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Meri-Liisa Airo

Susceptibilities, intensities of remanence and densities of Precambrian and recent volcanic rocks: Examples from Iceland and northern Fennoscandia

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Samples were collected from recent volcanic rocks in Iceland, and their densities, susceptibilities and intensities of remanence were measured for comparison with the corresponding properties of Precambrian metavolcanic rocks from northern Fennoscandia.

In both Icelandic and Finnish rock types the densities show unimodal frequency distributions, and different rock types are characterized by typical modal densities. The intensities of remanence in igneous rocks are mostly below 1 A/m in the Precambrian data, but generally above 1 A/m in the Icelandic data. Furthermore, in Iceland the average intensity of remanence is about ten times higher in Postglacial than it is in Tertiary and Pleistocene formations.

The susceptibility distributions of Fennoscandian metavolcanic rocks are bimodal, with a lower mode at about $1 \cdot 10^{-3}$ SI and a higher mode at about $70 \cdot 10^{-3}$ SI. The lower mode is dominant in the susceptibility distribution of basaltic rocks. In Iceland, the basaltic rocks show a unimodal distribution, with a susceptibility of about $30 \cdot 10^{-3}$ SI. The susceptibility values of Postglacial basaltic formations are clearly (60%) lower than those of older basalts in Iceland.

In both Precambrian and recent basaltic lavas, the significance of the lower susceptibility mode increases and the intensity of remanence decreases as the ages of rocks increase.

Key words: volcanic rocks, metavolcanic rocks, magnetic susceptibility, density, remanent magnetization, Precambrian, Tertiary, Quaternary, Iceland, Finland

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INTRODUCTION

Aeromagnetic anomalies reflect changes in the concentration of ferrimagnetic minerals in bedrock. Correlations of magnetic anomalies and anomaly-causing rock units have established that different rock units are characterized by distinct magnetic anomaly patterns and level of magnetization. Differences in the density, susceptibility and intensity of remanence are an indication of differences in the magnetic mineralogy, and can be used to classify lithostratigraphic units of bedrock.

The frequency distributions of susceptibility can be used to study differences in iron and magnetite content within and between geological units. Furthermore these distributions can be used together with detailed geological information to study the behaviour of magnetite in different geological environments and processes (Puranen, 1976 and 1989). Together with density data the susceptibility distributions can be applied (Henkel, 1976) to mineralogical and chemical studies.

The environment of crystallization influences the differentiation trend of a basaltic magma, and thus affects the primary magnetic mineralogy of the rock; other factors are i.e. oxygen fugacity and cooling rate. Secondary magnetite is formed by mechanical deformation, repeated metamorphism or high-temperature alteration. The different tectonic environments are reflected in the magnetic properties of rocks (Grant, 1985), and the premetamorphic lithostratigraphy is often recorded in the behaviour of magnetite in metamorphic terrains.

The petrophysical laboratories of the Geological Survey of Finland have measured the densities and susceptibilities of more than 40 000 bedrock samples, and the intensities of natural remanent magnetization of about 20 000 samples. These systematic measurements show bimodal susceptibility distributions for the most common rock types in Finland (Puranen, 1976 and 1989). In the bimodal distributions the lower frequency maximum, the paramagnetic part, is dominated by the paramagnetism of the mafic minerals. The higher maximum, the ferromagnetic part, is due to specimens carrying various amounts of ferrimagnetic minerals (Chernyuk, 1971 and Puranen, 1976). A practically linear relationship has been verified between the paramagnetic mean susceptibilities and the mean iron content of igneous rocks. The correlation between the ferromagnetic susceptibilities and the magnetite content of Finnish rocks is almost linear (Puranen et al., 1968).

According to systematic density measurements, the frequency distributions of individual rock type densities show one frequency maximum repeated in different areas. As an approximately linear relationship has been established between the mean mafic mineral contents and densities of igneous rocks (Puranen et al., 1978), simple density measurements can be used as an aid in rock type classifications.

The Finnish data offers a wide material for comparison of the petrophysical properties of metamorphosed rocks from different environments. It is of interest to know what these properties are at the beginning of the geological history of rocks. As an area of recent volcanic activity, Iceland provides just such an opportunity, permitting us to investigate the properties of unmetamorphosed volcanic rocks.

Paleomagnetic and rock magnetic research in Iceland has been conducted by several scientists (reviewed by Kristjansson, 1982), and many of the published papers contain also susceptibility data. To ensure consistency between the Icelandic and Finnish data, a rock sampling programme was carried out in Iceland in 1982, and the laboratory measurements were made at the Geological Survey of Finland. The results are summarized in the present paper, which examines the density, the susceptibility and intensity of remanence of recent volcanic rocks in Iceland and compares them with the same properties of Precambrian metavolcanic rocks. The material from Fennoscandia consists of the petrophysical data bases of the Geological Survey of Finland and the Nordkalott Project, and additional hand specimens collected for this study during 1982—1987.

ICELANDIC GEOLOGY

The geology of Iceland has been outlined by Saemundsson (1979). The exposed volcanic pile of Iceland is 80—85% basaltic and about 10% acidic to intermediate rocks. The volcanic pile (Fig. 1), which ranges in age from recent to about 16 m.y., corresponds to four different stratigraphic groups or series:

Postglacial, the last 9 000 to 13 000 years
Upper Pleistocene, back to 0.7 m.y.
Plio-Pleistocene, 0.7—3.1 m.y.
Tertiary, rocks older than 3.1 m.y.

The volcanically active areas are divided into rift zones and non-rifting zones, with different geochemical characteristics (Oskarsson et al., 1982). The rift zones are characterized by faults, open fissures and crater rows which tend to congregate into fissure swarms. These may evolve into central volcanoes. The fissure swarms primarily produce mid-ocean ridge basalts (MORB), i.e. the primitive tholeiites, known as olivine tholeiites.

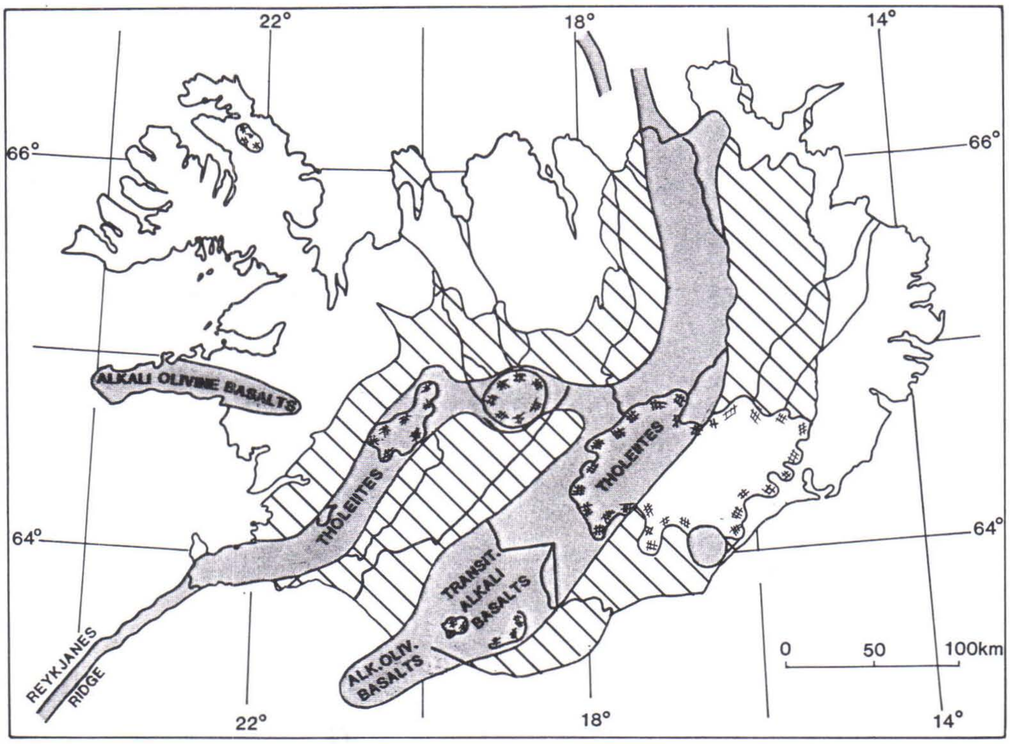


Fig. 1. Map of Iceland showing Postglacial and Upper Pleistocene petrological zones (shaded), Plio-Pleistocene formations (oblique lines) and Tertiary formations (blank). (After Saemundsson, 1979.)

The volcanism of the non-rifting zones mainly produces basalts of strong ferrotitaneous characteristics (FETI basalts) with marked alkaline affinities but generally little — and in most cases no — primitive tholeiitic rocks.

In addition to basalts, both zones produce small volumes of silicic and intermediate rocks. In Iceland silicic and intermediate rocks are formed in central volcanoes. Imsland (1983) defines the initiation of the central volcano stage at the first appearance of qz-normative rocks on the fissure swarm.

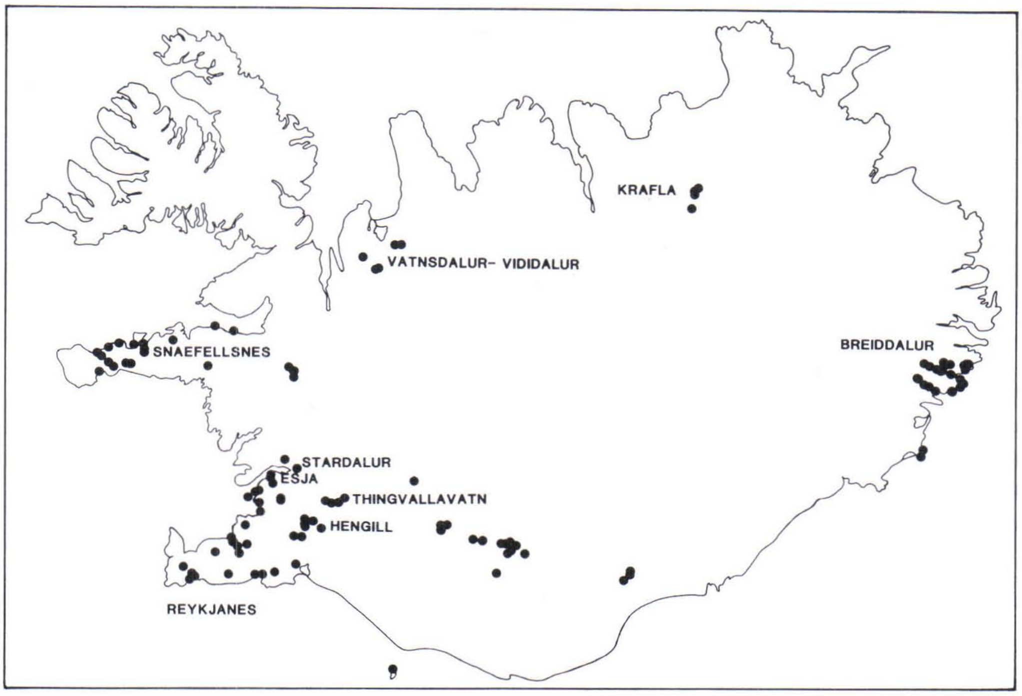


Fig. 2. Locations of sampling sites in Iceland.

