# Assessing the fidelity of palaeomagnetic records of geomagnetic reversal

Bradford M. Clement

*Phil. Trans. R. Soc. Lond. A* 2000 **358**, 1049-1064
doi: 10.1098/rsta.2000.0573

# Assessing the fidelity of palaeomagnetic records of geomagnetic reversal

By Bradford M. Clement

*Department of Geology, Florida International University, Miami, FL 33199, USA* (clementb@fiu.edu)

A major difficulty facing the study of geomagnetic polarity reversals lies in interpreting palaeomagnetic records of polarity transitions. These records are the sole source of information about what happens to the field as it reverses. In addition to comparison of records of the same reversal from different types of recorders to check for accuracy, we need some internal measure that can be used as a gauge of the temporal resolution provided by the data. This paper explores methods using the extent to which secular variation is recorded in the full polarity intervals bounding polarity transitions to estimate the temporal extent to which the transitional record should be interpreted. Cumulative dispersion and two autocorrelation methods are evaluated using datasets representative of different end-member palaeomagnetic records of secular variation and polarity transitions.

**Keywords: geomagnetic polarity reversals; polarity transitions; palaeomagnetism; secular variation**

## 1. Introduction

In recent years, an increasing number of palaeomagnetic records of polarity transitions have become available. These records provide the only source of information about the behaviour of the geomagnetic field as it reverses, so it is critical to find a way to assess their fidelity. Because transition records document the field with a wide range of resolution, it is important to develop a way of evaluating the extent to which a recorder has succeeded in documenting transitional field behaviour. This means not only figuring out the accuracy, but also the temporal resolution. This task is difficult because each palaeomagnetic recorder filters the record in ways that are not well understood. Perhaps what is more important is that there is not a predictive model of transitional field behaviour to test a record against, unlike records of full polarity intervals that can be tested against the geocentric axial dipole (GAD) hypothesis.

In developing basic criteria for assessing transition records, it is probably wise to make as much use of the predictive power of the GAD hypothesis as possible. The first measure of the accuracy of a polarity transition record must be the accuracy with which it records the Earth's magnetic field during full polarity intervals when the field is strong. The full polarity intervals bounding a transition record must be recorded by antipodal directions when averaged over appropriate time-scales. Only after it is shown that the material accurately records the field when it is strong should the transitional directions, recorded when the field is considerably weaker, be interpreted.

In this paper, this philosophy is taken a step further by using the capability of a recorder to record secular variation during full polarity intervals as a measure of the temporal resolution that the transition record provides. Again, this is difficult to determine because we do not know how the field was varying during the full polarity intervals, and we do not know the filtering effect that the recorder superimposes on the record. It is possible, however, to make a few assumptions that help make this problem tractable.

Palaeomagnetists have long used the dispersion of directions recorded at a site to find out if secular variation has been averaged out, leaving behind a mean direction that records the average GAD direction. By comparing the observed amount of dispersion with that predicted for the site latitude by global models of secular variation, it is possible to gauge how effectively secular variation has been averaged out. This approach can be extended by determining the stratigraphic interval that must be included to average out secular variation as recorded at a site.

If we assume that typical secular variation of the geomagnetic field occurs on a continuum of time-scales, as suggested by historical data (Courtillot & Valet 1995), it becomes clear that no palaeomagnetic recorder can capture all the detail. For each recorder there is likely to be a cutoff beyond which higher-frequency (sediments) or lower-frequency (lavas) information is not recorded. For sediments this is because the remanence is thought to be locked-in over a finite thickness of sediment, and the geomagnetic field behaviour is integrated over this interval. Lavas probably have a low-frequency cutoff because it is rare to find sequences where flows were erupted at frequent intervals for a geologically long time. If it were possible to determine the cutoff for a record, this would provide an important constraint on the temporal resolution provided by the record.

Two different approaches to this problem are discussed in this paper. The first method is an extension of the traditional analysis of dispersion at a site to include the temporal aspect. In this method, the dispersion about the unit-vector mean is determined as successively more stratigraphic intervals are included in the mean. The average interval required to obtain the value of dispersion that represents the whole section provides a measure of the extent to which secular variation has been recorded.

The second method applies standard autocorrelation processes to a unit-vector series. Within this method, two different, previously published, vector-correlation techniques are compared. As with standard autocorrelation functions, the initial slope of the function provides a measure of the memory of the system. In palaeomagnetic records, the slope may be used to estimate the average interval over which each direction is dependent on previous directions. Assuming that the field varied smoothly with time, the memory can be interpreted as a measure of the record's temporal resolution of secular variation.

## 2. Cumulative dispersion

In studies in which it is important that a time-averaged field direction is obtained, for example in palaeomagnetic pole determinations, the magnitude of the dispersion about the mean is compared with the magnitude predicted for the site latitude by global models of secular variation (McElhinny & McFadden 1997; Constable 1990; Vandamme 1994). If the observed dispersion is close to that predicted by the models, then it can be reasonably argued that enough time has been sampled at the site to effectively average out secular variation. Conversely, if the observed dispersion is too small, then it is likely that secular variation has not been averaged out.

This approach may be expanded to include the available stratigraphic information to determine the interval that must be included in the average, to obtain a dispersion that is representative of the dataset as a whole. That dispersion can also be compared with the dispersion predicted by global secular variation models. In this case, both the magnitude of the dispersion as well as the resolution of secular variation that the palaeomagnetic recorder provides can be examined.

Given a set of unit vectors with a Fisher distribution, it is possible to calculate an estimate, $k$, of the true dispersion, $\kappa$ (Fisher 1953). In the method used here, $k$ is calculated as a function of the stratigraphic interval that is included in the calculation of the mean. This is done by incrementally increasing the stratigraphic section included in the calculation of the mean. When the values of $k$ are plotted versus the number of samples included in the mean, it is possible to determine the stratigraphic thickness that must be averaged over in order to obtain the $k$ value of the entire dataset. This then provides an estimate of the characteristic time-scale of secular variation that is recorded in that record. This approach is referred to as the cumulative dispersion method.

