Palaeomagnetic results from the Lopra-1/1A re-entry well, Faroe Islands

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The palaeomagnetic dating and evolution of the Faroe Islands are discussed in the context of new density and rock magnetic results from the deepened Lopra-1/1A well. The reversal chronology of the *c.* 6½ km thick basalt succession is also described. The polarity record of the Faroe Islands may now be correlated in detail with the Geomagnetic Polarity Time Scale. The lowermost (hidden) part of the lower basalt formation correlates with Chron C26r (Selandian age), the top (exposed) part of the lower basalt formation correlates with Chrons C26n, C25r and C25n (Selandian and Thanetian age) and the middle and upper basalt formations correlate with Chron C24n.3r (Ypresian). Inclinations indicate a far-sided position of the palaeomagnetic poles, which is characteristic of results from most Palaeogene volcanics from the northern North Atlantic region.

The density, magnetic susceptibility and magnetic remanence of 20 specimens from one solid core (1½ m in length) and 26 sidewall cores from the well between –2219 and –3531 m below sea level (b.s.l.) suggest that the volcanic materials can be divided into two characteristic groups: solid unaltered basalts and altered basalts and tuffs. The magnetic properties are typically log-normally distributed and the carriers of remanence are Ti-poor Ti-magnetites with Curie temperatures close to 580°C. The inclination of the 1½ m core at 2380 m b.s.l. is dominantly negative (two plugs at the very top of the core do show normal polarity, but they are likely to be misoriented as all specimens appear to be from one flow). Magnetic logging (magnetic susceptibility and field intensity) down to 3515 m b.s.l. was made in Lopra-1/1A together with other geophysical logs but did not yield conclusive inclination data.

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Review of the geology

The Faroe Islands are situated on the eastern side of the northern North Atlantic between the Shetland Islands and Iceland on the northern part of the NE–SW-trending elongated Faroe Rise (Fig. 1). The volcanic islands are a result of the hotspot-related plume activity recorded by the Brito-Arctic Large Igneous Province (LIP) (Lawver & Muller 1994; Larsen & Saunders 1998; T.B. Larsen *et al.* 1999; Burke & Torsvik 2004) that stretches from present-day central West Greenland to the north-western parts of the UK.

Seismic (e.g. Richardson *et al.* 1998) and gravity investigations (e.g. Saxov & Abrahamsen 1964) suggest that the invisible basement of the islands is composed of continental lithospheric crust, somewhat thinned by lithospheric stretching processes during the continental break-up that formed the North Atlantic.

The exposed part of the Faroe Islands is composed of a *c.* 3 km thick pile of Palaeogene flood basalts (Rasmussen & Noe-Nygaard 1969, 1970; Noe-Nygaard & Rasmussen 1984) situated above a *c.* 3½ km unexposed volcanic sequence below sea level (Fig. 2). Only minor sedimenta-
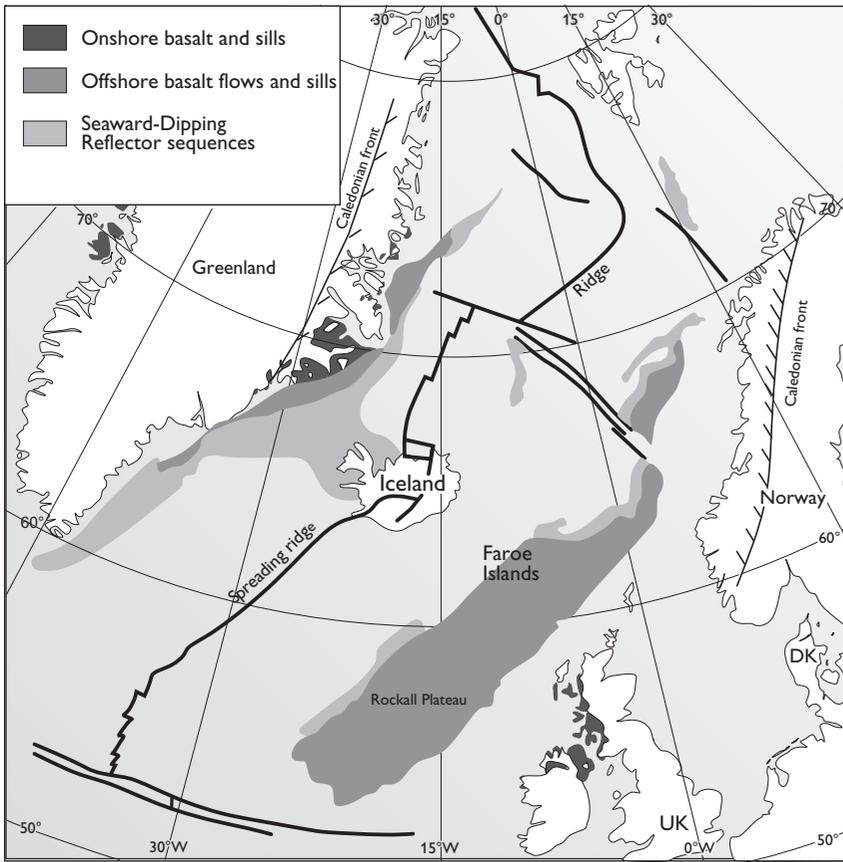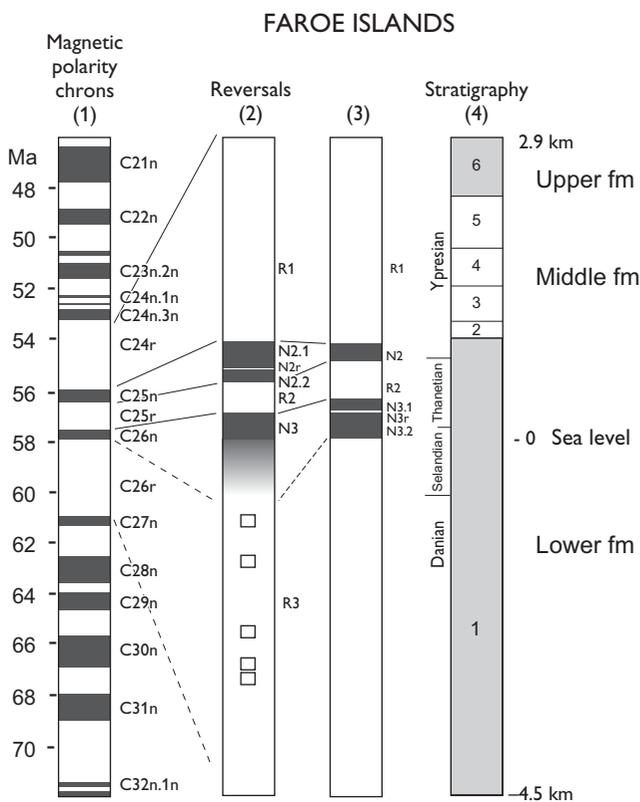
Fig. 1. Index map of the eastern North Atlantic showing the Faroe Islands (modified from Larsen *et al.* 1995).

ry layers are intercalated in the whole volcanic sequence.

The volcanic sequence, more than 6½ km in total thickness (Waagstein 1988; L.M. Larsen *et al.* 1999), is divided into three parts, the lower (> 4½ km thick), the middle (1.4 km thick) and the upper basalt (> 0.9 km thick) formations. The basalts are cut by numerous dykes and a few sills. An up to 10 m thick coal-bearing formation of lacustrine claystones and shales was deposited on top of the slightly eroded surface of the lower basalt formation (the A-level). Two other stratigraphical levels, B (in the middle formation) and C (separating the middle and upper formations), are also useful for stratigraphical purposes (Fig. 2).

