ADVANCING EARTH AND SPACE SCIENCES

Earth and Space Science

METHOD
10.1029/2025EA004863

Key Points:
- Magnetic-A is a comprehensive web-app for paleomagnetic analyses
- It includes up to date statistical approaches currently not available in a single platform
- Numerical and graphic results are easily exported and editable

Correspondence to:
E. Dallanave,
edoardo.dallanave@unimi.it

Citation:
Dallanave, E. (2026). Magnetic-A: The new R-based toolbox for analysis of paleomagnetic data. *Earth and Space Science*, *13*, e2025EA004863. https://doi.org/10.1029/2025EA004863

Received 28 OCT 2025
Accepted 4 MAR 2026

Author Contributions:
Conceptualization: E. Dallanave
Methodology: E. Dallanave
Software: E. Dallanave
Supervision: E. Dallanave
Validation: E. Dallanave
Visualization: E. Dallanave
Writing – original draft: E. Dallanave
Writing – review & editing: E. Dallanave

Magnetic-A: The New R-Based Toolbox for Analysis of Paleomagnetic Data

E. Dallanave[1,2]

[1]Department of Earth Sciences, University of Milan, Milan, Italy, [2]ALP-CIMaN Alpine Palaeomagnetic Laboratory, Peveragno, Italy

Abstract Paleomagnetic remanence in rocks and sediments provides a unique means to constrain stratigraphic records in both space and time. This is because of the symmetry of the paleomagnetic field with respect to Earth's spin axis over geological time, and the global synchronicity of magnetic field reversals. Several software packages for analysis of paleomagnetic directions and poles have been compiled through the years, each employing different programming languages and offering various computational solutions. However, these tools often face issues with incompatible file formats and challenge users in installation and application. To address these limitations, I introduce Magnetic-A, a comprehensive toolbox for paleomagnetic analysis. Magnetic-A helps users from the analysis of individual paleomagnetic directions to the generation of paleomagnetic poles and magnetostratigraphy. Magnetic-A features several advanced statistical methods for paleomagnetic directions analysis that, to date, are not present in a single analysis platform. Graphical results are easily exportable as editable vector files. Magnetic-A (https://doi.org/10.5281/zenodo.18220000) can be used as a web application (https://edoardodallanave.shinyapps.io/MagneticA/) without software installation or locally after installing R (https://www.r-project.org/).

1. Introduction

Paleomagnetism is the only geophysical tool that can (a) correlate a stratigraphic succession with the geomagnetic polarity time scale (GPTS; Ogg, 2020) as well as with other magnetic polarity-calibrated records (e.g., Dallanave et al., 2016), and (b) determine the paleo-position of a given locality with respect to the Earth's spin axis (Torsvik et al., 2008). The fundamental entity at the base of paleomagnetic studies is the paleomagnetic direction, which is a "fossil" (magnetic remanence) of the geomagnetic field at a specific time and place preserved within a rock or sediment. A paleomagnetic direction can be used to calculate the associated virtual geomagnetic pole (VGP). A VGP is the point on the Earth's surface where lies the imaginary pole that would result in the considered paleomagnetic direction. A set of VGPs from a locality can be averaged to determine a paleomagnetic pole. Following the geocentric axial dipole hypothesis, a paleomagnetic pole is assumed to approximate the position of the geographic pole with respect to the locality itself (Butler, 1992; Tauxe, 2010). A series of paleomagnetic poles of different age is used to build an apparent polar wander path (APWP; Torsvik et al., 2012; Vaes et al., 2023). It is called "apparent" because it is the tectonic plate on which the sampling locality lies that moves through time, rather than the pole itself. This concept is at the base of paleogeographic reconstructions, used by scientists for decades to place continents back to their paleo-position for times as old as the Paleoproterozoic (Kirscher et al., 2022) and the Archean (Brenner et al., 2022).

Since the introduction of principal component analysis (PCA) to isolate paleomagnetic directions (Kirschvink, 1980), significant advancements have been made to support the analysis and assess the quality of paleomagnetic data. These range from the analysis of a single paleomagnetic direction (Heslop & Roberts, 2016) to clusters of directions and VGPs (Dallanave & Kirscher, 2020; Hansma & Tohver, 2020; Tauxe & Kent, 2004; Vaes et al., 2021). Through the years, several software packages, web-platforms, or notebooks have been compiled and made available to the community to facilitate paleomagnetic analyses. These include PaleoMag (Jones, 2002), PaleoMac (Cogné, 2003), PuffinPlot (Lurcock & Wilson, 2012), Remasoft (Chadima & Hrouda, 2007), paleomagnetism.org (Koymans et al., 2016, 2020), IADP (Torsvik, 2016), PmagPy (Tauxe et al., 2016). Notwithstanding the versatility of all the listed packages, I believe that the community would benefit from a user-friendly software guiding the user from the analysis of paleomagnetic directions to the generation of paleomagnetic poles and magnetic polarity stratigraphy, applying of the most recent reliability tests without switching between different computational platforms. So, here I introduce Magnetic-A, a R-based software built

