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**Key Points:**

- Within-site data filters (maximum angular deviation cutoff, minimum *k* or *n*, eliminating outliers) do not significantly improve paleopole precision or position
- The precision of paleomagnetic poles is dominated by between-site scatter; within-site scatter has minimal contribution
- For paleopoles, efforts put into collecting multiple samples per site are more effectively spent on collecting more single-sample sites

**Supporting Information:**

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

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# Influence of Data Filters on the Position and Precision of Paleomagnetic Poles: What Is the Optimal Sampling Strategy?

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**Abstract** To determine a paleopole, the paleomagnetic community commonly applies a loosely defined set of quantitative data filters that were established for studies of geomagnetic field behavior. These filters require costly and time-consuming sampling procedures, but whether they improve the precision and influence the position of paleopoles has not yet been systematically analyzed. In this study, we performed a series of experiments on four datasets which consist of 73–125 lava sites with 6–7 samples per lava. The datasets are from different regions and ages, and are large enough to represent paleosecular variation, yet include demonstrably unreliable paleomagnetic directions. We show that the systematic application of data filters based on within-site scatter (a maximum angular deviation filter on individual directions, a *k*-cutoff, a minimum number of samples per site, and eliminating the farthest outliers per site) cannot identify unreliable directions. We find instead that excluding unreliable directions relies on the subjective interpretation of the expert, highlighting the importance of making all data available following the FAIR principles. In addition, data filters that decrease the number of sites even have an adverse effect; they decrease the precision of the paleopole. Between-site scatter often outweighs within-site scatter, and when collecting paleomagnetic poles, the extra efforts put into collecting multiple samples per site are more effectively spent on collecting more single-sample sites.

## 1. Introduction

Paleomagnetic poles, or paleopoles, quantify the past position of rocks relative to the geomagnetic pole and constrain tectonic reconstructions and apparent polar wander paths (APWPs; e.g., Besse & Courtillot, 2002; Torsvik et al., 2012). The calculation of paleopoles relies on the assumption that the time-averaged geomagnetic field approximates a geocentric axial dipole (GAD), but is complicated by short-term deviations from this field (e.g., Cromwell et al., 2018; Oliveira et al., 2021) known as paleosecular variation (PSV). To obtain a paleopole, paleomagnetists therefore average virtual geomagnetic poles (VGPs), whereby every VGP is then assumed a "spot reading": an instantaneous reading of the past geomagnetic field collected from a rock unit ("site") that represents an increment of geological time, such as a lava flow (Butler, 1992; Tauxe et al., 2010). However, not every VGP represents an accurate spot reading because artifacts may be introduced by measuring errors or remagnetization (e.g., Bilardello et al., 2018; Butler, 1992; Irving, 1961, 1964). Therefore, the paleomagnetic community commonly uses a set of data filters to acquire a set of reliable spot readings and to objectively eliminate outliers and unreliable data. However, these filters vary between authors and were not determined by studies aiming to constrain paleopoles.

The studies that established the data filters, investigated PSV and geomagnetic field behavior by determining the between-site scatter of a set of VGPs (e.g., Cromwell et al., 2018; de Oliveira et al., 2021; Johnson & Constable, 1996; Johnson et al., 2008; Tauxe et al., 2003). To this end, these studies aim to correct for within-site scatter induced by measuring errors and typically require well-determined directions with a low maximum angular deviation (MAD) and a minimum number of readings per site, although the cutoff values for these criteria vary between authors (e.g., Asefaw et al., 2021; Biggin et al., 2008; Cromwell et al., 2018; Doubrovine et al., 2019; Johnson et al., 2008). The resulting paleomagnetic directions are then averaged to a site-mean direction which is converted to a VGP if the site passes a criterion for the minimum within-site precision value ("cutoff"), typically expressed as a Fisher (1953) precision parameter $k$. This value also varies between authors, for example, $k \geq 50$ or $k \geq 100$ (e.g., Biggin et al., 2008; Cromwell et al., 2018; Johnson et al., 2008; Tauxe et al., 2003). Subsequently, similar procedures have become common for calculation of paleopoles (e.g., Butler, 1992; Lippert et al., 2014; Meert et al., 2020). However, does this time- and data-intensive procedure improve the precision and influence the position of paleopoles?

In this study, we analyze to what extent commonly applied paleomagnetic data filters established for PSV studies affect the position and precision of paleopoles. To this end, we study four large paleomagnetic datasets obtained from lava sequences from the Cretaceous of Mongolia, the Permian of Norway, the Miocene of Turkey, and the Quaternary of Antarctica. These datasets are large enough to represent PSV, but contain additional between-site and within-site scatter of varying magnitude due to measurement errors, lightning-induced remagnetization, and/or tectonic deformation. We perform a series of experiments to examine the effects of the systematic application of data filters on the position and precision of paleopoles. We evaluate whether these filters can exclude outliers and filter non-PSV induced scatter from the paleomagnetic datasets. We then assess how a given number of paleomagnetic directions is optimally distributed over a collection of paleomagnetic sites to acquire the best-constrained paleopole position. We discuss to what extent the filters used in PSV studies influence paleopole position and precision. Our results aim to aid paleomagnetists to optimize their sampling and data filtering strategies.

## 2. Background

When evaluating the reliability of a paleopole, it is common to apply certain criteria aimed at identifying whether the underlying paleomagnetic data set is representative of PSV (e.g., Butler, 1992; Irving, 1961; McElhinny, 1973; van Alstine & de Boer, 1978). In his landmark paper, van der Voo (1990) proposed a set of such reliability criteria that became widely adopted by the paleomagnetic community, and was only recently updated (Meert et al., 2020). van der Voo (1990) recommended to average a minimum set of 25 samples or sites (i.e., spot readings) for a paleopole, and formulated loosely defined filters using Fisher (1953) statistics. Those statistics are used to describe a paleomagnetic data set and can be applied to either directional data or VGPs. Three parameters are of importance in this statistical approach: the radius of the 95% confidence cone around the mean ($\alpha_{95}$ for directions and $A_{95}$ for VGPs), the precision parameter ($k$ for directions and K for VGPs), and the circular standard deviation (S) that quantifies the angular between-site dispersion of VGPs. van der Voo (1990) suggested filters for these parameters: $\alpha_{95}$ or $A_{95} \leq 16°$, and $k$ or K $\geq 10$. In later studies, filters were added to determine the reliability of each VGP based on quality filters used in PSV studies, such as $n > 4$ and $k > 50$ (e.g., Lippert et al., 2014).

For obtaining paleopoles, paleomagnetists usually sample multiple sites at a locality, where every site likely represents a spot reading of the paleomagnetic field. Lava flow units, which cool geologically instantaneously, are commonly such "spot reading recorders". Sediment samples are usually treated as spot readings (e.g., Tauxe & Kent, 2004; Vaes et al., 2021), but do average some geological time, and whether directions from the same sedimentary horizon represent the same spot reading is difficult to establish. Our analysis below thus focuses on lava sites.

Each paleomagnetic direction represents a paleomagnetic component determined with the principal component analysis of Kirschvink (1980) that is interpreted by the expert as the characteristic remanent magnetization (ChRM). Each of these components comes with a maximum angular deviation (MAD) value that describes component uncertainty, and MAD values of 15° are typically used as reliability filter (McElhinny & McFadden, 2000), although smaller angles (e.g., 5°, Asefaw et al. (2021)) are also used. The total scatter in a paleomagnetic data set then consists of within-site and between-site scatter (McElhinny & McFadden, 1997), whereby the uncertainties in paleomagnetic directions or VGPs are typically not propagated through the different levels of the hierarchical framework and directions/VGPs are typically given unit weight in the calculation of a mean direction/paleopole (e.g., Heslop & Roberts, 2020; Irving, 1964). Paleomagnetists collect multiple samples per site to test whether a paleomagnetic direction is reproducible and to average measurements and other random errors (e.g., Meert et al., 2020; van der Voo, 1990). A quality check for within-site precision is a $k$-cutoff (Tauxe et al., 2003), where sites with a $k$ value lower than an arbitrary value of 50 or 100 are discarded (e.g., Biggin et al., 2008; Johnson et al., 2008; Lippert et al., 2014). Furthermore, outliers are often subjectively discarded from sites based on the "expert eye" and experience of the interpreter. How many samples should be collected per site is not widely agreed upon. Based on Monte Carlo simulations, a minimum number of five independently oriented samples was deemed necessary to estimate $k$ reliably (Tauxe et al., 2003). Others suggest that three (Meert et al., 2020), four (Cromwell et al., 2018; Lippert et al., 2014), or six (Asefaw et al., 2021) samples are needed. Most paleomagnetic studies collected six to eight samples per lava site.

