Originally published as:

Shah, J., Koppers, A. A., Leitner, M., Leonhardt, R., Muxworthy, A. R., Heunemann, C., Bachtadse, V., Ashley, J. A., Matzka, J. (2016): Palaeomagnetic evidence for the persistence or recurrence of geomagnetic main field anomalies in the South Atlantic. - *Earth and Planetary Science Letters*, 441, pp. 113–124.

DOI: <http://doi.org/10.1016/j.epsl.2016.02.039>

Palaeomagnetic evidence for the persistence or recurrence of geomagnetic main field anomalies in the South Atlantic

Jay Shah^{1,*}, Anthony A.P Koppers², Marko Leitner³, Roman Leonhardt⁴, Adrian R. Muxworthy¹, Christoph Heunemann³, Valerian Bachtadse³, Jack A. D. Ashley¹, Jürgen Matzka⁵

¹ Department of Earth Science and Engineering, Imperial College London, London, UK

² College of Earth, Ocean & Atmospheric Sciences, Oregon State University, Corvallis, OR, USA

³ Dept. Geo- and Environmental Sciences, Ludwig-Maximilian Universität, Munich, Germany

⁴ Central Institute for Meteorology and Geodynamics, CONRAD Observatorium, Vienna, Austria

⁵ GFZ German Research Centre for Geosciences, Potsdam, Germany

* Corresponding author.

Corresponding author contact: jay.shah109@imperial.ac.uk

Abstract

We present a dataset of a full-vector palaeomagnetic study of Late Pleistocene lavas from the island Tristan da Cunha in the South Atlantic Ocean. The current day geomagnetic field intensity in this region is approximately 25 μT , compared to an expected value of $\sim 43 \mu\text{T}$; this phenomenon is known as the South Atlantic geomagnetic Anomaly (SAA). Geomagnetic field models extending back to the last 10 ka find no evidence for this being a persistent feature of the geomagnetic field, albeit, all models are constructed from data which is particularly sparse in the southern hemisphere. New $^{40}\text{Ar}/^{39}\text{Ar}$ incremental heating dating indicates the studied lavas from Tristan da Cunha extruded between 90 and 46 ka. Palaeointensity estimations of eight lava flows made using the Thellier method yield an average palaeointensity of $18 \pm 6 \mu\text{T}$ and virtual axial dipole moment (VADM) of $3.1 \pm 1.2 \times 10^{22} \text{ Am}^2$. The lava flows demonstrate four time intervals comparable to the present day SAA, where the average VADM of the Tristan da Cunha lavas is weaker than the global VADM average. This suggests a persistent or recurring low intensity anomaly to the main geomagnetic field similar to the SAA existed in the South Atlantic between 46 and 90 ka.

Keywords

Palaeomagnetic; Ar/Ar dating; Tristan da Cunha; South Atlantic Anomaly; Geomagnetic field; Magnetic anomaly

1. Introduction

From geomagnetic observations and palaeomagnetic records, we know that the Earth's magnetic field is dominated by an axial dipole, which is also dynamic and changing in terms of both its direction and intensity (e.g. Johnson and Constable, 1997; Thébault et al., 2015). Central to much palaeomagnetic research is the assumption that when averaged over time, this axial dipole aligns parallel with the spin axis of the Earth: the so-called geocentric axial dipole (GAD) hypothesis. Over very long periods, up to 200 million years, this hypothesis has been shown to hold true. However, it has been known for some time, that there are systematic departures from this simple model over shorter timescales and on more regional scales (Korte et al., 2011; Nilsson et al., 2014).

A complete understanding of the Earth's magnetic field requires not only a knowledge of the variation of the direction of the field over the surface of the Earth, but information about the variability of its intensity. The intensity of the present day magnetic field ranges from approximately 30 to 60 μT from low to high latitudes at sea level (Thébault et al., 2015). Our understanding of the geomagnetic field is limited by the quality of the palaeointensity (ancient geomagnetic field intensity) database, which is incomplete both spatially and temporally. The PINT08 database contains all published absolute palaeointensity data older than 50 ka (Biggin et al., 2009). Over recent years the palaeomagnetic community has made a great effort to populate this database, which now contain in excess of 4000 records. The PINT08 database is heavily biased towards northern latitudes, with large areas of the southern hemisphere poorly sampled, and only five localities in the South Atlantic (see supplementary material, Fig. A1). The South Atlantic data are from two studies: 100 to 300 ka ocean basalts with palaeointensity values similar to the present day field in the South Atlantic (Maksimochkin et al., 2010); and 15 Ma, 36 Ma, and 72 Ma ocean basalts with palaeointensities of 29 μT , 20 μT , and 51 μT (Juarez et al., 1998). The virtual axial dipole moment (VADM) of the Maksimochkin et al. (2010) data is within error of the $5.6 \pm 1.1 \times 10^{22} \text{ Am}^2$ VADM modelled by PADM2M (Ziegler et al., 2011) for 100 to 300 ka, indicating there was no geomagnetic anomaly in the South Atlantic during this period. These sparse data points highlight the need to expand the palaeomagnetic dataset temporally and spatially to be able to more accurately model and understand features of the geomagnetic field that differ from a GAD field.

58 The poor spatial coverage in southern high and mid-latitudes has left some key questions unanswered. For
59 example, the South Atlantic (geomagnetic) Anomaly (SAA) is a well-known feature of the current
60 geomagnetic field, which differs significantly from a GAD field by its low intensity (Hartmann and Pacca,
61 2009). The SAA has a very pronounced inclination anomaly, and currently a westerly declination. The
62 expected magnetic field strength at Tristan da Cunha for a GAD with today's Earth's dipole magnetic
63 moment of $7.75 \times 10^{22} \text{ Am}^2$ would be 43 μT , but the current geomagnetic main field intensity from the
64 International Geomagnetic Reference Field (IGRF) at Tristan da Cunha is 24 μT with a declination of -24°
65 and inclination of -64° (Thébault et al., 2015). This fits the data from the local geomagnetic observatory
66 (25 μT , -22° declination and -65° inclination), but the observed total field values range from 23 to 30 μT
67 due to gradients in the crustal magnetic field, as measured on the island (Matzka et al., 2009; Matzka et
68 al., 2011). Time averaged field models show a positive inclination anomaly in the South Atlantic region of
69 approximately $1\text{--}4^\circ$ (Aubert et al., 2010).

70 The gufm1 model is a model of the geomagnetic field from 1590 to 1990 based on historical observations
71 of the magnetic field (Jackson et al., 2000). A combination of the gufm1 and IGRF models, indicates that
72 the magnetic field intensity at Tristan da Cunha has been below 43 μT since 1593 AD, reducing in
73 intensity by approximately 50 nT per year since 1590 AD and thus comparable to the present-day five
74 percent decrease per century in geomagnetic field strength (Jackson et al., 2000; Gubbins et al., 2006;
75 Thébault et al., 2015). A recent study of southern African fired clays reports the SAA weak intensity
76 initiated around 1250 AD (Tarduno et al., 2015). Due to the limited palaeomagnetic sampling and analysis
77 of both volcanic and sedimentary lithologies in the South Atlantic, there is not enough data from this
78 region to help answer the question of whether the SAA is persistent on geological timescales.

79 Here we present results of a systematic palaeomagnetic sampling campaign on the island of Tristan da
80 Cunha in the South Atlantic (Fig. 1). Only two very limited palaeomagnetic studies from the early-sixties
81 have been reported for the island of Tristan da Cunha (Blundell, 1964; Creer, 1964). Our study
82 concentrates on a volcanic sequence extruded in the Late Pleistocene. Tristan da Cunha is an ideal locality
83 for testing the geological record of the SAA as it is located in the middle of the SAA, and being a volcanic
84 hotspot, lavas have been regularly extruded over the last few hundred thousand years. This study reports a

full-vector palaeomagnetic and $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology study of basalts from Tristan da Cunha. In addition to standard palaeomagnetic directional analysis, we determined the ancient geomagnetic field intensity (palaeointensity) using the modified Thellier-Thellier-Coe method (Coe, 1967) (hereafter referred to as the ‘Thellier’ method).

2. Geological Setting and Sampling

The Tristan da Cunha island group (37° 05' S, 12° 17' W) was formed by the Tristan hotspot as part of the Walvis Ridge east of the Mid-Atlantic Ridge (Ljung et al., 2006). The principal islands, Tristan da Cunha, Inaccessible, and Nightingale are separate volcanoes. Tristan da Cunha, the largest, is circular and approximately 12 km in diameter at sea level, and has a peak of 2,062 m above sea level. Inaccessible and Nightingale are eroded remnants of volcanoes and have smaller, irregular forms (McDougall and Ollier, 1982).

Detailed geological and volcanological descriptions of the island were presented by Baker et al. (1964) and Dunkley (2002). The samples in this study were collected on a visit in 2004, in the Main Cliff above Pigbite to the west of Big Point (Fig. 1), where well-stratified basanitic and tephritic flows are exposed (Hicks et al., 2012). There were no folding or faulting tectonic features in the sampling area, with the only alteration to the strata being igneous intrusions.

