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Fold Method in Paleomagnetism

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It is shown that using any modification of the paleomagnetic fold test it is possible to demonstrate the single-component nature of magnetization only with the simultaneous satisfaction of several initial geological and geophysical premises. It is demonstrated that the equalization method, based on a comparison of groupings of paleomagnetic vectors in different coordinate systems cannot be used in proving the single-component nature of magnetization and in validating the results. Two correct procedures for satisfying the fold test are proposed. These are applicable for any schemes for the testing of folded strata and are much more sensitive to deviations from a single-component character than is the equalization method. It is shown that in the case of a multicomponent character of I_n the discrimination of one of the components cannot be achieved by averaging. Different methods for stipulating the remagnetization circles based exclusively on experimental data are analyzed.

INTRODUCTION

The reliability of geological interpretation of paleomagnetic data is determined to a great extent by three characteristics: accuracy in separation of components of natural remanent magnetization I_n, dating and maximal accuracy in determining the direction of each of them (here and in the text which follows the chronological components of magnetization [1] are examined). So-called field methods play a major role in the solution of these problems. There are relatively few, they have long been known, and nevertheless they by no means are always used correctly. There are also debatable problems here. Progress in the development of instrumentation led field methods into scientific obscurity. Only recently, with the appearance of studies in which the secondary character of single-component magnetization was demonstrated, did their reputation begin to be gradually restored. One of the most widely used of these is the fold method [2], an analysis of which is the subject of this article.

We will define the terminology. We will call a "test" the procedure for checking a hypothesis, at the basis of which lie several assumptions of a geological and geophysical nature, including on the "behavior" of paleomagnetic directions. The checking is carried out either quantitatively, using statistics, or qualitatively. In this case some properties of magnetization are ascertained, but its direction is not determined. For brevity we will speak of a positive or negative test, depending on whether or not the hypothesis to be checked is demonstrated. The method is a procedure for discriminating some directions I_n for which the test is positive in those cases when the test for complete magnetization is negative. The basis of the method is the same assumptions as for the test, plus some additional conditions. In the method statistics plays an auxiliary role, for the most part for evaluations of errors and some geometric constructions and computations related to them predominate.

FOLD TEST

In the fold test the checked hypothesis includes the following assumptions: a) the initial position of layers crumpled into folds is known, b) during deformations the layers were rotated as solid bodies about a horizontal axis of rotation, c) the magnetization of rocks is single-component and was entirely formed either before or after deformation, d) this magnetization is uniform in direction. In a case of satisfaction of all the assumptions the paleomagnetic directions in one of the coordinate systems will be parallel for any beddings of the layers: in the ancient system the magnetization was prefolded, whereas in the modern coordinate system was post-folded, that is, the test is positive. However, if the test is negative, this does not necessarily mean that the magnetization is the sum of components different in direction and age, but instead indicates violation of one or more initial assumptions. It is still necessary to find which ones and to what extent. In a modern coordinate system a negative test may be a result, for example, of relative movements between sections after folding or the appearance of some additional I_n component in some of them (assumption d is violated).

In the ancient system there are still more variants of explanation of a negative test result than in the modern system. The initial slopes of the bedded strata, rarely taken into account when processing the results, may attain 10° for many continental formations and even 15 to 20° for lavas and tufis. The influence of the initial slopes can be clarified by studying a fold measuring tens and a few hundreds of meters; at such distances the slopes were probably one and the same.

The deformations themselves could be more complex than assumed. With the formation of folds, accompanied by the development of cleavage and schistosity, there can be a reorientation of the grains of magnetic minerals and, as a result, of paleomagnetic vectors. The very rotations of the layers may be more complex than simple rotation about the horizontal axis and the paleomagnetic directions will be nonparallel even with satisfaction of the remaining assumptions. Cases of quite reliable detection of complex rotations are known in the literature [3 - 5], but something else is far more interesting: in an enormous number of studies, even for relatively strongly dislocated strata, the fold test is positive. In other words, a simple deformation model is correct at least within the limits of errors in data.

The third assumption concerns the single-component nature of magnetization and is the proposition to be checked, the very reason for which the test is made. Precisely its violation most frequently leads to negative results.

The last assumption is that the paleomagnetic vectors are parallel. First, it will be satisfied only when by means of averaging there is a marked decrease in the influence of intra- and interstratum scatter, for example, of secular variations. Otherwise the test may be negative even with the satisfaction of the remaining assumptions. Second, due to an understatement of inclinations in sediments the paleomagnetic vectors even before deformations may be nonparallel. The more lithologically uniform the collection, the less probable is the influence of this effect. Third, pre- and post-folding I_n does not guarantee that magnetization developed simultaneously everywhere in a field of one direction; both before and after deformations an adequate time could pass for the formation of I_n components different in direction. The closer the collection rocks are in age and composition and the lesser the distances between the sampling points, the less probable is the appearance of such differences.

