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LOG Id: LOG_0016
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J. Geophys. 47, 43–56, 1980

Journal of Geophysics

Magnetic Anomalies (ΔZ) in NE-Iceland and Their Interpretation Based on Rock-Magnetic Investigations

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Abstract. A magnetic survey (ΔZ) was carried out on long profiles with 50 m spacing in northern and eastern Iceland combined with sampling for rock-magnetic investigations in 1967, 1970, and 1973 by the Institut für Allgemeine und Angewandte Geophysik, Universität München. Some of the profiles cross the neovolcanic zone from the western to the eastern Tertiary flood-basalts. Local and regional geomagnetic anomalies were separated by two-dimensional wavelength filtering and upward field continuation. Anomalies with shorter wavelengths (<5 km) could be interpreted by geological features such as dikes, groups of dikes, lavas, lava-piles, decreased magnetization at silicic centres caused by intensive hydrothermal activity, and terrain effects. The regional geomagnetic anomalies can be correlated along the strike of the neovolcanic zone. They strongly resemble rift anomalies and are interpreted with dike-swarms with mainly the same magnetic polarization over long distances. A magnetic survey in the Reydarfjördur-Thingmuli area crossing several well known dike-swarms could not prove this interpretation. The rock-magnetic investigation of more than 1,000 samples from the main geological formations show differences in the magnetic properties of lavas and dikes mainly in a higher magnetization and lower Curie temperature of the dikes. But investigations of later remagnetization at the dike contacts, as well as the primary magnetic properties of fresh dikes and of hydrothermally altered ones did not support the interpretation of the regional anomalies by dike-swarms.

Key words: Northern Iceland – Magnetic survey (ΔZ)-Magnetic properties of lavas and dikes – Interpretation of regional magnetic anomalies.

1. Introduction

Iceland should be considered a major anomaly of the Mid-Atlantic Ridge: the axial rift zone crosses Iceland in a complex way divided by fracture zones (Ward, 1971). Even in northern Iceland where at first sight the main structures appear clear and symmetric, one can demonstrate this complexity (Saemundsson, 1974). There are reasons to suggest that Iceland is not a suitable land laboratory for the study of geodynamic processes of mid-oceanic ridges. However, the most significant structures of Iceland are controlled by spreading and can in some way be described by its terminology. The complex structure of Iceland is also revealed by the geomagnetic anomalies which are a major feature in the concept of sea-floor spreading and plate tectonics. This is well illustrated by

Table 1. Magnetic surveys (ΔZ) 1967, 1970, and 1973 with 50 m point spacing

Year	Name of profile			Length in km		Measured by	Reference
1967	B	67	Haupt	150	245	G. + W. Schönharting	Schönharting (1969)
	E	67	Nord	95			
1970	A	70	Süd	70	325	H. Becker P. Mohr	Becker and Mohr (1971) Angenheister et al. (1972)
	C	70	Hlidarfjall	70			
	D	70	Krafla	100			
	F	70	Reykjaheidi	20			
	G	70	Gardur	65			
1973	L	73	Ljosavatnsskard	18	364	H. Becker C. Schweitzer H. Soffel	Angenheister et al. (1977) Becker (1978)
	P	73	Peistareykjabunga	80			
	F	73	Reykjaheidi	45			
	G	73	Gardur	25			
	S	73	Süd	30			
	Tj	73	Tjörnes-NS	40			
	Jo	73	Jökulsa-NS	42			
	RN	73	Reydarfjördur-N	40			
	RS	73	Reydarfjördur-S	44			

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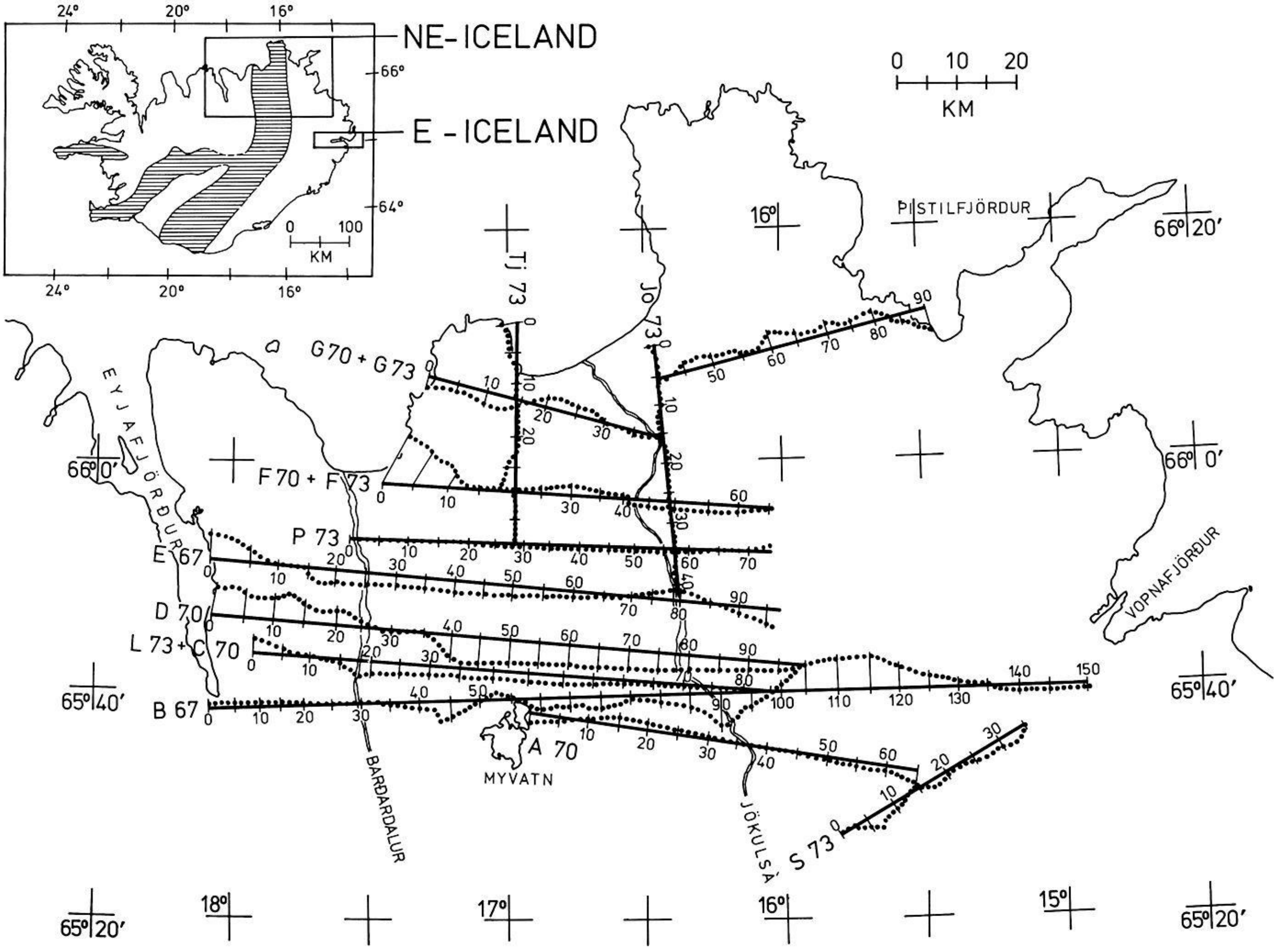

Fig. 1. Location map of the profiles (ΔZ) in NE-Iceland. The measured profiles are *dotted*; the lines with the 10 km marks are the projection for further presentation. The zone of postglacial volcanism is shaded. For location map of E-Iceland (Reydarfjördur) see Fig. 8

the aeromagnetic survey of Serson et al. (1968) with its symmetrical and linear anomalies over Reykjanes Ridge and its completely different characteristics over Iceland. Although the main geomagnetic anomalies follow roughly the branches of the neovolcanic zone, a detailed analysis of the two-dimensionality and spectrum of the anomalies (Rutten 1975) shows that there are no ridge-type anomalies over Iceland. This paper describes a ground magnetic survey in northern and eastern Iceland combined with rock-magnetic investigations in the same areas. This should assist the interpretation, especially when combined with thorough studies of geological and tectonic features (e.g., Walker, 1959; Saemundsson, 1974).

2. Magnetic Survey (ΔZ) in Northern and Eastern Iceland

In 1967, 1970, and 1973 field magnetic measurements were carried out on long profiles (total about 1,000 km) with 50 m point-distance by the Institut für Allgemeine und Angewandte Geophysik, Universität München (Table 1 and Fig. 1; see also Becker, 1978). In northern Iceland these profiles run from Eyjafjördur to Vopnafjördur crossing the neovolcanic zone; both profiles in the Reydarfjördur region in eastern Iceland are situated in Tertiary basalts. For all measurements torsion balances (Askania Gfz) were used; the data for all profiles were processed in the same way using the following programmes on a TR 440 computer:

(a) graduation, levelling, local, and regional correction;
(b) wavelength filtering (two-dimensional) (Fig. 3);
(c) field continuation upward (filtering in the frequency band; two-dimensional) (Fig. 4);
(d) graphical display;
(e) model computation (two-dimensional).

The reference field of ΔZ was calculated by averaging the values of the western and eastern half of the 150 km long profile B 67, which revealed an EW-gradient of 2 nT/km in agreement with the regional field derived from aeromagnetic (Serson et al., 1968; Sigurgeirsson, 1970). The N-S gradient of the aeromagnetic regional field was also considered; again there was good agreement with the gradient calculated by averaging ΔZ even for the distant profiles in eastern Iceland (for details and absolute value of regional field refer to Becker, 1978).

