Geophys. J. Int. (1998) **135,** 329–338

The fold test as an analytical tool

P. L. McFadden
Australian Geological Survey Organization, GPO Box 378, *Canberra,* ACT 2601, *Australia. E-mail: pmcfadde@agso.gov.au*

Accepted 1998 May 18. Received 1998 May 8; in original form 1997 December 19

SUMMARY

Two fold tests for palaeomagnetism have recently been proposed that rely on the assumption that the total population of magnetic vectors is most highly concentrated with the rocks in the orientation they had at the time of acquisition of the magnetization. This leads to appealing, simple tests based on parameter estimation. However, it is shown that the underlying assumption is flawed and can lead to incorrect conclusions. McFadden & Jones (1981) previously developed an inference test based on the concept that the between-group dispersion of magnetization should be consistent with the within-group dispersion when the rocks are in the orientation they had at the time of magnetic acquisition. That test made unrealistic demands upon the sampling scheme for typical, realistic folding geometries and so it has been under-utilized. The McFadden & Jones test is extended by recognizing that it is sufficient to use groups with similar bedding corrections and that it is not necessary to insist on groups with common bedding corrections. These groups may easily be determined with a clustering algorithm. The point is that with the rocks in the orientation at which the magnetization was acquired, it should be immaterial how the groups are chosen.

Key words: fold test, palaeomagnetism.

1 INTRODUCTION

Graham (1949) first suggested the fold test as a field test in palaeomagnetism for determining whether a magnetization was acquired pre or post-tectonic folding. However, he had no statistical method for judging the significance of such a test. Consequently, the test was applied sporadically and inconsistently until 15 years later when McElhinny (1964) suggested using the ratio of estimates, k, of Fisher's precision parameter κ (Fisher 1953) pre- and post-folding. The test, using McElhinny's criterion, became standard practice wherever possible and thereby created substantially improved discipline in palaeomagnetic investigations. As a consequence, the fold test became a critical and central aspect of palaeomagnetic investigation.

17 years later, McFadden & Jones (1981) showed that McElhinny's criterion is invalid and presented a different approach for assessing the significance of a fold test, referred to here as the M & J test. Whilst the M & J test is entirely valid, it demands a sampling scheme in which there are several sites each with the same tilt correction. In reality, however, palaeomagnetists often investigate rock formations with complex folds that do not lend themselves to such a sampling scheme. In such circumstances several investigators, while recognizing that it is invalid, reverted to the McElhinny (1964) test, often justifying its use on the basis that the criterion is typically conservative (McFadden & Jones 1981). Because of the nature of the flaw in the McElhinny test, it is difficult to quantify its level of conservatism, and indeed there are times when it is optimistic. Consequently, this was an unsatisfactory situation and so McFadden (1990) developed a new test based on correlation between the distribution of magnetic directions and the tectonic information to cater for most of the more complicated situations. Although this is an effective test it is apparently not physically intuitive, and so has not gained widespread use.

Watson & Enkin (1993) developed a fold test using Fisher's precision parameter that was based on the assumption that the total population of magnetization directions is most tightly grouped when the rocks are in the orientation in which the magnetization was acquired. Thus, under their assumption, the fold test is (nominally) reduced to a parameter estimation problem. Tauxe & Watson (1994) have extended this concept by using a measure of the clustering that does not assume a Fisher distribution and is independent of polarity. Their measure, τ_1, is the largest eigenvalue of the matrix

$$T = \frac{1}{N}\begin{pmatrix} \Sigma x_i^2 & \Sigma x_i y_i & \Sigma x_i z_i \\ \Sigma x_i y_i & \Sigma y_i^2 & \Sigma y_i z_i \\ \Sigma x_i z_i & \Sigma y_i z_i & \Sigma z_i^2 \end{pmatrix}, \quad (1)$$

where (x_i, y_i, z_i) are the direction cosines of the ith magnetic vector and $i = 1, \ldots, N$. The eigenvector associated with τ_1 is the axis about which the directions are most clustered, and for a given N, the tighter the clustering the greater is the value of

τ_1. Their approach is referred to here as the T & W test. The T & W test and the Watson & Enkin (1993) test are conceptually (and practically) so similar that only the T & W test is discussed further. Naturally one requires confidence limits for the population parameters as estimated from the available sample. For sufficiently large sample sizes a simple bootstrap approach is used by T & W to create pseudo-samples to determine confidence limits for the amount of unfolding associated with the maximum clustering, and for small samples they generate pseudo-random Fisher samples (a parametric bootstrap) to determine the confidence limits.

The T & W test is appealing: like the McElhinny (1964) test, it imposes no constraints on the sampling scheme; it does not require the investigator to make decisions about polarity; it does not rely on an underlying presupposed distribution; and it requires no data editing to sort into groups. As noted by the authors, 'the method is automatic'. However, despite its simplicity and consequent appeal, there appear to be problems with this test. First, there is the question as to the validity of the basic assumption that the magnetization was acquired where the magnetic directions cluster most tightly. This assumption appears to bias the method towards 'automatic' conclusions of syn-folding magnetizations. Second, the palaeomagnetist needs to infer whether the magnetization was pre, syn-, or postfolding, which forced the authors to implement the method with an uncomfortable process to draw such an inference from their parameter estimation approach. Third, the very fact that the method is 'automatic' means that it does not facilitate involvement of the investigator in the analysis. However, the fold test is sufficiently central to palaeomagnetic investigation, and provides enough opportunity as an analysis tool, that it is probably preferable to demand involvement of the investigator.

The intent of this paper is to elucidate the above concerns about the T & W test and to provide an extended implementation (referred to as the EMJ test) of the M & J test so that it imposes fewer constraints on the sampling scheme, thereby making it more widely applicable.

In order to simplify discussion it is helpful to define some terminology for use in this paper. The phrase 'correct orientation' will be used to refer to the orientation of the rocks at the time the magnetization was acquired. Thus if the magnetization was acquired prefolding then 'correct orientation' will mean stratigraphic orientation and if acquired postfolding it will then mean *in situ* or geographical orientation. The phrase 'incorrect orientation' will, naturally, invert this.

A central point that must be recognized is that the only way to assess a fold test statistically is to use the magnetic data themselves: the very data about which we are attempting to gather information regarding the direction of acquisition. This absence of an independent source of information demands that for any fold test (regardless of how it is formulated) to be valid it is necessary that all the magnetic directions originally belonged to a single population. For a prefolding magnetization it is also necessary to assume rigid-body rotation (i.e. no internal strain) for the samples providing the magnetic observations. (However, it is possible to 'destrain' the natural remanence in deformed rocks if a detailed knowledge of both the strain mechanism and the response of the magnetic grains and their remanence vectors to the strain can be measured, for example Cogné & Perroud 1987 or Borradaile 1993). These requirements will undoubtedly continue to plague assessment of the fold test.