A positive test means only that there is no basis for assuming that the magnetization of this collection is multicomponent. In other words, a component of a different age may also be present in it, but using the employed checking procedure at the selected significance level in this collection it cannot be detected with statistical reliability. By changing something (adopting a more sensitive procedure, increasing the collection, etc.), in these same rocks it will be possible to demonstrate a multicomponent character of I_n or, again, with greater accuracy, obtain a positive result. Thus, a positive test gives the researcher a formal basis for considering the magnetization to be single-component, but is no guarantee against errors associated with superposed magnetization. It is natural that their value will be less the greater the reliability of the test results (see below). The fold test also gives a dating of magnetization relative to a geological event--deformations, but the value of this information is highly dependent on the situation. For slumping folds arising prior to lithification of sediments, prefolding is virtually a synonym for the primacy of I_n, but for deformations associated with modern landslides it is almost noninformative. In general, the accuracy of dating is the greater the less the time which has elapsed between deformations and rock formation: for a test in the ancient coordinate system. The studied rocks could experience several phases of movements. A reliable positive test result in the ancient coordinate system means that magnetization developed before the most ancient epoch of fold formation itself.

The testing procedure can be performed in different ways. The most widely used variant is the "equalization (that is, test) method" and essentially involves a comparison of groupings of paleomagnetic directions in modern (K_m) and ancient (K_a) coordinate systems [6]. If the K_a/K_m ratio is much greater than unity, the magnetization is prefolded; if it is much less than unity, the magnetization is postfolded; if it is close to unity, no definite conclusion can be drawn: either the bedding variations are small in comparison with the scatter of paleomagnetic vectors or the contributions of the pre- and the postfolded components to total magnetization are commensurate. A checking of the significance of the difference of this ratio from unity is carried out using the statistical F-test using special tables (such as in [7]). Despite its simplicity and widespread use, the equalization test is incorrect for many reasons at the same time. It was demonstrated in [8] that such a procedure is incorrect mathematically. But it is not even its formal mathematical rigor which is pertinent. The following zero hypothesis is the basis of the test: in both coordinate systems the groupings of vectors are equal. It is checked and let us assume is refuted. Nothing follows from this other than that the zero hypothesis is not satisfied. Such a relation in actuality should be satisfied for single-component I_n; this is necessary but inadequate. It does not thereby follow in any way that in a real collection magnetization in actuality is single component and the most that can be said is that one of the components predominates. To what extent, it is impossible to say. It is clear from general considerations that the value of the ratios of groupings is dependent not only on the relation of

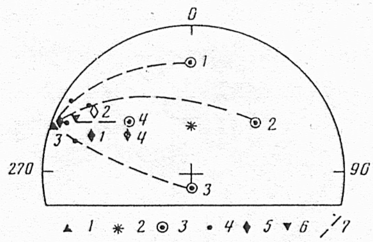

Fig. 1

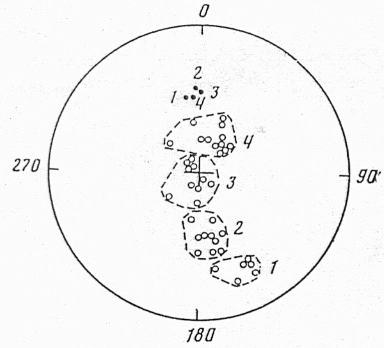

Fig. 2

Fig. 1. Influence of asymmetric superposed magnetization on determined paleomagnetic direction (model example): *1, 2*) "true" directions of prefolded (*1*) and postfolded (*2*) components; *3*) remagnetization direction for four "sections" (the dips are identical and the dip azimuths coincide with directions of the compass); *4, 5*) mean directions of magnetization of individual "sections;" *6*) total mean for four "sections;" *7*) remagnetization circles. *1, 3, 4, 6, 7*) Ancient coordinate system; *2, 5*) modern coordinate system. Here and hereafter the filled symbols represent projections onto the lower hemisphere and the open symbols represent projection onto the upper hemisphere.

Fig. 2. Paleomagnetic data for Upper Cretaceous gray limestones in Northern Armenia. Open circles represent normals to the strata; dashed lines represent the boundaries of groups (one of the breakdown variants); filled circles represent mean paleomagnetic directions for groups.

components but also on the difference in the bedding elements between sampling points; this is in no way taken into account in the formulas. In the test an attempt was made to take into account the grouping of the distribution of normals to the tested strata, but the formulas used for this were derived empirically and their correctness was not demonstrated. To be sure, if the ratio of groupings is about a hundred, in the collection there is actually only one I_n component. But indeed, in actuality the differences are far more modest, by a factor of 3 - 5, less frequently more. Such values, as will be demonstrated below, are statistically significant but are physically unreliable.

