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Geomagnetic secular variation and the statistics of palaeomagnetic directions

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SUMMARY

In this study, we examine the role of palaeosecular variation (PSV) in the use of statistics for palaeomagnetic studies, and we provide new reliability criteria for palaeomagnetic poles or directions. We first conclude that Fisher statistics should not be applied to average palaeomagnetic directions but to virtual geomagnetic pole (VGP) distributions instead.

Secondly, we strongly advocate that typical properties of geomagnetic field behaviour are taken into account in the assessment of palaeomagnetic data sets. The latitude-dependent properties (E, S, k) provide useful guidelines for the reliability of a palaeomagnetic data set. A reliable assessment of these properties depends on the (sufficient) number of palaeomagnetic samples being taken. Therefore, as an additional instrument of assessing data sets, we provide a N-dependent A95 envelope, bounded by an upper limit A95max, and a lower limit $A95_{min}$ that helps to ascertain whether or not a distribution has sufficiently well-sampled PSV and therefore geomagnetic field behaviour. Applying these criteria is indispensable for studies of geomagnetic behaviour, or for studies aiming at using TK03.GAD for inclination error correction through the elongation/inclination (E/I) method. For palaeomagnetic studies aimed at geological reconstructions, they form helpful guidelines and increase the confidence in the rocks having faithfully recorded the field.

An analysis of published Eastern Mediterranean data shows that the vast majority of studies do not conform to the Van der Voo criteria, in particular with respect to N and A95. We have provided criteria that are on the one hand more lenient (lower N may still provide relevant information), and on the other hand more strict (for high N the criterion of A95 $< 16^\circ$ should be adapted to a requirement of lower A95, e.g. A95 $< 5^\circ$ for $N > 80$).

Key words: Palaeomagnetic secular variation; Palaeomagnetism applied to tectonics; Palaeomagnetism applied to geologic processes.

1 INTRODUCTION AND RATIONALE

Palaeomagnetism provides a useful tool in many geological and geophysical studies to obtain quantitative information, for example, on dating, plate tectonic reconstructions and geomagnetic field behaviour during the geological past. As is usual in any physical discipline, the acquired and processed data have to be tested for their robustness and reliability. This inevitably involves statistical treatment of the data, the details of which depend on the type and purpose of the study. For example, in classical palaeomagnetic studies, like determining crustal kinematics or plate motion, one aims to average out secular variation to determine the palaeomagnetic pole. This approach relies on the hypothesis of a geocentric axial dipole (GAD) field: the geomagnetic field—averaged over 'sufficient time'—is that of a dipole in the centre of the Earth, and aligned along the Earth's rotation axis. This GAD hypothesis has proven very successful in palaeomagnetic reconstructions (Irving 1960). For other types of studies, however, this GAD approach is not taken. For example, if one wants to study short-term geomagnetic field behaviour like (palaeo)secular variation, then the angular standard deviation (ASD) of virtual geomagnetic pole (VGP) distributions, also known as 'VGP scatter' (S) may be calculated.

In this study, we focus mostly on the statistical treatment of classical palaeomagnetic data, and their reliability to portray crustal motions at all scales, for example, tectonic rotations and (palaeo)latitudinal drift. This involves (components of) motion with respect to a (absolute) reference pole, as used in, for example, (global) apparent polar wander (APW) paths or (regional) rotation

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Erratum: Geomagnetic secular variation and the statistics of palaeomagnetic directions

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In our recent paper, we defined a reliability envelope for palaeomagnetic data, based on the number of samples used to determine the mean (N). This envelope is defined by a lower and upper 95 per cent confidence envelope on model runs of Fisherian VGP distributions that can be expected from palaeosecular variation of the palaeomagnetic field. We used a VGP distribution with K = 12.5 for the maximum A95 ($A95_{max}$), and a distribution with $K = 50$ for the minimum $A95$ ($A95_{min}$; and 'not' $K = 25$ as erroneously indicated in the caption of Fig. 3).

Unfortunately, eq. (4) for $A95_{min}$ as printed in the main text is incorrect. The correct equations for the reliability envelope are given in the legend of Fig. 6 and are:

$$A95_{max} = 82 \times N^{-0.63} \quad (3)$$

$$A95_{min} = 12 \times N^{-0.40}. \quad (4)$$

We apologize to the readers of *Geophysical Journal International* for the inconvenience caused, and we wish to thank Valerian Bachtadse for noticing the error. For those who have used the published eq. (4) for $A95_{min}$: it was more stringent than the correct one. The correct equation is slightly more lenient and will accept more data as representing secular variation.

studies. Regardless of the scale, determination of directions or their corresponding poles is hampered by many sources of uncertainty. Therefore, many studies have proposed various statistical methods and approaches to assess the reliability of palaeomagnetic data. A first milestone paper concerned dispersion of palaeomagnetic vectors on a sphere (Fisher 1953), which enabled palaeomagnetists to determine a statistical mean of a number (N) of directions or poles with an associated dispersion (or precision) parameter (κ, estimated by k or K for directions and poles, respectively) and a cone of confidence around the mean at the required probability level, usually 95 per cent (α_{95} or A95 for directions and poles, respectively). Subsequently, many additional tests were developed to discriminate between different populations—such as fold, reversal and conglomerate tests—but usually assuming Fisherian distributions of the palaeomagnetic directions. We refer the reader to the usual textbooks in palaeomagnetism (Butler 1992; Tauxe *et al.* 2010).

An important criterion in palaeomagnetism has always been: what is the required (statistical) quality of the data and how many observations are needed to provide a reliable and robust result that allows a meaningful conclusion for the type of study we are performing. The most commonly used criteria were proposed by Van der Voo (1990), who introduced seven criteria to reliably determine a meaningful palaeomagnetic result, be it a mean direction, a mean VGP or palaeomagnetic pole. Several criteria verify the usefulness of the results in terms of accuracy of age or structural geological control, other criteria deal with the success of laboratory tests (proper demagnetization and vector analysis, rock magnetic properties) or field test (fold, reversal, conglomerate and baked contact tests). One important criterion requires a sufficiently robust statistical result. Van der Voo (1990) suggested that a significant mean would require $N > 24$, and k (or K) > 10 and α_{95} (or A95) $< 16°$. In practice, many palaeomagnetic studies do not satisfy the requirement of a sufficient number of samples ($N > 24$), and the requirements on k and α_{95} are often taken as k or α_{95}. The parameters N, k and α_{95} are not independent, however, and the requirements are not internally consistent: a Fisherian distribution with $N = 24$ and $\alpha_{95} = 16°$ implies a k value of 4.4, while $N = 24$ and $k = 10$ implies an α_{95} value of 9.9°.

Apart from recording pitfalls, the most important source of 'noise' in palaeomagnetic data distributions is palaeosecular variation (PSV) of the geomagnetic field. Secular variation can at any time and location easily lead to deviations in the geomagnetic field direction of tens of degrees. Because palaeomagnetic studies generally aim to detect changes on the order of ∼5°, PSV in the GAD hypothesis must be averaged out over 'sufficient time' which implies taking a 'sufficient number' of samples. Although what constitutes sufficient time is not yet clear, many palaeomagnetists usually assume that ∼10 kyr is adequate, but in some cases more than 100 kyr may be required. In any case, the GAD assumption seems to hold up well (Merrill & McFadden 2003).

Some criteria may include (fixed or variable) cut-off values for VGP distributions, to filter out large variations from the mean VGP or palaeomagnetic pole. Such large deviations are considered by some as not belonging to regular SV, although there is still considerable discussion on distinguishing between inherent geomagnetic field behaviour and (reversal) excursions, aborted reversals or transitional directions (e.g. Gubbins 1999; Tauxe & Kent 2004; Tauxe *et al.* 2008).