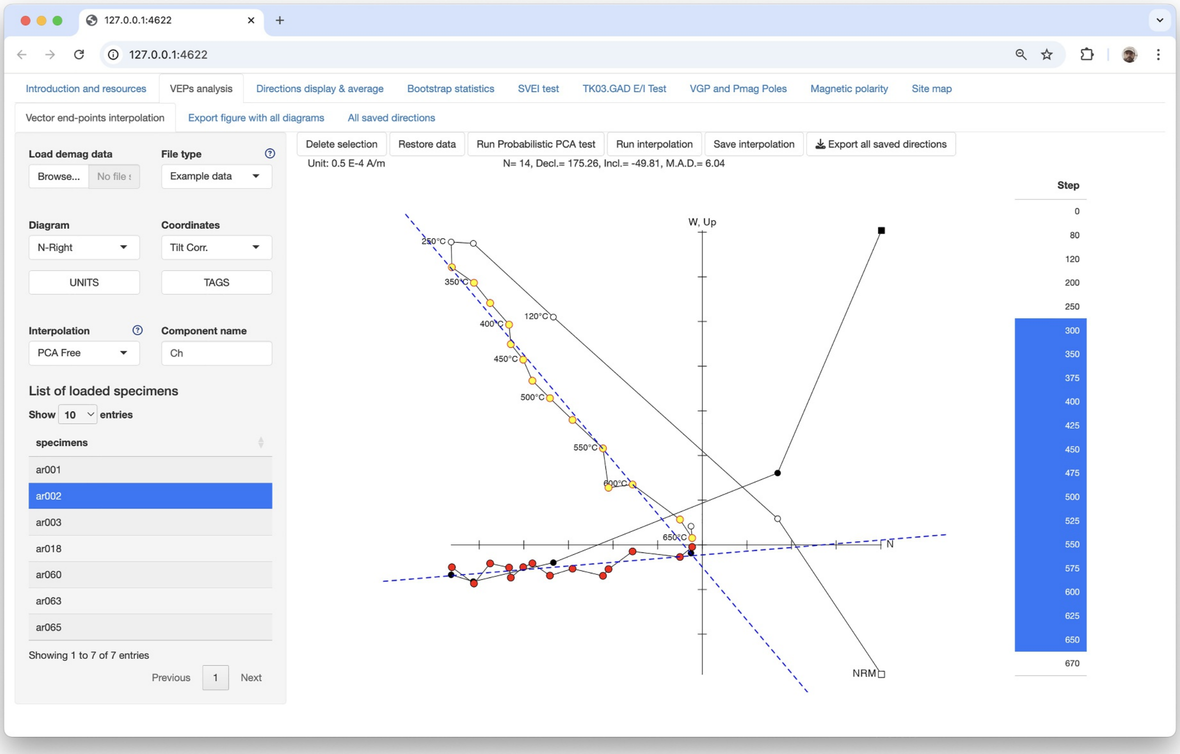

Figure 1. Example of Magnetic-A web graphical user interface.

by using Shiny (Chang et al., 2021). Shiny is a R package specifically designed to build web-platforms for data analysis, making all functionalities of R available to users in the form of a graphical user interface (GUI; Figure 1). Magnetic-A can be either accessed online (https://edoardodallanave.shinyapps.io/MagneticA/) or run locally after installation of R (https://doi.org/10.5281/zenodo.18220000). Magnetic-A uses many of the functions introduced by PmagDiR (Dallanave, 2024), a package originally compiled to assess the reliability of paleomagnetic direction clusters, but it is implemented with a series of computational and graphical functions, from directions analysis to paleomagnetic pole estimate. Here, I explain the features that make Magnetic-A a unique paleomagnetic data analysis toolbox.

2. Methods

Magnetic-A's GUI is organized as a series of interconnected left-to-right pages and sub-pages (Figure 1), guiding the user through the analyses that go from the isolation of the natural remanent magnetization components to the analysis of paleomagnetic pole and magnetic polarity stratigraphy. In any of the stages, data generated by using Magnetic-A or any other platform (when converted into the proper format) can be uploaded and processed. The user guide (see the Availability Statement section) provides details on file formats (imported and exported) and explains how to operate all commands of Magnetic-A.

2.1. Estimate Paleomagnetic Directions

Demagnetization data are traditionally displayed on a vector end-points (VEPs) diagram (Zijderveld, 1967). Magnetic-A allows users to display VEPs diagram by choosing between two commonly used axes orientation (North-Up and North-right). Alternatively, VEPs can be selected on an equal area stereonet. VEPs are either selected by mouse-dragging or by clicking on the demagnetization step list to the right-hand side of the GUI (Figure 1). Interpolation of the selected points can be performed by using several methods described as follows.

2.1.1. Principal Component Analysis (PCA) Interpolation

PCA interpolation of VEPs, first introduced by Kirschvink (1980), is likely the most used technique in paleomagnetic directions analysis. PCA interpolation can be performed by adopting different strategies, which can lead to significantly different estimated directions and associated confidence (the latter expressed as maximum angular deviation [MAD]). The two most adopted strategies are (a) PCA free from the demagnetization axes origin (*Free PCA*) and (b) PCA anchored to the origin (*Anchored PCA*). While a *Free PCA* generates an ellipsoid that interpolates in the three dimensions the selected VEPs, the *Anchored PCA* forces the center of the interpolating ellipsoid to coincide with the origin of the demagnetization axes. The *Anchored PCA* approach (often abused) may result in interpolations not representative of the VEPs trajectory, with artificially low MAD. To address this issue, Heslop and Roberts (2016) developed a probabilistic parameter called $p(Ha|D)$ representing the probability (p) that the anchoring hypothesis (Ha) is correct given the observed data (D). It ranges from 0 to 1 ($p < 0.5$ = *Anchored PCA* not supported; $p > 0.5$ = *Anchored PCA* supported) and serves as a guide to the appropriate interpolation. In the same work they also developed an alternative to the *Anchored PCA* option defined as *Constrained PCA*: it is a "more realistic" alternative to anchoring, because it constrains the direction through the origin of the axes without distorting the representation of the demagnetization data. Analogously to $p(Ha|D)$, the probabilistic parameter $p(Hc|D)$, where Hc is the constraining hypothesis, provides a metric for choosing between *Free* and *Constrained PCA* interpolation. Magnetic-A calculates both $p(Ha|D)$ and $p(Hc|D)$. Furthermore, a fourth PCA interpolation is available in Magnetic-A, called *Origin Included*, which adds the origin of the axes as a final (artificial) demagnetization point, without forcing the direction through it. This option is available in the widely used PaleoMag software (Jones, 2002).

2.1.2. Fisher (1953) Spherical and Demagnetization Plane Interpolation

In some cases, VEPs are organized in a visually coherent pattern without decaying with a clear linear trend to the origin of the axes. This could be the case of clustered VEPs, or MAD overcoming a defined threshold (e.g., 15°) when attempting PCA interpolation. In this case VEPs can be averaged by using the *Fisher* option, which simply applies the standard spherical statistics of Fisher (1953) to the selected points. This option is available in commonly used software like PuffinPlot (Lurcock & Wilson, 2012) or Pmag GUI (Tauxe et al., 2016).

