Comment on "Influence of data filters on the position and precision of paleomagnetic poles: what is the optimal sampling strategy? " by Gerritsen et al. (2022).

Pierrick Roperch[1]

[1]Géosciences Rennes

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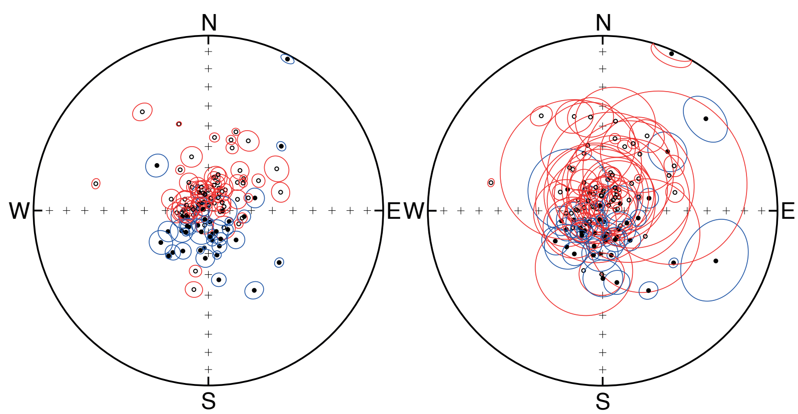
Abstract

In a recent paper, Gerritsen et al. (2022) propose to modify the well-accepted sampling strategy in paleomagnetism by collecting more single-sample sites. They also argue that the paleomagnetic community commonly applies a loosely defined set of quantitative data filters and that there is no need for an expert-eye to analyze and interpret paleomagnetic data. Many paleomagnetists will disagree with these claims as paleomagnetic methods provide very robust results at the site level when the study is done with sufficient rigor. As stated in Gerritsen et al. (2022) they deliberately kept directions that an experienced paleomagnetist would likely immediately discard as unreliable. Can we really draw conclusions from such an approach to paleomagnetism? The strategy proposed by Gerritsen et al. (2022) has serious drawbacks well illustrated by the datasets from Turkey (van Hinsbergen et al., 2010), Mongolia (van Hinsbergen et al., 2008), Norway (Haldan et al., 2014), and Antarctica (Asefaw et al., 2021) used by Gerritsen et al. (2022). The main objective of this comment is to support standard methods (Butler, 1992; Tauxe et al., 2018) for a well-defined determination of the paleomagnetic direction per site based on the sampling of several samples per site.



Comment on "Influence of data filters on the position and precision of paleomagnetic poles: what is the optimal sampling strategy? " by Gerritsen et al. (2022).

P. Roperch[1]

[1]Géosciences Rennes, CNRS-INSU & Université de Rennes, Campus de Beaulieu, 35042 Rennes, France

Corresponding author: Pierrick Roperch (Pierrick.roperch@univ-rennes1.fr)

Key Points:

- Seven is likely the minimum number of required samples per paleomagnetic site
- Outliers should be removed
- Oversampling the same paleomagnetic direction is the main problem for an accurate average of paleosecular variation

Abstract

In a recent paper, Gerritsen et al. (2022) propose to modify the well-accepted sampling strategy in paleomagnetism by collecting more single-sample sites. They also argue that the paleomagnetic community commonly applies a loosely defined set of quantitative data filters and that there is no need for an expert-eye to analyze and interpret paleomagnetic data. Many paleomagnetists will disagree with these claims as paleomagnetic methods provide very robust results at the site level when the study is done with sufficient rigor. As stated in Gerritsen et al. (2022) they deliberately kept directions that an experienced paleomagnetist would likely immediately discard as unreliable. Can we really draw conclusions from such an approach to paleomagnetism? The strategy proposed by Gerritsen et al. (2022) has serious drawbacks well illustrated by the datasets from Turkey (van Hinsbergen et al., 2010), Mongolia (van Hinsbergen et al., 2008), Norway (Haldan et al., 2014), and Antarctica (Asefaw et al., 2021) used by Gerritsen et al. (2022). The main objective of this comment is to support standard methods (Butler, 1992; Tauxe et al., 2018) for a well-defined determination of the paleomagnetic direction per site based on the sampling of several samples per site.

1 Introduction

It is well-known that paleosecular variation recorded in lava flows is important as illustrated by the extensive work done in lava flow sequences from Iceland (Kristjansson, 2002; Kristjansson & McDougall, 1982). It has also long been recognized that the scatter in virtual geomagnetic poles in paleomagnetic data is a function of latitude (M. W. McElhinny & R. T. Merrill, 1975). We need a well-defined paleomagnetic direction at each site if we want to better understand the eruption rate and the spatial extent of a lava flow as the main problem in paleomagnetic studies is the oversampling of the same geomagnetic direction recorded at several sites either in successive lava flows emplaced in a short time interval or from volcanic units flowing on tens of kilometers. The sampling strategy of one sample per site proposed by Gerritsen et al. (2022) (GVH) will impede the recognition of such situation. Moreover, GVH do not exclude unreliable directions. Using the same databases, we show that this approach alters the robustness of paleomagnetic methods.

Paleomagnetism in volcanic rocks without late metamorphism is usually straightforward and robust characteristic remanent magnetizations (ChRM) are often easily recovered. Unreliable directions are in most cases outliers that should be easy to identify because they are due to an unfortunate paleomagnetic sampling of poorly-defined outcrops, errors in the orientation of the samples and a poor estimation of the characteristic directions by inexperienced users. A reduced number of samples per site will not permit to identify these outliers. The interpretation of the data in GVH leads to an alarming number of sites with high scatter not seen in the original publications (Figure 1). The differences between the well-done determination of the paleomagnetic directions in Asefaw et al. (2021) and the "without expert-eye" GVH approach are striking (Figures 1 & S1, S2). Then is it really possible to accept the GVH sampling strategy based on a deliberately poorly done paleomagnetic analysis of the original data?

2 Materials and Methods

The same data analysed in GVH were downloaded from the MagIC database for a thorough evaluation of the nature of the numerous anomalous outliers reported in GVH in their supplementary data. The data from the MagIC database were plotted and processed using classic paleomagnetic tools providing the possibility to visualize the data at the site level in sample coordinate as well as in in situ and after bedding correction.