The main volcanic sequence was sampled in three profiles of consecutive lava flows (from bottom to top A, B and C, see Fig. 1). Palaeomagnetic sampling sites have been numbered according to their stratigraphic position ranging from T01 (oldest flow) to T38 (youngest flow) (see supplementary material for sample coordinates, Table A1). The profiles cover about 50 percent of the lava flows that form the lower two thirds of The Main Cliff at Pigbite (Fig. 1). The lowest and westerly most profile A was sampled from an inclining ramp of rock debris at the foot of the cliff. It consists of seven flows, with a gap of two flows (between T02 and T03) that were not sampled because of the close proximity to a dyke. Between profile A and B remain about 20 m vertical height of unsampled lava flows. In profile B, 20 flows were sampled close to or inside Plantation Gulch. Between profile B and C, about 60 m of lava flows were not sampled. In profile C, 11 flows were sampled in Councilor’s Gulch.

Standard palaeomagnetic cores were collected and prepared as 25 mm samples at Ludwig-Maximilian Universität, Munich, and stored in wooden containers away from strong magnetic fields prior to measurement. Palaeomagnetic cores were oriented with the sun compass except for T32 for which only magnetic compass orientations could be obtained and flow T23, for which part of the sun compass readings are missing. Magnetic compass readings were corrected for the local declination. Checking for differences between magnetic and sun compass orientation successfully avoided lightning strike remagnetisations from being sampled. One palaeomagnetic core per unit was reserved for $^{40}\text{Ar}/^{39}\text{Ar}$ groundmass age dating on ten different units. Samples having the least altered crystalline groundmass were selected for incremental heating dating.

3. Methods

3.1 Palaeomagnetic and Rock Magnetic Methods

The palaeomagnetic experiments were conducted at Ludwig-Maximilian Universität, Munich, and Imperial College London, using a combination of standard equipment: (1) Munich, a Molspin Minispin magnetometer, a Magnetic Measurement MMTD20 palaeomagnetic oven and a LP-RESEARCH Variable Field Translation Balance (VFTB), and in (2) London, an Agico JR5A spinner magnetometer, an ASC dual-chamber palaeomagnetic oven and a Princeton Measurements vibrating sample magnetometer (VSM). All the palaeomagnetic work was done on standard 25 mm cores.

For palaeodirectional analysis a total of 274 specimens from 231 cores were stepwise demagnetised. Half of the samples were thermally demagnetised (10 to 15 steps up to 600°C), and half of the samples were demagnetised by an alternating field (AF, 15 to 19 steps, up to 200 mT). Occasionally, a 10 mT AF pre-treatment was applied before thermal demagnetisation when AF demagnetisation showed a significant change during the first steps.

Palaeointensity analysis was conducted using the modified Thellier-Thellier-Coe method (Coe, 1967), with partial thermoremanent magnetisation (pTRM) checks and pTRM-tail checks (Walton, 1984; Riisager and Riisager, 2001). For the palaeointensity determination, a laboratory field of 30 μT was applied. Fifteen heating steps were made between 100°C and 570°C combined with five pTRM checks and

three pTRM tail-checks. The magnetic susceptibility of the samples was measured after each new temperature interval to test for chemical alteration.

Rock magnetic properties were measured for a few samples from each flow. Hysteresis curves were measured to determine the standard hysteresis parameters: saturation magnetisation, M_s , saturation remanence, M_{RS} , coercive force B_C , and coercivity of remanence, B_{CR} , and thermomagnetic curves were measured to determine the Curie temperature and chemical stability of the samples to heating in (1) Munich, an applied field of 880 mT in an argon atmosphere and (2) London, an applied field of 50 mT in a helium atmosphere.

3.2 $^{40}\text{Ar}/^{39}\text{Ar}$ Geochronology Methods

$^{40}\text{Ar}/^{39}\text{Ar}$ ages were obtained by incremental heating methods at Oregon State University. Samples were prepared by sawing, crushing, magnetic separation, acid leaching and hand picking according to methods described in Koppers et al. (2011). Ten samples were irradiated for 6 hours (13-OSU-03) in the TRIGA nuclear reactor at Oregon State University, along with Taylor Creek (TCR-2a) sanidine (28.53 ± 0.02 Ma, 1σ) flux monitors (consistent with the Fish Canyon Tuff sanidine age of 28.201 ± 0.023 Ma from Kuiper et al., 2008) to measure the required J-values for the age calibration. Individual J-values for each sample were calculated by parabolic extrapolation of the measured flux gradient against irradiation height and typically give $\sim 0.15\%$ uncertainties (1σ).

The $^{40}\text{Ar}/^{39}\text{Ar}$ incremental heating age determinations were performed on a multi-collector ARGUS-VI mass spectrometer with 5 Faraday collectors (all fitted with 10^{12} Ohm resistors) and 1 ion-counting CuBe electron multiplier (located in a position next to the lowest mass Faraday collector). This allows us to measure simultaneously all argon isotopes, with mass 36 on the multiplier and masses 37 through 40 on the four adjacent Faradays. This configuration provides the advantages of running in a full multi-collector mode while measuring the lowest peak (on mass 36) on the highly sensitive electron multiplier (which has an extremely low dark-noise and a very high peak/noise ratio). Collector calibrations (for mass 36 measured on the multiplier vs. the adjacent L2 faraday cup) were carried out by measuring air shots (daily) for typical intensity ranges and applied to all unknown samples and measured blanks. Irradiated samples were loaded into Cu-planchettes in an ultra-high vacuum sample chamber and incrementally heated by

scanning a defocused 25 W CO₂ laser beam in preset patterns across the sample, in order to release the argon evenly. After heating, reactive gases were cleaned up for ~10 minutes, using an SAES Zr-Al ST101 getter operated at 400°C and two SAES Fe-V-Zr ST172 getters operated at 200°C and room temperature, respectively.

All ages were calculated using the corrected Steiger and Jäger (1977) decay constant of $5.530 \pm 0.097 \times 10^{-10}$ 1/yr (2σ) as reported by Min et al. (2000). For all other constants used in the age calculations we refer to Table 2 in Koppers et al. (2003). Incremental heating plateau ages and isochron ages were calculated as weighted means with $1/\sigma^2$ as weighting factor (Taylor, 1997) and as YORK2 least-square fits with correlated errors (York, 1969) using the ArArCALC v2.6.2 software from Koppers (2002) available from the <http://earthref.org/ArArCALC/> website.

4. Results

4.1 Rock Magnetic Properties

The high-temperature thermomagnetic curves have been categorised into four groups, of which representative plots are displayed in Fig. 2, and all the lava flows are grouped in Table A1 in the supplementary material. Curie temperatures were derived using the second derivative method (Leonhardt, 2006) on the heating cycle (Table A1 in supplementary material). The curves are qualitatively grouped based upon their behaviour on the heating and cooling cycles, which are dependent on the Curie temperatures of the samples corresponding to the magnetic mineralogy (Fig. 2, Table A1). The majority of samples recovered 90-110% of the initial magnetisation on the cooling cycle. Group A (Fig. 2a) represents lava flows that have dominant Curie temperatures (T_C) ranging from 480-580°C, indicating multiple ferrimagnetic phases of titanomagnetite and magnetite. Group B (Fig. 2b) represents lava flows with a dominant T_C value at 260°C, indicating Ti-rich titanomagnetite, and a higher T_C between 480-580°C, indicating titanomagnetite and magnetite. Group C (Fig. 2c) represents lava flows that have T_C values in the range 520-580°C, indicating a single ferrimagnetic phase of magnetite. Group D (Fig. 2d) consists of lava flows with the dominant T_C ranging from 50-200°C, but with also a higher T_C component in the range 480-580°C. The 200 °C T_C is associated with titanomagnetite containing 60% titanium (TM₆₀), and lower

T_C values are due to increasing proportions of titanium. Groups A and C also have some samples with lower T_C . Curie points and bulk hysteresis parameters were measured for the majority of lava flows, and are tabulated in the supplementary material (Table A1).

4.2 *Palaeodirections*

Examples of orthogonal projection plots (“Zijderveld” plots (Zijderveld, 1967)) are shown in Fig. 3. A stable remanence component was usually isolated between 240° C and 320° C or above an AF peak field of 6 mT. Characteristic remanent magnetisation (ChRM) directions and appropriate mean values were unambiguously identified for most sites.

The flow declinations and inclinations are shown in Table 1 and Fig. 3. The declination shows moderate variations with a maximum deviation of 40° from an axial dipole. The inclination, which from an axial dipole would be expected to be -57°, steepens throughout the profiles, from -50° in the lower profile A to -80° at the top of profile C. Three units in profile C (T30, T31, T32), however, are characterised by shallow inclinations below -20°. The inclination and declinations are plotted on an equal area projection (Fig. 3b) and cluster about an approximate Fisher mean direction of 2.4° declination and -54.1° inclination with an error in declination (ΔD) of 7.0° and error in inclination (ΔI) of 5.4°. The IGRF field, observatory field, and dipole prediction at Tristan da Cunha are also plotted on Fig. 3b. The error was calculated from the Fisher mean of the calculated virtual geomagnetic poles (VGP) determined from the directional data, converting the α_{95} of the poles to individual ΔD and ΔI following Deenen et al. (2011).