Figure 2 shows the geomagnetic data (ΔZ) from northern Iceland. The main characteristics are a wide range in amplitude (up to 17000 nT) and wavelength which make the aforementioned

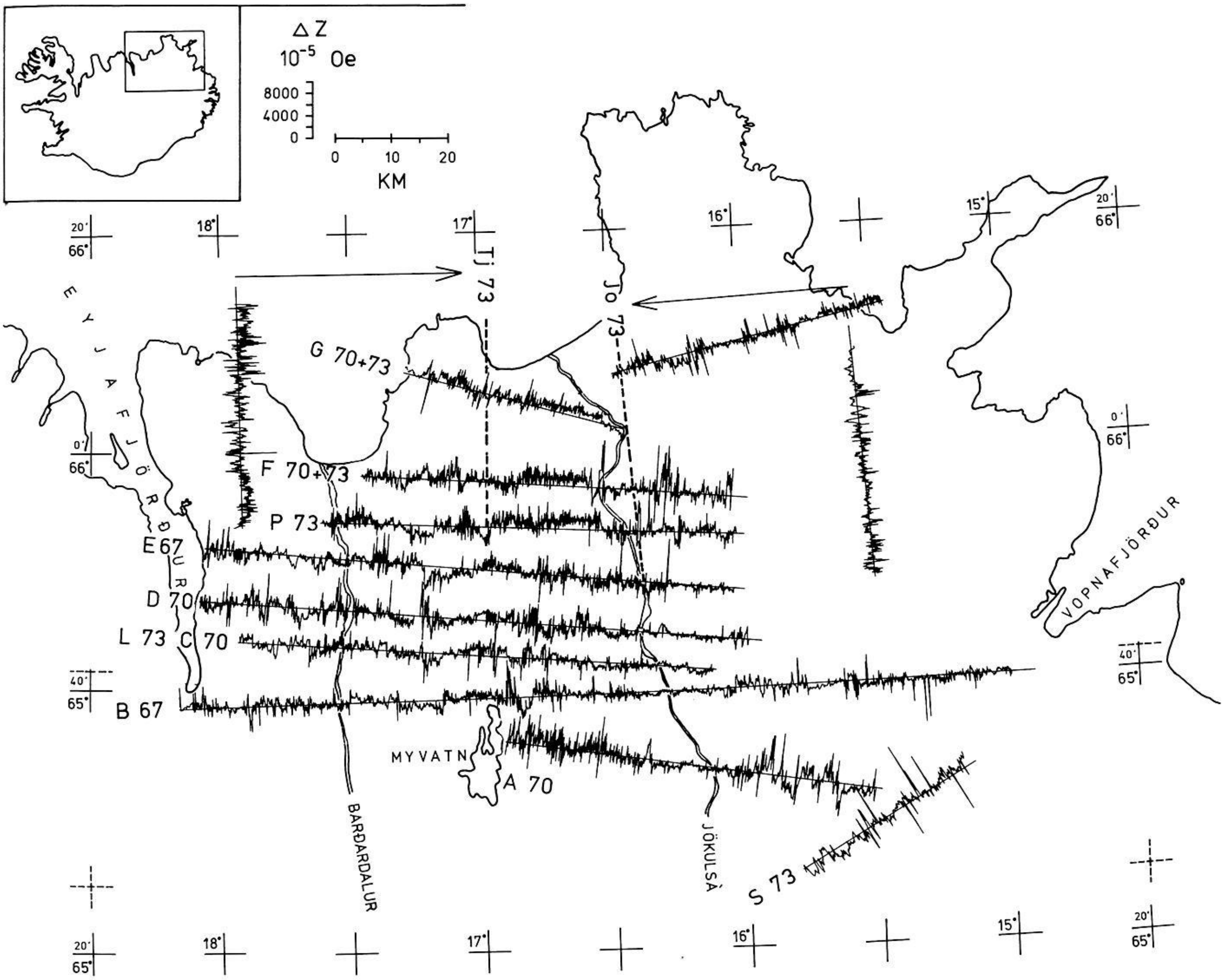

Fig. 2. Profiles of the magnetic survey (*Δ Z*) in NE-Iceland. The NS-scale from 65° 20′ to 65° 45′ has been omitted for clearer reproduction of the data; the two NS profiles are drawn separately

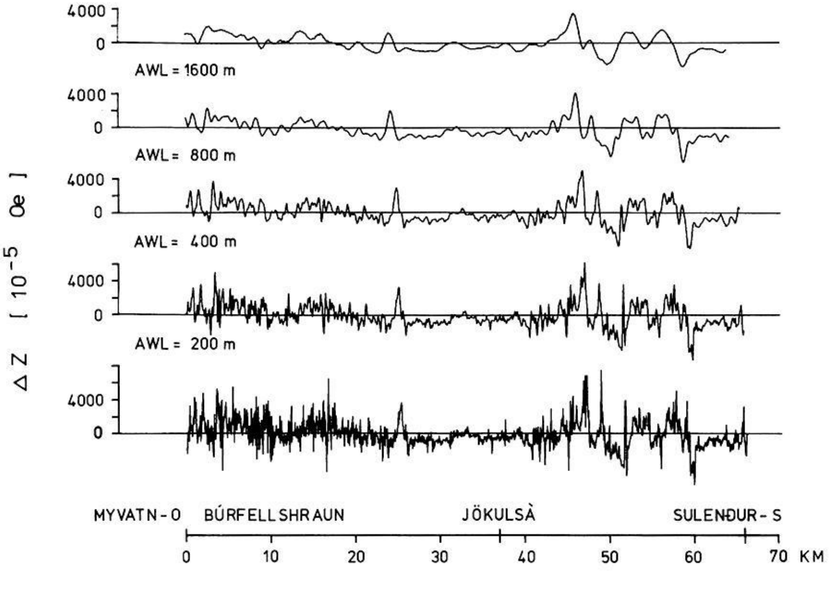

Fig. 3. Effect of wavelength filtering (low-pass). Part of the profile A 70 was filtered with increasing AWL = cut-off wavelength (point distance = 50 m). (For details see Becker, 1978)

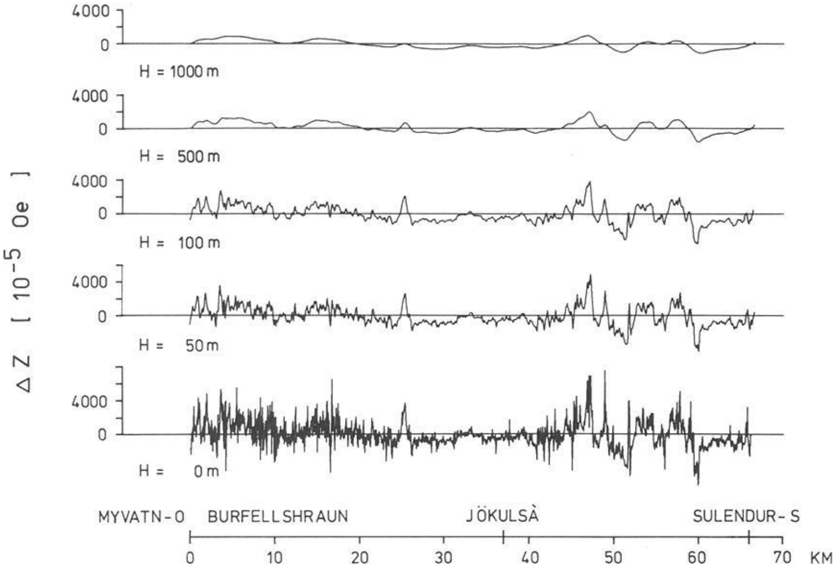

Fig. 4. Effect of the upward field continuation. The same part of profile A 70 was continued to increasing heights. $H=0$ stands for the ground data. Same scale for amplitude

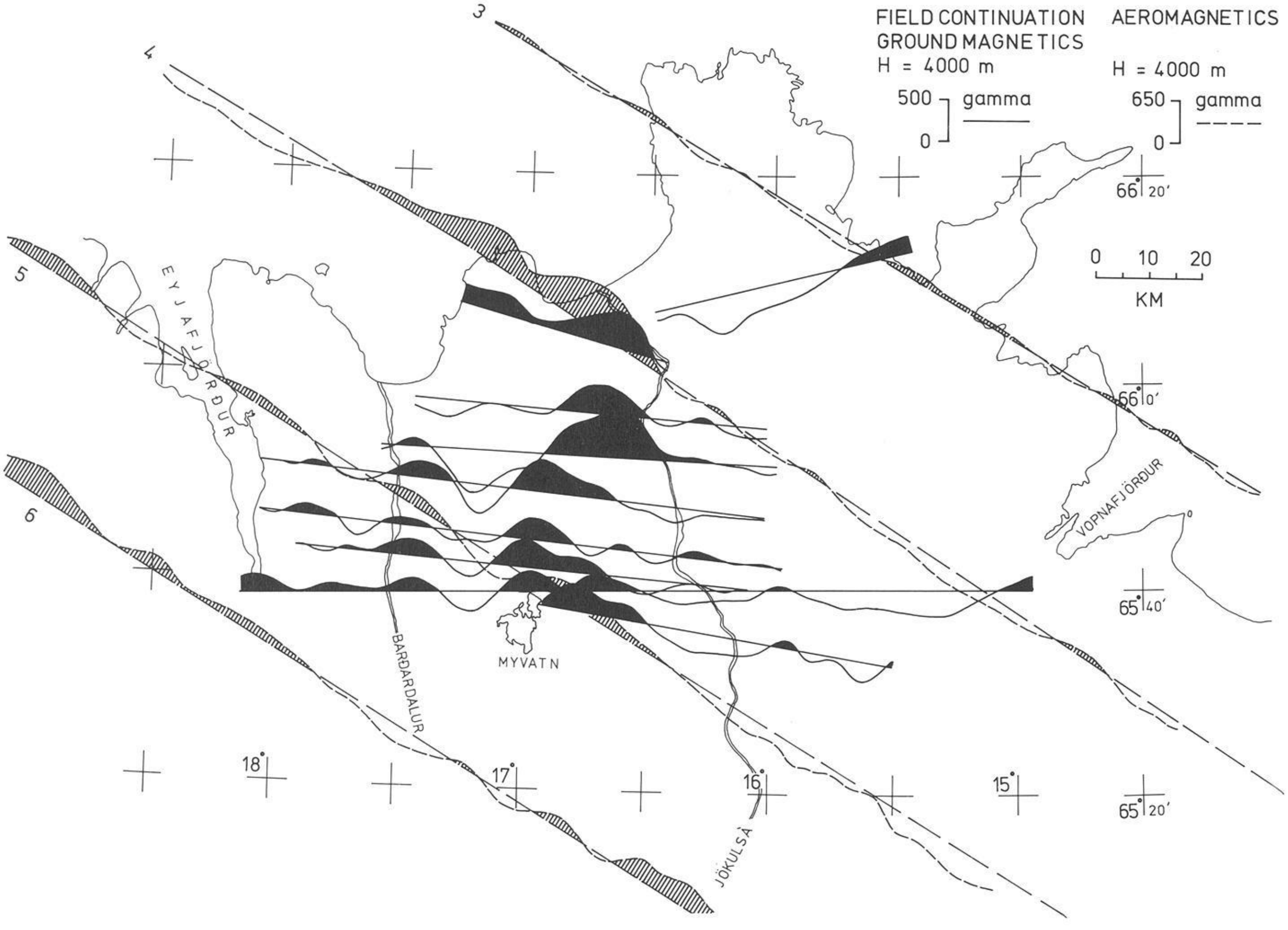

Fig. 5. Upward continuation to 4,000 m altitude and comparison of the anomalies calculated from ground-magnetics (ΔZ) with four aeromagnetic (T) profiles of Serson et al. (1968) (*hatched*)

