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The effects of aliasing and lock-in processes on palaeosecular variation records from sediments

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SUMMARY

Studies of sedimentary records of palaeointensity variation report periods as long as 50 kyr. Archaeointensity data show geomagnetic periods of 2 kyr with large amplitudes. Sampling of the sedimentary records can be as coarse as 8 kyr, so the apparent long periods could be caused by aliasing. The sedimentary lock-in process could smooth the record and remove short periods, thereby preventing aliasing from occurring. We examine possible effects of aliasing by creating a 100-kyr-long synthetic sequence of palaeointensity variation with a similar spectrum to that of archaeomagnetic data from the last 12 kyr and resampling at longer intervals. With no lock-in smoothing, aliasing produces spurious energy in the spectra at long periods. When smoothing by the sedimentation process is applied, the amplitudes of the aliased peaks are reduced but still cause significant, spurious, long-period energy in the spectra for some sedimentation rates. We restrict our analysis to palaeointensity data but similar problems may also exist for coarsely sampled directional data. To avoid aliasing we recommend a maximum sampling interval of 2 kyr.

Key words: palaeointensity, palaeomagnetism, sediments, spectral analysis.

1 INTRODUCTION

There are now several long records of secular variation from sediment cores (Guyodo & Valet 1999; Tauxe & Hartl 1997; Channell *et al.* 1997) giving relative intensity and inclination. Sediments have the potential for continuous recording for thousands or even millions of years and reasonable geographical distribution. They are rather poor magnetic recorders and can smooth the signal because the magnetization takes some time to 'lock in' (Kent 1973). Estimates of sedimentation rates can give an approximate timescale, and dating is improving dramatically (e.g. Langereis *et al.* 1997).

Secular variation is measured from the core either by sampling it at suitable intervals or by pulling the whole core through the magnetometer. Ideally, sampling gives a spot measurement of the field if the sedimentation rate is fast enough and the sample small enough. Pull-through gives an average over a length of core that depends on the size of the sensor. This can smooth a significant interval of secular variation (Constable & Parker 1991), and sampling is generally preferred.

There have been several spectral studies of sedimentary cores that report periods of about 30 kyr (e.g. Tauxe & Wu 1990; Tauxe & Shackleton 1994; Tauxe & Hartl 1997), which is a surprisingly long period for the geodynamo. Tauxe & Hartl (1997) have analysed an 11-Myr-long record of secular variation from the Oligocene and report a 30 kyr periodicity. They used sampling intervals corresponding to 4–8 kyr, which is longer than the dominant periods of the more recent secular variation found in the archaeomagnetic record (McElhinny & Senanayake 1982; Yang *et al.* 2000), so if the last 10 kyr is typical and the samples represent spot measurements of the field, there is the possibility of aliasing short periods into much longer periods.

When a continuous, real time-series is digitized with a sampling interval Δt, the spectrum is confined to frequencies below the Nyquist frequency, $\nu_N = 1/(2\Delta t)$. All energy in the continuous time-series at frequencies $\nu > \nu_N$ above the Nyquist frequency is folded into the range $(0, \nu_N)$ according to the formula

$$\nu_A = \pm(2n\nu_N - \nu)\,, \quad \text{where } n = 1, 2, 3 \ldots \infty\,, \tag{1}$$

where the positive integer n and the sign are chosen such that $0 < \nu_A < \nu_N$. This equation is a direct consequence of the periodicity of the discrete Fourier transform. Once aliasing occurs it is impossible to recover the original frequency information from the digitized time sequence. Aliasing affects all frequencies; it is therefore essential to remove all energy above the Nyquist frequency before digitizing, otherwise all meaningful information will be destroyed. This is done electronically by a low-pass anti-alias filter. Aliasing also occurs when a discrete time sequence is resampled at a longer interval. In this case aliasing is prevented by applying a digital low-pass filter to remove all energy above the new Nyquist frequency (Priestley 1981).

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Consider the 5 kyr sinusoid ($\nu = 1/5$) sampled at 4 kyr ($\nu_N = 1/8$) shown in Fig. 1. Applying eq. 1 with the constraint $0 < \nu_A < \nu_N$ gives $\nu_A = 1/20$, $n = 1$ and a $+$ sign, that is, the original 5 kyr period is aliased into a 20 kyr period. The period of 20 kyr has many frequencies $\nu > \nu_N$ that alias into it. Using eq. 1 for $\nu_A = 1/20$ and $\nu_N = 1/8$ we have the infinite set of periods ($1/\nu$): 5 kyr, 3.33 kyr ($n = 1$); 2.22 kyr, 1.82 kyr ($n = 2$); 1.43 kyr, 1.25 kyr ($n = 3$), etc., which all alias into the 20 kyr period.

The archaeomagnetic data suggest significant secular variation with changes in the virtual axial dipole moment (VADM) by up to a factor of two on a timescale of about 1 kyr. A faithful recording of such a signal in the sediment will be aliased into longer periods by sampling with $\Delta t > 500$ yr. In our example, a 4 kyr sampling interval would alias a monochromatic signal with a period of 1.25 kyr to a 20 kyr peak in the spectrum. In general, energy at all frequencies above the Nyquist, in this example periods of less than 8 kyr, would be aliased to longer periods. The whole record could then be spurious.