When calculated singly through a portion of a section, this method provides significant insight into the nature of different intervals of the record. The initial slope of the plot indicates how well the successive samples are serially correlated with one another. For example, if $k$ increases rapidly as additional samples are included in the average, it means that the directions are not tightly grouped in stratigraphic order, but exhibit little dispersion about some mean direction. If the initial slope is negative, then it means that the directions are tightly grouped in stratigraphic order and vary systematically about some mean. If the initial slope is negative and very steep, quickly reaching the stable value of $k$, it indicates that the directions are not serially correlated and instead they approximate a random sampling about the mean direction, with no systematic variation with stratigraphic position. As different directions are included in the mean, the value of $k$ will decrease until it reaches the value for the entire record.

Although this information is useful, the results are very sensitive to the starting position in some records. For this reason, we employed a jackknife approach, in which the process is repeated with the starting point progressing through the record. For each successive number of samples included in the mean, the average $k$ is calculated along with the variance about that mean $k$. Plotting the mean $k$ values and the variance provides results that are more representative of the entire section.

This technique of incrementing the starting point through the data sequence and then for each incremental offset calculating the average $k$ value and the variance about that average gives an indication of the stratigraphic interval that must be considered, on average, in order to average out secular variation. For example, applying this method to a set of directions that varies sinusoidally yields results such as those shown in figure 1. The initial values of $k$ are high because adjacent directions are closely grouped. As additional parts of the sine wave are included, the value of $k$ decreases, reaching a minimum at an interval corresponding to one-quarter of the wavelength of the directional variation. The values of $k$ then begin to increase until the values stabilize about the mean $k$ for the entire section.

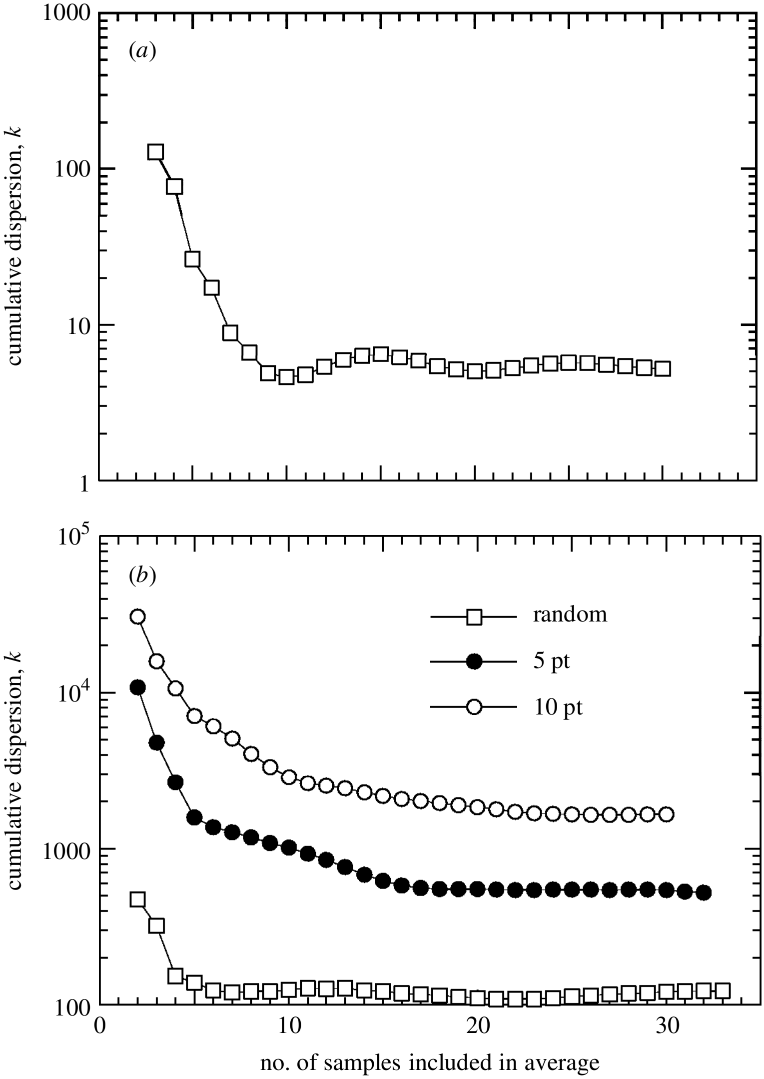



Figure 1. Cumulative dispersion for a sequence of unit vectors with a constant declination and sinusoidally varying inclination $(a)$. Comparison of cumulative dispersion plots obtained for a sequence of unit vectors randomly selected from a Fisher distribution with a specified mean and dispersion $(b)$. The effects of increased smoothing of the random sequence are also shown.

Plots of the mean $k$ (or variance about that mean), however, do not provide as much initial information about the nature of the record as the single sequence calculations. This can be seen by examining the cumulative dispersion plots obtained for a sequence of random directions selected from a Fisher distribution with a specified mean direction and dispersion ($\kappa$). The cumulative dispersion curve for the random sequence shows a rapid initial decrease to the stable value of $k$. If the same sequence is smoothed using a Gaussian filter over 5 and 10 points, the resulting curves exhibit progressively shallower slopes (note that larger values of $k$ correspond to decreases in dispersion caused by the smoothing). The dramatic change in $k$ values results from the effects of the smoothing on the dispersion.

Although comparing the average $k$ values obtained from the jackknife method loses some of the resolution about the serial correlation of the directions over short intervals, it appears to provide more robust estimates of the characteristic stratigraphic interval of secular variation in that particular record. This means that this method can succeed in providing some information about the temporal resolution of a sequence of data. As can be seen from figure 1, however, the results are not always readily interpreted in terms of the interval that secular variation is averaged over, particularly at higher smoothing levels.

## 3. Autocorrelation methods

The lack of resolution in the results of the cumulative dispersion method led me to explore additional approaches to estimating the characteristic interval of secular variation as recorded in a particular section. The two methods described below are based on autocorrelation of a series of unit vectors. The autocorrelation of a standard sequence of scalars is a useful exploratory statistical technique that requires no assumptions about the presence of periodicities in the data. In a standard autocorrelation, a sequence of scalars is compared with itself at increasing offsets or lags. The sum of the product of each pair of values (minus their means) is normalized by the number of values used in the sum (Priestley 1981).

