

Paleomagnetic study on a polarity transition and paleosecular variations from Saint Helena, South Atlantic

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Key Points:

- New paleomagnetic data from 8–9 Ma old volcanic sequences at Saint Helena, South Atlantic.
- In two parallel profiles a polarity transition was recorded, with three and two lava flows showing intermediate field directions, respectively.
- Most obtained paleointensities are substantially smaller than the present day and the long-term average field suggesting an influence of the South Atlantic Anomaly on geological timescales during the Upper Miocene.

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Abstract: The first paleomagnetic investigations on Saint Helena Island (Engbers et al., 2020) discovered a profile of six lava flows recording a reversed-to-normal polarity transition with three intermediate directions. In this new study, the profile was resampled, extended by four lava flows and another parallel profile with twelve lavas was added. Mean characteristic remanent magnetization directions have been obtained from four to seven specimens per flow with alternating field or thermal demagnetizations. They are reasonably defined for sixteen of the sites with Fisher precision parameters k above 50 and α_{95} confidence angles below 12.5° reproducing preliminary paleodirections measured by Engbers et al. (2020). For the majority of the flows, directions in the two parallel profiles were found to be very similar. Each profile yielded two or three intermediate directions with associated virtual geomagnetic pole latitudes between -18° and 29° . Therefore, the transitional nature of the lavas is well supported by two independent sampling campaigns and two parallel profiles. Another profile with 19 flows in the north of the island (Munden Hill) was also sampled but yielded no transitional directions. Hysteresis measurements reveal magnetic carriers of single or pseudo single domain grain size, while thermomagnetic analysis suggests titanomagnetites with both high and low Ti-content. Strong irreversibility of susceptibility with temperature suggests the presence of primary low-temperature oxidation or maghemitization. Paleointensity determination used the MT4 and IZZI protocols of the Thellier method with limited success. In agreement with previous paleointensity studies performed in the South Atlantic region, the reconstructed field was generally weak compared to the present day and the long-term average field. $^{40}\text{Ar}/^{39}\text{Ar}$ dating was attempted yielding approximate ages between 8 and 9 Ma, but accurate correlation to the geomagnetic polarity timescale is hindered by the imprecision introduced by the altered state of the samples.

Keywords: paleomagnetism; paleointensity; field transition; South Atlantic anomaly; $^{40}\text{Ar}/^{39}\text{Ar}$ dating; St. Helena (UK); volcanic rocks

1. Introduction

The geomagnetic field plays a fundamental role in protecting life on our planet from solar and galactic cosmic rays. During periods of weak global field strength, ionising particles can more easily

enter the Earth's atmosphere, triggering processes that could severely impact the biosphere (e.g. Arsenović et al., 2024). For example, the diversification of macroscopic, mobile animals is suggested to have been initiated by oxygenation during Ediacaran periods of ultra-low field strengths (Huang WT et al., 2024). Furthermore, changes in atmospheric ozone concentrations during geomagnetic transition phases might have led to an increase in UV radiation or paleoclimatic shifts, which have been connected to the extinction of mammalian megafauna (Channell and Vigliotti, 2019; Cooper et al., 2021).

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In this study, we present new paleomagnetic transitional records from volcanic sequences from the Upper Miocene on the island of Saint Helena. In general, the success rate of paleointensity experiments on ancient lava flows is low due to alteration, non-ideal grain sizes of remanence carriers, viscous overprints and reduced thermal stability, particularly if care is not taken in the choice of applied field (e.g. Murray et al., 2026). In the Miocene elevated paleosecular variation (Engbers et al., 2022b) and relatively weak field strengths (Biggin, 2026) are additional challenges. Nevertheless, volcanic records are crucial for improving our understanding of field reversal geometry. While relatively recent field excursions like the Blake event (e.g., Osete et al., 2012) can be studied with high resolution stalagmite records, most polarity transitions are examined using sedimentary records (e.g. Mahgoub et al., 2023). These can, however, suffer from temporal smoothing effects that obscure important details of transitional field behaviour such as relatively high local intensities, as revealed by lava flows on Gran Canaria (Leonhardt et al., 2000; van Grinsven et al., 2025). Additionally, absolute paleointensities provide constraints for geodynamo simulations potentially linking to mantle heterogeneity (e.g. Terra-Nova and Amit, 2024).

This study addresses the underrepresentation of the Southern hemisphere in global paleointensity databases (e.g., Bono et al., 2022a). The chosen study area also allows investigation of the South Atlantic Anomaly (SAA), a regional feature characterized by very low field strength that affects satellite communications (Heirtzler, 2002). SAA evolution has recently been studied using archeo- and paleomagnetic methods (Shah et al., 2016; Engbers et al., 2020, 2022a; Arneitz and Schnepf, 2023, Gómez-Paccard et al., 2026), and new data are presented here that shed light on whether this anomalous field behaviour persists on geological timescales.

2. Geology and Sampling

The sampling area is located on the island of Saint Helena in the southern Atlantic Ocean, connecting to a seamount chain created by hotspot volcanism on the African plate (O'Connor et al., 1999). Sub-aerial volcanism started about 14 Ma ago (Baker, 1969). An older shield volcano situated in the north east (NE, Figure 1) is separated by an erosional unconformity (Baker et al., 1967) from a younger one in the south west (SW). Different magmatic events of the upper, main, and lower SW shield produced alkali basalt, trachyte, and phonolite. The lava flows have a very variable thickness from about half a meter up to several meters or more and consist of thin scoriaceous basal layers, massive, often vesicular interiors and thick scoriaceous upper layers. Flows are sometimes separated by thin tuff layers, but, in our profiles, no soils are visible. Ages of the lavas and dykes on the island range from 8 to 12 Ma (Baker et al., 1967; Hanyu et al., 2014) and recent $^{40}\text{Ar}/^{39}\text{Ar}$ determinations (Engbers et al., 2022a) show contemporaneous activity of the upper and the main shield of the SW volcano around 8 Ma. More details on the geology can be found in the supplementary information of Engbers et al. (2020) and references therein.

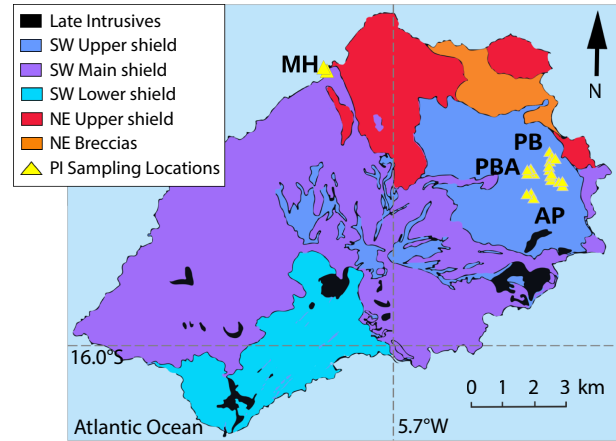


Figure 1. Geological map of St. Helena with the new sampling sites: profile P1 at the airport road (AP), the resampled sites of Engbers et al. (2020, PBA), the sites of profile P2 (PB) and the profiles on Munden Hill (MH). Adapted from Engbers et al. (2020).

Sampling in 2018 (Engbers et al., 2020) was augmented by a further campaign in 2019 for the present study (Figure 1) performed to better characterize a polarity transition observed in Prosperous Bay and to find other sequences with transitional lavas. Prosperous Bay profile consists of natural outcrops except for the uppermost flow (APA1, Table 1) which was sampled in a road cut opened for the airport. Between 4 and 11 paleomagnetic cores were taken per lava flow using an electrical or a gasoline powered drill with diamond bit. The within-flow sample-spread was maximized using distances of 10–100 m and collecting from different blocks, if present. Cores were orientated with inclinometer, magnetic compass and, whenever possible, with a sun compass. In most cases deviations of the magnetic azimuth did not exceed $\pm 8^\circ$.

The profile of Engbers et al. (2020) from Prosperous Bay Plain to Fisher's Valley (profile P1) from the SW upper shield volcano was resampled and augmented with 2 additional flows below the uppermost lava flow (Supplementary Material A, Figure S1, left, APA2, APA3, Table 1), and by one above and another below the lowermost flow (Figure S2, PBA2, PBA0). Profile P2 is situated east of P1 between the airport and Fisher's Valley (Table 1, Figure S1). Profile P1 and P2 comprise 10 and 12 flows respectively including two that were visibly correlated in the field (Figure S1, right).

Other sampling sections were difficult to access due to the severe topography, but one in the SW main shield on Munden Hill (Figure 1, MH) was feasible. A sequence of 19 lava flows was sampled (Figure S3) which followed old road cuts. This lava sequence east of Jamestown valley is presumed to represent flows of similar age as the Ladder Hill profile of Engbers et al. (2020) west of the narrow Jamestown valley, but no detailed geological map is available.

3. Methods

3.1 Rock and Paleomagnetic Measurements

Characterization of the magnetic minerals was performed in the

Table 1. Paleomagnetic results from Prosperous Bay profiles (P1, P2) and Munden Hill (PM).^a

