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An updated internet-based Global Paleomagnetic Database

S.A. Pisarevsky [a,*], Z.X. Li [a,*], M.G. Tetley [b,c], Y. Liu [a], J.P. Beardmore [a]

[a] Earth Dynamics Research Group, The Institute for Geoscience Research (TIGeR), School of Earth and Planetary Sciences, Curtin University, Bentley, Western Australia 6102, Australia

[b] University of Texas Institute for Geophysics, Jackson School of Geosciences, The University of Texas at Austin, TX 78758, United States

[c] EarthByte Group, School of Geosciences, The University of Sydney, NSW 2006, Australia

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ABSTRACT

The availability of global, uniformly formatted, and easily searchable databases is essential for big data-based and machine-leaning oriented geoscience research. We present a new and data-updated version of the online Global Paleomagnetic Database (GPMDB; http://gpmdb.net/). This version inherits most of the structure from the previous MS Access-based version of McElhinny and Lock (1996), but includes a new RELIABILITY table with Q and R quality factors, as well as the optional inclination shallowing-corrected data where applicable. It now contains 10,021 paleomagnetic poles (994 of them being high quality poles with Q > 5) from 8247 rock units, presented in 4175 publications. The database, publicly available from the GPMDB website, provides a user-friendly graphical interface with the navigation page, an interactive world map showing the localities of all paleomagnetically studied rock units and menu bars. Multi-parameter and multi-stage search of the database is available through a SEARCH menu bar, and users can export the search results as CSV files. We compare the Q and R quality factors for a selection of database entries, and provide examples of database queries. This database will be continuously updated, maintained and improved, providing a unique source of high-quality global paleomagnetic data for a wide range of Earth science research including paleogeographic reconstruction and testing of geodynamic models, and enabling future development of machine learning applications.

1. Introduction: significance and a history of Global Paleomagnetic Database development

With the assumption of a dominant geocentric axial dipole model for the geomagnetic field through much of Earth history (e.g., Merrill et al., 1996; McElhinny and McFadden, 2000; Van der Voo, 1993 text books; Evans, 2006; Biggin et al., 2020), paleomagnetism provides the only quantitative observational constraints on the latitudinal distribution of continents through time. Through the comparison of paired paleopoles of apparent polar wander paths (APWPs), it can also provide constraints on relative paleolongitude between continents (e.g., McElhinny and McFadden, 2000; Van der Voo, 1993). Paleomagnetic studies played a pivotal role in the development of the theory of plate tectonics (e.g., Runcorn, 1956; Irving, 1964; McElhinny, 1973; Tarling, 1983; Khramov, 1987). In more recent times, it facilitated the rapid recognition of the presence of supercontinent cycles in Earth history (Powell et al., 1993; Meert and Torsvik, 2003; Pisarevsky et al., 2003, 2014; Li et al., 2008, 2019; Evans et al., 2016). This in part led to the identification of major true polar wander (TPW) events throughout Earth history (e.g., Kirschvink et al., 1997; Evans et al., 1998; Li et al., 2004), leading to the characterization of geodynamic linkages between the supercontinent cycle and mantle dynamics (Evans, 1998; Li et al., 2004, 2008, 2022a; Steinberger and Torsvik, 2008; Li and Zhong, 2009).

Given the importance of paleomagnetic data and the need for easy access to the global dataset for both global and regional studies, it was recognized early that there was a need for the development of uniformly archived global paleomagnetic data. Since then, the development of scientific databases have becoming increasingly important with the advent of data science and machine leaning approaches being applied within Earth science research (Doucet et al., 2022; Li et al., 2022b).

1.1. First catalogues

The first global and regional catalogues of paleomagnetic data were published in the late 20th century (e.g. Irving et al., 1976; McElhinny and Cowley, 1977; Khramov, 1971; Piper, 1988; Pesonen et al., 1991). These catalogues typically contained short extracts from the published paleomagnetic studies, which are in most cases sufficient for the

* Corresponding authors.
E-mail addresses: sergei.pisarevskiy@curtin.edu.au (S.A. Pisarevsky), z.li@curtin.edu.au (Z.X. Li).

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reconstruction of paleolatitudes and azimuthal orientations of ancient continents and terranes. The catalogues also introduced an opportunity to consider quantifying rough quality estimates of paleomagnetic results. These catalogues were originally published and shared as simple tables with a number of columns containing information about the geological ages of the studied objects, their geographic locations, mean paleomagnetic directions, paleomagnetic poles and corresponding statistics. Each line in the table typically represented a single paleomagnetic study, resulting in a single paleomagnetic pole. Tables were also supplied with comments containing important information which could not be easily formalized, e.g. geological specifics of the studied rocks, bibliography, details of the dating etc.

These catalogues became quite popular not only within the paleomagnetic community, but also in the broader geoscientific community. Apart from plate tectonic reconstructions, paleomagnetic catalogues were also used for various other applications in geosciences such as studies of geomagnetic secular variations and reversals, generation of the geomagnetic field, and magnetostratigraphy.

1.2. GPMDB ACCESS database

Lock and McElhinny (1991) created the first computer-based Global Paleomagnetic Database (GPMDB) using the relational database management system *ORACLE*. This was a significant step forward in the compilation and sharing of paleomagnetic data for the geoscience community at the time, paving the way for many complimentary data sharing efforts. Compared to the simple catalogues described above, computer-based relational databases provided a much more powerful platform for the collection, editing and storage of paleomagnetic information, as well as greatly enhanced opportunities for data selection, bespoke queries, and export/import, all of which had not been previously possible.

The advent of affordable personal computing towards the end of the 20th century provided new opportunities for the use of computer databases by end-users in all fields of science including geosciences. McElhinny and Lock (1996) created and developed the first set of PC-based Paleomagnetic Databases using the *Microsoft Access* software, sponsored by the International Association of Geomagnetism and Aeronomy (IAGA). Initially there were four databases:

1) Global Paleomagnetic Database (GPMDB),
2) Paleointensity Database (PALIN),
3) Polarity Transitions Database (TRANS),
4) Secular Variations Database (SECVR).

In addition to McElhinny and Lock, several other workers contributed to the construction of the databases including R. Van der Voo, M. Perrin, H. Tanaka, M. Kono, K. Hoffman, M. Fuller, C. Barton, S. Lund and others (see McElhinny and Lock, 1996 and references therein).

The GPMDB in *Microsoft Access* format (McElhinny and Lock, 1996) has become the most well-known paleomagnetic database, featuring a user-friendly interface that did not require programming skills. The 'Access' database was designed with the same objectives as the above-mentioned original catalogues: to provide an accessible source of paleomagnetic data for use in paleogeographic reconstruction and geoscientific research containing sufficient information for quality evaluation of a given paleomagnetic pole without reading the full publication. However, unlike catalogues, the new computer-based database format was much more flexible, allowing for new data to be easily added, modified or removed, and providing much easier, flexible and less time-consuming search functions.

The GPMDB is a relational database enabling researchers to search for paleomagnetic data according to a range of selection and filtering criteria. The GPMDB structure includes the main details about each particular paleomagnetic study, brief geological, rock magnetic and geochronological information, and bibliographic data. The database contains three major tables REFERENCE, ROCKUNIT and PMAGRESULT (relations are "one to many"). Three additional tables are related to PMGAGRESULT: ALTRESULT (one to one), FIELDTESTS (many to one) and CROSSREF (many to one). There are 7 look-up tables: INFORMATION, TIMESCALE, JOURNAL, CONTINENTS, COUNTRY, TERRANE and VERSION. Further details of these tables can be found in Section 2. This version of the database was periodically updated by McElhinny until the year 2000, and then by Pisarevsky up to the end of 2004 (see Pisarevsky, 2005).

Building on the 'Access' GPMDB database described above, Pisarevsky and McElhinny (2003) further extended the GPMDB ecosystem to include a GIS systems-compatible analogue of the GPMDB called VisualDB. Compatible with ESRI *ArcView* 3.x versions, VisualDB provided a clear and easy to use graphical user interface (GUI) for the GPMDB capable of some online data processing and visualization. Unfortunately, the ESRI *Avenue* programming language, which was used to create VisualDB, was not supported in subsequent *ArcGIS* or *ArcMAP* software releases, so development for VisualDB ceased.

The major shortcoming of both the 'Access' based GPMDB (along with other IAGA databases) and VisualDB, is that they required commercial software and could not be provided or used directly via the internet with a user-friendly GUI. To overcome this, a simple internet GUI for the GPMDB was developed, provided and hosted by the Norwegian Geological Survey, however, the database was not maintained or updated, and is no longer available online.

During 2003– 2004, in an effort to provide online access to GPMDB data, the then current version of GPMDB was exported and integrated into the Magnetics Information Consortium (MagIC) online database (Jarboe et al., 2012; http://earthref.org/MAGIC/). However, as the MagIC database was designed mostly for rock magnetists and paleomagnetists who study the processes of generation of the geomagnetic field, it aims to archive all measurements as well as the derived properties from each rock magnetic or paleomagnetic study, requiring considerable maintenance and data clean up. More details can be found in Section 1.3.

Conversely, the GPMDB is designed to be a simple, lightweight and accessible resource for tectonic applications of paleomagnetic data. It is relatively small, compact in structure and only contains the most important paleomagnetic information for the application to plate tectonic and paleogeographic reconstructions. In 2014, as part of the IGCP 648: Supercontinent Cycles & Global Geodynamics project, work began on both updating the GPMDB with missing published global paleomagnetic data as well as creating a new, user-friendly online version of the GPMDB. The primary objective of this new version of the GPMDB is to make paleomagnetic data freely available not only to professional paleomagnetists, but to all scientists who wish to utilize paleomagnetic data in their research.

