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**Late Pliocene integrated age model for Bleiksmýrardalur,
north central Iceland (2.5-3.2 Ma), from
lithostratigraphy, magnetostratigraphy
and $^{40}\text{Ar}/^{39}\text{Ar}$ dating**

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Abstract

In this paper we have determined an age model for upper Bleiksmýrardalur, which is southeast of Akureyri. The Bayesian-framework age model was constructed from three lava sequences from a combination of lithostratigraphic and magnetostratigraphic data, plus new $^{40}\text{Ar}/^{39}\text{Ar}$ dates. We show that the lava sequences were extruded over a period of ~2.5-3.2 Ma, and have similar extrusion rates as the upper sections of neighbouring Eyjafjarðardalur. Ten lava units were used for $^{40}\text{Ar}/^{39}\text{Ar}$ dating, nine of which yielded ages from duplicate or triplicate specimens. A total of 37 lava units yielded palaeomagnetic polarities for the magnetostratigraphic study; however, due to the limited number of sun-reading orientations, only seven of these palaeomagnetic directions are considered sufficiently robust to yield virtual geomagnetic poles.

1 Introduction

In this short, data-driven paper we report a new age model for three volcanic sequences in Bleiksmýrardalur in northern Iceland (Fig. 1) using a combination of lithostratigraphy (field mapping), magnetostratigraphy and $^{40}\text{Ar}/^{39}\text{Ar}$ dating. Bleiksmýrardalur is a relatively remote valley in Iceland, with no 4×4 track, making access challenging. We were interested in constructing this age model as it is part of larger study to determine palaeomagnetic field behaviour at high latitudes over the last 8 Myr (Døssing *et al.*, 2016, Døssing *et al.*, 2020, Muxworthy *et al.*, 2024). Accurate age models are critical to studying paleomagnetic field behaviour; therefore, whilst this paper is intrinsic to this larger study, it does not deal directly with geomagnetic field behaviour and is standalone. The aim of this study was to extend back the time interval studied by Døssing *et al.* (2016, 2020) for Jökuldalur and Fljótsdalur, so that we could undertake full-palaeomagnetic vector and time-averaged field (TAF) analysis (Johnson *et al.*, 2008) on a longer Icelandic data set. The $^{40}\text{Ar}/^{39}\text{Ar}$ dates determined for Jökuldalur (Døssing *et al.*, 2016), Fljótsdalur (Døssing *et al.*, 2020) and Eyjafjarðardalur (Muxworthy *et al.*, 2024) were acquired after palaeomagnetically sampling all three valleys. We show below that our new dates for this fourth valley, Bleiksmýrardalur, are between ~2.5–3.2 Ma. We did not anticipate such a significant overlap between the ages of Fljótsdalur (~2.0–7.0 Ma) and Eyjafjarðardalur (~2.6–8.0 Ma) when planning the palaeomagnetic sampling.

Bleiksmýrardalur has not previously been mapped or dated in any sufficient detail. Here, we present new field mapping data, magnetostratigraphy data and new $^{40}\text{Ar}/^{39}\text{Ar}$ dating results from Bleiksmýrardalur. From this data we construct an age model similar to that of Døssing *et al.* (2016, 2020) and Muxworthy *et al.* (2024). A report of the ancient geomagnetic field intensity – palaeointensity – determined from the same rocks reported in Døssing *et al.* (2020), Muxworthy *et al.* (2024) and this study is in preparation.

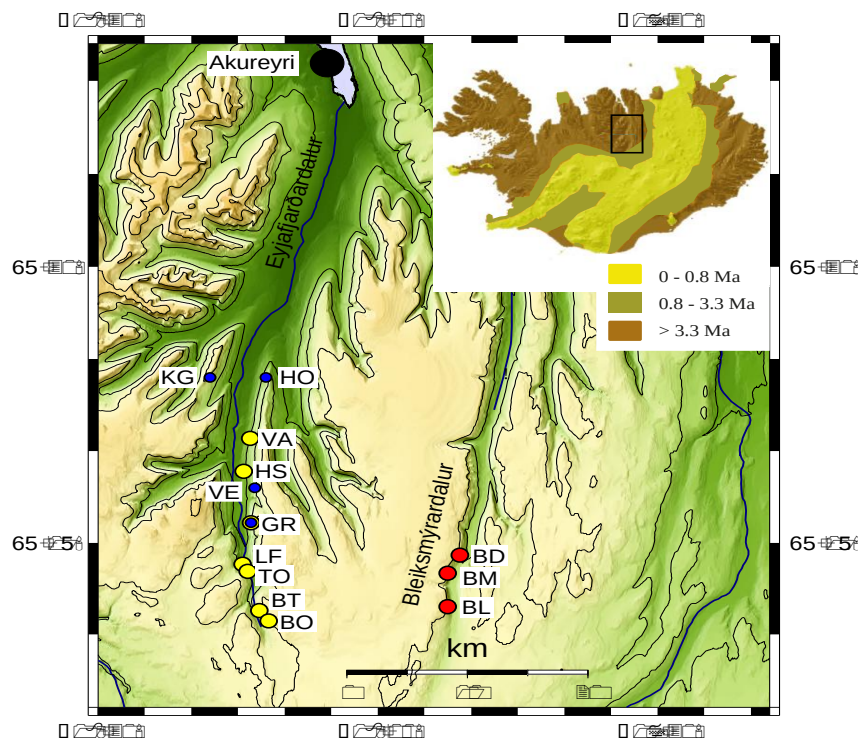


Figure 1. Map of Bleiksmýrardalur and Eyjafjarðardalur, in northern Iceland. The BD, BM and BL (red circles) sections are in Bleiksmýrardalur and are the focus of this study. The localities VA to BO (yellow circles) in Eyjafjarðardalur are the sections studied by Muxworthy *et al.* (2024), and the localities KG to GR are those of Kristjansson *et al.* (2004). The GR section was studied by both Kristjansson *et al.* (2004) and Muxworthy *et al.* (2024). The black circle is the centre of Akureyri city. Inset shows a location and general geology map of Iceland, with a rectangle highlighting the study area.

