MCADAM: A continuous paleomagnetic dipole moment model for at least 3.7 billion years

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Abstract

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Key Points:

- Continuous dipole moment models for the past 3.7-4.2 billion years are presented
- Our model reproduces salient features of the paleomagnetic dipole field
- Paleomagnetosphere estimates suggest Precambrian atmospheric shielding was much weaker than present day

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Abstract

Understanding the evolution of Earth's magnetic field can provide insights into core processes and can constrain plate tectonics and atmospheric shielding. The absolute paleointensity database PINT provides a curated repository of site mean, (i.e., cooling unit), estimates of the strength of the magnetic field. We present a minor update to the PINT database to version 8.1.0 by adding 248 records from 31 studies. The PINT database is used to define a continuous model of the dipole field, using an approach combining nonparametric and Monte Carlo resampling termed MCADAM. Three dipole field strength models spanning 50 ka to 3.7-4.2 Ga (MCADAM.1a-c) are presented, reflecting three tiers of increasingly more stringent data selection. The MCADAM models allow for the estimation of the magnetic standoff distance, constraining the shielding of Earth's atmosphere against solar wind erosion provided by the geodynamo.

Plain Language Summary

The geomagnetic field is a long-lived feature that provides critical shielding of Earth's atmosphere from solar wind erosion. Understanding changes in field strength can provide insight into the evolution of Earth's core. Here we use an updated database of paleointensity estimates to develop new continuous models of the strength of Earth's magnetic field. These models include plausible uncertainties, and capture variations in field strength spanning 50 thousand to over 3.7 billion years ago. Using our models, we suggest that the atmospheric shielding provided by the field was about 60% the present-day shielding for most of the Precambrian.

1 Introduction

The evolution of Earth's deep interior since core formation (Nimmo, 2015) > 4 billion years ago (Ga) remains a topic of considerable study. Obtaining information of the deep interior is generally restricted to present-day observations. Alternatively, insights on processes occurring before the modern era require sampling geologic materials that formed at, or were transported to, Earth's surface. However, the geomagnetic field is generated in the liquid fraction of Earth's core through the geodynamo, and changes in the morphology, strength and variability in the geodynamo may reflect the evolution of core processes and the pattern of heat flux across the core-mantle boundary (CMB). The geomagnetic field is also a critical component for Earth's habitability (Rodríguez-Mozos

& Moya, 2017) due to the protective envelope provided by the magnetosphere against atmospheric erosion by charged solar particles. It is speculated that changes in the paleomagnetosphere may have contributed to substantial changes in the evolution of life (e.g., Meert et al., 2016).

Paleomagnetic studies offer the potential to help close this gap: when rocks bearing magnetic carriers form, the geomagnetic field imparts a remanent magnetization that under ideal circumstances can be robustly preserved for billions of years. The strength of the geodynamo can be described by the magnitude of the dipole moment, the first-degree spherical harmonic component of the field, which should reflect $\sim 90\%$ of the surface field signal. A fundamental question regarding Earth's dynamo is how the dipole moment has changed over long timescales ($\gg$ millions of years). Paleointensities measured from the same geologic time (e.g., from the same cooling-unit, referred to as a "site") can be related to paleointensities from other locations by transforming the paleointensity (B) into a virtual (axial) dipole moment (V(A)DM) using the following equation (Merrill et al., 1996):

$$VDM = \frac{4\pi {R_E}^3}{2\mu_0} B(1+3\cos^2 I)^{0.5}, \tag{1}$$

where R_E is Earth's radius, μ_0 is vacuum permeability, and I is the inclination of the site derived from paleomagnetic directional measurements (there is an equivalent transformation to VADM using site paleolatitude; Merrill et al., 1996). Virtual dipole moment transformations assert that the mean paleointensity measured at the site level can be entirely described by the dipole field, this simplification allows for comparisons of globally distributed observations of field strength.

Characterizing the time-varying paleomagnetic field can be approached using several different methods. On geologically recent timescales ($<$ 100 thousand years, kyr), spherical harmonic models describe the morphology and strength of the field (e.g., Panovska et al., 2018). For the past 2 Myr, a continuous axial dipole moment model (Ziegler et al., 2011) can be constructed using relative paleointensity data from stacked sedimentary records combined with absolute paleointensity estimates, generally from volcanic sources. For longer timescales ($\gg$ 2 million years), dipole moment descriptions are substantially less well resolved. Tauxe and Staudigel (2004) report a mean value for the 0-300 Ma interval, whereas Ingham et al. (2014) and Kulakov et al. (2019) applied a more complex reversible-jump Markov Chain Monte Carlo approach to define Mesozoic trends.

Other approaches, applied to the Precambrian field, include binned data (e.g., Biggin et al., 2015), a low-degree polynomial fit (e.g., Bono et al., 2019), or sliding window average (e.g., Tarduno et al., 2020). These meta-analyses have proven important in providing observational constraints on dynamo and core evolution models (e.g., Biggin et al., 2015; Driscoll, 2016; Bono et al., 2019) and time-averaged and time-varying field estimates (e.g., Selkin & Tauxe, 2000; Ziegler et al., 2011).

In this study, we provide a minor version update to the PINT database (`http://www.pintdb.org/`; Biggin et al., 2009; Bono et al., 2022) that we use as the basis for a dipole moment evolution model (Section 2). In Section 3, we introduce a modeling framework, MCADAM (Monte Carlo Axial Dipole Average Model), that uses a combination of non-parametric site resampling, Monte Carlo simulations, and time-adaptive locally-weighted smoothing to produce a posterior distribution of field strength estimates from which a median dipole strength and associated predictive interval can be determined. Using the MCADAM framework and three filtered datasets from the PINT database that apply increasingly more stringent selection criteria, we present a suite of dipole moment evolution models that yield continuous predictions of the time-average (paleomagnetic) dipole moment extending back to the oldest paleomagnetic records from > 4 Ga, and compare these models with other time-average descriptions of field strength in deep time (Section 4) and the associated impact on the paleomagnetosphere (Section 5).

2 Updates to PINT v8.1.0

The PINT database, a curated repository of absolute paleointensity records derived from volcanic sources and reported at the site mean level with associated meta-data, underwent a significant update to version 8.0.0, and we refer readers to Bono et al. (2022) who describe the current structure of the database and broadly summarizes the distribution and quality of the paleointensity dataset. The most salient changes in PINT v8.0.0 with respect to prior versions of the PINT database (Biggin et al., 2015) are the inclusion of new paleointensity data published through the end of 2019, the removal of demonstrably biased paleointensity records (so-called "auto-zeros"), and the integration of Q_{PI} assessments for over 90% of the database. Q_{PI} (Quality of Paleointensity; Biggin & Paterson, 2014) is a semi-quantitative framework to describe the reliability of a site mean paleointensity record, and we again refer readers to Bono et al. (2022) for a complete description of Q_{PI} implementation in PINT v8.0.0.

