Magnetic logs from the Lopra-1/1A and Vestmanna-1 wells, Faroe Islands

Niels Abrahamsen and Regin Waagstein

Susceptibility measurements from cores (representing basalt, lapilli-tuffs and tuffs) and magnetic logs from the Lopra-1/1A well are presented. The basalts fall into high- and low-susceptibility groups with no overlap. The high-susceptibility basalts (seven cores) have susceptibilities between 4 and 88 $\times10^{-3}$ SI and consist of basalt with < 1% vesicles from thick massive units. The low-susceptibility basalts are intergranular, intersertal or hypocrystalline and contain no or very little (< 1%) visible magnetite, are generally more altered than the high-susceptibility basalts and have susceptibilities in the range from 0.6 to 1.4 × 10^{-3} SI (seven cores). The susceptibility of ten volcaniclastites of lapilli-tuff or tuff varies from 0.4 to 3.8 × 10^{-3} SI. The cores from the Lopra-1/1A well reveal a bimodal distribution of magnetic susceptibility. Low susceptibilities ranging from 0.4 to 4 are characteristic of altered basalts poor in magnetite, lapilli-tuffs and tuffs. Thus single measurements of susceptibility are of little use in discriminating between these three types of rock.

Susceptibility logs from the Lopra-1/1A well show that the variation below 3315 m distinguishes clearly between volcaniclastics (hyaloclastites) with low and fairly constant susceptibility and basalt beds of between 5 and 10 m thickness (with high susceptibility). The volcaniclastics comprise some 60–70% of the sequence between 3315 and 3515 m with the maximum continuous sediment layer being 80 m thick. A 1½ m core of solid basalt at 2381 m and sidewall cores of basalt from the Lopra-1/1A well have a mean susceptibility of 22.1 ± 3.5 × 10^{-3} SI (standard deviation (σ) = 23.6, number of samples (N) = 46), while samples of hyaloclastite (lapilli-tuff and tuff) have a mean susceptibility of 0.85 × 10^{-3} SI (σ = 0.39, N = 17).

The mean values of the rock magnetic parameters for 303 basalt plugs from the Vestmanna-1 well are: Q_{ave} = 13.3 ± 0.6 (σ = 11), S_{ave} = 11.8 ± 0.6 × 10^{-3} SI (σ = 11) and J_{ave} = 4.64 ± 0.25 A/m (σ = 4.4). The reversely polarised, lowermost (hidden) part of the *c.* 4½ km thick lower basalt formation correlates with Chron C26r. The upper (exposed) part of the lower basalt formation correlates with Chrons C26n, C25r and C25n and the more than 2.3 km thick middle and upper basalt formations correlate with Chron C24n.3r.

Keywords: Magnetic logging, rock magnetism, susceptibility, NRM, magnetic reversals, Faroe Islands, Lopra, Vestmanna, North Atlantic

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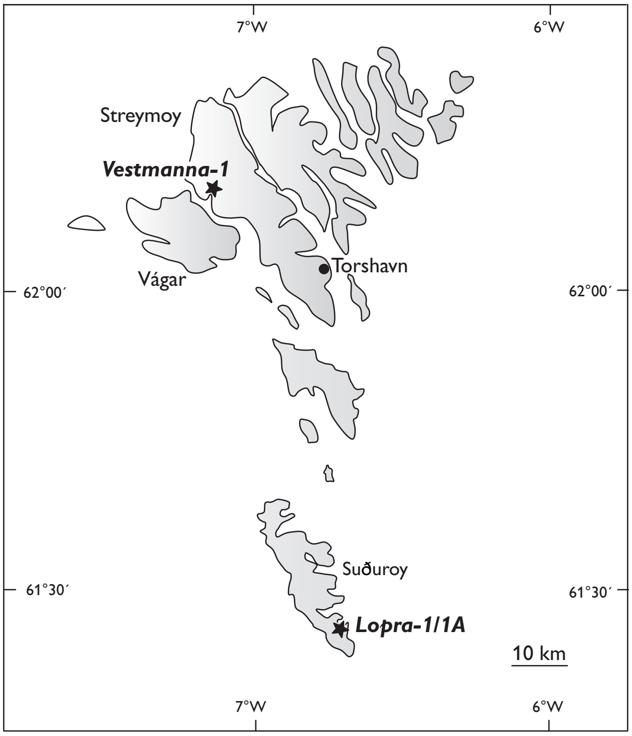

Fig. 1. Index map of the Faroe Islands with the positions of the Lopra-1/1A and Vestmanna-1 wells indicated with **stars**.

Information on rock magnetic properties, susceptibility and natural remanent magnetisation (NRM) may be useful for detecting changes in rock type, structure and magnetic mineral content of rocks penetrated by boreholes. Magnetic polarity is also a tool potentially of use in dating. Although magnetic surveying has a long history in prospecting and mining geophysics (e.g. Parasnis 1979), magnetic logging (using susceptibility) in boreholes was first developed in the 1950s with new electronic types of equipment (e.g. Broding *et al.*1952; Levanto 1958; Barthés *et al.* 1999).