To average between-site scatter, assumed predominantly to be the result of PSV, multiple sites are collected, but the minimum number of sites required for a "good" average, that is, the paleopole, is not well defined

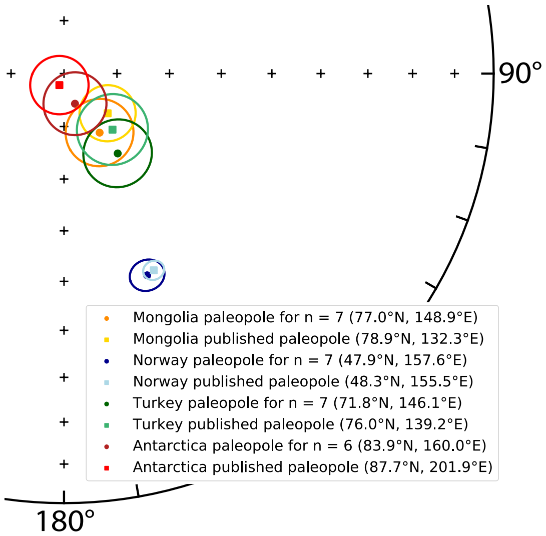


**Figure 1.** Equal angle projection showing the paleopoles and their $A_{95}$ following from our reinterpretation (used as reference paleopoles in this study), calculated with all sites and $n = 7$ (or $n = 6$, in case of Antarctica), and the published paleopoles and their $A_{95}$ of Mongolia, Norway, Turkey, and Antarctica. All paleopoles are plotted on the upper hemisphere, whereby the longitude increases clockwise and the center represents the northern geographic pole.

(Tauxe et al., 2010). Instead of providing such a minimum number, Deenen et al. (2011) provided a measure to identify whether the between-site scatter of a data set is straightforwardly explained by PSV alone, using a range of reconstructed values from detailed PSV studies. If datasets indeed represent PSV, the accuracy of the position of a paleopole is expected to increase with increasing number of underlying VGPs, which was recently shown to be true for the paleopoles behind the most recent global APWP (Vaes et al., 2022). Meert et al. (2020) suggested eight sites are sufficient to determine a paleopole, provided that each site is constrained by at least three samples. Based on a statistical simulation of PSV, Tauxe et al. (2003) showed that a minimum of approximately 100 sites may be required to fully sample PSV. However, this number is rarely obtained due to limited availability of sites and because resources are consumed by sampling a high number of samples for each site. Below, we analyze the effect of these different sampling and filtering strategies on the position and precision of the resulting paleopole.

## 3. Datasets and Approach

### 3.1. Datasets

As basis for our analysis, we use four paleomagnetic datasets derived from lavas from Mongolia (van Hinsbergen et al., 2008), Norway (Haldan et al., 2014), Turkey (van Hinsbergen et al., 2010), and Antarctica (Asefaw et al., 2021). We chose these datasets because they consist of a particularly large number of paleomagnetic sites (with $n \geq 6$ samples per site) and cover a broad range of paleolatitudes and ages. The results were previously published, but for the purpose of this study, we reinterpreted the demagnetization diagrams of all samples. We did this by identifying the characteristic remanent magnetization (ChRM) by principal component analysis (Kirschvink, 1980), using the online paleomagnetic analysis platform Paleomagnetism.org (Koymans et al., 2016, 2020). We have thereby not forced interpreted components through the origin, and we have not used the remagnetization great-circle method of McFadden and McElhinny (1988), as was occasionally done in the original interpretations. All interpretable diagrams were interpreted, and no samples were discarded based on obviously outlying directions, such as those with abnormally high intensities and rapid low-temperature decay that are suggestive of lightning strikes (Strik et al., 2003). In other words, we deliberately kept directions that an experienced paleomagnetist would likely immediately discard as unreliable. We also did not exclude sites that were collected from tectonically deformed regions. As a result, the datasets contain larger noise and a higher between-site scatter (lower K value) than the published values. This allows us to assess whether the quality filters alone can clean the data set from outliers, or whether this relies on a subjective "expert eye". The sites from Mongolia, Norway, and Turkey were sampled with a minimum of seven samples per site, and the sites from Antarctica with a minimum of six. Only sites with seven (or six, for Antarctica) interpretable directions are used in our analysis. If sites contain more samples, only the first seven (or six, for Antarctica) samples are used. All uninterpreted data are publicly available in the MagIC database (see Data Availability Statement). Our reinterpretations are provided in the supplementary information (Table S1) to this paper, but because our interpretations are (deliberately) not better than the original interpretations, we will not upload these to the MagIC database to avoid confusion. All paleopole positions from this study differ from the published paleopole positions, but still fall within the 95% confidence region of the respective published paleopoles (Figure 1). In the following, we use these paleopole positions, which followed from our reinterpretation and were calculated with all sites and $n = 7$ (or $n = 6$, in case of Antarctica), as our reference paleopoles.

After the reinterpretation, we arrive at a total of 108 sites with $n = 7$ of lower Cretaceous lavas, corresponding to the base of the Cretaceous Normal Superchron, from the NE Gobi Altai mountain range of southern Mongolia, which erupted at a paleolatitude of ~50°N (van Hinsbergen et al., 2008; vH08). We do not include samples from the Artz Bogd area from the original data set because these appear systematically rotated due to tectonic deformation. Furthermore, only the sites acquired by van Hinsbergen et al. (2008) are included. Our reinterpreted data set

(G22) leads to a higher scatter than the original interpretation of van Hinsbergen et al. (2008) for reasons outlined above ($A_{95,vH08} = 5.3°$ vs. $A_{95,G22} = 6.4°$, $K_{vH08} = 9.1$ vs. $K_{G22} = 5.5$). Most sites have limited within-site scatter and high *k* values, as expected for lava sites.

We arrive at a total of 73 sites with $n = 7$ from lavas of Permian age from the Oslo Graben in Norway, which erupted at a paleolatitude of ∼20°N (Haldan et al., 2014; H14). This data set contains lavas from the Permo-Carboniferous Reversed Superchron (PCRS). Interestingly, the between-site scatter is much lower than for the other three localities (Brandt et al., 2021; Handford et al., 2021). The within-site scatter of this data set, however, is higher. Our reinterpretation contains more scatter than the interpretation of Haldan et al. (2014) ($A_{95,H14} = 1.9°$ vs. $A_{95,G22} = 3.1°$, $K_{H14} = 52.2$ vs. $K_{G22} = 29.4$).

A total of 125 sites with $n = 7$ of lower to middle Miocene lavas and ignimbritic tuffs come from basins in the northern Menderes Massif in western Turkey, which formed at a paleolatitude of ∼35°N (van Hinsbergen et al., 2010; vH10). This data set was acquired in a tectonically active area and contains basins that were interpreted to be tectonically coherent, and basins that were interpreted by van Hinsbergen et al. (2010) to be internally tectonically disturbed (later confirmed and mapped out in detail by Uzel et al. (2015, 2017)). It also contained sites acquired by preceding studies, but only the sites acquired by van Hinsbergen et al. (2010) are included in our data set. Our re-interpreted data set contains a comparable scatter as the data set of van Hinsbergen et al. (2010) ($A_{95,vH10} = 6.7°$ vs. $A_{95,G22} = 6.4°$, $K_{vH10} = 4.6$ vs. $K_{G22} = 4.8$).

Finally, we use 107 sites with $n = 6$ from lavas of Plio-Pleistocene age of the Erebus volcanic province in Antarctica at a latitude of ∼75°S (Asefaw et al., 2021; A21). We did not reinterpret this data set and use the published interpretations, but only use sites with $n = 6$. We note that Asefaw et al. (2021) combined some sites; in our analysis, however, we still use the original, uncombined sites. Furthermore, we do not use the age constraint of <5 Ma and *k*-cutoff. Our reinterpretation does not significantly differ from the published one of Asefaw et al. (2021) ($A_{95,A21} = 5.5°$ vs. $A_{95,G22} = 5.9°$, $K_{A21} = 7.7$ vs. $K_{G22} = 6.3$).