In this study, we include a minor version update of PINT to v8.1.0 (Figure 1) that includes paleointensity records published in 2020 through July 2022. Included studies are not exhaustive of entire paleointensity dataset published during this interval, however, it represents a good-faith effort to identify as many relevant studies as possible. In total, 248 new sites from 31 studies have been added to the PINT v8.1.0 database, increasing the total number of site mean records (N_{Sites}) to 4601. These data include contributions constraining the field during the Cambrian/Ediacaran (e.g., Thallner, Biggin, & Halls, 2021; Thallner, Biggin, McCausland, & Fu, 2021; Thallner et al., 2022; Zhou et al., 2022) and Neoproterozoic (e.g., Lloyd, Biggin, Halls, & Hill, 2021), which remain under-sampled relative to other geologic intervals.

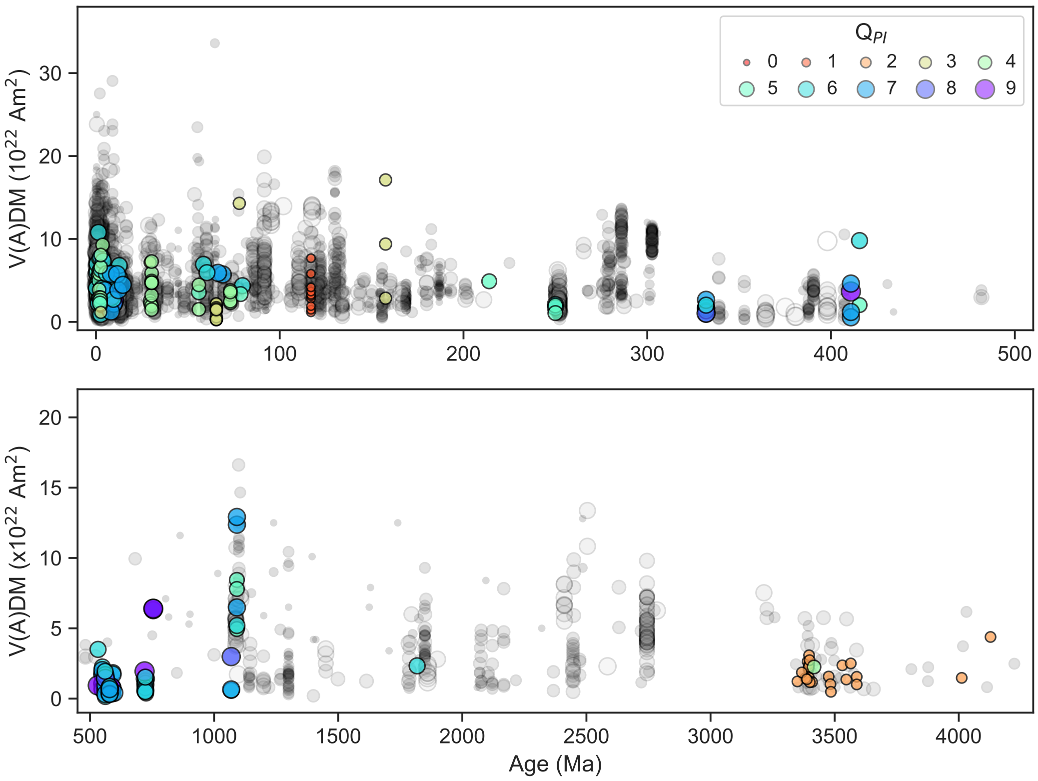

Figure 1. PINT v8.1.0 absolute paleointensity database. Colored circles show site mean records added since v8.0.0 (Bono et al., 2022); grey circles are data in v8.0.0. Symbol size and color shows Q_{PI} score. Top: Phanerozoic; bottom: Precambrian.

Q_{PI} criteria allow for a semi-quantitative, objective definition of requirements to filter data from the PINT database, with the goal of improving the robustness of meta-analyses (Biggin & Paterson, 2014; Bono et al., 2022). Field strength estimates are inherently challenging to extract from the rock record. Paleointensity specimens may be compromised by the presence of non-ideal magnetic recorders (e.g., multidomain grains) and/or laboratory alteration. The potential for remanences to be reset by thermal or chemical over-printing after emplacement must also be excluded before accepting a measured paleointensity as valid and meaningfully linked to the emplacement age. Since the data may reflect some non-ideal paleointensity biases, some fraction of the site mean data should be excluded from analyses in order to improve the robustness of any resulting conclusions drawn from using the PINT database. However, paleointensity data are sparse and imperfect individual records may still yield meaningful inferences in aggregate. Thus it is crucial to define selection criteria that balance data quality with data availability, specifically for the development of time-averaged and time-evolution field descriptions on million-to-billion-year timescales. Meta-analyses considering other topics will, of course, result in different optimal selection criteria choice.

Three different selection criteria are employed for model development (previously presented in Bono et al. (2022)). In addition to the following selection criteria, sites explicitly described as having a transitional polarity were excluded from all datasets. The first two filters are (a) all data (N_{Sites}: 4194) and (b) Q_{PI} $\geq$3 (N_{Sites}: 2283). The third filter (c), introduced by Kulakov et al. (2019), prioritizes records passing specific Q_{PI} criteria (N_{Sites}: 976). We require evidence that the site age is well constrained and the primary remanence is associated with the age estimate (QAGE) and there were experimental controls to limit the influence of laboratory alteration (QALT) and non-ideal (i.e., multidomain) magnetic carriers (QMD). We note that Smirnov et al. (2016) and Bono et al. (2019) previously identified paleointensity data which potentially under (over) estimate field strength by fitting the shallow (steep) components of two-slope or concave Arai diagrams. Since this level of analysis was not applied to all records within PINT v8.1.0, we have not excluded the identified sites *a priori*, however, we distinguish sites that may be biased in Figure 2b and all but two sites are independently excluded using our "strict" prioritized Q_{PI} selection criteria.

3 Time-varying paleofield models with uncertainties

Here, we consider whether a continuous time-varying dipole moment model can be realized for the entire paleointensity record. Ideally, this model should take several factors into consideration; we chose to focus on the following requirements:

1. Data selection should balance quality with availability of data.
2. Not be overly sensitive to any given data point due to the sparse and non-uniform distribution of paleointensity site mean data.
3. Reflect the uncertainty of individual site mean estimates in both age and field strength.
4. Seek to average secular variation, taking into account the increasing sparsity of data going further back into geologic time.

