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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), 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.

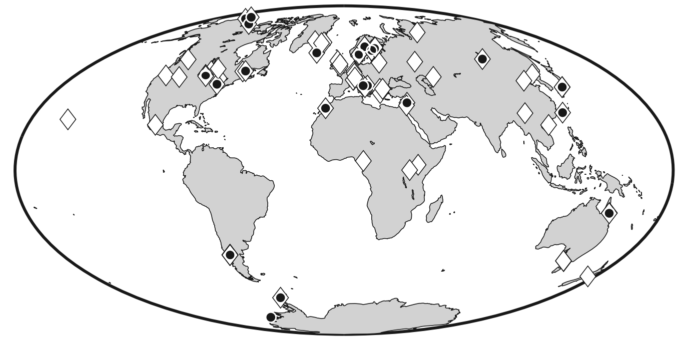

Fig. 1. The geographical distribution of Holocene sediment records used in this study, directional (D or I) data (white diamonds) and RPI (black circles). Only inclination data are available for the records from Adriatic Sea, Lake Pepin, Lake Turkana and the West Pacific sites.

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 paleointensity 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