Paleointensity.org: An Online, Open Source, Application for the Interpretation of Paleointensity Data

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Abstract Paleointensity.org is an online, open source, application to analyze paleointensity data produced by the most common paleointensity techniques. Our application currently supports four different methods: thermal Thellier (all variations), microwave Thellier, pseudo-Thellier, and the multispecimen protocol. Data can be imported using a variety of input file formats such as ThellierTool files, the generic PmagPy file format, and a number of lab-specific formats. The data for the individual paleointensity methods are visualized by the relevant graphs and parameters, which are updated dynamically while interpreting the data. Beyond manual interpretation, Paleointensity.org features an autointerpreter for specimen level Thellier-type data. Interpretations and data can be exported to csv and MagIC files. Moreover, it is possible to export the local storage containing all data, saved interpretations, and settings. This file can be shared among researchers or attached to a paper as supporting information. Because of its many features and ease of use, Paleointensity.org is a major step forward in enhancing an open paleomagnetic community in which data can be shared, checked, and reused in line with the findable, accessible, interoperable, and reusable data principles.

Plain Language Summary Obtaining reliable estimates of the past strength of Earth's magnetic field is very challenging. Over the past decades, different techniques were developed to obtain information on the paleointensity of Earth's magnetic field. Here we present a new online, open source application to ease and standardize the interpretation of the most commonly used paleointensity techniques. Paleointensity.org supports the import and export of multiple file formats, including the format used by the global paleomagnetic database MagIC. This promotes and supports the findable, accessible, interoperable, and reusable use of data by the paleointensity community worldwide.

1. Introduction

Obtaining reliable information on the past strength of Earth's magnetic field, or paleointensity, is notoriously difficult (e.g., review by Tauxe & Yamazaki, 2015). Rocks and archeological materials acquire a magnetization that is proportional to Earth's magnetic field when they cool. Most, if not all, paleointensity techniques often struggle to produce a reliable paleointensity estimate, especially for complex igneous samples. Over the past decades, different paleointensity techniques were proposed, together with sets of selection criteria that the interpretation should fulfill to be a reliable estimate of the paleofield's intensity. The common denominator for all paleointensity methods is that the natural remanent magnetization (NRM) is compared to laboratory-induced magnetizations. These laboratory magnetizations are imparted with known magnetic fields to assess the strength of the paleofield that imparted the NRM. The laboratory magnetizations are often imparted thermally, resulting in (partial) thermal remanent magnetizations ((p)TRMs), but sometimes microwave excitation is used, or strong asymmetric alternating magnetic fields, the latter resulting in anhysteretic remanent magnetizations (ARMs) in the specimen.

The most widely used paleointensity methods today are Thellier-style experiments. Originally proposed by Koenigsberger (1936) and adopted by Thellier and Thellier (1959), the Thellier-style protocols have seen a long evolution and there are various Thellier-style protocols. Apart from Thellier and Thellier's original double heating experiment, these protocols differ in the order in which in-field and zero-field steps are applied. The most commonly used Thellier protocol today is arguably the "IZZI" protocol (Tauxe & Staudigel, 2004; Yu et al., 2004), in which the order of the in-field (I) and zero-field (Z) steps are alternated. To discriminate

between good and bad (or reliable and unreliable) data, a multitude of selection criteria have been proposed. These selection criteria are outlined in detail in the Standard Paleointensity Definitions compiled by Paterson et al. (2014).

The modern multispecimen paleointensity protocol was proposed by Dekkers and Böhnel (2006) and later refined by Fabian and Leonhardt (2010). The thermal Thellier-style protocol relies on imparting magnetizations at stepwise increasingly higher temperatures, while applying the same laboratory field to the specimen. Conversely, the multispecimen protocol heats several specimens to the same temperature in different applied fields. Although this is a different approach in obtaining paleointensities from lavas, the success rate of the multispecimen technique is often similar to the success rate of Thellier-style techniques. More recently, the pseudo-Thellier technique was applied to obtain absolute estimates of the past strength of the paleofield. Originally, the pseudo-Thellier technique, a Thellier-style protocol using asymmetrical alternating fields to impart and remove magnetizations, was designed to obtain relative paleointensities from sediments (Tauxe et al., 1995). Several attempts to calibrate pseudo-Thellier results into absolute paleointensities have seen mixed successes over the past years (e.g., de Groot et al., 2013; Lerner et al., 2017; Paterson et al., 2016).

There is also a trend toward applying different paleointensity methods to the same set of samples in a single study (e.g., de Groot et al., 2013, 2015, 2016; Ertepinar et al., 2016; Greve et al., 2017; Hawkins et al., 2019; Hervé et al., 2017; Monster et al., 2015a, 2018). Such a "multimethod approach" dramatically increases the amount of reliable paleointensities produced for a set of sampled cooling units or sites (de Groot et al., 2013) and has been assigned its own paleointensity quality criterion (Biggin & Paterson, 2014).

Currently available software to analyze paleointensity data mostly focuses on thermal Thellier experiments (e.g., ThellierTool by Leonhardt et al. (2004) and the Thellier GUI by Shaar and Tauxe (2013)). For the interpretation of multispecimen data, MSP-Tool was developed by Monster et al. (2015b). The global storage of paleointensity data is facilitated by the Magnetics Information Consortium (MagIC) (https://earthref.org/MagIC) that provides a database for published data sets and strives to enable the FAIR (findable, accessible, interoperable, and reusable) use of paleomagnetic data (Wilkinson et al., 2016). Only the Thellier GUI is compatible with the MagIC format and allows easy uploading of data in this global database. Microwave Thellier data can be interpreted using the Thellier GUI through PmagPy (Tauxe et al., 2016). Besides the aforementioned software packages, there are many lab-specific programs, which can often make it difficult to share data between labs and assess data during peer review. These practices are incompatible with the principles of the FAIR use of data.

Here we present Paleointensity.org: an online, open source, application to ease and standardize the interpretation of the most commonly used paleointensity techniques. Our application currently supports four different paleointensity methods: thermal Thellier (all variations), microwave Thellier, pseudo-Thellier, and the multispecimen protocol. Paleointensity.org can import and export MagIC-files. Moreover, the entire state of the application, including the uploaded data, settings used, and interpretations, can be exported and shared with colleagues or appended to a publication. Paleointensity.org is therefore a major step forward in enhancing an open paleomagnetic community in which data can be shared, checked, and reused—in line with the FAIR data policy that is demanded by an increasing number of funding bodies and publishers.

Importantly, Paleointensity.org is a web-based application, but all data are kept locally, in the web browser's local storage, and the calculations are done on the client side. The data that are processed in Paleointensity. org are only ever stored on the user's computer.

