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The palaeomagnetism of six Early Proterozoic (~2440 Ma) layered intrusions in northern Finland was investigated using the multicomponent analysis techniques for natural remanent magnetization (NRM). Four remanence components were isolated by alternating field and thermal treatment. The most common magnetization, **A**, dominantly of normal polarity and with the mean direction D = 346°, I = 39°, k = 148, α 95 = 6°, N = 6 intrusions, is an overprint acquired during the peak of the Svecokarelian orogeny about 1880 Ma ago. The widespred hydrothermal activity during this orogeny also partly reset the U-Pb (Zr) isotopic system. Magnetization **B**, of normal polarity and with the mean direction D = 25°, I = 36°, k = 120, α 95 = 8°, N = 4, records either the termination of the Svecokarelian orogeny about 1750 Ma ago or a much younger geological event. Component **D** is dominantly of normal polarity and has the mean direction D = 114°, I = 48°, k = 15, α 95 = 21°, N = 5. Tentative contact and tilt tests suggest that this component was acquired during late stages of the primary cooling of the intrusions about 2400 Ma ago at the same time as the intrusions underwent tectonic tilting. The fourth component, **E**, with dual polarity, has the mean direction D = 261°, I = 51°, k = 87, α 95 = 10°, N = 4 and is interpreted as a thermochemical overprint acquired during the Jatulian (~2100 Ma) rifting and faulting period. Basement granitoids surrounding the intrusions exhibit distinct Archaean (~2700 Ma) magnetization (with dual polarity), which is often masked by Svecokarelian overprints. A thermotectonic model for the origin, nature and relative ages of the remanence components will be proposed in the light of blocking temperature spectra, tilt and baked contact tests and remanence carriers. Based on the new Apparent Polar Wander Path (APWP), the drift history of Fennoscandia for the period 2700-1750 Ma is presented.

Key words: paleomagnetism, layered intrusions, remanent magnetization, absolute age, pole positions, polar wandering, continental drift, Proterozoic, Koillismaa, Koitelainen, Finland

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CONTENTS

1. INTRODUCTION

As applied to Precambrian rocks, palaeomagnetism is a powerful method for unravelling the thermotectonic and kinematic histories of the shields. This is because the past movements of the tectonomagmatic blocks that form the present-day shields can be measured from their Apparent Polar Wander Paths (APWP) (e.g. Burke et al. 1976, Pesonen and Neuvonen 1981, Irving *et al*. 1984, Piper 1987). The basic requirement in applying palaeomagnetism to Precambrian tectonic problems is that the relative ages of the remanent magnetization components, which form the resultant natural remanent magnetization (NRM) vector, can be resolved by laboratory treatment of the rocks.

There exists a large gap (with no poles) between the Archaean (2700 Ma) and Svecokarelian (1900 Ma) APW segments (see also Pesonen and Neuvonen 1981, Elming 1985) in Fennoscandian palaeomagnetic database (Pesonen *et al*. 1989b). The only pole derived from Early Proterozoic rocks (Neuvonen 1975) is probably not primary as it is based on a study made before multicomponent analysis methods were invented. Therefore the drift of Fennoscandia during Early Proterozoic time is poorly defined, as is its position in relation with other shields (Piper 1982).

