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Synfolding magnetization: detection, testing and geological applications

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SUMMARY

A correct method for determining the direction of a synfolding remanence is described, and a new test, which in a number of cases can discriminate between a true synfolding remanence and a remanence that is the sum of pre- and post-folding components, is suggested. It is shown that it is possible to reveal the folding evolution of a local object under an assumption that the acquisition of the synfolding remanence was synchronous over this object.

Key words: folding, remanent magnetization.

1 INTRODUCTION

Palaeomagnetic data have played an ever increasing role in tectonics over the last decade; these data are often the only ones that are able to detect the mutual displacements and rotations of various crustal blocks. Applications of palaeomagnetic data are based mainly on directions of primary or pre-folding magnetization components from geological bodies. However, in some cases, post-folding components also can be used for tectonic interpretation.

Recently, the so-called synfolding remanence, acquired at intermediate stages of deformation, has also been used for tectonic purposes (see e.g. Miller & Kent 1986). There is, however, a serious obstacle to such applications, since it is impossible to distinguish a true synfolding remanence from a composite remanence that is the sum of pre- and post-folding components (McFadden 1990). A composite remanence, for which the two components cannot be separated, cannot be used for tectonic applications, since its direction is fictional in the sense that it does not correspond to any true field direction at any stage of deformation.

In addition, the common approaches used to isolate a presumably synfolding remanence are incorrect. The most common procedure uses the proportional incremental unfolding of fold limbs and looks for a stage of unfolding when desirable assumptions are satisfied in a certain way; for instance, when the concentration parameter of palaeomagnetic vectors under study reaches a maximum (e.g. McFadden 1990; Bazhenov & Shipunov 1991; Watson & Enkin 1993; Tauxe & Watson 1994).

The correctness of this proportional incremental unfolding approach has never been established. Moreover, from general considerations, it is difficult to imagine that the folding was really proportional in time. For instance, assuming that folding was proportional to time, the two limbs of a fold with dip directions/dips of 060°/90° and 240°/10° should have had the same dip directions but dips of 45° and 5°, respectively, in the middle of deformation—but how valid is this assumption? In any case, even if a synfolding remanence does exist in the rocks studied, the magnetization direction derived by the above approach will not be correct and will be biased.

The directions of a pre-folding and a post-folding component in two limbs of an isoclinal fold will be mutually parallel in stratigraphic coordinates and geographic coordinates, respectively, whereas that of a synfolding component will be different in both coordinates (Fig. 1). The synfolding component directions are parallel only at a certain intermediate stage of deformation which will be referred to below as synfolding coordinates.

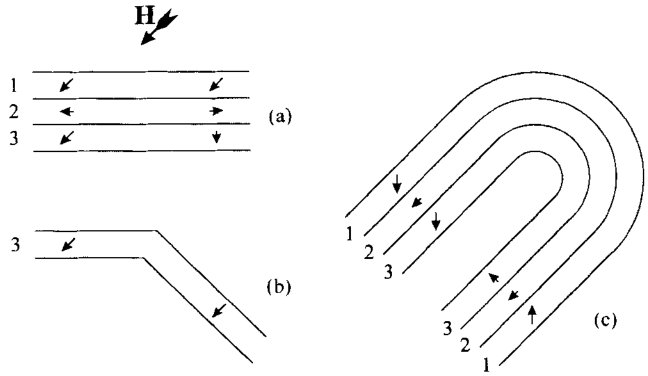

Figure 1. Disposition of palaeomagnetic components for different stages of folding. (a) primary horizontal bedding (stratigraphic coordinates); (b) intermediate stage of folding (synfolding coordinates); (c) geographic coordinates. 1, 2 and 3: remanence acquired before, after and at an intermediate stage of folding, respectively (arrows show the directions of remanence in different coordinates. H: direction of the ambient geomagnetic field.