Flow	Latitude (°N)	Longitude (°E)	Name	N	D (°)	I (°)	k	α_{95} (°)	Plat (°N)	Plong (°E)	dp (°)	dm (°)	Polarity	δ (°)	N_{PI}	PI (μT)	σ_{PI} (μT)	σ_{PI} (%)	VADM (10^{22} Am^2)	dVADM (10^{22} Am^2)
P1-10	-15.958	354.343	APA1	7+8	2.3	-18.8	56.0	5.2	79.9	1.1	2.8	5.4	N	168.3	10/2 (8/1)	8.4	5.1	60.7	1.9	1.1
P1-09	-15.957	354.344	APA2	7	353.5	-25.1	248.3	3.8	81.1	302.4	2.2	4.1	N	171.5	10/8	8.5	1.8	21.2	1.9	0.4
P1-08	-15.959	354.345	APA3	9	6.4	-47.9	317.5	2.9	78.9	137.6	2.5	3.8	N	161.2	7/4	9.5	2.9	30.5	2.1	0.6
P1-07	-15.954	354.345	PBA5	5+6	286.9	57.1	39.1	7.4	0.7	298.8	7.9	10.8	T	73.5	5/2 (6/0)	8.6	6.5	75.6	1.9	1.5
P1-06	-15.954	354.345	PBA4	7+7	320.3	46.7	51.2	5.6	29.0	307.8	4.6	7.2	T	97.0	(7/0)	—	—	—	—	—
P1-05	-15.954	354.345	PBA3	4+8	264.1	64.8	95.7	4.5	-18.0	302.2	5.8	7.2	T	61.8	6/5 (8/0)	9.1	4.4	48.4	2.0	1.0
P1-04	-15.954	354.345	PB02	8	212.3	40.8	38.6	9.0	-59.7	271.1	6.6	10.9	R	28.4	(10/1)	10.9	—	—	2.4	—
P1-03	-15.954	354.346	PBA2	5	186.7	42.8	93.8	8.2	-81.8	300.0	6.3	10.1	R	13.4	4/2	9.7	0.5	5.2	2.2	0.0
P1-02	-15.954	354.346	PBA1	7+5	195.3	36.2	107.1	4.2	-75.6	263.0	2.8	4.9	R	14.4	2/2 (5/0)	8.6	3.6	41.9	1.9	0.8
P1-01	-15.953	354.346	PBA0	7	172.7	30.0	396.4	3.0	-82.3	102.9	1.8	3.3	R	6.4	5/3	14.6	2.2	15.1	3.3	0.5
P2-12	-15.956	354.353	PB11	6	7.3	-14.7	168.1	5.2	76.0	19.5	2.7	5.3	N	162.6	8/2	25.2	11.5	45.6	5.6	2.6
P2-11	-15.955	354.352	PB12	5	309.2	55.1	144.4	6.4	16.8	306.8	6.5	9.1	T	83.8	4/0	—	—	—	—	—
P2-10	-15.955	354.353	PB13	9	315.2	62.6	16.1	13.3	14.5	316.4	16.3	20.8	T	83.3	7/1	59.0	—	—	13.2	—
P2-09	-15.954	354.351	PB26	5	199.2	51.7	56.1	10.3	-68.5	298.6	9.6	14.0	R	28.3	—	—	—	—	—	—
P2-08	-15.954	354.350	PB25	6	195.4	43.3	65.4	8.5	-74.7	282.7	6.6	10.6	R	17.0	3/0	—	—	—	—	—
P2-07	-15.953	354.350	PB24	7	156.2	21.1	47.1	9.0	-65.5	95.0	5.0	9.5	R	22.1	6/1	10.8	—	—	2.4	—
P2-06	-15.951	354.350	PB23	7	157.1	-31.1	24.1	12.7	-47.3	134.7	7.9	14.2	R	64.3	5/0	—	—	—	—	—
P2-05	-15.951	354.350	PB22	6	158.4	44.5	182.4	5.0	-69.0	55.5	4.0	6.3	R	22.7	4/0	—	—	—	—	—
P2-04	-15.949	354.351	PB21	6	165.4	15.9	72.1	7.9	-71.8	114.8	4.2	8.1	R	19.1	7/4	9.5	9.6	101.1	2.1	2.1
P2-03	-15.947	354.352	PB31	6	159.2	15.2	37.3	11.1	-66.7	105.4	5.9	11.4	R	24.8	7/0	—	—	—	—	—
P2-02	-15.947	354.352	PB32	6	355.4	-35.5	238.2	4.4	85.7	255.5	2.9	5.1	N	172.8	8/4	7.0	2.1	30.0	1.6	0.5
P2-01	-15.946	354.351	PB33	6	176.6	35.7	281.0	4.0	-86.8	72.7	2.7	4.6	R	6.4	5/1	4.0	—	—	1.0	—

Continued from Table 1

Flow	Latitude (°N)	Longitude (°E)	Name	N	D (°)	I (°)	k	α_{95} (°)	Plat (°N)	Plong (°E)	dp (°)	dm (°)	Polar-ity	δ (°)	N _{PI}	PI (μ T)	σ_{PI} (%)	VADM (10 ²² Am ²)	dVADM (10 ²² Am ²)	
PM-19	-15.921	354.284	MH18	9	12.2	-31.7	35.6	8.8	78.2	68.5	5.5	9.9	N	169.3	-	-	-	-	-	
PM-18	-15.921	354.284	MH17	11	165.7	-2.7	108.8	4.4	-64.9	132.5	2.2	4.4	R	35.2	-	-	-	-	-	
PM-17	-15.921	354.284	MH16	3	355.0	-6.7	333.5	6.8	73.1	330.5	3.4	6.8	N	156.5	-	-	-	-	-	
PM-16	-15.921	354.284	MH15	4	347.1	-2.1	379.2	4.7	67.6	312.1	2.4	4.7	N	149.8	4/0	-	-	-	-	
PM-15	-15.921	354.284	MH14	6	1.2	-28.9	99.3	6.8	85.8	3.9	4.1	7.5	N	178.7	10/5	40.1	4.6	11.5	9.0	1.0
PM-14	-15.920	354.283	MH13	4	357.0	-32.7	591.2	3.8	86.7	288.5	2.4	4.3	N	176.1	-	-	-	-	-	
PM-13	-15.921	354.284	MH-C	7	179.4	15.6	139.3	5.1	-78.4	165.0	2.7	5.2	R	14.1	-	-	-	-	-	
PM-12	-15.920	354.283	MH12	7	172.5	20.3	256.3	3.8	-78.4	128.2	2.1	4.0	R	11.6	6/2	27.7	24.4	88.1	6.2	5.5
PM-11	-15.920	354.283	MH11	9	195.5	42.3	15.9	13.3	-74.8	279.9	10.1	16.4	R	17.7	-	-	-	-	-	
PM-10	-15.920	354.283	MH10	6	191.4	51.3	167.4	5.2	-73.9	310.9	4.8	7.1	R	23.2	-	-	-	-	-	
PM-09	-15.920	354.283	MH09	8	194.4	53.0	203	3.9	-71.0	308.5	3.7	5.4	R	25.6	6/3	12.3	1.8	14.6	2.8	0.4
PM-08	-15.920	354.283	MH08	7	199.4	54.7	174.7	4.6	-66.8	304.6	4.6	6.5	R	28.6	-	-	-	-	-	
PM-07	-15.914	354.292	MH07	8	197.5	51.4	224.8	3.7	-69.9	300.1	3.4	5.0	R	25.3	-	-	-	-	-	
PM-06	-15.920	354.283	MH06	7	184.5	50.7	154.6	4.9	-77.4	330.1	4.4	6.6	R	21.3	-	-	-	-	-	
PM-05	-15.920	354.283	MH05	6	194.8	51.5	313.8	3.8	-71.7	304.6	3.5	5.2	R	24.4	-	-	-	-	-	
PM-04	-15.920	354.283	MH04	8	195.2	38.8	29	10.5	-75.6	270.2	7.4	12.5	R	15.5	4/1	11.9	-	-	2.7	-
PM-03	-15.920	354.283	MH03	5	188.8	25.3	261.1	4.7	-79.5	223.0	2.7	5.1	R	9.0	-	-	-	-	-	-
PM-02	-15.920	354.283	MH02	5	199.1	20.7	217.3	5.2	-69.6	235.2	2.9	5.5	R	19.4	3/0	-	-	-	-	-
PM-01	-15.920	354.283	MH01	4	204.3	43.1	72.4	10.9	-66.9	276.4	8.4	13.5	R	23.6	-	-	-	-	-	-

^aNumber for lava flow of Profile P1, P2 and PM; latitude and longitude of the site; flow name; number of samples (with + includes samples of Engbers et al. (2020)); declination (D) and inclination (I) of the mean characteristic remanent magnetization; precision parameter k and 95% confidence circle radius of the Fisher (1953) statistics α_{95} ; latitude (Plat) and longitude (Plong) of the virtual magnetic pole position with half angles of the error ellipses (dp, dm); polarity (N: normal, R: reversed, T: transitional); reversal angle δ (Prévot et al., 1985); number of paleointensity experiments (N_{PI} performed/accepted with IZZI in brackets), mean paleointensity (PI), with standard deviation and relative error (σ_{PI}); Virtual axial dipole moment (VADM) with its uncertainty (dVADM). Reliable paleointensities are highlighted in bold (see text for details).

laboratories of the Technical University of Leoben, the Gams laboratory, and of GeoSphere Austria through analyses of temperature dependence of magnetic susceptibility $\kappa(T)$, isothermal remanent magnetization (IRM) acquisition, and magnetic hysteresis. Hysteresis and IRM backfield curves were measured with a LakeShore 8600 Series vibration sample magnetometer (VSM) on mini-cores (4–5 mm) drilled from the same inch-specimens used to extract the specimen for paleointensity experiments. Hysteresis loops were measured between ± 500 mT, which was sufficient to saturate most of the samples. A backfield saturation field of 500 mT was chosen with steps of 1 or 2 mT according to the sample's coercivity. To obtain $\kappa(T)$ -curves crushed material (~ 200 mg) was measured in air with a AGICO MFK1-FA susceptibility meter with a CS-3 temperature control unit. At least one sample per lava flow was measured. For all samples used for paleointensity measurements either one cycle to a maximum temperature of 650 or 700 °C was done or thermal cycling with five peak temperatures between 150 and 650 °C to determine the onset of thermal alteration was performed.

Natural remanent magnetization (NRM) and demagnetization series were measured with a 2G Enterprises cryogenic magnetometer (in Gams laboratory) or a AGICO JR6 spinner magnetometer (GeoSphere Austria). Alternating field (AF) demagnetization was performed using an ASC D-2000 device or in line with the 2G magnetometer. A MMTDSC furnace (Magnetic Measurements) was used for thermal treatments. AF demagnetization was performed for 108 (94) specimens from Prosperous Bay (Munden Hill) with 9 to 16 steps up to a maximum field of 100 or 200 mT depending on the AF device. Thermal demagnetization of 42 (36) specimens started at 90 °C (100 °C) and with increments of 20 to 40 °C (11 to 18 steps) continued up to 610 °C (650 °C). For samples with low Curie temperature and weak alteration, a maximum temperature around 400 °C was sufficient. For determination of characteristic remanent magnetization (ChRM) the Remasoft 3.0 software was used for principal component analysis (PCA, Kirschvink, 1980) and lines were anchored to the origin.

Paleointensity experiments were carried out at the Conrad Observatory (GeoSphere Austria) using mini-specimens of 9 mm diameter drilled from 1-inch specimens. The Coe (1967) version of the Thellier technique with the MT4 protocol (Leonhardt et al., 2004) was applied in a MMTDSC furnace (Magnetic Measurements) using the rapid cooling rate setting (in less than 50 minutes from 500 °C to room temperature) in a laboratory field of 20 μ T. This field strength was chosen as a compromise between the current value of ~ 29 μ T (IGRF, Alken et al., 2021) and those reconstructed by Engbers et al. (2022a). The MT4 protocol included 4 to 7 pTRM-checks, 5 to 6 tail checks (Riisager and Riisager, 2001) and 3 to 6 additivity checks (Krása et al., 2003). Magnetization was measured with an AGICO JR-6A Dual Spinner Magnetometer and susceptibility was monitored after each temperature step using a Bartington MS2B/MS3 Magnetic Susceptibility Meter. Samples were pre-selected for MT4 experiments on the basis of sibling specimens having weak secondary components that were removed below 15 mT or 200 °C. Some 14 specimens were subject to a 15 mT AF demagnetization step (Marshall et al., 1988) applied prior to each magnetization measurement in order to remove overprints before

chemical alteration started (Table S1, additional files) but this was not found to be effective. Additionally, 15 specimens which needed higher demagnetization steps (15 to 30 mT or 230, 360, 440 °C) were tested, but also with little success. Attempts to pre-determine the onset of alteration using $\kappa(T)$ curves and thermal demagnetization yielded limited success due to a high level of inhomogeneity, even between specimens from the same cores.

Further paleointensity measurements were carried out in Liverpool using a 2G Cryogenic magnetometer for the six Prosperous Bay flows (five at Prosperous Bay named PB01–PB05 and one at Airport Road named AP01 which is stratigraphically above the other five as shown in Supplementary Material Figure S1) sampled and studied for paleomagnetic directions by Engbers et al. (2020). The thermal IZZI protocol (Thellier and Thellier, 1959; Yu et al., 2004) and the experimental setup of Engbers et al. (2022a) were used, including pTRM-checks and tail checks after every second pair of regular steps. Specimens were heated in alternating zero (Z) and in-field (I) steps using a MMTD24 thermal demagnetizer. The latter used a field of 5–30 μ T applied along the z-axis of the specimen.