The Early Proterozoic mafic layered intrusions (age 2440 Ma) in northern Finland intruded into the Archaean basement or between the basement and Early Proterozoic supracrustal rocks (Fig. 1). The layered intrusions have attained considerable geological and geophysical interest because of their PGE-bearing Cu-Ni sulphide occurrences (e.g. Vuorelainen *et al.* 1982, Lahtinen 1985, Alapieti and Lahtinen 1986). They are ideal targets for establishing the APW path for the Early Proterozoic for the following reasons. First, they have been extensively mapped both geologically (Piirainen *et al.* 1974, 1978, Alapieti *et al*. 1979, Mutanen 1979, Alapieti 1982, Söderholm and Inkinen 1982, Vuorelainen *et al.* 1982) and geophysically (Pesonen 1970, Saviaro 1976, Hjelt *et al.* 1977, Ruotsalainen 1977, Lammi 1986 and Rekola 1986). According to these studies, the intrusions are only slightly metamorphosed and thus warrant a search for a primary magnetization. Secondly, the intrusions are tectonically tilted and faulted (e.g. Alapieti 1982), making it feasible to test the possibility that some of the NRM components are pre-tilting. The intrusions have heated the nearby Archaean country rocks, enabling the baked contact test to be conducted and thus the type and age of the magnetizations to be established. Third, the U-Pb (Zr) isotopic age data (Alapieti 1982; and this study) reveal that although the intrusions were emplaced about 2440 Ma ago, there is evidence of isotopic resetting about 1900 Ma ago (H. Huhma, personal communication, 1984). Together with tectonic and contact tests, the age data create a favourable background against which to assign the absolute and relative ages of the palaeopoles and in this way to calibrate the Early Proterozoic APWP.

The purpose of this paper is to report new palaeomagnetic data on the Koillismaa and Koitelainen layered intrusions and on the surrounding Archaean terranes (see Fig. 1). We shall first report results from the multicomponent analysis of the NRM based on detailed demagnetization studies of the rocks. The relative ages of the components were established by investigating the blocking temperature spectra and hysteresis properties of the rocks and by gathering petrological information on the opaque oxides. The relationship between the magnetization ages and tectonics was then established with the aid of baked contact and tectonic tilt tests. From these, a model was deduced for the tectonomagmatic history of the intrusions and for the age, nature and origin of each component. In the