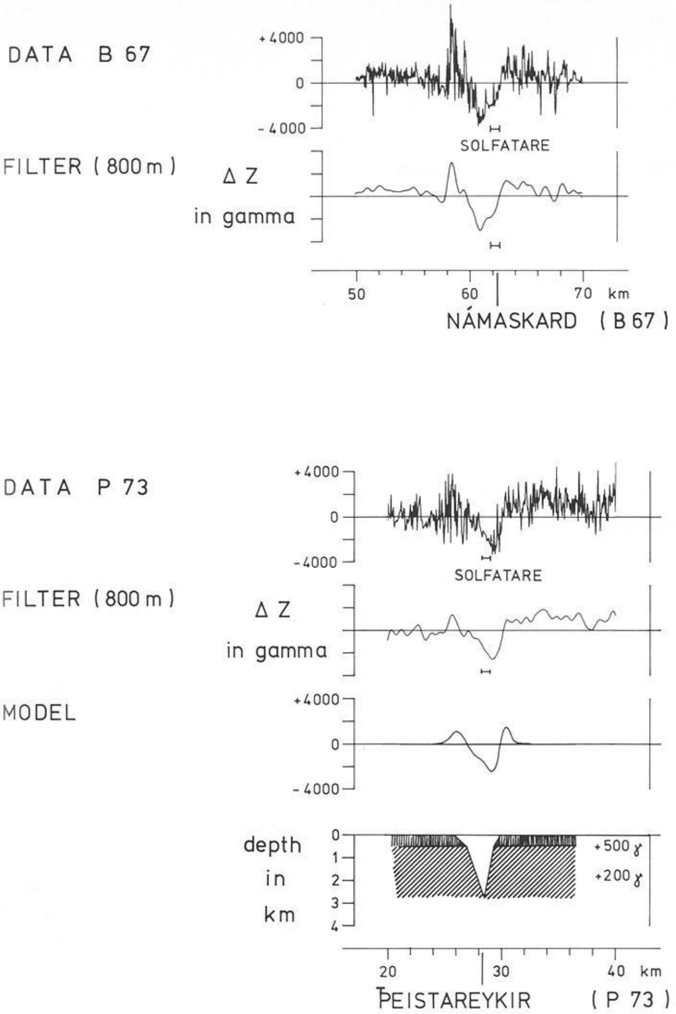

Fig. 6. Negative anomalies (ΔZ) in the central positive anomaly over high-temperature areas Námaskard (Profile B 67) and Peistareykir (Profile P 73) in the central neovolcanic zone. The anomalies were interpreted by decreased magnetization (see model) which may be caused by intensive hydrothermal alteration. (ΔZ in gamma $=10^{-5}$ Oe; magnetization in $\gamma=10^{-5}$ Gauss)

filtering procedures necessary for clear separation of local and regional anomalies. The various filtering effects are shown in Figs. 3 and 4. The upward continuation not only shows the filtering effect, but also renders possible a comparison with the aeromagnetic survey (e.g., for 1,000 m altitude Sigurgeirsson, 1970; 4,000 m altitude Serson et al., 1968; see Fig. 5).

There was no problem regarding the interpretation of anomalies of less than 5 km wavelength by means of observed near-surface geological features. The anomalies are mainly caused by the following (examples are given by Becker, 1978):

horizontal or slightly dipping plates which represent lavas or groups of lavas;
vertical dikes or dike swarms;
large intrusions (gabbro);
regions of low magnetization (silicic centres);
terrain effects.

The regional anomalies are revealed by upward continuation; a comparison with the aeromagnetic profiles which cross NE-Iceland (Serson et al., 1968), shows satisfactory correlation in the central positive anomaly. It is flanked by a negative anomaly (in the west) and by a positive one at the border of the neovolcanic zone (Fig. 5). The correlation ends at the western border of the neovolcanic zone near Bardardalur. East of the central positive anomaly there is a very broad negative anomaly which is interrupted by positive anomalies over postglacial fissure eruptions (dike-swarms of Kraeduborgir, Rauduborgir, Sveinagjá, Sveinar, Fjallagjá and other fissure eruptions east of Jökulsá á Fjöllum). Other interesting features are negative anomalies of more than 1 km width which were measured in the very centre of the zone of postglacial volcanism and of the central positive anomaly.

These negative anomalies were found over the high-temperature areas of Námaskard and Peistareykir (Fig. 6) and can be explained by the destruction of magnetization by hydrothermal alteration.

The regional anomalies of more than 5 km wavelength, cannot be explained by geological surface features apart from the central positive anomaly which correlates roughly with the zone of postglacial volcanism; other regional anomalies show to some extent the opposite polarity to that of the magnetic stratigraphy of lavas in northern Iceland described by Piper (1973).

The sources for these regional anomalies must be large and highly magnetized bodies whose surface should not be below 500 m as indicated by the steep gradients. They are interpreted by dike-swarms and described in terms of sea-floor spreading along the ideas of Bödvarsson and Walker (1964) and Schönharting (1969) (Fig. 7). This dike-swarm model requires at least the following assumptions:

(a) mainly one polarity of magnetization;
(b) higher magnetization of dikes;
(c) high Curie temperatures of dikes for Curie depths of more than 2–4 km;
(d) considerable percentage of dikes or substantial remagnetization at contacts.

In order to test this hypothesis, a magnetic survey crossing several exposed dike-swarms was carried out in eastern Iceland (Figs. 8 and 9); in addition rock-magnetic investigations should prove the difference between the magnetic properties of lavas and dikes and the effect of remagnetization and hydrothermal alteration.

The southern profile (ΔZ) RS 73 in the Reydarfjördur region stretches from the eastern border of the Thingmuli dike-swarm to the southern part of the Bardsnes dike-swarm passing through the Breiddalur dike-swarm following the shore of Reydarfjördur and then crossing the Reydarfjördur central volcano (Figs. 8 and 9).

K-Ar age determinations give roughly 1 Ma for the formation of such a dike-swarm which results in the distribution of polarity of the magnetization of the dikes as given in Table 2. A more recent palaeomagnetic investigation of the Reydarfjördur dike-swarm revealed a majority of reversed dikes, though without distinct polarity grouping (Piper et al., 1977). The magnetic profiles (ΔZ) in this area show a similar pattern with high-amplitude but short wavelength anomalies produced by single dikes or dike-groups (Fig. 9). Only the Breiddalur dike-swarm causes a broad negative anomaly with 3.5 km wavelength, which still is short in comparison with the ridge-type anomalies observed in the neovolcanic zone. The low amplitude of the anomalies over the centre of the Reydarfjördur dike-swarm illustrates the high hydrothermal alteration in the central volcanoes.

Most of the regional anomalies in the Reydarfjördur show the opposite sign of polarity to the lava-piles (Fig. 10); these anom-

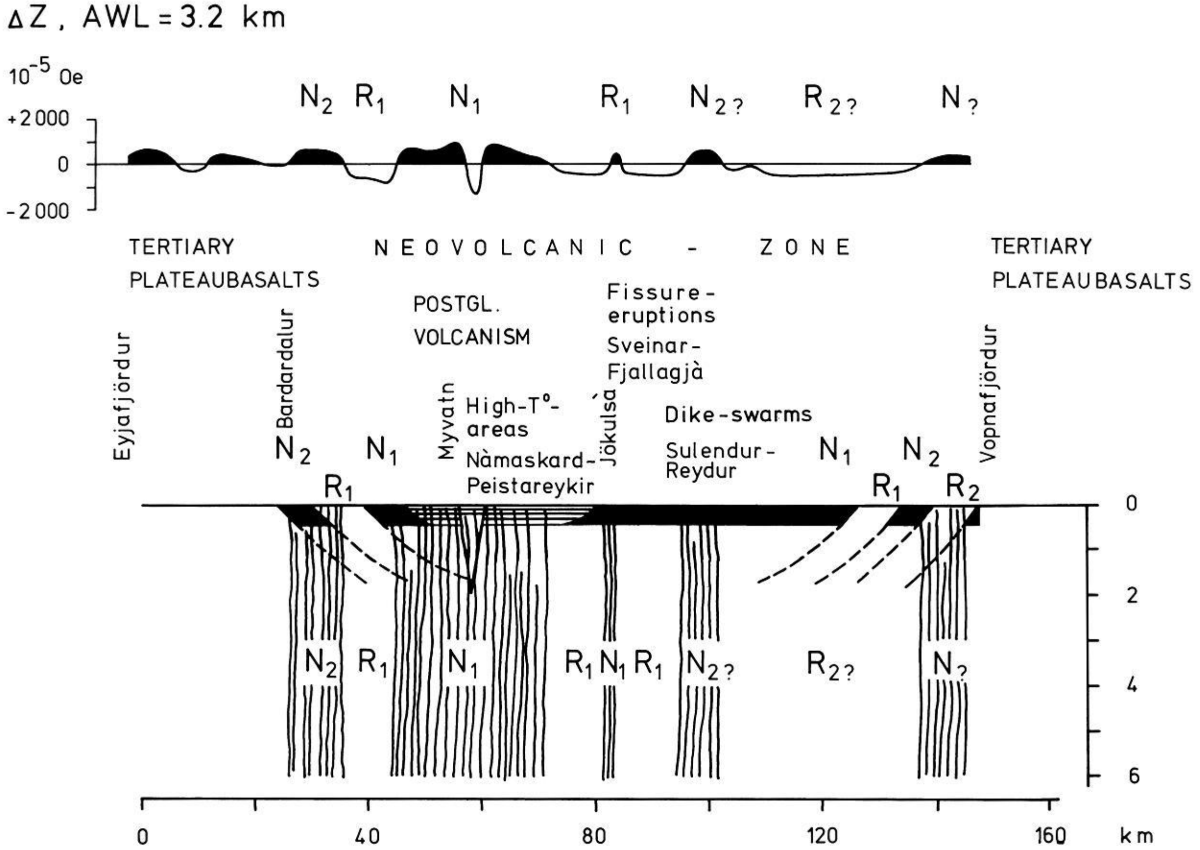

Fig. 7. Interpretation of the regional geomagnetic anomalies by dike-swarms. The regional anomalies ΔZ filtered with cut-off wavelength AWL = 3.2 km are shown schematically. The model gives the main structures of interpretation. The polarity of the magnetization of the lavas refer to Piper (1973); the existence and polarity of the dike-swarms are hypothetical. (N = normal polarity; R = reverse polarity)

