APWP-online.org: a global reference database and open-source tools for calculating apparent polar wander paths and relative paleomagnetic displacements

Bram Vaes[1*], Douwe J.J. van Hinsbergen[1] & Joren Paridaens[2]

[1]Department of Earth Sciences, Utrecht University, Utrecht, The Netherlands

[2]9de online, Utrecht, The Netherlands

* Corresponding author (e-mail: b.vaes@uu.nl)

Abstract

Paleomagnetism provides a quantitative tool for estimating paleogeographic displacements of rock units relative to the Earth's spin axis and is widely used to determine relative tectonic displacements (vertical-axis rotations and paleolatitudinal motions). These relative displacements are commonly determined 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. This conventional approach was recently shown to strongly overestimate the resolution at which paleomagnetic 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 weighed against the number of datapoints underlying the study-mean pole. To enable the application of this approach, a new global APWP was calculated for the last 320 Ma from (simulated) site-level paleomagnetic data. Applying this 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 new 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 exposed on Kamchatka.

Key words: paleomagnetism, apparent polar wander path, paleogeography, paleomagnetic pole**,** reference frame, paleolatitude, plate reconstruction

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1. Introduction

Paleomagnetic data – obtained from measurements of the remanence 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, 1986; Butler, 1992). One of the main tectonic applications of paleomagnetism is the identification and quantification of two types of relative 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). Conventional APWPs, computed by averaging a collection of study-mean paleopoles whose mean age fall into a fixed time window, provide reference poles with an A_{95} cone of confidence that allow a straightforward comparison with a study-mean pole and its A_{95}, computed instead by averaging a collection 'spot readings' of the past geomagnetic field. Statistical differences between a study-mean pole and a reference pole (from an APWP) are routinely interpreted as evidence for relative tectonic motions. However, Rowley (2019) recently showed that 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 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 than study-mean poles: the reference direction or pole is computed from site-means, whereas the study-level direction or pole is instead computed from a collection of spot readings (i.e., paleomagnetic sites). These authors 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 site-level datapoints in 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 synthetic 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 (combining all paleomagnetic data from stable plate interiors whose relative motions are well-constrained, e.g., by ocean basin reconstructions (Besse & Courtillot, 2002; Torsvik et al., 2008, 2012) calculated from

Fig. 1. Overview of the homepage of APWP-online.org.

parametrically re-sampled site-level data. This provides a new reference frame that allows the determination of paleomagnetic displacements by comparing paleomagnetic data on the same hierarchical level. However, this new approach requires a bootstrapped approach to determine the reference pole and its uncertainty, which is computationally more complex than the conventional approach.

Here, we present the online and open-source environment *APWP-online.org* that provides a set of tools to compute relative paleomagnetic displacements and custom APWPs using the approaches presented by Vaes et al. (2022, 2023). This web application also includes a portal providing access to the curated paleomagnetic database that was used to compute the global APWP of Vaes et al. (2023), together with an interface where paleomagnetists can request the addition of new high-quality paleomagnetic data, or revision of age constraints, that may be used for future updates of the global APWP. We illustrate how these two portals may contribute to solving tectonic problems by applying them to two case-studies: the timing and magnitude of the Neogene rotations of the Japanese islands and the paleolatitudinal evolution of the Late Cretaceous-Paleogene intra-oceanic Olyutorsky arc (Kamchatka).