### 3.2. Approach

We perform a series of experiments to study the effect on paleopole position and precision of filters that one may use when multiple samples per site are available. These filters are: (a) a MAD cutoff; (b) a *k*-cutoff; (c) the number of samples per site (*n*), and (d) discarding outliers of within-site dispersion. In addition, we assess how a given number of paleomagnetic directions may be optimally distributed over a collection of paleomagnetic sites (N) to acquire the best-constrained paleopole position. We tested whether the distributions of VGPs conform to a Fisher (1953) distribution by applying the quantile-quantile (Q-Q) method described by Fisher et al. (1987). We found that all studied datasets have circularly symmetric distributions of VGPs. The VGPs of the data set from Turkey are Fisherian, whereas the datasets from Norway and Mongolia conform to a Fisher distribution only after application of a 45° cutoff and the Antarctica data set after application of a Vandamme (1994) cutoff. Therefore, we will be using the standard Fisher (1953) parameters in our analyses: the radius of the 95% confidence cone ($p = 0.05$) around the paleopole,

$$\left(\mathrm{A}_{95} = \cos^{-1}\left(1 - \frac{N-R}{R}\left(\left(\frac{1}{p}\right)^{\frac{1}{N-1}} - 1\right)\right)\right) \quad (1)$$

the precision parameter ($K = \frac{N-1}{N-R}$), and the circular standard deviation $\left(S^2 = \frac{1}{N-1}\sum_{i=1}^{N}\Delta_i^2\right)$. Furthermore, we calculate the angular distance to the reference paleopole, which is shown in Figure 1. We perform experiments using a Python code, which we developed making extensive use of the freely available paleomagnetic software package PmagPy (Tauxe et al., 2016). We perform the calculations 1000 times, and each time different samples and/or sites are selected from the population. We then calculate the mean and standard deviation of the parameters (angular distance to the reference paleopole, $A_{95}$, K, and S). Our Python code is available on Zenodo (see Data Availability Statement).

## 4. Results

### 4.1. Effect of MAD Cutoff

First, we analyze whether application of a maximum angular deviation (MAD) cutoff improves paleopole precision. We apply MAD cutoffs of 5°, 10°, and 15° on each of our datasets. The Antarctica data are very well determined, and all data pass these filters. We thus concentrate our analysis on the data from Mongolia (6%–32% eliminated), Norway (7%–52% eliminated), and Turkey (3%–12% eliminated). After applying the filter, we randomly select one direction from each site such that $n = 1$, convert it to a VGP using the corresponding site longitude and latitude, and compute the paleopole with all sites for each analyzed filter. In no case the MAD cutoff eliminates all directions from a site, thus N is constant. Each analysis is conducted 1000 times, and we compute the average angular distance to the reference paleopole with $n = 7$, $A_{95}$, K, and S, and their 95% confidence interval. The results show that applying a MAD cutoff does not significantly change the position and precision of the paleopole (Figure 2).

### 4.2. Effect of a *k*-cutoff

A widely used filter to establish site-mean directions that represent spot readings of the paleomagnetic field is to check for high within-site scatter by applying a *k*-cutoff to the distribution of within-site directions. The Fisher (1953) precision parameter (*k*) is computed for the collection of ChRM directions per site, which are, in principle, expected to conform to a Fisher distribution, under the assumption that the within-site scatter results from randomly distributed errors such as measuring errors. The *k*-cutoff aims to eliminate sites that may not be representative of a spot reading, and sites with *k* values below a certain cutoff value are therefore discarded. We analyze the effect of the *k*-cutoff size on between-site scatter, and we test whether the eliminated sites indeed represent outliers. We apply the *k*-cutoff to all sites and increase its value by increments of ten. Afterward, we convert all remaining site-mean directions to VGPs using the corresponding site longitude and latitude, and from that calculate the paleopole (Figure 3; Figure S1) and its N, $A_{95}$, K, and S (Figure 4). The paleopole positions do not significantly change when applying a *k*-cutoff (Figure 3; Figure S1). When a low $k \geq 10$ cutoff is applied, the number of sites remaining in the data set decreases by approximately 15%–30% (Figure 4a), omitting sites with near-random direction distributions. Increasing the cutoff size beyond 20, the decay in sites decreases. The $A_{95}$ increases with increasing *k*-cutoff due to a decrease in N (Figure 4b). As expected, discarding sites with high within-site scatter leads to a higher K and lower S, although the effects are small (Figures 4c and 4d), except in the data set from Norway where K rises from 30 to 75. We note the K value of the data set from Mongolia approximately doubles from 6 to 11 when a *k*-cutoff of 200 is applied, but ~75% of the data is excluded while doing so. No major improvement becomes apparent in any of the variables at the commonly used cutoff sizes of 50 and 100. In addition, the elimination of sites is not demonstrably filtering outliers (Figure 3). Importantly, although the application of a *k*-cutoff may subtly decrease S and increase K, the decrease in N leads to an increase of the $A_{95}$, and thus to a decrease in precision of the paleopole when a *k*-cutoff is applied, whereas the paleopole position remains approximately the same.

### 4.3. Effect of the Number of Samples per Site (*n*)

Next, we analyze the benefits of collecting multiple samples per site to average within-site or between-sample errors. To this end, we study the influence of the number of samples per site (*n*) on the paleopole of a data set (Figure 5) and its angular distance to the reference paleopole with $n = 7$ (or 6, for Antarctica), $A_{95}$, K, and S (Figure 6). For each *n*, we perform the calculations 1000 times. Each calculation randomly collects *n* different samples from the total collection of samples per site. For each calculation, we compute a site-mean direction from these *n* samples, convert it to a VGP using the corresponding site longitude and latitude, and compute the paleopole by averaging N sites (Figure 5). We then calculate the mean and standard deviation of each parameter (angular distance to the reference paleopole, $A_{95}$, K, and S) from the 1000 values obtained for each of the paleopoles (Figure 6). The paleopole position calculated with $n = 1$ falls within the $A_{95}$ of the reference paleopole calculated with $n = 7$ in 100% of the calculations for the datasets from Mongolia, Turkey, and Antarctica (Figure 5). For the Norwegian data set, this is the case for 91% of the calculations. In other words, the paleopole position is barely influenced by the number of samples per site (Figure 6a) and stays within the 95% confidence interval. The influence on the $A_{95}$ is small, but there is a slight decrease in the $A_{95}$ when within-site scatter is averaged by

