Weaker axially dipolar time-averaged paleomagnetic field based on multidomain-corrected paleointensities from Galapagos lavas

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The geomagnetic field is predominantly dipolar today, and high-fidelity paleomagnetic mean directions from all over the globe strongly support the geocentric axial dipole (GAD) hypothesis for the past few million years. However, the bulk of paleointensity data fails to coincide with the axial dipole prediction of a factor-of-2 equator-to-pole increase in mean field strength, leaving the core dynamo process an enigma. Here, we obtain a multidomain-corrected Pliocene–Pleistocene average paleointensity of 21.6 ± 11.0 μT recorded by 27 lava flows from the Galapagos Archipelago near the Equator. Our new result in conjunction with a published comprehensive study by 27 lava flows from the Galapagos Archipelago near the Equator. This model has become elaborated for the time-averaged field intensity may simply be a return to a more average geomagnetic field based on multidomain-corrected paleointensities characterized by linear Arai SD-behaved paleointensity results characterized by linear Arai diagrams (7) and yield an overall mean value of 33.4 ± 13.9 μT (1σ, standard deviation; median value is 30.1 μT, geometric mean is 30.8 μT, and mode is ~28 μT). This is only about one-half of the present field intensity at the sampling locality (~63 μT according to the IGRF (3)) and under the GAD hypothesis would correspond to a VADM of 4.4 ± 1.8 × 1022 A m2 (1σ). The normal (32.3 ± 11.0 μT; 1σ) and reverse (34.6 ± 16.5 μT; 1σ) polarity sites have essentially equal intensities with mean directions that are antipodal and conform to the expectations of a time-averaged GAD field (SI Appendix). The dispersion in site-mean virtual geomagnetic poles was regarded as somewhat higher than expected from paleosecular variation models, with speculation that the high dispersion coincides with low paleointensity resulting from polar vortices in the geodynamo whereby vigorous upwellings were thought to coincide with magnetic flux minima along the inner core tangent cylinder that projects to a latitudinal band about the McMurdo locality. Biases from limited temporal sampling of high-latitude sites were inferred to result from near-polar lavas from Antarctica. This new evidence provides the maximum signal to resolve the first-order signature of a geocentric axial dipole field and also indicates that the time-averaged field is considerably weaker than the present-day field. The resulting dipole moment provides a new calibration standard for cosmogenic isotope production rates and suggests that the present decrease in geomagnetic field intensity may simply be a return to a more average magnitude rather than a harbinger of a polarity reversal.

Significance

Our multidomain-corrected paleointensity results from near-equatorial lavas from the Galapagos give a mean intensity only about one-half of that obtained from the only robust published result from near-polar lavas from Antarctica. This new evidence is consistent with the factor-of-2 equator-to-pole paleointensity signature of a geocentric axial dipole field and also indicates that the time-averaged field is considerably weaker than the present-day field.

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and other data artifacts may also contribute to the low paleointensities from McMurdo (5). Alternatively, the McMurdo mean paleointensities may in fact be representative of the GAD field whose documentation in the current paleointensity database is highly problematical (Fig. 1 and SI Appendix for qualification criteria). The database contains data from studies conducted in different eras by a variety of experimental protocols. SD recorders, an essential theoretical basis for the Thellier paleointensity technique, are usually assumed rather than demonstrated by rock magnetic evidence even though most published paleointensity data are collected from the more slowly cooled interiors of lava flows, where the magnetic grains are more likely to be multidomain (MD) and produce nonideal experimental results (8). On the other hand, data qualification criteria on samples tend to underestimate biases from prevalent MD behaviors, which combined with a tendency for selection of lower temperature treatment steps to avoid sample thermal alteration at higher temperatures, are likely to systematically result in overestimation (9–12). More generally, there are no robust paleointensity estimates from the equatorial belt of comparable quality to the comprehensive McMurdo dataset to ascertain with sufficient resolution whether the low mean paleointensity values from high latitudes are of global (geomagnetic dipole) or more restricted (core dynamo tangent cylinder) significance.

To test the GAD hypothesis in terms of paleointensity, we use standard Thellier-series experiments combined with a recently developed MD correction technique (11) to acquire high-fidelity paleointensity estimates from Pliocene–Pleistocene lavas from the near-equatorial (∼1° South) Galapagos Archipelago in the East Pacific (Fig. 2). Our samples are collected from Santa Cruz (Fig. 2B), San Cristobal (Fig. 2C), and Floreana (Fig. 2D) Islands that formed over the past ∼3 My (13), during which the Nazca plate moved east-southeast relative to the presumed Galapagos hot spot. The dispersed lava sites on different islands ensure a random temporal sampling over this time period (14, 15). Previous alternating field (AF) (16) and thermal demagnetization (TD) (13) studies showed shallow average paleomagnetic directions (AF mean I = 1.9° ± 3.0°; TD mean I = 2.3° ± 3.0°) from 51 lava sites, which agree with the GAD hypothesis. Like many lava samples that have been studied, most of the Galapagos

