PSVM: A global database for the Miocene indicating elevated paleosecular variation relative to the last 10 Myrs.

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Key Points

- We compiled a new database, PSVM comprising 1,454 paleomagnetic directions from 44 different localities of Miocene volcanics
- Virtual geomagnetic pole dispersions indicate a more variable field during the Miocene compared to the last 10 Myrs
- The elevated equatorial virtual geomagnetic pole dispersion may imply more vigorous convection in the outer core during this time

Abstract

Statistical studies of paleosecular variation (PSV) are used to infer the structure and behavior of the geomagnetic field. This study presents a new database, PSVM, of high-quality directional data from the Miocene era (5.3 – 23 Ma), compiled from 1,454 sites from 44 different localities. This database is used to model the latitude dependence of paleosecular variation with varying selection criteria using a quadratic form after Model G. Our fitted model parameter for latitude-invariant PSV (Model G a) is 15.7° and the latitude dependent PSV term (Model G b) is 0.23. The latitude invariant term is substantially higher than previously observed for the past 10 Myrs or any other studied era. We also present a new stochastic model of the time-average field, BB-M22, using a covariant giant Gaussian process (GGP) which is constrained using data from PSVM and Earth-like geodynamo numerical simulations. BB-M22 improves the fit to PSVM data relative to prior GGP models, as it reproduces the higher VGP dispersion observed during the Miocene. Our findings suggest a more variable magnetic field and more active geodynamo in the Miocene era than the past 10 Myrs, perhaps linked to stronger driving by elevated core-mantle heat flow. Although our results support that the average axial dipole dominance of the time-instantaneous field was lower than in more recent times, we note that based on inclination anomaly estimates cannot rule out that the Miocene time averaged field resembles a geocentric axial dipole.

Plain Language Summary

The variability of the magnetic field is dependent on characteristics of the geodynamo in the Earth's outer core. Changes of the geomagnetic field throughout Earth's history are important to study as they give us insight into the evolution of the interior of our planet. We study the changes of the magnetic field using data from volcanic rocks that preserved the magnetic field direction from when they were formed. In this study we gathered all the data from the Miocene period (23 – 5 million years ago) to see how the geomagnetic field was behaving during that time. The database shows that the magnetic field in the Miocene was more variable than in the past 10 million years. Studies that have produced simulations of the geodynamo suggest that when the outer core undergoes stronger convection, this produces a more variable and complicated geomagnetic field at the surface. The higher variability of the geomagnetic field in the Miocene therefore suggests more vigorous convection in the outer core at that time.

1. Introduction

Earth's magnetic field is generated by convecting iron in the liquid outer core, a system referred to as the geodynamo. Using paleomagnetic records and geomagnetic observations, knowledge on the changes of the structure and strength of the magnetic field through time can be acquired. These changes of the magnetic field on 10^2 – 10^6 year timescales are referred to as paleosecular variation (PSV). PSV is often used to study the field structure over timescales of several millions of years or longer (Johnson & McFadden, 2007). Multiple PSV studies investigating the last 5 myr (million years) have been carried out (Johnson et al., 2008; Johnson & Constable, 1996; McElhinny & McFadden, 1997). Cromwell et al. (2018) provided a database of the paleomagnetic directional data for 0 – 10 Ma (PSV10) for the purpose of studying PSV. Compilations of PSV data for older intervals have been published, including the Cretaceous and Jurassic (Doubrovine et al., 2019) and the Precambrian (Smirnov et al., 2011; Veikkolainen & Pesonen, 2014). Comparing the PSV behavior of the field in these different time periods allows for insight in the variability and evolution of the geodynamo.

In this study we present a compilation of published high-quality paleomagnetic directional data for the Miocene (5.3 – 23 Ma). We focus on rapidly cooled volcanic rocks, as they provide an instantaneous record of Earth's magnetic field. We compiled 1454 paleomagnetic directions from lava flows in the Miocene. With this new database, from here on referred to as PSVM (paleosecular variation of the Miocene), we aim to provide insight into the behavior of the magnetic field in the Miocene using statistical PSV models.

The latitudinal dependence of dispersion of virtual geomagnetic pole (VGP) positions is a useful tool to study PSV in a statistical manner. Model G (Mcfadden et al., 1988) is a commonly used description of the magnetic field variability versus latitude. This specific relationship between latitude and VGP dispersion was described by the functional form: $S_b(\lambda) = \sqrt{a^2 + (b\lambda)^2}$, where S_b is the VGP dispersion, λ is latitude and *a* and *b* represent the VGP dispersion at the equator and the latitudinal dependence of S_b, respectively. This relationship has previously been used to describe a similar timeframe as the Miocene. McFadden et al. (1991) created a Model G trend for the 5 – 22.5 Ma, based on 5 datapoints, which is arguably insufficient to robustly describe the variability of the geomagnetic field.

Another method of modelling the statistical variations of the paleomagnetic field are Giant Gaussian Process (GGP) models. These are originally described by CP88 (Constable & Parker, 1988) for the last 5 Myr, with alternative models including QC96 (Constable & Johnson, 1999; Quidelleur & Courtillot, 1996; Tauxe & Kent, 2004). More recently, renewed versions of these GGP family models, BB18 (Bono