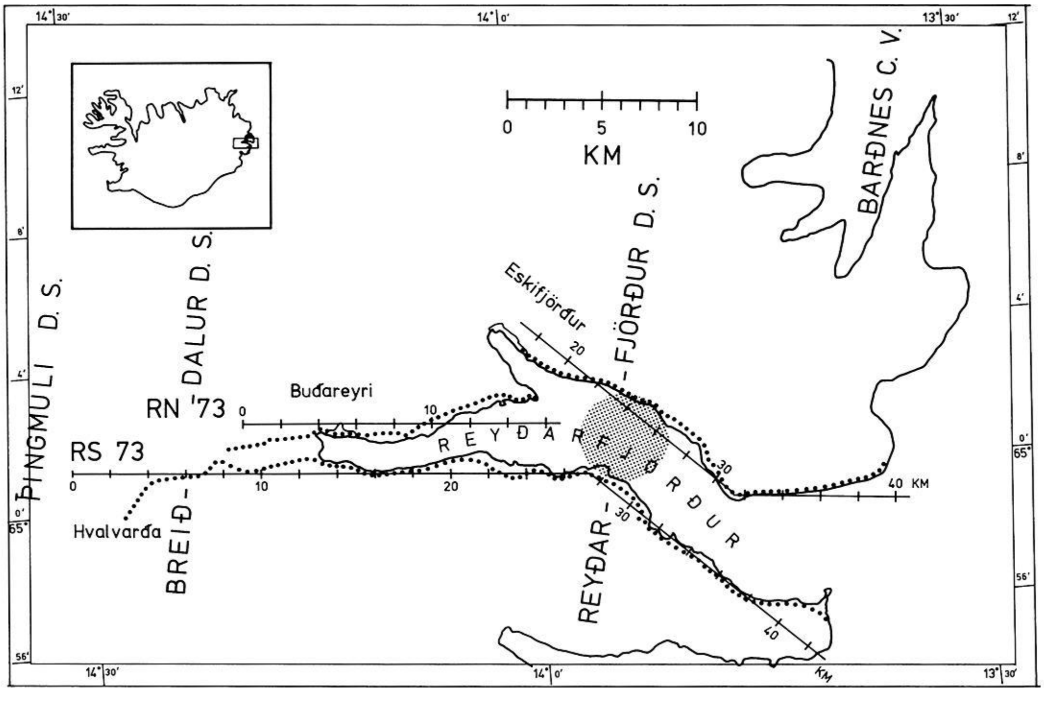

Fig. 8. Location map of the profiles (ΔZ) in the Reydarfjördur-Thingmuli area in E-Iceland with dike-swarms (D.S.) and approximate location of Reydarfjördur central volcano *(shaded)* after Walker (1959, 1963)

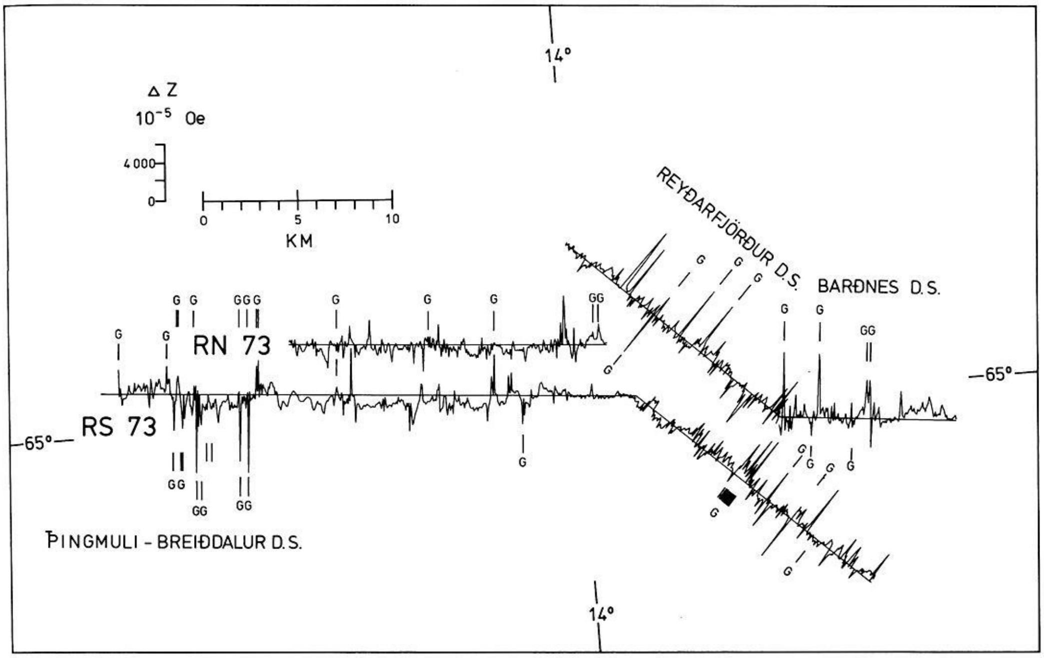

Fig. 9. Magnetic survey (ΔZ) in the Reydarfjördur-Thingmuli area. 'G' specifies dikes which are observed in the field

Table 2. Age and polarity of magnetization of the dike-swarms in the Thingmuli-Reydarfjördur region according to K-Ar determinations by Gale et al. (1966), Moorbath et al. (1968) and McDougall et al. (1976) and epoches of geomagnetic time scale from Heirtzler et al. (1968)

Central volcano	Thingmuli	Breiddalur	Reydarfjördur	Bardsnes
Age Ma	9.5	8.9 (10.5)	11.5	12.5
Epoch of geomagnetic time scale	9	8 (10)	12	13
Main geomagnetic polarity	N	R (R)	R	N

The age in brackets of the Breiddalur central volcano is based on the hypothesis of a continuous development of central volcanoes related to the axial rift-zone
N = Normal polarity, R = Reverse polarity

Table 3. Mean values (arithmetic) of natural remanent magnetization J_{nrm}, susceptibility K, and Q-ratio

	n Sites	n Samples	J_{nrm} 10^{-5} G	K 10^{-5} G/Oe	Q
Postglacial lavas	35	610	1520	78	45
Postglacial dikes	8	121	2250	120	40
Pleistocene lavas	30	177	545	114	13
Tertiary lavas	55	500	340	180	3.2
Tertiary dikes	37	460	500	310	3.2
Tertiary dikes + contacts			620	360	4
Gabbro	1	8	1850	1080	3.4
Hyaloclastite	4	11	4		
After Kristjansson (1970)					
Miocene dikes	10	126	420	140	6
Pliocene dikes	10	20	750		
Gabbro	10	21	650	500	2.6
After Piper (1973)					
Dike-swarms in E- and W-Iceland		500	500	320	3.1