1.3. MagIC (Magnetics Information Consortium) database

The two initial goals of the MagIC project (http://earthref.org/MAGIC/) supported by NSF were: a) merging the existing IAGA GPMDB, PALIN, TRANS and SECVR databases (see sections 1.1 and 1.2) into a single database, and b) collecting and archiving additional information from corresponding publications which was not included within the IAGA databases. In particular, this included the results of individual paleomagnetic and rock magnetic measurements. To curate and incorporate such a huge amount of data, the MagIC team encouraged the paleomagnetic and rock magnetic communities to submit the details of their studies to the MagIC website through the provided user interface. Unfortunately, as the collection of these highly specific data remains an uncommon practice within the paleomagnetic community, many paleomagnetic data are still not included in this database. For example, as of January 2022, the search tool in MagIC reports the presence of $n = 346$ paleomagnetic/rock magnetic related studies published between 2005 and 2022. However, only $n = 40$ of them contain paleomagnetic poles with ages >1 Ma, which are relevant to plate tectonics applications. In comparison, our new GPMDB contains $n = 720$ paleomagnetic poles with ages >1 Ma from the same publication period.

A complicating factor here is that the search tool in MagIC, although very powerful, is both sophisticated and time-consuming to use for both specialist and non-specialist users alike. In practice, to retrieve the minimum data required for tectonic reconstructions such as paleolatitudes and continental azimuthal orientations for a given location is unnecessarily difficult. As it was noted above (see section 1.1), making data easily accessible was an original aim of the first paleomagnetic catalogues and computer-based versions of GPMDB.

1.4. PALEOMAGIA

Veikkolainen et al. (2014) created the online, open-access PALEOMAGIA database specifically to curate Precambrian paleomagnetic data (https://paleomagia.it.helsinki.fi/). Unlike the GPMDB, which only contains data that meet the minimal community quality guidelines (see Section 2.2), the creators of PALEOMAGIA have taken a different approach in providing all available data regardless of quality assessment. Additionally, and perhaps the most useful innovation of Veikkolainen et al. (2014), is the attempt to relate each paleomagnetic pole to a certain geographic area, referred to within PALEOMAGIA as a 'terrane'. This is a significant advancement towards the aim of making paleomagnetic data more easily evaluated and applied to paleogeographic reconstructions. However, there are some shortcomings in applying this approach universally (which were correctly stated by Veikkolainen et al., 2014), particularly for terranes of a composite nature, such as the Altaids, Borborema, Kazakhstan, Avalonia, Scotland, and Taimyr terranes, or to any highly debatable geometries and margins.

2. Structure of the GPMDB: legacy and changes

2.1. Database structure

The new online GPMDB presented here inherits most of its structure from the original 'Access' data structure of McElhinny and Lock (1996). The core of the database is composed of three main tables: REFERENCE, ROCKUNIT and PMAGRESULT (Fig. 1).

The REFERENCE table contains bibliographical information of publications containing the paleomagnetic data. The first field in this table (REFNO) contains a unique digital identification for each unique publication. Other field names are typically self-explanatory including AUTHORS, YEAR, JOURNAL, VOLUME, VPAGES, TITLE and REMARKS.

As some publications present paleomagnetic studies on more than one geological object (or rock unit), the REFERENCE table is related ("one to many") to the ROCKUNIT table (Fig. 1). The latter contains simplified geological, geochronological and geographic information about rock units (e.g. 'formation name', 'dyke swarm', 'magmatic complex' etc.). To establish this "one to many" relationship, the ROCKUNIT table also contains the REFNO field, which is followed by the ROCKUNITNO field containing unique digital identification of each rock unit. There are a further 16 fields within the ROCKUNIT table (see Table 1).

The paleomagnetic study of one rock unit might produce several paleomagnetic results (directions and/or poles). This is typical in cases of multi-component magnetization, when multiple stable remanent components of multiple ages are found within the same rock unit. To handle these cases, the ROCKUNIT table is also related ("one to many") to the PMAGRESULT table (Fig. 1). The PMAGRESULT table contains the essential information describing the paleomagnetic study. For this relationship, the first field in the PMAGRESULT table is the ROCKUNITNO field, which is related to the eponymous field in the ROCKUNIT table. This field is followed by the RESULTNO field, containing a unique digital identification of each paleomagnetic result. There are a further 45 fields in the PMAGRESULT table (see Table 2).

There are three additional tables, related to the PMAGRESULT table (Fig. 1): ALTRESULT (provides statistics for the mean of VGPs, if available), FIELDTESTS (some additional information for the TESTS field in the PMAGRESULT table) and CROSSREF (cross references to the

Table 1
ROCKUNIT relational table field names and descriptions.

Field name	Description
ROCKNAME	Name of rock unit studied (e.g. West Branch Volcanics, Bangemall Sills, Dayao Red Sandstone)
PLACE	Locality of sampling ending with the name of a Country (e.g. Armorican Massif, France)
CONTINENT	The Earth is conventionally divided into 12 "continents" (Africa, Antarctica, Asia, Atlantic Ocean, Australia, Europe, Greenland, Indian Ocean, Middle East, North America, Pacific Ocean, South America)
TERRANE	Geological terrane (e.g. Iberia, Lhasa, Colorado Plateau)
RLAT	Average latitude coordinate of the studied rockunit
RLONG	Average longitude coordinate of the studied rockunit
ROCKTYPE	Contains 4 "key" rocktypes (extrusives, intrusives, sediments, metamorphics), the usage of at least one of them is mandatory, and optional additional words (e.g. redbeds, lavas, dykes, basalts etc.) are allowed
STRATA	Biostratigraphic or other age information (e.g., Campanian, Fransian, Stenian)
STRATAGE	Symbols for geological age (e.g. D3 – upper Devonian, T1 – lower Triassic, NP3 - Ediacaran)
LATSPREAD	Lateral spread or thickness sampled
LOWAGE	Youngest age of sampled rocks (Ma)
HIGHAGE	Oldest age of sampled rocks (Ma)
METHOD	Method of determining age (e.g. 40Ar/39Ar, U—Pb, fossils, correlation)
ISOTOPEDATA	Details of isotope age information available
STRUCTURE	Strikes/dips of sampling sites, age of folding etc.
STATUS	Indicates whether the result is a superseded study

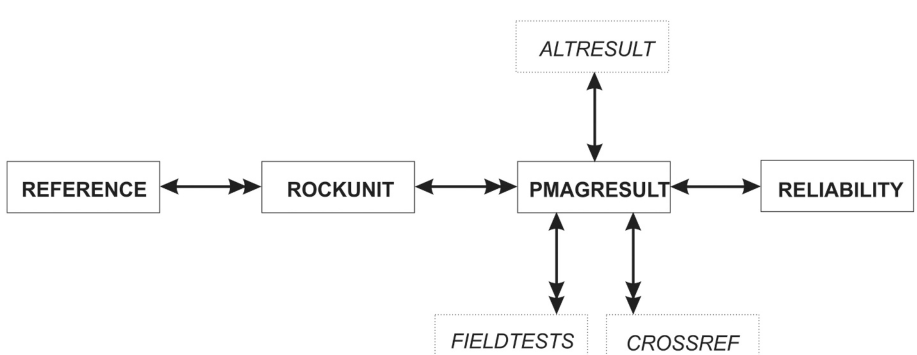


Fig. 1. GPMDB block diagram describing the relationships between database tables (see their descriptions in Tables 1-5). The blocks outlined in dashed lines are features currently unavailable in the online GPMDB initial release.

Table 2
PMAGRESULT relational table field names and descriptions.

Field name	Description
COMPONENT	In most cases this is the remanent magnetic component name introduced by the authors of the paleomagnetic study (e.g. Component 1, Component A, HT Component, Magnetite, Hematite). However, in some cases (such as studies of thick sedimentary successions), this field has been also used to indicate studies of separate parts of the succession (e.g. Locality 1, Locality 2, …, Locality 8, Combined result)
LOMAGAGE	Youngest limit of the remanent magnetization age (Ma). This age can be the same as found in LOWAGE in the ROCKUNIT table, if the remanence is considered to be primary.
HIMAGAGE	Oldest limit of the remanent magnetization age (Ma). This age can be the same as found in HIGHAGE in the ROCKUNIT table, if the remanence is considered to be primary.
TESTS	Summary of paleomagnetic field tests using standard symbols: G (conglomerate test), G*(intra-formational conglomerate test), C (contact test), C*(inverse contact test), F (fold test), F*(synfold test), Fs (fold test with strain removal – see section 3.3.2 of McElhinny and McFadden, 2000 and references therein), U (unconformity test), R (reversal test), M (rock magnetic tests), N (no tests). These symbols are followed by "+" (positive), "-" (negative), or "o" (indeterminate) signs. In the case of reversal test Ra, Rb and Rc indicate a positive test at levels A, B, and C, correspondingly (McFadden and McElhinny, 1990)
TILT	Percent tilt correction applied to obtain result cited. In most cases this field contains either 0 (in situ), or 100 (tilt corrected), but in rare cases of *syn*-folding remanence it may contain some intermediate number.
SLAT	Latitude (−90° to 90°). This coordinate may be close, but not necessarily identical to RLAT in the ROCKUNIT table.
SLONG	Longitude (−180° to 180°). This coordinate may be close, but not necessarily identical to RLONG in the ROCKUNIT table.
B	Number of sites sampled (number of localities/formations for combined results and grand MEANS)
N	Number of samples studied.
DEC	Declination of magnetization (DEC and all other angular values are in degrees).
INC	Inclination of magnetization.
KD	Fisher's precision parameter *k*
ED95	a_{95}, the semi-angle of the 95% cone of confidence.
PLAT	Latitude (−90° to 90°) of the paleomagnetic pole.
PLONG	Longitude (0° to 360°) of the paleomagnetic pole.
PTYPE	This field contains "D" if the pole is calculated from the mean paleomagnetic direction, or "V" if the pole is averaged from Virtual Geomagnetic Poles (VGPs) calculated for each site, or sample.
DP	Small semi-axes of the oval of confidence for the paleomagnetic pole. DP < DM if PTYPE is "D", DP=DM = A_{95} if PTYPE is "V".
DM	Large semi-axes of the oval of confidence for the paleomagnetic pole. DP < DM if PTYPE is "D", DP=DM = A_{95} if PTYPE is "V".
NOREVERSED	Percentage of reverse data.
ANTIPODAL	Angle between mean normal and mean reverse magnetizations.
N_NORM	Number (of sites or samples) used for normal mean.
D_NORM	Declination of normal mean.
I_NORM	Inclination of normal mean.
K_NORM	Precision parameter *k* of normal mean
ED_NORM	Semi-angle of the 95% cone of confidence of normal mean.
N_REV	Number (of sites or samples) used for reverse mean.
D_REV	Declination of reverse mean.
I_REV	Inclination of reverse mean.
K_REV	Precision parameter k of reverse mean.
ED_REV	Semi-angle of the 95% cone of confidence of Reverse mean.
DEMAGCODE	Code 0 to 5 describing demagnetization procedure (0 – no demagnetization; 1 – only pilot demagnetization on some samples; 2 – bulk demagnetization of all samples; 3 – stereonets with M/Mo, or vector plots provided; 4 – PCA (Principal Component Analysis) of Zijderveldt diagrams provided; 5 – Magnetic vectors isolated using two or more demagnetizations methods (e.g. AF and thermal) with PCA.
TREATMENT	Symbols describing demagnetization technique used (A = AF, T = thermal, H = chemical, N = no treatment)
LABDETAILS	Short description of laboratory procedures used.
ROCKMAG	Description of rock magnetic experiments carried out.
N_TILT	Number of sites or samples used for means after tilt correction.
D_UNCOR	Declination in situ.
I_UNCOR	Inclination in situ.
K1	Precision parameter *k* in situ.
ED1	Semi-angle of the 95% cone of confidence in situ.
D_COR	Declination after tilt correction.
I_COR	Inclination after tilt correction.
K2	Precision parameter *k* after tilt correction.
ED2	Semi-angle of the 95% cone of confidence after tilt correction.
COMMENTS	Comments, e.g. in relation to determining magnetic ages
STATUS	Indicates whether the result is old (i.e. published before 1990), and/or superseded, superceding, or combined with other results.

