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Observed periodicities and the spectrum of field variations in Holocene magnetic records

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ABSTRACT

In order to understand mechanisms that maintain and drive the evolution of the Earth's magnetic field, a characterization of its behavior on time scales of centuries to millennia is required. We have conducted a search for periodicities in Holocene sediment magnetic records, by applying three techniques: multitaper spectral estimation, wavelet analysis and empirical mode decomposition. When records are grouped according to their geographical locations, we find encouraging consistency amongst the observed periods, especially in nearby inclination records. No evidence was obtained for discrete, globally observed, periods. Rather we find a continuous broadband spectrum, with a slope corresponding to a power law with exponent of -2.3 ± 0.6 for the period range between 300 and 4000 yr. This is consistent with the hypothesis that chaotic convection in the outer core drives the majority of secular variation.

1. Introduction

Remanent magnetization of lacustrine and rapidly deposited marine sediments provides crucial information needed to reconstruct the past geomagnetic field (Korte and Constable, 2005; Korte et al., 2009, 2011; Nilsson et al., 2010; Pavón-Carrasco et al., 2010). Proposed reconstructions show complex patterns of geomagnetic field change, including fluctuations of the dipole field (Constable, 2007a; Nilsson et al., 2010), regional non-dipole field changes (Constable, 2007b; Amit et al., 2011), westward (or eastwards) drift of field structures (Dumberry and Bloxham, 2006; Dumberry and Finlay, 2007; Wardinski and Korte, 2008), and suggestions of a continuous spectrum of variability (Constable and Johnson, 2005).

Here, we investigate whether there is any evidence for persistent, globally observed, periodicities in Holocene sediment magnetic records. Such periodicities may be indicative of specific global modes of core dynamics; they are therefore of great importance in understanding the mechanisms underlying geomagnetic secular variation. Recently, Nilsson et al. (2011) identified a period of 1350 yr in the tilt of a dipole field model derived from five high quality records from lake sediments. This has provided fresh impetus to early ideas by Braginsky (1972, 1974), and more recent suggestions by Dumberry and Bloxham (2006) and Wardinski and Korte (2008) that there may be important global modes of core dynamics on millennial time scales. On the other hand, studies of rotating magneto-convection and self-consistent geodynamo simulations suggest that secular variation may simply be an outcome of chaotic convection in the outer core giving rise to localized oscillations and episodic drift of flux patches (Sakuraba and Hamano, 2007; Amit et al., 2010, 2011). Such models predict a broadband continuous spectrum of field variability (Tanriverdi and Tilgner, 2011; Olson et al., 2012). By searching for periodicities in the global database of Holocene magnetic records we are able to distinguish between these scenarios.

Several previous studies of secular variation in sediment records have reported evidence for periodicities, but no global analysis of the contemporary Holocene compilation (Korte et al., 2011) has yet been carried out. For example, Barton (1983) performed spectral analysis of declination and inclination time series, concluding that there was no evidence for discrete periods but rather for bands of preferred periods i.e. 60–70, 400–600, 1000–3000 and 5000–8000 yr. Constable and Johnson (2005) later produced a composite paleomagnetic power spectrum for the dipole moment, including a contribution from the CALS7k.2 field model (Korte and Constable, 2005); they found no evidence for discrete periodic dipole variations on time scales of 100 to 10 000 yr. Periodicities

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have however been reported in the studies of individual sediment records with identified periods spanning 200 to 8000 yr (e.g. Turner and Thompson, 1981; Brown, 1991; Peng and King, 1992; Zhu et al., 1994; Nourgaliev et al., 1996, 2003; Peck et al., 1996; Gogorza et al., 1999; St-Onge et al., 2003).

Currie (1968) has argued that the temporal power spectrum of geomagnetic field observations is governed by a power law, i.e., f^n, where f is the frequency. More recently, Olson et al. (2012) have made a detailed study of the frequency spectrum of dipole field variations from numerical geodynamo simulations and also find broadband variability well described by power laws. Their results agree well with the composite paleomagnetic dipole spectrum of Constable and Johnson (2005), the PADM2M spectrum of Ziegler et al. (2011) and long-standing estimates of the spectral slope on millennial time scales (Barton, 1982; Courtillot and Le Mouël, 1988). In principle, the slope of the spectrum of magnetic variations may also provide information on the kinetic energy spectrum of the underlying core flow (Tanriverdi and Tilgner, 2011). In this study we undertake a new observation-based characterization of millennial time scale periodicities of Earth's magnetic field, and the associated spectrum of temporal variations, taking advantage of robust models of Holocene lake sediment magnetic records recently derived by Panovska et al. (2012).