3.2 Isotopic Dating

Sub-samples from the drill cores obtained for paleomagnetic investigations were crushed and sieved to obtain 180–250 μ m fractions. The finer particles were decanted in tap water, and the coarser residue was ultrasonically washed in acetone and deionized water several times. Phenocrysts were too scarce to be considered. Groundmass grains were handpicked under a stereomicroscope but optically good material was severely limited due to alteration. Samples were packed in aluminum capsules with the flux monitor standard Adler Creek (AC), zero-age reagent grade K_2SO_4 , and optical grade CaF_2 salts for interference corrections. The samples were irradiated at the Budapest Research Reactor (Hungary) for 1 hour, with a nominal fast neutron flux density of $\sim 5.5^{+1.3}_n$ (n is the number of neutrons; $cm^{-2} \cdot s^{-1}$). The interference correction factors for the production of isotopes from Ca and K are given in Supplementary Material Table S3. Samples were placed in a 3.5 mm pit-size aluminum sample disk and step heated using a defocused 3.5 mm CO_2 laser beam from Photon Machine Fusions 10.6 with a flat energy spectrum. The extracted gases from the sample cell were expanded into a Piston-Free Stirling Cryocooler for trapping potential water vapor and then in a two-stage low-volume extraction line (~ 350 cm^3). Both stages were equipped with SAES GP-50 (st101 alloy) getters, the first running hot (~ 350 °C) and the second running at room temperature. They were analyzed with an IsotopX NGX noble gas mass spectrometer installed at the Geological Survey of Norway. Peaks and baselines were determined by multicollection on the different masses (40 – 36 AMU, baseline: mass-shift -0.2 AMU) on Faraday detectors utilizing ATONA amplifier technology and these were regressed back to zero inlet time by 2nd degree polynomial fit (baselines by ordinary average). Blanks were analyzed for every third measurement. After blank correction, a correction for mass fractionation, ^{37}Ar and ^{39}Ar decay, and neutron-induced interference reactions was undertaken using in-house software AgeMonster, written by M. Ganerød. This implements the equations of McDougall and

Harrison (1999) and the newly proposed decay constant for ^{40}K after Renne et al. (2010). A $^{40}\text{Ar}/^{36}\text{Ar}$ ratio of 298.56 ± 0.31 from Lee et al. (2006) was used for the atmospheric argon correction and mass discrimination calculation using a power law distribution of the masses. We calculated J-values relative to an age of 1.2061 ± 0.0019 Ma for the AC sanidine flux monitor (Renne et al., 2010). We define a plateau according to the following requirements: at least three consecutive steps overlapping at the 95% confidence level (1.96σ) using the strict test:

$$\text{overlapif} : |(age_n - age_{n+1})| < 1.96 \sqrt{(\sigma_n^2 + \sigma_{n+1}^2)} \text{ (if errors quoted at } 1\sigma),$$

$\geq 50\%$ cumulative ^{39}Ar released, and mean square of weighted deviates (MSWD) less than the two tailed student T critical test statistics for $n-1$. Weighted mean ages are calculated by weighting on the inverse of the analytical variance.

4. Results

4.1 Rock Magnetism

Hysteresis and IRM backfield curves were obtained for 103 samples. The data are summarized in Table S2 and results are shown in Figure 2 in separate Day-diagrams (Day et al., 1977) for each profile. The saturation magnetization M_s was estimated using the approach to saturation method of Fabian (2006) by fitting the closed high-field range of the hysteresis loop with the model curve $M(B) = M_s + X_{hf} \times B - A/B^p$, where X_{hf} is the high-field susceptibility, A is a positive constant, and $p > 0$ is the approach to saturation exponent. The actual field range has been adjusted to yield physically meaningful p values comprised between 1 and 2. This method avoids the systematic underestimation of M_s resulting from the commonly applied tangent method.

Day plot parameters for both Prosperous Bay profiles (Figures 2a and 2b) follow the SD-MD trends expected for titanomagnetites (Dunlop, 2002a, b). The SD endmember of P1 display M_{rs}/M_s values slightly exceeding the theoretical value of 0.5 for randomly oriented particles with uniaxial anisotropy. Given corresponding p -values of ~ 1.5 , compared to $p = 2$ for ideal uniaxial SD particles, these are unlikely to be biased high. Rather they point to assemblages of SD particles with minor multiaxial anisotropy components, presumably from titanomagnetite particles with competing magnetocrystalline and magnetoelastic anisotropies (Dunlop and Özdemir, 1997).

Hysteresis loops (see insets in Figure 2) for both Prosperous Bay series support a single magnetic component (Tauxe et al., 1996). B_{cr} values are highly scattered between 10 and 100 mT (see Figure S4) with no systematic relationship to M_{rs}/M_s , so that this scatter is not dominated by domain state variation. The MH series (Figure 2c) feature hysteresis loops with “wasp-waisted” shapes produced by strongly bimodal coercivity distributions. This increases B_{cr}/B_c , populating the region of the Day plot between the SD-MD and SD-SP mixing lines.

Thermomagnetic measurements of bulk susceptibility were classified into 3 types and examples are shown in Figure 3 and Figure S5 (Supplementary Material B). For 37 % of the samples a clear attribution was not possible (see also Supplementary Material Table S2).

$\kappa(T)$ -Type L (Figure 3, Figure S5a, Table S2) is dominated by grains indicating low Curie temperatures ($\leq 310^\circ\text{C}$) and a Hopkinson peak below 250°C . According to $\kappa(T)$ -cycling, type L curves are almost reversible up to $\sim 300^\circ\text{C}$ and the mineral is most likely a Ti-rich titanomagnetite. Since no bumps above 350° were detected during heating, maghemitization of the minerals seems not to have occurred. After heating above 650°C , the $\kappa(T)$ -curves are strongly irreversible and the final cooling curve has a Hopkinson peak above 400°C indicating production of magnetite with some impurities.

$\kappa(T)$ -Type H (Figure 3, Figure S5b, Table S2) has a single high Curie temperature between 570 – 640°C . It is almost reversible up to $\sim 300^\circ\text{C}$ or higher and in most cases a Hopkinson effect peak is present. Little change of T_c together with a decrease of bulk susceptibility after heating is observed. The mineral presumably is a Ti-poor titanomagnetite with impurities or a titanohematite. Sometimes a bump above 300°C is seen, that disappears after heating, indicating some maghemitization.

$\kappa(T)$ -curves attributed to Type M (Figure 3, Figure S5c, Table S2) reveal intermediate alteration products ending up in a single magnetic phase after maximal heating. Often a Hopkinson peak is seen but in a higher temperature range than for type L. Determination of the initial Curie temperature is not possible because of gradual alteration. Irreversibility is strong and variable and can start below 300°C . An increase of susceptibility above 400°C indicates the inversion of (titano)maghemite with final transformation to titanohematite or Ti-poor titanomagnetite. It is considered possible that Ti-rich titanomagnetite formed the primary mineral but that this underwent low-temperature alteration through e.g. weathering.

It was often difficult to clearly attribute samples to a single one of these types. Samples with low or medium T_c frequently showed evidence of another pre-existing or newly created mineral phase with higher Curie temperature. Up to 300°C , only weak or moderate thermal alteration is present but this becomes strong above 400°C . Such samples were classified as L/M (Figure 3 lower right, Table S2 or Figure S5d), L/H (Figure S5e), and M/H (Figure S5f).

For determination of the highest T_c during heating, the inverse of susceptibility was used following Petrovský and Kapička (2006). This was difficult or impossible for the lower T_c present in samples not classified as type H. Here the two-tangent method of Grommé et al. (1979) was applied keeping in mind that it leads to an overestimate of T_c up to some tens of degrees (Petrovský and Kapička, 2006). In cases with more than two mineral phases, only the lowest and highest Curie temperature (T_c) during heating was evaluated.

Three ranges of Curie temperature in correlation with $\kappa(T)$ -type were found (Figure 4). For the 81 samples from Prosperous Bay types L, L/M and L/H cover the range from 94 – 307°C , for Type M (M/H) 286 – 487°C and for type H 575 – 636°C . The second T_c , if present, vary from 491 to 629°C (Table S2). For the 44 samples from Munden Hill, the variation of Curie temperatures is smaller (see Figure 4). While the Prosperous Bay flows are dominated by samples with low or medium Curie temperatures, high T_c phases

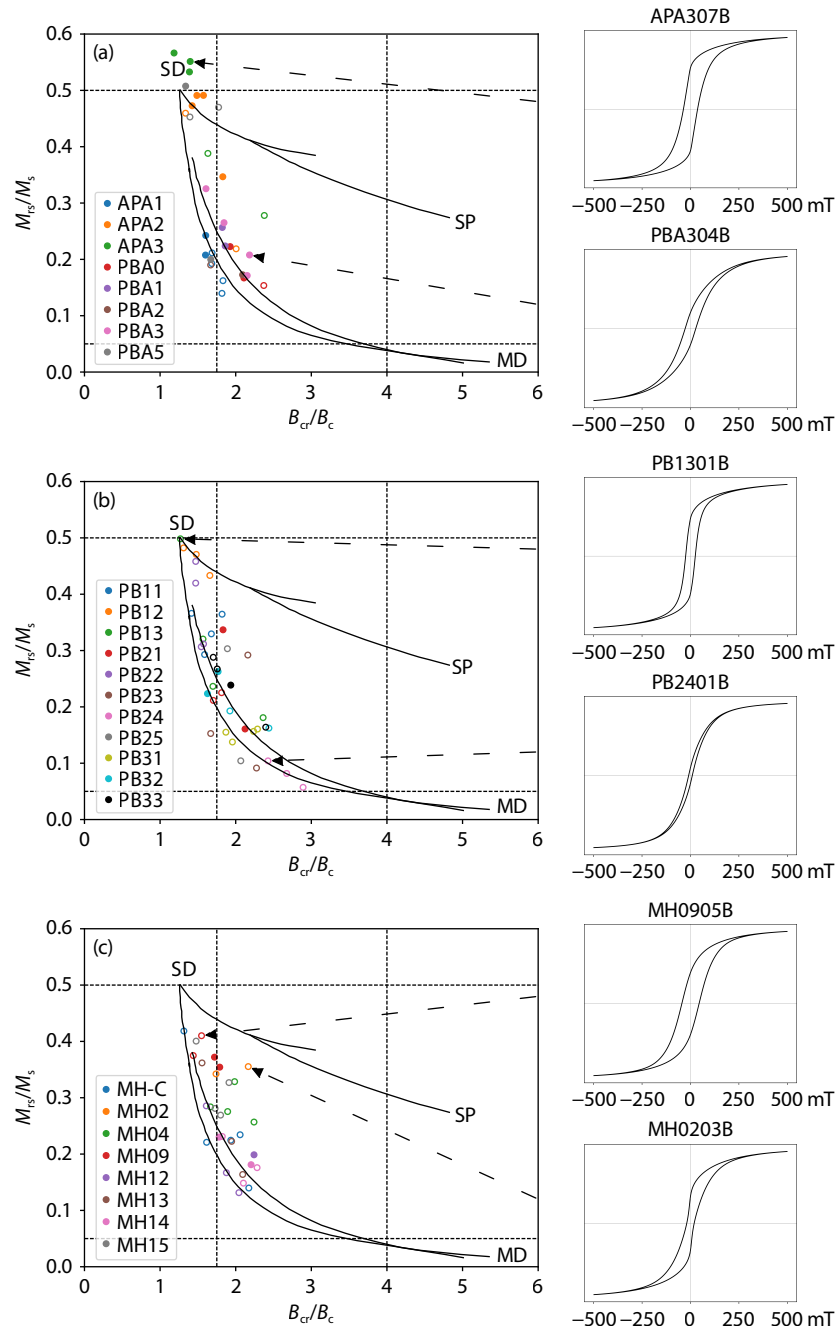


Figure 2. Ratio of saturation magnetizations obtained from hysteresis is plotted versus ratio of coercivity in a Day-diagram (Day et al., 1977). Black lines indicate mixtures of SD and MD magnetite grains (Dunlop, 2002b). Solid circles represent specimens associated with successful paleointensity experiments, while open circle depict failed ones. Data are presented for Prosperous Bay profile P1 (a), for profile P2 (b) and for Munden Hill (c), respectively. Representative hysteresis examples of endmembers are presented on the right with arrows indicating their location in the Day-diagram.

dominate Munden Hill (Figure 4).