FIELD WORK IN ICELAND

The primary objective of the rock sampling programme in Iceland was to collect a large volume of susceptibility data and thus to investigate the magnetization level of different rock types. Rock outcrops were chosen from both Tertiary and Pleistocene series and from active volcanic zones to ensure that different volcanic rock suites were covered (Fig. 2). One to three representative hand samples were taken at all sampling sites, and several susceptibility readings were made for each rock unit. In a lava layer the susceptibility varies in accordance with the geometry of the flows, and 1—2 samples were chosen to gange this variation. Wherever possible, the samples were taken in vertical sections to study variation in magnetic properties in a lava succession. Altogether 718 hand samples were collected in Iceland. Oriented samples were not taken.

With an average weight of 400 grams, most of the samples were taken with a hammer. A portable drill (Minidrill, Kupinniemen Konepaja Ky, Finland) was used when it was difficult to get an unweathered hand specimen manually. In-situ magnetic susceptibility measurements were made with a susceptibility meter, type JH-8 (Geoinstruments Ky, Finland).

LABORATORY MEASUREMENTS

The rock samples were measured in the petrophysical laboratory of the Geological Survey of Finland. The magnetic susceptibility was determined with the aid of a low-field AC bridge composed of two inductance coils and two resistors. Remanence measurements were made using a fluxgate magnetometer element in a magnetically shielded space. The remanent magnetization was determined by measuring the magnetic field of a sample alternately aligned in six cartesian directions. The measuring apparatus has been described in detail by Puranen and Sulkanen (1985) and Puranen (1989).

The densities were determined by weighing the samples in air and water. Two methods were tested to eliminate the effect of porosity on the density measurements:

1) soaking in water before weighing (2 days at room pressure)
2) crushing before soaking and weighing.

The test material consisted of nine samples with vesicles of varying volume and size. The porosities of the test samples were also determined from thin sections by point-counting at the Petrological Department of the Geological Survey of Finland.

In the first experiment the porosities calculated from the density data tended to be smaller than those obtained by point-counting (Fig. 3). The reason for this may be that the first method only measures open interconnected pore spaces but not disconnected vesicles inside the sample.

For the second experiment the test material was crushed to a grain size of less than 5 mm, and weighed dry and wet. The porosities calculated from this material are in general higher than those obtained with point-counting. Exceptions are sample No. 6, which contains abundant large vesicles and sample No. 9, which is full of vesicles of varying sizes.

As the densities of crushed samples generally correlate better with modal composition, it was decided to crush all the porous samples before weighing them. A similar procedure for determining the density of samples from pyroclastic deposits has been described by Cas and Wright (1987).

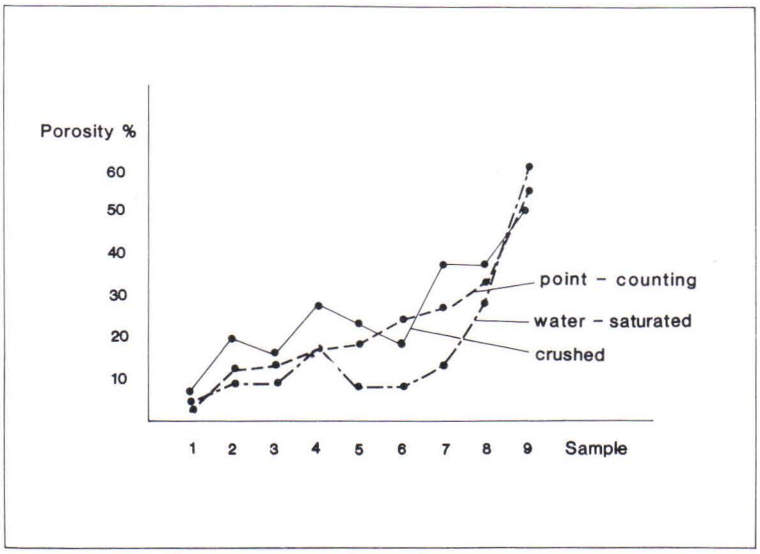


Fig. 3. Porosities of test samples by different methods.

The rocks were classified with the assistance of Icelandic geologists. The difference between tholeiites and olivine tholeiites is not always clear macroscopically, and there may be some misclassification of these groups in the present data. Chemical analyses have not yet been made. In the following graphs the densities measured after crushing and the corrected magnetic properties are used for all porous samples. The visually non-porous samples were not crushed. Some of these may have contained disconnected vesicles invisible to the eye, and therefore their measured densities may be erroneously low. These small systematic errors, however have little effect on the averages of large numbers of densities.

RESULTS FROM ICELAND

The petrophysical register maintained by the Geological Survey of Finland is managed with a special program package (Hongisto, 1986), and all the processing for this study was done using that package. The division of the sampled Icelandic rock types into basic, intermediate and silicic rocks used in the following paragraphs is shown in Table 1, which gives the average densities and magnetic properties of the Icelandic collection. Although some of the rock types are represented by only a few samples, they are included to give an idea of the level of the properties. Caution should be exercised in drawing conclusions from a small number of samples.

The mean densities of silicic rock types are well below the 2600 kg/m^3 level, but those of basaltic rock types above that (2701—3030 kg/m^3). Olivine tholeiites and andesites have similar average densities (2903 kg/m^3 and 2893 kg/m^3), being higher than the density of tholeiites (2741 kg/m^3) or of basalts (2812 kg/m^3).

In the present data the gabbros, dolerites, basic dykes, basic cone sheets, diorites, acid dykes and granophyres are included in the group of intrusive rock types, the remainder in the group of extrusive rock types. In general, the intrusive rocks yield higher susceptibility values than the extrusive rocks. This is as expected, because intrusions generally cool more slowly than lavas and therefore they may contain coarser magnetite grains. Diorites reveal one of the highest susceptibilities (about $66 \cdot 10^{-3}$ SI). Grant (1985) too, expects the highest magnetic susceptibilities to be found in rocks of intermediate composition. The high susceptibility of andesites in Iceland has already been pointed out by Kristjansson et al. (1977).

The intensities of remanence for extrusive basaltic rocks are 20—40 A/m, and for basic intrusives 1.2—6.1 A/m. The values of silicic rocks are below 1.1 A/m. The high values in

Table 1. The average density, susceptibility and intensity of remanence of Icelandic rock types. Grouping into basaltic, intermediate and silicic rocks is shown.

		Density kg/m^3		Susceptibility 10^{-6} SI		Intensity of remanence A/m	
Rock type	N	mean	std	mean	std	mean	std
Picrite basalt	16	3030	54	14678	14354	21.2	25.3
Alkali basalt	1	2991	—	66508	—	24.7	—
Basalt	96	2812	164	46116	29880	4.6	5.9
Olivine tholeiite	43	2903	163	17338	15155	19.6	11.5
Pillow lava	44	2792	195	8222	5765	24.7	8.2
Tholeiite	161	2741	209	31566	25045	26.1	58.7
Quartz tholeiite	12	2701	493	21013	20553	30.5	23.0
Transitional alkali basalt	7	2833	86	39474	17274	40.7	21.8
Gabbro	18	2879	131	70258	47158	3.4	4.1
Dolerite	43	2903	103	33866	30071	2.5	3.6
Basic dyke (diabase)	48	2841	158	39428	17257	6.1	5.6
Basic cone sheet	32	2782	148	42885	31045	2.8	2.5
Basic hyaloclastite	17	2235	363	5138	5870	1.2	1.6
Andesite	36	2893	80	44654	25263	6.1	7.2
Icelandite	1	2995	—	22258	—	28.1	—
Diorite	8	2692	59	66018	7956	.6	.6
Dacite	2	2385	162	3936	5250	.4	.5
Rhyolite	67	2366	187	6680	8790	1.1	4.4
Acid tuffite	3	2388	32	14146	2097	.2	.0
Ignimbrite	4	2227	107	18531	19975	1.0	1.7
Obsidian	3	2222	30	810	30	.0	.0
Acid dyke (felsite)	6	2520	168	26682	14973	.5	.3
Granophyre	20	2519	128	20859	17731	1.0	1.8

Table 2. Average petrophysical parameters of extrusive rock types representing the three geochemical series of Iceland.

Rock type		Tholeiitic mean	Tholeiitic std	Transitional mean	Transitional std	Alkalic mean	Alkalic std
Basalt	N	320	—	9	—	38	—
	D	2796	206	2834	126	2816	124
	S	28875	25007	35768	44518	41202	31958
	R	21055	43067	18562	19455	7716	14316
Andesite	N	32	—	2	—	—	—
	D	2898	70	2982	18	—	—
	S	47178	25114	15129	10082	—	—
	R	4763	4920	15512	17793	—	—
Dacite-rhyolite	N	20	—	10	—	39	—
	D	2396	170	2343	200	2357	192
	S	9145	6550	4777	5921	5763	10028
	R	895	1561	5676	10577	222	395

N = number of samples
D = density kg/m^3
S = susceptibility 10^{-6} SI
R = intensity of remanence 10^{-3} A/m