2 THE M & J TEST

The basic geological geometry required for the M & J test is outlined in Fig. 1, in which the arrows are perpendiculars to the surface. Fig. 1(a) shows the original geometry of a rock stratum and Fig. 1(b) shows, with four 'limbs', the type of idealized folding geometry assumed by the M & J test. Given such an idealized geometry it is possible to use a sampling scheme that ensures there are several sites on each limb. The sites on each limb may be considered as a separate group, each group having its own common tilt correction. Thus it is possible to get an estimate of the original scatter in site-mean directions from each group. As noted in McFadden & Jones (1981), the requirement for a common original population demands that the scatter observed in different groups be consistent with a common precision, κ.

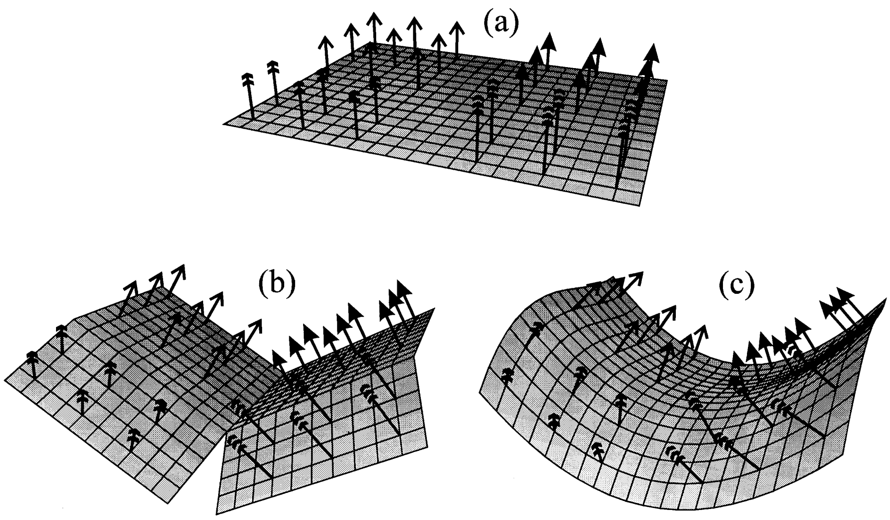

Figure 1. (a) Original geometry of rock stratum. (b) Idealized folding geometry as assumed by the M & J test. (c) More typical actual folding geometry.

Given this as an essential starting point, all that the M & J test does is to determine, with the rocks in a given orientation, whether the scatter observed between groups (on different fold limbs) is consistent with the observed scatter within groups. If each of the groups has n observations and an estimated precision parameter of about k, we would expect the group means to have a precision of about nk. If the precision of the group means were to differ too much from this, we would conclude that the scatter observed between groups is not consistent with the observed scatter within groups and therefore that it is unlikely the magnetization was acquired with the rocks in that particular orientation.

As shown by McFadden & Jones (1981) the relevant distribution for the fold test is

$$\left(\frac{N-m}{m-1}\right)\frac{\Sigma R_i - R^2/\Sigma R_i}{2(N-\Sigma R_i)} = f \sim \mathrm{F}[2(m-1), 2(N-m)], \quad (2)$$

where the summations are for $i=1$ to m, the R_i are the lengths of the vector resultants from each limb of the site mean unit vectors, R is the length of the resultant vector of all the site mean directions (i.e. the vector sum of the $\vec{R}_i$) and N is the total number of unit vectors. $\mathrm{F}[2(m-1), 2(N-m)]$ is the F distribution on $2(m-1)$ and $2(N-m)$ degrees of freedom and the symbol '$\sim$' is to be read as 'is distributed as'.

Given the tilt corrections for each group and the particular set of observations, ΣR_i is constant, but R varies as the group mean directions change with respect to each other with the tilt corrections. The maximum value of R is ΣR_i, so the term $(\Sigma R_i - R^2/\Sigma R_i)$ on the top line of eq. (2) gives the dispersion of the group mean directions independent of the dispersion within groups. Similarly, the term $(N-\Sigma R_i) = \Sigma(n_i - R_i)$, where n_i is the number of observations in each group, on the bottom line of eq. (2) is the sum of the dispersions within the groups. Thus f gives the ratio (with division by the appropriate degrees of freedom) of the dispersion of group means to the within-group dispersion. The expectation, or mean, of f is given by $\langle f \rangle = (N-m)/(N-m-1)$, so we would expect f to be close to unity for consistency.

If the observed value of f exceeds the upper critical value of the F distribution at the required level of significance then the hypothesis of a common true mean direction may be rejected, as the dispersion of group mean directions is large compared with the within-group dispersion. This is equivalent to inferring that the rocks are in an incorrect orientation.

If the observed value of f is within the critical values of the F distribution at the required level of significance then the hypothesis of a common true mean direction is accepted. This is equivalent to saying that the dispersion of the group mean directions is consistent with the observed within-group dispersion and there is no reason to reject the null hypothesis that the magnetization was acquired with the rocks in that particular geometry. That is, if the dispersions are consistent with the rocks in the geometry of Fig. 1(a) (i.e. 'tilt corrected' or '100 per cent unfolded'), then there is no reason to suppose the magnetization was not acquired prefolding. Similarly, if the dispersions are consistent with the rocks in the geometry of Fig. 1(b) (i.e. 'geographical' or '0 per cent unfolded'), then there is no reason to suppose the magnetization was not acquired postfolding. Naturally, there are times when the folding would not have been sufficient to reject either of these hypotheses with the available data, and the test is then indeterminate for that given set of observations.

With particular reference to the T & W test, it should also be noted that if the observed value of f is less than the lower critical value of the F distribution at the required level of significance then the group mean directions are too tightly concentrated to be consistent with the overall population dispersion.

3 INFERENCE WITH THE T & W TEST

Fig. 2 shows what is, in effect, a crisis of identity with the T & W test. Tauxe & Watson (1994) claim that 'the problem is really one of parameter estimation'. However, if the point estimate of the parameter estimation were always accepted, then the values of 0 per cent unfolded (postfolding magnetization) or 100 per cent unfolded (prefolding magnetization) would virtually never occur; the resulting conclusion would be that almost all magnetizations are syn-folding, or the consequence of a complex fold. In order to overcome this problem, the T & W test is implemented by requiring that the result is assumed to be 0 per cent if the confidence limits include 0 per cent, 100 per cent if the confidence limits include 100 per cent, but the point estimate of the parameter otherwise. This is inconsistent, and indicates that the problem is not simply one of parameter estimation. For example, it would not be appropriate to fit the equation $y = mx + c$ to some data and then conclude that the data are drawn from a straight line passing through the origin if the confidence limits on $\hat{c}$, the estimate of c, include zero. Instead, to arrive at such a conclusion, one would test whether the model $y = mx$ provides an adequate description of the data.