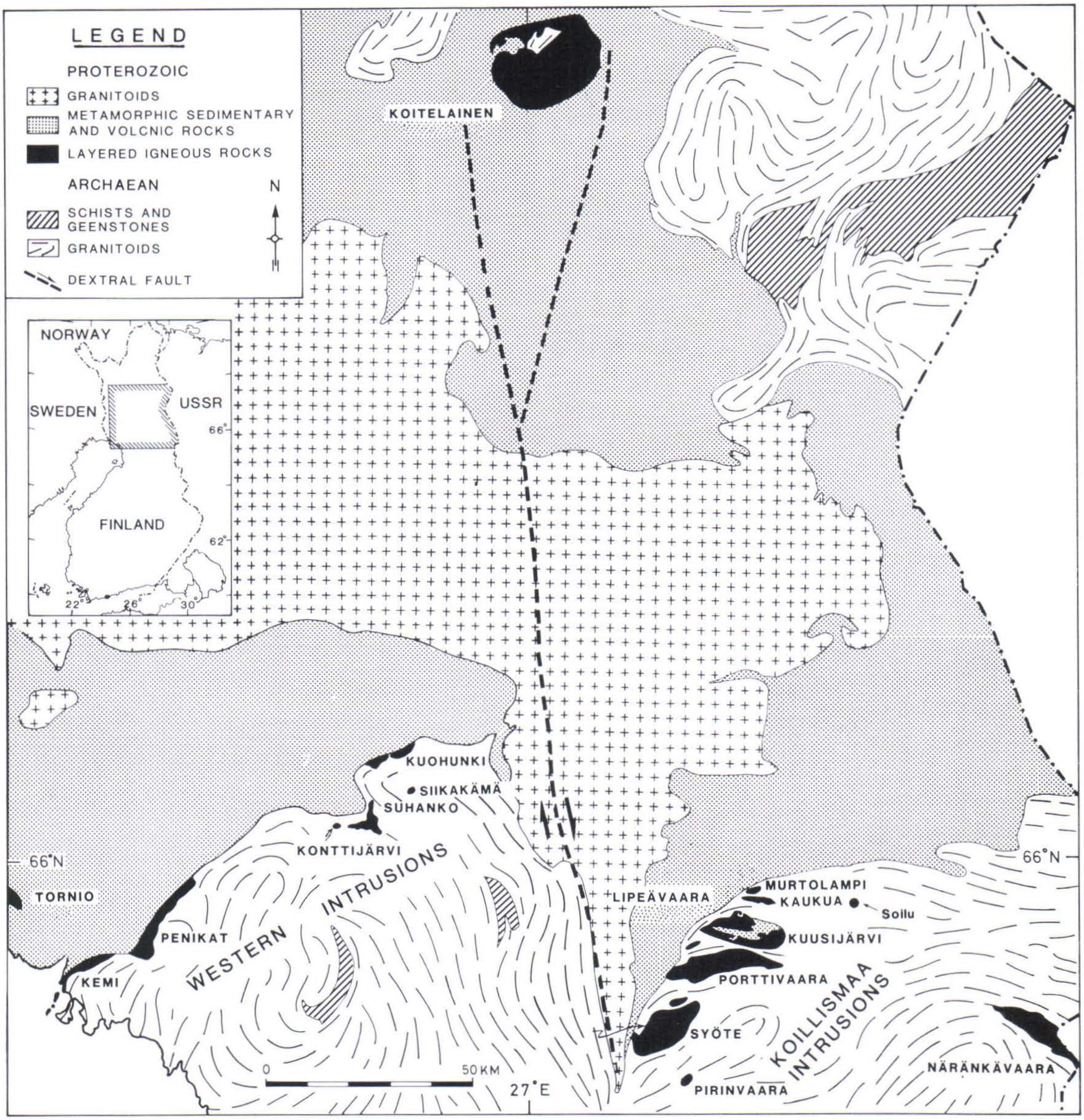

Fig. 1. General geological map of central northern Finland (after Simonen 1980 and Alapieti 1982). The black areas delineate the present locations of the Early Proterozoic layered intrusions that form two major belts, the western intrusions and the Koillismaa intrusions. These belts are separated by a major dextral strike-slip fault that passes either west (Gaál 1985) or east (Korhonen 1981) of the separated Koitelainen intrusion. The six intrusions studied in this work are Näränkävaara, Syöte, Lipeävaara, Kaukua, Murtolampi and Koitelainen.

light of these data we propose a new APW segment, calibrated with new, precise U-Pb (Zr) ages, for northern Fennoscandia 2700—1750 Ma ago. From the APW curve we calculated the palaeolatitudinal drift for Fennoscandia during Early Proterozoic times. The tectonic and kinematic implications of this curve for the evolution of the Fennoscandian Shield during the Late Archaean - Early Proterozoic are discussed.

2. GEOLOGICAL SETTING OF THE INTRUSIONS

Figure 1 shows a general geological map of the study area in northern Fennoscandia. The major bedrock units are the Early Proterozoic granitoid and supracrustal units in the north and the Archaean granitic and gneissic basement terrane in the south. The Early Proterozoic layered intrusions, comprising about twenty separate bodies in a belt extending from eastern Sweden via western Finland to northwestern USSR (Alapieti and Lahtinen 1986), intrude the boundary between these major crustal units.

The mafic to ultramafic layered intrusions form two distinct belts in northern Finland: the western intrusions and the eastern Koillismaa complex (Fig. 1). The western belt comprises the bodies of Tornio, Kemi, Penikat, Suhanko-Konttijärvi, Kuohunki and Siikakämä and the Koillismaa complex consists of the Näränkävaara, Pirinvaara, Syöte, Porttivaara, Kuusijärvi, Lipeävaara, Kaukua and Murtolampi bodies. The largest layered intrusion body is the Koitelainen intrusion, which lies some 200 km north of the Koillismaa complex (Fig. 1). In this study we have concentrated on five Koillismaa intrusions (Näränkävaara, Syöte, Lipeävaara, Kaukua and Murtolampi) and on the Koitelainen intrusion.

2.1. Geology of the Koillismaa and Koitelainen intrusions

2.1.1. Näränkävaara

The sequence of the Näränkävaara intrusion (Fig. 2) begins with peridotites, which grade upwards into pyroxenites. The northeastern part of the intrusion consists of gabbroids, quartz diorites and granodiorites without any distinct layering. Although generally well preserved the rocks have locally undergone partial alteration, probably during the Svecokarelian orogeny (~1900 Ma ago) as evidenced by serpentinization of the ultramafic rocks.