Alternatively, if the VEPs are moving along a plane rather than trending linearly to the origin of the demagnetization axes, they can be interpolated through PCA by using a plane (Kirschvink, 1980). Magnetic-A can combine multiple planes and stable directions (if present) with the reiterative protocol proposed by McFadden and McElhinny (1988).

2.2. Direction Clusters

Magnetic-A allows to work on directions isolated internally or uploaded in different formats (please refer to the User Guide). Different graphical options are available (i.e., color and symbol). The average direction of a cluster can be estimated by using the approach of Fisher (1953; circular 95% confidence), or the approach described in Deenen et al. (2011), which result in an elliptic 95% confidence. In case of bimodal distribution of directions (record of both normal and reversed paleomagnetic field), Magnetic-A calculates automatically the average and 95% confidence of the two modes, as well as the statistical details of the whole set "flipped" toward a common polarity (Figure 2a).

Paleomagnetic directions from deep-sea or continental drilled sites are very often determined from azimuthally unoriented specimens. In this case it is required an inclination-only estimate of the average direction and the associated 95% confidence angle (e.g., Dallanave & Chang, 2020). Magnetic-A is implemented with the algorithm proposed by Arason and Levi (2010), which minimizes the shallow-biased error that can occur when calculating mean inclination in the absence of declination data (Figure 2b).

A series of data filtering (cut-off) methods is also available to eliminate directional outliers from a given cluster. Nonetheless, it is advised caution in using any cut-off. A recent study on paleosecular variations and expected paleomagnetic direction distributions (Tauxe et al., 2024) strongly discourage the use of such filters, especially before correction of inclination flattening typical of sedimentary records.

10.1029/2025EA004863

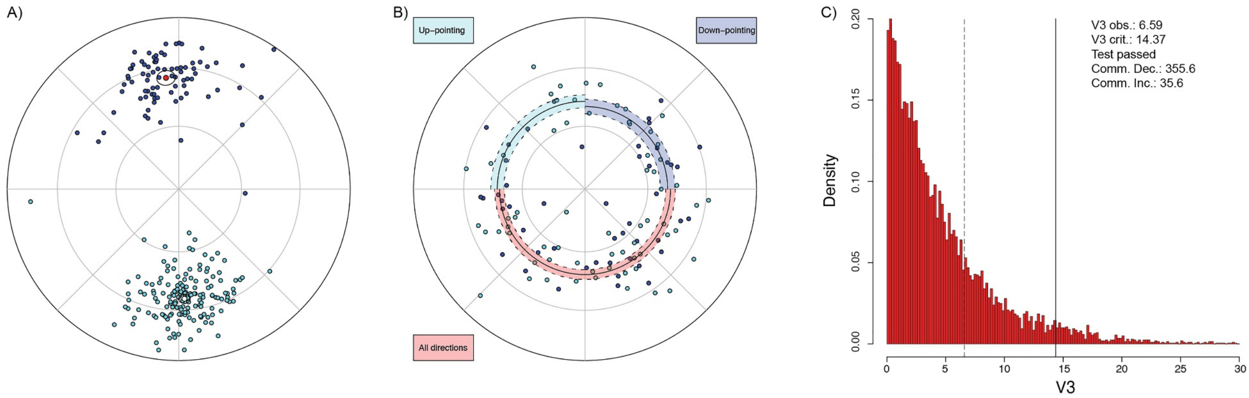

Figure 2. Example of equal area diagrams of paleomagnetic directions as exported from Magnetic-A. (a) Standard spherical average and 95% confidence (Fisher, 1953) of the paleomagnetic directions from Dallanave et al. (2012). (b) Average paleomagnetic inclination from the Eocene–Miocene record of International Ocean Discovery Program Hole U1507B (Exp. 371; Dallanave et al., 2022). (c) Results of the common mean directions test applied to the directions shown in panel (a). Figure shows the histogram of the minimum eigenvalues v3 density (i.e., the frequency normalized by the number of total simulation) of the resampled data as detailed in Heslop et al. (2023). If the empirical v3 value (dashed line, V3 obs.) is lower than the 95% confidence value (solid line, V3 crit.), the test is passed. Numerical values are here copied in the upper hand part of the Figure, where Comm. Dec. and Comm. Inc. are the declination and inclination of the resultant common mean direction.

2.3. Bootstrapped Confidence Ellipse and Reversal Test

Parametric statistical tests (like the commonly adopted strategy of Fisher, 1953) are not always suitable for paleomagnetic distributions. This is because a given distribution does not necessarily meet the assumptions that underpin parametric tests. Non-parametric tests based on bootstrapping do not rely on any assumption about the distribution shape, and are thus more applicable (e.g., Constable & Tauxe, 1990; Tauxe et al., 1991). Heslop et al. (2023) developed a strategy for estimating a non-parametric confidence ellipse around the average paleomagnetic direction of a given distribution, and a test for assessing if two separate distributions share a common mean direction. By flipping the two modes of a bimodal distribution onto a common polarity, this can be used as a reversal test, one of the fundamental stability tests for paleomagnetic data (Van der Voo, 1990). Magnetic-A calculates the empirical 95% ellipse around an average paleomagnetic direction and performs the common mean direction test of Heslop et al. (2023, Figure 2c).

2.4. Distribution Consistency With the THG24 Field Model and Inclination Flattening Estimate

Tauxe et al. (2024) developed a new paleosecular variation model (THG24) based on a compilation of paleomagnetic data for the last 10 Myr (PSV10-24 compilation). In contrast to older data compilations (e.g., McElhinny & McFadden, 1997; MM97), PSV10-24 relies on entries that were not subjected to the application of any arbitrary cut-off (e.g., Vandamme, 1994). Hence, the directions drawn from the THG24 model are expected to be a more realistic representation of the paleosecular variations then older models (e.g., Constable & Parker, 1988; Tauxe & Kent, 2004). Starting from this assumption, one can test whether a given set of paleomagnetic directions is consistent with the THG24 model. This test, introduced and discussed thoroughly in Tauxe et al. (2024), is called SVEI. While I recommend referring to Tauxe et al. (2024) for the details on the SVEI method, in synthesis, a given set of paleomagnetic directions is compared with a number (default is 1,000) of directional sets drawn from the THG24 model. The comparison includes the expected declination, inclination, elongation and its orientation. The elongation is defined as the ratio of the intermediate and minimum eigenvalues of the distribution matrix of Scheidegger (1965), a 3×3 matrix that describes the shape of the distribution (see also Tauxe, 2010). Tauxe et al. (2024) published a Jupyter notebook to perform the SVEI test. Starting from their work, I translated the original Python code within Magnetic-A, to perform it on directions either saved internally or uploaded as declination-inclination file. As suggested by Tauxe et al. (2024), if the directions are bimodal (normal and reversed), the SVEI test should be performed only after a positive reversal test.

