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APWP-online.org: A Global Reference Database and Open-Source Tools for Calculating Apparent Polar Wander Paths and Relative Paleomagnetic Displacements

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Abstract Paleomagnetism provides a quantitative tool for estimating the paleoposition of rock units relative to the Earth's spin axis and is widely used to determine relative tectonic motions (vertical-axis rotations and paleolatitudinal motions). These motions are commonly quantified as relative paleomagnetic displacements by comparing a study-mean paleomagnetic pole with a reference pole provided by an apparent polar wander path (APWP), even though these poles are calculated by averaging paleomagnetic data from different hierarchical levels. However, this conventional approach was shown to strongly overestimate the resolution at which such displacements can be determined. This problem was recently overcome by comparing paleomagnetic poles computed at the same hierarchical level, whereby the uncertainty of the reference pole is weighted against the number of sites underlying the study-mean pole. To enable the application of this approach, a new global APWP was calculated for the last 320 Myr from (simulated) site-level paleomagnetic data. Applying this comparison method requires a computationally more intensive procedure, however. Here, we therefore present the online, open-source environment (APWP-online.org) that provides user-friendly tools to determine relative paleomagnetic displacements and to compute APWPs from site-level paleomagnetic data. In addition, the website hosts the curated paleomagnetic database used to compute the most recent global APWP and includes an interface for adding high-quality paleomagnetic data that may be used for future iterations of the global APWP. We illustrate how the tools can be used through two case studies: the vertical-axis rotation history of the Japanese Islands and the paleolatitudinal motion of the intra-oceanic Olyutorsky arc.

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1 Introduction

Paleomagnetic data – obtained from measurements of the remanent magnetization recorded in rocks – provide a quantitative tool for studying the paleogeographic history and interpreting the relative and absolute motions of tectonic plates and smaller, fault-bounded terranes (e.g., *Cox and Hart*, 1991; *Butler*, 1992). One of the main tectonic applications of paleomagnetism is the identification and quantification of two types of relative paleomagnetic displacements: vertical-axis rotations and paleolatitudinal motions. To quantify such displacements, paleomagnetists typically compare a study-mean paleomagnetic direction or pole from a studied geological record, e.g., a fault-bounded block – with a reference direction or pole that represents a nearby stable tectonic plate, often provided by an apparent polar wander path (APWP) (e.g., *Demarest*, 1983; *Coe et al.*, 1985; *Butler*, 1992). Statistically significant differences between a study-mean pole and a reference pole (from an APWP) are then routinely interpreted as evidence for relative tectonic motions. However, *Rowley* (2019) recently showed that – using the conventional statistical approach - more than half of the study-mean poles that were used to compute the widely used global APWP of *Torsvik et al.* (2012) are statistically distinct (or 'discordant') from the reference pole position to which they contributed. This shows that the conventional approach to determine relative paleomagnetic displacements cannot reliably demonstrate tectonically meaningful displacements (*Rowley*, 2019).

Vaes et al. (2022) showed that the underlying problem is that conventional APWPs have been computed from paleomagnetic data at a different hierarchical level compared to individual study-mean

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poles. Namely, the reference pole from the APWP is computed from a collection of study-mean poles derived from stable plate interiors, whereas the study-mean direction or pole obtained from a mobile terrane is instead computed from a collection of spot readings of the past geomagnetic field (i.e., paleomagnetic sites). *Vaes et al.* (2022) demonstrated that an alternative approach computing APWPs on site-level paleomagnetic data, rather than pole-level data, offers a solution to this problem. They showed that when the uncertainty of the reference pole is weighted against the number of sites used to compute the study-mean pole, a statistical difference can be interpreted as geologically meaningful. In this approach, the reference pole position and its uncertainty are determined from a large number (>1000) of simulated reference poles that are calculated from the same number of sites in the studied paleomagnetic dataset. The resolution at which a statistical difference, and thus a tectonic displacement, may be determined is thus directly controlled by the size of the studied dataset.

In contrast to the conventional approach, the methodology developed by *Vaes et al.* (2022) also weights the spatial and temporal uncertainties in the underlying paleomagnetic data in the computation of the reference pole and its confidence region. Building on this study, *Vaes et al.* (2023) presented a global APWP calculated from parametrically re-sampled site-level data. A global APWP combines paleomagnetic data from all stable plate interiors whose relative motions are well-constrained, e.g., by retro-fitting marine magnetic anomalies (e.g., *Besse and Courtillot*, 2002; *Torsvik et al.*, 2008, 2012). Such an APWP computed from site-level paleomagnetic data then allows the determination of relative paleomagnetic displacements by comparing paleomagnetic data on the same hierarchical level (*Vaes et al.*, 2022, 2023). However, this new parametric re-sampling approach is computationally more complex than the conventional approach and not yet incorporated in any existing paleomagnetic software.

Here, we present the online and open-source environment APWP-online.org (Figure 1) that provides a set of user-friendly tools to compute relative paleomagnetic displacements and APWPs using the approaches presented by *Vaes et al.* (2022, 2023). This web application aims to enable specialist users to apply these new statistical methods to specific tectonic and paleogeographic problems. In addition, APWP-online.org includes a portal that hosts the curated paleomagnetic reference database that was used to compute the global APWP of *Vaes et al.* (2023). Through this portal, paleomagnetists can request the addition of new high-quality paleomagnetic data, or the revision of age constraints, which may be used for future updates of the global APWP. We illustrate how the new tools may contribute to solving tectonic problems by applying them to two case-studies: the timing and magnitude of the Neogene vertical-axis rotations of the Japanese islands and the paleolatitudinal evolution of the Late Cretaceous-Paleogene intra-oceanic Olyutorsky arc that is now exposed on Kamchatka.

2 Background

APWP-online.org facilitates the construction of custom-made APWPs and the use of APWPs as a reference to identify and quantify relative paleomagnetic displacements. APWPs are generally constructed as a 'path' of successive paleomagnetic pole positions at a chosen time step (e.g., 10 Myr). These paleomagnetic pole positions provide reference poles for different ages in the coordinates of a specific tectonic plate. Each reference pole corresponds to the estimated position of the geomagnetic pole at a given age relative to the present-day position of that plate, under the assumption that the time-averaged Earth's magnetic field corresponds to a geocentric axial dipole (GAD) field, see e.g., *Butler* (1992). In the conventional approach, APWPs are computed using a running-mean approach: by averaging a collection of study-mean poles whose mean age falls into a sliding time window (e.g., 20 Myr). An APWP is often computed from paleomagnetic data derived from a single tectonic plate or terrane. Alternatively, an APWP (such as a global APWP) may also include data from other tectonic plates after rotating these data to the reference plate, using a plate circuit that describes the plate motions relative to the reference plate through geological time. For additional background on APWP computation, see *Vaes et al.* (2023) and *Gallo et al.* (2023).

To determine a relative paleomagnetic displacement, a reference pole of an APWP is typically compared with an independent study-mean pole (Figure 2a). These poles are, however, computed from paleomagnetic data on different hierarchical levels (*Bazhenov et al.*, 2016; *Rowley*, 2019). Namely, the study-mean pole is computed instead by averaging a collection of virtual geomagnetic pole (VGPs), each obtained from a distinct paleomagnetic 'site'. A paleomagnetic site is defined as a rock unit, such as lava flow or a single sedimentary horizon, that represents an increment of geological time relative to the timescale at which the geomagnetic field changes (*McElhinny and McFadden*, 1999). Each VGP should thus represent a 'spot reading' of the past geomagnetic field and can be derived from a site-level paleomagnetic direction, which itself is often computed by averaging paleomagnetic directions obtained from different samples of the same site. For more details on these procedures and the hierarchical data framework used in paleomagnetism, we refer the reader to widely used textbooks on paleomagnetism such as *Butler* (1992), *McElhinny and McFadden* (1999), and *Tauxe* (2010).

Figure 1 – Overview of the homepage of APWP-online.org. This page provides direct access to the different tools and portals. In addition, the user manual may be downloaded as pdf.