Examining a plot of the autocorrelation coefficient as a function of offset may provide considerable insight into the nature of a sequence. Cyclicity in the data will be indicated by a corresponding cyclicity in the correlation coefficient. Conversely, a sequence of random values about a mean will produce an autocorrelation function that plummets immediately from a value of 1 to values varying about 0. If some serial correlation exists in the data, then the slope of the autocorrelation function will be more gradual. The initial slope can, in general, be interpreted as an indication of the memory in the process (Priestley 1981).

By extending this method to a sequence of unit vectors it may be possible to use the autocorrelation functions in a similar manner to characterize the statistical nature of the sequence. Ideally, a sequence with true periodicity will produce a periodic autocorrelation function. Likewise, a random sampling of directions about a mean will produce a very steep initial slope in the autocorrelation function. Sequences in which each direction is not truly independent of the directions immediately above or below will produce more gentle initial slopes, with the slope dependent on how many samples separate directions that are independent. This latter case provides a way of assessing the average stratigraphic interval over which the directions are independent. If the directions are recording a smoothly varying field on some time-scales, we would expect the directions to be dependent on previous directions in the sequence corresponding to those time-scales.

## 4. Orthogonal transformation method

Fisher *et al.* (1987) developed a technique for estimating how well one sequence of unit vectors correlates with another. This method is based on determining how well one series can be matched by the second by performing an orthogonal transformation of the second series. If the match is best when the orthogonal transformation is a rotation, then the association is positive. If the match-up is better when the transformation is a reflection, then the association is negative. If the first vector series is $X$ and the second is $X^*$, then an estimate of the correlation may be obtained by calculating the following quantities

$$S_{XX^*} = \det \left| \sum_{i=1}^{n} X_i X_i^{*\mathrm{o}} \right| = \det \begin{Bmatrix} \sum x_i x_i^* & \sum y_i x_i^* & \sum z_i x_i^* \\ \sum x_i y_i^* & \sum y_i y_i^* & \sum z_i y_i^* \\ \sum x_i z_i^* & \sum y_i z_i^* & \sum z_i z_i^* \end{Bmatrix},$$

$$S_{XX} = \det \left| \sum_{i=1}^{n} X_i X_i^{\mathrm{o}} \right|,$$

$$S_{X^*X^*} = \det \left| \sum_{i=1}^{n} X_i^* X_i^{*\mathrm{o}} \right|,$$

where the prime indicates the transpose. The correlation coefficient is given by

$$L = S_{XX^*}/(S_{XX}S_{X^*X^*})^{1/2}.$$

This correlation coefficient has the intuitive advantage that if only a pure rotation is required to bring the sequences into agreement, the coefficient has a value of +1. Conversely, if a reflection is required, then the coefficient has a value of −1.

This method may be applied to our problem by using it to calculate the autocorrelation function for our sequences of unit vectors. We follow the standard approach of comparing the sequence with a successively offset series of itself, and normalize by $N$. The resulting plot provides a measure of the memory in the process, or the interval over which the vectors are not independent.

## 5. Serial-correlation (dot-product) method

Watson & Beran (1967) and Epp *et al.* (1971) developed a method of estimating the serial correlation of unit vectors in a series by comparing the sum of the dot products of the pairs of vectors immediately above and immediately below each sample. This method can be used specifically to test the hypothesis that any two successive unit vectors are independent. This approach provides an intuitively appealing estimate of the correlation coefficient in that for two perfectly aligned unit vectors the coefficient will be +1, and for two antipodal vectors, it will be −1. We have modified this method in order to compare a data series with itself at increasing offsets, as in calculating a standard autocorrelation function. In other words, we sum $L$, for $i$ offsets. At each offset we plot the value of the correlation coefficient $L$:

$$L = \sum_{i}^{n-1} X_i X_{i+1}.$$

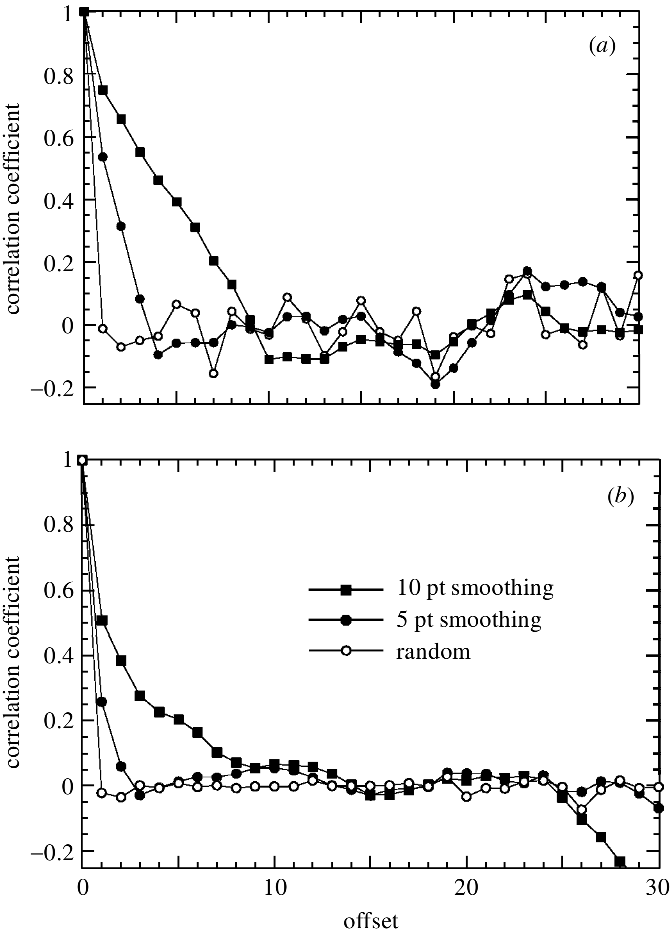



Figure 2. Comparison of (*a*) the dot-product and (*b*) the rotation-matrix correlation methods as autocorrelation tools. The open circles represent results from a sequence of randomly unit vectors drawn from a Fisher distribution with a known mean and dispersion. The solid circles and squares show the results obtained as the random record is smoothed over 5 and 10 points, respectively.

