On pole position: causes of dispersion of the paleomagnetic poles behind apparent polar wander paths

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Abstract

Paleomagnetic poles used to compute apparent polar wander paths (APWPs) are strongly dispersed, which was recently shown to cause a large fraction (>50%) of these poles to be statistically distinct from the APWP to which they contributed, suggesting that current statistical approaches overestimate paleomagnetic resolution. Here, we analyze why coeval paleopoles are so dispersed, using the paleopoles behind the most recent global APWP and a compilation of paleomagnetic data obtained from <10 Ma volcanic rocks (PSV10). We find that paleopoles derived from sedimentary rocks, or from data sets underrepresenting paleosecular variation (PSV), are more dispersed and more frequently displaced. We show that paleopoles based on a smaller number of paleomagnetic sites are more dispersed than poles based on larger data sets, revealing that the degree to which PSV is averaged is an important contributor to the pole dispersion. We identify as fundamental problem, however, that the amount of paleomagnetic data used to calculate a paleopole, and thus the dispersion of coeval paleopoles, is essentially arbitrary. We therefore explore a different approach in which reference poles of APWPs are calculated from site-level data instead of paleopoles, thereby assigning larger weight to larger data sets. We introduce a bootstrap-based method for comparing a collection of paleomagnetic data with a reference data set on the same hierarchical level, whereby the uncertainty is weighted against the number of paleomagnetic sites. Finally, our study highlights that demonstrating smaller tectonic displacements requires larger paleomagnetic data sets, and that such data sets can strongly improve future APWPs.

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Key Points:

- Paleopoles do not average 'out' paleosecular variation, which forms a first-order contributor to the dispersion of coeval paleopoles
- The amount of data used to compute a paleopole and the number of paleopoles calculated from a given dataset is essentially arbitrary
- Calculating apparent polar wander paths from site-level data instead of poles allows the weighting of uncertainties and the amount of data

Abstract

Paleomagnetic poles used to compute apparent polar wander paths (APWPs) are strongly dispersed, which was recently shown to cause a large fraction (>50%) of these poles to be statistically distinct from the APWP to which they contributed, suggesting that current statistical approaches overestimate paleomagnetic resolution. Here, we analyze why coeval paleopoles are so dispersed, using the paleopoles behind the most recent global APWP and a compilation of paleomagnetic data obtained from <10 Ma volcanic rocks (PSV10). We find that paleopoles derived from sedimentary rocks, or from data sets underrepresenting paleosecular variation (PSV), are more dispersed and more frequently displaced. We show that paleopoles based on a smaller number of paleomagnetic sites are more dispersed than poles based on larger data sets, revealing that the degree to which PSV is averaged is an important contributor to the pole dispersion. We identify as fundamental problem, however, that the amount of paleomagnetic data used to calculate a paleopole, and thus the dispersion of coeval paleopoles, is essentially arbitrary. We therefore explore a different approach in which reference poles of APWPs are calculated from site-level data instead of paleopoles, thereby assigning larger weight to larger data sets. We introduce a bootstrap-based method for comparing a collection of paleomagnetic data with a reference data set on the same hierarchical level, whereby the uncertainty is weighted against the number of paleomagnetic sites. Finally, our study highlights that demonstrating smaller tectonic displacements requires larger paleomagnetic data sets, and that such data sets can strongly improve future APWPs.

Plain Language Summary

Apparent polar wander paths (APWPs) are widely used to reconstruct the position of continents relative to the Earth's rotation axis. These paths are typically calculated by averaging paleomagnetic poles obtained from rocks of similar age. Although these poles are expected to be tightly grouped, they are strongly scattered. Notably, this causes >50% of the poles used in recent APWPs to be statistically different from the APWP itself. Here, we investigate to what extent errors in these poles may explain the observed scatter. We find that poles derived from sedimentary rocks are more scattered than those derived from igneous rocks. Also, poles based on smaller data sets are more dispersed than those based on larger data sets. Our analysis shows that the amount of paleomagnetic data used to determine a pole is often arbitrary. To overcome the subjectivity in pole calculation, we propose a new approach in which an APWP is calculated from individual data

points instead of from paleopoles. This allows comparing paleomagnetic data on the same statistical level, and the development of APWPs in which larger data sets have larger weight. Our study thus emphasizes the value of collecting large paleomagnetic data sets, which may improve future APWPs.

1 Introduction

Apparent polar wander paths (APWPs) are computed to constrain the past position and motion of tectonic plates and continents relative to the Earth's rotation axis. They provide the reference frame for paleogeography, paleoclimate and paleoenvironment studies, and serve as the reference against which we compare paleomagnetic data collections obtained from deformed terranes to assess relative latitudinal motions or vertical-axis rotations (e.g., Besse & Courtillot, 2002; Butler, 1992; Creer et al., 1954; Irving, 1964; Torsvik et al., 2008, 2012; van Hinsbergen et al. 2015). APWPs are commonly calculated from paleomagnetic poles (hereafter 'paleopoles') that are assumed to represent stable plate interiors and to provide an accurate representation of the time-averaged geomagnetic field, which is in turn assumed to approximate a geocentric axial dipole (GAD) (e.g., Butler, 1992; Creer et al., 1954; Tauxe & Kent, 2004). In the absence of errors in the data, these paleopoles are expected to plot close to, and be statistically indistinguishable from, the reference pole to which they contribute (Butler, 1992; Rowley, 2019; Tauxe, 2010). But they do not.

Harrison and Lindh (1982) and, more recently, Rowley (2019) demonstrated that with commonly used comparison metrics, as much as 50% of the paleopoles used to compute APWPs are statistically distinct from the reference pole to which they contributed (Fig. 1). Rowley (2019) argued that it is inappropriate to determine tectonic displacements from the angular difference and combined uncertainty of a paleopole and a reference pole, as is typically done, because these poles and their confidence limits are calculated on a different hierarchical level (e.g., Bazhenov et al., 2016). Instead, Rowley (2019) pointed out that a geologically meaningful difference can only be interpreted from individual paleopoles that lie beyond the angular dispersion of the paleopoles that underlie the APWP. He proposed that the uncertainty of an APWP should then be determined by the angular distance from the APWP that includes 95% of the input paleopoles (his K_{95}), which for the widely used global APWP of Torsvik et al. (2012) is often as large as ~15-20° (Fig. 1). In this approach, the resolution of an APWP is governed by the dispersion of the input paleopoles. Rowley (2019) thus emphasized that the reliable use and future improvement of APWPs requires thorough understanding of the nature and causes of the dispersion of input poles and their possible displacement relative to the APWP.

The sources of uncertainty that likely contribute to the dispersion of paleopoles have so far mostly been sought in the inadequate estimation of individual pole positions (e.g., Domeier et al., 2012; Harrison and Lindh, 1982; Kent & Muttoni, 2020; van der Voo, 1990), caused by e.g., inadequate representation of paleosecular variation (PSV), unremoved magnetic overprints, age uncertainties, measurement errors, inclination shallowing in sediments, or unrecognized deformation (e.g., Butler, 1992; Harrison & Lindh, 1982; Rowley, 2019; Tauxe, 2010; Vaes et al., 2021). In addition, the dispersion may be enhanced by non-dipole contributions to the paleomagnetic field, or by errors in the relative plate motion reconstructions that were used to transfer paleopoles to a common coordinate frame (e.g., Butler, 1992; Domeier et al., 2012; Tauxe, 2010). But even though the problem of the large dispersion of paleopoles has long been acknowledged (e.g., Bazhenov et al., 2016; Harrison and Lindh, 1982; van der Voo, 1990), how the above sources of scatter, and any other, contribute to the dispersion of paleopoles has not been systematically analyzed.

In this study, we investigate to what extent uncertainties and errors in the paleopoles themselves, as well as in the way these poles are defined, may explain pole dispersion. We further examine why a large fraction of those poles is statistically displaced from the APWP to which they contribute using classical comparison metrics. To this end, we analyzed high-quality data sets of volcanic rocks from the last 10 Ma (PSV10; Cromwell et al., 2018), in which plate reconstruction uncertainties, tectonic deformation-induced deviations, and common pitfalls related to sedimentary rocks such as inclination shallowing, play no significant role. We first use this data set to evaluate the pole dispersion is influenced by the extent to which PSV is sampled. Then, we analyze which other factors may further enhance the large dispersion, and which factors may cause so many paleopoles to be displaced from the reference to which they contributed. For this purpose we also used the compilation of paleopoles behind the global APWP of Torsvik et al. (2012) (Fig. 2). Based on our analyses, we explore an optimal approach to calculate APWPs and their use to quantify tectonic displacements, in such a way that statistical differences with an APWP can be used to draw geologically meaningful conclusions.

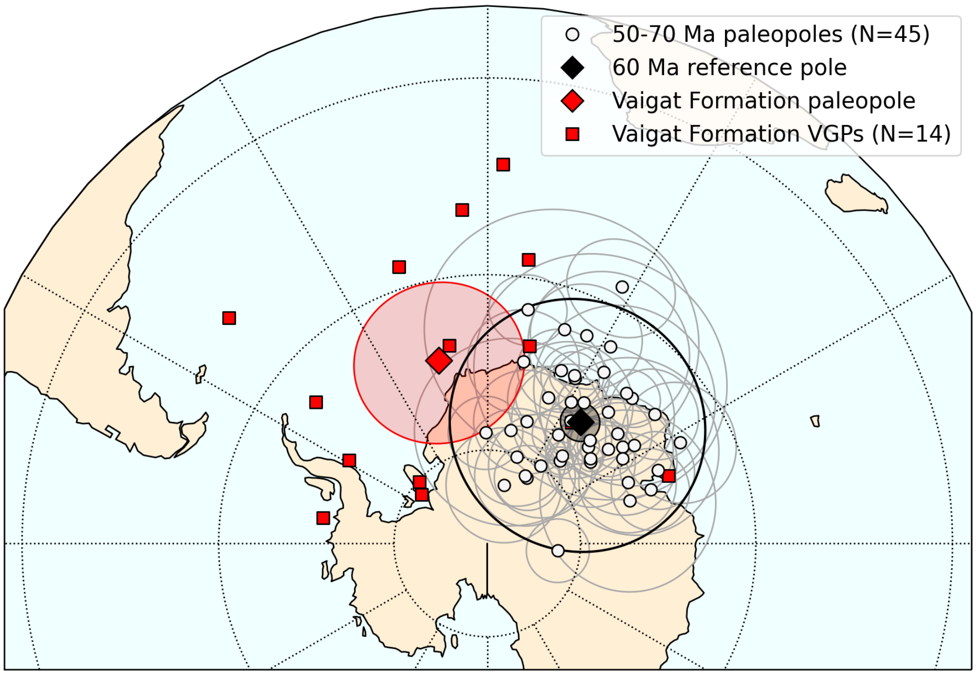


Fig. 1. Orthographic projection of the 50-70 Ma paleopoles (white circles, with 95% confidence ellipses (A_{95}) in grey) used to compute the 60 Ma reference pole (black diamond) of the global APWP of Torsvik et al. (2012). The A_{95} and K_{95} are 2.1° and 14.0° and are indicated by the filled and unfilled black circles around the reference pole. The paleopole derived from the Vaigat Formation (Riisager et al., 2003; red diamond, with A_{95}=9.2° in red) is shown as an example of a statistically 'displaced' paleopole. The VGPs used to calculate this paleopole are plotted as red squares. Please note that all poles and VGPs are shown in south pole coordinates in a South African coordinate frame.

