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Journal
Journal of Geophysical Research: Solid Earth, 126(2)

ISSN
2169-9313

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Publication Date
2021-02-01

DOI
10.1029/2020jb020834

Peer reviewed

Four-Dimensional Paleomagnetic Dataset: Plio-Pleistocene Paleodirection and Paleointensity Data from the Erebus Volcanic Province, Antarctica

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Key Points:

- Eleven new ^{40}Ar/^{39}Ar age determinations from the Erebus Volcanic Province, Antarctica (-77.84°, 166.69°)
- One hundred and twenty-six site mean directions recover a paleopole (176.24°, 86.89°) consistent with a GAD field over the Plio-Pleistocene
- Twenty-eight site intensity estimates pass a set of strict selection criteria and recover a 35.75 $\mu T \pm$ 7.30 μT time averaged field over the Plio-Pleistocene

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Abstract

The primary structure of the modern geomagnetic field may be accounted for by a Geocentric Axial Dipole (GAD) field. A GAD field is a magnetic field produced by a dipole positioned in the center of the Earth and aligned with the spin axis. Paleogeographic reconstructions of plate motion are based on the assumption that this predominately GAD structure extends to the paleomagnetic field structure so it is crucial to determine whether globally distributed paleodirectional and paleointensity datasets recover a GAD field. Global paleodirectional compilations that span 0 - 5 Myr support a field structure dominated by a GAD with minor non-GAD contributions. However, paleointensity datasets over the same period lack the global intensity structure expected of a GAD derived field. A notable deviation is the depressed intensities observed at the high latitudes which should preserve the highest average intensity in a purely GAD field. To determine whether the low intensities reflect the structure of the field, low quality data or inadequate temporal sampling, we have conducted a robust study of the paleomagnetic field at the high southerly latitudes. This study focuses on the paleomagnetic field structure over the Plio-Pleistocene to avoid corrections for plate motion. We present the results from one hundred and twenty-six site mean directions that were thermally or AF demagnetized and then subjected to a set of strict selection criteria. Along with twenty-eight new paleointensity estimates from samples that underwent the IZZI modified Thellier-Thellier experiment and were subjected to the strict CCRIT set of criteria. The recovered paleopole (176.24 °, 86.89 °) and its corresponding α_{95} (4.92 °), supports the GAD hypothesis. Our time averaged field estimate, $35.75\mu T$± 7.30 μT, is consistent with the low intensities measured at the poles in the global compilations.

1 Introduction

The spatial structure of modern geomagnetic field intensity (Figure) reveals latitudinal variability, longitudinal features, and regions with anomalously low intensities (the South Atlantic Anomaly). However, in mathematical representations of the geomagnetic field structure [*Thébault et al.*, 2015] the geocentric axial dipole (GAD) accounts for much of the field [*McElhinny*, 2007; *Lowes*, 1973]. A geocentric axial dipole field is the magnetic field generated by a dipole positioned in the center of the Earth and aligned along the spin axis. In an ideal GAD field, both the intensity of the geomagnetic field (B) and the inclination (I) would vary with latitude (λ) by

$$B = M(1 + 3cos^2\theta)^{\frac{1}{2}} \tag{1}$$

$$tan(I) = 2tan(\lambda) \tag{2}$$

where M is intensity of the field at the equator (nT) and is co-latitude (°). The paleomagnetic field structure is preserved in the geological record and various techniques [*Thellier and Thellier*, 1959; *Shaw*, 1974; *Coe*, 1967; *Yu et al.*, 2004; *Walton and Shaw*, 1922; *Hoffman and Biggin*, 2005] allow us to the recover paleodirections and paleointensities. Independent studies of the paleofield are then compiled in paleodirectional and paleointensity databases [*Cromwell et al.*, 2018; *Brown et al.*, 2015; *Biggin et al.*, 2009] which we can use to characterize the behavior of the time averaged field (TAF). The structure of the geomagnetic field reflects the dynamics and motion occurring in the fluid outer core so it is important to characterize the TAF. The GAD hypothesis is also central to paleogeographic reconstructions of plate motion.