It was suggested recently (McFadden 1990; Bazhenov & Shipunov 1991) that various modifications of the fold test, namely the correlation tests, be used in order to identify whether a remanence is truly synfolding in origin. Below, an approach is suggested to overcome the two principal difficulties outlined above, namely the incorrect determination of the true synfolding remanence direction and the problem of discriminating between a synfolding remanence and the sum of post- and pre-folding components. The suggested approach is then used to trace fold propagation.

2 CORRECT DETERMINATION OF THE DIRECTION OF SYNFOLDING MAGNETIZATION

It is well known that a simple transformation from geographic to stratigraphic coordinates (i.e. tilt correction) makes the magnetization vector of a sample move along a particular small circle through an angular distance equal to the measured dip (e.g. Kirschvink 1985). Then, if the component under study is synfolding and was acquired at an intermediate stage of folding, its true direction should lie somewhere on this circle. If the same synfolding component is present in several samples taken from beds with different attitudes, its direction can be determined from the intersections of the small circles (Fig. 2).

The solution can be achieved by the least-square method, by minimizing the sum of squares of this best-fit direction from each small circle (see Appendix A). One can use the projection of the best-fit vector onto each small circle as the approximate distribution of unit vectors of the synfolding magnetization (Fig. 2). This is, however, just an approximation, as the dispersion of the unit-vector distribution will be underestimated (the concentration parameter is larger than that for the distribution of the true synfolding directions).

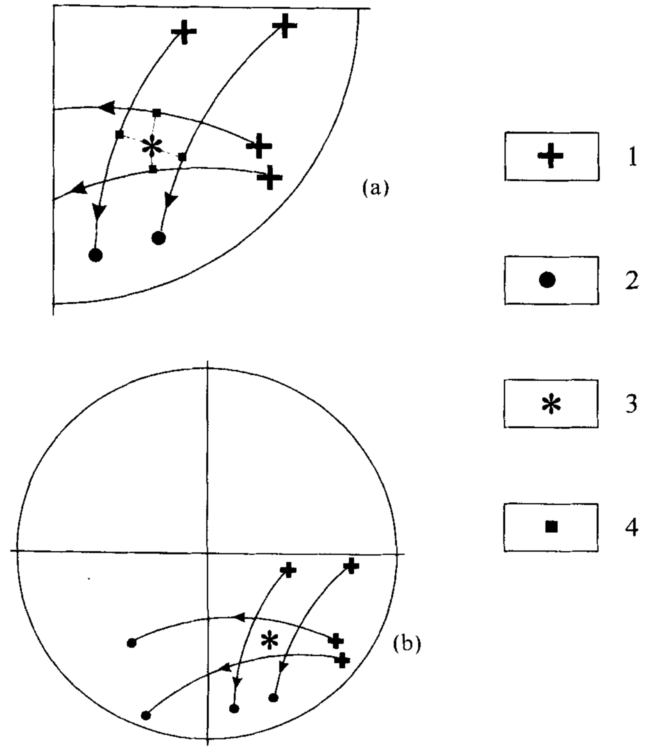

Figure 2. Disposition of small circles for synfolding magnetization. 1, 2: directions in geographic and stratigraphic coordinates, respectively; 3: determined direction of synfolding magnetization; 4: directions of synfolding magnetization in individual samples.

3 DISTINGUISHING A TRULY SYNFOLDING REMANENCE

In order to determine whether a component is truly synfolding or is the sum of post- and pre-folding components it is necessary to carry out the following tests. If certain observed vectors were really acquired at an intermediate stage of deformation there should be no correlation between palaeomagnetic directions in synfolding coordinates and bedding attitudes (Fig. 1). This statement is similar to the main assumption of the correlation fold test (Bazhenov & Shipunov 1988; McFadden 1990; Bazhenov & Shipunov 1991). The fact that the concentration parameter of the observed distribution is overvalued is of no importance, since any correlation between palaeomagnetic directions and bedding attitudes should be absent just because the projections of the mean synfolding vector onto unit small circles are randomly displaced along each small circle. In contrast, a correlation should exist if the data are the sum of post- and pre-folding components. In this case, the characteristics of the observed vector distribution in synfolding coordinates result from the recalculation of bot' components using the measured bedding attitudes; therefor there must be a correlation.