4.3 *Thellier Palaeointensity Determinations*

The palaeointensity study conducted followed the standard double-heating protocol of Coe (1967), with pTRM checks and pTRM-tail checks. A laboratory field of 30 μ T was applied at a random angle to the NRM during both heating and cooling cycles for each in-field treatment. In total 166 samples were tested, representing 38 units, T01-T38, which are all lava flows except T30-T32, which were later determined to be intrusions.

Arai plots with corresponding NRM orthogonal-projection demagnetisation plots are shown for typical samples in Fig. 4. The results were analysed with the ThellierTool (v. 4.22) software of Leonhardt et al.

(2004). ThellierTool's default selection criteria (Table 2) were used to classify the results, and points on the Arai plot were selected in order to optimise the quality factor (q). Of the 166 samples tested, 31 samples met the selection criteria (Table 2), providing data for 8 of the initial 35 lava flows, and one potential sill (T30) (Table 3). The samples that passed the selection criteria were typically of thermomagnetic curve groups A and B (Fig. 2a, b), which are mostly reversible on heating and cooling cycles indicating low chemical alteration. Representative Arai plots for selected samples are depicted in Fig. 4. Most of the samples that failed were of group D (Fig. 2d), and displayed evidence for chemical alteration during the experiments, as evident through pTRM checks (CK parameter). Chemical alteration is also evident in samples that passed the selection criteria, but to a lesser degree (Fig. 4). A large contribution of multidomain grains is also evident in the pTRM tail checks ($\delta(\text{TR})$) of T09 and T10 (Table 3). These samples were typically of group C (Fig. 2c) and the larger proportion of multidomain grains may explain why they yielded the weakest palaeointensities. To avoid analysis of the chemically altered temperature range without introducing user bias, the ThellierTool automatic temperature range selection tool was used with every sample, which applies an algorithm to find the slope with maximum the maximum quality factor (q). Averaged palaeointensity estimates for lava flows have been calculated in Table 3.

Magnetic susceptibility measurements were made at every increase in temperature for lava flows tested at Imperial College London (T06, T07, T11, T12, T19, T25, and T26). Lava flow T06 decreases in susceptibility by 78% between 420-570°C. T07 increases in susceptibility by 5% in three samples between 150-570°C, and decreases in susceptibility by 27% in two samples between 330-570°C. T11 decreases in susceptibility by 8% between 420-570°C. T12 decreases in susceptibility by 11% between 420-570°C. T19 decreases in susceptibility by 21% between 420-570°C. T25 decreases in susceptibility by 20% between 480-570°C. T26 decreases in susceptibility by 30% between 420-570°C. Magnetic susceptibility variations are directly related to the degree of chemical alteration of the rock.

4.4 $^{40}\text{Ar}/^{39}\text{Ar}$ Geochronology

The earliest radiometric age determinations for Tristan da Cunha island using the K/Ar technique were published 25 years ago (McDougall and Ollier, 1982). Subsequently new $^{40}\text{Ar}/^{39}\text{Ar}$ dating was conducted

by Dunkley (2002) and more recently by Hicks et al. (2012), who dated the lowermost and uppermost exposed lava flows at Big Point as 81 ± 10 ka (about 5 flows below T01) and 34 ± 1 ka (about 200 m above T38), respectively (recalibrated to the TCR standard age of 28.53 ± 0.02 Ma). For this study additional $^{40}\text{Ar}/^{39}\text{Ar}$ ages were determined for flows T02 and T04 (profile A), T08, T09, T10, T11 and T23 (profile B), and T29, T30 and T38 (profile C) (Table 4; Fig. 5). Our preferred $^{40}\text{Ar}/^{39}\text{Ar}$ dates are plateau ages accompanied by 2σ standard errors on the weighted means. Independently determined $^{40}\text{Ar}/^{39}\text{Ar}$ ages by Hicks et al. (2012), $^{40}\text{Ar}/^{39}\text{Ar}$ ages by Dunkley (2002), and K/Ar ages by McDougall and Ollier (1982) agree well with the ages determined for this study. Our ages also are consistent with volcanic stratigraphy, except sample T30-6A from flow T30, which provides a plateau age of 29.2 ± 12.7 ka and seemingly is younger than surrounding lava flows and the youngest flow (34 ± 1 ka; Hicks et al., 2012) observed in the profiles. Although its uncertainty overlaps at 2σ (but not at the 1σ) confidence intervals with other nearby lava flows, sample T30-6A may be interpreted as an unrecognised dike or sill intrusion, which may also explain the shallow magnetic inclination of -14° , shallower than all other observed inclinations in this study.

To test for accuracy in the ARGUS-VI, we analysed 150 Alder Creek sanidine (AC-2) standards that gave us an average age of 1184.9 ± 4.2 ka and 1192.6 ± 4.2 ka (2σ , $n = 141/150$, respectively based on the Fish Canyon Tuff sanidine flux monitor ages of 28.02 Ma of Renne et al. (1998) and 28.201 Ma of Kuiper et al. (2008)). The 150 AC-2 runs for OSU include measurements from in total 5 irradiations in the OSU TRIGA reactor (4 of 6 hours; 1 of 10 hours). Typical sample loads were 1-2 crystals for AC-2 (16-20 mesh) and 2-6 for AC-2 (20-40 mesh). The OSU data are consistent between runs with different crystal size and when considering only the data that are most radiogenic with $^{40}\text{Ar}^* > 90\%$ or 95% , for example. Our mean AC-2 age of 1184.9 ± 4.2 ka overlaps within 1σ and 2σ confidence levels with average AC-2 ages of 1.1940 ± 0.0140 Ma (2σ) of Renne et al. (1998), 1.1910 ± 0.0140 Ma (2σ) of Mark et al. (2009) and 1.1930 ± 0.0020 Ma (2σ) of Nomade et al. (2005).

All samples dated with the ARGUS-VI multi-collector mass spectrometer provided consistent age spectra upon incremental heating (Fig. 5) and all (but one) sample included 80-100% of the total amount of gas released in the age plateaus. The Mean Squared Weighted Deviation (MSWD) for all samples are lower

than 1.9 and isochron calculations provided $^{40}\text{Ar}/^{36}\text{Ar}$ intercept values consistent with the atmospheric ratio of 295.5 within 2σ confidence intervals (Table 4). Finally, in all cases (recombined) total fusion ages are also consistent with the plateau ages, underlying the fact that all samples retained closed systems after their eruption in the Late Pleistocene.

5. Discussion

5.1 Palaeodirections

In the absence of tectonic influence on the sampled section, the steady change in both declination and inclination evident in Fig. 6 appears to be a true feature of the palaeomagnetic field. The palaeomagnetic directions of the all the units cluster about a Fisher mean of 2.4° declination and -54.1° inclination with ΔD of 7.0° and ΔI of 5.4° (Fig. 3b). The error was calculated from the Fisher mean of the calculated VGPs determined from the directional data, converting the α_{95} of the poles to individual ΔD and ΔI following Deenen et al. (2011). T30, T31, and T32 have significantly shallower inclination values than the mean (Fig. 3). The young $^{40}\text{Ar}/^{39}\text{Ar}$ age for T30 (29.2 ± 12.7 ka) and coarser mineralogy (pyroxene up to 10 mm) suggest that T30, T31, and T32 are intrusive sills rather than lava flows. Removing these units from the calculation of the Fisher mean results in a new mean of -0.1° declination and -57.0° inclination with a ΔD of 6.6° and ΔI of 5.1° . Within its error, the mean inclination agrees well with the -56° GAD prediction and with the palaeosecular variation model of a $1-4^\circ$ positive inclination anomaly in the South Atlantic (Aubert et al., 2010).

The VGPs of each unit are in Table 1, and their Fisher mean is 72.7° longitude and 88.0° latitude with an α_{95} of 5.6° and kappa of 18.1. Not including T30, T31, and T32 the Fisher mean of the VGPs is 155.2° longitude and 87.9° latitude with an α_{95} of 5.3° and kappa of 21.7. Deenen et al. (2011) determined the α_{95} window of VGPs demonstrating scatter attributed to palaeosecular variation rather than tectonic influence (α_{95} greater than $\alpha_{95_{\max}}$) or remineralisation (α_{95} less than $\alpha_{95_{\min}}$). For this study, the window is between 4.0° and 8.3° , and α_{95} is 5.6° including or 5.3° excluding the sills, indicating the palaeodirections are a temporal correlation of palaeosecular variation. This suggests the palaeodirections are representing the palaeomagnetic field directions.

The difference in palaeodirection between successive flows can be tested for statistical significance. Assuming a modal secular variation rate of $\sim 2^\circ/100$ years, lava flows of statistically homogeneous direction can be placed into directional groups of flows separated by less than a century in eruption time, or potentially one large eruptive event (Chenet et al., 2008). By implementing the test outlined in Chenet et al., (2008), six groups are evident in the sequence: T03-T07, T10-T13, T15-T16, T19-T20, T25-T29, and T36-T37 (Table 1). The lava flows that don't fall into directional groups are assumed to have erupted greater than a century apart.