Logging with the purpose of magnetic polarity determinations began even later (e.g. Pozzi *et al.*1988, 1993; Bouisset & Augustin 1993; Ito & Nogi 1995). Magnetic logging instruments were developed for down-hole mapping of the magnetic field as a correlation- and dating-tool using magnetostratigraphy. Reversals recorded in a borehole may be used for dating if they can be correlated with the geomagnetic polarity time scale (GPTS). The GPTS was firmly established in the early 1960s by radiometric dating of reversals recorded in young volcanic sequences on land (e.g. Cox *et al.*1963) and by relating the polarity reversals from land to marine magnetic anomalies observed over the oceans (Vine & Matthews 1963). This revived the idea of continental drift and supported the new paradigm of plate tectonics. In the following years the polarity scale was extended linearly backwards through Mesozoic time by correlation of long sequences of marine anomalies with the shorter land-based records (Heirtzler *et al.*1968).

The present paper deals with the results of magnetic logging of the Lopra-1/1A well, situated on Suðuroy, the southernmost of the Faroe Islands (Fig. 1). The magnetic logs were acquired by Schlumberger Ltd. in 1997 as part of an extensive logging programme run in connection with deepening of the well. The logs cover a major part of the Faroes lower basalt formation (Waagstein 1988, Waagstein *et al.* 2001). The log-like results of rock magnetic properties obtained from the continuously cored Vestmanna-1 well through a younger part of the Faroes basalt succession (Abrahamsen *et al.* 1984) are summarised for comparison.

Magnetic logging in Lopra-1/1A

A geological high-resolution magnetometer tool (GHMT) was run by Slumberger Ltd. from 3101 to 2168 m in the deepened part of the Lopra-1 well and subsequently from 3519 to 2998 m in the sidetracked Lopra-1A.The kick-off depth of the sidetrack is 3091 m, which means that the two log sections overlap from 3091 to 2998 m. The two logs have been combined into a single log using an arbitrary splicing point at 3000 m.

The GHMT tool records two types of magnetic measurements; the magnetic susceptibility (RMAGS) and the total magnetic induction (MAGB). Examples of the records obtained are shown for the whole sequence in Figs 2–5. A shorter section is shown in more detail in Fig. 6.

The main objective of the deepening of the Lopra-1 well was to drill through the basalt formations to the expected underlying sediments. The dipole–dipole sensor susceptibility measurement tool (SUMT) was therefore set to the low-resolution mode. The nuclear magnetic resonance magnetometer (NRMT) was designed to measure the total magnetic induction in the borehole within a working range of only 5000 nT around a preset expected value (Schlumberger Ltd., personal communication 1997) which was unfortunately much less than the actual ranges of 30 000 and 70 000 nT present within the hole. Another purpose of the short working ranges applied was to protect the tool electronics, which were designed for weakly magnetic sediments rather than strongly magnetic volcanic rocks.

The settings for the magnetic tools were not optimal for the basalt-dominated section actually drilled, as the

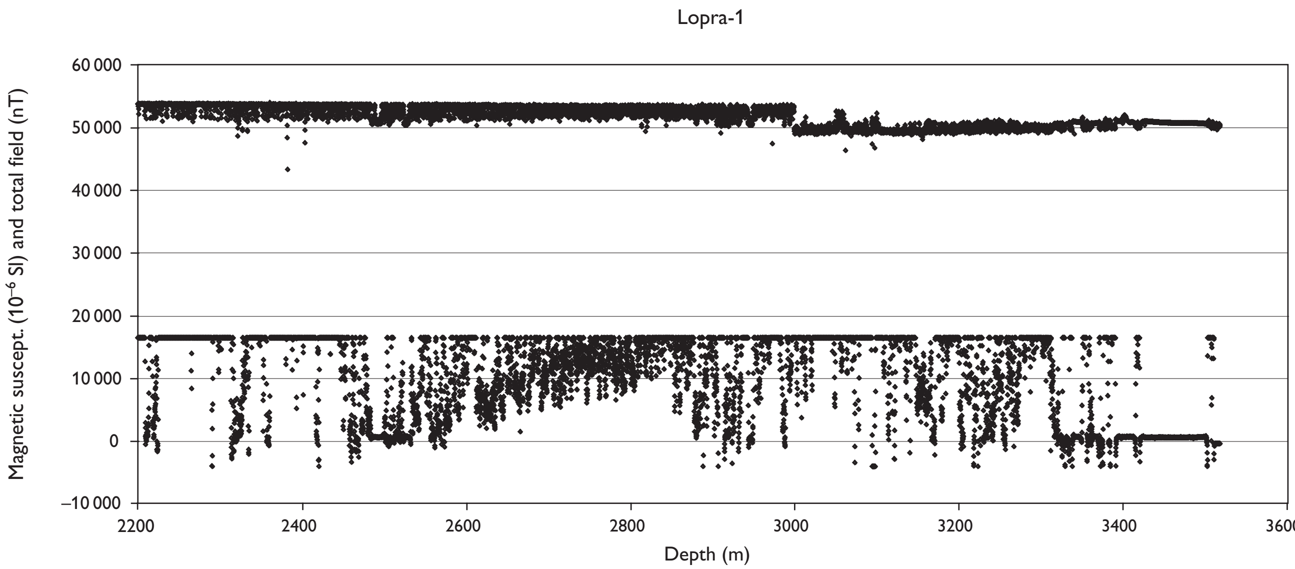

Fig. 2. Magnetic susceptibility (× 10^{-6} SI) and the magnetic induction total field (nT) logged in the Lopra-1/1A well between depths of 2200 and 3520 m.