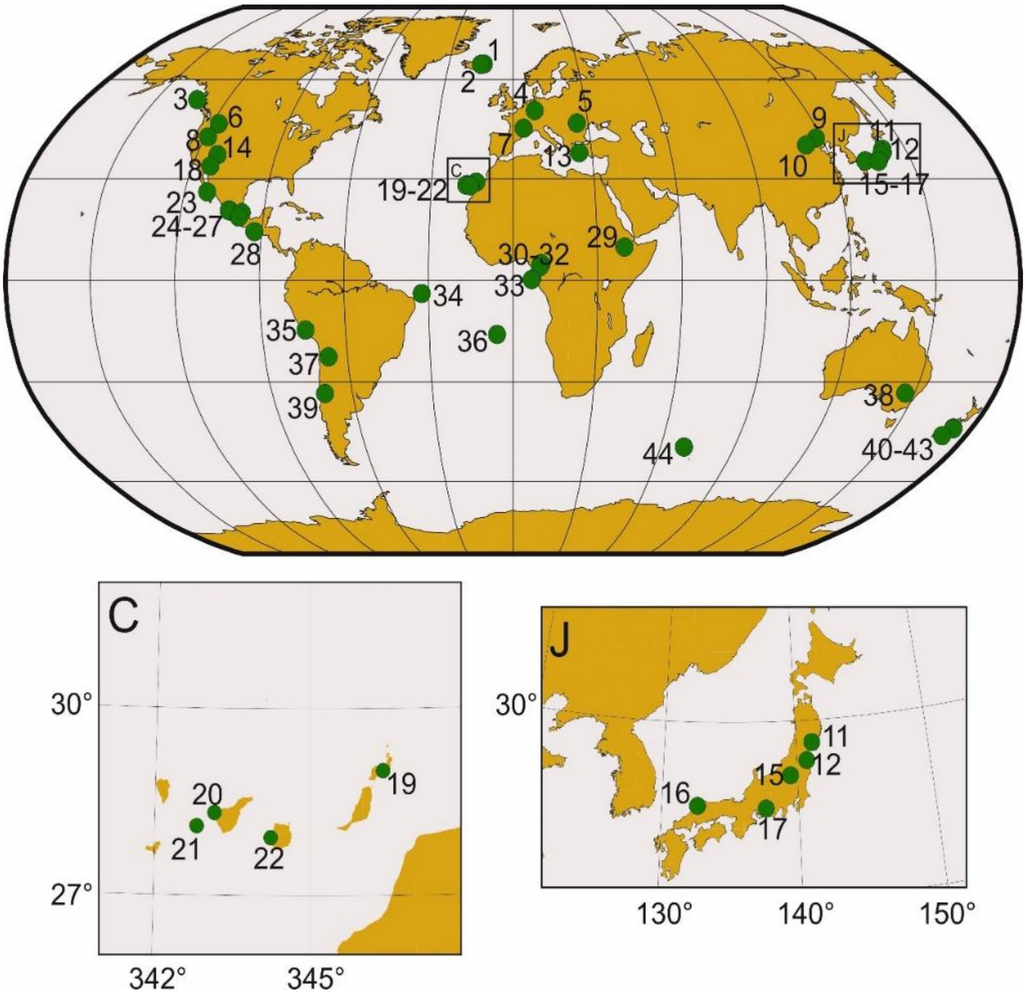

Figure 1; PSVM locality locations. Numbers correspond to the groups listed in Table 1. Boxes C and J are enlargements of the Canary Islands and Japan, respectively.

et al., 2020) and BCE19 (Brandt et al., 2020) were presented. These GGP models describe PSV through a description of statistical variability in the Gauss coefficients. They assume most of the non-dipole terms have a zero mean and standard deviation which varies as a function of degree *l* using a scaling term α. The only coefficients that do not have a zero mean are the axial dipolar term g_1^0 and, in some models, the quadrupole term g_2^0 (e.g., CP88; Constable & Parker, 1988). BB18.Z3 (Bono et al., 2020) also introduced a mean octupole g_3^0 term in addition to the non-zero mean g_2^0 term. TK03 added an additional scaling term, β, for the specific Gauss coefficients for which *l* - *m* is odd (describing the equatorially asymmetric field), as well as setting the quadrupole term to 0 resulting in a geocentric axial dipole (GAD) only model. GGP models are statistical descriptions of the magnetic field that assume the Gauss coefficients g_l^m and h_l^m are normally distributed. Except for BB18, GGP models also assume that Gauss coefficient distributions are independent. In Bono et al. (2020), a new family of the GGP style models, BB18, was presented where a covariance was defined between certain Gauss coefficients ($l \leq 4$) based on a wide range of "Earth-like" dynamo simulations. BB18 is created by incorporating that covariance between certain Gauss coefficients and with g_1^0, and α and β based on paleointensity and PSV data from the PINT database (Biggin et al., 2015; Biggin et al., 2009) for the past 10 Myrs and PSV10 (Cromwell et al., 2018), respectively. Combining the covariance observations derived from dynamo simulations with PSV and V(A)DM data from other intervals it is possible to create new covariant GGP models within the same BB18-style family. In this study, the PSVM and the PINT databases were used to create a new BB18-style model that describes the magnetic field in the Miocene.

Comparisons will be made between our data from PSVM and PSV for the last 10 Myrs (PSV10; (Cromwell et al., 2018)). Additionally, new Model G and BB18 like descriptions specified for the Miocene are presented and compared to those existing for the last 10 Myrs. The new Model G predictions will also be used to relate the magnetic field in the Miocene to studies from other eras such as the Permian-Carboniferous Reverse Super Chron (PCRS) (Handford et al., 2021; de Oliveira et al., 2018), the Post-PCRS (Handford et al., 2021) and the Jurassic and the Cretaceous Normal Super Chron (CNS) (Biggin et al., 2008; Doubrovine et al., 2019). For the last 10 million years both PSV10 (Cromwell et al., 2018) as the updated version of PSV10 (here after referred to as PSV10a) by de Oliveira et al. (2021) will be used.

2. The PSVM compilation

2.1. General selection criteria

PSVM is a compilation of published studies that report directional data from volcanic sites. We used multiple online resources to find as many Miocene directional studies as possible. These included the online MagIC Database *(http://earthref.org/MAGIC)*, online search engines like Scopus, Google Scholar and the global paleomagnetic database GPMDB *(http://www.iggl.no/resources.html)*. In total 1454 sites were included, all of which met the following criteria:

1. The age of the rock was constrained to a precision that was sufficient to demonstrate that they formed within the Miocene.
2. Principle component analyses (PCA) (Kirschvink, 1980) was used to determine the ChRM component, ensuring that the characteristic direction is isolated. Sites where the characteristic component was suspected to have been affected by remagnetization were excluded.
3. The sites studied were free from significant deformation unless a structural correction could be applied based on field observations (i.e. restored to paleohorizontal). Sites that showed evidence for post-emplacement tilt or other deformation that could not structurally be corrected were left out of the database.

(a) Sites that showed post emplacement block rotation that was the same for the entire locality were still included in the study as this does not affect PSV, but they were excluded from the inclination anomaly analyses as the mean direction cannot be trusted. This was the case for 6 localities.

4. Studies included were not aimed at transitions or excursions. Transitional results are acceptable, however it had to be clear that the entire study area was sampled, and not just the flows that captured the transition or excursion.
5. Sufficient time was sampled such that secular variation was likely to have been averaged sufficiently in the included studies. As typical for paleomagnetic study, we consider a site to be a singular cooling unit that records a geologically instantaneous snapshot of the magnetic field. At least 10 sites ($N \geq 10$) per locality were required for inclusion in our dataset. If the authors of the original study commented on a rapid eruption rate or other reason to believe secular variation was not sufficiently sampled, those studies were excluded. We imposed a further constraint to ensure time-averaging: the paleomagnetic direction for each site within a locality must be determined from at least 3 samples ($n \geq 3$) with a precision parameter, k, of 30 or higher.

Together, the requirements defined above are named Selection Criteria Set 1 (CS1) and were the minimum requirements for inclusion in PSVM. Additional selection criteria were implemented for various further analyses of PSVM and these are discussed in section 3.

2.2. General statistics of PSVM

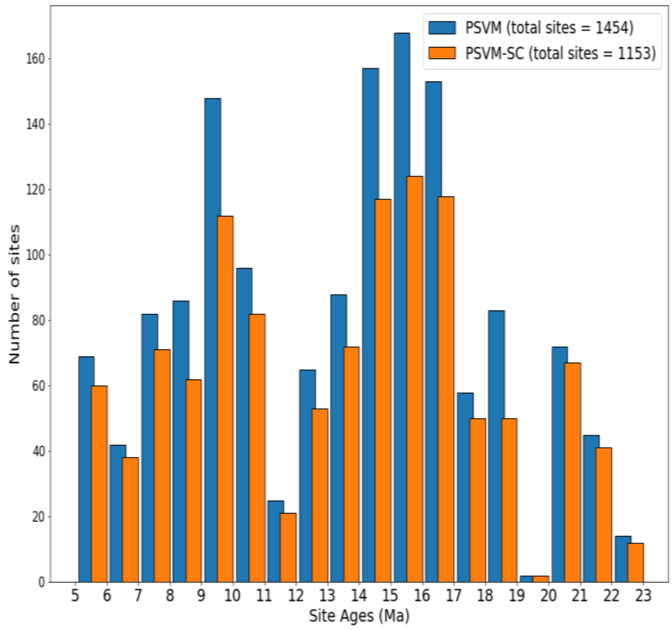

Figure 2; Age distribution of all PSVM sites (blue) and all PSVM-SC (serial correlation correction) sites (orange) in 1 myr intervals.