A palaeomagnetic data set that passes the required criteria is in principle considered to reliably determine the location of a palaeomagnetic pole position. Additional tests have been developed to test whether palaeomagnetic data set share a common mean, such as the reversal test (e.g. McFadden & McElhinny 1990) or, more generally, a common true mean direction (CTMD) test. These tests either determine a CTMD on the basis of the statistics developed by McFadden & Lowes (1981) or—if one chooses Monte Carlo simulation—on the basis of the so-called V_w test statistic of Watson (1983). The result can then be classified according to a critical angle (γ_c) as A, B, C, indeterminate or as negative. Recently, also Tauxe & Kodama (2009) argued for using the Watson V_w statistic, although it should be realized that this test usually pertains to Fisherian distributions of directions.

It is important to realize that these tests determine whether two data sets are significantly different, but do not identify the source(s) or implications of the dispersions of each of their dispersion. In this study, we provide quantitative reliability criteria to determine whether dispersion of a palaeomagnetic data set can be explained by PSV alone, or if additional noise or smoothing of the signal must be invoked to explain the data. These criteria will provide an essential new tool to discriminate geologically induced changes (rotations and latitudinal drift) from PSV. We concentrate on VGP distributions rather than directional distributions, and determine characteristic values of the statistical parameters K and A95 as a function of N, when the only source of dispersion is PSV.

We therefore need a statistical model that adequately describes secular variation.

2 MODELS OF PSV

Since the end of the fifties, many models have been proposed to describe secular variation. According to Irving (1964), these have been referred to as model A (Irving & Ward 1964), model B (Creer *et al.* 1959), model C (Cox 1962) and model D (Cox 1970). Model A considers only variations in the non-dipole field, while model B considers only the effects of dipole wobble. The earliest model B of secular variation (Creer *et al.* 1959) simulates 'dipole wobble' by random variations in the three dipole spherical harmonic terms of the field. It produces Fisher (1953) distributed sets of VGPs that average to the spin axis and hence supports the GAD assumption. Creer *et al.* (1959) pointed out that directions from such a set of VGPs would not be circularly symmetric but increasingly elongated with lower latitude. The model also predicted the highest VGP scatter (S) at the equator, contrary to what is generally observed. Subsequently, Creer (1962) compiled data from lavas which were consistent with model B with a Fisher dispersion parameter K of ∼35. Models C and D may be considered as physically more plausible because they include contributions from both the dipole and the non-dipole field. Model D is the most comprehensive and essentially includes aspects of models A, B and C, and it describes mathematically the non-dipole field; otherwise, it is the same as model C. A further modification was given by Baag & Helsley (1974) who introduced model E. For characteristics and details of these early models, we refer to the comprehensive overview of McElhinny & Merrill (1975) in which they also proposed their new model M that fits both the palaeomagnetic data and the variation expected from analysis of the present field.

Model G (McFadden *et al.* 1988) is an empirical model to account for the observation of increasing VGP scatter with latitude, both in the international geomagnetic reference field (IGRF), in historical and archaeomagnetic data and in a compilation of the lava data of the past 5 Myr. It separates the geomagnetic field into two families, the dipole (primary, antisymmetric) and quadrupole (secondary, symmetric) families, corresponding to the odd and even spherical harmonics, respectively. The quadrupole family contributes more strongly to scatter in VGPs at low latitudes than the antisymmetric terms but otherwise remains constant with latitude. The antisymmetric terms in Model G predict increasing average VGP scatter as a function of latitude. However, Model G cannot predict distributions of field vectors.

Other models describe VGP properties as a function of latitude by a Fisher distribution plus a uniform distribution, or as two Fisher distributions, an approach that can considerably improve the fit with observational data (Harrison 2009).

As recently pointed out by Tauxe *et al.* (2008), what we need instead is a statistical PSV model that builds on the idea of Model B. The most influential model is CP88 introduced in the milestone paper of Constable & Parker (1988) that models the time varying geomagnetic field as a Giant Gaussian Process (GGP) whereby the Gauss coefficients have zero mean and standard deviations that are a function of degree l, except for the axial dipole term g_1^0 and the axial quadrupole term g_2^0. For a lucid introduction and overview of GGP models, we refer the reader to Tauxe *et al.* (2008). Model CP88 has the disadvantage, however, that it predicts that VGP scatter is virtually independent of latitude (see e.g. Tauxe & Kent 2004). In contrast, the most recent GGP model TK03.GAD of Tauxe & Kent (2004) does not assign special status to the axial dipole, but adjusts the power in all the antisymmetric Gauss coefficients (including the axial dipole) relative to all the symmetric ones with a constant factor β. TK03.GAD predicts slightly increasing VGP scatter with latitude, but not as much as seen in the present field and in compilations of the last 5 Myr. The model also provides a circular VGP—but not Fisherian—distribution, with corresponding elliptical directional distributions with increasing elongation towards the equator (Fig. 1). Moreover, it does not include a non-zero quadrupole term and thus has the advantage that it averages out to a GAD field, as is still the reigning assumption in palaeomagnetic studies.

Both models like TK03.GAD and recent compilations of observations of the field from lavas of the last 5 Myr (Johnson *et al.* 2008; Harrison 2009; Lawrence *et al.* 2009) show that the VGP distribution is non-Fisherian, but sufficiently approaches GAD. Since these models and compilations are restricted to the last 5 Myr, one cannot know or assume that this non-Fisherian behaviour applies also to observations of the more ancient field. There are simply insufficient data available for older times—also hampered by plate tectonic movement which is well constrained for the last 100 Myr and reasonably constrained since 320 Ma (Torsvik *et al.* 2008) but increasingly unconstrained for earlier times—to put faith in any model. Indeed, there is reason to believe that the older field may have behaved quite differently than today (Biggin *et al.* 2008a,b; Haldan *et al.* 2009), which would necessitate a 'differently tuned' GGP model. Hence, we realize that a Fisherian approach for VGP distributions may not be optimal or accurate, but through lack of better knowledge we adhere to the simplest approach tolerable.

3 FISHERIAN DIRECTIONS OR FISHERIAN VGPs?

It is common practice to average palaeomagnetic directions using Fisher (1953) statistics; the corresponding VGPs may also be averaged in the same way but this is less commonly done. Fisher statistics assume a circularly symmetrical Gaussian distribution of vectors on a sphere. Application of Fisher statistics provides a 95 per cent cone of confidence around the mean (α_{95} and A95 for directions and VGPs, respectively), and an estimate of the dispersion (or precision) parameter κ (estimated from the data as k or K, respectively), which is zero for a distribution uniformly distributed over the sphere and approaches infinity as all directions become parallel. N, k (or K) and α_{95} (or A95) are interrelated (see e.g. Butler 1992; Tauxe *et al.* 2010).

As was already noted more than 40 yr ago (Creer *et al.* 1959; Creer 1962; Cox 1970), and more recently emphasized again by Beck (1999) and Tauxe & Kent (2004), distributions of palaeomagnetic directions at any location on the globe are elongated in a N–S direction (see also Figs 1 and 2C and D). This elongation varies gradually as a function of latitude, decreasing with increasing latitude. Tauxe & Kent (2004) conclude that there is no dipolar field structure that can give rise to Fisherian distributed directions everywhere, and that it is therefore 'inappropriate to use Fisher statistics on directional data sets'. Naturally, this only applies for PSV-induced scatter. Directions obtained, for example, from individual lavas represent spot readings of the Earth's magnetic field; the mean direction per lava is subject to errors that can be considered random, and is accurately approached by Fisher statistics. Here, we focus on procedures to average PSV, using mean directions from lavas or directions from single sediment samples, preferably from sediments with high enough accumulation rates to provide what are to a large extent spot-readings of the geomagnetic field direction.