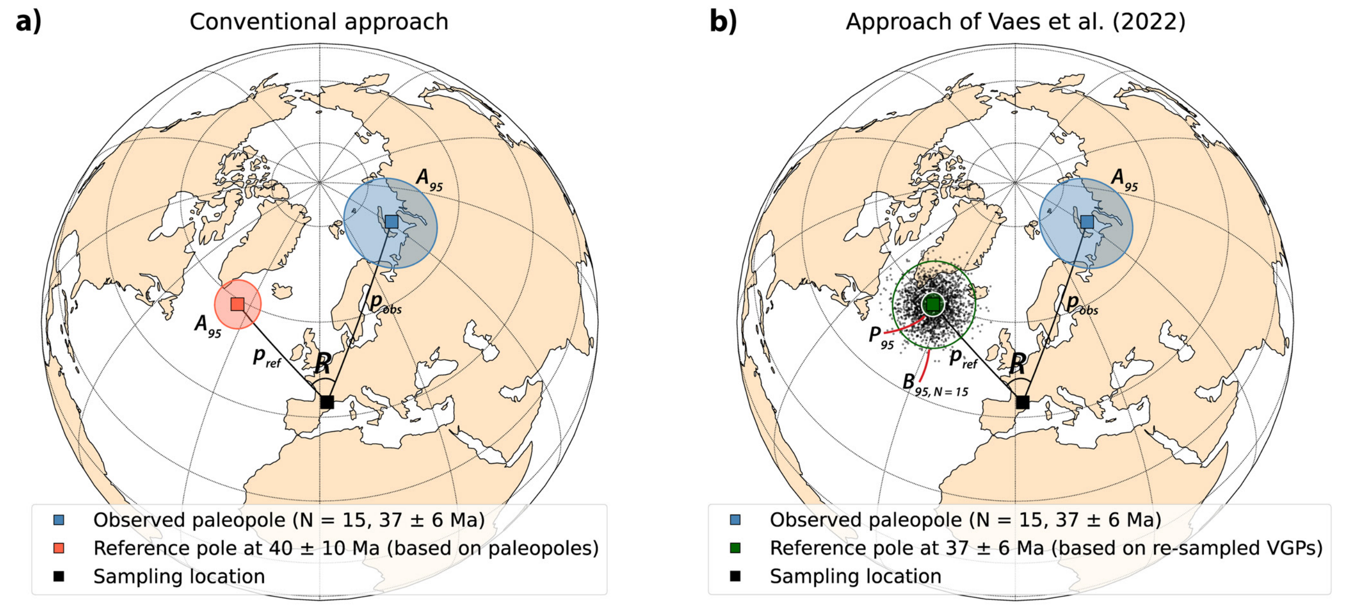

Figure 2 – Comparison between the conventional approach and the recently developed approach by *Vaes et al.* (2022) for the determination of relative tectonic displacements. The observed paleopole corresponds to a study-mean pole based on 15 site-level VGPs (N) and is plotted with its 95% confidence region (A_{95}). In the conventional approach **(a)**, this study-mean pole would be compared to a reference pole from an APWP (often with different age) and its A_{95}, which were computed from a collection of study-mean poles. In the approach of *Vaes et al.* (2022) **(b)**, the reference pole is computed at the mean age of the study-mean pole (37 Ma) and its confidence region (B_{95}) is weighted against the number of sites that underlie the study-mean pole (N=15). Note that this confidence region is larger than the actual confidence region of the unweighted reference pole of the APWP (P_{95}). The procedures for computing the relative paleomagnetic displacements are explained in Section 3.2.

Rowley (2019) and *Vaes et al.* (2022) showed that comparing these different types of paleomagnetic poles should be avoided as it is statistically flawed and may lead to erroneous tectonic interpretations. To overcome this problem, a parametric re-sampling approach was developed by *Vaes et al.* (2022) that allows the computation of simulated VGPs from the study-mean poles used to compute an APWP. For more details on parametric re-sampling of paleomagnetic data, we also refer to the textbook of Tauxe et al. (2010). In this approach, reference poles of an APWP (and their confidence regions) are computed from re-sampled VGPs instead of from a collection of study-mean poles (see section 3.1). This may be used to construct an APWP or to compute a reference pole at a specific age to compare it against an independent study-mean pole (Figure 2b). In the latter case, the 95% confidence region of the reference pole can be directly weighted against the number of sites used to compute that study-mean pole (see Section 3.2, *Vaes et al.*, 2022). Importantly, such comparisons are made between paleomagnetic poles computed at the same hierarchical level, providing a more robust means to constrain geologically meaningful relative displacements compared to the conventional statistical approach.

An additional advantage of using (simulated) site-level paleomagnetic data for the computation of APWPs and relative paleomagnetic displacements is that it enables improved incorporation of spatial and temporal uncertainties in the underlying data. Recently, statistical approaches have also been developed to compute APWPs from actual site-level paleomagnetic data (*Gallo et al.*, 2023) and to compute relative vertical-axis rotations by comparing datasets compiled on the site-level (*Montheil et al.*, 2023). Although using real site-level paleomagnetic data is, evidently, preferred over simulated site-level data, we note that compiling paleomagnetic data on the site-level is often an arduous task (*Gallo et al.*, 2023; *Vaes et al.*, 2023). The tools of APWP-online.org require a compilation of study-mean poles (and associated statistical parameters) as input, making it more convenient in practice. Compilations of study-mean poles can be obtained from online, widely used paleomagnetic databases such as the MagIC Database (*Jarboe et al.*, 2012), the Global Paleomagnetic Database (GPMDB, *Pisarevsky et al.*, 2022) and PALEOMAGIA (*Veikkolainen et al.*, 2014, 2017). These community databases may provide a useful starting point for building a custom-made compilation of reliable study-mean poles for the tectonic plate or geological terrane of interest.

3 Tools

In the following sections, we provide an overview of the technical background of the two tools of APWP-online.org and its input and output files. For more practical details on how to use these tools, we refer to the user manual that can be found and downloaded on the web application.

3.1 APWP Tool

The APWP tool allows users to compute an APWP based on (simulated) site-level paleomagnetic data using the approach of *Vaes et al.* (2023). The APWP is calculated from VGPs that are parametrically re-sampled from a collection of study-mean poles, which are provided by the user using the input file (see Section 3.3). To compute the APWP, the user first needs to specify the age range for the APWP, the size of the time window and the time step at which the reference poles of the APWP are computed (Figure 3). This tool can be used to construct an APWP for any plate or terrane regardless of the age of rocks from which the data are derived. Prior to initializing the APWP tool, the user can also choose the number of iterations used for the computation of the path and the estimation of its 95% confidence region (the P_{95} of *Vaes et al.*, 2023, see Figure 2b), like the Relative Paleomagnetic Displacement tool described in the next section. It is important to note that a very large number (1000s) of iterations will significantly increase the total computation time.

For each iteration of the APWP computation, VGPs are parametrically re-sampled from each study-mean pole listed in the input file. These VGPs are generated from a *Fisher* (1953) distribution centered on each study-mean pole and described by its precision parameter K, where the number of re-sampled VGPs equals the number of sites (N) used to compute that paleomagnetic pole. The re-sampled VGPs are then assigned a random age within the age uncertainty range of the paleomagnetic pole from which they are generated. Next, a sliding window is applied to the VGPs, computing an estimate of the reference pole for each time step by averaging the re-sampled VGPs that fall within the time window centered on that age. The final APWP is computed as the mean of the simulated reference poles per time window, with the P_{95} confidence region defined as the circle that includes 95% of those simulated reference poles. For a more detailed explanation of the workflow, we refer the reader to Section 3 of *Vaes et al.* (2023).

The tool also facilitates the straightforward reproduction of the global APWP of *Vaes et al.* (2023). To re-compute the global APWP, the latest version of the reference database can be downloaded from the Reference database portal (see Section 4) and uploaded as input file in the APWP tool. In addition, the APWP tool allows users to compute APWPs from a chosen set of study-mean poles included in that database. For instance, one may calculate an APWP solely based on the data derived from a specific tectonic plate, e.g., South America, using a different window size and time step from those used by *Vaes et al.* (2023). Finally, researchers may also apply this tool to evaluate the effect of adding a new paleomagnetic dataset to the global APWP.