4.2 Paleomagnetic Directions

Examples of demagnetization experiments from Prosperous Bay are shown in Figures 5 and 6. The majority (~80%) of specimens exhibited moderate or strong secondary overprints. Typically 10–20 mT or 120–200 °C demagnetization was sufficient to remove the overprint but ~10% of specimens needed 50 mT or 480 °C. Unstable directional behavior was observed for 7 thermal

demagnetizations that suffered from strong alteration and for 8 specimens a well-defined great circle was obtained. During AF demagnetization acquisition of gyroremanence (GRM) was observed for 19 specimens, indicated by an increase of intensity and a departure from the trend to origin in the orthogonal plots. Consequently, 5 specimens failed to provide a characteristic remanent magnetization (ChRM). For 3 specimens subjected to AF demagnetization, a great circle was fitted. For a few specimens the acquired gyroremanence was rather strong and in 7 cases the

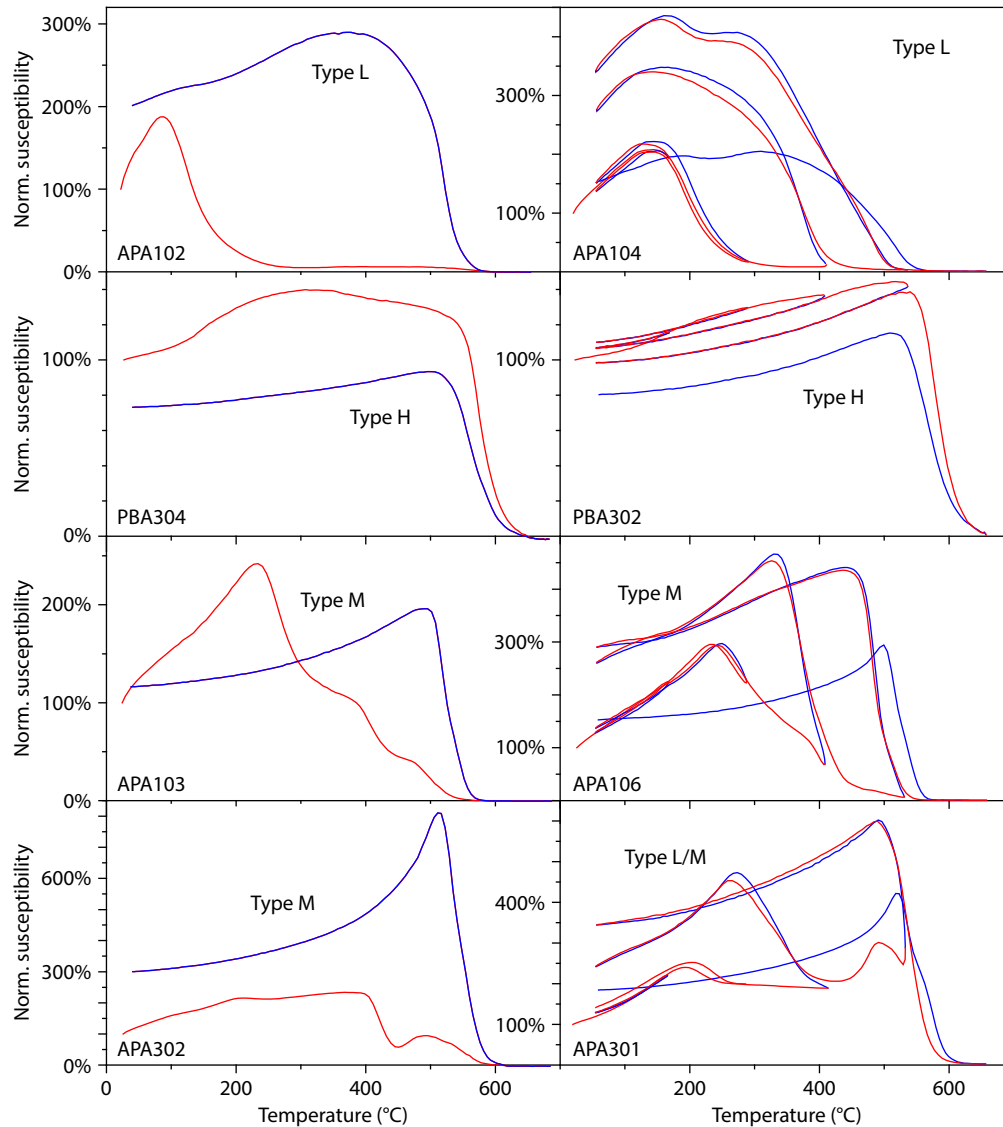


Figure 3. Representative examples of types of bulk susceptibility thermomagnetic and thermal cycling curves (thin lines). Heating is shown in red, cooling in blue.

elimination of GRM was successfully tested (see Figure S6 and the corresponding caption for details) following Finn and Coe (2016). Problems with GRM were also present for 6 flows (9 specimens) from Munden Hill, but a ChRM direction could be obtained in all cases (Figure S7).

Generally, the demagnetization behavior of Munden Hill samples was similar. About 19% of the specimens had no or very weak secondary components, while rather strong secondary overprints were present in 9 % of the specimens. For the majority of specimens, demagnetization to 5–20 mT or 120–220 °C was necessary to remove the secondary components. Some 9 specimens were rejected due to unstable behavior or misorientation in the field.

For Prosperous Bay (Munden Hill) 101 (87) ChRMs were obtained after AF demagnetization and a further 41 (34) using thermal demagnetization. Furthermore, results with a stable and well-defined ChRM from 89 (29) paleointensity experiments were included for Prosperous Bay (Munden Hill).

Mean ChRM directions at the site level (Table 1) were calculated using Fisher (1953) statistics after first averaging at the core sample level. For the Prosperous Bay profile P1, our new site-means agree well with those of Engbers et al. 2020 (see Figure S8) and these were combined for those flows that were sampled in both studies. All site-mean ChRM directions with a_{95} circles are shown together with the corresponding sample directions in Figure S9. These 22 mean ChRM directions are based on 5 to 15 independently oriented samples with precision parameter k values ranging from 16 to 423 (Table 1). Nine are very well defined with $k > 100$ while 5 have $k < 50$, uncertainties (a_{95}) range from 2.9° to 13.3°. The directions of the upper part of profile P2 (5 flows, PB25 to PB11) compare well with those of P1 (Figure 7a). Both profiles commence with reversed field directions, followed by 3 (2) intermediate directions for profile P1 (P2) and end with 3 (1) normal directions. Where sites in both profiles were directly correlated in the field (Figure 7a, left, black arrows), their directions have overlapping a_{95} circles. Furthermore, the directions of the

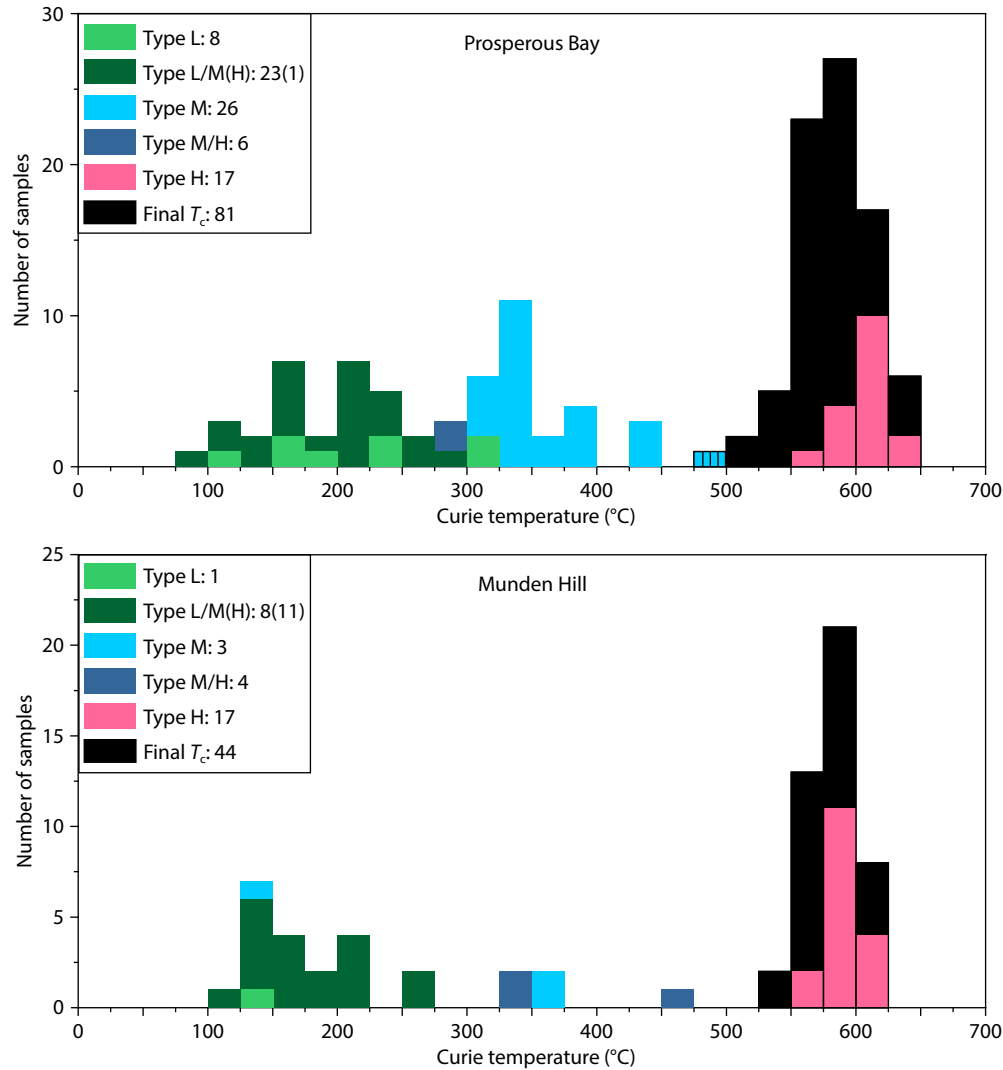


Figure 4. Distribution of Curie temperatures. While for $\kappa(T)$ -type H only a single high T_c was obtained for the other types the lowest and highest T_c (final T_c), which represents the alteration product, is shown. In the legends the number of samples is given.

uppermost flow and two other flows (Figure 7a, left, blue arrows) also agree. Profile P2 shows, in the deeper part (7 flows, PB33 to PB24), another cluster of reversed directions with one flip to negative inclination (PB23) and another to normal polarity (PB32).