The testing procedure is similar to that for the correlation fold test (Bazhenov & Shipunov 1991) (see also Appendix 2). As the distributions of both palaeomagnetic directions and bedding attitudes are not normal and the desired relationships are not linear, the matrix of Spearman's rank correlation coefficients (Kendall & Stuart 1968) is used. The test is performed in geographic, synfolding and stratigraphic coordinates with the aid of Barnard's Monte Carlo test (Barnard 1963; Marriott 1979). In each coordinate system, the tested hypothesis is the absence of correlation between palaeomagnetic directions and bedding attitudes.

From the testing the following outcomes are possible:

(1) a statistically significant correlation is observed only *in situ* and after tilt correction; hence, the studied remanence is synfolding;

(2) if the correlation is significant in all three coordinates the remanence is not synfolding but may be the sum of two components;

(3) if no correlation is found in all three coordinates the test is inconclusive because of an insufficient amount of data or variance in bedding attitudes;

(4) if the correlation is significant only *in situ* and in synfolding coordinates the remanence is pre-folding;

(5) if the correlation is significant only in synfolding and stratigraphic coordinates the remanence is post-folding.

The last two outcomes, corresponding to situations when purely pre- or post-folding components are present, can be detected with the aid of the other fold tests (e.g. the correlation tests).

The conclusions reached with the above testing procedure are of a statistical nature. For instance, if a correlation is significant and therefore a certain component is recognized, the probability that this conclusion is correct is equal to the chosen confidence level (usually 95 per cent). In contrast, if a correlation is insignificant and no conclusion can be reached as to the nature of a component, the probability that this component is indeed absent is not specified (for more details on the inference problems in palaeomagnetism see Fisher, Lewis & Embleton (1987), Shipunov (1993) and Watson & Enkin (1993).

Thus, if the above test leads to outcome (2) and the component under analysis is actually the sum of pre- and post-folding components, this result is reliable, and the probability that it is correct is 95 per cent. However, if outcome (1) is obtained, that is the correlation in synfolding coordinates is insignificant, the ambiguity of interpretation is usually retained. The possible conclusion here is that the hypothesis of truly synfolding remanence cannot be rejected, and the available data are compatible with this hypothesis.

The procedure discussed above was tested on simulated data sets of 'synfolding' remanence and of remanence produced by the sum of two components. The simulation showed that the general patterns for these two situations are very similar, and, although the ability to recognize these situations does exist in principle, it is not always possible to do so in practice. Most often, outcome (1) was obtained, although the sum of two components (outcome 2) was also found.

4 ANALYSIS OF FOLDING PROPAGATION

Using unit synfolding directions (the projections of the mean vector of synfolding remanence onto unit small circles), it is possible to determine the position of corresponding strata (degree of deformation f) at a moment when this remanence was acquired, provided that the acquisition is synchronous everywhere. This condition is most probably true for a local object and for rocks whose properties are similar everywhere.

The degree of deformation f as the ratio of the calculated dips at the moment of remanence acquisition to observed dips may be interpreted in terms of the propagation of folding over an area. For instance, if the degrees of deformation at two particular points are, say, 90 per cent and 10 per cent when the synfolding magnetization was acquired, it is clear that the folding propagated from the first point, where deformation was nearly complete, to the second point, where it had just started. This interpretation of the spatial distribution of the parameter f is qualitative (its accuracy cannot be evaluated) and non-unique.

If the duration of folding is much less than the duration of synfolding magnetization acquisition and thus the assumption of synchroneity of this remanence is not valid, the same parameter f may be interpreted as the spatial variation of the condition under which this remanence was acquired.

The parameter f can be considered not only as a function of the geographical coordinates but also as a function of the bedding attitudes. For simple structures, for instance linear folds, the latter dependence may be easier for interpretation.

5 EXAMPLES

Two cases are considered as examples of the recognition of synfolding remanence and the propagation of deformation.