catalogues mentioned in section 1.1). These tables are not yet available to users in the current release of the online GPMDB.

2.2. RELIABILITY table, quality criteria and evaluation

>30 years ago, Van der Voo (1990) introduced 7 semi-quantitative metrics to describe the quality of paleomagnetic poles. A quality score for a given paleomagnetic pole is calculated by first assigning 1 point for each satisfied criterion below, then summing the total points out of a maximum of 7 (see Table 3).

More recently, in response to developments in paleomagnetic and geochronological research methods, Meert et al. (2020) proposed to modernize the quality assessment of paleomagnetic data, introducing a new set of 7 R-parameters (see Table 4).

The original GPMDB did not have any special fields for Q or R indexes, nor any functionality for an "automatic" calculation of them. The main reason for not including any quality assessment was the strong element of subjectivity in such a process. In this version, we modified the structure of the GPMDB by adding an additional table RELIABILITY (see Table 5). This table is linked ("one to one") to the PMAGRESULT table using the RESULTNO field.

We used a conservative approach in our estimation of the Q factor. For example, we considered only positive field tests to be satisfactory for meeting the Q4 criterion (field tests). In cases when only indeterminate results of field tests were provided in the publication, the corresponding Q4 field in the RELIABILITY table is assigned a zero value. If the reversal test is indeterminate (Ro), the Q6 field in the RELIABILITY table is also assigned a zero value. However, in these cases explanations are provided for clarity in the QCOMMENT field. Similar conservative approaches were applied in our estimations of the R factor.

All paleomagnetic poles in the GPMDB are currently provided with our estimation of the Q factor in the RELIABILITY table. However, the evaluation of the newly proposed R criteria for all poles in the GPMDB will take a significant amount of time to complete, because this process requires revisiting approximately 4000 publications. Currently only 180 poles (most of them have been published recently) are supplied with our

Table 3
'Van der Voo' criteria.

Criteria name	Criteria description
Q1	Well-determined age of the studied rocks and a presumption that the remanent magnetization age is the same (within half-period or ± 4%, whichever is larger, for Phanerozoic; ± 4% or ± 40 my, whichever is smaller, for Precambrian).
Q2	Sufficient (≥ 25) number of samples, Fisherian precision parameter *k* (or K) ≥ 10, circle of confidence a_{95} (or A_{95}) ≤ 16°.
Q3	Adequate demagnetization including vector subtraction information. McElhinny and McFadden (2000) proposed that the result passes this criterion, if the DEMAGCODE ≥ 3
Q4	Field tests that constrain the age of remanent magnetization
Q5	Structural control and tectonic coherence with craton or terrane involved.
Q6	Documented evidence of the presence of reversals.
Q7	No resemblance to paleomagnetic poles of younger age by more than a period.

Table 4
R-parameters criteria.

Criteria name	Criteria description
R1	Basically the same as Q1, but with tougher age precision (± 15 my) for the whole time scale.
R2	The combination of Q2 and Q3, but with stronger restrictions: >7 sites (with at least 3 samples from each), >24 samples, $10 \leq k \leq 70$, PSV (Paleo Secular Variation) test averaging geomagnetic secular variations, and stepwise demagnetization by multiple methods.
R3	A new criterion – rock magnetic and optical studies for identification of magnetic carriers.
R4	Same as Q4
R5	Same as Q5
R6	Basically the same as Q6, but with mandatory application of the reversal test of McFadden and McElhinny (1990), or Heslop and Roberts (2018).
R7	Same as Q7, but with more specific definition of "resemblance" to younger poles, based on overlapping A_{95}. However, the poles with proven (by field tests) older remanence than the "resembled" younger poles, are passing this criterion.

Table 5
RELIABILITY relational table field names and descriptions.

Field name	Description
Q1-Q7	Seven binary (0 or 1) fields (Q1 to Q7) corresponding to the satisfaction of the seven criteria of Van der Voo (1990).
QSUM	Van der Voo score/summary field (Q1 + Q2 + … + Q7).
QCOMMENT	Free text with comments concerning the Q factor.
R1-R7	Seven binary (0 or 1) fields (R1 to R7) corresponding to the satisfaction of the seven criteria of Meert et al. (2020).
RSUM	Meert score/summary field (R1 + R2 + … + R7).
RCOMMENT	Free text with comments concerning the R factor.

estimations of the R factor. We shall continue to maintain and add the R criteria to the rest of the poles in subsequent GPMDB releases.

There are some additional criteria which we use to select data for inclusion in the GPMDB to remain consistent with the main objective of the GPMDB to provide paleomagnetic information for global and regional tectonic reconstructions. Consequently, we excluded results when they: a) are from tectonically complicated areas with highly debated tilting or rotational histories, or b) are calculated based on data with no certain connection with any well-defined ancient continents or widely recognized terranes. We recognize the importance of such data for studies such as reconstructing the histories of oroclines, but to accurately curate such data requires a database with a different structure. We also do not include highly scattered data, the results of paleomagnetic studies on the fine structure of the geomagnetic field (e.g. secular variations), or data describing the behavior of the geomagnetic field during its unstable regimes such as geomagnetic excursions and reversals. Such data would be more suitable for curation in the MagIC database (http://earthref.org/MAGIC/).

A relatively large proportion of paleomagnetic studies are focused on the Quaternary age. Despite their importance, only a few such studies (most of those are from the early days of paleomagnetism) are included in the GPMDB as they contain very little information about plate tectonic movements. Again, we refer researchers who are interested in such studies to use the MagIC database.

Unfortunately, some publications contain miscalculations. Such cases are rare, but before entering a new pole to GPMDB we check the consistency between sampling location coordinates (latitude SLAT and longitude SLONG), paleomagnetic directions (declination D, inclination I and α_{95}) and coordinates of the corresponding paleomagnetic pole (latitude PLAT, longitude PLONG, DP/DM and/or A_{95}). In the rare cases when our calculations show significant difference (e.g. >3–4°) from the published values, we normally try to communicate with the authors and discuss this issue before entering the pole into the GPMDB.

3. Status of the current GPMDB

The GPMDB currently contains $n = 10{,}021$ paleomagnetic poles from 8247 rock units sourced from 4175 publications. These include:

~2500 Cenozoic poles (2521 poles with LOMAGAGE <67 Ma), ~2600 Mesozoic poles (2607 poles with LOMAGAGE >66 Ma, but <252 Ma), ~2600 Paleozoic poles (2635 poles with LOMAGAGE >251 Ma, but <542 Ma) and ~ 2200 Precambrian poles (2259 poles with LOMAGAGE >541 Ma).

The distribution of poles by Q-factor of Van der Voo (1990) is shown in Fig. 2. Most of the poles have QSUM of 3 or 4.

Evans et al. (2021) recently published a compilation of the most reliable Precambrian paleopoles as selected at the 8th Nordic Paleomagnetism Workshop in Leirubakki (Iceland) in 2017 (Brown et al., 2018). This compilation consists of two pole grades: Grade-A and Grade-B poles (Table 19.1 and 19.2 in Evans et al., 2021, respectively). Evans et al. (2021) gave the following definitions for this designation: "Grade-A results are judged to provide essential constraints on tectonic reconstructions; Grade-B poles are judged to be suggestive of high-quality, but not yet demonstrated to be primary, or perhaps lacking precise geochronologic or other constraints". There are a total of $n = 298$ poles in the Evans et al. (2021) compilation, with $n = 277$ of them included in the current release of the GPMDB. Of the 21 poles not included, 19 are the so-called 'MEAN' poles from the compilation of Evans et al. (2021). They are calculated by averaging several previously published or unpublished poles in later reviews or during paleomagnetic workshops. Typically, we include only results from original published studies into the GPMDB. The remaining two poles that are not included in the current release of the GPMDB are: (i) the ~1440 Ma Tieling Formation pole (North China), which was presented in a PhD thesis; and (ii) the ~1758 Ma Jan Lake Granite pole (Trans-Hudson orogeny, North America), which was presented in the report of a local Geological Survey as we do not have access to these sources at present and cannot qualify their inclusion.

