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# A new conglomerate test in palaeomagnetism

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## SUMMARY

The conglomerate test is widely used in palaeomagnetism to date components of natural remanent magnetization with respect to deposition of conglomerates. It has been demonstrated, however, that this test may be positive even if the data are strongly contaminated by a secondary remanence, especially for the commonly used small number of clasts (Starkey & Palmer 1970). Here we show with the aid of numerical simulations that different statistical procedures employed in this test have similar low sensitivities to remagnetization. We suggest a new conglomerate test which incorporates additional information on the direction of a secondary palaeomagnetic component which is isolated from either clasts themselves or their host rocks. Numerical simulations show that this new test is about twice as sensitive to remagnetization as the previous procedures and is robust with respect to small errors in the direction of a secondary component.

**Key words:** conglomerate test, palaeomagnetism, sensitivity of field tests.

## INTRODUCTION

The geological validity of palaeomagnetic data depends upon many factors, the age of palaeomagnetic components being one of the most important. Remanences are usually dated with respect to geological events of known age with the aid of field tests (Graham 1949). It is also very important to obtain unbiased mean directions of remanence components. The replacement of the first statistical fold test (McElhinny 1964) by more accurate tests (McFadden & Jones 1981; McFadden 1990, etc.) led to improvements in the recognition of pre- and post-folding components of magnetization. Intuitively, it is clear that a more accurate field test decreases the likelihood that a palaeomagnetic result may be biased by unrecognized components of different age and direction. This is the reason why new modifications of field tests continue to appear.

One of the most common field tests dates a remanence with respect to the deposition of clasts in conglomerates. This conglomerate test assumes that if a remanence has not been altered since the deposition, magnetization directions from different clasts will be randomly distributed. The accuracy of the dating depends on the time interval between the formation of the host rock and the formation of the clasts in the conglomerate. If an intraformational conglomerate is studied, this test constitutes perhaps the most unequivocal proof that the remanence is primary.

It has been shown, however, that the sensitivity of this test to the presence of secondary components is limited (Starkey & Palmer 1970). Usually, the number of clasts sampled is between 10 and 20, and a uniformly directed secondary component with an intensity of 30–50 per cent of a randomly distributed primary component can pass unrecognized with a high probability. This alarm signal sounded when palaeomagnetic results were based on vector endpoints determined after a certain demagnetization step, and an unrecognized secondary contamination was quite likely. Component analysis (Kirschvink 1980) reduced the probability of erroneous interpretation of the conglomerate test but did not eliminate it altogether. Seemingly linear segments on demagnetization plots may result from the perfect overlap of unblocking-temperature or coercivity spectra. Also, the isolation of a high-temperature or high-coercivity component of presumed primary origin may be based on a few scattered points, thus data 'purity' remains problematic. These situations can adversely affect the results of tests such as the Rayleigh test (Mardia 1972), which was used both by Starkey & Palmer (1970) and by most authors dealing with the conglomerate test in practice. The possibility of erroneous conclusions due to contaminated data remains, and more powerful tools of data analysis are still needed. In this paper, we present a more accurate conglomerate test which overcomes some of these problems.

## COMPARISON OF CURRENTLY AVAILABLE TESTS

The conglomerate test is based on two assumptions: (1) the orientation of clasts in the conglomerate is random; and (2)

**Table 1.** Description of the procedures which can be used as the uniformity test.

| Procedure | Test statistics | Alternative hypothesis (models) |
|---|---|---|
| Rayleigh test (Mardia 1972) | $r=R/n$ | $k>0$, true mean direction is unknown |
| Beran test (Fisher *et al.* 1987) | $A_n=n-(4/n\pi)\sum_{i=1}^{n-1}\sum_{j=i+1}^{n}\psi_{ij}$<br>$\psi_{ij}$—the angle between the $i$th and $j$th directions | not symmetric with respect to the centre of the sphere |
| Gine test (Fisher *et al.* 1987) | $A_n=n-(4/n\pi)\sum_{i=1}^{n-1}\sum_{j=j+1}^{n}\sin\psi_{ij}$ | symmetric with respect to the centre of the sphere |
| Fisher *et al.* test (Fisher *et al.* 1987) | $F_n=A_n+G_n$ | All alternative models |
| New conglomerate test (this paper) | $\rho=1/n\sum_{i=1}^{n}\cos\varphi_i$<br>$\varphi_i$ is the angle between the $i$th unit vector and the given direction | The specified preferred direction is present |