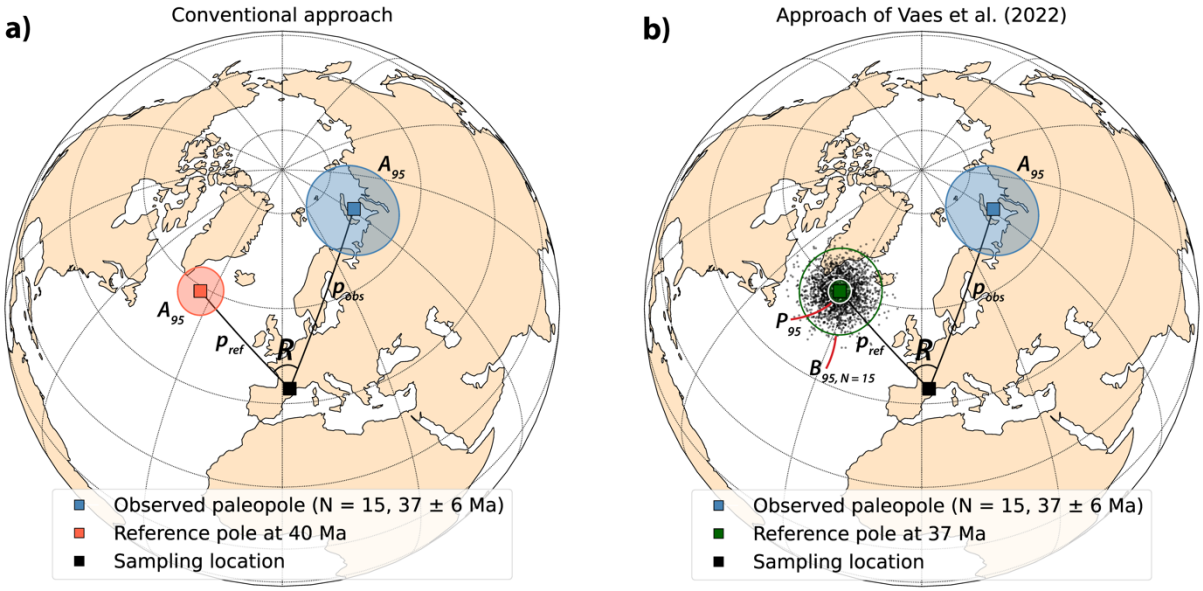

Fig. 2. Comparison between the conventional approach and the recently developed approach by Vaes et al. (2022) for the determination of relative tectonic displacements.

2. Tools

2.1. APWP tool

The APWP tool allows users to compute an APWP based on site-level paleomagnetic data using the approach of Vaes et al. (2023). The APWP is calculated from virtual geomagnetic poles (VGPs) that are parametrically re-sampled from a custom-provided collection of paleopoles, rather than from those paleopoles itself. To compute the APWP, the user first needs to specific the age range for the APWP, size of the time window and the time step at which the reference poles of the APWP are computed (Fig. 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, as long as the input data are provided in the coordinate system of the same plate or terrane. The website includes a tool to rotate paleopoles into the coordinates of a different plate based on user-provided relative Euler rotation poles (Fig. 3). 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 Fig. 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 slow down the computation time.

For each iteration of the APWP computation, the re-sampled VGPs are assigned a random age within the age uncertainty range of the 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 *pseudo*-VGPs that fall within the time window centered on that age. The final APWP is computed as the average 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).