The strike of the layering is norhtwest-southwest being nearly parallel to the long axis of the intrusion. Dips in the northwestern part are about 20° to the northeast and in the southeastern part about 10-15° to the southeast. The intrusion is cut by a northeast-trending fault. This faulting took place after the Svecokarelian orogeny (Alapieti, pers. comm. 1986).

Both a gabbro pegmatoid and a granodioritic late differentiate yield an U-Pb zircon age of about 2440 Ma (Alapieti 1982). Seventeen sites from different stratigraphic levels in the Näränkävaara intrusion were sampled (see Fig. 2).

2.1.2. Syöte

The lower part of the Syöte intrusion (Fig. 3) consists of gabbro norites and the upper part is mainly of leuco-gabbros and anorthosites. A horizon of magnetite gabbro is found in the lower part of the leuco-gabbro and anorthosite sequence (Alapieti *et al.* 1979). Typical iron oxide minerals are titaniferous magnetite with ferrian ilmenite lamellae intergrown with homogeneous ilmenite. The intrusion is only slightly metamorphosed.

The Syöte intrusion tilts 30-40° to the northwest, exposing a complete stratigraphic sequence. The intrusion is characterized by several faults. The U-Pb zircon age for a mafic pegmatoid is about 2440 Ma (Alapieti 1982). Samples were collected from all stratigraphic units (Fig. 3).

2.1.3. Lipeävaara

The Lipeävaara intrusion forms the northern part of a syncline with the southern Kuusijärvi intrusion (Fig. 4). Most of the rocks are plagioclase cumulates forming gabbro norites and gabbros. The Lipeävaara intrusion is more strongly metamorphosed (greenschist to amphibolite facies) than the Näränkävaara and Syöte intrusions, as indicated by the replacement of pyroxene by uralite, magnetite by amphibole and ilmenite by leucoxene. The layering strikes northwest-southeast and dips about