natural remanent magnetization (NRM) of the clasts or one of its components has been directionally stable since the erosion of the host rocks. If these assumptions are fulfilled, remanence directions from different clasts will be randomly distributed on the unit sphere. In contrast, if a secondary remanence was acquired after deposition of the conglomerate, the resulting distribution would not be uniform. Thus, a null hypothesis $H_0$ of the conglomerate (uniformity) test that 'the distribution is uniform' is tested against an alternative hypothesis, $H_1$, the formulation of which depends upon the mathematical method used (Table 1).

Several mathematically different approaches to the uniformity test have been suggested (Table 1) and are briefly reviewed here. [Note that all tests accept $H_0$ if a test statistic is smaller than a critical value at a certain (usually 95 per cent) confidence level; otherwise, $H_0$ is rejected.]

(1) The Rayleigh test ($r$) utilizes the normalized length of the vector resultant (Mardia 1972);

(2) the Beran statistic ($A_n$) uses the sum of all angular distances between vectors of a sample (Fisher *et al.* 1987);

(3) The Gine statistic ($G_n$) employs the sum of sines of all angles between vectors of a sample (Fisher *et al.* 1987);

(4) The statistic $F_n$ is the sum of the two previous statistics (Fisher *et al.* 1987).

The above statistics were compared as follows. A sample of unit vectors randomly drawn from a uniformly distributed population was treated as a primary remanence, $J_1$. Simultaneously, another sample denoting a secondary remanence, $J_2$, was randomly drawn from a Fisherian population with a concentration parameter, $k$, of 50 (Fisher 1953). It has been shown elsewhere (Shipunov 1994) that the outcome of the simulation does not vary for $k$ ranging from 30 to 100. Then, a composite sample was created as the sum of vectors from the above two samples for various ratios of their relative intensities $t=J_2/J_1$ ranging from 0 to 1. This composite sample of 'partly remagnetized palaeomagnetic directions' was analysed using the different tests outlined above. The results of the simulation are based on 5000 trials for each sample size, which varied from 10 to 50.

Numerical simulation showed that all statistical tests have a low sensitivity to the presence of 'remagnetization', as illustrated for samples of 10 unit vectors (Table 2); even for a sample of 30 vectors, which is regarded as a large collection of clasts in palaeomagnetic studies, only a strong overprint ($t>0.5$) can be reliably detected (Fig. 1). All the tests have comparable sensitivities, except for the $G_n$ statistic, which is much worse than the others. The most commonly used Rayleigh test appears to be slightly better than the others, but the difference is negligible. In addition, we used other statistical tests [for example based on eigenvalue analysis (Mardia 1972)] which are not discussed here for the sake of brevity; inclusion of these tests does not change the above conclusion.

## A NEW CONGLOMERATE TEST

Despite quite different alternative hypotheses $H_1$ and mathematical procedures, all the statistical tests described above have a common feature: they are all used to detect the presence of a secondary remanence in conglomerates but do not utilize the frequently available information on the direction of this remanence. In practice, the conglomerate test is almost always performed jointly with the study of the host rocks, and some secondary components are often recognized during the study.