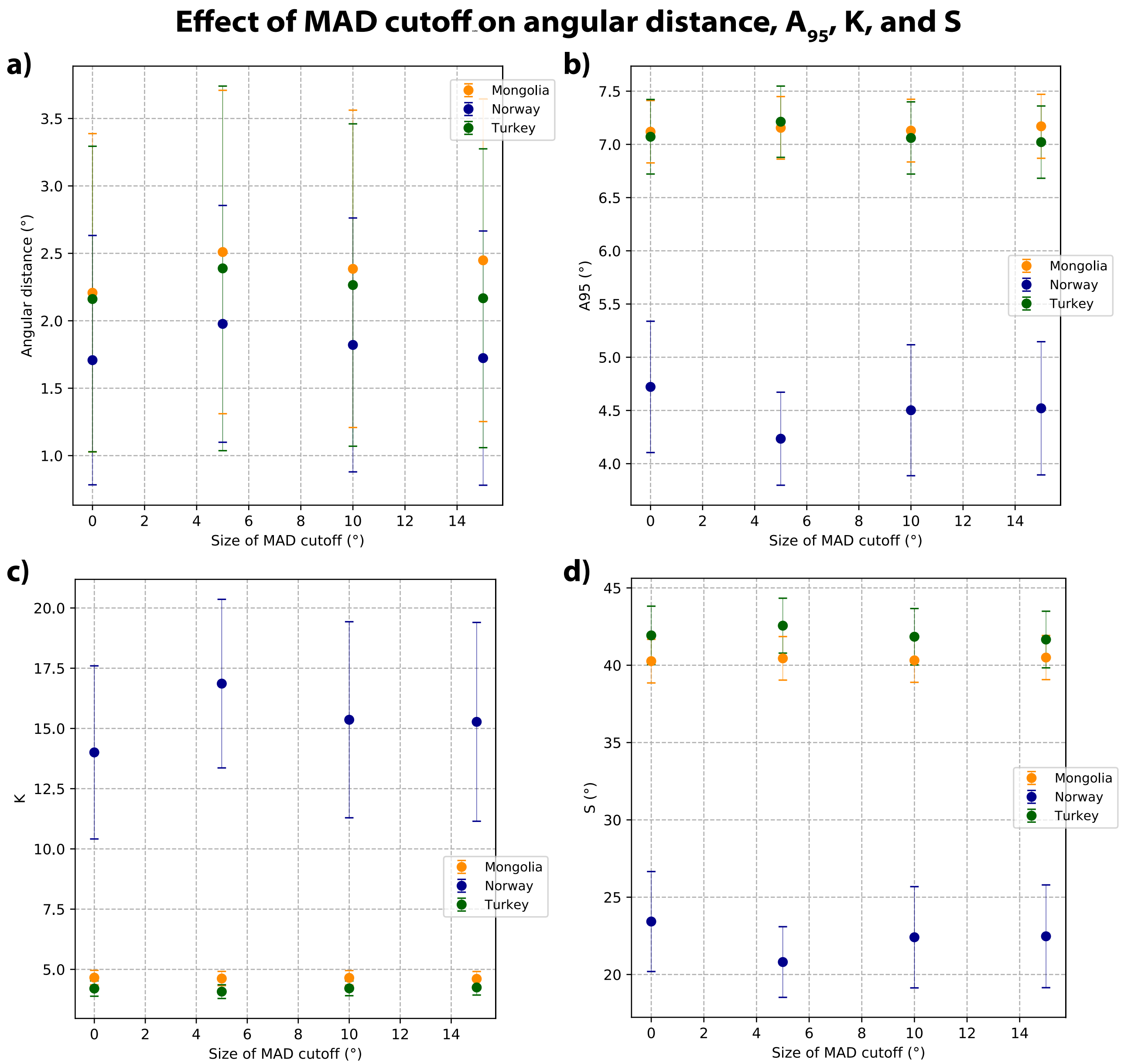


**Figure 2.** Effect of a MAD cutoff on the (a) angular distance of the acquired paleopole to the reference paleopole whereby all sites have $n = 7$ (or 6, for Antarctica), and the (b) $A_{95}$, (c) K, and (d) S of the acquired paleopole. Every datapoint represents 1000 calculations, with error bars indicating the 95% confidence interval of these 1000 calculations. Each calculation, one random sample per site was selected, such that $n = 1$ and N is constant.

increasing $n$ (Figure 6b). This varies from less than 0.5°–1.5°, with the largest effect occurring for the data set from Norway, whose sites have the largest within-site scatter. We find that the number of samples per site has a minor influence on K and S (Figures 6c and 6d). Only Norway shows an increase in K from approximately 14 to 29 and a drecrease in S from 23° to 16°. This experiment shows that the effect of the number of samples per site on determining a paleopole position is surprisingly small, even if between-site scatter is somewhat decreasing.

### 4.4. Effect of Discarding Outliers on Site Level

One potential benefit of having multiple samples per site is to discard outliers, commonly done in the paleomagnetic community based on the "expert eye" of the interpreter. Here, we study the effect of discarding outliers on site level, by eliminating the farthest directions from the site mean. We do this three times, eliminating the one, two, or three most outlying directions. Interestingly, we find generally no effect of eliminating within-site outliers

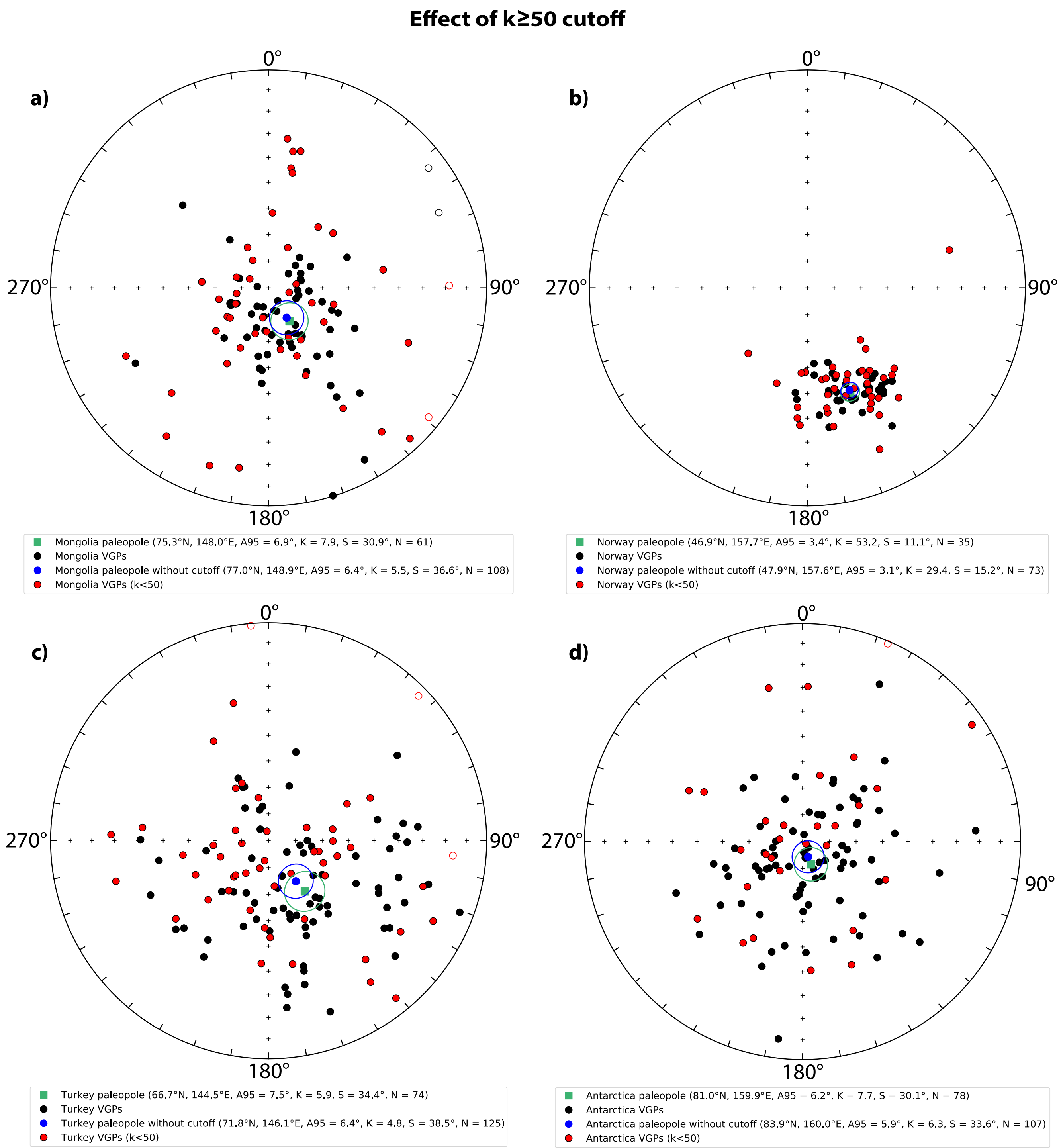


**Figure 3.** Equal angle projections showing the VGPs of the data set from (a) Mongolia whereby each site has $n = 7$, (b) Norway whereby each site has $n = 7$, (c) Turkey whereby each site has $n = 7$, and (d) Antarctica whereby each site has $n = 6$. Solid (open) symbols are plotted on the upper (lower) hemisphere, whereby the longitude increases clockwise. The center of each subplot represents the northern geographic pole. Sites discarded by a $k \geq 50$ cutoff are indicated in red. In green, the paleopole and its $A_{95}$ with application of the cutoff are indicated. In blue, the reference paleopole and its $A_{95}$ (without application of the cutoff) are indicated.