For this purpose we employ three different signal analysis techniques: multitaper spectral estimation, wavelet analysis and empirical mode decomposition (EMD). Multitaper methods (Thomson, 1982; Riedel and Sidorenko, 1995; Percival and Walden, 1998) provide reduced variance and minimum bias spectral estimates compared to the conventional periodogram. Due to the short lengths of the time series compared to the time scales of interest, as well as the fact that geophysical systems are rarely exactly periodic and likely nonstationary, we also explore two alternative methods. Wavelet analysis, a spectrum analysis method developed in the 1990s (e.g., Chui, 1992), provides further complementary information, enabling the study of the nonstationary nature of signals, and providing access to the time–frequency distribution, i.e., how the power is distributed over time (e.g., Strang and Nguyen, 1996). Previously, wavelet analysis has proved useful in the study of relative paleointensity records and archaeomagnetic field intensity in order to search for significant frequencies (Guyodo et al., 2000; Gurarii and Aleksyutin, 2009) as well as in studies of geomagnetic jerks (Alexandrescu et al., 1996). The EMD method was introduced by Huang et al. (1998) with the purpose of analyzing nonlinear and nonstationary data by decomposition into so-called 'intrinsic mode functions' possessing characteristic frequencies. Roberts et al. (2007) have successfully used this method to study both geomagnetic secular variation in the observatory era and decadal changes in the length of day, in particular detecting the existence of an approximately 60-yr period. Jackson and Mound (2010) later succeeded in identifying periods of 11.5 yr, corresponding to the solar cycle, 30.5 and 81 yr by applying the same method to a larger database of observatory annual means. By investigating Holocene lake and marine sediment records with these three techniques, we are able to characterize possible modes of variability, even if these are nonstationary and quasi-periodic.

2. Data and methodology

The basis for this study is the compilation of Holocene sediment magnetic records of Korte et al. (2011) in which the majority of the records are from lakes, with only 10% from marine sediments. Although the database has been enhanced by a number of new studies in recent years, the Southern hemisphere is still poorly represented and the highest concentration of observations is in the European region (Fig. 1). This database contains 72 inclination (I),

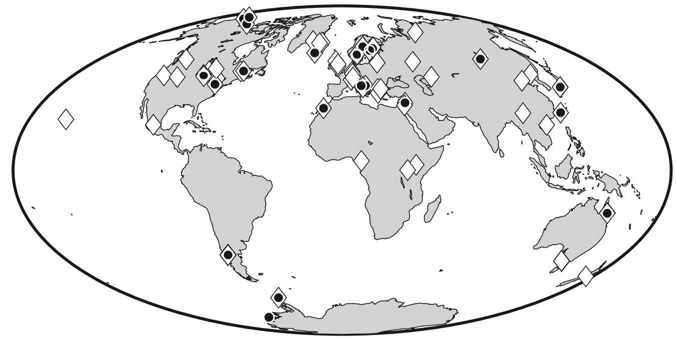

Fig. 1. The geographical distribution of Holocene sediment records used in this study, directional (D or I) data (white diamonds) and RPI (black circles). Only inclination data are available for the records from Adriatic Sea, Lake Pepin, Lake Turkana and the West Pacific sites.

68 declination (D) and 27 relative paleointensity (RPI) records. We have previously derived individual spline models that capture the most robust aspects of each of these records (Panovska et al., 2012) (e.g. blue lines in Figs. 2c, 3c and 4c); this provides a convenient means by which to search for periodicities and carry out spectral analysis.

Here we illustrate our investigations using the following examples on three different components: 1) a declination record from Eifel Maars, Germany (Stockhausen, 1998), 2) an inclination record from Lake Waiau, Hawaii (Peng and King, 1992) and 3) a relative paleonintensity record from Cape Ghir, NW African Margin (Bleil and Dillon, 2008) (Figs. 2, 3 and 4). Similar plots for all the other records where periods were identified are available online at http://earthref.org/ERDA/1737.

We first applied the multitaper spectral analysis method. This involves multiplication of the data by several orthogonal tapers, Fourier-transforming and then averaging the independent spectral estimates (cf. Prieto et al., 2007, 2009; Smith-Boughner et al., 2011; Smith-Boughner and Constable, 2012). For all records we computed power spectral estimates using both prolate tapers (Slepian, 1978; Thomson, 1982) and minimum bias tapers (Riedel and Sidorenko, 1995), varying the number of tapers between 5 and 9. We found that the spectral estimates obtained with different tapers agreed well for a subset of frequencies that were well constrained by the data. In Figs. 2a, 3a and 4a we show examples of the spectral estimates obtained with the minimum bias tapers computed with 5 tapers. The well-defined frequency ranges in this case are noted in the figure captions. We then calculated the best fitting power law slope for the well-determined range of each spectrum. These results are summarized in Fig. 5a. Only records whose slopes are estimated for a range > 1000 yr on a period scale were considered for the spectral slope analysis. In addition, we only included records with a relative difference between the spectral slopes $< 10\%$, based on prolate and minimum bias tapers.