4 VALIDITY OF THE BASIC ASSUMPTION IN THE T & W TEST

The T & W test is based on the assumption that the population of directions of magnetization is most tightly grouped with the rocks in the orientation in which the magnetization was acquired. Thus, as already noted, the test is implemented

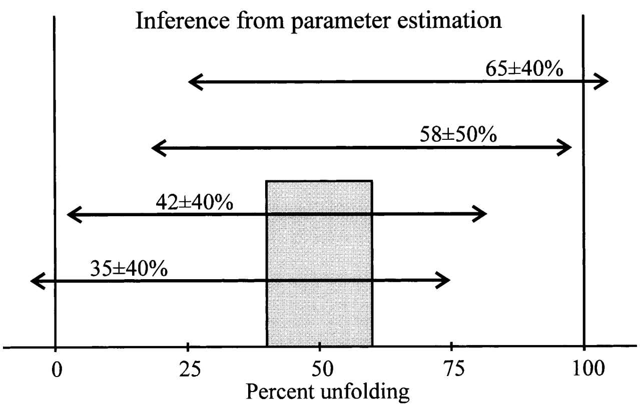

Figure 2. If the confidence limits from the bootstrap process include 0 per cent unfolding, then it is inferred that the correct value is 0 per cent. Similarly for 100 per cent unfolding. Otherwise the point estimate for the amount of unfolding is accepted. With confidence limits of ± 40 per cent the only possible results are 0 per cent, the shaded area from 40 to 60 per cent, and 100 per cent.

essentially as a parameter estimation problem by unfolding the rocks to find the position of maximum clustering. A bootstrap process with a large number of pseudo-samples is actually used to obtain a distribution of the percentage of unfolding that gives maximum clustering, and 95 per cent confidence limits are obtained from this distribution. If the confidence limits include 0 per cent or 100 per cent (post or prefolding magnetization), then this is the value assumed; otherwise, syn-folding magnetization is concluded.

Assuming a prefolding (postfolding) magnetization, the basic assumption requires that the geometry of the folding relative to the magnetic directions be such that as the rocks are folded (unfolded) the population of magnetic vectors will become more dispersed. Although this is often the case, and typically approximately the case, there is no fundamental reason why this should be so, and there are instances when it is not the case. As noted, for example, by McCabe *et al.* (1983), a significantly more concentrated distribution does not necessarily imply the correct result.

The validity of the basic assumption has been tested in this study with synthetic data for symmetric and non-symmetric folds, using sets of 500 trials for each test. In both cases the magnetic data for each trial were generated as postfolding pseudo-random samples from a Fisher distribution, and for each magnetic vector the dip of the bed was chosen as a uniform random value within the range 10°–30°. For the symmetric fold, for each magnetic vector the direction of dip of the bed was chosen as a uniform random value within the range 0°–360°, so that on average the overall magnetic mean direction did not change on unfolding. For the non-symmetric fold, for each magnetic vector the direction of dip of the bed was chosen as a uniform random value within the range 0°–30°, so that in each trial the overall magnetic mean direction was moved about 20° on unfolding.

Using 95 per cent confidence limits, the trials showed that on a symmetric fold the T & W test gave an incorrect result (i.e. a syn-folding result instead of the correct result of 0 per cent unfolded) about 5 per cent of the time. That is, the test seems to perform as desired. The results were, however, quite different with non-symmetric folds: as the sample size per trial rose to 200 the number of incorrect results rose to about 45 per cent. Thus we have the apparently surprising result that the larger the sample size the more likely the T & W test is to give an incorrect result (at least with a non-symmetric fold). The reason for this can be seen by considering the geometry. Assume that as we start the unfolding process the observations will become less concentrated. Then, if we were simply to invert all of the tilt corrections, the observations would become more concentrated just as the unfolding process started. Thus there is approximately a 50–50 chance of the concentration increasing as the unfolding process is initiated, regardless of the number of observations. If the number of observations is large then the position of maximum concentration will be significantly different from 0 per cent unfolding. To some extent, therefore, the question whether the estimated parameter is significantly different from 0 or 100 per cent is often just a matter of the number of observations. As the allowed dip of the beds increases, smaller sample sizes are, naturally, able to show the problem.

A somewhat artificial example serves to highlight what is happening with a non-symmetric fold. The example was set up to be testable by the M & J test. 10 groups, each of 10 observations, were drawn from a Fisher distribution with precision parameter $\kappa = 10$, the bedding corrections being the same for all observations within a group. Fig. 3 shows a lower-hemisphere stereographic plot of the 10 group means, together with their individual circles of 95 per cent confidence (α_{95}) and values of the test statistic, f, for 0 per cent ($f = 0.8$), 34 per cent ($f = 0$), and 100 per cent ($f = 1.9$) unfolding. The value of 34 per cent was chosen because this is the value (with 95 per cent confidence limits of 16 per cent and 50 per cent) given (incorrectly) by the T & W test as the percentage of unfolding at which the magnetization was acquired (see Fig. 4). The histogram gives the fraction of pseudo-samples that gave the maximum value of τ_1 within each range of percentage unfolding.

The M & J test shows that at 0 per cent unfolding the dispersion of group means is compatible with the dispersion of observations within the groups ($f = 0.8$). This is to be expected because this is where the magnetization was (synthetically) acquired. Thus, on the basis of the proposition that the directions are most closely grouped when the rocks are in their correct orientation, the T & W test incorrectly suggests that it was a syn-folding magnetization acquired at 34 per cent unfolding. However, the M & J test shows that at 34 per cent unfolding the dispersion of group means is unacceptably small ($f = 0$) compared with the dispersion of observations within the groups. Clearly, it is not just a matter of determining where the directions cluster most. It would appear that with a non-symmetric fold (i.e. one in which the mean direction moves during the folding process) the geometry of the fold can interact with the geometry of the group mean directions to give an incorrect result with the T & W assumption. The fact that the T & W test can fail so spectacularly under such circumstances implies that it should be viewed with some caution.

5 EXTENDING THE M & J TEST

Fig. 1(c) is a more realistic picture of what actually happens in the field. No two of the arrows perpendicular to the surface are parallel and it is not possible to define a 'limb' across which there is a common tilt correction. Thus the geology does not fit the idealized geometry required for application of the M & J test. Conceptually, however, it is a simple matter to extend the M & J test so that it is much more flexible and makes few demands on the sampling scheme. The critical point with the extension to the M & J test is that (together with the necessary assumption of a common distribution throughout) with the rocks in the correct orientation it should not matter how one chooses to group the observations (sites) to perform an M & J test. Obviously it does have an impact with the rocks in some other attitude, as is apparent from Fig. 1(c). However, it will usually be quite sufficient to group together those magnetic directions whose bedding corrections are similar, instead of requiring that the magnetic directions in a group all have the same bedding correction. This, then, significantly reduces any demands upon the sampling scheme, although with perhaps some reduction in the power of the test to reject the null hypothesis with the rocks in the incorrect orientation. As an aside, it suggests an alternative (but weak) test in that there should be greater inhomogeneity of precision with the rocks in the incorrect orientation if the groups do not have common tilt corrections.