3 Paleomagnetic observations

3.1 Unreliable sites.

The sampling of a cold volcanic breccia would result in a large scatter between the paleomagnetic characteristic directions within a site. Such a situation is likely found at sites AH4 or AH7 in the Turkey database (supplementary Figure S3). Perhaps, the breccias were not identified in the field but this is the information given by the paleomagnetic data due to the high magnetic stability of the samples upon AF demagnetization.

The sampling of several samples per site thus permits to discard data from such sites provided that the samples are not drilled in a single block that is not representative of the site. This information is however rarely quantified. Unfortunately for the Turkey database, while the magnetization was stable at the sample level, the large scatter at several sites suggests that too many breccias or poor quality outcrops were sampled at several localities. One third of the directions listed by GVH are at more than 40° from the mean. Can we draw robust conclusions from such data?.

3.2 Outliers du to errors in sample orientation.

During drilling in fractured rocks, it is frequent that cores get broken and their orientation may be complicated. This leads to small errors in orientation of individual cores and these errors are cancelled providing that several cores are drilled at each site. Another common error is the bad sense of the arrow marked along the core. This should be easily recognized in the laboratory as this error leads to a change of sign in the magnetization along Y and Z but not along X. Such errors are thus easily observed in the paleomagnetic data in sample coordinates. Examples of such errors are found at several sites in the Mongolian and Turkey databases. There are even sites where this simple error is found twice. Obviously, these outliers are easily corrected or rejected providing the number of cores within a site is sufficient. But these outliers should never be included in further interpretations as done in GVH . There is no need for an expert-eye to find such basic errors. Other common errors are in the azimuth of the sample orientation often easily spotted as the ChRM outlier declination seems associated to a very different sample azimuth from other samples. In any case, most situations are similar to site JI VI with a clear outlier (Figure S4) that will be rejected by most paleomagnetists.

3.3 Problems in the laboratory.

Volcanic rocks may have high remanent magnetizations above 10 Am^{-1} for some samples. The measurement of such magnetizations with cryogenic magnetometers requires low speed of sample translation to avoid flux jumps. The data from Mongolia are unusually noisy possibly due to this problem. Fortunately the remanent magnetization in volcanic rocks is so stable that it was possible to recover the ChRMs at the end of the demagnetization when the intensity of the remanent magnetization is sufficiently low to prevent flux jumps (site KU VI in Figure S5). However more information should be given in the database to confirm such interpretation. Obviously an expert-eye in the laboratory is often needed to superwise the data acquisition.

3.4 Lightning strikes

The main source of secondary magnetizations in fresh outcrop in volcanic rocks is due to high fields generated by lightning strikes. This is very common in natural outcrops in mountainous areas. Their high Natural Remanent Magnetizations (NRM) and low coercivities are the main characteristic of this spurious magnetization and these samples should always be demagnetized by AF. In some sites, all samples may be fully overprinted and these data should be discarded. Fortunately, AF demagnetizations often provide well-defined great circle paths whose intersections is the ChRM providing that several samples are drilled several meters apart to augment the chance of a random orientation of the spurious components. Otherwise all the great circles have the same orientation within a site. Contrary to GVH, the use of great circles following the method of (McFadden & McElhinny, 1988) is often the only option to obtain an accurate site-mean direction for sites with such overprints.

3.5 Determination of the ChRM

In order to get an accurate ChRM, it is important to understand the nature of the NRM. During AF demagnetization along three static axes, gyroremanent magnetizations (GRM) should be detected and it is important not to use the same sequence of axes at all steps during AF. If GRMs are not detected and not corrected (Dankers & Zijderveld, 1981; Finn & Coe, 2016; Roperch & Taylor, 1986), the determination of the ChRM will be biased if the ChRM is not anchored to the origin. An example is provided with site YD10 of the Turkey database (supplementary Figure S6). In volcanic rocks without late hydrothermal alteration or metamorphism, it is wise to force interpreted components through the origin contradicting the approach of GVH. In case of a strong overprint due to lightning, the demagnetization path at high AF fields should go towards the ChRM. But this path might be deflected by GRM if the samples are prone to acquire GRM impeding the use of great circles to better determine the ChRM. It is also important not to confuse great circles due to GRM and lightning. For example van Hinbergen et al. (2010) describe "*an excellent example of lightning-induced random remagnetization great circles which crosscut in the direction of the ChRM*" (site AY4, Figure 6m) that corresponds to GRMs as discussed above for site YD10 and not to a lightning overprint.

Great circles were often wrongly and abusively used in the original processing of the data from Turkey and Mongolia leading to an incredible large number of wrong site-mean directions as illustrated for the Yuntdag locality (Figure S7).

In the study of paleosecular variation of Antarctica (Asefaw et al., 2021), numerous paleointensity experiments were performed and some ChRMs were determined from these samples. However, chemical remanent magnetizations (CRM) may be acquired during heating in the applied laboratory field. In these cases, the ChRM not anchored to the origin is strongly biased and the difference between the ChRM anchored and not anchored to the origin (dang value) is usually used to illustrate this CRM acquisition. Asefaw et al. (2021) did not take these ChRMs in their determination of the site-mean direction but GVH did not recognize the problem and selected the wrong data for their analysis. While Asefaw et al. (2021) provided very well-defined directions at each site with k values above 100 (Figure S2), the selected data from GVH induced a very high scatter which has nothing to do with secular variation and do not reflect the true quality of the original paleomagnetic data (Figure 1). In addition to the high scatter per site, there are even site-mean directions calculated by GVH that are different from the right ones determined by Asefaw et al. (2021). How robust is the GVH statistical analysis when the high quality data of the Antarctic dataset is deliberately downgraded?

4 Discussion

4.1 What is the best strategy at the site level?

GVH argue that the filtering of poorly defined site-mean direction is not needed. For that purpose, they use the site-mean directions using 7 samples per sites. In some sites, they decided to keep one or two outliers that in the end reduces the Fisher concentration parameter per site even below 10. But the mean direction per site is still mainly controlled by the 5 or 6 well oriented samples (Figure S3). This is well illustrated by the data from Antarctica where site-mean directions were accurately determined by Asefaw et al. with all sites having k values greater than 100. The unfortunate selection of one or two wrong directions by GVH reduces significantly the Fisher k values per site but the mean direction is not strongly modified at most sites (Figures 1, S2). In the end, the mean-site VGP calculated from the poorly selected GVH data is not very different from the mean-site pole calculated from well-defined site-mean poles

(Asefaw et al.) but the scatter is significantly increased. This should not be a reason to say that there is no need to filter the data.