To meet these requirements, we employ a combination of techniques, which we refer to as a Monte Carlo Axial Dipole Average Model (MCADAM). The modeling framework was tested using a synthetic data set with a known "true" dipole moment and a temporal distribution derived from PINT v8.1.0 (Supplementary Text S1, Supplementary Fig. S1). The MCADAM time-varying model is constructed as follows:

1. Randomly resample the selected sites with replacement (similar to bootstrap sampling, following Efron and Tibshirani (1993)). A non-parametric resampling approach is preferred since the temporal distribution of paleointensity records is highly non-uniform. Unlike a formal bootstrap, duplicate samples are discarded, resulting in a realization with the same or fewer records than the entire selected data set. In this sense, we employ a conservative resampling technique.
2. For each resampled site mean, we use Monte Carlo (MC) resampling to generate a new dipole moment and age constrained by the site mean and variance. Each dipole moment realization is calculated from a random realization of inclination (drawn from a Fisher distribution with k precision parameter from the PINT record) and a site mean field intensity (B) drawn from a normal distribution with a mean defined from the record. The variance for field strength, σ_B^2, is determined from the unbiased estimate of standard deviation (Holtzman, 1950). In cases where site mean inclination is unavailable, the MC realization is drawn from a Fisher distribution with a mean inclination of 30.6° and k of 15, which describes a distribution approximately covering the entire hemisphere. In cases where paleointensity uncertainty is unavailable, σ_B is set to 20% of B (estimated from the median dBn(%) of the entire PINT database). Similarly, if there is no uncertainty in site mean age, a standard deviation of 10% the site mean age is assigned (arbitrarily chosen based on the upper uncertainty bound for QAGE).

3. A weighted average is found for each sample using the weighting kernel defined below, based on a LOWESS averaging method (Cleveland (1979); also described as a Savitzky and Golay (1964) filter). For each point in the resampled record, define a weighting kernel:

   - Kernel shape is defined using a tricube function where weights range from 0 to 1 centered on sample age with a prescribed bandwidth outside of which the weight is 0.

   - Bandwidth is defined as the minimum age interval that both samples at least 5 sites and the maximum of either 250 kyr or 2% of the age of the site (e.g., at least 76 Myr at 3.7 Ga), up to a maximum of 500 Myr. If there are fewer than 5 sites within a 500 Myr interval, that point in the realization is dropped.

4. To ease compilation, since each realization will return different number and distribution of time steps, a linear interpolated curve with uniform, high-resolution time steps (here, 50 kyr) is determined from the weighted average for each realization.
5. Steps 1-4 are repeated a large number of times (e.g., 10^4).
6. Average statistics (mean, standard deviation, median, mode, 75% and 95% intervals) for each step in the set of interpolated curves are determined.

4 Comparing MCADAM to other compilations

Applying the MCADAM approach with the PINT v8.1 dataset restricted by the three selection filters previously discussed (Section 2), the resulting time-varying models (MCADAM.1a-c) are presented in Figure 2 and available for download in the EarthRef Data Archive (`http://www.earthref.org/ERDA/2537/`). Our preferred model is MCADAM.1b, which uses a moderately restrictive data selection requiring that paleointensity site records meet at least three of the Q_{PI} criteria. In general, these models reproduce several characteristic features previously observed in the paleofield (Figure 3 and Supplementary Figures S2-S3), such as rise in field strength from the Matuyama to Brunhes chrons, intervals of high field strength during the Cretaceous Normal Superchron preceded by a weaker field (cf. Kulakov et al., 2019), and a high field during the Kiaman Superchron (e.g., Cottrell et al., 2008) preceded by sustained weak field during the Devonian (Hawkins et al., 2019). For the 50 kyr to 2 Ma interval, there is good agreement between our model and

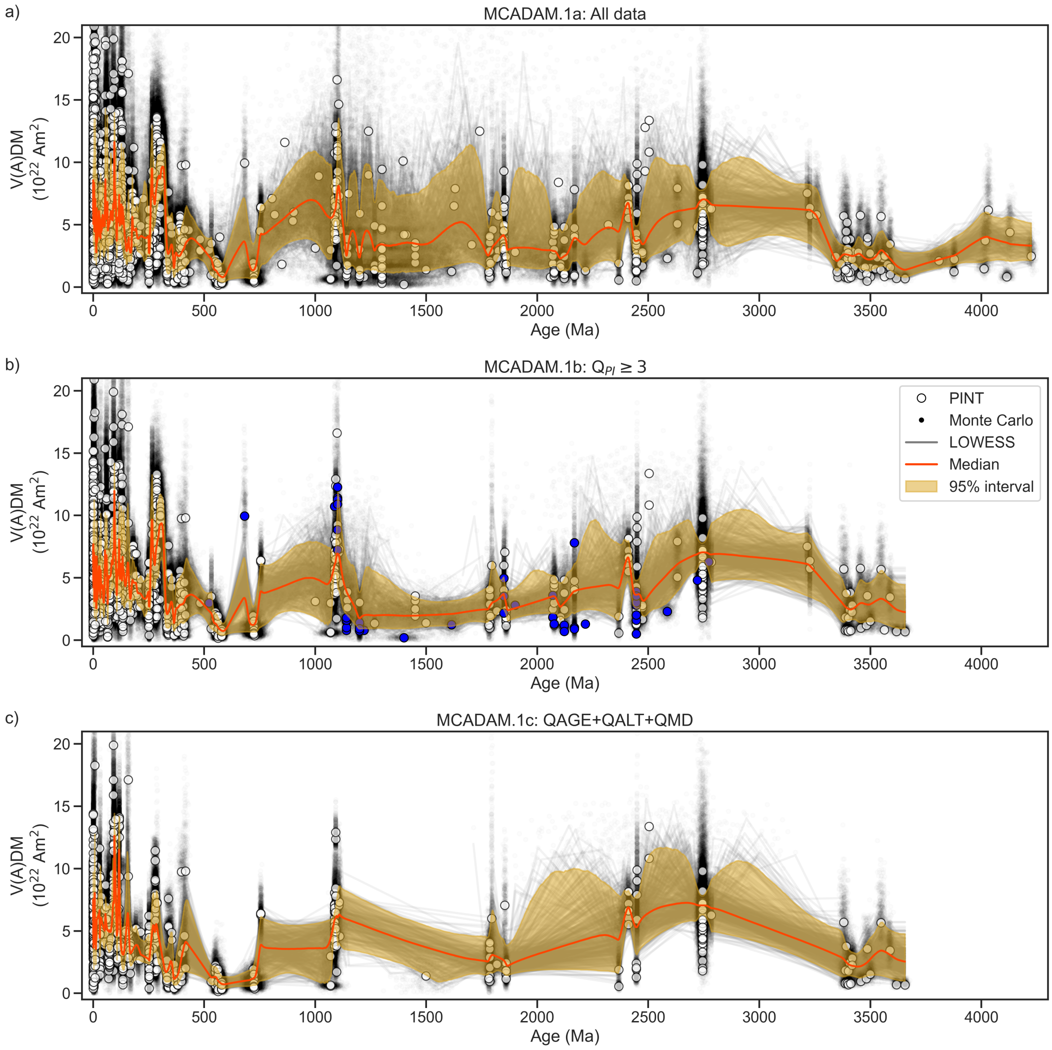

Figure 2. MCADAM time-varying model of dipole strength for the past 3.7 to 4.2 billion years from PINT v8.1.0 data. White circles: selected site mean V(A)DMs; black points, Monte Carlo realizations; grey lines, individual interpolated realizations; orange line, median dipole moment with shaded 95% interval. a) MCADAM.1a, all non-transitional polarity data in PINT v8.1.0; b) MCADAM.1b, Q_{PI} $\geq$3, blue circles mark sites that may be biased as identified by Smirnov et al. (2016) or Bono et al. (2019); c) MCADAM.1c, prioritized Q_{PI}.

that of PADM2M (Ziegler et al., 2011). Given the denser temporal sampling during the Phanerozoic, more variation in the field can be resolved with a smaller confidence interval for the resulting model relative to the Precambrian.