(1) A palaeomagnetic study of Devonian rocks in West Pennsylvania (Miller & Kent 1986) revealed a magnetization component of presumably synfolding origin. The relevant palaeomagnetic data *in situ* and after tilt correction are given here (Table 1), as well as the site latitudes and longitudes and bedding attitudes. The studied sites are from both limbs of a linear fold, with the mean strike of the fold axis equal to about 61°.

The fold test after McFadden & Jones (1981) shows that the analysed component can be considered as either the sum of post- and pre-folding components or synfolding magnetization. The calculated values of F statistics are 34.2 and 16.9 for geographic and stratigraphic coordinates, respectively, whereas the 95 per cent critical value is 3.7. The probability of the correct conclusion is greater than 95 per cent.

The plot of the concentration parameter during the incremental unfolding has a significant maximum at approximately 74 per cent unfolding. The synfolding test for the data obtained in the manner described above confirms the hypothesis that the analysed component is of synfolding origin. The degree of deformation f is consistent for the data from each fold limb but differs considerably between the limbs. This parameter f is 47 and 14 per cent, on average, for the north and south limbs, respectively. The incremental unfolding yields

Table 1. Palaeomagnetic data for synfolding magnetization (Miller & Kent 1986).

Sites	λ	ϕ	A	B	D_S	I_S	D_g	I_g	D_{syn}	I_{syn}	f%
K	76.33	41.09	168	36	167.2	−7.2	167.3	28.8	167.2	−7.2	3
L	76.28	41.09	164	35	169.4	−15.2	169.5	19.5	169.3	−8.2	23
M	76.12	41.11	346	40	153.3	7.1	151.1	−31.9	153.3	−8.5	43
N	76.00	41.13	347	40	163.0	10.6	162.4	−29.5	163.0	−8.4	50
O–P	76.16	40.99	156	18	172.3	−9.1	172.2	8.2	172.3	−8.1	11
Q	76.16	40.99	155	24	167.1	−15.7	166.8	7.9	166.8	−8.9	33
R	76.16	40.99	164	53	172.6	−11.5	175.4	40.8	172.5	−8.5	8
S	75.95	41.06	153	17	166.2	−0.9	166.7	15.8	166.2	−0.9	6
T	75.92	41.15	349	41	170.5	10.2	170.7	−30.8	170.5	−8.8	49
Mean			151.0*	−81.9*	166.7	−3.6	166.9	3.5	166.8	−7.5	
κ			5.0*		44.8		8.5		161.9		
α_{95}			20.9*		7.8		18.7		3.7		

λ, ϕ: longitude and latitude of site locations; A, B: bedding orientations (dip direction and dip); D, I: declination and inclination of vectors; s, g and syn: stratigraphic, geographic and synfolding coordinates; f: degree of folding; κ, α_{95}: concentration parameter and 95 per cent confidence radius for mean direction; *: mean direction calculated for normals to bedding surface.

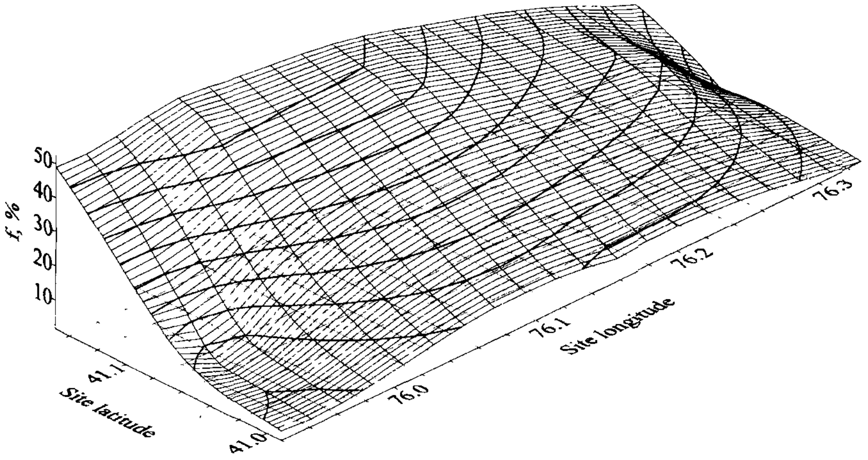

Figure 3. Dependence of folding degree on site location for the palaeomagnetic data of Miller & Kent (1986).

the best data grouping at the 26 per cent stage of deformation, which is an intermediate value for the entire structure.