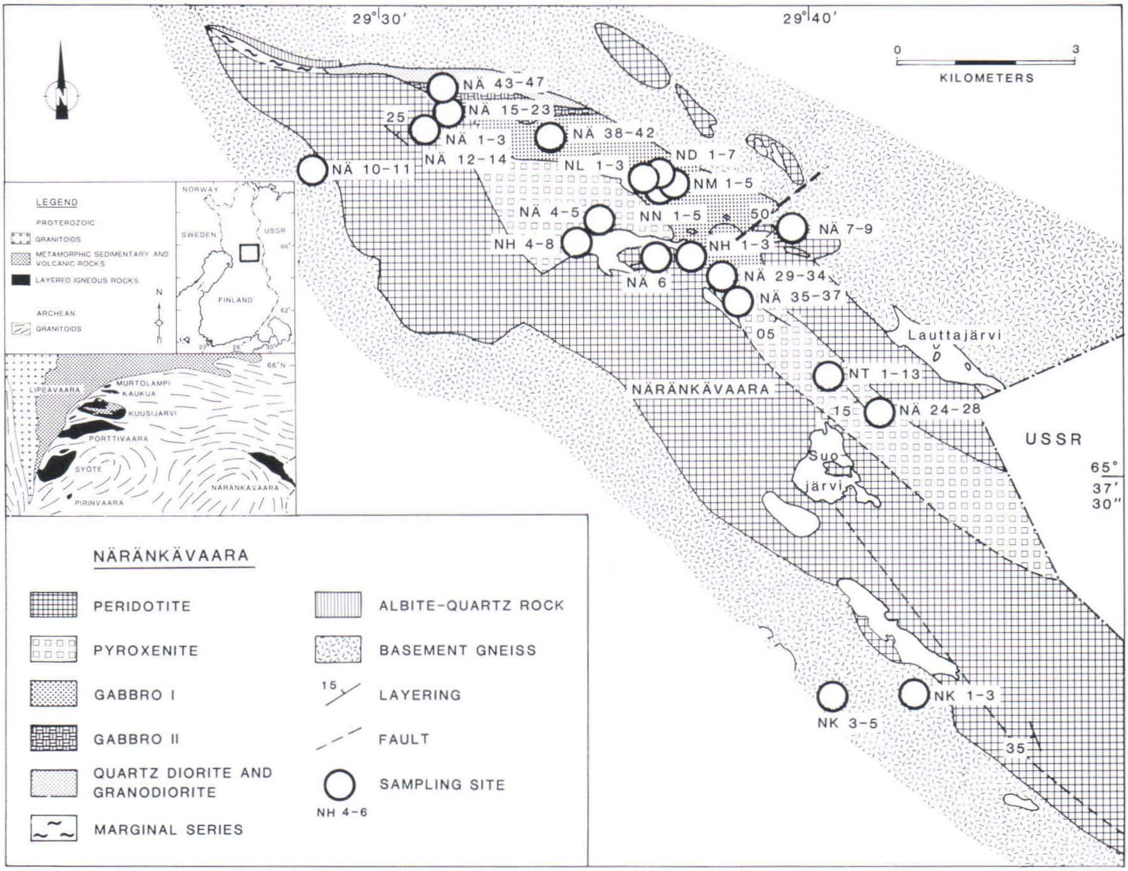

Fig. 2. The layered intrusion of Näränkävaara (after Piirainen *et al.* 1978 and Alapieti 1982). The open circles denote sampling sites.

30° to the southwest. Mafic pegmatoids dated by the U-Pb (Zr) method are about 2440 Ma old (Alapieti 1982). The sampling sites are shown in Fig. 4.

2.1.4. Kaukua and Murtolampi

The Kaukua and Murtolampi intrusions, the smallest bodies in the Koillismaa complex (Fig. 5), are composed mostly of gabbro norites.

Their crystallization trend and metamorphism resemble those of the Lipeävaara intrusion. The Kaukua section tilts approximately 20° towards the south. Igneous layering in the Murtolampi intrusion is horizontal.

2.1.5. Koitelainen

The large circular intrusion of Koitelainen covers an area of about 400 km² (Fig. 6) and is surrounded by Lapponian metavolcanites and metasediments. Koitelainen is a typical layered intrusion, having a whole differentiation series from peridotites to gabbros and granophyres. The rocks are fairly metamorphosed, as indicated by uralitization, serpentinization and other mineral alterations (Mutanen 1979). Igneous layering dips gently (<15°) to the east or southeast. The intrusion has been dated (U-Pb) to about 2450 Ma (Mutanen 1980). Samples were taken from gabbros at three sites.