The application is organized as four pages: *home*, *analyses*, *about*, and *contact* (Figure 1). On the *home* page the user is introduced to the website and, with one click, can import demo data allowing them to easily acquaint themselves with the application. Reference information on the application, its source code, and possible input formats can be found on the *about* page. The *contact* page is self-explanatory. The bulk of Paleointensity.org's functionality is accessed through the *analyses* page, and the contents of this are described in the remainder of this paper.

2. Interpreting Paleointensity Data

Paleointensity data are imported, managed, interpreted, and exported on the *analyses* page; each of the supported paleointensity methods has its own tab (Figure 1) for import and processing. Interpretations that are
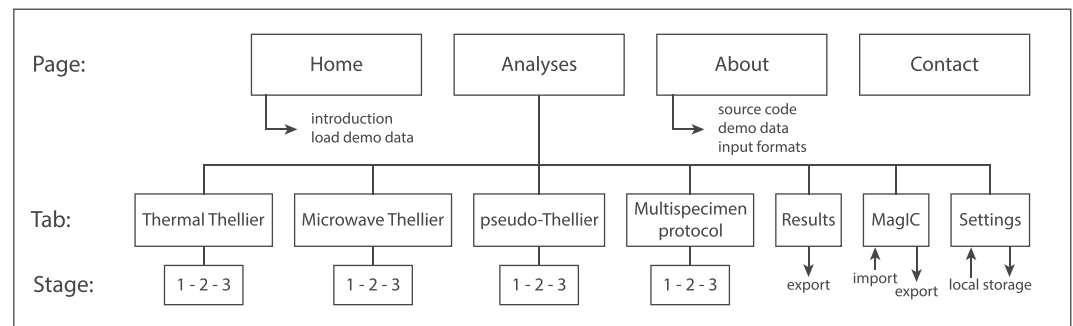
Figure 1. Structure of the website. There are four pages; the analyses page is subdivided in seven tabs. The paleointensity tabs are subdivided in three stages, import (1), manage (2), and interpretation (3).

saved during analyses can be found on the *results* tab. The import and generation of MagIC files has its own *MagIC* tab. Settings that are necessary during the analyses of paleointensity data, such as thresholds for Thellier selection criteria and parameters for the interpretation of multispecimen experiments, can be changed on the *settings* tab.

The tabs of the four paleointensity methods, thermal Thellier, microwave Thellier, pseudo-Thellier, and the multispecimen protocol, are subdivided in three stages: *import* (1), *manage* (2), and *interpretation* (3). Paleointensity.org supports different import file formats such as ThellierTool's tdt files (Leonhardt et al., 2004), the generic format used by the PmagPy suite (Shaar & Tauxe, 2013), the MagIC file format, and laboratory specific files (e.g., Utrecht University and University of Liverpool specific formats). The supported file formats are stipulated in section 3. After importing your files, details on sites, specimens, and measurements can be viewed and manipulated in the *manage* stage. The *interpretation* stage allows visualization and user interaction with the data sets at the specimen level.

2.1. Thermal Thellier

2.1.1. Import Stage

Measurement data files can be imported by drag-and-drop or by clicking within the import field. Since several import files are supported, the format of the imported files needs to be selected using the dialog box. The import module supports importing multiple files at once (e.g., multiple tdt files that contain information for only one specimen each can be imported in one go by dropping multiple tdt files on the import box simultaneously). Additional information that is necessary for the interpretation of the data but is missing in the imported files (e.g., the strength and direction of applied laboratory field) must be specified in the dialog box. Before the file(s) can be imported, the unit of the magnetization or moment must be specified. If the import is successful, a summary with an overview of the imported measurements is shown. See section 3 for details on the supported file formats.

Paleointensity.org supports all common Thellier protocols such as the original (double heating) Thellier protocol (Thellier & Thellier, 1959) or one of its modifications (e.g., Coe (Coe, 1967), Aitken (Aitken et al., 1988) or 'IZZI' (Tauxe & Staudigel, 2004)). The application determines the type of the experiment based on the order of the measurement steps found in the data file. Also, anisotropy measurements are recognized and properly considered if found in the data file during import; see section 2.1.4 for more information.

2.1.2. Manage Stage

After importing data, the table in the *manage* stage is populated (Figure 2). From left to right, the imported sites, samples, specimens, measurement steps, and actual data are shown. Sites and specimens can be removed from Paleointensity.org by clicking the trashcan icon in the appropriate column. The measurement steps for the selected specimen are displayed by the temperature and the type of step (e.g., zero field, in field, and pTRM check), in the order in which they were found in the import file. Single steps can be flagged as bad measurements (e.g., those affected by user error) and can be disregarded based on lab notes taken during the experiment. The flagged measurements and all corresponding measurements (e.g., the corresponding in-field or zero-field step) will not be considered and shown in the *interpretation* stage but are kept in

Figure 2. The manage stage of a thermal Thellier experiment shows an overview of the different sites, samples, specimens, measurements, and measurement details. Sites and specimens can be removed from by clicking the trashcan icon, and single steps can be flagged as bad measurements; in the example above the 150 steps are flagged as a bad measurement.

Paleointensity.org's buffer and are included in the export files for MagIC. Detailed information on step level (e.g., the declination, inclination, applied lab field, and time stamps) are specified in the rightmost column.

2.1.3. Interpretation Stage

The *interpretation* stage for thermal Thellier experiments consists of four graphs: the Arai plot (Nagata et al., 1963), Zijderveld plot (Zijderveld, 1967), equal area plot, and the demagnetization/remagnetization plot (Figure 3a). On the left side of the window, the temperature (T) steps are shown. These can be selected by clicking the tick box next to the temperature; only the selected temperatures are considered in the interpretation and calculation of the selection criteria that are provided below the graphs. The graphs are updated dynamically; that is, deselected temperatures become open dots in the Arai plot, and the fits in the Arai and Zijderveld diagrams (the green and red lines) are updated to represent only the selected data points, and selection criteria are updated immediately.

The Arai plot shows the NRM remaining on the vertical axis and the partial TRM gained on the horizontal axis, both are scaled to the initial magnetization, NRM_0. The color of the dots in the Arai plot depends on the measurement sequence of the corresponding zero-field (Z) and in-field (I) steps; ZI steps are displayed in blue, and IZ in red, following the convention used by Thellier GUI (Shaar & Tauxe, 2013). pTRM checks are visualized by black triangles connected with a gray line to the temperature step after which the pTRM check is performed. By default, the horizontal and vertical axes of the Arai plot are proportional (i.e., the visualized slope of the fit in the graph corresponds to its actual, mathematical, slope). Traditionally, the axes of Arai plots are often scaled so that, visually, the slope appears to be approximately −1, leading to a square Arai diagram. To switch between these views, click the appropriate icon in the top right of the Arai diagram: the rectangle for proportional axes, the square for scaled axes (and a square plot).