The importance of a single outlier is illustrated by a synthetic test with 3 sets of data with 10, 7 and 4 samples. The Fisher concentration parameter k drops rapidly with the angular distance of the outlier from the expected direction (Supplementary Figure S8). For example, for a site with 7 samples, k will drop below 50 with an outlier at more than 30° from the mean. The mean direction is deflected from the expected mean direction by about 11° and 7° with an outlier at ~80° from the expected direction for a population of 7 and 10 samples per site respectively. In these two cases with 10 or 7 samples per site, the angular departure of the outlier is at more than twice the standard angular deviation and applying a basic cutoff at twice the standard deviation is still a good rule. With a low number of samples per site, this basic cutoff will not work.

A site-mean direction with a k value lower than 20 that is the result of a single outlier with a departure from the mean at more than twice the angular standard deviation within the site just indicates that this sample is a true outlier very likely due to an error as discussed above and this outlier should be removed. In contrast, a site-mean direction with a low k value without clear evidence of an outlier within the site (Figure S3) is usually also the indication that there is a difficulty. A site-mean direction with low k value could also be the result of a magnetic mineralogy dominated by multidomain grains as it is often the ase in intrusive rocks. Lava flows emplaced during a reversal or an excursion in a field with intensity less than 20% of the normal paleofield will also record a weakest NRM and these sites tend to provide mean direction with lower k values (see data from Chauvin et al., 1990). Anyway, in the calculation of the mean paleofield, most of these intermediate directions will be removed by applying a cutoff at 45°. There may be some good reasons to keep or reject sites with low k values. Obviously, a site with low k value in a brecciated volcanic unit should be rejected.

GVH do not consider the fundamental importance of the k parameter. Operator errors should be corrected or the outlier should be removed. Then site-means with high k and low a95 will just confirm the quality of the site-mean direction in most cases. In contrast, low k values and high a95 will definitely suggest a problem with the data that should be discussed. To attain this goal, seven samples per site is a good strategy. The fact that GVH are not able to differentiate the source of the scatter (ie, human errors as in Figure S2 versus natural situation like breccias type sites as in Figure S1) rules out their conclusion that filtering of site-means with low k values is not needed.

Volcanic rocks that have not been subjected to metamorphism usually provide site-means with high k values. The distribution of k values as the one from the original Antarctic results (Figure S2) just indicate an accurate paleomagnetic sampling, well-done demagnetizations and determinations of the ChRMs. If the k distribution in your dataset departs significantly from the Antarctic one as an example, it might indicate that several of the problems listed above affect your data.

GVH also do a simulation whose purpose is to convince readers that it is not necessary to have more than one sample per site because the mean is well within the confidence interval (Figure 5 of GVH). This test is a bit misleading. It is well known that the scatter in paleosecular variation (between sites) is much larger than the within site scatter. If the same test had been performed using the correct Antarctic results (all sites with $k > 100$), then one could have seen that the scatterplot was very small because the angular difference between a mean-site calculated from one direction per site and the mean-site calculated from the site-means is less than 1° when the sites have high k values. This is also illustrated from a simulation of populations with known Fisherian distributions (Figure S9). In contrast to the GVH interpretations, their test still present a significant scatter in the mean point cloud due to the strong noise in the data. The test that is supposed to show the advantage of sampling several sites by taking fewer samples (their Figure 9) is not robust either, knowing that the between-site scatter is obviously much greater than the within-site scatter.

4.2 Sampling of paleosecular variation.

Geomagnetic fields during reversals and excursions correspond to non-dipolar fields with low paleointensities (Chauvin et al., 1990). The low paleointensity of the field usually results in a lower remanent magnetization with a slightly enhanced possibility of a larger late magnetic overprint. In contrast, a site at more than 45° from the mean but with NRM intensity similar to those of normal and reverse magnetization is often an indication that the sampled site was not *in situ* or that the bedding correction is not correct. It is thus also necessary to remove these data. A basic cutoff of 45° is sufficient in most cases and this cutoff should be applied.

The main problem in averaging secular variation is the oversampling of one spot reading of the field by sampling several successive flows emplaced in a short time interval (see for example the Steens Mountain record (Mankinen et al., 1985)) or due to several distinct sites spatially distributed over the same volcanic unit. While lava flows covering tens of thousands of km2 are exceptional as for example the Roza member of the Columbia River Basalts (Audunsson & Levi, 1997), large volume ignimbrites also cover large surface (see examples in Paquereau-Lebti et al., 2008). Sampling the same volcanic units at several localities over a few kilometers is common. The oversampling of the same volcanic unit is encountered in the data set of Mongolia (example in Figure S10) and Turkey (examples in Figure S7). This observation in paleomagnetic results can be substantiated by a number of 6 to 7 directions per site. In cases like the Khatavch area, we can however question the reason why 7 sites were drilled in apparently the same volcanic unit. It is important to take several samples per site but the oversampling by several sites of the same volcanic unit, moreover on short distance as observed in the Mongolia and Turkey database should be avoided. Unfortunately the situation illustrated in the Khatavch area is also found in other areas suggesting that the number of independent volcanic units is indeed low and this always constitutes the main problem in the determination of a mean paleopole. Observations in the field are often difficult but Google Earth often provides sufficient information to test situations like the one at Khatawch. GVH do not address the right problem. The sampling strategy should not be to take single sample sites but to avoid drilling several sites over a short distance in the same volcanic unit.

4.3 Uncertainties in bedding corrections

On Quaternary volcanoes, lavas are often flowing on natural slopes of about 5°. In tectonically deformed areas, estimation of bedding may be difficult without intercalated sedimentary layers. For the dataset from Turkey, no bedding correction is applied by (van Hinsbergen et al., 2010) while other authors report evidence for tectonic deformation (Kissel et al., 1987) and tectonic rotations. What is the meaning of a single pole from an area likely affected by such deformation?

The Mongolia data also suggest that significant outliers are likely due to uncertain tectonic corrections (Figure S11). Sites from areas with nearly flat flow attitudes are indeed well clustered in *in situ* and after tilt correction. In contrast, sites from areas with significant deformations and large bedding corrections show a highly scattered pattern of site-mean directions. Ultimately, the main pole is controlled by the least deformed areas. The main problem is not due to a large secular variation of the Earth's magnetic field but to poor structural control. I recognize that this situation is widely encountered in many studies and not only in the sole examples of Mongolia and Turkey used by GVH. In addition to a rigorous paleomagnetic sampling, it is also critical to spend more time in the field to improve the structural geology.

