity. This claim needs to be rigorously tested because other similar suggestions have not survived close scrutiny. A recent claim that the intensity of the geomagnetic field is modulated by orbital obliquity [2] was later retracted [8] because wavelet analysis indicated that the magnetic parameter used for the relative paleointensity normalization was also affected by the same periodicities over the same time intervals. This suggested that the paleointensity record was contaminated by climatically related lithological variations and that the detected 41-kyr periodicity is not characteristic of the geodynamo. Lithological artefacts would not be expected to adversely affect paleomagnetic inclination data in the same way, as argued by Yamazaki and Oda [3], so their hypothesis of orbital influence on the geodynamo needs further examination.

2. Results

Yamazaki and Oda [3] did not show significance levels on their Blackman–Tukey power spectra [9] from which they claim an orbital eccentricity modulation of paleomagnetic inclination. Estimation of statistical confidence levels is important because even randomly distributed data can give rise to spectral peaks with three times the mean value of the power distribution, and, at the 90% confidence level, 10% of ‘significant’ peaks in any data set would be expected from random fluctuations [10]. Using the data of Yamazaki and Oda [3], we calculated a fast Fourier transform (FFT) power spectrum (Fig. 1a) and assessed the significance of the spectral peaks against the null hypothesis of a red-noise process [11,12]. Our power spectrum is similar to that reported by Yamazaki and Oda [3], and contains a marked peak at a period of 100 kyr. Importantly, however, the 100-kyr peak is not significant at the 90% confidence level. When computing the FFT power spectrum of the inclination record for the more

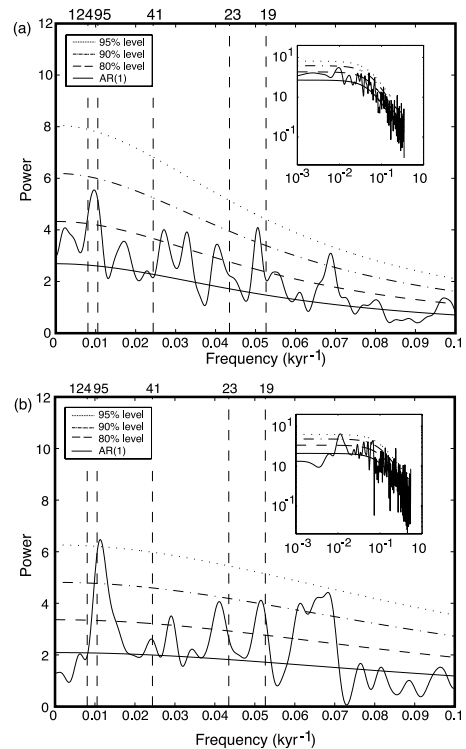
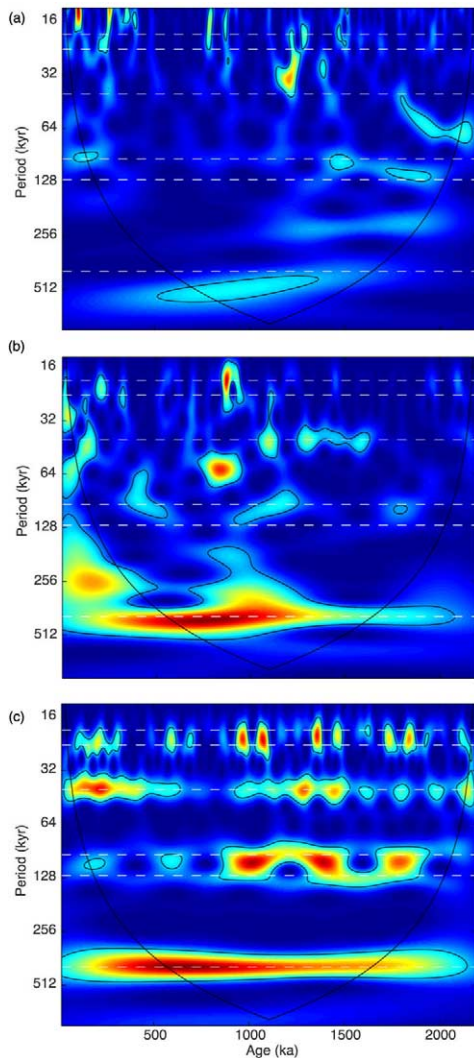