3.2 Relative Paleomagnetic Displacement (RPD) Tool

The second tool featured on APWP-online.org (Figure 4) allows the determination of a relative paleomagnetic displacement (RPD) using the comparison metric that was introduced by *Vaes et al.* (2022). Central to this approach is the comparison between a study-mean pole and a reference pole in which the number of paleomagnetic sites used to compute the study-mean pole is taken into consideration. The 95% confidence region of the reference pole (the B_{95}) is estimated as if it had been derived from the same number of sites as the study-mean pole (N_s) (see Figure 2). To determine the reference and the B_{95} we use the parametric re-sampling approach described by *Vaes et al.* (2022). For each run the tool computes a single estimate for the position of the reference pole – a pseudopole – using two steps. First, VGPs are generated by parametric re-sampling of all study-mean poles included in the reference database, whose age uncertainty range overlaps with that of the studied dataset. For each study-mean pole, VGPs are re-sampled from a *Fisher* (1953) distribution centered on the pole position and defined by the reported precision parameter K, whereby the number of VGPs corresponds to the number of sites used by the original authors to compute that study-mean pole.

Next, a pseudopole is computed by averaging Ns randomly drawn re-sampled VGPs whose age falls within the time window (provided as user input) around the mean age of the studied dataset. A distribution of pseudopoles is then obtained after repeating this procedure hundreds to thousands of times (as specified by the user, see Figure 4). *Vaes et al.* (2022) defined the B_{95} as the radius of the circle about the principal vector of the pseudopoles that includes 95% of those pseudopoles (Figure 2). The size of the B_{95} is directly dependent on the N_s and becomes larger with decreasing N_s, such that the resolution of the statistics comparison is adjusted to the amount of information contained in the studied dataset. This way, the reference pole and the B_{95} simply show the uncertainty in the position of the reference pole, predicting where it could be located if it would have been calculated from the same number of VGPs as included in the studied dataset.

The reference data used to compute the relative paleomagnetic displacements can be chosen by the user (Figure 4). To determine the displacements of a collection of study-mean poles relative to a large tectonic plate (North America, South America, Eurasia, Iberia, Africa, India, Antarctica, Australia, Pacific), the reference pole position is computed from the database underlying the global APWP of *Vaes et al.* (2023). To this end, all re-sampled VGPs are rotated to the chosen reference plate using pre-calculated Euler rotation poles that are derived from the global plate circuit used by *Vaes et al.* (2023). For each input paleomagnetic pole, a default age range of 10 Myr

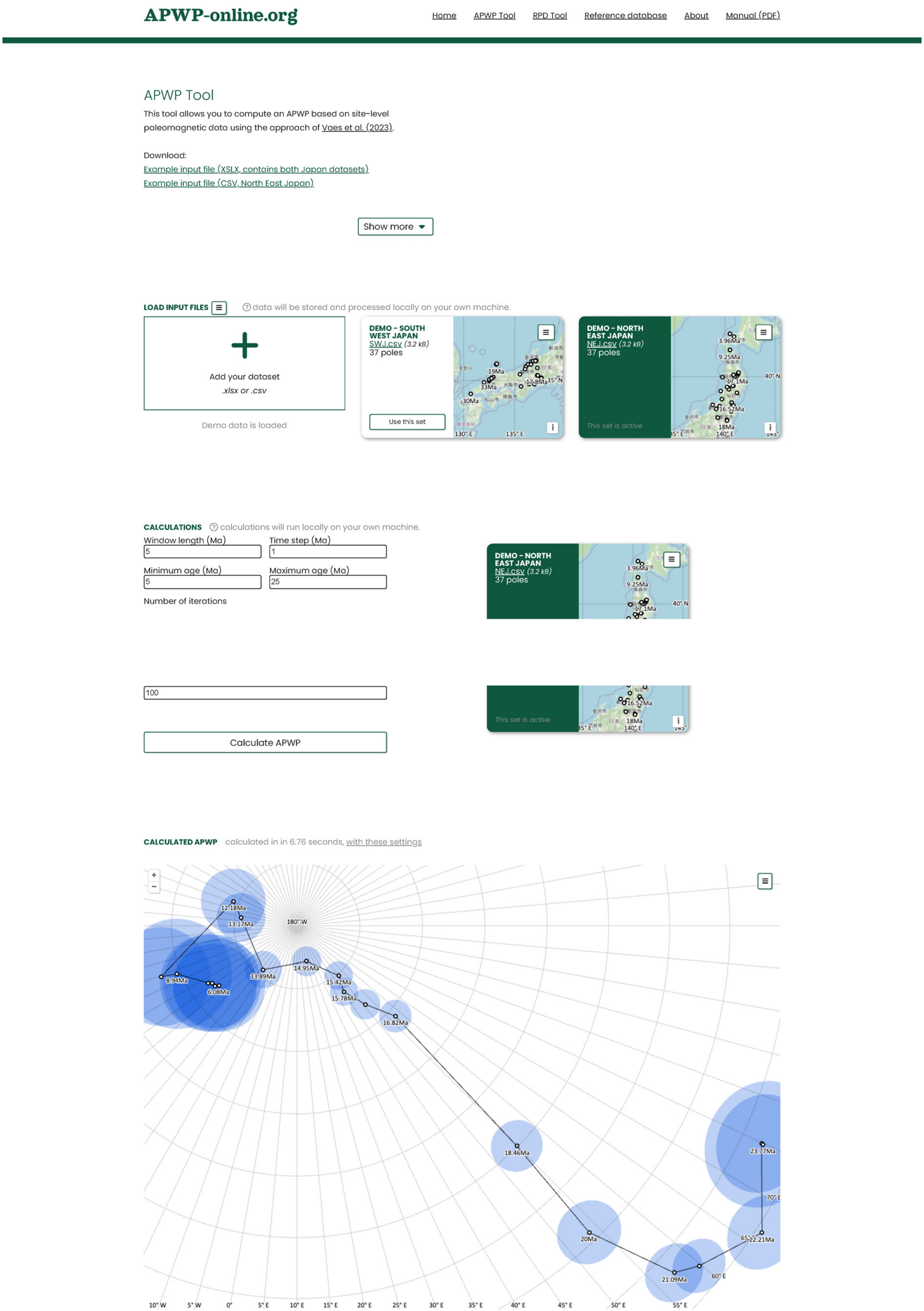

Figure 3 – Overview of the APWP tool showing an APWP computed for northeast Japan using the compilation provided by the demo data file. The following parameters were used: window length = 5 Myr, time step = 1 Myr, number of iterations = 1000, minimum/maximum age = 5/25 Ma. See the user manual for more details on the different buttons and options.

Figure 4 – Overview of the relative paleomagnetic displacement (RPD) tool showing the application of the tool to the compilation of study-mean poles of northeast Japan provided by the demo data file. The paleomagnetic displacements were computed relative to Eurasia, using the global APWP of *Vaes et al.* (2023) in the coordinates of the Eurasian plate and for a reference location computed from the input data itself. The following parameters were used for the calculations: window length of reference pole = 10 Myr, number of iterations = 200.

around the mean age of the pole is used. This age range can be modified by the user (Figure 4), e.g., to exactly match the age range of the study-mean pole. With age uncertainties of up to 10 Myr, this is not likely to affect the result, but this can be evaluated for each individual case by the user.

The user may also upload a custom reference database to the RPD tool, allowing the determination of RPDs using reference poles computed from this database. This can be done by choosing an uploaded file under 'Choose reference' (Figure 4). It is important to note that the reference data should be provided using the template input file (see Section 3.3), as all reference study-mean poles require age, age uncertainty range, number of sites and the *Fisher* (1953) precision parameter K. This allows the determination of the reference pole position and its B_{95} following the procedures described above. Alternatively, the user may also compute the RPDs relative to the geographic pole. The estimated vertical-axis rotation for each study-mean pole then simply corresponds to the absolute paleomagnetic declination at the chosen reference location based on that pole (Figure 5a, b). The relative paleolatitudinal displacement corresponds to the absolute difference between the observed paleolatitude and the present-day latitude of the reference location. Because the position of the geographic pole has no uncertainty (i.e., it has a latitude of 90 degrees), the uncertainty of these results is determined by the A_{95} of the study-mean pole.