2 Geological setting

Bleiksmýrardalur is located ~50 km south-east of Akureyri (Fig. 1), near the vicinity of a Neogene central volcano, that is, the Torfufell Central Volcano (Saemundsson *et al.*, 1980, Kristjansson *et al.*, 2004). We sampled three lava sections ordering from BD (north, oldest) to BM (middle) to BL in the south (youngest) (Fig. 2). The sections mostly consisted of small gullies cut by streams, with clear *in situ* exposures. We studied a total of 41 lava units, which were identified by observations of palaeosol interbeds (red beds). The lava piles in the valley mostly consists of tholeiite (aphyric), porphyritic and olivine basalt, with small contribution of mild-alkaline basalts (Fig. 2) similar to the lava piles in Eyjafjarðardalur (Kristjansson *et al.*, 2004, Muxworthy *et al.*, 2024). We measured

regional south-east tectonic tilts of $\sim 1^\circ$ south east; these compare to regional tectonic tilts of $\sim 2^\circ$ reported for the upper sections of Eyjafjarðardalur (Muxworthy *et al.*, 2024). The 41 lava piles are shown in this study to cover a time span ~ 2.5 -3.2 Ma.

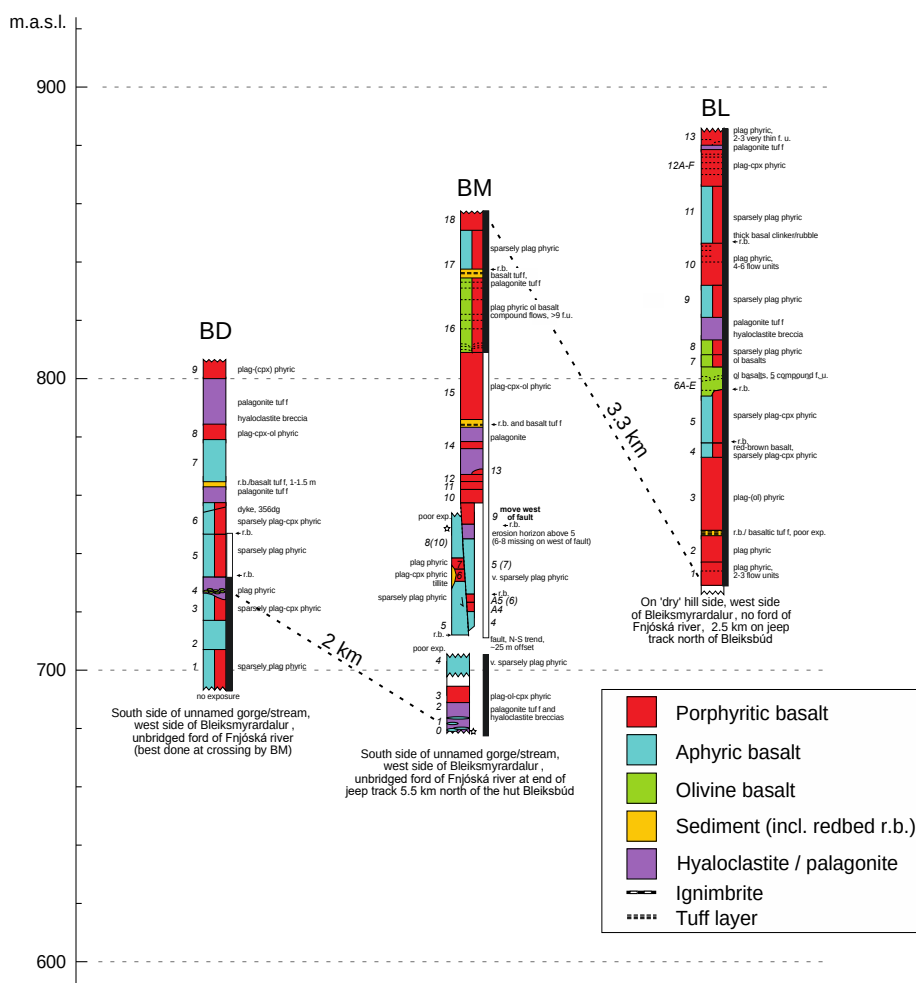


Figure 2. Stratigraphic map of Bleiksmýrardalur showing sections BD, BM and BL. Grey dash line presents possible correlations according to regional dip, altitudes and lithology. Palaeomagnetic polarity is also shown for each of the units; taken from Table 2.

Bleiksmýrardalur was originally mapped in the summer 2015, and palaeomagnetic and $^{40}\text{Ar}/^{39}\text{Ar}$ samples collected in the summer of 2016. A standard palaeomagnetic drill was used to collect ~7-14 oriented cores from 37 of the 41 lava flows; flows BD6, B7 and BD8 and BM5 were not palaeomagnetically sampled. The high number of cores was because of our intention to also conduct a palaeointensity study for which sister samples are required. To make sure that the samples were not collected from rotated outcrops and to avoid the possibility of lightning strikes, where possible, we traversed along the base of individual lava units to sample cores from the same flow over ranges up to 50 m. We also avoided sampling from the top of the flow units as upper contacts are more likely to be re-magnetised by overlying flows. The cores were orientated using a magnetic compass, and where possible sun-compass readings were taken; due to limited sun during the fieldwork only ~24 % of the cores (426 in total) had sun readings; profile BD had zero sun readings from 55 cores, BM 99 from 221 cores and BL 4 from 155 cores. For the samples with sun readings, we found a median deviation between sun and magnetic compass readings of $\sim 6^\circ$, with a maximum of deviation of 27° . These values are comparable to previous studies in Iceland where deviations of up to 30° have been reported (e.g., Døssing *et al.*, 2016). Samples were also collected from ten units for $^{40}\text{Ar}/^{39}\text{Ar}$ dating (Table 1). These samples were melon-sized (1–2 kg) and taken from fresh surfaces of lava to avoid glass and weathered material.

Table 1. Summary of incremental heating $^{40}\text{Ar}/^{39}\text{Ar}$ age determinations for Bleiksmýrardalur. Age estimations for the Plateau spectrum, Inverse isochron and Integrated (total fusion age) are presented with associated 2 standard deviation uncertainties with (w/) and without (w/o) the inclusion of J uncertainty. N is incremental heating steps used in plateau and isochron age calculations and N_{tot} is the total incremental heating steps. MSWD (mean sum weighted deviation) values for the age plateaus and inverse isochrons are calculated using total- $N-1$ and total- $N-2$ degrees of freedom, respectively. ^{39}Ar is the gas percentage, and for the inverse isochron calculation the $^{40}\text{Ar}/^{36}\text{Ar}$ intercept and error are provided. Unless indicated, each sample is an inverse variance weighted composite of all accepted plateau steps from three independent specimens. Not all sites yielded three estimates for the Plateau spectrum and Inverse isochron ages.