2 Background: current ways to calculate and use APWPs

The calculation and use of APWPs rely on the fundamental assumption that the time-averaged geomagnetic field approximates that of a GAD field, whereby the time-averaged geomagnetic pole coincides with the Earth's rotation axis. Through this assumption, APWPs describe the apparent wandering of the rotation axis relative to a geographical reference location through geological time and provide a paleomagnetic reference frame for the paleogeographic reconstruction of continents and geological terranes (e.g., Butler, 1992). APWPs are typically constructed as a sequence of paleomagnetic poles that each represent the geomagnetic pole position relative to a reference (usually a continent, e.g., Africa) for a chosen geological time interval (Fig. 2a).

The first APWP was constructed by Creer et al. (1954), who connected a time series of individual paleopoles obtained from rocks of the British Isles. When more paleopoles became available, reference poles were calculated for selected geological periods by averaging all paleopoles obtained from rocks of that period (e.g., Irving, 1964; Phillips & Forsyth, 1972; Van der Voo & French, 1974). In the last four decades, most APWPs have been constructed using paleopoles as input, in one of two ways: either by a running mean method (e.g., Irving, 1977; Van Alstine & De Boer, 1978), or by fitting a smoothed spline path through a selection of paleopoles (e.g., Jupp & Kent, 1987; Thompson & Clark, 1981, 1982). The presently most widely used reference APWPs were calculated using the running mean method (e.g., Besse & Courtillot, 2002; Torsvik et al., 2012). The main advantage of this method is that it is relatively simple and intuitive, allowing the APWP to be straightforwardly reproduced by other workers. In the running mean approach, a series of reference poles is calculated at a chosen time interval (e.g., 10 Ma) by averaging collections of paleopoles whose mean rock age falls within a chosen time window (e.g., 20 Ma) (e.g., Besse & Courtillot, 2002; Kent & Irving, 2010; Torsvik et al., 2008, 2012, Wu et al. 2021). The input paleopoles may either be derived from a single continent or tectonic plate, yielding a continental/single plate APWP, or from poles obtained from multiple continents and plates after rotating them to a common coordinate frame using relative plate reconstructions, yielding a global (or 'master') APWP (e.g., Besse & Courtillot, 1991, 2002; Phillips & Forsyth, 1972; Torsvik et al. 2008, 2012).

The paleopoles used to calculate an APWP typically represent a 'study mean' paleomagnetic pole, corresponding to the main result of an individual paleomagnetic study (e.g., Hospers, 1954). On the other hand, there are also studies that produce multiple paleopoles and sometimes poles obtained in different studies of the same sedimentary or volcanic sequence are averaged to a single paleopole (e.g., Torsvik et al., 2012). A single paleopole is typically obtained through averaging a set of virtual geomagnetic poles (VGPs) that are each calculated from a site-mean paleomagnetic direction through the assumption of a GAD field (Fig. 1; see Ch. 7 in Butler (1992) for a detailed explanation). A paleomagnetic 'site' is defined as a geological unit that represents an increment of geological time relative to the time scale over which the Earth's magnetic field changes (following McElhinny & McFadden, 2000), such that the corresponding VGP represents a 'spot reading' of the field. Whether or not a rock unit represents an increment of geological time is up to the interpretation of the paleomagnetist: lava flow units are typically assumed to provide such spot readings (e.g., Biggin et al., 2008; Cromwell et al., 2018; Johnson et al., 2008). But whether paleomagnetic directions from sediments provide spot readings, either at sample level or at sedimentary 'bed' level, is more subjective (e.g., Meert et al., 2020; Tauxe & Kent, 2004; Vaes et

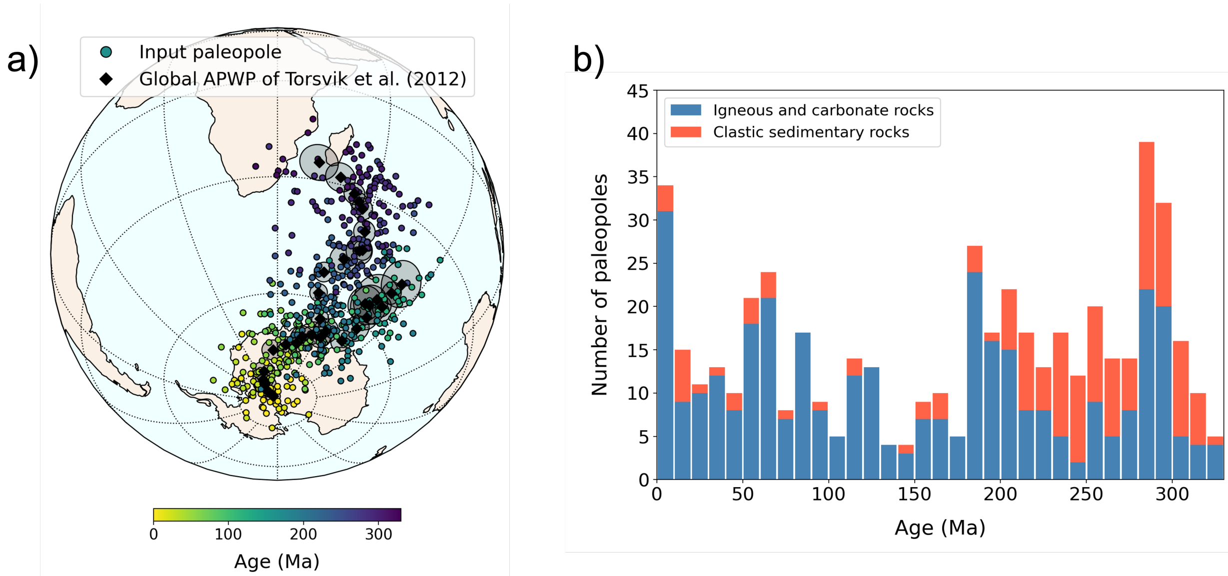


Fig. 2. **a)** Orthographic projection of the global APWP of Torsvik et al. (2012) in South African coordinates (black diamonds, each shown with their A_{95}), computed using a running mean approach with a time window of 20 Ma. The input paleopoles are plotted as circles that are colored by age. **b)** Histogram of the number of input paleopoles per 10 Ma time interval (after Torsvik et al., 2012).

al., 2021). Paleomagnetists aim to acquire a collection of independent spot readings of the paleomagnetic field that is sufficiently large and contains enough geological time to 'average out' PSV. But the number of VGPs (N) required to accurately represent PSV is subjective, and the amount of VGPs used to compute a paleopole is mostly arbitrary and differs among authors. Van der Voo (1990) advised in his widely used list of reliability criteria to use at least 25 paleomagnetic samples to calculate a paleopole, whereas the recently updated 'van der Voo' criteria of Meert et al. (2020) suggested using N≥8 paleomagnetic sites (each representing a spot reading) for the calculation of a paleopole. On the other hand, a statistical analysis of Tauxe et al. (2003) showed that N>100 may be required for a robust representation of PSV. In practice, each individual paleopole that is included in the calculation of an APWP is assumed to provide an accurate estimate, within its confidence limits, of the time-averaged geomagnetic pole relative to the sampling location, regardless of N.

If the paleopoles obtained from rocks of similar age indeed provide accurate estimates of the time-averaged field, and this field approximates that of a GAD field, then the scatter of paleopoles around the mean pole should only be caused by measurement errors and plate reconstruction errors (e.g., Butler, 1992; Irving, 1964; Rowley, 2019). By incorporating multiple paleopoles in the calculation of a reference pole of an APWP, paleomagnetists aim to average 'out' this scatter (e.g., Irving, 1964). The uncertainty in the position of the reference pole is traditionally expressed by the 95% cone of confidence about the pole ($A_{95,ref}$), which is computed using Fisher (1953) statistics under the implicit assumption that the input paleopoles conform to a Fisher (1953) distribution (Heslop & Roberts, 2019; Rowley, 2019). In this approach, it is common to assign unit weight to each input paleopole, regardless of the uncertainty in the position or age of the pole, or the number of VGPs used to calculate it (e.g., Besse & Courtillot, 2002; Irving & Irving, 1982; Morel & Irving, 1981; Torsvik et al., 2008, 2012).

But already 40 years ago, Harrison and Lindh (1982) noted that the scatter of poles obtained from stable plate interiors is much larger than expected (see Fig. 1, Fig. 2a) and consequently argued against the uniform weighting of paleopoles in the calculation of APWPs. They suspected that the paleopole scatter was, for a large part, the incomplete averaging of PSV in many paleopoles. To overcome this problem, they proposed a method for calculating APWPs in which individual paleopoles are weighted according to e.g., the number of underlying VGPs and the age range of the sampled rocks. Over the years, different weighting schemes have been proposed, in which individual paleopoles are weighted either quantitatively or against a set of qualitative criteria (e.g., Gallo et al., 2021; Hansma & Tohver, 2020; Harrison & Lindh, 1982; Le Goff et al., 1992; McFadden & McElhinny, 1995; Musgrave, 1989; Schettino & Scotese, 2005; Swanson-Hysell et al., 2019; Thompson & Clark, 1981; Torsvik et al., 1992, 1996, 2008, 2012; Wu et al., 2021). Some authors calculated the reference poles of single-continent APWPs by averaging VGPs rather than paleopoles (Hansma & Tohver, 2020; McElhinny et al., 1974; McElhinny & McFadden, 2000; Swanson-Hysell et al., 2019; van Hinsbergen et al., 2017), thereby assigning larger weight to larger data sets of independent measurements of the past geomagnetic field. Because the weighting of poles based on a chosen set of criteria inevitably introduces more subjectivity (e.g., Irving & Irving, 1982; Morel & Irving, 1981), the currently most widely used APWPs are still based on a running mean approach in which all poles are weighted equally and in which errors are not propagated (Besse & Courtillot, 2002; Torsvik et al., 2012).

One of the prime applications of APWPs is the identification and quantification of tectonic displacements of tectonic blocks or plates relative to a certain reference continent (see Ch. 11 of Butler (1992) for an extensive review). To determine a tectonic displacement - expressed either as a relative vertical-axis rotation or latitudinal displacement - paleomagnetists typically compare an individual paleopole derived from the studied tectonic block with a reference APWP. If the paleopole is shown to be statistically distinct from the APWP, according to some comparison metric, this is typically interpreted as evidence for a relative vertical-axis rotation and/or latitudinal displacement. To assess whether a paleopole is statistically distinct (or 'discordant') with respect to the reference pole (Butler, 1992; Rowley, 2019), paleomagnetists typically compare the 95% confidence regions about the paleopole with that of a reference pole, even though these are of a different statistical 'rank' (following the terminology of Bazhenov et al., 2016). The uncertainty in the position of the individual paleopole ($A_{95,PP}$) is typically calculated from the distribution of VGPs using Fisher (1953) statistics (see Heslop & Roberts (2019) for a review). In the classical approach, a paleopole is considered statistically displaced if its angular distance to the reference pole exceeds the combined uncertainty of the paleopole and the reference pole, calculated using:

$$\sqrt{A_{95,ref}^2 + A_{95,PP}^2} \quad (1)$$

whereby the $A_{95,ref}$ and the $A_{95,PP}$ are the radius of the 95% confidence circle around the reference pole and the independent paleopole, respectively. It is important to note that the uncertainty in the position of the underlying paleopoles (their $A_{95,PP}$) is typically not propagated in the calculation of the $A_{95,ref}$, which may thus be an underestimate of the uncertainty in the reference pole position (Heslop & Roberts, 2020).