The Munden Hill profile provided 19 mean ChRM directions calculated from 3 to 11 independently oriented samples. Values of the precision parameter k range from 16 to 591 with α_{95} angles ranging from 3.7° to 13.3° (Table 1). Fourteen mean ChRM directions are very well defined with $k > 100$ while only 3 are poorly defined with $k < 50$. All site-mean ChRM directions with α_{95} circles are shown together with the corresponding sample directions in Figure S10b. No intermediate paleomagnetic directions were found. Flows MH01-MH-C along with MH17 represent reversed polarity records, while MH13-MH16 and MH18 yield normal field directions.

Our reconstructed virtual geomagnetic poles (VGP) were calculated using a paleolatitude of -19.5° and a paleolongitude of -12° following Engbers et al. (2020). They lie mostly above $\pm 60^\circ$ showing normal secular variation (Table 1). Engbers et al. (2020) used a

Vandamme (1994) cutoff angle of 44.4° VGP latitude for identification of transitional directions. By this measure, Prosperous Bay Profiles P1 and P2 recorded 3 and 2 transitional directions, respectively, whereas Munden Hill did not record any (Table 1). In P2, one additional flow (PB23) only slightly exceeds the cutoff angle with a VGP latitude of -47.3° .

4.3 Paleointensities

Strong overprints precluded paleointensity determination in two flows (PBA4, PB26). MT4 experiments were started at 90 or 100 °C for specimens with $\kappa(T)$ -Type L while 200 or 250 °C was used for Type H or M. Small temperature increments (15–30 °C) were used in the expected range of TRM unblocking resulting in up to 15 heating steps in total.

MT4 paleointensity experiments were made on 113 (46) mini-specimens from 19 (8) flows of Prosperous Bay (Munden Hill, Table S1, additional files). IZZI experiments were performed on 44 specimens from 6 flows from Prosperous Bay (Table S1, AP01 and PB05–PB01).

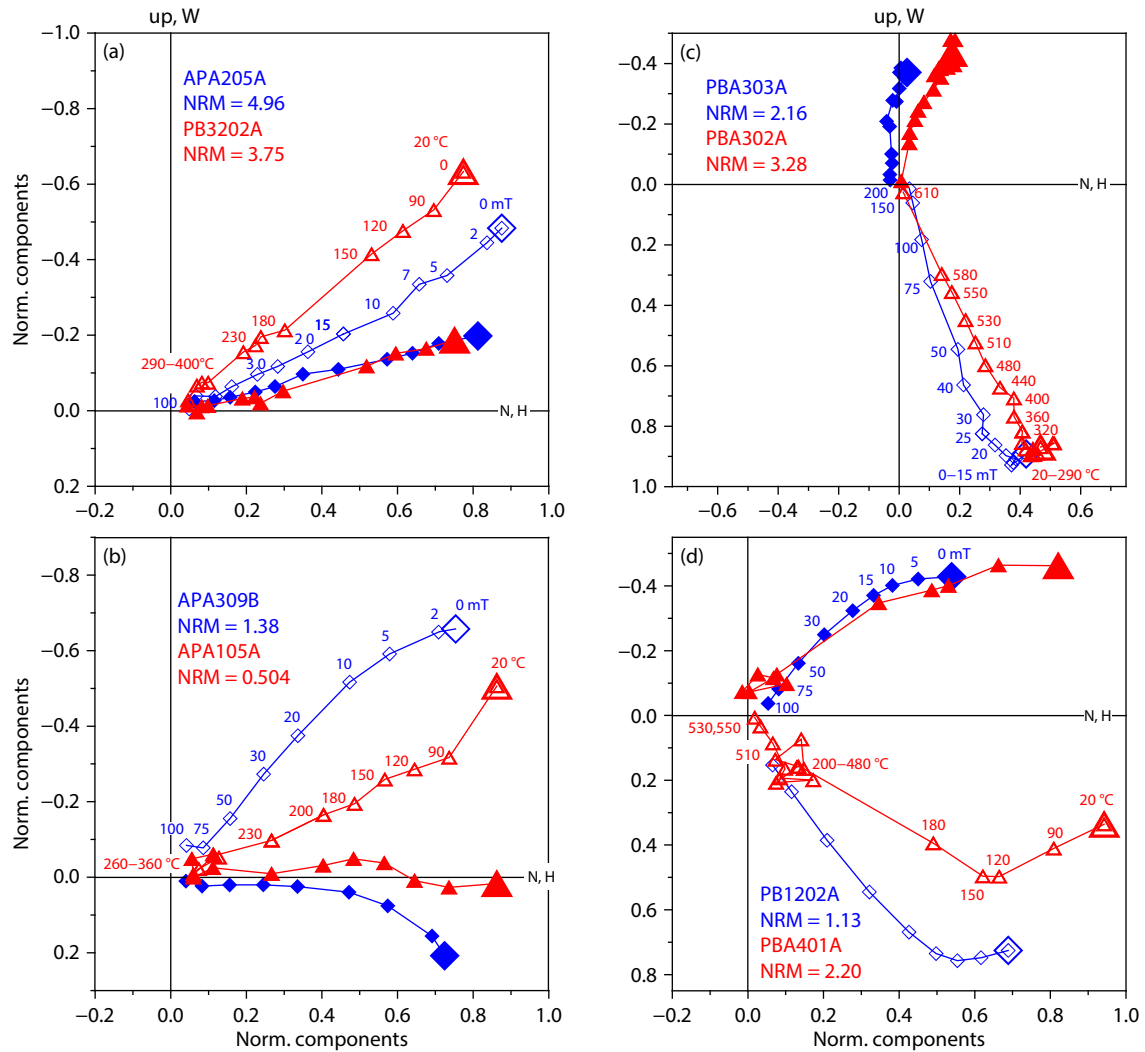


Figure 5. Orthogonal projections from AF (blue) and thermal (red) demagnetization of Prosperous Bay lava flows with normal (a, b) or transitional direction (c, d), specimen names and NRM intensity (A/m) are given. The larger symbol indicates NRM. North component versus East component is shown by closed symbols, vertical component versus horizontal component by open symbols. Numbers give demagnetization steps in mT or °C.

Results were analyzed using ThellierTool4.22 software (Leonhardt et al., 2004) and Paleointensity.org (Béguin et al., 2020). Paleointensity.org follows the Standard Paleointensity Definitions of Paterson et al. (2014) while ThellierTool is stricter in using the results of pTRM, tail, and additivity checks that were measured above the selected temperature range: the subsequent pTRM and additivity check with $T > T_{\max}$ is considered, when $T_{\max}$ is situated between two check temperatures, while for the normalized tail Δt^* all tail checks are regarded. This more conservative approach was followed here.

Our acceptance criteria, based on the set “TTB (modified)” of Paterson et al. (2014), are: Number of data points used for the linear fit $n \geq 5$, fraction factor $f \geq 0.35$, standard deviation of slope $\beta \leq 0.15$, quality factor (Coe et al., 1978) $q \geq 1$, maximum angular deviation of anchored line $MAD_{\text{Anc}} \leq 15$, angular difference between anchored and not-anchored solution $\alpha \leq 13$, maximum pTRM check difference $\delta CK \leq 9$, cumulative check difference $\delta \text{pal} \leq 50$, relative intensity difference of tail checks $\delta \text{TR} \leq 15$, normalized

tail of pTRM $\Delta t^* \leq 50$, Arai plot curvature $k' = 0.48$, and maximum absolute additivity check difference normalized by the total TRM $\delta AC \leq 25$. An interpretation of the Arai plot based on these criteria was only possible for 41 (11) out of 113 (46) experiments for Prosperous Bay (Munden Hill) specimens (Table S1). Accordingly, the failure rate was 64% (76%). For the majority of specimens paleointensity determination is based on only 5–7 data points but the associated fraction factor f is larger than 0.5 and the relative slope error β is less than 0.1 (Figure S11 a to c). The fitted line in the Arai plots is therefore reasonably defined but other parameters, e. g. a small quality factor or a large curvature (Figure S11 d to e) indicate that many Arai plots are not ideal. The maximum angular deviation of the anchored line (MAD_{Anc}) does not exceed 8° (Table S1) and the angular difference between it and a free floating is rarely larger than 10° (Figure S11f). The correlation coefficient (Figure S11g) is in most cases very large ($r^2 \geq 0.97$). Many specimens have relatively large values of relative intensity difference of tail checks (δTR) as well as large normalized tails of pTRM (Δt^*) and/or cumu-

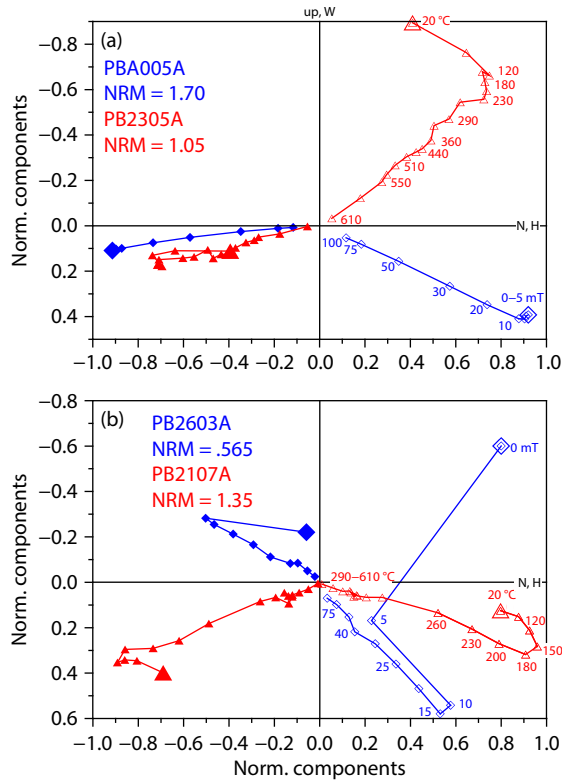


Figure 6. Examples of demagnetizations curves from Prosperous Bay lava flows with reverse directions. Same representation as in Figure 5.

relative check difference (δ_{pal}). For the latter criterion, only 7 successful experiments exceed the threshold value of 18 proposed by Paterson et al. (2014) for “TTB (modified)”. Maximum deviation of the pTRM checks (δ_{CK}) and the maximum absolute additivity check difference normalized by the total TRM (δ_{AC}) play a minor role (Figure S11h to l).