In a second step we carried out a 'Mexican hat' wavelet transform in order to map the temporal evolution of the spectral power in the records (e.g., Foufoula-Georgiou and Kumar, 1994). To analyze variability at different periods, the number of scales used in the wavelet analysis was chosen to be 90, these were later converted into frequencies (10^{-4} to 10^{-2} yr^{-1}) (Trauth, 2010). Absolute values of the wavelet coefficients are plotted as contour maps constituting the wavelet power spectrum (Figs. 2b, 3b and 4b) with the frequency/period (right/left) axis plotted using a logarithmic scale.

Finally, we used the implementation of EMD analysis by Flandrin (2009) to decompose each record into a small number of oscillation modes known as intrinsic mode functions (IMF) together with a residual. An IMF satisfies two requirements: (i) the

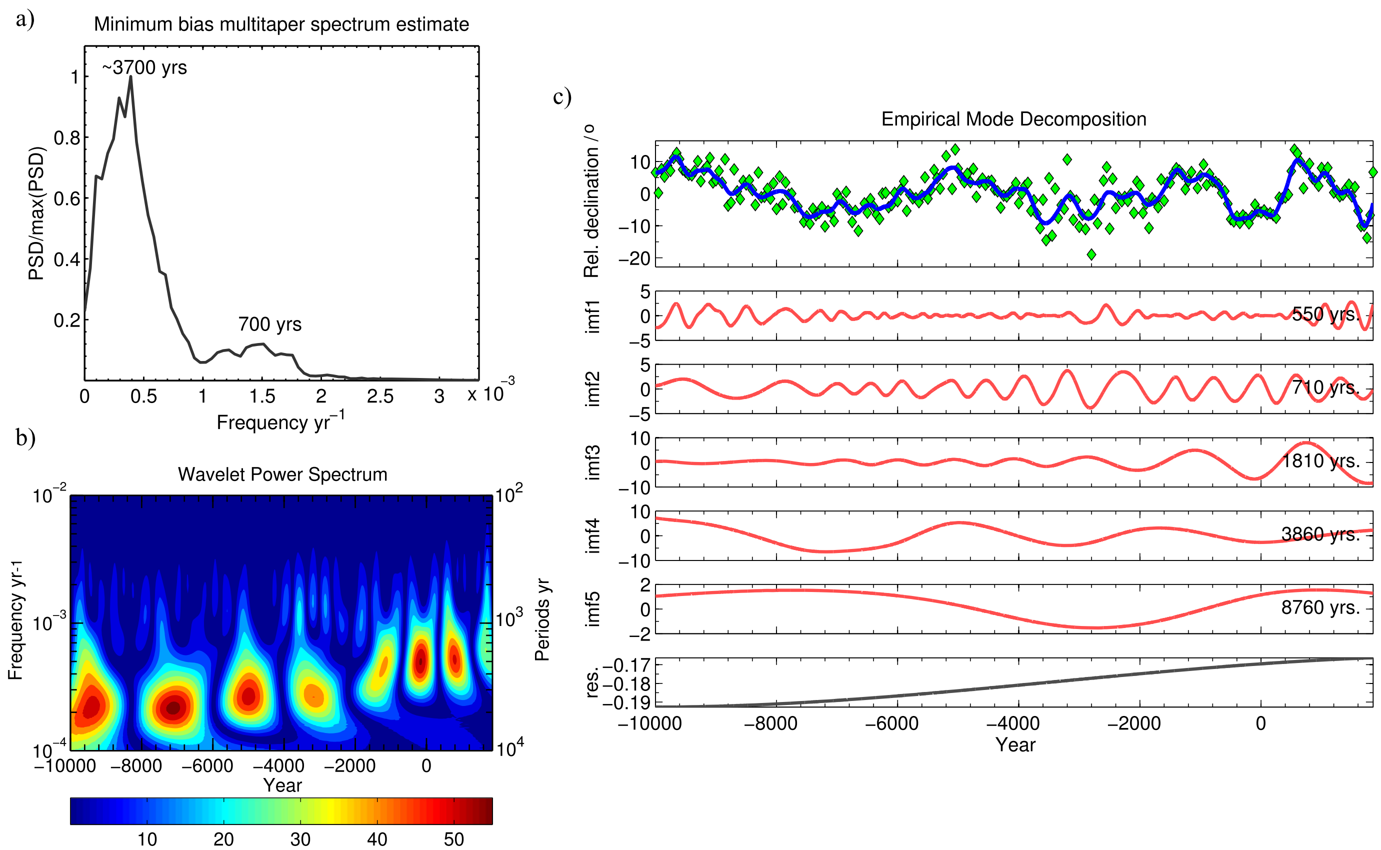

Fig. 2. Comparison of techniques for periodicity analysis for an example declination record from Eifel Maars, Germany: a) Multitaper spectrum using 5 minimum bias tapers, b) 'Mexican hat' wavelet analysis and c) Empirical Mode Decomposition. Peaks in the multitaper spectrum are noted along with the corresponding periods. The spectral slope is calculated in the period range from 300 to 2500 yr. The wavelet power spectrum is given as a function of frequency (left axis) and associated periods (right axis). The color scale denotes contours of the absolute value of the wavelet coefficients. Green diamonds denote the sediment magnetic data while the robust smoothing spline model is plotted as a blue curve. The EMD method decomposes the record into five IMFs (red curves) and a residual (grey curve). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

number of extrema and the number of zero-crossings are equal or differ at most by one; (ii) the mean value of the envelopes defined by the local maxima and local minima is zero across the whole record (Roberts et al., 2007). The method works iteratively, extracting the highest frequency mode first, then forming a new signal by subtracting the first mode from the original signal and then repeating the procedure (Rilling et al., 2003). Usually, the first IMF separated out by EMD is noise; this is not the case in our study because the input signals are already smooth. Using the spline model predictions as the input enables us to avoid problems in the analysis associated with the presence of outliers and gaps in the original time series. We present three examples of the EMD analyses in