Rowley (2019) showed that, with the above equation, >50% of the paleopoles used in the global APWP of Torsvik et al. (2012) are statistically displaced relative to the APWP itself. He pointed out that a significant difference between an independent paleopole and a reference pole can therefore not be straightforwardly interpreted as a signal of tectonic motion. Instead, he argued, significant tectonic motion can only be concluded if the independent paleopole falls outside the circle that contains 95% of the input paleopoles from which the mean poles of the APWP is computed (which he referred to as the K_{95}). This confidence circle was previously used by Bazhenov et al. (2016) to define 'alarm bands' around APWPs, which they used to identify potential remagnetization events. Using the K_{95} as a confidence estimate of the APWP, rather than the $A_{95,ref}$, essentially means that the resolution at which we can discern relative tectonic displacements is for a large part determined by the angular deviation of the paleopoles that lie furthest from the mean pole of the APWP. Increasing the resolution of APWPs for tectonic purposes would then require decreasing the scatter of input poles around the APWP. Below, we therefore analyze what causes the scatter of poles behind an APWP, and what causes their displacement relative to the mean pole to which they contributed.

3 Data and methods

We conduct a series of experiments to explore and identify the main contributors to the dispersion of paleopoles that are used as input for current APWPs and to determine why a large fraction of poles are statistically distinct - in the traditional statistical framework (see Eq. 1) - from the APWP to which they contribute. With this aim, we assess the influence on the pole dispersion, and pole displacement, of a range of parameters associated with each input pole, such as the number of independent measurements of the geomagnetic field used to calculate the pole (N), lithology, the uncertainties in the pole position itself and the age uncertainty of the sampled rocks.

We use two data sets: the PSV10 database, and the compilation of paleopoles used for the Torsvik et al. (2012) global APWP. The PSV10 database contains 83 paleomagnetic data sets (from 81 publications) obtained from volcanic rocks that formed in stable plate interiors in the last 10 Ma, as compiled by Cromwell et al. (2018). This data set is the most recent update of a compilation of paleomagnetic data that fulfill all commonly used quality criteria of volcanic rocks that erupted so recently that age uncertainty, plate motion, tectonic deformation, or artifacts common in sedimentary rocks such as inclination shallowing, are considered negligible. The PSV10 compilation and its predecessors (e.g., PSVRL; McElhinny & McFadden, 1997) are typically used to study the behavior of the recent geomagnetic field, including paleosecular variation, and serves as the standard of statistical models of the geomagnetic field such TK03.GAD (Tauxe & Kent, 2004) and BCE19 (Brand et al., 2020). Each VGP included in the compilation has been interpreted as an 'instantaneous' reading of the magnetic field and is calculated by averaging multiple paleomagnetic directions obtained from the same lava flow unit to decrease the effect of (small) measuring errors. We use the PSV10 database to assess the influence of representation of PSV on paleopole scatter around a mean for the geomagnetic field of the last 10 Ma. We calculated a paleopole from each paleomagnetic data set included in PSV10 using Fisher (1953) statistics, providing a pole position and associated A_{95} and Fisher precision parameter K (Table S1).

We quantify the dispersion of VGPs or paleopoles using three different statistical parameters: the Fisher (1953) precision parameter K, the angular standard deviation (or VGP scatter) S, and the mean angular distance to the reference S'. S is a widely used measure of the scatter of VGPs and is commonly used to assess PSV in studies of geomagnetic field behavior (see eq. 14.1, Tauxe, 2010). S' provides an alternative measure of the dispersion and has the advantage that it is less affected by outliers (Suttie et al., 2015; Doubrovine et al., 2019). In addition, we tested whether the paleopoles whose data were used in the PSV10 database would be deemed statistically displaced according to the traditional comparison metric of Eq. (1). Because tectonic motions of lithology-based artifacts are considered irrelevant for the PSV10 data set, we use the observed scatter of poles about the 'true' mean pole to evaluate the effect of incomplete averaging of PSV, or non-dipole contributions to the geomagnetic field.

Next, we explore to what extent other common sources of error in paleomagnetic data may have further enhanced the dispersion of paleopoles that were used to calculate the global APWP of Torsvik et al. (2012). We first used to entire database of 501 paleopoles that were obtained from 0-330 Ma old rocks to assess the magnitude of pole dispersion, and whether this varies with age and between different lithological groups. Then, for a selection of 167 paleopoles that fall within the 0-110 Ma age range, we compiled additional characteristics of each paleomagnetic data set including the number of paleomagnetic sites used to calculate the pole, the uncertainties in the pole position, and in the age uncertainty of the sampled rocks (Table S2). To assess the influence of specific parameters on the dispersion of individual paleopoles, we used the angular distance of each paleopole to the mean pole of the APWP, following e.g., Harrison & Lindh (1982). In addition, to quantify the clustering of poles that fall within a specific time interval of, e.g., 20 Ma, we used the Fisher (1953) precision parameter, analogous to K for distributions of VGPs. We performed these calculations using a set of inhouse-developed Python codes, for which we made extensive use of the functions and programs from the freely available paleomagnetic software package PmagPy (Tauxe et al., 2016). The Python codes used for this analysis are provided at an online repository (see Data Availability Statement).

4 Results

4.1 Analysis of PSV10

The 83 paleomagnetic data sets included in the PSV10 database (Table S1) vary in size from N=3 to N=128 VGPs, with an average N of ~29, and from each of these collections of VGPs we computed a paleopole (Fig. 3a). We calculated the time-averaged 'reference' geomagnetic pole for the last 10 Ma by computing the Fisher (1953) mean of all 2401 VGPs, as well as by averaging

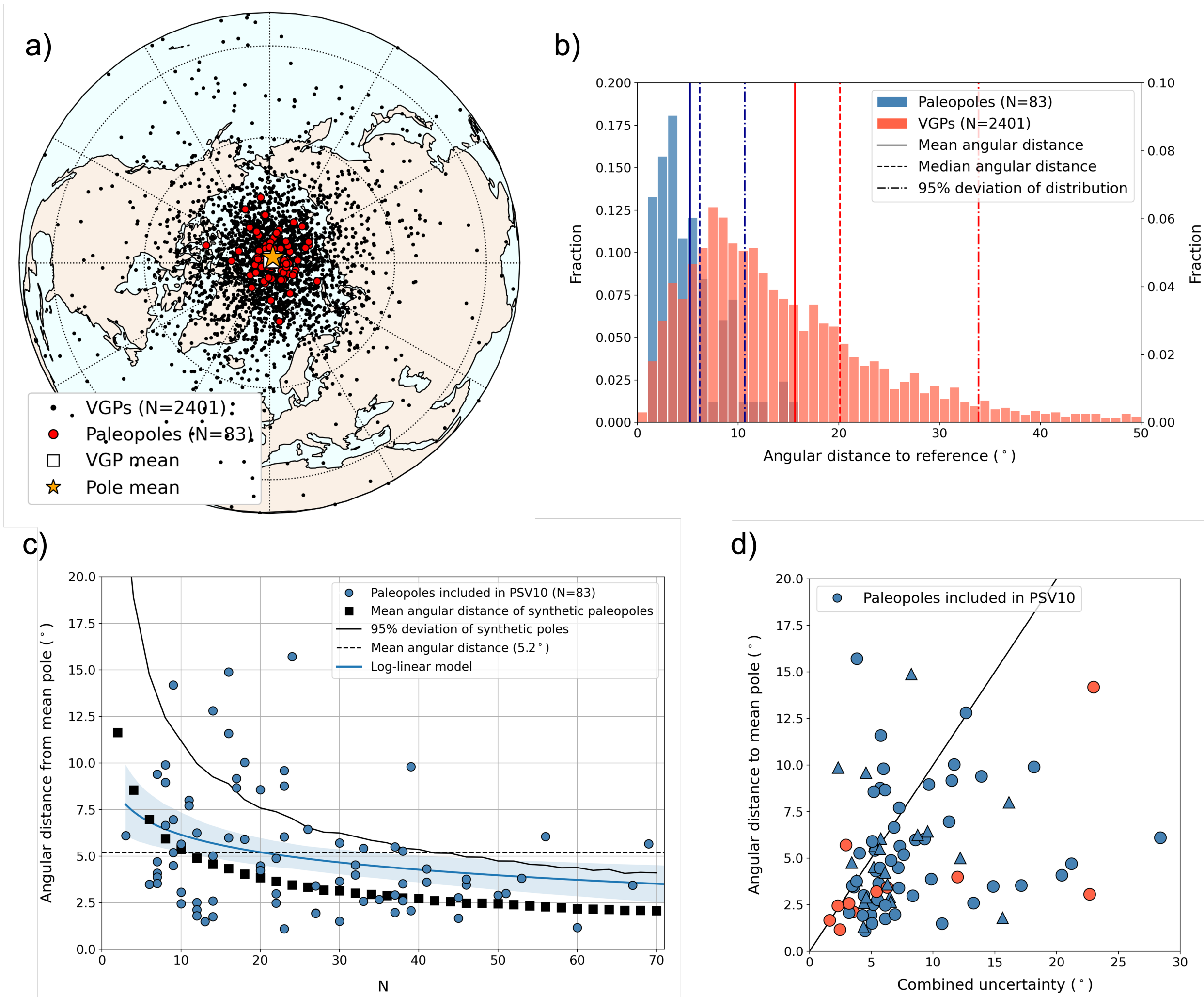


Fig. 3. **a)** Orthographic projection of the VGPs included in the PSV10 database (Cromwell et al., 2018). The paleopoles computed from the 83 data sets of PSV10 are plotted as red circles. The reference poles calculated from the VGPs and paleopoles are shown by the white square and orange star, respectively. **b)** Histogram of the angular distance from their reference pole of the VGPs and paleopoles shown in a). **c)** Angular distance from the mean pole of the 83 paleopoles versus the number of VGPs (N). The mean angular distance and 95% deviation of the 5000 synthetic paleopoles, which are computed for every second value of N, are depicted by black squares (see text for explanation). A log-linear regression curve computed for the paleopoles included in PSV10 is shown in blue (with bootstrapped 95% confidence regions). **d)** Plot of the angular distance of each paleopole against the combined uncertainty, as calculated using Eq. 1 (after Rowley, 2019). Poles that do not satisfy the Deenen et al. (2011) criterion or which underlying VGPs do not conform to a Fisher (1953) distribution are plotted as red circles or blue triangles, respectively.

the paleopoles without taking their uncertainties into account, as is common when computing APWPs (Fig. 3a). The angular distance between the two references poles (0.6°) is statistically insignificant; the VGP-based mean has an $A_{95,VGPs}$=0.7° and pole-based mean has $A_{95,poles}$=1.2°.

As measure of the dispersion of VGPs and paleopoles we calculated the angular distance of each VGP and each paleopole to the respective reference pole positions (Fig. 3b). The dispersion of the paleopoles, each averaging a different number of VGPs that were obtained within a single study, is, logically, smaller than that of the individual VGPs. The total distribution of VGPs has K=17.1, S=20.1° and S'=15.6°, compared to the distribution of paleopoles which has K=172.3, S=6.2°, and S'=5.2°. The 95% deviation of the population of VGPs is 33.8°, whereas that of the population of paleopoles, corresponding to the K_{95}, is 10.7°. So even though averaging collections of VGPs to paleopoles considerably decreases the scatter, the 'study mean' paleopoles are still significantly dispersed around the reference pole (Fig. 3a, b).