sample	Plateau spectrum						Inverse isochron						Integrated (total fusion)	
	Age (Ma)	$\pm 2\sigma$ w/o J	$\pm 2\sigma$ w/J	MSWD	N/N_{tot}	^{39}Ar (%)	Age (Ma)	$\pm 2\sigma$ w/o J	$\pm 2\sigma$ w/J	$^{40}\text{Ar}/^{36}\text{Ar}$ intercept	$\pm 2\sigma$	MSWD	Age (Ma)	$\pm 2\sigma$ w/J
BD2 (4)	2.98	0.06	0.06	0.61	8/15	71	3.03	0.27	0.27	297.8	3.8	0.68	2.76	0.08
BD2 (5)	3.06	0.06	0.06	1.30	12/15	76	3.26	0.17	0.17	295.3	2.8	0.89	2.89	0.09
BD2 (6)	3.03	0.10	0.10	0.71	13/15	85	3.27	0.34	0.35	295.9	3.7	0.59	2.81	0.14
BD8 (4)*	-	-	-	-	-	-	3.68	0.28	0.28	291.5	2.5	2.13	2.70	0.07
BD8 (5)*	3.13	0.07	0.07	1.63	10/15	59	3.08	0.30	0.30	299.2	3.8	1.81	3.01	0.08
BD8 (6)*	3.11	0.08	0.08	0.82	12/15	69	2.99	0.26	0.26	299.9	2.9	0.81	2.80	0.10
BM4 (4)	3.22	0.10	0.10	1.21	9/15	68	3.13	0.30	0.30	299.8	3.5	1.30	2.81	0.11
BM4 (5)	3.11	0.15	0.15	0.81	12/15	68	3.37	0.50	0.50	295.6	5.5	0.78	2.62	0.19
BM4 (6)	3.12	0.09	0.09	1.86	11/15	56	3.28	0.45	0.45	296.5	5.7	1.95	2.22	0.11
BM7 (4)	3.28	0.13	0.13	1.06	11/15	76	3.32	0.31	0.31	297.7	5.5	1.16	2.87	0.14
BM7 (5)	3.33	0.11	0.11	1.03	9/15	71	3.33	0.31	0.31	298.6	5.6	1.17	3.02	0.12
BM7 (6)	3.24	0.10	0.10	1.28	12/15	77	3.33	0.30	0.30	297.1	4.5	1.35	2.87	0.12
BM10 (4)	-	-	-	-	-	-	-	-	-	-	-	-	2.81	0.10
BM10 (5)	-	-	-	-	-	-	-	-	-	-	-	-	2.75	0.10
BM10 (6)	-	-	-	-	-	-	3.48	0.69	0.69	302.7	7.8	0.82	3.12	0.16
BM17 (4)	3.18	0.13	0.13	0.90	11/15	66	3.34	0.30	0.30	297.1	2.6	0.86	2.83	0.14
BM17 (5)	3.34	0.14	0.14	1.15	12/15	64	3.74	0.32	0.32	294.6	2.9	0.57	2.96	0.16
BM17 (6)	3.27	0.09	0.09	1.63	7/15	78	3.47	0.36	0.36	296.7	3.2	1.53	3.14	0.12
BL1 (4)	2.84	0.13	0.13	0.99	11/15	70	2.82	0.57	0.57	298.7	4.3	1.10	2.53	0.12
BL1 (5)	2.89	0.09	0.09	1.23	12/15	67	3.19	0.38	0.38	296.2	2.9	1.08	2.67	0.11
BL1 (6)	2.79	0.10	0.10	0.80	9/15	78	3.12	0.65	0.65	296.1	4.9	0.77	2.57	0.13
BL5 (4)	2.87	0.15	0.15	0.82	11/15	68	3.04	0.41	0.41	296.2	5.4	0.83	2.59	0.16
BL5 (5)	2.91	0.14	0.14	0.75	11/15	57	2.95	0.47	0.47	298.1	6.5	0.83	2.36	0.13
BL5 (6)	2.80	0.11	0.11	1.00	12/15	83	3.14	0.32	0.32	294.5	3.7	0.63	2.55	0.14
BL9 (4)	2.90	0.16	0.16	0.82	13/15	96	3.12	0.33	0.33	295.2	4.5	0.69	2.80	0.20
BL9 (5)	2.74	0.15	0.15	1.14	11/15	91	2.59	0.31	0.31	300.9	3.9	1.11	2.38	0.19
BL9 (6)	2.88	0.19	0.19	1.12	13/15	96	3.16	0.36	0.36	294.6	4.5	0.94	2.60	0.20
BL12F (4)	2.55	0.08	0.08	0.45	7/15	81	2.49	0.22	0.22	300.2	5.9	0.48	2.38	0.12
BL12F (5)	2.48	0.09	0.09	0.79	14/15	96	2.56	0.23	0.23	296.0	7.1	0.81	2.25	0.14
BL12F (6)	2.50	0.12	0.12	0.62	15/15	100	2.54	0.22	0.22	297.2	5.3	0.65	2.41	0.16

3 Methods

3.1 $^{40}\text{Ar}/^{39}\text{Ar}$ dating

The $^{40}\text{Ar}/^{39}\text{Ar}$ geochronology was performed at the NEIF Argon Isotope Laboratory, Scottish Universities Environment Research Centre (SUERC). Samples and neutron flux monitors were stacked in quartz tubes with the relative positions of packets precisely measured for later reconstruction of neutron flux gradients. The sample package was irradiated in the Oregon State University reactor, Cd-shielded facility for 6 hours. Fish Canyon sanidine (28.294 ± 0.036 Ma (1σ , (Renne *et al.*, 2011)) was used to monitor ^{39}Ar production and establish neutron flux values (J) for the samples. Gas was extracted from samples via step-heating using a mid-infrared ($10.6\ \mu\text{m}$) CO_2 laser with a non-gaussian, uniform energy profile and a 3.5 mm beam diameter. The samples were housed in a doubly pumped ZnS-window laser cell and loaded into a copper planchette containing four 2.6 cm² square wells. Liberated argon was purified of active gases, e.g., CO_2 , H_2O , H_2 , N_2 , CH_4 , using three Zr-Al getters; one at 16°C and two at 400°C . Data were collected on an ARGUS V multi-collector mass spectrometer using a variable sensitivity faraday collector array in static collection (non-peak hopping) mode (Mark *et al.*, 2009). Time-intensity data are regressed to t_0 with second-order polynomial fits to the data. Blank corrections employed the average value and standard deviation of multiple blanks bracketing and interspersed with the sample and air standard runs. Mass discrimination was monitored daily, both between and within sample runs, by comparison to running-average values of an air standard. All data were blank, interference and mass discrimination corrected using the MassSpec software package (MassSpec, Berkeley Geochronology Center, Version 8.058). Decay constants and corrections after Renne *et al.* (2011).