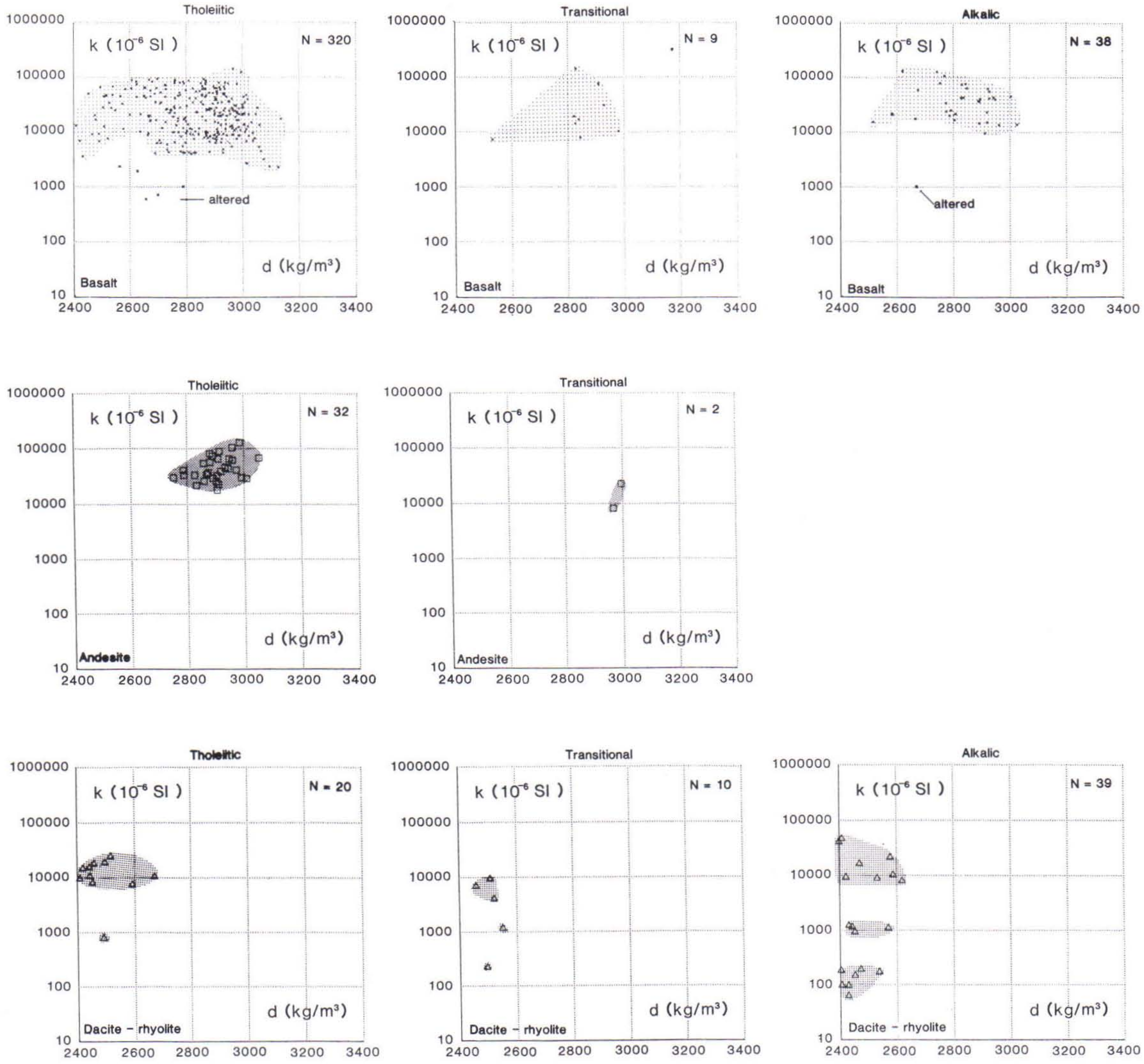


Fig. 4. Susceptibility versus density diagrams of extrusive rock types representing the three geochemical series of Iceland.

extrusive basalts are explained by the fine-grained ferrimagnetic minerals produced by rapid cooling (Hargraves & Petersen, 1971).

The extrusive rocks in Iceland are divided into three geochemical rock series: tholeiitic, transitional and alkalic (Jakobsson, 1979). The division of the present data is based on the volcanic system to which the samples belong, not on chemical analysis. The three series are further divided into basic, intermediate and silicic populations. The density and magnetic properties of the samples grouped in the three series are shown in Table 2.

The susceptibility versus density distributions of these three series (Fig. 4) show typical high susceptibilities (5—100 $\cdot 10^{-3}$ SI). In addition to the high susceptibility mode at 10 $\cdot 10^{-3}$ SI, the silicic rocks in the alkalic series reveal two additional modes at about 0.1 and 1. The lowest mode for basaltic rocks at about 1 $\cdot 10^{-3}$ SI represents hydrothermally altered samples. The intermediate rock types are characteristically dense (about 2900 kg/m^3) and of high susceptibility (47 $\cdot 10^{-3}$ SI), but the basaltic rocks in all three series also display many density values lower than 2700 kg/m^3.

The Q-ratios (the ratio of remanent to induced magnetization) reflect the magnetic mineralogy and the significance of remanence in the total magnetization of rock. Low Q-ratios generally indicate coarse magnetite grains, and high Q-ratios fine-grained magnetite, hematite or pyrrhotite. Hargraves and Petersen (1971) have studied the correlation between the petrology and magnetic properties of basaltic rocks, and attribute the high Q-ratios (10 to 100) of extrusives to rapid cooling. Q-ratios higher than unity reflect the enhanced remanent magnetization component relative to the total magnetic vector.

The susceptibility versus Q-ratio diagrams for the three series (Fig. 5) show that the Icelandic extrusive rock types are characterized by high Q-ratios. For the tholeiitic series the Q-ratios are mostly 0.5—10, but the basic rocks also display a considerable number of values above 10. As the susceptibilities are in the ferromagnetic range, it is possible that magnetiza-

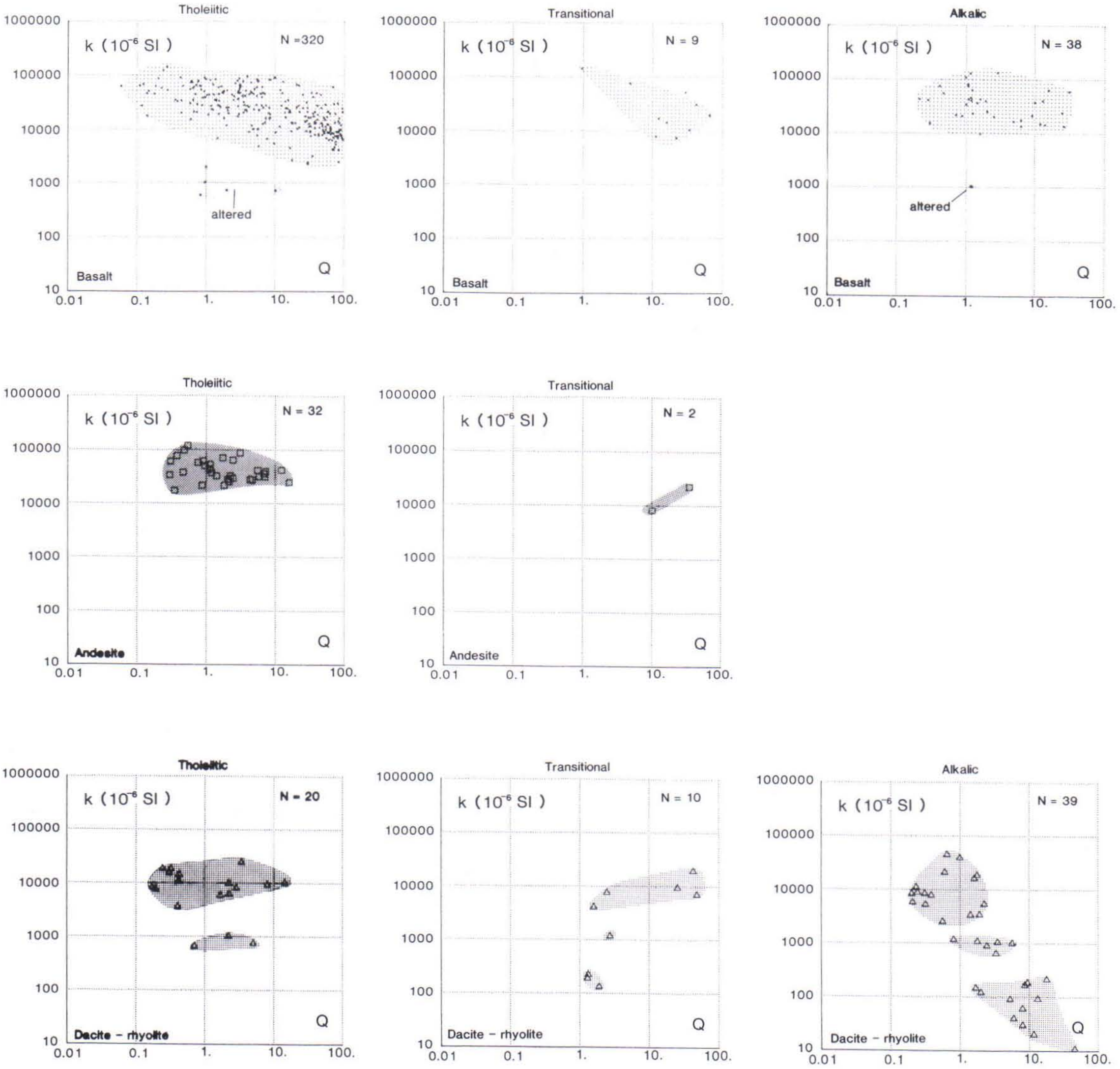


Fig. 5. Susceptibility versus Q-ratio diagrams of extrusive rock types representing the three geochemical series of Iceland.

Table 3. Average petrophysical parameters of intrusive rock suites in Iceland.

		Density kg/m³		Susceptibility 10⁻⁶ SI		Intensity of remanence 10⁻³A/m	
Rock suite	N	mean	std	mean	std	mean	std
Basic	136	2868	115	43076	31479	3683	4178
Intermediate	7	2706	46	66227	8570	564	613
Silicic	26	2520	135	22202	17030	856	1577

tion in these rocks is carried by both fine- and coarse-grained ferrimagnetic minerals. The transitional series is characterized by both high susceptibilities and high Q-ratios, and it is expected that their magnetization is mostly due to fine-grained ferrimagnetic material. The basaltic rocks in the alkalic series exhibit high susceptibility and medium Q-ratios much as do the rocks of the tholeiitic series. The silicic rocks in the alkalic series have three magnetic modes, the highest susceptibility mode referring to low Q-ratios and the lowest mode to high Q-ratios.

The average intensity of remanence of Icelandic intrusive basic rocks is about 20% that of extrusive rocks, but the susceptibility is higher by about 50% (Tables 2 and 3). This is also generally reflected in lower Q-ratios, all of which are below 20 (Fig. 6). Low Q-ratios are expected for intrusives by Hargraves and Petersen (1971), who reported Q-ratios of 0.5 to 15 for gabbros, dolerite dykes and sills, and ascribe this to a slow cooling rate.