Application of Fisher statistics to palaeomagnetic directions provides the correct mean direction—the mean here being simply the vector resultant of the normalized directions—but an incorrect circular error estimate, the α_{95} cone of confidence. This causes an equally incorrect elliptical error estimate around the corresponding mean VGP or palaeomagnetic pole, described by dp/dm, where dm is the uncertainty in the longitude and dp is the uncertainty in the latitude (Irving 1956; Cox & Doell 1960). Here, we apply 'Fisher statistics only on VGPs', yielding a mean VGP with A95 and K, and an average direction with a separate error for the declination (ΔD_x) and for the inclination (ΔI_x). These are given by Butler (1992) as

$$\Delta D_x = \sin^{-1}\left(\frac{\sin A_{95}}{\cos\lambda}\right), \tag{1}$$

$$\Delta I_x = \frac{2A_{95}}{(1+3\sin^2\lambda)}, \tag{2}$$

where λ is the palaeolatitude derived from the inclination (of the data set) according to the dipole formula. ΔD_x and ΔI_x are clearly more realistic error estimates to describe the errors in a directional distribution. At high latitudes, for example, the declination is ill determined and ΔD_x quickly increases, as it should, while at the equator ΔD_x becomes equal to A95.

4 APPROACH

We determine the typical range of A95 (with simulated 95 per cent error envelopes), and from that ΔD_x and ΔI_x, as a function of N. We express this range of A95 values as a reliability envelope with an upper limit ($A95_{max}$) and a lower limit ($A95_{min}$). We prefer A95 over K, because this parameter is intuitively comprehensible in palaeomagnetism, but the A95 values are easily converted to their K equivalents. A data set with an A95 higher than $A95_{max}$ must then contain an additional source of scatter in addition to PSV (e.g. tectonic) and must thus be considered 'unreliable' for the purpose of the study. Alternatively, in a data set with an A95 lower than $A95_{min}$, PSV is underrepresented (e.g. as a result of remagnetization or insufficient time averaging), and is equally unreliable. The

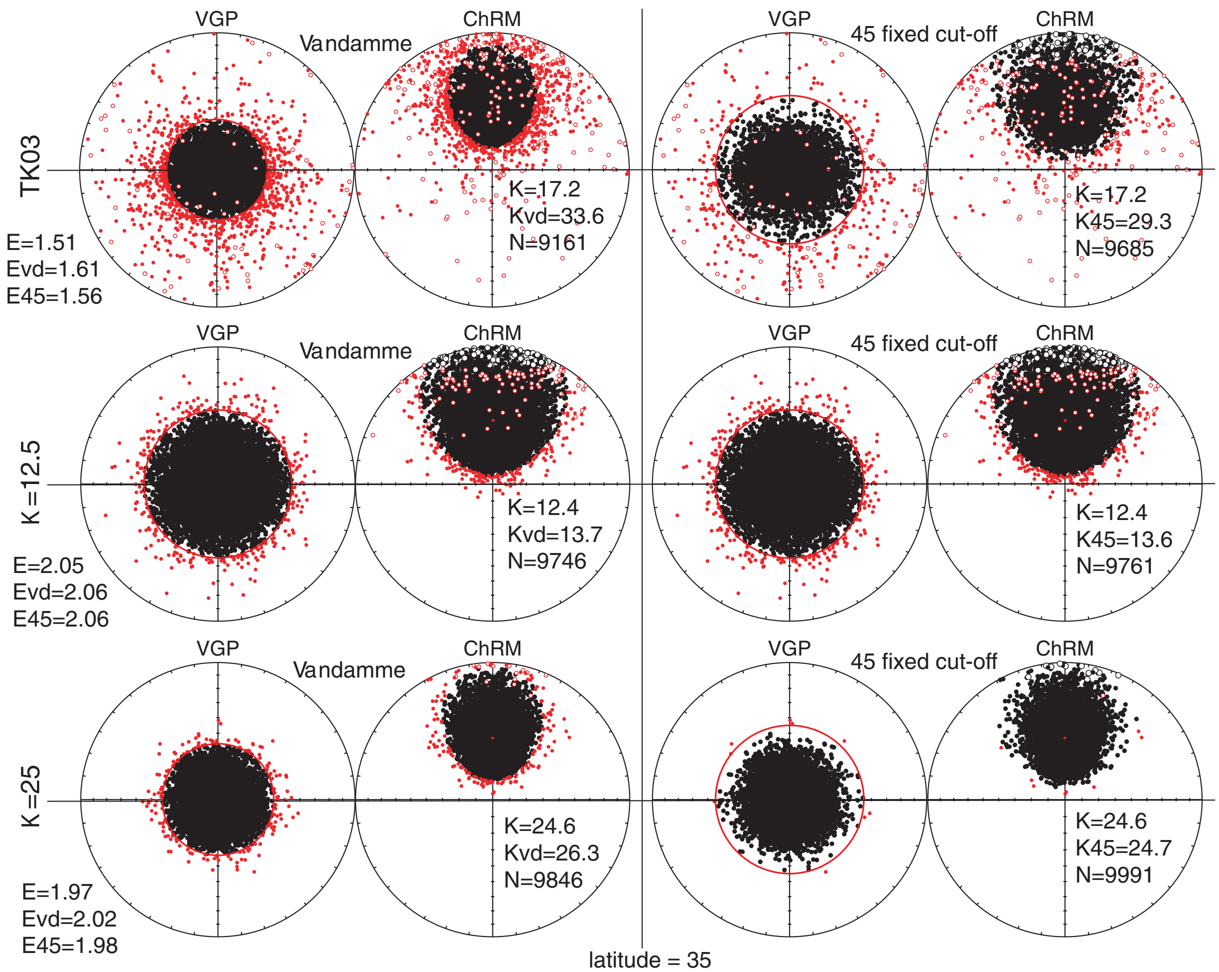

Figure 1. Examples of sets of 10,000 VGPs drawn at random from TK03.GAD and simple Fisher distributions (with $K = 12.5$ and $K = 25$). The VGPs are shown alongside their associated directions assuming a site latitude of 35°. A variable cut-off (Vandamme, 1994) is applied to the data sets on the left and a fixed cut-off (45°) to those on the right-hand side. Data excluded by these are shown as red.

random scatter introduced to palaeomagnetic directions from sample marking errors, measurement errors, etc. may be estimated as within-site scatter in studies performed on lava flows (where multiple samples record the same spot-reading of the field) but is entirely unknown in studies performed on sedimentary rocks. Since we expect these effects to be small relative to SV-induced scatter (as has been shown for some lava-based studies, Biggin *et al.* 2008b), we neglect them entirely in this study. We also assume that the data quality of the individual palaeomagnetic directions is 'sufficient', and are not contaminated by, for example, unremoved overprints, an assumption that clearly cannot always be proven.

We obtained VGP data sets by randomly drawing 10 000 VGPs from a Fisher distribution at the pole (Fisher *et al.* 1987) with κ values 12.5, 25 and 50. From TK03.GAD we draw sets of 10 000 spherical harmonic coefficients with degree and order 8, from which we sampled directional data sets at different latitudes. We show examples at a latitude of 35° of the resulting distributions in Fig. 1, as well as the effect of using a fixed 45°, or a variable Vandamme (1994) cut-off.

5 RESULTS

First, we consider several properties of the modelled distributions as a function of latitude, in particular VGP scatter (S), and at elongation (E) and dispersion parameter (k) of the resulting directional distribution. In the case of TK03.GAD, we also consider the dispersion parameter (K) of the VGP distribution. In addition, we show the effect of no cut-off, a fixed (45°) and a variable (Vandamme 1994) cut-off applied on the VGP distribution.