It is possible that smoothing imparted by the magnetization process acts to remove higher frequencies. Lund & Keigwin (1994) have shown that attenuation of high frequencies in secular variation records increases as sedimentation rate decreases due to lock-in effects. Thus lock-in effects, rather than impairing the record obtained from the sediments, might actually help by acting as an anti-alias filter. Smoothing by the pass-through magnetometer could act similarly. It would be fortunate indeed if lock-in effects were exactly right to prevent aliasing.

In this paper we conduct a synthetic study to examine the effects of coarse sampling on secular variation records, both with and without smoothing by lock-in effects. First, in Section 2 we construct a 100-kyr-long synthetic record of secular variation that has the same spectrum as the archaeomagnetic record up to periods of 10 kyr, but contains no energy in periods above 10 kyr. In Section 3 this long series is resampled at a range of longer sampling intervals and the spectrum recalculated to assess the effects of aliasing. In Section 4 we design suitable lock-in filters to represent the smoothing imparted by the magnetization process and apply them to the synthetic sequence. We then repeat the sampling process to re-examine the aliasing.

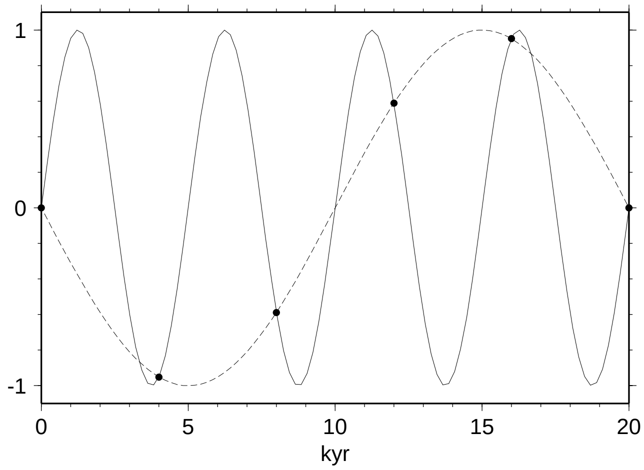

Figure 1. Example of aliasing: a 5 kyr signal (solid line) is coarsely sampled at 4 kyr intervals (solid circles); the period of the resulting aliased signal is 20 kyr (dashed line). All signals with frequencies above the Nyquist of $1/8$ kyr^{-1} are aliased into lower frequencies.

2 SYNTHETIC SEQUENCE

The archaeomagnetic record of geomagnetic intensity consists of thermoremanent magnetization data from sources such as lavas, baked clays and ancient fireplaces. The age control on these intensity measurements is usually from radiometric ^{14}C or historical information. For example, Tanaka (1980) used dates of volcanic eruptions from historical records to date lavas; these are generally much more accurate than the radiometric methods used to date palaeomagnetic data. The archaeomagnetic data thus provide a good basis on which to construct a synthetic sequence that models short-period geomagnetic secular variation. The archaeomagnetic data extend to about 50 ka, most of the data being younger than 12 ka (McElhinny & Senanayake 1982; Yang *et al.* 2000).

The archaeomagnetic data used is a compilation of thermoremanent intensity data from Mankinen & Champion (1993), Gonzalez *et al.* (1997) and a compilation by Tanaka *et al.* (1994). We call these collectively 'Compilation 2000'. We also use a database for the last 12 kyr compiled by Yang *et al.* (2000) covering America, Asia and Europe. The archaeomagnetic data are shown in Fig. 2; they show that the geomagnetic intensity changed by at least a factor of two from 2–7 ka, so if this is typical of the last few hundred kiloyears, a 5 kyr sampling interval will fail to define the palaeosecular variation because of aliasing.

Selkin & Tauxe (2000) have analysed 300 Myr of palaeointensity data from lavas and submarine basaltic glass and found that the palaeointensity in the interval 0–0.3 Ma is $8.4 \pm 3.1 \times 10^{22}$ A m^2 compared to $4.6 \pm 3.2 \times 10^{22}$ A m^2 from 0.3 to 300 Ma. The means are quite different but the standard deviations for 0–0.3 Ma and 0.3–300 Ma are very similar, indicating that the variability of the field intensity has remained at a similar level for at least 300 Myr. Although the long-term mean intensity will be lower, the archaeomagnetic data should provide a sound basis on which to build a representation of the short-term variability of the geomagnetic field.

The first step in creating our synthetic record was to smooth the archaeomagnetic data. Cubic B-splines (Lancaster & Šalkauskas 1986) with a knot spacing of 1 kyr were fitted to the data by least squares. The published error bars were not used and each datum was weighted equally. The smooth curve was constrained to have the present VADM value of 8.0×10^{22} A m^2 at 0 ka. Fig. 3 shows the best-fitting smooth curve to the data; it also shows the data averaged over 1 kyr intervals for comparison with the database of McElhinny & Senanayake (1982). The two archaeointensity profiles are very similar except around 9 ka, where the more recent compilation of Yang *et al.* (2000) shows a greater intensity peak than the compilation of McElhinny & Senanayake (1982). The factor of two variation in the raw data remains an important feature of the smoothed data. In the following analysis we assume that the intensity variations in this smoothed archaeomagnetic record are a good representation of the general field behaviour with timescales of about 10 kyr throughout the palaeomagnetic record.