The purpose of the present contribution is to present

Fig. 2. Compilation of magnetic reversals within the *c.* 6½ km thick basalt pile of the Faroe Islands, showing stratigraphy and the correlation with the Geomagnetic Polarity Time Scale. The four columns are based upon information compiled from: (1) Ogg (1995); (2) Abrahamsen (1965, 1967), Abrahamsen *et al.* (1984), Waagstein (1988) and Riisager *et al.* 2002a; (3) Tarling & Gale (1968); (4) Rasmussen & Noe-Nygaard (1970), Waagstein (1988) and L.M. Larsen *et al.* (1999).

Table 1. Palaeomagnetic results from the Faroe Islands

Formation/site/core depth	N(Dg)	Decl °	Incl °	α95 °	k	Plat °N	Plon °E	δ95 °	A95 °	Paleo-lat (°N)	No.	Polarity	Reference
All formations	33	176.0	± 69.0	6	14	80.0	159.0	10.3		52.5	1	R&N	(1)
All formations	1809	185.0	± 66.4	1.9		76.7	161.0	3.1		48.9	2	R&N	(2)
ubf, Torshavn	34	171.9	−72.2	3.5	53	84.0	218.0	6.3		57.3	3	R	(3)
ubf, Argir	8	175.1	−53.9*	2.2	258	62.3	182.4	3.1		34.4*	*	R	(3)
mbf, Argisfossar	18	156.0	−36.0*			48				20.0*	*	R	(4)
mbf, Vestmanna core	275		−61.8	1.2	53.4	70.8		1.9		43.0	4	R	(5)
lbf, Vestmanna core	28		± 63.4	6.3	19.4	72.8		10.0		45.0	5	R&N	(5)
mbf + lbf, Vestm. core	303		± 61.9*	1.2	46.1	70.9		1.9		43.1*	*	R&N	(5)
mbf + lbf	548(43)	7.7	± 60.9	4.5	24.5	71.4	154.7		6.0	41.9	6	R&N	(6)
lbf, Lopra-1; 862 mbf	6		−75.0	1						61.8	7	R	(7)
lbf, Lopra-1; 1219 mbf	8		−62.0							43.2	8	?R	(7)
lbf, Lopra-1; 1923 mbf	5		−73.0	3						58.6	9	R	(7)
lbf, Lopra-1; 2178 mbf	7		−55.0*							35.5*	*	?R	(7)
lbf, Lopra-1A; 2380 mbf	20		−71.7	2.0	709					56.5	10	R	(8)
Average, Nos 1–10, except *	(10)		± 67.2	1.4						50.0	11	R&N	(8)
Average, Nos 1, 2, 3 & 6	(4)	181.2	± 67.3	6.3	213	78.7	164.4		8.0	50.1	12	R&N	(8)

lbf, mbf, ubf: lower, middle and upper basalt formations; No.: number in palaeolatitude figure; * Not used in average; N: number of samples; Dg: directional groups; Decl: mean of cleaned declination; Incl: mean of cleaned inclination; α_{95}: cone of 95% confidence. For core data the inclination statistics of Kono (1980) were used for k and α_{95} (Tarling 1983); k: Fisher precision parameter; Plat: latitude of apparent palaeomagnetic pole; Plon: longitude of apparent palaeomagnetic pole; δ_{95} and A_{95}: error angles of app. latitude and app. palaeopole at 95% confidence level; (1) Abrahamsen 1967; (2) Tarling 1970; (3) Løvlie & Kvingedahl 1975; (4) Løvlie 1975; (5) Abrahamsen et al. 1984; (6) Riisager et al. 2002a; (7) Schönharting & Abrahamsen 1984; (8) This work.

the magnetic results from a core of basaltic rock obtained from the Lopra-1/1A reentry well and to discuss these data in relation to other palaeomagnetic results from the Faroe Islands.

Previous work

Magnetic investigations in relation to the Faroe Islands have been made since the early 1960s (Abrahamsen 1965, 1967; Saxov & Abrahamsen 1966; Tarling & Gale 1968; Tarling 1970; Schrøder 1971; Løvlie 1975; Løvlie & Kvingedal 1975; Abrahamsen et al.1984; Schönharting & Abrahamsen 1984; Tarling et al. 1988). Density determinations (Saxov & Abrahamsen 1964) as well as gravity measurements (Saxov 1969) and seismic investigations (Pálmason 1965; Bott et al. 1974, 1976; Casten 1974; Nielsen et al. 1981; Richardson et al. 1998) have been made on and around the islands. Geophysical logs from the Lopra-1/1A and Vestmanna-1 boreholes have been published by Nielsen et al. (1984), Boldreel (2006, this volume) and Abrahamsen & Waagstein (2006, this volume). Geothermal measurements were described by Balling et al. (1984) and Balling et al. (2006, this volume).

Palaeomagnetic results from the Faroe Islands have been published by Abrahamsen (1965, 1967), Tarling & Gale (1968), Tarling (1970), Løvlie (1975), Løvlie & Kvingedal (1975), Abrahamsen et al. (1984), Schönharting & Abrahamsen (1984) and Riisager et al. (2002a, b). A comparison of palaeomagnetic results from East Greenland and other results from the Palaeogene of the North Atlantic Igneous Province (NAIP) was published by Tarling et al. (1988) and a critical review of palaeomagnetic poles from the Eurasian part of the NAIP together with a new pole for the Faroe Islands was presented by Riisager et al. (2002a). A summary of all published palaeomagnetic directional data from the Faroe Islands is shown in Table 1.

The magnetic results for the exposed part of the basalt succession were extended by the wells at Vestmanna-1 and Lopra-1 in 1980–1981 (Abrahamsen et al. 1984; Schönharting & Abrahamsen 1984) and by the re-entry of the Lopra-1/1A hole in 1996, the results of which are presented in this paper. Despite intentions, the re-entry hole at Lopra-1/1A reached a depth of 3565 m without penetrating to the base of the lower basalt formation volcanics.

The polarity sequence and the compiled total stratigraphic column of the Faroe Islands as now known are shown in Fig. 2, together with the Geomagnetic Polarity Time Scale (GPTS). Essentially we find three intervals of reverse magnetic polarity (R1, R2, R3) with two normal
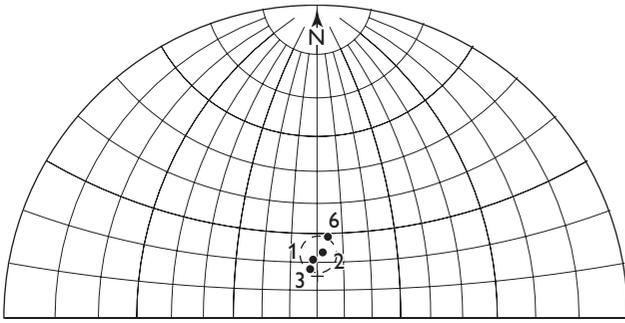
Fig. 3. Palaeomagnetic directions from the Faroe Islands (from Table 1, results Nos 1, 2, 3 and 6) with α₉₅ circle. The axial dipole field direction is indicated by a **cross**.

polarity intervals in between (N2 and N3). Minor differences between columns (2) and (3) in Fig. 2 are likely to be due to somewhat different positions of the profiles investigated on Suðuroy, the southernmost of the Faroe Islands.