Locality	Study	Lat	Long	Mlat	Mlong	Age	*N*	*N*-SC	2R	ΔI	Location	Reference
1	1	65.157	346.344	63.320	344.100	12 - 13	65	49	Y	Y	Iceland	Linder & Leonhardt (2009)
2	2	65.012	344.988	64.118	343.932	5.3 – 7.0	22	20	Y	Y	Iceland	Døssing et al. (2020)
3	3	53.700	227.300	57.125	231.858	21.5	13	11	N	N	Canada	Irving et al. (2000)
4	4	50.375	8.895	48.157	5.005	16.5	34	28	Y	Y	Germany	Sherwood (1990)
5	5	46.526	25.553	45.912	24.045	5.6	28	23	N	Y	Romania	Vişan et al. (2016)
6	6	46.371	242.609	47.977	245.287	6.2 - 15.6	92	63	Y	Y	USA	Dominguez & Van der Voo (2014)
7	7	44.991	4.175	43.686	2.129	7.9 - 13.6	13	13	N	Y	France	Riisager et al. (2000)
8	8	42.418	241.150	44.508	244.076	16.7 – 18.0	82	61	Y	N	USA	Jarboe et al. (2008)
9	9	42.019	117.793	43.189	114.552	6.5 - 22.9	25	20	Y	Y	China	Zheng et al. (2002)
10	10	40.000	112.800	41.588	107.945	18	30	17	Y	Y	China	Pan et al. (2005)
11	11	38.752	141.211	40.934	138.158	14	10	10	N	Y	Japan	Hoshi & Teranishi (2007)
12	12	37.754	140.750	40.226	137.289	16	11	10	N	Y	Japan	Takahashi et al. (1999)
13	13	37.700	25.200	36.378	22.362	11.3 - 15.5	11	*< 10*	N	N	Greece	Avigad et al. (1998)
14	14	37.138	247.867	38.232	248.309	5.7 - 9.9	20	19	Y	Y	USA	Mankinen (2008)
15	15	36.953	139.481	38.481	137.346	5.5 - 15.5	29	26	Y	Y	Japan	Otofuji et al. (1997)
16	16	35.282	132.603	37.025	128.719	10.8 - 16.2	14	14	Y	Y	Japan	Otofuji et al. (1991)
17	17	35.135	137.609	37.152	133.228	15.0 - 15.5	35	34	Y	Y	Japan	Hoshi & Yokoyama (2001)
17	18	-	-	-	-	-	-	-	-	-	-	Hoshi & Sano (2013)
18	19	33.792	246.681	35.552	248.927	8.5 - 20.1	164	106	Y	Y	USA	Calderone et al. (1990)
19	20	29.000	346.400	27.534	344.949	6.0 - 14.5	30	26	Y	Y	Lanzarote	Carracedo & Soler (1995)
20	21	28.325	343.145	27.457	342.261	5.7	26	23	Y	Y	Tenerife	Leonhardt & Soffel (2006)
21	22	28.109	342.809	26.637	341.338	9.7 - 9.8	54	30	N	Y	La Gomera	Glen et al. (2003)
21	23	-	-	-	-	-	-	-	-	-	-	Caccavari et al. (2015)
22	24	27.930	344.231	25.760	342.029	14.1 - 14.3	93	67	N	Y	Gran Canaria	Leonhardt & Soffel (2002)
22	25	-	-	-	-	-	-	-	-	-	-	Leonhardt et al. (2000)
23	26	26.099	248.220	27.546	249.691	6.0 - 23.2	41	39	Y	Y	Mexico	Hagstrum et al. (1987)
24	27	20.762	257.319	21.486	258.166	7.8 - 10.2	13	13	Y	Y	Mexico	Ruiz-Martínez et al., (2010)

Table 1 is continued on next page

Locality	Study	Lat	Long	Mlat	Mlong	Age	*N*	*N*-SC	2R	ΔI	Location	Reference
25	28	20.605	257.265	21.430	258.259	5.9 - 13.0	44	33	Y	Y	Mexico	Goguitchaichvili et al. (2011)
26	29	20.024	262.071	20.538	262.849	6.5 - 14.0	10	10	Y	Y	Mexico	Ruiz-Martínez et al. (2000)
27	30	18.680	261.252	19.961	263.071	20.7	22	22	Y	Y	Mexico	Duarte et al. (2015)
28	31	14.380	267.389	13.636	264.640	15.5	34	24	Y	Y	Honduras	Garza et al. (2012)
29	32	9.873	39.745	7.431	36.823	13	36	35	Y	Y	Ethiopia	Lhuillier & Gilder (2019)
30	33	4.909	9.864	0.903	5.370	20.1 – 23.0	22	19	Y	Y	Cameroon	Ubangoh et al. (1998)
31	33	4.886	10.091	1.944	6.803	14.8 - 16.1	22	20	Y	Y	Cameroon	Ubangoh et al. (1998)
32	33	4.000	9.500	2.270	7.563	6.5 - 11.4	10	10	Y	Y	Cameroon	Ubangoh et al. (1998)
33	34	0.294	6.620	-1.024	5.106	7	38	33	Y	Y	São Tomé	Opdyke et al. (2015)
34	35	-3.857	327.586	-4.844	327.969	9.4 - 10.8	13	11	Y	Y	Fernando de Noronha	Leonhardt et al. (2003)
35	36	-14.600	285.700	-15.851	286.117	20	21	21	Y	Y	Peru	Roperch et al. (2011)
36	37	-15.932	354.295	-17.553	351.996	8.8 - 10.3	41	35	Y	Y	Saint Helena	Engbers et al. (2020)
37	38	-22.500	293.100	-23.143	293.191	9	13	10	N	Y	Argentina	Somoza et al., (1996)
38	39	-33.240	146.494	-41.125	142.637	16	13	*< 10*	N	Y	Australia	Hansma & Tohver (2018)
39	40	-33.359	289.723	-34.545	289.560	17.6	29	27	N	N	Chile	Goguitchaichvili et al. (2000)
40	41	-43.600	172.750	-46.259	177.404	10.6	23	19	Y	Y	New Zealand	Sherwood (1988)
41	41	-43.600	172.800	-45.467	176.083	7.5	14	11	N	N	New Zealand	Sherwood (1988)
42	41	-43.800	173.000	-46.003	176.856	8.8	50	34	Y	N	New Zealand	Sherwood (1988)
43	41	-45.848	170.637	-48.799	175.648	12	14	12	Y	Y	New Zealand	Sherwood (1988)
44	42	-49.300	69.500	-49.044	67.231	21	30	28	Y	Y	Kerguelen Islands	Henry & Plessard (1997)

Table 1; Locality included in the PSVM compilation. 'Locality' is the Locality number which corresponds to the numbers in Figure 1. 'Study' is the Study number. Lat (N) and Long (E) are the average latitude and longitude of the group sites. Mlat (N) and Mlong (E) are the average paleolatitude and paleolongitude corrected for plate motion with the NNR-Morvel model (Argus et al., 2011). Age is the average age or age range in Ma for the studies in one locality group, the precision is given as it is reported in the original study. *N* is the number of sites included in the group, *N*-SC is the number of sites in the group after a serial correlation correction has been applied. The 2R column shows if the locality has at least 2 reversals covered in the data. The ΔI column shows if the locality did or did not experience block rotation and is therefore appropriate for the inclination anomaly analysis. Location refers to the country or island that the group is in. Reference is the short name for the study including first (and sometimes second) author and year of publication.