VGP scatter (S)

A characteristic feature observed in lavas from the last 5 Myr is the increase in scatter S of VGPs with latitude. A recent compilation for the last 5 Myr by Johnson *et al.* (2008, J08 from here on) indicates that PSV, as measured by dispersion of VGPs, shows less latitudinal variation than predicted by current field models (e.g. model G, McElhinny & McFadden 1997). Naturally, dispersion of VGPs in the Fisherian sets is constant with latitude. The κ-values of 12.5, 25 and 50 correspond to VGP scatters of, respectively, 23°, 16° and 11° (Fig. 2B), covering the majority of VGP scatter values observed throughout the Earth's history and across the globe (Biggin *et al*. 2008b; Johnson *et al*. 2008; Haldan *et al.* 2009; Lawrence *et al.* 2009), with the exception of those for Archean volcanic rocks at low (<30°) latitudes (Biggin *et al.* 2008a) and for volcanic (Biggin *et al.* 2008b) and sedimentary (Haldan *et al.* 2009) rocks from superchrons. These observations are still few and require further confirmation.

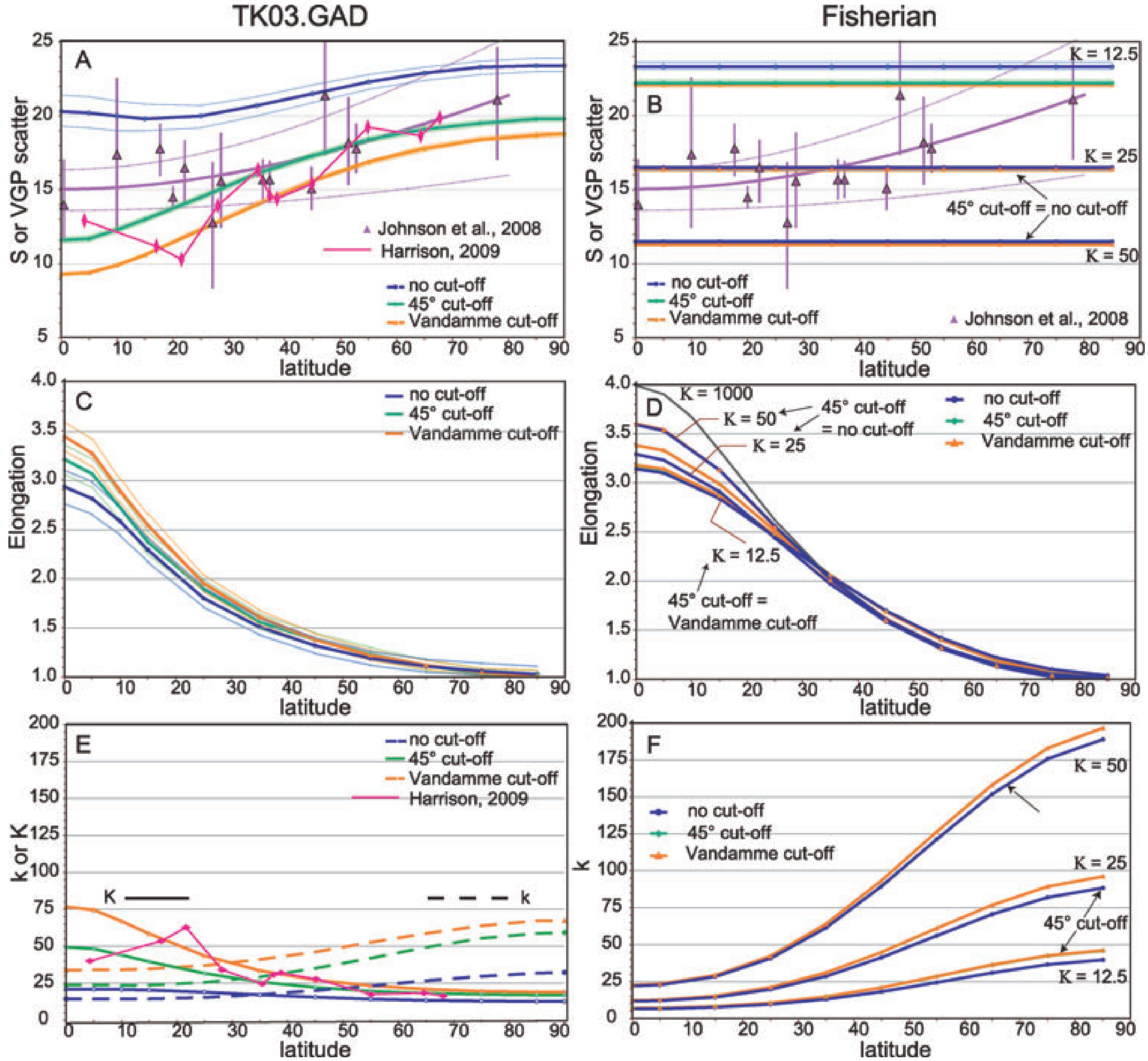

Figure 2. Statistical properties of data sets ($N = 10.000$) derived from TK03.GAD (A, C and F) and Fisherian VGPs ($K = 12.5$, 25 & 50) (B, D and F). Data are shown for data sets without cut-off, with a fixed 45° cut-off and the Vandamme (1994) cut-off. In figures A & B we additionally show the Johnson *et al.* (2008) VGP scatter curve derived from high-quality data sets. VGP scatter (S) and dispersion (K) have been derived from VGPs, Elongation (E) and dispersion (k) from the directional data sets, respectively. Overlapping data sets (panels B, D and F) are annotated with arrows. In panels A & E we additionally show latitude-binned VGP data from the data compilation by Harrison (2009).

The VGP scatter of the J08 compilation fits best with a Fisherian distribution with $\kappa = 25$ or with TK03.GAD (after applying a fixed 45° cut-off, following J08). The TK03.GAD field model was tuned by Tauxe & Kent (2004) to represent an increase of S with latitude, by taking a non-iterative version of the Vandamme cut-off, enabling comparison with the 0–5 Ma compilation of McElhinny & McFadden (1997). Indeed, applying a cut-off on TK03.GAD leads to an increase of S with latitude (Fig. 2A). Without any cut-off, S predicted by TK03.GAD is quite constant with latitude, ranging 20–23°. A 45° cut-off causes S to be similar to the J08 compilation, except for the lower latitude range where TK03.GAD predicts lower S. The tuning of any GGP model to field observations inevitably implies future retuning as new data sets become available.

Elongation (E)

The ellipticity of directional distributions increases at lower latitudes and this is expressed as an increasing value of the associated elongation parameter E (Fig. 2), calculated according to Tauxe & Kent (2004) as the ratio of the eigenvalues τ_2/τ_3 of the distribution. This parameter can be used to test whether a directional distribution obtained from sediments is flattened, so that it can be corrected accordingly (elongation/inclination or E/I correction method, Tauxe & Kent 2004; Tauxe 2005). When using volcanic data, it is also a useful parameter to test whether a distribution fits the model (Tauxe *et al.* 2008; Tauxe & Kodama 2009). Fig. 2 illustrates that both TK03.GAD, as well as the Fisherian VGP models predict a decrease of E with latitude, from a value around 3 (NS elongated) at the equator to a value around 1 (circular) at the poles. The TK03.GAD model, however, shows a faster decrease of E at mid-latitudes.

The fixed cut-off has little effect on E in the case of the Fisherian VGP models, but the effect is more pronounced on TK03.GAD. The variable cut-off has some influence on E in the ($\kappa = 12.5$ & 25) Fisherian models, and slightly more in TK03.GAD. In general, however, there is a good correspondence between all models.