To study the effects of aliasing we require a record of geomagnetic secular variation with a duration comparable to

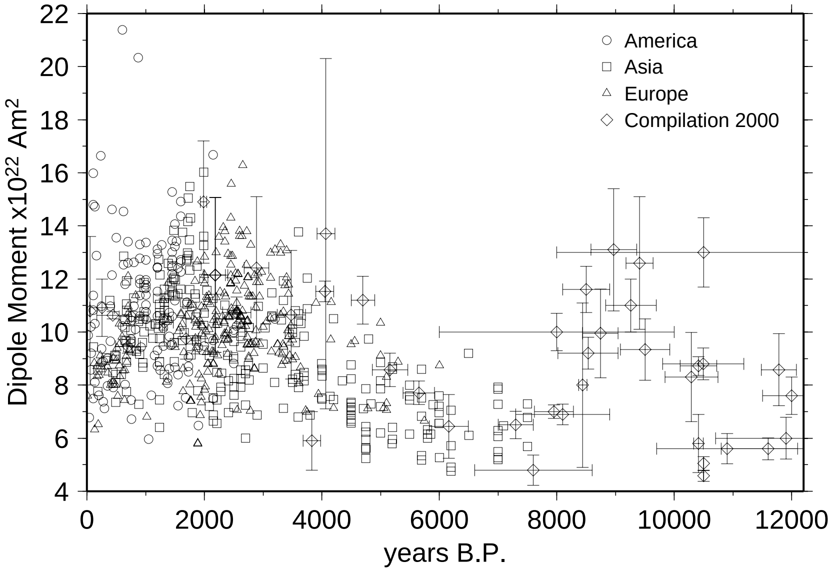

Figure 2. Archaeomagnetic data. Error bars on the data from America, Asia and Europe have been omitted for clarity.

typical sedimentary cores; we use 100 kyr as a compromise between sequence length and computation time. We produce the longer record from the smoothed archaeomagnetic data by convolving it with a long white-noise series. White noise has a flat spectrum so the convolution will not alter the basic shape of the spectrum of the smoothed data. This is equivalent to filtering the white noise series using the spectrum of the archaeomagnetic data as a filter.

The trend of the smoothed data was removed prior to convolution to prevent the spectrum being dominated by a large zero-frequency component. The resulting time-series was tapered with a 10 per cent cosine taper to prevent contamination of the spectrum by sharp jumps to zero at the ends. This series was then convolved with white noise. The resulting synthetic sequence was high-pass filtered using a 16 pole, 45 dB octave^{-1} Butterworth filter with a cut-off period of 10 kyr, ensuring that only short geomagnetic periods were present. Finally, the series was rescaled to have the same mean and variance as the smoothed archaeomagnetic data.

The final 100 kyr synthetic intensity record is shown in Fig. 4. In Fig. 5 the spectra of the archaeomagnetic data and synthetic sequence are compared; the distribution of energy is the same in both cases, apart from below 0.1 kyr^{-1}, which has been removed from the synthetic sequence by high-pass filtering. Also, the synthetic and archaeomagnetic data are similar in appearance, hence the synthetic sequence is a reasonable simulation of palaeosecular variation in the period range 1–10 kyr.

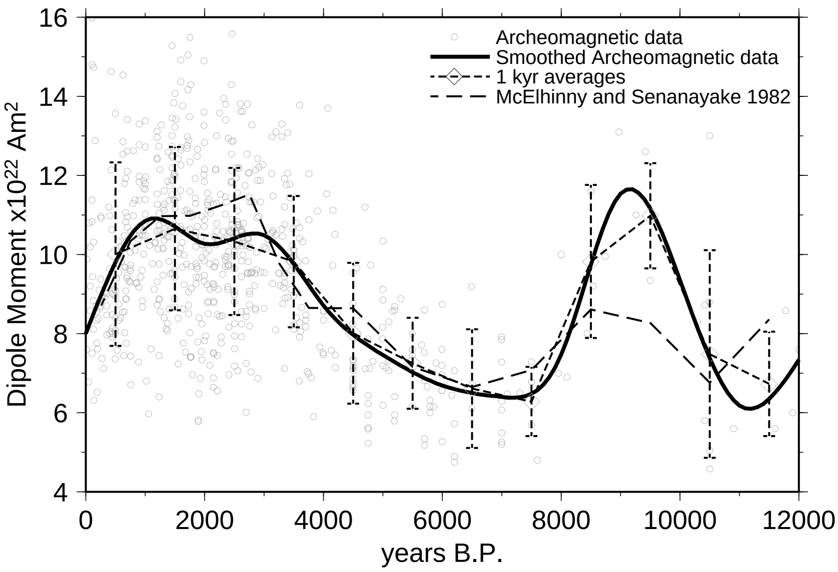

Figure 3. The archaeomagnetic data and best-fitting smooth curve. The 1000 year averages are also shown for comparison with the compilation of McElhinny & Senanayake (1982).