Inverse-variance-weighted plateau ages, or composite plateau ages for replicated samples, are chosen as the best estimates of the emplacement ages. Plateau-age acceptance criteria were: 1) The ages of at least five steps on a plateau release diagram are indistinguishable within 2σ uncertainty, 2) the accepted plateau steps form an isochron on a correlation diagram, 3) the trapped component composition, derived from this inverse isochron, is indistinguishable from the composition of air ($^{40}\text{Ar}/^{39}\text{Ar}_{\text{ATM}} = 298.56 \pm 0.31$) at the 2σ uncertainty level, 4) the dispersion of data points on the isochron and plateau diagrams are comparable to the expected analytical scatter, e.g., MSWD (mean sum weighted deviation) is close to 1, and 5) the isochron and plateau ages are indistinguishable within 2σ uncertainty. All ages are expressed at 2σ uncertainty level.

3.2 Rock magnetic characterisation

Knowledge of the magnetic mineralogy of and magnetic domain state helps to quantify the recording fidelity of the magnetic minerals with the rocks. The recording fidelity is controlled by the magnetic domain state, which is strongly related to grain size and magnetic mineralogy. To characterise the magnetic mineralogy high-temperature susceptibility (HT- χ) measurements were made using a Agico MFK1 Kappabridge fitted with a CS3 oven located at Imperial College. The HT- χ measurements allow for the determination of mineral-specific Curie temperatures (Muxworthy *et al.*, 2023). The characteristic magnetic domain states were determined by measuring room-temperature magnetic hysteresis made using a Princeton Measurements vibrating sample magnetometer (VSM) also located at Imperial College. Combining the major hysteresis loops with backfield curves allows for the plotting of the so-called domain-state ‘Day plot’ (Day *et al.*, 1977). The ‘Day’ plot is split into three regions representing the three domain states: single-domain (SD), pseudo-SD (PSD) and multidomain (MD). SD particles are the finest particles and are magnetically uniform (< 100 nm for magnetite), slightly larger PSD grains (>100 nm for magnetite) are magnetically non-uniform, but display SD-like behaviour and the very largest grains (>10 μm) for magnetite are MD (Nagy *et al.*, 2019). The best recorders of the geomagnetic field are SD and PSD particles (Nagy *et al.*, 2022).

3.3 Palaeomagnetic directional measurements

To determine the direction of a palaeomagnetic sample it is standard to determine the recorded characteristic palaeomagnetic direction of 4 to 5 independent specimens from an outcrop. To collect the specimens standard one-inch (25.4 mm) cores were drilled at each unit and then cut into 22 mm length specimens. In total 426 cores were drilled. Details of the site locations are given in Table 1. The palaeodirection measurements were performed at the palaeomagnetic laboratories at both Imperial College London and the University of Oxford. Approximately 4–7 oriented unbroken cores per lava flow were submitted to progressive alternating-field (AF) demagnetisation. The natural remanent magnetisation (NRM) was measured with either an AGICO JR5A spinner magnetometer or a Molspin Minispin magnetometer. Progressive tumbling AF demagnetisation (Molspin AF tumbler) was applied in field between 5–100 mT until the NRM dropped below 5%. For samples where 100 mT was not sufficient, then higher fields (up to 200 mT) were applied using a static-AF DTECH 2000. In accordance with TAF protocol (Johnson *et al.*, 2008), thermal demagnetisation was performed for at least one specimen per lava flow. A stepwise heating protocol was applied between 100°C and 620°C, using an ASC single-chamber palaeomagnetic oven (Imperial) or a MMTD palaeomagnetic oven (Oxford). The characteristic components of NRM were determined by principal-component analysis (PCA) (Kirschvink, 1980) on orthogonal project plots. Five points or more were employed to determine the palaeodirections. Typically 5–8 specimens per site were used to determine site

mean directions using Fisher statistics (Fisher, 1953) on PuffinPlot (Lurcock and Wilson, 2012), with a few exceptions, e.g., BM3, BM4 and BM6, where only four specimens were studied (Table 2).

Table 2. Summary of site palaeomagnetic data: λ and φ are the latitude and longitude of the site location; h stratigraphic height measured with a Garmin etrex30 (± 10 m, WGS84), dec and inc are the palaeomagnetic declination and inclination of the ChRM as determined in this study, with the given α_{95} ; κ is the precision parameter (Fisher, 1953), n is the number of specimens used to determine the ChRM from a total of N measured specimens measured; R is the resultant vector; sun the number of samples with sun readings used, λ_p and φ_p are the VGP positions for each site with precision parameters d_m and d_p ; age is the each of each unit as shown in the age model in Fig. 8 and range the age range estimated from the Bayesian-framework. VGPs are only calculated for sites with at least three sun readings. Rejected samples are highlighted.