If paleomagnetic directions from sedimentary records do not match the THG24 model, it is recommended to test whether the progressive correction of the inclination flattening leads to a distribution that matches the model criteria. This is done by apply to each direction the tangent function introduced by King (1955):

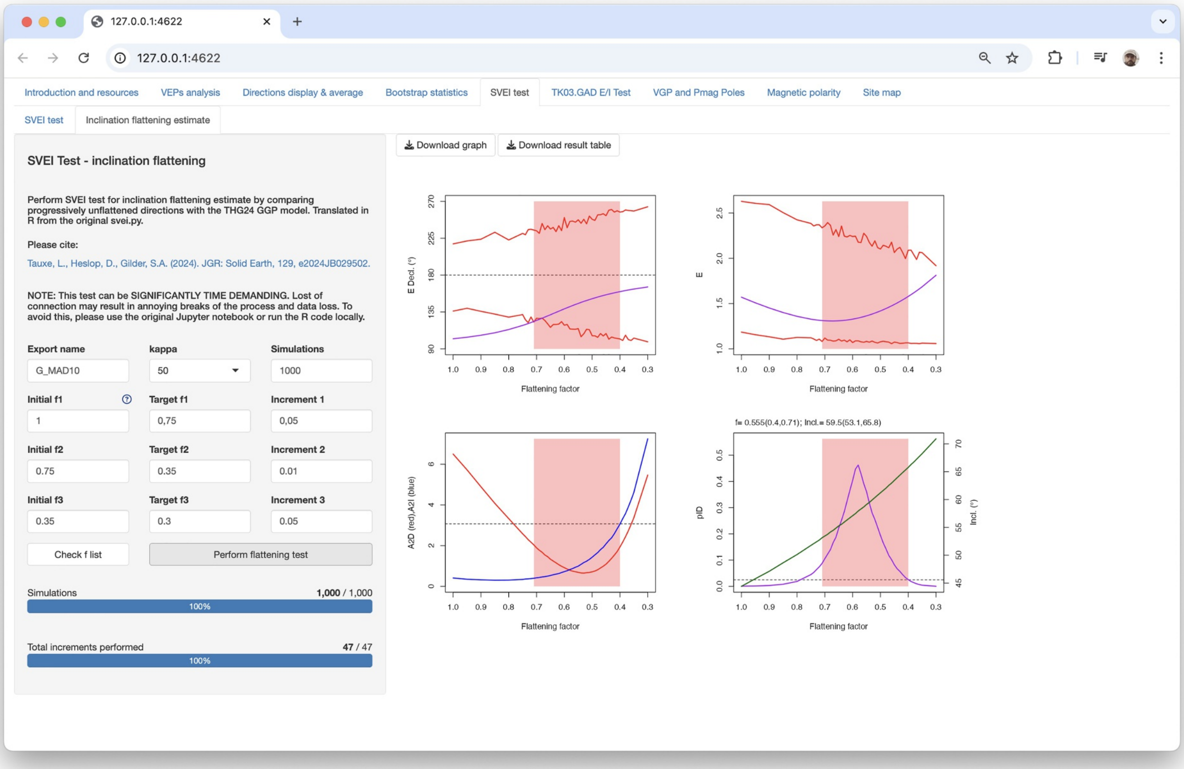

Figure 3. Magnetic-A page performing progressive unflattening of the paleomagnetic directions coupled with the test for consistency with the THG24 field mode. The example shows the test performed on the paleomagnetic directions of Gilder et al. (2001) filtered for MAD ≤ 10. Within the figure panel, top left: declination of the elongation (E) plotted against the flattening factor (f); the purple line is E of the real distribution, while the red lines are the confidence bounds drawn from the simulated distribution. Top right: evolution of E during unflattening; lines color is like top left panel. Bottom left: result of the Anderson-Darling test for both declination (A^2D) and inclination (A^2I) (see Tauxe et al., 2024 for the computational details); the dashed horizontal line is the 95% confidence boundary for both curves, where higher values indicate negative test. Bottom right: the purple line is the *p*-value determined from both A^2D and A^2I (pID) during unflattening, where values lower than 0.025 (dashed line) indicate negative test; the green line is the inclination progression during unflattening. In all diagrams, the pink rectangle envelops the range of f where all conditions are matched. The numerical results are indicated on top of the bottom right diagram. For the details about the input parameters controlling the test, please refer to the Magnetic-A User Guide and the original publication (Tauxe et al., 2024).

$$\tan I_o = \frac{\tan I_f}{f}$$

where I_o, I_f, and f are respectively the corrected inclination, the measured inclination, and the flattening factor ranging from 1 to 0. With the widely used test originally proposed by Tauxe and Kent (2004), also performable with Magnetic-A, the degree of unflattening is evaluated comparing the relationship between the elongation and the inclination of the gradually unflattened directions with the values expected by their TK03.GAD paleosecular variation model. The SVEI test goes beyond this concept. While monitoring the elongation and its orientation during unflattening, the SVEI protocol also checks the declination and inclination of the directions for full consistency with the THG24 model (Figure 3). If the test is positive, it results in a range of f values within which the distribution is consistent with the model. In case of positive solution, in the *Directions display & average* page of Magnetic-A, the median f can be applied to the original distribution to calculate, for example, the corrected paleomagnetic pole.