The analysis of plots of parameter f versus geographic locations (Fig. 3) and bedding attitudes (Fig. 4) leads to the conclusion that the folding propagated from the northwest to the southeast. This propagation was systematic and allows the determination of the area where deformation started. It indicates that, after the intense start, the deformation spread smoothly, with some oscillations at the final stage. These features are noticeable in both plots (Figs 3 and 4), but are more distinct with respect to bedding attitudes. The last observation is most probably due to the fact that a simple linear fold was sampled and the deformation propagated perpendicularly to the fold strike.

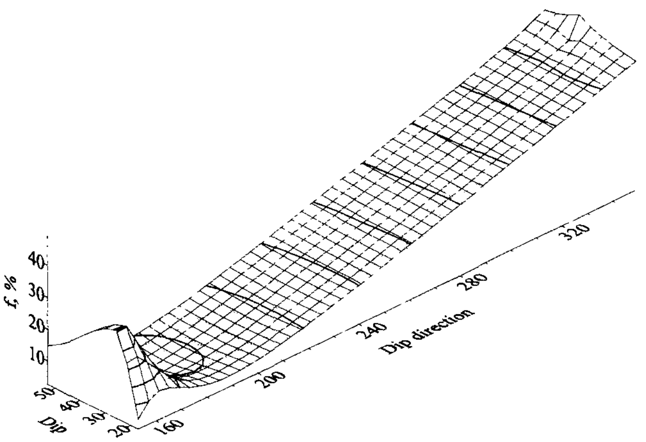

Figure 4. Dependence of folding degree on bedding orientations for the palaeomagnetic data of Miller & Kent (1986).

(2) Red limestones of the Katav Formation with an age of c. 1000 Ma were sampled from six localities in the South Urals (Shipunov 1991). The natural remanent magnetization, NRM, is accounted for by a single component that persists from 200 up to 680 °C. This characteristic component is bipolar, and the reversal test points to the perfect antipodality of normal and reversed directions. For the data from all six localities, the fold test of McFadden & Jones (1981) shows that this component may be regarded as the sum of post- and pre-folding components or synfolding magnetization.

Working under an assumption of partial post-folding remagnetization of the beds studied, the directions of post- and pre-folding components were found to be rather similar (Shipunov 1991; Shipunov 1993). This implies a close similarity in the acquisition times of these components, and therefore a possibility that these components were acquired at an intermediate stage of deformation.

The intersecting small-circles method and then the synfolding test were applied to locality means of the Katav Formation (Table 2). The latter test was positive and thus allowed us to treat the data as a synfolding remanence, the degree of deformation f varying from 0 to 100 per cent. In particular, the fold test at the within-locality level points to a purely pre-folding origin of remanence at localities 1 and 4, in agreement with earlier findings (Shipunov 1991).

Table 2. Palaeomagnetic data for synfolding magnetization (Shipunov 1991).

Locality	λ	ϕ	A	B	D_s	I_s	D_g	I_g	D_{syn}	I_{syn}	f%
1	57.4	55.0	10	15	51	33	60	44	51	33	0
2	57.5	54.9	148	39	57	29	38	22	49	28	39
3	57.6	54.3	30	16	38	10	39	26	39	26	100
4	57.1	54.2	288	84	63	36	66	−30	63	36	0
5	57.2	54.1	114	37	12	30	356	17	12	30	0
6	58.3	54.7	156	59	74	31	42	22	50	28	69
Mean			148*	12*	49	30	39	19	44	31	
κ			3.3*		15.0		6.0		28.2		
α_{95}			83.7*		14.8		23.4		10.8		

See Table 1 for explanation.