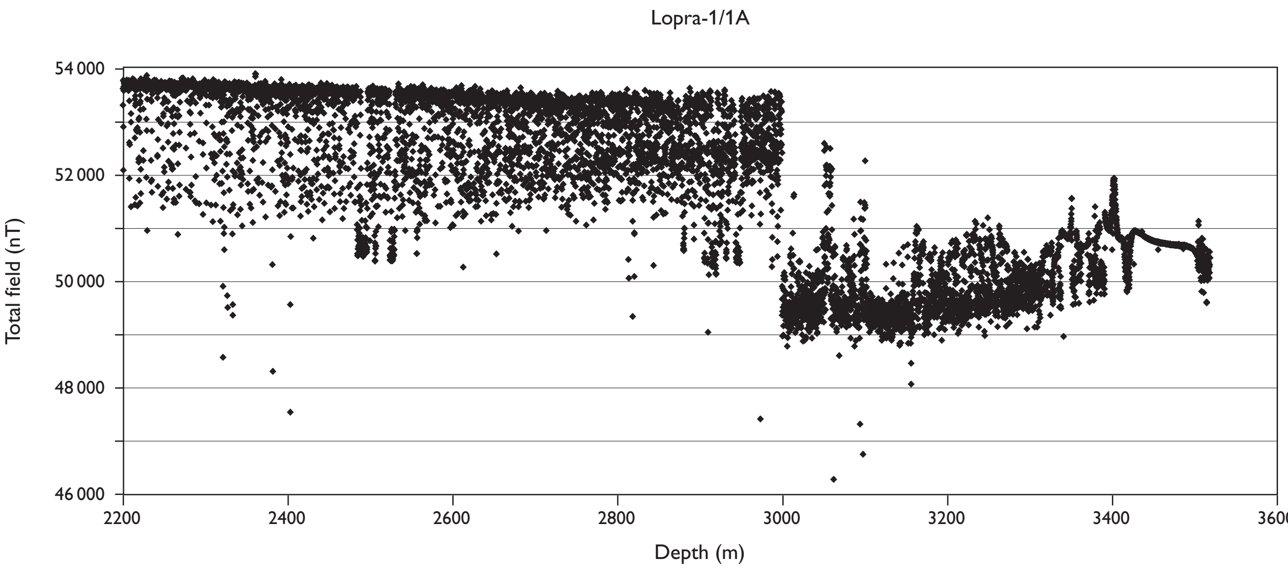

Fig. 3. Total magnetic field (magnetic induction, nT) in the Lopra-1/1A well. A jump in the general level of about 4000 nT is seen at 3000 m.

susceptibility was mostly outside the working range of the susceptometer. Because of this, the polarity of the remanent magnetisation and hence the interplay between the susceptibility and the induced magnetisation could not be deduced from these results and a reversal chronology could not be obtained from the *in situ* logged data.

Information about the remanent polarity of the rocks drilled by the Lopra-1/1A and Vestmanna-1 wells (Fig. 1) has, however, been obtained from drilled cores. These cores were investigated by traditional palaeomagnetic laboratory techniques and the results have been reported and presented elsewhere (Schönharting & Abrahamsen 1984; Abrahamsen *et al* 1984; Waagstein 1988; Abrahamsen 2006, this volume). Abrahamsen (2006, this volume) correlated the lowermost (unexposed) part of the *c.* 4½ km thick lower basalt formation with Chron 26r (Selandian) and the upper (exposed) part of the lower basalt formation with Chrons C26n, C25r and C25n (Selandian and Thanetian). The more than 2.3 km thick middle and upper basalt formations are correlated with Chron C24n.3r (Ypresian).