To assess to what extent PSV underlies this pole scatter, we first conducted a numerical simulation in which we generated sets of synthetic paleomagnetic poles by randomly sampling (with replacement) N VGPs from the PSV10 database. For every second value of N (from 2 to 70) we generated 5000 pseudosamples from which we calculated synthetic poles along with their angular distance to the reference pole. We note that magnitude VGP dispersion is latitude-dependent, at least for the last 10 Ma (e.g., Biggin et al., 2008; Cox, 1962, 1970; Doubrovine et al., 2019; McFadden et al., 1991), but because paleopoles used to calculate APWPs are often derived from a wide latitude range, we draw VGPs from the entire data set in our experiment. Figure 3c shows how the scatter of these synthetic paleopoles decreases with N, with the mean angular distance to the reference pole (S') gradually decreasing from almost 9° for N=4 to ~2° for N=70. The observed angular distances of the paleopoles calculated from the PSV10 data sets clearly follow the trend obtained for the synthetic poles (Fig. 3c). Also, we find that the majority of these paleopoles that are at a relativaly large angular distance to the reference pole, that is larger than the mean value of 5.2° (S'), have N<25 (Fig. 3c). Overall, these results illustrate that PSV is never averaged 'out': larger data sets simply provide a more accurate estimate of the grand mean pole position.

Next, we estimated the expected pole dispersion resulting from PSV by randomly distributing the 2401 VGPs over 83 collections of VGPs with the same N as the data sets that contributed to PSV10. We then determined the mean angular distance to the reference pole (S') of

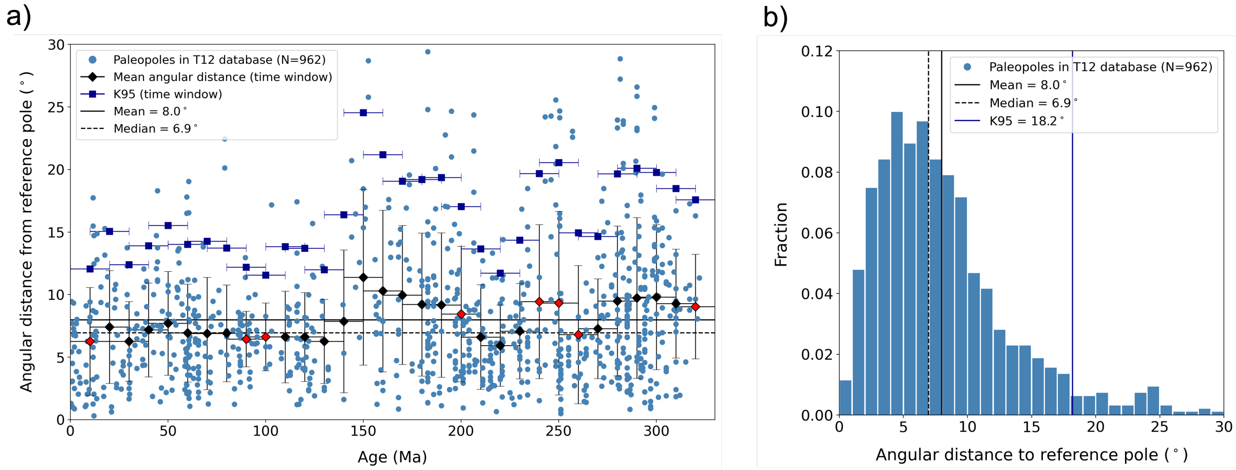


Fig. 4. a) Angular distance from the reference pole of all 0-330 Ma paleopoles used to compute the global APWP (in South African coordinates) of Torsvik et al. (2012). The mean angular distance and K_{95} computed from the poles from 20 Ma time window are plotted as black diamonds and blue squares, respectively. The mean angular distance is plotted in red if the distribution of paleopoles does not confor to a Fisher (1953) distribution. **b)** Histogram of the angular distance to the reference pole for all paleopoles in the database. Note that because in most paleopoles are used twice in the running mean approach, the number of poles in this figure is higher than the actual number of paleopoles (501).

the 83 paleopoles that were calculated from those 83 collections of VGPs. We repeated this procedure 5000 times and obtained an average S' of 3.9° (with 95% bootstrap confidence bounds of 3.4° and 4.4°) instead of the 5.2° obtained from the published data sets. This suggests that the majority (~4°) of the dispersion of poles in the PSV10 database is a signal of PSV and that a relatively small contribution to the scatter (~1.3°) results from other artifacts that may affect a data set of a particular study (e.g., regional magnetic field anomalies, geomagnetic excursions, undersampling of PSV, unremoved magnetic overprints, measurement errors).

Finally, we tested whether the poles calculated for the PSV10 data set are statistically displaced from the mean pole position, using Eq. 1. We find that 26.5% (22 out of 83) of the paleopoles that are used in the PSV10 data set are, under this comparison statistic, distinct from the mean pole (Fig. 3d). This result cannot be entirely attributed to the relatively low A_{95} of 1.2°; even if we would use an A_{95} of 3.0° instead, which is a typical A_{95} value for a mean pole of the global APWP of Torsvik et al. (2012), then 15.7% (13 out of 83) of the poles would still be displaced. We find that the data set used to compute three of the 22 displaced poles may have undersampled PSV, as indicated by their A_{95} values that are smaller than the lower limit of the $A_{95min-max}$ envelope of Deenen et al., 2011 (Fig. 3d, Table S1). In addition, seven of the displaced poles do not conform to a Fisher (1953) distribution, as indicated by the quantile-quantile method

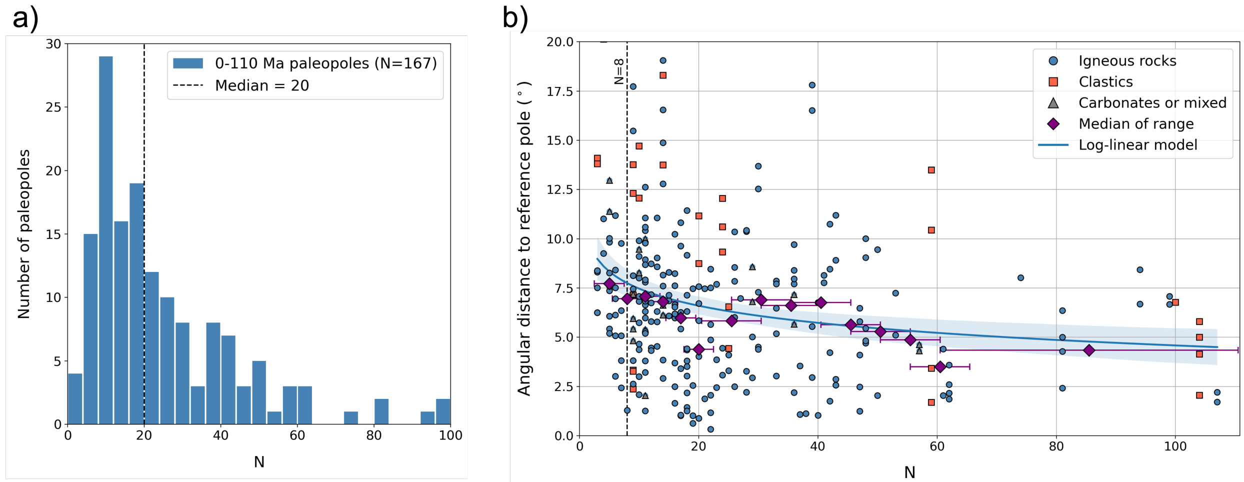


Fig. 5. a) Histogram of the number of VGPs (N) used to compute each of the 0-110 Ma paleopoles behind the global APWP of Torsvik et al. (2012). **b)** Angular distance from the reference pole versus N. Each paleopole is plotted by their lithology. The median angular distance is computed for 15 ranges of N and shown as purple diamonds. A log-linear regression curve (blue, with bootstrapped 95% confidence region) highlights the trend.

of Fisher et al. (1987). The other 12 poles pass all common reliability criteria, however. If we would exclude all data sets that do not pass these additional criteria, we find that 23.5% is statistically displaced according to Eq. 1. This illustrates that even in the PSV10 data set, which should contain little or no artifacts, a significant fraction of poles are statistically displaced relative to the reference to which they contributed.

4.2 Analysis of the paleopoles used for the global APWP

The mean (median) angular distance to the reference pole of the 962 paleopoles (most poles count twice) used for the global APWP for the last 320 Ma of Torsvik et al. (2012) is 8.0° (6.9°) (Fig. 4, Table S2). This is higher than for PSV10, suggesting that there are additional sources of scatter. This trend is also obvious from the 95% angular deviation (K_{95}) of the total population of paleopoles of 18.2° (Fig. 4a). The magnitude of pole dispersion is relatively constant with time with an average angular distance of ~7°, and up to 9-10° between 140-200 Ma and 280-330 Ma (Fig. 4b). The K_{95} of the paleopoles for the majority of 20 Ma time windows is around 12-15°, but the time windows with increased dispersion yield a K_{95} values of up to ~20° (Fig. 4b). For most time windows, the application of the quantile-quantile method of Fisher et al. (1987) indicates that the input paleopoles conform to a Fisher (1953) distribution around the reference pole (Fig. 4b).

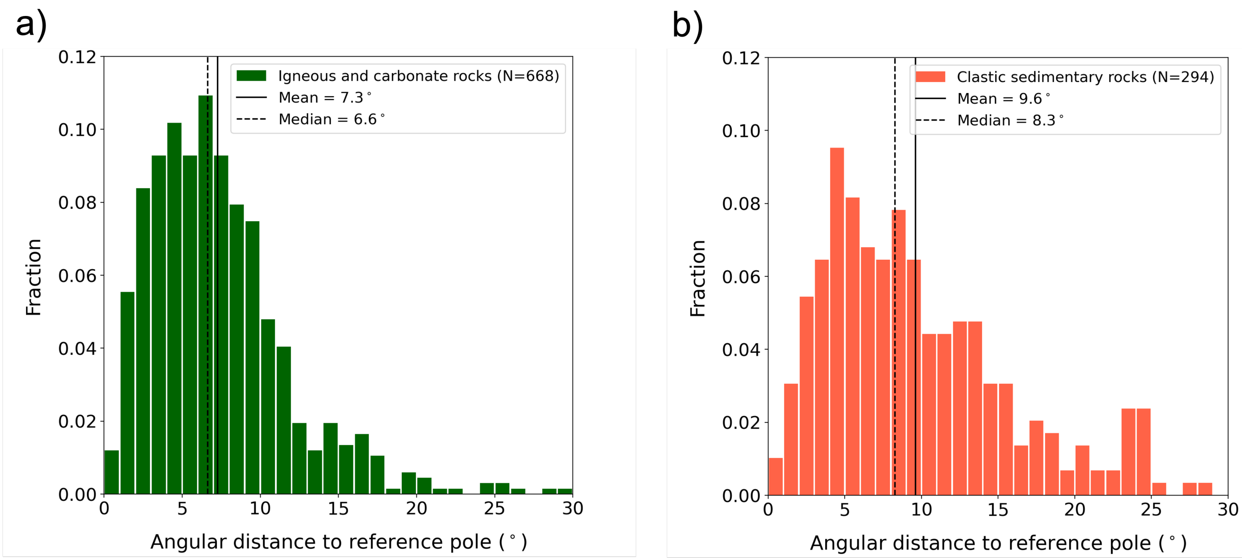


Fig. 6. Histograms of the angular distance to the reference pole of all 0-330 Ma paleopoles that are derived from igneous and carbonate rocks **(a)** and clastic sedimentary rocks **(b)**. The poles derived from the latter rocks are corrected for inclination shallowing using a 'blanket' flattening factor of f=0.6, following Torsvik et al. (2012). The mean (median) values are indicated by the vertical straight (dashed) lines.