There is still another important reason for considering the equalization test to be incorrect. It follows from the very character of the statistical *F*-test that with an increase in the collection the values of the K_a/K_m ratio increasingly closer to unity must be considered statistically significant, that is, with increasingly more commensurate contributions of components to total magnetization there will be a formal basis for speaking of a single-component character of I_n. There is a paradox: with an increase in the sample the test sensitivity decreases. The reason for this is clear; it is all in a substitution of concepts, an incorrect interpretation of the zero hypothesis, which has already been mentioned.

Embodied in the equalization test there is still another tacitly understood hypothesis: with predominance of one of the components the other may be almost completely averaged. There is a grain of truth here: if the post-folded superposed magnetization "draws out" the paleomagnetic vectors symmetrically in different directions from the prefolded direction, averaging is actually justified. It is all a matter of symmetry. Unfortunately, *a priori* there is no possibility of being sure of this even when making a choice within the limits of a dome with identical dips on the flanks; even in this case superposed magnetization in a general case is asymmetric (Fig. 1) if the directions of the components differ greatly. It is always possible to average, but in a general case the result will be equal to the vector sum of the prefolded and mean value of the post-folded components.

In a correct procedure for performance of the fold test the mean vectors for the sections (two or more) with monoclinal beddings in each are compared [8]. The checking is carried out in one of the coordinate systems using the *F*-test for the entire set of means for the sections. A positive test means that this set at some significance level, usually 5%, is indistinguishable from a sample of purely single-component I_n. This is the most which can be asserted on the basis of available data; the final result is found as the total mean for the entire set. In general the sensitivity of this test increases proportionally to the differences in the beddings and the accuracy in computing each mean, that is, it increases with an increase in the volume of the collection.

Asymmetry is expressed here only due to the influence of an undetected small component of a different age and also decreases with an increase in the sample. In performing the test it is first necessary to demonstrate that all the groupings are statistically uniform when using the χ^2-test; and then, using the *F*-test, make an analysis of the paleomagnetic directions (see Appendix).

The test has its limitations. First, the requirement of an approximate equality of the groupings will probably be satisfied when sampling the same rocks. If the groupings are sharply different, the test can be performed qualitatively: it is considered positive if all the confidence circles around the means for the sections overlap and negative in the opposite case. Such an approach is more or less justified with a small number of means (3 - 5) since with a great number of them it is already entirely probable that some two circles will not overlap simply due to sample fluctuations. For the time being more rigorous approaches [9] are not used in practical work. The second limitation, the monoclinality of beddings in each section, is more important because it is not always possible to find suitable objects. If the beddings are variable or the shows are too few for selecting large collections, it is necessary to take a small number of samples at a large number of points (the word "point" is approximately equivalent to "site" in the English-language literature). With such sampling the mean vectors may differ simply due to inadequate averaging of the scatter (see above). However, very frequently it is impossible to say which assumption serving as a basis for the fold test is violated and is responsible for a negative result.

However, nothing hinders laboratory simulation of a monocline. The blurred distribution of normals to the strata for the entire collection is broken down into groups sufficiently large for acceptable averaging of the scatter of paleomagnetic vectors in each and sufficiently small in order that the beddings be considered identical. In this case it is possible to neglect the real positioning of the sampling sites. As is customary in grouping, the groups must be convex and nonoverlapping. The procedure itself and the interpretation of the results are identical to the test of the means for the sections described above; here the means for groups are used instead of them. This is illustrated in a collection of Upper Cretaceous limestones from northwestern Armenia (Fig. 2). In the breakdown into groups there is definite arbitrariness and some loss of information, but this is no greater than in the choice of monoclinal layers from all available shows.

In general, it is possible to avoid grouping entirely. The formulation of the test is slightly variable: with satisfaction of all the initial assumptions there should be no dependence between the beddings of the layers and the paleomagnetic directions. The correlation coefficients between the Cartesian coordinates of two precentered sets

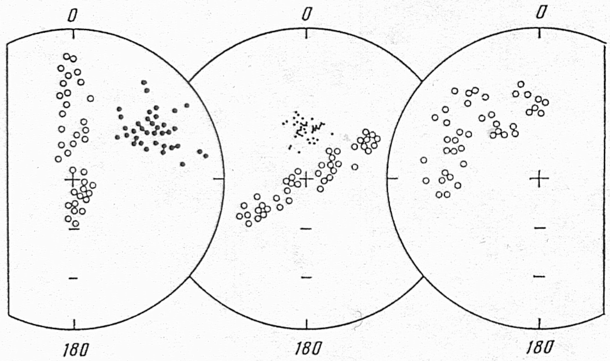

Fig. 3. Model examples of distribution of normals (open circles), directions of prefolded (filled circles) and postfolded (dots) components.

of vectors--I_n and the normals to the strata [10]--are used for checking the presence of such a dependence. Since these sets do not have a normal distribution and the detected dependencies are nonlinear, rank correlation is used [11]. We used only two Cartesian coordinates (x and y) since all the information for the unit vectors is contained in any pair of components and for the centered vectors these components vary greatly (see Appendix for the test algorithm).