The susceptibilities of basic intrusives in the present data, i.e. dolerites and gabbros, range from 10 to 100 $\cdot 10^{-3}$ SI (Fig. 6a). The very high susceptibility values in the diagram are associated with gabbros. The small unit with average densities of about 3000 kg/m^3 and susceptibilities below 10 $\cdot 10^{-3}$ SI is due to samples from the Plio-Pleistocene dolerite intrusion, Stardalshnukur at Stardalur. Hydrothermally altered samples display the lowest susceptibility values.

All the intermediate intrusive rock samples are from Snaefellsnes. Although there are only seven of them, they suggest a high level of susceptibility (about 66 $\cdot 10^{-3}$ SI in Table 3 and in Fig. 6b) and lower Q-ratios than do the basaltic intrusives. The plots of the silicic intrusives resemble those of the silicic extrusive rocks (Figs. 4 and 5).

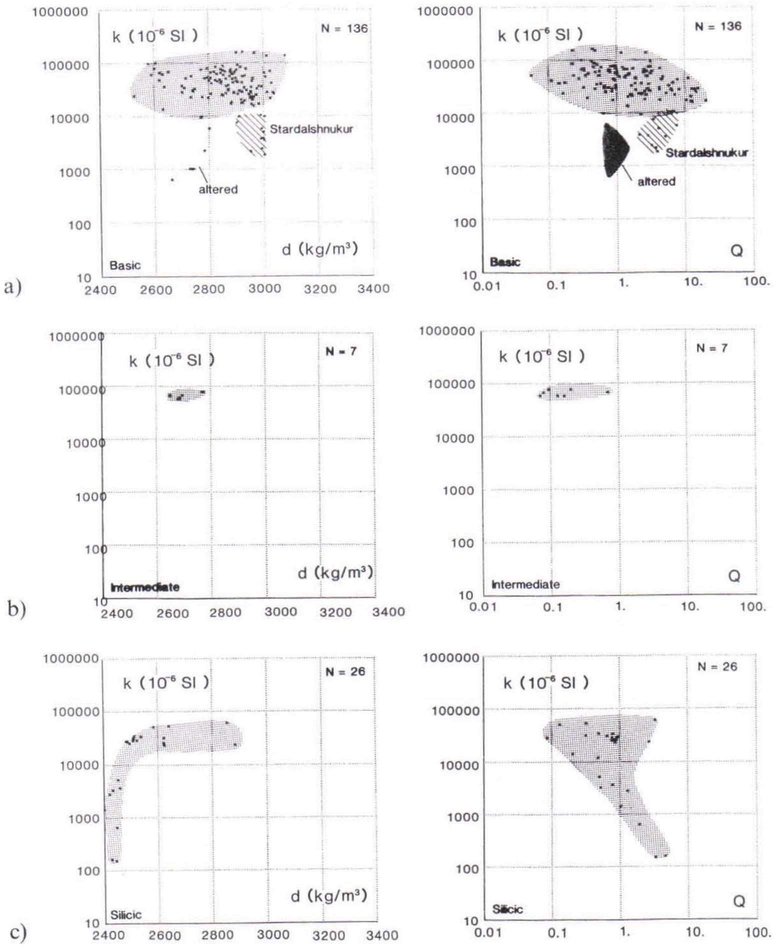


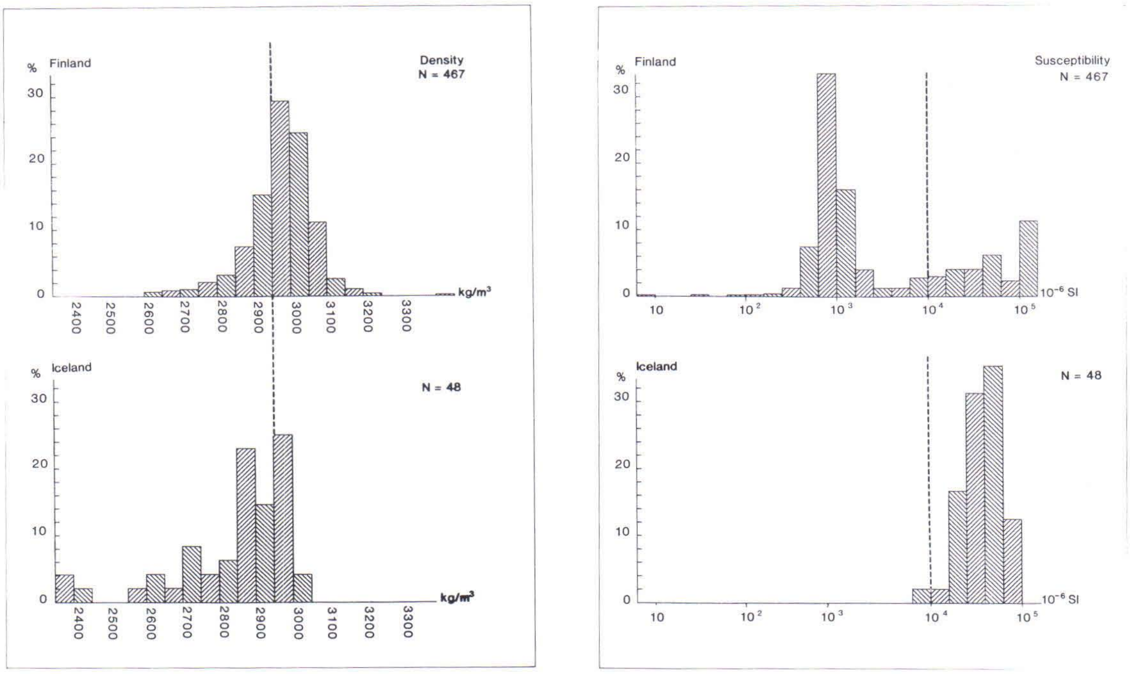
Fig. 6. Relations between density, susceptibility and Q-ratio of a) basic, b) intermediate and c) silicic intrusive rock types of Iceland.

COMPARISONS BETWEEN ICELAND AND NORTHERN FENNOSCANDIA

In the following chapters the magnetic properties of Icelandic and Fennoscandian rocks are compared, first between intrusive and then between extrusive rock types. The basaltic extrusive rocks are discussed separately.

In the Icelandic data on intrusive rocks, there are too few intermediate and silicic samples for comparison, and therefore only basic intrusives are considered. The Icelandic diabase and gabbro samples are from eastern Iceland, Snaefellsnes and the Esja-Stardalur area (locations in Fig. 2).

The densities of diabases in Iceland (Fig. 7) are lower than they are in northern Finland, but their intensities of remanence are considerably higher. The Icelandic diabases are in the ferromagnetic susceptibility range, but the Finnish diabases exhibit both paramagnetic and ferromagnetic susceptibilities. The susceptibilities in the Icelandic data average $39 \cdot 10^{-3}$ SI, and thus they are well in harmony with those of an earlier study by Kristjansson (1984). He determined the magnetic properties of 30 dykes in various parts of Iceland, obtaining an average susceptibility of about $30 \cdot 10^{-3}$ SI. These values correspond to the ferromagnetic susceptibilities of diabases in northern Finland.



a)

b)

c)

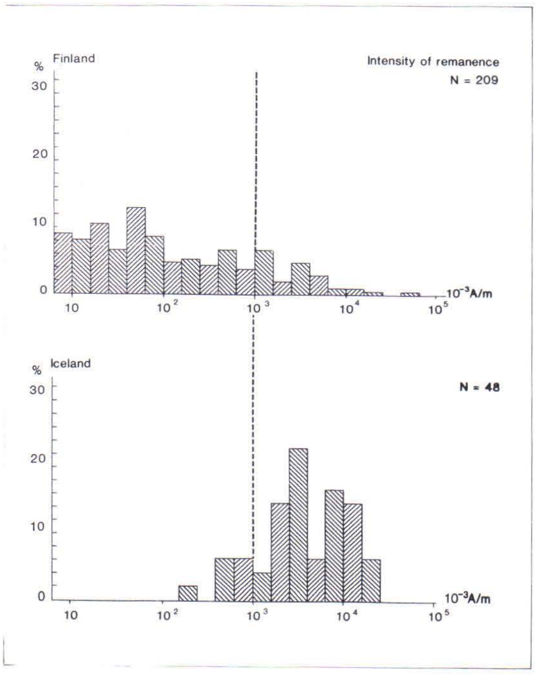
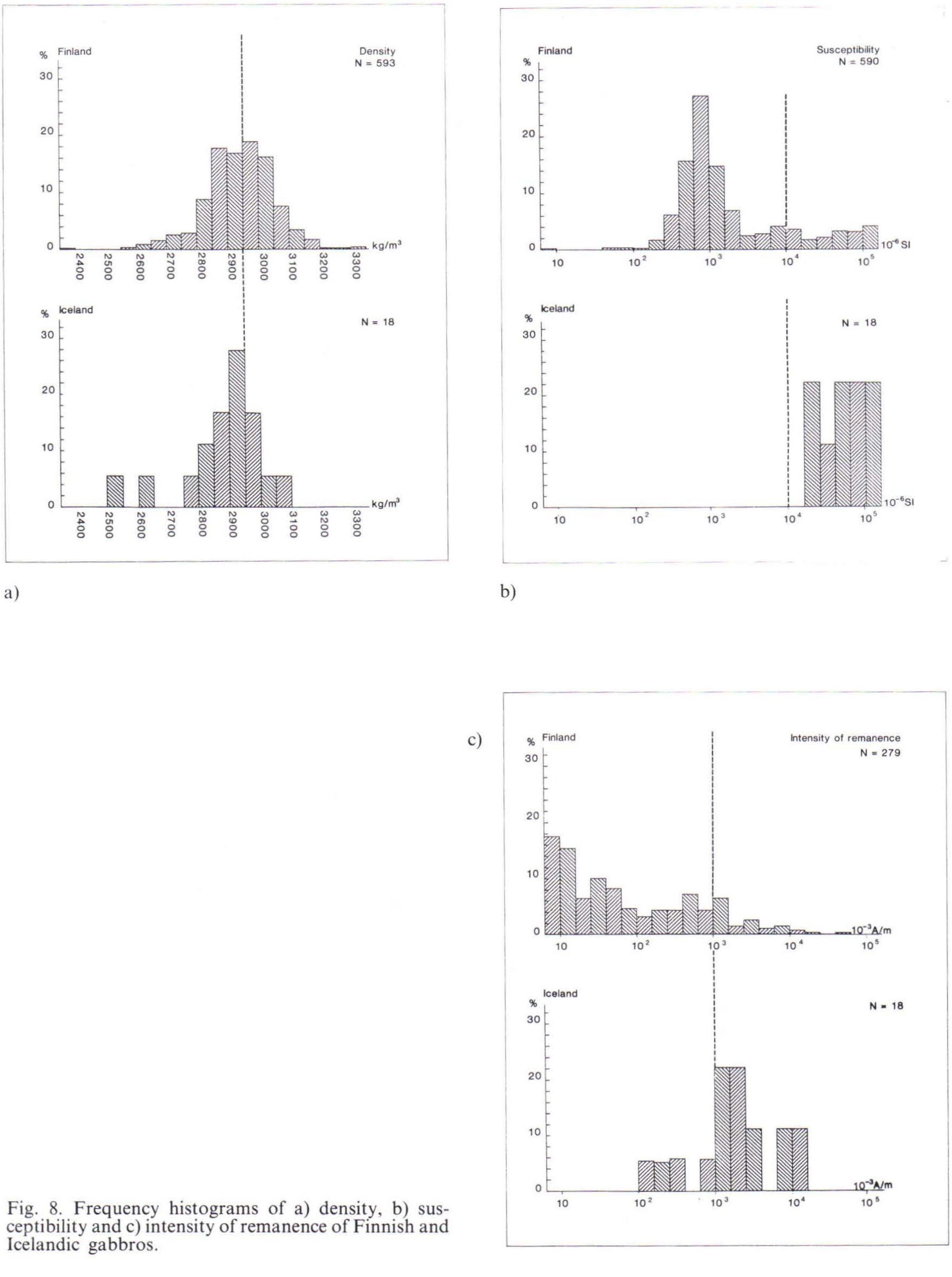