In the following, we assess the potential relationships between the observed dispersion of paleopoles and specific characteristics of the paleomagnetic data sets used to calculate those poles.

The adequate sampling and averaging of the PSV are key requirements for determining an accurate paleopole (Deenen et al., 2011; Meert et al., 2020; Van der Voo, 1990). Paleomagnetic poles based on a larger number of independent measurements of the geomagnetic field should provide a more accurate estimate of the time-averaged geomagnetic field and thus lie closer to the position of the 'true' time-averaged geomagnetic pole. We compiled the number paleomagnetic sites (N) used for the calculation of the 167 paleopoles included for the 0-110 Ma segment of the global APWP of Torsvik et al. (2012). The number of sites used to calculate a pole varies widely between different studies, from N=3 to N=507, with a median value of 20 (Fig. 5a). For sedimentary rocks, the number of sites may represent individual samples, but sometimes also averages of multiple samples from one or multiple beds. Notably, 12% of the poles (20 in total) are calculated from less than the minimum of eight paleomagnetic sites formulated by Meert et al. (2020) in their recent update of the Van der Voo (1990) criteria. Fig. 5b shows the angular distance of each paleopole against the number of sites used to compute that pole. For this compilation of paleopoles, we observe a general decrease of the angular distance of paleopoles to the reference pole with increasing N, from ~8° for N<8 to ~5° for N>50. This trend is similar to that observed for the PSV10 database (Fig. 3c) and reflects the degree to which PSV is represented by the data. The mean angular distance is, however, a few degrees higher which may reflect additional sources of scatter, which we analyze below.

Contrary to the PSV10 database, the global APWP also contains poles from intrusive igneous rocks, carbonate rocks and clastic sedimentary rocks. Differences exist between these broad lithological groups in terms of how they record the past geomagnetic field and the properties and robustness of paleomagnetic data derived from them. Clastic sedimentary rocks are typically considered to be the least reliable paleomagnetic recorders because of their weaker remanent magnetization compared to that of igneous rocks and the common shallowing of the paleomagnetic inclination, caused by syn- and post-depositional processes (e.g., Bilardello et al., 2013; King, 1955; Kodama, 2012; Tauxe & Kent, 2004; Vaes et al., 2021). The mean (median) angular distance of paleopoles derived from clastic sedimentary rocks is indeed larger (9.6° (8.3°)) than those derived from igneous rocks (7.3° (6.6°)) (Fig. 6).

Torsvik et al. (2012) corrected the poles derived from clastic sedimentary rocks by applying a so-called 'blanket' flattening factor of f=0.6, except for poles that were calculated from data sets on which the original authors already applied an inclination shallowing-correction. We also find that the application of this 'blanket' correction factor does not significantly reduce the dispersion of sediment-derived paleopoles: using the uncorrected poles yields a mean (median) angular distance of 9.7° (8.3°). Clastic sedimentary poles thus scatter more widely than igneous poles and a blanket correction factor does not decrease this scatter. The number of paleopoles in the Torsvik et al. (2012) database that were derived either from carbonate rocks or from clastic sediments that were corrected for inclination shallowing by the original authors is too low for a meaningful calculation of the mean angular distance.

Next, we evaluate the relationship between the dispersion of paleopoles and the commonly used statistical parameters K and A_{95}. The range of K values thought be representative for PSV is ~10-50 (Deenen et al., 2011) or 10-70 (Meert et al., 2020) and collections of VGPs with higher values likely underrepresent PSV. The angular distance of igneous-based poles relative to the reference pole is ~5.4° at K-values of 20-30, increasing to higher values of ~6.6° at K-values higher than 80 (Fig. 7a). We also find that the angular distance increases with increasing A_{95} (Fig. 7b). The A_{95} confidence circle is a function of both K and N and considering the observed trends in K (Fig. 7a) and N (Fig. 5b), these results suggests that although the dispersion increases with a tighter

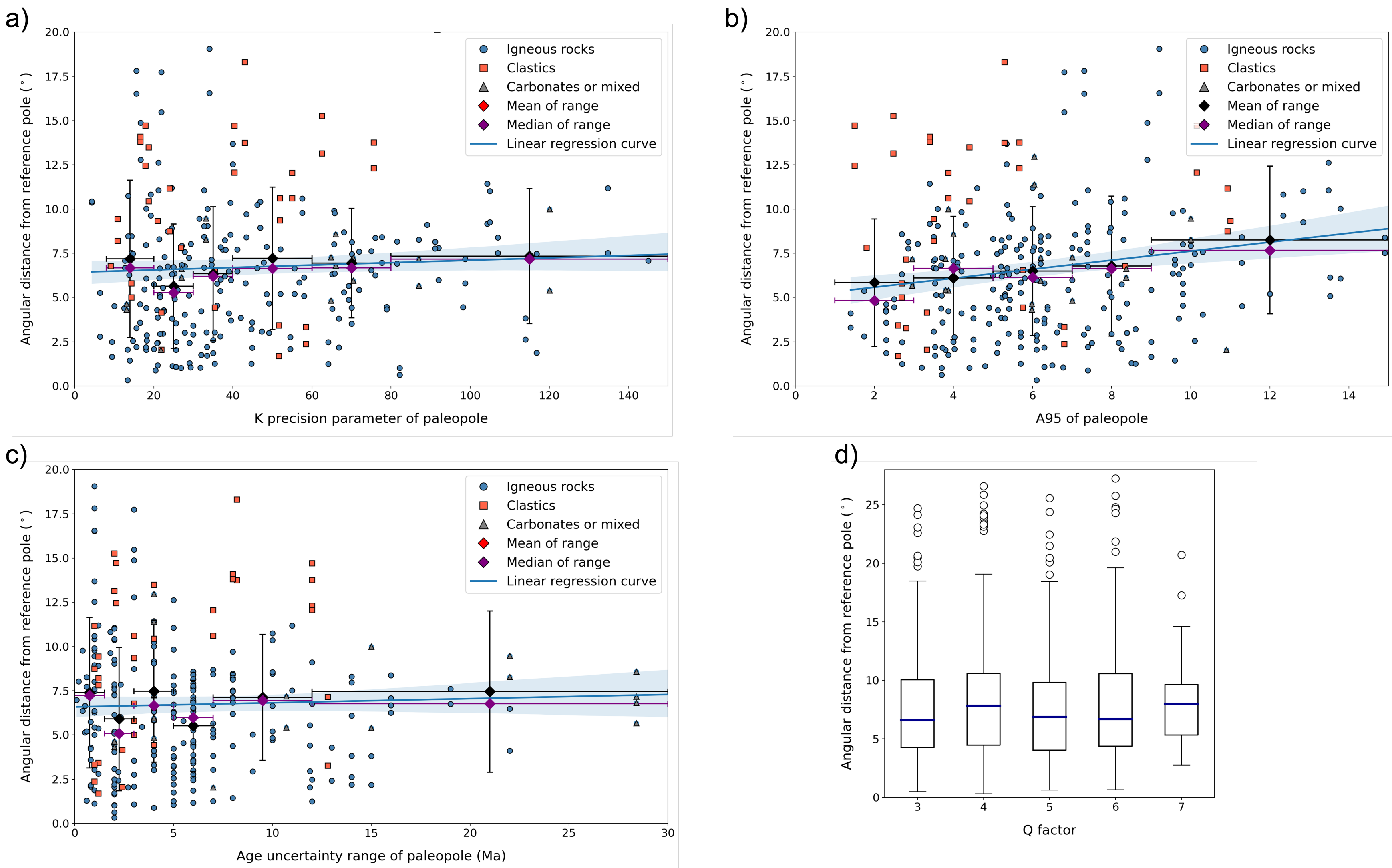


Fig. 7. Angular distance to the reference pole for all 0-110 Ma paleopoles in the compilation of Torsvik et al. (2012) against the Fisher (1953) precision parameter K **(a),** A_{95} **(b)** and the age uncertainty range **(c)**. The median angular distance is computed for several intervals and shown as purple diamonds. A log-linear regression curve (blue, with bootstrapped 95% confidence region) highlights the trend for each parameter. **d)** Boxplots showing the median angular distance and its distribution of the 0-330 Ma paleopoles behind the global APWP with a given Q-factor (Van der Voo, 1990).

clustering of VGPs, this effect is counteracted by the decrease in dispersion with increasing N. These combined effects may explain the relatively low mean angular distance for paleopoles with relatively small A_{95} values.

There does not seem to be a clear correlation between angular distance and age uncertainty of paleopoles (Fig. 7c), whether derived from igneous or sedimentary rocks. We note, however, that the rocks sampled to compute the 0-110 Ma paleopoles have age uncertainties rarely exceeding 15 Ma, which may be higher for poles from lower Mesozoic and Paleozoic rocks.

A common selection criterion to include poles into an APWP is the Q-factor of Van der Voo (1990), whose underlying quality criteria were recently updated by Meert et al. (2020). The Q-factor ranges from 1-7, indicating how many of each of the seven quality criteria of Van der Voo (1990) are satisfied by the paleomagnetic data set. In the calculation of some recent APWPs, such as the spline paths of Torsvik et al. (2012) and the APWPs of Wu et al. (2021), larger statistical weight was assigned to paleopoles with a higher Q-factor compared to those with low Q. We used the entire data set of Torsvik et al. (2012) from 0-330 Ma, which only included paleopoles with $Q \geq 3$, to assess whether there is a correlation between the Q-factor and its angular distance to the mean pole to which it contributes. We find no correlation between the quality factor Q and the angular distance of these poles (Fig. 7d). Our finding confirms the analysis by Van der Voo (1990) based on his compilation of Phanerozoic poles from Europe and North America, based on which he showed that there was no substantial decrease in the mean angular distance for $Q>2$ (see Fig. 7 of Van der Voo, 1990).

According to the traditional comparison approach (eq. 1) we find that 54.4% of the 0-110 Ma paleopoles used for the 0-100 Ma segment of the global APWP of Torsvik et al. (2012) is statistically different from the reference pole to which they contribute, i.e., the angular distance to the reference pole exceeds the combined uncertainty of both poles (Fig. 8). Paleopoles derived from clastic sedimentary rocks are not only more scattered around the reference pole to which they contribute (Fig. 6) but are also more often statistically displaced than paleopoles derived from igneous rocks (Fig. 8a). About 80% (31 of 39) of the clastic sedimentary poles are displaced compared to ~50% (117 of 236) of the igneous poles.