According to recent high-precision ⁴⁰Ar-³⁹Ar datings (Storey *et al.* 1996; L.M. Larsen *et al.* 1999), the basalt formations in the Faroe Islands as well as the contemporaneous East Greenland basalts can be divided into an older part with ages of about 59–56 Ma, followed (after a pause or a period with much reduced volcanic activity) by a younger part, with ages of 56–55.5 Ma for the Faroes and 56–54.5 for East Greenland.

Based upon these radiometric datings, the polarity record of the Faroe Islands may now be correlated to the GPTS as shown in Fig. 2. The lowermost (hidden) part of the lower basalt formation correlates with Chron C26r (Selandian age), the upper (exposed) part of the lower basalt formation correlates with Chrons C26n, C25r and C25n (Selandian and Thanetian) and the middle and upper basalt formations correlate with Chron C24r (Ypresian). This correlation follows the suggestion by Waagstein (1988), who revised the original interpretation of Abrahamsen *et al.* (1984) by suggesting that R3 belongs to Chron C26r rather than to C24r. More details in relation to magnetic inclinations from the Lopra-1/1A data are discussed below.

Assuming the geomagnetic field to have been a central, axial dipole field, the palaeolatitude may be determined from the characteristic (primary) inclination of the volcanics, combining both polarities. A compilation of all inclination values obtained from the Faroe Islands is listed in Table 1. Using inclination statistics (Kono 1980; Tarling 1983) the fisherian mean of published inclinations (group numbers 1–10, Table 1) is 67.2° ± 1.4° (equivalent to a palaeolatitude of 50.0° ± 2.1°), whereas the average of the palaeolatitudes listed is 50.9° ± 2.3° (± 1
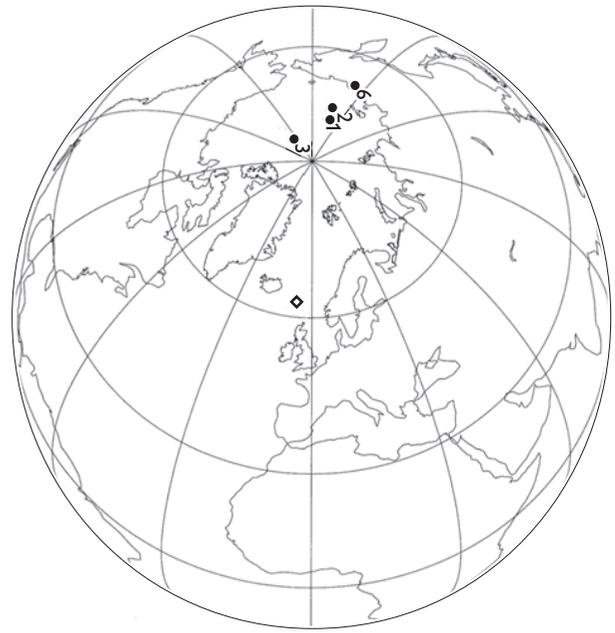

Fig. 4. Apparent palaeomagnetic pole positions (solid circles) with 95% significance circle (Table 1, poles Nos 1, 2, 3 and 6). All poles appear 'farsided' as seen from the Faroe Islands (**diamond**). Further discussion in the text.

sigma). Further discussion of the shallow inclinations and the palaeolatitude question will be given below.

Palaeogeography

Many palaeogeographic reconstructions of the North Atlantic have been published since the early work of Bullard *et al.* (1965) (e.g. Ziegler 1990; Knott *et al.* 1993; L.M. Larsen *et al.* 1999; Torsvik *et al.* 2001; Mosar *et al.* 2002). Before about 60 Ma, the supposed mantle hotspot (just south-east of Iceland at the present day) lay under the volcanic areas of Disko and Nuussuaq in West Greenland (O'Connor *et al.* 2000; Nielsen *et al.* 2002; Chambers *et al.* 2005), far from the Faroe Islands that are situated just north-west of the continental margin of Europe. The whole volcanic pile of the Faroe Islands, more than 6½ km thick, was formed in the time interval between Chron 26 (61.65 Ma) and Chron 24n.3n (*c.* 53.286 Ma) (Chron ages are the orbitally tuned age calibration of Gradstein *et al.* 2004, table 5.2). During this time interval, the hotspot moved eastwards under Greenland as Greenland moved west-north-west relative to Europe and the North Atlantic gradually opened between the Faroe Islands and Greenland.

Absolute declinations are known from only four of the palaeomagnetic investigations from the Faroe Islands (Ta-
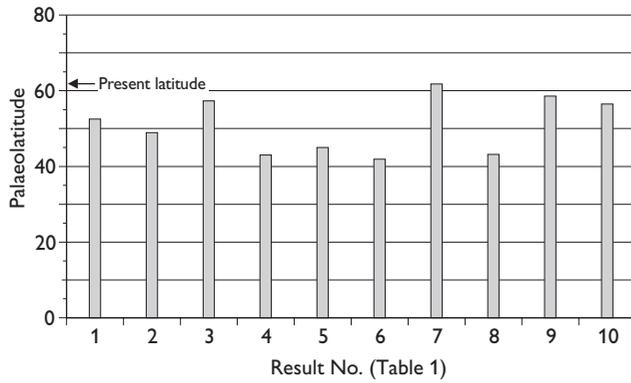
Fig. 5. Histogram of apparent palaeolatitudes according to Table 1 (poles Nos 1–10). Most results appear systematically low compared to the present-day latitude. For further discussion see the text.

ble 1, Nos 1, 2, 3 and 6). If both normal and reverse polarities are combined and assumed to be normal directions towards the north with steep down-dip (positive) inclinations, the four directions appear as shown in Fig. 3. The equivalent apparent palaeomagnetic pole positions are shown in Fig. 4. All four poles are seen to be 'farsided' (Wilson 1971; Merrill *et al.* 1998), the apparent palaeomagnetic poles falling beyond the geographic pole as seen from the Faroe Islands. An equivalent histogram of all published apparent palaeolatitudes (Table 1) is also illustrated in Fig. 5, most of which show low values as compared to the present-day latitude.

Lopra-1/1A investigations

Sampling, instruments and techniques used

The material investigated from the extended Lopra-1/1A well consists of two types: core plugs from the solid core (2380.0 to 2381.3 m) and sidewall cores (between 2219 and 3531 m). The solid core is 1.4 m long and in several pieces, but some fit together, as shown in Fig. 6. After marking the core with an upward directed arrow in the core lab at GEUS, 20 plugs with a diameter of 2.5 cm were drilled orthogonal to the main core and cut to a standard length of 2.2 cm. The major part of the present magnetic investigation is concentrated upon these 20 plugs. In addition some rotary sidewall cores were investigated. The pieces from the sidewall cores had a diameter of 2.33 cm and varied in length, which limited the possibility of fitting these samples into the magnetic instrument holders.
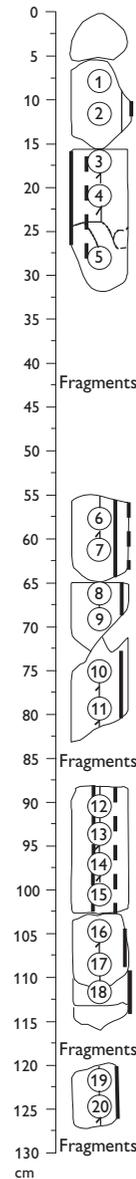

Fig. 6. Sketch from a photograph of the Lopra-1/1A core between 2380 and 2381.4 m. The fragments containing the numbered 1-inch core plugs are indicated. The absolute azimuths of the individual segments and fragments are not known. The top segment containing plugs Nos 1 and 2 appears to have been turned upside-down before the core was archived.