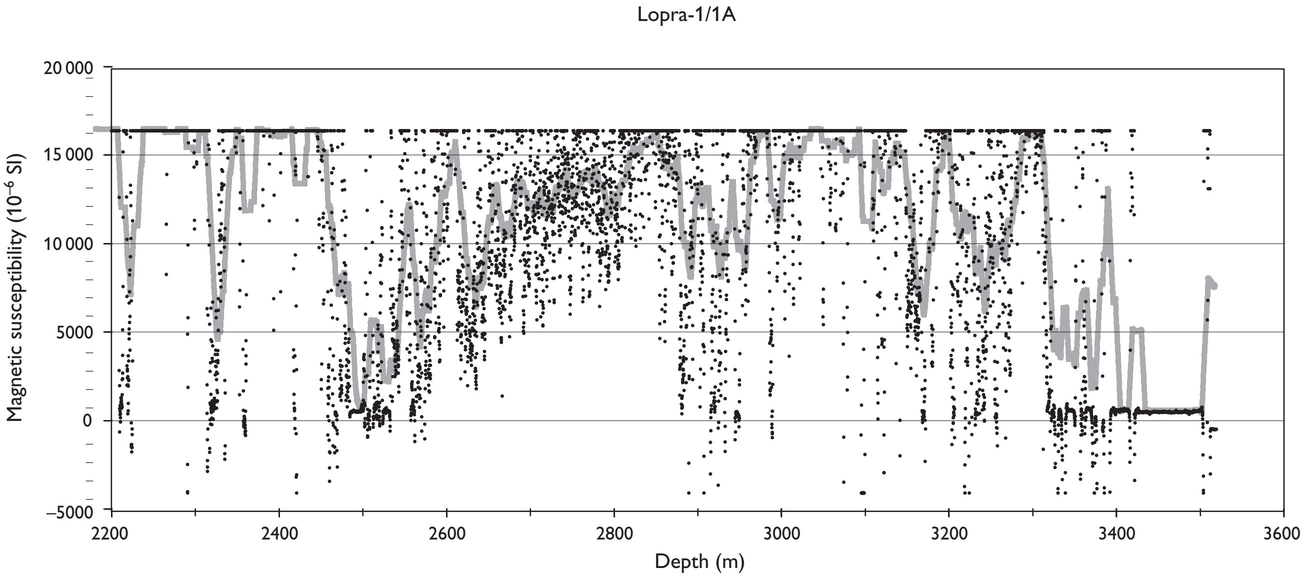

Fig. 4. Magnetic susceptibility log from the Lopra-1/1A well. The **solid pale curve** is a 100 point moving average (likely to be biased due to saturation of the instrument).

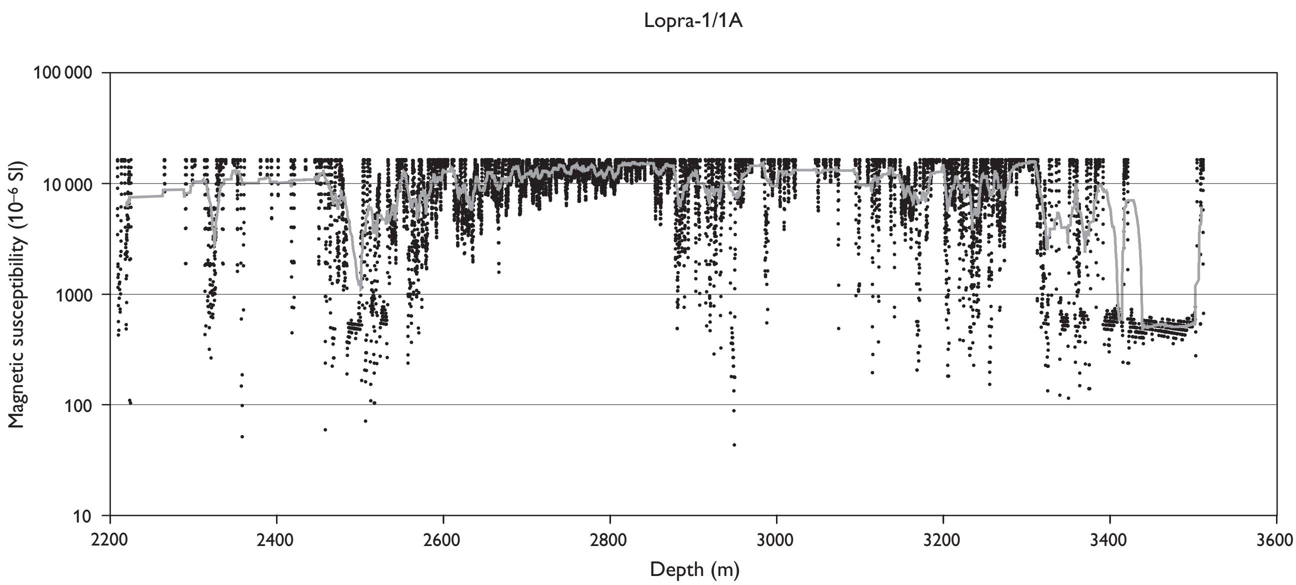

Fig. 5. Magnetic susceptibility from the Lopra-1/1A well (logarithmic scale). The **solid pale curve** is a 100 point moving average (likely to be strongly biased due to saturation of the instrument).

Susceptibility of cores from the Lopra-1/1A borehole

The magnetic susceptibility of 1 conventional and 24 rotary sidewall cores drilled at regular intervals within the deepened part of the Lopra-1/1A well between 2275 and 3514.5 m has been measured in the laboratory. The cores include 14 basalts, 8 lapilli-tuffs and 2 tuffs (Table 1). A single plug from each sidewall core and 22 plugs from the 1.5 m long conventional core were measured.