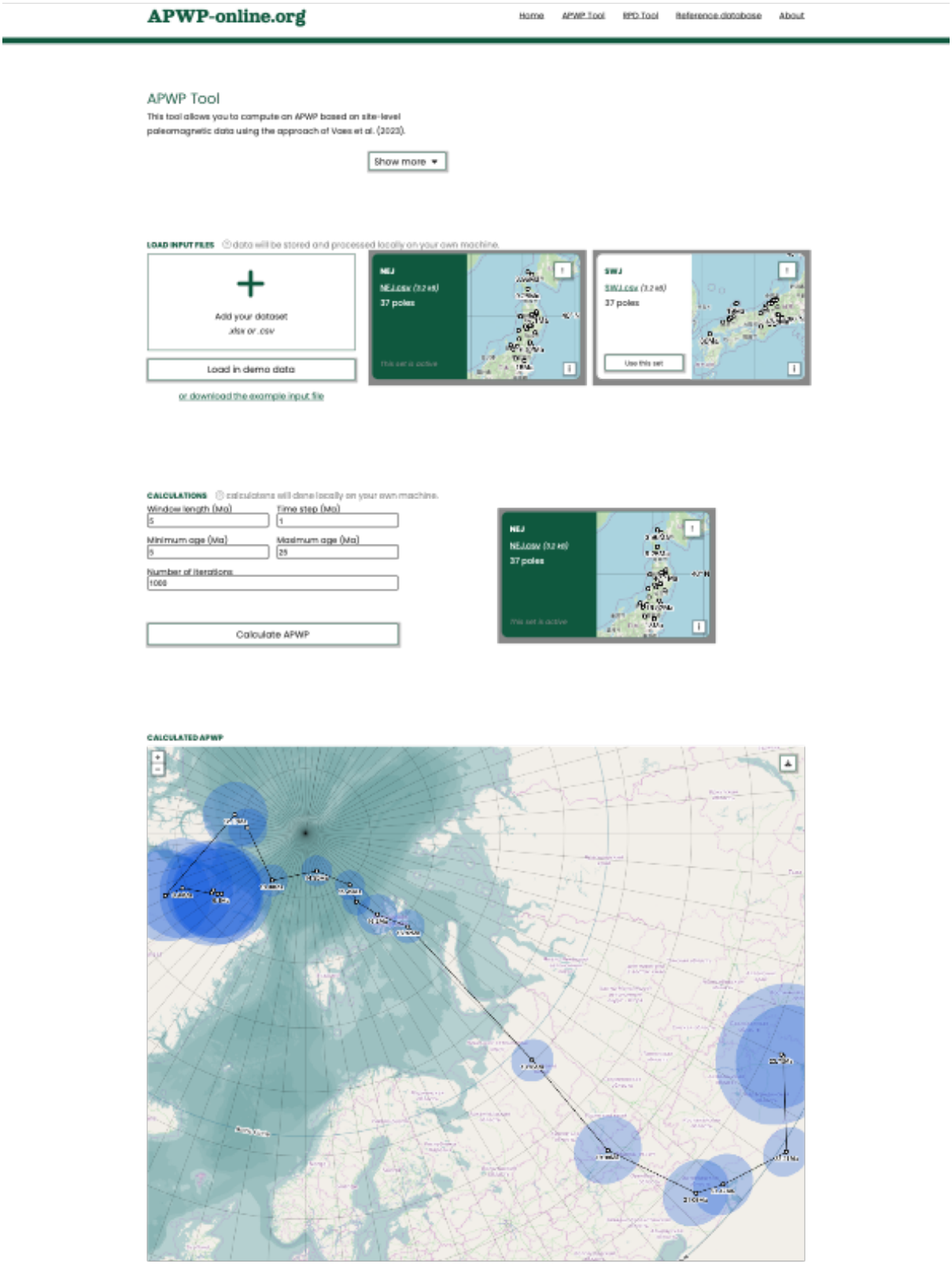

Fig. 3. Overview of the APWP tool.

The tool also facilitates the straightforward reproduction of the global APWP of Vaes et al. (2023) and can be directly applied to the reference database that is available under the Reference

database portal (see section 5). Moreover, it allows users to compute custom APWPs from a filtered set of paleopoles included in that database. For instance, one may calculate an APWP solely based on the data derived from a chosen plate, e.g., South America, using a different window size and time step as used by Vaes et al. (2023). Researchers may also apply this tool to evaluate the effect of a new paleomagnetic dataset on the global APWP.

2.2. Relative Paleomagnetic Displacement (RPD) tool

The second tool of APWP-online.org (Fig. 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 an observed paleopole and a reference pole in which the number of paleomagnetic sites used to compute the paleopole 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 observed paleopole (N_s) (see Fig. 2). To determine the reference and the B_{95} we use the parametric bootstrap 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 paleopoles included in the reference database, whose age uncertainty range overlaps with that of the studied dataset. For each paleopole, VGPs are re-sampled from a Fisher (1953) distribution centered on the paleopole 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 pole. Next, a pseudopole is computed by averaging N_s randomly drawn VGPs whose age falls within the age uncertainty range 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 Fig. 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 (Fig. 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 (Fig. 4). To determine the displacements of a collection of paleopoles 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 paleopole, a default age range of 10 Ma around the mean age of the pole is used. This age range can be modified by the user (Fig. 4), e.g., to exactly match the age range of the observed