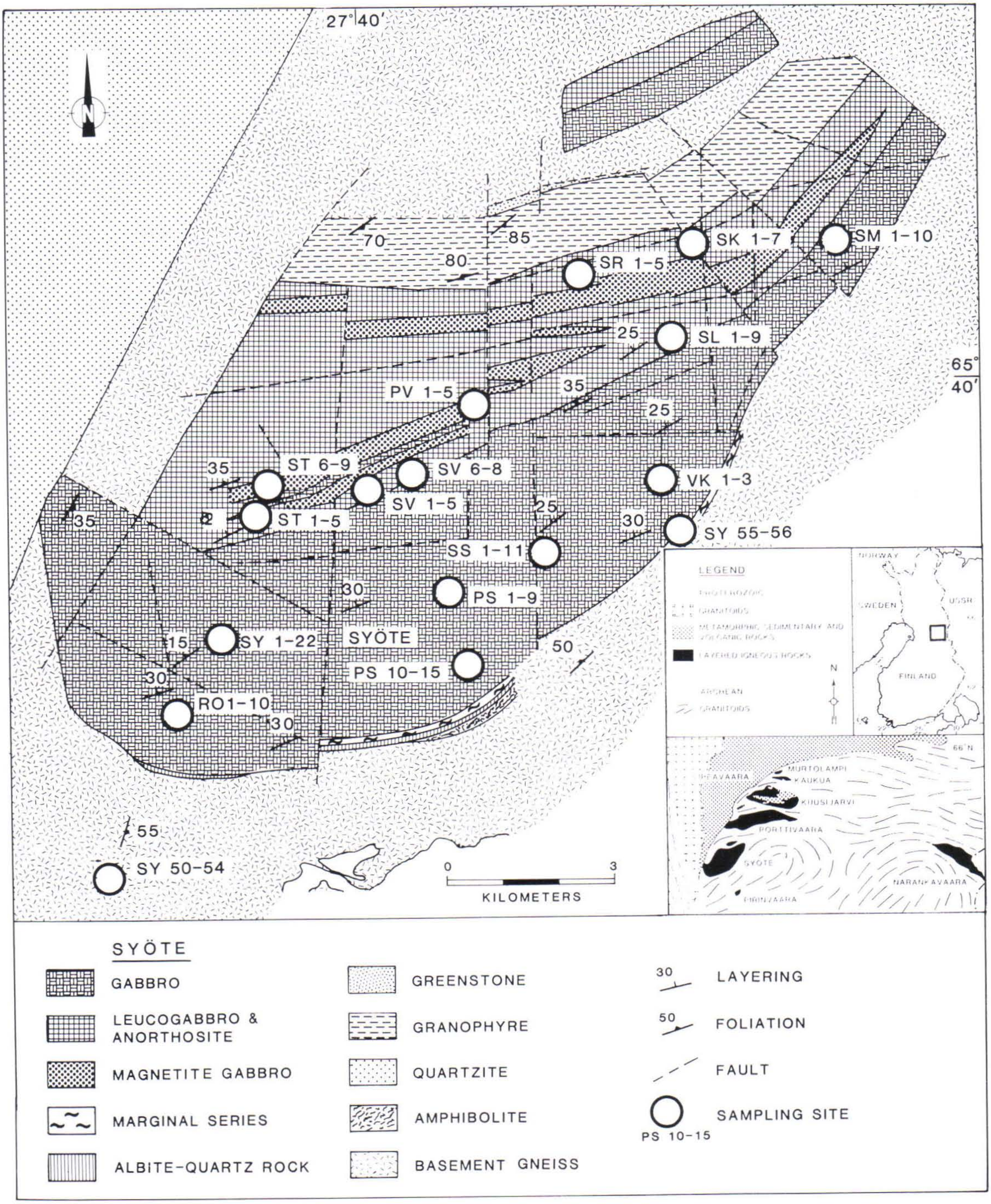

Fig. 3. The layered intrusion of Syöte (after Alapieti *et al.* 1979 and Alapieti 1982).