The basalts fall into high- and low-susceptibility groups with no overlap. The high-susceptibility basalts are represented by seven cores with susceptibilities between 4 and 88 × 10^{-3} SI. They consist of basalt with < 1% vesicles from thick massive units. The texture of the groundmass varies from intergranular with a few per cent matrix (mesostasis) to hyaline with almost 50% matrix. The matrix consists of cryptocrystalline quench crystals and secondary minerals replacing glass or filling interstitial voids. The groundmass of the intergranular basalts has an estimated

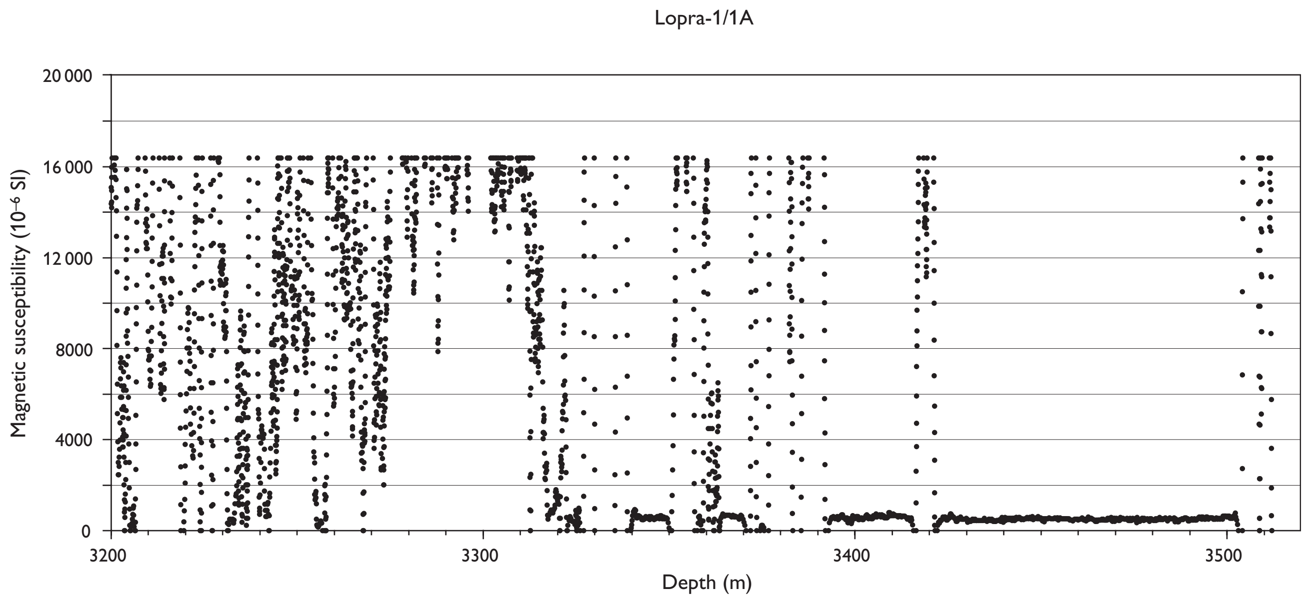

Fig. 6. Magnetic susceptibility details between 3200 and 3510 m of the Lopra-1/1A well.

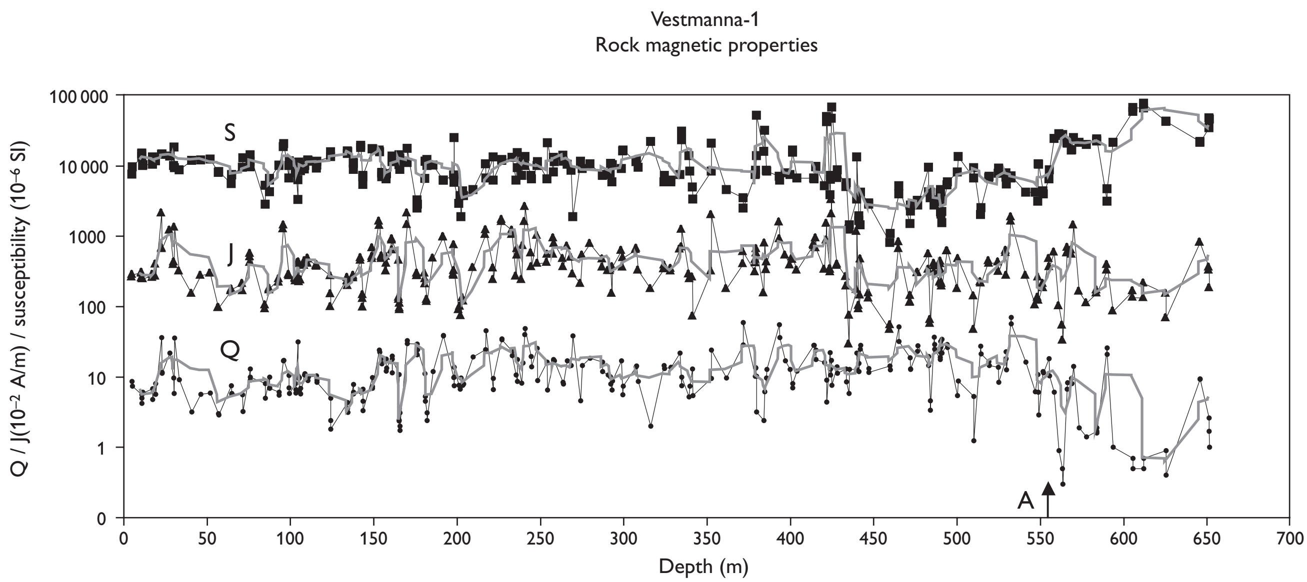

Fig. 7. Rock magnetic properties (susceptibility, NRM and Q-ratio) of the Vestmanna-1 well (modified from Abrahamsen *et al.* 1984). **Pale curves** are 5 point moving averages (logarithmic scale). The A horizon, between the lower and upper basalt formations, is marked by an **arrow** and the letter **A** at 557 m.