In total, our PSVM dataset contains directional data from 42 different studies (Table 1), all published between 1987 and 2020. Within the compilation there are 2 studies (Sherwood, 1988; Ubangoh et al., 1998) that sampled different localities within the study, that were divided into separate entries in the database. Other studies were so close in proximity (e.g. when they came from the same small island, or are separated by less than 5°) and sometimes even a continuation of the previous fieldwork or study, we combined them as one locality (e.g. Leonhardt & Soffel, 2002; Leonhardt et al., 2000). Our final database comprises 44 distinct localities. The global distribution of the PSVM localities is portrayed in Figure 1. Most of the localities (32/44) in the database are in the northern hemisphere, due to the large number of localities sampling North America. The age distribution of sites tends to decline for ages older than 20 Ma (Figure 2), however, there does not appear to be the strong prioritization of any given interval. The uniformity of site ages is in contrast with the last 10 myr, where the Brunhes chron (0-0.78 Ma) is heavily sampled relative to older time intervals (Cromwell et al., 2018).

2.3. Additional selection criteria

Defining selection criteria for a paleomagnetic database, particularly for paleosecular variation, is non-trivial due to the need to balance between data quantity and data quality. Common criteria for directional data are based on defining a minimum number of specimens used to define the site-mean (n) and the maximum amount of within-site dispersion permitted (either the precision parameter k or the corresponding 95% confidence ellipsoid about the mean direction, α_{95})(Fisher, 1953). When the number of samples, n, is reported, precision parameter k and α_{95} can be related using the following equation:

$$\cos \alpha_{(1-p)} = 1 - \frac{n-R}{R}\left\{\left(\frac{1}{p}\right)^{\frac{1}{n-1}} - 1\right\}, \qquad k = \frac{n-1}{n-R} \tag{1}$$

Where p is the significance level, typically set to 0.05 to obtain the confidence limit $\alpha_{95,}$ n is the numbers of samples used to calculate the site-mean and R is the resultant vector of the site-mean. A relatively relaxed set of selection criteria (CS1; $k > 30$, $n \geq 3$) was chosen to maximize the amount of data compiled for the Miocene, to allow for future PSVM users to define their own selection criteria. For our PSV analyses, we explored combinations of minimum thresholds ($k > 30$ and $n \geq 3$, $k > 50$ and $n \geq 4$, $k > 50$ and $n \geq 5$, $k > 75$ and $n \geq 5$).

A common concern with PSV studies is ensuring that the minimum number of sites (e.g., $N \geq 10$) for a given locality is sufficient to average secular variation properly. To address this concern, we apply a further criterion to our analyses of requiring that at least 2 reversals were sampled within a locality.

Any locality that did not contain at least two reversals were excluded from the subset of the database called PSVM^{2R}. PSVM contains 12 localities with less than 2 reversals, leading to PSVM^{2R} containing 32 localities, when the general selection criteria (CS1) are applied. Localities consisting of a large stack of lava flows may have formed on shorter timescales than required to average secular variation (referred to as serial correlation, SC). Localities where serial correlation is a concern can be handled through the application of a correction, for which the method is described in Supplementary Material Section S1. PSVM^{SC} is the subset of the database when corrected for SC, and PSVM$^{SC\text{-}2R}$ is the subset when corrected for SC after excluding the localities with less than 2 reversals.

In total we have 5 different subsets of the PSVM database (PSVM, PSVM^{SC}, PSVM^{2R}, PSVM$^{SC\text{-}2R}$, PSVM$^{\Delta I}$). The last version, PSVM$^{\Delta I}$ is the version used for inclination anomaly (ΔI). As we need the true inclination to calculate the inclination anomaly, the six localities that have experienced block rotations that could not be corrected for with plate corrections are excluded, as described in criteria 3a in section 2.1. Different sets of selection criteria (for *k* and *n)* can be applied to each of these subsets, leading to 16 different subsets of the database with different criteria (CS1 – CS16) that we used for our statistical analyses (Supplementary Material Table S1).

3. VGP dispersion and Inclination anomaly

Virtual geomagnetic poles (VGPs) and their dispersion were calculated for each locality for each set of selection criteria using the PSVM database. The VGP latitude and longitude for each site were calculated using the provided inclination and declination and a modeled paleolocation. Paleolocations were determined by reconstructing present day site locations to the mean reported age for the sampled cooling units using the NNR-MORVEL56 plate motion model (Argus et al., 2011). For the VGP dispersion, our sites were grouped into the localities as described in section 2. We chose not to calculate the VGP dispersion based on latitude bins as done in some other PSV studies (e.g. Cromwell et al., 2018) to be able to include the studies that experienced coherent block rotation and to be able to compare to older eras for which latitude binning is impossible due to imprecise paleogeographic constraints. The VGP dispersion was calculated based on the equation:

$$S_b = \sqrt{\frac{1}{N-1}\sum_{i=1}^{N}\left(\Delta_i^2 - \frac{S_{w_i}^2}{n_i}\right)} \tag{2}$$

Where Δ_i represents the angular deviation of *i*th sites VGP to the mean of the VGPs, N is the number of sites, and *n* is the number of samples within the site, S_w is the within site dispersion calculated from *k*. S_b represents the dispersion of the magnetic signal, after correcting for the within-site dispersion S_w determined from *n* samples (Dominguez & Van der Voo, 2014; Johnson et al., 2008). The VGP dispersion was calculated using both the iterative Vandamme cut-off (Vandamme, 1994) and a fixed 45° cut-off for all 16 different subsets.

3.1. Model G values *a* and *b* with different selection criteria

The VGP dispersion for each locality is plotted with their paleolatitude (i.e. Figure 3, Supplementary Material Figure S1 and S2). For each subset, different Model G *a* and *b* parameters were calculated by finding the minimum of the squared deviations between S_b for the data and the Model G-style fit. A confidence interval for those *a* and *b* values was estimated through a nonparametric resampling with replacement of the S_b data that were used as input for the Model G calculations (Doubrovine et al., 2019; Sprain et al., 2019). The *a* and *b* values for each of the PSVM selection criteria subsets can be found in Supplementary Material Table S1. Henceforth, we will focus on subsets with the following 7 selection criteria sets (CS 1 – 4, CS7, CS11, CS15) from Supplementary Material Table S1:

CS1: all data in PSVM, $k > 30$, $n \geq 3$
CS2: $k > 50$, $n \geq 4$, same selection criteria as PSV10
CS3: $k > 50$, $n \geq 5$
CS4: $k > 75$, $n \geq 5$
CS7: $k > 50$, $n \geq 5$, at least 2 reversals per locality (PSVM^{2R})
CS11: $k > 50$, $n \geq 5$, corrected for serial correlation (PSVM^{SC})
CS15: $k > 50$, $n \geq 5$, corrected for serial correlation, at least 2 reversals per locality (PSVM$^{SC\text{-}2R}$)

The Model G predictions for these 7 subsets of PSVM are presented in Table 2 and plotted in Supplementary Material Figures S1 and S2, for both Vandamme and 45° cut-off, with their 95% uncertainty bounds. For each Model G prediction, we calculated the root mean square (RMS) misfit and χ^2 between the trend and the datapoints (Table 2). The χ^2 (Eq. 3; Pearson, 1900; Press et al., 1992) represents the cumulative value of the square of the misfits between the expected value (E_i, or Model G prediction) and the observed value (O_i, S_b from the data) divided by the expected value.

$$\chi^2 = \sum \frac{(O_i - E_i)^2}{E_i} \tag{3}$$

For all the scenarios where a 45° cut-off was applied, the hypothesis that Model G is an appropriate description of the data could not be rejected with 95% confidence. The PSVM database produces some localities with relatively high dispersions, most likely due to a higher variability of the field, causing the variable cut-off angle from Vandamme (1994) to increase and include data that the non-variable 45° cut-off angle will reject. The Vandamme cut-off therefore produces a latitudinal dependence for the VGP dispersion that does not follow the Model G trend as well as the 45° cut-off.