We quantify the relative paleomagnetic displacements as relative rotation (R) and latitudinal displacement (L) based on the difference in pole position between a study-mean pole and reference pole, calculated using a spherical triangle (Figure 2). The rotation R (following the nomenclature of, for instance, *Beck*, 1980; *Demarest*, 1983) is quantified by the angle between the great-circle segments that connect the sampling location with both study-mean poles, which is identical to the difference between the paleomagnetic declinations predicted by the poles at the sampling location. To determine whether the rotation is clockwise or counterclockwise needs to be inferred from these declination values, as the angle in rotation space does not contain this information (see Chapter 11 and the Appendix of *Butler*, 1992, for more detail). The paleolatitudinal displacement (L) is then determined by the difference between the angular distances p_{ref} and p_{obs} (i.e., the paleomagnetic colatitude of both poles) of the two great-circle segments, where $L = p_{ref} - p_{obs}$. A positive displacement value thus indicates that the paleomagnetic latitude of the study-mean pole is larger than that of the reference pole. Please note that L has the opposite sign of the poleward transport (P) defined by *Butler* (1992), whereby a positive value indicates a northward motion toward the reference pole, corresponding instead to a lower paleolatitude of the study-mean pole than predicted by the reference pole. We found the resulting plots counterintuitive, and therefore plot a more northerly (southerly) paleolatitude than expected from the reference pole position above (below) the 0° reference line, following e.g., *Kent and Irving* (2010, their Figure 8). To quantify the uncertainties on relative paleomagnetic displacements, we follow the square-root formulas developed by *Demarest* (1983) and defined by *Butler* (1992) for a pole-space approach (see equations A.66 and A.76 in the Appendix of *Butler*, 1992), whereby the 95% confidence region on the reference pole ($A_{95,ref}$) is replaced by the B_{95}.

3.3 Input and Output

The input for the APWP and RPD tools should be provided through the template file that can be downloaded from the website as a comma-separated values (CSV) or spreadsheet (.xlsx) ('Download the example input file'). This file consists of a header with column names under which the relevant data and metadata should be added. Each entry that is included in the input file must contain the following parameters: the age and age uncertainty range of the sampled rocks, the longitude and latitude of the mean sampling location, the longitude and latitude of the study-mean pole, the number of paleomagnetic sites (N, i.e., the number of spot readings of the paleomagnetic field), the *Fisher* (1953) precision parameter (K) and the 95% cone of confidence about the pole (A_{95}).

The input file also includes an optional column for the incorporation of the uncertainty in the elongation-inclination (E/I) correction for inclination shallowing of *Tauxe and Kent* (2004). For the global APWP of *Vaes et al.* (2023), only sediment-derived datasets that were corrected for inclination shallowing using this correction method and that satisfied the criteria proposed by Vaes et al. (2021) were used. This reduces the variable bias posed by potential inclination shallowing and allows propagating the uncertainty associated with the E/I correction in the calculation of an APWP. This source of uncertainty can be accounted for by adding the standard deviation of the colatitude distribution obtained from the E/I correction (pstd) (following the approach of *Pierce et al.* (2022); see Section 3 in *Vaes et al.* (2023) for more details), which can be approximated by taking the mean difference between the shallowing-corrected paleolatitude and its 95% confidence limits and dividing it by two.

The output of the APWP tool consists of a plot of the APWP on a northern hemisphere map projection. The output APWP may be directly downloaded from the web interface and contains the longitude and latitude values of the APWP, the center age of the window, the mean age and number of the re-sampled VGPs for each time window, as well as the P_{95} values and all other relevant statistical parameters. The APWP may be used directly in the RPD tool to

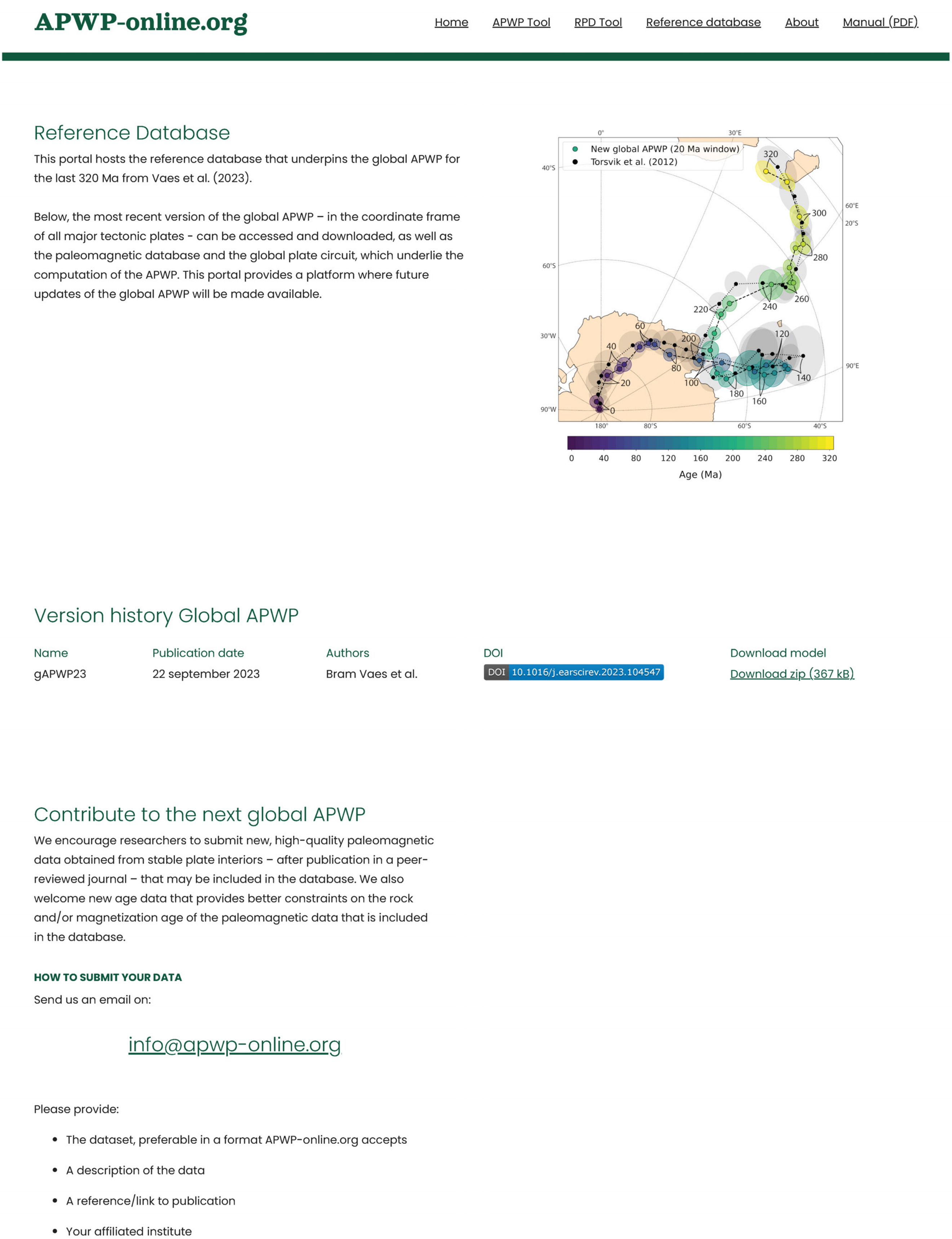

Figure 5 – Overview of the Reference Database portal. Here, the most recent version of the global APWP – in the coordinate frame of all major tectonic plates - can be accessed and downloaded, as well as the paleomagnetic database and the global plate circuit, which underlie the computation of the APWP. This portal provides a platform where future updates of the global APWP will be made available and described in a change log. New data and correction to existing data can be provided by sending an email to info@apwp-online.org.

determine the relative paleomagnetic displacements between the studied tectonic plate or terrane and a chosen reference plate (see examples in Section 5).

For the computation of the RPDs in the RPD tool, the user may specify a few input parameters, similar to the APWP tool. The number of iterations and time window (default is 10 Myr) used to compute the reference pole position and its uncertainty (the B_{95}) can be provided as direct input on-screen. Instead of using the sampling location of each entry in the input file, a reference location may instead be chosen by the user to compute the RPDs (Figure 4). Note that specifying a reference location is required when using an APWP as input for this tool. As described in the previous section, the user may choose the reference against which the uploaded input data are compared. The output of the RPD tool consists of two figures on the web interface that show the relative vertical-axis rotations and paleolatitudinal displacement computed for each input paleomagnetic pole, which can be downloaded as raster (PNG or JPG) or vector (SVG) image. As for the APWP tool, the output results may also be downloaded as a CSV file or spreadsheet. Finally, we note that additional tools for the analysis and visualization of paleomagnetic results are available on the online, open-source web application Paleomagnetism.org (*Koymans et al.*, 2016, 2020). For instance, APWPs constructed with the APWP tool may be uploaded to the Geography Portal of Paleomagnetism.org (after providing it in the correct input format) to plot declination, inclination and paleolatitude curves based on this APWP. Using this portal, these curves may then be compared to curves derived from the global APWP (e.g., *Vaes et al.*, 2023) for large tectonic plates such as Africa, Eurasia, and North America.