4.4 Publication of the Raw data

The main outcome of the GVH analysis is simply to show the robustness of paleomagnetism, even in the worst case scenario where many human errors (sample orientation, field uncertainties, poor determination of the ChRMs) do not change the final result that much, but this is not a good reason to support a careless approach to paleomagnetism. In the original publications on Mogolia (van Hinsbergen et al., 2008) and Turkey (van Hinsbergen et al., 2010) several unreliable site-mean directions were determined by great circles. These directions have high k and low a95 ruling out the use of filters on k to select data. The only way to detect such errors is the access to the raw paleomagnetic data in an open database, with as much information as possible about the nature of the rocks, the magnetic experiments, etc. The MagIC repository offers the possibility to publish all these data (Tauxe, 2010). However, adding a kind of readme text file where the authors could explain technical problems or specificities encountered at some sites might be useful. For example, in the Permian dataset of Haldan et al. there are many problems like a huge scatter in the AF data which is not explained in the original paper.

5 Conclusions

The low K values (~5) reported in GVH for the Turkey and Mongolia data, located at intermediate latitude, correspond to the mixing of two populations, the largest one due to paleosecular variation (~70% of the sites) and a second one which is mainly random noise. The too high number of unreliable data precludes further discussion.

A well-defined site-mean direction per site is the essential building block of paleomagnetism. Obviously, when all the samples within a site in volcanic rocks provide excellent results, it does not matter whether the mean is calculated from 5, 10 or 15 samples but we do not have this information during the sampling. Sampling a minimum of seven samples per site will likely secure the determination of a robust site-mean direction for most purpose but studies of high resolution secular variation and archeomagnetic dating often require a more dense sampling, even with several sites in the same volcanic unit (Roperch et al., 2015). Low grade metamorphism, maghemitization may also alter the primary magnetization and it is often important to sample as much as possible the subtile lithological differences even within the same outcrop. The characteristic site-mean directions with a sufficient number of samples per sites should almost always be well-determined as shown in the Antractic data (Asefaw et al., 2021).

The problem in the field is often not the time spent taking 7 or 12 samples at a site, but the time spent looking for good sampling sites. These are unfortunately not so numerous. This is one more reason to sample them with sufficient rigor.

An in-depth investigation of the data from Mongolia or Turkey however highlights problems related to the sampling of unreliable lithology and experimental errors. These problems must be recognized and such data discarded provided the sampling of several samples per site. The difficulties in the determination of an accurate mean paleopole are not due to problems with the paleomagnetic method itself and time-consuming laboratory procedures but often to an initial poorly designed sampling strategy due to the lack of reliable outcrops, uncertain tectonic corrections and several paleomagnetic nearby sites in the same volcanic unit reducing significantly the number of independent spot-reading of the paleofield as in the cases of the Turkey and Mongolia surveys. To obtain an accurate mean pole, 30 to 50 sites are probably sufficient only if they are really independent spot-readings of the geomagnetic field and that tectonic corrections are well documented.

Acknowledgments

Discussions with several colleagues, also concerned about the proposal to take only one sample per site, prompted me to write this comment

Open Research

The data are available from the MagIC database.

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Figure 1. Comparison of site-mean directions determined in original study of Antarctica and in GVH. Equal-area projection of the site-mean directions from Asefaw et al. (2021) (left) and site-mean directions calculated from the supplementary data provided and used by GVH. Open/ filled symbols with associated red/blue angle of confidence at 95% are projection in the upper/lower hemisphere.The site-mean directions were calculated from the individual directions given by Gerritsen et al including the outliers. In GVH, the outliers at more than 90° from the mean were apparently inverted prior to the Fisher statistics of the site-mean directions. This is correct when both polarities are found at one site in sediments for example but difficult to justify at a single site in volcanic rocks

[Geochemistry, Geophysics, Geosystems]

Supporting Information for

Comment on “Influence of data filters on the position and precision of paleomagnetic poles: what is the optimal sampling strategy? “ by Gerritsen et al. (2022)

Pierrick Roperch

Géosciences Rennes

Contents of this file

Figures S1 to S11

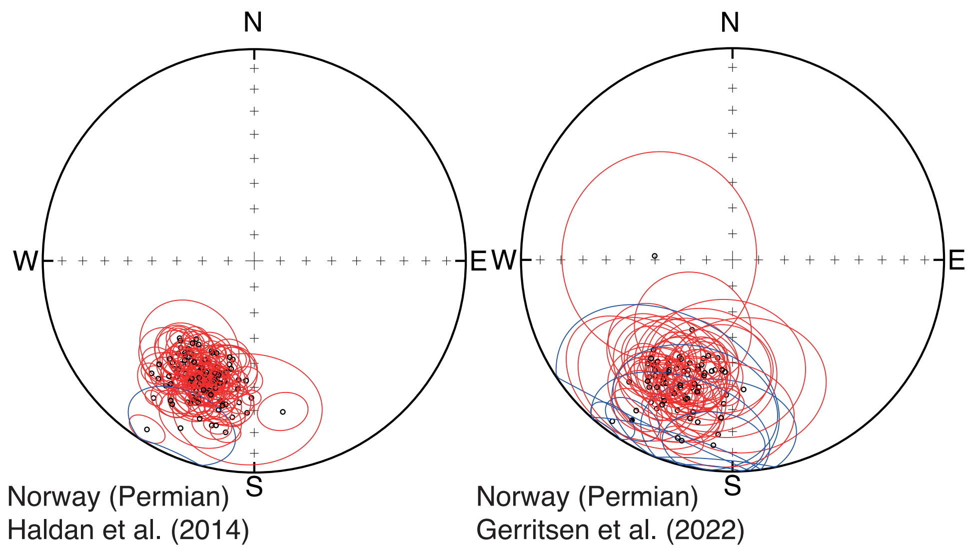

Figure S1.
Equal-area projections of site-mean directions from the original paper of Haldan et al. (2014) and the directions calculated from the directions in the supplementary data of Gerritsen et al.