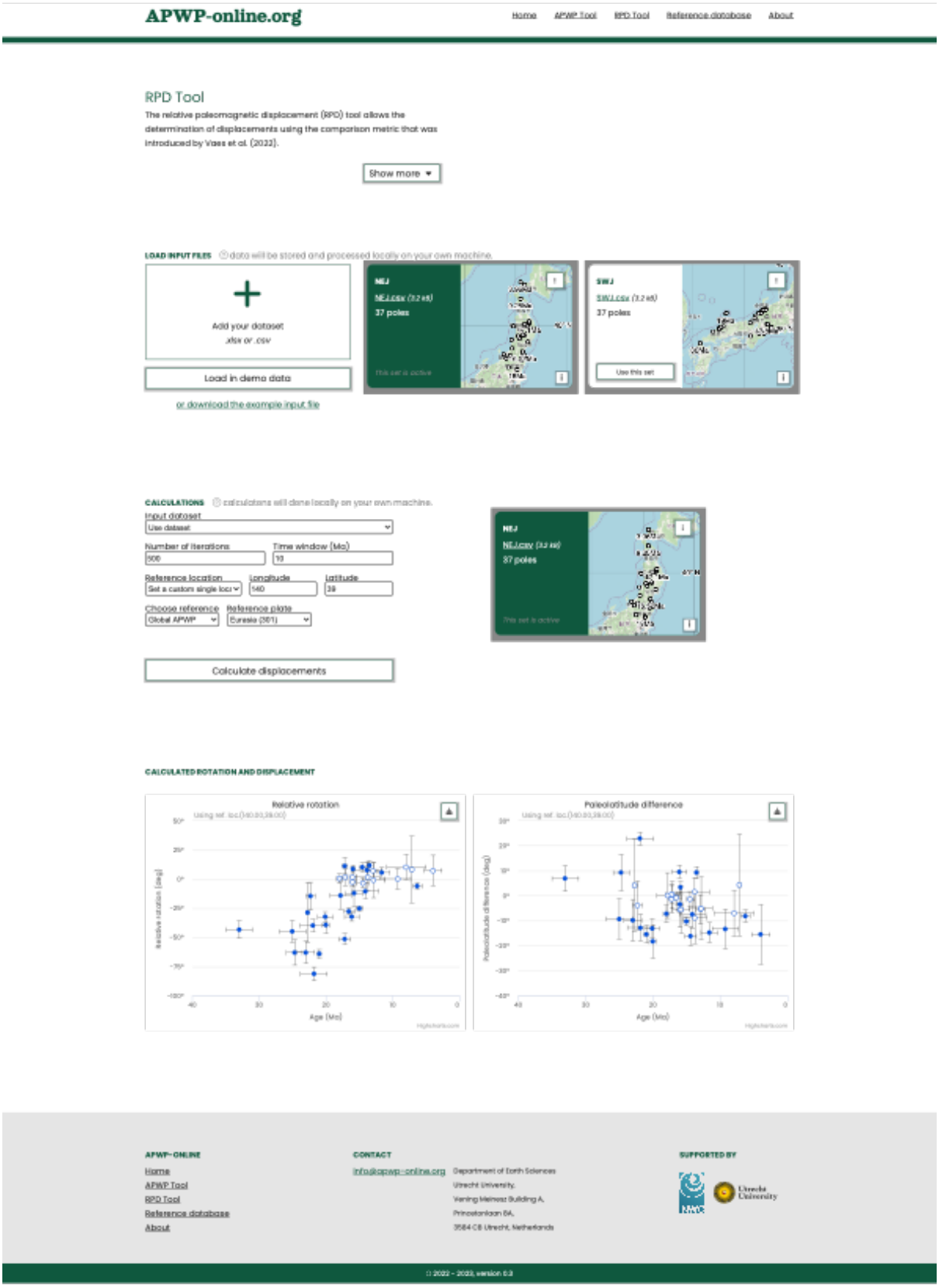

Fig. 4. Overview of the relative paleomagnetic displacement (RPD) tool.

paleopole. With age uncertainties of a few to ten million years, 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 the right uploaded file under 'Choose reference' (Fig. 4). It is important to note that the reference data should be provided using the template input file (see section 2.3), hence consisting of a collection of paleopoles whereby relevant parameters such as age, age uncertainty range, number of sites and the Fisher (1953) precision parameter K are provided. 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 observed paleopole then simply corresponds to the absolute paleomagnetic declination at the chosen reference location based on that paleopole (Figs. 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, the uncertainty of these results is determined by the A_{95} of the observed pole.

We quantify the relative paleomagnetic displacements as relative rotation (R) and latitudinal displacement (L) based on the difference in pole position between an observed paleopole and reference pole, calculated using a spherical triangle (Fig. 2). The rotation R (following the nomenclature of, for instance, Beck (1980) and Demarest (1983)) and is quantified by the angle between the great-circle segments that connect the sampling location with both paleopoles, 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 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 observed 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 observed 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 (Fig. 7), 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), whereby the 95% confidence region on the reference pole ($A_{95, ref}$) is replaced by the B_{95}.

196 **2.3. Input and output**

197 The input for the APWP and RPD tools should be provided through the template file that can be
198 downloaded from the website ('Download the example input file'). This comma-separated values
199 (CSV) file consists of a header with column names under which the relevant data and metadata should
200 be added. Each entry that is included in the input file should contain the following parameters: the age
201 and age uncertainty range of the sampled rocks, the longitude and latitude of the mean sampling
202 location, the longitude and latitude of the paleopole, the number of paleomagnetic sites (N, i.e., the
203 number of spot readings of the paleomagnetic field), the Fisher (1953) precision parameter (K) and
204 the 95% cone of confidence about the pole (A_{95}). For the global APWP of Vaes et al. (2023), we only
205 used sediment-derived paleopoles that were corrected for inclination shallowing using the
206 elongation-inclination (E/I) correction of Tauxe and Kent (2004) and that satisfied the criteria
207 proposed by Vaes et al. (2021). This avoided the variable bias posed by potential inclination
208 shallowing and allows propagating the uncertainty associated with the E/I correction in the
209 calculation of the APWP (following the approach of Pierce et al. (2022); see section 3 in Vaes et al.
210 (2023) for more details). The input file thus includes an optional column for the uncertainty of the E/I
211 correction. This source of uncertainty can be accounted for in the computation of a custom APWP by
212 adding the mean difference between the shallowing-corrected paleolatitude estimate and the
213 associated 95% confidence limits.

214 The output of the APWP tool consists of a plot of the APWP on a northern hemisphere map
215 projection. The age and relevant parameters of each reference pole of the APWP is easily inspected by
216 hoovering the mouse over the path. The custom APWP may be visually compared to the global APWP
217 of Vaes et al. (2023) – in the reference frame of a chosen plate – by adding a reference APWP to the
218 map using the 'Add reference APWP' button. The output APWP may be directly downloaded from the
219 web interface as a CSV file that contains the longitude and latitude values of the APWP, the center age
220 of the window, the mean age and number of the re-sampled VGPs for each time window, as well as the
221 P_{95} values and all other relevant statistical parameters. The custom APWP may be used directly in the
222 RPD portal to determine the relative paleomagnetic displacements between the studied tectonic plate
223 or terrane and a chosen reference plate (see examples in section 4).