4 Reference Database Portal

The Reference database portal of APWP-online.org hosts the paleomagnetic database that underpins the global APWP for the last 320 Myr from *Vaes et al.* (2023). Through this web interface (Figure 5), the most recent version of the global APWP (in the coordinate frame of all major tectonic plates), the paleomagnetic database and the global plate circuit which together underpin the computation of the APWP may be accessed and downloaded. This portal provides a platform where future updates of the global APWP will be made available. We refer the reader to *Vaes et al.* (2023) for a detailed description of the methodology and plate circuit. Any future updates of the APWP will be described in a change log on the website and indicated with a version number (see Figure 5), and any major future updates will be accompanied by a peer-reviewed publication.

We intend to update the paleomagnetic database that underlies the computation of the global APWP on an annual basis. The database is intended as a community effort, and a steering committee of specialists will be maintained that will meet on an annual basis to evaluate new entries (see APWP-online.org for the latest composition of the committee).

We encourage researchers to submit new datasets that may contribute to the improvement of the database. First, we welcome any new, high-quality paleomagnetic data obtained from stable plate interiors – after publication in a peer-reviewed journal – that may be included in the database. New data will be reviewed and evaluated against the reliability criteria described in *Vaes et al.* (2023). For sedimentary data, these criteria require that the collection of paleomagnetic directions is corrected for potential inclination shallowing. Inclusion of sediment-based data will be evaluated using the quality criteria proposed by *Vaes et al.* (2021).

Second, we also welcome new age data that provides better constraints on the rock and/or magnetization age of the paleomagnetic data that is included in the database. Any suggestions for updating the age of specific study-mean poles are highly appreciated and may be submitted through the query form. We note that many of the age uncertainty ranges quoted in the current database correspond to available age constraints at the time of the original publication of the paleomagnetic data. Therefore, useful age data may also be provided by peer-reviewed articles that were already published before the database of *Vaes et al.* (2023) was compiled. Finally, we welcome any corrections to mistakes in our database, as well as new insights or doubts related to the reliability of specific paleomagnetic datasets.

5 Application to Case Studies

We illustrate the functionalities of the two main tools of the APWP-online.org application by applying them to two different case studies: the opening of the Japan Sea and the paleolatitudinal motion of the intra-oceanic Olyutorsky arc (Figures 6, 7, and 8). We revisit the paleomagnetic data analyses performed by Vaes et al. (2019) that was used to test their plate-kinematic reconstruction of the northwest Pacific region. Vaes et al. (2019) reconstructed the motions of tectonic blocks relative to major plates (e.g., Pacific, North America, or Eurasia) based on marine magnetic and structural geological data. By placing their reconstruction in a paleomagnetic reference frame (of *Torsvik et al.*, 2012), they predicted the declination and paleolatitude for these tectonic blocks through time, at 10 Myr intervals. They then compared the predicted declinations or paleolatitudes against paleomagnetic data from these tectonic blocks and adjusted the reconstruction where required by paleomagnetic data and permitted by structural data (see also *Li et al.*, 2017, for more details on these procedures). Rather than comparing such predictions against observed data, we show here how

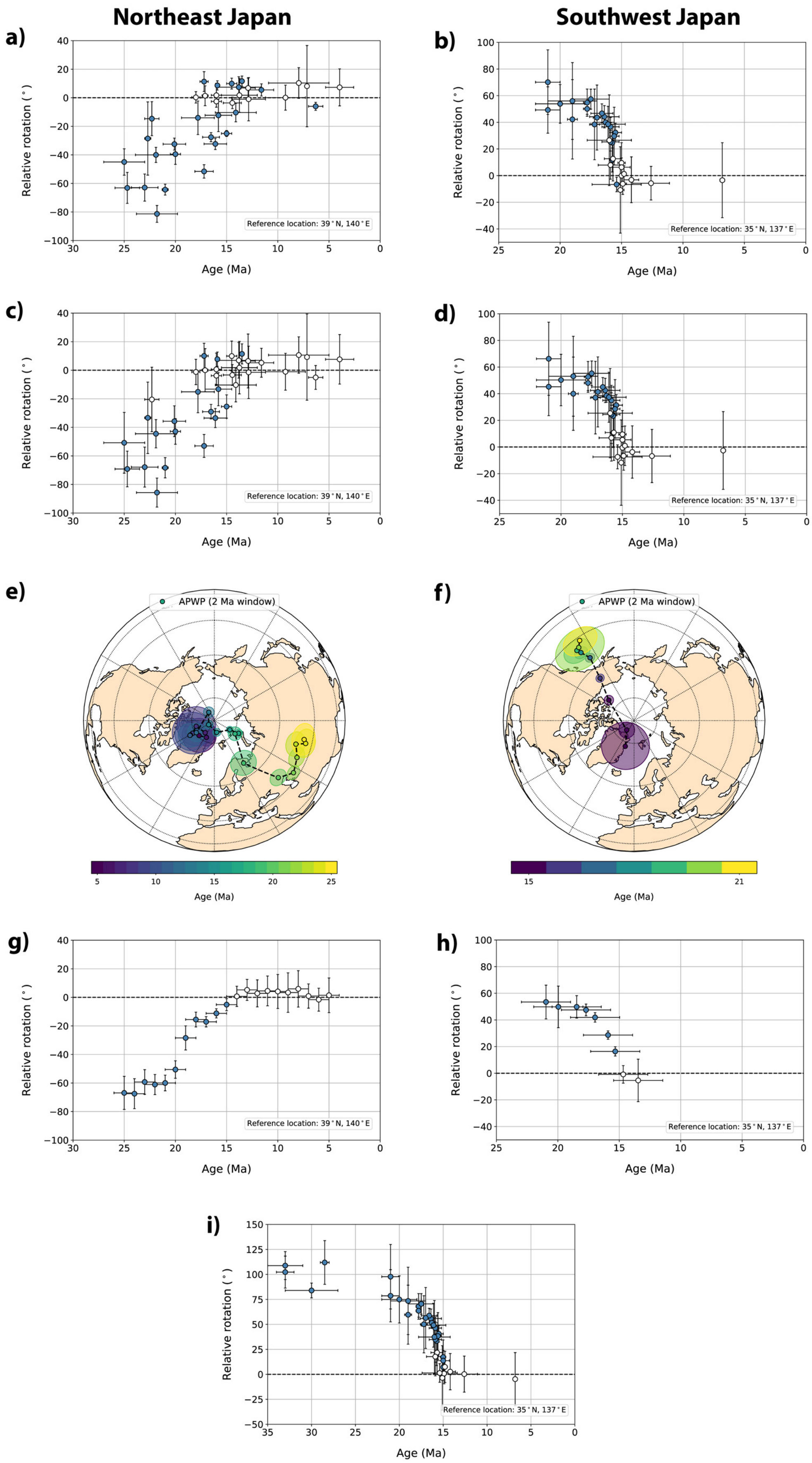

Figure 6 – Application of the APWP and RPD tools to the northeast and southwest Japan blocks. Vertical-axis rotations of each dataset relative to the geographic pole are shown in **(a)** and **(b)**. A positive value indicates a clockwise rotation since that time. Rotations relative to Eurasia – using the global APWP of *Vaes et al.* (2023) – are shown in **(c)** and **(d)**. Custom APWPs computed with the APWP tool, using a time window of 2 Myr and a temporal resolution of 1 Myr, are shown on orthographic plots in **(e)** and **(f)**. Vertical-axis rotations relative to Eurasia are computed using these APWPs in **(g)** and **(h)**. Finally, the rotation through time of southwest Japan relative to northeast Japan is shown in **(i)**.

the APWP and RPD tools may be used to directly quantify the magnitude, timing, and uncertainty of vertical-axis rotations and paleolatitudinal motions relative to a chosen reference.