5.2 Magnetic mineralogy and reliability of palaeointensity estimates

Multiple magnetic phases in the lava flows are evident in the conducted thermomagnetic analysis, which shows that most tested samples have T_C indicative of magnetite and titanomagnetite of varying Ti-content. Thermomagnetic curves showing little chemical alteration had T_C of 500°C - 580°C , consistent with magnetite and Ti-poor titanomagnetite as the dominant carriers of remanence (supplementary material, Table A1). Maghemitisation is evident through irreversibility of thermomagnetic curves and change in magnetic susceptibility on heating (Fig. 2). These samples were typically of thermomagnetic curve type D (Fig. 2d). Samples from curve type C yielded the weakest palaeointensities of the samples that passed the selection criteria (T09, T10), which may be due to a larger proportion of multidomain grains, evident through the pTRM tail checks ($\delta(\text{TR})$ in Table 3).

The Thellier experiment experienced a very high failure rate, with only 31 samples meeting the selection criteria (Table 2) out of the total 166 (19%). The high failure rate was in most cases the result of maghemitisation during the experiments, recognised in the analysis by pTRM checks; those samples failed the Thellier experiment as they had $\delta(\text{CK})$ values $\geq 7\%$ and/or cumulative differences produced by pTRM checks $\geq 10\%$ (δ_{pal}) (Table 2). As maghemitisation can result in weak palaeointensity estimation, these samples were rejected. In a few other cases failure appears to have been associated with the presence of non-ideal MD grains, as indicated by concave curvature in the Arai plots and pTRM tail checks. The pTRM tail check rejects samples with $\geq 5\%$ tail after correction for angular dependence ($\delta(t^*)$), and/or $\geq 20\%$ maximum difference produced by a tail check normalised by the NRM ($\delta(\text{TR})$) (Table 2).

However, sufficient palaeointensities met the selection criteria (Table 2) to compare the palaeointensity of the studied Late Pleistocene Tristan da Cunha rocks (Table 3) to the Late Pleistocene geocentric axial dipole.

5.3 Persistent nature of the SAA

The current geomagnetic field intensity at Tristan da Cunha is approximately 25 μT , compared to an expected GAD value of $\sim 43 \mu\text{T}$. The average palaeointensity of the lava flows in this study is $18 \pm 6 \mu\text{T}$. This does not include T30, which is likely an intrusive sill aged $29.2 \pm 12.7 \text{ ka}$ with a palaeointensity estimate from a single sample of $56 \pm 7 \mu\text{T}$. The VADM data was calculated for all of the lava flows that met the selection criteria for palaeointensity estimation (Table 3, Fig. 6). The average VADM of the lava flows in this study is $3.1 \pm 1.2 \times 10^{22} \text{ Am}^2$.

As the VADM data can be used to compare field intensities irrespective of geographical position, the SINT-800 and PADM2M databases (Guyodo and Valet, 1999; Ziegler et al., 2011) of the Earth's dipole field intensity over the last 800 ka and 2 Ma respectively can be used for comparison with our data. The only time the global VADM has been of a similar magnitude to the VADM of the Tristan da Cunha lavas over the last 800 ka is during the Laschamp excursion around 41.3 ka (Bourne et al., 2013). The VGP_{lat} is not low enough to be considered an excursion of the geomagnetic field (Fig. 6) (Verosub and Banerjee, 1977; Guyodo and Valet, 1999). The radiometric dating indicates that the lava flows are older than the Laschamp excursion, having been extruded from 46 to 90 ka, and 56 to 83 ka for the lava flows with palaeointensity estimates. For this time period, the global VADM was $6.2 \times 10^{22} \text{ Am}^2$ according to the SINT-800, $6.0 \times 10^{22} \text{ Am}^2$ according to the PADM2M, and $6.4 \times 10^{22} \text{ Am}^2$ according to the PINT08 database. The VADM of our dataset is weaker than the global absolute dataset at the 95% confidence level.

The radiometric dating indicates that the lava flows represent at least four distinct periods of anomalously weak intensity, as the ages for T08-T11 are indistinguishable. At a finer resolution, the grouping of lava flows based on directional analysis following Chenet et al., (2008) indicates that the lava flows may represent up to five discrete time intervals from 56 to 83 ka of apparent anomalously weak, non-dipolar intensity (Table 3, Fig. 6). The weaker average VADM of the Tristan da Cunha lavas is not a global trend

but is likely a localised anomaly in the South Atlantic. These data indicate main geomagnetic field anomalies were present in the Late Pleistocene, and main geomagnetic field anomalies in the South Atlantic are a persistent (or recurring) feature of the geomagnetic field at 100 ka time scales. As addressed by Lawrence et al. (2009) other causes for a weak anomaly could be: (1) poor quality or biased palaeointensity estimates due to the selection criteria, (2) insufficient temporal or spatial sampling. With regards to the quality of the data, the selection criteria used in this study (Table 2) are widely used, and prevent chemically altered samples and samples with a significant multidomain contribution being considered. When applying the less stringent selection criteria of Paterson et al. (2014), similar results were produced, suggesting our dataset is robust. Although our data set, coming from one volcanic source, is limited in spatial resolution, we have a well-constrained $^{40}\text{Ar}/^{39}\text{Ar}$ dated history of the palaeointensity records. As is always the case for volcanic samples, the data could be reflecting a short time interval rather than the entire 46 to 90 ka time period. However, with the youngest palaeointensity results (T25 and T26) being maximum $56.2 + 13.7 = 69.9$ ka old and the oldest palaeointensity result (T06) being minimum $83.0 - 8.3 = 74.7$ ka old, the low field intensity is at least lasting from 70 to 75 ka. This highlights scientific interest in palaeomagnetically sampling older and younger flows of the volcanic sequence of Tristan da Cunha. This period of weak intensity slightly predates the age interval 55 to 65 ka, which is known from relative palaeointensity stacks of the North and South Atlantic to show a peak weak intensity in both the North and South Atlantic records (Stoner et al., 2002).

The latest geomagnetic field models constructed from archaeomagnetic and lake-sediment data for the last 10 ka, indicate that the SAA is not a persistent feature of the geomagnetic field (Hartmann and Pacca, 2009; Korte and Muscheler, 2012). The SAA appears to not be present before 1600 AD. An earlier model by Korte et al. (2010) suggested that the SAA might be a long term feature, however newer models have revised that notion (Korte et al., 2011). In a recent archaeomagnetic study from southern Africa on fired clays from 1000 to 1600 AD, Tarduno et al. (2015) report a rapid decrease in palaeointensity from 1250 AD (18 μT) with a low intensity peak at 1370 AD (9 μT) not captured by models, returning to a full field strength of ~ 39 μT around 1600 AD. Tarduno et al. (2015) attribute this to core flux expulsion due to the composition and structure at the core-mantle boundary beneath the South Atlantic, seismically defined as

a large low shear velocity province (Wen et al., 2001). The data from South Atlantic basalts reported by Maksimochkin et al. (2010) suggest no geomagnetic anomaly during 100 to 300 ka, possibly a result of the periodicity in the core flux behaviour, however, this study may suffer from insufficient temporal and spatial resolution.

The dataset in this study, which shows a decrease in the geomagnetic field strength between at least 70 and 75 ka, does not agree with the latest geomagnetic field models, that do not show any signs of weakening. However, as noted by Korte et al. (2011), these models are poorly constrained within the southern hemisphere, where South Atlantic geomagnetic field behaviour is constrained only by data from equatorial Africa and mid-latitude South America. While the time-scales of these models and our data are not comparable, the palaeointensity estimates are weak in direct comparison to the PINT08 palaeointensity records and the SINT-800 and PADM2M models. We therefore propose that an anomalous low intensity of the Earth's magnetic field in the South Atlantic existed in the Late Pleistocene, which may be due to a reversed flux patch at the core-mantle boundary (Hulot et al., 2002). Similar anomalous palaeointensity lows found by Tarduno et al., (2015) from 1250 to 1600 AD in the South Atlantic region may suggest that flux reversal at the core-mantle boundary is a persistent or recurring feature below the South Atlantic region.