Numerous studies [*Opdyke and Henry*, 1969; *Cromwell et al.*, 2018; *Behar et al.*, 2019] have recovered paleodirections from the Plio-Pleistocene that are consistent with a GAD field. However, a GAD structure does not emerge in the PINT (absolute paleointensity) database over the same time period [*Biggin et al.*, 2009]. The latitudinal variation of intensity, expected of a GAD field, is not evident in the PINT database for estimates that span the last 5 Myr. The field intensity at the high latitudes appears depressed, which may either reflect a feature of the paleomagnetic field or the quality of the data underlying the database. Recovering paleointensity is challenging due to the complex magnetization acquisition behavior of non-ideal magnetic grains [*Dunlop et al.*, 2004; *Dunlop and Özdemir*, 2001] and the tendency for magnetomineralogical alteration during paleointensity experiments [*Smirnov and Tarduno*, 2003]. To determine whether the low intensities measured at the high southerly latitudes accurately represent the structure of the paleomagnetic field or if they are an artifact of non-ideal magnetic recorders, we conducted an extensive study of the paleomagnetic field in the Erebus Volcanic Province, Antarctica (-77.84°, 166.69°).

2 Methods

2.1 Sample Collection

Our study examines 141 independent sites around the Erebus Volcanic Province, Antarctica (Figure). Samples were collected during the 2016/2017 Antarctic Summer field season. Site selection was based on the work of *Mankinen and Cox* [1988], *Tauxe et al.* [2004], and *Lawrence et al.* [2009] who collected samples from the interior of lava flows primarily for directional analysis. A compilation of all the paleodirectional and paleointensity experiments were summarized in *Lawrence et al.* [2009]. Only a dozen of those sites yield paleointensity data that pass modern, strict selection criteria (i.e. CCRIT of *Cromwell et al.* [2015]), therefore, we re-sampled nearly all of the original sites for this study. Both *Mankinen and Cox* [1988] and *Lawrence et al.* [2009] collected between four and seven cores with a gas-powered drill. We used the 1-inch drill holes remaining in the outcrop to identify many of the original sites (Figure) . The remainder were located by GPS coordinates from *Lawrence et al.* [2009] and approximated from the maps and descriptions in *Mankinen and Cox* [1988]. Once we identified the sites, we re-sampled the finest-grained, glassy material from the lava flow top or flow bottom. We collected hand samples using hammers and chisels. The outcrops included lava flows, pillow lavas, and hyaloclastite cones that formed over the Plio-pleistocene (Figure).

2.2 Paleointensity

2.2.1 Recovering paleointensity

Magnetic grains in igneous rocks acquire a Thermal Remanent Magnetization (TRM) by cooling from temperatures well above their curie temperature through their blocking temperatures (T_b). The resulting TRM captures an instantaneous record of the geomagnetic field that remains stable over long timescales. The degree of alignment, between the magnetic grains and the ambient field, depends on the strength of the field (B) at the time of cooling [*Néel*, 1955]

$$M_{TRM} = M_{rs} \tanh \frac{v M_s(T_b) B}{k T_b} \tag{3}$$

where T_b is blocking temperature, k is the Boltzmann constant, v is volume, and $M_s(T_b)$ is spontaneous magnetization at T_b. In a weak magnetic field, on the order of the modern geomagnetic field, TRM acquisition is linearly proportional to the strength of the ambient field. This proportionality allows us to recover the intensity of the geomagnetic field when the rock formed. The Natural Remanent Magnetization (NRM) may be removed by heating the rock and a new partial Thermal Remanent Magnetization (pTRM) may overwrite the NRM by cooling the rock in a controlled applied field. The ratio of the TRM acquired to the field applied is proportional to the ratio of the NRM to the paleomagnetic field [*Néel*, 1955]. We then estimate the intensity of the paleomagnetic field by

$$B_{anc} = \frac{M_{NRM}}{M_{pTRM}} B_{lab}, \tag{4}$$

where M_{NRM} is the natural remanent magnetization, M_{pTRM} is the partial thermal remanent magnetization imparted by heating the sample in an applied field, B_{lab} is the field applied in the lab, and B_{anc} is the strength of the paleomagnetic field. A rock contains an assemblage of magnetic grains and each grain traps its magnetization at a different temperature, therefore incrementally demagnetizing and remagnetizing a rock sample results in several independent estimates of the paleofield.