The direction of the demagnetization (zero-field steps) is given in the Zijderveld plot, open (closed) dots represent the vertical (horizontal) projection, and the red (green) line represents the mean-free floating direction for the selected steps. The presentation of the Zijderveld plot can be changed from Up/North to Up/West in specimen coordinates. The direction of the NRM remaining is also displayed in the equal area projection by the blue dots, red dots represent the direction of the partial TRM gained per step, and negative inclinations will appear as open symbols. The demagnetization/remagnetization plot visualizes the total magnetization per step; both the NRM remaining (blue) and the partial TRM gained (red) are scaled to NRM_0.
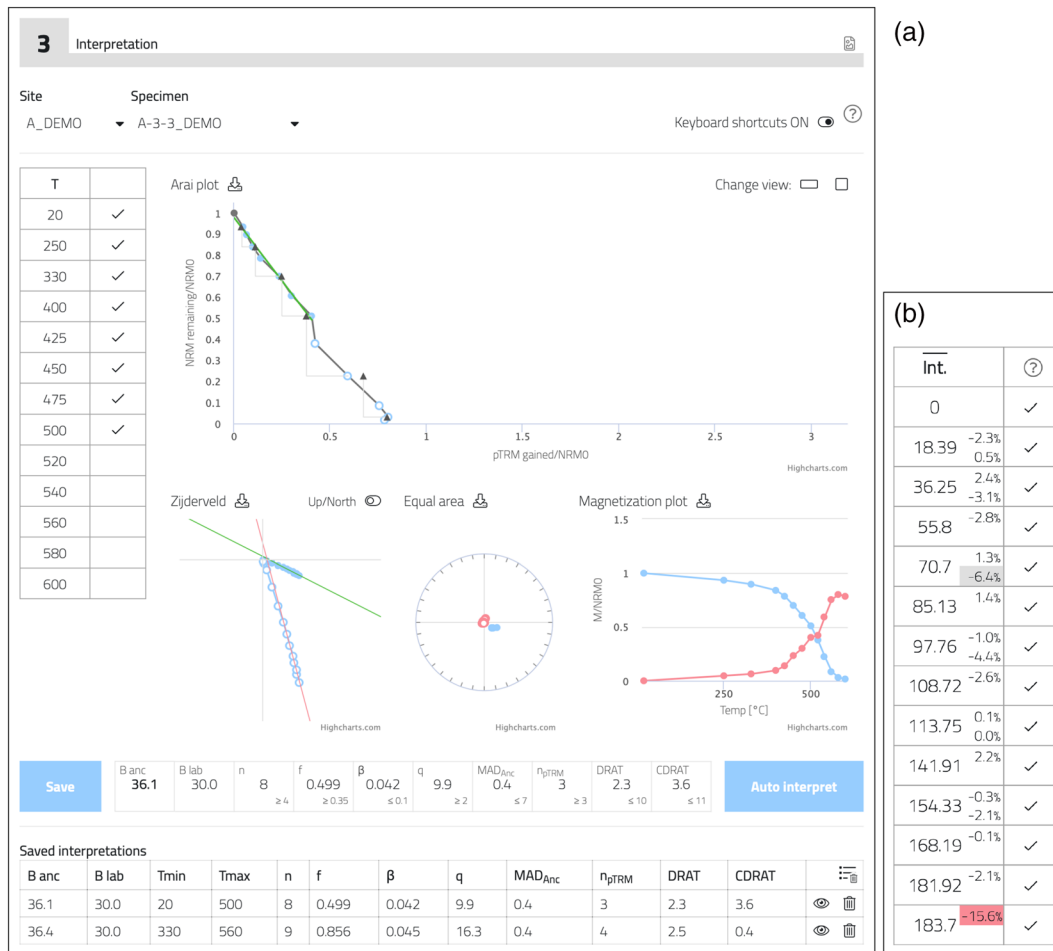
Figure 3. Thellier-type interpretation stage (a) for a thermal Thellier specimen. The Arai plot is in the center, with the Zijderveld, equal area, and magnetization plots below. The data can be selected in the data table on the left; the results and calculated selection criteria are given in the results table below the plots. Saved interpretations are available on the bottom of the page. The window for microwave Thellier results is similar to the thermal Thellier results, except that the average microwave integral is displayed instead of temperature (b). See main text for details.

At the lower part of the *interpretation* stage, the results of the selection criteria—calculated for the selected temperature steps—are displayed, together with their set cutoff value in small print in the bottom right of each cell. The selection criteria that are displayed in the *interpretation* stage and their thresholds for passing or failing can be changed in the *settings* tab. If the threshold of a selection criterion is not met, the respective box is highlighted in red. When changing the selection of the temperature steps, the selection criteria will automatically be recalculated.

An interpretation is saved by clicking the *save* button; all saved interpretations from the same specimen are added to the *saved interpretations* list at the bottom of the *interpretation* stage. This will display up to 16 selection criteria; more selection criteria are available in the export. Saved interpretations can be viewed by clicking on the eye icon or deleted with the trashcan icon. It is only possible to save an interpretation if the selected steps are a continuous series. In-between steps can be deselected for the interpretation of data; such an interpretation, however, will not be saved as a valid one.

An automatic interpretation option on specimen level can be used to add all interpretations that pass the set of selection criteria as specified in the *settings* tab to the saved interpretations list using the *auto interpret* button; this option is designed along the same lines as the autointerpreter of the Thellier GUI (Shaar & Tauxe, 2013). If an interpretation passes the criteria, it is added to *saved interpretations* list, the table on the bottom of the *interpretation* stage. Duplicates of the same interpretations will not be added. The

automatic interpretation is performed on specimen level to ensure that a user can view the separate interpretations directly by clicking the eye icon that is in the right-hand column of the *saved interpretations* table. To delete all saved interpretations for one specimen, use the clear list trashcan icon in the header of the *saved interpretations* table. The saved interpretations are forwarded to the *results* tab where the results can be exported as a comma separated variable (csv) file.

Keyboard shortcuts can be used to browse through specimens (left/right arrows) or steps (up/down arrows), selecting steps (x), changing the projection of the Zijderveld (3), saving an interpretation (s), or running the autointerpreter (a). The toggle to turn the keyboard controls on or off is to the top right of the Arai diagram.