Dispersion (k, K)

Although the Fisherian VGP distributions produce of course a constant measured value of K with latitude, the resulting dispersion parameter, k strongly increases with latitude. Both cut-offs have little effect (Fig. 2F). For TK03.GAD, K is not constant but decreases with latitude. Without cut-off, K decreases with latitude from $K = 20$ to approximately $K = 10$. However, both the fixed and, even more so, the variable cut-offs strongly increase K values at low latitudes, converging to typical values (25–15) at latitudes >60°. The K curve of TK03.GAD with (fixed or variable) cut-off agrees remarkably well with the latitude-dependent K values calculated by Harrison (2009) for the last 5 Myr (Fig. 2E). The directional dispersion k increases with latitude in all models, but much stronger in the case of Fisherian VGPs, from $k = \frac{1}{2}K$ at the equator to $k = 4K$ at the poles (*cf.* Cox 1970). Applying a cut-off on TK03.GAD, however, leads to a k curve that is comparable to the VGP distributions with $\kappa = 12.5 - 25$.

In general, we observe that the statistical properties of the Fisherian VGPs and TK03.GAD are comparable in many cases. However, the best agreement in all properties of the distributions is seen between TK03.GAD with a fixed cut-off of 45° and a Fisherian distribution with $\kappa = 25$.

6 CONFIDENCE ENVELOPES FOR A95 AS A MEASURE OF PSV BEHAVIOUR

Assuming that Fisherian VGP distributions and/or TK03.GAD are a reasonable representation of geomagnetic field behaviour, and hence PSV, we determine the ranges of A95 values as a function of N, the number of (palaeomagnetic) samples per site. From the Fisherian and TK03.GAD models, we sampled 10 000 data sets for values of N ranging 5–1000. Fig. 3(A) shows the resulting A95(N) curve, cut-off at $N = 100$ as results converge at higher N and most published palaeomagnetic studies fall within this range. Per model, we averaged 10.000 A95 values for each N and calculated a 95 per cent bootstrap error envelope. Logically, the envelopes for the three Fisherian VGP models are similar in shape, and only differ in values of A95. Since K (but not k, Fig. 2) is constant for all latitudes, results from the Fisherian VGP models are independent of latitude. We also determined the A95 envelopes for TK03.GAD, shown at 45° latitude (Fig. 3A), of which the lower limit of the error envelope coincides closely with that of $\kappa = 25$. We do note, however, that K values (and hence A95) are not latitude independent for TK03.GAD: for low latitudes, the A95 minimum error limit is close to that of $\kappa = 50$, for mid-latitudes to that of $\kappa = 25$ and for high latitudes midway between $\kappa = 12.5$ and $\kappa = 25$. The TK03.GAD A95 maximum error limit, on the other hand, coincides closely with that of $\kappa = 12.5$ for all latitudes. This is in line with the observation that TK03.GAD best fits Fisherian distribution (in S, E, k; Fig. 2) for κ ranging 12.5–25.

As pointed out earlier, the Fisherian VGP models with κ ranging 12.5–50 cover practically the entire range of palaeomagnetic data sets that sample PSV. However, from our simulations of sampling the Fisherian and TK03.GAD distributions, it becomes also clear that at low values of N (<15), there is considerable chance to obtain values of A95 that are very low (4–5°) for the number of samples. These low A95 values at low N correspond to values of $K > 90$ which is characteristic for a lava that records a spot reading of the field, but not for a site that is expected to sample PSV. Similarly, very high values of A95 at $N < 15$ correspond with K values lower than 10 (Fig. 3B), suggesting too much dispersion ('noise') in the data.

We suggest that any A95 for a given palaeomagnetic data set that lies between the upper limit of the $\kappa = 12.5$ model, and the lower limit of the $\kappa = 50$ model fits both with realistic Fisherian VGP distributions and with TK03.GAD, with the caveat that at N lower than 15 the increase of this error envelope quickly leads to increasingly unrealistic values of A95 or K. We propose that such a data set can reasonably be explained by geomagnetic field behaviour and PSV and, in this sense, can be considered reliable. We thus define an A95 envelope as a function of N, where we take $A95_{max}$ as the upper 95 per cent error limit on the $\kappa = 12.5$ curve, and $A95_{min}$ as the lower error limit on the $\kappa = 50$ curve.

$$A95_{max} = 82 \times N^{-0.63}, \tag{3}$$

$$A95_{min} = 17 \times N^{-0.40}. \tag{4}$$

By expressing the reliability of palaeomagnetic data sets as a function of N, we abandon the criterion of $N > 24$ of Van der Voo (1990) which may be too strict: acceptable A95 values can be reached with $N > 15$. On the other hand, the criterion of A95 < 16° of Van der Voo (1990) is not stringent enough and seems increasingly too lenient for $N > 15$.

Obviously, any set of statistical criteria cannot prove that a palaeomagnetic data set is reliable, and each data set must first and foremost meet rigorous palaeomagnetic criteria, like good age constraints and a proven primary signal. If there is evidence for, for example, remagnetization these statistical criteria lose their meaning.

The expected values for the properties of the recorded distribution (S, E, k) with latitude are helpful additional indications of the reliability of the recorded geomagnetic field, and we advocate to use these properties as an additional reliability criterion (*cf.* Tauxe *et al.* 2008, 2010). If a data set does not meet these criteria, this requires explanation.

Values of A95 below $A95_{min}$ can be caused by smoothing of the signal, for example, in low sedimentation rate environments where PSV is already averaged in a single sample. In this case, the low A95 values can be adequately explained, and the site can be considered reliable for geological purposes, but not for adequately sampling PSV. On the other hand, a low A95 value obtained from averaging a sufficiently long ($N > 15$) series of lava flows, each representing a spot reading of the field may not adequately sample PSV, possibly caused insufficient time averaging, which needs checking (see McElhinny & McFadden 1997; Biggin *et al.* 2008a,b).

Values of A95 values higher than $A95_{max}$ suggest an additional source of scatter besides PSV, for example, caused by averaging rotations between sites within the data set. The data set must in principle be considered as suspect, and the origin of the additional scatter requires assessment. The reliability envelope we present here therefore distinguishes data sets that are statistically reliable (i.e.

