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The reliability of paleomagnetic data

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ABSTRACT

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A set of seven reliability criteria has been applied to a previously published Phanerozoic paleopole database for Europe and North America and a Late Precambrian data set for Africa. A quality factor ($0 \leqslant Q \leqslant 7$) is assigned to a result, based on the number of criteria satisfied. Three criteria, dealing with age reliability, structural control and laboratory demagnetization analysis are deemed the most important; for the Phanerozoic results these are satisfied by a large majority of the results, whereas for the majority (up to 80%) of the African Late Precambrian results such criteria are not met. Criteria based on tests that constrain the age of the magnetization, such as those dealing with folds, conglomerates, contacts or reversals, enhance the reliability of a result; for the Phanerozoic, they are generally satisfied by about one third of the data, but for the Precambrian only a few results incorporate such tests.

The assertion is made in this study that these criteria indeed qualitatively describe the reliability of results in broad terms, so that a data set satisfying on average most of the criteria ($Q \geqslant 4$) can be described as more robust than a data set with average $Q = 2$. Statistical evaluations illustrate the difference in robustness of paleopole data sets between the well-studied Phanerozoic Era and the much more uncertain Late Precambrian.

Introduction

A rough estimate of the number of paleomagnetic pole positions currently available for tectonic purposes easily exceeds several thousand and may reach a total of well over 5000 in the near future. These results, published in ever increasing numbers since the 1950s, are of variable quality and nowadays almost every study that utilizes previously published paleopoles applies a quality filter to the data set. There is, however, no consensus on what the quality criteria should be.

Certainly, paleomagnetic laboratory and analysis techniques have seen technological and computational advances in the past 30 years, but it would be inappropriate to simply apply a filter according to the date of publication; some results published in the 1960s are still very valid today and other results from the most recent decade have already been shown to be inaccurate in, for instance, their age determination, structural correction or determination of characteristic directions.

The ambiguity about reliability criteria results not so much from the fashion by which paleomagnetists judge paleomagnetic data, but rather from the inevitably fragmentary nature of paleomagnetic determinations on rock units that are imperfectly characterized and limited in occurrence, i.e., the very fact that nature provides only limited opportunities to have its secrets unraveled.

As more results become available for a given continent, the criteria may become more stringent. However, this is not true globally, because some tectonic elements (e.g., Greenland, Antarctica) are very inaccessible and in other areas it is very difficult to obtain the necessary funding to repeat incomplete previous studies. Thus, reliability criteria are strongly dependent on the scope of the analysis. A paleopole selection for, say, the Permian of the well-studied European continent may well reject many more imperfect results than a

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compilation for the Proterozoic of Siberia, because in the latter case too few results would survive harsh rejection criteria and the end result would be a starkly underdetermined apparent polar wander path. As an example, I quote from a review of Australian Precambrian results (3.45–0.57 Ga), in which the authors state "... [our] criteria may be regarded as rather lenient. Despite this, application of the scheme to the poles allows only four poles to be regarded as key poles. In a dramatic manner, this emphasizes the generally low quality of Australian Precambrian paleomagnetic data" (Idnurm and Giddings, 1988).

It should not come as a surprise therefore that rejection criteria have been and will continue to be applied in different fashions, so as to allow a minimum number of results to "survive" the onslaught.

This review will try to shift emphasis away from rejection per se, and intends instead to initiate a discussion about what makes a pole more (or less) reliable. It seems clear that for a large data set, "more is better" and that rejection criteria can be stringent, but for smaller data sets the judgments applied should initially be more lenient although they can be a function of time as the database grows. To give a paleopole compilation lasting value, it should incorporate the full range of criteria without any a-priori rejection. The flexible solution then, it seems to me, is to list all results in a compilation with a listing of the criteria that are satisfied. The number of fulfilled criteria leads to a quality factor (Q), such that each time use is made of the data set an individual judgment can be made as to which criteria or what minimum number should be satisfied. This has the additional advantage that readers and users do not have to guess whether (or even why) results not listed were rejected or whether they were simply overlooked in the compilation process.