All graphs can be saved by clicking on the download icon next to the name of the title of the graph. This provides a high-resolution vector svg-file image of the applicable graph. Also, the entire panel of the *interpretation* stage can be downloaded as png-file image file by clicking on the image icon in the top right of the *interpretation* stage panel.

2.1.4. Anisotropy Correction and Cooling Rate

To correct a paleointensity for TRM anisotropy, anisotropy tensor measurements need to be present in the original import file. Paleointensity.org supports this with specific measurement types that are supported in all Thellier file formats (see supporting information S1 for details). When a file is imported with such measurements, a dialog box will appear notifying the user that anisotropy correction data are detected and that the user should turn on the anisotropy statistics at the *settings* page. After doing so, both the original paleointensity, B_{anc}, and the anisotropy-corrected paleointensity, B_{anc_anis}, will be provided in the *interpretation* stage. To test for alteration during the measurements of the anisotropy tensor, a repeated remagnetization step can be performed to the first treatment position. It is therefore important that the data are in the order that they were measured (i.e., the treatment order of measuring the anisotropy tensor). If this repeated remagnetization step is available in the data file, the selection criterion δTRM_{anis} is calculated. The six independent elements of the anisotropy tensor (s1–s6) are available in the export using the *export interpretations to csv* button on the *results* tab.

Measurement files can also contain cooling rate data (Data Type 9). The cooling rate correction is currently not supported by Paleointensity.org, foremostly because there is no standard routine for performing a cooling rate correction. Moreover, different approaches to the cooling rate correction were recently shown to result in different paleointensity outcomes (Santos & Tauxe, 2019). If cooling rate measurements are present in the data files, these measurements will be written into the internal data structure and will show under the *manage* stage.

2.2. Microwave Thellier

2.2.1. Import Stage

Most microwave Thellier data are produced by the microwave systems at the University of Liverpool. The data files of these machines can be imported in Paleointensity.org in a similar fashion as the thermal Thellier import (i.e., either by drag-and-drop or by clicking the import field). For the Liverpool data format, no additional information is necessary for interpreting the data. Before importing the file, the unit of the magnetization or moment must be selected. After importing a file, a summary of the imported measurements is displayed.

2.2.2. Manage Stage

The work flow for the interpretation of microwave Thellier data is similar to the work flow for thermal Thellier data (see section 2.1). An overview of all imported sites, specimens, and measurements can be found in the *manage* stage; sites and specimens can be deleted by clicking the trashcan icon. An important difference between microwave and thermal Thellier experiments is that the repeatability between the in-field and zero-field steps is frequently less precise for microwave Thellier experiments. The demagnetization/remagnetization in a microwave Thellier experiment is done by exerting a microwave power for a certain time to a specimen; the amount of the energy that is absorbed by the specimen is expressed by the microwave integral. The microwave integral can be slightly different for a repeated power/time step. The microwave integrals for corresponding (in-field/zero-field) steps are averaged into the average integral ($\overline{int}$); the difference between the integrals of the in-field and zero-field steps is expressed as delta integral. These additional parameters are available in the rightmost column of the *manage* stage, together with the magnetization, time stamp, and applied field.

2.2.3. Interpretation Stage

The *interpretation* stage for microwave Thellier experiments shows the same four graphs as for thermal Thellier experiments: the Arai plot, Zijderveld plot, equal area plot, and the demagnetization/remagnetization plot. The main difference between the *interpretation* stage of microwave and thermal Thellier data is in the table with steps on the left side of the panel (Figure 3b). For microwave Thellier data the average integrals (int⁻.) are shown together with their delta integrals. The change in the integral (i.e., the delta integral, between corresponding steps of zero-field and in-field measurements) is displayed in the upper right corner of the corresponding average integral step. The delta integral between an in-field step and a check, if available, is given in the lower right corner of the corresponding step. For a reliable interpretation of the data it is paramount that the delta integral is low. When the delta integral is >5%, the values are highlighted in gray; when the delta integral exceeds 10%, the background color changes to red. These steps should not be considered during the interpretation and can be flagged as bad measurement in the *manage* stage. Flagging a step as bad measurement removes the data point and possible corresponding checks from the *interpretation* stage, but these bad measurements are retained in the data storage of Paleointensity.org and are included in export files.

2.3. Pseudo-Thellier
2.3.1. Import Stage

Two different protocols are supported to import pseudo-Thellier data. Since the NRM demagnetization and ARM remagnetization experiments for pseudo-Thellier are often done sequentially, Paleointensity.org supports uploading these two data series as separate files. Paleointensity.org then combines these files into a usable pseudo-Thellier data set. Alternatively, a data file containing data from a demagnetization experiment following the ARM remagnetization can also be uploaded and included in the pseudo-Thellier analyses. Importing pseudo-Thellier data as separate files requires that all files use the same alternating field steps for all specimens, and specimen names are consistent throughout the files. The order of the specimens within the two (or three) files is unimportant. A dialog box summarizes the imported data. It is also possible to upload pseudo-Thellier data as a generic format file that contains both the zero-field and in-field steps; see supporting information S1 for details on this input format.

2.3.2. Manage Stage

An overview of all imported sites, specimens, and measurements is given in the *manage* stage; sites and specimens can be deleted by clicking the trashcan icon. The alternating field steps found in the measurement files and the type of measurement are displayed; also, the details of single measurements are available in the rightermost column.

2.3.3. Interpretation Stage

The *interpretation* stage for the pseudo-Thellier protocol shows the same four graphs as for the thermal and microwave Thellier protocols: the Arai plot, Zijderveld plot, equal area plot, and the demagnetization/remagnetization plot. Additionally, the demag-demag and ARM-ARM plots can be viewed using the pTh-plots toggle in the top right of the Arai diagram. These plots will be populated if ARM demagnetization data are imported. On the left side of the window, the alternating field steps can be selected to interpret the pseudo-Thellier data, or the autointerpreter can be used. The graphs and calculated parameters are again updated dynamically. Additional to the selection criteria, the grain size parameter $B_{1/2ARM}$ (de Groot et al., 2013) is calculated. Since the pseudo-Thellier method is a relative paleointensity technique, the slope and its corresponding standard deviation are displayed as the final result for this method. The potential calibration of this slope into an absolute intensity is left to the user and must be done outside Paleointensity.org.