## 6. Examples

Each of the methods described above was tested using a cyclicly varying sequence of directions, and a sequence of random directions selected from a Fisher distribution with a specified mean and $\kappa$ with different degrees of smoothing applied. We present analysis of two datasets that might be considered representative of these examples.

Just as in an autocorrelation plot of a sequence of scalars, if the sequence of unit vectors is a series of random variations about a mean, with no serial correlation, then the correlation coefficient will very rapidly fall from a value of 1 to values that fluctuate about 0. If we consider a series of scalars that define a sine wave, the autocorrelation function will vary systematically between +1 and −1, with the offset equal to the wavelength in the scalar series. A series of unit vectors that vary sinusoidally, however, will not produce a variation between +1 and −1, because, unlike

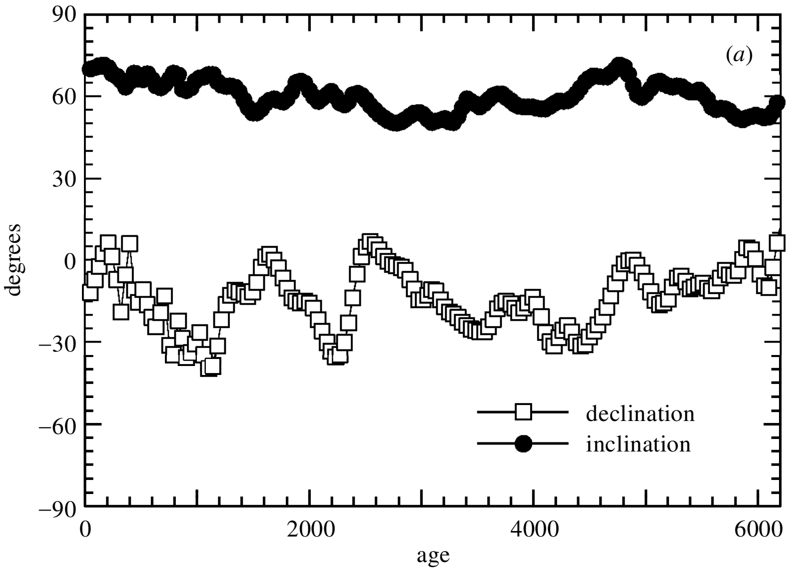


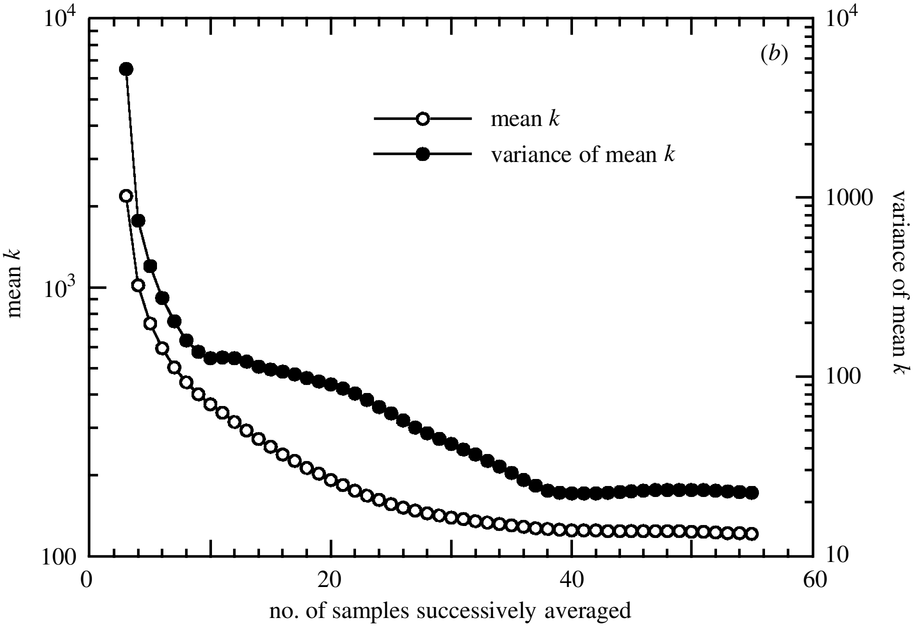

Figure 3. Palaeomagnetic directions obtained from a high-resolution record of recent secular variation obtained from Fish Lake, Oregon (*a*).

the scalar series, when the directions pass through zero (i.e. when the inclination are zero, or the directions are horizontal), the vectors still have magnitude equal to 1. Therefore, even when the directional sine waves are perfectly out of phase, a perfectly negative correlation is not obtained, because at each of the cross points at zero, two of the vectors are in perfect alignment.

Considering a random sequence of unit vectors produces a clearly different result. Sequences of unit vectors were created by selecting random samples from a Fisher distribution with a specified mean and dispersion. The resulting autocorrelation functions are shown in figure 2 obtained from both methods described above. In each case, the coefficient drops from a value of 1 to 0 in only one offset (lag). This agrees with the interpretation that each direction of our sequence of unit vectors is independent of the vector immediately preceding it.

If the series of random unit vectors is smoothed so that each direction is dependent upon the preceding directions to some extent, very different results are obtained. The autocorrelation functions determined using both the dot-product and the rotation-matrix methods for a random sequence of unit vectors that is smoothed over 5 and 10 points are also shown in figure 2. In each case, the initial slope of the autocorrelation function becomes more gentle as the smoothing interval is increased. The results from both methods also suggest that the slope and intersection of the initial part of the function may be used to determine the memory or dependence of the vector sequence. This suggests that these methods may be useful in examining the stratigraphic intervals in which secular variation is recorded.