Paleomagnetic databases

Books, catalogues, and published pole lists are thus far the principal global compilations of paleomagnetic results, although in the last two years compilations have also been made available on computer ("flat file") diskettes. Pole lists in books (Irving, 1964; McElhinny, 1973; Piper, 1988) and in the Ottawa and Russian catalogues (Khramov, 1971, 1973, 1975, 1979, 1984; Hicken et al., 1972; Irving and Hastie, 1975; Irving et al., 1976a, b, c) have been widely used, and have been complemented by the pole list updates published in the Geophysical Journal of the Royal Astronomical Society (McElhinny 1968a, b, 1969, 1970, 1972a, b; McElhinny and Cowley, 1974, 1978, 1980). Some of the later updates and pole lists (e.g., McElhinny and Cowley, 1974, 1978, 1980; Piper, 1988) and some recent regional compilations (e.g., Westphal, 1989) are computer based. A few of these compilations have applied reliability criteria (e.g., B, A, A*, A** in Irving and Hastie, 1975; Irving et al., 1976a, b, c), while listing all results. In addition, many research papers and reviews, too numerous to mention, have given partial lists with selections of paleopoles according to the needs of the topic. A recent and useful summary for many parts of the world, for instance, can be found in McElhinny and Valencio (1981).

Different computer compilations, based on Data Base Management Systems (DBMS; e.g., ORACLE with SQL), are currently being prepared (E. Irving, pers. commun., 1989; Van der Voo and McElhinny, 1989; McElhinny and Lock, 1990). In the DBMS, the compilations are true databases and they can be searched according to any of the entry categories (48 in the case of McElhinny and Lock, 1990). If the design of the entries allows this, one can search simultaneously according to a set of acceptance (or rejection) criteria that must be satisfied. With DBMS it will be easy to apply reliability criteria and arrive at quality or information factors. However, the problem is which criteria to apply; in the following, I will make the case that criteria are necessary, but that it will not be of primary importance that all criteria be satisfied. Thus it becomes valuable to have the criteria *information*, while leaving the rejection up to the goals of a given analysis.

Reliability criteria

There are three basic criteria for a good paleomagnetic paleopole determination that are gener-

TABLE 1

Reliability criteria

No.	Brief description
1	Well-determined rock age and a presumption that magnetization is the same age
2	Sufficient number of samples ($N > 24$), k (or K) $\geq$ 10 and α_{95} (A_{95}) ≤ 16.0
3	Adequate demagnetization that demonstrably includes vector subtraction
4	Field tests that constrain the age of magnetization
5	Structural control and tectonic coherence with craton or block involved
6	The presence of reversals
7	No resemblance to paleopoles of younger age (by more than a period)

For detailed explanation of these criteria, see text.

ally recognized: structural control, age of the paleopole, and paleomagnetic laboratory treatment of sufficient samples. The problem, once again, is not that there is disagreement about this; instead, the problem is that if some criteria are not satisfied, the paleopole may still be a valid record of the ancient field, while poles that meet more than the minimum criteria may occasionally turn out to be seriously in error. Beyond the three basic criteria, moreover, there is a wide variety of individual preferences, and even for the basic "requirements" mentioned above, the minima are not always uniformly set. For example, what is the acceptable minimum in terms of the number of sites or samples? What uncertainty and error limits are allowed on the age? When is laboratory treatment (demagnetization) adequate and when has it been insufficient? It is easier to know when a paleopole has been well determined than it is to know with any certainty that it is flawed.

In recent papers (Van der Voo, 1989, 1990), I have proposed seven reliability criteria (see Table 1), in addition to a basic requirement that demagnetization must have been performed on all samples. This last requirement excludes many early results in the 1950s and 1960s that were based on untreated natural remanent magnetizations (NRMs) only. Many of the seven criteria are frequently not satisfied; it is, for example, extremely rare to find Early Permian rocks that show reversals. Thus, I emphasize that these criteria, when satisfied, do add to the reliability of a result, but I also stress that a result may still be reliable even if several criteria are not met.