In addition to the Evans et al. (2021) compilation, the GPMDB contains $n = 27$ new A-Grade and $n = 8$ new B-Grade Precambrian poles, all published since 2017. Consequently, the high-quality Precambrian data included in the GPMDB is up to date as at 2022.

As well as adding new poles to GPMDB, we also reviewed if new geochronological data were available on the paleomagnetically studied rocks. In cases when the new and/or higher quality dating were published, we made the corresponding corrections within the GPMDB by modifying the age, adding specific comments and adding a new publication to the REFERENCE table. For example, Poorter (1972; REFNO 689) obtained a paleomagnetic pole from Egersund dykes in southern Norway. At that time these dykes were not studied geochronologically, so their age was broadly considered as Late Precambrian. Later, Bingen

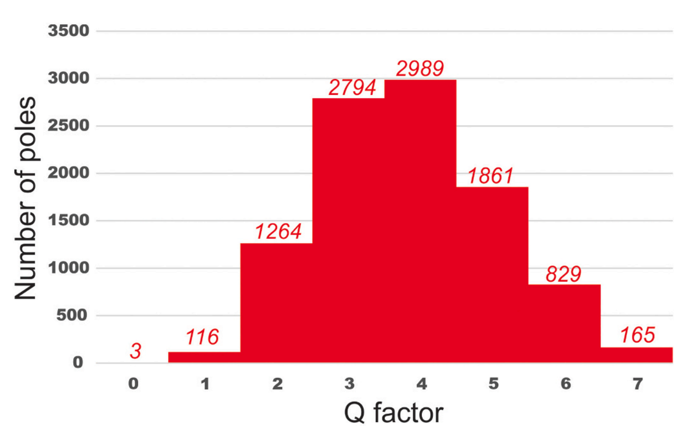


Fig. 2. The distribution of the GPMDB poles by the Q quality factor (Van der Voo, 1990).

et al. (1998, REFNO 3679) precisely dated the Egersund dykes with U—Pb baddeleyite age at 616 ± 3 Ma. In this case, we updated the data within the GPMDB, and now this pole plays an important role in the Neoproterozoic paleogeography.

4. Website and interface

4.1. Main page

The online GPMDB is lightweight, utilising a SQL database and Django backend together with an HTML, CSS and Javascipt frontend. It can be freely accessed through the GPMDB website (http://gpmdb.net/). Following this link, users are greeted with the main navigation page (Fig. 3). It contains the general database information, latest news and the main navigation menu bar (for the first release of the GPMDB, only the "Search GPMDB" item is available, with the subsequent menu items to be activated in upcoming releases of the database), and a map of the world displaying all spatial data localities of available rock units. Users can zoom to the area of interest by clicking the "+/−" icon, or by scrolling the mouse (Fig. 4A). Selecting a rock unit shown on the map (Fig. 4B) queries the database and returns the corresponding ROCKUNITNO, ROCKNAME and PMAGRESULT values related to this ROCKUNIT (Fig. 4C). The full paleomagnetic information of the selected PMAGRESULT is displayed as a table popup (Fig. 4D). Users then have the opportunity to export this data as a CSV file and analyze them with their preferred software.

4.2. Search tool

After selecting the "Search GPMDB" menu item, a search window with 20 optional search parameters appears as a popup form (Fig. 5). The list of these parameters is shown in Table 6.

The Query Result is returned as a table (Fig. 6A) with the following columns: REFNO, RESULTNO, YEAR (of publication), AUTHORS, JOURNAL, VPAGES, CONTINENT, ROCKTYPE, LOWAGE, HIGHAGE, LOMAGAGE, HIMAGAGE, SLAT, SLONG, PLAT, PLONG, DP, DM, QSUM and RSUM. The user may need to use the horizontal scroll bar to see all columns. The RSUM column will be mostly empty in the current release as only few R-Factors are included in the data (see section 2.2). The user can sort the Query Result table by any column by clicking on the header of the chosen column. A search function for the Query Result table is found at the top right (Fig. 6A). For example, if we enter the word "Fraser" in the window shown in Fig. 6A, the table will be filtered, displaying only two lines (with ROCKNAMES "Fraser Belt Metamorphics" and "Fraser Dyke"). If we enter "Chamalaun", the table will contain just four lines related to the studies of this author. After erasing of this word from the "Search" window, the table will return into its initial state.

The user can export the Query Result table as a CSV file by clicking 'Save as CSV file'. Additionally, upon a successful database query the world map in the main page will only display those rock unit localities returned by the search criteria (Fig. 6B inset).

To start a new search, or modify the current search parameters, the user must click "Search Again" (Fig. 6A) to display the editable query form containing the parameters of the previous search (Fig. 7A). In the example shown in Fig. 7 we added a minimum value of 5 in the QSUM parameter frame, leaving previously entered parameters unchanged. After clicking "Search" a new Query Result table with just two lines will appear (Fig. 7B) and only two rock units with QSUM >4 will appear on the map (Fig. 7C).

The user can continue this process several times. To restore the original settings, the user can click "Reset Form" which will clear all

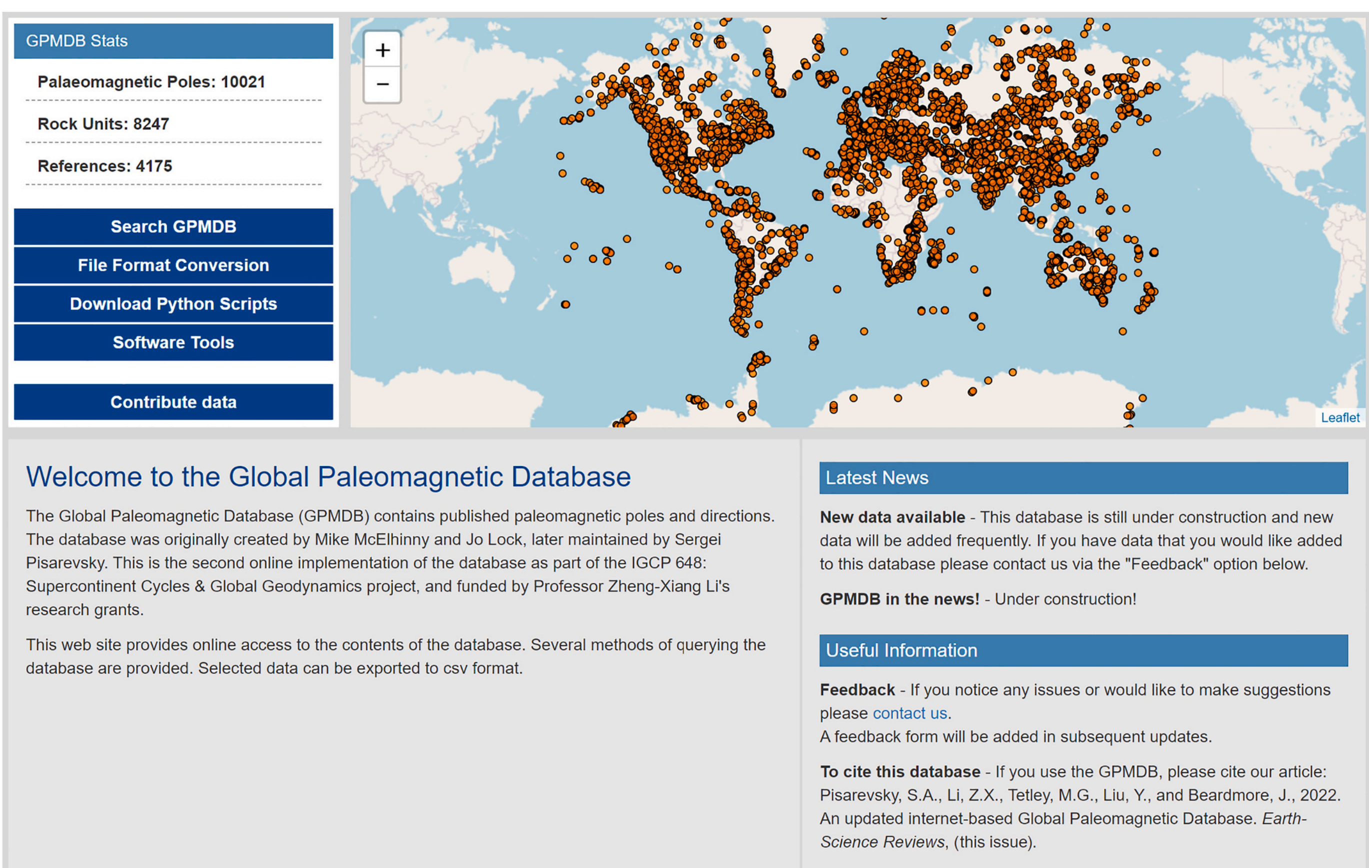
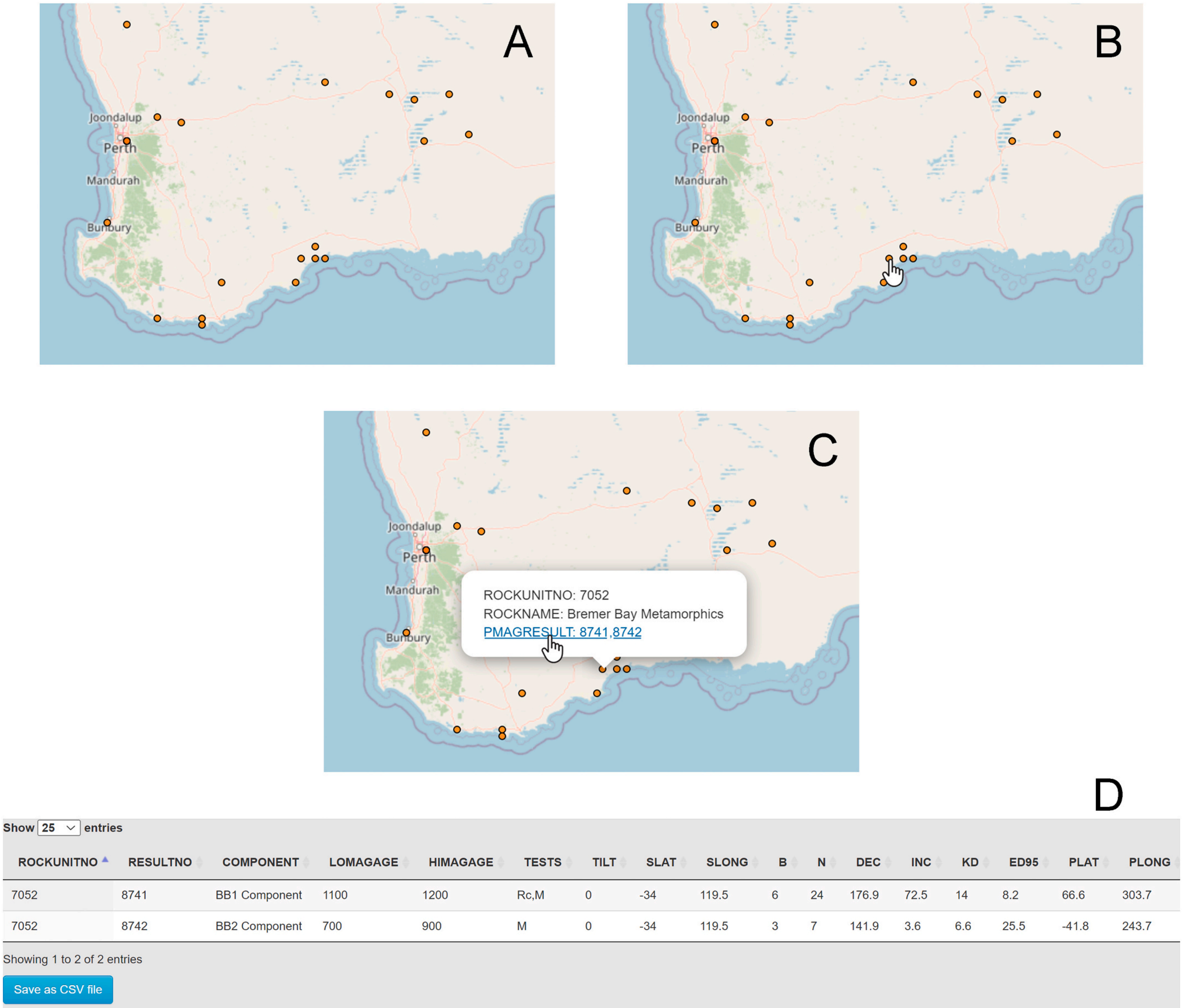