Table 2; Model G prediction values for the 7 different selection criteria subsets of PSVM with both Vandamme (Vandamme, 1994) and 45° cut-off applied. N_g is the number of localities that the Model G prediction is based on. Values a and b are the Model G parameters and their uncertainties. RMS is the root-mean-square misfit between the S_b data and the model curve. For each Model G prediction and database, χ^2 is the statistic for how well the model fits the data. χ^2_{95} is the upper 5% critical value for χ^2. Selection criteria marked with bold italics is our preferred dataset.

	Vandamme cut-off						
Subset:	N_g	*a*(°)	*b*	RMS(°)	χ^2	χ^2_{95}	
CS1	44	19.1 +3.3/-4.1	0.21 +0.15/-0.20	7.0	108.9	59.3	Rejected
CS2	31	17.4 +3.2/-3.4	0.21 +0.14/-0.21	6.0	59.9	43.8	Rejected
CS3	30	18.0 +3.0/-3.7	0.17 +0.15/-0.17	6.1	58.1	42.6	Rejected
CS4	28	17.7 +3.0/-3.7	0.17 +0.17/-0.17	6.1	61.2	43.8	Rejected
CS7	***23***	***15.7 +3.0/-2.7***	***0.23 +0.14/-0.23***	***4.6***	***27.0***	***33.9***	-
CS11	28	18.0 +4.8/-3.9	0.26 +0.18/-0.26	6.6	59.0	40.1	Rejected
CS15	20	15.2 +4.4/-3.9	0.32 +0.17/-0.32	5.4	26.5	30.1	-
	45° cut-off						
	N_g	*a*(°)	*b*	RMS(°)	χ^2	χ^2_{95}	
CS1	41	16.6 +2.1/-2.1	0.25 +0.07/-0.09	3.1	22.6	55.8	-
CS2	31	15.9 +2.4/-2.4	0.27 +0.07/-0.08	3.5	21.0	43.8	-
CS3	30	16.0 +2.4/-2.2	0.27 +0.07/-0.09	3.4	20.0	42.6	-
CS4	27	15.7 +2.4/-2.1	0.27 +0.06/-0.10	3.3	16.6	38.9	-
CS7	***24***	***15.5 +2.1/-2.2***	***0.27 +0.07/-0.09***	***3.0***	***12.3***	***35.2***	**-**
CS11	28	17.2 +2.7/-2.9	0.24 +0.09/-0.16	3.5	18.7	40.1	-
CS15	20	16.5 +2.8/-2.6	0.25 +0.10/-0.14	3.0	9.0	30.1	-

Table 3; Model parameters and misfit statistics of selected GGP models, PSVM database is with subset $CS7_{vD}$. Parameters α, β are the scaling parameters according to Constable and Parker (1988) and Tauxe and Kent (2004). g_1^0 is the mean Gauss coefficient of degree 0 and order 1. $\sigma_{g_1^0}$ is the standard deviation of the g_1^0 term. α, g_1^0 and $\sigma_{g_1^0}$ terms are expressed in μT. χ^2_{VGP} is the misfit between the VGP dispersion estimations of the specified model and the datapoints in the PSVM database (subset $CS7_{vD}$). $\chi^2_{95}VGP$ is the critical value of χ^2_{VGP} which, when exceeded, implies a rejection of that model is a good description of the database within the 95% confidence bounds. $\chi^2_{\Delta I}$ is the misfit between the inclination anomaly estimation of the specified model and the datapoints in the PSVM database, and $\chi^2_{95}\Delta I$ is again the critical value to determine if a model can be rejected as a good description of our database within the 95% confidence bounds.

Model *(database)*	α	β	g_1^0	$\sigma_{g_1^0}$	χ^2_{VGP}	$\chi^2_{95}VGP$	$\chi^2_{\Delta I}$	$\chi^2_{95}\Delta I$
Model G (*PSVM*)	-	-	-	-	27.0	33.9	-	-
BB-M22 (*PSVM*)	12.33	2.2	-15.08	10.3	26.9	33.9	6.5	15.5
BB18 (*PSV10*)	12.25	2.82	-22.04	10.8	48.2	33.9	21.8	15.5
TK03 (*PSVRL*)	7.3	3.8	-18	-	67.0	33.9	17.1	15.5

Both scenarios are presented in this study, but the Vandamme cut-off is preferred to allow the comparison to other eras where PSV was studied and to avoid rejecting sites that are not transitional but simply outliers due to anomalously large PSV. Applying the Vandamme cut-off, the subsets CS1 – 4 and CS11 can all be rejected as well-described by Model G as the χ^2 value exceeds the critical χ^2_{95}

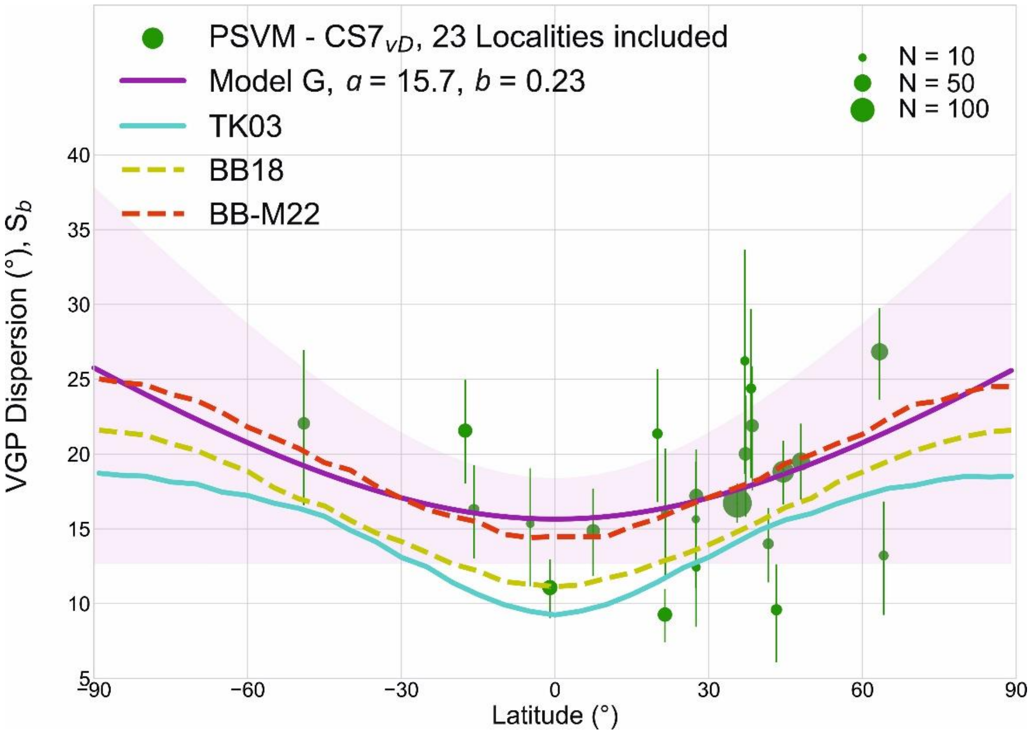

Figure 3; The VGP dispersion versus latitude for our preferred model for PSVM (CS7$_{vD}$) in green dots (size of dot represents the number of sites in the locality (N)) with the VGP dispersion predictions for Model G (purple line, with pink shaded area as bootstrapped 95% confidence bounds), TK03 (cyan line), BB18 (beige dashed line) and BB-M22 (red dashed line).