The seven reliability criteria, in no specific order, are:

(1) A well determined age for the rock unit from which the results are derived, and a presumption that the magnetization is of about the same age. My personal preference is that the age for Phanerozoic units must be constrained to be within a half-period, such as Late Jurassic or Early Silurian, or be within a numerical age range of $\pm 4\%$, whichever is larger. For Precambrian rocks, the limits should probably be set to $\pm 4\%$ or ± 40 Ma, whichever is smaller, because any uncertainty larger than that would diminish the usefulness of the result in terms of tectonic interpretations when the magnitude of typical apparent polar wander is taken into account. For a Precambrian rock unit of 1000 ± 40 Ma, the total uncertainty of 80 Ma would imply an angular uncertainty of $\pm 16°$, when a typical Cenozoic apparent polar wander rate of 32° per 80 Ma is assumed. This apparent polar wander rate implies a plate velocity with respect to the pole of no more than 4.4 cm/yr, which is certainly not high; thus the Precambrian age limits of less than ± 40 Ma are not overly restrictive.

(2) A sufficient quantity of entries (samples) and adequate statistical precision. My preference is to have this criterion satisfied when the number of samples used is greater than 24, *and* the precision parameter, κ (or K for the mean of virtual geomagnetic poles), is greater than 10.0 *and* α_{95} (or A_{95}) is less than 16°. Previous compilations have used smaller as well as larger limits; e.g., a minimum of 10 samples and a maximum α_{95} of 20° was used by the Ottawa catalogues for the A category (Irving and Hastie, 1975) and a minimum of 10 sites (presumably more than 30 samples), and a maximum α_{95} of 15° was used by May and Butler (1986), with κ constrained to lie between 20 and 150.

(3) Adequate demagnetization. It is generally agreed that results obtained without demagnetization of all samples should not be used for tectonic analyses. However, even if demagnetization was performed, it cannot be assumed that magnetic

components are appropriately isolated, e.g., in the case of blanket treatment in low alternating fields (AF) or with low temperatures. Only when vector subtraction is performed, as illustrated by orthogonal vector diagrams (Zijderveld, 1967), by the use of stereonets giving change in direction combined with intensity decay plots, or by Principal Component Analysis (PCA; Kirschvink, 1980), can one be assured that magnetic components are isolated as well as possible. It is granted here that simultaneous removal of two or more components always remains a possibility, given the limitations of AF, thermal or chemical demagnetization, and may escape detection even with vector plots or PCA, but at least every attempt has been made to maximize the chance of detection of individual magnetic components. Thus, this criterion is satisfied when vector subtraction techniques have demonstrably been used.

(4) Field tests that constrain the age of magnetization. Tests, such as the fold, conglomerate and contact tests, may not always be possible because of the limitations of outcrop and field settings. However if such tests are positive and statistically significant, they make paleopoles more reliable and hence, satisfy this criterion.

(5) Structural control and tectonic coherence, including a presumption that the area studied belonged to the craton or tectonic block involved, should be complete for this condition to be met. For orogenic belts, results from intrusives with ages older than the last tectonic phase or results from thrust sheets, which may have rotated, will generally not satisfy this criterion.

(6) The presence of reversals. This is a powerful test that enough time has lapsed for secular variation to be averaged. Moreover, antipodal reversals generally preclude a systematic bias caused by a small but unrecognized overprint. Although reversals are no guarantee that a rock unit is not remagnetized, they add reliability to a result and, hence, will satisfy this sixth criterion.

(7) No suspicion of remagnetization. This criterion is satisfied when a paleopole does not resemble results for rocks of (much) younger age than that of the ones studied. Unless field tests are available to constrain the age of magnetization, such a resemblance is usually a strong indication that remagnetization has occurred. If a paleopole is based on a remagnetization it can only be included in a compilation if the age of the remagnetization is constrained by independent means, such as in the case of a synfolding result.