The Thellier experiments performed on most Prosperous Bay specimens yielded non-ideal behavior. Data points in the Arai plot exhibited sagging, two slopes, and/or zigzagging behavior. The success rate of paleointensity determinations is generally unrelated to hysteresis properties, with the only exception of the SD endmember of profile P1 (see Figure 2). The success rate of samples plotting in the PSD region is likely determined by the prevalence of small PSD particles with ideal recording properties (Nikolaisen et al., 2020). The direction of pTRM acquisition in palaeointensity experiments showed no significant systematic deviation from that of the applied field suggesting that obtained measurements required no correction for anisotropy.

As already mentioned above, specimens having no secondary components and a very high thermal stability against alteration were rare in our collection. In many cases there was no better choice than testing specimens for which sister specimens had a secondary component. Some examples of successful behavior during the Thellier experiments are shown in Figure 8. Specimen APA2-06-BA (Figure 8a) is a typical example with good linearity, that fulfills the selection criteria. In this case, the NRM has only a weak viscous component and low unblocking temperatures ($\kappa(T)$ -type L/M). The pTRM checks indicate severe loss of TRM capacity

above 270 °C where the NRM remaining is already below 5%. It remains low until, at 400 °C, creation of another magnetic mineral commenced and the experiment was stopped. A large NRM fraction is used for paleointensity determination, but only 5 data points are available. The curvature ($k' = 0.39$, Table S1) is relatively strong and indicates sagging. A similar behavior is observed for about half of the specimens but the secondary component may be stronger, the NRM fraction smaller and change of TRM capacity and/or creation of the new mineral may start earlier.

Specimen PBA3-03-BA (Figure 8b) has a high Curie temperature ($\kappa(T)$ -type H) and a relatively strong secondary component. Nevertheless, after erasing the overprint a linear section was found in the Arai plot fulfilling the relaxed criteria along with a small curvature. While data points appear to have concave-up curvature, the tail checks agree very well suggesting that the curvature is caused by the secondary component.

The next example (PB32-06-BA, Figure 8c) has a weak secondary component and low blocking temperature ($\kappa(T)$ -type L/M) but, after half of the NRM is removed (above 220 °C), no further unblocking is seen while the TRM capacity decreases strongly and data points in the Arai plot are strongly scattered. The low temperature range provides an approximately linear segment fulfilling the criteria very well, only the tail checks are rather high (Table S1). Similar behavior was observed for about 25 % of the successful specimens.

IZZl experiments yielded just 2 results out of 44 experiments (Table S1). The main reasons for failure were substantial unblocking of the NRM at the first temperature step of 200 °C, strongly concave-up curvature, and alteration.

Only one specimen from Munden Hill exhibited ideal behavior during the Thellier experiment (MH14-01-AA, see Figure 8d); generally, the same problems with secondary components, sagging, two slopes or zigzag behavior were observed. No striking difference in the distribution of the classification parameters is obtained compared to Prosperous Bay (Figure S11). For flow MH14, two specimens (from sample MH14-04) were rejected due to systematically lower PI estimates with respect to the remaining samples ($n = 5$). These lower intensity values originate from the evaluation of the high temperature range, while for the other samples a wider range could be selected (see Figure 8d, Table S1).

Results of the MT4 and IZZl experiments were averaged together and the mean paleointensities per flow are listed in Table 1. Two flows in Prosperous Bay (PBA4, PB26) were not studied and a further 7 gave no acceptable results. Of the 16 Prosperous Bay flows yielding acceptable paleointensities, only 5 produced mean values based on 4 or more specimens.

For Munden Hill only 8 out of 19 lava flows had promising properties for the Thellier experiments, for 4 of these flows no results were obtained and only 1 flow provided at least 4 successful paleointensity determinations. Relative standard errors of the obtained paleointensity values range from 11 to about 90%. Only four Prosperous Bay flows (APA2, APA3, PBA3, PB32) produced means satisfying our criteria of being based on at least 4 specimens with a standard deviation $< 5 \mu\text{T}$. These range from 7–9.5 μT ,

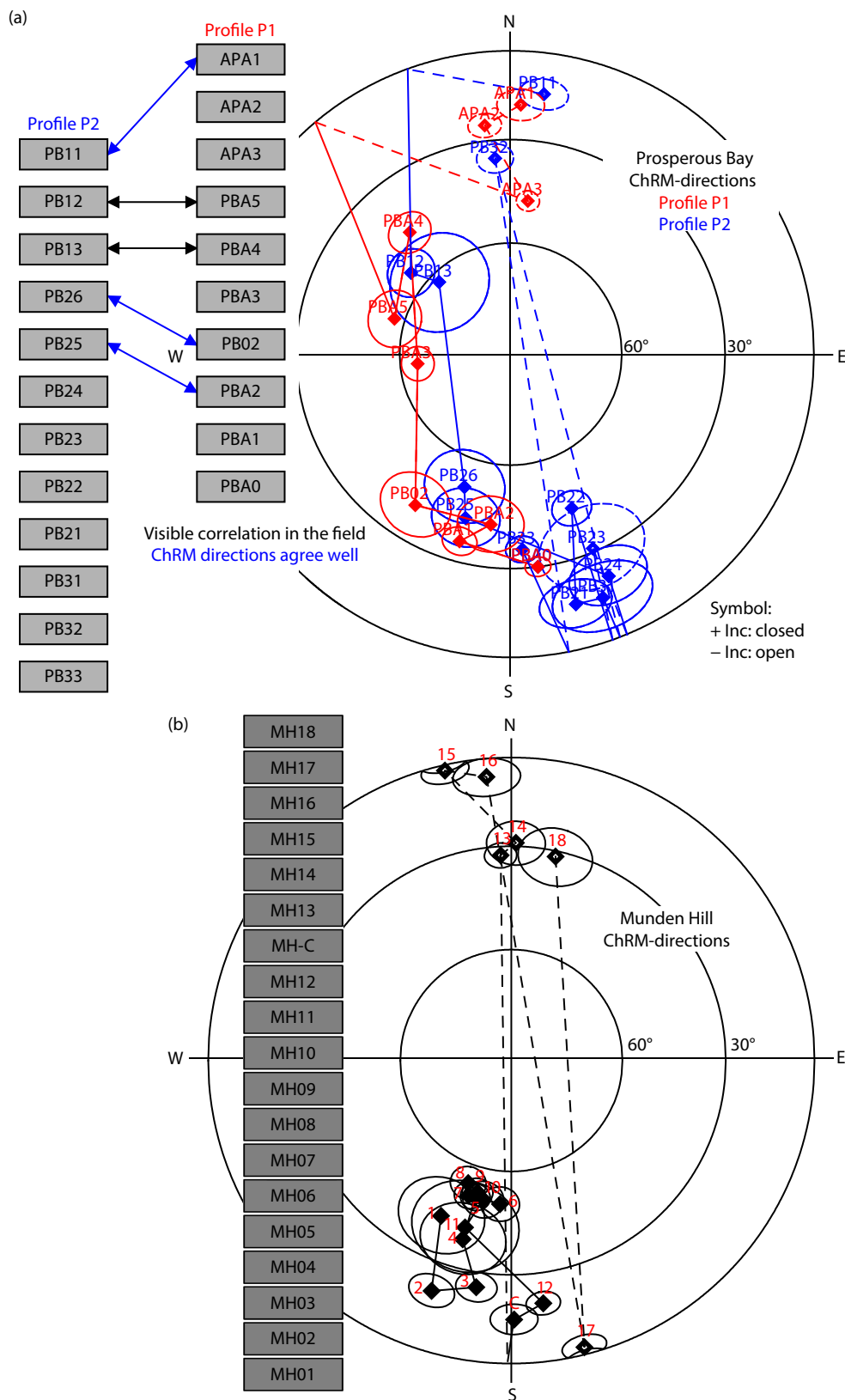


Figure 7. Mean characteristic remanent magnetizations directions with a_{95} from Prosperous Bay (a) and Munden Hill (b) together with the profiles (left).

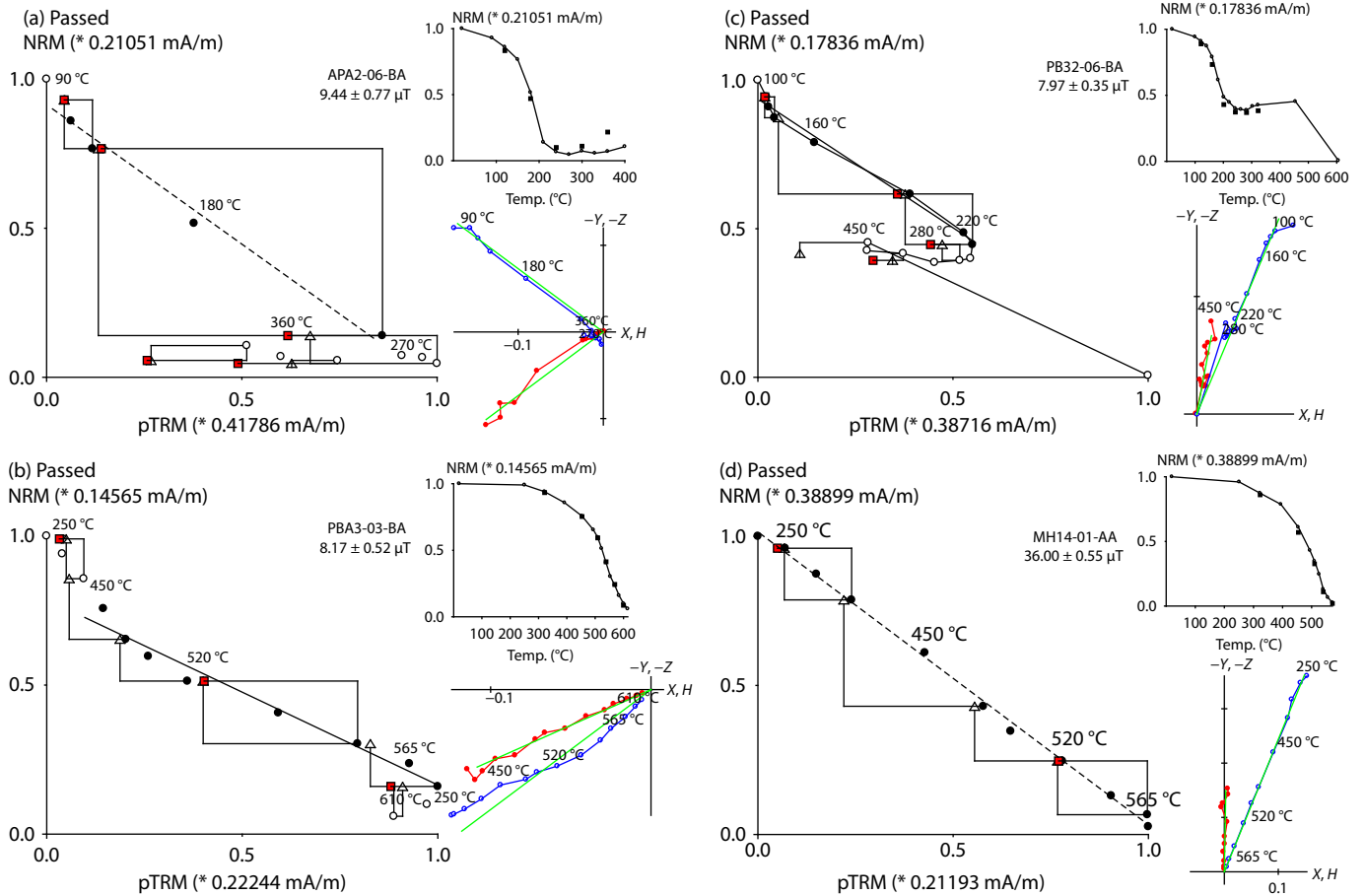


Figure 8. Arai plots of Thellier-Coe experiments with accepted steps (dots), pTRM checks (triangles), and additivity checks (red squares) and fit line. Upper right of each panel: decay plots with tail checks (black squares); Lower right: orthogonal vector component projections in sample coordinates (vertical plane: open, blue symbols; horizontal plane: solid, red symbols; green line: mean direction associated with the chosen temperature interval). Further information can be found in [Figure S12](#) and [Table S1](#).

substantially lower than the present-day geomagnetic intensity of $\sim 29 \mu\text{T}$ (IGRF, [Alken et al., 2021](#)). The only reliable flow mean from Munden Hill yields a higher value of $40.1 \mu\text{T}$.