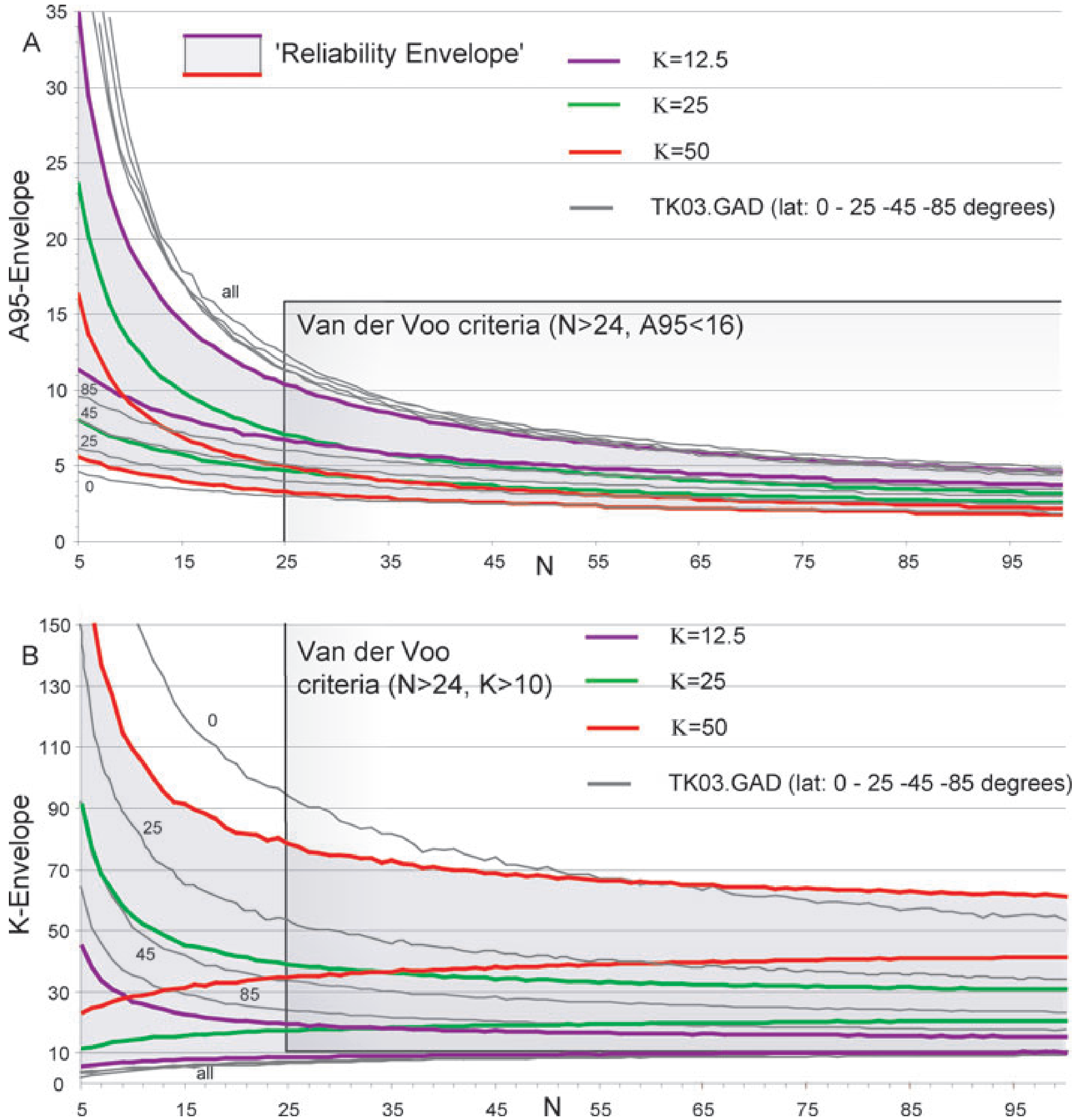

Figure 3. (A) A95—envelopes at the 95 per cent (only dependent on N) for our Fisherian VGPs models ($K = 12.5$, 25 and 50). $A95_{max}$ and $A95_{min}$ (eqs 3 and 4) are derived from the upper and lower boundaries from the Fisherian models with $K = 12.5$ and $K = 25$, respectively. For comparison we also show the expected A95 envelope for the TK03.GAD model ($\lambda = 45°$). The box indicated with the black lines and grey shaded area shows the statistical requirements for a reliable direction or pole suggested by Van der Voo (1990). (B) K-envelopes at the 95 per cent bootstrap error level that correspond with the A95 envelopes. At low N, the K values of sampled distributions values may become very high, as in lavas.

within the envelope) from data sets of which the reliability should be further assessed.

6 PRECISION AND DISCRIMINATION OF DIRECTIONS

The precision required for a meaningful conclusion in palaeomagnetic-geological research may vary from study to study. In many cases, the absolute palaeomagnetic directions or poles with their errors are translated into relative (rotational or latitudinal) motions of geological units. To this end, testing whether two distributions share a CTMD is widely used.

Particularly the precision of the declination and inclination at a given N vary strongly with latitude, as illustrated in Fig. 4. Consider a rotation study that requires a precision of the declination of 5° (i.e. $\Delta D_x \le 5°$), or a palaeolatitude study that requires a precision on inclination $\Delta I_x \le 5°$(see eqs 1 and 2). In these studies, the (expected) palaeolatitude of the geological target determines to a large extent the sampling strategy. For example, the rotation study would require at least 25 samples of PSV over sufficient time (preferably > 100 kyr) for latitudes below 20°, but this increases quickly to 50–80 samples at mid-latitudes (Fig. 4, declination), and requires an exponentially growing amount of samples at higher latitudes. A similar, but inverse line of reasoning pertains to inclination as a measure of palaeolatitude: at low latitudes significantly more samples are required than at higher latitudes to arrive at the same precision (Fig. 4, inclination). The statistical reliability of, for example, fold test and reversal tests only assesses whether two data sets are indistinguishable, and they depend largely on the precision of the

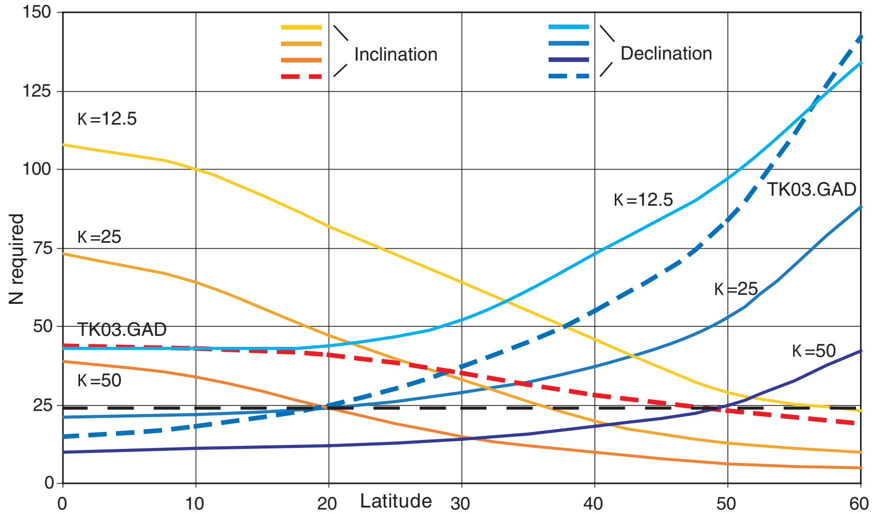

Figure 4. Number of unique modelled readings of the magnetic field (directions) that are necessary to obtain an inclination **or** declination within 5° of the true mean (of the parental – $N = 10.000$ – data set) (in 95 per cent of the cases) for all models considered in this study.

tested data sets. A positive fold test between two sites with an A95 of 30° each may be positive, but hardly meaningful.

7 APPLICATION TO PUBLISHED PALAEOMAGNETIC DATA

Since it has become common practice to apply Fisher statistics on palaeomagnetic directions rather than on VGPs, many published palaeomagnetic studies only provide mean directions with α_{95} and k, or poles with dp/dm. This is especially the case for sedimentary data sets, where it is not common to publish the individual directions per sample or even per level. To allow application of the N-dependent reliability envelope to published data, it is therefore necessary to convert published values of α_{95} to the corresponding A95 of the VGP distribution.

Both Creer (1962) and Cox (1970) introduced a conversion equation (assuming Fisherian VGPs) between k and K, and hence α_{95} and A95. These are

Cox (1970): $$\frac{k_s}{K_p} = \frac{2(1 + 3\sin^2\lambda)^2}{(5 + 3\sin^2\lambda)}; \quad (5)$$

Creer (1962): $$\frac{k_s}{K_p} = \frac{2(1 + 3\sin^2\lambda)}{(5 - 3\sin^2\lambda)}. \quad (6)$$

Cox (1970) also provides a conversion in the case of Fisherian distributions of directions.

$$K_p = \frac{8k_s}{(5 + 18\sin^2\lambda + 9\sin^4\lambda)}. \quad (7)$$

In Fig. 5(A), we show the curves for Fisherian VGPs and Fisherian directions (Cox 1970) together with the A95/α_{95} ratios derived from the TK03.GAD and the Fisherian VGP models. We also determined the A95/α_{95} ratios for the data from the PSV database of lavas (PSVRL) for the last 5 Myr. We only used lava sites with $k > 50$ and $N > 3$ from the northern hemisphere. We also included the new data sets reported by Johnson *et al.* (2008).