![Fig. 1. (A) Paleointensities from PINT2014.01 database (4) with ages younger than 5 Ma from normal and reversed polarity chron. Qualified paleointensities versus Northern–Southern hemisphere folded latitude (blue circles) with red dots showing the 15° latitude binned averages (see SI Appendix for qualification criteria). Vertical error bars show the standard deviation of binned data; horizontal error bars show the binning latitude range. Green dashed line shows the present-day dipolar geomagnetic intensity latitudinal variation. (B) Ages of qualified paleointensities from PINT2014.1 database versus Northern–Southern hemisphere folded latitude (pink circles). Orange and yellow bars show the number of paleointensity data inside each latitude bin for ages between 0.03–0.5 and 0.5–5 Ma, respectively.](image-url)
lavas have saturation-remanent to saturation-induced magnetization ratios between 0.1 and 0.3 (13), which is consistent with a mixture of SD and MD properties (17). We also conducted additional comprehensive rock magnetic studies, which suggest most of the Galapagos lavas are good candidates for MD-corrected paleointensity experiments (SI Appendix, Figs. S2–S5 and Table S1).

In total, out of 209 studied, 80 independently oriented specimens from 31 sampling sites provided qualified MD-corrected paleointensity estimates (examples in Fig. 3 and SI Appendix, Figs. S6–S8 and Table S2). For most of the Arai diagrams from these specimens, we found significant improvement in paleointensity data quality after applying MD correction, with consistent increase of linearity for corrected Arai diagrams (Fig. 3). After combining sampling sites that are likely from the same lava flow (SI Appendix), qualified site-level MD-corrected paleointensity results were obtained from 27 lava flows (SI Appendix, Fig. S9 and Table S3) out of 47 experimented upon (success rate, ∼57%). The overall average paleointensity is $21.6 \pm 11.0 \mu T$ (1σ) (median value is $19.9 \mu T$, geometric mean is $18.8 \mu T$, and mode is $\sim 15 \mu T$) providing a VADM of $5.6 \pm 2.9 \times 10^{22} \text{A-m}^{-2}$ (1σ). Among them, 8 normal polarity sites yield an average paleointensity of $19.6 \pm 15.6 \mu T$ (1σ), whereas 19 reverse polarity sites yield $22.4 \pm 8.9 \mu T$ (1σ), values that are not significantly different. Moreover, the mean directions of the 8 normal polarity sites (declination, $D = 354.7^\circ$; $I = 2.6^\circ$) and 19 reverse polarity sites ($D = 178.6^\circ$; $I = 2.4^\circ$) are statistically antipodal within $6.3^\circ$, passing the reversal test [classification C (16)] and each polarity dataset is within a few degrees of that expected from the GAD hypothesis ($D = 0^\circ/180^\circ$; $I = -2^\circ/+2^\circ$), indicating that these data are representative of the time-averaged paleomagnetic field for this near-equatorial locality (SI Appendix).

Paleointensity histograms from Galapagos (1° South) and McMurdo (78° South) show that the mode for McMurdo (∼28 μT) is about twice that of the Galapagos (∼15 μT), which is also approximately the case within uncertainties for the mean values (33.4 ± 13.9 μT versus 21.6 ± 11.0 μT) (Fig. 4 and SI Appendix, Table S4). This satisfies the GAD prediction, heretofore unrealized, of a factor-of-2 equator-to-pole increase in time-averaged

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**Fig. 2.** (A) Map of Galapagos Archipelago just south of the Equator. Current Galapagos hot spot eruptive center (red star) is on Fernandina at 0°22′S, 91°33′W. (B–D) Blown-up maps of boxes in A show Santa Cruz, San Cristobal, and Floreana where lava samples were collected. Black and white triangles indicate sampling locations of what turned out to be normal and reverse polarity sites, respectively. Parenthesized sites offer no qualified MD-corrected paleointensity estimates. Inset in C is a blowup of the sites (black dots) that are combined into site GA-0 (SI Appendix).
paleointensity. Complicated upwelling fluxes along the tangent cylinder in the core dynamo are not needed to explain the apparently low average paleointensity at McMurdo, which in conjunction with the Galapagos average, is now seen to simply reflect a weaker overall dipolar paleomagnetic field strength characterized by an average VADM of $4.9 \pm 2.4 \times 10^{22}$ A·m$^2$ (1σ) only.