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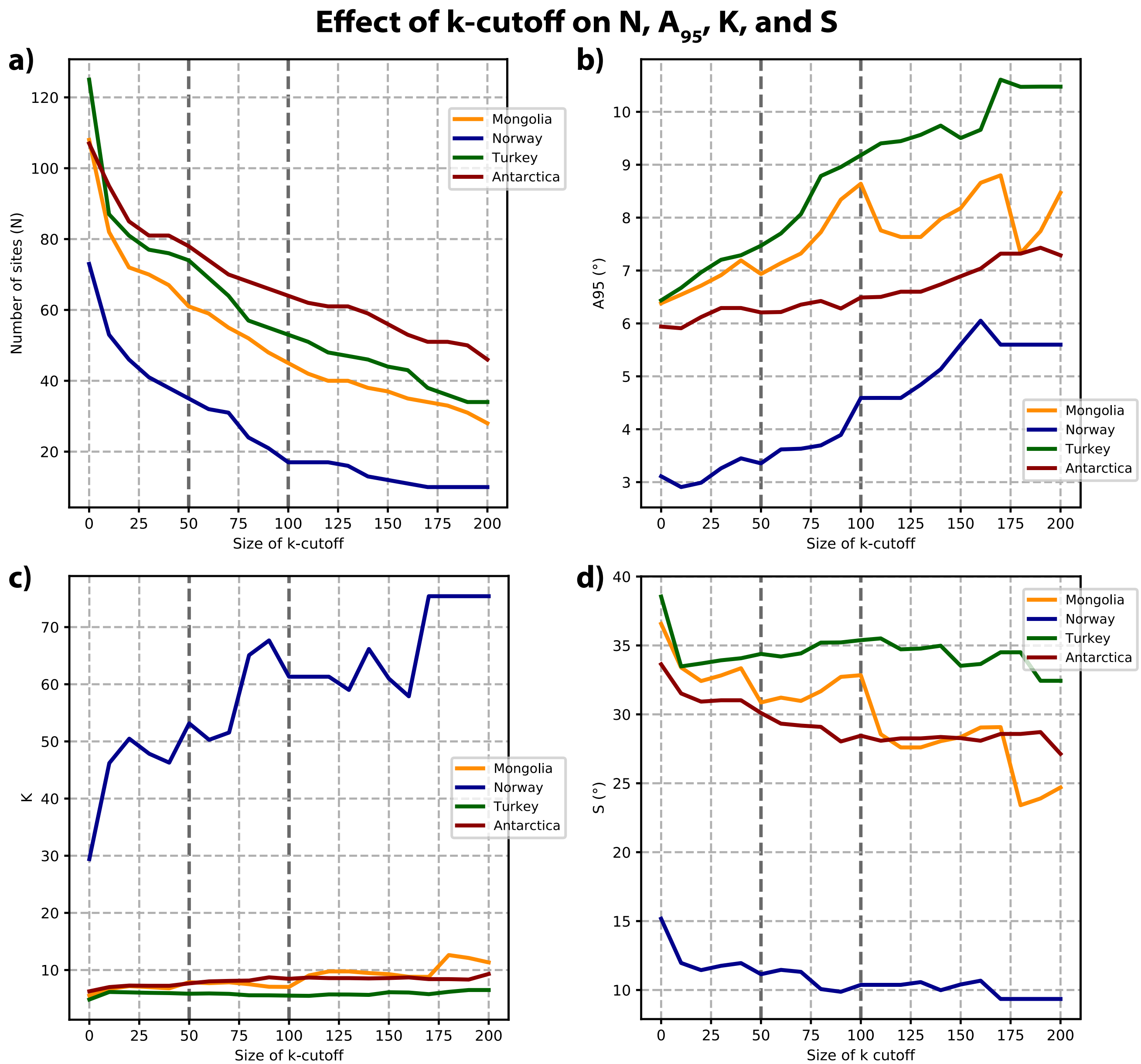


**Figure 4.** Effect of the size of the *k*-cutoff on (a) the number of sites (N) remaining in the data set after application of the cutoff, and the (b) $A_{95}$, (c) K, and (d) S of the acquired paleopole. Commonly applied cutoff sizes of 50 and 100 are indicated with gray dashed lines.

on paleopole position and its $A_{95}$, K, and S (Figure 7), and for the Norway data set, the between-site scatter even increases. This is because VGP positions do not systematically shift toward or away from the paleopole (Figures S2-S5). As a result, decreasing the within-site scatter by removing outlying directions has little effect on the between-site dispersion of VGPs.

### 4.5. Effect of Filters on Small Data Collections

The datasets that we analyzed above are unusually large. In most cases, paleomagnetic datasets are much smaller due to either the limited availability of lavas, or due to time constraints and the choice to collect multiple samples per site, rather than more sites with lower *n*. We thus briefly illustrate whether the filters we applied above on the large datasets yield different results for small datasets. To this end, we analyze the Turkey data set, which has the largest scatter. We again test the effect of a MAD cutoff, *k*-cutoff, minimum *n* per site, and number of

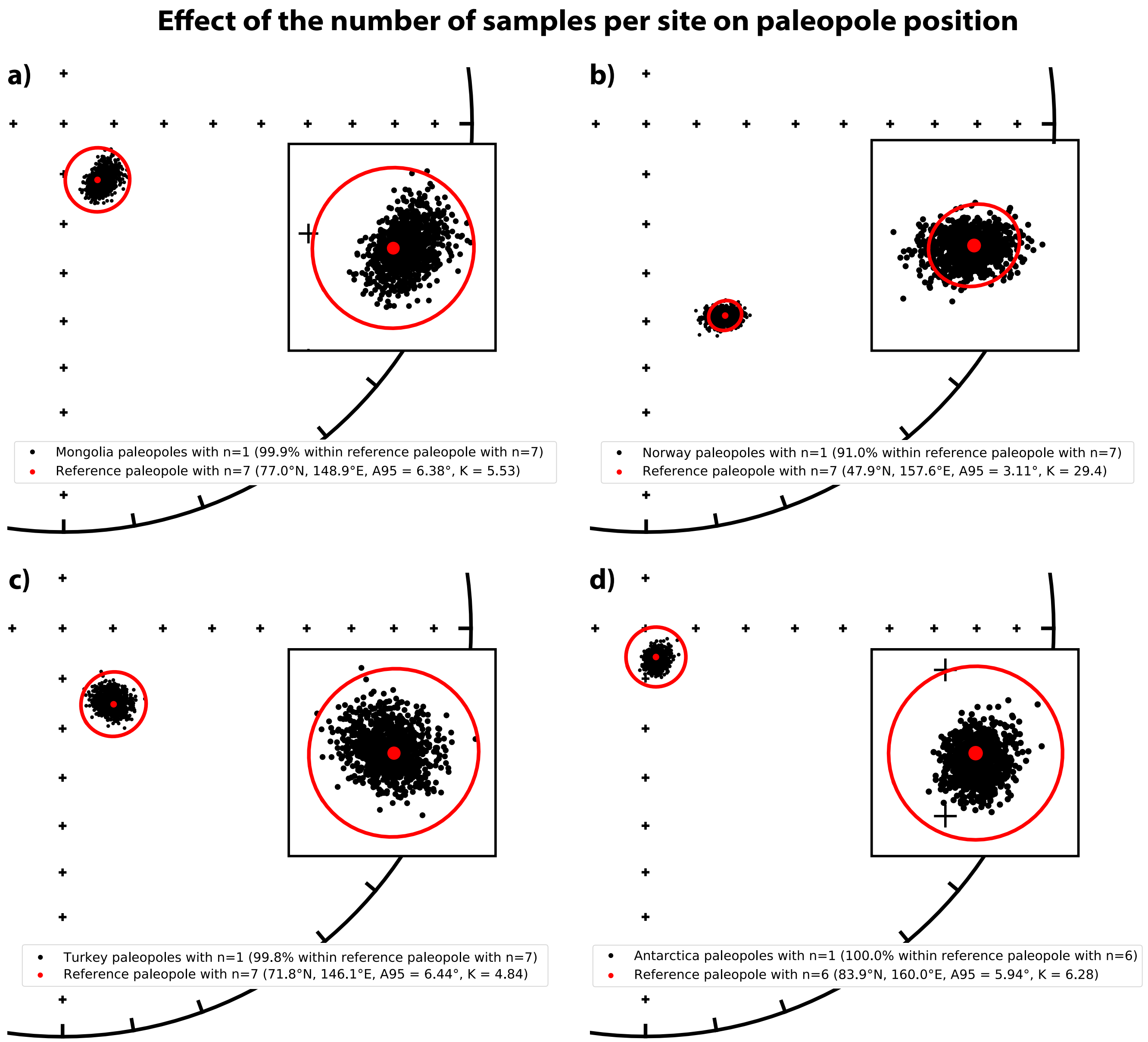


**Figure 5.** Equal angle projection with in black 1000 paleopole positions whereby all sites have $n = 1$ and in red the reference paleopole position and its $A_{95}$ whereby all sites have $n = 7$ (or 6, for Antarctica) for (a) Mongolia, (b) Norway, (c) Turkey, and (d) Antarctica. All paleopoles are plotted on the upper hemisphere, whereby the longitude increases clockwise. The center of each subplot represents the northern geographic pole. Inset shows a zoom-in on the data.

outliers discarded on $A_{95}$, but now based on randomly choosing N = 10 or N = 25 from the total collection of sites (Figure 8; for the effects on angular deviation, K, and S see Figures S6-8). As for the large datasets, a MAD cutoff, eliminating the farthest outliers, or a minimum $n$ per site, has no significant influence on paleopole precision (Figures 8a, 8c and 8d). A marginal improvement of $A_{95}$ value is obtained when eliminating sites with $k < 10$, but more stringent $k$ filters have no significant effect (Figure 8b).