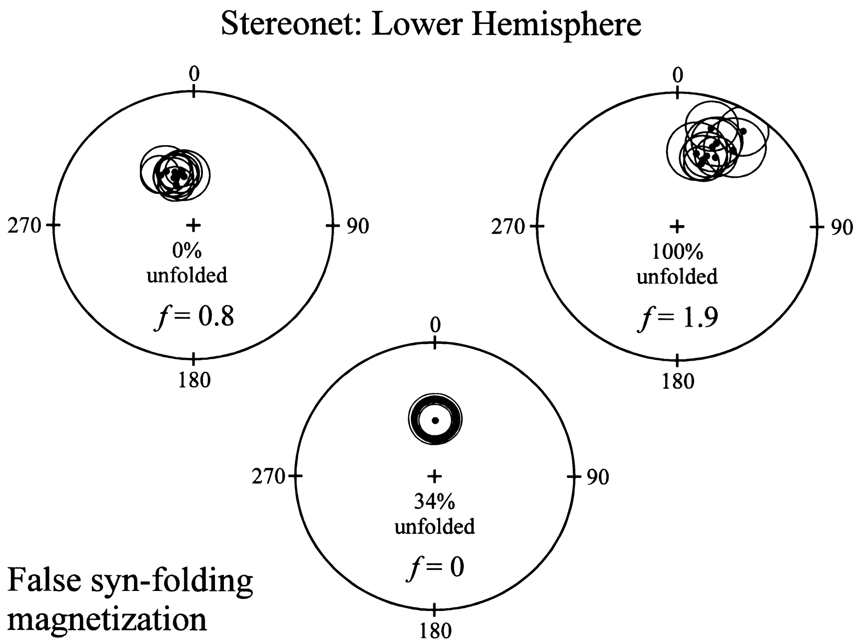

Figure 3. Plot of the 10 synthesized group means, each of 10 observations, together with their individual circles of 95 per cent confidence for 0 per cent, 34 per cent, and 100 per cent unfolding. All observations within a given group have the same bedding correction. At 0 per cent unfolding all observations are drawn from a common Fisher distribution with precision parameter $\kappa = 10$; $f = 0.8$ showing that the dispersion of group means is compatible with the within-group dispersion as expected. At 34 per cent unfolding $f = 0$, showing that the dispersion of group means is ridiculously small compared with the within-group dispersion, so the magnetization could not have been acquired here. At 100 per cent unfolding $f = 1.9$, showing that the dispersion of group means is a bit large compared with the within-group dispersion.

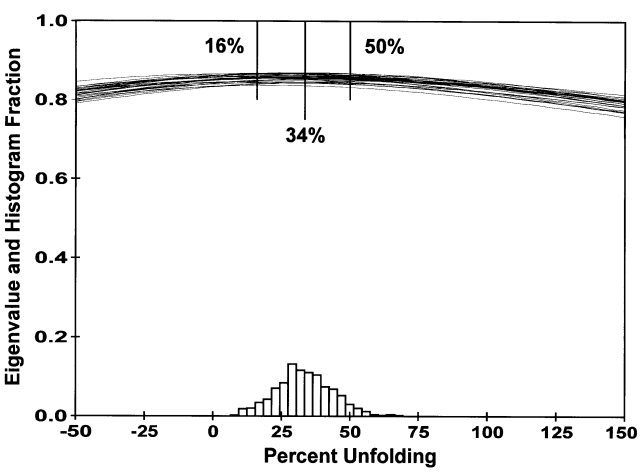

Figure 4. Eigenvalue and histogram fraction for the T & W test used on the data of Fig. 3.

The extended test is performed simply by using a clustering algorithm applied to the bedding corrections and then performing the M & J test with the groups defined by the clusters of bedding corrections. The clustering algorithm used is that of Shanley & Mahtab (1976) and is implemented using doubly linked lists for speed. A doubly linked list is simply a list of items with pointers to the previous and subsequent items. This means that removing an item from one cluster and placing it in another is just a matter of reassigning the pointers. The software is written so that it is a simple matter to use the mouse to alter the clusters. This is necessary because any clustering algorithm will at some time create unrealistically small groups. A choice has been included in the software to cluster on directions rather than bedding corrections. This then makes it easy to separate out different aspects of any given sample set. The software is written in C for an MS-DOS platform and is available (with code for inclusion into other software) from the author.

The formulation has been given here assuming that the underlying distribution is Fisher (1953) and the software has also been written with this assumption. In most instances the assumption of a Fisher distribution is, in fact, quite acceptable. If the magnetization has been properly cleaned, departures of the underlying distribution from Fisher are usually not large enough to have a major impact on the conclusions that will be drawn. However, for those who prefer not to use the Fisher distribution, it is a simple matter to apply the concept and use a bootstrap approach without making assumptions about the underlying distribution.

6 EXAMPLES OF APPLICATION

Two of the examples used by Tauxe & Watson (1994) serve as examples of analysis using the EMJ test. The first is that of the Juarez *et al.* (1994) ‘P-component’ and the second is that of the Xinlong formation from Gilder *et al.* (1993).

Fig. 5 is, in effect, a repeat of the T & W analysis of the Juarez P-component, using 500 pseudo-samples. This analysis shows that the maximum value of τ_1 is at 98.9 per cent unfolding with 95 per cent confidence limits at 96 and 100 per cent unfolding. The precise figure does not, in fact, quite include 100 per cent unfolding and so if one wished to be pedantic, one could conclude that the magnetization is a syn-folding magnetization at 98.9 per cent unfolded.

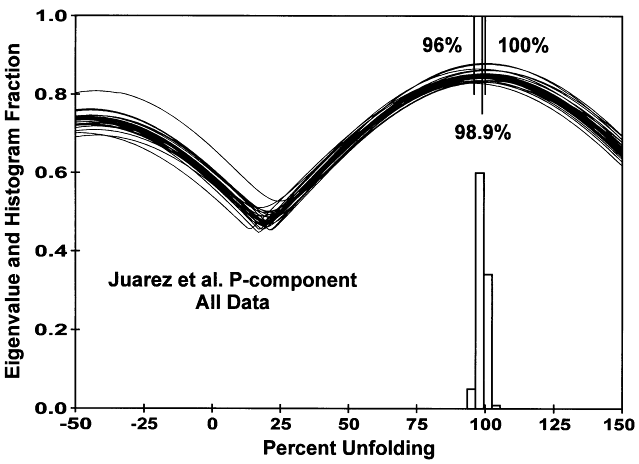

Figure 5. Analysis of the Juarez *et al.* (1994) P-component using the T & W test with 500 pseudo-samples.