Bulk density

To avoid problems with air bubbles adhering to the relatively small specimens if they were weighted in water, the bulk density was determined by weighing in air only (to an accuracy of ± 0.001 g), then determining the volume by measuring the shape of the specimens (to an accuracy of ± 0.02 cm). The likely accuracy in the finally determined density is about ± 2–3%, depending on the rough-

Sample No.	Depth m	Rock type	Weight g	Density g/cm³	NRM corr mA/m	Suscept-bridge 10⁻³ SI	Q-ratio NRM/(F × Sus)
1V	2380.08	basalt	69.040	2.992			
1H	2380.08	basalt	36.000	2.981		46.26	
1	2380.08	basalt	31.79		17997	41.62	10.868
2	2380.12	basalt	28.66		3258	17.32	4.728
3	2380.17	basalt	30.38		327	3.903	2.105
4	2380.21	basalt	28.78		1247	6.945	4.513
5	2380.28	basalt	29.76		673	4.340	3.897
6	2380.58	basalt	28.22		2319	11.773	4.951
6V	2380.58	basalt	38.240	2.885			
6H	2380.58	basalt	44.907	2.868			
7	2380.62	basalt	31.37		2553	18.850	3.404
8	2380.66	basalt	26.24		1227	11.459	2.691
9	2380.69	basalt	28.84		1391	16.865	2.073
10	2380.75	basalt	29.92		971	33.756	0.723
11	2380.79	basalt	27.31		1539	34.636	1.117
12	2380.91	basalt	29.37		333	32.987	0.254
13	2380.94	basalt	30.07		1782	37.825	1.184
14	2380.97	basalt	27.08		1628	36.450	1.123
15	2381.00	basalt	26.96		984	38.704	0.639
16	2381.05	basalt	30.99		359	43.323	0.208
17	2381.09	basalt	29.11		887	31.722	0.703
18	2381.12	basalt	30.24		322	35.241	0.230
19	2381.22	basalt	29.87		2616	41.288	1.592
20	2381.25	basalt	25.87		2705	36.890	1.843
20V	2381.25	basalt	71.848	2.922			
20H	2381.25	basalt	27.740	2.869		43.15	
a:	Mean			2.92	2256	28.40	2.44
	Standard deviation			0.05	3808	14.00	2.51
	Mean error			0.02	851	2.98	0.56
	N			6	20	22	20

ness of the shape. A total of 34 specimens were determined (Table 2).

Susceptibility

Two types of susceptibility instruments were used. Initial whole core measurements were made by a handheld Czech kappameter KT5 (sensitivity ± 0.00001 SI) before drilling plugs from the core. A Molspin bulk susceptibility bridge (sensitivity ± 0.000001 SI) was then used to measure the susceptibility of the core plugs and to monitor possible chemical changes during thermal demagnetisation experiments. A total of 46 specimens were measured (Table 2).

Remanence

The direction (declination and inclination) and intensity of the natural remanent magnetisation (NRM) was determined using a Molspin spinner magnetometer. The plugs with preferred dimensions of 2.2 cm in length and a diameter of 2.5 cm (plugs from the solid core) were all measured and demagnetised in detail, see below. The NRM of the sidewall cores was also measured but, due to the variable length of the core pieces, only one (SWC57) was investigated in detail (Table 2). The sensitivity of the Molspin spinner is ± 0.02 mA/m and the direction of the remanence within the plug was determined to within ± 1°. The declination and inclination is given with respect to the local specimen coordinates, assuming the axis of the plug (= specimen) to be approximately horizontal (i.e. orthogonal to the Lopra-1/1A drill hole). As the azimuth of the vertical core is not known, the true magnetic decli-

Table 2b. Lopra-1/1A: magnetic susceptibility, NRM, Q-ratio, density
Sidewall cores (d = 23.3 mm)

Sample No.	Depth m	Rock type	Weight g	Density g/cm³	NRM mA/m	Suscept-bridge 10⁻³ SI	High > 2 × 10⁻³ 10⁻³ SI	Low < 2 × 10⁻³ 10⁻³ SI	Q-ratio NRM/(F × Sus)
59	2219.00	basalt	18.966	2.361	4406	1.43		1.43	77.4
57	2275.00	basalt	22.222	2.857	2180	87.96	87.96		0.623
46	2441.00	basalt	23.857	2.865	9027	46.65	46.65		4.864
44	2456.00	basalt, ves.	33.653	2.488					
43	2475.00	basalt, ves.	18.421	1.981	0.7	0.55		0.55	0.032
40	2558.00	basalt, ves.	17.973	2.708	1.3	0.71		0.71	0.046
39	2559.80	basalt, ves.	22.920	2.711	1.5	0.64		0.64	0.060
38	2560.20	tuff, lapilli	21.428	2.336	0.4	0.61		0.61	0.015
37	2562.00	tuff	29.838	2.345					
36	2570.00	basalt	9.353	2.379	38.5	0.69		0.69	1.406
34	2610.00	basalt, alt.	18.741	3.167	3412	69.17	69.17		1.240
33	2630.00	tuff, lapilli	13.720	2.404	587	1.60		1.60	9.224
31	2690.00	tuf, lapilli	8.082	2.276	365	1.83		1.83	5.022
30	2780.00	basalt	21.170	2.929	7171	76.89	76.89		2.344
26	2970.00	tuf, lapilli	18.744	2.553	304	3.77	3.77		2.030
25	3030.00	basalt	18.515	2.808	1146	26.67	26.67		1.080
19	3233.50	tuff	9.915	2.572		0.72		0.72	
16	3328.00	basalt	18.471	2.875	106	1.13		1.13	2.346
15	3382.00	basalt	14.066	2.919		63.36	63.36		
13	3438.00	tuf, lapilli	19.505	2.549	1.8	0.62		0.62	0.074
12	3464.50	tuf, lapilli	17.287	2.605	12.0	0.64		0.64	0.470
9	3500.50	basalt	16.494	3.001	0.8	0.83		0.83	0.024
6	3512.50	tuff	23.953	2.648	38.2	0.39		0.39	2.433
5	3514.50	tuf, lapilli	13.372	2.511		0.58		0.58	
5	3514.50	tuf, lapilli	15.648	2.607		0.58		0.58	
4	3531.00	basalt	27.341	2.940		0.88		0.88	
	b:	Mean		2.63	1516	16.20	34.47	0.85	1.85
		Standard deviation		0.27	2585	28.80	21.00	0.39	2.34
		Mean error		0.05	593	5.88	3.90	0.10	0.55
		N		26	19	24	29	17	18*)
	a & b:	Mean		2.68	1895	22.1	34.5		2.16
		Standard deviation		0.27	3276	23.6	21.4		2.45
		Mean error		0.05	525	3.5	4.0		0.40
		N		32	39	46	29		38*)

*) Excluding sample No. 59

nation is not known. A further description of the palaeomagnetic experimental standard laboratory procedures may be found in e.g. Butler (1992).