Fig. 1. (a) Estimate of the power spectrum for the WCB paleomagnetic inclination record [3] for the time interval from 15 to 2200 ka (Rayleigh frequency, $f_R = 0.0005 \text{ kyr}^{-1}$), computed using a FFT. The spectral estimate represents the average over seven segments (zero-mean, Hanning-tapered, zero-padded) with 50% overlap (the resulting bandwidth is $\Delta f_{\text{FFT}} = 0.0002 \text{ kyr}^{-1}$). The statistical significance of the spectral peaks is tested against the null hypothesis of a lag-1 autoregressive (AR1 ‘red-noise’) process [11]. 80%, 90%, and 95% confidence levels were calculated from the power spectrum of an AR1 process with persistence time 2.8 kyr [12]. The red-noise process represents a good fit to the power spectrum (inset, bi-logarithmic scale). The 100-kyr period of interest is not significant at the 90% level. (b) Power spectral estimate for the same record for the time interval from 15 to 780 ka ($f_R = 0.0013 \text{ kyr}^{-1}$; three-segment average, zero-padded, $\Delta f_{\text{FFT}} = 0.0003 \text{ kyr}^{-1}$). Although the ‘100-kyr peak’ is now statistically significant at the 95% confidence level, it is centered at 0.0115 kyr^{-1} rather than at 0.010 kyr^{-1} (i.e., it has a period of $\sim 87 \text{ kyr}$ rather than of 100 kyr). For the FFT power spectra, the time series was resampled using a grid size of 1.5 kyr (the mean sampling interval). To make sure that our conclusions are not based on artefacts from resampling, we also calculated a Lomb–Scargle periodogram for the original (unevenly spaced) time series and determined the statistical significance of conspicuous spectral peaks using the program REDFIT [20]. Both methods yielded comparable results.

restricted time interval from 15 to 780 ka, the peak in question becomes statistically significant at the 95% confidence level (Fig. 1b), however, it drifts to a period of ~ 87 kyr rather than 100 kyr. This drift might result from spectral leakage [10] or from drift in the age model [13], so it does not necessarily discount the possibility of an eccentricity modulated inclination signal. Nevertheless, the dominance of mainly non-Milankovitch periodicities in the periodogram, which might arise from random fluctuations in the data set, provides cause for concern.



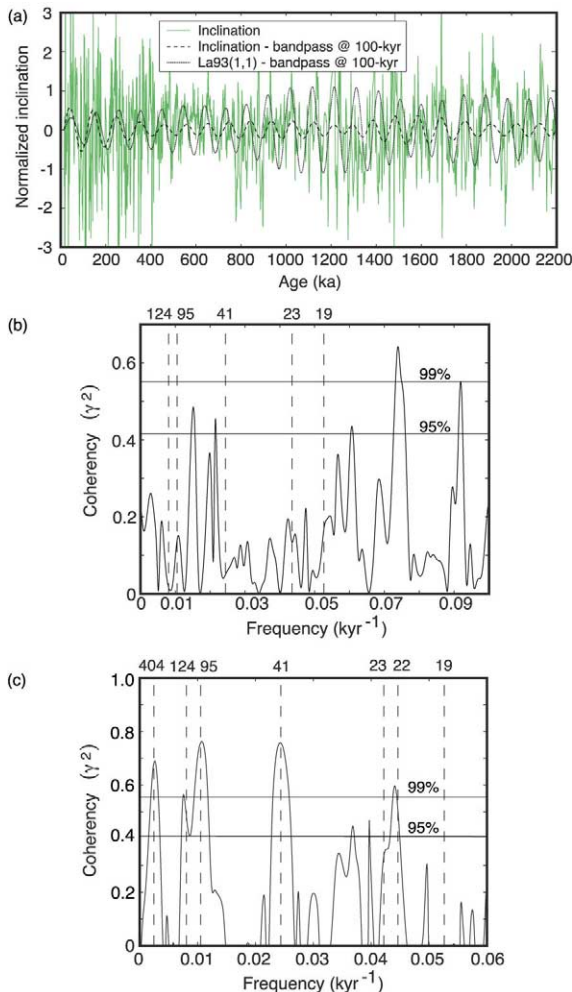
Wavelet analysis [14] is a highly suitable tool for detecting the dominant modes of variability and how those modes vary throughout a time series. A wavelet power spectrum for the paleomagnetic inclination record of Yamazaki and Oda [3] confirms their statements that a 100-kyr signal is present over the past 200 ka (Fig. 2a). A band of statistically significant power is also present between the 124-kyr and 95-kyr orbital eccentricity bands from 2000 to 1400 ka. Nevertheless, the record also contains significant power at other periods, with no obvious relation to any of the orbital periodicities. When compared with a wavelet analysis of a time series representing the variations in the orbital forcing signal (e.g., the eccentricity-tilt-precession (ETP) parameter from the data of [15]) (Fig. 2c), there is no obvious relationship between the forcing signal and the WCB inclination record [3] (Fig. 2a). The ~ 100 -kyr orbital eccentricity signal is strongly modulated by the 404-kyr eccentricity component (Fig. 2c; [15]), therefore, one would expect to see