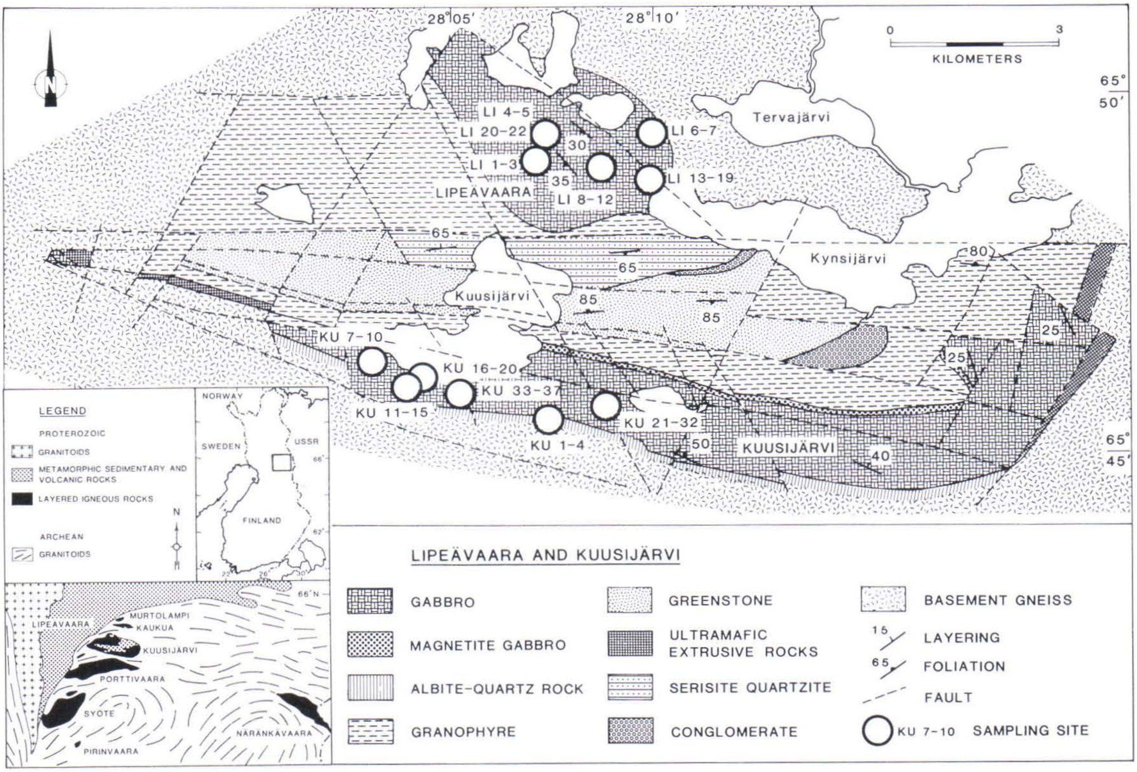

Fig. 4. The layered intrusions of Lipeävaara and Kuusijärvi (after Piirainen *et al.* 1978 and Alapieti 1982).

3. U-Pb ISOTOPIC RESULTS

The bulk of the U-Pb zircon data have previously been published by Alapieti (1982), and here we only report new data on the Siikakämä body in the western complex (Fig. 1). The investigated sample is from one of the few gabbro pegmatoids that yielded zircon for the U-Pb determinations. The sulphide bearing gabbro pegmatoid consists mainly of coarse-grained hornblende and partly of sericitized plagioclase. The Ti-bearing phase is rutile. Zircon occurs largely as brown subhedral grains with poorly developed crystal faces. Some grains have a distinct core.

The U-Pb isotopic data on zircon are given in Table A1 (Appendix). It is obvious that the zircon fractions do not give a precise age as do zircons from the blocks of the Koillismaa intrusion (Fig. 7). In a normal situation (e.g. Koillismaa), the zircons with the highest densities are the most concordant and give the oldest 207Pb/206Pb ages. In this case, however, the heaviest zircons (A454A, A454B, A460A in Table A1) yield the youngest 207Pb/206Pb ages. This pattern is quite unusual and indicates a dual origin for the zircons. Zircons with density above 4.6 g/cm^3 are distinct from other fractions for two reasons: 1) They are mostly transparent, whereas the others are turbid and 2) they have a low concentration of U and a high radiogenic 206Pb/208Pb ratio, indicating a source with a comparatively high U/Th ratio (Table A1).

The following model is proposed. Zircon formed primarily during the crystallization of the gabbro pegmatoid about 2440 Ma ago. In the course of the Svecokarelian orogeny, about 1900 Ma ago, the U-Pb system of zircon was partly reset, forming new zircon grains and mantles on the older zircon grains. The analysed zircon fractions are mixtures of these two generations. The HF-leached fraction, A454B, contains the highest proportion of transparent new