content of 3–10 vol.% titanomagnetite with a maximum size between < 0.03 and 0.2 mm. The titanomagnetite in the less crystalline basalts is too fine-grained to be estimated or cannot be seen, although the presence of an opaque or dark turbid matrix suggests that it is likely to be present.

Susceptibilities from seven cores from the low-susceptibility basalts vary from 0.6 to 1.4 × 10^{-3} SI. The low-susceptibility basalts are intergranular, intersertal or hypocrystalline and contain no or very little (< 1%) visible magnetite. They are generally more altered than the high-susceptibility basalts and lose on average about 3.7 wt% volatiles on ignition compared to 1.8 wt% for the latter group (Table 1). The volatiles are dominantly crystal-bound water in secondary minerals including clay, zeolites, pumpellyite and phrenite. Three of the basalts are highly vesicular with 20–25% vesicles filled with secondary minerals.

The susceptibility of the ten volcaniclastites of lapilli-tuff or tuff varies from 0.4 to 3.8 × 10^{-3} SI with an average of 1.1 × 10^{-3} SI. The susceptibilities of the four deepest

Table 1. Petrography and magnetic susceptibility of core samples from Lopra-1/1A

Sample ID	Rock type	Depth	Max. clast size (mm)	Volatiles wt%	Groundmass texture	Magnetite vol.%	Magnetite max. size (mm)	Vesicles vol.%	Core suscept. x 10^{-3} SI	Mean log suscept. x 10^{-3} SI	Min. log suscept. x 10^{-3} SI	Max. log suscept. x 10^{-3} SI
L1-swc57	High-suscept. basalt	2275		1.26	intergranular	7%	≤ 0.1	< 1	88	> 16.4	> 16.4	> 16.4
L1-core 1	High-suscept. basalt	2380–2381.5		1.72	intergranular	3%	≤ 0.2		4–46	> 15.7	12.1	> 16.4
L1-swc46	High-suscept. basalt	2441		2.31	intergranular	sparse	≤ 0.06	0.5	47	> 16.4	> 16.4	> 16.4
L1-swc34	High-suscept. basalt	2610		1.89	cryptocrystalline	abundant		0	69	> 15.7	13.9	> 16.4
L1-swc30	High-suscept. basalt	2780		1.3	hyaline			0	77	> 13.5	10.5	> 16.4
L1-swc25	High-suscept. basalt	3030		2.33	intergr.-intersertal	no		0	27	> 16.4	> 16.4	> 16.4
L1A-swc15	High-suscept. basalt	3382		1.51	intergranular	10%	≤ 0.03	0	63	> 14.3	7.2	> 16.4
L1-swc59	Low-suscept. basalt	2219		6.84	intergranular			0	1.4	1.4	0.4	2.9
L1-swc43	Low-suscept. basalt	2475		4.94	intergr.-intersertal	no		20	0.6	5.5	1.7	13.5
L1-swc40	Low-suscept. basalt	2558		3.16	hypocrystalline			25	0.7	1.1	0.4	2.1
L1-swc39	Low-suscept. basalt	2559.8		2.89	intersertal	< 1%	≤ 0.1	20	0.6	1.1	0.9	1.2
L1A-swc16	Low-suscept. basalt	3328		2.22	intergranular	no		0	1.1	> 16.4		> 16.4
L1A-swc9	Low-suscept. basalt	3500.5		2.62	intergranular	no		0	0.8	0.6	0.5	0.6
L1A-swc4	Low-suscept. basalt	3531		3.13	intergranular			0	0.9			
L1-swc38	Lapilli-tuff	2560.2	10	5.37	hyaline	no		5	0.6	1.0	0.8	1.2
L1-swc36	Lapilli-tuff	2570	10	4.05	hypocrystalline	no		0	0.7	2.4	0.2	10.0
L1-swc33	Lapilli-tuff	2630	> 15	4.35	hyaline			2	1.6	3.9	3.1	4.2
L1-swc31	Lapilli-tuff	2690	14	5.28	hyaline			< 1	1.8	> 16.3	16.1	> 16.4
L1-swc26	Lapilli-tuff	2970	> 23	5.63	hyaline			2	3.8	> 14.8	12.4	> 16.4
L1A-swc13	Lapilli-tuff	3438	12	4.02	hypocrystalline	sparse	≤ 0.08	< 1	0.6	0.4	0.4	0.5
L1A-swc12	Lapilli-tuff	3464.5	25	3.84	hypocrystalline	no		2	0.6	0.5	0.4	0.5
L1A-swc5	Lapilli-tuff	3514.5	30	8.43	hypocrystalline	no		1	0.6			
L1A-swc19	Tuff	3233.5	0.5	6.62	hyaline			+	0.7	1.5	0.4	5.5
L1A-swc6	Tuff	3512.5	2	4.16	hyaline			2	0.4			