The opening of the Sea of Japan since ∼25 Ma is well-known to have led to opposing rotations of the northeastern and southwestern parts of Japan (e.g., *Otofuji et al.*, 1985; *Martin*, 2011), and an extensive paleomagnetic database has been collected over the years (*Vaes et al.*, 2019). Using the RPD tool, we may plot the individual study-mean poles compiled by *Vaes et al.* (2019) relative to the north geographic pole (i.e., only the declination and the associated uncertainty are shown) (Figure 6a, b). Next, we may plot these data relative to the global APWP of *Vaes et al.* (2023) in the coordinates of Eurasia, because these are the values that are relevant for kinematic restoration of the opening of the Japan Sea (Figure 6c, d). The differences between Figure 6a-b and 6c-d are small as Eurasia did not rotate much (<5°) relative to the north pole in the last 25 Myr, but the confidence regions are slightly larger in Figure 6c-d as the uncertainty in the position of the reference pole contributes to the overall uncertainty. While the general amount and timing of the coherent rotation of northeast Japan is easily estimated from these plots, the dispersion of the study-mean poles is large, owing to the limited number (<10) of paleomagnetic directions underpinning many of these study-mean poles (*Vaes et al.*, 2022; *Gerritsen et al.*, 2022) and, potentially, to minor differential rotations of smaller blocks (*Yamaji et al.*, 1999).

To obtain a better estimate of the magnitude and timing of the counterclockwise rotation, we constructed an APWP for the Japan blocks using the APWP tool: for the period of 25 to 5 Ma for northeast Japan and of 21 to 13 Ma for southwest Japan. The underlying database is identical as the one used for the plots of Figure 6a-d. The high data density allows the computation of the APWP using a time step of only 1 Myr and a sliding window of 2 Myr. This is a much higher temporal resolution than typically used in the construction of (global) APWPs, which often have a resolution of 10 Myr (e.g., *Besse and Courtillot*, 2002; *Torsvik et al.*, 2008, 2012; *Vaes et al.*, 2023). For the northeast Japan block, the APWP shows a phase of rapid polar wander between ∼20 and 15 Ma followed by a stillstand of the paleomagnetic pole position after ∼14 Ma (Figure 6e). Likewise, southwest Japan reveals a rapid phase of polar wander between ∼21-13 Ma, but the data density before and after this period is insufficient for a meaningful APWP calculation (Figure 6f). We assess whether these polar wander phases indeed correspond to a relative rotation by using the APWPs as input in the RPD tool and computing the vertical-axis rotation through time relative to the global APWP in the coordinates of Eurasia (Figure 6g, h). For illustration, we also compared the compilation of study-mean poles from southwest Japan to the database of northeast Japan, by adding the latter as a custom reference database in the RPD tool (Figure 6i). The results reveal a relative rotation of ∼100° during the opening of the Sea of Japan until ∼15 Ma. Finally, we uploaded the new APWPs for northeast and southwest Japan in the Geography Portal of Paleomagnetism.org (*Koymans et al.*, 2016, 2020) to show how the declination values predicted by these APWPs compare to the declination curves predicted from the plate reconstruction of *Vaes et al.* (2019) (Figure 7). The main difference between the curves obtained by *Vaes et al.* (2019) and those presented here is that the latter are purely based on paleomagnetic data and are computed at a much finer temporal resolution, providing tight paleomagnetic constraints on the rotation history of the Japanese islands during the Miocene opening of the Japan Sea.

We illustrate the application of the paleolatitudinal displacement (L) tool using a case study of the Olyutorsky arc (Figure 8). The Olyutorsky arc is an extensive intra-oceanic arc complex that was emplaced onto continental crust of Kamchatka in the Eocene (∼55-45 Ma, *Vaes et al.*, 2019). Paleomagnetic data reveal that the arc was located far south of its present-day location (e.g., *Kovalenko*, 1996; *Levashova et al.*, 1997, 1998; *Konstantinovskaia*, 2001; *Shapiro and Solov'ev*, 2009; *Domeier et al.*, 2017; *Vaes et al.*, 2019). In Figure 8a, we show the paleolatitudinal displacement relative to the stable North American plate (of which the Kamchatka peninsula is currently a part). In this case, computing an APWP for the Olyutorsky arc is not meaningful, because sediment-derived datasets have not been corrected for inclination shallowing and because of large vertical-axis rotations (see strongly scattered poles in Figure 8b). Nonetheless, the data reveal a systematic decrease in the paleolatitude relative to North America of ∼20-30° between the onset of arc magmatism around ∼85-80 Ma and the obduction age of ∼50 Ma Figure 8a), which is more informative for plate kinematic reconstruction purposes than the absolute paleolatitudes of the study-mean poles and the global APWP in North American coordinates that were used by *Vaes et al.* (2019).

6 Availability, Data Storage and License

The APWP-online.org application can be freely accessed with the latest versions of commonly used internet browsers, such as Google Chrome, Mozilla Firefox, and Safari. The source codes of the web applications and the Python scripts that are used to perform the calculations are publicly available on GitHub and can be accessed from the About page on the website. The Python codes used for the computations build on those previously written by *Vaes et al.* (2022, 2023) and rely heavily on existing functions included in the freely available paleomagnetic software package PmagPy (*Tauxe et al.*, 2016). Future updates to APWP-online.org will

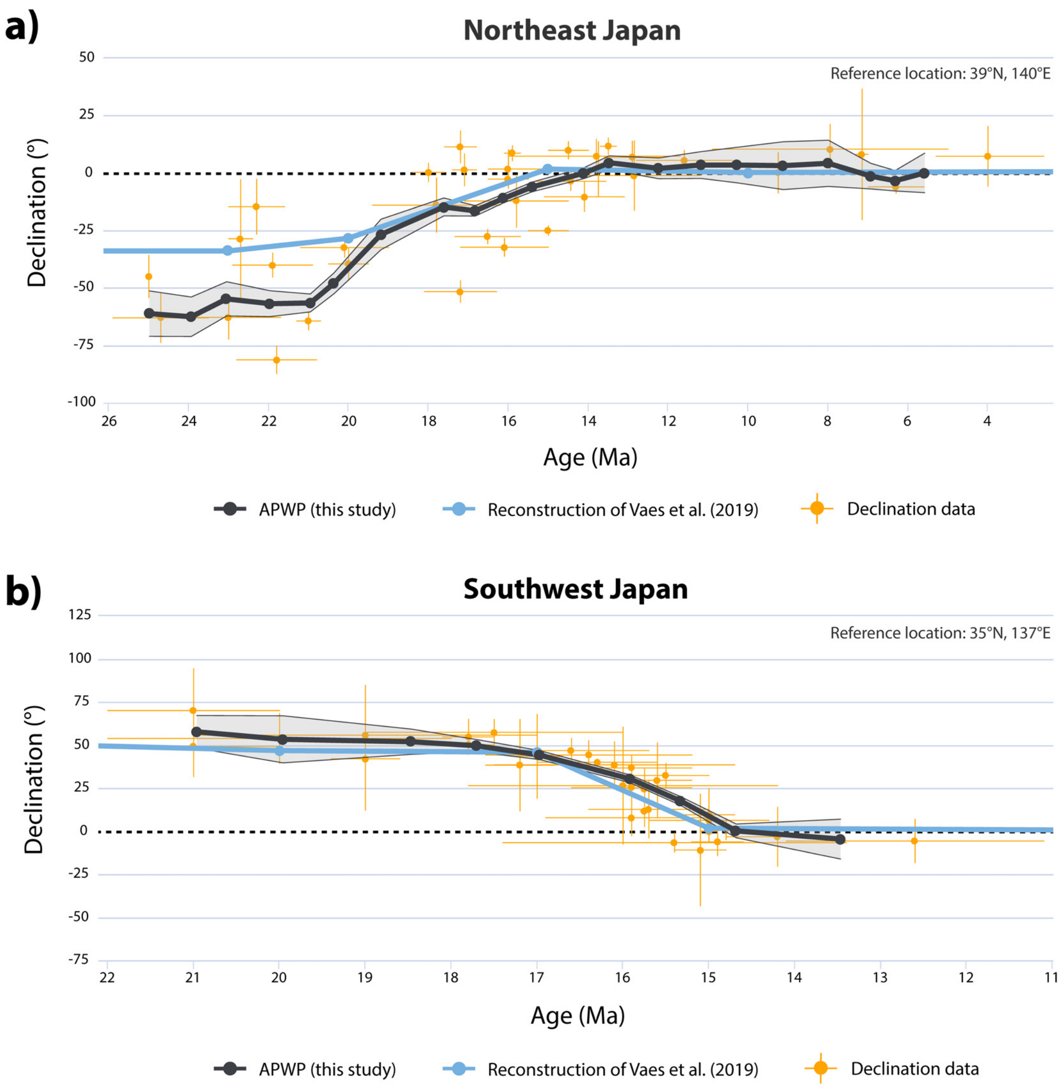

Figure 7 – Comparison of the declination curves predicted for northeast Japan **(a)** and southwest Japan **(b)** for a chosen reference location using the APWPs computed in this study (Figure 5e, f) and using the plate-kinematic reconstruction of *Vaes et al.* (2019). These figures were made using Paleomagnetism.org (*Koymans et al.*, 2016, 2020).

be documented on the About page of the website.