In order to assess how well these methods might work on real datasets, I selected two palaeomagnetic records that, in a sense, represent end members in terms of how well they might be expected to record secular variation. For the first case, we examine the secular variation record obtained from Fish Lake, Oregon (Hanna & Verosub 1989). This record was chosen because it documents large-amplitude field variations



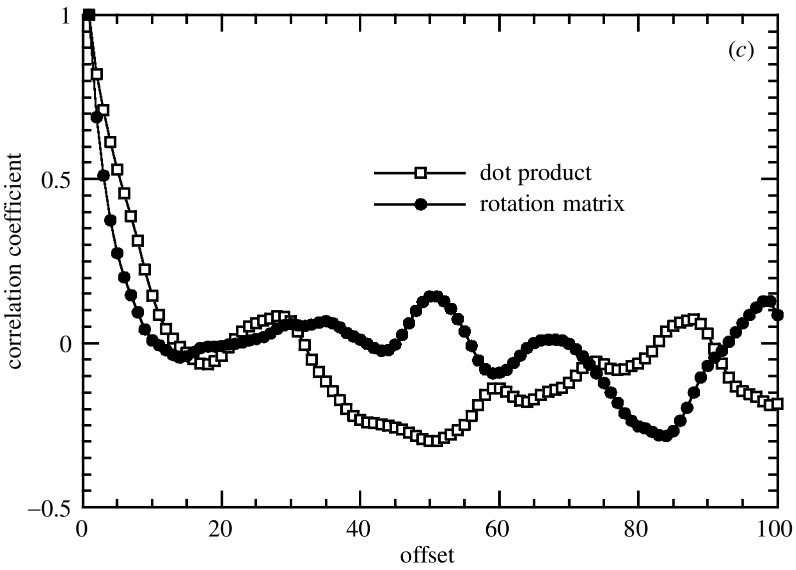




Figure 3. (*Cont.*) The results from the cumulative dispersion method (*b*) and from the autocorrelation methods obtained using both the dot-product method and the rotation-matrix method (*c*). All three results appear to be successful in indicating the nature of the smoothly varying secular variation record.

that were recorded over time-scales of hundreds of years. The second example is the record obtained from deep-sea core K78019. These data were obtained from very slowly accumulating sediments ($10\,\mathrm{m\,Myr}^{-1}$) that are not expected to document secular variation in much detail.

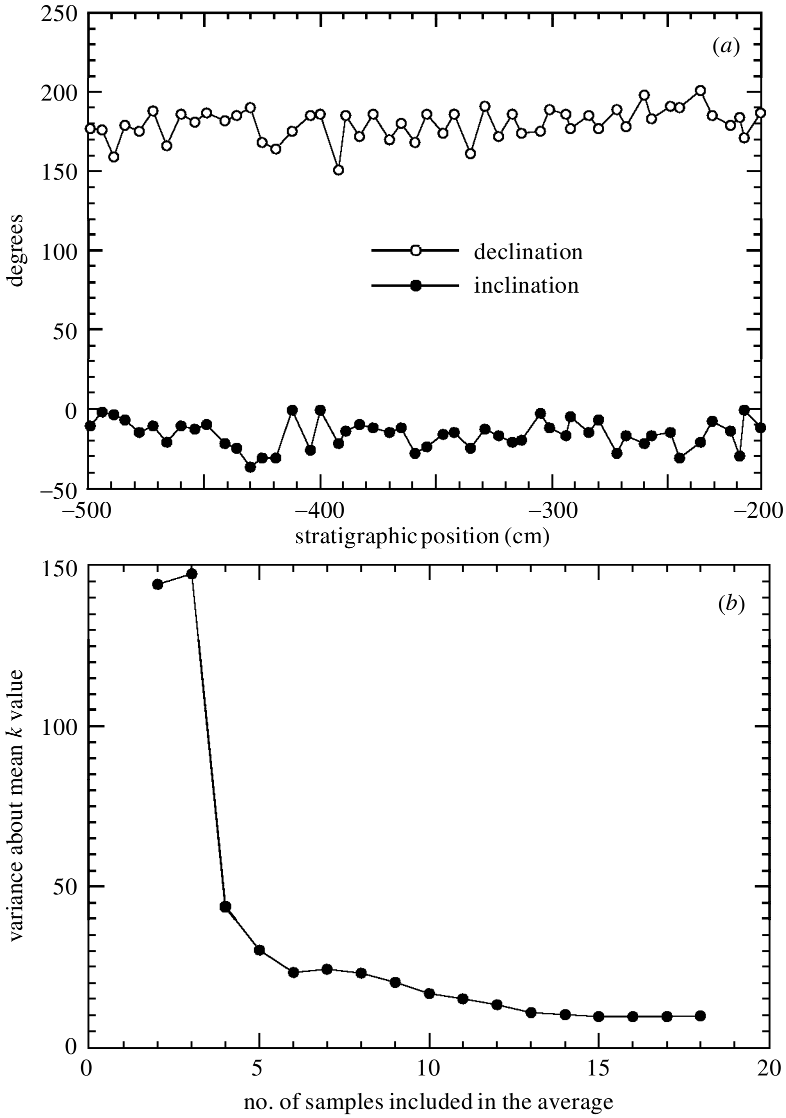



Figure 4. Results obtained from a much lower resolution record (*a*) obtained from deep sea core K78019 (Theyer *et al*. 1989). The palaeomagnetic directions shown here correspond to the interval of full reverse-polarity that was used in this analysis. The results from the cumulative dispersion method (*b*) are plotted here showing the variance about the mean estimate of $k$ at each incremental averaging.