Figs. 2c, 3c and 4c. The top plot is always the input signal, our robust spline model, with the original data also shown for reference. The number of IMFs obtained differs from record to record, depending on the number of coherent oscillations that can be extracted. The residual trend can be a monotonic function or an incomplete cycle with a period longer than the length of the record. Two methods suggested by Roberts et al. (2007) have been used to estimate the periods of the IMFs: the autocorrelation function (ACF) based on identifying peaks that exceed the 95% confidence level, and averaging of time interval lengths between successive maxima, successive minima, and successive ascending and descending zero crossing points. Periods with a difference larger than 10% between these two estimates are omitted from the analysis. Hereafter we report only the ACF periodicity results. To assess the mode significance, the average power of each mode compared to the power of the signal minus the residual was estimated. Only modes that explain more than 10% of the power of the decomposed signal were included in the summary plot in Fig. 5b. Additionally, we omit periods obtained from records with uncertainty estimates greater than 20° for D, 7° for I and 1 in standardized units of RPI (see Panovska et al., 2012). According to tests performed by Jackson and Mound (2010), the longest meaningful period will not exceed 75% of the time series length. Consequently the longest retrieved periods are about 9000 yr. The shortest periods are bounded by a record's intrinsic smoothing time (due to the sedimentation process), which has an estimated mean value of 160 yr for these records (Panovska et al., 2012).

3. Results

As illustrated by the examples in Figs. 2, 3 and 4, the periods extracted by EMD analysis generally agree well with the periods obtained by the multitaper spectral estimates, although in some instances periods obtained with one method do not obviously correspond to periods obtained with the other method.

A summary plot of the minimum bias multitaper spectra of all D, I and RPI records satisfying the criteria discussed above is presented in Fig. 5a. Considering power law fits to all the spectra a mean power law exponent of −2.3 and a standard deviation of 0.6 is obtained. Slopes were calculated by a least squares fit on logarithmic axes for each considered record and component. Considering the observed components separately we found similar slopes, for D a slope of -2.4 ± 0.6, for I -2.4 ± 0.6 and for RPI