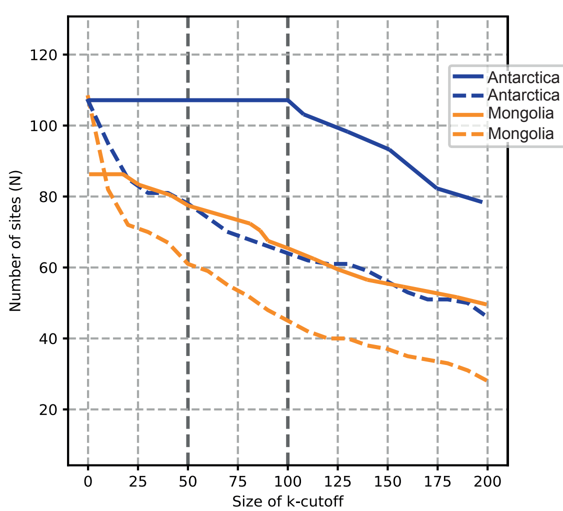

Figure S2.
Comparison of the number of sites above a certain k value as shown in Figure 4a of Gerritsen et al. (2022). The dashed line is with the selected GVH data. Solid line from Antarctica is from the original data of Asefaw et al. where all sites have k values greater than 100. The solid line from Mongolia corresponds to the present analysis of the original paleomagnetic data downloaded from Magic. 20 sites without well-defined characteristic directions are rejected.

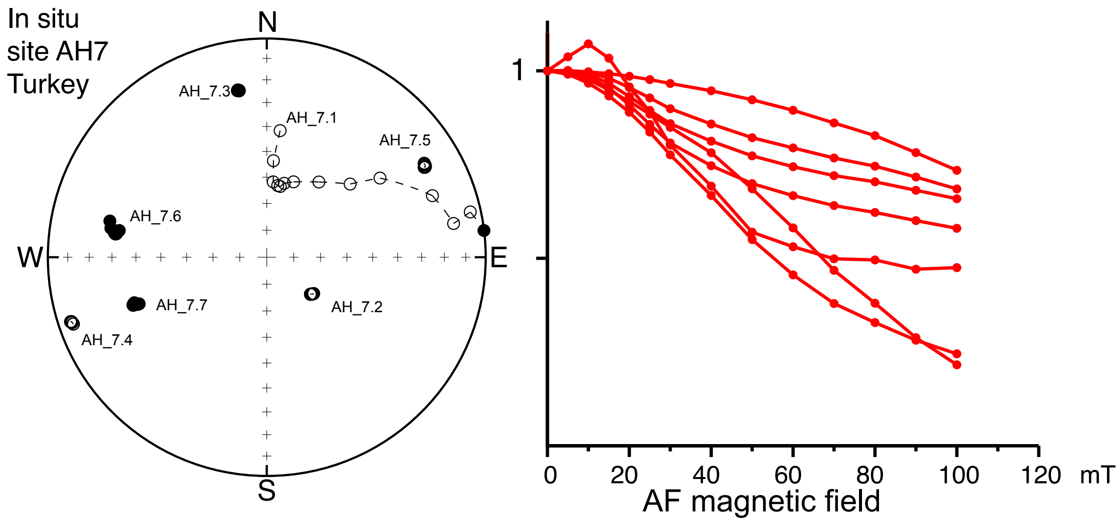

Figure S3.

Paleomagnetic results at site AH7 from the Turkey database. Left) Equal-area plot of the directions for the seven samples during Alternating field demagnetization. The paleomagnetic data are clearly scattered between samples but with a stable ChRM for 6 out of 7 samples and high medium destructive field values.

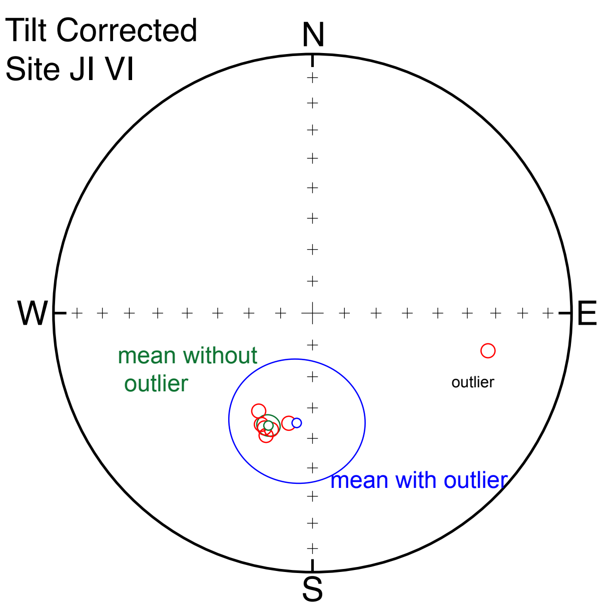

Figure S4.

Stereonet projection of ChRMs components (red circles) for site JI VI (Mongolia). There is clearly an outlier. The mean was calculated without (green circle) or with the outlier (blue circle) as done by Gerritsen et al. (2022).

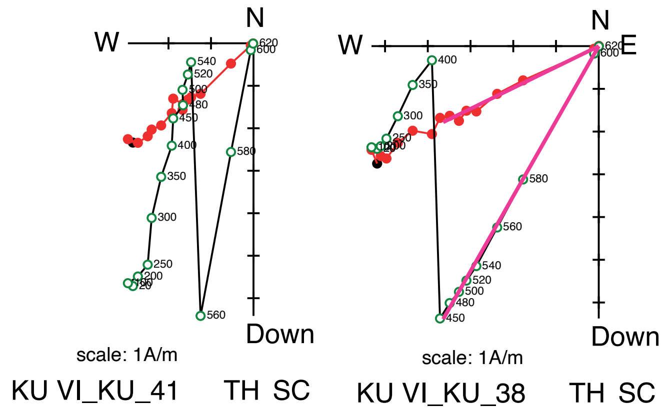

Figure S5.

Orthogonal plot of thermal demagnetization in sample coordinate. Examples of problems in measurements with a jump in the Z component possibly due to either problems while uploading data in the database or in the laboratory. All the samples from the site(KU VI, Mongolia) are affected by this problem but not at the same temperature. The ChRM was calculated using the high temperature data.