6. Conclusion

New results from $^{40}\text{Ar}/^{39}\text{Ar}$ incremental heating indicate that the 35 lava flows from Tristan da Cunha extruded over a time period of approximately 35 kyr in the Late Pleistocene. Analysis of the VGPs has determined that the palaeodirections reported are a temporal correlation of palaeosecular variation, however, it should be noted that T30, T31, and T32 are igneous intrusions younger than the sequence of lava flows. The current geomagnetic field intensity at Tristan da Cunha is approximately 25 μT and thus significantly weaker than observed global ~ 43 μT intensities at similar latitudes. For all lava flows tested in this study, the average palaeointensity found by the Thellier method is 18 ± 6 μT , yielding an average VADM of $3.1 \pm 1.2 \times 10^{22}$ Am^2 . This is significantly weak compared to the average VADM for the 56 to 83 ka extrusion period of the lava flows with palaeointensity estimates: 6.2×10^{22} Am^2 from the SINT-

800, 6.0×10^{22} Am² from the PADM2M, and 6.4×10^{22} Am² from absolute values in the PINT08 database. This indicates that the weak palaeointensity estimates for the Tristan da Cunha lavas are a localised anomaly in Earth's geomagnetic field. Weakly constrained geomagnetic field models suggest low intensity anomalies in the geomagnetic field are short lived. However, this dataset provides evidence for a main geomagnetic field anomaly in the South Atlantic during the Late Pleistocene that is similar to present observations, which could suggest a persistent (or recurring) feature of the geomagnetic field due to maybe an insistent core-mantle boundary flux reversal below the South Atlantic.

Acknowledgements

We are grateful to the Administrator M. Hentley, Chief Islander A. Green and the Island Council for admission to Tristan da Cunha and the permit to take samples there. J. Glass and N. Glass helped sampling. We thank P. Kotze and the Hermanus Magnetic Observatory for support in South Africa. JM acknowledges financial support by Deutsche Forschungsgemeinschaft (grant Ma 2578/2-1). JADA was funded by a Geology Society Undergraduate Research Bursary.

References

- Aubert, J., Tarduno, J.A., Johnson, C.L., 2010. Observations and models of the long-term evolution of Earth's magnetic field. *Space science reviews* 155 (1-4), 337-370. <http://dx.doi.org/10.1007/s11214-010-9684-5>
- Baker, P.E., Gass, I.G., Harris, P.G., and Le Maitre, R.W., 1964, The volcanological report of the Royal Society Expedition to Tristan da Cunha, 1962: *Phil. Trans. R. Soc. A*, v. 256, no. 1075, p. 439-575.
- Biggin, A.J., Strik, G.H.M.A., and Langereis, C.G., 2009, The intensity of the geomagnetic field in the late-Archaeon: new measurements and an analysis of the updated IAGA paleointensity database: *Earth Planets Space*, v. 61, p. 9-22.
- Blundell, D.J., 1964, Paleomagnetism of some recent volcanic rocks from Tristan da Cunha (lat. 37°S, long. 13°W): *British Antarc. Surv. B.*, v. 4, p. 15-21.
- Bourne, M.D., Mac Niocaill, C., Thomas, A.L., and Henderson, G.M., 2013, High-resolution record of the Laschamp geomagnetic excursion at the Blake-Bahama Outer Ridge: *Geophys. J. Int.*, doi: 10.1093/gji/ggt327.
- Chenet, A.L., Fluteau, F., Courtillot, V., Gérard, M., and Subbarao, K.V., 2008, Determination of rapid Deccan eruptions across the Cretaceous-Tertiary boundary using paleomagnetic secular variation: Results from a 1200-m-thick section in the Mahabaleshwar escarpment: *J. Geophys. Res.*, v. 113, no. B04101, doi:10.1029/2006JB004635.
- Coe, R.S., 1967, Paleointensities of the Earth's magnetic field determined from Tertiary and Quaternary rocks: *J. Geophys. Res.*, v. 72, no. 12, p. 3247-3262, doi: 10.1029/JZ072i012p03247.
- Creer, K.M., 1964, Paleomagnetic measurements on lavas from Tristan and Inaccessible Island, Volcanological Report on Tristan da Cunha: *Phil. Trans. R. Soc. A*, v. 256, p. 569-573.
- Deenen, M.H.L., Langereis, C.G., van Hinsbergen, D.J.J., and Biggin, A.J., 2011, Geomagnetic secular variation and the statistic of palaeomagnetic directions: *Geophys. J. Int.*, v. 186, no. 2, p. 509-520, doi: 10.1111/j.1365-246X.2011.05050.x
- Dunkley, P.N., and Baptie, B.J., 2002, Volcanic hazard assessment of Tristan da Cunha: British Geological Survey.
- Gubbins, D., Jones, A.L., Finlay, C.C., 2006, Fall in Earth's magnetic field is erratic. *Science* 312 (5775), 900-902. <http://dx.doi.org/10.1126/science.1124855>.
- Guyodo, Y., and Valet, J.-P., 1999, Global changes in intensity of the Earth's magnetic field during the past 800 kyr: *Nature*, v. 399, no. 6733, p. 249-252, doi: 10.1038/20420.
- Hartmann, G. A., and Pacca, I. G., 2009, Time evolution of the South Atlantic magnetic anomaly: *Anais da Academia Brasileira de Ciências*, v. 81, no. 2, p. 243-255.
- Hicks, A., Barclay, J., Mark, D.F., and Loughlin, S., 2012, Tristan da Cunha: Constraining eruptive behavior using the ⁴⁰Ar/³⁹Ar dating technique: *Geology*, v. 40, no. 8, p. 723-726.
- Hulot, G., Eymin, C., Langlais, B., Manda, M., and Olsen, N., 2002, Small-scale structure of the geodynamo inferred from Oersted and Magsat satellite data: *Nature*, v. 416, no. 6881, p. 620-623, doi: 10.1038/416620a.
- Jackson, A., Jonkers, A.R.T., and Walker, M.R., 2000, Four centuries of geomagnetic secular variation from historical records: *Phil. Trans. R. Soc. A*, v. 358, no. 1768, p. 957-990, doi: 10.1098/rsta.2000.0569.