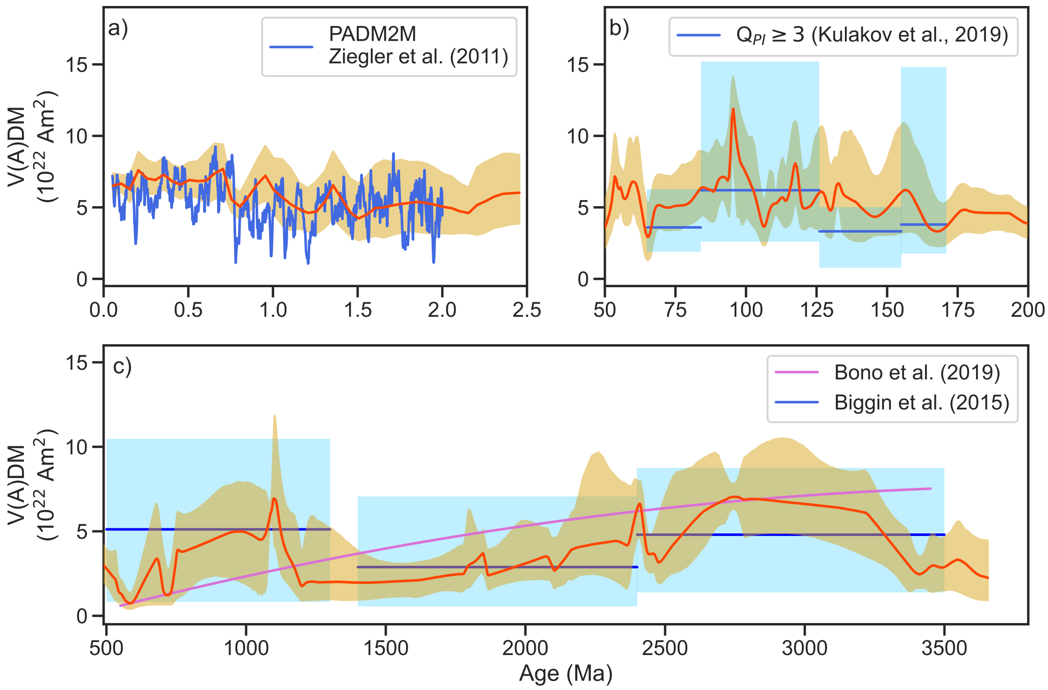

Figure 3. MCADAM.1b time-varying model of paleofield strength for the past 3.7 billion years from PINT v8.1.0 data meeting $Q_{PI} \geq$ 3 criteria. In all panels, the orange line represents the median time-varying model from MCADAM.1b with shaded 95% interval. a) Quaternary; blue line shows PADM2M model (Ziegler et al., 2011); b) Mesozoic; blue line and field shows median and 95% interval estimates of (Kulakov et al., 2019); c) Precambrian; purple line shows polynomial fit of Bono et al. (2019), blue lines show bin medians with shaded 95% confidence intervals of Biggin et al. (2015).

The Paleozoic through the Precambrian poses the greatest challenge for characterizing the time-varying field due to large gaps in the PINT database. In our model, we use a linear interpolation between sampling, however given that intervals spanning ∼100 Myr may not sample the field at all, it is almost certain there are field variations that are not captured in our model. Given the combination of non-parametric resampling for site selection, the Monte Carlo resampler, and locally-weighted regression, therefore, the MCADAM should represent an overly smoothed description of the time varying field, particularly where the data are are sparse. Despite our best efforts, in intervals when data is particularly sparse the model may be susceptible to bias from anomalous data For example, in Figure 2, the difference between MCADAM.1b and MCADAM.1c at ∼680 Ma due to the contribution of a potentially biased record; the authors of the study reporting the anomalous site mean paleointensity, Salminen et al. (2006), explicitly acknowledge the potential for high-field bias in their data. We note that the oldest field records of the Archean are dominated by the Thellier-Coe zircon experiments of Tarduno et al. (2015, 2020), which due to their lack of orientation, represent a source of uncertainty in our model during the Eoarchean/Hadean. The fall and rise in field strength during the Mid- to Late- Proterozoic (as suggested by Biggin et al., 2015) is supported by our model, as well as the drop in field strength at the end of the Proterozoic reported in Bono et al. (2019).

There are some general differences in the analyses of Biggin et al. (2015), Bono et al. (2019) and our study that can explain the apparent disagreement in estimated field trends. First, there are differences in the data sets used between both analyses, as summarized by Bono et al. (2019). Second, Biggin et al. (2015) divided the data sets into Early, Mid and Late Proterozoic bins and summarized the statistical properties each bin. Bono et al. (2019) focused *a priori* on estimates from slow-cooling intrusives (or select sites demonstrating time-averaged statistics) resulting in a substantially reduced data set compared to either this study or Biggin et al. (2015), and from this restricted data set fit a 2^{nd} degree polynomial trend. In this study, we forgo both dividing the data into prescribed bins or focusing *a priori* on intrinsically time-averaged records. Our study uses a broader dataset, supplemented by new data published since the prior studies, that results in more variation in the interpreted dipole field strength relative to prior work.

5 Implications for the paleomagnetosphere

The geodynamo and the associated magnetic field extending into space provides shielding of Earth's atmosphere and surface water from erosion due to solar wind (Tarduno et al., 2014). In addition to increasing erosion of the atmosphere, reductions in magnetic shielding can drive breakdown of atmospheric ozone, which limits penetration of UVB radiation (Glassmeier & Vogt, 2010). Currently, modelling the paleomagnetosphere in detail requires fully coupled dynamo and solar activity simulations beyond the scope of what is available. However, a first-order approximation can be estimated using a series of reasonable simplifications, chiefly that the field is axial dipole-dominated (Biggin et