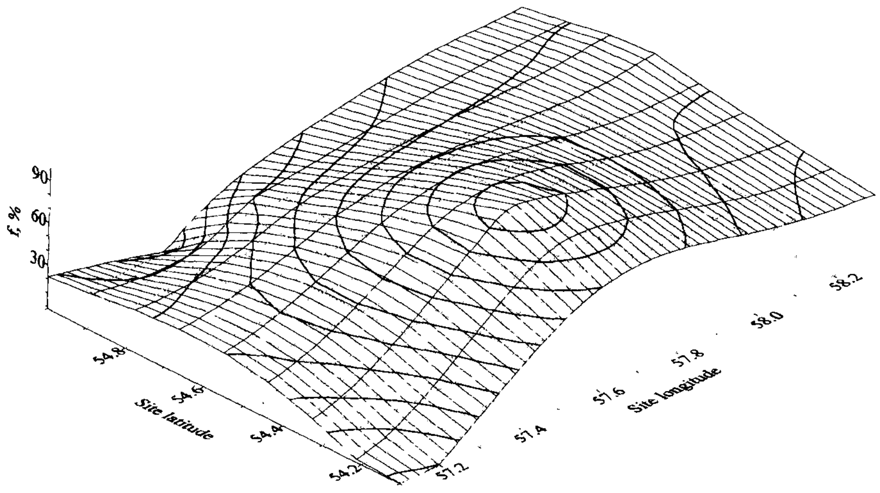

Figure 5. Dependence of folding degree on site location for the palaeomagnetic data of Shipunov (1991).

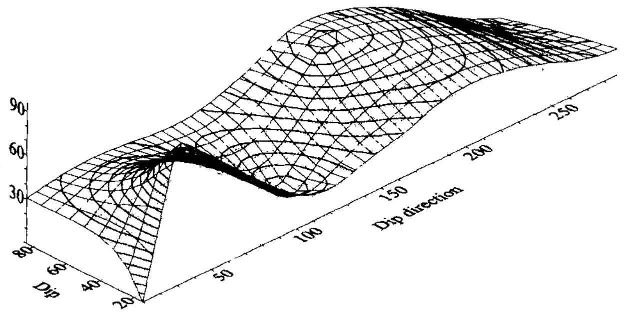

Figure 6. Dependence of folding degree on bedding orientations for the palaeomagnetic data of Shipunov (1991).

The plots of parameter f versus geographic locations (Fig. 5) and bedding attitudes (Fig. 6) are more complicated than for the previous example. The folding commenced at localities 3 and 6 and propagated approximately from the southeast to the northwest. The degree of deformation f in Fig. 6 depends mainly on the structure strikes and not the dips. This finding may be accounted for by a complicated deformation pattern: the structures with strikes of about 120° were created first, then those with strikes of about 60° and finally those with strikes of 20° and 100°.

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REFERENCES

Barnard, G.A., 1963. In discussion following a paper by Bartlett, *J. R. stat. Soc.*, B, **25,** 294.

Bazhenov, M.L. & Shipunov, S.V., 1988. Fold method in paleomagnetism, Izvestiya, Academy of Sciences USSR, *Phys. Solid Earth* (English edn), **24,** 576–585.

Bazhenov, M.L. & Shipunov, S.V., 1991. Fold test in paleomagnetism: new approaches and reappraisal of data, *Earth planet. Sci. Lett.*, **104,** 16–24.

Fisher, N.I., Lewis, T. & Embleton, B.J.J., 1987. *Statistical Analysis of Spherical Data,* Cambridge University Press, London.

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

Kendall, M.G. & Stuart, A., 1968. *The Advanced Theory of Statistics, Inference and Relationship,* Vol. 2, Griffin, London.

Kirschvink, J.L., 1985. A method for finding a paleomagnetic pole position from sediments remagnetized during folding, *JAGA/JAMAP Abstracts,* Prague, 177.

Marriott, F.H.C., 1979. Barnard's Monte Carlo tests: How many simulations?, *Appl. Stat.*, **28,** 75–77.