All processing of paleomagnetic data and calculations are performed on the machine of the user. No imported data or results are stored externally on a server or sent over the internet, ensuring the integrity of the data and user. The input data and results are instead stored locally within the local storage of the browser, and thus allow the user to continue using the webtools offline. The APWP-online.org is an open-source web application licensed under the GNU General Public License v3.0.

7 Conclusions

APWP-online.org is an online, open-source application that enables paleomagnetists to compute custom apparent polar wander paths and relative paleomagnetic displacements (RPD) using a statistical approach that was recently developed by *Vaes et al.* (2022, 2023). The application consists of three different portals: the APWP tool, the RPD tool and the Reference database portal. The APWP tool enables researchers to compute an APWP from site-level paleomagnetic from a collection of study-mean poles, using a chosen temporal resolution. The RPD tool allows the identification and quantification of vertical-axis rotations and paleolatitudinal displacements relative to a chosen APWP or pole, in which temporal and spatial uncertainties are propagated, and in which the uncertainty of the reference pole is weighted against the number of paleomagnetic sites used to compute the study-mean paleomagnetic direction or pole. In addition, the RPD tool allows the comparison between an APWP computed with the APWP tool and a reference APWP to determine relative paleomagnetic displacements through time. Finally, the Reference database portal provides an up-to-date version of the global APWP for the last 320 Myr in the coordinate frame of all major plates, as well as the paleomagnetic database and

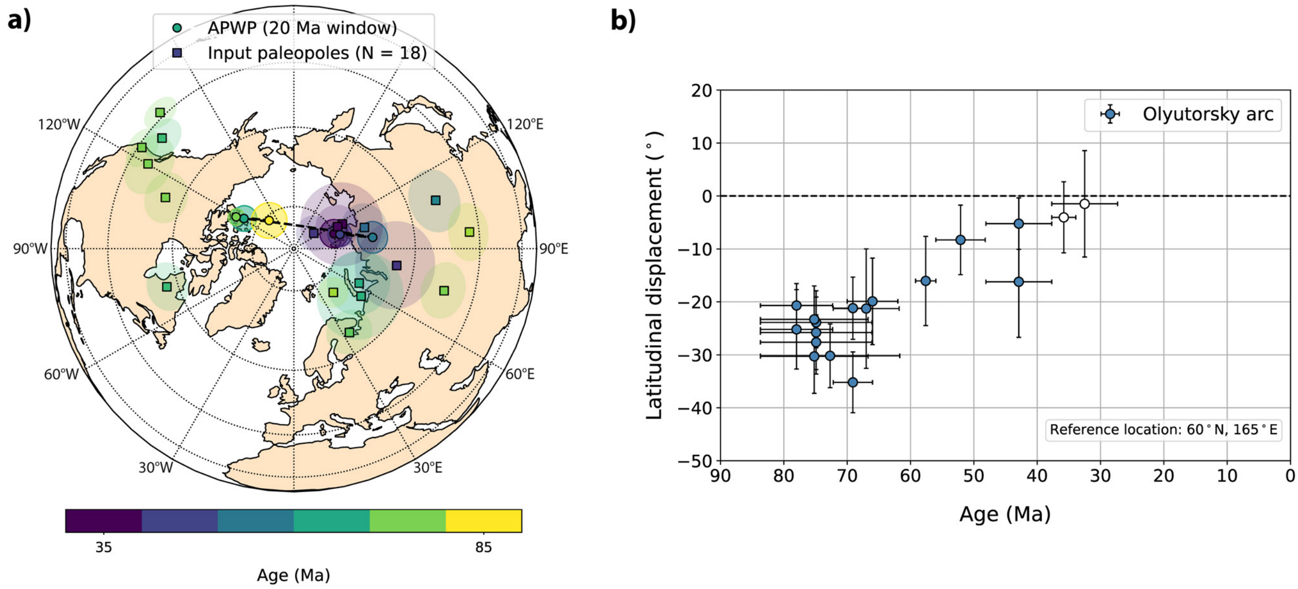

Figure 8 – (a) Custom-made APWP computed for the data compilation of the Olyutorsky arc. **(b)** Plot of the latitudinal displacement relative to the North American plate against age, computed for each study-mean pole included in the data compilation.

plate circuit that underlie its computation. We invite paleomagnetists to submit new, high-quality paleomagnetic data, or recommend modification of the existing database (e.g., the revision of age constraints) through the query form included in this portal, such that the global APWP can be regularly updated in the future. An international steering committee will update the database and the global APWP behind APWP-online.org on an annual basis. We foresee that the accessible and easy-to-use tools of APWP-online.org will enable specialist users to apply state-of-the-art methods for computing apparent polar wander paths and tectonic displacements, which may contribute to solving detailed tectonic or paleogeographic problems.

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Author contributions

BV: conceptualization of study, data compilation and analyses, development of codes, figure drafting and paper writing. **DJJvH**: conceptualization of study, paper writing and reviewing. **JP**: development of web application, development of codes, paper reviewing.

Data availability

No new paleomagnetic data were used in this study. The paleomagnetic datasets used to illustrate the applications of the tools were previously compiled by Vaes et al. (2019). We refer the reader to Vaes et al. (2019) for more details on the paleomagnetic data compilation and for the references to the original sources of the data.

Competing interests

The authors declare no competing interests.

Peer review

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References

Bazhenov, M. L., N. M. Levashova, and J. G. Meert (2016), How well do precambrian paleomagnetic data agree with the phanerozoic apparent polar wander path? a baltica case study, *Precambrian research*, *285*, 80–90, doi: 10.1016/j.precamres.2016.09.008.

Beck, M. E., Jr (1980), Paleomagnetic record of plate-margin tectonic processes along the western edge of north america, *Journal of geophysical research*, *85*(B12), 7115–7131, doi: 10.1029/jb085ib12p07115.

Besse, J., and V. Courtillot (2002), Apparent and true polar wander and the geometry of the geomagnetic field over the last 200 myr, *Journal of geophysical research*, *107*(B11), EPM 6–1–EPM 6–31, doi: 10.1029/2000jb000050.

Butler, R. F. (1992), *Paleomagnetism: magnetic domains to geologic terranes*, vol. 319, Blackwell Scientific Publications.

Coe, R., B. R. Globerman, P. W. Plumley, and G. Thrupp (1985), Paleomagnetic results from alaska and their tectonic implications, *Precambrian research*.

Cox, A., and R. B. Hart (1991), *Plate Tectonics: How It Works*, John Wiley & Sons.

Demarest, H. H., Jr (1983), Error analysis for the determination of tectonic rotation from paleomagnetic data, *Journal of geophysical research*, *88*(B5), 4321–4328, doi: 10.1029/jb088ib05p04321.

Domeier, M., G. E. Shephard, J. Jakob, C. Gaina, P. V. Doubrovine, and T. H. Torsvik (2017), Intraoceanic subduction spanned the pacific in the late Cretaceous-Paleocene, *Science advances*, *3*(11), eaao2303, doi: 10.1126/sciadv.aao2303.

Fisher, R. (1953), Dispersion on a sphere, *Proceedings. Mathematical, physical, and engineering sciences / the Royal Society*, *217*(1130), 295–305, doi: 10.1098/rspa.1953.0064.

Gallo, L., M. Domeier, F. Sapienza, N. Swanson-Hysell, B. Vaes, Y. Zhang, M. Arnould, A. Eyster, D. Gürer, Á. Király, B. Robert, T. Rolf, G. Shephard, and A. van der Boon (2023), Embracing uncertainty to resolve polar wander: A case study of cenozoic north america, *Geophysical research letters*, *50*(11), e2023GL103,436, doi: 10.1029/2023GL103436.