Assessment of reliability criteria

The seven criteria enumerated above have been used to assess the pre-Late Jurassic Phanerozoic

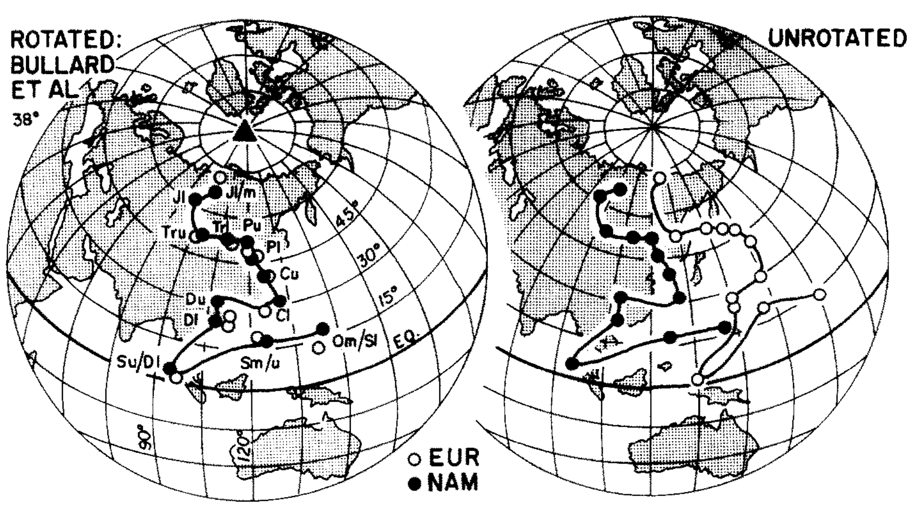

Fig. 1. Mean paleopoles for Europe and North America for the interval between Lower Ordovician and Middle Jurassic time (from Van der Voo, 1990), in present-day coordinates (right) and North American coordinates (left) after closure of the Atlantic Ocean (Bullard et al., 1965).

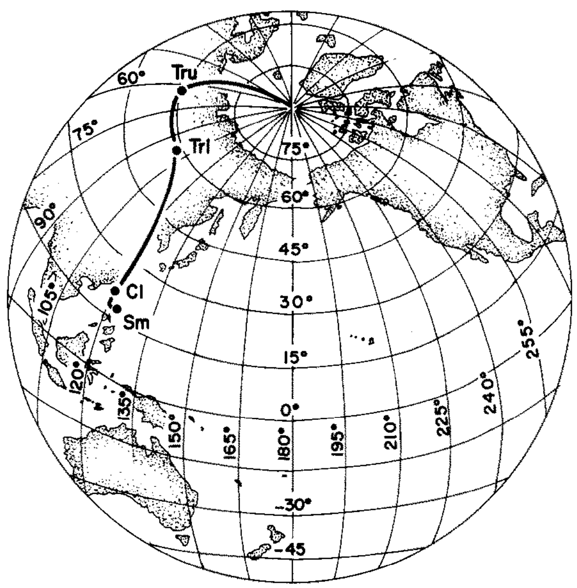

Fig. 2. The Phanerozoic paleopoles for North America which meet all reliability criteria (i.e., $Q = 7$). This plot shows that very stringent use of the seven reliability criteria (as a means to reject paleopoles) produces a starkly underdetermined apparent polar wander path. In contrast, 131 paleopoles for North America meet 3 or more criteria; most of their means are shown in Fig. 1.

paleopoles of Europe and North America (Van der Voo, 1990) and the Late Proterozoic-Cambrian paleopoles of Africa (Van der Voo and Meert, 1991). The number of criteria satisfied for each paleopole has been used to determine a quality factor, Q, which can range from 0 to 7, keeping in mind that only results based on demagnetization of all samples have been entered. From these compilations a number of important conclusions can be drawn, based on correlations between Q, the age of the result, and an angular distance, p, which is the arc length between the location of a paleopole and that of the mean paleopole for the half-period interval for the continental block involved. For Europe and North America these mean paleopoles are shown in Fig. 1 in present-day coordinates as well as in North American coordinates with the Atlantic Ocean closed according to the parameters of Bullard et al. (1965).