- Johnson, C.L., and Constable, C.G., 1997, The time-averaged geomagnetic field: Global and regional biases for 0-5 Ma: *Geophys. J. Int.*, v. 131, no. 3, p. 643–666, doi: 10.1111/j.1365-246X.1997.tb06604.x.
- Juarez, M.T., Tauxe, L., Gee, J.S., and Pick, T., 1998, The intensity of the Earth's magnetic field over the past 160 million years: *Nature*, v. 394 no. 6696, p. 878–881.
- Koppers, A.A.P., 2002, ArArCALC—Software for 40Ar/39Ar age calculations: *Comput. Geosci.*, v. 28, p. 605–619, (Available at <http://earthref.org/tools/ararcalc.htm>.)
- Koppers, A.A.P., Staudigel, H., Wijbrans, J.R., and Pringle, M., 2003, Short-lived and discontinuous intraplate volcanism in the South Pacific: Hot spots or extensional volcanism?: *Geochem. Geophys. Geosyst.*, v. 4, no. 10, doi:10.1029/2003GC000533.
- Koppers, A.A.P., Russell, J.A., Roberts, J., Jackson, M.G., Konter, J.G., Wright, D.J., Staudigel, H., and Hart, S.R., 2011, Age Systematics of Two Young En Echelon Samoan Volcanic Trails: *Geochem. Geophys. Geosyst.*, v. 12, no. 7, doi: 10.1029/2010GC003438
- Korte, M., and Holme, R., 2010, On the persistence of geomagnetic flux lobes in global Holocene field models: *Physics Earth Planet. Int.*, v. 182, no. 3–4, p. 179–186, doi: 10.1016/j.pepi.2010.08.006.
- Korte, M., Constable, C., Donadini, F., and Holme, R., 2011, Reconstructing the Holocene geomagnetic field: *Earth Planet. Sci. Lett.*, v. 312, no. 3–4, p. 497–505, doi: 10.1016/j.epsl.2011.10.031.
- Korte, M., and Muscheler, R., 2012, Centennial to millennial geomagnetic field variations: *JSWC*, v. 2, no. A08.
- Kuiper, K.F., Deino, A., Hilgen, F.J., Krijgsman, W., Renne, P.R., and Wijbrans, J.R., 2008, Synchronizing Rock Clocks of Earth History: *Science* v. 320, no. 500, doi: 10.1126/science.1154339.
- Lawrence, K.P., Tauxe, L., Staudigel, H., Constable, C.G., Koppers, A., McIntosh, W., and Johnson, C.L., 2009, Paleomagnetic field properties at high southern latitude: *Geochem. Geophys. Geosys.*, v. 10, no. 1, p. Q01005, doi: 10.1029/2008GC002072.
- Leonhardt, R., 2006, Analyzing rock magnetic measurements: The RockMagAnalyzer 1.0 software: *Comput. Geosci.*, v. 32, no. 9, p. 1420–1431, doi: 10.1016/j.cageo.2006.01.006.
- Leonhardt, R., Heunemann, C., and Krása, D., 2004, Analyzing absolute paleointensity determinations: Acceptance criteria and the software ThellierTool4. 0: *Geochem. Geophys. Geosys.*, v. 5, no. 12, p. n/a–n/a, doi: 10.1029/2004GC000807.
- Ljung, K., Björck, S., Hammarlund, D., and Barnekow, L., 2006, Late Holocene multi-proxy records of environmental change on the South Atlantic island Tristan da Cunha: *Paleogeogr. Paleoclimatol. Paleoecol.*, v. 241, no. 3, p. 539–560, doi: 10.1016/j.paleo.2006.05.007.
- Maksimochkin, V.I., Mbele, J.R., Trukhin, V.I., and Schreider, A.A., 2010, Paleointensity of the geomagnetic field in the last half-million years in regions of the Red Sea and south of the Mid-Atlantic Ridge: *Moscow Univ. Phys. Bull.*, v. 65 no. 6, p. 531–538.
- Mark, D.F., Barfod, D., Stuart, F.M., and Imlach, J., 2009, The ARGUS multicollector noble gas mass spectrometer: Performance for 40Ar/39Ar geochronology: *Geochem. Geophys. Geosyst.*, v. 10, no. 2, doi: 10.1029/2009GC002643
- Matzka, J., Olsen, N., Maule, C.F., Pedersen, L.W., Berarducci, A.M., and Macmillan, S., Danish Meteorological Institute, National Space Institute Denmark, U.S. G.S., and Survey, B.G., 2009, Geomagnetic observations on Tristan da Cunha, South Atlantic Ocean: *Ann. Geophys.*, v. 52, no. 1, p. 97–105, doi: 10.4401/ag-4633.
- Matzka, J., Husøy, B.-O., Berarducci, A., Wright, D., Pedersen, L.W., Stolle, C., Repetto, R., Genin, L., Merenyi, L., and Green, J., 2011, The geomagnetic observatory on Tristan da Cunha: Setup, operation and experiences: *Data Sci. J.*, v. 10, p. IAGA151-IAGA158
- McDougall, I., and Ollier, C.D., 1982, Potassium-argon ages from Tristan da Cunha, south Atlantic: *Geol. Mag.*, v. 119, no. 1, p. 87–93.
- Min, K., Mundil, R., Renne, P.R., and Ludwig, K.R., 2000, A test for systematic errors in 40Ar/39Ar geochronology through comparison with U/Pb analysis of a 1.1-Ga rhyolite: *Geochim. Cosmochim. Acta*, v. 64, p. 73–98.
- Nomade, S., Renne, P.R., Vogel, N., Deino, A.L., Sharp, W.D., Becker, T.A., Jaouni, A.R., and Mundil, R., 2005, Alder Creek sanidine (ACS-2): A Quaternary Ar-40/Ar-39 dating standard tied to the Cobb Mountain geomagnetic event: *Chem. Geol.*, v. 218, no. 3–4, p. 315–338.
- Nilsson, A., Holme, R., Korte, M., Suttie, N., and Hill, M., 2014, Reconstructing Holocene geomagnetic field variation: new methods, models and implications: *Geophys. J. Int.*, v. 198, no. 1, p. 229–248, doi: 10.1093/gji/ggu120.
- Paterson, G.A., Tauxe, L., Biggin, A.J., Shaar, R., and Jonestrask, L.C., 2014, On improving the selection of Thellier-type paleointensity data: *Geochem., Geophys., Geosyst.*, v. 15 no. 4, p. 1180–1192.
- Renne, P.R., Swisher, C.C., Deino, A.L., Karner, D.B., Owens, T.L., and DePaolo, D.J., 1998, Intercalibration of standards, absolute ages and uncertainties in 40Ar/39Ar dating: *Chem. Geol.*, v. 145 no. 1–2, p. 117–152.
- Riisager, P., and Riisager, J., 2001, Detecting multidomain magnetic grains in Thellier paleointensity experiments: *Physics Earth Planet. Int.*, v. 125, no. 1–4, p. 111–117, doi: 10.1016/S0031-9201(01)00236-9.
- Steiger, R.H., and Jäger, E., 1977, Subcommission on geochronology: Convention on the use of decay constant in geo- and cosmochronology: *Earth Planet. Sci. Lett.*, v. 36, p. 359–362.
- Stoner, J.S., Laj, C., Channell, J.E.T., and Kissel, C., 2002, South Atlantic and North Atlantic geomagnetic paleointensity stacks (0–80ka): implications for inter-hemispheric correlation: *Quat. Sci. Rev.*, v. 21 no. 10, p. 1141–1151.
- Tarduno, J.A., Watkeys, M.K., Huffman, T.N., Cottrell, R.D., Blackman, E.G., Wendt, A., Scribner, C.A., and Wagner, C.L., 2015, Antiquity of the South Atlantic Anomaly and evidence for top-down control on the geodynamo: *Nature communications*, v. 6, doi:10.1038/ncomms8865.
- Taylor, J.R., 1997, An introduction to error analysis: the study of uncertainties in physical measurements: *Univ. Sci., Sausalito, CA*, p. 45–92.
- Thébault, E., Finlay, C.C., Beggan, C.D., Alken, P., Aubert, J., Barrois, O., et al., 2015, International Geomagnetic Reference Field: the 12th generation: *Earth Planets Space*, v. 67, no. 79.
- Verosub, K.L., and Banerjee, S.K., 1977, Geomagnetic excursions and their paleomagnetic record: *Rev. Geophys.*, v. 15, no. 2, p. 145–155, doi: 10.1029/RG015i002p00145.
- Walton, D., 1984, Re-evaluation of Greek archaeomagnitudes: *Nature*, v. 310, no. 5980, p. 740–743, doi: 10.1038/310740a0.

517 Wen, L., Silver, P., James, D., and Kuehnel, R., 2001, Seismic evidence for a thermo-chemical boundary at the base of the Earth's
 518 mantle: *Earth Planet. Sci. Lett.*, v. 189 no. 3, p. 141-153.
 519 York, D., 1969, Least squares fitting of a straight line with correlated errors: *Earth Planet. Sci. Lett.*, v. 5, p. 320-324.
 520 Ziegler, L.B., Constable, C.G., Johnson, C.L., and Tauxe, L., 2011, PADM2M: a penalized maximum likelihood model of the 0-2
 521 Ma palaeomagnetic axial dipole moment: *Geophys. J. Int.*, v. 184, no. 3, p. 1069-1089
 522 Zijdeveld, J.D.A., 1967, AC demagnetization of rocks: analysis of results: *Methods in Paleomagnetism*, p. 254-286.
 523

Figure Captions

Figure 1. (a) Map of the South Atlantic indicating the location of Tristan da Cunha. (b) Map of Tristan da Cunha indicating sampling locations. (c) Photograph of Tristan da Cunha displaying the locations of the three sampled profiles.

Figure 2. Thermomagnetic curves for selected samples representing the four different groups all the lava flows have been divided into: A, B, C, and D. Heating and cooling cycles have been labelled. The Curie temperatures are detailed in Table A1 in supplementary material.

Figure 3. (a) Zijderveld plots showing samples that were thermally demagnetised, AF demagnetised, and both thermally and AF demagnetised. (b) Equal area projection of the inclination and declination of the lava flows in this study. The three outliers are T30, T31, and T32. The Fisher mean is the green triangle, the International Geomagnetic Reference Field (IGRF) field is the red circle, the observatory field is the blue diamond, and the geocentric axial dipole (GAD) is the grey square.

Figure 4. Representative Arai plots for six lava flows with Thellier palaeointensity results: (a) T06, (b) T11, (c) T12 (data rejected), (d) T19, (e) T25, and (f) T26. The inset figure in the upper right and bottom left (d) of each figure presents the demagnetisation behaviour of the sample on a vector component plot. The palaeointensities were determined using the criteria described in Table 2. The palaeointensities with error is listed on each figure and in Table 3.

Figure 5. High-resolution incremental heating $^{40}\text{Ar}/^{39}\text{Ar}$ age spectra for Tristan da Cunha lava flows. The $^{40}\text{Ar}/^{39}\text{Ar}$ ages are weighted age estimates with errors reported at the 95% confidence level, including 0.15% standard deviations in the J-value. All samples were monitored against TCR-2a sanidine (28.53 ± 0.02 Ma, 1σ) as calibrated by Kuiper et al. (2008). Data are listed in the Electronic Supplement and ArArCALC age calculation files can be downloaded from the EarthRef.org Digital Archive (ERDA).

Figure 6. Declination (D), inclination (I), virtual geomagnetic pole longitude (VGP_{long}), virtual geomagnetic pole latitude (VGP_{lat}), palaeointensity, and virtual axial dipolar moment (VADM) of the units in stratigraphic order (T01 oldest, T38 youngest). The geocentric axial dipole (GAD) value for inclination is labelled. There is a gap between T02 and T03 of two unsampled lava flows and a dike intrusion. There is a 20 m vertical height gap of unsampled lava flows between profile A and B, and 60 m vertical height of unsampled lava flows between B and C. The young age of T30, and the shallow inclinations of T30, T31, and T32 suggest they are intrusive sills emplaced into the lava sequence. The palaeointensities and VADMs are presented as averages of the directional groups, except for T09, which does not fall within a group.

Figure 1 (a,b,c)

Figure 2

Figure 2 (black and white)

Figure 3 (a,b).

Figure 4.

Figure 5.

Figure 5 (black and white)

Figure 6

Table 1. The three profiles mapped and photographed in Fig. 1 are listed here with their vertical height above sea level and directional group (DG) indicated. The Fisher mean declination (D) and inclination (I) of each unit is presented with the associated kappa (κ), number of samples demagnetised (N), number of samples for which a direction could be isolated (n), and calculated virtual geomagnetic pole longitude (VGP_{long}) and latitude (VGP_{lat}).