The directional record obtained from Fish Lake is shown in figure 3*a* together with the results of cumulative dispersion and autocorrelation analysis. The results of the cumulative dispersion analysis are plotted in figure 3*b*. Both the mean $k$ values and the variance about those means exhibit gentle slopes indicating that a significant interval must be averaged over before arriving at the $k$ value of the total population. The mean $k$ values very gradually approach the mean, making it difficult to determine a specific interval. The variance, however, shows a dramatic change in slope at 10

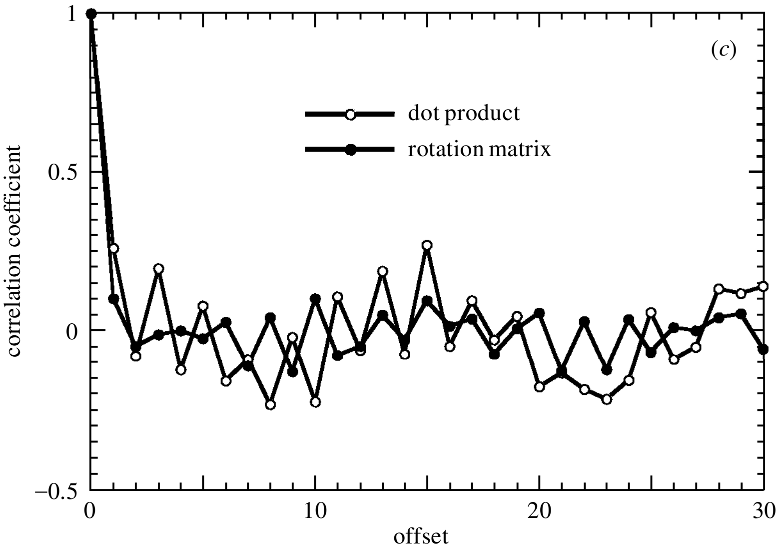



Figure 4. (*Cont.*) The autocorrelation results ($c$) using both the dot-product and the rotation-matrix method are similar to the cumulative dispersion results, showing a very rapid decrease to low values, consistent with a nearly random scatter about a mean direction.

samples, indicating that when 10 or more samples are included in the mean, the variance about the mean $k$ value becomes significantly smaller. The variance also shows a marked change in slope at 40 samples. In this record 40 samples correspond roughly to 1600 yr. When more than 40 samples are included in the mean, both the mean $k$ is very stable and the variance about that estimate of $k$ no longer decreases with increasing numbers of samples. An extremely smooth record that is serially correlated appears to exhibit a variation in mean $k$ that is only a function of $n$.

The autocorrelation results obtained using both methods described above are shown in figure 3$c$. Both curves exhibit gentle initial slopes, reaching zero between 12 and 20 offsets. These values represent a measure of the independence of the samples in this sequence, suggesting that, on average, only every 10th to 20th sample may be considered to be independent. Therefore, the initial slopes of these plots indicate the memory of the process to be significant in this record; a conclusion that agrees with the observation that this is a smoothly varying sequence of directions with wavelengths of the order of 10–20 cm.

In contrast to the Fish Lake record, the record obtained from deep-sea core K78019 (Theyer *et al*. 1989) visually appears to have recorded a much-diminished record of secular variation, both in amplitude and wavelength (figure 4$a$). Cumulative dispersion analysis of this record produces a plot of mean $k$ values that exhibits a very steep initial slope (figure 4$b$). Only five successive samples, on average, need to be included in order to obtain a mean with the dispersion characteristic of the whole record. This core was sampled at an interval of 0.5 cm. Given a sedimentation rate of 10 m $Myr^{-1}$, this corresponds to an interval of 500 yr. The results from autocorrelation analysis are even more dramatic. Both results show an initial drop to values close to zero, indicating that this record cannot be distinguished from a random set of directions about a mean (figure 4$c$).

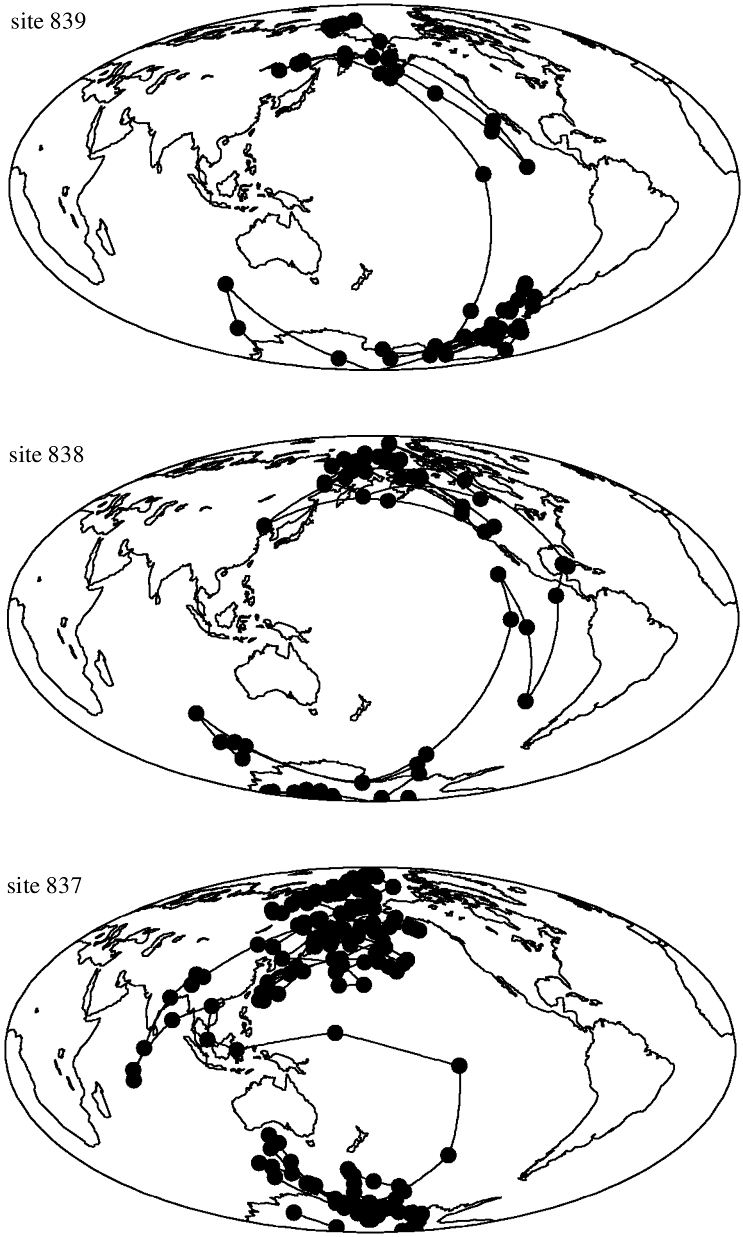



Figure 5. Virtual geomagnetic pole paths of three records of the Cobb Mountain Subchron obtained from ODP Sites 837, 838 and 839 in the Lau Basin in the central equatorial Pacific. Although the records were obtained from closely located sites, significant differences exist between the records.