Fig. 3. The main navigation page layout of the GPMDB.



ROCKUNITNO	RESULTNO	COMPONENT	LOMAGAGE	HIMAGAGE	TESTS	TILT	SLAT	SLONG	B	N	DEC	INC	KD	ED95	PLAT	PLONG
7052	8741	BB1 Component	1100	1200	Rc,M	0	-34	119.5	6	24	176.9	72.5	14	8.2	66.6	303.7
7052	8742	BB2 Component	700	900	M	0	-34	119.5	3	7	141.9	3.6	6.6	25.5	-41.8	243.7

Fig. 4. Search by geographic locality.

previously entered parameters, then click “Search”. All rock units on the world map will be displayed again (Fig. 3).

5. Examples of using GPMDB and a comparison of the two quality assessment schemes

5.1. High quality paleomagnetic data

One of the most important considerations in the use of paleomagnetic data to constrain plate tectonic reconstructions is the ability for all users to assess, understand and quantify the quality of the data. However, there are several key reasons why achieving this is an ongoing challenge within both the paleomagnetic and wider scientific community:

1) changing standards with the increasing quality of paleomagnetic research methods;
2) improvement in geochronological dating methods;
3) the provision and clear and up to date communication of available quality evaluation metrics for individual and groups of poles to the growing number of scientists who are not specialists in paleomagnetism, but wish to incorporate paleomagnetic poles in plate tectonic and paleogeographic models.

Legacy paleomagnetic catalogues and many existing paleomagnetic databases do not contain explicit fields quantifying either quality or reliability criteria, with the notable exception of the PALEOMAGIA database (see section 1.4). However, PALEOMAGIA contains only Precambrian data and provides only a “truncated” Q-factor (estimated by database administrators), which excludes the Q7 criterion (no resemblance to paleopoles of younger age). This exclusion of Q7 for Precambrian poles has been fiercely debated among paleomagnetists for many years. However, it is widely acknowledged that Q7 is a useful criterion for Precambrian poles, especially for poles not supported by rigorous field tests. For example, in the current release of the GPMDB, only 19% of Precambrian poles are supported by positive contact, conglomerate and/or fold tests. Moreover, a positive fold test often cannot prove primary remanence (depending on the age of folding, which in many cases is hundreds of millions years younger than the age of the rocks), leaving only 12% of Precambrian poles proven to be primary by positive contact

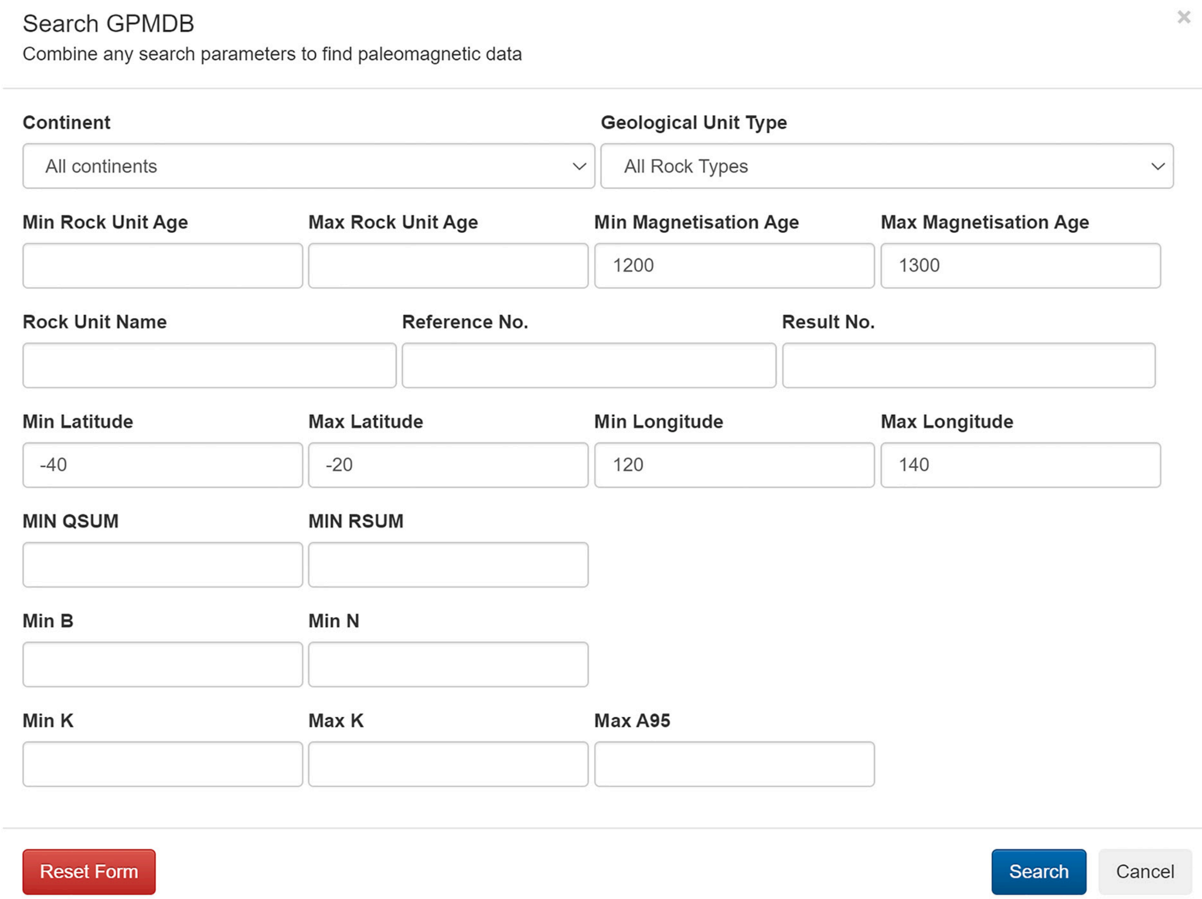


Fig. 5. Search tool, showing the query example: paleomagnetic poles with magnetisation ages between 1200 and 1300 Ma with sample localities with latitudes between 20°S and 40°S and longitudes between 120°E and 140°E.

or conglomerate tests. In our view, this demonstrates the usefulness of Q7 for the quality estimation of Precambrian poles. Recognition of both the importance and notable absence of quality criteria fields in paleomagnetic data compilations was one of the reasons for organizing several paleomagnetic workshops, including the abovementioned 8th Nordic Paleomagnetism Workshop in Leirubakki (Iceland) in 2017 (Brown et al., 2018; Evans et al., 2021). During such workshops, groups of paleomagnetic experts from many countries all over the world evaluate, discuss and quantify the quality of paleomagnetic data, together selecting only the most reliable studies for inclusion in the resulting data publications.