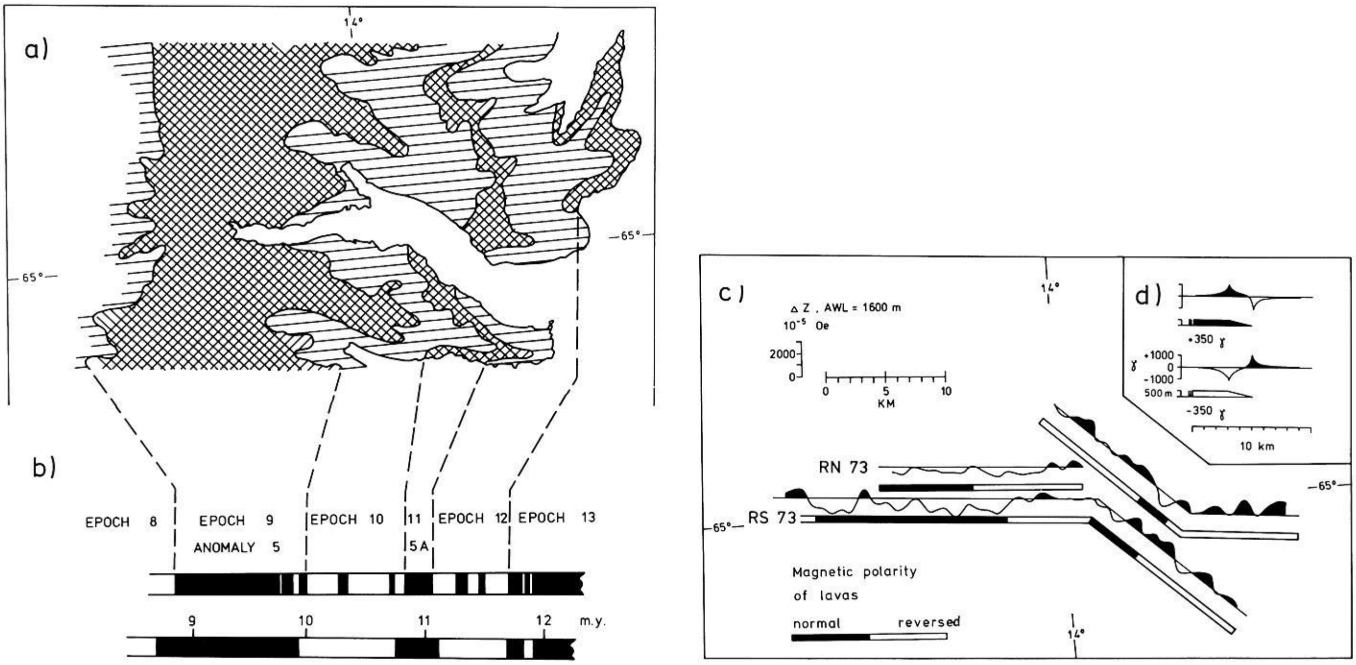

Fig. 10a–d. Comparison of the polarity of the floodbasalts magnetization at Reydarfjördur with the low-pass filtered profiles (ΔZ) and calculation of the terrain effect. **a** Polarity zones of the flood basalts after Piper (1973) (checked = normally magnetized; hatched = reversely magnetized). **b** Measured polarity of the floodbasalts after Dagley et al. (1967) and Piper (1973) and geomagnetic time scale after Heirtzler et al. (1968). **c** Long wavelength anomalies (ΔZ) and polarity of the magnetization of the flood basalts. **d** Calculated terrain effect of a 500 m oblique step having normal and reverse magnetization of 350 γ ($=10^{-5}$ Gauss)

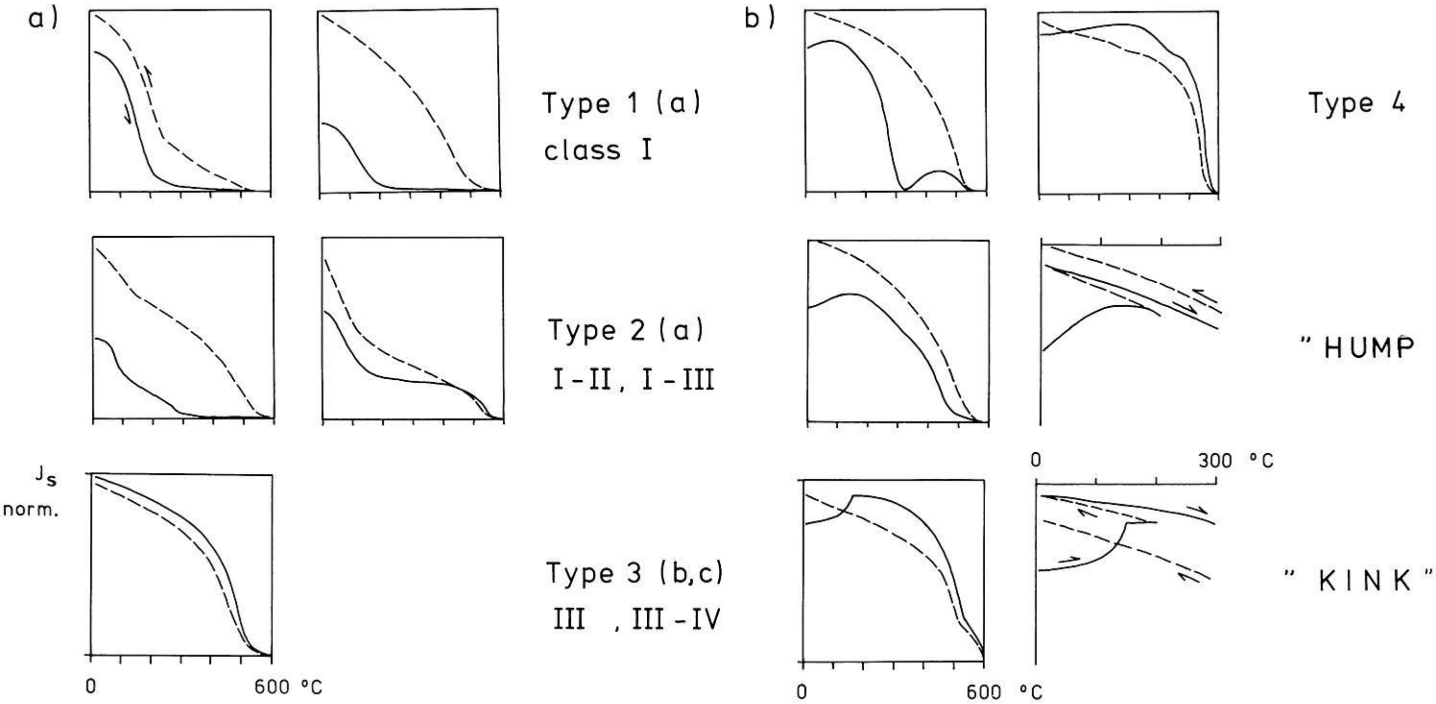

Fig. 11a. Type of J_sT-curve (saturation magnetization versus temperature) and class of deuteric oxidation (HTO). Measurement in air at 240 KA/m (3,000 Oe) with 40 min heating-cooling cycle; a, b, c = cooling curve above, below heating curve, reversible. *Type 1:* homogeneous titanomagnetite (HTO class I); *Type 2:* titanomagnetite with rare dissolution lamellae of ilmenite (left side: 'internal dissolution'; HTO class I/II); right side: partial oxidation by air, HTO class I–III); *Type 3:* internally dissolved titanomagnetite (HTO) class III–V) or highly oxidized titanomagnetite (e.g., reheating). **b** Type of J_sT-curve after low-temperature oxidation and hydrothermal alteration; *Type 4:* maghemitization of homogeneous titanomagnetite (*left side*); maghemitization and hydrothermal alteration of titanomagnetite (*right side*); *'Hump'* hydrothermal alteration of titanomagnetite at temperatures under 200° C; *'Kink'* (right side gives details of the heating and cooling curve)

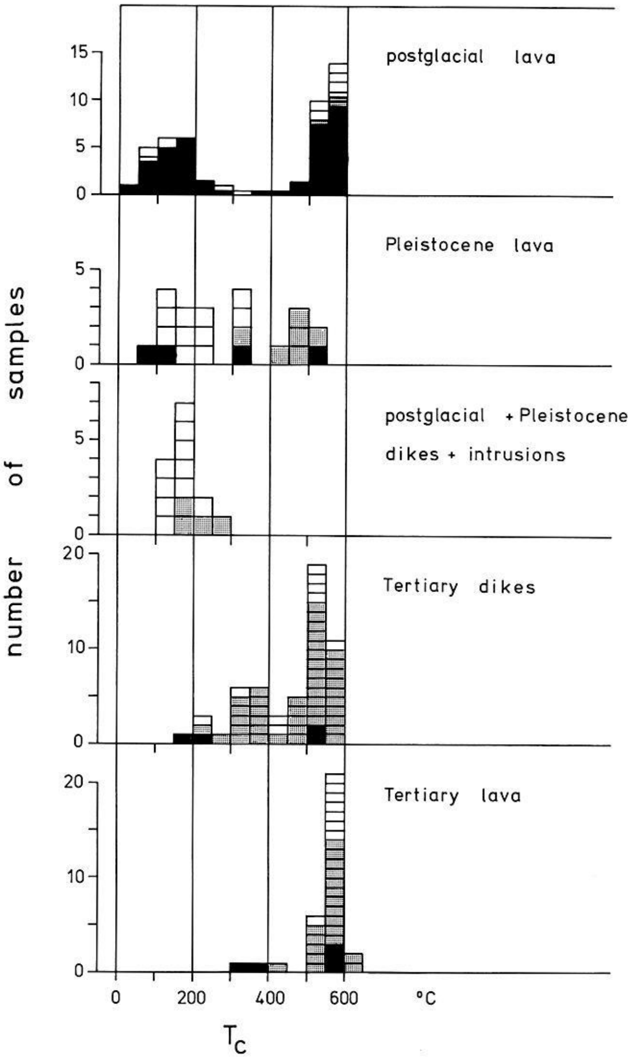

Fig. 12. Normalized histogram of the Curie temperature T_c of lavas and dikes in chronological sequence: *White:* one Curie-point (J_sT-type 1; $0° < T_c < 300°$ C; J_sT-type 3; $500 < T_c < 600°$ C); *black:* two or more Curie-points (J_sT-type 2; $0° < T_{c1} < 200°$ C; $500 < T_{c2} < 600°$ C); *shaded:* low temperature oxidation or hydrothermal alteration (J_sT-type hump or kink)

alies are obviously caused by the terrain effect of the steep slopes of the fjord as modelled in Fig. 10c.

3. Rock-Magnetic Investigation: Primary Magnetic Properties, Remagnetization and Hydrothermal Alteration of Lavas and Dikes

More than 1,000 rock samples from 170 sites (mostly tholeiitic basalts) were drilled covering the main geological formations (for sample list and localities refer to Becker, 1978). The investigation concentrated on properties which are important for the interpretation of the geomagnetic anomalies, such as natural remanence J_{nrm}, susceptibility K and Curie temperature T_c.

Verifying the dike-swarm model, one has to prove the differences of these parameters between dike and lava. As far as possible the samples were taken at various sections of the dikes, lavas, and their contacts in order to study the variation of the magnetic parameters in a single structure and the effect of remagnetization.

Table 4. Internal dissolution of titanomagnetite. Changes in the grade of deuteric oxidation (HTO class) with increasing width of dikes

Number of dikes	Width in m	HTO class				
		I	I/II	II	II/III	III
1	0.15	*				
1	0.5	*				
2	1.0	**				
1	1.5	*				
2	2.0	*	*			
1	2.5		*			
4	3.0	*—	—***	*		
2	4.0	*			*	
3	5.0	*—	—	—**	*	
2	6.0	*	*			
1	7.0			*		
1	9.0					*
1	12.0			*		
1	15.0					*
1	20.0		*—	—*—	—*	
1	150.0					*

The comparison of the bulk magnetic properties gives some systematic differences between lavas and dikes of various geological ages which in this case represent also different stages of hydrothermal alteration (Table 3). Most of the Tertiary samples are hydrothermally altered on a regional scale, whereas the Pleistocene and postglacial ones are not altered but locally. The magnetization of dikes is clearly higher than that of lavas, especially if one takes into account the remagnetized contact zones.