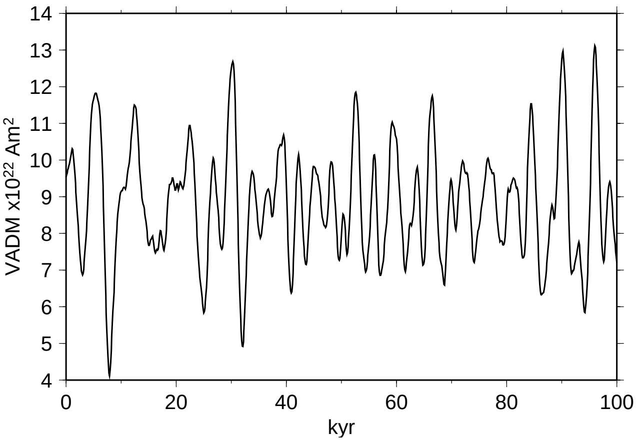

Figure 4. Filtered synthetic palaeointensity sequence that contains no energy with periods greater than 10 kyr.

3 RESAMPLING

We now explore the effects of aliasing by resampling the synthetic sequence at 2, 5 and 8 kyr intervals using three sampling methods. In palaeomagnetism, measurements are taken from discrete samples with widths of 1 or 2 cm, or by using a pass-through magnetometer on 'u-channels' of sediment. To simulate the discrete sampling we use a 2 cm boxcar averaging function, and to simulate the response of pass-through magnetometers we use a Gaussian averaging function with a width of 4 cm. These are typical values and realistically represent experimental sampling. We also use point samples for comparison.

We studied the resampled spectra for sedimentation rates of 0.5, 1, 2, 5, 10, 20 and 40 cm kyr^{-1}, which covers the majority of sedimentation rates encountered in palaeomagnetic studies. Fig. 6 shows the original spectrum of the synthetic sequence and the spectra of each resampled sequence using the three sampling methods for a sedimentation rate of 1 cm kyr^{-1}. To summarize the results from diagrams such as Fig. 6 for all the sedimentation rates studied, the spectral intensity is shown as a function of sedimentation rate for 2-cm-wide samples and pass-through magnetometer in Figs 7 and 8 respectively.

For both methods, sampling at 2 kyr recovers the spectrum of the synthetic palaeointensity record reasonably well and no contamination by aliasing is present. However, 5 and 8 kyr sampling cause energy to appear at periods greater than 10 kyr. There was no energy at these frequencies in the original spectrum, therefore the peaks are spurious and caused by aliasing. When using u-channels, smoothing by the magnetometer's response function reduces the amplitude of these aliased peaks to below 10 per cent of that of the true spectral peaks for sedimentation rates of 1 cm kyr^{-1} or lower. However, when using the 2-cm-wide samples, even for the lowest sedimentation rate of 0.5 cm kyr^{-1}, the amplitudes of the aliased peaks do not drop below 20 per cent of that of the true peaks in the 2–10 kyr period band. This is because of the significant frequency-domain sidelobes of a boxcar averaging function. It should be noted that for sampling intervals of 5 kyr or more, almost the entire spectrum consists of aliased energy.

Consider the case in Fig. 6 of 2-cm-wide samples at 8 kyr intervals. There is a large peak at a frequency of about 0.04 kyr^{-1}, which corresponds to a period of 25 kyr. Using eq. (1) for $\Delta t = 8$ kyr, $\nu_{\mathrm{N}} = 0.0625$ kyr^{-1} and $\nu_{\mathrm{A}} = 1/25$ kyr^{-1}, the corresponding periods with frequencies above the Nyquist are 11.76 kyr, 6.06 kyr ($n=1$); 4.76 kyr, 3.45 kyr ($n=2$); 2.99 kyr, 2.41 kyr ($n=3$). The peak in the original spectrum near 6 kyr (0.167 kyr^{-1}) is the likely source. Aliasing does not just cause spurious peaks but mimics everything above the Nyquist, and the effect is large.