2.2.2 Sample preparation

We conducted a preliminary IZZI-modified Thellier Thellier experiment on 144 specimens with, at minimum, two specimens from each site. The results from this preliminary experiment refined our sites to the most promising from which we selected up to six additional specimens. Samples were crushed into 100 – 500 mg fragments. The fragments were then examined under a binocular microscope to select the individual specimen that appeared glassy. These glassy specimens may contain the uniaxial single domain grains of magnetite needed to recover paleointensity. Each individual specimen was swaddled in glass microfiber filter paper and affixed inside a borosilicate glass vial with K_2SiO_3. The specimen were then placed in a transformer steel shielded room at the Paleomagnetic Laboratory at Scripps Institution of Oceanography for the duration of the experiment.

2.2.3 IZZI modified Thellier-Thellier Experiment

We conducted the IZZI-modified Thellier-Thellier protocol [*Yu et al.*, 2004], whereby specimens are incrementally heated and cooled either in the absence of a magnetic field to demagnetize the NRM (a zero-field step) or in the presence of an applied lab field to impart a pTRM (an in-field step). Specimen were subjected to both an In-field (I) and Zero-field (Z) treatments at each temperature step. Temperature steps were conducted at 100°C intervals from 0°C to 400°C, then 25°C intervals to 500°C, and finally at 10°C intervals until each specimen completely demagnetized. Specimens were heated in custom-built furnaces with thermocouples in non-inductively wound heating elements to control the temperature to within a few degrees. Specimen were rapidly air-cooled following treatment. During in-field treatment steps, specimen were cooled in a 30μT field. The order of the treatment, IZ or ZI [*Coe*, 1967], alternated with each temperature step in order to detect tails and zero-field memory effects [*Aitken et al.*, 1988] in the ZI sequence. We applied a partial Thermal Remanent (pTRM) check, an additional in-field treatment at a previously measured temperature step, between IZ-ZI sequences in order to monitor mineral neoformation and magnetomineral alteration. Immediately following treatment, we measured the magnetic remanence with a 2G Cryogenic SQUID (Super Conducting Quantum Interference Device) magnetometer.

2.2.4 Cooling Rate

The TRM acquired by each specimen is affected by its rate of cooling [*Dodson and McClelland-Brown*, 1980; *Halgedahl and Fuller*, 1980; *Fox and Aitken*, 1980]. After each treatment, specimens were rapidly air-cooled to match the rate at which we suspect they initially cooled. To assess the impact of cooling rate on TRM acquisition in our specimens, we conducted a cooling rate experiment. We heated the specimens to 620° in a 50 μT field, air-cooled them in under an hour, and then measured their TRM. We then re-heated the specimens to 620 ° in a 50 μT field, naturally cooled them over 12 hours, and then measured the resulting TRM.

2.2.5 Non-linear TRM Acquisition

Néel theory is based on SD non-interacting grains of magnetite that acquire a TRM in proportion to the ambient field, yet several studies have detected non-linear TRM acquisition [*Selkin et al.*, 2007; *Dunlop et al.*, 2004]. Therefore after we completed the IZZI-experiment, we selected the successful specimens to perform an additional set of steps that detect non-linear TRM acquisition behavior. We subjected these specimens to a total TRM, at 630° C, in several treatment fields. We treated the specimens in a 0 μT , 15 μT , 20 μT , 30 μT, 40 μT , 50 μT , and 60 μT field.

2.3 Paleodirection

2.3.1 Alternating Field Demagnetization and Thermal Demagnetization

We recovered paleodirection by stepwise thermal demagnetization and Alternating Field (AF) demagnetization. Each oriented drill core was cut into one-inch specimens for AF demagnetization or thermal demagnetization. At least five specimens per site were stepwise demagnetized. 461 specimens were AF demagnetized in a Sapphire Instruments SI-4 uniaxial AF demagnetizer. Specimens were treated in 5 mT steps from 5 mT – 20 mT, 10 mT steps from 20 mT – 100 mT, and then at 120 mT, 150 mT, and 180 mT or until the NRM was removed. An additional 323 specimens were thermally demagnetized by stepwise heating in 50°C intervals from 0°C – 500°C, in 25°C intervals from 520°C to 560°C and in 5°C-10°C intervals until the samples were entirely demagnetized. After each treatment, the remaining NRM was measured. The demagnetization path, calculated from the resultant vector of the NRM between treatment steps, monitors the stability and behavior of the magnetization.