Fig. 6 shows the bedding corrections for the individual specimens. Visually it is quite apparent that they fall into four groups that may be used as the groups for the EMJ test. The software allows us to alter the groups manually by throwing a loop (as shown in Fig. 6) around a set of bedding corrections to include all of those bedding corrections into a single group. At 0 per cent unfolding, the EMJ test shows that the cluster mean directions are excessively dispersed compared with the within-cluster dispersion (probability of exceeding the observed value of f is 0.05 per cent). Thus it is unlikely that the magnetization could have been acquired with the rocks *in situ*, in agreement with the conclusion of the T & W test. Also consistent with the conclusion of the T & W test, the EMJ test finds that with 100 per cent unfolding the dispersion of cluster means is (just) compatible with the within-cluster dispersion (probability of exceeding the observed value of f is 6.9 per cent). However, the EMJ test shows highly variable dispersion in the groups.

Fig. 7 shows all of the Juarez *et al.* P-component directions 100 per cent unfolded. The automated clustering algorithm appears to assign two directions inappropriately. Consequently the software has been used to throw a loop around those

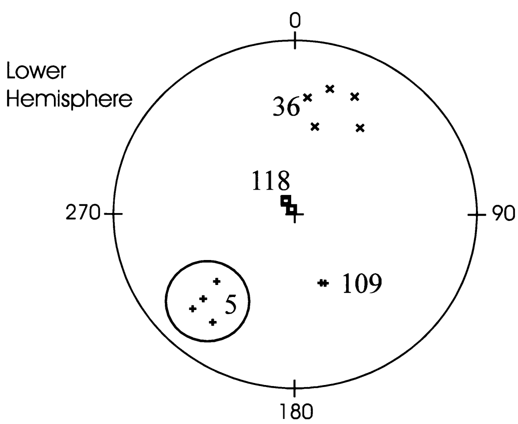

Figure 6. Equal-angle lower-hemisphere plot of the bedding corrections for the Juarez *et al.* (1994) P-component sorted into four clusters. The numbers show how many observations there are in each cluster.

directions grouping in the upper left-hand corner of the lower-hemisphere plot to assign these directions all to one cluster. This set of directions is identified as group B and the remainder as group A. Contrary to the assertion of Tauxe & Watson (1994) that it is tedious at best under such circumstances to calculate the Fisher concentration parameter, it is simply a question of having the appropriate software. Fig. 8 shows a T & W analysis of the data separated into these two groups and it is immediately apparent that their characteristics are distinctly different. The A group results are much more highly dispersed but definitely include 100 per cent unfolding within the confidence limits whereas the B group results do not quite include 100 per cent unfolding.

Fig. 9 shows an EMJ analysis of the A group data. This shows that the group means are highly dispersed compared with the within-group dispersion (probability of exceeding the observed value of $f = 122.9$ is 0.00 per cent) when 0 per cent unfolded, consistent with the conclusion of the T & W test. However, when 100 per cent unfolded the EMJ test still shows that the group-mean dispersion is large compared with that expected from the within-group dispersion (probability of exceeding the observed value of $f = 3.1$ is 1.8 per cent), so that it is unlikely the magnetization was acquired prefolding. This is, of course, in contrast to the conclusion of the T & W test, and indicates that there is, perhaps, a problem with the data. Fig. 10 shows an EMJ analysis of the B group data. It is quite evident in the plot that the magnetization was not acquired at 0 per cent unfolding. The test shows that it is indeed likely that the magnetization was acquired at 100 per cent unfolding (probability of exceeding the observed value of $f = 1.1$ is 37.9 per cent), whereas the T & W test only just includes 100 per cent unfolding within the 95 per cent confidence limits. Clearly, however, the EMJ test provides for a more subtle analysis of the data thereby providing a better understanding.

The second example is provided by the data of Gilder *et al.* (1993). Tauxe & Watson (1994) concluded that both geographical and 100 per cent unfolded coordinate systems are excluded at the 95 per cent confidence level, suggesting either a complex magnetization, complex folding regime, or a synfolding remanence acquisition at about 70 per cent unfolding. This conclusion differs quite strikingly from the conclusion of Gilder *et al.* (1993) that the magnetization was acquired prefolding. Fig. 11 shows an EMJ analysis of their sites at 0 per cent (probability of exceeding the observed value of $f = 11.6$ is 0.00 per cent), 100 per cent (probability of exceeding the observed value of $f = 4.2$ is 0.00 per cent) and 70 per cent (probability of exceeding the observed value of $f = 3.1$ is 0.03 per cent) unfolding. The test shows that the group means are highly dispersed compared with the within-group dispersion, even for 70 per cent unfolding. Thus, although the T & W test shows that the maximum grouping at 70 per cent unfolding is significant, and it is suggested that the magnetization was acquired here, the EMJ test shows that this is most unlikely, confirming that the position of maximum concentration does not necessarily identify the position at which the magnetization was acquired.

Fig. 12 shows an EMJ analysis of the Gilder *et al.* (1993) data with sites L130 and L138 removed. This was done because Gilder *et al.* noted tectonic problems with site L138 and because site L130 seems to have quite a different dispersion from the other sites. It is immediately apparent that the magnetization was not acquired at 0 per cent unfolding but

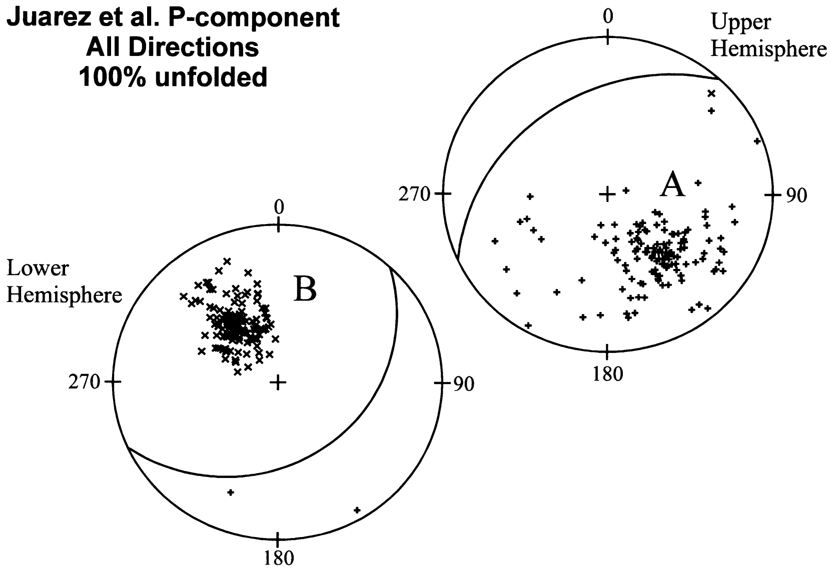

Figure 7. Equal-angle plot of all of the Juarez *et al.* (1994) P-component directions showing their segregation into groups A and B.