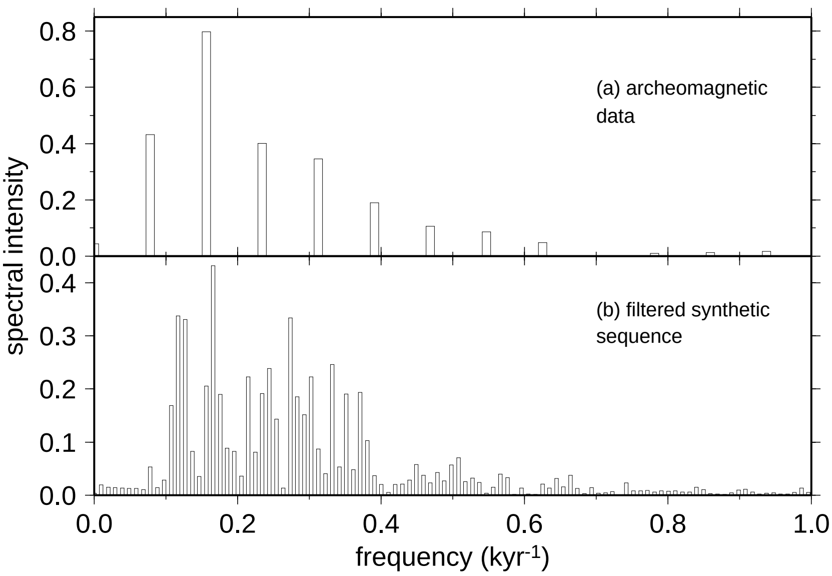

Figure 5. (a) Spectrum of smoothed archaeomagnetic data and (b) spectrum of filtered synthetic sequence. Above 0.1 kyr^{-1} both spectra have the same basic shape with all the energy in the 0.1–0.5 kyr^{-1} frequency range. Spectral intensity is the Fourier coefficient normalized by the length of each series.

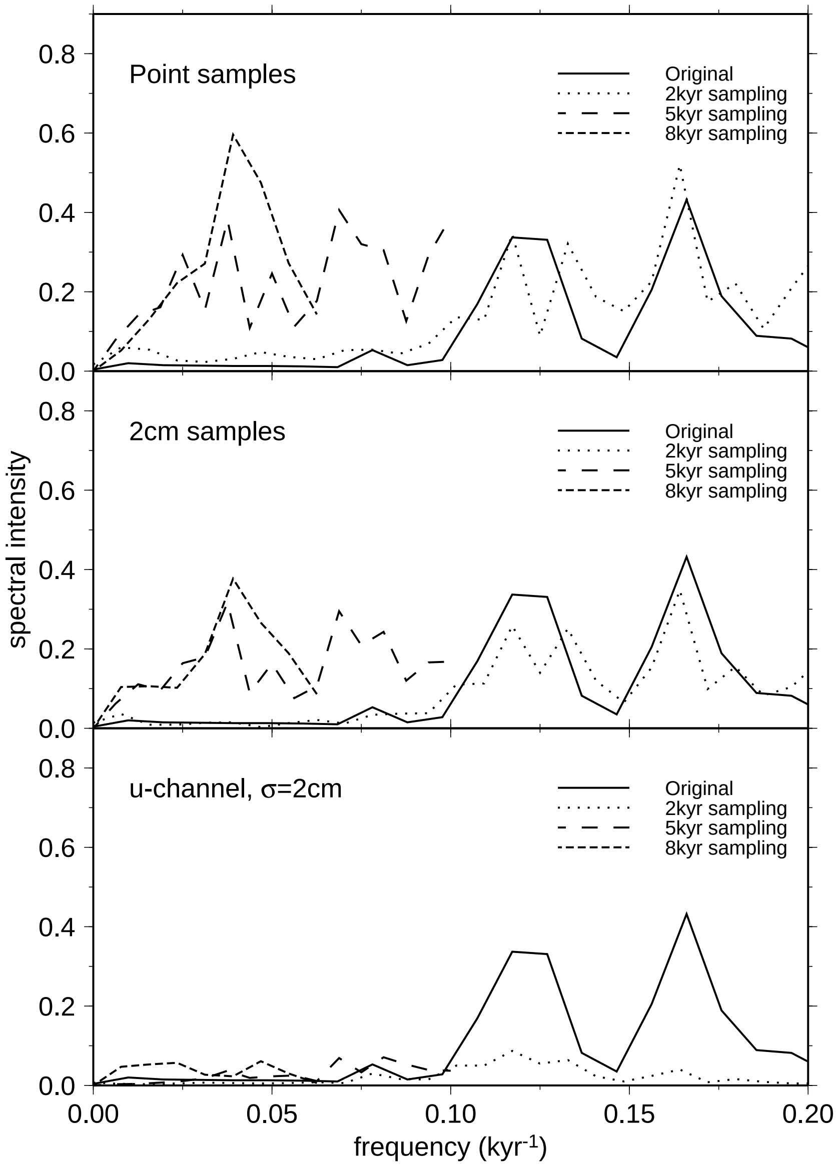

Figure 6. Spectrum of original filtered synthetic palaeointensity sequence and spectra of sequence resampled at 2, 5 and 8 kyr for each of the three sampling methods used. Results shown are for a sedimentation rate of 1 cm kyr^{-1}. Note the large-amplitude aliased peaks present in the spectra for point and discrete sampling.

4 LOCK-IN

For aliasing to occur, the intensity record must contain energy at frequencies greater than the Nyquist frequency. Lock-in can attenuate high frequencies and this may limit aliasing. Reorientation of the magnetic grains can occur in the top of the sediment column where the sediment is relatively unconsolidated. At greater depths the sediment is compacted and the magnetic grains are gradually locked into place. Remanent magnetization gained in this way is known as post-depositional remanent magnetization (PDRM) (Kent 1973). As well as compaction, any lock-in model must take into account bioturbation in the top sediment layer. Peng *et al.* (1979) examined the radiocarbon age of deep-sea sediment as a function of depth: this revealed that the top ≈ 8 cm of sediment was well mixed by bioturbation. Lock-in occurring below this depth, which we call the lock-in transition depth, x_0, will be preserved.