About 300 polished sections (at least one for every site) were examined and classified into stages of high temperature oxidation (Wilson and Haggerty, 1966) and hydrothermal alteration (Ade-Hall et al., 1971). In addition thermomagnetic measurements were taken. The type of the thermomagnetic curve (J_sT-curve) corresponds to the stage of deuteric oxidation and hydrothermal alteration (Fig. 11; see also Ade Hall et al., 1971). Again there are distinct differences between lavas and dikes from the same formations mainly in the higher Curie temperature range and higher grade of deuteric oxidation and hydrothermal alteration of the lavas (Fig. 12). This is important for the interpretation of geomagnetic anomalies as the Curie temperature determines the maximum depth (Curie depth) of a body for modelling.

Assuming an average temperature gradient of 85° C/km (Pálmason, 1973) in an active rift zone, the carrier of remanence must be magnetite for a Curie depth of about 5 km. Models with dike swarms require the tacit assumption of a high Curie temperature of dikes. The question is now at what dike width primary magnetite develops due to internal decomposition (Petersen, 1976). As most of the Icelandic dikes have been altered in some way, the J_sT-curve does not give the primary composition of titanomagnetites. A better indicator of their primary state is the grade of deuteric oxidation which is normally identifiable by microscope examination even after hydrothermal alteration.

By plotting dike width against grade of deuteric oxidation, one obtains class III for a 10 m dike which suggests the existence of internally decomposed magnetite (Table 4). Walker (1959) describes dike-swarms in the Reydarfjördur area and finds the aver-

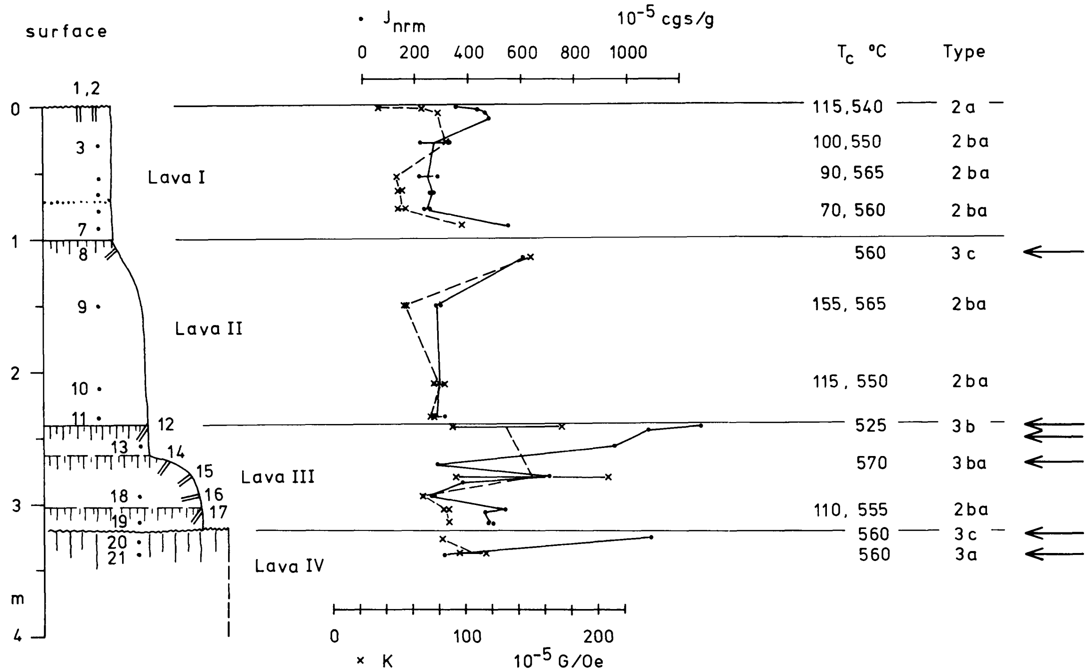

Fig. 13. Remagnetization at lava contacts. The upper four flow-units of the Peistareykjabunga are shown. The uppermost lava (still original surface) is not remagnetized but partially oxidized by atmospheric oxygen. All the other contacts are remagnetized as seen in increased J_{nrm}, T_c, and type of J_sT-curve (*arrows*). J_{nrm} = specific natural remanence (10^{-5} cgs/g); K = susceptibility (10^{-5} Gauss/Oe); T_c = Curie temperature (° C); Type = type of the J_sT-curve (see also Fig. 11a)

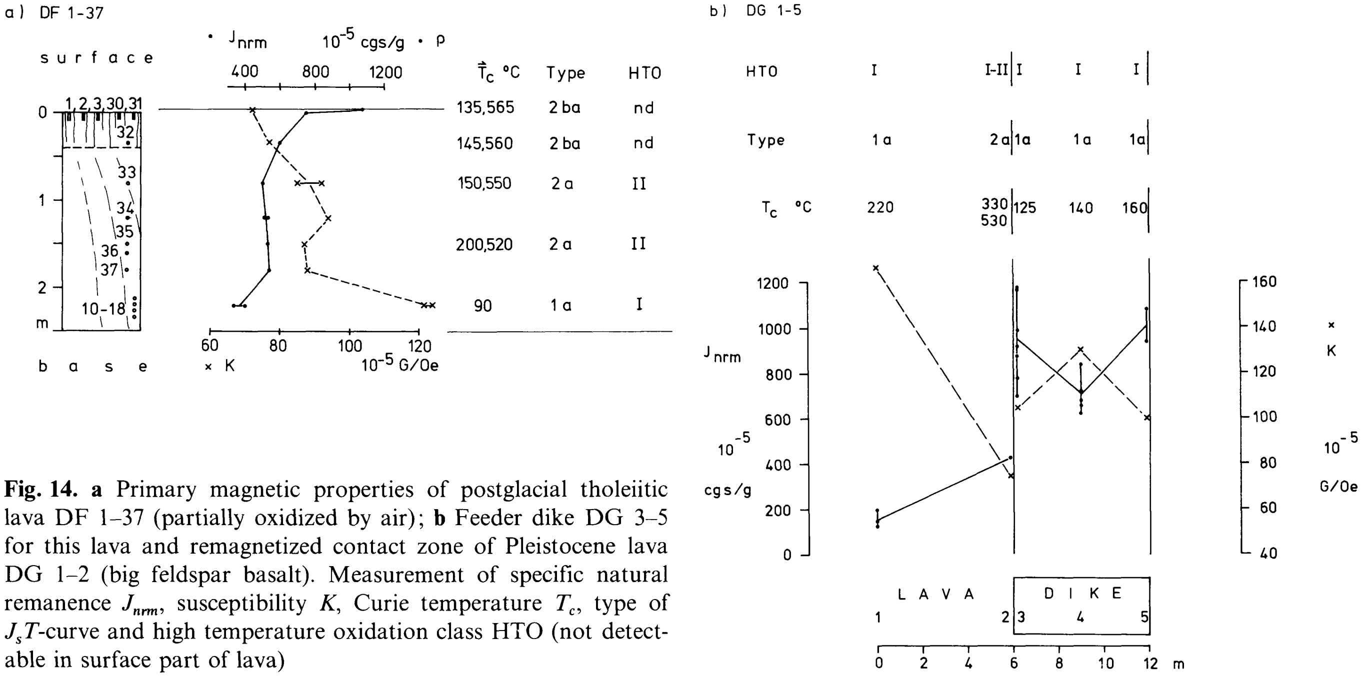

Fig. 14. a Primary magnetic properties of postglacial tholeiitic lava DF 1–37 (partially oxidized by air); **b** Feeder dike DG 3–5 for this lava and remagnetized contact zone of Pleistocene lava DG 1–2 (big feldspar basalt). Measurement of specific natural remanence J_{nrm}, susceptibility K, Curie temperature T_c, type of J_sT-curve and high temperature oxidation class HTO (not detectable in surface part of lava)

age width to be roughly 3.5 m which means that the primary Fe-Ti-oxides are homogeneous or only partly decomposed titanomagnetite. The low primary Curie temperature of dikes therefore restricts the Curie depth – a fact which does not support the interpretation of the regional anomalies by dike-swarms.

On the other hand, remagnetization of the dike contact zones would support a dike-swarm model for the interpretation of the regional geomagnetic anomalies. One can show that remagnetization fundamentally changes the initial magnetic properties (Figs. 13–16; Table 5) by increasing the intensity of the magnetization and the Curie temperature. On the basis of the model calculations one would expect a highly remagnetized contact zone of about 20% of the width of a lava or dike which actually should be more when taking into account multiple activity of feeder dikes and convection of heated groundwater (Jaeger, 1957; Mundry, 1968; for more details see Becker, 1978): The observed remagnetization of lava and dike contacts was also found to be in the range of 20% (Table 5), which again is rather unsatisfactory con-