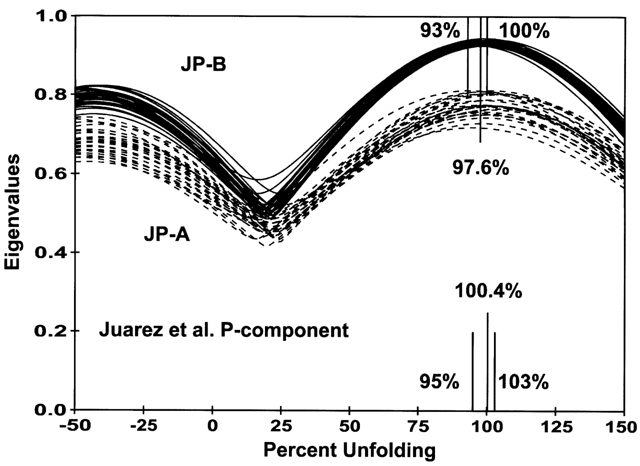

Figure 8. T & W analysis of the Juarez *et al.* (1994) P-component directions separated into groups A and B.

the test shows that it was likely to have been acquired at 100 per cent unfolding (probability of exceeding the observed value of $f = 1.3$ is 26.7 per cent). This concurs with the original conclusion of Gilder *et al.* that the magnetization was acquired prefolding.

7 SYN-FOLDING MAGNETIZATIONS

The proper identification of a syn-folding magnetization (e.g. Perroud 1983; McClelland Brown 1983; Schwartz & Van der Voo 1984; Kent & Opdyke 1985; Schmidt & Embleton 1985; Granirer *et al.* 1986; Miller & Kent 1986; Torsvik *et al.* 1986) is a vexed question indeed. Tauxe & Watson (1994) noted that what appears to be a syn-folding magnetization can, in fact, be the consequence of a complex fold with multiple rotations. Sometimes it may also be the result of internal strain of a pre-existing magnetization (Facer 1983; Spariosu *et al.* 1984; Kodama 1986a,b; Van der Pluijm 1987).

Shipunov (1997) has addressed some aspects of the statistical detection of a syn-folding magnetization. For folding to occur there must be either brittle fracture or plastic flow at an elevated temperature. It is the internal strains and elevated temperatures that can lead to acquisition of a syn-folding magnetization. Thus although on the specimen scale remagnetization is likely to take place over a relatively short time compared with folding, it is extremely unlikely that a syn-folding magnetization would be acquired contemporaneously across a suite of samples and at only one point in time at different locations (e.g. Lackie & Schmidt 1993). The process that leads to acquisition of a syn-folding magnetization suggests that the magnetization will be acquired dynamically as the folding proceeds. Thus one would expect the syn-folding magnetization across a suite to be a composite of magnetizations and that these magnetic directions would lie on small circles with poles parallel to the folding axes. This would imply that the only statistical way to identify a syn-folding magnetization with certainty would be to identify during demagnetization components that do, in fact, lie on a small circle with pole parallel to the folding axis. Having identified such a syn-folding magnetization, it is quite clear that one cannot then uniquely identify the actual direction of that magnetization from the statistics. Clearly, interpretations of syn-folding remanence should be based not only on statistics but also on rock magnetism tests and geological factors.

8 CONCLUSIONS

In an attempt to create a fold test that makes no demands on the sampling scheme and no assumptions about the folding geometry, Tauxe & Watson (1994), following Watson & Enkin (1993), developed a test using an eigen-analysis approach based on the assumption that the total population of magnetic vectors is most tightly grouped with the rocks in the orientation at which the magnetization was acquired. This led to an appealing, simple and intuitive test using parameter estimation. Unfortunately, the basic assumption is flawed and this can lead to incorrect conclusions.

The McFadden & Jones (1981) test, although valid, makes unrealistic demands upon the sampling scheme in all but the

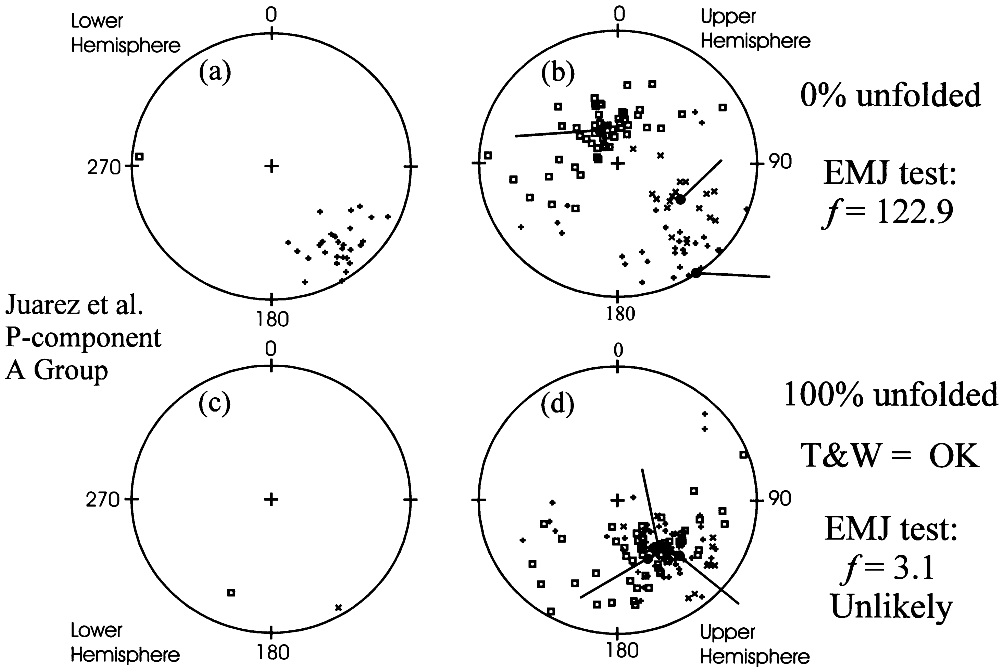

Figure 9. EMJ analysis of the A group from the Juarez *et al.* (1994) P-component directions. (a) and (b) give the lower- and upper-hemisphere plots of the individual directions *in situ* (0 per cent unfolded) while (c) and (d) plot the individual directions 100 per cent unfolded. The plotted symbols indicate the bedding correction cluster (or group) for the observation (see Fig. 6). The indicator lines show the mean directions for each of the bedding-correction clusters. At 0 per cent unfolding $f = 122.9$, so the mean directions are massively dispersed compared with the within-group dispersion. At 100 per cent unfolding $f = 3.1$, so the group means are still highly dispersed compared with the within-group dispersion, which contrasts with the conclusion of the T & W test.