First, it is evident that the assumption of Fisherian directions does not predict the data set correctly. As expected, a much better fit is obtained assuming Fisherian VGPs. Secondly the A95/α_{95} curves from the Fisherian VGPs fit the observations better than TK03.GAD with no cut-off. TK03.GAD yields a much better fit, however, when a cut-off is applied. The Fisherian VGP model with $\kappa = 25$ provides the best representation of the data, especially at latitudes >20°. We use the α_{95}/A95 conversion assuming a Fisherian distribution with $K = 25$ as a standard. In the following case study, we use this conversion on published data from the eastern Mediterranean.

7.1 A case study: the eastern Mediterranean

We have compiled all published sedimentary data sets obtained from Eocene and younger sediments in the eastern Mediterranean region. This results in a database of 549 sites with N varying between 3 and 200 (see the Supporting Information). We have chosen the eastern Mediterranean region as the case study mainly because of the wealth of published palaeomagnetic sites. In addition, Europe has undergone little palaeolatitudinal motion since the Eocene, within only a few degrees (Torsvik *et al.* 2008). Hence, the present latitude approximates the palaeolatitude since the Eocene. Finally, there is good control on the age and timing of the accretion of blocks to Europe (Sengör & Yilmaz 1981; van Hinsbergen *et al.* 2005a), which allows us to select only data from those blocks that were already accreted to Eurasia at the timing the sampled sediments were deposited. All sites are within a few degrees of a palaeolatitude of ∼35°, and this enabled us to simply recalculate A95 from the published values of α_{95} by using a constant factor of ∼1.1, as derived from the conversion of eq. (6) for this nearly constant latitude. We show the data as A95 versus the number of samples N, including the $A95_{max}$ and $A95_{min}$ reliability envelope as we have proposed earlier (Fig. 3).

The results of all sites shows that the distribution of A95 values versus N matches remarkably well the predicted shape of the $A95_{min/max}$ envelope, particularly for $N > 20$. At lower N, however, the distribution of A95s appears to be offset to lower A95 values. In many cases this is likely caused by averaging PSV within sedimentary samples, caused by a low sedimentation rate. Hence, application of an A95 envelope as a criterion for acceptance of palaeomagnetic sites would eliminate a large number of

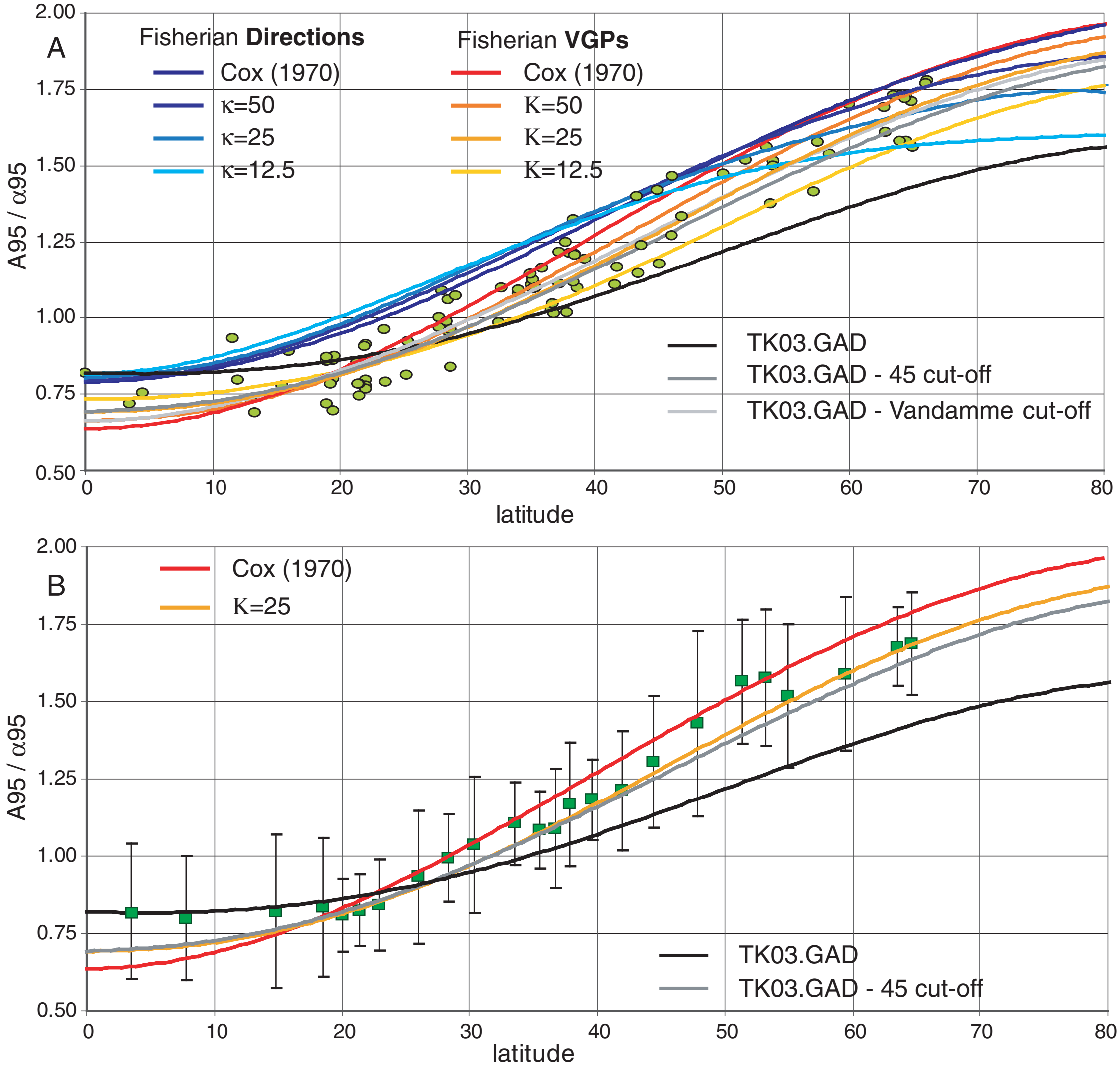

Figure 5. (A) A95/a95 versus latitude (derived from K/k ratios) for all models discussed in this study shown together with selected data ($N > 3$ and $K > 50$) from the PSVRL (version) database and new TAFI (see Johnson *et al.* 2008) studies (see text for further information). The theoretical curves described by Cox (1970) for both Fisherian VGPs and Fisherian directions, are derived from eqs 5 and 7. (B) The same as for Fig. 5(a), but with a 10-point moving average (with two standard-deviation error-bars) of the PSVRL + TAFI data.

sites: 103 of the 549, or 19 per cent. On the contrary, application of $A95_{max,}$ leads to elimination of only 14 sites having too high A95, corresponding to only 2.6 per cent. The sites that fall above $A95_{max}$, are 'unreliable' in the sense that their scatter cannot be explained by PSV alone, and an additional source of scatter must be inferred.

Our A95 envelope would eliminate sediment sites in roughly 20 per cent of the cases for studies of geomagnetic field behaviour because they under-represent PSV, either as a result of some averaging of PSV within the time represented by the sediment sample, or by sampling insufficient time within a single site. The final result in terms of geological relevance may still be justified: averaging of PSV is often desirable and forms the fundament of the GAD hypothesis. An assessment of the sedimentation rate is then required.

A possible alternative explanation for (too) low A95 is the removal of outliers. This is quite often applied, and usually indicated in the tables, but mostly without strict criteria other than that outliers 'do not fit the general picture'. Here, the objective application of a fixed or variable cut-off procedure is advocated. We noted that in several studies many samples that were removed as outliers would not have been removed by applying a cut-off. Many 'outliers' can be simply explained by PSV, and could potentially provide valuable information. The reliability envelope makes it furthermore clear that—although perhaps counterintuitive—lower errors do not necessarily indicate higher reliability. From our case study it also follows that too low A95 values typically occur at low values of N. For N larger than ~15, there are virtually no studies that show too low A95, and only few that show too high A95.