4.4 $^{40}\text{Ar}/^{39}\text{Ar}$ Dating Results

The $^{40}\text{Ar}/^{39}\text{Ar}$ dataset obtained from lava flows at Prosperous Bay (PB) as well as Munden Hill (MH) can be found in [Table 2](#) and in the Supplementary Materials ([Table S3](#), [Figures S13](#) and [S14](#)). Most samples display well-defined release spectra and statistically acceptable plateau MSWD values, indicating coherent step-heating behaviour and minimal intra-sample heterogeneity. Inverse isochron regressions are broadly concordant with the plateau ages, and the calculated trapped $^{40}\text{Ar}/^{36}\text{Ar}$ ratios cluster around values near the atmospheric composition, suggesting that excess argon is negligible within analytical uncertainty. A subset of analyses, particularly those characterised by low gas yields and a reduced number of contributing steps, exhibit correspondingly larger uncertainties and wider isochron spreads.

5. Discussion

In total, ages of 15 lava flows were determined using the $^{40}\text{Ar}/^{39}\text{Ar}$ -dating technique (see [Table 2](#)) in order to obtain temporal infor-

mation for both studied locations. The dating results of 9 flows from Prosperous Bay are characterized by rather large uncertainties due to low gas yields. Given the altered state of the samples, effects due to ^{39}Ar recoil (pulling ages up) and sericite (potentially pulling ages down) cannot be ruled out, which complicates the chronological classification.

Even though most new age data show an inverse trend with respect to stratigraphy, a correlation with the GPTS ([Ogg, 2020](#)) was tentatively performed, additionally taking into account previous $^{40}\text{Ar}/^{39}\text{Ar}$ ages from [Engbers et al. \(2022a\)](#), which are characterized by significantly lower uncertainties (< 30 ka). These results suggested an age of 7.8 Ma for the uppermost flow (APA1) and 8.22 Ma for a transitional flow (PBA4) in profile P1 ([Figure 9](#)). Thus, the recorded reverse-to-normal polarity transition can be most likely related to the chrons C4r.1r and C4r.2n, respectively. Taking into account the associated uncertainty, this attribution is also consistent with the age of flow PBA5 from profile P1 investigated in this study. This age agrees statistically with the age of the underlying flow PBA4 and the age uncertainties would also allow a correlation with C4r.2r to C4r.1n transition. Conversely, a sample from flow PB13 in profile P2, which was correlated with PBA4 in the field, yields a significantly older age of 9.1 Ma. This estimate

Table 2. ⁴⁰Ar/³⁹Ar results with preferred ages indicated by bold numbers.^a

Spectrum						Inverse Isochron			
Sample	Steps (n)	% ³⁹ Ar	Age ± 1.96σ	MSWD (P)	K/Ca ± 1.96σ	Age ± 1.96σ	MSWD (P)	Trapped ⁴⁰ Ar/ ³⁶ Ar	Spread (%)
PB Profile 1									
PB-13	9–12(4)	38.95	9.09 ± 0.13	0.46(0.71)	0.44 ± 0.02	9.43 ± 0.66	0.26(0.77)	275.3 ± 45.3	11.5
PB-A4	4–13(10)	97.17	8.46 ± 0.17	0.71(0.70)	0.251 ± 0.002	8.36 ± 0.22	0.59(0.79)	300.2 ± 2.34	46.5
PB-21	6–12(7)	56.38	8.69 ± 0.17	0.67(0.67)	0.18 ± 0.002	8.56 ± 0.70	0.80(0.55)	300.0 ± 7.5	15.4
PB-32	6–12(7)	74.68	8.38 ± 0.12	0.76(0.60)	0.32 ± 0.01	8.09 ± 0.45	0.57(0.73)	315.5 ± 26.7	37.3
PB-33	5–13(9)	95.13	9.10 ± 0.16	0.66(0.73)	0.172 ± 0.002	9.20 ± 0.27	0.66(0.71)	297.6 ± 2.2	30.7
PB Profile 2									
APA1	4–13(10)	97.7	8.79 ± 0.23	1.15(0.32)	0.323 ± 0.003	8.42 ± 0.52	1.02(0.42)	303.7 ± 6.9	28.3
APA2	8–14(7)	67.54	8.56 ± 0.24	1.28(0.26)	0.195 ± 0.004	7.90 ± 0.59	0.44(0.82)	306.6 ± 6.9	33.8
PB-A5	1–13(13)	100	8.30 ± 0.24	0.86(0.58)	0.298 ± 0.003	8.17 ± 0.51	0.92(0.52)	299.8 ± 4.6	45.9
PB-A0	5–12(8)	79.53	8.31 ± 0.06	1.46(0.18)	1.09 ± 0.04	8.26 ± 0.37	1.69(0.12)	301.6 ± 21.8	23.1
MH									
MH-18	9–11(3)	36.52	8.68 ± 0.26	0.05(0.95)	0.40 ± 0.02	8.78 ± 1.16	0.07(0.00)	297.3 ± 13.2	9.3
MH-17	1–12(12)	100	8.11 ± 0.30	1.08(0.37)	0.318 ± 0.004	8.12 ± 0.46	1.20(0.29)	298.5 ± 2.1	29.6
MH-C	2–12(11)	97.78	8.44 ± 0.31	0.51(0.89)	0.199 ± 0.002	8.52 ± 0.80	0.58(0.82)	298.2 ± 3.3	21.1
MH-13	7–14(8)	74.36	8.54 ± 0.11	1.56(0.14)	0.67 ± 0.02	8.27 ± 0.23	0.82(0.56)	304.5 ± 4.7	27.7
MH-12	3–12(10)	94.86	8.37 ± 0.27	0.50(0.88)	0.223 ± 0.002	7.92 ± 0.78	0.42(0.91)	300.4 ± 3.0	12.5
MH-01	10–12(3)	57.07	8.27 ± 0.26	0.06(0.94)	0.268 ± 0.003	8.52 ± 1.47	0.01(0.00)	296.2 ± 13.8	9.5

^aResults are reported at the 95% confidence level (1.96σ) and in stratigraphic order in each profile. MSWD (P) denotes mean squared weighted deviance and probability of fit, respectively. K/Ca is calculated as ³⁹Ar_{rad}/³⁷Ar_{Ca}. Spread (%) is the spread along the isochron line.

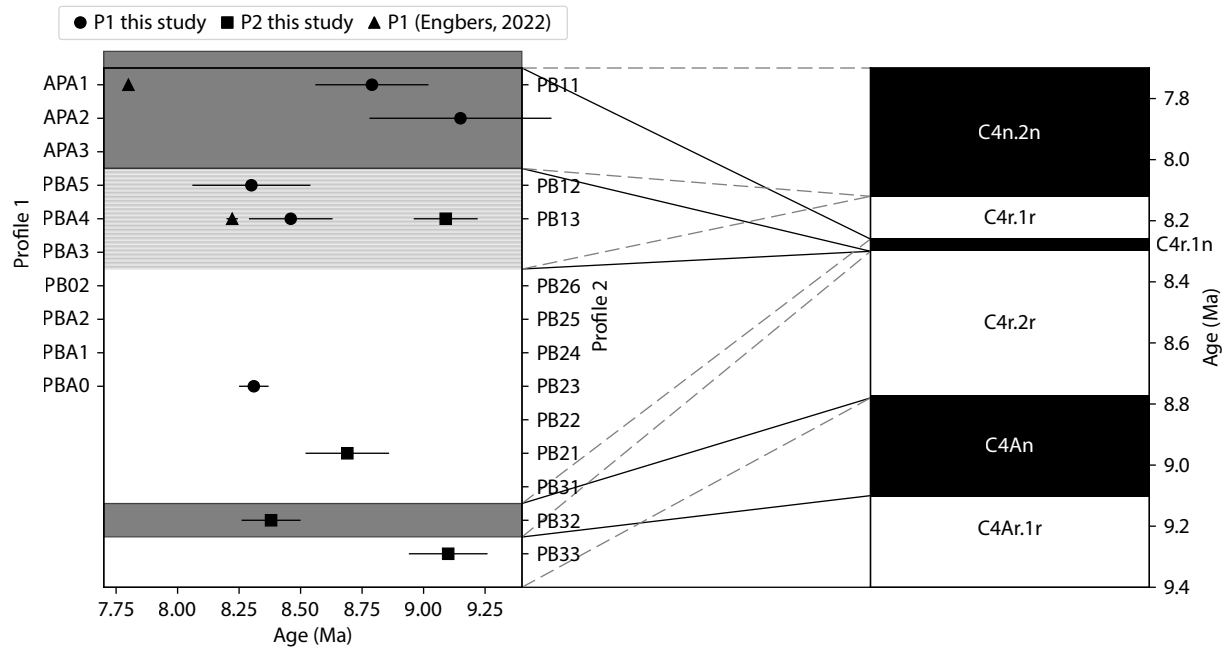


Figure 9. Correlation of Prosperous Bay flows from both profiles with the GPTS (Ogg, 2020) on the right. In the left panel new ⁴⁰Ar/³⁹Ar-dating results are shown in stratigraphic order by the circles/squares (see legend). Dark/white shaded areas represent normal/reverse polarity according to the obtained paleodirection, while the striped area in the left panel depicts transitional flows. Solid lines give the first conceivable assignment, while dashed lines depict another possibility.

should be treated with caution, however, because two younger ages (8.69 Ma and 8.38 Ma) are determined from underlying flows (PB21 and PB32) in profile P2, which would contradict the stratigraphic sequence. Therefore, the dating results for PB13 are interpreted as unreliable. It seems more likely that PB32 was deposited in the normal chron C4An, rather than C4r.1n. Based on this assumption, the lowest flow of profile P2 (PB33) has to be assigned to C4Ar.1r which is compatible with its age. In summary, correlation of Prosperous Bay profiles with the GPTS faces challenges that prevent a clear identification of the field reversal.

Engbers et al. (2022a) also investigated lava flows from the SW main shield located at Ladder Hill with $^{40}\text{Ar}/^{39}\text{Ar}$ ages varying between 8 and 10 Ma. According to the geological map (Engbers et al., 2020), the second study area, Munden Hill (Figure 1), belongs to the same volcanic shield and is separated from Ladder Hill by the ravine, where Jamestown is located. The corresponding ages determined in this study, fall within the same temporal range between 8.1 and 8.7 Ma but dating uncertainties alongside inconsistencies between the ages, polarity and the stratigraphy prevent a meaningful correlation with the GPTS.