We compared the sensitivity, that is, the capability for detecting a weak component of a different nature, of three procedures for performing the fold test: 1) from the ratio of groupings, 2) by grouping, and 3) by correlation, using numerical modeling and in real collections. Modeling was carried out using three distributions of normals to the strata, one sample of the distribution from the postfolded component (D = 0, J = 60, K = 1000 and three random samples of the prefolded component from a general set with the parameters D = 60, J = 30, K = 30 (Fig. 3). Each sample was gradually "contaminated" by another component; the I_k values (in fractions of I_a) were randomly varied in the range ±0.05 and then checking was carried out by each of the three tests. The computations were made for three distributions of the normals and each I_a sample (nine variants in all) with different superposed magnetization values. It is shown in the histograms (Fig. 4) with what value of the superposed magnetization the ratios of components in these nine variants was discovered by each test and the change in the values of the criteria for one of the variants is also shown.

The number of combinations of the varied parameters (directions of groupings of components, distributions of normals to the strata) is so great that it is impossible to review them all. We nevertheless feel that some conclusions can already be drawn. The sensitivities of tests 2 and 3 are entirely commensurate, although for the

Table 1

Coordinate system		Conclusion
Ancient	Modern	
−	−	I_n is multicomponent and/or other initial test premises are violated
+	−	Prefolded
−	+	Postfolded
−	+	Nothing can be said with the given volume of the collection and bedding variations

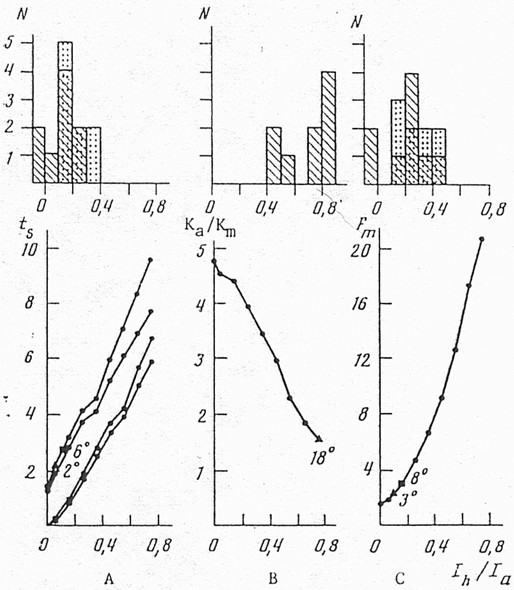

Fig. 4. Histograms characterizing threshold of detection of superposed magnetization for different variants of fold test and examples of change in values of computed criteria (all dependent on ratio of postfolded and prefolded components). On histograms: hatching and dots--for significance levels 5 and 1% respectively. The figures on the curves denote the difference in degrees between the mean vectors of the initial and superposed magnetization distributions for I_h/I_a values for which a two-component character is detected (triangle and square--for significance levels 5 and 1% respectively; A, B, C--tests 3, 1, 2, respectively.

latter it is seemingly somewhat greater. They are both much better than test 1. The sensitivity of tests 2 and 3 is so high that in two variants they gave a negative result directly for the initial distributions of prefolded magnetization at the 5% significance level. This is no evidence of test unreliability: with a probability 37% in nine tests in at least one case the test will be negative simply due to sample fluctuations in the distribution of the prefolded component. With "coarsening" of the tests, an increase in the significance level, all the initial distributions were "approved" by the tests. We feel that such a high sensitivity of tests 2 and 3 is an important advantage: it is sometimes better to question the correctness of a result than to remain unsure when using a low-sensitivity test. In model examples weak superposed magnetization I_h/I_a = 10 - 20% was not always discovered but in this case the differences between the true and measured vectors averaged 5 - 6°, in only one variant attaining 9°. As a comparison: test 1 gave a positive result with differences up to 12 - 30°. And still another comment: in one variant the grouping was increased from 30 to 140. For a K_a/K_m ratio equal to 7.2 and 3.6 the differences between the true and computed directions attained 11° and 17°, respectively. This example is indicative of the impossibility of setting any limit on the value of the ratio of groupings above which the equalization test would always be correct. The numerical values themselves may vary somewhat for other sets of initial data, but we are sure that the picture is qualitatively conserved: tests 2 and 3 will always be much more sensitive than test 1. We add that both tests proposed in this study are also applicable with a considerable scatter of paleomagnetic directions.