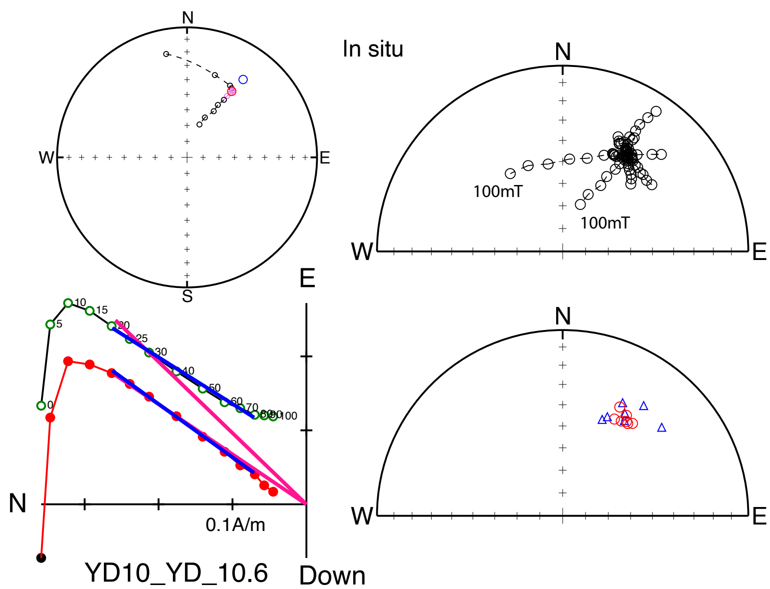

Figure S6.

Examples of AF demagnetization with possible deflection of the ChRM due to GRM acquisition. Left) demagnetization data for sample YD10.6 with the ChRM calculated by forcing the calculation of the ChRM though the origin (red line) or without (blue line). Upper right) Plot of the demagnetization data above 20mT for all samples from the site. Bottom right) ChRM directions for the seven samples (red circles forcing to the origin and blue triangles (GVH)

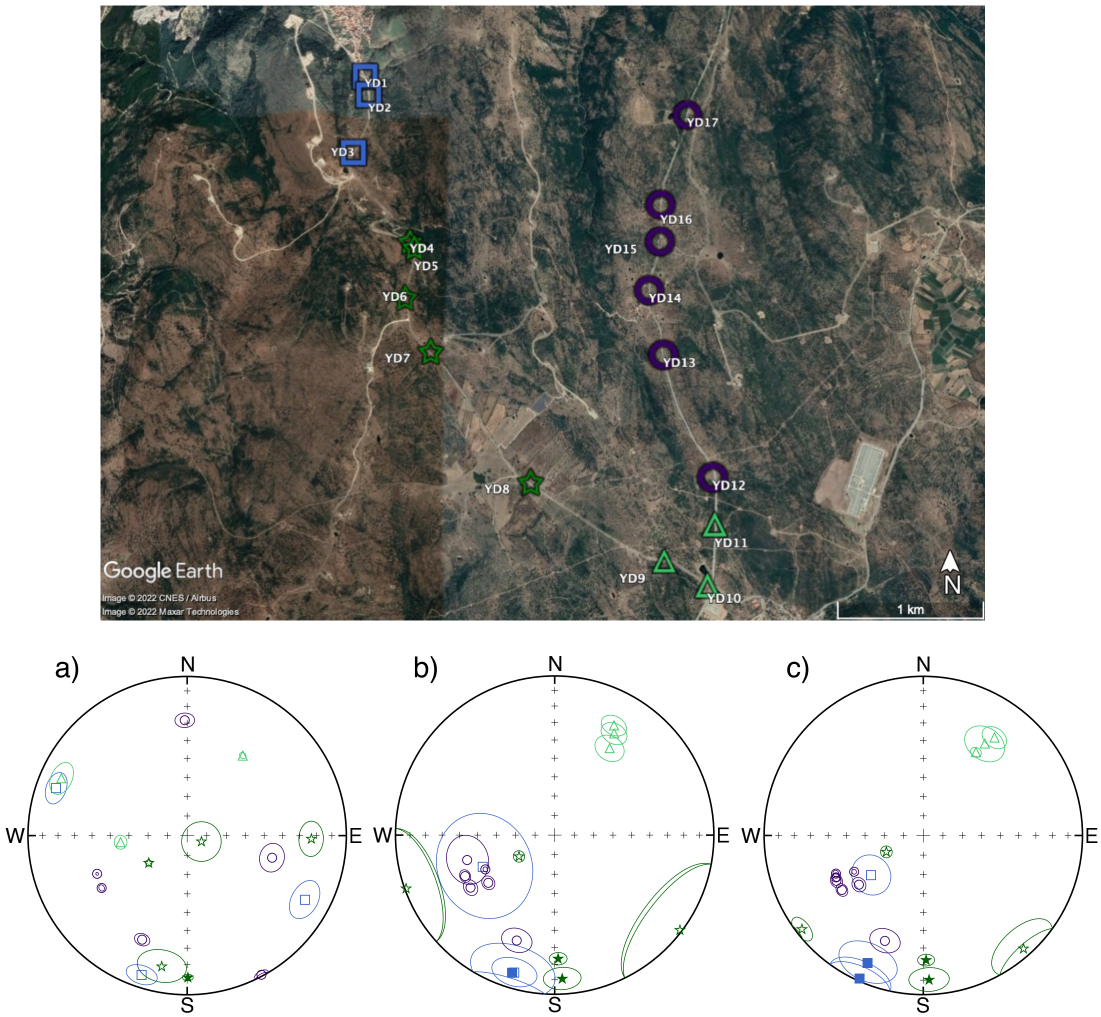

Figure S7.

Top) Google Earth image with the paleomagnetic sampling of the Yuntdag area (Turkey) from van Hinsbergen et al. (2010). a) Stereonet of the ChRM site-mean directions reported by van Hinsbergen et al. in their original publication. b) Stereonet of the site-mean directions calculated from ChRMs defined by GVH. c) Stereonet of the ChRMs determined in this study. There are slight differences between the site-mean directions determined in the present study (c) and those in GVH (b) due to the inclusion of outliers and deflection of the ChRMs by GRMs. But several of the site-mean directions calculated in the original publication, especially using great circles are unreliable.