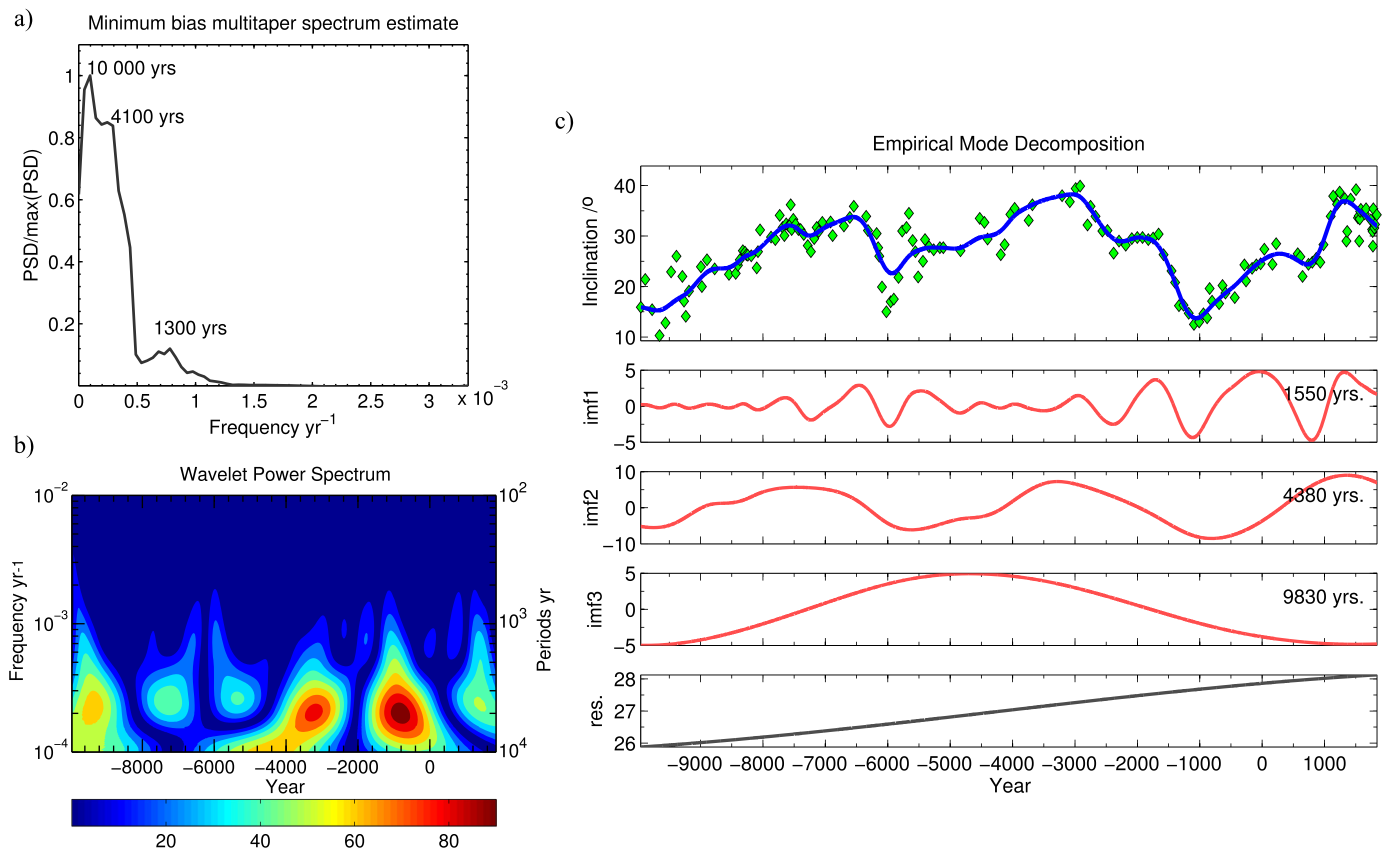

Fig. 3. Comparison of techniques for periodicity analysis for an example inclination record from Lake Waiau, Hawaii: a) Multitaper spectrum using 5 minimum bias tapers, b) 'Mexican hat' wavelet analysis and c) Empirical Mode Decomposition. The spectral slope is calculated in the period range from 600 to 3500 yr. Details are given in the caption of Fig. 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

-2.2 ± 0.6. The mean slope was estimated for the best constrained period range of 300 to 4000 yr. Very similar results were obtained when the number of tapers (5, 7 and 9), the time-bandwidth product (3, 4 and 5) and choice of taper (minimum bias and prolate) were varied. The spectral slope for periods longer than 4000 yr appears shallower, whereas the high frequency end of the spectrum appears to possess a steeper slope but these portions of the spectrum are less well constrained in the records considered here.

Our wavelet analysis demonstrates the nonstationary nature of the analyzed records with peaks observed in the time–frequency spectrum not persisting throughout the full length of the record. This nonstationarity motivated our use of the EMD technique in order to characterize the quasi-periodic and transient oscillations embedded in the records.

Fig. 5b presents an alternative summary of the periodicities present in these records in terms of a histogram, collecting all the periods identified by the EMD analysis. This analysis also indicates broadband variability across the entire period range to which these records are sensitive. The number of retrieved modes drops at the ends of the period range where only a few lakes, with either high sedimentation rate, or very long records, contribute. A similar broadband result is obtained when periods are grouped by individual components, i.e. inclination, declination or RPI.