Lava Flow	DG	Height (m)	N	D (°)	I (°)	κ	VGP _{long}	VGP _{lat}
Profile C								
T38		327	8/8	-6.5	-73.8	51	176.0	66.9
T37	DG6	323	5/7	-23	-74.4	108	191.8	62.2
T36	DG6	321	6/8	-5.9	-75.9	302	173.6	63.5
T35		319	7/8	26	-68	61	123.2	66.9
T34		315	5/5	27.4	-78.2	133	149.2	56.0
T33		309	7/8	9.4	-78.6	61	161.0	58.6
T32*		303	3/3	16.4	-17.9	274	19.8	58.4
T31*		295	5/9	22.7	-20.8	117	31.3	56.7
T30*		288	7/10	17.4	-13.8	64	19.8	56.0
T29	DG5	285	7/7	37.2	-63.4	571	105.3	61.1
T28	DG5	281	8/9	41	-62.6	116	103.3	58.4
Profile B								
T27	DG5	215	8/8	21.5	-61.6	168	103.5	72.6
T26	DG5	213	7/7	26.9	-62.4	606	104.2	68.6
T25	DG5	209	7/7	17.5	-60.1	417	99.3	75.9
T24		202	6/7	-1.4	-46.4	321	340.1	80.6
T23		199	7/9	6.5	-61.3	309	126.6	82.7
T22		196	8/10	-14	-39.9	80	303.8	71.2
T21		188	7/7	5.2	-50.7	393	26.5	82.9
T20	DG4	182	7/7	-5.5	-53.8	215	287.5	84.8
T19	DG4	177	6/6	-3.1	-53.9	312	303.1	86.4
T18		171	5/5	15.4	-55.6	329	78.0	77.6
T17		168	4/6	-14.3	-58.7	1086	241.4	78.5
T16	DG3	166	6/6	-11	-46.7	535	299.1	77.0
T15	DG3	164	8/8	-11.4	-47	94	297.2	76.9
T14		160	5/9	-18.2	-61.3	208	231.2	75.1
T13	DG2	157	7/7	-2.7	-48	323	331.2	81.7
T12	DG2	153	6/6	1.7	-47.8	1773	358.0	81.7
T11	DG2	151	6/6	-6.5	-51.8	107	296.8	82.9
T10	DG2	148	4/6	-3.5	-47	153	328.4	80.7
T9		145	7/7	-12.6	-56.2	586	255.7	79.9
T8		140	7/7	16.8	-47	260	50.4	73.3
Profile A								
T7	DG1	120	7/7	-6.1	-48	56	313.5	80.5
T6	DG1	115	5/5	-8.7	-49.6	319	297.7	80.2
T5	DG1	108	5/5	-7.8	-49.5	252	301.5	80.7
T4	DG1	103	5/5	-7.6	-44.3	370	315.3	77.2
T3	DG1	100	5/5	3.6	-46.6	202	7.0	80.3
T2		77	5/5	-19.4	-44.1	307	286.4	70.1
T1		72	6/7	-8.9	-50.1	83	295.1	80.4

* Igneous intrusion

6 Table 2. Summarizing the Thellier Tool 4.22 default criteria. These parameters are described in more detail in
7 Leonhardt et al. (2004) and references therein. Common abbreviations for the parameters are bracketed.

Criteria description	Class A	Class B
<i>Linear fit criteria</i>		
number of points (N) used to determine the paleointensity	≥ 5	≥ 5
normalized standard deviation of slope (β)	≤ 0.1	≤ 0.15
fraction of NRM (f)	≥ 0.3	≥ 0.3
quality factor (q)	≥ 1	≥ 0
<i>Directional criteria</i>		
maximum angular deviation (MAD) of the anchored fit	$\leq 6^\circ$	$\leq 15^\circ$
angular difference between the anchored and non-anchored solution (α)	$\leq 15^\circ$	$\leq 15^\circ$
<i>Alteration criteria</i>		
maximum difference produced by a pTRM check, normalized by the TRM ($\delta(\text{CK})$)	$\leq 5 \%$	$\leq 7 \%$
cumulative difference produced by pTRM checks (δ_{pat})	$\leq 5 \%$	$\leq 10 \%$
<i>Repeated demagnetization steps</i>		
extent of pTRM tail after correction for angular dependence pTRM ($\delta(t^*)$)	$\leq 3 \%$	$\leq 5 \%$
maximum difference produced by a pTRM tail check, normalized by the NRM ($\delta(\text{TR})$)	$\leq 10 \%$	$\leq 20 \%$
<i>Additivity checks</i>		
cumulative difference produced by pTRM additivity checks ($\delta(\text{AC})$)	$\leq 3 \%$	$\leq 5 \%$

8
9

Table 3. The accepted Thellier palaeointensity estimates (F), and the mean palaeointensity ($\bar{F}$) and virtual axial dipole moment (VADM) for each unit with greater than one sample. The $\bar{F}$ values are averaged over the directional groups for sequential lava flows erupted over a <100-year time period. See Table 2 for definitions of each of the parameters.

Sample	$F \pm \sigma$ (μT)	ΔT ($^{\circ}\text{C}$) ¹	N	f	g	q	w	$\delta(\text{CK})$	$\delta(\text{TR})$	$\delta(\text{AC})$	Class	$\bar{F} \pm \sigma$ (μT)	VADM $\pm \sigma \times 10^{22}$ (Am^2)
T06-1	23.95 ± 0.61	400 - 610	8	0.83	0.72	23.5	9.6	1.9	3.4	5	A	22 ± 3	3.9 ± 0.6
T06-5A	19.05 ± 1.66	480 - 570	5	0.75	0.68	5.8	3.4	5.7	6.4	...	B		
T09-3	8.09 ± 0.33	200 - 580	12	0.88	0.68	14.7	4.7	6.1	8.6	5	B		
T09-4	8.44 ± 0.62	100 - 520	11	0.38	0.61	3.1	1	3.1	4	3.2	B	8 ± 1	1.5 ± 0.2
T09-4B	9.53 ± 0.39	480 - 600	6	0.76	0.7	12.9	6.4	6.4	8.1	...	B		
T09-5	8.21 ± 0.63	250 - 520	9	0.52	0.63	4.3	1.6	2.7	5.6	4.2	A		
T09-5B	6.62 ± 0.53	480 - 600	6	0.76	0.68	6.5	3.2	6.7	10.8	...	B	15 ± 3	2.7 ± 0.5
T10-1	12.38 ± 0.78	200 - 520	10	0.47	0.69	5.2	1.8	2	4.4	3.7	A		
T10-2	13.46 ± 0.91	100 - 550	12	0.69	0.67	6.9	2.2	3.7	14.9	3.6	B		
T10-3	13.55 ± 0.59	250 - 520	9	0.42	0.64	6.2	2.4	2.7	2.7	3.5	A	22 ± 5	3.9 ± 0.9
T10-3B	12.43 ± 0.63	480 - 570	5	0.81	0.66	10.6	6.1	5.7	7.7	...	B		
T10-4	17.58 ± 1.86	340 - 520	7	0.34	0.78	2.5	1.1	2.2	3.8	2.6	B		
T11-1	17.04 ± 1.44	20 - 610	15	0.86	0.87	8.8	2.4	6	0.3	4.9	B	24 ± 4	4.3 ± 0.6
T11-1B	16.39 ± 1.47	300 - 480	7	0.3	0.76	2.6	1.2	5	0.9	...	A		
T11-1C	19.78 ± 1.97	300 - 480	7	0.33	0.74	2.5	1.1	6.6	0.6	...	B		
T11-2	14.84 ± 1.47	20 - 520	12	0.65	0.85	5.6	1.8	5.5	0.2	5.5	B	$...$	$...$
T11-4	15.24 ± 0.5	250 - 520	9	0.69	0.75	15.8	6	4.6	1.2	3.3	A		
T11-4C	10.99 ± 1.08	250 - 390	5	0.49	0.69	3.5	2	1.6	4.7	...	B		
T19-1A	21.74 ± 1.49	200 - 570	13	0.84	0.81	9.9	3	4.1	6.9	...	A	$...$	$...$
T19-5	22.42 ± 1.38	250 - 520	9	0.58	0.76	7.2	2.7	5.3	3.8	6.2	B		
T19-5B	22.67 ± 1.75	300 - 570	11	0.8	0.8	8.4	2.8	5	2.2	...	A		
T19-6	28.87 ± 0.8	370 - 490	5	0.31	0.72	8.1	4.7	6.3	5.8	5.8	B	$...$	$...$
T19-7B	14.11 ± 1.34	360 - 570	9	0.85	0.8	7.2	2.7	3.4	1.3	...	A		
T25-4A	20.04 ± 1.21	360 - 570	9	0.82	0.82	11.2	4.2	6	2.4	...	B		
T25-6	26.11 ± 2.3	100 - 520	11	0.62	0.74	5.2	1.7	5	2.8	4.7	A	$...$	$...$
T25-7	29.62 ± 1.13	400 - 550	6	0.72	0.7	13.1	6.5	4	4.8	2.2	A		
T26-1B	19.98 ± 1.8	390 - 570	8	0.86	0.8	7.6	3.1	3.9	2	...	A		
T26-4	22.89 ± 0.51	340 - 580	9	0.81	0.72	26.4	10	4.8	4.6	7.6	B	$...$	$...$
T26-7D	26.94 ± 1.65	360 - 570	9	0.85	0.8	11	4.2	5.6	5.4	...	B		
T28-2	23.01 ± 2.15	250 - 520	9	0.42	0.78	3.5	1.3	4.3	2.2	3.7	B		
T30-4	55.7 ± 7.41	20 - 340	6	0.4	0.72	2.2	1.1	4	0.9	5.8	B	$...$	$...$

¹ ΔT is the temperature range used to make the paleointensity estimate.