**Table 2** Probabilities (in per cent) of detecting a remagnetization for samples of 10 unit vectors.

| $t=J_2/J_1$ | $r$ | $A_n$ | $G_n$ | $F_n$ | $\rho$ |
|---|---|---|---|---|---|
| 0 | 3.3 | 3.0 | 3.9 | 3.1 | 4.8 |
| 0.1 | 6.2 | 5.6 | 4.1 | 5.2 | 9.8 |
| 0.2 | 7.9 | 6.9 | 5.7 | 6.6 | 17.6 |
| 0.3 | 11.9 | 10.9 | 4.0 | 10.5 | 28.3 |
| 0.4 | 18.1 | 17.3 | 4.4 | 17.3 | 43.7 |
| 0.5 | 27.9 | 26.3 | 4.2 | 24.8 | 58.9 |
| 0.6 | 38.9 | 36.1 | 4.5 | 34.9 | 73.2 |
| 0.7 | 57.9 | 56.2 | 5.2 | 53.4 | 86.9 |
| 0.8 | 75.1 | 71.8 | 8.2 | 69.7 | 95.4 |
| 0.9 | 89.3 | 88.6 | 10.8 | 86.5 | 99.4 |
| 1.0 | 99.0 | 98.8 | 19.3 | 98.1 | 100.0 |

$t$ is the ratio of intensities of secondary systematic $J_2$ and primary random $J_1$ components; $r$ is the Rayleigh statistic (Mardia 1972); $A_n$ is the Beran statistic (Fisher *et al.* 1987); $G_n$ is the Gine statistic (Fisher *et al.* 1987); $F_n$ is the sum of the two previous statistics (Fisher *et al.* 1987) (see text for details); $\rho$ is the new statistic presented here.

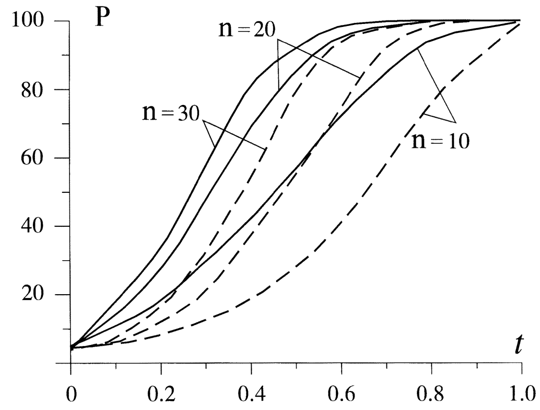

**Figure 1.** Plots of the probability $p$ of rejecting the null hypothesis versus the ratio $t$ of intensities of secondary systematic $J_2$ and primary random $J_1$ components for various sample sizes with the aid of the Rayleigh statistic (dashed lines) and the suggested procedure (solid lines).

Therefore, we tried to find a statistical procedure which incorporates other available geological and palaeomagnetic data, and not just an isolated set of presumably primary NRM components from clasts.

This test proved to be very simple. Projections of uniformly distributed unit vectors (that is their direction cosines) on a given direction are uniformly distributed on the interval $(-1, 1)$ (Mardia 1972). If unit vectors tend to cluster about the given direction, a value $\rho = n^{-1}\Sigma \cos \varphi_i$, where $n$ is the sample size and $\varphi_i$ is the angle between the $i$th unit vector and the given direction, will be large and can be used as a statistic. The statistic $\rho$ has a rather complex distribution under the null hypothesis $H_0$ that the sample is drawn from a uniformly distributed population. The 95 per cent confidence values of this statistic for different sample sizes are calculated after Barnard (1963). For large samples ($n > 12$), $\rho$ can be approximated by a normal distribution with zero mean and dispersion of $1/(3n)$ (Mardia 1972). 95 per cent confidence values of $\rho$ for $n \leq 30$ are presented in Table 3. This test is analogous to the uniformity test with a given mean direction for the circular case (Mardia 1972, pp. 132–133).

For a sample, $H_0$ is tested against an alternative hypothesis $H_1$ that a preferred direction is present: if the calculated $\rho$-value is less than the critical value at a certain confidence level, $H_0$ is accepted; otherwise, $H_0$ is rejected. As the preferred direction, we suggest that the direction of a secondary remanence isolated from either the clasts themselves or their host rocks is used. Numerical simulations show that the sensitivity of the $\rho$ statistic is twice that of any other test for the same sample size and degree of remagnetization. Should the direction of remagnetization not be known precisely, our analysis shows that the sensitivity of the $\rho$-test is reduced by only a few per cent if the estimated direction deviates by less than 20° from the true direction. Even for a deviation of 30°, the sensitivity drops by less than 15 per cent, that is this test still performs much better than the other tests.

