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

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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 ~43 μT; 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}Ar/^{39}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 ± 6 μT and virtual axial dipole moment (VADM) of $3.1 \pm 1.2 \times 10^{22}$ 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.

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,

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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 $5.6 \pm 1.1 \times 10^{22}$ 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.

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

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

Here we present results of a systematic palaeomagnetic sampling campaign on the island of Tristan da Cunha in the South Atlantic (Fig. 1). Only two very limited palaeomagnetic studies from the early-sixties have been reported for the island of Tristan da Cunha (Blundell, 1964; Creer, 1964). Our study concentrates on a volcanic sequence extruded in the Late Pleistocene. Tristan da Cunha is an ideal locality for testing the geological record of the SAA as it is located in the middle of the SAA, and being a volcanic hotspot, lavas have been regularly extruded over the last few hundred thousand years. This study reports a full-vector palaeomagnetic and $^{40}Ar/^{39}Ar$ 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 2062 m above sea level. Inaccessible and Nightingale are eroded remnants of volcanoes and have smaller, irregular forms (McDougall and Ollier, 1982).

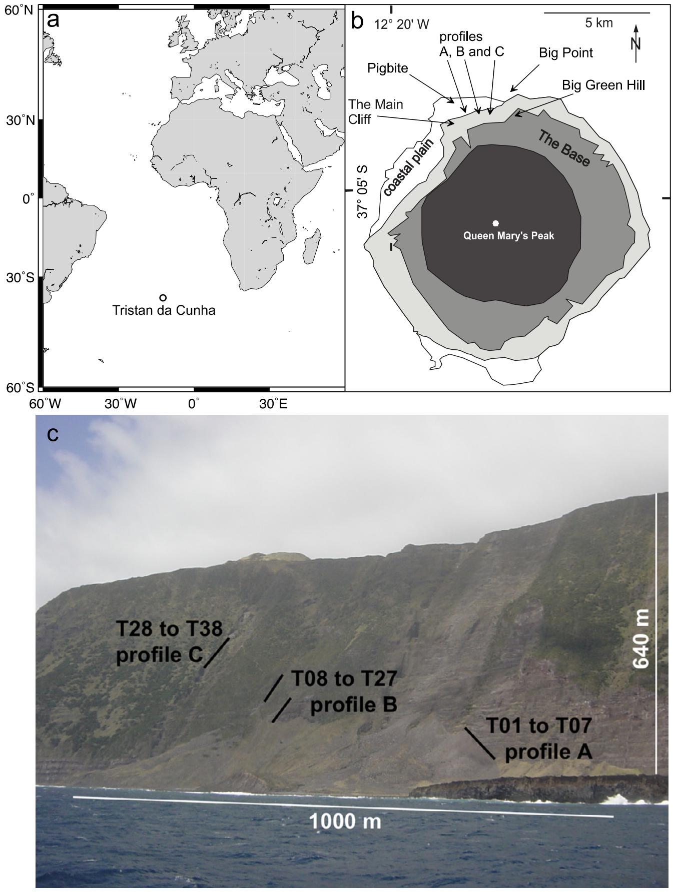

Fig. 1. (a) Map of the South Atlantic indicating the location of Tristan da Cunha. (b) Map of Tristan da Cunha indicating sampling locations. (c) Photograph of Tristan da Cunha displaying the locations of the three sampled profiles.

Detailed geological and volcanological descriptions of the island were presented by Baker et al. (1964) and Dunkley and Baptie (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% 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 remains 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