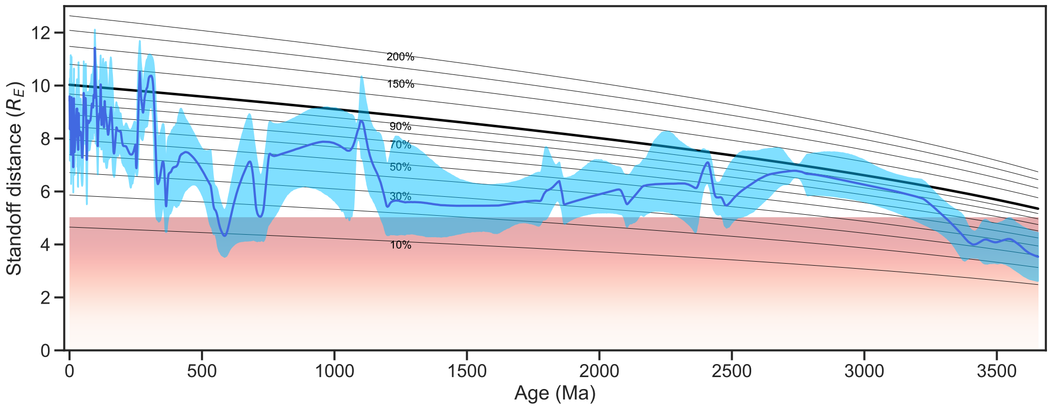

Figure 4. Magnetopause standoff distance estimate using equation 2 and the MCADAM.1b modeled dipole moment curve with PINT v8.1.0 data meeting $Q_{PI} \geq$ 3 criteria. Blue curve is the predicted median dipole moment and blue field is the 95% predicted interval. Contour lines show standoff distance relative to the present day dipole field. Red gradient shows standoff distance associated with the Halloween 2003 solar storm (Rosenqvist et al., 2005).

al., 2020) and that magnetic shielding can be approximated by the magnetic standoff distance, or magnetopause, where solar wind pressure is balanced by the repelling force of a dipole field (Siscoe & Sibeck, 1980). The present-day magnetopause is $\sim 10\ R_E$ (Earth radii) and will fluctuate on annual timescales as the magnetic pole moves about the spin axis (Shue et al., 1997).

Following the approach of Tarduno et al. (2010), the magnetic standoff distance, $R_s(t)$ for a given time t, can be estimated (Siscoe & Chen, 1975) by

$$R_s(t) = \left[\frac{\mu_0^2 f_0^2 M_E(t)^2}{4\pi^2(2\mu_0 P_{SW}(t) + B_{IMF}^2)}\right] \quad (2)$$

where μ_0 is vacuum permeability, f_0 is a field shape parameter for the magnetosphere (1.16 for present day Earth, Voigt (1995), held constant here), and B_{IMF} is the interplanetary field (which is neglected in our calculations since it is small, $\ll 10$ nT). $M_E(t)$ is the (paleo)magnetic dipole moment as a function of time. $P_{SW}(t)$ is the solar wind ram pressure, which is dependent on the mass loss rate of the sun and velocity of solar wind as a function of time. Extrapolating present day P_{SW} ($\sim$1.915 nPa; Shue et al., 1997) back through time can be done with power-law model $(t/t_0)^{-2.33}$ based on solar analogs (e.g., Wood et al., 2005), at least until the young Hadean sun.

Using MCADAM the magnetic standoff distance from 50 ka to 3.7-4.2 Ga can be estimated (Figure 4 and Supplementary Figures S4-S5). The magnetopause responds rapidly to changes in either solar wind activity or the geomagnetic field and will vary by ∼1-2 R_E during typical space weather (Voigt, 1995). Coronal mass ejections and solar flares can suppress the standoff distance by half (e.g., the Halloween 2003 event was observed to reduce the magnetopause to $\sim 5\ R_E$; Rosenqvist et al., 2005). While short term reductions ($\ll$ millions of years) in magnetic shielding are unlikely to impact the biosphere significantly, protracted intervals of reduced shielding may have affected evolutionary processes (e.g., Meert et al., 2016; van der Boon et al., 2022). Our analysis suggests that for the Precambrian the combination of the generally weaker dipole field and the increased solar wind associated with a younger, more active sun resulted in a long-term average standoff of $\sim 6\ R_E$, which is about 60% the present-day distance and consistent with early Archean estimates (Tarduno et al., 2010). Individual time-averaged estimates (on million-year or shorter timescales) suggest there were intervals with even further reduced standoff distances (e.g., the Ediacaran or Devonian; Meert et al., 2016; van der Boon et al., 2022). These values represent a baseline standoff distance, which could be further reduced due to internal changes in the field (e.g., reduction or loss of dipolarity) or increases in solar wind activity (e.g., coronal mass ejections, solar flares). This implies that during the Precambrian, atmospheric shielding by the magnetic field was potentially tenuous despite the robust, albeit weaker than present day, dipole field.

6 Conclusions

Using an updated PINT database, we have developed a new continuous dipole field modelling approach (MCADAM). Based on three approaches of selection data using Q_{PI} criteria, our MCADAM models can robustly recover the average dipole field strength and captures key features previously identified in the Quaternary, the Mesozoic, and the Precambrian.

Paleomagnetic standoff distance is estimated using our preferred model MCADAM.1b and suggests that following the earliest Archean, the Precambrian standoff distance was $\sim 6\ R_E$. At the end of the Precambrian, the paleomagnetosphere experienced a protracted ($\sim 20-100$ Myr) minima during the Ediacaran, that was followed by a highly variable, generally (but not monotonically) increasing standoff distance in the Phanerozoic.

The MCADAM models produce a continuous description of the time-averaged paleomagnetic field strength, accompanied by plausible uncertainty bounds defined by the underlying data, spanning an interval starting 50 ka and extending into the earliest Archean. We envision that the MCADAM approach will help bridge the gap between discrete paleomagnetic observations and both geodynamical and paleomagnetospheric investigations that require predictive time series grounded in empirical datasets.

Acknowledgments

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Open Research – Data Availability

PINT v8.1.0 is available at `http://www.pintdb.org/`. MCADAM.1a-c model outputs are available in the EarthRef Data Archive at `http://www.earthref.org/ERDA/2537/`.

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Supporting Information for "MCADAM: A continuous paleomagnetic dipole moment model for at least 3.7 billion years"

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1. Text S1

2. Figures S1 to S5

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Additional Supporting Information (Files uploaded separately)

1. PINT v8.1.0 database. Available at `http://www.pintdb.org`, see website or Bono et al. (2022) for complete description.

2. MCADAM.1a – MCADAM.1c. Available at `http://www.earthref.org/ERDA/2537/`.

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Columns:

(i) `0..N` : Time step index

(ii) `age` : Age step realization (Ma)

(iii) `mean` : MCADAM mean dipole (1e22 Am^2)

(iv) `std` : MCADAM dipole standard deviation (1e22 Am^2)

(v) `mode` : MCADAM dipole mode (1e22 Am^2)

(vi) `2.5%` : MCADAM dipole 2.5% percentile (1e22 Am^2)

(vii) `25%` : MCADAM dipole 25% percentile (1e22 Am^2)

(viii) `50%` : MCADAM dipole 50% percentile (1e22 Am^2)

(ix) `75%` : MCADAM dipole 75% percentile (1e22 Am^2)

(x) `97.5%` : MCADAM dipole 97.5% percentile (1e22 Am^2)

Text S1. MCADAM sensitivity testing

To test the ability for the MCADAM modeling approach to recover true temporal variation of the average paleomagnetic field, we conducted a series of synthetic tests exploring models sensitivity to sampling density and distribution, as well as the data uncertainty in site mean age and dipole moment. We first define a “true” time-varying dipole field, here a combination of sine waves with the variation of PADM2M (Ziegler et al., 2011) superimposed over the baselines signal. Site mean age distributions are defined to mimic the PINT v8.1.0 distribution of ages. Synthetic paleointensity samples are realized from this “true” mean trend using a Gaussian distribution with a mean corresponding to the mean field predicted by the true dipole moment and a σ inferred from PINT v8.1.0, this variation represents a combination of secular variation and measurement noise, and Gaussian draw for the site age with increasing age uncertainty from 100 kyr to 20 Myr depending on site age ($<$ 1 Myr and $>$ 1 Gyr, respectively). While the “true” mean field does not resemble the paleomagnetic field, and the variation is arbitrarily defined, visually this synthetic field record appears to share broadly similar features to the paleomagnetic record in the PINT v8.1.0 database such that we feel it represents a reasonably synthetic analogue for sensitivity testing. The MCADAM modelling approach is applied to this synthetic dataset, using the synthetic VDM realizations to estimate the mean dipole field strength.