2.4. Multispecimen Protocol
2.4.1. Import Stage

For the multispecimen protocol, a paleointensity is obtained by analyzing multiple specimens from the same site and subjected to the same peak temperature but exposed to different magnetic field strengths during the experiment. For the original protocol, MSP-DB (Dekkers & Böhnel, 2006), the NRM, and only one in-field step (M1) are needed for each specimen. Fabian and Leonhardt (2010) proposed a modified protocol to correct for the domain state of the magnetic grains: the domain state-corrected protocol, MSP-DSC. For this protocol additional three measurements are performed per specimen (M2, M3, and M4). Both protocols are supported by Paleointensity.org; MSP data files can be imported by drag-and-drop or by clicking the
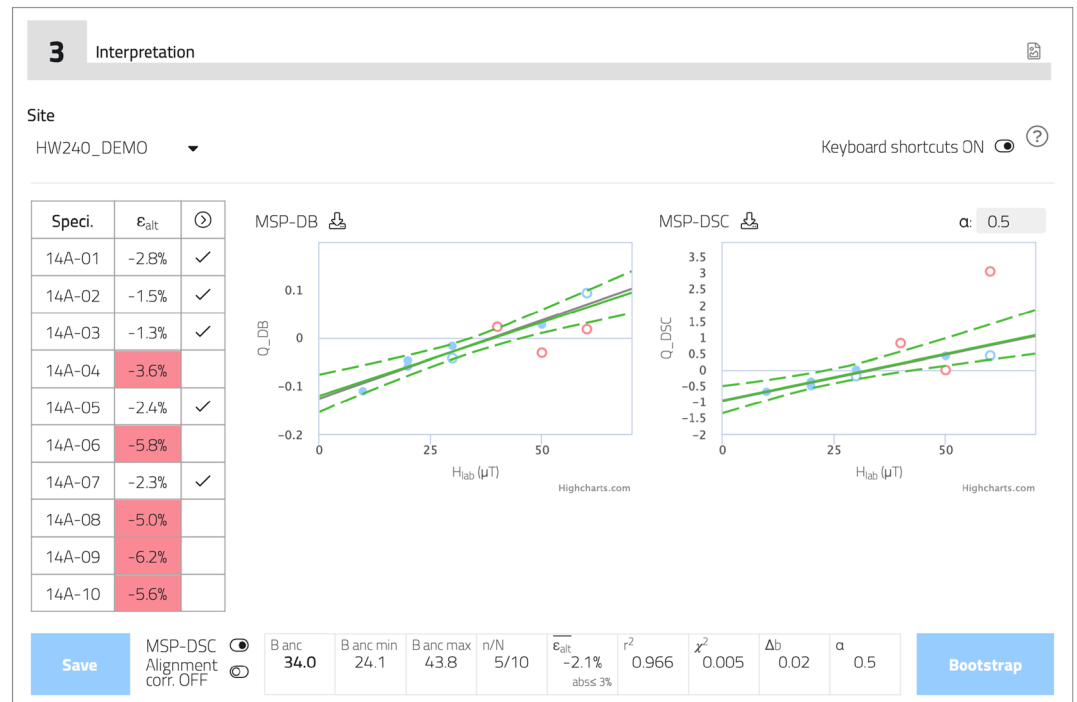
Figure 4. Interpretation stage of the MSP analyses page. The two MSP plots, for the MSP-DB and MSP-DSC protocols, are displayed simultaneously. Specimens can be reviewed and selected in the data table on the left, and the results of the MSP interpretation are in the results table below the figures. See main text for details.

import field. When importing a file, the user is asked to specify the site, temperature, and lab field used for the specimens; a file may contain specimens from different sites and experiments done at different temperatures. Since it is possible that MSP experiments are done at different temperatures for the same site, the temperature at which the experiment was done is added to the specimen name. The unit of the magnetization or moment must be selected before the file can be imported.

2.4.2. Manage Stage

An overview of all imported sites, specimens, and measurements is given in the *manage* stage; sites and specimens can be deleted by clicking the trashcan icon. The number of measurements for a specimen can either be two (NRM and M1) or five (NRM and M1 to M4); the details of all measurements are displayed in the rightmost column of the table.

2.4.3. Interpretation Stage

Sites can be selected from the dropdown menu in the interpretation window or by using the back and forth arrows on the keyboard. The *interpretation* stage (Figure 4) has two graphs, the MSP-DB plot and the MSP-DSC plot. The table on the left lists the specimens and their alteration estimate (ε_{alt}). The ε_{alt} cells are highlighted in red if its absolute value is >3%. These specimens should be rejected during the interpretation of MSP-DSC results (e.g., de Groot et al., 2013). Individual specimens can therefore be toggled on/off using the tick boxes in the right-hand column of the data table. By expanding the data table using the arrow in the top right cell, the other MSP-DSC parameters can be inspected. These parameters are: μ_{DS}, H_{max}, H_{est}, $(\Delta Q_{DSC}, alt)^2$, $(\Delta Q_{DSC}, ds)^2$, and $(\Delta Q_i)^2$, for an explanation on the parameters and how these are calculated; see Fabian and Leonhardt (2010). The MSP-DSC α parameter can be changed in the box above the MSP-DSC plot; α is set to 0.5 by default following the recommendation of Fabian and Leonhardt (2010). Fabian and Leonhardt (2010) also described the fraction-corrected MSP experiment; this is de facto an MSP-DSC experiment with α set to 0 and is therefore not to displayed as a separate figure.

Both the original fraction (Q_{DB}) and the domain state-corrected fraction (Q_{DSC}) are plotted against the applied laboratory field for all specimens (blue dots) in two corresponding plots. If the imported data only

contain MSP-DB data (the NRM and M1 steps), the MSP-DSC diagram will not be plotted, and the cells of the MSP-DSC parameters in the data table will be empty. A linear regression (black line) through the selected specimens (deselected specimens will show as open dots) results in a paleointensity estimate (i.e., the x axis intersection of the linear regression). The paleointensity estimate is given in the results table at the bottom of the *interpretation* stage, which automatically updates when selecting or deselecting specimens. The results table also shows the number of specimens used for the calculation of the paleointensity over the number of specimens measured (n/N), the average alteration estimate of all specimens ($\bar{\varepsilon}_{alt}$), the correlation coefficient of the linear fit (r^2), the chi-square test statistic (χ^2), the difference between the actual y axis intercept of the linear fit through the data, and the theoretically predicted y axis intercept, -1, (Δb), and the α used for the Q_{DSC} calculations. The linear regression line in the MSP-DSC plot is not forced through -1 and is calculated only using the data. The Δb parameter is therefore an important indication of how well the data fit the theoretical model behind this method.