224 For the computation of the RPDs in the RPD tool, the user may specify a few input parameters,
225 similar to the APWP tool. The number of iterations and time window (default is 10 Ma) used to
226 compute the reference pole position and its uncertainty (the B95) can be provided as direct input on-
227 screen. Instead of using the sampling location of each entry in the input file, a reference location may
228 instead be chosen by the user to compute the RPDs (Fig. 4). Note that specifying a reference location
229 is required when using a custom APWP as input for this tool. As described in the previous section, the
230 user may choose the reference against which the uploaded input data are compared. The output of the
231 RPD tool consists of two figures on the web interface that show the relative vertical-axis rotations and
232 paleolatitudinal displacement computed for each input paleopole, which can be downloaded as raster

(PNG) or vector (SVG) image. As for the APWP tool, the output results may also be downloaded as a CSV file.

3. Reference database portal

The final portal of APWP-Online.org hosts the reference database that underpins the global APWP for the last 320 Ma from Vaes et al. (2023). Through this web interface (Fig. 8), the most recent version of the global APWP – in the coordinate frame of all major tectonic plates - may 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. 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 Fig. 8), 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). Moreover, the database will be coupled to the MagIC database (Jarboe et al., 2012).

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 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 (see e.g., Paleomagnetism.org (Koymans et al., 2016; 2020). 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 paleopoles 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 certain paleomagnetic datasets.

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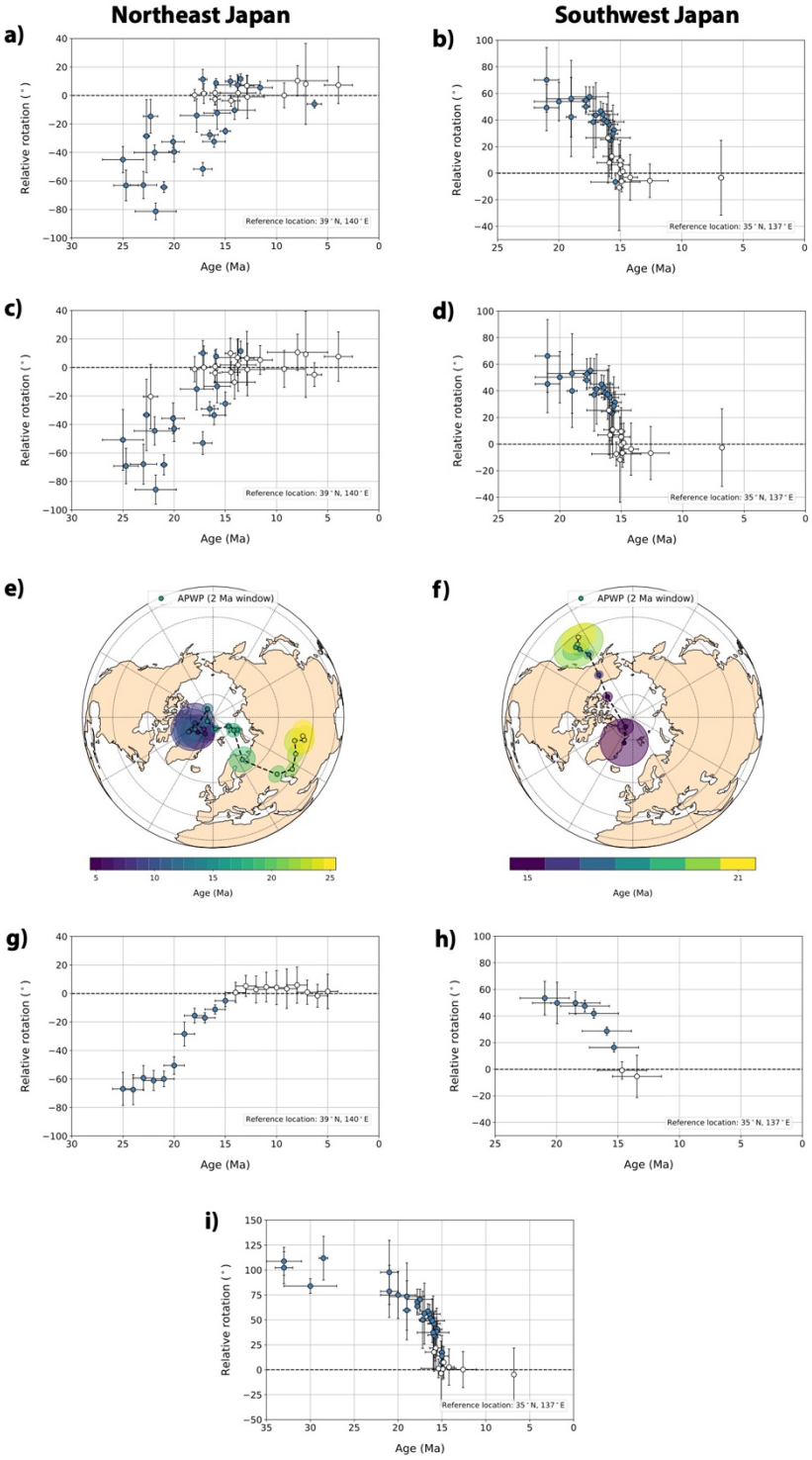