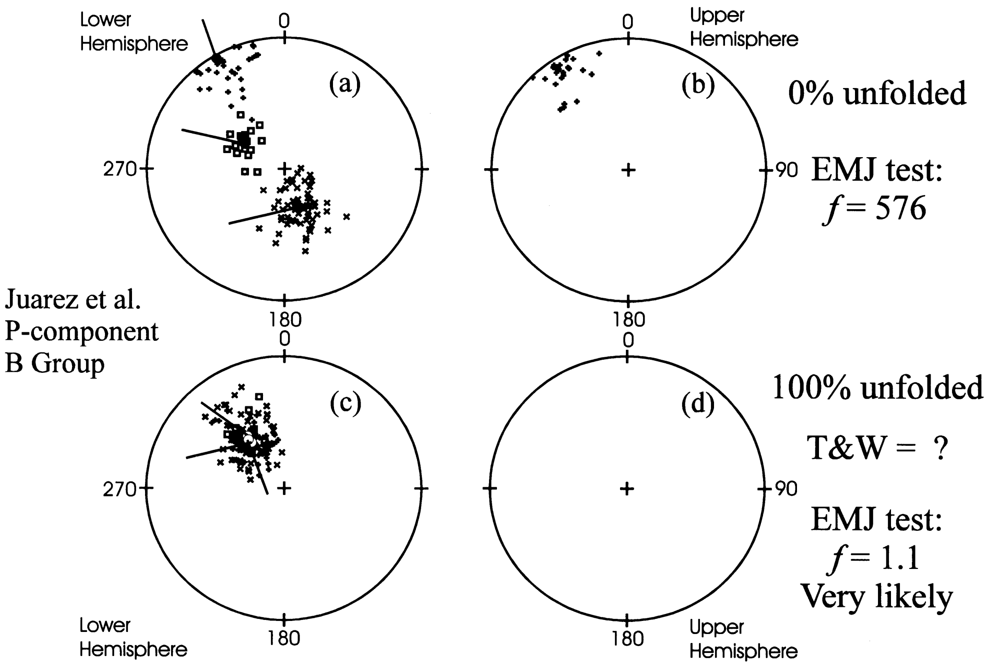

Figure 10. EMJ analysis of the B group from the Juarez *et al.* (1994) P-component directions. (a) and (b) give the lower- and upper-hemisphere plots of the individual directions *in situ* (0 per cent unfolded) while (c) and (d) plot the individual directions 100 per cent unfolded. Plotted symbols and indicator lines as in Fig. 9. At 0 per cent unfolding $f = 576$, so the mean directions are massively dispersed compared with the within-group dispersion. At 100 per cent unfolding $f = 1.1$, so the group-mean dispersion is entirely consistent with the within-group dispersion, which strongly suggests that the magnetization was acquired here.

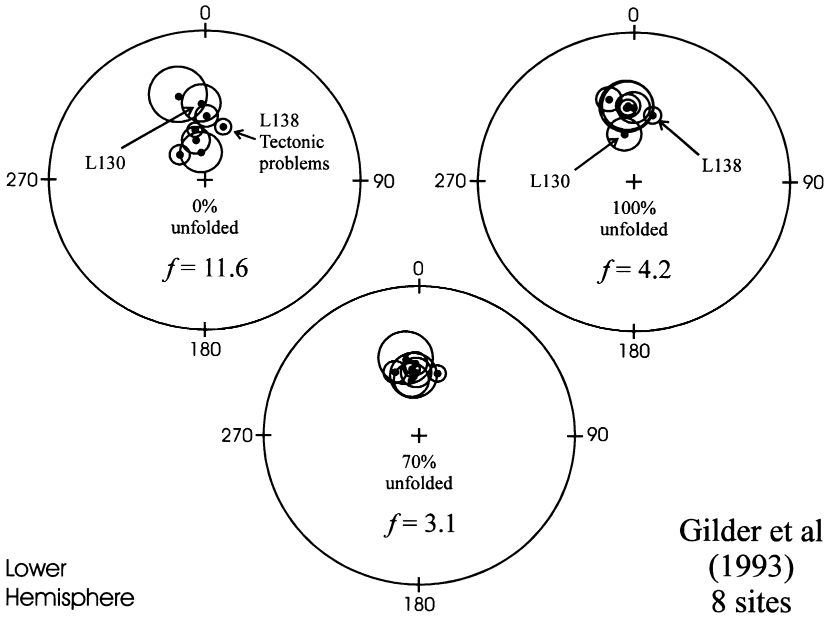

Figure 11. EMJ analysis of all sites from Gilder *et al.* (1993). The T & W test shows that the maximum grouping occurs at 70 per cent unfolding and that this maximum is significant. However, the M & J test shows that, even though the grouping is at a maximum, $f = 3.1$ and so the group means are highly dispersed compared with the within-group dispersion, suggesting that it is unlikely that the magnetization was acquired here.

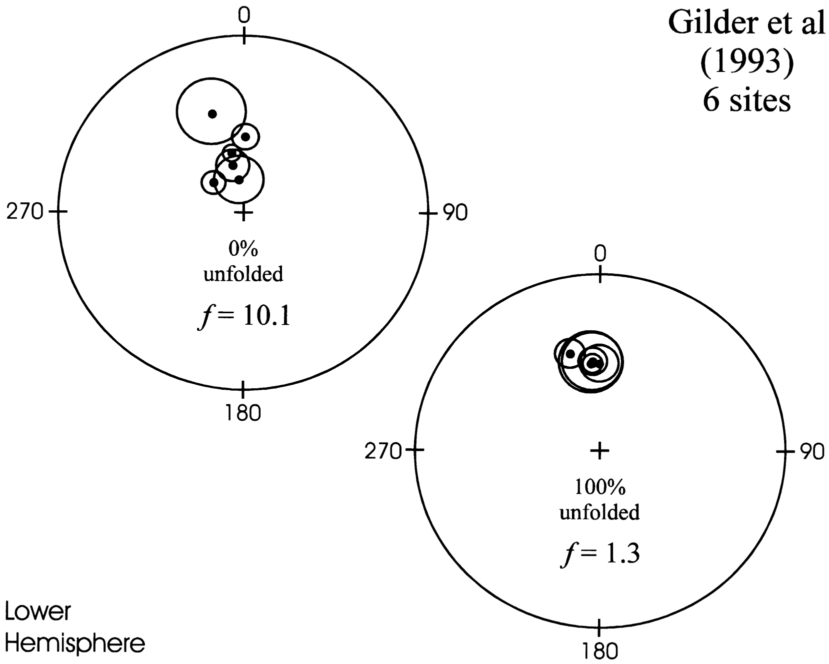

Figure 12. EMJ analysis of the Gilder *et al.* (1993) data with sites L130 and L138 removed. At 0 per cent unfolding $f = 10.1$, showing that the group-mean directions are highly dispersed compared with the within-group dispersion. At 100 per cent unfolding $f = 1.3$, showing that the group-mean dispersion is entirely consistent with the within-group dispersion, suggesting that the magnetization was acquired here.

most simplistic of folds. However, it is a simple matter to extend this test to avoid these demands upon the sampling scheme by recognizing that it is sufficient to use groups of similar bedding corrections and not necessary to demand groups of common bedding corrections. This grouping can be achieved easily using a clustering algorithm. With this extension the McFadden & Jones (1981) test can be applied to most situations, the only drawback being some reduction in the power of the test to reject the null hypothesis with the rocks in an incorrect orientation.