### 4.6. Effect of Sample Distribution Over Sites

To average between-site scatter, it is common to collect multiple sites at a locality. The minimum number of sites recommended for determining a paleopole varies between authors (e.g., Meert et al., 2020; van der Voo, 1990), but as shown by (Vaes et al., 2022), paleopoles with larger N tend to plot closer to a best estimate of the time-averaged paleopole. We perform experiments varying the number of samples per site and the number of sites, with

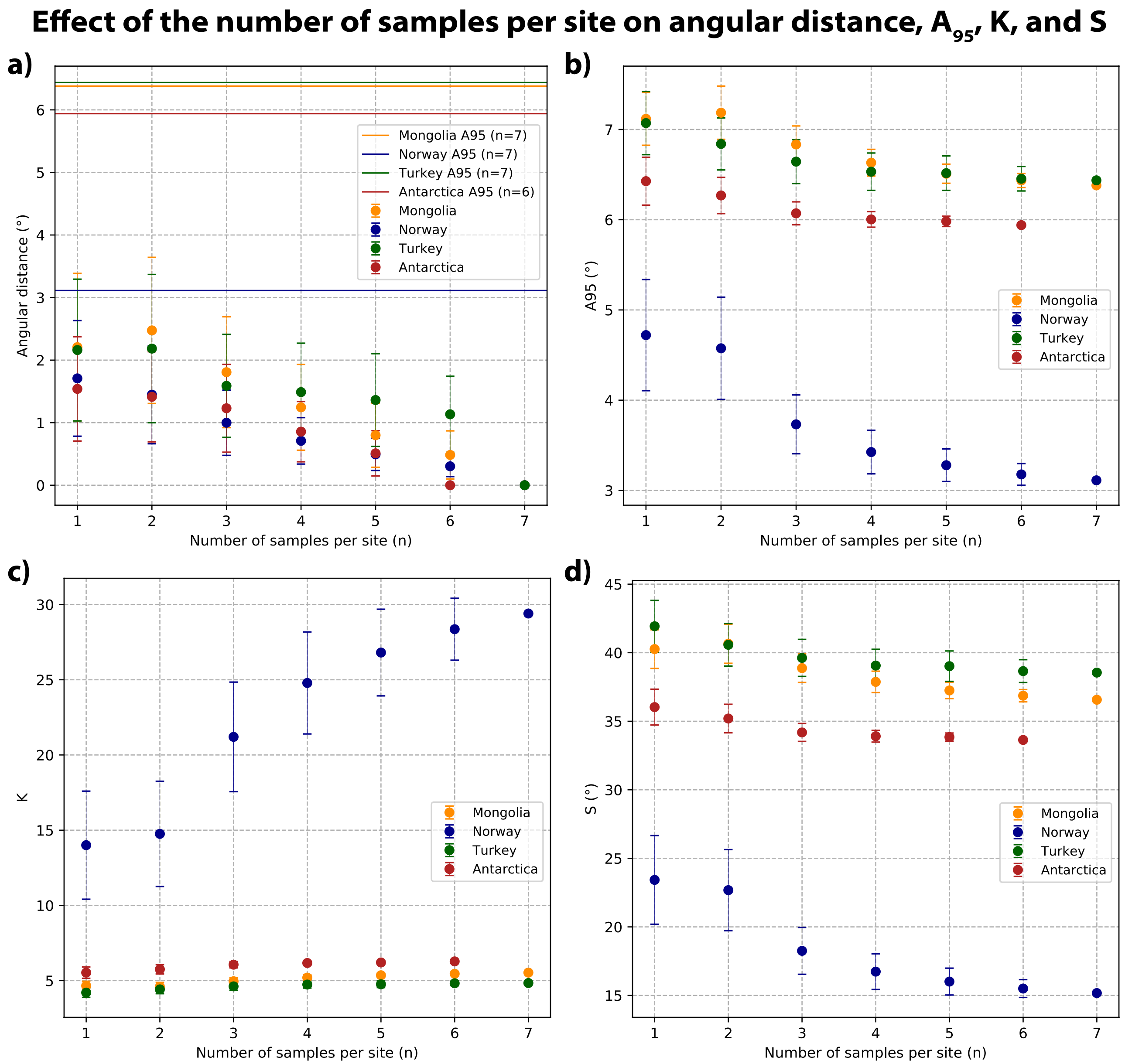


**Figure 6.** Effect of the number of samples per paleomagnetic site ($n$) on the (a) angular distance of the acquired paleopole to the reference paleopole whereby all sites have $n = 7$ (or 6, for Antarctica), and the (b) $A_{95}$, (c) K, and (d) S of the acquired paleopole. Every datapoint represents 1000 calculations, with error bars indicating the 95% confidence interval of these 1000 calculations.

combinations chosen such that the total amount of paleomagnetic samples remains approximately 100. We study the effect on angular distance to the reference paleopole, $A_{95}$, K, and S (Figure 9) of the acquired paleopole. The means are calculated from 1000 runs of the specific number of samples per site and number of sites, where the number of samples and sites is randomly selected from the total population during each run.

The paleopole position is strongly influenced by the distribution of samples over sites in case of Mongolia, Turkey, and Antarctica, and lies further from the reference paleopole if the samples are distributed over fewer sites (Figure 9a). There also is a major effect on the $A_{95}$. For all datasets, the $A_{95}$ is by far the smallest when it is constrained by 100 sites of $n = 1$, and the highest when it is constrained by 15 sites of $n = 7$ (Figure 9b). The effect on K and S is small, except in the data set from Norway (Figures 9c and 9d). In that data set, K is highest and S is lowest for 15 sites with $n = 7$. Nonetheless, the paleopole position is far better determined when taking many sites with few samples.