Fig. 7. Frequency histograms of a) density, b) susceptibility and c) intensity of remanence of Finnish and Icelandic diabases.

The paramagnetic susceptibility mode is totally lacking in the Icelandic data, but it is dominant in the Finnish data. Korhonen (1987) has studied the petrophysical properties of mafic dyke swarms in Finland. He attributes mean ferromagnetic susceptibilities higher than $43 \cdot 10^{-3}$ to opening and susceptibilities lower than $38 \cdot 10^{-3}$ SI to closing stages of the crust.

The data on gabbros show similar distributions of densities and magnetic properties as (Fig. 8) do those on diabases. Again the Finnish susceptibilities have two modes, but the significance of the ferromagnetic mode is lower than in diabases.

In the Icelandic data, the extrusive tholeiitic rocks associated with the rift zone are highly magnetic and their densities mainly cluster in the 2700—3000 kg/m^3 range. The transitional and alkalic rocks from non-rifting environments display wide variations in petrophysical properties (Figs. 4 and 5), in their susceptibilities in particular. It is postulated that areas of rifting and non-rifting can be characterized by distinct distributions of density and susceptibility. These distributions for Icelandic rocks are illustrated in Fig. 9.



a)

b)

c)

Fig. 8. Frequency histograms of a) density, b) susceptibility and c) intensity of remanence of Finnish and Icelandic gabbros.

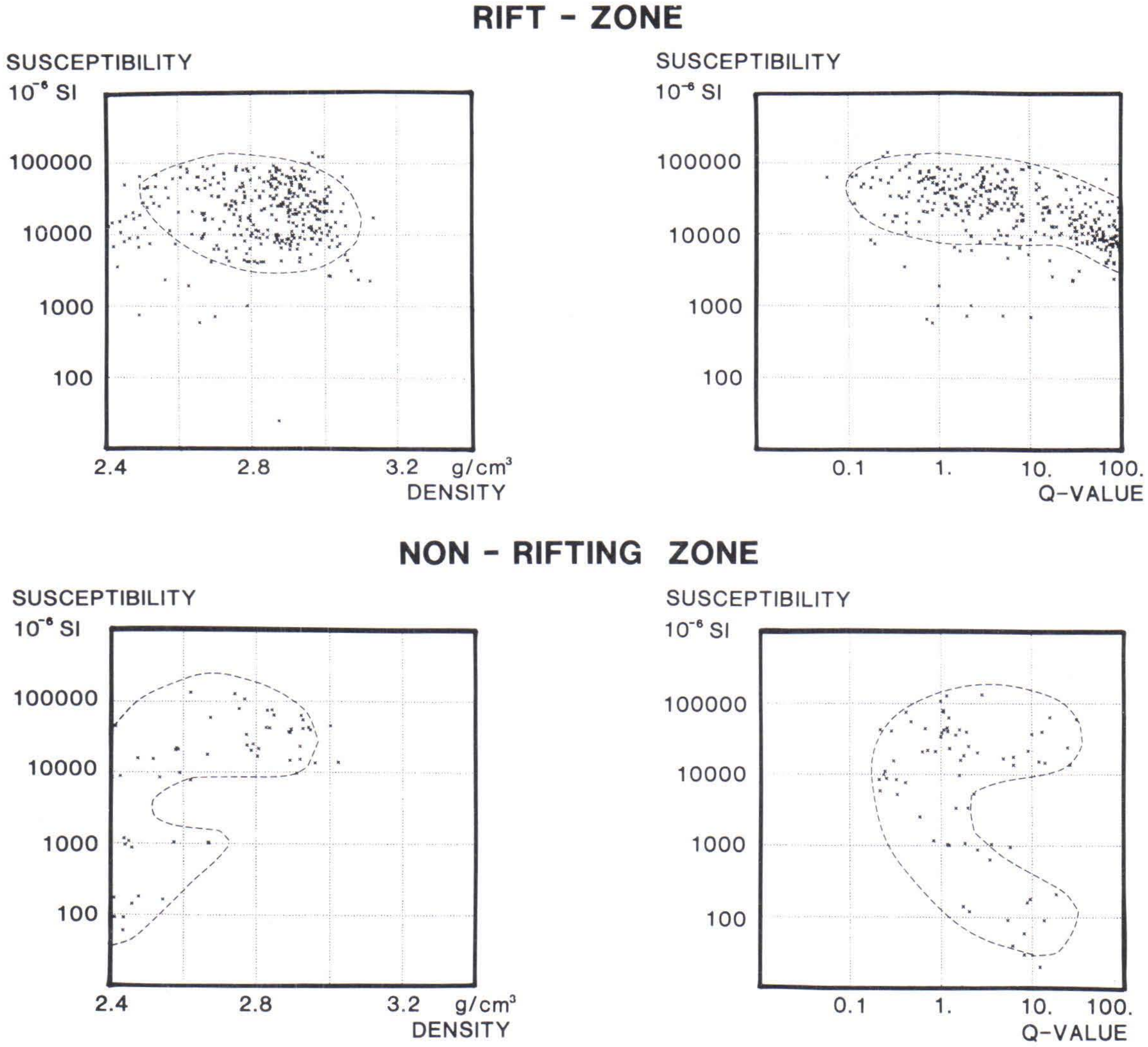


Fig. 9. Density and magnetic properties of Icelandic extrusive rocks associated with areas of rifting and non-rifting.

The lithostratigraphic supergroups in northern Fennoscandia may represent different geotectonic environments. The possibility that these differences are reflected in the physical properties of volcanic rocks was studied by comparing the densities and magnetic properties of volcanic rocks from various stratigraphic groups and also of the Icelandic and Fennoscandian data. In his study on the relations of susceptibilities to the iron and magnetite content of Precambrian rocks, Puranen (1989) concludes that the proportion of magnetite-bearing samples which can be estimated from the cumulative susceptibility distributions characterizes the mode of occurrence of magnetite and the oxidation ratio of iron. This in turn reflects the formation conditions of geological units and magnetite.

An outline of the Precambrian in Finland has been given by Simonen (1980). The sample localities in northern Fennoscandia (Fig. 10) refer to the following lithostratigraphic groups: Lapponian (age ca. 2.5—2.3 Ga), Karelian (age ca. 2.3—2.16 Ga) and Svecofennian (age ca. 1.9—1.8 Ga). The basic lavas and pyroclastic rocks from the Lapponian group are mainly tholeiitic basalts (Lehtonen et al., 1985). The Karelian group is dominated by tholeiitic volcanism and the Svecofennian group by felsic to intermediate calc-alkaline volcanism (Gaál & Gorbatschev, 1987).

The distributions of susceptibility versus the density and Q-ratio of the Fennoscandian metavolcanic extrusives (Fig. 11) show typical magnetic bimodality, with the paramagnetic susceptibility component in particular indicating a tendency towards increasing densities. This reflects the effect of increasing ferromagnesian mineral abundance.

Partioning into high and low susceptibilities is common to all three Precambrian groups. In the samples from the Lapponian and Karelian supergroups, the weakly magnetic unit dominates and the densities are high (averaging about 2900 kg/m^3), thus representing the densities of mafic rocks. In the samples of the Svecofennian supergroup, silicic rocks are more abundant than mafic rocks. In the susceptibility-density diagram this manifests itself as a dominance of low densities (below 2700 kg/m^3). A distinctive high susceptibility component at 10—100 $\cdot 10^{-3}$ SI is associated with silicic rocks. The absence of this component from the Lapponian and Karelian rocks is the major difference between the three groups.

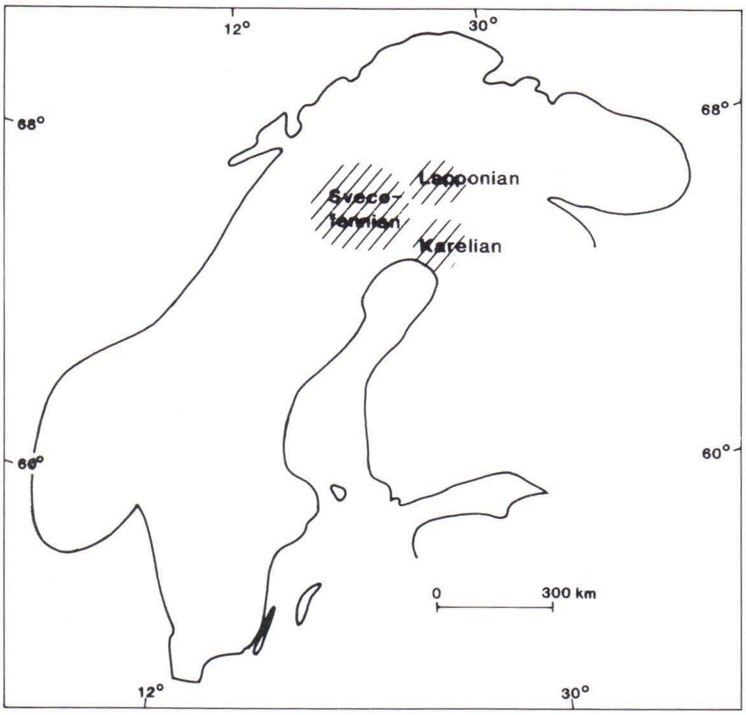


Fig. 10. Sample localities and corresponding lithostratigraphic supergroups in northern Fennoscandia.