As mentioned above, the current release of the GPMDB contains an additional RELIABILITY table, which contains the values of Q factor of Van der Voo (1990) for all poles in the database, and values of the modified R-factor (Meert et al., 2020) for $n = 180$ poles. The presence of the quality factor in the GPMDB provides an opportunity to select the highest quality paleomagnetic poles by a chosen score, relevant for each particular study in an objective and unbiased way, making the data both more accessible and reliable to non-specialists.

As an example of retrieving high quality poles from the GPMDB, we show two distributions of the number of paleomagnetic poles in age bins of 100 myr with a QSUM >4 (Fig. 8A). There are a total of $n = 2842$ such high quality poles in the GPMDB. 62% of them are younger than 300 Ma, 20% have ages between 300 and 600 Ma, 14% have ages between 600 and 2000 Ma, and 2% are older than 2000 Ma. Fig. 8B shows a similar histogram for the "top" quality poles (QSUM >5), with a total of 994 such poles. Their age distribution is: ≤300 Ma – 62%, 301–600 Ma – 16%, 601–2000 Ma – 14%, and > 2000 Ma – 2%.

The quality factor Q is also important for the construction of apparent polar wander paths (APWPs). For example, a recent algorithm for calculating running mean APWPs uses several parameters, including Q factors of each pole, to assign a weight to this pole in the relevant moving windows (Wu et al., 2021). The weights of all poles that fall within a moving window are utilized to calculate the weighted mean pole for this window. The generated weighted running means can be used as inputs for spline fitting, or directly for paleogeographic reconstructions.

5.2. Q vs R quality factor

To compare Q and R quality factors, we analyzed the difference in quality estimations of paleomagnetic poles by Q and by R from a sample of 180 poles, for which both QSUM and RSUM are present in the RELIABILITY table. Fig. 9 demonstrates the number of poles with RSUM >4 is significantly smaller than the number of poles with QSUM >4, but the situation is reversed for the less reliable results.

Of the sampled data, a total of 98 poles (out of the 180 analyzed, or 54%) returned QSUM = RSUM. For the remaining 82 poles, we found:

- 3 cases when Q1 = 1, but R1 = 0. These are caused by the more strict criteria for the precision of the age.
- 54 cases when Q2 = 1, but R2 = 0. There are two major reasons for this. First, the R2 criterion represents a combination of Q2 and Q3, so if Q2 = 1, but Q3 = 0, then R2 = 0, and secondly, the tougher requirements for statistics introduced by Meert et al. (2020). In particular, the test for averaging PSV. Most of the authors who contributed to the GPMDB in the past did not carry out such tests.
- 40 cases where R3 is different (mainly less) from Q3. This is primarily because Q3 represents adequate demagnetizations and R3

Table 6
Search parameters.

Search parameter	Function / Description
Continent	Default option is "All continents", otherwise one of 12 main modern "continents" and oceans (see Table 1) are to be chosen from the drop-down menu.
Geological unit type	Default option is "All Rock Types", otherwise extrusives, intrusives, sediments, or metamorphics ("key" rocktypes in the ROCKTYPE field of Table 1) can be chosen from the drop-down menu (see section 5.3).
Minimum and Maximum Rock Unit Age / Minimum and Maximum Magnetisation Age	Returns any pole whose age data overlap in any way with these upper and lower bounds. For example, in the query shown in Fig. 5 we selected minimum – maximum magnetisation ages at 1200–1300 Ma for the rock units in SW Australia. The query result (Fig. 6A) includes 9 poles with the following LOMAGAGE-HIMAGAGE pairs (in Ma): 1202–1222, 1150–1250, 1200–1500, 1270–1670, 1000–1480, 650–1800, 650-1800, 650-–1800, 650—3000 (the last four poles with very imprecise remanence ages are from old studies of hematite ores). This approach is intended to help prevent excluding potentially useful poles. Exported data can be further filtered if required.
Rock Unit Name	At present, the user must use the exact spelling as it is in the database (e.g. "Bangemall Sills", not "Bangemall sills"). We are working on making this search parameter more flexible in subsequent releases.
Reference No.	REFNO
Result No.	RESULTNO
Minimum and Maximum Latitude	SLAT (−90° - 90°)
Minimum and Maximum Longitude	SLONG (−180° – 180°)
MIN QSUM	Minimum value of the Q-factor of Van der Voo (1990). Default value is 0.
MIN RSUM	Minimum value of the R-factor of Meert et al. (2020). Default value is 0. *Please note (see section 2) that at present most of the GPMDB poles are not supplied with R-factor.*
MIN B	Minimum number of sites in result.
MIN N	Minimum number of samples in result.
MIN K / MAX K	Minimum / Maximum value of Fisher's precision parameter k (KD).
MAX A95	Maximum value of α_{95} (ED95).

represents identification of magnetic carriers (no analogue in the Q-factor).

- All Q4 are the same as R4.
- All Q5 are the same as R5.
- All Q6 are the same as R6.
- 2 cases with Q7 = 0 and R7 = 1. Both are due to exemptions for the poles with ages supported by rigorous field tests.

The analysis of 180 (out of a total of 10,021) poles can give only preliminary results, however, these suggest the major source of difference between the distributions of QSUM and RSUM (Fig. 9) are the second and third criterions (Q2-Q3 vs R2-R3). In particular, the introduction of tougher requirements for the statistical parameters, demagnetization procedures, introduction of mandatory PSV tests and identification of the magnetic carriers. These factors play a major role in the reduced number of poles with RSUM >4 compared with the number of poles with QSUM >4, and increased number of poles with RSUM <4 compared to the number of poles with QSUM <4. Additionally, the ROCKMAG field in the PMAGRESULT table exists to capture information related to rock magnetic and microscopic identification of magnetic carriers. At present, less than half of all records contain information in this field (4428 out of 10,021 records), so most records have R3 = 0. The introduction of R-criteria will stimulate the inclusion of rock magnetic and microscopic analyses in paleomagnetic studies. It will also motivate workers to increase the quality of sampling and laboratory procedures, in particular for tests averaging PSV.

5.3. Rock types

Some paleomagnetic and rock magnetic studies require the analysis of paleomagnetic data from specific rock types. For example, such datasets may be useful for the investigation of inclination shallowing (e.g. Tauxe and Kent, 2004; Kodama, 2009). The ROCKTYPE field in the ROCKUNIT table contains 4 "key" rock types: extrusives, intrusives, sediments, and metamorphics, with the association of at least one being mandatory (see section 2). To find paleomagnetic data from one of these rock types it is necessary to select it as the "Geological Unit Type" parameter (Fig. 5) from the drop-down menu.

As in previous examples, in Fig. 10 we show the distribution of high quality data by rock type (QSUM >4, Fig. 10A, and with QSUM >5, Fig. 10B). The overall counts (3336 and 1220, respectively) are larger than the abovementioned counts of high quality poles in the GPMDB of 2842 (QSUM >4) and 994 (QSUM >5), respectively. The reason for this difference is that some paleomagnetic poles are calculated from more than one type of rock. For example, a pole is obtained from a study of interbedded sedimentary strata and lava flows (i.e. sediments and extrusives), or from dykes and their baked contacts (i.e. intrusives and metamorphics).

5.4. Inclination shallowing correction

The problem of remanence inclination shallowing in clastic sediments has been known since the pioneering works of King (1955). Verosub (1977) analyzed available data and existing models, concluding that inclination shallowing could occur in various types of clastic sediments during the initial sedimentation processes, but can be compensated for during post-depositional processes (e.g. bioturbation) of magnetic carrier re-orientation in residual water (e.g. Khramov, 1968; Kent, 1973; Lovlie, 1974; Stober and Thompson, 1979). This might explain the absence of inclination shallowing in many cases, demonstrated by analyses of deep sea cores data (e.g. Opdyke and Henry, 1969).