suscept.: susceptibility; intergr.: intergranular.
Petrographic parameters are based on visual estimates of cores and thin-sections.
Volatiles are determined from loss on ignition corrected for oxidation of iron.
Core susceptibility is measured on 8–32 mm long sections of sidewall core with a diameter of 23.2 mm and on several plugs from conventional core 1.
Mean, minimum and maximum log susceptibilities are based on 1 m intervals of the GHMT log centred at the core.
The mean is computed assuming a log-normal distribution of magnetic susceptibilities.
The sign '>' indicates that some susceptibility measurements exceed the saturation level of the tool (16.4 x 10^{-3} SI).
The differences between core and log values probably partly reflect the uncertainty in depths of sidewall-cores (0.5 m) and magnetic logs (0–2 m).

volcaniclastites from between 3438 and 3514.50 m average only 0.6×10^{-3} SI.

The study of cores from the Lopra-1/1A well thus reveals a bimodal distribution of magnetic susceptibility. High-susceptibility rocks range between 4 and 88×10^{-3} SI with the great majority falling above 15×10^{-3} SI. These rocks are all relatively fresh basalts from thick massive units cooled slowly enough to crystallise titanomagnetite (visible or not). The five cores from the original Lopra-1 well all consist of intergranular basalts from the massive centre of thick flows (Hald & Waagstein 1984) with susceptibilities between 16 and 39×10^{-3} SI (Schönharting & Abrahamsen 1984) and thus belong to the group of high-susceptibility basalts.

Low susceptibilities from the Lopra-1/1A borehole, ranging from 0.4 to 4×10^{-3} SI, are characteristic of both altered basalts poor in magnetite ($0.6–1.4 \times 10^{-3}$ SI), lapilli-tuffs ($0.6–3.8 \times 10^{-3}$ SI) and tuffs ($0.4–0.7 \times 10^{-3}$ SI). This means that single measurements of susceptibility are of little use in discriminating between these three types of rock.

The Lopra-1/1A magnetic log

Because the recorder was run in its low-resolution mode, the susceptibilities of most of the rocks through which it passed were mostly outside its recording range. Nevertheless, some general lithological features may be deduced (Schlumberger Ltd., personal communication 1997). The upper recording limit of 16.4×10^{-3} SI is close to the typical lower limit of relatively fresh, massive basalt. This means that major intervals of saturation are a good indicator of massive basalt units.

This makes it possible to divide the logged interval into two parts, below and above 3315 m (cf. Figs 4–6).

Below 3315 m

The lower part displays a highly bimodal pattern with two distinct susceptibility levels. About 85% of the logged section below 3315 m shows average susceptibilities around 0.7×10^{-3} SI that we interpret as hyaloclastites. Basalt layers with a thickness from 2 to 6 m are clearly identifiable within the hyaloclastites showing sharp contacts and much higher susceptibility values (to above the recorded saturation limit of 16.4×10^{-3} SI). Low-susceptibility basalt has been cored nearby (Table 1) so the high-susceptibility intervals give only a minimum estimate of the thickness of basalt present.

For comparison, a 1½ m solid basalt core from 2381 m and 24 sidewall basalt cores (Abrahamsen 2006, this volume) had a mean susceptibility of 22.1×10^{-3} SI ± 3.5 (one standard deviation (σ) = 23.6, number of samples (N) = 46), whereas samples of hyaloclastite (tuffs and lapilli-tuff) had a mean value of 0.85×10^{-3} SI (σ = 0.39, N = 17). These results thus compare quite well with the average of the susceptibility log data.

The total magnetic field (magnetic induction) shows a jump of about 4000 nT between the two partly overlapping log runs (log sections spliced at 3000 m; Figs 2–3), which must be an artifact. The magnetometer record of the total field below 3315 m (Fig. 3) shows the typical effect of a highly magnetised layer within a weakly magnetised formation. The induction recorded through the volcaniclastics below and above the basalt is strongly affected by the distance to the basalt. Several occurrences of such basaltic layers give rise to mixed effects through the volcaniclastics.

Above 3315 m

The total-field magnetometer was saturated above 53 500 nT during most of the first logged section between 3101 and 2168 m (Figs 2–3). This value is stronger than the local Earth's magnetic field of around 50 000 nT and could indicate a large local magnetic source of unknown origin, but is more likely a tool or calibration error. In contrast, despite the very variable character of the lower section, this is not the case for the uppermost part of the lower section (below 3315 m, Fig. 3). In both cases the magnetometer was preset for maximum sensitivity of values centred at the expected value of the local Earth's magnetic field strength of 50 000 nT.