value, which is the upper 5 percent of the χ^2 distribution depending on the degrees of freedom (Table 2; Pearson, 1900). This is apparent from Supplementary Material Figures S1 and S2 and further supports that the criterion of at least 2 reversals is needed to ensure that secular variation is well-represented. The correction for Serial Correlation (SC) as done in CS11 and CS15 runs the risk of overcorrecting, particularly if the field is in a more stable state. As the criterion of 2 reversals already reduces the likelihood that secular variation is not fully captured, we chose CS7 with the Vandamme cut-off (CS7$_{vD}$) as our preferred subset and this is shown in Figure 3. The results for each locality in this preferred subset are presented in Supplementary Material Table S2.

3.2. New covariant GGP model, BB-M22, based on PSVM and PINT

A new covariant giant Gaussian process (GGP) model, following (Bono et al., 2020) was created using our preferred subset of PSVM (CS7$_{vD}$). The PINT database (Biggin et al., 2009; Bono et al., 2022) was used to define the paleointensity record from the Miocene needed to determine a mean g_1^0 value for this renewed model. The selection criteria *Nint* ≥ 3, σ < 5 μT or σ/F < 25% and only methods that include pTRM checks, were applied to the Miocene data from the PINT database (Engbers et al. 2022). The parameters α (scaled variance for all Gauss coefficients, defined in Constable & Parker, 1988) and β (additional scalar variance of spherical harmonic l-m odd terms, defined in Tauxe & Kent, 2004) are determined with the use of PSVM divided into 10° latitudinal bins. These values are presented in Table 3, together with the g_1^0 , α and β values of BB18 and TK03. The mean g_1^0 value was directly determined from the distribution of dipole moment data from PINT, whereas the $\sigma_{g_1^0}$, α and β terms were determined by minimizing the model misfit to VDM variance and VGP dispersion data. In the case of β, due to the high scatter of VGP dispersion estimates, a local minimum in misfit of 2.2 was chosen since this represents some degree of latitude dependence in VGP dispersion. Nevertheless, the absence of a latitude dependence in VGP dispersion cannot be excluded with 95% confidence from our data, resulting in Model G *b* value of 0 and GGP β value of 1 falling within our confidence interval for model values. Our first model, BB-M22, was built on the same concepts as BB18, and applies the same correlation values between certain Gauss coefficients that was observed in Earth-like dynamo simulations (Bono et al., 2020). Figure 3 shows the BB-M22 VGP dispersion curve for PSVM, plus its Model G prediction and the BB18 VGP dispersion curve based on PSV10 (Bono et al., 2020; Cromwell et al., 2018). BB-M22 shows an increased VGP dispersion relative BB18, resulting in a better fit to PSVM observations.

The slightly lower minimum (equatorial) VGP dispersion predicted by BB-M22 seems like a better fit to PSVM than the Model G prediction based on that same dataset. The χ^2 value, as presented in Table 3, to describe the statistical relationship between the PSVM data and BB-M22 (26.9) is indistinguishable from that which describes the relationship between the PSVM data and our Model G prediction curve (27.0). The χ^2 values for the BB-M22 and Model G predictions are lower than the critical χ^2_{95} value (33.9) suggesting these predictions cannot be rejected as a good description of the data within the 95% confidence bounds. The χ^2 values that describe the fit of the BB18 and TK03 predictions to the PSVM data, exceed the χ^2_{95} value (48.2 and 67.0, Table 3), and can be rejected as explaining the data at the 95% confidence level.

3.3. Inclination Anomaly from PSVM data

Inclination anomaly behavior was studied using the preferred subset of our PSVM database ($CS7_{VD}$). The mean inclination of locality #8 (Steens mountain; Jarboe et al., 2008), was not considered as this study covers a location that experienced local block rotation, which is unsuitable for inclination anomaly analyses (Table 1). Other studies or localities that experienced local block rotations were already excluded due to the strict selection criteria of our preferred subset. The data was split into 10° latitude bins, before calculating the Fisher mean inclination (Fisher, 1953). The mean inclinations were compared to the expected inclination at the specified latitudes as predicted by a GAD field. These predictions follow the equation: $\tan I_{GAD} = 2\ \tan\lambda$, where λ is the latitude. The inclination anomaly (ΔI) (Johnson & McFadden, 2015) is the difference between the mean inclination and the predicted GAD inclination at the average paleolatitude of the directional locality within PSVM. In Figure 4, these ΔI values are compared with the trend in inclination anomaly according to BB18 and BB-M22 and TK03

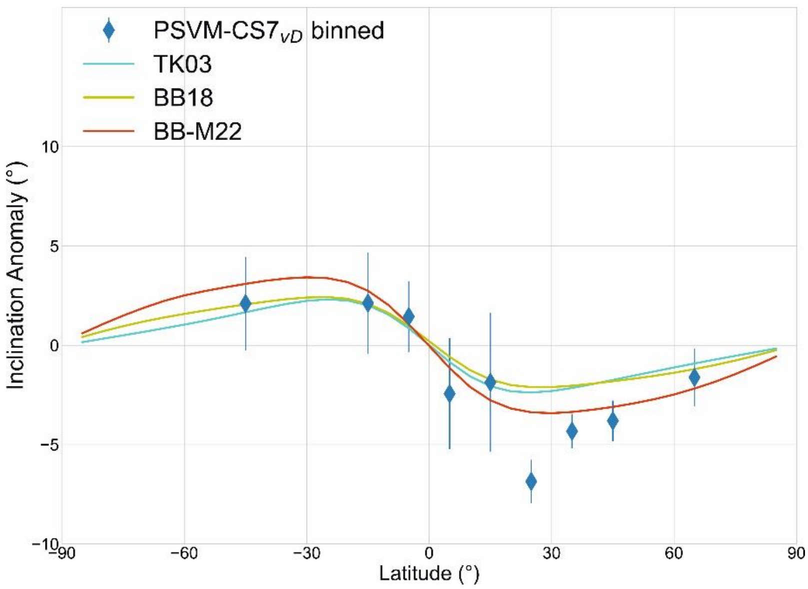

Figure 4; The inclination anomaly versus latitude for our preferred subset of PSVM (CS7$_{VD}$ excluding locality #8) binned into 10° latitude bins, with the inclination anomaly predictions for TK03 (cyan line), BB18 (beige line) and BB-M22 (red line).