2.5. Virtual Geomagnetic Poles and Paleomagnetic Pole Analysis

Magnetic-A can perform several calculations on VGPs and paleomagnetic poles. The different possible operations are synthetized in the block diagram of Figure 4.

10.1029/2025EA004863

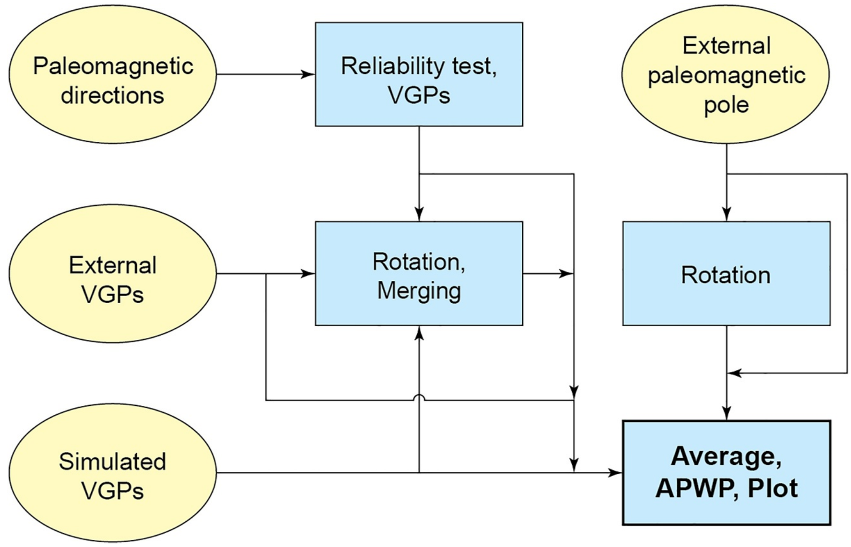

Figure 4. Block diagram synthesizing the algorithm used for calculating and plotting virtual geomagnetic poles, paleomagnetic poles, and apparent polar wander paths.

VGPs from paleomagnetic directions: Magnetic-A calculates the VGP associated to each paleomagnetic direction and plots them automatically on a stereographic projection. Any set of VGPs can be averaged to determine the paleomagnetic pole, and the 95% confidence bounds can be estimated by either standard (Fisher, 1953) statistic (A95) or by averaging a number (default is 2,000) of randomly selected pseudosamples from the original distribution (B95; see Dallanave, 2024).

External VGPs: Existing VGPs sets (expressed as list of longitude-latitude pairs) can be uploaded and plot together with any of the set already present in the system (Figure 5a). Any set of VGPs can be rotated on the globe if the Euler parameters (longitude and latitude of the rotational pole, degree of rotation) are known.

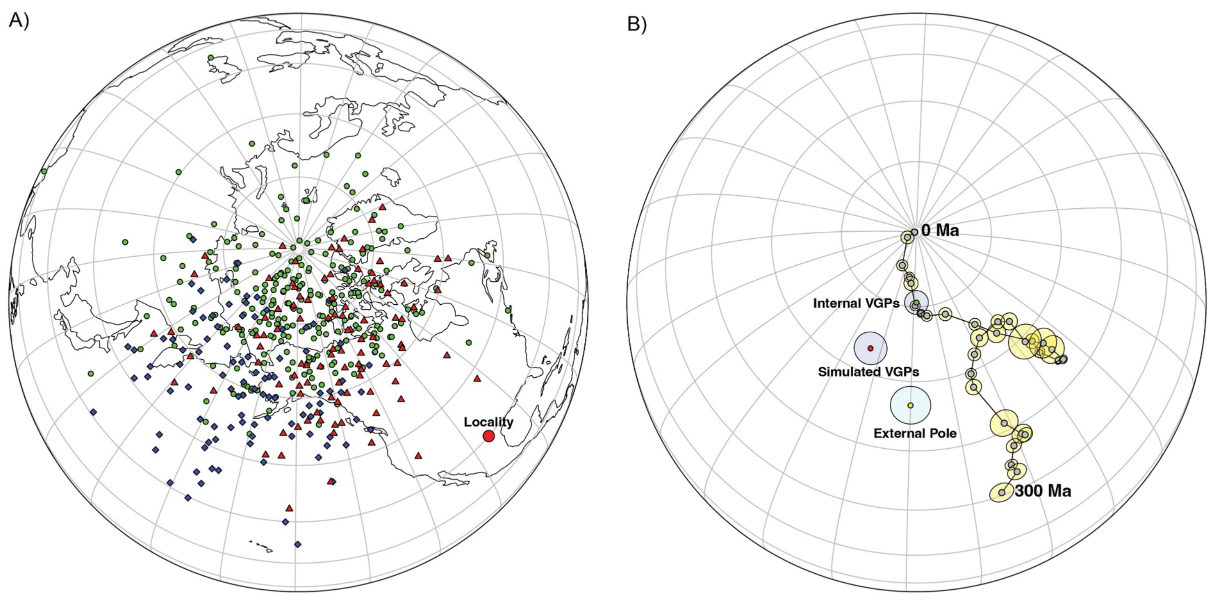

Figure 5. Examples of virtual geomagnetic poles (VGPs) and paleomagnetic poles plots. (a) Three sets of VGPs (blue diamonds, green circles, and red triangles) are plotted on the same stereographic projection, together with a geographic locality. (b) Average position of two sets of VGPs with 95% confidence (Internal VGPs and Simulated VGPs) are plotted together with a typed-in paleomagnetic pole (External Pole) and the global synthetic apparent polar wander path (GAPWP) of Vaes et al. (2023) in African coordinates. The coastline can be omitted from the plot for clarity.