A comparison was also made of different modifications of the fold test for real collections. In the Upper Cretaceous gray limestones of the Sevan-Akerinsk zone of the Lesser Caucasus, in addition to the prefolded component with direct polarity, a second component antiparallel to it was discriminated by the difference vectors method [12]. The K_a/K_m = 2.0 value for it is a little less than the critical value at the 5% level and a little more at the level 10%, that is, the result is ambiguous, "with a reserve," and indicate a single-component nature of this magnetization in the modern coordinate system. For four Turnonian-Campanian sections of directly magnetized deposits of the Western Kopetdag [13], after heating to 220°, the ratio $K_a/K_m = 2.68$, which is unquestionably significant. However, the means test here is negative: its computed value $F_m = 26.5$ is much greater than the critical value 2.25. Still another restatement of what was said earlier: even a statistically significant ratio of groupings proves nothing.

Thus, in both models and in real collections a conclusion drawn on the basis of theoretical considerations is confirmed: the equalization test is unsuitable for a rigorous analysis of paleomagnetic data. In order to solve this problem it is necessary, separately or jointly, to use the three correct tests described above. For any of them the following combination of checking results is possible (Table 1) in ancient and modern coordinate systems. The first row--the investigated magnetization is not single-component and/or the other initial assumptions of the fold test are violated. The second and third--pre- and postfolded I_n, respectively, is indicated. Above it was assumed everywhere that the differences in beddings are sufficiently great for drawing definite conclusions. This, to be sure, is not always the case, and the fourth row is an adequacy test: if the test is positive in both coordinate systems, the differences in beddings for the particular collection are inadequate for an unambiguous answer. There must be an additional selection either from a large number of samples or from layers differing more greatly in their beddings. The fold test thus must be carried out for both coordinate systems.

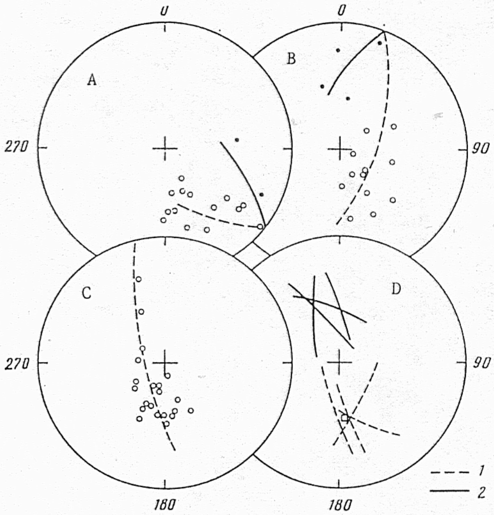

Fig. 5. Paleomagnetic data for Eocene rocks of Adzharia. A, B, C--Results for three sections (the fourth section is not shown); D--intersection of remagnetization circles: *1*) based on band distributions, *2*) using modern field as remagnetization directions (inverted for greater clarity); the square represents the direction of the prefolded component determined from band distributions.

FOLD METHOD

The fold method is a procedure for discriminating from the total magnetization, for which the fold test is negative, that component for which the test will be positive. In all its modifications (see below) the method is based on the hypothesis that only one of the four initial test assumptions is incorrect: that concerning the single-component nature of I_n. The necessity for some additional assumptions is also common for all the modifications. It must be taken into account that the latter may not be satisfied and, as a result, the paleomagnetic result itself may be incorrect. The control method, it seems, is the same: the convergence of data obtained in different ways, not mandatorily only by modifications of the fold method, based on additional assumptions differing as greatly as possible.

It would seem that the averaging of everything would be a way to avoid such assumptions. In actuality, such an approach requires a very strong hypothesis on the symmetry of the influence of all the I_n components on the sought-for magnetization. It was already demonstrated above that in a general case such symmetry is absent. The "overlapping of distributions method" was proposed earlier in [14]. In that method a search was made for the region of mutual overlapping of several distributions of individual paleomagnetic vectors for sections with different rock beddings; the total mean of all individual vectors in the overlap region was used as the direction of prefolded magnetization. A subsequent analysis indicated that for the reliability of the results obtained by such a method it is also necessary to have a very high symmetry of superposed magnetization, which sharply limits the practical possibility of using such an approach.

The most commonly used modification of the fold method is the intersection of remagnetization circles (IRCM) method [15]. At its basis is the fact that two vector-terms and their sum always lie on a single plane which intersects a unit sphere along the arc of a great circle passing through a stereographic projection of these vectors. A mandatory additional assumption: the prefolded component has a lesser scatter in the ancient coordinate system, whereas the postfolded component has a lesser scatter in the modern coordinate system. In this case the point of intersection of individual circles gives the direction of the corresponding component. In all cases it is also necessary that the sought-for I_n direction be uniform in direction. With respect to the second component, as will be demonstrated below, requirements on its uniformity in direction will be different. For using the IRCM it is necessary to have a set of differently oriented remagnetization planes (circles) or, which is the mathematical equivalent, a set of normals to these planes. For the set of normals the least squares method is used in seeking an approximating plane, the normal to which also gives an optimal evaluation of the point of intersection of the individual planes [16] and the value of the errors [9] (see Appendix).