site	λ (°N)	φ (°W)	h (m)	dec (°)	inc (°)	α_{95} (°)	κ	n/N	R	sun	λ_p (°N)	φ_p (°E)	d_m (°)	d_p (°)	age (Ma)	range (Ma)
BD1	65.23885	17.84362	694	22	75	4	181	8/8	8.0	0	...	...	...	...	3.160	3.117–3.303
BD2*	65.23908	17.84401	709	350	79	5	159	7/8	7.0	0	...	...	...	...	3.130	3.116–3.178
BD3*	65.23918	17.84422	716	331	83	2	826	6/7	6.0	0	...	...	...	...	3.124	3.116–3.143
BD2-BD3				343	81	3	214	13/15	12.9	0					3.130	3.116–3.178
BD4d	65.23905	17.84450	724	26	67	6	151	5/7	5.0	0	...	...	...	...	3.122	3.116–3.137
BD5	65.23924	17.84503	739	179	-71	4	232	6/7	6.0	0	...	...	...	...	3.113	3.102–3.116
BD6 λ	65.23934	17.84548	750	...	...	...	...	...	...	...	...	...	...	...	3.111	3.098–3.116
BD7 λ	65.23900	17.84578	770	...	...	...	...	...	...	...	...	...	...	...	3.107	3.090–3.116
BD8 λ	65.23954	17.84620	785	...	...	...	...	...	...	...	...	...	...	...	3.100	3.063–3.115
BM0d*	65.22232	17.86135	694	352	68	5	218	5/5	5.0	4	76	183	9	7	3.122	3.116–3.137
BM1*	65.22233	17.86159	695	359	63	5	286	5/6	5.0	3	70	165	7	3.145	3.122	3.116–3.137
BD4-BM0-BM1				7	68	4	95	15/18	13.9	7	74	147	7	6	3.122	3.116–3.137
BM2	65.22242	17.86191	699	334	71	6	144	6/8	6.0	8	74	226	10	8	3.122	3.116–3.136
BM3†	65.22241	17.86275	707	312	79	6	207	4/4	4.0	4	...	...	...	...	3.121	3.116–3.135
BM4†	65.22235	17.86309	710	289	76	10	94	4/4	4.0	3	...	...	...	...	3.119	3.110–3.134
BM5 λ	65.22235	17.86453	...	...	...	...	...	...	...	...	...	...	...	...		
BMA6	65.22242	17.86530	736	33	60	17	17	6/7	5.7	1	...	...	...	...	3.116	3.116–3.117
BM6*†	65.22194	17.86589	762	246	-83	7	184	4/4	4.0	4	...	...	...	...	3.113	3.102–3.116
BM7*	65.22210	17.86515	771	264	-81	3	584	6/6	6.0	3	-62	200	5	5	3.111	3.099–3.116
BM8*	65.22207	17.86466	777	243	-80	5	289	5/5	5.0	5	-67	212	9	8	3.110	3.097–3.116
BM9*	65.22197	17.86456	780	279	-84	6	109	6/7	5.9	7	-61	186	13	12	3.110	3.096–3.116
BM10*	65.22204	17.86449	793	232	-80	3	320	7/8	7.0	6	-70	214	6	6	3.107	3.090–3.116
BM6-BM10				250	-82	2	191	28/30	27.9	25	-66	201	4	4	3.113	3.090–3.116
BM11*	65.22179	17.86496	793	137	-70	9	77	5/7	4.9	0	...	...	...	...	3.107	3.090–3.116
BM12*	65.22177	17.86508	795	141	-73	4	295	6/6	6.0	0	...	...	...	...	3.107	3.089–3.116
BM11-BM12				139	-71	4	139	11/13	10.9	0					3.107	3.089–3.116
BM13*	65.22181	17.86537	804	166	-68	4	165	8/8	8.0	8	-74	16	7	6	3.103	3.078–3.115
BM14*	65.22176	17.86541	805	150	-69	7	75	7/7	6.9	6	-70	45	12	10	3.102	3.075–3.115
BM13-BM14				159	-68	4	99	15/15	14.9	14	-73	31	7	6	3.103	3.075–3.115
BM15	65.22184	17.86566	816	158	-70	5	151	7/8	7.0	6	-74	37	8	7	3.037	2.952–3.104
BM16	65.22216	17.86679	822	65	85	4	336	6/7	6.0	0	...	...	...	...	3.013	2.934–3.098
BM17	65.22178	17.86639	826	82	80	8	71	6/6	5.9	0	...	...	...	...	2.951	2.876–3.029
BM18d*	65.22179	17.86684	831	27	79	3	539	7/7	7.0	6	79	43	5	5	2.937	2.867–3.016
BL1d*	65.19202	17.86156	725	356	73	9	58	6/7	5.9	0	83	178	16	14	2.930	2.863–3.009
BM18-BL1				10	77	5	87	13/14	12.9	6	86	75	8	8	2.937	2.863–3.016
BL2	65.19203	17.86170	729	343	69	6	188	5/6	5.0	1	...	...	...	...	2.922	2.860–2.999
BL3	65.19218	17.86205	747	4	72	4	277	7/7	7.0	0	...	...	...	...	2.857	2.799–2.907
BL4*	65.19206	17.86287	771	338	67	6	89	8/8	7.9	0	...	...	...	...	2.838	2.779–2.890
BL5*	65.19210	17.86314	773	354	67	3	351	7/7	7.0	0	...	...	...	...	2.836	2.776–2.889
BL4-BL5				345	67	4	119	15/15	14.9	0					2.838	2.776–2.890
BL6*	65.19204	17.86354	790	347	77	20	10	7/7	6.4	0	...	...	...	...	2.821	2.754–2.879
BL7*	65.19200	17.86367	800	331	76	2	537	8/8	8.0	0	...	...	...	...	2.812	2.742–2.874
BL8*	65.19196	17.86370	808	348	77	3	264	8/8	8.0	0	...	...	...	...	2.802	2.725–2.868
BL9*	65.19183	17.86429	820	357	81	4	347	5/7	5.0	0	...	...	...	...	2.783	2.687–2.859
BL10*	65.19200	17.86451	830	345	82	4	210	8/8	8.0	0	...	...	...	...	2.757	2.639–2.848
BL6-BL10				344	79	4	48	36/38	35.3	0					2.821	2.639–2.879
BL11	65.19195	17.86482	864	345	69	9	77	5/5	4.9	3	75	200	15	13	2.715	2.600–2.829
BL12	65.19195	17.86569	875	350	71	14	25	6/8	5.8	0	...	...	...	...	2.579	2.482–2.698
BL13	65.19214	17.86593	881	20	69	13	35	5/6	4.9	0	...	...	...	...	2.581	2.581–2.482

d part of a cross-section 'double': BD4-BM0 and BM18-BL1

λ No samples collected for palaeomagnetic study/

* Combined into a single group using directional-group analysis (Chenet *et al.*, 2008).

† VGP calculation rejected as $n < 5$.

4 Results

4.1 $^{40}\text{Ar}/^{39}\text{Ar}$ dating

$^{40}\text{Ar}/^{39}\text{Ar}$ age estimates were determined for ten lava flows in Bleiksmýrardalur valley (Table 1 and Fig. 3). At all localities, triplicate specimens were measured. At eight localities this yielded three plateau ages with replicate ages that are

indistinguishable at 2σ . For BD8 only two plateau ages were successfully returned, and at BM10 no plateau ages were determined from the three specimens. The nine sites yielding plateau ages range from $\sim 3.33 \pm 0.11$ Ma for BM7 (5) to 2.48 ± 0.09 Ma for BL12F (5) (Table 1, Figs. 2 and 3).