The MSP-DB/MSP-DSC toggle to left of the results table allows inspection of either the results of the MSP-DB or the MSP-DSC interpretation. An alignment correction of the result as proposed by Monster et al. (2015b) can be switched on or off by clicking the alignment correction toggle below the MSP-DB/MSP-DSC toggle if the MSP-DSC result is selected. The alignment-corrected data can only be obtained for the MSP-DSC data, since the alignment correction is calculated using the direction of the NRM remaining, which in turn is calculated using both the M1 and M2 measurements (Monster et al., 2015b).

Uncertainty estimates for the calculated paleointensity (PI_{min} and PI_{max}) are provided by a bootstrap of the data following the method outlined in Monster et al. (2015b). Clicking the *bootstrap* button to the right of the results table calculates the uncertainty estimates based on the selected specimens in the data table. The bootstrap average (solid green line) and the confidence intervals (dashed green lines) are plotted in both the MSP-DB and MSP-DSC plots. The number of bootstraps and the confidence interval can be changed in the *settings* tab. Specimens that fall outside the bootstrap confidence level are displayed in red. Such outliers may be deselected in the data table, after which the bootstrap can be repeated. An MSP interpretation cannot be saved without running the bootstrap first; the *save* button is grayed out. After running the bootstrap, the result can be saved; if a specimen is selected or deselected from the list, however, the save button is again grayed out and the bootstrap must be run again to obtain the confidence intervals that pertain to the selected specimens. This allows the user to identify potential outliers (i.e., specimens that are outside the bootstrap confidence, displayed in red) and deselect these before rerunning the bootstrap. We suggest the following order of interpreting the MSP results:

1. Check the ε_{alt} for the specimens individually, deselect specimens with $\varepsilon_{alt} > 3\%$. Note that ε_{alt} may be reduced by the alignment correction that is available to MSP-DSC results.
2. Run the bootstrap for the first time.
3. Deselect outliers (red dots).
4. Run the bootstrap for the second time.
5. This is your final result; save the MSP-DSC or MSP-DB interpretation.

2.5. Results Tab and Data Export

An overview of all saved interpretations is provided on the *results* tab (Figure 5a). Here results can be selected, compared, and exported using the different options provided. Clicking on a specimen in the table shows the particular specimen and the interpretation. Clicking back and forth between the *results* tab and other tabs of Paleointensity.org does not affect selections made on the *results* tab. If multiple specimens are selected, their average and standard deviation are calculated using all specimen interpretations for that paleointensity method. It is important to note that these calculated averages are meaningless if specimens from different sites, locations, or ages are selected. As there is no standardized way to combine results from different paleointensity methods from the same site, location, and/or age, the results of the different methods are presented separately. How the obtained paleointensity results are weighted when combining results from different methods is up to the researcher.

Paleointensity.org allows for exporting the selected data in two ways: First, the interpretations of the selected specimens can be exported as a csv file. Second, the measurement data of the selected specimens can be downloaded as a csv file. To export the interpretations as a csv file, click the *export interpretations to csv*
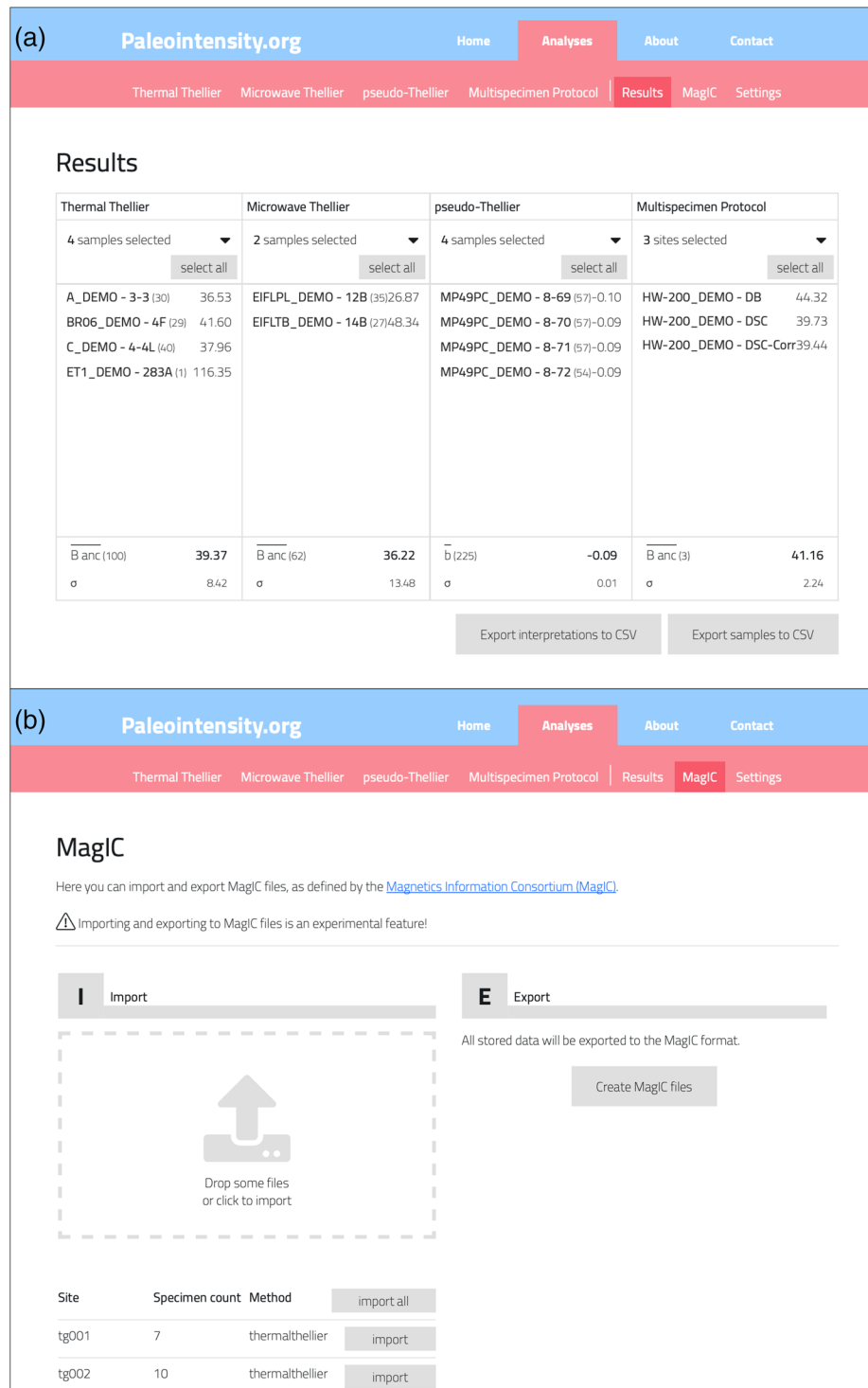
Figure 5. The results and MagIC tabs. Saved interpretations can be compared on the results tab (a). For each specimen the number of interpretations is given between brackets, and the average paleointensity or slope is given. The total average and standard deviation are given for all selected specimens and sites. Selected specimens and sites can be exported using one of the two export buttons. The MagIC tab (b) allows the import of MagIC files and to export all the measurement data in the local storage to MagIC data tables.