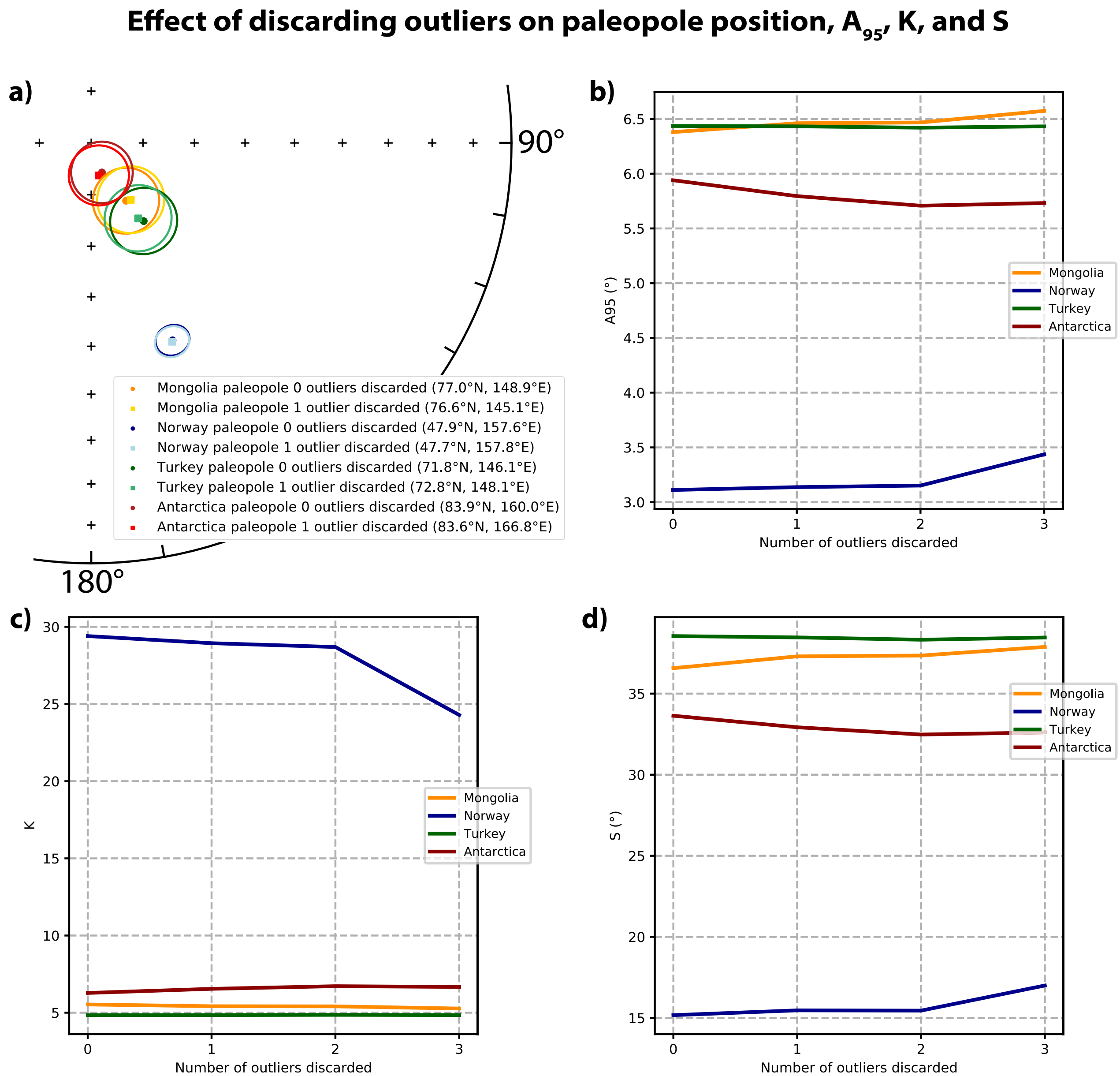


**Figure 7.** Effect of the number of samples discarded per paleomagnetic site on (a) paleopole position in equal angle projection, shown without outliers discarded and with one outlier discarded, and the (b) $A_{95}$, (c) K, and (d) S of the acquired paleopole. All paleopoles in subplot (a) are plotted on the upper hemisphere, whereby the longitude increases clockwise and the center represents the northern geographic pole.

## 5. Discussion and Conclusions

The results above show that none of the widely used data filters and cutoffs that aim to eliminate outliers and unreliable data, significantly improves paleopole precision. The application of these filters may even have an adverse effect; because these filters eliminate data, the filtered paleopoles often have lower N, and thus higher uncertainty without a significant change in position. Below, we briefly discuss why these filters do not have the desired effect.

The datasets we analyzed are all lava-based, and demagnetization behavior is typically stable, leading to ChRM directions with low MAD values. High MAD values may thus be considered suspect. Nonetheless, filtering of data with high MAD values led to no improvement in paleopole precision (Figure 2). From this we may infer that the noise due to higher MAD values does not significantly influence between-site scatter. Moreover, the fartherst

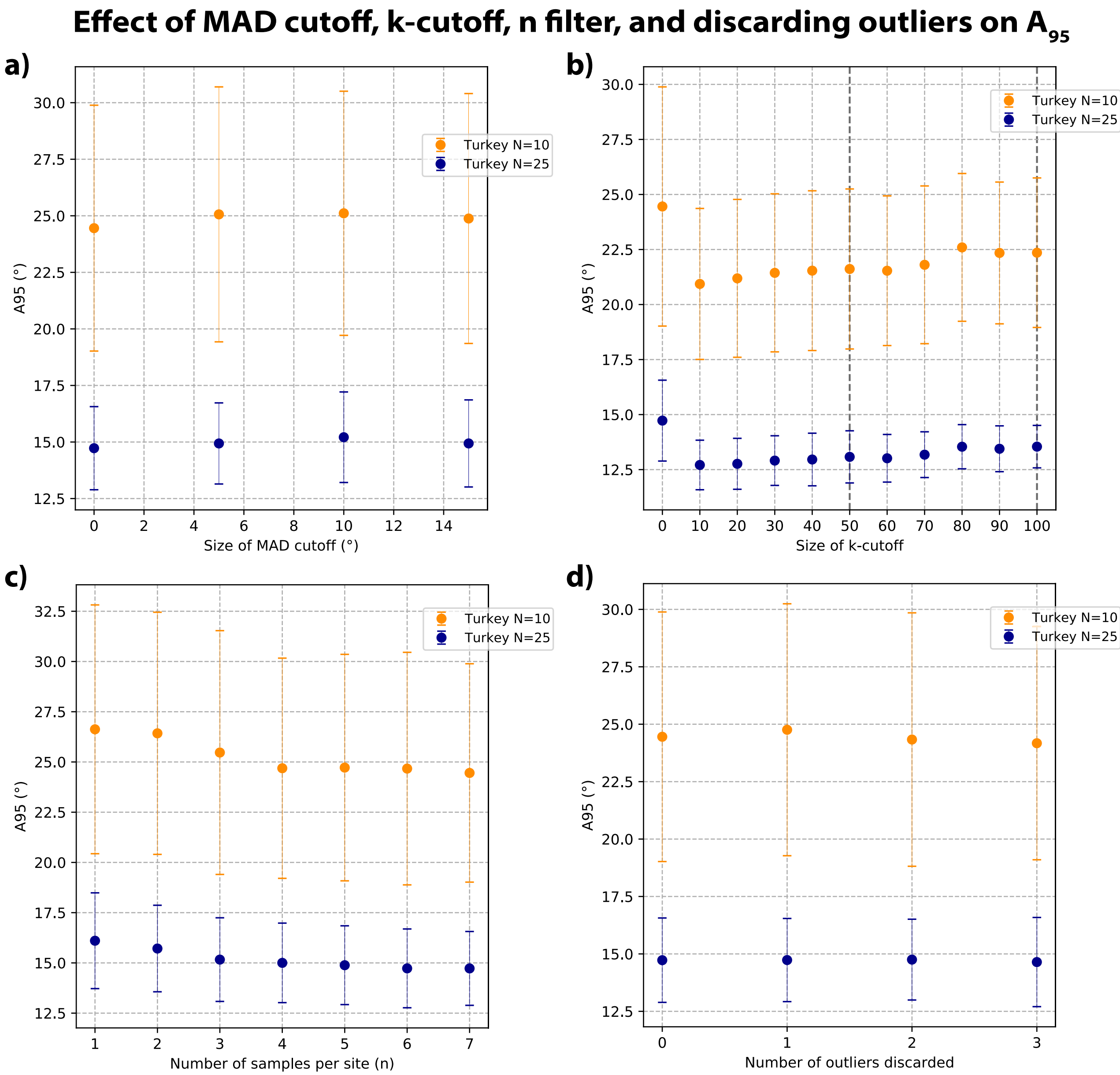


**Figure 8.** Effect of (a) a MAD cutoff, (b) a *k*-cutoff, (c) varying the number of samples per site (*n*), and (d) discarding outliers on the $A_{95}$ of the obtained paleopole, when taking N = 10 or N = 25 from the total collection of sites of the Turkey data set. Every datapoint represents 1000 calculations, with error bars indicating the 95% confidence interval of these 1000 calculations.

outliers are not systematically correlated with high MAD values. These farthest outliers are often very well determined directions with high intensities and stable demagnetization behavior, and their strong deviation from the reference direction was by the original authors interpreted as a lightning strike, which presents a common problem in lava sites (e.g., Strik et al., 2003). Such strongly overprinted outliers pass all MAD cutoffs.