2.4 Hysteresis and FORCs

We conducted paleointensity experiments on samples that were drilled from the interior of the lava flows [*Mankinen and Cox*, 1988; *Tauxe and Staudigel*, 2004] and samples that were hand collected from the surface or base of the lava flow. At six sites, we recovered intensity estimates from specimen collected from both the interior and the surface. We selected sister specimens from these sites and measured hysteresis loops and FORC diagrams with a Princeton Measurements Corporation Micromag Alternating Gradient Magnetometer to diagnose domain state.

2.5 Ar-Ar

3 Results

3.1 Paleointensity

We present the results of our IZZI experiment as Arai diagrams [*Nagata and Arai*, 1963], in order to compare the pTRM acquired and the NRM removed at each temperature step and to monitor any changes in this ratio between different temperature intervals. We present the magnetization directions as zijderveld diagrams [*Zijderveld*, 1967] and calculate the best fitting direction, or plane, through the vectors using Principal Component Analysis [*Kirschvink*, 1980]. Our specimens rarely behave like the non-interacting uniaxial single domain grains of magnetite assumed by Neel theory. Instead, many specimens exhibit non-ideal behavior (i.e. zig-zagging, failed pTRM checks, or multiple components of magnetization) resulting in unreliable paleointensity estimates.

3.1.1 Non-ideal behavior: Zig-zagging

Zig-zagging in the Arai diagram, (Figure a). occurs when the ratio of NRM removed to pTRM acquired varies between different temperature intervals based on the sequence of treatment steps (IZ or ZI). The IZZI modified Thellier-Thellier experiment alternates the order in which the treatments are applied for each temperature step [*Yu et al.*, 2004]. The alternating sequence, In-field then Zero-field or Zero-field then In-field, is used to detect the presence of tails and zero-field memory effects [*Aitken et al.*, 1988]. Tails occur when the pTRM acquired by heating to temperature T in a field is not entirely removed when the specimen is reheated to temperature T and cooled in a zero-field. This may indicate the presence of MD grains.

3.1.2 Non-ideal behavior: Failed pTRM checks

A pTRM check, where a previously measured in-field treatment is repeated, is inserted into every IZ-ZI sequence [*Shaw*, 1974]. Any deviation in the remanence (**??** b) indicates magneto-mineral alteration or changes in the blocking and unblocking temperature spectra due to multidomain grains

3.2 Ideal behavior and Selection Criteria

To filter out the specimen that exhibit non-ideal behavior, (**??**) we apply a set of selection criteria at the specimen and site level. A wide range of selection criteria [*Leonhardt et al.*, 2004; *Kissel and Laj*, 2004] and paleointensity statistics [*Paterson et al.*, 2014] exist to separate low and high quality paleointensity data. We modeled our criteria (Table) after those of *Cromwell et al.* [2015], where they successfully recovered the paleointensity of the 1960 Hawaiian lava flow. CCRIT applies two directional statistics, Deviation ANGle (DANG [*Tanaka and Kobayashi*, 2003]) and Maximum Angle of Deviation (MAD [*Kirschvink*, 1980]) to determine the variability in the direction of the NRM. MAD (maximum angle of deviation) quantifies the amount of scatter in the directions while DANG (deviation angle) calculates the angle between the center of the demagnetization direction and the origin. Three additional parameters, SCAT, Frac [*Shaar and Tauxe*, 2013], and k [*Paterson*, 2011], are applied to test the assumption of linearity. SCAT constrains the amount of scatter permitted between the best fit proportionality constant and the demagnetization data and pTRM checks; frac ensures the majority of the remanence is used to calculate paleointensity; k detects deviations from linearity by fitting a circle to the data to determine the amount of curvature. CCRIT also tests for consistency between estimates at the site level by setting thresholds on the percentage of scatter, $\beta_{\%}$ and intensity of scatter, β_{σ} permitted at a site. Twenty-eight of our original 135 sites passed these selection criteria (Table)