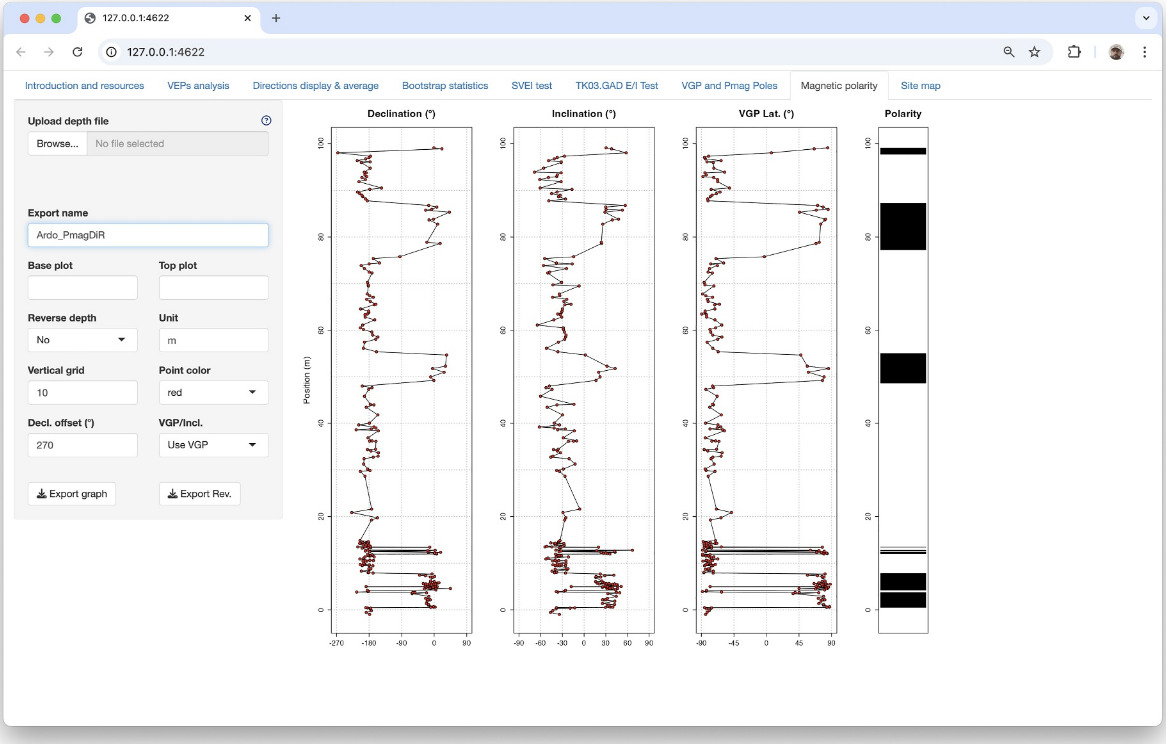

Figure 6. Magnetic polarity stratigraphy plot generated by using the data from the Paleocene Ardo sedimentary record (Dallanave et al., 2012); note the 270° offset in the Declination column. The offset can be modified depending on the data, to avoid "left and right" flips of the declination, for example, when it wobbles around zero.

Simulated VGPs: Magnetic-A provides the possibility of generating a VGPs set drawn from a Fisher (1953) distribution. This option is useful for calculating site-level paleomagnetic poles, similarly to the approach of Vaes et al. (2023) to generate their global synthetic APWP (GAPWP). This approach is based on the idea that, when two or more paleomagnetic poles are averaged by simple spherical mean, any uncertainty on the poles themselves is ignored (e.g., 95% confidence, number of data points). By knowing the coordinates, number of data points (VGPs), and the k precision parameter (Fisher, 1953) of a paleomagnetic pole, a new set of VGPs with the same characteristic can be generated. When averaging sets of VGPs rather than paleomagnetic poles, uncertainty is weighted against the number of data points of each pole (Vaes et al., 2022).

External paleomagnetic pole: Standard paleomagnetic poles can be uploaded in Magnetic-A by typing the coordinates (longitude and latitude) and the 95% confidence angle (A95). Multiple paleomagnetic poles (including poles calculated internally from VGPs sets) can be averaged by standard Fisher (1953) statistic for comparison with the GAPWP (Figure 5b). The GAPWPs of Vaes et al. (2023) and Torsvik et al. (2012) are available in Magnetic-A, but any custom APWP can be compiled and uploaded (see User Guide). The location and name for one or more sites can be added to the projection.

2.6. Magnetic Polarity Stratigraphy

Paleomagnetic declination and inclination, if associated to stratigraphic position (see User Guide for the file format), can be converted in a magnetic polarity diagram (Figure 6). To facilitate the display of the declination data, the "zero" position (horizontal) can be shifted laterally. The polarity is either determined by using the VGPs latitude (after centering the VGPs to the present-day geographic north, as standard procedure) or, in case of azimuthally unoriented data, by using the sign of the inclination (down- or up-pointing).

3. Conclusions

Paleomagnetism provides the only geophysical data that anchors the paleo-position of a plate with respect the Earth's spin axis and allows correlation of stratigraphic records with time points (geomagnetic reversals) that are globally synchronous. Magnetic-A provides a toolbox that is specifically designed to guide the user through the analysis of paleomagnetic directions, paleomagnetic poles, and magnetic polarity stratigraphy. It includes some of the most recent statistical approaches and generates figures that are easily exportable and editable. Magnetic-A is a freeware that can be used either online or locally after installation of R. The Magnetic-A project is open to future development from insights of all members of the paleomagnetic community.

Conflict of Interest

The author declares no conflicts of interest relevant to this study.

Availability Statement

Magnetic-A is deployed online at https://edoardodallanave.shinyapps.io/MagneticA/. Data is available from Dallanave (2026).

Acknowledgments
E.D. warmly thanks Janice Scealy and Justin Tonti-Filippini for the comments that greatly improved the quality of this work, and for the very helpful suggestions about future Magnetic-A developments. This research was funded through MUR for ECORD-IODP Italia. Open access publishing facilitated by Universita degli Studi di Milano, as part of the Wiley - CRUI-CARE agreement.