**Table 3.** 95 per cent critical values of the $\rho$ statistic for different sample sizes $n$.

| $n$ | $\rho$ | $n$ | $\rho$ | $n$ | $\rho$ |
|---|---|---|---|---|---|
| 5 | 0.430 | 14 | 0.254 | 23 | 0.198 |
| 6 | 0.392 | 15 | 0.245 | 24 | 0.194 |
| 7 | 0.362 | 16 | 0.237 | 25 | 0.190 |
| 8 | 0.338 | 17 | 0.230 | 26 | 0.186 |
| 9 | 0.319 | 18 | 0.224 | 27 | 0.183 |
| 10 | 0.301 | 19 | 0.218 | 28 | 0.179 |
| 11 | 0.287 | 20 | 0.212 | 29 | 0.176 |
| 12 | 0.274 | 21 | 0.207 | 30 | 0.173 |
| 13 | 0.263 | 22 | 0.202 | $\infty$ | $\rho_c = 1.645/\sqrt{(3n)}$ |

## EXAMPLES OF APPLICATION OF THE NEW TEST

One must know both the direction of remagnetization and the unit vectors from each clast to perform the suggested test. While the former can be found in many publications, the latter are never presented. Thus we had to draw on our own data in order to evaluate the new test in real situations. Four examples are presented below.

(a) Middle–Upper Triassic volcanics and lava boulders from intraformational conglomerates were sampled in the North Pamirs (Bazhenov 1996). Strong overlapping of unblocking-temperature spectra of two components, one close to the present-day field and the other representing the pre-folding and presumably primary component of reversed polarity, was found in many samples of the host rock volcanics. In contrast, a characteristic remanent magnetization component (ChRM) appeared to be reliably isolated from 18 lava boulders (Fig. 2a). These directions were widely scattered and the Rayleigh test was positive. Nevertheless, the danger of partial remagnetization by undetected secondary components remained.

The new conglomerate test proved to be positive too, with the present-day field direction being used as a possible remagnetization direction. Thus, the earlier conclusion that the ChRM of the Triassic volcanics is of primary origin is sup-

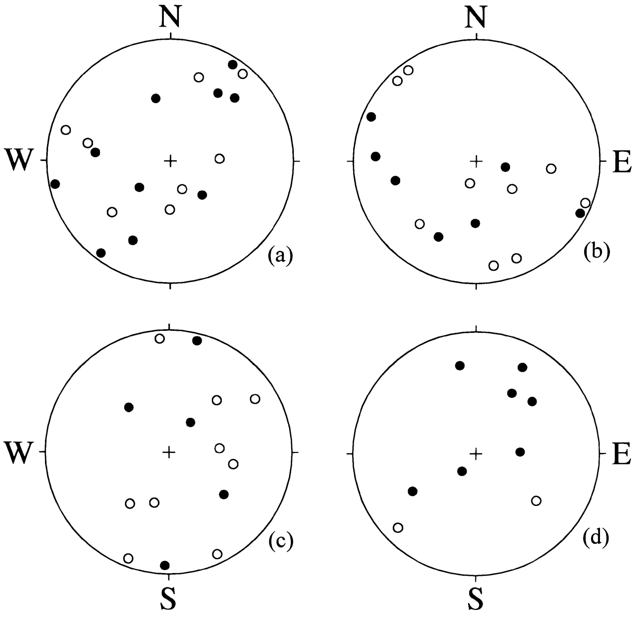

**Figure 2.** Equal-area projections of conglomerate data of four examples labelled as in the text. Solid (open) dots are projected onto the lower (upper) hemisphere. All data are *in situ*, that is not corrected for the general dip of conglomerate beds.

ported and the reliability of the ChRM mean direction is better justified.

(b) Upper Permian tuffaceous red sandstones and boulders of various lithologies from Upper Permian conglomerates overlying the redbeds with an erosional disconformity were sampled in another part of the North Pamirs (Bazhenov 1996). The Rayleigh test for the ChRMs from 16 boulders is positive (Fig. 2b). An intermediate-temperature component isolated from the boulders was used as the remagnetization direction in the new test, which is also positive and confirms the earlier conclusion.