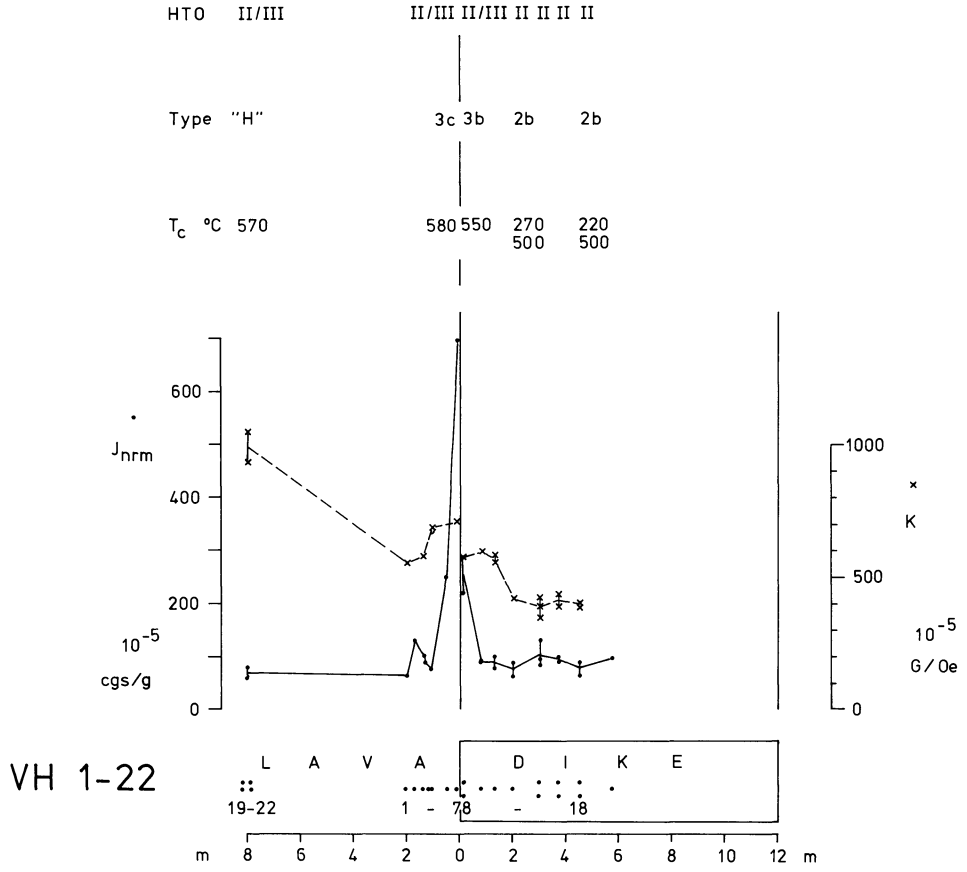

Fig. 15. Remagnetization at the contact of a 12 m Tertiary dike near Vikurvatn (site number *VH 1–22*) at 600 m altitude (stage D of hydrothermal alteration = mesolite/scolecite zone after Ade-Hall et al., 1971, see Figs. 13 and 14 for legend

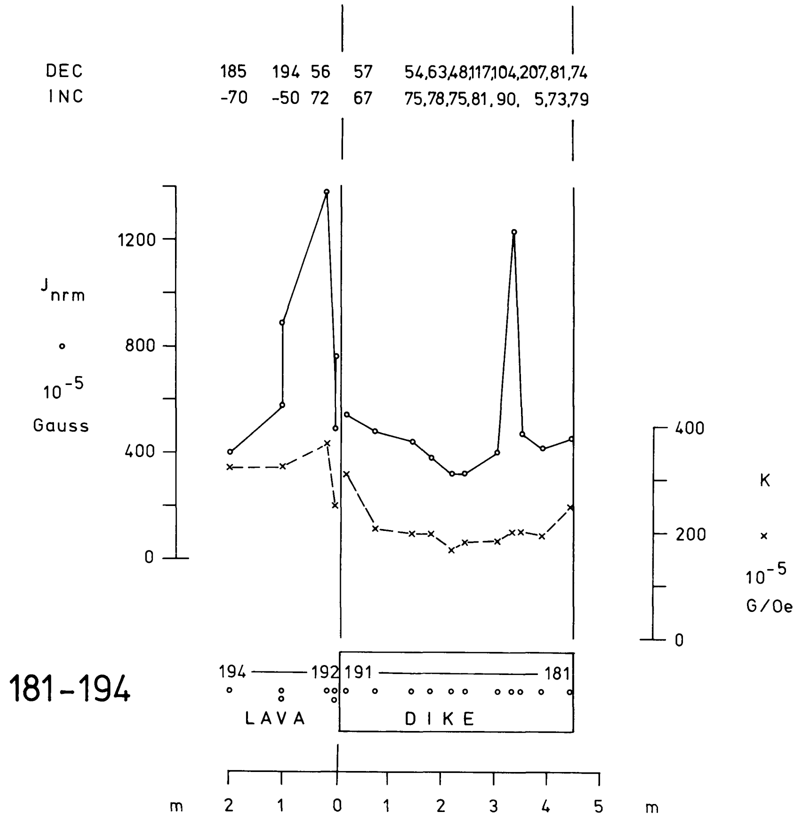

Fig. 16. Remagnetization at a dike contact (see Fig. 14 for legend). A 4.5-m-thick normally magnetized dike has remagnetized a reversely magnetized lava; dike and lava are hydrothermally altered (stage F = laumontite zone after Ade-Hall et al., 1971).
Dike. deuteric oxidation class II, J_sT-curve type: hump, $T_c = 470$, (550)° C.
Lava. deuteric oxidation class II/III; J_sT-curve type: kink, $T_c = 565$° C.

Table 5. Remagnetization (J_{re}) of the natural remanent magnetization (J_{nrmo}=undisturbed remanence) at contacts of dikes

1 Site number	2 Width of dike in m	3 Remagnetized contact zone with $J_{re}=2\times J_{nrmo}$ in m	4 in %	5 J_{re} total in m	6 J_{nrmo} in 10^{-5}G	7 J_{re} in 10^{-5}G
RF45–79	1.0	0.2–0.7	50	(1.8)	40	3000
Ba1–18	3.0?	0.6	20	0.8	210	2500
(263–280)	3.0?	0.6?		1.5	300	20
(181–194) (Fig. 16)	4.5	0.5?			600?	1350
RF32–44	5.0	0.8	16	1.0	150	1000
DG1–5 (Fig. 14)	6.0				150	1300
RN21–35	7.0	1.2	17	1.5	40	1000
VH1–21 (Fig. 15)	12.0	1.0	8	2.0	80	2000
RF1–31	7 (1)	1.5	21	1.6	25	1000
RF94–128	9(1)	–	1	–	80	
Mean.			20%			

1 Site number referring to sample list (Becker, 1978); see also Figs. 13–16
2: Width of dike in m
3: Width of remagnetized contact zone with $J_{re}=2\times J_{nrmo}$
4: Same in % of dike width
5: Total width of remagnetized zone with observable increase of magnetization
6: Intensity of natural remanence not remagnetized; J_{nrmo} in 10^{-5} Gauss
7: Maximum intensity of remanence due to remagnetization J_{re} in 10^{-5} Gauss

sidering the large bodies which must have been magnetized in the same polarity in order to cause the regional anomalies described.

Regarding the differences of primary magnetic properties between dike and lava, only the natural remanence gives evidence for the dike-swarm model. In thin tholeiitic dikes and lavas one expects homogeneous titanomagnetite with Curie temperature below 200° C (Petersen, 1976) which was also observed (Figs. 12 and 14b). Very often lavas are partially oxidized during effusion by the influence of air (Fig. 12; top lava in Fig. 13; Fig. 14). Only in thick lavas or thick dikes an internal decomposition takes places which results in the development of magnetite as a high Curie temperature phase (Petersen, 1976). For dikes a minimum width of about 10 m was observed for high primary Curie temperature (Table 4). This is rather rare; dikes are normally about 3 m in width (Walker, 1959; Piper et al., 1977).

Reheating of the basalt by further intrusion or effusion causes the titanomagnetite to oxidize into magnetite (Figs. 13–16). It was found that the remagnetized contact zone with a considerable increase of natural remanence and Curie temperature is only about 20% of the width of the dike or thickness of lava (Table 5). In view of the observed intensity of dike-swarms with less than 10% strain (Walker, 1959, 1974), this percentage is not sufficient to remagnetize the required large bodies of one polarity and high Curie temperature.

Apart from these processes at high temperature the magnetic minerals are altered at relatively low temperature. One should distinguish between normal weathering at temperatures less than 50° C, which produce maghemite, and hydrothermal alteration which is caused by active solutions at temperatures of 50°–300° C. Therefore one should consider that for model calculations the original magnetic properties are not correct – especially not for older rocks or rocks at depth. A good indicator for all of the above mentioned processes at high and low temperature is the type of the J_sT-curve which shows the alteration of the thermomagnetic properties and in the case of hydrothermal alteration the characteristic hump and kink type (Fig. 17; see also Ade-Hall et al., 1971).

In eastern Iceland the hydrothermal alteration can be studied at 1.5 km depth of burial at maximum temperatures of 200° C using the zeolitization as an indicator for the paleo-temperature (Walker, 1960; Ade-Hall et al., 1971). The magnetic properties of the basalts are strongly affected by hydrothermal alteration (Table 3; Figs. 12 and 17). The intensity of natural remanence decreases while the Curie temperature and susceptibility increase (for a quantitative graph of the decrease of magnetization versus stage of hydrothermal alteration see Watkins and Walker, 1977). It seems that the Curie temperatures of dikes are less affected than those of lavas at the same stage of regional metamorphism (Fig. 12). This could be explained by the greater water content of the porous lava. But the trend in the hydrothermal alteration due to burial leads to the suggestion, that at a depth of about 2 km the magnetic properties of lavas and dikes will be equalized. The simple dike-swarm model therefore should be modified to one in which gabbros are connected at depth with the dike-swarms.