AF-demagnetisation

After measuring the initial NRM intensity, 16 of the 20 plugs were AF-demagnetised in stepwise increasing alternating magnetic fields (Table 3) using a Molspin AF-demagnetiser. Minimum and maximum AF-fields were 2.5 mT (25 Oe) and 100 mT (1000 Oe), respectively.

Thermal demagnetisation

Stepwise thermal demagnetisation was made in a Schonstedt furnace on four plugs from the solid core. An initially moderate AF-demagnetisation of up to between 7.5 and 15 mT removed recently induced viscous magnetisation components, most likely acquired during the drilling operations (details in Table 2), after which the thermal demagnetisation was applied.

Table 3. Lopra-1/1A: palaeomagnetic results

Sample No.	Depth m	Polarity	Weight g	Treatment AF mT/°C	NRM intensity A/m	Characteristic direction Decl (rel.)	Incl	MAD Degrees	Demag interval AF thermal mT	Tmax °C
1	2380.08	(?N)	31.79	0–40	18.00	335	81	6	15–50	
2	2380.12	(?N)	28.66	0–40	3.26	350	71	2	5–40	
3	2380.17	R	30.38	0–70	0.33	358	−70	2	15–70	
4	2380.21	R	28.78	0–7.5	1.25	175	−70	4		
5	2380.28	R	29.76	0–95	0.67	345	−69	1	10–95	
6	2380.58	R	28.22	0–40	2.32	51	−67	1	5–40	
7	2380.62	R	31.37	0–70	2.55	62	−71	1	5–70	
8	2380.66	R	26.24	0–40	1.23	75	−69	1	5–40	
9	2380.69	R	28.84	0–50	1.39	80	−71	1	5–50	T630
10	2380.75	R	29.92	0–630	0.97	289	−75	3		
11	2380.79	R	27.21	0–50	1.54	106	−72	2	5–50	T600
12	2380.91	R	29.37	0–600	0.33	7	−72	2		
13	2380.94	R	30.07	0–50	1.78	169	−70	2	5–50	
14	2380.97	R	27.08	0–40	1.63	204	−71	1	5–40	
15	2381.00	R	26.96	0–50	0.98	195	−70	2	5–50	T630
16	2381.05	R	30.99	0–630	0.36	334	−74	2		
17	2381.09	R	29.11	0–70	0.89	163	−73	3	10–70	T630
18	2381.12	R	30.24	0–630	0.32	334	−74	2		
19	2381.22	R	29.87	0–50	2.62	32	−73	3	5–50	
20	2381.25	R	25.87	0–50	2.71	24	−71	4	0–50	

Results

Bulk density

The bulk density of sidewall cores and plugs are listed in Table 2. The mean bulk density of the solid basaltic core was well-determined as 2.92 ± 0.02 (standard deviation (σ) = 0.05) g/cm³, although the determination was based on only six specimens. The bulk density of the SWC-cores was lower and much more scattered, 2.63 ± 0.05 (σ = 0.27) g/cm³. The low bulk density and high scatter is likely to be due to differences in porosity and the abundance of secondary minerals.

Susceptibility

The magnetic susceptibility is also listed in Table 2 and shown in Fig. 7. In contrast to for instance the bulk density, the magnetic susceptibility and remanence intensity may vary considerably, and they are known typically to be logarithmically normal distributed (e.g. Tarling 1983; Abrahamsen & Nordgerd 1994). This is also the case here, as two log-normal distributions are found. The core susceptibility varies between 4 and 46 × 10⁻³ SI, and the susceptibility of the SWC-cores varies even more, between 0.4 and 88 × 10⁻³ SI. The data thus fall into two populations,

Rev.:	Mean inclination	−71.22	
	Standard deviation	1.99	
	N	18	
Norm:	Mean inclination	76.00	
	Standard deviation	5	
	N	2	
All Rev:	Mean inclination	−71.70	
	Standard deviation	2.85	α_{95} = 1.95
	N	20	k = 709

the limit between the two groups being about 2 × 10⁻³ SI. The higher group yields an average susceptibility of 34 ± 4 (σ = 21) × 10⁻³ SI and the lower group an average susceptibility of 0.85 ± 0.1 (σ = 0.39) × 10⁻³ SI.

The more strongly magnetised group is represented mostly by unaltered basalts, whereas the less strongly magnetised group is more typical of most sediments including tuffaceous sediments, as well as vitrinites and deuterically altered or weathered basalts. In the present case the difference between high and low values in the basalts is likely to be caused by alterations of the primary Ti-magnetites, since Ti-magnetite is the main carrier of the remanence (see below).

NRM intensity

The intensity of the NRM (natural remanent magnetisation) is listed in Table 2 and shown in Fig. 7. Values of the
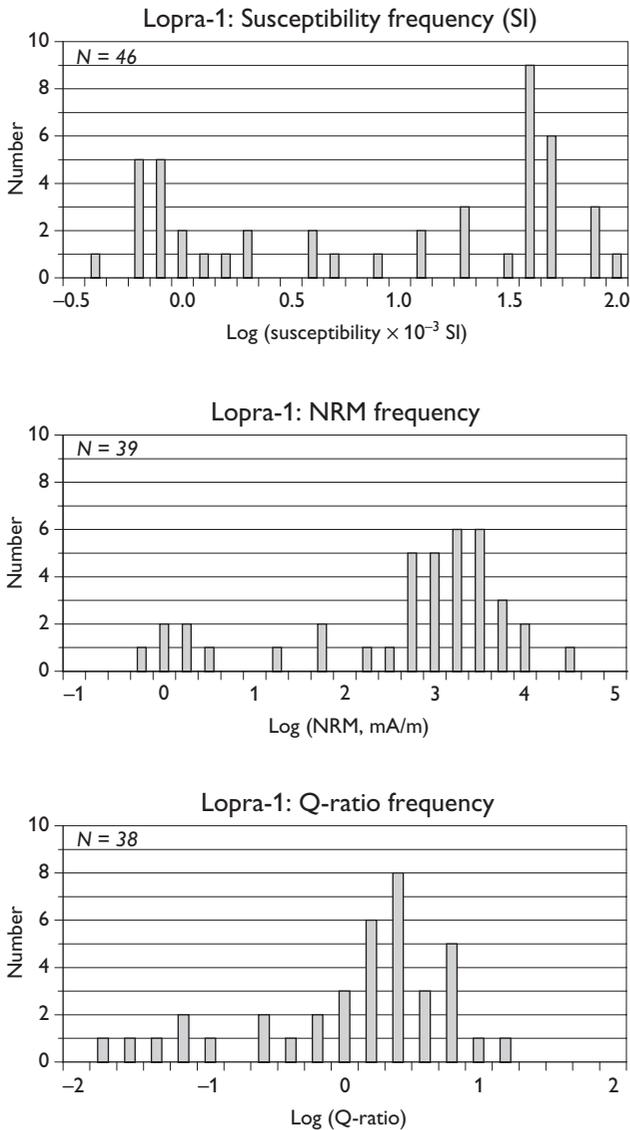
Fig. 7. Histograms of susceptibility, NRM intensity and Q-ratio. All appear bimodal on a logarithmic scale.

order of 1 A/m are typical for the unaltered basalts, whereas tuffs and altered basalts may have lower values. The mean NRM intensity value of the core plugs is 2.26 ± 0.85 ($\sigma = 3.8$) A/m, and the mean NRM intensity value of the SWC-cores is 1.52 ± 0.59 ($\sigma = 2.6$) A/m. Due to the high scatter, the mean NRM intensities of the two groups are not significantly different. The combined populations plotted logarithmically (Fig. 9) again show two overlapping log-normal distributions, as do the susceptibilities (Fig. 8).