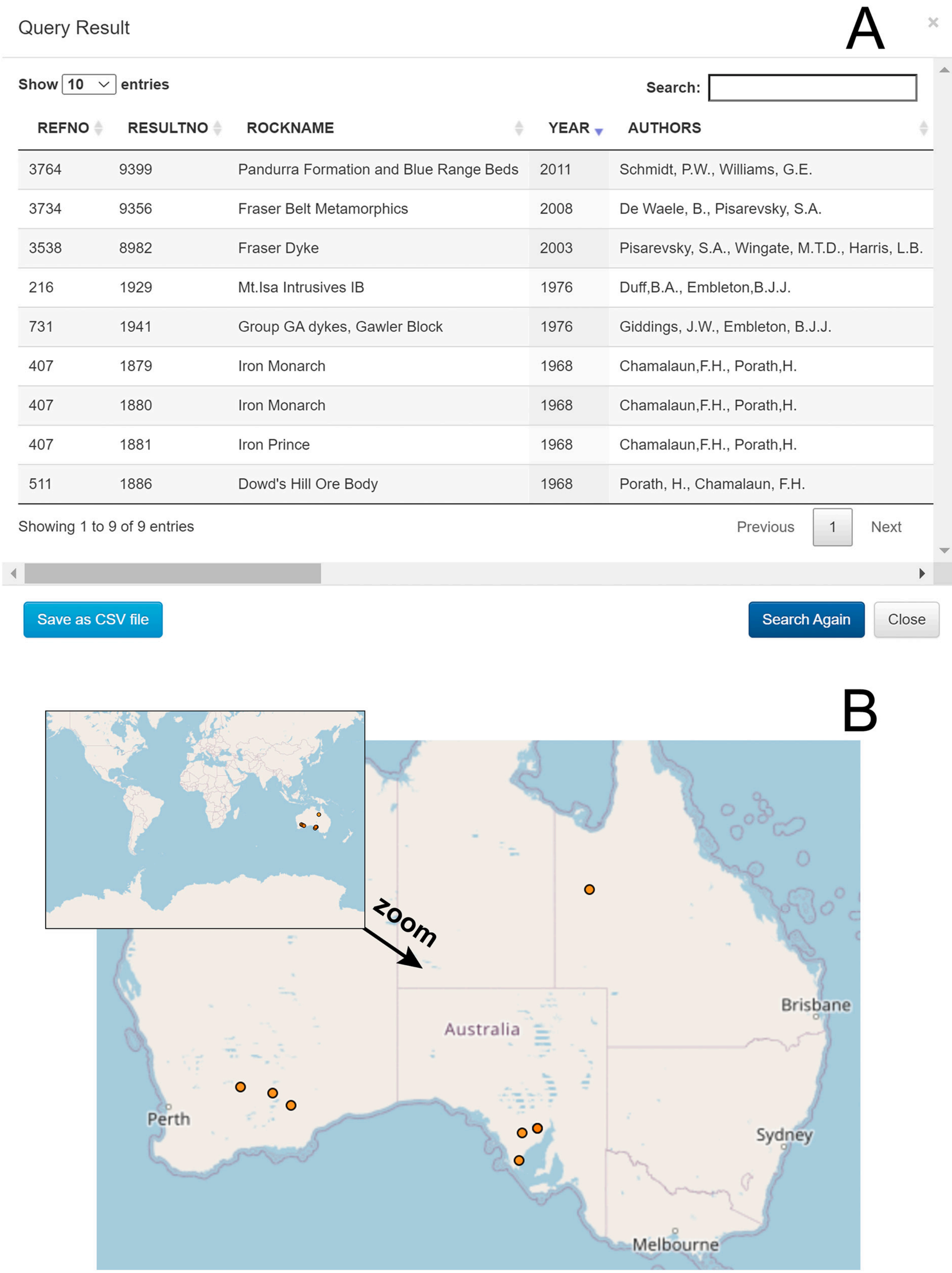
On the other hand, another post-depositional process, sedimentary compaction, can also cause inclination shallowing (e.g., Anson and Kodama, 1987; Kim and Kodama, 2004 and references therein). Compilation of paleomagnetic data for the Central Asian Cenozoic and Mesozoic rocks (Gilder et al., 2003) and their analysis by Tauxe and Kent (2004) demonstrated that the studied sedimentary rocks have systematically shallower remanence inclinations than the coeval igneous rocks. Tauxe and Kent (2004) tested these data with the geocentric axial dipole (GAD) hypothesis and concluded that significant inclination shallowing occurred in the sedimentary rocks studied by Gilder et al. (2003). Similar observations were found in other regions (e.g. Bazhenov and Mikolaichuk, 2002; Van der Voo and Torsvik, 2004; Iglesia Llanos et al., 2006).

The quantitative value of the inclination shallowing correction is represented by the f factor in the following equation:

$$\mathrm{Tan}(\mathrm{INC}_{\mathrm{measured}}) = f\ \mathrm{Tan}(\mathrm{INC}_{\mathrm{corrected}})$$

where INC is the paleomagnetic inclination and $f = 1$ if there is no correction. There are various methods for estimation of f factor. They include:

1. Laboratory redeposition of sediments in an external magnetic field with various inclinations (Tauxe and Kent, 1984).



REFNO	RESULTNO	ROCKNAME	YEAR	AUTHORS
3764	9399	Pandurra Formation and Blue Range Beds	2011	Schmidt, P.W., Williams, G.E.
3734	9356	Fraser Belt Metamorphics	2008	De Waele, B., Pisarevsky, S.A.
3538	8982	Fraser Dyke	2003	Pisarevsky, S.A., Wingate, M.T.D., Harris, L.B.
216	1929	Mt.Isa Intrusives IB	1976	Duff,B.A., Embleton,B.J.J.
731	1941	Group GA dykes, Gawler Block	1976	Giddings, J.W., Embleton, B.J.J.
407	1879	Iron Monarch	1968	Chamalaun,F.H., Porath,H.
407	1880	Iron Monarch	1968	Chamalaun,F.H., Porath,H.
407	1881	Iron Prince	1968	Chamalaun,F.H., Porath,H.
511	1886	Dowd's Hill Ore Body	1968	Porath, H., Chamalaun, F.H.

Fig. 6. Example query result.

2. Elongation/Inclination method (Tauxe and Kent, 2004). This method requires large data sets.
3. Magnetic anisotropy-based method (Kodama, 2009).
4. Comparison of inclination in sedimentary rocks with those in coeval igneous rocks (Iglesia Llanos et al., 2006).

In recent years several studies gave examples where the inclination shallowing correction led to smoother apparent polar wander paths for certain time intervals, producing more accurate plate tectonic models during these intervals (e.g. Van der Voo and Torsvik, 2004; Kent and Irving, 2010).

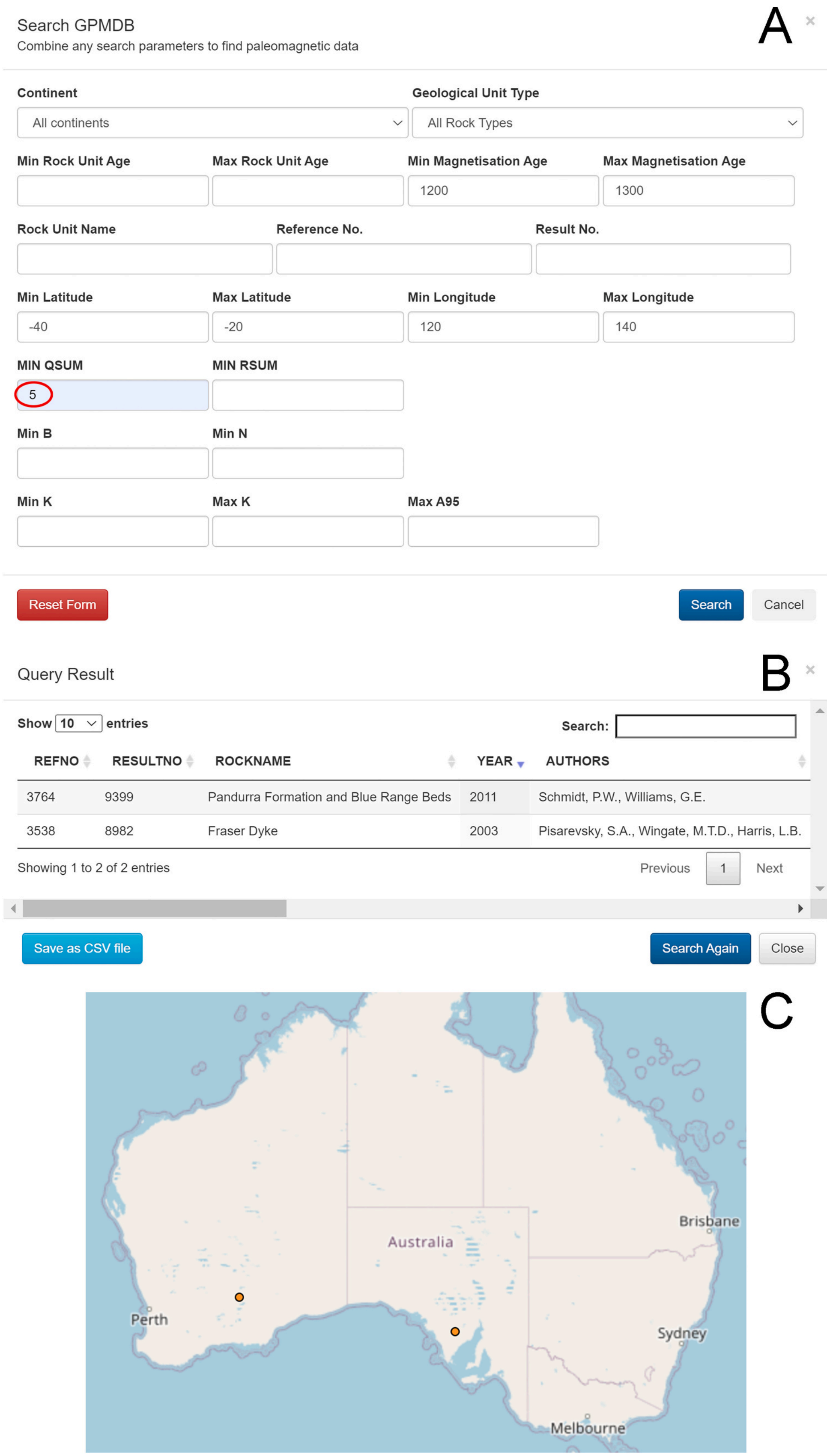


Fig. 7. Modified search: find paleomagnetic poles with magnetisation ages between 1200 and 1300 Ma, and sample localities with latitudes between 20°S and 40°S and longitudes between 120°E and 140°E, and with quality Q-factor (QSUM) >4.