The remagnetization planes can be stipulated differently. The distributions of paleomagnetic vectors for individual sections may be planar. In this case by the same method [16] an approximating plane for each distribution is found first and then the point of intersection of these planes. Such a method was used in finding the direction of prefolded magnetization: $D = 175°$, $J = -49°$ for four sections (Fig. 5) of volcanogenic-sedimentary rocks of Adzharia (materials supplied by M. L. Bazhenov and V. S. Burtman). In other cases in the course of magnetic cleanings the paleomagnetic directions of individual samples may be displaced along the arc of a great circle. The Halls method is again used twice: first the remagnetization plane of each sample is sought and then the point of intersection of the totality of these planes. Such an approach is justified if the total displacement is much greater than the laboratory errors. The properties of the rocks themselves determine the applicability of one of these variants. If the spectra of the blocking temperatures or the coercive spectra of the components are sharply different, in the course of cleaning the magnetization vector will be displaced along the arc of a great circle and the second approach or both approaches at the same time will be applicable. On the other hand, the ratios of the values of the components may differ sharply from sample to sample despite similar spectra--banded distributions arise. In particular, in the rocks of Adzharia the remagnetization circles are determined reliably for a very small number of samples; most of the spectra are stable during cleanings.

If there are nonantiparallel directions of different polarity in each of the sections with different rock beddings, the arc of a great circle passing through them is determined unambiguously for the corresponding pairs of mean *R*- and *N*-vectors. The intersection of these arcs in ancient and modern coordinate systems corresponds to pre- and postfolded magnetization. The principal limitation here is the need for having both polarities, at least for some of the sections.

A merit of all three variants of the remagnetization circles method is that other than the hypothesis of a two-component character of I_n no additional assumptions are made concerning the directions of these components. They are also applicable in those cases when one of them is different for different sections. For example, postfolded magnetization in the Upper Cretaceous rocks of the Kopetdag, found using *RN* circles, is identical for the entire region, although the directions of the prefolded component differ in declination by approximately 50° [13].

In the most satisfactory IRCM variant [15] the direction of the postfolded component is assumed to be known and the remagnetization circle is drawn through its direction in the ancient coordinate system and the measured mean vector of the collection. It is clear that such constructions can always be made when there are sections with different beddings. The weak point of the method is also clear: the direction of postfolded magnetization is "known;" the error in its choice almost always leads to an incorrect result. The direction of the modern field in the work region is most frequently used as the direction of the postfolded component, in many cases without validation. We will return to the results for the Eocene of Adzharia. We computed the mean directions for each section (a few samples with positive inclinations were omitted) and remagnetization circles were constructed by this method. It can be seen (Fig. 5D) that one of the circles deviates so much from the others that it could possibly be regarded as an "anomaly"--for example, as a result of tectonic rotation of the section. However, the direction of the post-folded component determined from the band distributions and the direction of the modern field are quite similar: $D = 25°$, $J = 55°$ and $D = 0°$, $J = 60°$, respectively.

This inadequacy of the method is so evident that an effort was made to overcome it. For example, the curve of wandering of the pole of one of the large plates was scaled into a series of magnetization directions for the work region, each of them was tested as the direction of the postfolded component and that which led to the most compact region of intersection of the remagnetization planes was adopted as the true value. The procedure was ended under one invariable condition: there should be no relative movements between the plate and the work region, at least from the time of rock bending into folds. In actuality, if the investigated block moved after acquisition of postfolded magnetization, such an approach would scarcely give a true result. In the successive approximations method [1] an arbitrary direction of the secondary component is used for constructing remagnetization circles; the point of their intersection, however poorly it may be determined, is then used in the modern coordinate system for constructing a new series of circles whose intersection gives the refined direction of the secondary component; then the cycle is repeated. However, the convergence of this procedure to the true directions of the components was not demonstrated. Our checking of this in a numerical example demonstrated that there is convergence, but not to the initial directions of the components. Thus, for reliable use of the "classical" method there must be experimental validation of the direction of the secondary component, such as by the difference vectors method or employing another variant of the IRCM, at least for part of the collection.

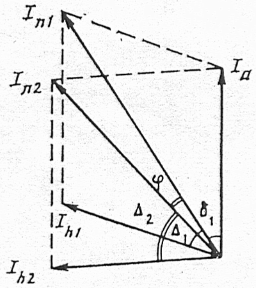

Fig. 6. Determination of direction of prefolded component for parallel remagnetization planes.

The reliability of the results obtained using any IRCM modification is dependent on the angle at which the circles intersect. The smaller it is, the lesser is the accuracy with which the point of intersection is determined. There is also a solution for rigorously parallel circles. It must be assumed additionally that the relation of the values of the pre- and postfolded components in rock, its paleomagnetic stability, is identical in all sections. Then the direction of the prefolded component, with a known postfolded component, can be found using the formula (Fig. 6)

$$\operatorname{tg} \delta_2 = \sin \varphi / (\sin \Delta_1 / \sin \Delta_2 - \cos \varphi).$$

It is clear that the additional assumption will be plausible only when studying the very same rocks; in addition, here for the time being there is no method for evaluating the accuracy of the result.