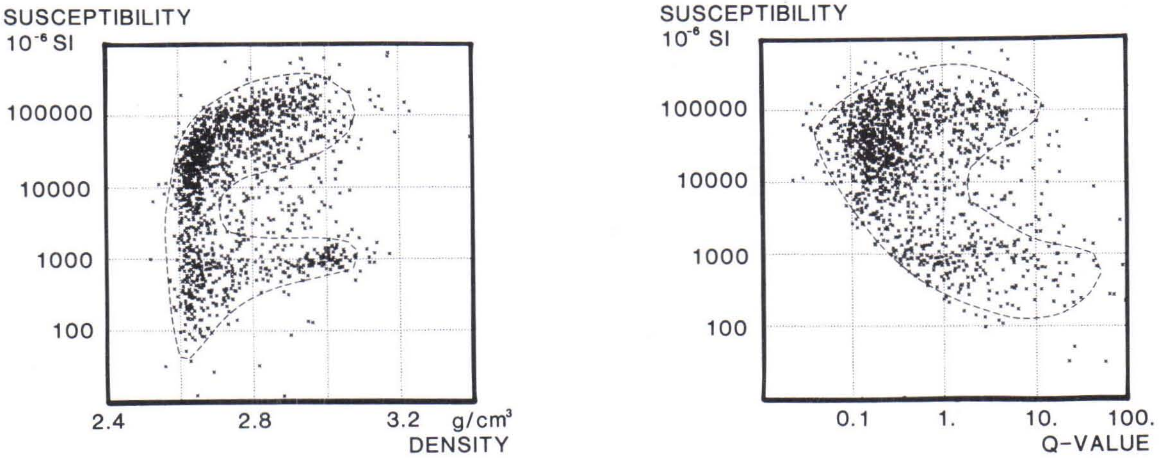
The Q-ratios associated with samples of paramagnetic susceptibility (Fig. 11) are similar in all three groups. A large number of susceptibility values in the range 1—10·10^{-3} SI with Q-ratios of 0.1—10 separate the Svecofennian samples from the two other groups. All the Q-ratios of the Karelian samples in the ferromagnetic susceptibility range are below 1. One reason for these differences is that the ferrimagnetic minerals in mafic metavolcanic rocks from the Karelian Supergroup are more coarse grained than are those in the rocks from the Lapponian and, especially, from the Svecofennian group. Also the higher average number of ferromagnetic susceptibilities in the Svecofennian group may be due to the dominant silicic rocks, which have higher oxidation states than the mafic rocks. Grant (1985) points out that igneous rocks of acidic composition contain oxides with a higher magnetite to ilmenite ratio than do basic rocks, although the total abundance of iron-titanium oxides in acid igneous rocks is usually much less than that in basic rocks.

The lower susceptibility mode in the paramagnetic range at about 1·10^{-3} SI is dominant in the Fennoscandian data. The higher mode in the ferromagnetic susceptibility range clusters around 70·10^{-3} SI; the Icelandic susceptibilities are between these two modes. A small low magnetic component is also observed in Icelandic rocks, contributed by hydrothermally altered rocks. Also the susceptibility/density plots of silicic rock types (Fig. 4) suggest that there is more than one magnetic unit.

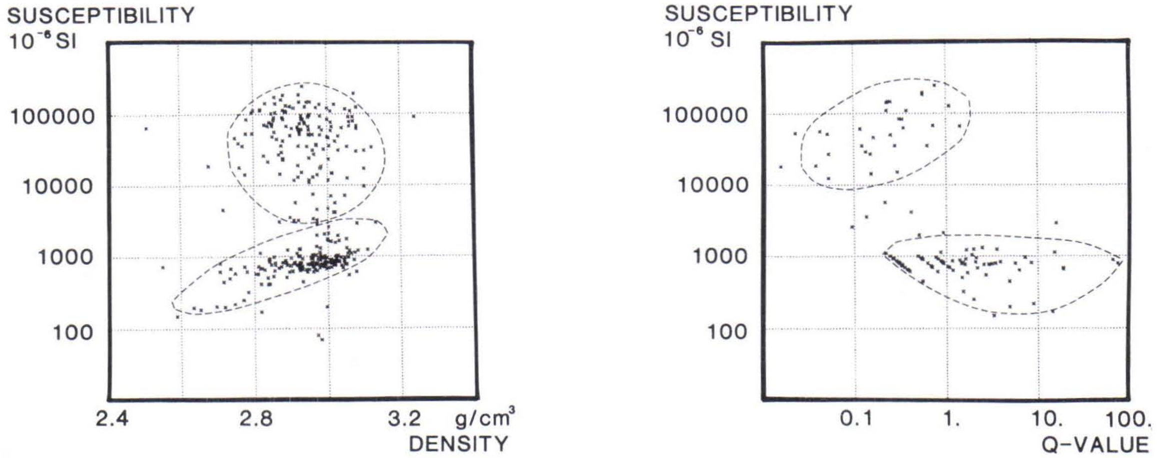
The difference in magnetic properties between Iceland and Fennoscandia is also evident in the average Q-ratios, which are about ten times higher in Iceland than in Fennoscandia. The intensities of remanence of Fennoscandian rocks are low, mostly below 1 A/m, whereas the Icelandic intensities are above 1 A/m.

The high susceptibility components of the samples from the Lapponian and Karelian groups resemble the rift zone data from Iceland. The distribution of densities and susceptibilities of the Svecofennian samples resemble the non-rifting data.

SVECOFENNIA



KARELIA



LAPPONIA

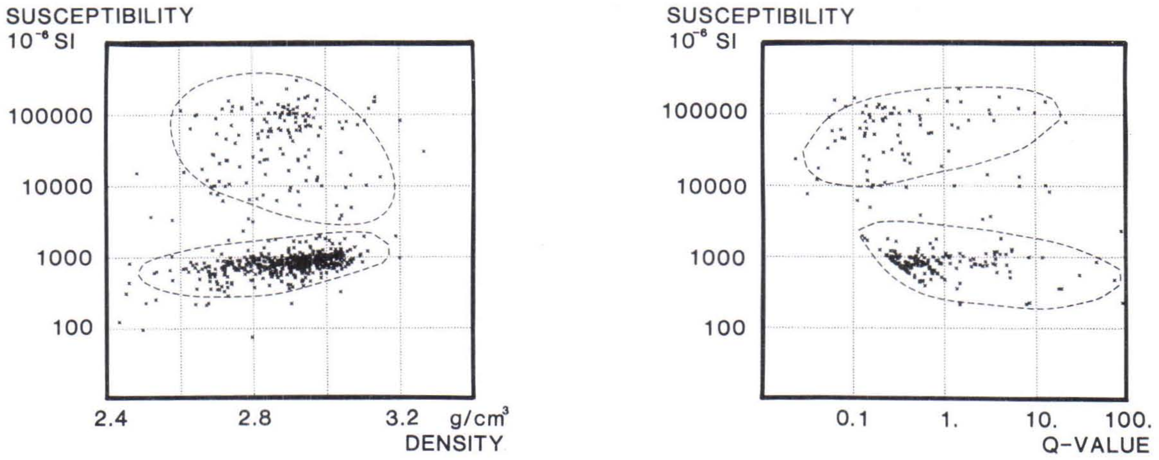


Fig. 11. Density and magnetic properties of metavolcanic rocks associated with various stratigraphic groups in northern Fennoscandia.

COMPARISONS OF BASALTIC EXTRUSIVE ROCKS

The varying distributions of petrophysical properties of rocks representing rift zone and non-rifting zone environments are mainly due to the larger proportion of felsic rocks in the non-rifting environment. It is of interest to establish if there are any differences between exclusively mafic rocks.

The samples in the group of basalt lavas derive from basalts, tholeiites and olivine tholeiites. The partial destruction of titanomagnetite grains in the process of submarine weathering of basalts reduces the magnetization of pillow basalts (Rapeyev et al., 1981). The mean susceptibility of pillow lavas in the present data is about half that of subaerial olivine tholeiites. Pillow lavas are not here included in the group of basalt lavas. The following comparisons are made first between geological units of Iceland and then between those of Iceland and Fennoscandia.

The frequency histograms of the susceptibilities and intensities of remanence display similar values for subaerial basalt lavas in different parts of the active rift zone (Reykjanes, Hengill and Krafla, Fig. 12a). The histograms associated with Tertiary and Pleistocene formations (samples from Breiddalur, Stardalur and Esja, also Table 4) also reveal similarities in properties. Kristjansson (1984) has shown that the magnetic properties of basaltic lavas do not vary greatly between regions outside the active volcanic zone. However, the modal intensities of remanence in different areas tend to grow with the decreasing age of formations.

In Tertiary formations, most susceptibilities are above $25 \cdot 10^{-3}$ SI, but in Postglacial formations below that. On the basis of susceptibility and remanence histograms the samples can be divided into two groups: samples from Tertiary and Pleistocene formations with higher susceptibilities, averaging $44 \cdot 10^{-3}$ SI, and lower intensities of remanence, averaging 6 A/m (Fig. 12b); and samples from Postglacial formations of the active rift zone with corresponding mean values of $18 \cdot 10^{-3}$ SI and 43 A/m. The average susceptibilities are 60% lower and the mean density is 2% lower in the samples from the Tertiary formations than in the Postglacial samples.

The density and magnetic properties of basaltic metalavas from various supergroups in northern Fennoscandia were compared with the same properties of three groups of Icelandic basaltic lavas. These groups are the Tertiary formations of Breiddalur, representing rocks of older rift, the non-rifting zone of Snaefellsnes and the active rift zone.

The modal densities of Icelandic and Fennoscandian mafic igneous extrusive rocks are 2900—3000 kg/m^3 (Fig. 13). The frequency histograms are alike, suggesting similar bulk compositions. Younger rock groups have higher mean densities than older groups (Table 5).

The mean susceptibilities of Fennoscandian rocks decrease as the age of the group increases (Table 5). In the bimodal histograms this is indicated by a growing proportion of paramagnetic susceptibilities while the significance of the higher mode, in the ferromagnetic range, decreases. In all three age groups the lower mode is at 1 and the higher mode at $100 \cdot 10^{-3}$ SI. The Lapponian samples contribute to the highest paramagnetic susceptibility peak and the lowest ferromagnetic peak.