## 7. Application to transition records

As a test to see if these methods are useful in assessing the temporal resolution of polarity transition records, we analysed a set of records of the same polarity

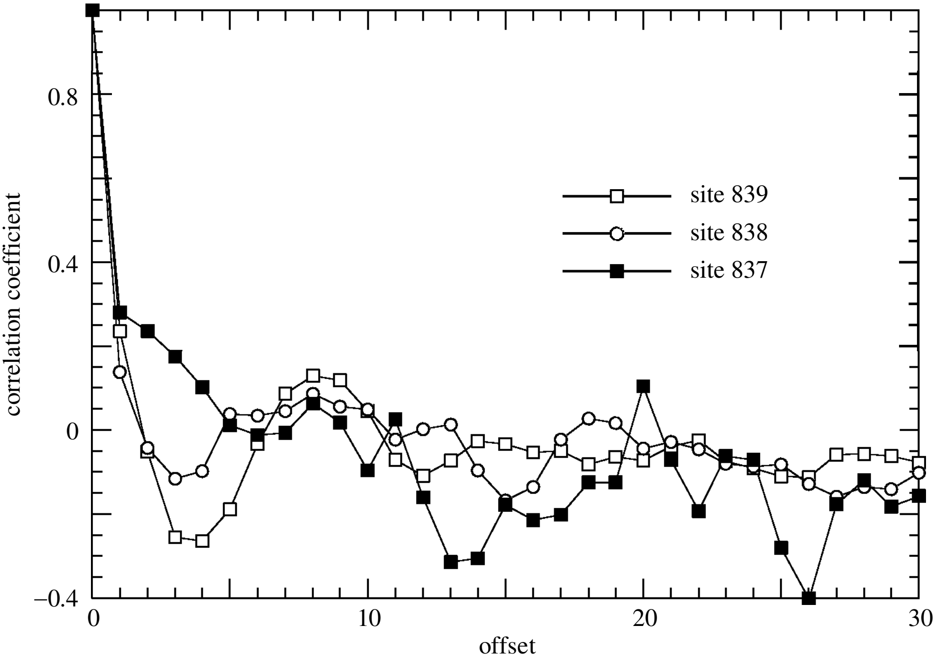



Figure 6. Autocorrelation results from the Lau Basin Cobb Mountain records obtained using the dot-product method. The initial slopes are much steeper at Sites 838 and 839, whereas the initial slope is significantly less steep for the record from Site 837. This indicates that the records from Site 873 exhibit a greater degree of serial correlation in the full polarity interval and, therefore, may be expected to provide a slightly more-detailed transition record.

reversal that were obtained from different sedimentation rate sequences. For the first case, we consider the records of the Cobb Mountain Subchron obtained from the Lau Basin (Abrahamsen & Sager 1994). These records are interesting because the same geomagnetic feature is recorded at three different sites with slightly varying sedimentation rates. The major features of the transition records are remarkably similar, but some significant differences also exist (figure 5; see also Clement (2000)). Are these differences a result of the different resolution with which the sediments have recorded the field, or do they mean that the recording is simply unreliable on these scales?

The autocorrelation analysis is a useful way of addressing this question. In figure 6, the results from the analysis of the same corresponding reverse polarity interval are shown from Sites 837, 838 and 839. These results indicate that in general, the records from Sites 838 and 839 exhibit shorter-scale memory, suggesting that the characteristic interval for averaging out secular variation is approximately only three to four samples. This is consistent with the somewhat noisy nature of these records. The results from Site 837, however, indicate a characteristic interval nearly twice that of the other two records.

These results are interesting because the record from Site 837 exhibits considerably more detail in the polarity transition than the records from Sites 838 and 839. And even between Sites 838 and 839, these results mean that differences in the records

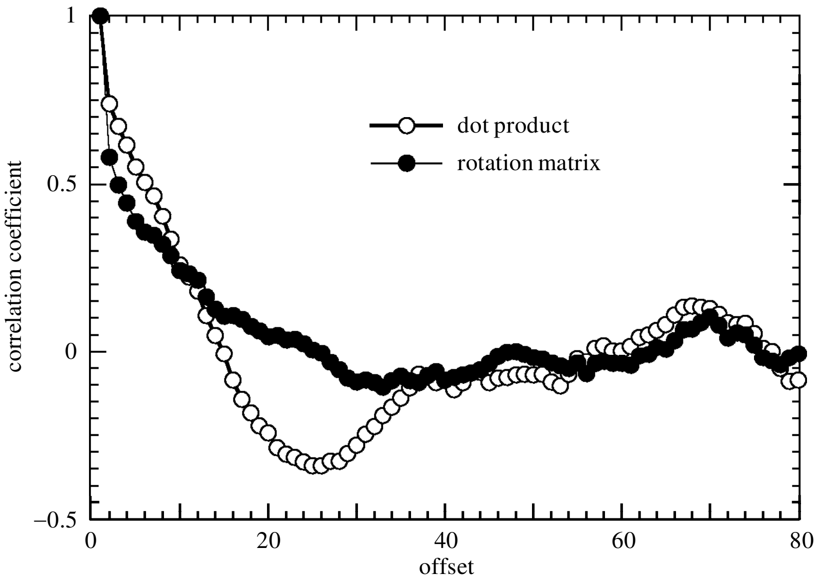



Figure 7. Autocorrelation results obtained from the upper, full reverse-polarity interval just above the Cobb Mountain at DSDP Site 609. This plot shows that both methods indicate a high degree of serial correlation that is consistent with the interpretation that this record provides greater resolution of the polarity transitions bounding the Cobb Mountain Subchron.

on intervals shorter than three to four samples should be considered to be due to the differences in the temporal resolution of these records.