Periods grouped according to geographical regions show notable consistency, for example, periods of 1100, 1300, 1700, 2100, 2400 and 2800 commonly observed in Europe, including in the Eifel Maars, Germany (Stockhausen, 1998), Finnish Lakes (Haltia-Hovi et al., 2010), Lago di Mezzano, Italy (Brandt et al., 1999) and Lake Windermere, UK (Turner and Thompson, 1981). Asian records commonly display periods in intervals around 400, 700, 1000, 1500–2000, 2800, 5000 and 8000 yr; North and South American continents share a pronounced peak at around 1800 yr, with periods of 500, 1200 and 2800 also appearing prominently. This demonstrates that independent, high quality, sediment records that are geographically close, are capable of recording the same secular variation signal.

4. Discussion

Our application of three different time series analysis techniques to the contemporary database of Holocene sediment magnetic records demonstrates that millennial time scale geomagnetic field variability should be understood as a superposition of broadband variations. This conclusion is compatible with previous studies of periodicities in sediment magnetic records, based on a less comprehensive data collection (Barton, 1982, 1983) and with recent findings regarding the spectrum of the geomagnetic dipole (Constable and Johnson, 2005; Ziegler et al., 2011; Olson et al., 2012). We find no evidence for discrete, globally observed, periodic signals capable of accounting for large portions of the secular variation. Nilsson et al. (2011) have recently identified a 1350 yr cycle in modeled dipole tilt variations for the past 9000 yr based on five high quality sediment records. We find that although power is present at this period when considering the global database of records, it does not dominate the observed secular variation spectrum. Change in the dipole tilt is a very specific aspect of the geomagnetic field evolution (e.g. Amit and Olson, 2008) and the field variations associated with it constitute only a small part of the observed secular variation.