The results of these sensitivity tests demonstrate that generally the modeling approach is capable of reproducing the “true” median field temporal trend within the 75-95% interval of time trends. The MCADAM-derived model was able to estimate the true field strength within the 95% predictive interval over 99% of the time, within the 75% predictive interval over 80% of the time, and yields a root-mean-square misfit of 1.7 ZAm^2. Visually, the MCADAM model's predictive interval reacts appropriately for the data density and distribution, with the predictive interval shrinking when the density of observations is high and enlarging when the density is low or the scatter is high.

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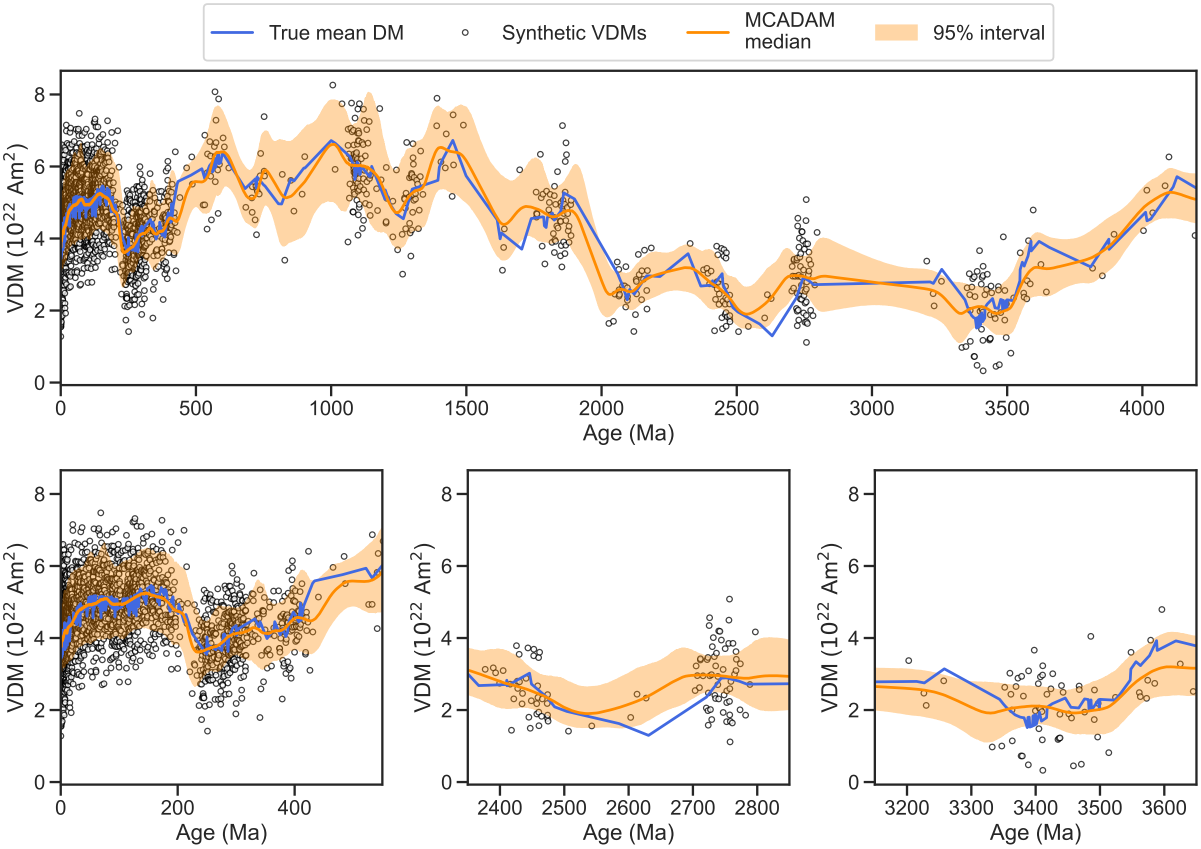

Figure S1. Synthetic test of MCADAM using a known dipole mean field with realistic variation. Blue line: true mean dipole moment; grey circles: synthetic VDMs drawn from true mean dipole moment with plausible variance; orange line and field, MCADAM model median field strength estimate and 95% predictive interval.