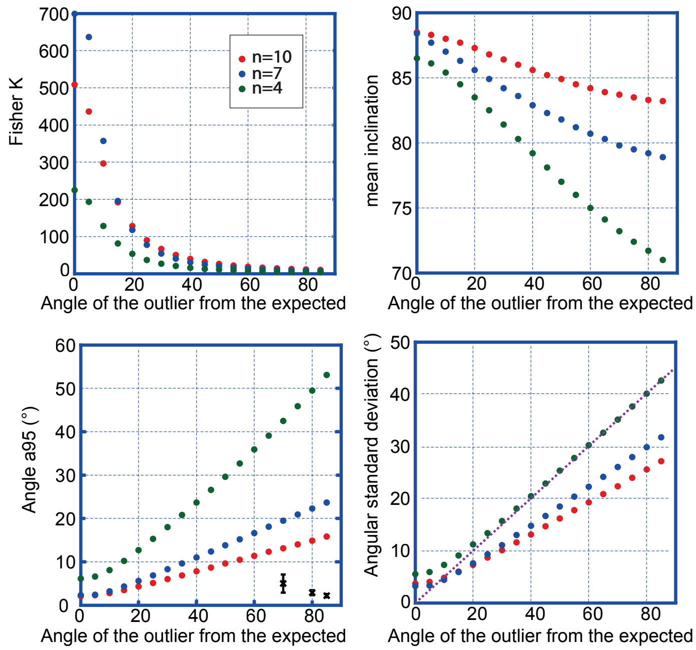

Figure S8.

Effect of an outlier in the calculation of a site-mean direction calculated with 4, 7 or 10 samples. A Fisher population was generated with an initial Fisher parameter k of 500 around a direction with an inclination of 90°. The outlier was progressively shifted from the mean by steps of 5° and Fisher statistics were calculated.

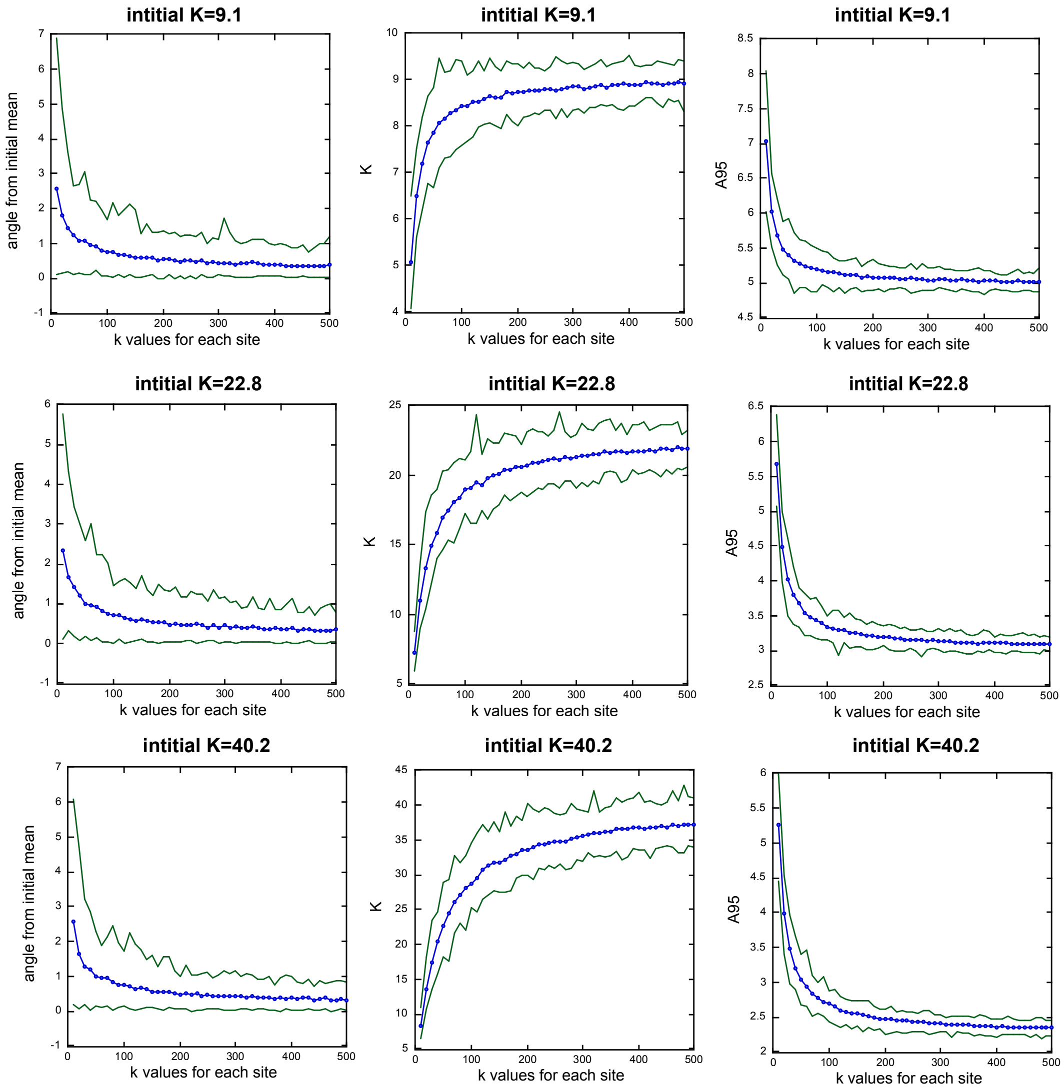

Figure S9.

Comparison of the effect of selecting one sample per site in the calculation of the mean direction for three initial populations of 100 directions with an initial Fisherian distribution with k of 9.1, 22.8 and 40.2. For each site one direction was simulated from a Fisherian population of k values ranging from 10 to 500. The process was repeated 100 times to establish the mean (blue circles) and the min and max values. When all sites have a Fisher parameter greater than 100, the angles of the mean direction from the initial mean direction are on average at less than 1° from the mean. This figure illustrates the between site scatter control on the statistical characteristics over the within-site scatter except when an unusual large number of sites have directions defined by low-k values