The susceptibility mode of the Icelandic basaltic rocks is between the high- and low-susceptibility modes of the Fennoscandian metavolcanic rocks. Older rift basalts have higher susceptibilities than the active rift basalt lavas. The samples from Snaefellsnes include both recent and Pleistocene basalts. Thus the susceptibility histogram of the non-rifting zone displays two peaks.

The intensities of remanence of basaltic metalavas in northern Fennoscandia are typically low, usually less than 1 A/m (Fig. 13 and Table 5). Only the Svecofennian supergroup reaches the average level of remanence values in Iceland, being about 3 A/m. The Fennoscandian intensities of remanence decrease as the age of the group increases. In Iceland the older rift basalts display lower intensities of remanence than do the active rift basalts. The mean values are less than 6 A/m in the Tertiary and non-rifting group but about ten times higher in the active rift zone.

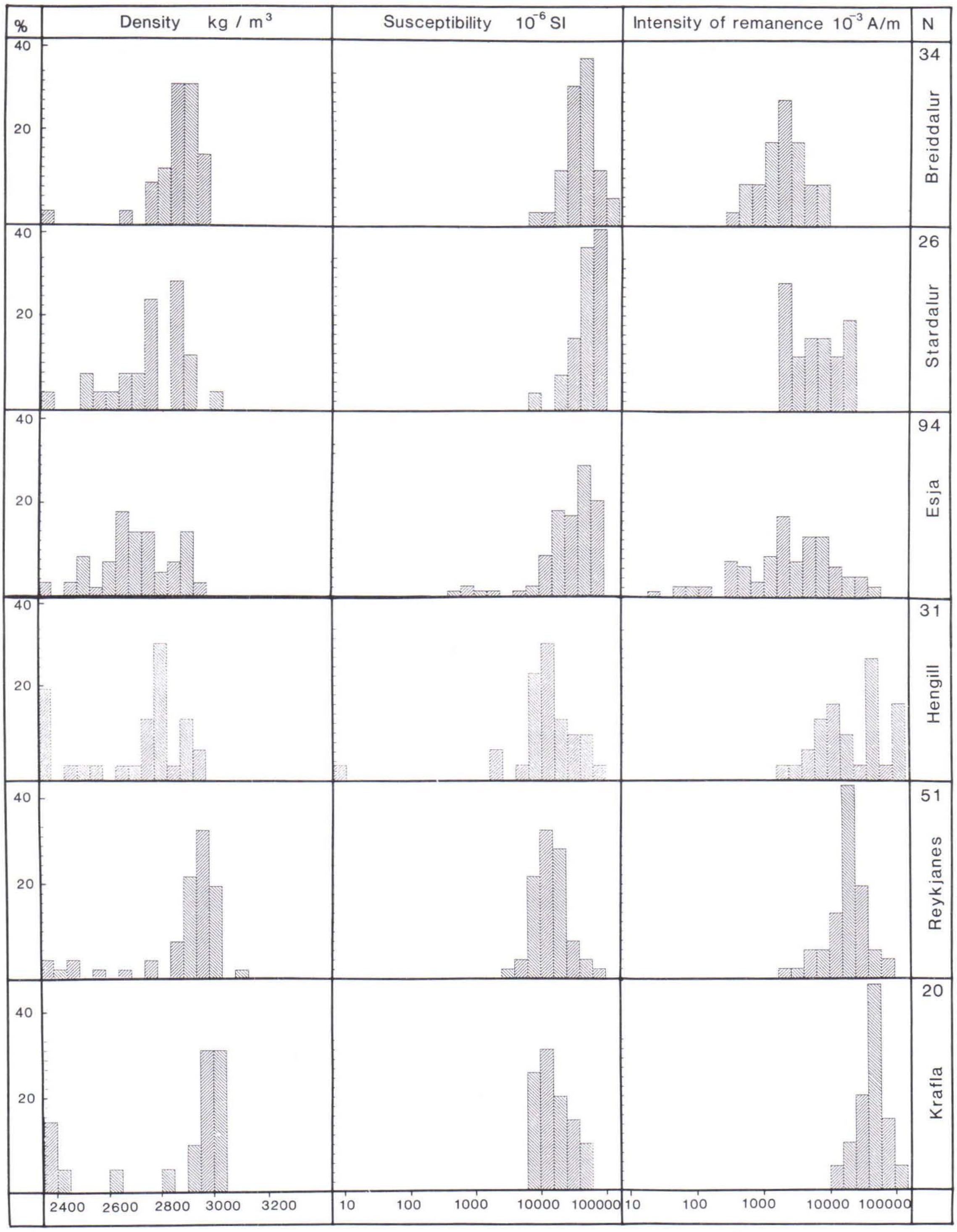


Fig. 12a. Petrophysical properties of basaltic extrusives in different areas of Iceland.

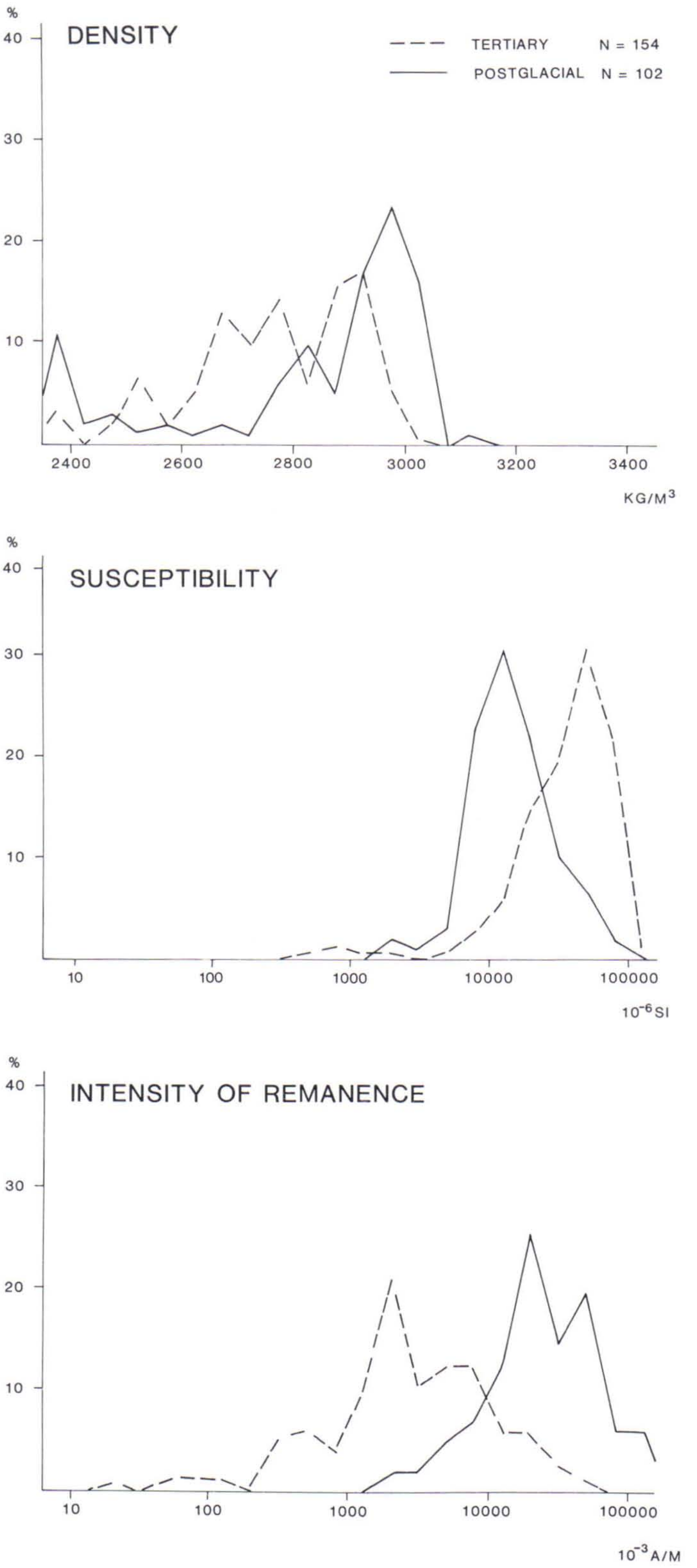
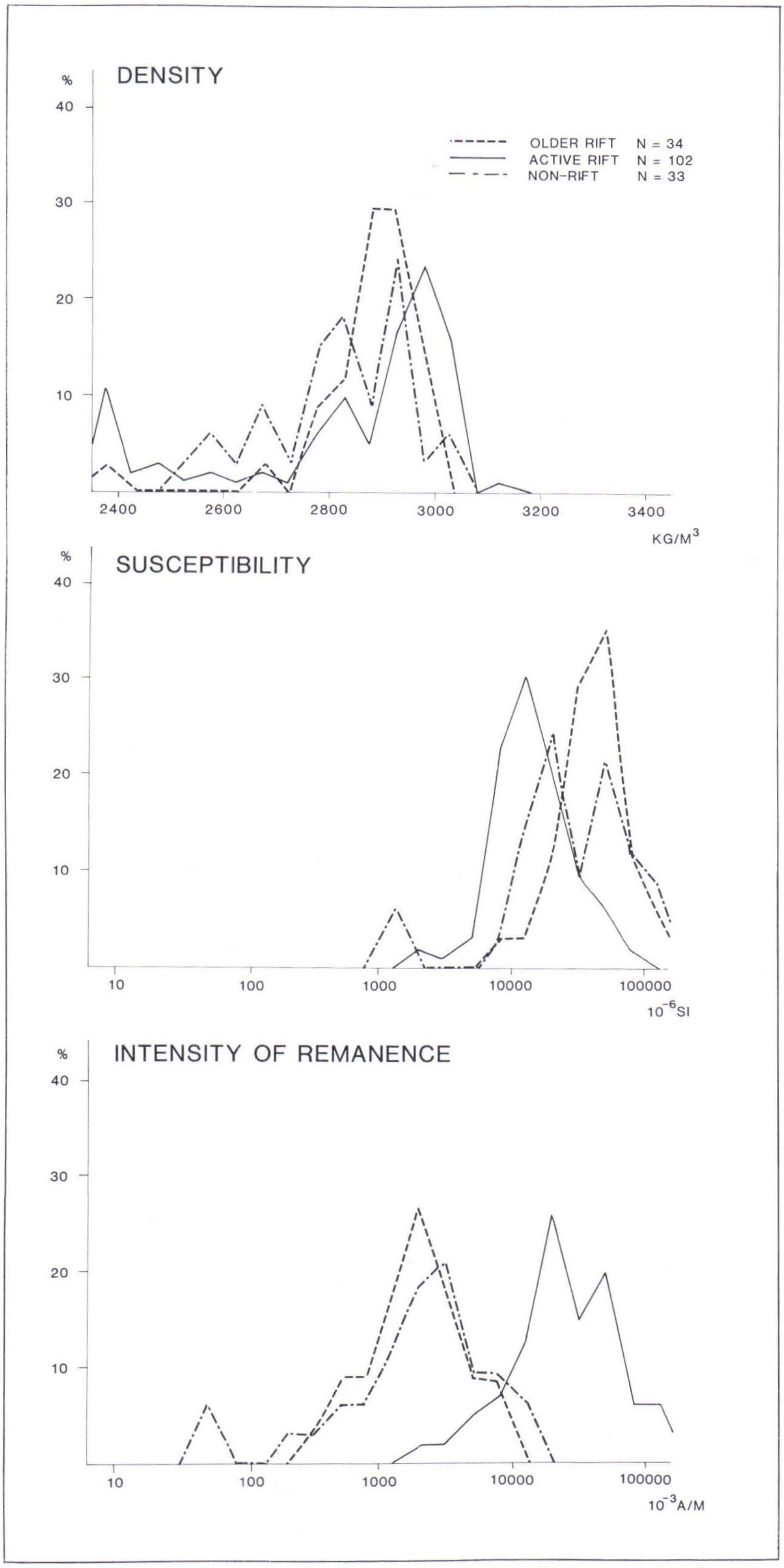
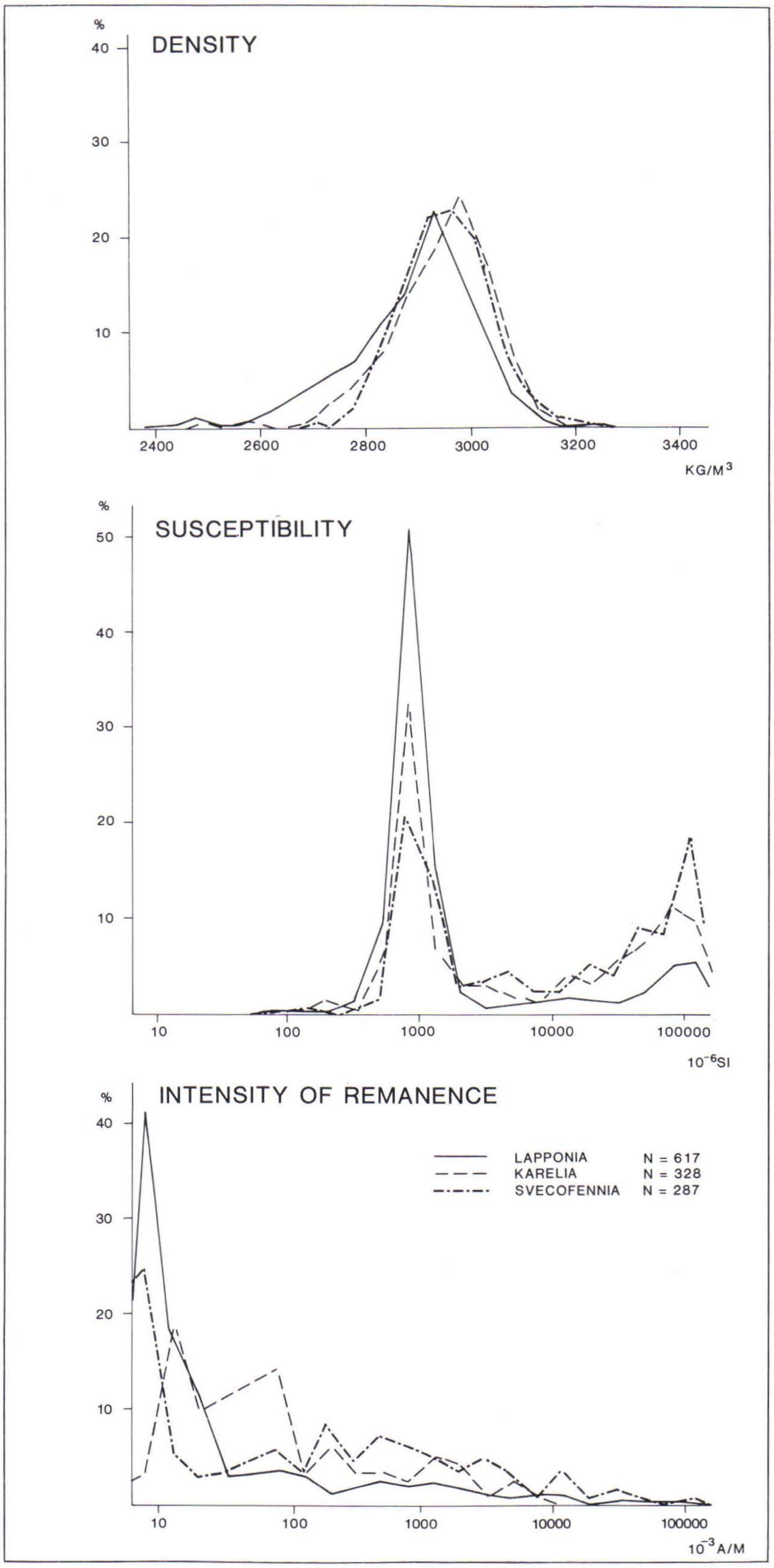