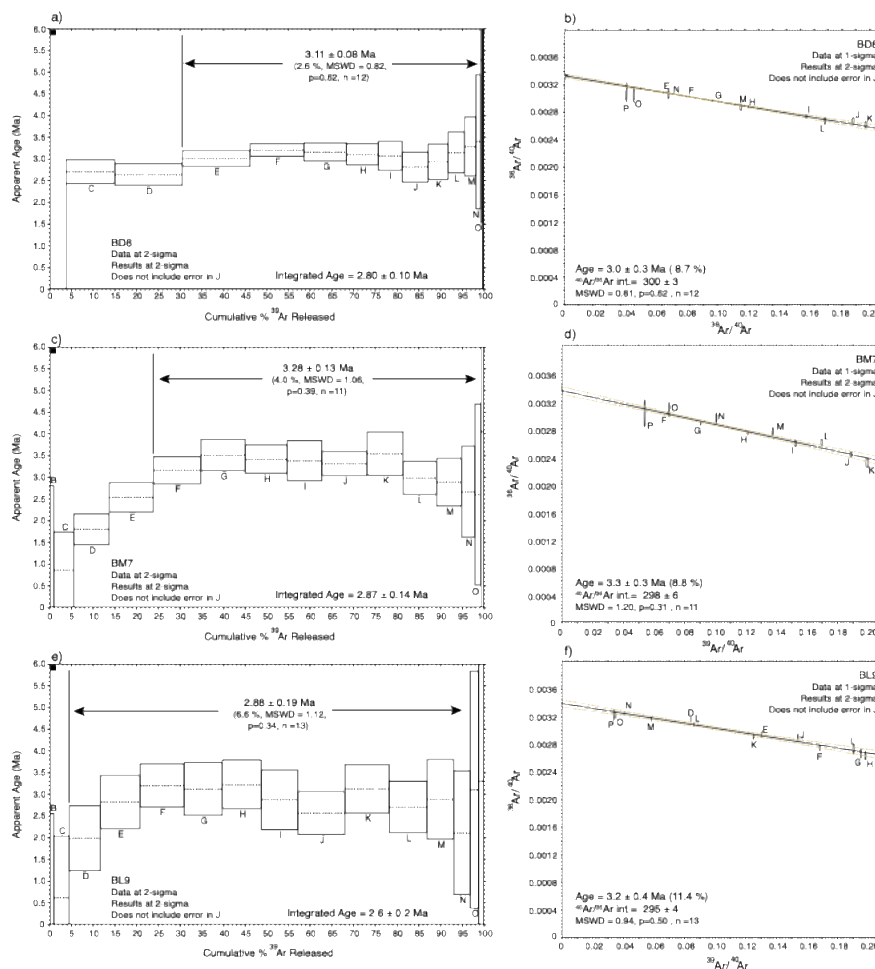


Figure 3. Examples of $^{40}\text{Ar}/^{39}\text{Ar}$ data for samples: (a, b) BD8, (c, d) BM7 and (e, f) BL9. The left column shows the age spectrum diagrams, and the right column inverse isochron data from step-up heating. Integrated age (total fusion age) is also marked in the age spectrum diagrams. The light grey ellipses in the inverse isochron diagram indicate data from step heating that are excluded from the plateau age calculation.

The relative uncertainties of plateau ages range from 1.3 to 6.6%. All plateau ages agree with the isochron ages at 2σ . Some of the specimens from BL12F and BM17 show younger ages in the high-temperature steps suggesting potential ^{37}Ar recoil loss (Fig. 4e) (Schaen *et al.*, 2020).

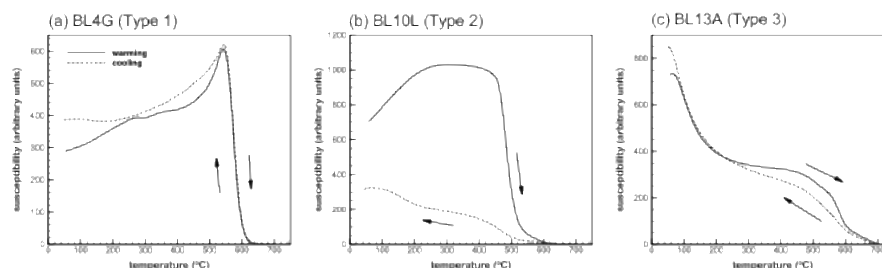


Figure 4. High-temperature susceptibility curves for three samples (a) BL4G, (b) BL10L and (c) BL13A, which respectively display the three general types of behaviour discussed in the text. Type 1 curves are mostly ‘reversible’ displaying high Curie temperatures near $\sim 580^\circ\text{C}$ (low-Ti titanomagnetite), Type 2 curves are highly irreversible, with the cooling curve displaying a far lower susceptibility, indicating a phase transformation, likely that of a maghemite-like phase to hematite-like phase, and Type 3 curves display typical Ti-rich titanomagnetite behaviour, i.e., a Curie temperature near $\sim 200^\circ\text{C}$ with a second near Curie temperature near 580°C .

4.2 Rock magnetic analysis

The HT- χ data analysis shows titanium compositional variations in the samples, from Ti-poor titanomagnetite to Ti-rich titanomagnetite (Muxworthy *et al.*, 2023). Three general types of HT- χ curve were found (Fig. 4): Type 1 curves are indicative of Ti-poor titanomagnetite (Curie temperature $\sim 580^\circ\text{C}$) and reversible or nearly reversible on heating/cooling, with a clear Hopkinson peak (Fig. 4a); Type 2 behaviour was highly irreversible with a large reduction in susceptibility after heating to 700°C (Fig. 4b); Type 3 behaviour is indicative of high-Ti content, with a mix of low and high Curie temperatures and reversible behaviour (Fig. 4c). Type 1 curves were the most common and were found in most of the units. Type 2 behaviour was rare and was only seen in BL10; such behaviour suggests that the lava was likely to have been oxidised to form a maghemite phase, which inverts to hematite on heating during HT- χ measurement. Type 3 behaviour was found in only in a few units, notably from BL3 and BL13. That there are two Curie temperatures at $\sim 200^\circ\text{C}$ and 580°C is typical for titanomagnetites, as there is a tendency for the Ti to reside in the larger crystals, i.e., $> 1\ \mu\text{m}$, leaving the finer titanomagnetite SD and PSD grains Ti-poor (Almeida *et al.*, 2014).

Room-temperature hysteresis data and HT- χ curves were collected for representative samples to characterise the magnetic domain size and magnetic

carrier of the magnetic remanence. Hysteresis loops were generated for each site using rock chips obtained during the trimming of cores. From the hysteresis curves, combined with back-field curves, the following parameters were extracted: the coercive force (B_C), coercivity of remanence (B_{CR}), saturation magnetisation (M_S) and saturation remanence (M_{RS}), which we plot on a ‘Day’ plot in Fig. 5 (Day *et al.*, 1977). Most of the data plots in the PSD range towards the SD box which is typical for Icelandic basalts (Tonti-Filippini and Brown, 2019, Døssing *et al.*, 2024).