4. Conclusions

The regional geomagnetic anomalies of more than 5 km wavelength and strong resemblance to ocean-ridge anomalies, can only be interpreted by highly magnetized bodies several kilometres thick. Lava piles can therefore be excluded because of their change of polarity every 100 m on average (e.g., Dagley et al., 1967; Watkins and Walker, 1977). The magnetic survey which crossed several dike-swarms in the Reydarfjördur-Thingmuli region, as well as rock magnetic investigations of dikes and the remagnetization of their contacts do not support the interpretation of the elongated anomalies by dike-swarms either. Nevertheless, at least some of

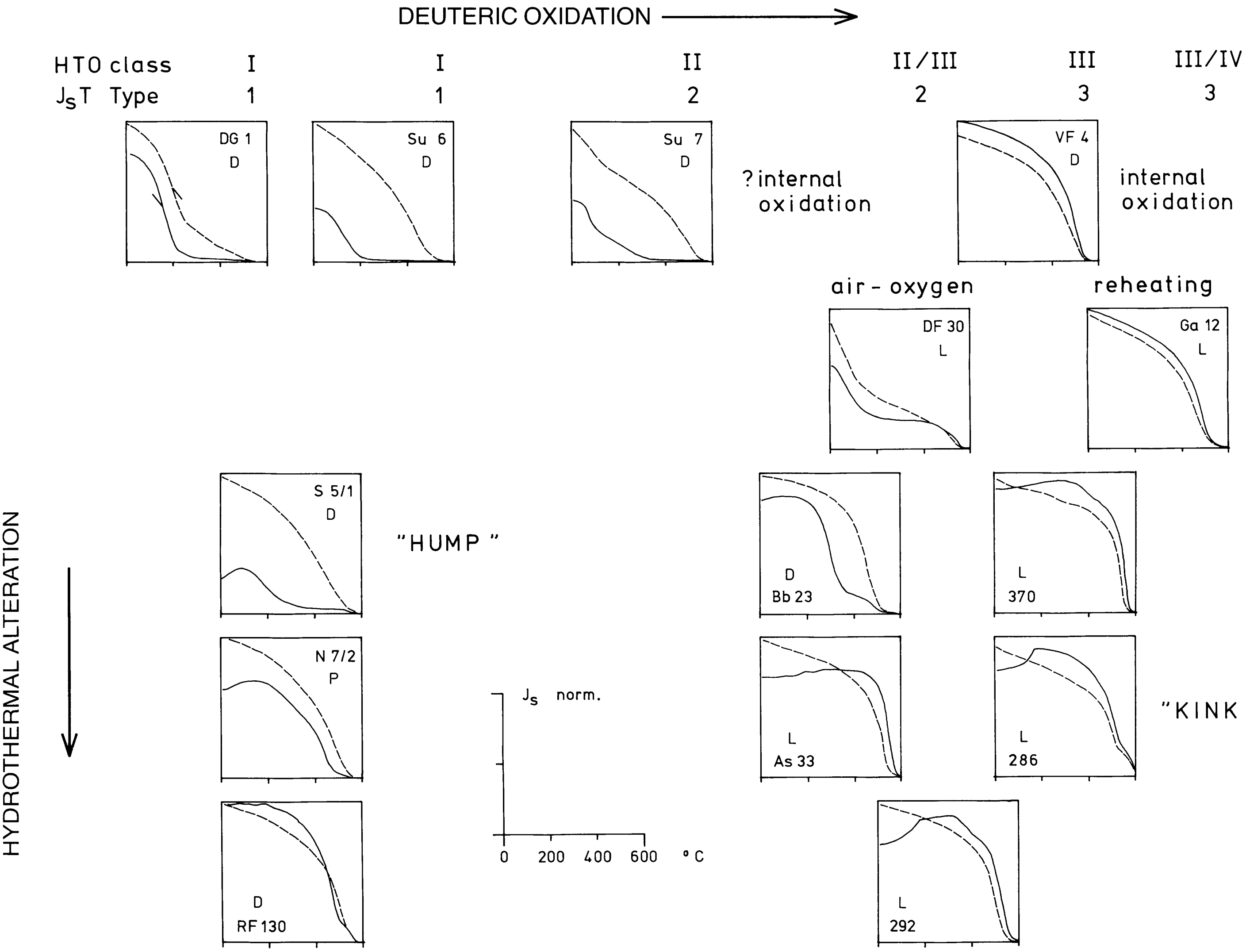

Fig. 17. Alteration of the primary magnetic properties of titanomagnetite by deuteric oxidation, influence of athmospheric oxygen, reheating and hydrothermal alteration indicated by the type of the J_sT-curve (numbers refer to sample list of Becker (1978); L=lava, D=dike or intrusion, P=pillow)

the regional anomalies may be caused by dike-swarms such as the Breiddalur dike-swarm. Another possible explanation for the regional geomagnetic anomalies observed is given by gabbros at depth which should be studied more closely.

5. *Acknowledgements.* Many thanks are due to Professor Dr. H. Soffel, Dr. C. Schweitzer, Dr. U. Kramm, and Dipl. Min. T Sachtleben for their help during the 1973 campaign in Iceland as well to Dr. G. Pálmasson, Dr. K. Saemundsson, Professor T Sigurgeirsson and Dr. L. Kristjansson. The evaluation of the field data and the rock-magnetic investigations were made at the Institut für Allgemeine und Angewandte Geophysik, Universität München under the supervision of Professor Dr. H. Soffel who also read this article. I have benefited greatly from discussions with Professor Dr G. Angenheister, Dr. N. Petersen, Dr. J. Pohl, Dr. A. Schult, Dr. G. Schönharting, Dr. C. Schweitzer, and Dr. L. Kristjansson. Most of the microscope work was done at Mineralogisch-Petrographisches Institut, Universität zu Köln under the supervision of Dr. U. Kramm. The financial support of Deutsche Forschungsgemeinschaft is gratefully acknowledged.

References

Ade-Hall, J.M., Palmer, H.C., Hubbard, T.R. The magnetic and opaque petrological response of basalts to regional hydrothermal alteration. Geophys. J. R. Astron. Soc. **24**, 137–174, 1971

Angenheister, G., Becker, H., Mohr, H.P.: Bodenvermessung des erdmagnetischen Feldes (ΔZ) in Nord-Island längs Profilen. In: Das Unternehmen Erdmantel, W. Kertz et al. eds.; pp. 113–118. Wiesbaden 1972

Angenheister, G., Petersen, N., Schönharting, G. Zur Interpretation der Anomalien des Erdmagnetfeldes in Island. Fortschr. Mineral. **54**, 54–92, 1977

Becker, H. Vermessung des erdmagnetischen Feldes (ΔZ) längs Profilen in Nordost- und Ost-Island und der Versuch der Interpretation unter Berücksichtigung gesteinsmagnetischer Untersuchungen. Diss. Universität München, 1–269, 1978

Becker, H., Mohr, H.P. Vermessung des erdmagnetischen Feldes längs einiger Profile in Nord-Island, deren Auswertung und Interpretation. Dipl. Arbeit. Universität München 1971

Bödvarsson, G., Walker, G.P.L. Crustal drift in Iceland. Geophys. J.R. Astron. Soc. **8**, 285–300, 1964

Dagley, P., Wilson, R.L., Ade-Hall, J.M., Walker, G.P.L., Haggerty, S.E., Sigurgeirsson, T., Watkins, N.D., Smith, P.J., Edwards, J., Grasty, P.L. Geomagnetic polarity zones for Icelandic lavas. Nature **216**, 25–29, 1967

Gale, N.H., Moorbath, S., Simons, J., Walker, G.P.L.· K-Ar ages of acid intrusive rocks from Iceland. Earth Planet. Sci. Lett. **1**, 284–288, 1966

Heirtzler, J.R., Dickson, G.O., Harron, E.M., LePichon, X.. Marine magnetic anomalies, geomagnetic reversals and motions of the ocean floor and continents. J. Geophys. Res. **73**, 2119–2136, 1968

Jaeger, J.C.. The temperature in the neighbourhood of a cooling intrusive sheet. Am. J. Sci. **255**, 306–318, 1957

Kristjansson, L.. Palaeomagnetism and magnetic surveys in Iceland. Earth Planet. Sci. Lett. **8**, 101–108, 1970

McDougall, I.M., Watkins, N.D., Walker, G.P.L., Kristjansson, L. Potassium-Argon and paleomagnetic analysis of Icelandic lava flows: Limits on the age of anomaly 5. J. Geophys. Res. **81**, 1505–1512, 1976

Moorbath, S., Sigurdsson, H., Goodwin, R. K-Ar ages of the oldest exposed rocks in Iceland. Earth Planet. Sci. Lett. **4**, 197–205, 1968

Mundry, E. Über die Abkühlung magmatischer Körper. Geol. Jahrb. **85**, 775–776, 1968

Pálmason, G.. Kinematics and heat flow in a volcanic rift zone, with application to Iceland. Geophys. J.R. Astron. Soc. **33**, 451–481, 1973

Petersen, N.. Notes on the variation of magnetization within basalt lava flows and dikes. Pure Appl. Geophys. **114**, 177–193, 1976

Piper, J.D.A.: Interpretation of some magnetic anomalies over Iceland. Tectonophysics **16**, 163–187, 1973

Piper, J.D.A., Fowler, M.G., Gipson, I.L.. Dyke magnetization and upper crustal structure in the Reydarfjördur area of Eastern Iceland. Tectonophysics **40**, 227–244, 1977

Rutten, K.. Two-dimensionality of magnetic anomalies over Iceland and Reykjanes Ridge. Marine Geophys. Res. **2**, 243–263, 1975

Saemundsson, K. Evolution of the axial rifting zone in Northern Iceland and the Tjörnes Fracture Zone. Bull. Geol. Soc. Am. **85**, 495–504, 1974

Schönharting, G.. Vermessung des erdmagnetischen Feldes längs einiger Profile in Nord-Island, deren Auswertung und Interpretation. Diss. Universität München, 1–121, 1969

Serson, P.H., Hannaford, W., Haines, G.V.. Magnetic anomalies over Iceland. Science **162**, 355–357, 1968

Sigurgeirsson, T.: Aeromagnetic survey of SW-Iceland. Science in Iceland **2**, 13, 1970

Walker, G.P.L.. Geology of the Reydarfjördur area, E-Iceland. Q. J. Geol. Soc. London **114**, 367–393, 1959

Walker, G.P.L.: Zeolithe zones and dike distribution in relation to the structure of the basalts of Eastern Iceland. J. Geol. **68**, 515–528, 1960

Walker, G.P.L.: The Breiddalur central volcano, E-Iceland. Q. J. Geol. Soc. London **119**, 29–63, 1963

Walker, G.P.L.: The structure of eastern Iceland. In. Geodynamics of Iceland and the North Atlantic area. L. Kristjansson, ed.; pp. 177–188. Dordrecht: Reidel 1974

Ward, P.L. New interpretation of the geology of Iceland. Bull. Geol. Soc. Am. **280**, 2991–3312, 1971

Watkins, N.D., Walker, G.P.L.: Magnetostratigraphy of eastern Iceland. Am. J. Sci. **277**, 513–584, 1977

Wilson, R.L., Haggerty, S.E.. Reversals of the earth's magnetic field. Endeavour **25**, 104–109, 1966

Received August 1, 1979; Revised Version November 12, 1979