In our reinterpretation of the data, we closed our "expert eye" and included sites that were excluded in the original studies because of subjective interpretations such as lightning struck sites. Our analysis illustrates that systematic application of filters, such as a *k*-cutoff, a minimum number of samples per site, or eliminating the farthest outliers per site, is incapable of filtering these unreliable VGPs. We point out that in absence of a demonstrable improvement of paleopole precision above a particular threshold, the choice of such a threshold is essentially arbitrary. The subjective judgment of the expert is needed to determine which samples and sites are included in

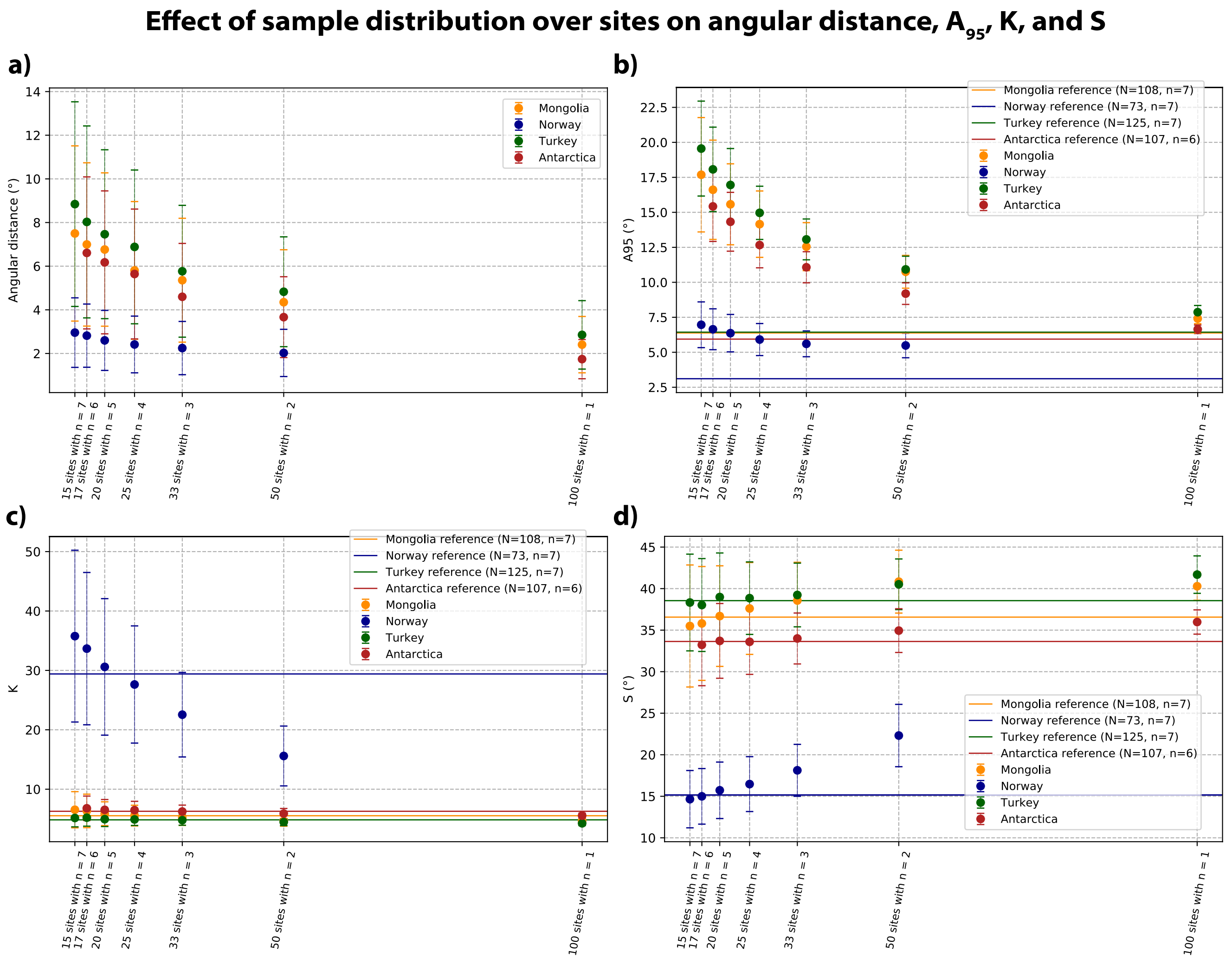


**Figure 9.** Effect of distributing 100 paleomagnetic samples over a varying number of paleomagnetic sites on the (a) angular distance of the acquired paleopole to the reference paleopole whereby all sites have $n = 7$ (or 6, for Antarctica), and the (b) $A_{95}$, (c) K, and (d) S of the acquired paleopole. Every datapoint represents 1000 calculations of a distribution, with error bars indicating the 95% confidence interval of these 1000 calculations.

the calculation of the paleopole, which should be explained in a paper describing the analysis (and all data should be made available following the FAIR principles (Wilkinson et al., 2016)).

Our analysis next shows that for the three datasets with high between-site scatter and low within-site scatter (i.e., Turkey, Mongolia, and Antarctica), applying the within-site scatter-based criteria leads to a marginal increase in data clustering (i.e., an increase in K and decrease in S). For the Norwegian data set, which has the rare combination of high within-site scatter and low between-site scatter, these criteria even lead to significantly higher clustering of the data. This deviation might be explained by the formation of the lavas during a long period of dominantly single polarity in the Permo-Carboniferous Reversed Superchron (PCRS; Haldan et al., 2014; Handford et al., 2021). This improvement may lend support to using these data filters for PSV studies.

But applying these filters when calculating paleopoles often leads to a decrease in paleopole precision (i.e., an increase in $A_{95}$), as demonstrated by the decrease in N that is caused by applying data filters and the corresponding decrease in paleopole precision (Figure 9). Our experiments thus show that the effect of between-site scatter on paleopole precision is often dominant over within-site scatter. Because the accuracy of paleopoles generally decreases with decreasing N, as illustrated by Vaes et al. (2022) for the paleopoles behind the global APWP of Torsvik et al. (2012), applying within-site scatter filters may systematically decrease paleopole accuracy as well as precision (see also Figure 9).

Our analysis shows that - for a fixed number of samples - collecting and averaging multiple samples per site leads to a relatively small improvement of the overall precision of the paleopole, whereas distributing the same number of samples over single-sample sites generates a much larger increase in paleopole precision (compare Figure 6 with Figure 9). Likewise, increasing the number of samples per site only leads to statistically insignificant changes in the position of the paleopole (Figures 5 and 6a), whereas the position of a paleopole is much better constrained by increasing the number of sites (Figure 9a), even when those sites are based on only a single sample. These results demonstrate a major benefit of collecting more sites instead of collecting more samples from the same site with the aim of reproducing the same spot reading multiple times. This suggests that also for sediment-based paleomagnetic datasets, reproduction of a spot reading, which is much more difficult to establish, is not essential. Datasets derived from long magnetostratigraphies, in which $n = 1$ per site is common, are thus in principle well-suited to calculate paleomagnetic poles from, provided common sedimentary artifacts such as inclination shallowing are corrected for (Kent & Tauxe, 2005; Tauxe & Kent, 2004; Vaes et al., 2021).

In case only few sites are available, or there is reason to question data quality, collecting multiple samples per site, as recommended by Meert et al. (2020), may still be a useful strategy. However, even for data collections with a low number of sites, we find that applying filters does not improve the resulting paleopole (Figure 8). Therefore, we do not recommend collecting more samples per site to allow for the application of the data filters studied in this paper. Nonetheless, demonstrating the reproducibility of a paleomagnetic direction within a lava site may help a paleomagnetist to confirm that these sites have the tight clustering of data expected for spot readings and support the reliability of the paleomagnetic data. Rather than demonstrating this for each site, we recommend to apply this on a small selection of sites, which may serve as a field test in addition to for example, a fold, reversal, and/or conglomerate test.

Key information on the reliability of a paleomagnetic pole may be better determined using data distributions. For instance, the common problem of inclination shallowing (e.g., Tauxe & Kent, 2004), as well as suspected remagnetization may be identified from a non-Fisherian, elongated distribution of VGPs (e.g., Beck, 1999; Bilardello, 2020; Bilardello et al., 2018; Schmidt, 1990). Accurate determination of the shape of such data distributions requires large datasets (e.g., >100 sites; Tauxe et al., 2003; Tauxe & Kent, 2004; Vaes et al., 2021). However, the number of sites used to compute a paleomagnetic pole is often relatively low; the average number of sites behind the >8000 paleopoles of the global paleomagnetic database (GPMDB; Pisarevsky, 2005) is only ∼15, and the median number of sites that underlie the 0–110 Ma paleopoles behind the global APWP of Torsvik et al. (2012) is 20 (Vaes et al., 2022). For future calculation of paleomagnetic poles, the extra efforts put into collecting multiple samples per site are thus more effectively spent on collecting more single-sample sites.

## Data Availability Statement

All uninterpreted paleomagnetic data are publicly available in the MagIC database (Tauxe et al., 2016); Mongolia data set: https://earthref.org/MagIC/19428, Norway data set: https://earthref.org/MagIC/19429, Turkey data set: https://earthref.org/MagIC/19430, and Antarctica data set: https://earthref.org/MagIC/17076. The Python code used for our analysis is available on Zenodo (Gerritsen, 2022): https://doi.org/10.5281/zenodo.6323434.

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