3.3 Paleodirection

The results of the demagnetization experiment vary (Figure) from a single stable direction to multiple unstable directions. Multiple directions with distinct coercivity and blocking temperature spectra decay along one direction at low field and temperature treatments then abruptly shift and decay along a different direction for the final characteristic remanent magnetization (ChRM) (Figure a). The low temperature and low coercivity component may result from a viscous remanent magnetization or a partial overprint that is typically removed after the first or second treatment. Multiple components with overlapping coercivity or blocking temperature spectra appear as zig-zagging or gradual shifts in the demagnetization curve. The zig-zagging may result from tails, if the thermal demagnetization data was derived from an IZZI experiment. If the directional components are removed in different proportions between each treatment step, then we would observe gradual changes in the magnetization direction. We applied a set of criteria (Table) to determine the final stable component of the demagnetization vector, the ChRM (Figure b). We set n - the minimum number of consecutive demagnetization steps - to 4 and constrained the direction with MAD and DANG. To ensure consistency within a site, we set N, the minimum number of samples per site, to 5, set a maximum threshold for α_{95} and a minimum threshold for κ [*Fisher*, 1953] a precision parameter to quantify the dispersion in the directions. One-hundred and twenty-six sites yield reliable paleodirections (Table)

3.4 Hysteresis and FORC

Several sites- mc1030, mc1115, mc1147, and mc1157 – passed CCRIT and included estimates from samples that were collected from the interior [*Mankinen and Cox*, 1988; *Tauxe and Staudigel*, 2004; *Lawrence et al.*, 2009] and from the surface of the same lava flow (Figure). At each of these sites, the estimates from the interior are 2° – 8° lower than the paleointensity estimates from the lava flow tops. We selected sister specimen for hysteresis loops and FORCs to examine the micromagnetic components - domain state and interaction- that may explain the difference.

Although the sites passed CCRIT, the specimen exhibit a mixture of magnetic components (Figure). We interpret the ridge in the FORC diagram at $B_u = 0$ (Figure Xb) as the contribution from single domain grains after *Roberts and Verosub* [2000] and *Pike et al.* [2001]. The distribution of coercivities (B_c) ranges from 0 and 50 mT and peaks between 0 and 20 mT. The contours spread vertically from this ridge which reflects the level of interaction fields between the single domain grains. In multi-domain grains this peak is offset from the $B_u = 0$ mT axis and the contours follow a steep gradient that extends beyond 30 mT(Figure a). Each specimen contains some degree of superparamagnetic behavior as inferred from the vertical ridge at $B_c = 0$ mT that peaks around $B_u = 0$ mT (Figure c).

3.5 Ar-Ar

4 Discussion

4.1 Examining the GAD structure

4.1.1 Paleodirections

Our new, robust dataset consists of 126 site-mean directions that pass our selection criteria (**table 3**). It includes 54 reverse polarity and 79 normal polarity site-mean directions (**table 5**). The paleomagnetic site-mean directions were separated by polarity then transformed to their corresponding Virtual Geomagnetic Poles (VGPs) (Figure).VGP is the position of the geomagnetic dipole that would generate the direction measured at a particular latitude. We calculated the paleomagnetic pole and α_{95} by taking the average of the VGPs for the normal polarity sites (declination 208.3°, inclination 86.2°, and α_{95} 5.66 °) and the reverse polarity sites (declination 308.7°, inclination −85.6°, and α_{95} 8.88 °). We applied a bootstrap reversal test ([*Tauxe et al.*, 1991]) on the reverse and normal directions. The directions pass the reversal test, so the two sets are indistinguishable (see the supplementary material) and we can calculate the paleopole from the successful VGPs of the entire dataset (declination 176.24°, inclination 86.89°, and α_{95} 4.92 °). The 95% confidence bounds of the paleopole includes the spin axis (Figure), so the paleodirections from our study are consistent with a GAD.

4.1.2 Paleointensities

Our new paleointensity dataset consists of twenty-eight sites that pass CCRIT **(table 1)** and include both normal and reverse directions **(table 6)**. We converted the paleointensities to their corresponding Virtual Axial Dipole Moment (VADM) to compare intensity estimates across latitudes (Figure). VADM is the strength of the axial dipole moment that would generate the intensity observed at a given latitude. Our twenty-eight sites yield a 35.75 ± 7.30 median intensity and a 44.02 ZAm^2± 3.05 ZAm^2 median VADM. Our median intensity estimate is consistent with *Lawrence et al.* [2009] and half of the modern intensity measured in the Erebus Volcanic Province (~62 μT).