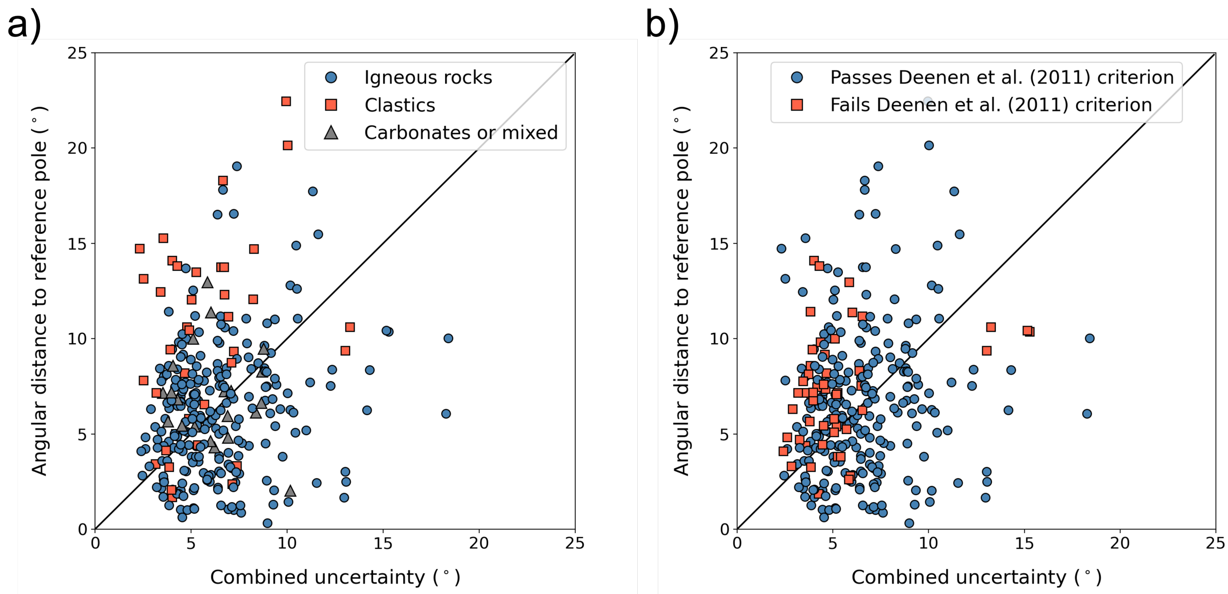


Fig. 8. Plots of the angular distance of each paleopole against the combined uncertainty, as calculated using Eq. 1 (after Rowley, 2019). Poles are coloured by lithology **(a)** or by whether the underlying VGPs conform to a Fisher (1953) distribution **(b)**.

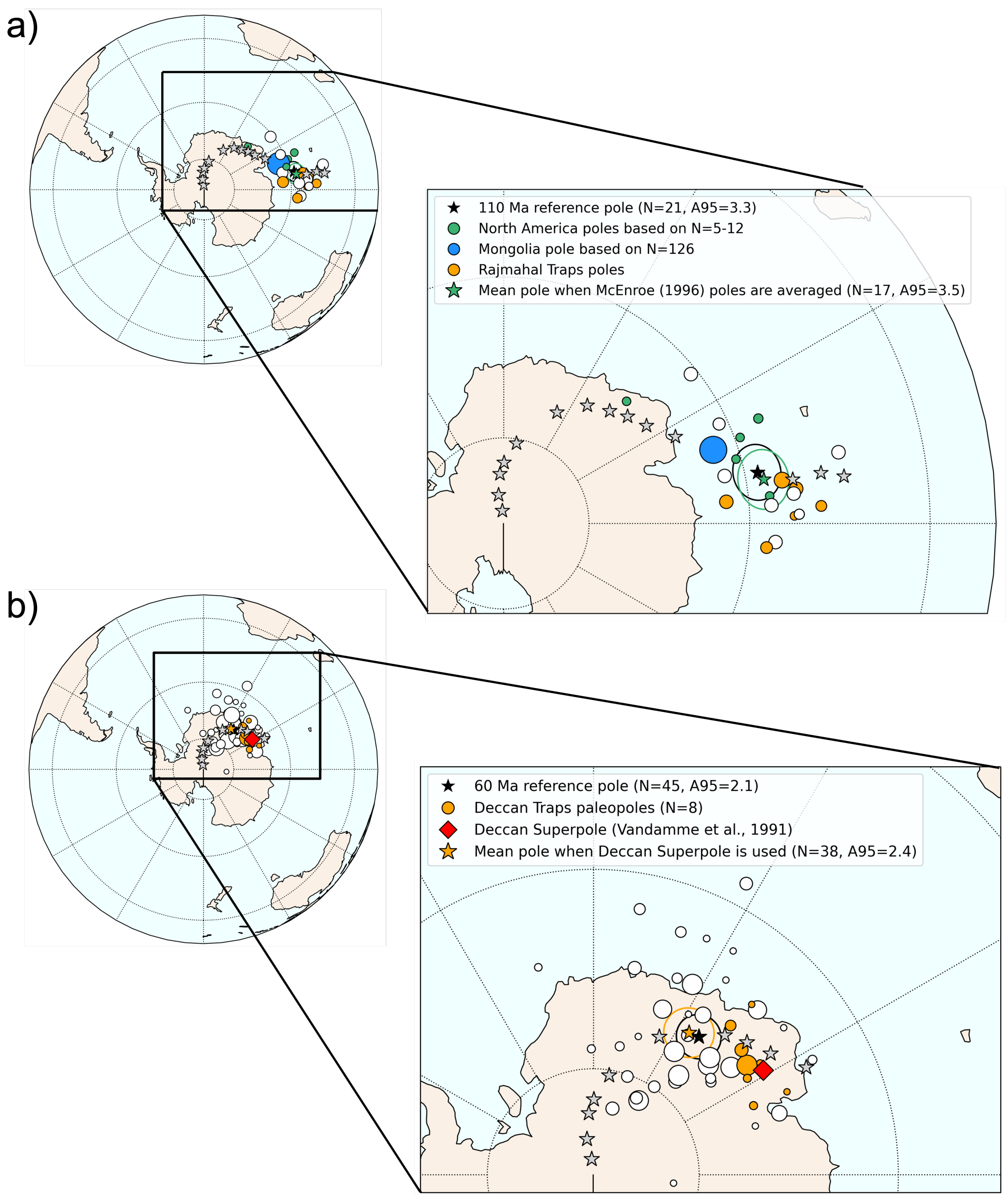
Finally, of all paleopoles that have an A_{95} that falls outside of the N-dependent reliability envelope of Deenen et al. (2011), which assesses whether the scatter is straightforwardly explained by PSV alone, ~70% is found to be statistically displaced (Fig. 8b), mostly because of low scatter of the underlying VGPs, yielding an $A_{95}<A_{95,min}$. This supports the conclusion of Harrison & Lindh (1982) that underrepresentation of PSV by the paleomagnetic data set is an important cause of individual paleopoles to be statistically displaced from the reference pole to which they contribute. Together with the trend that poles with higher K-values have larger angular distances to the reference pole, this shows that undersampling of PSV increases the dispersion of paleopoles used in current APWPs, and the number of statistically displaced poles.

5 Discussion

5.1 The problem of using paleopoles

Rowley (2019) argued that the traditional method used to determine a statistically significant difference between independent paleopoles and an APWP is flawed, because a large fraction of input poles is statistically ‘displaced’ from the reference pole to which they contribute. Such statistical differences therefore do not necessarily represent the tectonically meaningful difference that is commonly interpreted from them (e.g., Butler, 1992; Coe et al., 1985; Harrison & Lindh, 1982; Rowley, 2019). What causes these paleopoles to be displaced (according to the traditional statistical framework)? Our analysis in part confirms the widely held suspicion that common errors and uncertainties in paleomagnetic data contribute to this. We find that paleopoles are more often statistically distinct when derived from data sets in which PSV is likely underrepresented (indicated by high K values (e.g., $K>70$; Meert et al., 2020), and an A_{95} that is below the $A_{95,\,min}$ of the reliability envelope of Deenen et al. (2011)), or from clastic sedimentary rocks, regardless of whether they are corrected for inclination shallowing using a 'blanket' correction factor of 0.6 or not (*sensu* Torsvik et al., 2012). Excluding paleopoles based on such data sets may thus decrease the dispersion of paleopoles. We also find, however, that the dispersion of paleopoles, and their statistical difference with the reference pole to which they contribute, cannot solely be attributed to the 'insufficient' quality of the paleopoles themselves.

Our analysis reveals that even when paleomagnetic data sets pass stringent and widely applied quality criteria, the paleopoles derived from them are frequently statistically different from the reference pole to which they contribute. Our analysis of 0-110 Ma paleopoles behind the APWP of Torsvik et al. (2012) shows that ~50% of the igneous-based paleopoles, that have a high Q-factor and that satisfy the criterion of Deenen et al. (2011), are statistically displaced from the reference pole to which they contribute. Moreover, ~26% of the paleopoles obtained from the high-quality data sets of recently erupted lavas included in PSV10 are statistically displaced from the mean pole calculated for the recent (<10 Ma) geomagnetic field. These findings illustrate that the accuracy at which we can determine the time-averaged geomagnetic pole position using a single paleopole is not as high as our statistical metrics suggest, and that the formal confidence region (the A_{95}) may underestimate the true uncertainty of an individual paleopole (e.g., Coe et al., 1985; Harrison & Lindh, 1982; Rowley, 2019). This may be partly explained by the fact that uncertainties are typically not propagated through each hierarchical level in standard paleomagnetic analyses (Heslop & Roberts, 2020). Our results show that there are often sources of scatter that cause poles to be displaced that cannot be, or at least were not, recognized by the paleomagnetists that collected the data sets, and that cannot be straightforwardly identified using commonly applied quality criteria. Such sources of dispersion may include non-dipole contributions to past geomagnetic field or unrecognized intra-plate deformation (e.g., Besse & Courtillot, 2002; Butler, 1992). Overall, our results support the notion from Rowley (2019) that the observed dispersion may be inherent to paleomagnetic data, and the paleopoles derived from them. But because the dispersion of coeval



483 **Fig. 9.** Examples of how subjective choices related to the definition and inclusion of certain paleopoles may influence the reference pole position and associated parameters. See text for discussion. **a)** Orthographic projection of the 100-120 Ma paleopoles used to compute the 110 Ma reference pole of the global APWP of Torsvik et al. (2012). Two reference poles are plotted: computed from all paleopoles (black star) or if the McEnroe (1996) poles are replaced by a 'study mean' pole (green star). The difference between the reference poles is 1.2°. **b)** Same as a), but this time showing the 50-70 Ma paleopoles used to compute the 60 Ma reference pole. Again two reference poles are plotted: computed from all paleopoles (black star) or if the Deccan Traps poles are replaced by the Deccan Superpole of Vandamme et al. (1991). The difference between the reference poles is 1.0°.

an alternative approach in which the uncertainty of an APWP is directly determined by the dispersion of input poles, irrespective of the sources of the dispersion. The magnitude of dispersion depends, however, on subjective choices, which we illustrate below.

Our results show that the number of VGPs used to compute paleopoles (N) is a first-order contributor to the dispersion of coeval paleopoles (Fig. 3c, 5a). And this introduces a fundamental problem: there is no definition of the amount of paleomagnetic data that defines paleopole. Widely used quality criteria only include a minimum amount of data needed to calculate a reliable paleopole: Van der Voo (1990) proposed a minimum of 25 samples, to which Meert et al. (2020) recently added that these samples should preferably be derived from N≥8 paleomagnetic sites. Because these values only provide a minimum, this allows the calculation, and inclusion in an APWP, of paleopoles based on a highly variable number of paleomagnetic data, as illustrated by the poles used in the most recent global APWP (Fig. 5a). Although the number of VGPs behind a paleopole is often simply determined by the amount of 'reliable' paleomagnetic data presented in a single study, multiple paleopoles from the same study are sometimes included as separate poles in the calculation of an APWP, or a single 'grand' mean pole is computed from data obtained in different studies of the same volcanic or sedimentary sequence. For example, in the global APWP of Torsvik et al. (2012), a Cretaceous paleomagnetic pole from Mongolia was calculated from N=126 lava sites (van Hinsbergen et al., 2008), whereas 42 sites from North American intrusive rocks of approximately the same age (McEnroe, 1996) were used to compute five different input poles of N=5-12 (Fig. 9a). Likewise, that APWP includes seven poles from seven published data sets of the Deccan Traps of India constrained by N varying from 3 to 130 (Fig. 9b), whereas these data sets could instead be combined into a single mean pole for the Deccan Traps, as done by Vandamme et al. (1991), or in dozens of poles when using the N≥8 criterion of Meert et al. (2020).