McFadden, P.L., 1990. A new fold test for palaeomagnetic 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 magnetizations in the Upper Devonian Catskill Formation of Eastern Pennsylvania: implications for the tectonic history of Acadia, *J. geophys. Res.*, **91,** 12 791–12 803.

Shipunov, S.V., 1991. Paleomagnetism of Katav Suite of Southern Ural, Izvestiya, Academy of Sciences USSR, *Phys. Solid Earth* (English edn), **27,** 241–249.

Shipunov, S.V., 1993. *Principles of Paleomagnetic Analysis. Theory and Practice,* Nauka, Moscow (in Russian).

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

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

Wilkinson, J.H. & Reinsch, C., 1971. *Handbook for Automatic Computation, Linear Algebra,* Springer-Verlag, New York, NY.

APPENDIX A: ESTIMATION OF THE SYNFOLDING MAGNETIZATION DIRECTION

A small circle calculated from the directions of the palaeomagnetic vectors in geographic and stratigraphic coordinates is identified by the coefficients in the following equation:

$$a_i x + b_i y + d_i = 0, \tag{A1}$$

where a_i and b_i are components of the normal of the ith small circle in Cartesian coordinates and d_i is the distance between the small circle and the origin. The third coordinate z is equal to zero because the normal of the small circle is always horizontal (using a horizontal-axis rotation).

The distance s from some point on the unit sphere (x, y, z) to the small circle is

$$s = a_i x + b_i y + d_i \tag{A2}$$

A solution (an optimal point of the intersection of small circles) is then determined, minimizing the sum of the squares of the distances:

$$S = \sum (a_i x + b_i y + d_i)^2 \rightarrow \min \tag{A3}$$

The minimization of this expression may be realized by the method of least squares (Wilkinson & Reinsch 1971). In this way, two coordinates (x and y) are determined. The third coordinate is calculated using the condition

$$x^2 + y^2 + z^2 = 1 \tag{A4}$$

Finally, an estimate of the direction in spherical polar coordinates is made.

APPENDIX B: CORRELATION BETWEEN TWO VECTOR DISTRIBUTIONS (MODIFIED FROM BAZHENOV & SHIPUNOV 1991)

Let J_i and N_i, $i = 1, \ldots, n$, be the observed directions of two distributions (the distribution of palaeomagnetic vectors and the distribution of normals to a bedding surface, respectively), where n is the number of samples.

(1) The spherical mean direction and concentration parameter for the distribution of palaeomagnetic vectors are calculated.

(2) The principal components (eigenvectors) for both distributions of vectors (vectors of magnetization and normals to a bedding surface) are determined.

(3) The projections of the palaeomagnetic vectors on the eigenvectors are calculated.

(4) The projections of the normals to a bedding surface on the eigenvectors are calculated.

(5) A matrix of Spearman's rank correlation coefficients is formed (Kendall & Stuart 1968):

$$\mathbf{R} = \begin{bmatrix} r_{11} & r_{12} & r_{13} \\ r_{21} & r_{22} & r_{23} \\ r_{31} & r_{32} & r_{33} \end{bmatrix}, \tag{B1}$$

where r_{kl} is Spearman's rank correlation coefficient between the projection of the palaeomagnetic vectors on the kth principal vector of the magnetization distribution and the projection of normals to a bedding surface on the lth principal vector of the bedding normal distribution.

(6) The test statistic (ρ) is the maximum element of the matrix $\mathbf{R}$ $\{\rho = \max[\mathrm{abs}(r_{kl})]\}$.

(7) M times (say $M = 1000$) Fisherian distribution (Fisher 1953) is simulated with the same concentration parameter and mean direction as those for a given site (see e.g. Fisher *et al.* 1987). For such a distribution, the test statistic ρ_j, $j = 1, \ldots, M$ (see points 2–6) is calculated. Note that instead of the Fisherian distribution simulation the random replacement from the original data set may be used (Tauxe & Watson 1994).

(8) The listing of ρ_j is sorted and compared with the test statistic ρ. If the calculated value of ρ is greater than the $0.95M$th value in the sorting list then the correlation of the two vector distributions is significant. The probability of that conclusion is 95 per cent.