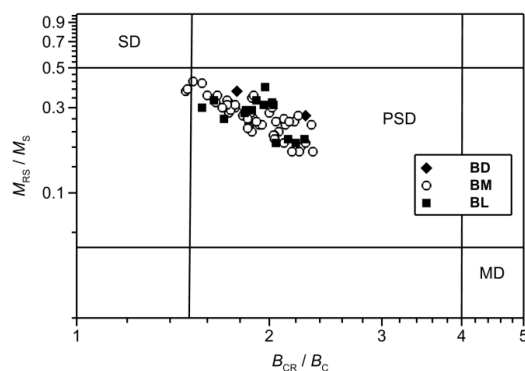


Figure 5. A ‘Day plot’ diagram (Day *et al.*, 1977) showing the domain state of samples from all sites. Majority of samples fell in pseudo-single domain (PSD) region towards the SD region, suggesting stable carriers.

4.3 Palaeomagnetic directional analysis

The palaeodirections were successfully determined for 37 lava flows (Table 2, Fig. 6). Typically, an overprint was removed by AF steps of 5–10 mT, e.g., Figs. 6a, or heating to 150 °C (Fig. 6b); the overprint is most likely a viscous remanent magnetisation (VRM) overprint. After removal of the VRM overprint, most demagnetisation data displayed a clear single component on the orthogonal projection plots (Figs. 6), i.e., the characteristic remanent magnetisation (ChRM), which is likely the primary remanence. During thermal demagnetisation the NRM typically decayed to < 5% after heating to ~500–600 °C (Fig. 6). There was no evidence for secondary re-heating and thermal overprints other than VRMs.

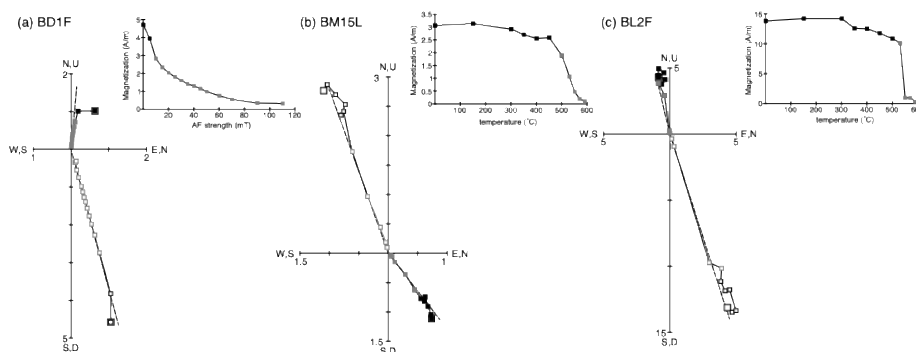


Figure 6. Example demagnetisation data for three samples: (a) BD1F (AF), (b) BM15L (thermal) and (c) BL2F (thermal). Each figure includes an orthogonal projection plot data and NRM intensity demagnetisation data. The data selected to determine the ChRM are in gray. The thermal demagnetisation data of sample BL2F displays a sharp unblocking spectra.

Characteristic remanent magnetisations (ChRM) were identified, and for any given lava unit these ChRM directions were grouped on equal area projection plots (Fig. 7). The directions have been tilt corrected by 1° to the south east, which is the same correction as applied to the BO section reported in Muxworthy *et al.* (2024). This yielded 37 site mean directions, of which 26 display normal polarities and 11 reversed polarities (Table 2).

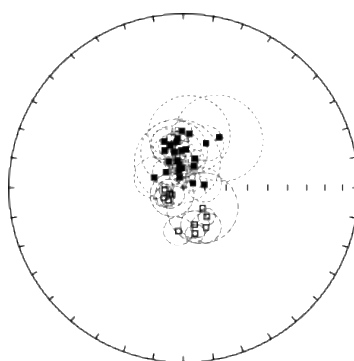


Figure 7. Stereonet plot showing the mean directions for each of the sites. Each mean direction has a α_{95} error cone around it, with closed squares for normal polarity and open squares representing reversed polarity. The data are tabulated in Table 2.

5 Discussion

The palaeomagnetic data were well behaved overall yielding a high-quality dataset, with little ambiguity in the determined directions; however, many of the sites were reliant on magnetic-compass readings only. Given the likely errors associated with these samples, i.e., a median $\sim 6^\circ$ deviation, we do not consider the orientations without sun-compass readings suitable for TAF analysis (Johnson *et al.*, 2008), however, we still use this data magnetostratigraphically in the construction of the age model, as the errors in the magnetic-compass readings are considered relatively small.

5.1 Constructing an age for model for Bleiksmýrardalur

We used the lithostratigraphic, palaeomagnetic and $^{40}\text{Ar}/^{39}\text{Ar}$ data from the 41 lava units to construct a consistent age model for the valley. First, we consider the palaeomagnetic data for sites, which have erupted coeval or near-coeval. Four units did not have palaeomagnetic data, leaving 37 units with palaeomagnetic directions. The sampling was designed so that there would be some overlap between the three lava sequences BD, BM and BL, allowing for cross calibration between sequences. To test these overlaps, we used Watson's V_w test (Watson, 1983). We expected to find several lava units to have the same palaeomagnetic directions based on field observations, however, we identified only two lava-unit pairs to have the same directions, i.e., BD4-BM0 and BM18-BL1 (Table 2). This reduced the total number of independent units to 35. To remove sequential lava flows that do not capture secular variation and are hence difficult to independently date, we used the directional-group (DG) analysis protocol of Chenet *et al.* (2008). DG analysis identifies lava flows that have been erupted in a very short time interval and are treated as a single event and are combined; this is similar to Watson's V_w test, but a little more relaxed. A total of 8 DGs across Bleiksmýrardalur were found, and the directional data were combined to yield new combined DG directions (Table 2), yielding 24 palaeomagnetic mean directions.

To construct the age model for the Bleiksmýrardalur valley we used a modified version of the Julia program Chron.jl (Keller *et al.*, 2018). Chron.jl uses a Bayesian framework to estimate an age-height/depth model based on $^{40}\text{Ar}/^{39}\text{Ar}$ and height/depth data, by applying a Markov-Chain Monte Carlo approach to incorporate superposition, uncertainty and features such as hiatuses (Schoene *et al.*, 2019). We modified Chron.jl to include magnetostratigraphy data (Fig. 5).