References

Arason, P., & Levi, S. (2010). Maximum likelihood solution for inclination-only data in paleomagnetism. *Geophysical Journal International*, *182*(2), 753–771. https://doi.org/10.1111/j.1365-246X.2010.04671.x

Brenner, A. R., Fu, R. R., Kylander-Clark, A. R. C., Hudak, G. J., & Foley, B. J. (2022). Plate motion and a dipolar geomagnetic field at 3.25 Ga. *Proceedings of the National Academy of Sciences of the United States of America*, *119*(44), 1–7. https://doi.org/10.1073/pnas.2210258119

Butler, R. F. (1992). *Paleomagnetism: Magnetic domains to geologic terranes*. Blackwell Scientific Publication. Retrieved from https://www.geo.arizona.edu/Paleomag/

Chadima, M., & Hrouda, F. (2007). Remasoft 3.0 a user-friendly paleomagnetic data browser and analyzer. Retrieved from https://www.agico.cz/text/software/remasoft/remasoft.php

Chang, W., Cheng, J., Allaire, J. J., Sievert, C., Schloerke, B., Xie, Y., et al. (2021). Shiny: Web application framework for R. Retrieved from https://cran.r-project.org/package=shiny

Cogné, J. P. (2003). PaleoMac: A MacintoshTM application for treating paleomagnetic data and making plate reconstructions. *Geochemistry, Geophysics, Geosystems*, *4*(1), 1–8. https://doi.org/10.1029/2001GC000227

Constable, C., & Parker, R. L. (1988). Statistics of the geomagnetic secular variation for the past 5 m.y. *Journal of Geophysical Research*, *93*(B10), 11569–11581. https://doi.org/10.1029/jb093ib10p11569

Constable, C., & Tauxe, L. (1990). The bootstrap for magnetic susceptibility tensors. *Journal of Geophysical Research*, *95*(B6), 8383–8395. https://doi.org/10.1029/JB095iB06p08383

Dallanave, E. (2024). Assessing the reliability of paleomagnetic datasets using the R package PmagDiR. *Scientific Reports*, *14*(1666), 1666. https://doi.org/10.1038/s41598-024-52001-x

Dallanave, E. (2026). edoardo-paleomag/Magnetic-A: Magnetic-A: The new R-based toolbox for analysis of paleomagnetic data (v1.0.0) [Software]. *Zenodo*. https://doi.org/10.5281/zenodo.18220000

Dallanave, E., Agnini, C., Muttoni, G., & Rio, D. (2012). Paleocene magneto-biostratigraphy and climate-controlled rock magnetism from the Belluno Basin, Tethys Ocean, Italy. *Palaeogeography, Palaeoclimatology, Palaeoecology*, *337*(338), 130–142. https://doi.org/10.1016/j.palaeo.2012.04.007

Dallanave, E., Bachtadse, V., Crouch, E. M., Tauxe, L., Shepherd, C. L., Morgans, H. E. G., et al. (2016). Constraining early to middle Eocene climate evolution of the southwest Pacific and Southern Ocean. *Earth and Planetary Science Letters*, *433*, 380–392. https://doi.org/10.1016/j.epsl.2015.11.010

Dallanave, E., & Chang, L. (2020). Early Eocene to early Miocene magnetostratigraphic framework for IODP Expedition 371 (Tasman Frontier Subduction Initiation and Paleogene Climate). *Newsletters on Stratigraphy*, *53*(4), 365–387. https://doi.org/10.1127/nos/2019/0556

Dallanave, E., & Kirscher, U. (2020). Testing the reliability of sedimentary paleomagnetic datasets for paleogeographic reconstructions. *Frontiers in Earth Science, Geomagnetism and Paleomagnetism*, *8*, 1–16. https://doi.org/10.3389/feart.2020.592277

Dallanave, E., Sutherland, R., Dickens, G. R., Chang, L., Tema, E., Alegret, L., et al. (2022). Absolute paleolatitude of Northern Zealandia from the middle Eocene to the early Miocene. *Journal of Geophysical Research: Solid Earth*, *127*, 1–19. https://doi.org/10.1029/2022JB024736

Deenen, M. H. L., Langereis, C. G., van Hinsbergen, D. J. J., & Biggin, A. J. (2011). Geomagnetic secular variation and the statistics of palaeomagnetic directions. *Geophysical Journal International*, *186*(2), 509–520. https://doi.org/10.1111/j.1365-246X.2011.05050.x

Fisher, R. (1953). Dispersion on a sphere. *Proceedings of the Royal Society of London*, *A217*(1130), 295–305. https://doi.org/10.1098/rspa.1953.0064

Gilder, S. A., Chen, Y., & Sen, S. (2001). Oligo-Miocene magnetostratigraphy and rock magnetism of the Xishuigou section, Subei (Gansu Province, western China) and implications for shallow inclinations in central Asia. *Journal of Geophysical Research*, *106*(12), 30505–30521. https://doi.org/10.1029/2001JB000325

Hansma, J., & Tohver, E. (2020). Southward drift of Eastern Australian hotspots in the paleomagnetic reference frame is consistent with global true polar wander estimates. *Frontiers in Earth Science*, *8*(November), 1–16. https://doi.org/10.3389/feart.2020.544496

Heslop, D., & Roberts, A. P. (2016). Analyzing paleomagnetic data: To anchor or not to anchor? *Journal of Geophysical Research: Solid Earth*, *121*(11), 7742–7753. https://doi.org/10.1002/2016JB013387

Heslop, D., Scealy, J. L., Wood, A. T. A., Tauxe, L., & Roberts, A. P. (2023). A bootstrap common mean direction test. *Journal of Geophysical Research: Solid Earth*, *128*(8), 1–12. https://doi.org/10.1029/2023JB026983

Jones, C. H. (2002). User-driven integrated software lives: "paleomag" paleomagnetics analysis on the Macintosh. *Computers & Geosciences*, *28*(10), 1145–1151. https://doi.org/10.1016/S0098-3004(02)00032-8

King, R. F. (1955). The remanent magnetism of artificially deposited sediments. *Monograph of the Natural Royal Astronomica Society, Geophysical Supplement*, *7*, 115–134. https://doi.org/10.1111/j.1365-246X.1955.tb06558.x

Kirscher, U., Mitchell, R. N., Liu, Y., Pisarevsky, S. A., Giddings, J., & Li, Z. X. (2022). Paleomagnetic evidence for a Paleoproterozoic rotational assembly of the north Australian craton in the leadup to supercontinent Formation. *Geophysical Research Letters*, *49*(22), e2022GL099842. https://doi.org/10.1029/2022GL099842