Fig. 3. Arai diagrams of original (black lines) and MD-corrected (red lines) paleointensity experiments with original partial thermoremanent magnetization (pTRM) checks (yellow triangles) for typical qualified specimens: (A) GA06.1c, (B) GA22.3c, (C) GA24.7c, and (D) GA67.2c. Blue dashed lines are least-square fittings from temperatures between 400 °C and 575 °C for MD-corrected Arai diagrams that are used to calculate MD-corrected paleointensities. Values of original and corrected paleointensities (P-Int) and corrected paleointensity linear regression correlation coefficient (P-Int R) are also shown. Numbers on the Arai diagrams indicate temperature steps in °C.
about 60% of the present-day field intensity ($V_{ADM} \sim 8 \times 10^{22}$ A·m$^2$; Fig. 4). These results show that, for the past few million years, the time-averaged paleomagnetic field is predominately GAD in latitudinal variation in direction as well as intensity. Recent paleointensity results (18) from glassy volcanic material from Iceland (64° North) provide a median value of 33.1 ± 8.3 μT that is in good agreement with the McMurdo data and our conclusions for a GAD field. However, we regard the overall results in the paleointensity database, which do not show a clear latitudinal dependency expected for the GAD (Fig. 1), as generally biased mainly due to inadequate data qualification criteria to identify only SD-behaved samples (8). This points to the necessity of using experimental designs that avoid or correct for pervasive MD behaviors with sufficient independent cooling units to obtain reliable time-averaged paleointensities.

The consistency of our high-fidelity MD-corrected Galapagos lava paleointensity results and the reported SD-behaved McMurdo (and now also Iceland) results with GAD predictions allows us to confirm with more confidence that the Pliocene–Pleistocene average paleointensity is indeed much weaker than today’s geomagnetic field, as already suspected from results from targeted SD recorders like submarine basaltic glass (19). This has several significant implications. Foremost, these results show that the past several-million-year-long time-averaged geomagnetic field is predominantly that of a GAD in direction as well as intensity, validating, for example, the calculation of VADMs and various total field models [e.g., TK03 (20)]. Second, our average dipolar paleointensity estimation for the past ~5 My is consistent with average paleointensities estimated for the most SD material for the past 140 My [$V_{ADM} \sim 4.2 \times 10^{22}$ A·m$^2$ (21)] and even the past 300 My [$V_{ADM} \sim 4.6 \times 10^{22}$ A·m$^2$ (19)], values that are also only about 50–60% of the present-day magnitude. Third, a lower average paleointensity over at least the past few million years results in a shorter average steady-state magnetopause standoff distance of only ~9 Earth radii ($R_E$) compared with ~11 $R_E$ today (22). A shorter standoff distance results in stronger solar and cosmic radiation fluxes at Earth’s surface and also in the atmosphere, which can cause widespread aurora at lower latitudes. Because vertical cutoff rigidity is proportional to $V_{ADM}$ (23), a weaker geomagnetic field will result in higher production rates of cosmogenic isotopes (such as $^{10}$Be) that are used for geochronology (24). Last, although the geomagnetic field intensity is known to be dropping at a rapid rate of ~10% for nearly the past two centuries (25) with suggestions that a collapse of the field and a magnetic polarity reversal may be on the horizon (26), the present-day geomagnetic field may simply be decreasing from an anomalously high historical value compared with the average paleointensity over the past few million years.

Methods

The MD correction technique for paleointensity (11) uses the thermoremanent magnetization (TRM) recording property of the same sample, acquired by repeating its Thellier-series experiment, to generate a linear corrected Arai diagram (Fig. 3). The standard Thellier-series experimental data can thus also be used to estimate paleointensities by traditional methods (27), which allows us to evaluate the effectiveness of the MD correction. The MD correction technique does require that samples have not experienced significant thermostatschemical alteration upon completion of the original
Thellier-series heating steps, which can be supported independently by hysteresis and thermomagnetic measurements on subsample chips for the Galapagos lavas (SI Appendix).

We also calculated traditional paleointensity estimates using only the original Arai diagrams without applying MD correction, which yield ~26 μT average values for both a loose set (88 qualified specimens from 26 lavas) and a strict set (51 qualified specimens from 21 lavas) of data qualification criteria (SI Appendix, Fig. 510 and Table 55). We suggest that the difference between the traditional paleointensity results and the MD-corrected paleointensities is because of systematic overestimation, due to MD-behaved concave-up Arai diagrams (10, 12) and the tendency to use low-temperature segments to estimate paleointensity based on apparent failure of partial TRM checks at higher temperatures. We argue that the MD-corrected paleointensities are more accurate because the correction technique is designed specifically to account for concave-up Arai diagrams caused by MD effects; moreover, temperature steps above 400 °C were used to preclude contamination by present-day viscous remanent magnetization overprints.

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