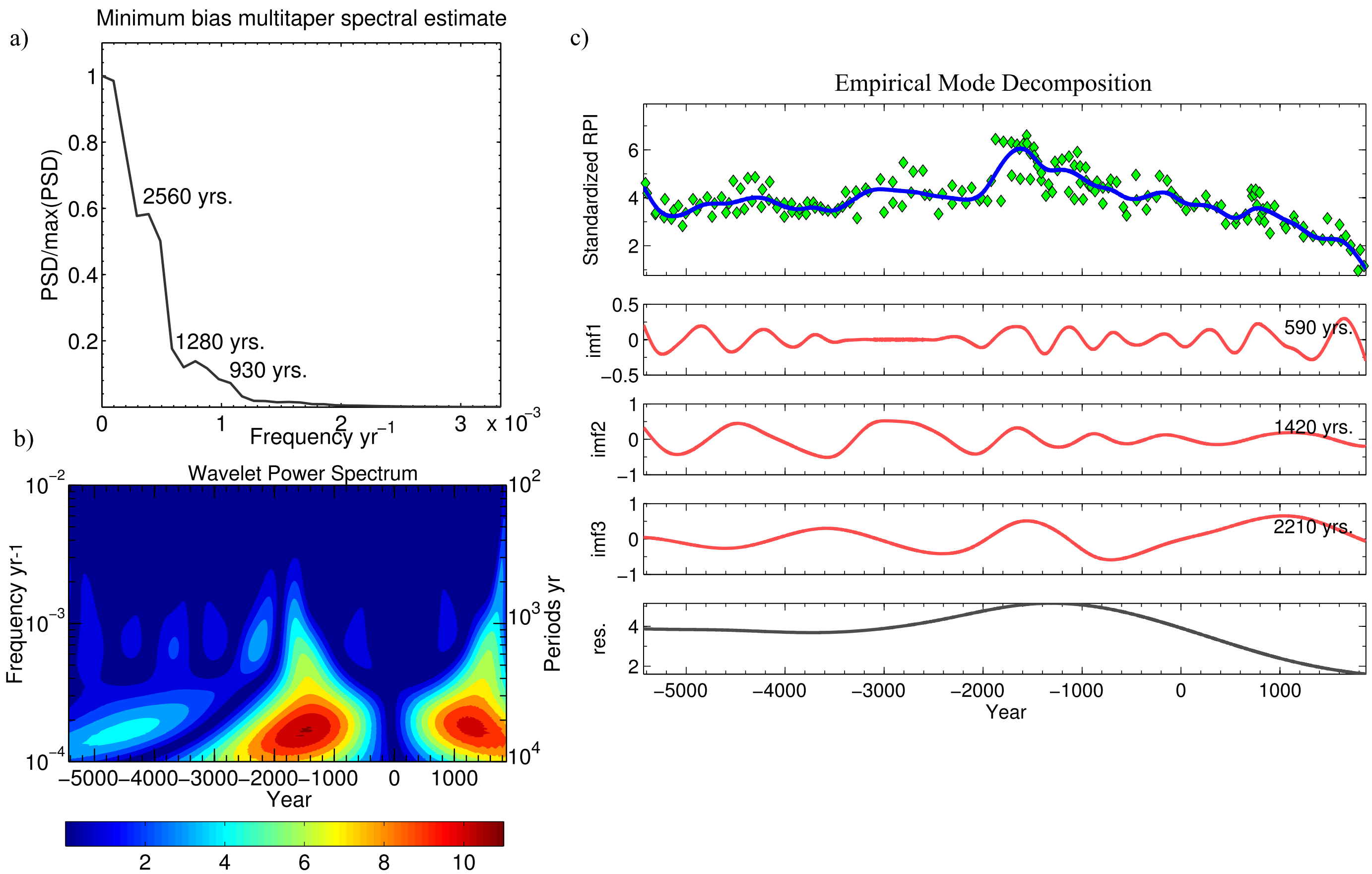

Fig. 4. Comparison of techniques for periodicity analysis for an example inclination record from Cape Ghir, NW Afr. Margin: a) Multitaper spectrum using 5 minimum bias tapers, b) 'Mexican hat' wavelet analysis and c) Empirical Mode Decomposition. The spectral slope is calculated in the period range from 900 to 3000 yr. Details are given in the caption of Fig. 2. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

The lack of any dominant global periodicities in Holocene sediment magnetic records, while at the same time there are broad regions where similar periods are obtained (see Fig. 6), is a scenario compatible with recent inferences of regions of enhanced secular variation from satellite magnetic data (Holme et al., 2011). Such regions of enhanced secular variation may be indicative of locations in Earth's core were convective forcing is systematically more vigorous (leading to localized flow fluctuations and magnetic flux expulsion) as a result of regional variations in the heat flux at the core–mantle boundary (Holme et al., 2011) or in the light element flux at the inner core boundary (Aubert, 2013). The sparsity of sites available in the present study and inconsistencies between some nearby sites unfortunately prevents us from determining the complete geographical distribution of secular variation on millennial time scales. It would certainly be of interest to obtain further sediment records in regions such as Indonesia where enhanced or anomalous secular variation has been consistently observed during the historical era (Bloxham and Gubbins, 1985), to test whether or not this is a long term feature of the geodynamo.

We find a mean power law exponent of -2.3 ± 0.6 in the period range from 300–4000 yr (Fig. 5a). This is in good agreement with a previous observation-based estimate by Barton (1982) of -2 using a much smaller data collection and compares well with values of $-5/3$ for the range 500 to 50 000 yr and $-11/3$ for shorter periods obtained by Constable and Johnson (2005) for their composite spectrum for the dipole moment. Furthermore it is in remarkably good agreement with the exponent of $-9/5$ recently obtained from geodynamo simulations by Olson et al. (2012) for the band of periods between 500 yr and 200 kyr and similar to the exponent of $-5/3$ obtained in a high resolution rotating magneto-convection simulation by Sakuraba and Hamano (2007), considering frequencies up to 3 kyr^{-1}. Tanriverdi and Tilgner (2011) have demonstrated that, for small amplitude fluctuations, a power law exponent of -2 for the magnetic energy indicates an underlying, bandlimited, white spectrum of temporal fluctuations in the core flow. Our results therefore suggest that the present (Holocene) mode of operation of the geodynamo, with no excursions or reversals and a power law exponent of approximately -2 for its magnetic fluctuations, is a consequence of chaotic convection producing a white spectrum of flow fluctuations and broadband variations in magnetic induction.

It should be remembered that the analyses presented here cannot rigorously distinguish between geomagnetic and environmental sources of variability. Consequently, the possibility of some contamination from environmental sources cannot be excluded. For example, the recovery of the paleointensity variation in sediments requires a normalization to reduce the environmental effects, and any inadequately treated records may remain biased with respect to non-geomagnetic signals (Constable and Johnson, 2005). It is also noteworthy that the same periods are not always seen in different components at the same site. This may partly be due to sensitivity kernels for D, I and RPI (Johnson and Constable, 1997) sampling different regions of the core–mantle boundary, but may also reflect differences in the recording fidelity of the different components. Radiocarbon dating, often along with independent dating points e.g. tephra, varves or pollen, is the most commonly used method of age determination in records analyzed here. It involves dating uncertainties ranging from a few decades up to a few