If the number of paleomagnetic sites/VGPs (N) behind a single paleopole is essentially arbitrary, as illustrated above, and N is a first-order contributor to the dispersion of poles, then the K_{95} value is dependent on arbitrary choices as well. Given a data set of VGPs, we may calculate reference poles of an APWP with low A_{95} and high K_{95} by including many paleopoles based on low N, or with high A_{95} and low K_{95} by combining the same data over a few paleopoles with high N. Below we will therefore explore the alternative avenue of calculating a reference APWP from VGP-level data directly, instead of from paleopoles that each represent an average of an arbitrarily defined collection of VGPs.

5.2 Towards a VGP-based comparison method

Calculating a reference data set from VGPs instead of paleopoles allows the comparison with an independent paleomagnetic data set of VGPs on the same hierarchical level and avoids subjective choices regarding the amount of paleomagnetic data that is used to determine a single paleopole. VGP-based APWPs have been constructed before, for e.g., Australia (Hansma & Tohver, 2020; McElhinny et al., 1974), Iberia (van Hinsbergen et al., 2017), and Laurentia (Swanson-Hysell et al., 2019), and for all major continents by McElhinny & McFadden (2000). Also, paleomagnetic data from different studies and locations have been combined on the VGP level in studies of geomagnetic field behavior (e.g., Brandt et al. 2021; Cromwell et al., 2018). Calculating APWPs from VGPs poses several challenges, however. First, a method needs to be designed to avoid the 'displacement' problem highlighted by Rowley (2019). Second, for many published paleomagnetic data sets, individual VGPs have not been reported and estimates need to be developed from published statistical descriptions of the data.

The problem of displaced paleopoles that follows from the application of the traditional comparison metric (Eq. 1) will be even more prominent for VGP-based APWPs. Because the total number of VGPs (N) is much higher than the number of paleopoles, the A_{95} calculated from all individual VGPs is even smaller than that calculated from the associated paleopoles. With so many paleopoles already statistically displaced from the APWP using classical comparison metrics (see Eq. 1), this problem will also exist or be even larger for VGP-based APWPs. To illustrate this: for the PSV10 data set, the A_{95} calculated from the 'study mean' poles that contributed to the PSV10 data set is 1.2°, and from the VGPs is 0.7°. Using the VGP-based A_{95} as the $A_{95,\,ref}$ instead of the pole-based A_{95}, the number of displaced poles determined with Eq. 1 increases from 22 to 23. This shows that a different measure needs to be developed that ensures that ~95% of the input data sets do not statistically differ from the reference data set. Below, we use the PSV10 data set to explore such an alternative approach.

Our analysis shows that the angular difference between a paleopole and a reference pole decreases with an increasing number of VGPs (N) (Fig. 3c, 5a). We therefore introduce a new comparison metric between paleopoles and reference data sets that takes N into account. Central to this approach is an alternative expression for the confidence limit of the reference pole (of an APWP), which we refer to as the 'B_{95}'. The B_{95} is an estimate of the 95% confidence limit that the

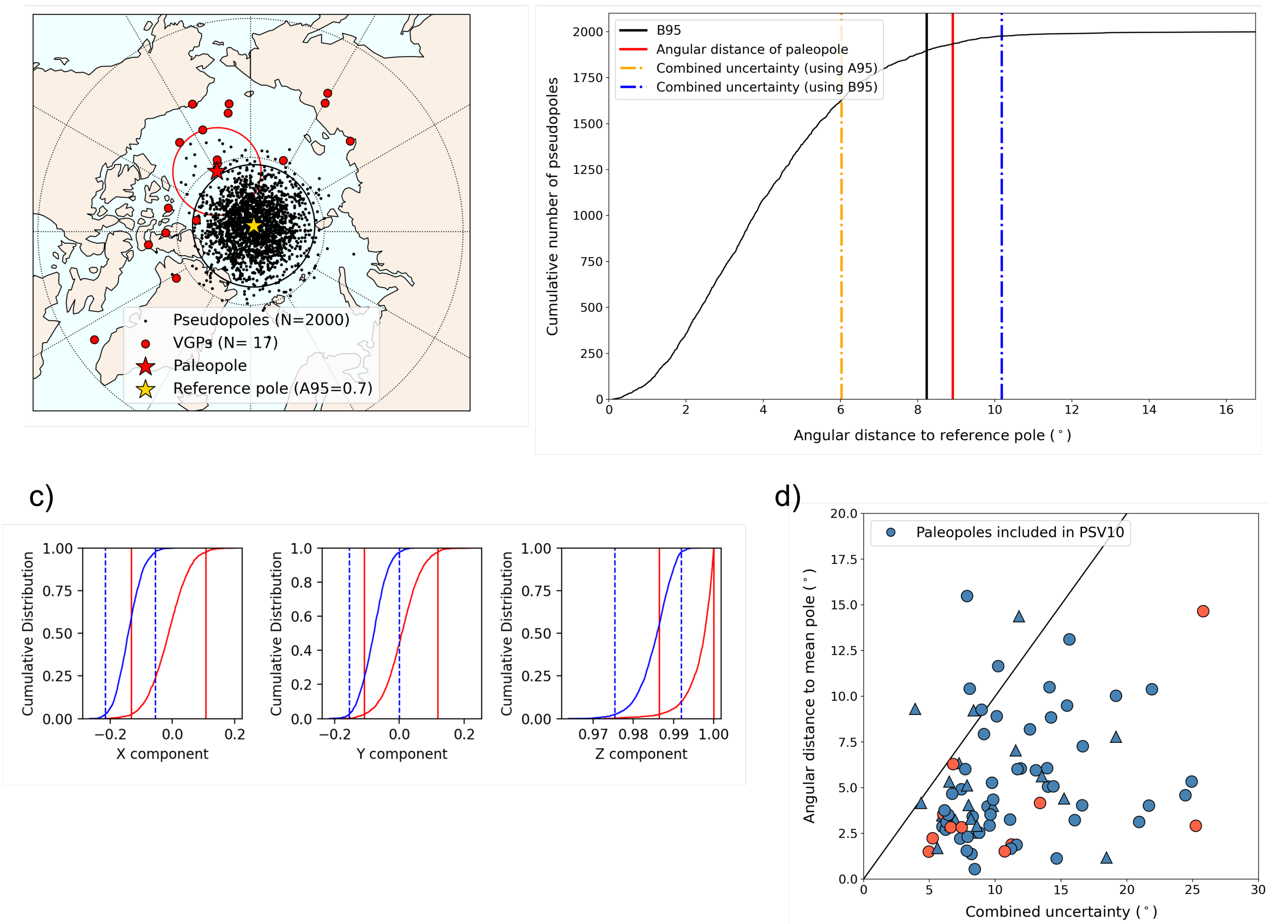


Fig. 10. Example of the proposed VGP-based comparison method (see text for more detailed discussion). **a)** Orthographic projection of the paleomagnetic data set of Oliva-Urcia et al. (2016) that was included in PSV10. The VGPs and the paleopole computed from those VGPs are plotted as red circles and a red star (with A_{95}), respectively. To assess whether this paleopole is statistically distinct from the reference data set, 2000 pseudopoles are computed by randomly drawing the same number of VGPs (17) from the total data set (small black dots). The B_{95} is then defined as the 95% angular deviation of these pseudopoles from the principal vector of the distribution of pseudopoles, and is indicated by the black circle. **b)** Cumulative distribution of the pseudopoles plotted against the angular distance from the reference pole. Vertical lines show the angular distance of the paleopole, the B_{95} and the combined uncertainty computed (i) following the traditional framework (see Eq. 1) and (ii) by replacing the $A_{95,ref}$ with the B_{95}. This figure indicates that the studied paleopole is not statistically 'displaced' according to our new metric, whereas it is displaced according to the traditional statistical framework. **c)** Bootstrap common mean test of Tauxe (2010) applied to the studied data set (blue), showing that the data set is not statistically different on the 95% confidence level from the set of pseudopoles (red). The three subplots each show the cumulative distribution of bootstrapped means in the three Cartesian coordinates x, y and z. **d)** Plot of the angular distance of each paleopole against the combined uncertainty for all data sets included in PSV10, whereby the combined uncertainty is computed after replacing the $A_{95,ref}$ in Eq. 1 by the B_{95} (see also Table S1). Using the VGP-based approach, the number of displaced poles decreases from 22 to 7 (out of 83).

reference data set, represented by a reference pole, would have had if it had been constrained by the same N as the studied paleopole. In other words, the B_{95} represents a prediction of the pole position of a paleopole with given N, if that paleopole would have sampled N VGPs from the total cloud of 'reference' VGPs. This way, the resolution of a comparison between a reference data set and a collection of VGPs obtained by a paleomagnetic study is directly dependent on the N of the latter data set, and thus naturally reflects the amount of information included in the statistical comparison.

To determine the B_{95}, we use a bootstrap approach: for each bootstrap run we compute a pseudopole from N randomly drawn VGPs from the reference data cloud. By repeating this procedure a few thousand times, we obtain thousands of pseudopoles, each derived from the same amount of VGPs as included in the studied paleomagnetic data set. Next, we calculate the B_{95} as the angular distance from the principal vector of the cloud of pseudopoles that contains 95% of the pseudopoles (Fig. 10a, b). Evidently, the B_{95} becomes larger when these pseudopoles are calculated from a smaller number of VGPs and is thus directly proportional to the number of VGPs included in the studied data set. This approach makes no a priori assumptions about the behavior or statistical properties of the geomagnetic field, but simply predicts where poles based on N VGPs could lie, as a function of the scatter in the reference data set, regardless of the sources of this scatter.

We now assess how this equal-N approach performs by determining the number of 'displaced' paleomagnetic data sets included in the PSV10 database. To this end, we compute the B_{95} for each 'study mean' pole using its underlying number of VGPs, and then replace the $A_{95,ref}$ by the B_{95} in Eq. 1. Again, we consider a data set statistically distinct from the reference if the angular distance of the study mean pole exceeds the combined uncertainty, which in this approach is a function of the B_{95} of the reference and the A_{95} of the compared paleopole. We find that this comparison method reduces the percentage of displaced poles from 26.5% to 8.4% (7 out of the 83 data sets, Fig. 10d). Some of these data sets are thus still 'displaced', also according to our proposed comparison metric. We note, however, that four of these data sets were almost entirely derived from a sequence of successive lava flows, which led Cromwell et al. (2018) to discard most of the VGPs in their filtered PSV10 data sets, since those VGPs may not have provided entirely independent spot readings of the field.

The above results suggest that replacing the $A_{95,ref}$ with the bootstrapped B_{95} in Eq. 1 may provide an alternative solution for the 'displacement' problem pointed out by Rowley (2019). The application of this approach requires, however, that the reference data set (of an APWP) is calculated from VGPs, which are not always available.