Fig. 5. Application of the APWP and RPD tools to the northeast and southwest Japan blocks. Vertical-axis rotations of each dataset relative to the geographic pole are shown in (a) and (b). A positive value indicates a clockwise rotation since that time. Rotations relative to Eurasia – using the global 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 Ma and a temporal resolution of 1 Ma, 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).

4. 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 (Figs. 5-7). 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, and 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 Ma 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 procedures). Rather than comparing such predictions against observed data, we show here how 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 opposite 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) (Fig. 5a, 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 (Fig. 5c, d). The difference between Figs. 5a-b and 5c-d are minor as Eurasia did not rotate much relative to the north pole in the last 25 Ma, but the confidence regions are slightly larger in Fig. 5c-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 Figs. 5a-d. The high data density allows the computation of the APWP using a time step of only 1 Ma and a sliding window of 2 Ma. This is a much higher temporal resolution than typically used in the construction of (global) APWPs, which often have a resolution of 10 Ma (e.g., Besse & 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

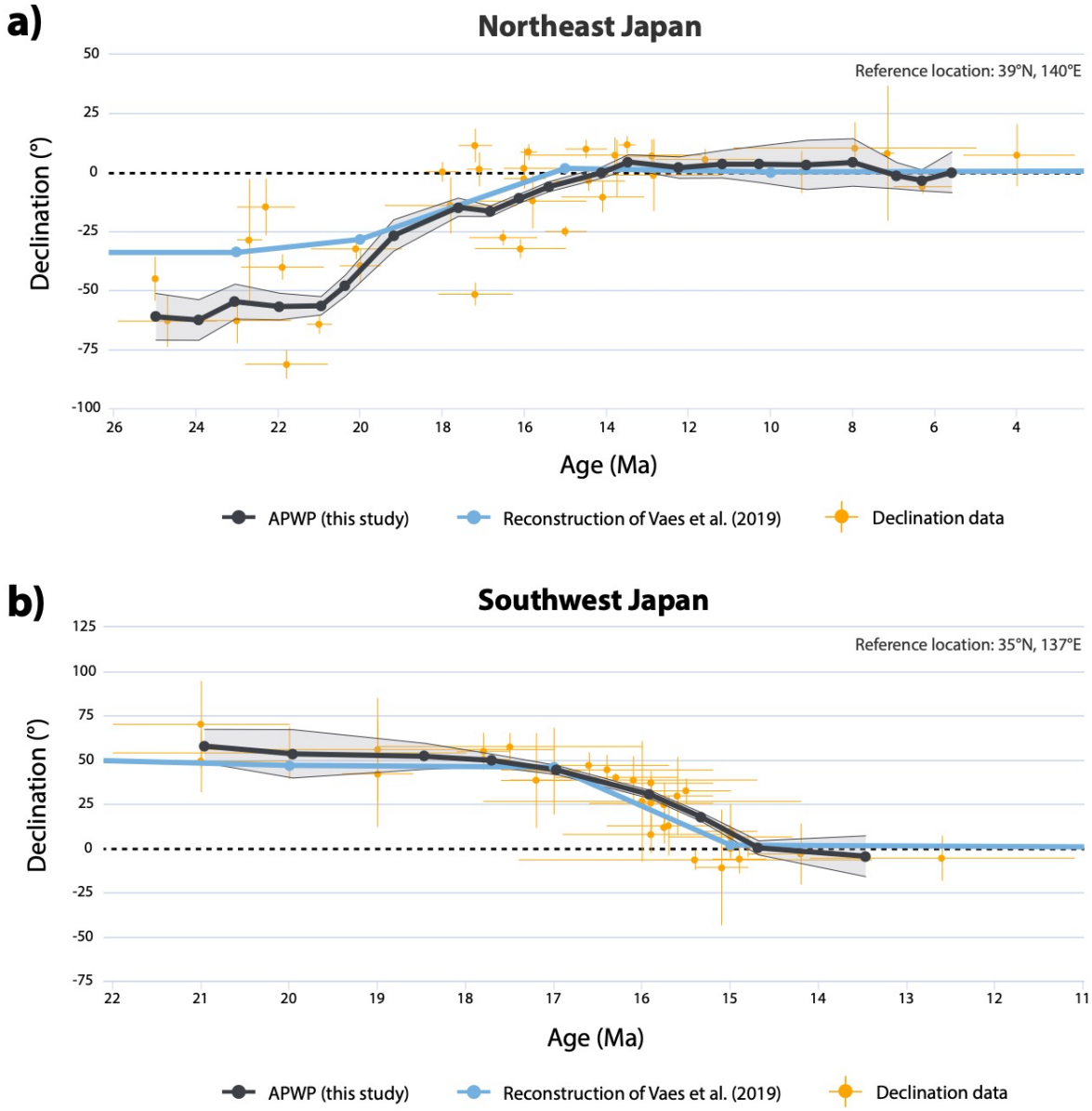

Fig. 6. Comparison of the declination curves predicted for northeast Japan (a) and southwest Japan (b) for a chosen reference location using the APWPs computed in this study (Figs. 5e, f) and using the plate-kinematic reconstruction of Vaes et al. (2019).