Above 3315 m, *c.* 70% of the susceptibility data (Figs 2, 4–6) are greater than 16.4×10^{-3} SI (the saturation level of the instrument). Thick intervals above saturation level are dominant above 2550 m and reflect subaerial basalt flows. Between about 2550 and 3315 m, the susceptibility log is characterised by large short-scale variations. Strong variability is especially observed in the interval from 2613 to 2816 m (Fig. 4). The high-frequency pattern originates from a succession of hyaloclastites and minor basalt beds. The hyaloclastites consist of lapilli-tuffs, tuff-breccias, breccias and subordinate tuffs. The variability may be explained by the presence of large clasts of basalts showing high susceptibilities set in a low-susceptibility tuffaceous matrix. Only a few longer intervals of low susceptibility ($< 1 \times 10^{-3}$ SI) can be recognised above 3315 m, the thickest ones being between 2945 and 2950 m, between 2523 and 2533 and between 2484 and 2500 m.

The other rock magnetic properties of the Lopra-1/1A well, including the magnetic polarity and correlation with the GPTS, have been summarised and discussed in details elsewhere (Abrahamsen 2006, this volume).

Rock magnetic properties in the Vestmanna-1 well

The 660 m deep Vestmanna-1 well on Streymoy (Fig. 1) was drilled in 1980 through the lower part of the Faroes middle basalt formation and into the top of the lower basalt formation using wireline coring technique.

No magnetic in-hole logging was made during or after the drilling. However, detailed magnetic laboratory investigations of sub-sampled plugs of the fully recovered core have been published (Abrahamsen *et al.* 1984). An illustration of most of the rock magnetic information obtained (susceptibility S, NRM intensity J, and Q-ratio) is shown in Fig. 7 on logarithmic scales (modified from the original data presented by Abrahamsen *et al.* 1984). The thick pale curves are five point moving averages.

The well reached 101 m into the upper part of the *c.* 4½ km thick lower basalt formation (Waagstein 1988) whose top is indicated in Fig. 7, where a 0.7 m thick basaltic conglomerate of local origin separates the lower and the middle basalt formations (Waagstein & Hald 1984). Rocks penetrated by the overlying part of the well (0–557 m in Fig. 7) all belong to the middle basalt formation. The conglomerate is stratigraphically equivalent to a *c.* 10 m thick sediment sequence in the south and southwestern parts of the Faroe Islands that includes thin beds of coal indicating a long quiescence in the magmatic activity between eruption of the lower and middle basalt formations.

All three rock magnetic parameters vary more than one order of magnitude, which is not uncommon for the magnetic properties of volcanic rocks. The mean values for each of them (N = 303 samples) are $Q_{ave} = 13.3 \pm 0.6$ (σ = 11), $S_{ave} = 11.8 \pm 0.6 \times 10^{-3}$ SI (σ = 11) and $J_{ave} = 4.64 \pm 0.25$ A/m (σ = 4.4). The only readily apparent systematic trend appears to be a decrease in the susceptibility from high values at 610 m to low values at 440 m. At shallower depths, the susceptibility fluctuates around 10^{-2} SI. The trend is mirrored in the Q-ratio below 470 m, but with a slight decrease in Q above this level, whereas no systematic trends appear visible in the NRM intensity.

The magnetic polarity of the Vestmanna-1 well was determined in detail by palaeomagnetic investigations of 303 up-oriented plugs from the fully cored borehole, that indicate a short normal polarity interval between 660 and 640 m only, all the younger samples (N = 275) being reversed (Abrahamsen *et al.* 1984).

Conclusions

Due to instrument problems, the valuable information from the magnetic logs of the Lopra-1/1A well is limited. Based upon the logged susceptibility, the variation below 3315 m is clearly diagnostic between volcaniclastics (with low and fairly constant susceptibility) and basalt flows of between 5 and 10 m in thickness (with high susceptibility). Between 3315 and 3515 m the volcaniclastics comprise some 60–70% of the sequence, the maximum continuous layer being 80 m thick.

A 1½ m long core of solid basalt from 2381 m and sidewall cores of basalt from the Lopra-1/1A well have a mean susceptibility of 22.1×10^{-3} SI ± 3.5 (σ = 23.6, N = 46), while samples of volcaniclastics (lapilli-tuff and tuff) have a mean value of 0.85×10^{-3} SI (σ = 0.39, N = 17).

The mean values of rock magnetic parameters for 303 basalt plugs from the Vestmanna-1 well are: $Q_{ave} = 13.3 \pm 0.6$ (σ = 11), $S_{ave} = 11.8 \pm 0.6 \times 10^{-3}$ SI (σ = 11) and $J_{ave} = 4.64 \pm 0.25$ A/m (σ = 4.4). The reversely polarised, lowermost (hidden) part of the *c.* 4½ km thick lower basalt formation correlates with Chron C26r. The upper (exposed) part of the lower basalt formation correlates with Chrons C26n, C25r and C25n and the more than 2.3 km thick middle and upper basalt formations correlate with Chron C24n.3r.

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Manuscript received 22 December 2000; revision accepted 13 September 2005.