(c) A collection of lower Upper Permian volcanics and lava boulders from overlying Upper Permian conglomerates was sampled in the West Tien Shan Mountains, Central Asia (Bazhenov *et al.* unpublished data). Redbeds intercalating with the conglomerate were also studied. ChRMs were reliably isolated from both the volcanics and the redbeds. Two components, one carried by magnetite and another by haematite, were recognized in the boulders. The haematite component isolated from nine boulders is well clustered, and its direction ($D=173°$, $I=-54°$, $\alpha95=10°$) closely agrees with the ChRM in the redbeds ($D=170°$, $I=-57°$, $\alpha95=5°$). This agreement suggests that the acquisition of the haematite component by the boulders occurred during the reddening and haematitization of these redbeds. In contrast, the magnetite component is scattered (Fig. 2c), and the Rayleigh test for this component is positive. The haematite component was used as the remagnetization direction, and the new test proved to be positive too.

(d) A bipolar ChRM reliably isolated from Lower Jurassic basalts from the Lesser Caucasus (Bazhenov *et al.* 1996) passes both reversal and fold tests. Nine lava boulders were sampled from the Aalenian basal conglomerate directly overlying these Lower Jurassic basalts. Optical observations on thin sections showed that the lava boulders are petrographically very similar to the host volcanics. Despite this similarity, NRM intensities of the lava boulders are two orders of magnitude lower than those of the host rocks, and the isolation of ChRM components was less straightforward. Nevertheless, the Rayleigh uniformity test proved to be positive (Fig. 2d).

No well-defined secondary components were isolated from either the host rock volcanics or the lava boulders. However, Middle Jurassic sediments just above the conglomerate layer were also studied (Bazhenov *et al.* 1996). The ChRM in the sediments does not pass the fold test and is probably of synfolding origin. The mean direction of this remanence was used as the remagnetization direction, and the new conglomerate test proved to be definitely negative, the intensity of the secondary component being comparable to that of the randomly distributed primary component. Nevertheless, we think that the ChRM in the host rock volcanics is primary and is not noticeably contaminated by secondary components as evidenced by the positive fold and reversal tests. In contrast, this contamination is stronger in the lava boulders; this may be attributed to the strong alteration of NRM carriers during erosion and subsequent conglomerate formation. Much weaker NRM intensities in lava boulders confirm this interpretation.

Thus the traditional Rayleigh test and the suggested new procedure yielded similar results for three of the four examples above, and the merits of the new test were demonstrated with only the rather limited clast collection of the last example. Unfortunately, we do not have larger data sets of our own at this stage with which to illustrate better the suggested procedure.

## DISCUSSION

The new conglomerate test is based on three assumptions: (1) clasts have a random orientation; (2) magnetization of the clasts has directional stability; and (3) the direction of possible remagnetization is known. The first assumption appears to be valid almost always for well-rounded pebbles and boulders. It may be invalid, however, for strongly oblate pebbles, for example of fine-bedded sandstones, which tend to take bedding-parallel positions. In this case, a primary component will be uniformly distributed along two small circles corresponding to the cases of upright and overturned clasts. Half of the angular distance between these two small circles will correspond to the inclination of the primary component in the host rocks. If the primary inclination is low, the two small circles will coincide and the unit vectors will outline a girdle distribution along a single great circle. A similar pattern may originate if layered clasts are studied, and the palaeomagnetic direction of each clast is tilt-corrected, as in the case of large blocks in a tectonic melange (Alvarez *et al.* 1980).