Due to the limited number of transitional records and chronological information, the duration and detailed local evolution of the polarity transition cannot be determined. The transitional VGPs of both profiles are located close to each other to the west-northwest of Saint Helena in South America and the Atlantic Ocean (see Figure 10). It is unclear whether this small cluster has a volcanic (i.e. short-term volcanic activity) or geomagnetic (i.e. stable field geometry) origin. The similarity of sequential paleomagnetic directions in both Prosperous Bay profiles (Figure 7) were investigated using the F-test (McFadden and Lowes, 1981; Figure S15). Statistically indistinguishable directions were not found in profile P1 and, while a few were observed in profile P2, these were isolated. The visual correlation of the three flows from P1 to P2 was not corroborated by F-tests but the directions are similar and transitional (Figure 7a). Overall, we consider that strong evidence for the existence of eruption pulses has not been found. Several studies have concluded that no systematic VGP cluster locations are found in different, globally distributed volcanic reversal records (e.g. Valet and Fournier, 2016). Conversely, Hoffman et al. (2020) identified VGP clusters to the west of Australia based on lava records that suggest an increased influence of the lowermost mantle during polarity transitions since the Pliocene. However, that compilation does not indicate an increased occurrence of VGP around South America, as derived from the Prosperous Bay records. We do note that one VGP (PB23), which represents a borderline case for being transitional, is close to Australia (Figure 10).

While the polarity transition is clearly indicated by well-defined paleomagnetic directions in both (parallel) profiles in Prosperous Bay, the associated paleointensity results are less robust (Figure 11a). In the figure, solid symbols represent more reliable mean paleointensities based on more than three successful PI experiments and a standard deviation $< 5 \mu\text{T}$. In general, flows fulfilling these criteria yield low intensities of less than $10 \mu\text{T}$ ($2.2 \times 10^{22} \text{ Am}^2$). Therefore, the only reliable intensity value from a transitional

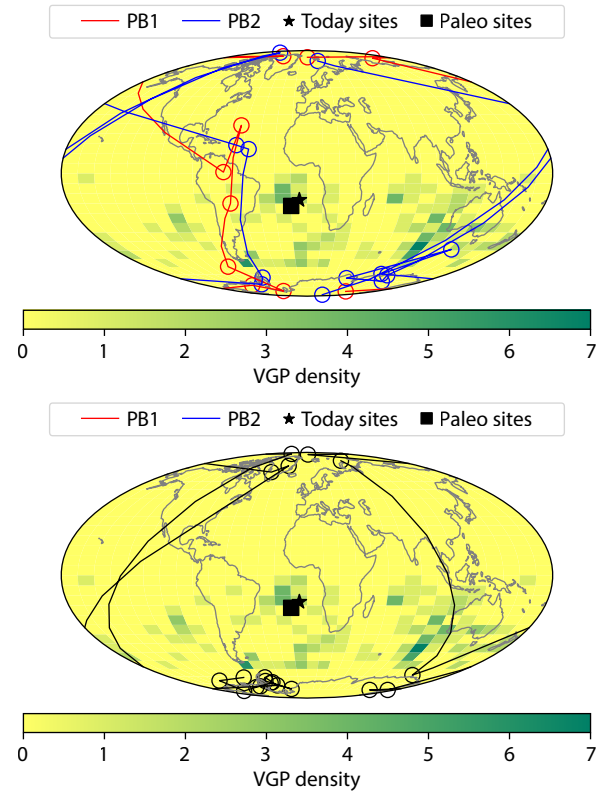


Figure 10. VGPs from Prosperous Bay profiles P1 and P2 (top) and Munden Hill (bottom). The density of VGPs from Cenozoic palaeomagnetic transitional field records after employing the geomagnetic convention is retrieved from Hoffman et al. (2019).

lava flow (PBA3 with $9.1 \pm 4.4 \mu\text{T}$) is not significantly lower than those associated with stable field directions (APA2, APA3, PB32). One possible explanation for this observation is a sustained decay (e.g. Mahgoub et al., 2023), which is characterized by low field intensities prior to the actual polarity transition. However, this is not valid for flows APA2 and APA3, which have been formed later than PBA3 according to our stratigraphy. Alternatively, it has been reported that paleointensity can fluctuate significantly locally during a field reversal reaching values similar to those of stable field configurations (Leonhardt et al., 2000; van Grinsven et al., 2025). Previous studies (Shah et al., 2016; Engbers et al., 2022a; Gómez-Paccard et al., 2026) revealed low PI estimates from the South Atlantic region suggesting a persistence or recurrence of the SAA on geological timescales during the Late Pleistocene and Upper Miocene and also recent centuries to millennia. Numerous mechanisms exist with the potential to bias ancient paleointensity estimates from volcanic rocks to low values (Smirnov et al., 2017; Tauxe et al., 2021; Shcherbakov et al., 2024). Nevertheless, a significantly lower VADM compared to that derived from the average axial dipole model MCADAM.1b between 8 and 9 Ma ($5.1 \pm 1.4 \times 10^{22} \text{ Am}^2$, Bono et al., 2022b), indicates anomalous field behavior in the study area. This was also recently supported by a Miocene time-averaged field model based solely on paleodirections (Engbers et al., 2024).

One flow from Munden Hill (MH14), which is based on relatively robust Arai interpretations, reveals a rather high PI associated with a VADM of $\sim 9 \times 10^{22} \text{ Am}^2$, which clearly exceeds the value

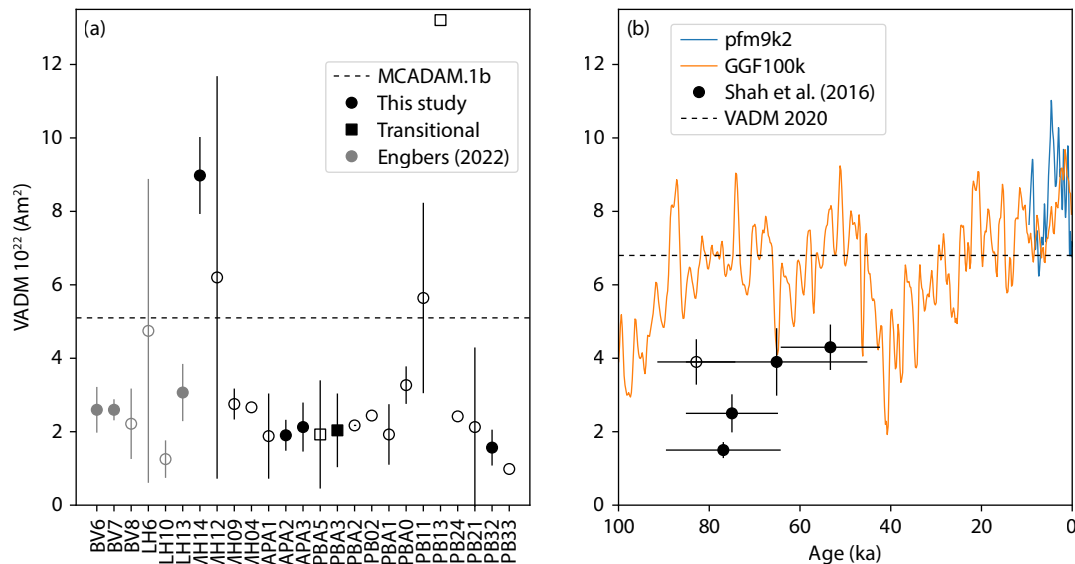


Figure 11. (a) VADMs calculated for the paleo-location of Saint Helena. Solid symbols represent flows with more than three specimens evaluated and a standard deviation $\leq 5 \mu\text{T}$, while open symbols are associated with flows that do not fulfill these criteria. b) VADMs calculated from pfm9k2 (Nilsson et al., 2022) and GGF100k (Panovska et al., 2018) models for the last 100 kyrs. Volcanic records from Shah et al. (2016) are also depicted (some ages have been interpolated).

determined from the current field strength in Saint Helena ($6.8 \times 10^{22} \text{ Am}^2$, Alken et al., 2021). This value is significantly higher than those determined by previous studies (Shah et al., 2016; Engbers et al., 2022a) and suggests a strong paleomagnetic field variability within this region. Paleomagnetic field models (Panovska et al., 2018; Nilsson et al., 2022) also predict such a wide range of field strengths for the Holocene and Late Pleistocene (Figure 11b). However, it should be noted that these models are not well constrained within the South Atlantic region, particularly due to the lack of absolute paleointensities in the global databases (e.g., Bono et al., 2022a).

6. Conclusions

This study investigated new paleomagnetic data from 8–9 Ma old volcanic sequences on the island of Saint Helena, sampled at two locations. Two parallel profiles from Prosperous Bay revealed a polarity transition, with three and two flows showing intermediate field directions, respectively. The associated VGPs are located across South America and the Atlantic and do not support a previously reported cluster west of Australia which was linked to mantle heterogeneities (Hoffman et al., 2020). The recorded field reversal most likely corresponds to the transition from chron C4r.2r to C4r.1n around 8.3 Ma, even though the uncertainties of $^{40}\text{Ar}/^{39}\text{Ar}$ ages prevent definitive conclusions and do not allow for estimation of the reversal duration. The possibility that the transitional directions recorded a geomagnetic excursion cannot be excluded.

Reliable paleointensities could be obtained for four flows at Prosperous Bay, all of which yield values $< 10 \mu\text{T}$ ($2.2 \times 10^{22} \text{ Am}^2$). These values are substantially smaller than those observed today ($6.8 \times 10^{22} \text{ Am}^2$, Alken et al., 2021) and the reconstructed value for the period between 8 and 9 Ma ($5.1 \times 10^{22} \text{ Am}^2$, Bono et al., 2022b). No significant differences in the paleointensities are detected

between the three flows associated with stable field behavior and the one transitional flow. This observation could be linked to the influence of SAA as suggested by previous studies (Shah et al., 2016; Engbers et al., 2022a, 2024). By contrast, the only reliable paleointensity at the second location, Munden Hill, yields a relatively high VADM of $9 \times 10^{22} \text{ Am}^2$, which highlights strong paleosecular variation activity in the South Atlantic (Engbers et al., 2020) and might hint at a (temporary) disappearance or attenuation of the SAA over time as recently suggested by Gómez-Paccard et al. (2026) on centennial to millennial timescales. The work presented here contributes much-needed data concerning field behavior across a Miocene-age polarity transition recorded in the Southern Hemisphere, where data are scarce. They may prove useful in constraining the SAA in the Miocene if, indeed, it existed at this time.

Availability of data and materials

The directional and paleointensity measurement files associated with this publication are available from https://github.com/Paleoint/St_Helena_Reversal.

Competing interests

The authors declare that they have no competing interests.

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Authors' Contributions

Field work was done by ES, PA, YE, AB. Paleo and rock magnetic

results were produced by ES, PA, RS, YE and RE. Dating was performed by MG. ES and PA wrote the paper with contributions of MG, YE, AB, RL, RE and RS. All authors read and approved the final manuscript.

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