To model the response of a sediment to applied palaeomagnetic changes, we define the lock-in function, $f(x)$, where $f(x)dx$ is the proportion of magnetic moment locked at depths between x and $x+dx$. The exact shape of the lock-in function is unknown, although various models have been proposed (e.g. Hyodo 1984; Hoffman & Slade 1986; Rochette 1990). Here we use the exponential model proposed by Hyodo (1984) and modify it to take into account the bioturbation zone:

$$f(x) = \begin{cases} 0 & \text{if } x < x_0 \\ C\exp\left(\dfrac{-(x-x_0)}{a}\right) & \text{if } x > x_0 \end{cases}, \tag{2}$$

where x_0 is the depth of the bioturbation layer, a is the $1/e$ lock-in depth and C is a constant. Half the magnetization is locked in by depth $x_{1/2}$, where $x_{1/2} = x_0 + a\ln 2$. Normalizing the total proportion of magnetic moment locked in to unity

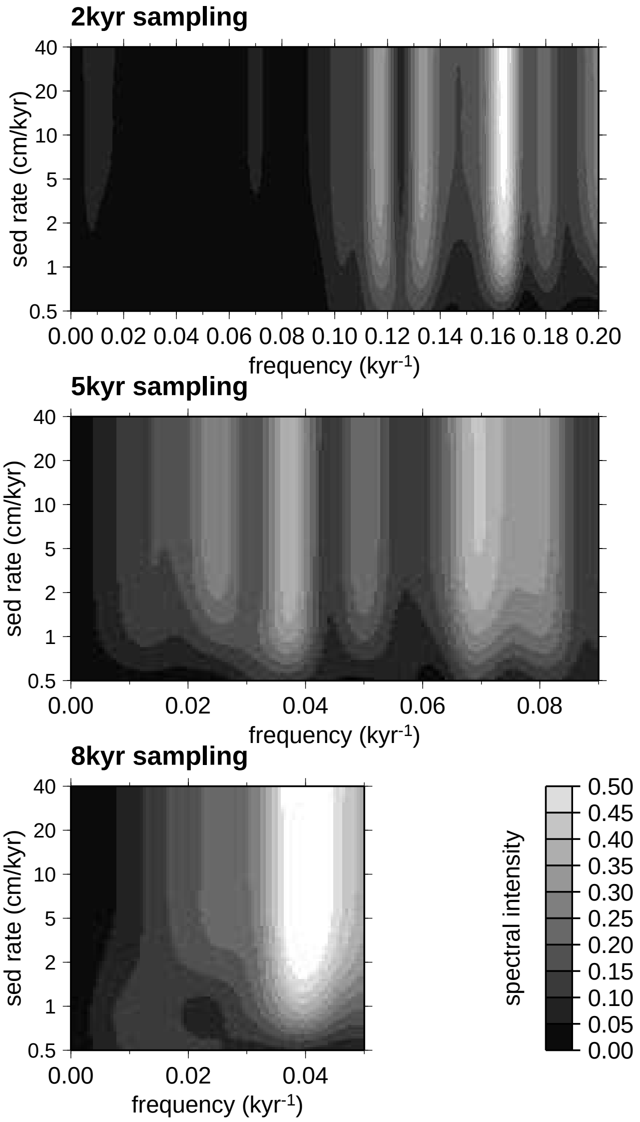

Figure 7. Spectral intensity as a function of frequency and sedimentation rate for 2-cm-wide samples with sampling intervals of 2, 5 and 8 kyr. As the original series has no energy with frequencies below 0.1 kyr^{-1}, any energy in the range 0–0.1 kyr^{-1} is aliased. For all sedimentation rates, 5 and 8 kyr sampling cause aliased energy to appear in the spectrum.