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Fig. 2. (a) Wavelet power spectrum for the WCB inclination time series. Orbital periods of precession (19, 23 kyr), obliquity (41 kyr), and eccentricity (95, 124 and 404 kyr) are shown as dashed lines. Black contours confine areas with statistically significant power at the 95% confidence level for red-noise (see [14]). Curved lines on either side of the figure indicate the 'cone of confidence' where edge effects become important. (b) Wavelet power spectrum for an orbitally modulated time series of Saharan dust input into the eastern Mediterranean Sea over the same time interval as the WCB time series [16]. (c) Wavelet power spectrum for an idealized orbitally modulated time series (ETP parameter from the data of [15]) for comparison with the WCB inclination and Saharan dust time series. The Saharan dust record is clearly modulated by orbital forcing at a range of periods, including the 404-kyr and ~ 100 -kyr eccentricity, 41-kyr obliquity and 19–23-kyr precession bands (the major peak with ~ 60 -kyr period at 0.9 Ma is related to a large increase in dust flux at the mid-Pleistocene transition; see Larrasoana et al. [16] for details). Note that while the relative amplitudes of the signals in (b) and (c) are not linearly related, the frequencies in (b) are fully consistent with orbital forcing of dust supply. In contrast, while some statistically significant power is evident at about the 100-kyr period in parts of the WCB inclination record, there is also power at a range of other periods and no clear relationship is evident between this signal and the orbital eccentricity signal.

a 404-kyr component in a long inclination time series if the geodynamo was modulated by orbital eccentricity. This is not evident in Fig. 2a. In contrast, a wavelet power spectrum is shown in Fig. 2b for the last 2200 ka of a record of Saharan dust input into the eastern Mediterranean Sea [16], where a clear expression of orbital forcing is evident at the 404-kyr, ~ 100 -kyr, 41-kyr and 19–23-kyr bands. This demonstrates that a genuinely orbitally forced sedimentary record will clearly manifest components of an idealized orbital signal even though marine sediments are imperfect recorders.

The wavelet power spectrum provides informa-



tion about amplitude of the signal rather than phase. Information about phase can be obtained by comparing a band-pass filter of the inclination record with orbital eccentricity over the rather broad bandwidth used by Yamazaki and Oda [3]. The phase relationship is highly variable (Fig. 3a), which is not what one might expect if the geomagnetic signal was orbitally modulated. It is possible that some of these phase shifts might result from the relatively low resolution of the age model (e.g., [13]), or that orbital influence on the dynamo might produce non-linear effects that could cause phase shifts. Regardless, these possible effects weaken the interpretation put forward by Yamazaki and Oda [3]. Furthermore, there is no statistically significant coherency between the WCB inclination record and the ETP parameter [15] at the 100-kyr period or at any other Milankovitch periodicity (Fig. 3b), which is also not what would be expected if the WCB inclination signal was orbitally modulated. In contrast, a genuinely orbitally forced time series should have statistically significant coherency with the ETP parameter at all relevant periods over which orbital forcing has affected the record. For example, the

Fig. 3. (a) The WCB inclination record and a band-pass filtered representation (same bandwidth as in [3], $f=0.01 \pm 0.001 \text{ kyr}^{-1}$) of this record (dashed line), compared with the 100-kyr orbital eccentricity component from Laskar et al. [15] (dotted line). The WCB inclination and the eccentricity component from [15] were de-trended and normalized to unit variance before being subjected to band-pass filtering. Roughly 5% of the variance of the inclination record can be explained by the 100-kyr band-pass filtered signal. Importantly, the phase relationship between the inclination and orbital eccentricity is not consistent throughout the time series, which does not provide a convincing indication of orbital modulation of the inclination signal. (b) Bias-corrected coherency (γ^2) function [21] for the ETP parameter from the data of [15] and the WCB inclination record [3] (the same parameters were used as in Fig. 1a). There is no statistically significant coherency at the 100-kyr period (or at any other Milankovitch periodicity). (c) Coherency for the orbital data of [15] and the Saharan dust record of Larrasoana et al. [16] for the last 3 million years. Orbital forcing of the dust record is clearly demonstrated, with statistically significant coherency between the orbital solutions and dust fluctuations at the 99% confidence level.

Saharan dust record of Larrasoña et al. [16] has statistically significant coherency at the 99% confidence level for the full range of orbital periods discussed above (Fig. 3c) despite the fact that the relationship between orbital forcing and climatic response is highly non-linear. All of these pieces of evidence suggest that, while there appears to be a ~ 100 -kyr periodic influence on parts of the WCB inclination record [3], the hypothesis of orbital influence on the geomagnetic field is far from convincingly demonstrated.

3. Conclusions

Yamazaki and Oda [3] suggested that their paleomagnetic inclination record is influenced by the fact that the WCB lies within a zone in the western equatorial Pacific Ocean where there is a persistent non-dipole inclination anomaly [17,18]. They claim that their model for orbital modulation of the geomagnetic field can be tested by examining other paleomagnetic records located within this and other areas affected by long-term inclination anomalies. Horng et al. [19] recently published a coeval high-resolution paleomagnetic record from the western Philippine Sea (WPS), which also lies within the same long-term inclination anomaly [17,18]. Good serial correlation between the WCB and WPS paleointensity records indicates that both cores provide a high-quality record of geomagnetic field behavior [3,19]. Nevertheless, wavelet analysis of the WPS record does not provide evidence for a 100-kyr inclination or paleointensity periodicity [19]. We, therefore, suggest that the claim of orbital modulation of the geomagnetic field from the WCB record [3] is not supported by a consistent relationship with appropriate orbital parameters and that it is premature to accept the hypothesis concerning energization of the geomagnetic field by orbital forcing in the absence of more robust evidence.

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