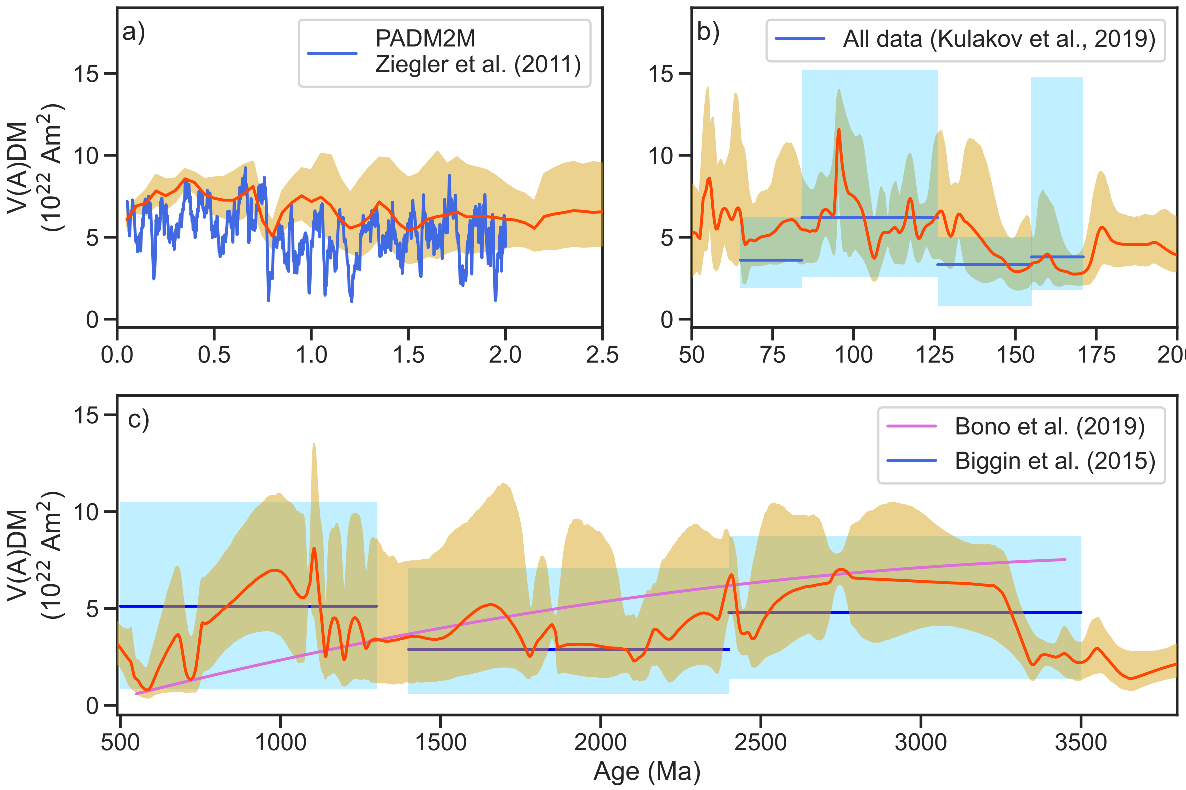

Figure S2. MCADAM.1a time-varying model of paleofield strength for the past 3.7 billion years from all non-transitional sites in the PINT v8.1.0 database. In all panels, the orange line represents the median time-varying model from MCADAM.1b with shaded 95% interval. a) Quaternary; blue line shows PADM2M model (Ziegler et al., 2011); b) Mesozoic; blue line and field shows median and 95% interval of Q_{PI} binned following (Kulakov et al., 2019); c) Precambrian; purple line shows polynomial fit of Bono et al. (2019), blue lines show bin medians with shaded 95% confidence intervals of Biggin et al. (2015).

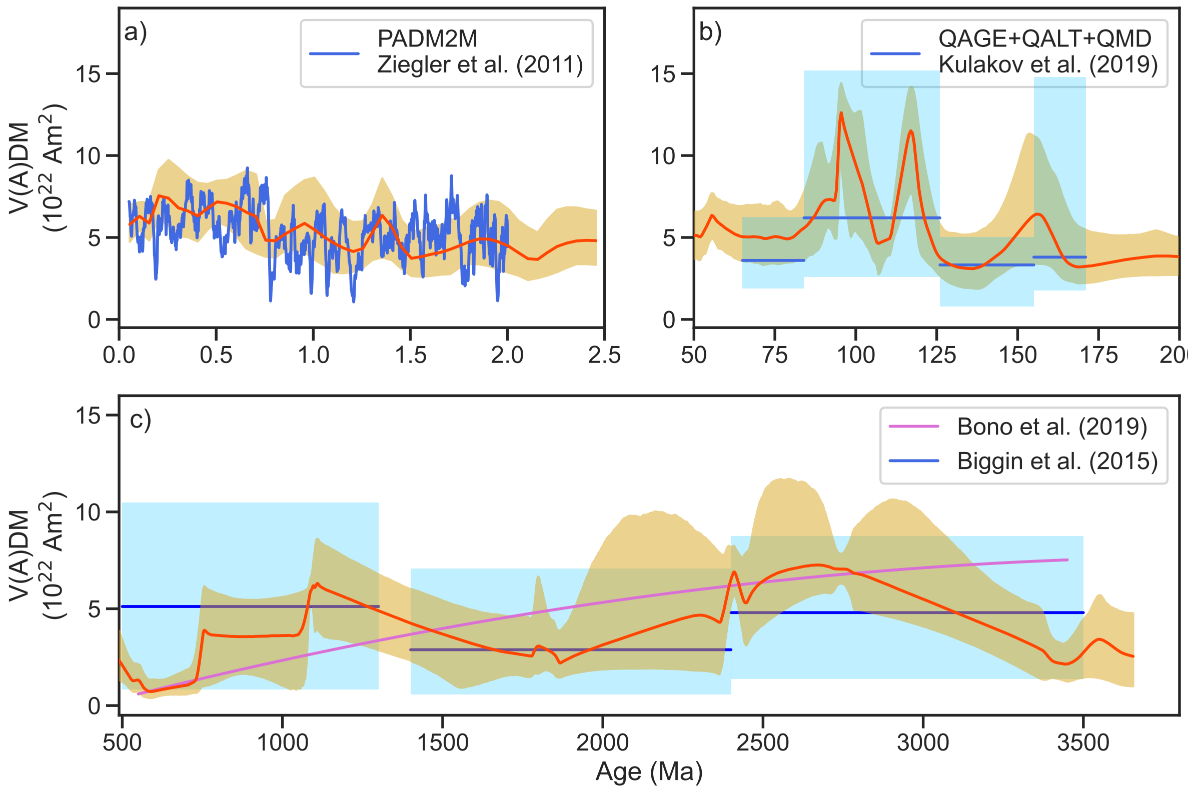

Figure S3. MCADAM.1c time-varying model of paleofield strength for the past 3.7 billion years from PINT v8.1.0 data meeting the prioritized Q_{PI} criteria: QAGE + QALT + QMD. In all panels, the orange line represents the median time-varying model from MCADAM.1b with shaded 95% interval. a) Quaternary; blue line shows PADM2M model (Ziegler et al., 2011); b) Mesozoic; blue line and field shows median and 95% interval of Q_{PI} binned following (Kulakov et al., 2019); c) Precambrian; purple line shows polynomial fit of Bono et al. (2019), blue lines show bin medians with shaded 95% confidence intervals of Biggin et al. (2015).

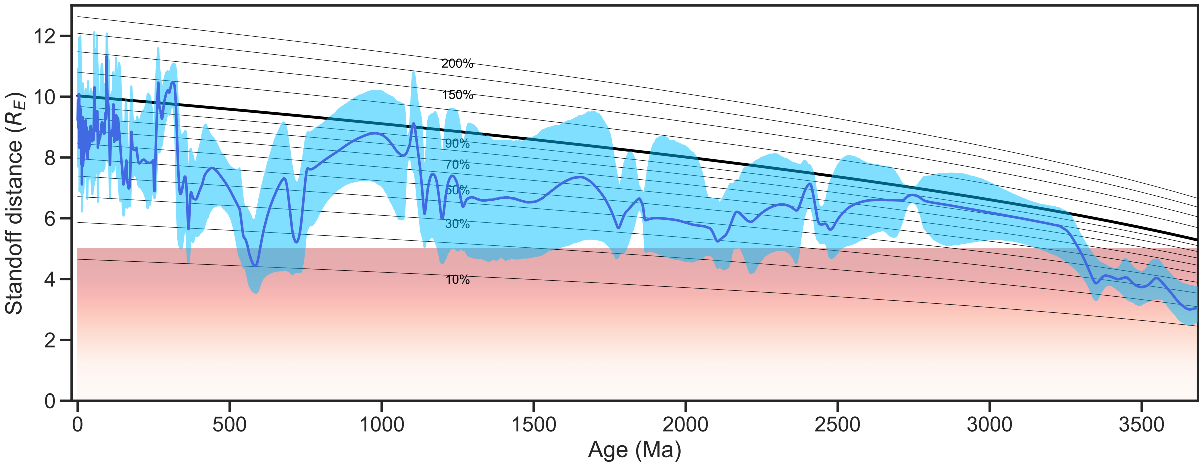

Figure S4. Magnetopause standoff distance estimate using equation 2 in the main text and the MCADAM.1a modeled dipole moment curve with from all non-transitional sites in the PINT v8.1.0 database. Blue curve is the predicted median dipole moment and blue field is the 95% predicted interval. Contour lines show standoff distance relative to the present day. Red gradient shows standoff distance associated with the Halloween 2003 solar storm (Rosenqvist et al., 2005).