(Tauxe & Kent, 2004). Figure 4 shows that BB-M22 trend matches our analysis of the PSVM database somewhat better than BB18 and TK03, and that the inclination anomaly is well described by this zonal GAD based model. This is supported by a statistical analysis (Table 3) as χ^2 does not exceed χ^2_{95}. TK03, BB18 and BB-M22 assert a GAD-like field in which only the dipole coefficient, g_1^0, is held at a non-zero average. For the last 10 million years, these GAD based GGP models did not describe the inclination anomaly well, motivating Bono et al. (2020) to create BB18.Z3 with non-zero mean g_2^0 and g_3^0 coefficients. This zonally non-GAD model better described the shape of the inclination anomaly datapoints for PSV10, suggesting non-GAD features are needed to describe the magnetic field behavior in the last 10 million years. For PSVM, these zonal non-GAD features are not needed to provide a good description of the inclination anomaly behavior.

4. Discussion

4.1. Model G fit

The Model G fit does a relatively poor job of describing the VGP dispersion versus latitude in PSVM. This was similarly seen for the PSV10 database by Doubrovine et al. (2019). Regardless, the *a* and *b* values may still provide important information about the behavior of the field (Biggin et al., 2020). The *a* value is much more precisely defined than the *b* value and the scatter in VGP dispersion estimates makes it difficult to comment on the strength of the latitudinal dependency in VGP dispersion data for the Miocene. In predicting VGP dispersion at the equator, the Model G parameter *a* provides important information on the minimum expected variability of the Earth's magnetic field during the Miocene. Table 2 shows *a* values that vary depending on the applied selection criteria and cut-off.

They are all substantially higher than the Model G prediction based on PSV10 according to Doubrovine et al. (2019) and, in most cases, the differences are statistically significant. In the study of Doubrovine et al. (2019), the PSV10 database (Cromwell et al., 2018) was used to provide a new Model G prediction for the magnetic field, where a_{PSV10} = 11.3° (10.2° – 12.6°). These uncertainty bounds do not overlap with those of the Model G prediction for our preferred subset of PSVM, where a_{PSVM} = 15.7° (13.0° – 18.7°). None of the subsets have a lower average *a* value than $CS7_{VD}$ with the exception of $CS15_{VD}$, which has an uncertainty bound (10.8° - 19.1°) that is substantially wider than the other subsets.

*Table 4; Different databases for different eras with their Model G predictions. The Age is reported in Ma, Ng reports the number of Localities or Bins used for the Model G prediction. Model G parameters a and b with their 95% uncertainties are reported for each Database, as well as the study that the numbers were taken from. *Note that the recalculation of PSV10a was done in this study by not applying the envelope criteria suggested by Deenen et al. (2011), but the database PSV10a came from de Oliveira et al. (2021), and that the calculation of Model G parameters for 0-5 Ma was done by Doubrovine et al. (2019), but the database came from Opdyke et al. (2015).*

Database	Age	N_g	*a*(°)	b	Study reference
PSV – 0-5*	0 – 5	29	11.6 +1.4/-1.3	0.26 +0.03/-0.04	Doubrovine et al. (2019)
PSV10 (Bins)	0 – 10	16	11.3 +1.3/-1.1	0.27 +0.04/-0.08	Doubrovine et al. (2019)
PSV10 (Localities)	0 – 10	51	11.3 +1.9/-1.6	0.26 +0.04/-0.05	Sprain et al. (2019)
PSV10a (Studies)	0 – 10	70	12.2 +1.5/-1.3	0.22 +0.04/-0.07	de Oliveira et al. (2021)
PSV10a recalculated*	0 – 10	80	11.1 +1.5/-1.5	0.25 +0.04/-0.05	This study
PSVM – $CS7_{VD}$	5 – 23	23	15.7 +3.0/-2.7	0.23 +0.14/-0.23	This study
PSVM – $CS2_{VD}$	5 – 23	31	17.4 +3.2/-3.4	0.21 +0.14/-0.21	This study
PSVM – $CS7_{VD}$ (Bins)	5 – 23	9	15.9 +2.9/-3.2	0.28 +0.07/-0.28	This study
PSV – CNS	84 – 126	19	10.7 +2.2/-2.4	0.21 +0.05/-0.16	Doubrovine et al. (2019)
PSV – Pre CNS	126 – 198	20	12.7 +1.9/-2.7	0.13 +0.13/-0.13	Doubrovine et al. (2019)
PSV – Post PCRS	200 – 264	21	14.2 +3.9/-0.9	0.15 +0.12/-0.10	Handford et al. (2021)
PSV – PCRS	265 – 318	16	5.5 + 3.1/-4.7	0.33 + 0.09/-0.09	Handford et al. (2021)

The comparison between the Model G prediction by Doubrovine et al. (2019), hereafter referred to as Model G_{D19}, and our Model G prediction for the Miocene must be interpreted carefully due to differences in how VGP dispersion data are treated. Model G_{D19} is based on the PSV10 database being binned in 10° latitude bins from which VGP dispersion was calculated, the criteria of at least 2 reversals per locality was not implemented for PSV10, and the criterion $n \geq 4$ (instead *of* $n \geq 5$) was applied to the PSV10 database and therefore also to Model G_{D19}. Because of this incompatibility, the decision was made to compare the Model G prediction for our $CS2_{VD}$ subset, which has the same selection criteria as PSV10, with Model G_{S19} the Model G prediction produced by Sprain et al. (2019). Sprain et al (2019) used the PSV10 database but divided in localities instead of 10° bins, allowing for a better comparison with our datasets. $CS2_{VD}$ gives an *a* value of 17.4° (14.0° – 20.6°), which is higher than the *a* value of Model G_{S19}, 11.3° (9.7° – 13.3°), strengthening our confidence that VGP dispersion in the

Miocene was significantly higher than in the past 10 Myrs (Sprain et al., 2019). For completeness, a Model G prediction was created for our preferred subset ($CS7_{vD}$), in 10° latitude bins. Locality #8 (Steens mountain, Jarboe et al., 2008) was excluded from this analysis as it has experienced local block rotation and can therefore not be combined with other localities in that latitude bin. This Model G fit (Table 4, Supplementary Material Figure S3, Table S3) has an *a* parameter of 15.9° (12.6° - 18.7°). An updated PSV database for the past 10 Myrs, PSV10a (de Oliveira et al., 2021), produced a higher *a* value of 12.2° (10.8° – 13.6°) than that of Model G_{D19} and Model G_{S19}. However, to calculate the VGP dispersion, de Oliveira et al. (2021) added a criterion proposed by Deenen et al. (2011) defined by an envelope A_{95}, to eliminate outliers. To avoid the risk of neglecting valid large values in the Miocene dataset, we do not apply the envelope method proposed by Deenen et al. (2011) to our database, making comparison with PSV10a more difficult. We recalculated the *a* and *b* values for the Model G prediction based on PSV10a without the envelope applied (Table 4). This analysis did not show an increase in *a* relative to Model G_{D19}. The *a* value for the recalculated Model G prediction based on PSV10a is 11.1° (9.6° – 12.6°), which does not overlap with the 95% confidence bounds of the *a* values for the Model G prediction for PSVM. Table 4 gives an overview of the *a* and *b* values for the different Model G predictions.