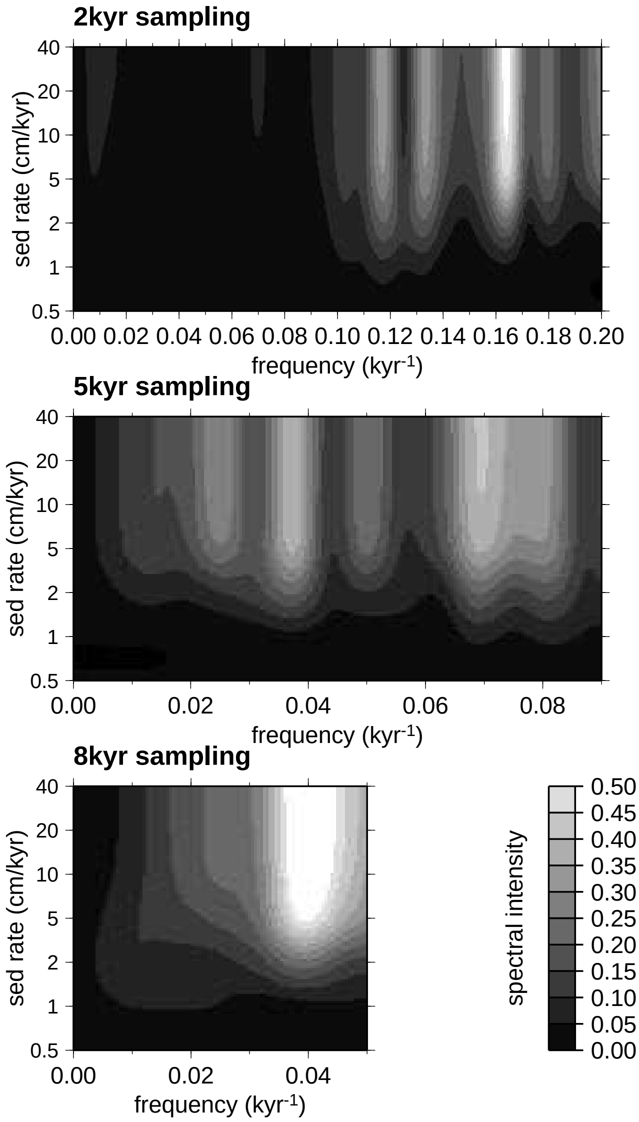

Figure 8. Spectral intensity as a function of frequency and sedimentation rate for u-channels measured in a magnetometer with a 4-cm-width response function with sampling intervals of 2, 5 and 8 kyr. Any energy in the range 0–0.1 kyr^{-1} is aliased. For sedimentation rates of 2 cm kyr^{-1} and higher, 5 and 8 kyr sampling cause aliased energy to appear in the spectrum; below 2 cm kyr^{-1} smoothing due to the response function of the magnetometer reduces the amplitude of the aliased peaks.

gives $C=1/a$. We assume that the axis of magnetic moment locked in at time t is parallel to the ambient palaeomagnetic field and that the magnetic moments are additive. The magnetization, $\boldsymbol{m}(T)$, recorded by a sediment layer deposited at time T is given by

$$\boldsymbol{m}(T)=\int_{t_0}^{\infty} \boldsymbol{b}(t)\, f(T-t)\, dt\,, \tag{3}$$

where $\boldsymbol{b}(t)$ is the ambient magnetic field at time t. From eq. (2) the limits of this integral can be extended to

$$\boldsymbol{m}(T)=\int_{-\infty}^{\infty} \boldsymbol{b}(t)\, f(T-t)\, dt\,, \tag{4}$$

which is the formula for convolution. The final magnetization is thus given by the convolution of the palaeomagnetic field with the lock-in function of the sediment that records it:

$$\boldsymbol{m}(T)=\boldsymbol{b}(t) * f(t)\,. \tag{5}$$

For uniform sedimentation rate s, the relation between x and t is $x=st$. Hence $t_0=x_0/s$.

To smooth the synthetic sequence we use a lock-in function with $x_0=8$ cm (Peng *et al.* 1979) and $x_{1/2}=16$ cm (Kent & Schneider 1995), which corresponds to $a=11.5$ cm in eq. (2). As before, sedimentation rates of 0.5, 1, 2, 5, 10, 20 and 40 cm kyr^{-1} were used. After smoothing by applying eq. (5) the spectrum is estimated by resampling, removing the trend, tapering with a 10 per cent cosine taper and Fourier transforming.

As before, the smoothed series was resampled at 2, 5, and 8 kyr intervals using 2-cm-wide samples, a 4 cm Gaussian pass-through response and point samples. In this case any smoothing due to the sampling method was dominated by the smoothing due to the lock-in filter, with the spectra from all three sampling methods being very similar. The resampled spectra for the case of 2-cm-wide samples are displayed as plots of spectral intensity in Fig. 9.

As in the case of the unsmoothed synthetic sequence, the 2 kyr sampled series does not suffer from much aliasing, with only a small amount of energy at low frequency (long period). This is not the case for sampling intervals of 5 and 8 kyr, which again have significant energy due to aliasing at low frequency (long period) for sedimentation rates of 5 cm kyr^{-1} and above. However, for sedimentation rates of 2 cm kyr^{-1} and lower, the lock-in response of the sediments acts as an effective anti-aliasing filter, reducing the amplitudes of the aliased peaks to below 10 per cent of that of the true spectral peaks for all sampling methods.