the paleomagnetic pole position after ~14 Ma (Fig. 5e). Likewise, southwest Japan reveals a rapid phase of polar wander between ~21-13 Ma, but data density before and after is insufficient for a meaningful APWP calculation (Fig. 5f). We assess whether these polar wander phases indeed correspond to a relative rotation by using the custom APWPs as input in the RPD tool and compute the vertical-axis rotation through time relative to Eurasia, which tightly constrains the timing and amount of the vertical-axis rotation phases (Fig. 5g, h). For illustration, we also compared the compilation of study-mean paleopoles from southwest Japan to the database of northeast Japan, by adding the latter as a 'custom reference database' in the RPD tool (Fig. 5i). The results reveal a relative rotation of ~100° during the opening of the Sea of Japan until ~15 Ma. Finally, we uploaded the new

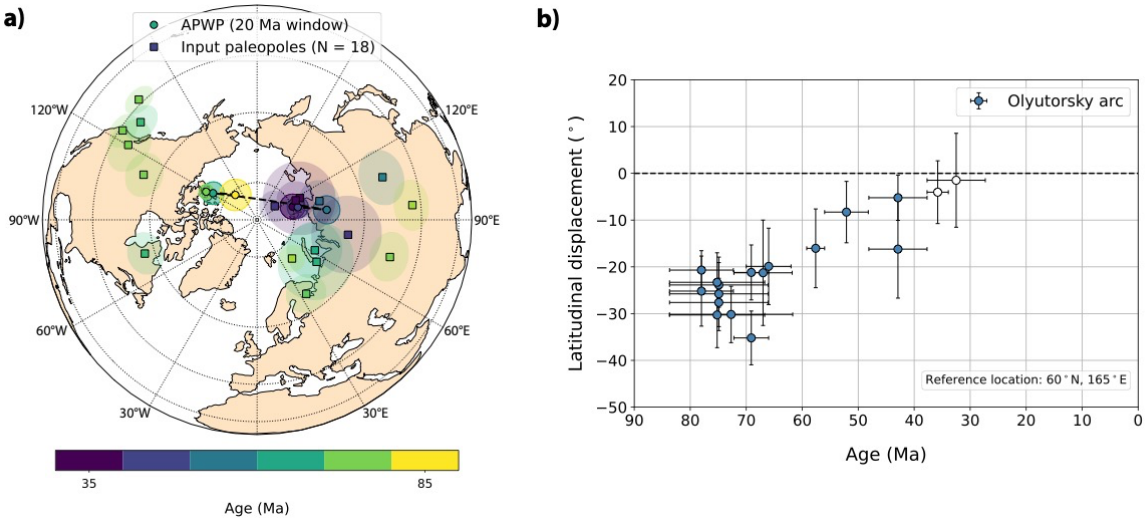

Fig. 7. Custom APWP computed for the data compilation of the Olyutorsky arc (a). Latitudinal displacement against age, relative to the North American plate.

APWPs for northeast and southwest Japan in the Geography Portal of Paleomagnetism.org 2.0 (Koymans et al., 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) (Fig. 6). 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 (Fig. 7). 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, Konstantinovskaya, 2001; Shapiro and Soloviev, 2009; Domeier et el., 2017; Vaes et al., 2019). In Fig. 7a, we show the relative paleolatitudinal displacement relative to the stable North American plate (of which the Kamchatka peninsula is currently part). In this case, computing an APWP for Olyutorsky is not meaningful, because sediment-derived datasets that have not been corrected for inclination shallowing and datasets have been strongly rotated relative to each other (see strongly scattered poles in Fig. 7b). 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 (Fig. 7a), 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 was used by Vaes et al. (2019).