button. This downloads a csv file with the results for all selected interpretations. This includes all selection criteria values for Thellier-type analyses, independent of the selection criteria set used during interpretation. The measurement data of the selected specimens that were uploaded into Paleointensity.org, including bad measurement flags, can be downloaded with the *export specimens to csv* button. This produces a human-readable csv file with all available data on the measurements that is in the local storage of Paleointensity.org. Export to MagIC is available on the *MagIC* tab (see section 2.7). It is important to note that the entire state of Paleointensity.org (i.e., all imported data, and also the selections, calculated parameters, and interpretations) can be downloaded on the *settings* tab (see section 2.7).

2.6. The MagIC Tab

The *MagIC* tab (Figure 5b) allows for importing MagIC files into Paleointensity.org and to export MagIC data tables that are ready to import into the MagIC database. Paleointensity.org supports MagIC files that are formatted in version 3.0 of the MagIC data table. These files should contain measurement data and should be formatted as is described by MagIC (https://earthref.org/MagIC/); if a file is not correctly formatted, it cannot be imported in the website and an error message will appear. To import data from a MagIC file into Paleointensity.org, simply drag and drop a MagIC file on the import panel on the *MagIC* tab. This can be a MagIC contribution downloaded from the database or a MagIC measurement text file. Paleointensity.org will then import the data for the different methods, independent of the protocol used. After importing a file through the *MagIC* tab, a short summary displays the kind of measurements found in the file. The user can choose which data should be imported and kept in the local storage, with the possibility to add all data in the file or only specific sites from specific methods. It is important to note that due to memory restrictions, only the measurement data are imported from a MagIC file. Any other information (e.g., metadata of sites and locations) are ignored. The MagIC export functionality is an easy way to generate MagIC files from data that are uploaded in Paleointensity.org. This is done with the export button on the *MagIC* tab; this generates a zipped folder with five MagIC data tables: locations, sites, samples, specimens, and measurements. Paleointensity.org supports only the bare minimum of metadata requested in a MagIC file. Remaining metadata may be added to the MagIC data tables before uploading to MagIC, for example, "latitude," "longitude," and "ages" of the sites.

2.7. Settings Tab

The settings that are used throughout Paleointensity.org, such as selection criteria for the paleointensity methods and options to download or clear the local storage, are centralized on the *settings* tab. First, the selection criteria for Thellier-style experiments can be set. Second, the bootstrap parameters for the multi-specimen protocol can be changed, and third, the local storage can be downloaded, imported, or cleared.

2.7.1. Thellier Selection Criteria

By clicking the *selection criteria* button, the different selection criteria as provided in the Standard Paleointensity Definitions (Paterson et al., 2014) can be toggled on or off using the toggle on the right. Toggling a selection criterion on makes it appear in the results table at the bottom of the *interpretation* stage of the Thellier pages. The autointerpreter uses the specified values for the selection criteria that are toggled on as cutoffs for an interpretation to pass. A number of standard sets of criteria can be set using the buttons at the top of the dialog box: TTA and TTB (Leonhardt et al., 2004), SELCRIT2 (Biggin et al., 2007), and PICRIT03 (Kissel & Laj, 2004), as modified by Paterson et al. (2014); Class A (de Groot et al., 2014) and CCRIT (Cromwell et al., 2015); and a newly proposed set of selection criteria for pseudo-Thellier data (pTh-SCRIT). One of these standard sets can be chosen, but it is also possible to select different criteria or modify the thresholds. The selection criteria and the threshold values are saved in the local storage and are included when the local storage is exported and/or shared amongst users.

For pseudo-Thellier experiments we propose a new standard set of selection criteria, pTh-SCRIT, after Paterson et al. (2016) (Table 1). This set of selection criteria aims at identifying only the most linear part of the Arai diagram ($|k'| \leq 0.2$; Paterson, 2011) that has the direction of the characteristic remanent magnetization of the NRM. This new proposed set strongly focuses on only selecting the data points for which the interpreted direction shows no signs of overprints, with the MAD_{free} and α both ≤ 5 and the DANG ≤ 4. The additional selection criteria for pseudo-Thellier as proposed by Paterson et al. (2016) are included in pTh-SCRIT. The grain size parameter $B_{1/2ARM}$ (de Groot et al., 2013) is always calculated for pseudo-Thellier experiments but is not considered as a selection criterion.

Table 1

Newly Proposed Selection Criteria for Pseudo-Thellier (pTh-SCRIT), After Paterson et al. (2016)

Statistic	Threshold	Applied plot
n	≥ 5	All
f	≥ 0.35	Arai
β	≤ 0.1	Arai
MADFree	≤ 5	—
α	≤ 5	—
DANG	≤ 4	—
$|k'|$	≤ 0.2	All
R^2_{corr}	≥ 0.995	All
f_{Resid}	≤ 0.15	Demag-Demag

2.7.2. Multispecimen Bootstrap Values

The bootstrap parameters for multispecimen paleointensity experiments can be changed by clicking the *bootstrap values* button. The number of bootstrap values and the confidence level can be changed; by default, these parameters are set to 3,000 and 95%, respectively.

2.7.3. Storage Options

A powerful option of Paleointensity.org is the possibility to download and share the local storage of the user's browser using the *download storage* button. These local storage files contain all uploaded data, the settings, and the interpretations made—the files are a snapshot of the entire state of Paleointensity.org. Importing a local storage file using the *import storage* button puts Paleointensity.org in the exact same configuration as when the storage file was created. These local storage files can therefore be easily shared among colleagues, and even uploaded as supporting information to a manuscript to help the review process or to comply with the FAIR use of data. The local storage can also be cleared by using the *delete interpretations*, *delete measurements*, or *delete complete storage* buttons.