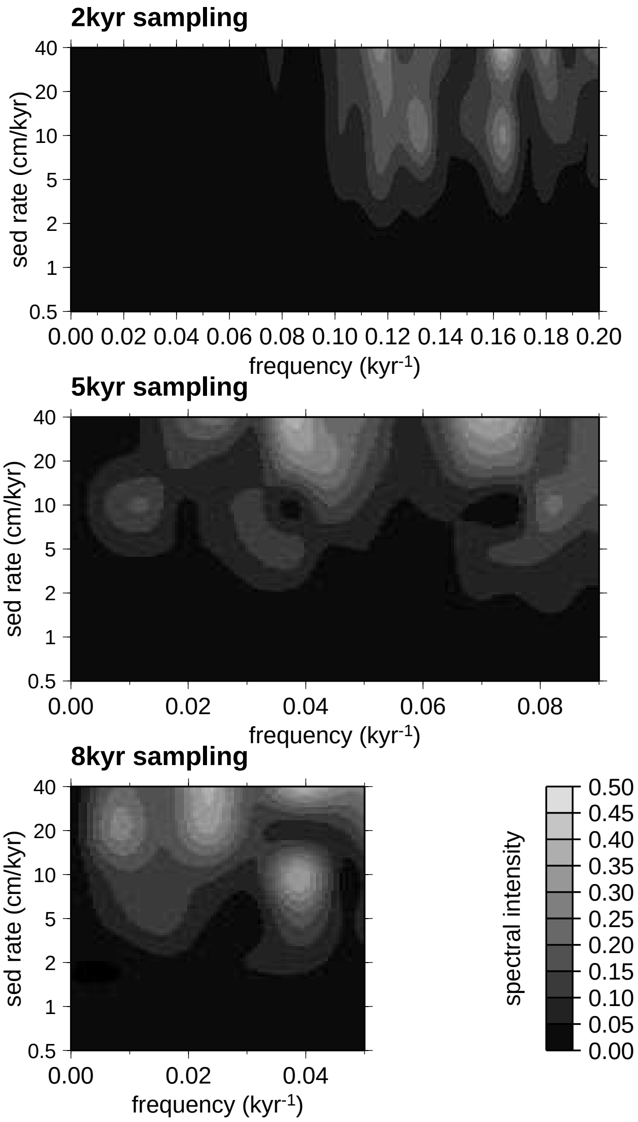

Figure 9. Spectral intensity as a function of frequency and sedimentation rate for 2-cm-wide samples of the lock-in smoothed synthetic record for sampling intervals of 2, 5 and 8 kyr. Any energy in the range 0–0.1 kyr^{-1} is aliased. For sedimentation rates higher than 2 cm kyr^{-1}, 5 and 8 kyr sampling cause aliased energy to appear in the spectrum; below 2 cm kyr^{-1} lock-in acts as an anti-alias filter.

To see how the amplitudes of the aliased peaks would compare with the amplitude of a true geomagnetic 30 kyr signal, we used a 30 kyr period sine wave with the same mean and variance as the archaeomagnetic data. This signal was subjected to the same resampling and spectral analysis as the synthetic sequence. For the unsmoothed case the aliased peaks had approximately the same amplitude as the true 30 kyr signal for sedimentation rates over 2 cm kyr^{-1}. For sedimentation rates of 2 cm kyr^{-1} or less, the sampling methods imparted some smoothing that reduced the amplitudes of the aliased peaks by a factor of ≈ 2 at 1–2 cm kyr^{-1} for the 2-cm-wide samples, ≈ 10 at 1 cm kyr^{-1} and ≈ 5 at 2 cm kyr^{-1} for the pass-through method. When both the 30 kyr signal and the synthetic sequence are passed through the lock-in filter, the amplitudes of the aliased peaks are lower than the amplitude of the peak from the 30 kyr signal by a factor of ≈ 20 at 1 cm kyr^{-1}, ≈ 10 at 2 cm kyr^{-1}, ≈ 4 at 5 cm kyr^{-1} and ≈ 2 at 40 cm kyr^{-1}.

5 CONCLUSIONS

We created a synthetic palaeosecular variation series 100 kyr in length with the same spectrum as the 12 ka archaeomagnetic record. The synthetic sequence contained no periods longer than 10 kyr. The sequence was resampled at 2, 5 and 8 kyr using 2-cm-wide samples as well as pass-through sampling with a Gaussian response of width 4 cm for sedimentation rates from 0.5 to 40 cm kyr^{-1}. For the 2-cm-wide samples, significant aliasing was present in the resampled spectra for sampling intervals greater than 2 kyr. The smoothing effect of pass-through measurements effectively reduce the aliasing for sedimentation rates below 1 cm kyr^{-1} but, as for the discrete samples, significant aliasing was present at higher sedimentation rates. Hence, long periods observed in the spectra of geomagnetic intensity variations could be due to aliasing, an artefact of coarse sampling, if sedimentary smoothing is absent or weak.

Smoothing by a reasonable exponential lock-in filter acts as an anti-alias filter for sedimentation rates lower than 2 cm kyr^{-1} but for higher sedimentation rates the lock-in filter allows enough high-frequency geomagnetic secular variation to be recorded to cause significant aliasing when coarsely sampled. It is encouraging that lock-in processes prevent aliasing in low-sedimentation-rate cores, where the sampling is inevitably coarse. Although the reported 30 kyr period in Tauxe & Hartl (1997) has been retracted (Constable *et al.* 1998) for statistical reasons, lock-in processes for this low-sedimentation-rate core could act as an anti-alias filter and prevent the spectrum from being contaminated with significant aliasing. Without lock-in, the entire spectrum would be spurious aliased energy. Higher sedimentation rates allow more detailed sampling, and provided the sampling interval is less than 2 kyr, there should be no problem with aliasing. Lock-in processes may thus aid and not hinder study of the palaeomagnetic field with sediments.

It should be noted that the lock-in properties of most sedimentary cores are not well known and thus cannot be relied upon to remove aliasing effects. For the case where the sediment faithfully records the geomagnetic field variations, the amplitudes of the aliased peaks are significant and may be confused with actual geomagnetic signals. We therefore recommend using an absolute maximum sampling interval of 2 kyr.

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