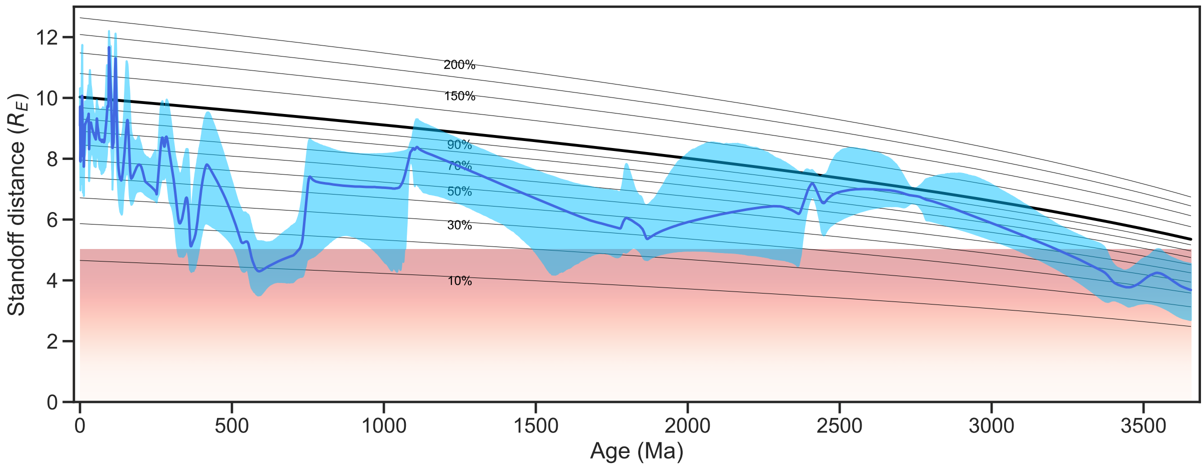

Figure S5. Magnetopause standoff distance estimate using equation 2 in the main text and the MCADAM.1c modeled dipole moment curve with PINT v8.1.0 data meeting the prioritized Q_{PI} criteria: QAGE + QALT + QMD. Blue curve is the predicted median dipole moment and blue field is the 95% predicted interval. Contour lines show standoff distance relative to the present day. Red gradient shows standoff distance associated with the Halloween 2003 solar storm (Rosenqvist et al., 2005).

Table S1. New entries to PINT v8.1.0

REF	Site Lat.	Site Long.	Age	N_{Sites}	V(A)DM	Q_{PI}	Author (Year)
745	36.8	-116.5	12.7	2	6.09	6.0	Abdulghafur and Bowles (2019)
746	41.4	43.3	3.6	8	3.89	4.6	Sánchez-Moreno et al. (2020)
747	-33.5	-55.9	157.6	3	9.79	3.0	Cervantes-Solano et al. (2020)
749	64.4	-51.4	1818.0	1	2.33	6.0	Miki et al. (2020)
750	51.5	26.0	568.5	4	0.90	7.8	Shcherbakova et al. (2020)
751	-26.2	117.0	3495.5	24	1.88	2.1	Tarduno et al. (2020)
752	13.3	37.9	30.1	11	4.19	3.9	Yoshimura et al. (2020)
753	40.2	75.3	63.6	4	6.13	6.5	Meng et al. (2020)
754	17.3	73.7	65.5	10	1.18	3.0	Radhakrishna, Asanulla, Venkateshwarlu, and Soumya (2020)
755	-78.0	164.9	1.9	26	4.36	5.6	Asefaw, Tauxe, Koppers, and Staudigel (2021)
756	41.4	44.0	67.4	6	5.26	4.5	Calvo-Rathert et al. (2021)
757	56.3	-3.0	366.4	14	2.48	6.8	Hawkins et al. (2021)
758	25.1	88.7	117.0	10	3.50	1.0	Kapawar and Mamilla (2021)
759	76.4	-77.1	723.0	11	1.00	6.5	Lloyd, Biggin, Halls, and Hill (2021)
760	41.4	43.3	3.5	18	4.36	7.1	Sánchez-Moreno et al. (2021)
761	46.0	279.3	589.8	7	0.92	7.4	Thallner, Biggin, and Halls (2021)
762	-23.8	116.1	912.0	6	3.89	7.5	Lloyd, Biggin, and Li (2021)
763	54.8	87.1	250.0	4	1.72	5.5	Eliseev et al. (2021)
764	49.5	301.9	550.0	8	1.40	6.8	Thallner, Biggin, McCausland, and Fu (2021)
765	-15.9	-5.7	9.2	5	2.33	7.8	Engbers, Grappone, Mark, and Biggin (2022)
767	-16.8	208.6	2.6	2	7.34	4.0	Chauvin, Roperch, and Levi (2005)
768	41.5	43.3	3.8	6	6.89	1.0	Goguitchaichvili, Alva-Valdivia, Urrutia-Fucugauchi, Morales, and Ferrari (2000)
769	38.0	127.4	73.1	5	3.10	4.0	Chang, Kim, Doh, and Yu (2013)
770	65.1	-15.5	1.5	6	5.97	4.2	Døssing, Muxworthy, Supakulopas, Riishuus, and Mac Niocaill (2016)
772	51.5	-68.9	214.0	1	4.90	5.0	Eitel, Gilder, Spray, Thompson, and Pohl (2016)
774	29.1	-114.1	7.4	9	5.34	6.4	Mahgoub, García-Amador, and Alva-Valdivia (2021)
775	46.9	15.9	2.3	9	5.37	4.0	Schnepp et al. (2021)
777	42.7	268.9	1091.8	7	8.31	6.0	Zhang, Swanson-Hysell, Avery, and Fu (2022)
778	34.8	-98.9	532.5	1	3.50	6.0	Zhou et al. (2022)
779	45.7	-74.6	531.4	1	0.94	9.0	Lloyd, Biggin, Paterson, and McCausland (2022)
780	51.7	24.7	571.0	17	0.81	6.8	Thallner et al. (2022)

REF: study reference number in PINT v8.1.0; mean site location, Lat., Long. in degrees; mean site age in Ma; N_{Sites}: number of sites associated with the study; mean V(A)DM: virtual (axial) dipole moment, in 10^{22} Am^2; Q_{PI}: mean Q_{PI} score of sites associated with the study.