3. Data Format and Demo Data

3.1. Internal Data Structure

Although Paleointensity.org is opened in a web browser, all calculations are done locally on the user's computer. The imported data are not sent over the internet. The local data structure of the website is a table that consists of columns containing all necessary information for analyzing and interpreting the data. A description of all columns is available in the supporting information (S2). For the currently supported paleointensity methods, the necessary information needed for interpretation of the data is quite similar. Site and specimen names should be specified; also, the x, y, and z coordinates or the declination, inclination, and moment of the magnetization per step should be provided. For the Thellier-type protocols the step types are required (e.g., in field or zero field) as well as the direction and strength of the applied laboratory field. For the multispecimen protocol the steps must be specified as NRM or M1 to M4 and only the strength of the applied field is necessary since, as per method requirement, the specimens' NRMs aligned with the applied field.

3.2. Input Formats

Since the necessary information needed for the different paleointensity protocols is slightly different, the supported input formats also differ for each protocol (Table 2). If the necessary information for interpreting the data cannot be obtained from the input file, the user is asked for additional information in a dialog box. For example, when importing a ThellierTool file (.tdt) including a header, the strength of the laboratory field is given in the header, but the direction of the applied laboratory field cannot be obtained from the input file; this should be specified by the user. Detailed information on the supported input files, their format, and codes to denote the different steps are described in the supporting information (S1).

Table 2

Currently Supported Input Formats per measurement Protocol

Date format Protocol	.tdt files ThellierTool	Generic format (PmagPy)	.TH or.AF Utrecht format	Liverpool format	pTh format	JR6 output/MSP generic format	MagIC
Thermal Thellier	✓	✓	✓	✓			✓
Microwave Thellier				✓			✓
pseudo-Thellier		✓	✓		✓		✓
Multispecimen						✓	✓

Note. For pseudo-Thellier a new format is developed (pTh format), for the use of NRM demagnetization, ARM acquisition, and optional ARM demagnetization measurements. Detailed information on the supported input files are described in the supporting information (S1).

The available input files cover the most commonly used data formats. As the data structure of the website is well documented and the necessary information for each protocol is known (Table S2), it is relatively easy to add new input formats to Paleointensity.org, and requests for additional formats are welcome. An input format should be well defined, consistently used, and should at least contain (1) the specimen names; (2) x, y, and z coordinates (or dec, inc, moment) of measured magnetizations; and (3) information on the step (temperature, microwave integral, or alternating field) and step type (e.g., in field or zero field) using the codes that were introduced by ThellierTool (Leonhardt et al., 2004) and are already supported by Paleointensity. org. Nevertheless, we encourage new users of Paleointensity.org to adopt a generic file format such as tdt files or the PmagPy generic format whenever possible.

3.3. Naming Convention, Distinguishing Between Sites, Samples, and Specimens

Site, sample, and specimen names are detected when importing files. The specimen name is the complete string, when no delimiters are provided the sample and site name is the same as the specimen name. Delimiters that can be used are a hyphen (-), underscore(_), or period (.). When only one delimiter is present, the sample name is the same as the specimen name and the site name is the part of the string prior the delimiter. When two or more delimiters are present in the specimen name, the site is the part of the string prior the first delimiter and the sample is the part of the string prior the second delimiter. For example, for specimen PI02-1-2, the sample is PI02-1 and the site is PI02. Specimen AL2773-3b only has one delimiter; therefore, the sample is the same as the specimen, AL2773-3b, and the site is AL2773. If Paleointensity.org encounters an identical name while importing data, the new data will be imported with an index appended to the sample name depending on how many times the sample is added (e.g., two instances of AL2773-3b will be imported as *site* AL2773, *sample* AL2773-3b, and *specimens* AL2773-3b and AL2773-3b(2)).

3.4. Input Validation and Data Managing

Input validation is an important part of the user friendliness of an application. Therefore, all files are checked during the *import* stage and Paleointensity.org produces an error message if the format of the file does not agree with the format as specified while uploading the data. This message should help the user to identify issues in the imported data file and how they can be resolved. Duplicate measurements are not allowed; if these are present in the data, an error message will appear during the interpretation of the specimen containing duplicates. For the multispecimen protocol an addition check is performed after the import of the data. If the file import is successful, but there are missing or duplicate data points (e.g., the M1 step is missing), the *interpretation* stage will not produce the relevant diagrams but will show an error message stipulating what is wrong. In the case of duplicate measurements, these duplicates can be removed in the *manage* stage.

3.5. Demo Data

To try the website and the different paleointensity protocols, a set of demo data for each protocol is available. The demo data can be imported at the *home* page or at the *analyses* page. The demo data for thermal Thellier consist of a subset of the calibration data set presented with the Standard Paleointensity Definitions (Paterson et al., 2014). The microwave Thellier demo data include two specimens from the East Eifel, Germany (Monster et al., 2018). For pseudo-Thellier the demo data consist of four sediment specimens from the Taranto Gulf in the Mediterranean, providing relative intensity values (Béguin et al., 2019). For the multispecimen protocol the demo data comprise a subset of the test data for the VBA-based MSP-Tool (Monster et al., 2015b) and two sites from Hawaii (de Groot et al., 2013).

3.6. Local Storage and Browser Compatibility

All data and interpretations are stored in the local storage of the browser; no data are sent over the internet for its interpretation; that is, the data and calculations are handled on the client site. The size of the browsers local storage limits the number of measurements that can be handled by Paleointensity.org, often the local storage is 5 MB, which translates in approximately 20,000 measurements; the size of the local storage may be higher on newer systems. If the storage is full, a warning message is displayed and new interpretations cannot be saved. To ensure that data can be imported, interpreted, and exported, it is wise to split data files >3 MB in multiple smaller files and do the interpretation in stages. The local storage containing all measurements and saved interpretations can be downloaded at the *settings* tab. This file can later be imported at the *settings* tab to continue working on the project or to view current interpretations. Paleointensity.org is

compatible with the latest versions of Mozilla Firefox (68.0), Google Chrome (77.0.3865.90), and Safari (13.0).

4. Summary

Paleointensity.org is an open source platform that aims to provide an easy to use and intuitive way to interpret paleointensity data from the most commonly used paleointensity techniques. The website is modular, which allows the addition of new paleointensity techniques as needed. Our application currently supports a variety of input file formats for four different paleointensity methods: thermal Thellier (all variations), microwave Thellier, pseudo-Thellier, and the multispecimen protocol. Although Paleointensity.org is opened in a web browser, all calculations are done locally, with no data transfer over the internet. The entire state of the application, including the uploaded data, settings used, and interpretations, can be exported and shared with colleagues or appended to a publication. Paleointensity.org complies with common practices and existing infrastructure such as the MagIC database (https://earthref.org/MagIC/) and the Standard Paleointensity Definitions (Paterson et al., 2014). Paleointensity.org therefore is a major step forward in enhancing an open paleomagnetic community in which paleointensity data can be shared, checked, and reused in line with the FAIR data policy.

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