It is a common and logical practice to determine a palaeomagnetic direction or pole in a locality by sampling multiple sites, because the quality of palaeomagnetic signal may change from place to place, small local rotations can be recognized and outliers, for example, caused by hillside creep or local deformation, can be identified and filtered, thereby increasing the chance of success. For averaging out PSV, it is usually not relevant whether the samples are derived from a single locality (with high N) or from multiple sites (each of low N) making up a locality, as long as sufficient samples are used to

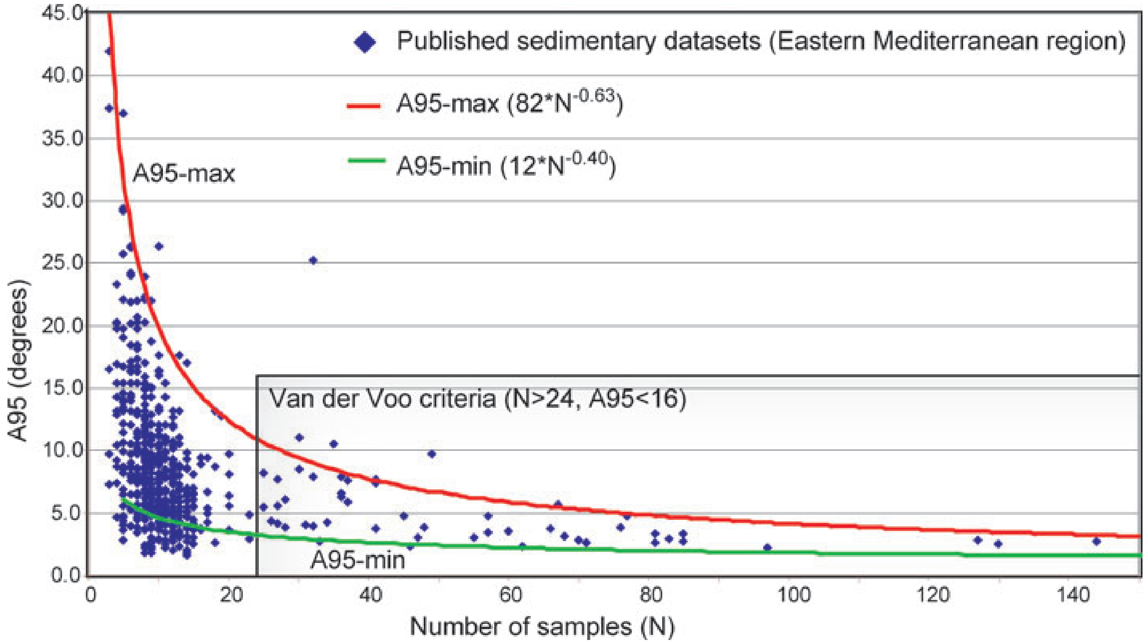

Figure 6. All data published from sites in Eocene and younger sediments (549 sites) in the eastern Mediterranean region, used to illustrate the effect of our new reliability criteria (green and red lines for A95-min and A95-max, respectively).

obtain the required precision. Therefore, we advocate to not only publish site means, but also the individual directions (in electronic appendices) obtained from all sites that make up a locality result. This enables to assess the VGP distributions in terms of successfully recording the geomagnetic field, using our A95 envelop and other useful parameters like E, S and k.

8 CONCLUSIONS

In this study, we examine the role of PSV in the use of statistics for palaeomagnetic studies, and we provide new reliability criteria for palaeomagnetic poles or directions. We derive the criteria from simulations by sampling Fisherian VGP distributions that are an approximate (Harrison 2009) but for most palaeomagnetic purposes practical representation of field behaviour. We find useful properties of the field that are latitude dependent. We compare the simulations with those from sampling a GGP model (TK03.GAD). We show that the TK03.GAD model with a fixed (45°) cut-off and the Fisherian VGP distribution with $\kappa = 25$, are remarkably similar and well fit the observations of the last 5 Myr (Johnson *et al.* 2008; Harrison 2009) as well as older compilations of VGP scatter (Biggin 2008a,b).

Considering PSV models that are in line with reconstructed values for PSV through time and across the globe, and the observation that VGP distributions are circular, we first conclude that Fisher statistics should not be applied to average palaeomagnetic directions but to VGP distributions instead. The resulting Fisherian A95 of the mean VGP is then easily converted into errors in declination (ΔD_x) and inclination (ΔI_x) separately, following Butler (1992). Secondly, we strongly advocate that typical properties of geomagnetic field behaviour, as derived from Fisherian VGP or GGP models like TK03.GAD, are taken into account in the assessment of palaeomagnetic data sets. The latitude-dependent properties (E, S, k) provide useful guidelines for the reliability of a palaeomagnetic data set (e.g. Tauxe *et al.* 2008; Tauxe & Kodama 2009). A reliable assessment of these properties depends on the (sufficient) number of palaeomagnetic samples being taken. Therefore, as an additional instrument of assessing data sets, we provide an N-dependent A95 envelope, bounded by an upper limit $A95_{max}$, and a lower limit $A95_{min}$ that helps to ascertain whether or not a distribution has sufficiently well-sampled PSV and therefore geomagnetic field behaviour. Applying these criteria is indispensable for studies of geomagnetic behaviour, or for studies aiming at using TK03.GAD for inclination error correction through the E/I method. For palaeomagnetic studies aimed at geological reconstructions, they form helpful guidelines and increase the confidence in the rocks having faithfully recorded the field. Additional constraints (fold test, reversal test and laboratory test) remain of course essential.

From our analysis of published eastern Mediterranean data (Fig. 6) it follows that the vast majority of studies do not conform to the Van der Voo criteria, in particular with respect to N and A95. We have provided criteria that are on the one hand more lenient (lower N may still provide relevant information), and on the other hand more strict (for high N the criterion of A95 $< 16°$ should be adapted to a requirement of lower A95, e.g. A95 $< 5°$ for $N >$ 80; Fig. 3).

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Appendix. All data published from sites in Eocene and younger sediments (549 sites) in the eastern Mediterranean region, used to illustrate the effect of our new reliability criteria, and to construct Fig. 6. Lat = latitude; lon = Longitude; N = number of samples; dec = declination; inc = inclination; λ = latitude of the constructed pole; φ = longitude of the constructed pole; α_{95} = published 95 per cent confidence limits determined on directions; k = published Fisher (1953) precision parameter determined on directions, A95 = 95 per cent confidence limit on the pole, calculated by multiplying α_{95} by 1.1 using the convergence of α_{95} to A95 illustrated in Fig. 5, assuming a 35° palaeolatitude for the entire region (see text for further explanation); age-min = minimum numerical age; age-max = maximum numerical age; age = qualitative age; references: data are taken from (Laj *et al.* 1982; Valente *et al.* 1982; Horner & Freeman 1983; Kissel *et al.* 1985,1986,1989,1993,1995,2003; Kissel & Poisson 1986,1987; Sen & Valet 1986; Sen *et al.* 1986; Birch 1990; Marton *et al.* 1990; Speranza *et al.* 1992,1995; Morris & Robertson 1993; Kondopoulou 1994; Morris 1995; Krijgsman *et al.* 1996,2002; Gürsoy *et al.* 1997; Haubold *et al*. 1997; Duermeijer *et al.* 1998,1999,2000; Beck *et al.* 2001; Kaymakci *et al.* 2003; Kostopoulos *et al.* 2003; Krijgsman 2003; Mattei *et al.* 2004; van Hinsbergen *et al.* 2005b,2007)

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