² No additivity check conducted.

17 Table 4 40Ar/39Ar geochronology summary of ages as measured using the ARGUS-VI. All ages derived from the samples' groundmass. P is probability in percent; n is number
 18 of increments out of a total of N increments that are included in plateau and isochron ages; K/Ca is the atomic ratio of potassium over calcium as measured over the age plateau
 19 or for the entire incremental heating experiment. MSWD is the mean squared weighted deviation (York, 1969).

Sample	Experiment	Age Spectrum					Total Fusion				Inverse Isochron Analyses			
		Age $\pm 2\sigma$ (ka)	39Ar (%)	K/Ca	MSWD	P (%)	n	N	Age $\pm 2\sigma$ (ka)	K/Ca	Age $\pm 2\sigma$ (ka)	40Ar/ 36Ar intercept	MSWD	P (%)
T02-4A	14D01043	89.7 $\pm$ 5.1	99	0.189	0.64	89	22	23	89.2 $\pm$ 5.8	0.312	95.3 $\pm$ 11.1	293.5 $\pm$ 4.5	0.62	90
T04-3A	14D00683	83.0 $\pm$ 8.3	100	0.017	0.39	100	34	34	86.9 $\pm$ 10.2	0.204	77.8 $\pm$ 11.5	297.2 $\pm$ 2.8	0.35	100
T08-4B	14D00958	78.5 $\pm$ 4.1	100	0.254	0.42	99	22	23	78.9 $\pm$ 4.8	0.521	79.9 $\pm$ 9.7	294.9 $\pm$ 4.1	0.43	99
T09-8A	14D00763	76.9 $\pm$ 12.5	98	0.022	0.44	98	20	23	80.6 $\pm$ 15.3	0.120	79.3 $\pm$ 23.7	294.9 $\pm$ 6.3	0.46	97
T10-3A	14D00860	78.1 $\pm$ 13.5	83	0.112	1.14	31	16	23	77.0 $\pm$ 14.5	0.113	68.1 $\pm$ 23.0	296.9 $\pm$ 3.6	1.18	28
T11-6A	14D01104	75.0 $\pm$ 10.0	69	0.489	1.87	3	13	23	25.6 $\pm$ 26.7	0.355	92.2 $\pm$ 13.7	292.5 $\pm$ 2.1	1.17	30
T23-7B	14D00825	54.7 $\pm$ 9.4	100	0.046	0.75	79	23	23	51.4 $\pm$ 10.6	0.138	61.9 $\pm$ 16.2	294.1 $\pm$ 3.3	0.75	79
T29-4B	14D00731	56.2 $\pm$ 13.7	98	0.018	0.21	100	20	23	60.3 $\pm$ 17.0	0.110	49.2 $\pm$ 24.6	296.8 $\pm$ 4.8	0.21	100
T30-6A	14D00895	29.2 $\pm$ 12.7	99	0.035	1.39	12	20	22	24.6 $\pm$ 12.7	0.126	40.6 $\pm$ 15.0	293.6 $\pm$ 3.5	1.38	13
T38-7A	14D01008	45.6 $\pm$ 9.4	94	0.169	1.12	33	17	23	45.8 $\pm$ 10.2	0.242	69.5 $\pm$ 21.7	288.8 $\pm$ 7.5	0.99	46

Paleomagnetic evidence for the persistence or recurrence of geomagnetic main field anomalies in the South Atlantic

Jay Shah^{1,*}, Anthony A.P Koppers², Marko Leitner³, Roman Leonhardt⁴, Adrian R. Muxworthy¹, Christoph Heunemann³, Valerian Bachtadse³, Jack A. D. Ashley¹, Jürgen Matzka⁵

¹ Department of Earth Science and Engineering, Imperial College London, London, UK

² College of Earth, Ocean & Atmospheric Sciences, Oregon State University, Corvallis, OR, USA

³ Dept. Geo- and Environmental Sciences, Ludwig-Maximilian Universität, Munich, Germany

⁴ Central Institute for Meteorology and Geodynamics, CONRAD Observatorium, Vienna, Austria

⁵ GFZ German Research Centre for Geosciences, Potsdam, Germany

* corresponding author.

Supplementary Material

Table A1. This table presents the bulk hysteresis parameters and Curie temperatures of the samples tested in this study. Bulk hysteresis parameters determined by ratios of: saturation magnetisation, M_s , saturation remanence, M_{RS} , coercive force B_C , and coercivity of remanence, B_{CR} . Coordinates are in UTM 28H.

Sample	Group	M_{rs}/M_s	B_{cr}/B_c	$T_c(^{\circ}C)$	Sample Coordinates
T01-1	D	0	12980.14	57-207	740605 5894149
T02-1	D	0.06	5.61	159-179	
T03-2	D	0.2	2642.14	189-579	
T04-4	D	0.28	3.16	517-567	
T05-2	D	0.11	8.27	139	
T06-3	A	0.25	2.7	519-579	
T07-3	D	0.09	5.89	117	
T08-1	D	0.1	8.29	66-106	
T09-2	C	0.17	2.34	294	
T09-2	C	0.15	11600.63	555-575	
T10-4	C	0.22	2.19	...	
T10-4	C	0.17	6.21	157-589	
T11-4D	B	0.09	19.34	260-537	
T11-6	B	0.13	2.64	523-573	
T12-4	D	0.12	21.42	63-143	741100 5894213
T13-4	A	0.26	2.18	501-571	741080 5894190
T14-6	D	0.16	72805.71	70-499	741079 5894199
T15-4	D	0.22	2.54	66-106	741077 5894181
T17-1	D	0.19	2.24	79-226	741075 5894177
T18-4	D	0.11	8.87	103-133	741165 5894183
T19-3	C	0.15	17115.6	539-579	741170 5894176
T20-1	B	0.13	19.93	491-571	741173 5894178
T21-7B	D	0.31	2.35	540-559	741172 5894157
T21-1	D	0.13	2.86	189-439	741172 5894157
T22-5B	D	0.33	2.25	487-550	741176 5894157
T22-1	D	0.23	1.99	67	741176 5894157
T23-4	A	0.21	2.53	209-559	741199 5894169

T24-1	D	0.21	2.05	55-184	
T25-3	A	0.15	2.78	578	741176 5894135
T25-5	A	0.19	2.27	...	741176 5894135
T25-3	A	0.17	1789.76	86-346	741176 5894135
T26-2	A	0.22	2.02	569	741188 5894145
T26-4	A	0.2	2.4	...	741188 5894145
T26-4	A	0.2	2.4	118-183	741188 5894145
T26-2C	A	0.21	2.19	490-541	741188 5894145
T26-2	A	0.17	2172.04	84-204	741188 5894145
T27-6	A	0.17	2.95	150	741186 5894132
T27-2C	A	0.27	2.13	480-537	741186 5894132
T27-2	A	0.19	3.3	509-579	741186 5894132
T28-3	D	0.11	2.58	120-437	741382 5894155
T28-7	D	0.18	2.25	...	741382 5894155
T28-6C	C	0.13	2.5	120-397	741382 5894155
T28-3	D	0.08	3.8	199-439	741382 5894155
T29-5	D	0.09	4.61	109-139	741393 5894148
T30-1	D	0.24	1.94	131	741402 5894121
T30-4	D	0.22	2.61	500-540	741402 5894121
T30-2	D	0.08	3.56	204-434	741402 5894121
T31-4	A	0.12	3.45	209-559	741401 5894126
T32-2	D	0.09	3.85	573-623	741439 5894055
T32-2b	D	0.08	4.2	54-124	741439 5894055
T33-3	D	0.1	3.85	107-415	741405 5894079
T34-2	D	0.1	3.63	89	741410 5894076
T35-3	D	0.11	3.66	107	741409 5894077
T36-4	D	0.1	4.6	92	741417 5895075
T37-2	D	0.13	3.12	67-157	741417 5894074
T38-4	A	0.2	2.99	129-586	741409 5894064

Figure A1. A map of the PINT database, with the location of the lava flows from Tristan da Cunha analysed in this study labelled and highlighted in red. There is a significant bias to northern hemisphere latitudes, and only five localities sampled in the South Atlantic, aged 0.1 to 72 Ma.