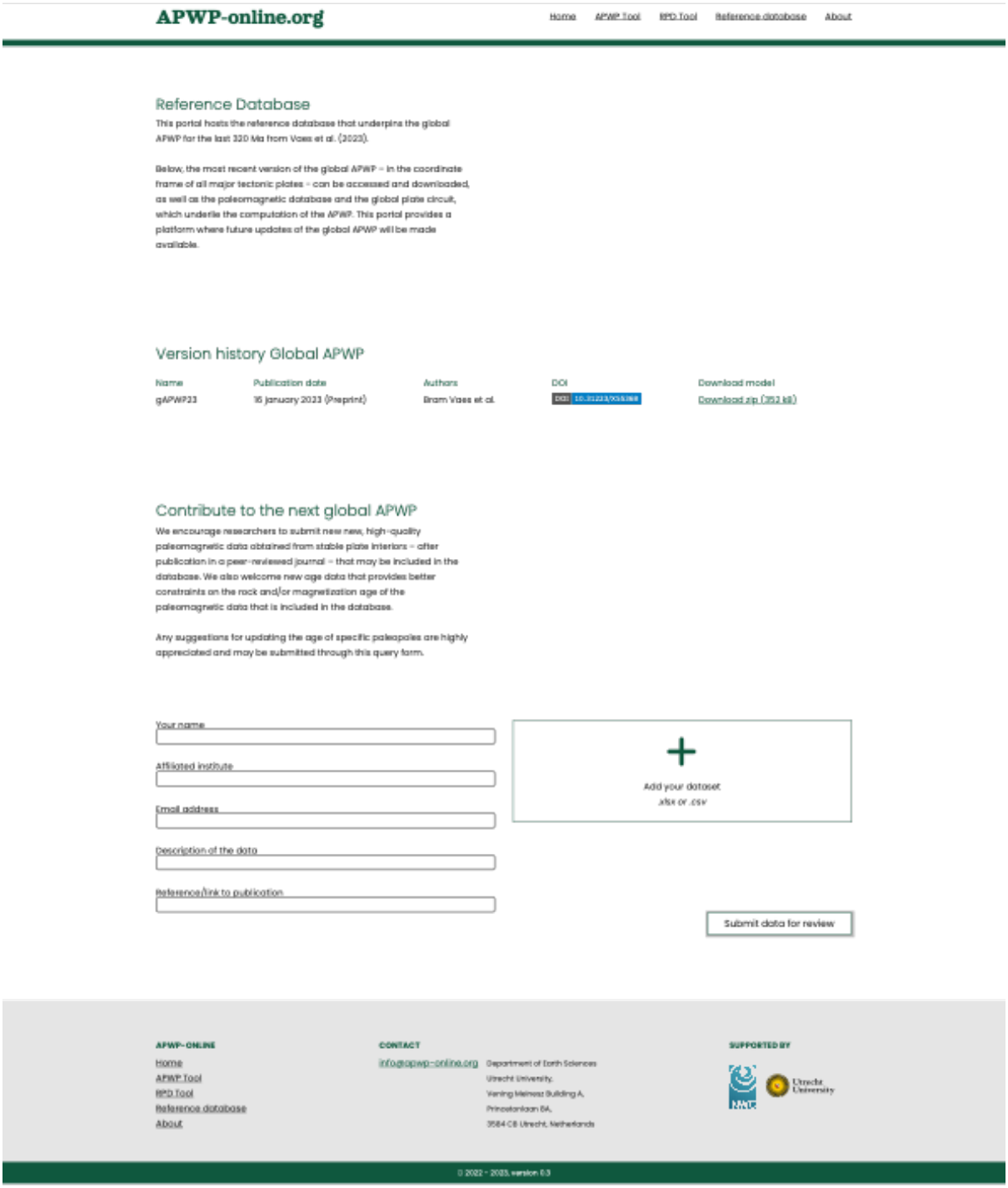

Fig. 8. Overview of the 'Reference database' portal.

5. Availability, data storage and license

The APWP-online.org application (https://apwp-online.org) 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 will be made publicly available on Github and archived on Zenodo upon acceptance of the manuscript.

All processing of paleomagnetic data and calculations are performed locally 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 local storage may also be downloaded by pressing the 'Download session' button, enabling users to continue working with the input data and results at any later moment by re-uploading this file. In addition, the local storage file may be shared among colleagues or added as a supplementary file to a paper to facilitate evaluation and reproducibility of the analyses by peers. APWP-online.org is an open-source web application licensed under the GNU General Public License v3.0.

6. 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 portal, the RPD portal and the Reference Database portal. The APWP portal enables researchers to compute a custom APWP from site-level paleomagnetic from a collection of paleopoles, using a chosen temporal resolution. The resulting APWP can then be compared to a reference APWP using the RPD tool to determine the relative paleomagnetic displacements through time. The RPD tools allow 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 studied paleomagnetic direction or paleopole. Finally, the Global Database portal provides an up-to-date version of the global APWP for the last 320 Ma in the coordinate frame of all major plates, as well as the paleomagnetic database and 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) and the original sources are cited in the text of the current paper. We refer the reader to Vaes et al. (2019) for more details.

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