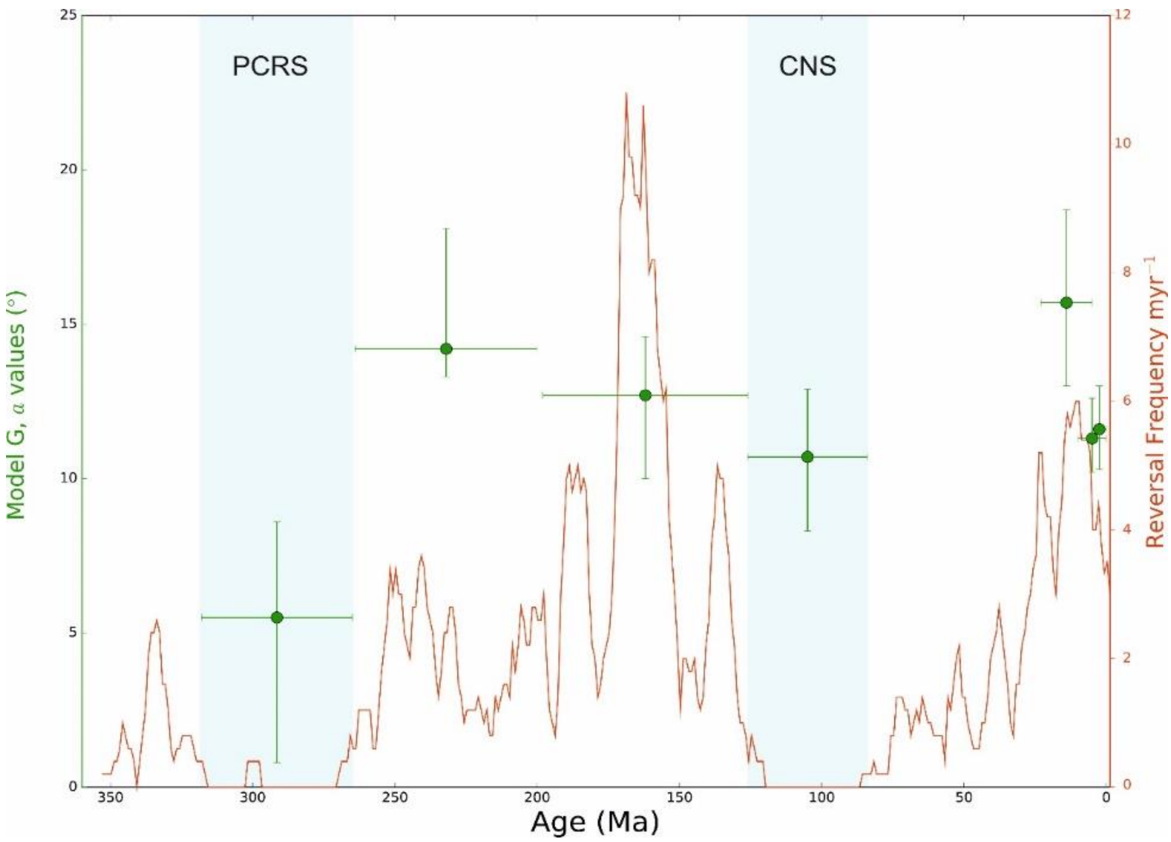

Figure 5; The Model G parameter a in degrees vs Age. Each green dot with error bounds represents a PSV study with respective Model G prediction. The highlighted eras are the superchrons: CNS = Cretaceous Super Chron, PCRS = In orange the reversal frequency (calculated from Ogg. 2020) is presented for each Myrs, averaged over 5 myr.

4.2. Comparison with different eras

Included in Table 4 are a selection of PSV studies performed in other time intervals. For the last 5 Ma specifically, several different databases and updates have been compiled, but the most recent was by Opdyke et al. (2015), which was used by Doubrovine et al. (2019) to calculate a Model G prediction for the past 5 Myrs. For the Cretaceous and Jurassic (CNS and Pre-CNS, respectively), an updated database was published by Doubrovine et al. (2019). For the Permian-Carboniferous Reversed Superchron (PCRS) multiple PSV studies have been published (Handford et al., 2021; de Oliveira et al., 2018); Handford et al. (2021) also reported on PSV in the Triassic (Post-PCRS). Table 4 and Figure 5 show the *a* parameter values for the most recent Model G predictions published for different time periods. The equatorial VGP dispersion obtained for the Miocene is higher than that of any recently published Model G predictions.

4.3. Implications for core processes in the Deep Earth during the Miocene

The high equatorial VGP dispersion of our preferred compilation reveals information about the geodynamo behavior in the Miocene. An analysis of a large and diverse set of geodynamo simulations (Biggin et al., 2020) has shown a clear relationship between the equatorial VGP dispersion (Model G parameter *a*) and the ratio between the dipolar and non-dipolar contributions of the geomagnetic field (AD/NAD). This relationship can be described by the equation:

$$\log\left(\frac{AD}{NAD}\right) \approx k_1 \times \log a + k_2 \tag{4}$$

Where AD/NAD represents the relative dipolarity, *a* is the equatorial VGP dispersion parameter for Model G, and k_1 and k_2 are the empirically obtained values -2.26 and 3.44, respectively (Biggin et al., 2020). Equation 4 gives our preferred subset of PSVM (*a* = 15.7° +3.0/-2.7), an AD/NAD estimate of 5.5 (+2.9/-1.8), which falls within the range that is described by Biggin et al. (2020) as Earth-like (3.5 – 45.0). It has previously been claimed (McFadden et al., 1991; Franco et al., 2019) that the ratio of Model G parameters b/a has an inverse relationship to the reversal frequency of the field at that time (Franco et al., 2019). Due to the wide range of *b* values recovered by our analyses, we are not able to comment on the validity of their hypothesis. Our low AD/NAD value nevertheless suggests a higher contribution of the non-dipolar geomagnetic field structures in the Miocene compared to most other eras, and the Miocene does show a higher reversal rate compared to the last 10 Myrs. We argue that the higher equatorial VGP dispersion in the Miocene is sufficient reason to suggest that the field in the Miocene was structurally less stable than in other eras, especially than in the past 5 Myrs. In Earth-like geodynamo simulations, equatorial VGP dispersion increases with Rayleigh number reflecting more vigorous convection in the outer core destabilizing the magnetic field (Meduri et al., 2021).

Convectional vigor is enhanced by elevating CMB heat flow, itself a consequence of decreased temperatures and/or increased thermal conductivity of the lowermost mantle. While we cannot rule out other causes of destabilization, our study is consistent with the idea that outer core flow was substantially more vigorous during the Miocene than it has been in most other eras. This could potentially have been a consequence of an increased flux of cold material into the lowermost mantle triggered by enhanced subduction at some earlier time (Hounslow et al., 2018).

5. Conclusions

We have compiled a new data set, PSVM, of high-quality paleodirectional data from the Miocene. The database includes 1,454 directions from 42 studies, divided in 44 different localities. The database has been used to perform statistical analyses on the behavior of the magnetic field in the Miocene. The observations of VGP dispersion versus latitude, and the Model G, BB-M22 and BB-M22.Z3 fits to them, suggest that the field did not behave similarly to the past 10 Myrs. The Model G descriptions for each version of the database do not strongly constrain the latitude dependence of VGP dispersion. The *b* values of the Model G predictions have 95% confidence bounds that extend to zero, preventing the possibility of no latitude dependence from being excluded. The *a* values for our Model G predictions yielded statistically significant results and show higher values than for the PSV10 and PSV10a compilations (Cromwell et al., 2018; de Oliveira et al., 2021). This suggests that on average the Miocene experienced a geomagnetic field which was less stable, and less dipolar compared to the average of the past 10 Myrs. These findings may imply an outer core that was convecting more vigorously.

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