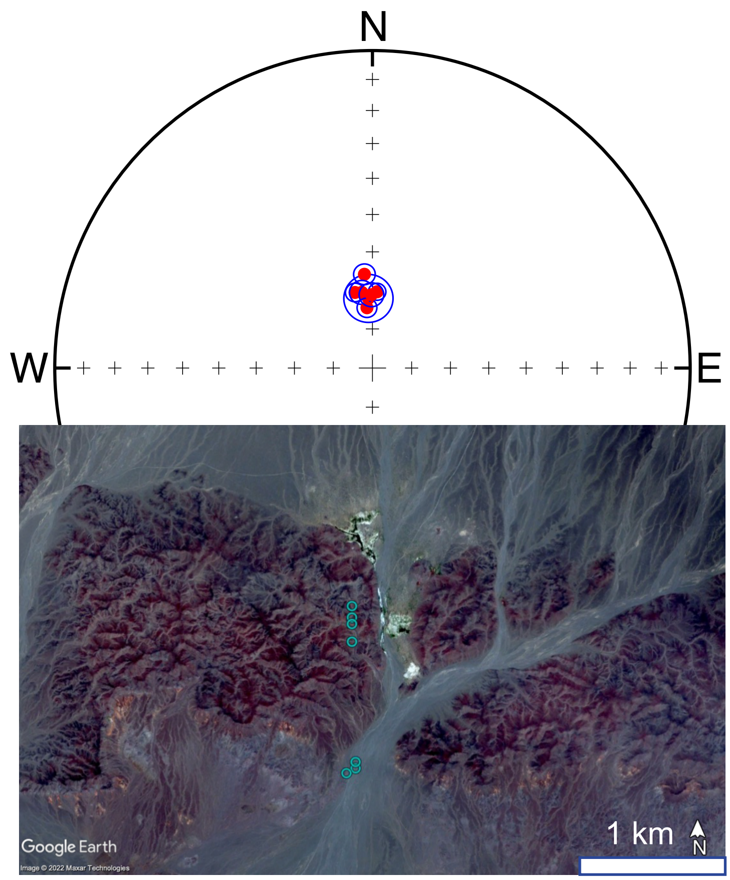

Figure S10.

Paleomagnetic directions from seven nearby sites apparently drilled in the same volcanic unit. Top) Stereograph showing the tight grouping of the seven site-mean directions. Bottom, Google earth image showing the location of the sites. All sites are drilled over a distance of about 1 km at an elevation of ~1450 ±10m suggesting that it is a single flat lying volcanic unit.

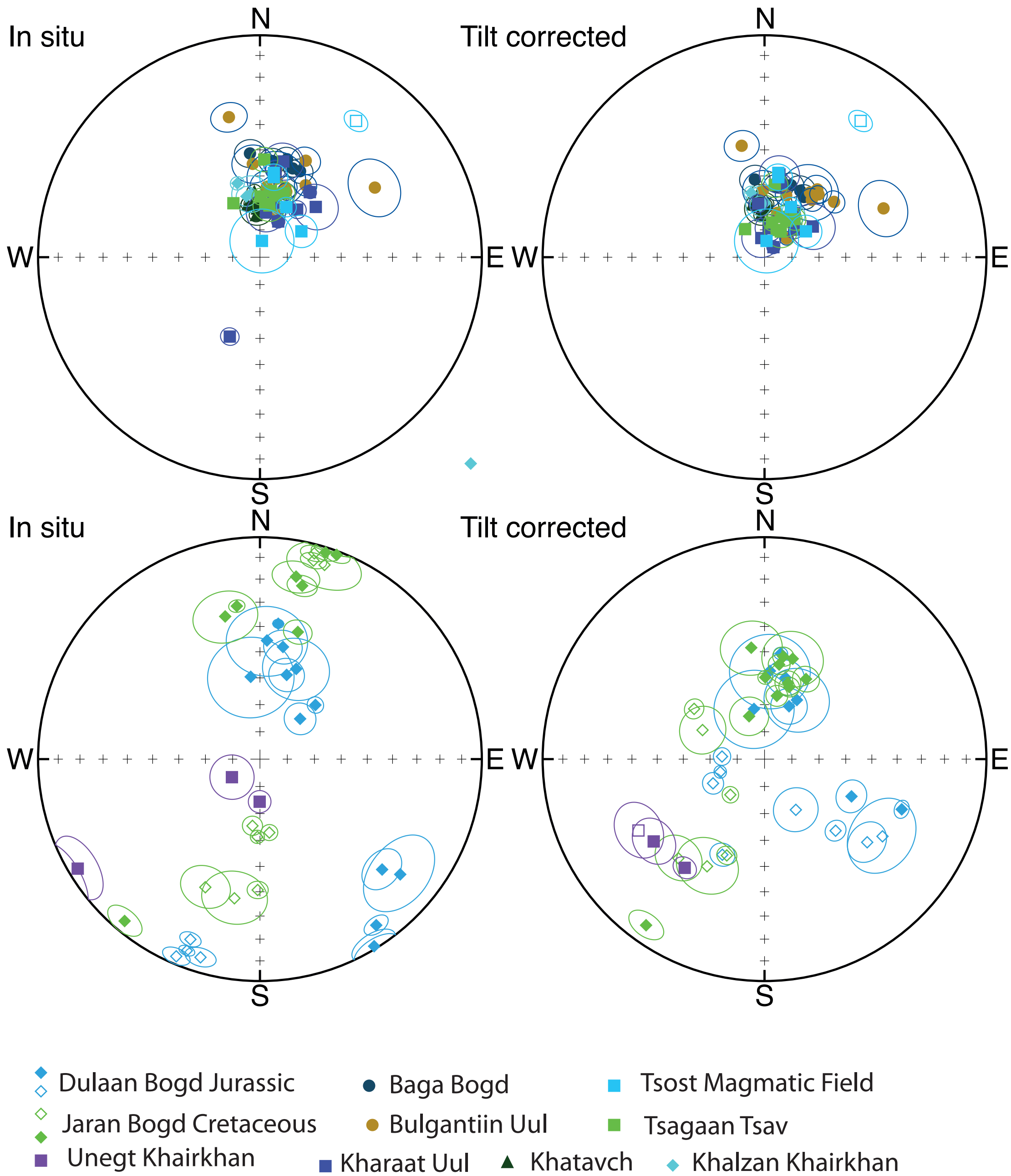

Figure S11.

Stereographic projections of Site-mean directions calculated from the database from Mongolia in in situ (left) and after bedding correction (right). The upper stereonets correspond to areas with mostly flat lying bedding. The lowermost stereonets correspond to areas with more complex bedding and these areas record the farthest site-mean directions from the mean. Most of the outliers may be due to incorrect bedding corrections rather than secular variation.