ACKNOWLEDGMENTS

I thank Lisa Tauxe for providing data for the tests. I thank Helen McFadden and Helen Hunt for assistance in preparing the manuscript. I thank Mike McElhinny, Phil Schmidt, Dennis Kent, and an anonymous referee for helpful comments. This paper is published with the permission of the Executive Director of the Australian Geological Survey Organization.

REFERENCES

Borradaile, G.J., 1993. Strain and magnetic remanence, *J. struct. Geol.,* **15,** 383–390.

Cogné, J.-P. & Perroud, H., 1987. Unstraining paleomagnetic vectors: the current state of debate, *EOS, Trans. Am. geophys. Un.,* **68,** 711–712.

Facer, R.A., 1983. Folding, strain and Graham's fold test in palaeomagnetic investigations, *Geophys. J. R. astr. Soc.,* **72,** 165–171.

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

Gilder, S.A., Coe, R.S., Wu, H., Kuang, G., Zhao, X., Wu, Q. & Tang, X., 1993. Cretaceous and Tertiary paleomagnetic results from Southeast China and their tectonic implications, *Earth planet Sci. Lett.,* **117,** 637–652.

Graham, J.W., 1949. The stability and significance of magnetism in sedimentary rocks, *J. geophys. Res.,* **54,** 131–168.

Granirer, J.L., Burmester, R.F. & Beck, M.E., 1986. Cretaceous paleomagnetism of the Methow-Pasayten Belt, Washington, *Geophys. Res. Lett.,* **13,** 733–736.

Juarez, M.T., Osete, M.L., Meléndez, G., Langereis, C.G. & Zijderveld, J.D.A., 1994. Oxfordian magnetostratigraphy of the Aguilón and Tosos sections (Iberian Range, Spain) and evidence of a pre-Oligocene overprint, *Phys. Earth planet. Inter.,* **85,** 195–211.

Kent, D.V. & Opdyke, N.D., 1985. Multicomponent magnetisations from the Mississippian Mauch Chunk Formation of the Central Appalachians and their tectonic implications, *J. geophys. Res.,* **90,** 5371–5383.

Kodama, K.P., 1986a. The effect of deformation on the fold test, *EOS, Trans. Am. geophys. Un.,* **67,** 268.

Kodama, K.P., 1986b. Effect of flexural slip on Fisherian distributions: implications for the fold test, *EOS, Trans. Am. geophys. Un.,* **67,** 924.

Lackie, M. & Schmidt, P.W., 1993. Remagnetisation of strata during the Hunter-Bowen Orogeny, *Explor. Geophys.,* **24,** 269–274.

McCabe, C., Van der Voo, R., Peacor, C.R., Scotese, C.R. & Freeman, R., 1983. Diagenetic magnetite carries ancient yet secondary remanence in some Paleozoic carbonates, *Geology,* **11,** 221–223.

McClelland Brown, E., 1983. Palaeomagnetic studies of fold development and propagation in the Pembrokeshire Old Red Sandstone, *Tectonophysics,* **98,** 131–149.

McElhinny, M.W., 1964. Statistical significance of the fold test in palaeomagnetism, *Geophys. J. R. astr. Soc.,* **8,** 338–340.

McFadden, P.L., 1990. A new fold test for paleomagnetic studies, *Geophys. J. Int.,* **103,** 163–169.

McFadden, P.L. & Jones, D.L., 1981. The fold test in palaeomagnetism, *Geophys. J. R. astr. Soc.,* **67,** 53–58.

Miller, J.D. & Kent, D.V., 1986. Synfolding and prefolding magnetisations in the Upper Pennsylvanian: implications for the tectonic history of Acadia, *J. geophys. Res.,* **91,** 12 791–12 803.

Perroud, H., 1983. Palaeomagnetism of Palaeozoic rocks from the Cabo de Penas, Asturia, Spain, *Geophys. J. R. astr. Soc.,* **75,** 201–215.

van der Pluijm, B.A., 1987. Grain-scale deformation and the fold test—evaluation of syn-folding remagnetisation, *Geophys. Res. Lett.,* **14,** 155–157.

Schmidt, P.W. & Embleton, B.J.J., 1985. Prefolding and overprint magnetic signatures in Precambrian (2.9–2.7 Ga) igneous rocks from the Pilbara Craton and Hamersley Basin, NW Australia, *J. geophys. Res.,* **90,** 2967–2984.

Schwartz, S.Y. & Van der Voo, R., 1984. Paleomagnetic study of thrust sheet rotation during foreland impingement in the Wyoming-Idaho Overthrust Belt, *J. geophys. Res.,* **89,** 10 077–10 086.

Shanley, R.J. & Mahtab, M.A., 1976. Delineation and analysis of clusters in orientation data, *Math. Geol.,* **8,** 9–23.

Shipunov, S.V., 1997. Synfolding magnetization: detection, testing and geological applications, *Geophys. J. Int.,* **130,** 405–410.

Spariosu, D.J., Kent, D.V. & Keppie, J.D., 1984. Late Paleozoic motion of the Meguma Terrane, Nova Scotia: new paleomagnetic evidence, in *Plate Reconstructions from Paleozoic Paleomagnetism,* eds Van der Voo, R., Scotese, C.R. & Bonhjommet, N., *Geodynamics Ser.,* **12,** 82–98.

Tauxe, L. & Watson, G.S., 1994. The fold test: an eigen analysis approach, *Earth planet. Sci. Lett.,* **122,** 331–341.

Torsvik, T.H., Sturt, B.A., Ramsay, D.M., Kisch, H.J. & Bering, D., 1986. The tectonic implications of Solundian (Upper Devonian) rocks of Kvamshesten, western Norway, *Earth planet. Sci. Lett.,* **80,** 337–347.

Watson, G.S. & Enkin, R.J., 1993. The fold test in paleomagnetism as a parameter estimation problem, *Geophys. Res. Lett.,* **20,** 2135–2137.