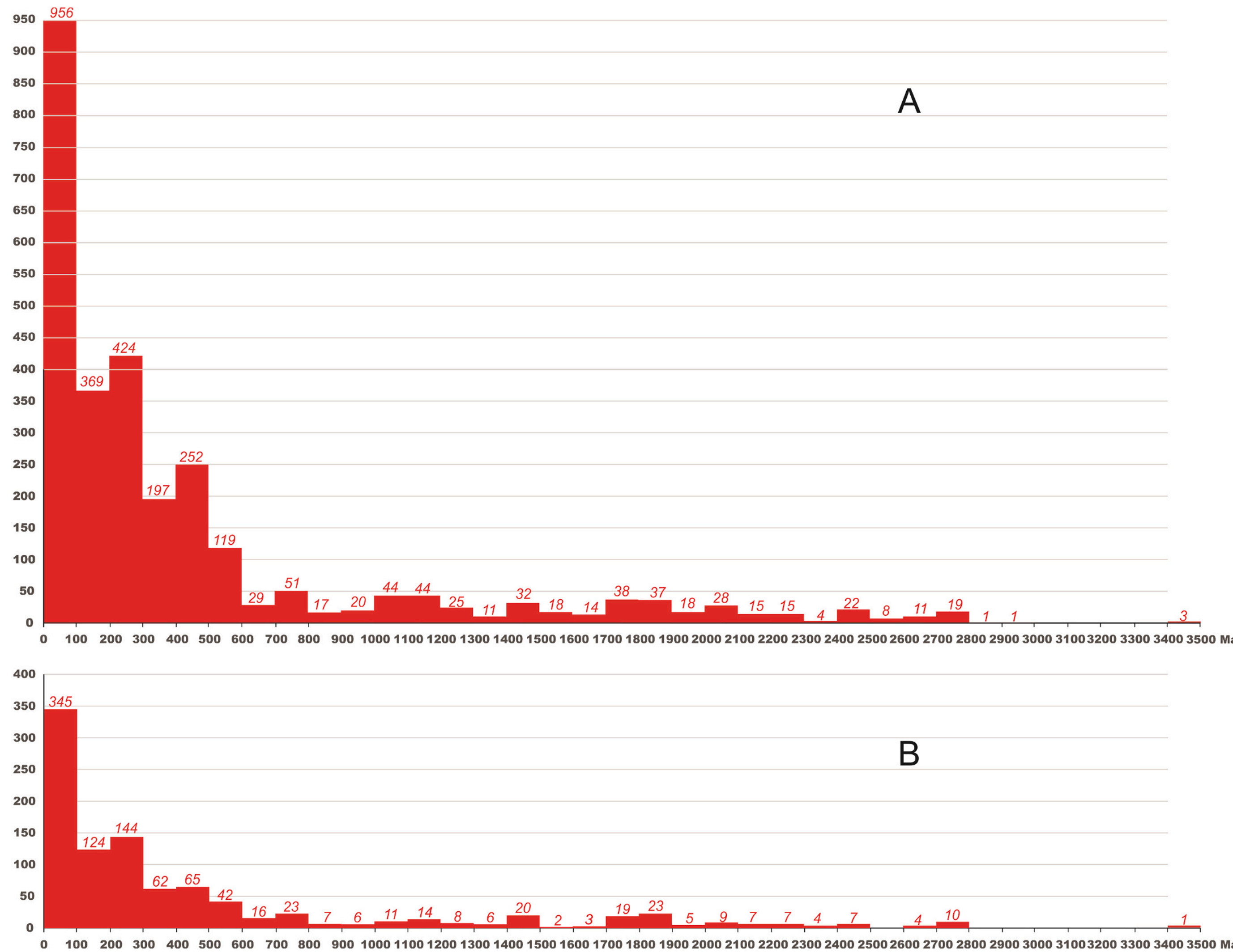


Fig. 8. Numbers of high-quality with QSUM >4 (A) and QSUM >5 (B) paleomagnetic poles with <3500 Ma ages, distributed in 100 myr bins.

In their compilation of Phanerozoic paleomagnetic data, Torsvik et al. (2012) applied a bulk 'constant' inclination shallowing correction of $f = 0.6$ to all data from clastic sedimentary rocks, except to those already corrected in the original publications. Similar approaches have been recently used by other workers (e.g. Wu et al., 2021; Li et al., 2022a). Unfortunately, this release of the GPMDB does not contain sufficient information to allow users to extract data exclusively from clastic sedimentary rocks. However, we are willing to develop and include such a feature in future. As a first step, we standardized datasets where the original authors conducted inclination shallowing correction in the following manner.

The majority of paleomagnetic directions from sedimentary rocks included in GPMDB are not corrected for inclination shallowing. Only about 20 relatively recent studies provide inclination corrected data. For consistency and future database development (in particular, to prevent double-correction when users want to apply a universal correction to relevant datasets, see above), such data are presented in the updated GPMDB (PMAGRESULT table) in the following way. Fields DEC, INC, KD, ED95, PLAT, PLONG, DP, DM contain original data without inclination shallowing correction, and the COMMENT field contains the words "Inclination shallowing corrected by author (f=…):" followed by the corrected data values.

6. Conclusions and future developments

We present a significantly revised and updated online Global Paleomagnetic Database (GPMDB) designed for community access to high quality paleomagnetic data, and to facilitate big-data and machine learning applications to geoscience. Major improvements from the previous GPMDB release in 2004–2005 include: (1) the addition of 762 paleomagnetic poles, bringing the total to 10,021 poles compared to a total of 9259 poles in the 2005 version; (2) the inclusion of both Van der Voo (1990) quality factors (Q) for all poles, and the implementation of the recently revised Meert quality factors (R) for some (this process is ongoing); and (3) a greater range of data search and filtering options.

We shall continue to regularly update the GPMDB database by adding newly published results and by making corrections in the older records where required. *Re*-dating of previously studied rocks and re-estimations of the quality of paleomagnetic data using the R criteria will be the primary, and most frequent causes for such corrections.

One of our first priorities following the release of the GPMDB will be the creation of a community feedback function, which will give users the opportunity to send us their suggestions and comments. We expect that these suggestions will bring our attention to new publications, new geochronological studies for rock units already included in the GPMDB, and to new feature/functionality requests. Such feedback will also help to find and correct any unnoticed errors and typos in the available data.

Depending on feedback and development progress, future releases

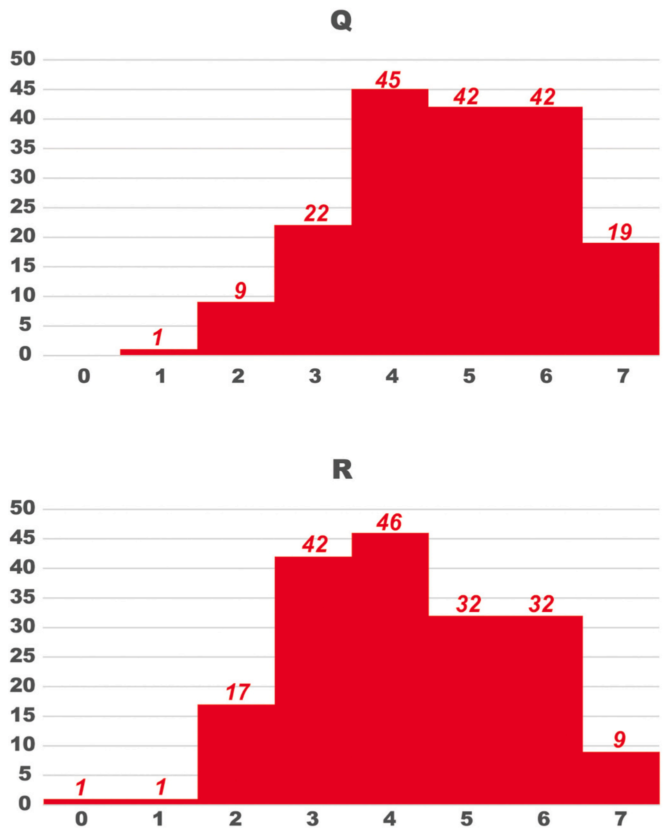


Fig. 9. The distribution of the quality QSUM and RSUM factors for 180 paleomagnetic poles in GPMDB.

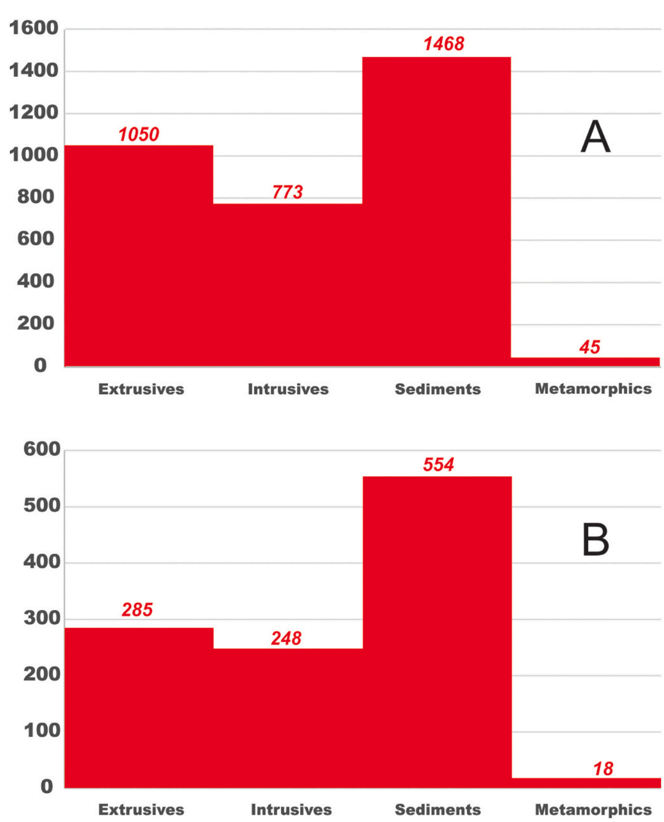


Fig. 10. Distribution of high quality GPMDB data with QSUM >4 (A) and QSUM >5 (B) by rock types.

may include updates to the main menu (Fig. 3) to add active menu items such as "File Format Conversion", "Download Python Scripts", "Software Tools" and "Contribute Data". In particular, we are planning to develop a range of web services for the quick conversion of query results into *GPlates* software supported formats (Boyden et al., 2011; http://www.gplates.org/). These services will include the ability to intersect a given plate model with selected paleomagnetic data to assign a plate id, a digital index, corresponding to the ancient continent, craton, or terrane used in *GPlates* paleogeographic reconstructions (e.g. Merdith et al., 2017, 2021; Müller et al., 2019; Tetley et al., 2019; Li et al., 2013). Additional new menu items may also include an option for inclination shallowing correction of selected data.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

All data used in this article are publicly available from the link provided in the text.

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