Q-ratio

The Q-ratio (Koenigsberger ratio) illustrated in Fig. 10 is the ratio between the remanent (J_{NRM}) and the induced ($J_i = k \cdot F$) magnetisation, $Q = J_{NRM}/J_i = J_{NRM}/(k \cdot F)$, F being the intensity of the local geomagnetic field, $F \approx 0.05$ mT. For basaltic rocks, values between 0.2 and 10 are characteristic. Generally, the higher value the more fresh and unaltered the samples are. Mean values for Q is found to be 2.4 ± 0.6 ($\sigma = 2.5$) for the core plugs, and 1.8 ± 0.6 ($\sigma = 2.3$) for the SWC-cores, respectively (omitting a single extraordinary high value of Q = 77 for SWC59). The Q-ratios of the two groups are not significantly different, but again the combined population has a tendency to two log-normal distributions.

Magnetic carriers

Two examples of isothermal remanent magnetisation (IRM) acquisition of plugs Nos 3 and 7 are shown in Fig. 11. Both specimens show magnetic saturation around 0.1 T, which indicate that the dominant carrier of the remanence is magnetite or Ti-magnetite, although maghemite may also be present. The thermal demagnetisations (see below) show blocking temperatures between 560 and

Fig. 8. Magnetic susceptibility of side-wall cores (**diamonds**) and core plugs (**dotted line** shows extent), logarithmic scale.
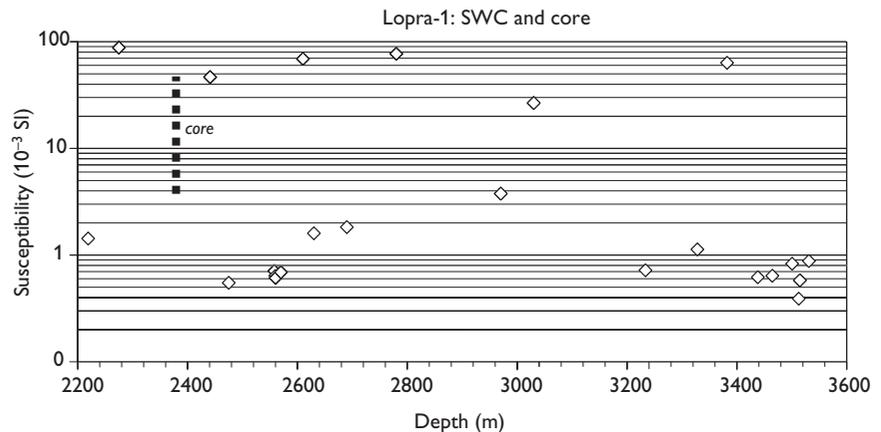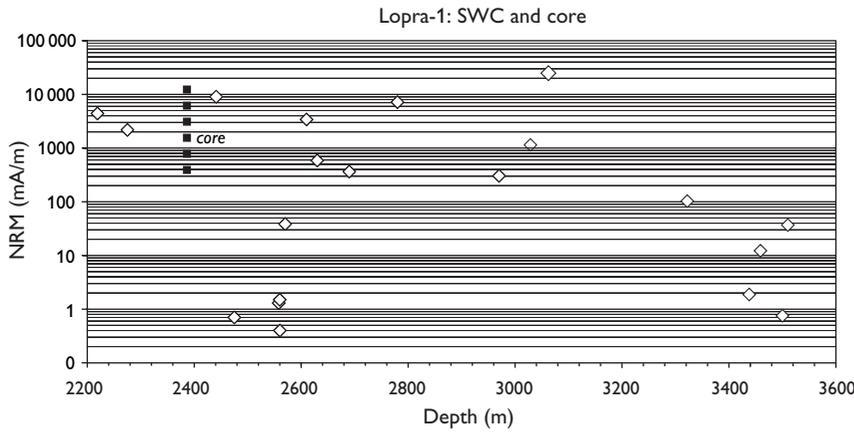
Fig. 9. NRM intensity of side-wall cores (**diamonds**) and core plugs (**dotted line** shows extent), logarithmic scale.

580°C, indicating that the Ti-content is low, pure magnetite having a Curie temperature of 580°C (e.g. Dunlop & Özdemir 1997).

AF and thermal demagnetisations

The NRM values of the 20 cores and the SWC-cores are listed in Tables 2a & b, and examples of characteristic results of the AF and thermal demagnetisation experiments performed are illustrated in Fig. 12. Thermal demagnetisations were made on cores Nos 10, 12, 16 and 18 and AF-demagnetisations were made on the remaining 16 cores. Values chosen for the AF-field were in most cases 0, 5, 7.5, 10, 15, 20, 25, 30, 40, 50 and 60 mT. Some plugs were further demagnetised to 70, 80, 90 and 100 mT. Four thermally demagnetised plugs were first AF-demagnetised in 2.5, 5, 7.5, and 10 mT fields, to remove the recent drillstem-induced viscous remanence (see below), and then stepwise demagnetised at temperatures of 150, 250, 350, 450, 550, 570, 600 and 630°C.

The examples in Fig. 12 show stereographic plots (left) of the direction of the unit vector of the remanent magnetisation (solid signature: positive inclination, open signature: negative inclination). All except the first example show characteristic stable negative inclinations. To the right, the corresponding intensity decay of the sample is shown (normalised to the initial value $J_0 = J_{NRM}$), the horizontal scale indicating the peak value of the applied alternating field in Oe ($\times$ 0.1 mT), or the temperature in C.

Inclination

Prior to the demagnetisation experiments, about half of the plugs showed a low coercivity NRM with positive inclination (down-dip), which is most likely due to a drillstem induced viscous remanent magnetisation (VRM). The VRM was easily removed by AF-demagnetisation in low fields, typically between 2.5 and 5 mT.