Gerritsen, D., B. Vaes, and D. J. J. Hinsbergen (2022), Influence of data filters on the position and precision of paleomagnetic poles: What is the optimal sampling strategy?, *Geochemistry, Geophysics, Geosystems*, *23*(4), e2021GC010,269, doi: 10.1029/2021gc010269.

Jarboe, N. A., A. A. Koppers, L. Tauxe, R. Minnett, and C. Constable (2012), The online MagIC database: Data archiving, compilation, and visualization for the geomagnetic, paleomagnetic and rock magnetic communities, in *AGU Fall Meeting Abstracts*, vol. 2012, pp. GP31A–1063.

Kent, D. V., and E. Irving (2010), Influence of inclination error in sedimentary rocks on the triassic and jurassic apparent pole wander path for north america and implications for cordilleran tectonics, *Journal of geophysical research*, *115*(B10), doi: 10.1029/2009jb007205.

Konstantinovskaia, E. A. (2001), Arc–continent collision and subduction reversal in the cenozoic evolution of the northwest pacific: an example from kamchatka (NE russia), *Tectonophysics*, *333*, 75–94, doi: 10.1016/S0040-1951(00)00268-7.

Kovalenko, D. (1996), Paleomagnetism and kinematics of the central olyutorsky range, koryak highland, *Geotectonics/Geotektonika*, *30*, 243.

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

Koymans, M., D. Hinsbergen, D. Pastor-Galán, B. Vaes, and C. Langereis (2020), Towards FAIR paleomagnetic data management through Paleomagnetism.Org 2.0, *Geochemistry, Geophysics, Geosystems*, *21*(2), e2019GC008,838, doi: 10.1029/2019GC008838.

Levashova, N. M., M. L. Bazhenov, and M. N. Shapiro (1997), Late cretaceous paleomagnetism of the east ranges island arc complex, kamchatka: Implications for terrane movements and kinematics of the northwest pacific, *Journal of geophysical research*, *102*(B11), 24,843–24,857, doi: 10.1029/97jb00780.

Levashova, N. M., M. N. Shapiro, and M. L. Bazhenov (1998), Late cretaceous paleomagnetic data from the median range of kamchatka, russia: tectonic implications, *Earth and planetary science letters*, *163*(1-4), 235–246, doi: 10.1016/s0012-821x(98)00190-3.

Li, S., E. Advokaat, D. Hinsbergen, M. Koymans, C. Deng, and R. Zhu (2017), Paleomagnetic constraints on the Mesozoic-Cenozoic paleolatitudinal and rotational history of indochina and south china: Review and updated kinematic reconstruction, *Earth-Science Reviews*, *171*, 58–77, doi: 10.1016/J.EARSCIREV.2017.05.007.

Martin, A. K. (2011), Double saloon door tectonics in the japan sea, fossa magna, and the japanese island arc, *Tectonophysics*, *498*(1-4), 45–65, doi: 10.1016/j.tecto.2010.11.016.

McElhinny, M. W., and P. L. McFadden (1999), *Paleomagnetism: Continents and Oceans*, Elsevier.

Montheil, L., M. Philippon, P. Münch, P. Camps, B. Vaes, J.-J. Cornée, T. Poidras, and D. J. J. van Hinsbergen (2023), Paleomagnetic rotations in the northeastern caribbean region reveal major intraplate deformation since the eocene, *Tectonics*, *42*(8), e2022TC007,706, doi: 10.1029/2022tc007706.

Otofuji, Y., T. Matsuda, and S. Nohda (1985), Opening mode of the japan sea inferred from the palaeomagnetism of the japan arc, *Nature*, *317*(6038), 603–604, doi: 10.1038/317603A0.

Pierce, J., Y. Zhang, E. B. Hodgin, and N. L. Swanson-Hysell (2022), Quantifying inclination shallowing and representing flattening uncertainty in sedimentary paleomagnetic poles, *Geochemistry, Geophysics, Geosystems*, *23*(11), e2022GC010,682, doi: 10.1029/2022gc010682.

Pisarevsky, S. A., Z. X. Li, M. G. Tetley, Y. Liu, and J. P. Beardmore (2022), An updated internet-based global paleomagnetic database, *Earth-Science Reviews*, *235*, 104,258, doi: 10.1016/j.earscirev.2022.104258.

Rowley, D. B. (2019), Comparing paleomagnetic study means with apparent wander paths: A case study and paleomagnetic test of the greater india versus greater indian basin hypotheses, *Tectonics*, *38*(2), 722–740, doi: 10.1029/2017tc004802.

Shapiro, M. N., and A. Solov'ev (2009), Formation of the Olyutorsky-Kamchatka foldbelt: a kinematic model, *Russian Geology and Geophysics*, *50*, 668–681, doi: 10.1016/J.RGG.2008.10.006.

Tauxe, L. (2010), *Essentials of Paleomagnetism*, Univ of California Press.

Tauxe, L., and D. Kent (2004), A simplified statistical model for the geomagnetic field and the detection of shallow bias in paleomagnetic inclinations: Was the ancient magnetic field dipolar?, *Geophysical monograph*, *145*, 101–115, doi: 10.1029/145GM08.

Tauxe, L., R. Shaar, L. Jonestrask, N. L. Swanson-Hysell, R. Minnett, A. A. P. Koppers, C. G. Constable, N. Jarboe, K. Gaastra, and L. Fairchild (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, doi: 10.1002/2016gc006307.

Torsvik, T., R. Müller, R. Van der Voo, B. Steinberger, and C. Gaina (2008), Global plate motion frames: Toward a unified model, *Reviews of geophysics*, *46*(3), doi: 10.1029/2007RG000227.

Torsvik, T., R. Van der Voo, U. Preeden, C. Mac Niocaill, B. Steinberger, P. V. Doubrovine, D. V. van Hinsbergen, M. Domeier, C. Gaina, E. Tohver, J. Meert, P. J. A. McCausland, and L. Cocks (2012), Phanerozoic polar wander, palaeogeography and dynamics, *Earth-Science Reviews*, *114*(3–4), 325–368, doi: 10.1016/J.EARSCIREV.2012.06.007.

Vaes, B., D. Hinsbergen, and L. Boschman (2019), Reconstruction of subduction and back-arc spreading in the NW pacific and aleutian basin: Clues to causes of cretaceous and eocene plate reorganizations, *Tectonics*, *38*(4), 1367–1413, doi: 10.1029/2018TC005164.

Vaes, B., S. Li, C. Langereis, and D. V. van Hinsbergen (2021), Reliability of palaeomagnetic poles from sedimentary rocks, *Geophysical Journal International*, *225*(2), 1281–1303, doi: 10.1093/GJI/GGAB016.

Vaes, B., L. C. Gallo, and D. J. J. van Hinsbergen (2022), On pole position: Causes of dispersion of the paleomagnetic poles behind apparent polar wander paths, *Journal of Geophysical Research, [Solid Earth]*, *127*(4), doi: 10.1029/2022jb023953.

Vaes, B., D. V. van Hinsbergen, S. van de Lagemaat, E. van der Wiel, N. Lom, E. Advokaat, L. Boschman, L. Gallo, A. Greve, C. Guilmette, S. Li, P. Lippert, L. Montheil, A. Qayyum, and C. Langereis (2023), A global apparent polar wander path for the last 320 ma calculated from site-level paleomagnetic data, *Earth-science reviews*, p. 104547, doi: 10.1016/j.earscirev.2023.104547.

Veikkolainen, T., L. J. Pesonen, and D. A. D. Evans (2014), PALEOMAGIA: A PHP/MYSQL database of the precambrian paleomagnetic data, *Studia Geophysica et Geodaetica*, *58*(3), 425–441, doi: 10.1007/s11200-013-0382-0.

Veikkolainen, T. H., A. J. Biggin, L. J. Pesonen, D. A. Evans, and N. A. Jarboe (2017), Advancing precambrian palaeomagnetism with the PALEOMAGIA and PINT(QPI) databases, *Scientific data*, *4*(1), 170,068, doi: 10.1038/sdata.2017.68.

Yamaji, A., H. Momose, and M. Torii (1999), Paleomagnetic evidence for miocene transtensional deformations at the eastern margin of the japan sea, *Earth, Planets and Space*, *51*(2), 81–92, doi: 10.1186/bf03352213.