5.3 Parametric re-sampling of VGPs

Paleomagnetic data sets available for computation of APWPs often have not been reported on the VGP level, but only per paleopole, and the vast majority of published paleomagnetic data has not been included in modern paleomagnetic databases (e.g., MagIC (Jarboe et al., 2012), Paleomagnetism.org (Koymans et al., 2020). To overcome this problem, we may parametrically re-sample VGPs from the paleopoles given the published statistical properties of such poles. To evaluate whether this is appropriate, we reproduce the PSV10 data set through parametric re-sampling of VGPs from the 'study mean' poles and their statistical parameters (referred to as a 'parametric bootstrap', following Tauxe, 2010). For each data set included in PSV10, we created the same number of VGPs as included in the published data set from a Fisher (1953) distribution around the 'study mean' pole and its associated precision parameter K, which were both calculated from the published VGPs. The parametrically sampled data cloud is very similar to that of the published VGPs (Fig. 11a), with little difference in the associated statistical parameters. We observe a slightly larger dispersion of the parametrically sampled VGPs (indicated by a lower K value) compared to the published VGPs (Fig. 11b). This is explained by the outlying VGPs in the published data sets that lower the K value for that data set, such that when these data sets are parametrically re-sampled, a larger fraction of the simulated VGPs are between ~15° and ~50° from the mean pole of all VGPs (Fig. 11a).

We now test whether the data sets that contributed to the PSV10 database are displaced relative to a reference data set consisting of parametrically re-sampled VGPs instead of the published VGPs. From the collection of 2401 parametrically sampled VGPs, we compute a pseudopole by drawing the required N, which is again equal to the N that is behind the investigated data set included in PSV10. We then repeated this procedure 2000 times, each time generating a new set of parametrically sampled VGPs, to obtain the set of pseudopoles from which we compute the B_{95}. We find that this B_{95} is typically ~0.1-0.4˚ larger than that obtained from the published VGPs (Table S1). This illustrates that using parametrically sampled VGPs instead of the 'real' VGPs is slightly more conservative, making it thus slightly more difficult to demonstrate a significant displacement between a paleopole and the reference data set. We find that using

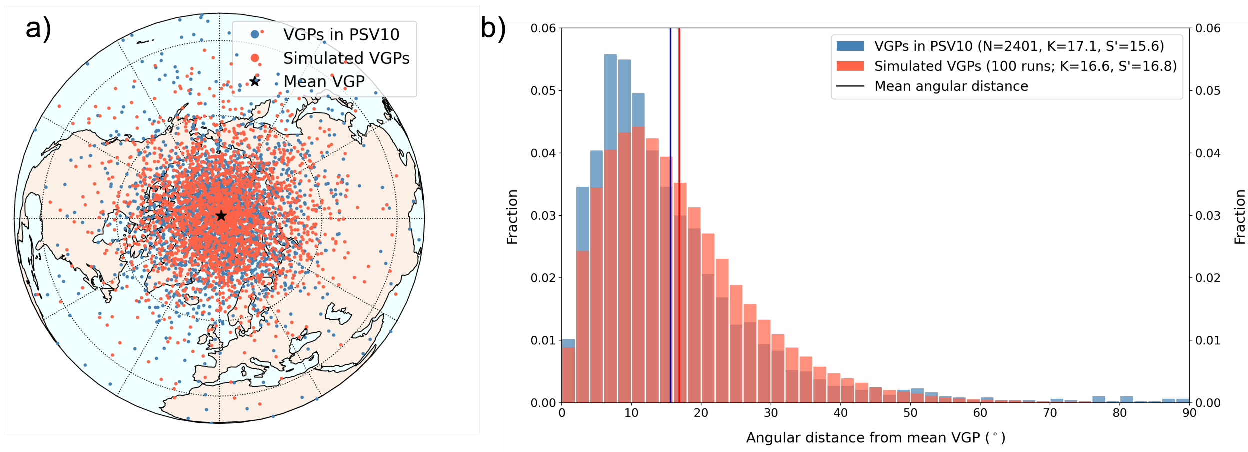


Fig. 11. Comparison between the VGPs included in the PSV10 compilation and the parametrically sampled VGPs derived from the paleopoles and their statistical parameters. **a)** Orthographic projection of the VGPs included in PSV10 (blue dots) and parametrically sampled VGPs (red dots) from one simulation whereby these VGPs were generated for each data set of PSV10 from a Fisher (1953) distribution around the paleopole and described by the K value of the underlying VGPs. **b)** Histogram of the angular distance from the reference pole of the published VGPs (blue) and parametrically sampled VGPs (obtained from 100 simulations). The mean angular distance of the simulated VGPs (red line) is slightly larger than that of the published VGPs (blue line).

parametrically sampled VGPs to compute the B_{95} makes no difference for the data sets included in PSV10: the number of 'displaced' paleopoles remains the same (7 out of 83; Table S1). This therefore opens the opportunity to compute future APWPs, including a global APWP, from VGP-level data, even if all the original VGPs are not available.

5.4 Outlook: future APWPs and their application

We show here that calculating APWPs from VGP-level data provides a way to resolve the 'displacement' problem in current pole-based APWPs, whereby subjective choices related to the definition of individual paleopoles are avoided and paleomagnetic data can be compared with a chosen reference on the same hierarchical level. Computing APWPs from VGPs has more benefits: it allows the incorporation and propagation of key uncertainties and errors in paleomagnetic data, such as age uncertainty, as demonstrated by the bootstrap or Monte Carlo-based methods recently developed by Swanson-Hysell et al. (2019) and Hansma & Tohver (2020). The uncertainty in the position of a 'study mean' paleopole, which is determined by the number and scatter of the underlying VGPs, is automatically accounted for in a VGP-based approach. To incorporate age uncertainty, a reference pole and its B_{95} can be computed from only those VGPs that fall in a chosen age range. Age uncertainty could then be weighed by parametrically sampling VGPs from all reference paleopoles that overlap in age with the chosen time window and assigning a random age within the age range of the reference paleopole to each VGP. Each pseudopole from which the reference pole position and its B_{95} is computed is then drawn from only those VGPs whose ages fall within the time window. When comparing an independent paleomagnetic data set with a VGP-based APWP, the age range may be equated to the age range of the sampled rocks, thereby accounting for both the number of VGPs that data set and its age uncertainty.

On the other hand, the VGP-based approach also comes with a necessity for larger data scrutiny, particularly for large data sets. In the VGP-approach unit weight is assigned to each VGP, such that largest weight is assigned to largest paleomagnetic data sets. This essentially means that the accuracy of each paleopole is assumed to be a function of N alone; with increasing N, PSV and other sources of noise are increasingly averaged. However, some paleomagnetic data sets may be affected by systematic bias that is unrelated to N, such as local deformation, errors in tilt correction, systematic magnetic overprints, a local/regional magnetic field anomaly, inclination shallowing, and undersampling of PSV. The majority of poles from the data set underlying the APWP of Torvsik et al. (2012) that are displaced according to classical comparison metrics likely suffer from one or more of these artifacts. It is thus important to apply stringent and objective selection criteria, such as those from Meert et al. (2020) and Vaes et al. (2021), for inclusion of data into the APWP.

We foresee that VGP-based APWPs, which have confidence intervals that better reflect the scatter of the underlying paleomagnetic data and do not depend on subjective choices, will provide more accurate and robust paleomagnetic reference frames, at shorter time intervals, to underpin paleogeography studies (e.g., van Hinsbergen et al., 2015), or e.g., true polar wander calculations (e.g., Kulakov et al., 2021; Muttoni & Kent, 2019; Torsvik et al., 2012). At the same time, the B_{95} makes that the resolution of the reference is adjusted to the resolution of the paleomagnetic data set that is compared with the reference, such that demonstrating smaller statistical differences requires larger data sets. It also opens novel opportunities to compute high-resolution reference poles for specific times of rapid Earth system change by collecting large, well-dated paleomagnetic data sets. We emphasize that for VGP-based APWPs, it is of key importance that the paleomagnetic community makes all their published data publicly available, e.g., in databases such as MagIC (Jarboe et al., 2012) or paleomagnetism.org (Koymans et al., 2020), as this will strongly improve future APWPs and contribute to solving detailed Earth system problems.

6 Conclusions

In this study, we investigated the causes of the large dispersion of paleopoles obtained from similar aged rocks that causes a large fraction of these poles to be statistically displaced from the mean pole to which they contribute. To this end, we used a previously compiled global data set from <10 Ma old volcanic rocks (PSV10) without tectonics-induced pole dispersion, and the compilation of paleopoles used to compute the most recent global APWP of Torsvik et al. (2012). Based on our analyses, we conclude the following:

- The dispersion of paleopoles, defined by their angular distance to the reference pole to which they contribute, decreases with an increasing number of VGPs from which they are calculated. Individual paleopoles, which are commonly based on a few dozen VGPs, do not average 'out' PSV and their angular distance to the reference pole is, in part, dependent on the extent to which PSV has been sampled by the underlying paleomagnetic data set.
- Paleopoles that are statistically displaced from the reference pole of the APWP, according to the traditional statistical framework, are more often derived paleomagnetic data sets in which PSV is likely underrepresented, or from clastic sedimentary rocks, regardless of whether they are corrected for inclination shallowing using a 'blanket' correction factor.
- The dispersion of paleopoles, and their statistical difference with a given reference pole, cannot solely be attributed to the insufficient quality of the paleopoles. This is demonstrated by the absence of a correlation between the Q-factor of Van der Voo (1990) and the pole dispersion, as well as the high percentage (~26%) of displaced paleopoles derived from the data sets included in PSV10 that are devoid of tectonic or sedimentary artifacts. The high percentage of displaced poles indicates that the formal confidence region (the A_{95}) of individual paleopoles may underestimate the true uncertainty in pole position. This implies that sources of uncertainty cause poles to be displaced that are not straightforwardly identified by applying common quality criteria, which may include non-dipole contributions or unrecognized intra-plate deformation.
- There is no clear definition of the amount of data that underpins a single paleopole. Although all input paleopoles are typically assigned equal weight in APWP computation, they are an average of a collection of VGPs of essentially arbitrary size, and the number of VGPs that underlie paleopoles varies considerably. Also, the number of paleopoles derived from a single paleomagnetic data set or from a specific volcanic or sedimentary sequence is often

determined by subjective choices. Such choices may potentially bias the position of reference poles of an APWP and the size of its confidence regions.

- Calculating a reference data set from VGP-level data avoids the problem of arbitrarily defined paleopoles. We explored a bootstrap-based approach to comparing a given paleomagnetic data set against such a VGP-based reference data set, whereby the resolution is determined by the number of VGPs in the studied data set. We show that this comparison metric significantly reduces the percentage of displaced data sets included in PSV10 (from ~24% to ~8%) and thus provides an alternative solution to the problem of displaced paleopoles in current pole-based APWPs highlighted by Rowley (2019).
- Constructing APWPs from VGP-level data instead of from paleopoles allows giving more weight to larger data sets and incorporating key uncertainties associated with paleomagnetic data sets. This enables the comparison of paleomagnetic data sets with a reference APWP on the same hierarchical level, such that physically meaningful differences and associated uncertainties may be determined. Such an approach also implies that constraining smaller relative tectonic displacements requires larger, better dated paleomagnetic data sets. Moreover, future APWPs may thus be strongly improved by collecting large, high-quality data sets from stable plate interiors.

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Data Availability Statement

No new paleomagnetic data is used in this study. The paleomagnetic data sets are derived from previous compilations by Torsvik et al. (2012) and Cromwell et al. (2018), and can be found both in the original publications as well as in the tables of the Supporting Information. The Python codes used for our analysis will be made publicly available on Github upon acceptance of this manuscript.

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