Very few results satisfy all seven criteria (e.g., Fig. 2, showing results with $Q = 7$ for the Phanerozoic of North America), and it should be noted that a Q of 7 for a given paleopole is absolutely no guarantee that a result is a better indication of the geomagnetic field at the time of rock formation than, say, a result with $Q = 4$. In fact, some results such as the Catskill red bed poles of Kent and Opdyke (1978) and Van der Voo et al. (1979) may have a high Q and yet are now known to be based on remagnetizations (Miller and Kent, 1986). Such results have been entered in the paleopole compilation with $Q = *$, implying that they should not be used for tectonic analyses. A histogram of Q for the European and North American pre-Late Jurassic Phanerozoic paleopoles is shown in Fig. 3a and illustrates that the mode and median for 252 entries are found at Q between 4 and 5. In contrast, a similar histogram (Fig. 3b) for the Late Proterozoic and Cambrian of Africa shows a mode of $Q = 2.5$, reflecting poor age control, less advanced demagnetization, and a generally greater chance to resemble younger paleopoles.

The parameter p, reflecting the distance away from the mean for a given half-period (Van der Voo, 1990) is shown in Fig. 4 for all pre-Late Jurassic Phanerozoic results with $Q = 3$ or greater derived from Europe and North America. The distribution shows an asymmetrical shape with a mode at $p = 5°$, but ranging up to p values of more than 30°. Because of the two-dimensional

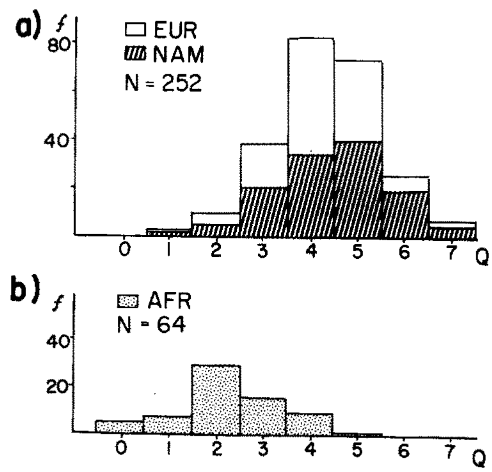

Fig. 3. (a) Histograms of all paleopole entries for the same Phanerozoic time interval as used in Fig. 1 for Europe and North America and (b) for the Late Proterozoic–Cambrian (1150–500 Ma) of Africa, for Q, the quality factor discussed in the text. Note that median Q is much higher for the Phanerozoic results than for the Late Proterozoic poles.

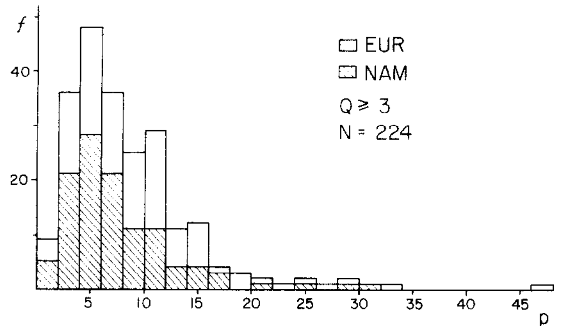

Fig. 4. Histogram of the distance p (in degrees), as measured between a paleopole location and the mean paleopole for the appropriate half-period interval (as shown in Fig. 1), for all results with $Q \geqslant 3$ in the Phanerozoic data set of Europe and North America.