Besides the random orientation of clasts during conglomerate deposition, other mechanisms may randomize palaeomagnetic directions. A large scatter of palaeomagnetic directions at the within-clast level, for instance due to poor orientation of magnetic particles during the acquisition of detrital remanent magnetization, can be detected if sister specimens from at least part of the collection are studied. A few cases were reported where a bipolar overprint was found in host rocks, for instance during the late Palaeozoic remagnetization of Precambrian rocks of the Urals (Shipunov 1991). In principle, a bipolar overprint may also be present in conglomerates. We performed modelling of the effects of such bipolar overprints and found that all uniformity tests, including a test similar to the new test ($\rho^*=n^{-1}\Sigma|\cos\varphi|$), proved to be manifoldly less sensitive than in the case of unipolar remagnetization (however, the sensitivity of the $\rho^*$ statistic was still found to be twice that of the other tests examined). This is not surprising because the superposition of two antipodal or nearly antipodal components may lead to a very large scatter of resultant vectors. Naturally, it is more difficult to discriminate between two randomizing processes than to detect a regularizing process. However, we are unaware of reported cases of a well-defined bipolar overprint in conglomerates acquired after conglomerate deposition and, for the sake of brevity, the results of the modelling for a bipolar overprint are not presented here.

The direction of a secondary component must be known to perform the new conglomerate test. For this it is best to select an overprint direction in the host rocks (examples 1 and 2) or the clasts themselves (example 3). A less reliable approach is to use an overprint identified in overlying remagnetized rocks. Still less reliable is the transfer of results from clasts of one lithology to the results from host rocks of a different composition (example 4). If no secondary component has been determined directly, it is possible to use an alternative direction such as a reference vector for the study area. In this case, however, a positive test may mean that the choice of remagnetization direction was erroneous.

It should be stressed that one cannot use the vector resultant of a collection in the new test as this leads to statistical distortion of the results. Let us consider a sample of 10 unit directions, where the vector resultant is used as the overprint direction. In this case, the calculated $\rho$ statistic and the Rayleigh statistic $r$ are equal. At the same time, the critical values of these statistics are different ($\rho_c = 0.301$ and $r_c = 0.503$, respectively). Therefore, the $\rho$ statistic will erroneously reject the null hypothesis that the sample is drawn from a uniformly distributed population in a considerable number of cases, that is when the calculated value of $\rho$ falls in the range 0.301–0.503.

The aim of field tests, such as fold and conglomerate tests, is to date NRM components in relation to geological events. However, a positive field test, the fold test, does not prove that a component is free from contamination by a post-folding magnetization. It merely indicates that the tested data do not contradict the null hypothesis of the statistical test used at a certain confidence level; a minor overprint may still pass undetected. Our own data and published results show that, as a rule, the observed values of the $F$ statistic used in the fold test (McFadden & Jones 1981) fall between 1 and the corresponding critical values, whereas the 50 percentile of the $F$ distribution is very close to 1 irrespective of the number of degrees of freedom. In other words, most data sets are to be rejected at the 50 per cent confidence level, whereas only half of these collections should have been rejected if the tested components had been of purely pre-folding origin. In general, an undetected post-folding contamination may bias the corresponding mean direction of a collection. On the regional scale, such a contamination of even a fraction of a data set may enlarge the scatter or bias the regional mean. We suspect that this is one of the main reasons why palaeomagnetic poles of a rigid plate do not always show perfect consistency.

With the aid of computer simulations, it is possible to determine the relative intensity of a secondary component ($t = J_2/J_1$) which may pass undetected in a collection of clasts of a given sample size with a certain probability (Shipunov 1994). In principle, knowing the intensity and direction of this secondary component and primary remanence in the host rocks, it is possible to calculate a maximum possible bias (MPB) of the palaeomagnetic result obtained from the host rocks. This can be achieved more accurately with the aid of the new conglomerate test. One can further apply this value to the result on host rocks in order to estimate a maximum bias of the latter under the assumption that the same secondary remanence is present in the host rocks. For a reasonable number of clasts, however, this procedure gives rather large MPB values. One solution is to increase considerably the number of clasts, but this may be difficult in many cases. From our point of view, a better solution would have been to perform a similar analysis for the fold test too. Moreover, it can also be performed jointly for the conglomerate and fold tests. Although such an analysis is not yet perfected, we strongly suspect that the use of results from both conglomerates and folded host rocks will help to reduce the MPB greatly. When this aim is achieved, it should be possible not only to calculate the precision of a result but also to estimate the possible influence of systematic errors.

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