To assess the structure of the paleomagnetic field over the Plio-Pleistocene, we compare our results to globally distributed paleointensity data stored in the PINT database. We do not observe the latitudinal dependence of intensity expected of a GAD generated field. The paleointensity measured at the high southerly latitudes still appears depressed when compared to the global paleointensity dataset over the Plio-Pleistocene. Before we conclude this depressed intensity near the pole reflects the structure of the paleomagnetic field, we must repeat this same robust study of the 0 – 5 Myr paleomagnetic field at several latitudes [*Dossing et al.*, 2016; *Wang et al.*, 2015].

4.2 Examining the role of sampling material

Several of our sites that passed CCRIT include specimens from both the interior and the surface of the same lava flow. We assume a single lava flow cooled instantaneously, so the surface and interior of the flow should preserve identical intensities however, at several sites the interior yields systematically lower paleointensities (Figure) than the samples from the surface. A slower cooling rate may result in a higher intensity of magnetization [*Dodson and McClelland-Brown*, 1980] so we tested the effect of cooling rate on the TRM of these samples by conducting a cooling rate experiment. Each specimen measured a higher remanence following rapid cooling than slow cooling, but the correction required for the slowly cooled specimens from the interiors is greaterthan the corrections required for slowly cooled flow tops at the same site (see the supplementary material). Therefore differences in the cooling history between the two sampling regions does not explain the lower paleointensities we measure in the interior.

Next, we tested whether differences in domain state and interaction could explain the behavior by measuring hysteresis loops and FORC diagrams. The magnetic moments in specimen from mc1115 (Figure) and mc1147 (see the supplementary material) include a superparamagnetic component, a single domain component and some degree of interaction [*Roberts and Verosub*, 2000], but the domain structure of specimen from the interiors appears identical to those from the flow tops at the same site. Therefore, differences in domain states does not account for the higher paleointensities measured in the samples collected from the surface.

In addition to cooling rate and domain state, we investigated whether non-linear TRM acquisition could explain the bias in the intensity estimates from the interior. During the in-field step of the IZZI experiment, we applied a 30 μT field to our specimens collected from the surface during the 2016/2017 field season. *Lawrence et al.* [2009] cooled some specimen from the interior in a 25 μT field and others in a 30 μT field . Therefore, we performed a non-linear TRM acquisition test to determine whether the lower intensities measured in the interiors resulted from the lower intensities applied during the IZZI experiment. Each successful specimen was subjected to a total TRM in a 10 μT, 20 μT, 30 μT, 40 μT, 50 μT, and 60 μT field and each specimen acquired a remanence in proportion to the strength of the applied field (see the see the supplementary materialary material). Neither cooling rate, domain state, nor non-linear TRM acquisition accounts for the lower intensities recorded by the specimen sampled from the interior of the lava flows. Only six of our twenty-eight successful sites include paleointensity estimates from both the surface and the interior, so a full investigation on the role of sampling material on paleointensity estimates would require a larger sample size.

5 Conclusions

We present a robust study of the paleomagnetic field over the Plio-Pleistocene in the Erebus Volcanic Province, Antarctica (-77.84°, 166.69°) and eleven new ^{40}Ar/^{39}Ar results. We recovered a paleopole at 176.24°, 86.89° from 126 independent sites that were subjected to both thermal and AF demagnetization and then filtered using a set of strict selection criteria. The α_{95} of the paleopole is 4.92° and encompasses the spin axis so the paleodirections measured from the EVP during the Plio-Pleistocene are consistent with a GAD field. We also conducted an IZZI-modified Thellier-Thellier experiment and applied the CCRIT set of selection criteria to estimate paleointensity. Twenty-eight sites passed our criteria and recorded a $35.75\mu T \pm 7.30\mu T$ median intensity and a 44.02 ZAm^2± 3.05 ZAm^2 median VADM. Compared with global paleointensity estimates stored in the PINT database, our results from Antarctica are lower than expected for a purely GAD generated field. Before we conclude that this result is representative of the paleomagnetic field structure, we recommend that this extensive study is replicated at different latitudes to ensure high quality paleointensity estimates, appropriate temporal overlap, and adequate global coverage.

Acknowledgments

This work was funded by the National Science Foundation Grant OPP1541285. We thank the United States Antarctic Program for their ground support in Antarctica. We thank Christeanne Santos for her assistance with data collection and Cathy Constable, Jeff Gee, and Brendan Cych for their helpful discussions.

The supporting information can be found —— and the entire data set at —-

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