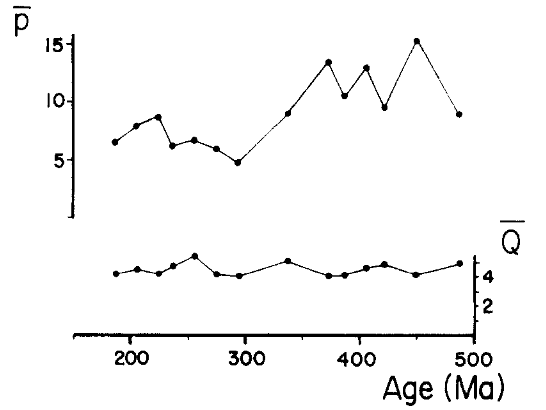

Fig. 6. The distance p (as in Fig. 4) and the quality factor Q, averaged for half-period time intervals, plotted as a function of age, for all results in the Phanerozoic data set of Europe and North America.

distribution of paleopoles about a mean (on the surface of a unit sphere), allowance must be made for the statistical chance that p attains a given value in such a spherical distribution (e.g., Fisher et al., 1988). This is illustrated in Fig. 5 from which it appears that the observed asymmetrical pattern of Fig. 4 is about what one would expect for a Fisherian distribution for which the precision parameter is 100.

Figure 6 illustrates mean Q and p, averaged by half-period, as a function of age for the European and North American database. Average Q shows a flat spectrum, indicating that the average quality factor does not greatly depend on rock age, whereas average p shows an increase for times earlier than Late Carboniferous. This last observation illustrates the greater uncertainty and dispersion of the available paleopoles for Middle and Early Paleozoic time, which is not surprising given the greater difficulties in obtaining reliable results for rocks that generally have seen more orogenic and diagenetic events. What is more surprising, however, is that when average p and average Q are plotted against each other there appears to be no correlation for $Q \geqslant 3$ (Fig. 7). The average distance between a result and the mean for its appropriate time interval does not depend, therefore, on the quality factor for that result. Only for $Q = 2$ is there a greater average p, showing that for such a low Q factor the results will begin to show appreciable scatter, at least for the North

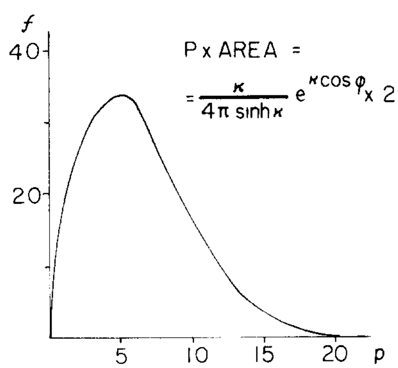

Fig. 5. Smoothed theoretical histogram (as in Fig. 4) of the distance p for a Fisherian distribution with precision parameter (κ) of 100. The histogram is computed by calculating the product of the Probability Density Element, P (Fisher et al., 1987, pp. 67–69) and the area on a unit sphere for 2° increments in colatitude φ with respect to the mean ($\varphi 2 - \varphi 1$). Comparison of Figs. 4 and 5 shows that the observed pattern of Fig. 4 approximates a Fisherian distribution.

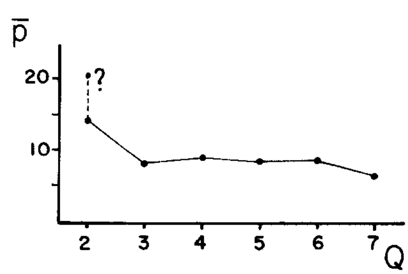

Fig. 7. The distance p (as in Fig. 4) averaged for the quality factor Q for all results in the Phanerozoic data set of Europe and North America. There is an ambiguity in a single result with $Q = 2$ in the database, leading to two alternative mean p values, depending on whether this pole (with large p) is included or excluded from consideration.

American and European paleopoles. It would be of interest to test this further with databases for other continents.

One should note that mean Phanerozoic paleopoles, averaged by half-period for a given continent, are themselves spaced some 12° apart on average (Fig. 1). Thus, individual paleopoles falling in between successive half-period means would show a p of 6°, on average; in other words, average p cannot be expected to show a very low value even for a "perfectly" determined apparent polar wander path. A reasonable guess for the minimum average p for such a perfect distribution would be 3.5°. The average p of about 7.5° for $Q \geqslant 3$ illustrated in Fig. 7 is therefore in excess of the minimum average by only 4°; to me this appears to be a small excess, indicating low scatter and a relatively robust data set.