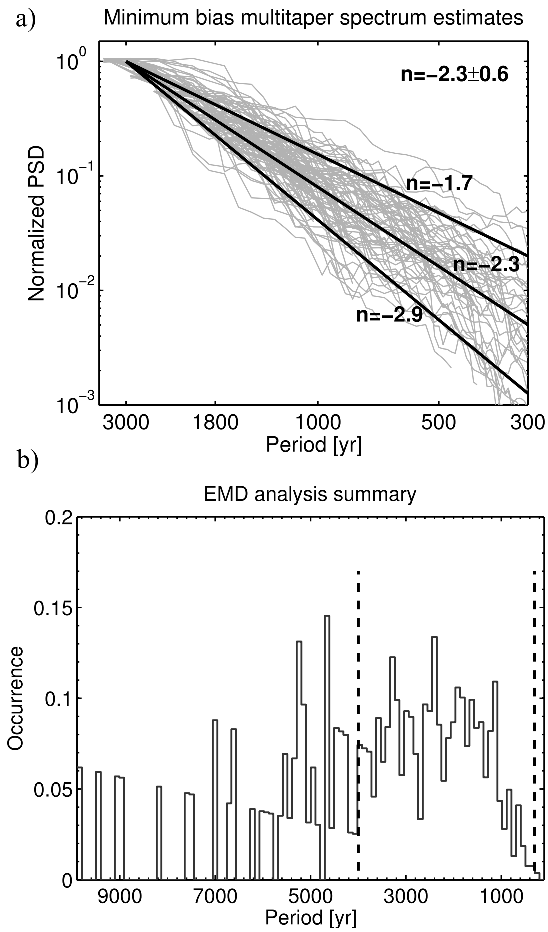

Fig. 5. (a) Multitaper spectra (individually normalized to their maximum) computed using 5 minimum bias tapers. A power law exponent (spectral slope) of -2.3 ± 0.6 is estimated for the best constrained part of the spectrum [300 to 4000 yr]. (b) Histogram of periodicities obtained from the EMD analysis of all components from all records. Occurrence of periods is normalized by the number of records occurring in each period bin. The period range used for the spectral slope estimation in (a) is indicated by the dashed lines.

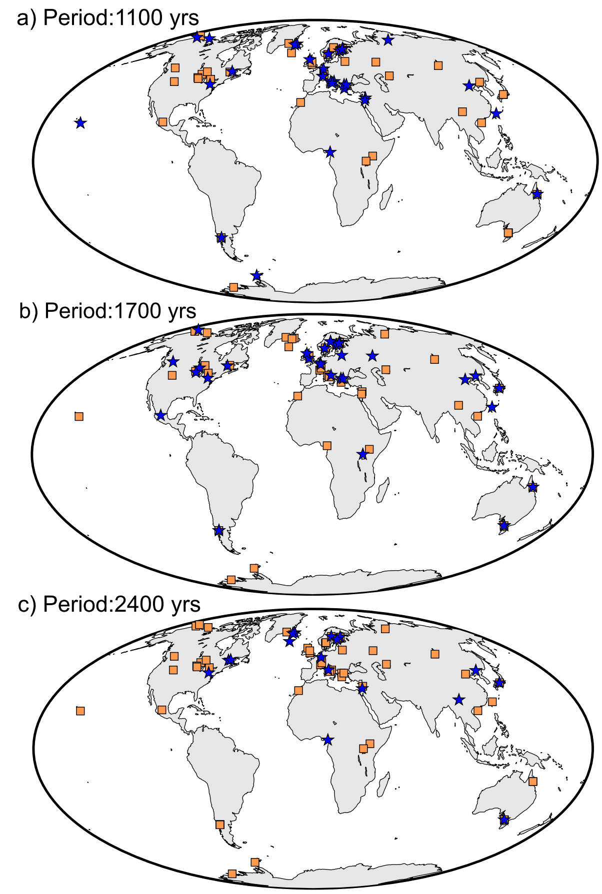

Fig. 6. Maps showing locations of Holocene sediment magnetic records where periods of 1100 yr (a), 1700 yr (b) and 2400 yr (c) are observed (blue stars) and locations where these periods are not observed (orange squares). These particular periods are commonly observed in European region. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

centuries that should be borne in mind when interpreting the inferred periods.

5. Conclusions

Holocene sediment magnetic records possess a continuous spectrum of variations on time scales from 300 to 4000 yr, with some local variability. This is compatible with the hypothesis of chaotic convection in the Earth's core driving secular variation as suggested by recent numerical simulations of the geodynamo (Sakuraba and Hamano, 2007; Amit et al., 2010; Tanriverdi and Tilgner, 2011; Olson et al., 2012). On the other hand, our findings are more difficult to reconcile with models of secular variation consisting of only a small number of global modes possessing very simple space and time dependence.

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