Fig. 12a. Petrophysical properties of basaltic extrusives in different areas of Iceland.



a)

Fig. 13. Petrophysical properties of basaltic rocks in different stratigraphic groups: a) in Iceland, b) in northern Fennoscandia.


%
DENSITY
40
30
20
10
2400
2600
2800
3000
3200
3400
KG/M³
%
SUSCEPTIBILITY
50
40
30
20
10
10
100
1000
10000
100000
10⁻⁶SI
%
INTENSITY OF REMANENCE
40
30
20
10
LAPPONIA N = 617
KARELIA N = 328
SVECOFENNIA N = 287
10
100
1000
10000
100000
10⁻³A/M

b)

Table 4. Mean petrophysical properties of subaerial basalt lavas from different areas in Iceland.

		Density kg/m^3		Susceptibility 10^{-6} SI		Intensity of remanence 10^{-3} A/m	
	N	mean	std	mean	std	mean	std
Breiddalur	34	2868	115	46820	29295	2590	2083
Stardalur	26	2762	151	54634	24714	8004	6502
Esja	94	2723	154	39689	24584	6488	9830
Reykjanes	51	2890	186	17256	14160	22677	13692
Hengill	31	2672	303	18523	17137	71234	117886
Krafla	20	2817	290	18600	10728	49262	24638
Snaefellsnes	33	2816	129	40577	33801	3414	3775

Table 5. Density, susceptibility and intensity of remanence of basic metavolcanic rock samples representing various stratigraphic groups referred in text.

		Density kg/m^3	Susceptibility 10^{-6} SI	Intensity of remanence 10^{-3} A/m
Lapponian	N	617	595	403
	mean	2895	14416	1014
	std	120	36355	6202
Karelian	N	328	328	121
	mean	2939	29702	441
	std	95	44362	1116
Svecofennian	N	287	287	287
	mean	2962	58054	3016
	std	84	77082	11344
Tertiary	N	154	154	154
	mean	2761	43787	5883
	std	156	26165	8365
Postglacial	N	102	102	102
	mean	2809	17905	42647
	std	264	14442	69251
Non-rifting	N	33	33	33
	mean	2816	40577	3414
	std	129	33801	3775

DISCUSSION

The partitioning of volcanic rocks into highly and weakly magnetic units observed in the Fennoscandian data is not evident in the Icelandic data. The ferromagnetic susceptibilities of Fennoscandian rocks between 10 and 300 $\cdot 10^{-3}$ SI, which are mainly due to the ferrimagnetic mineral content, are higher on average than the susceptibilities of Icelandic basaltic lavas also in the ferromagnetic range. One explanation for this difference may simply be the variation in grain size of the ferrimagnetic minerals. Finely crystalline iron oxides have lower magnetic susceptibilities and higher remanences than coarse-grained iron oxides.

The paramagnetic component in Fennoscandian rocks at about $1 \cdot 10^{-3}$ SI is mainly due to mafic silicates. According to these data no paramagnetic susceptibilities are associated with unaltered Icelandic basaltic rocks. Paramagnetic units are formed later by hydrothermal low-temperature alteration, as shown by measurements on altered basalts. In the more evolved Icelandic volcanic centres, which also produce silicic rocks, the variation in magnetic properties is wider, and a paramagnetic susceptibility component can also be distinguished.

The abundance of paramagnetic susceptibility values in Fennoscandian rocks grows with the increasing geological age of the lithostratigraphic groups. The present data show that the intensities of remanence and the densities tend to decrease with growing age.

These petrophysical trends can be explained by changes in magnetic mineralogy, either in the internal structure or in the abundance or grain size of the magnetic minerals. Several reactions have been reported that either form or destroy magnetite (Grant, 1985). It is suggested that the change in mineralogy from highly magnetic minerals into minerals of low magnetization by later metamorphic and deformation processes, as seen in the Fennoscandian data on metavolcanic rocks, is mostly due to the migration of iron from ferrimagnetic minerals into mafic silicates, as described by Rapeyev et al. (1981) in their study on alterations in titanomagnetites from oceanic basalts. Also, for example in Bergslagen, Sweden, metamorphism has had a reducing effect on the magnetite content and hence on the magnetic susceptibility of rocks (Aaro, 1981). Puranen (1989) points out that metamorphism seems to increase the abundance of fine-grained iron oxides in basic rocks. The samples that contain these secondary alteration products are characterized by high Q-ratios.

Another explanation for the different magnetic properties between Iceland and Fennoscandia may be that the geotectonic environments have an effect on the magnetic properties. The low-magnetic component in Precambrian rocks may be partly primary, caused by differences in the composition or conditions of the source magma, and partly a result of later deformation processes. Furthermore, a weakly magnetic but dense component may typically be attributed to continental rift volcanism. Since oceanic stages have also existed during the evolution of the Precambrian bedrock of Finland, the bimodal susceptibility distributions may contain signs of both marine and continental environments. In that case, the dense and highly magnetic unit is associated with settings such as oceanic rifts, and the dense and weakly magnetic component with more continental riftlike settings.

In general, Finnish rocks are thought to have been petrophysically similar to Icelandic rocks at the time of their extrusion. It is postulated that either submarine alteration or metamorphic processes have obliterated the ferromagnetic component in many of the Finnish rocks.

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