For the Late Proterozoic data set of Africa, such an analysis correlating p and Q would not be meaningful, since there are only about 65 poles for the interval of 1150 to 500 Ma and given that there may well have been relative motions between the African cratonic blocks (West African, Congo and Kalahari cratons) as well as inside the Panafrican mobile belts. A common apparent polar wander path for all of Africa for the time between 1150 and 500 Ma must be regarded with circumspection until we have reasonable evidence that relative motions did not occur. Mean poles for individual African blocks would be based on very few entries only. Thus, this African data set cannot yet be called robust, echoing the earlier quoted comments about the Australian Precambrian data.

What are the criteria that are most commonly failed? Figure 8 illustrates this in a histogram of criteria not satisfied for each of the paleopoles in the databases for the pre-Late Jurassic Phanerozoic of Europe and North America and the Late Precambrian-Cambrian of Africa. The most prevalent "flaw" in the data set is found for criterion 4, which is satisfied only when fold, conglomerate, or contact tests are positive. In the Phanerozoic databases, the next criterion most commonly missed is #6, satisfied when reversals are present, whereas for the Precambrian of Africa it is #1, dealing with the age reliability. The histograms of

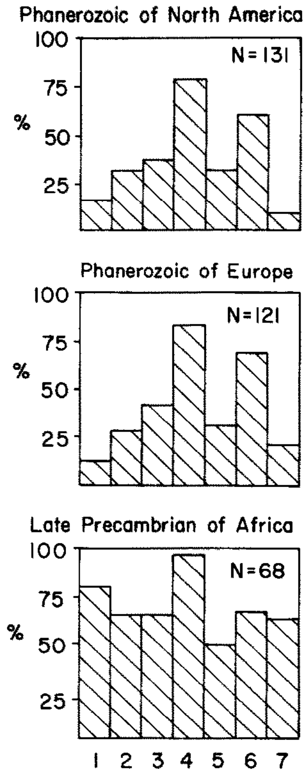

Fig. 8. Percentages of paleopoles that do not satisfy a given reliability criterion (*1* through *7*), for the paleopoles in the Phanerozoic databases of North America and Europe and the Late Precambrian paleopoles of Africa. More than half of the Phanerozoic paleopoles generally satisfy the criteria (except #4 and #6 dealing with fold, conglomerate, contact and reversal tests), whereas a majority of the Late Precambrian data fail the criteria.

Fig. 8 for the Phanerozoic results of Europe and North America are more uneven ("peaked") than that for Africa, reflecting the fact that Africa's Late Precambrian paleopoles have on average much lower Q, i.e., individual paleopoles meet only few criteria generally. The most important criteria, at least in my opinion, are the ones dealing with age (#1), demagnetization (#3), and structure (#5), and each of these is satisfied for about two-thirds or more of the Phanerozoic data, whereas for the Precambrian of Africa they are satisfied by about half or (much) less of the entries. Criteria based on tests that constrain the age of the magnetization, such as those dealing with folds, conglomerates, or contacts, certainly enhance the reliability of a result; for the Phanerozoic, they are generally satisfied by more than one quarter of the data, but for the Precambrian only a few results incorporate such tests. If the Proterozoic database is to improve in reliability in the future, positive field tests will become very important, in addition to better age determinations of the rocks.

Conclusions

This paper describes a set of seven reliability criteria applied to a Phanerozoic paleopole database for Europe and North America and a Late Precambrian–Cambrian data set for Africa. Three of these, dealing with age reliability, structural control and laboratory demagnetization analysis are deemed the most important; for the Phanerozoic results these are satisfied by a large majority of the results, whereas for the majority (up to 80%) of the Precambrian results these criteria are not met. Criteria based on tests that constrain the age of the magnetization, such as those dealing with folds, conglomerates, contacts or reversals, certainly enhance the reliability of a result; for the Phanerozoic, they are generally satisfied by more than one third of the data, but for the Precambrian only a few results incorporate such tests.

These statistical evaluations illustrate the difference in robustness of paleopole data sets between the well-studied Phanerozoic Era and the much more uncertain Late Precambrian.

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