For input into the modified Chron.jl model we included the palaeomagnetic polarity data plus the $^{40}\text{Ar}/^{39}\text{Ar}$ data. We treated repeat $^{40}\text{Ar}/^{39}\text{Ar}$ measurements for each site separately to be consistent with the approach of (Døssing *et al.*, 2016). The altitude of the bottom of BD1 was set to zero and the cumulative heights were calculated for the lava sections corresponding to a successive ~ 300 m lava pile (Fig. 5). Relative heights were adjusted for a fault between sections BM and BD, and the tilt based on field lithographic field observations. We correlated our magnetostratigraphic data to the geomagnetic polarity time scale (GPTS) (Ogg, 2020), and combined this with the lithostratigraphic field observations (Figs. 2 and 8). That is, the model was constructed using dates tied to reversals in the GPTS

record and the $^{40}\text{Ar}/^{39}\text{Ar}$ ages, with linear volcanic build-up rates constant within the lava piles. Such an approach has been reported elsewhere (e.g., Døssing *et al.*, 2016, Døssing *et al.*, 2020, Muxworthy *et al.*, 2024), though the application of the Bayesian model differs to these previous age models. There were issues with some of the $^{40}\text{Ar}/^{39}\text{Ar}$ ages dates, e.g., the $^{40}\text{Ar}/^{39}\text{Ar}$ ages did not fit the relatively simple lithographic chronology, e.g., BM7 and BL12F, or the $^{40}\text{Ar}/^{39}\text{Ar}$ ages did not match the GPTS polarity, e.g., BM17. In some cases, this might be due to subsequent resetting of the argon system; however, no $^{40}\text{Ar}/^{39}\text{Ar}$ ages were excluded and the modified Chron.jl code produced an age model that was consistent with the lithology and magnetic polarity data. We identified three significant hiatuses, which we included as input into the modified Chron.jl model: 1) 50 ± 20 kyr between BM14 and BM15, 2) 100 ± 50 kyr between sites BM16 and BM17, and 3) 50 ± 20 kyr between BL2 and BL3 which were all separated by sedimentary layers (Figs. 2 and 5). Estimates for the age of each lava unit are provided in Table 2. The age estimates for BL12 and BL13 at the very top of the sequence are poorly constrained and are possibly too young.

The age-model for the BD, BM and BL sections, overlaps with the upper most section, i.e., the BO section (3.216 to 2.581 Ma) (Fig. 1), of the Eyjafjarðardalur study which is ~20 km distant (Muxworthy *et al.*, 2024). The age models are similar, with the Bleiksmýrardalur extrusion rates slightly higher.

5.2 Time-averaged field analysis

Part of the original goal of this study, was to conduct time-averaged field analysis (Johnson *et al.*, 2008, de Oliveira *et al.*, 2021) of the Bleiksmýrardalur; however, after DG analysis and considering only units of DGs with at least three sun-readings, we only have seven new independent virtual geomagnetic pole (VGP) estimates (Table 2). These seven VGPs yield a mean position $84^\circ\text{N}/235^\circ\text{E}$ and $A_{95} = 12^\circ$, with no transitional VGPs found. In terms of TAF analysis, which was the focus of our previous Icelandic studies, i.e., Døssing *et al.* (2016, 2020) and Muxworthy *et al.* (2024), the size of A_{95} is too large to draw any significant conclusions, though the VGP from these seven sites does agree with geocentric axial dipole (GAD) theory. Adding the seven new VGPs to the data of Døssing *et al.* (2016, 2020) and Muxworthy *et al.* (2024) does not change any of the VGP statistics discussed in these papers, which have a total of 320 independent VGPs.

6 Conclusion

We have determined the first age model for the upper section of Bleiksmýrardalur in northern Iceland, for the time period ~2.5-3.2 Ma determined through a combination of $^{40}\text{Ar}/^{39}\text{Ar}$ dating, magnetostratigraphy and lithostratigraphy (Fig. 8 and Table 2).

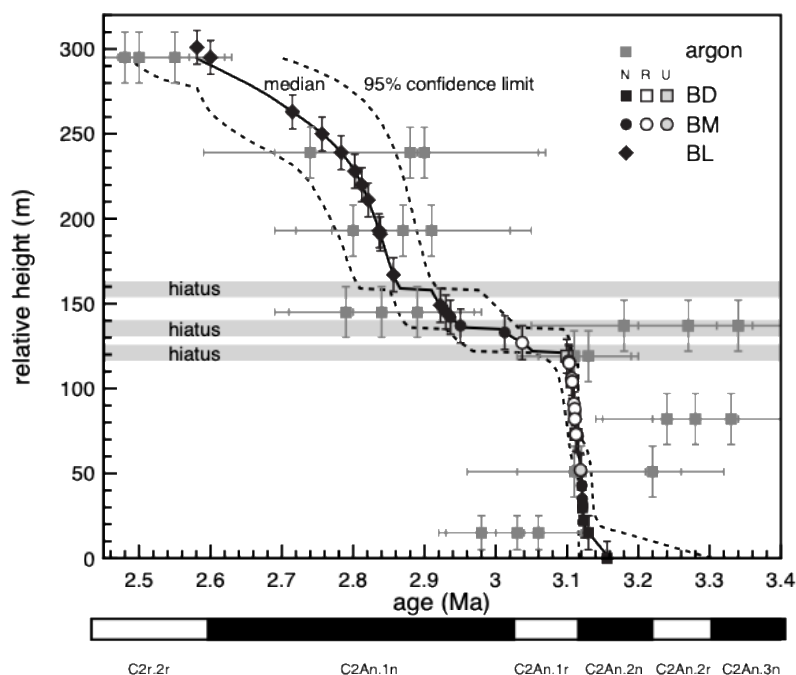


Figure 8. An age model of relative height versus age for Bleiksmýrardalur constructed from the $^{40}\text{Ar}/^{39}\text{Ar}$ dates (Table 1 and Fig. 3), the magnetostratigraphy (Table 2) and the lithostratigraphy (Fig. 2) using a modified version of the Bayesian-framework Chron.jl (Keller *et al.*, 2018). There are three hiatuses as highlighted, which were included in the Chron.jl code. The site ages are tabulated in Table 2.

The ages and extrusion rates correspond to those for the upper sections of the neighbouring Eyjafjarðardalur, in particular BT and BO (Fig. 1) reported in Muxworthy *et al.* (2024). Due to the limited number of sun readings (Table 2) a robust TAF study was not feasible as was originally planned, and only seven new VGPs are reported. The new data does not change interpretations of much larger studies on coeval rocks from Iceland (Muxworthy *et al.*, 2024). The new data adds to the existing extensive palaeomagnetic datasets for Iceland (Kristjánsson, 2013, Tonti-Filippini and Brown, 2019).

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Data Availability

The palaeomagnetic data will be made publicly available on the ICEPMAG database (www.icepmag.org) on acceptance of the paper. All the palaeomagnetic, rock magnetic and $^{40}\text{Ar}/^{39}\text{Ar}$ data are available at [10.5281/zenodo.17094433](https://doi.org/10.5281/zenodo.17094433).

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