Three variants of results obtained by the remagnetization planes method are possible. First: all the circles intersect in a small part of the sphere (the normals to the remagnetization planes lie close to the approximating plane). This means that all the assumptions made, in both the test and in the method, are true and the result itself most probably has geological or geophysical importance. Second: all the intersections are scattered. Here something is probably incorrect in the assumptions of the test and/or method; the magnetization is not two-component, the direction of the secondary component was selected incorrectly or the nature of the deformations is complex; accordingly, the formally determined result may also not have real significance. Third: most of the circles intersect within the limits of a compact region, and there are few "anomalies." Here it is most probable that something is incorrect for individual sections, but everything is in order with the initial premises. The reason for the anomalies may be tectonic movements of the corresponding crustal sectors. By rotation of the anomalous circle about its vertical axis it can be made to pass through a "general pile;" its angle of rotation will be equal to the angle of rotation of the crustal sector itself about its vertical axis [1]. This method for quantitative evaluation of tectonic movements with incomplete separation of the magnetization components is used quite extensively. In our opinion, however, its use requires caution. The example of Adzhiria (Fig. 5D) shows that the anomaly may be spurious due to the incorrect choice of the direction of the postfolded component, especially when using a small number of sections. Such an approach is correct only with rotations about the vertical axis, but in practice it is not always possible to speak of the type of movements. Finally, even if the anomalous circle is in actuality a result of rotations, the reverse, generally speaking, is incorrect: for an inverted section the circle may well pass through a "general pile." Such a random coincidence is improbable for a large number of sections, but is not precluded for one.

The last question: precisely how does the intersection of the circles determine the direction of the less scattered magnetization component? It was recently demonstrated by numerical modeling [17] that a systematic error may arise in this case. Its value is maximal with a ratio of groupings of components close to unity and is negligible with ratios of about 10. When using data on sections with distinctly different beddings the ratio of groupings of components will in all probability be sufficiently great that the systematic error can be neglected. In general, however, this matter has not been fully clarified, especially since in the cited study nothing is mentioned on the mechanism of appearance of such errors.

SUMMARY

1. The principles of the fold test were examined and it was shown that for a positive result of the checks it is necessary that there be simultaneous satisfaction of several geological and geophysical premises.

2. It was shown that the equalization test can be used only for qualitative, preliminary evaluations of the component composition of magnetization, not for demonstration of its single-component character.

3. Two new variants for performance of the fold test were proposed which are suitable for collections from layers with beddings varying from point to point and more sensitive to deviations from a single-component character than the equalization test.

4. Different modifications of the fold method were examined and the conditions for their applicability were analyzed.

Finally, a general methodological, seemingly evident conclusion. The fold test is based on a lesser number of premises than any modification of the method. Accordingly, a result confirmed by a correctly made test will be more reliable

than that obtained using additional constructions. It is therefore first necessary, using magnetic cleanings, to attempt to separate the I_n components. Only if this cannot be done is it necessary to use the fold method, preferably in different modifications.

APPENDIX

Equality of groupings of two sets of vectors. The hypothesis to be checked is $K_a = K_m$. The K_a/K_m value is used as a test. If the ratio of the groupings is greater than $F[2(N-1), 2(N-1), p]$, the checked hypothesis deviates at the significance level p [7, 9]. Here and below $F[\mu_1, \mu_2, p]$ are the critical values of the Fisher distribution with the degrees of freedom μ_1 and μ_2; N is the total number of the samples.

Homogeneity of m sets ($m > 2$). The hypothesis to be checked is that groupings of m samples are equal. The computed statistics (for a grouping of a combined sample >3) [9] is:

$$U = \frac{\nu \ln \frac{N-\Sigma R_i}{\nu} - \Sigma\left(\nu_i \ln \frac{n_i - R_i}{\nu_i}\right)}{1+d},$$

where $\nu_i = 2(n_i - 1)$, $\nu = 2(N-m)$, $d = (\Sigma\nu_i^{-1} - \nu^{-1})/[3(m-1)]$. If the test value is greater than $\chi^2[2(m-1), p]$, the checked hypothesis deviates at the significance level p. $\chi^2[\mu, p]$ are the critical values of the χ^2 distribution with the degree of freedom μ.

Equality of mean directions of two distributions of vectors. The hypothesis to be checked is that the means are equal. The used statistics are:

$$F_2 = \frac{[R_1 + R_2 - R^2/(R_1+R_2)]}{2(N - R_1 - R_2)},$$

where R_1, R_2 are the lengths of the total vectors of the first and second sets, respectively; R and N are the length of the total vector and the number of individual samples in the combined sample. If the test value is greater than

$$\left(\frac{1}{p}\right)^{1/(N-2)} - 1$$

(p is the significance level), the checked hypothesis is rejected [8].