Kirschvink, J. L. (1980). The least-squares line and plane and the analysis of palaeomagnetic data. *Geophysical Journal of the Royal Astronomical Society*, *62*(3), 699–718. https://doi.org/10.1111/j.1365-246X.1980.tb02601.x

Koymans, M. R., Langereis, C. G., Pastor-Galán, D., & van Hinsbergen, D. J. J. (2016). Paleomagnetism.org: An online multi-platform open source environment for paleomagnetic data analysis. *Computers & Geosciences*, *93*, 127–137. https://doi.org/10.1016/j.cageo.2016.05.007

Koymans, M. R., van Hinsbergen, D. J. J., Pastor-Galán, D., Vaes, B., & Langereis, C. G. (2020). Towards FAIR Paleomagnetic Data Management through Paleomagnetism.org 2.0. *Geochemistry, Geophysics, Geosystems*, *21*(2), 1–7. https://doi.org/10.1029/2019GC008838

Lurcock, P. C., & Wilson, G. S. (2012). PuffinPlot: A versatile, user-friendly program for paleomagnetic analysis. *Geochemistry, Geophysics, Geosystems*, *13*(6), 1–6. https://doi.org/10.1029/2012GC004098

McElhinny, M. W., & McFadden, P. L. (1997). Palaeosecular variation over the past 5 Myr based on a new generalized database. *Geophysical Journal International*, *131*(2), 240–252. https://doi.org/10.1111/j.1365-246X.1997.tb01219.x

McFadden, P. L., & McElhinny, M. W. (1988). The combined analysis of remagnetization circles and direct observations in palaeomagnetism. *Earth and Planetary Science Letters*, *87*(1–2), 161–172. https://doi.org/10.1016/0012-821X(88)90072-6

Ogg, J. G. (2020). Geomagnetic polarity time Scale. In F. M. Gradstein, J. G. Ogg, M. D. Schmitz, & G. M. Ogg (Eds.), *Geologic Time Scale 2020* (pp. 159–192). Elsevier B.V. https://doi.org/10.1016/b978-0-12-824360-2.00005-x

Scheidegger, A. E. (1965). On the statistics of the orientation of bedding planes, grain axes, and similar sedimentological data. In *U. S. Geological Survey professional paper* (Vol. 525, pp. 164–167).

Tauxe, L., Kylstra, N., & Constable, C. (1991). Bootstrap statistics for paleomagnetic data. *Journal of Geophysical Research*, *96*(B7), 11723–117490. https://doi.org/10.1029/91jb00572

Tauxe, L. (2010). *Paleomagnetic principle and practice*. Kluwer Academic Publishers.

Tauxe, L., Heslop, D., & Gilder, S. A. (2024). Assessing paleosecular variation averaging and correcting paleomagnetic inclination shallowing. *Journal of Geophysical Research: Solid Earth*, *129*(8), e2024JB029502. https://doi.org/10.1029/2024JB029502

Tauxe, L., & Kent, D. V. (2004). A simplified statistical model for the geomagnetic field and the detection of shallow bias in paleomagnetic inclinations: Was the ancient magnetic field dipolar? In J. E. T. Channell, D. V. Kent, W. Lowrie, & J. G. Meert (Eds.), *Timescales of the paleomagnetic field, Geophysical Monograph* (Vol. 145, pp. 101–115). American Geophysical Union. https://doi.org/10.1029/145gm08

Tauxe, L., Shaar, R., Jonestrask, L., Swanson-Hysell, N. L., Minnett, R., Koppers, A. A. P., et al. (2016). PmagPy: Software package for paleomagnetic data analysis and a bridge to the Magnetics Information Consortium (MagIC) database. *Geochemistry, Geophysics, Geosystems*, *17*(6), 2450–2463. https://doi.org/10.1002/2016gc006307

Torsvik, T. H. (2016). IADP: Interactive analysis of paleomagnetic data. https://www.iggl.no/resources.html

Torsvik, T. H., Müller, R. D., Van der Voo, R., Steinberger, B., & Gaina, C. (2008). Global plate motion frames: Toward a unified model. *Reviews of Geophysics*, *46*, 1–54. https://doi.org/10.1029/2007RG000227.1

Torsvik, T. H., Van der Voo, R., Preeden, U., Mac Niocaill, C., Steinberger, B., Doubrovine, P. V., et al. (2012). Phanerozoic polar wander, palaeogeography and dynamics. *Earth-Science Reviews*, *114*(3–4), 325–368. https://doi.org/10.1016/j.earscirev.2012.06.007

Vaes, B., Gallo, L. C., & van Hinsbergen, D. J. J. (2022). On pole position: Causes of dispersion of the paleomagnetic poles behind apparent polar wander paths. *Journal of Geophysical Research: Solid Earth*, *127*(4), 1–22. https://doi.org/10.1029/2022JB023953

Vaes, B., Li, S., Langereis, C. G., & van Hinsbergen, D. J. J. (2021). Reliability of palaeomagnetic poles from sedimentary rocks. *Geophysical Journal International*, *225*(2), 1281–1303. https://doi.org/10.1093/gji/ggab016

Vaes, B., van Hinsbergen, D. J. J., van de Lagemaat, S. H. A., van der Wiel, E., Lom, N., Advokaat, E., et al. (2023). A global apparent polar wander path for the last 320 Ma calculated from site-level paleomagnetic data. *Earth-Science Reviews*, *245*(104547), 1–35. https://doi.org/10.1016/j.earscirev.2023.104547

Vandamme, D. (1994). A new method to determine paleosecular variation. *Physics of the Earth and Planetary Interiors*, *85*(1–2), 131–142. https://doi.org/10.1016/0031-9201(94)90012-4

Van der Voo, R. (1990). The reliability of paleomagnetic data. *Tectonophysics*, *184*, 1–9. https://doi.org/10.1016/0040-1951(90)90116-P

Zijderveld, J. D. A. (1967). A.C. demagnetization of rocks: Analysis of results. In D. W. Collinson, K. M. Creer, & S. K. Runcorn (Eds.), *Methods in paleomagnetism* (pp. 254–286). Elsevier.