Based upon the AF- and Thermal demagnetisation data, the characteristic (stable) remanent magnetisations for each plug were determined by the principal component analysis (PCA) method of Kirschvink (1980), as implemented in the IAPD-programme by Torsvik (1986). In all cases a stable characteristic, supposed primary, mag-
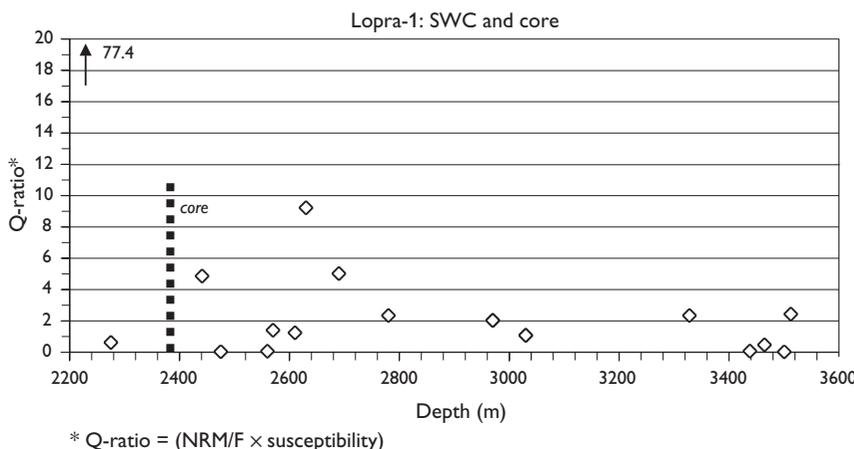

Fig. 10. Q-ratio of side-wall cores (**diamonds**) and core plugs (**dotted line** shows extent).
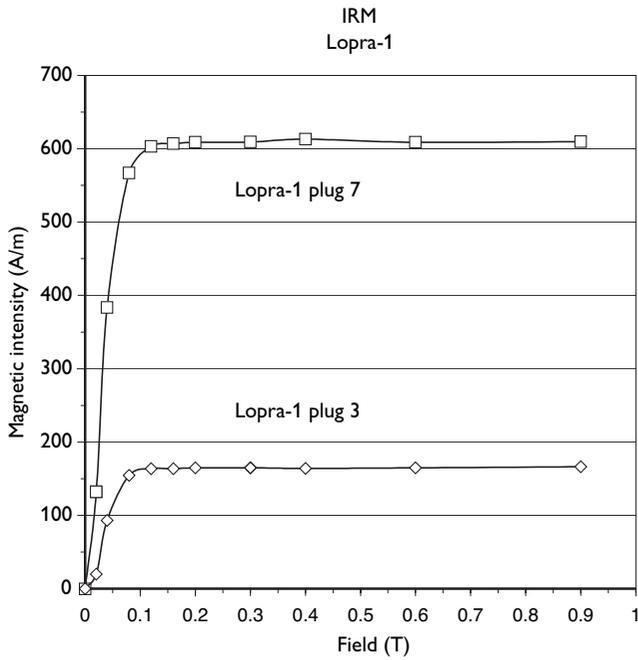
* Q-ratio = (NRM/F × susceptibility)

Fig. 11. Isothermal remanent magnetisation (IRM) of plugs Nos 3 and 7. Both specimens show magnetic saturation around 0.1 T, indicating that the dominating carrier of the remanent magnetisation is magnetite.

netisation was isolated, as listed in Table 3, and illustrated in the stereogram of Fig. 13. (Bearing in mind that the azimuth of the core is not known, only the inclinations are diagnostic, declinations being relative.)

After cleaning, plugs Nos 3 to 20 show typical steep negative inclinations. Only plugs 1 and 2 show normal inclinations and they are both from the topmost 10 cm long core-piece. The broken core is from the massive centre of a very thick flow and it is most unlikely that the inclination should shift the sign within the core. It is therefore suggested that the top part of the core has been turned upside-down, most likely during the initial handling at the core site.

As the azimuth of the core is not known, ordinary Fisher statistics are not applicable, but the modified inclination statistics of Kono (1980) may be used. Supposing all 20 plugs to have negative inclinations, the mean value is found to be:

$$I_m = -71.7°, \text{ with } \alpha_{95} = 1.95° \text{ (k = 709, N = 20)}$$

provided that the drilling was truly vertical. This would give an unusually accurate determination of the palaeofield inclination. However, as the geomagnetic secular variation cannot be recorded from one flow only, this low value
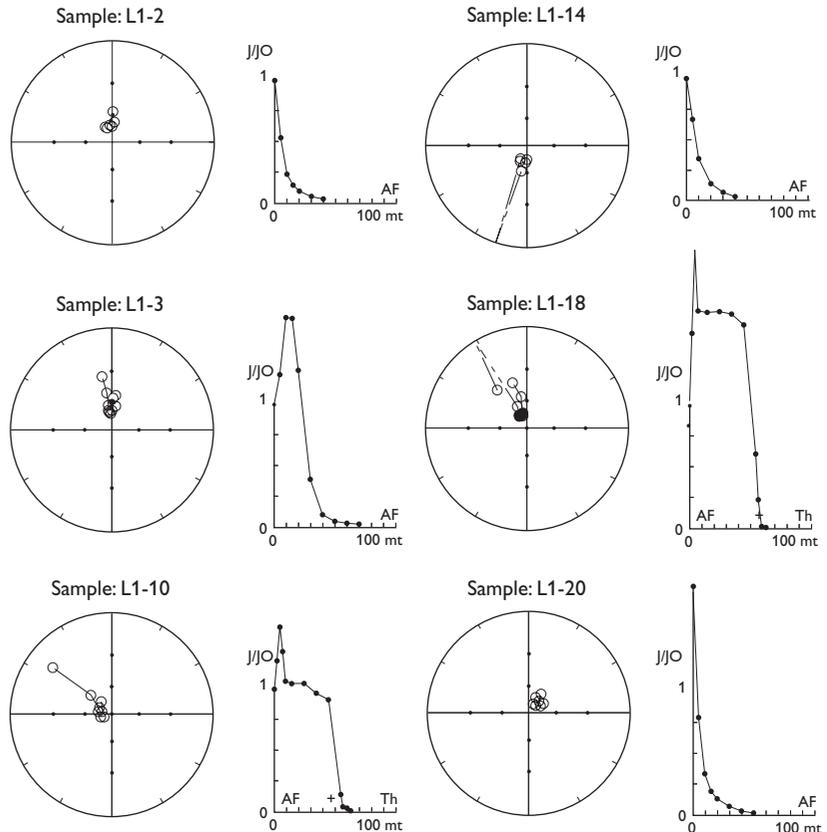

Fig. 12. Examples of typical behaviour of samples during AF and thermal demagnetisation. Plugs Nos 2 (AF 0–40 mT), 3 (AF 0–70 mT) and 10 (AF 0–10 mT, combined with heating up to 630°C). Plugs Nos 14 (AF 0–40 mT), 18 (AF 0–10 mT, combined with heating up to 630°C) and 20 (AF 0–50 mT).
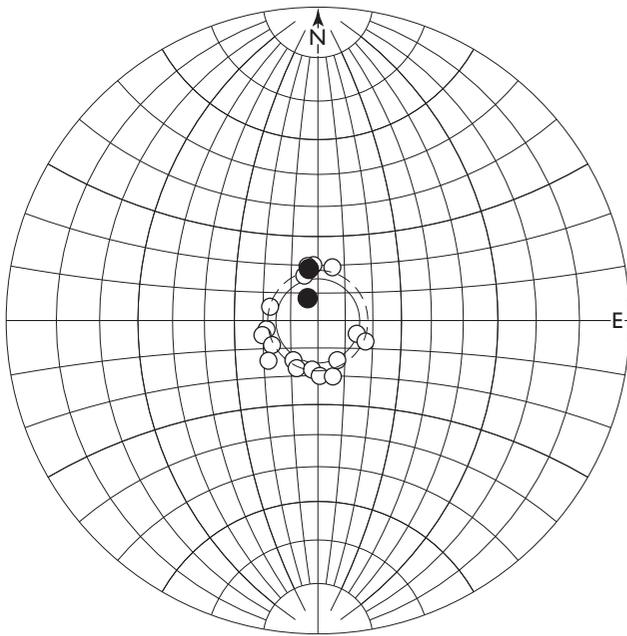
Fig. 13. Characteristic AF-cleaned inclinations of the 20 plugs from the Lopra-1/1A core at depths between 2380 and 2381.4 m. Plugs other than Nos 1 and 2 (with positive inclinations, **solid symbols**) have negative inclinations (**open symbols**). The declinations are arbitrary since the azimuth of the core is not known. **Full circle** shows the expected axially centred dipole inclination of 74.7° at the Lopra-1/1A drill site, i.e. 3° steeper than the numerical average of −71.7° (**dashed circle**) of the 20 core plugs (See Table 1).

of α_{95} does not give a realistic estimate for the accuracy of the average palaeomagnetic field inclination. Furthermore an angle of *c.* 2.5° from the vertical towards the southeast has been obtained from the GHMT-log of the hole at 2380 m (R. Waagstein, personal communication 2005).