For comparison, analysis of the same corresponding part of the full reverse polarity section of the Cobb Mountain record from Site 609 is shown in figure 7 (Clement & Kent 1987). This record is from a core with almost an order of magnitude difference in sedimentation rate and visually appears to have recorded secular variation in greater detail than the Lau Basin records. The autocorrelation plots for this record indicate that only every 20th–30th sample can be considered to be independent. This interval, therefore, probably corresponds to the characteristic stratigraphic interval that secular variation is recorded over. The greater length suggests that the corresponding transition record may be interpreted as a comparable increase in resolution.

## 8. Discussion

The tests of the three methods discussed above—using sequences of sinusoidally varying, random, and progressively smoothed unit vectors—suggest that these methods may be a useful tool in assessing the temporal resolution provided by a palaeomagnetic record of field behaviour. This information will be of use as we attempt to compile multiple records of the same reversals. It will be helpful to assess just how much of the differences between two records may be related solely to the temporal resolution of the records and how much represents real differences in the field behaviour or the recording process.

For example, if the autocorrelation results indicate a random sequence during full polarity, then that particular record should not be interpreted on the scales of transitional field behaviour. These methods, therefore, provide a way of addressing the question of whether a very rapid polarity change (i.e. between two adjacent samples) should be interpreted as an incredibly fast reversal. If the autocorrelation analysis indicates that the full polarity data are not significantly different from a random selection of directions about a mean, then the interpretation of rapid reversal is not warranted. However, if the autocorrelation analysis indicates that a significant interval is required to average out secular variation, then field variations may be interpreted to that scale.

The arguments used above assume that a smoothly varying field is a good indicator that secular variation has been recorded. However, it is often argued that the remanence acquisition process in sediments effectively smoothes the record of field behaviour. Therefore, one could interpret the initial slope in the autocorrelation plots as an indicator of the extent of smoothing. This can best be addressed by examining palaeomagnetic records that are considered to have recorded secular variation. In this paper, the two end members have been examined, and the more smoothly varying record is the one that provides the better record of secular variation. The low sedimentation rate record is an example of a case where the secular variation has been effectively completely averaged out, and the variation between adjacent samples probably results from random errors about the mean smoothed direction.

A major question that remains in this approach is that of separating the memory of the palaeomagnetic recorder (how smoothed the signal is) from the memory of the geomagnetic field. In this paper, the assumption is made that the geomagnetic field varies on shorter time-scales than can possibly be recorded by a sedimentary recorder. By making this assumption, the methods outlined here can provide a way of examining the lower limit to which a palaeomagnetic recorder has captured those changes in the geomagnetic field.

## 9. Conclusions

The methods described in this paper provide a mechanism to assess the temporal resolution of palaeomagnetic records without making any assumptions about the nature of the field behaviour in detail. These methods are also internal to each record. The cumulative dispersion method provides a way (that will be familiar to most palaeomagnetists) to determine, on average, the stratigraphic interval that must be included in order to average out secular variation. This may be interpreted as the characteristic interval over which secular variation is recorded. As such, it provides important constraints on the extent to which the record should be interpreted in terms of temporal resolution. The other two methods involve calculating the autocorrelation function for a series of unit vectors. Two previously published approaches to vector correlation were tried in the autocorrelation analyses. As in the case of traditional autocorrelation of a scalar series, the initial slope of the plot may be interpreted in terms of the memory of the process. This, in turn, may also be interpreted in terms of a characteristic interval defined by the recorded secular variation in that record.

Further testing of this approach using records that may be tested using independent means should help determine just how suitable it is. For now, this method appears to provide a valuable quantitative measure of the temporal extent to which a record should be interpreted.

Comments by Nicholas Teanby significantly improved this manuscript. This work was supported by NSF grant EAR9614447.

## References

Abrahamsen, N. & Sager, W. 1994 Cobb Mountain geomagnetic polarity event and transition in three deep-sea sediment cores from the Lau Basin. In *Proceedings of the Ocean Drilling Program, Scientific Results* (ed. J. Hawkins, L. Parson & J. Allan). College Station, TX: Ocean Drilling Program.

Clement, B. M. 2000 The Lau Basin Cobb Mountain records revisited: evidence for large scale transitional field symmetry. *Phys. Earth Planet. Interiors* (In the press.)

Clement, B. M. & Kent, D. V. 1987 Short polarity intervals within the Matuyama: transitional field records from hydraulic piston cored sediments from the North Atlantic. *Earth Planet. Sci. Lett.* **81**, 253–264.

Constable, C. G. 1990 A simple statistical model for geomagnetic reversals. *J. Geophys. Res.* **95**, 4587–4596.

Courtillot, V. & Valet, J.-P. 1995 Secular variation of the Earth's magnetic field: from jerks to reversals. *C. R. Acad. Sci. Paris* **320**, 903–922.

Epp, R. J., Tukey, J. W. & Watson, G. S. 1971 Testing unit vectors for correlation. *J. Geophys. Res.* **76**, 8480–8483.

Fisher, N. I., Lewis, T. & Embleton, B. J. J. 1987 *Statistical analysis of spherical data*. Cambridge University Press.

Fisher, R. A. 1953 Dispersion on a sphere. *Proc. R. Soc. Lond.* A **217**, 295–305.

Hanna, R. & Verosub, K. L. 1989 A review of lacustrine paleomagnetic records from western North America: 0–40 000 years BP. *Phys. Earth Planet. Interiors* **56**, 76–95.

McElhinny, M. W. & McFadden, P. L. 1997 Palaeosecular variation over the past 5 Myr based on a new generalized database. *Geophys. J. Int.* **131**, 240–252.

Priestley, M. B. 1981 Spectral analysis and time series. In *Probability and mathematical statistics*. Academic.

Theyer, F., Herrero-Bervera, E. & Hsu, V. 1989 The zonal harmonic model of polarity transitions: a test using successive reversals. *J. Geophys. Res.* **90**, 1963–1982.

Vandamme, D. 1994 A new method to determine paleosecular variation. *Phys. Earth Planet. Interiors* **85**, 131–142.

Watson, G. S. & Beran, R. J. 1967 Testing a sequence of unit vectors for randomness. *J. Geophys. Res.* **72**, 5655–5659.