Equality of several means ($m > 2$). The hypothesis to be checked is that the means are equal. The computed criterial statistics [8] is

$$F_m = \left(\frac{N-m}{m-1}\right)\frac{\Sigma R_i - R^2/\Sigma R_i}{2(N-\Sigma R_i)}$$

where R_i is the length of the total vector of the i-th set. If the test value is greater than $F[2(m-1), 2(N-m), p]$, the checked hypothesis is rejected.

Noncorrelation of two sets of vectors. The hypothesis to be checked is that two sets of vectors (directions of I_n and the normal to the strata) are uncorrelated. First both distributions are centered, that is, the mean direction to the sphere pole is set using the formulas

$$\cos J_{2i} = \sin J_0 \sin J_{1i} + \cos J_0 \cos J_{1i} \cos(D_{1i} - D_0),$$

$$D_{2i} = \arccos\left[\frac{\sin J_{1i} - \sin J_0 \cos J_{2i}}{\cos J_0 \sin J_{2i}}\right] \mathrm{sign}[\sin(D_{1i} - D_0)],$$

where D_{1i}, J_{1i} are the coordinates (declination and inclination) of the initial vectors; D_{2i}, J_{2i} are the coordinates of the centered vectors; D_0, J_0 are the coordinates of the center of the distribution, and sign (x) is the sign on the number x. The centered vectors are transformed to Cartesian coordinates [1]. The used criterial statistics are nine coefficients of the Spearman rank correlation r_S between the Cartesian coordinates of the two sets of vectors.

The rank correlation coefficient r_S for a sample (u_i, v_i) of the volume N is determined as an ordinary correlation coefficient of rank variables [11]. For this purpose the u values are ranked in order of increase, assigning them ranks from 1 to N. A similar operation is also performed with v. The value of the rank correlation coefficient is

$$r_S = 1 - 6(d_1^2 + \ldots + d_N^2)/(N^3 - N),$$

where d_i is the difference between the values of the ranks of the i-th u value and the corresponding v value. If the value of at least one of the nine computed r_S tests is greater than some critical value (see Table in 11] for $N \leqslant 30$), the checked hypothesis is rejected [10]. For $N > 30$ the value

$$t_S = r_S\sqrt{(N-2)/(1-r_S^2)}.$$

can be used as a test.

The hypothesis is rejected if $t_S > t[N-2, p]$, where $t[\mu, p]$ are the critical values of the Student t-distribution with a significance level p with the degree of freedom μ.

Evaluation of accuracy of Halls method. 1. Case of one plane (N vectors). The (1 - p) 100% confidence cone around the normal to the plane determined by the Halls method [16] in elements of polar coordinates (α, β) is given by the equation [9]

$$\lambda_1 \cos^2\alpha + (\lambda_2 \cos^2\beta + \lambda_3 \sin^2\beta)\sin^2\alpha = q,$$

where $q = \lambda_1(N - 2 + 2F_0[2, N-2, p])/(N-2)$, and $\lambda_1 < \lambda_2 < \lambda_3$ are the eigenvalues of the symmetric matrix

$$V = \begin{bmatrix} \sum x_i^2 & \sum x_i y_i & \sum x_i z_i \\ & \sum y_i^2 & \sum y_i z_i \\ & & \sum z_i^2 \end{bmatrix}$$

Here x_i, y_i, z_i are the Cartesian coordinates of the i-th paleomagnetic vector ($i = 1, \ldots, N$).

Taking into account that the mean values for $\cos^2 \beta$ and $\sin^2 \beta$ are equal to 1/2, for the mean value $\bar{\alpha}$ we have

$$\sin \bar{\lambda} = \sqrt{2F_0\lambda_1/[(N-2)(\lambda^{\cdot}-\lambda_1)]},$$

where $\lambda^{\cdot} = (\lambda_2+\lambda_3)/2$.

2. Case of q planes with n_j vectors in each ($j = 1, \ldots, q$). First for each plane we obtain an evaluation $\bar{\alpha}_j$ using formula (1). Then we again solve the problem in eigenvalues for the matrix

$$W = \begin{bmatrix} \sum R_j x_j^2 & \sum R_j x_j y_j & \sum R_j x_j z_j \\ & \sum R_j y_j^2 & \sum R_j y_j z_j \\ & & \sum R_j z_j^2 \end{bmatrix}.$$

Here x_j, y_j, z_j are the Cartesian coordinates of the normal to the j-th plane and $R_j = n_j(1 - n_j\bar{\alpha}_j/19{,}600)$ is a weight equal to the length of the resultant vector of a fictitious "Fisher" sample of the volume n_j and $\alpha_{95} = \bar{\alpha}_j$.

An evaluation of the mean $\bar{\alpha}$ value is computed using formula (1), where $N = \Sigma n_j$, and $F_0 = F[q-2, 2(N-q), p]$.

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