The inclination I_0 of the geocentral axial dipole (GAD) field at the site of Lopra/Suðuroy with a latitude of 61.4°N is equivalent to a value of $I_0 = 74.8°$, which is about 3° steeper than that found for the core. Based on McElhinny & McFadden's (1997) analysis of a large number of volcanic data from the last 5 Ma in the global palaeomagntic database, the expected geomagnetic dispersion of a VGP (virtual geomagnetic pole) at the latitude of the Faroe Islands may further be estimated to be *c.* 20°. Earlier palaeomagnetic investigations have typically given systematically lower mean values (see Figs 3, 5) for the palaeomagnetic inclination (Table 1) except the one of −72° for a site near Torshavn (Løvlie & Kvingedal 1975). If we suppose the value from the Lopra-1/1A core of $I_m = −71.7°$ to be the optimum one, this would correspond to an axial dipole palaeolatitude for the Lopra-1/1A site of 56.2°N at the time of extrusion. Most Cenozoic palaeopoles tend to

be 'farsided' (Wilson 1971; Merrill *et al.* 1998), i.e. the palaeofield recorded in the rocks shows a more shallow inclination than does the present-day geomagnetic field at the site and biased shallow inclinations are also the case for most of the Palaeogene volcanic palaeomagnetic data from the North Atlantic region. This phenomenon may be due either to northward plate tectonic movements after the formation of the sample, non-symmetric behaviour of the geomagnetic field at the time of formation or unusual magnetic properties of the rocks investigated – or a combination of all three effects. A systematic error due to the latter cause (magnetic refraction) is not likely, as this requires rather strong values of the magnetic properties of the lavas (e.g. Knudsen *et al.* 2003). If the palaeogeomagnetic field was exactly a geocentral axial dipole field (the GAD-hypothesis), this would imply that the lithospheric plate carrying the Faroe Islands had moved about 5.2° northward during the last *c.* 60 Ma with an average northward component of velocity of *c.* 1 cm/year. An octopole contribution of the order of 10% (i.e. $g_3°/g_1° = 0.1$) to the central axial dipole field would alone suffice to explain the observed farsidedness of the Faroe Islands. An octopole contribution of this order of magnitude has been considered for Precambrian and Palaeozoic as well as Mesozoic times (e.g. Kent & Smethurst 1998; Torsvik *et al.* 2001; Van der Voo & Torsvik 2001). However, Merrill & McFadden's (2003) analysis of data in the palaeomagnetic global database for the last 5 Ma concluded that a nondipole bias appears less likely for the younger periods.

Therefore, rather than claming that the shallower value of inclination indicates fully either a northward plate movement of 5.2° (the 'traditional' palaeomagnetic interpretation), or is due entirely to a deficiency in the GAD-hypothesis, a more cautious interpretation may be a combination of both, implying that the GAD-hypothesis may not be exactly valid for the early Palaeogene, i.e. that the palaeomagnetic field was not a perfect central and axial dipole field at that time. To solve this palaeomagnetic important question fully, more global data from the period is needed.

Reversal stratigraphy and age at Lopra-1/1A

As mentioned above, the reversal stratigraphy of the 6½ km thick Faroe basalt formations was re-interpreted by Waagstein (1988), based upon published data then available (Abrahamsen 1967; Tarling & Gale 1968; Schönharting & Abrahamsen 1984; Abrahamsen *et al.* 1984), including the former palaeomagnetic results from Lopra-

1, the cored information of which at that time reached a depth of 2178 m. All five cores from Lopra-1, at depths of 338, 862, 1219, 1923 and 2178 m, showed negative inclinations, i.e. reversed polarity, although no stable values were obtained after demagnetising the cores from 338 and 1219 m (Schönharting & Abrahamsen 1984). The bottom of Lopra-1 was interpreted by Waagstein (1988) to match marine anomaly 26r, thus superseding two earlier alternative correlations discussed by Abrahamsen *et al.* (1984), in which this level was suggested to match either marine anomaly 25r or 24r.

The present data from Lopra-1/1A, with negative inclinations in the single core from 2380 m depth, indicates a reversed polarity at this level. Provided that there are no reversals in the unsampled interval above, the present data extend the reversed sequence of the lower basalt formation from the core at TD of the original well (2178 m) to the present level of the solid core at 2380 m. The SWC-cores reach the deeper level of 3531 m. However, as the up–down orientation of the individual SWC-cores is not known, no inclination information has yet been obtained from below 2381 m.

Combining all polarity evidence available from the Faroe Islands and comparing with the Paleocene time scale by Berggren *et al.* (2000), we conclude that the lower part (below sea level) of the lower basalt formation may be correlated with Chron C26r (Selandian age), while the upper (exposed) part of the lower basalt formation correlates with Chrons C26n, C25r and C25n (Selandian and Thanetian age). The middle and upper basalt formations correlate with Chron C24r (Ypresian age).

Magnetic logging (magnetic susceptibility and field intensity) was also attempted in the Lopra-1/1A well together with other geophysical logs (Boldreel 2006, this volume) but, due to technical problems with the magnetic logging tool, no reliable inclination data were obtained (Abrahamsen & Waagstein 2006, this volume).

Summary and conclusions

A compilation of the palaeomagnetic age, the reversal chronology and evolution of the *c.* 6½ km thick basalt formations of the Faroe Islands is presented, together with new petrophysical results from the Lopra-1/1A well.

1. The polarity record of the Faroe Islands has been correlated in detail with the Global Polarity Time Scale. The lower part (below sea level) of the lower basalt formation correlates with Chron C26r (Selandian age). The upper (exposed) part of the lower basalt for-

mation correlates with Chrons C26n, C25r and C25n (Selandian and Thanetian age). The middle and upper basalt formations correlate with Chron C24r (Ypresian age).

2. The inclinations yield farsided positions for the palaeomagnetic poles, which is characteristic of most Palaeogene volcanics and sediments from the North Atlantic region.

3. The density and the rock magnetic properties of a solid core (1½ m in length) and 26 sidewall cores from the Lopra-1/1A well between –2219 and –3531 m are bimodal and suggest two characteristic groups of volcanic materials, solid unaltered basalts and altered basalts and tuffs.

4. The magnetic properties are typically log-normally distributed and the carriers of remanence appear to be Ti-poor Ti-magnetites with Curie temperatures close to 580°C.

5. The inclination of the 1½ m core at –2380 m is predominantly negative.

6. Magnetic logging of magnetic susceptibility and field intensity was made in Lopra-1/1A down to –3515 m together with other geophysical logging, but yielded inconclusive inclinations.

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