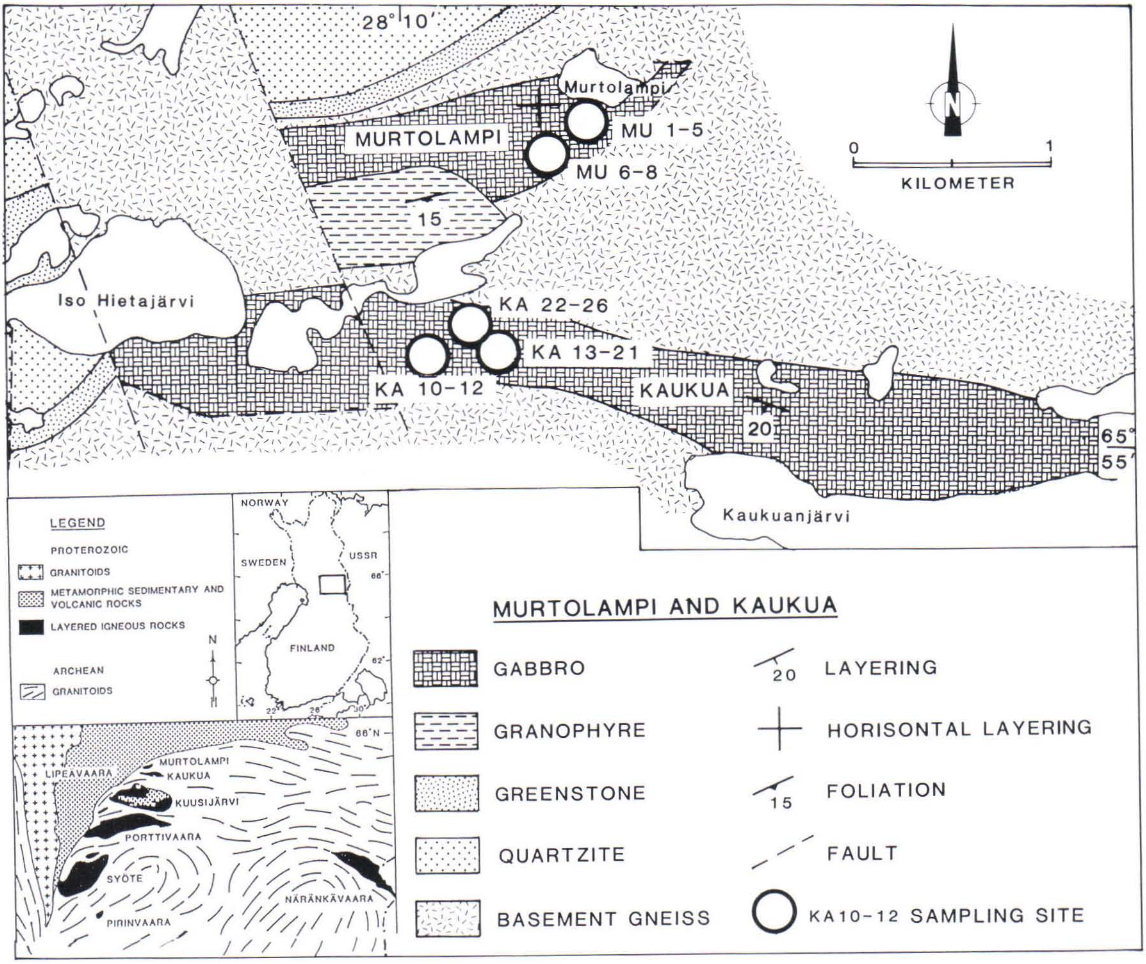

Fig. 5. The layered intrusions of Murtolampi and Kaukua (after Piirainen *et al.* 1978 and Alapieti 1982).

zircon, the fractions with density less than 4.2 g/cm^3 having the highest proportion of original turbid zircon. Fractions A454E and A454F, with high U content, have lost lead by subsequent diffusion (Fig. 7). It is well known that zircon is generally resistant to metamorphic alteration, and the pattern observed here can probably be attributed to locally intense hydrothermal activity resulting in an open metamict zircon system. This finding provides a key to interpreting the relative ages of NRM components.

4. PALAEOMAGNETIC MEASUREMENTS

4.1. Field sampling

Altogether 570 oriented samples were collected from the fifteen layered intrusions shown in Fig. 1: 290 from the western intrusions and 280 from the Koillismaa complex. Another 20 samples were collected from the Soilu Archaean basement granite, located about 15 km east of the Kaukua layered

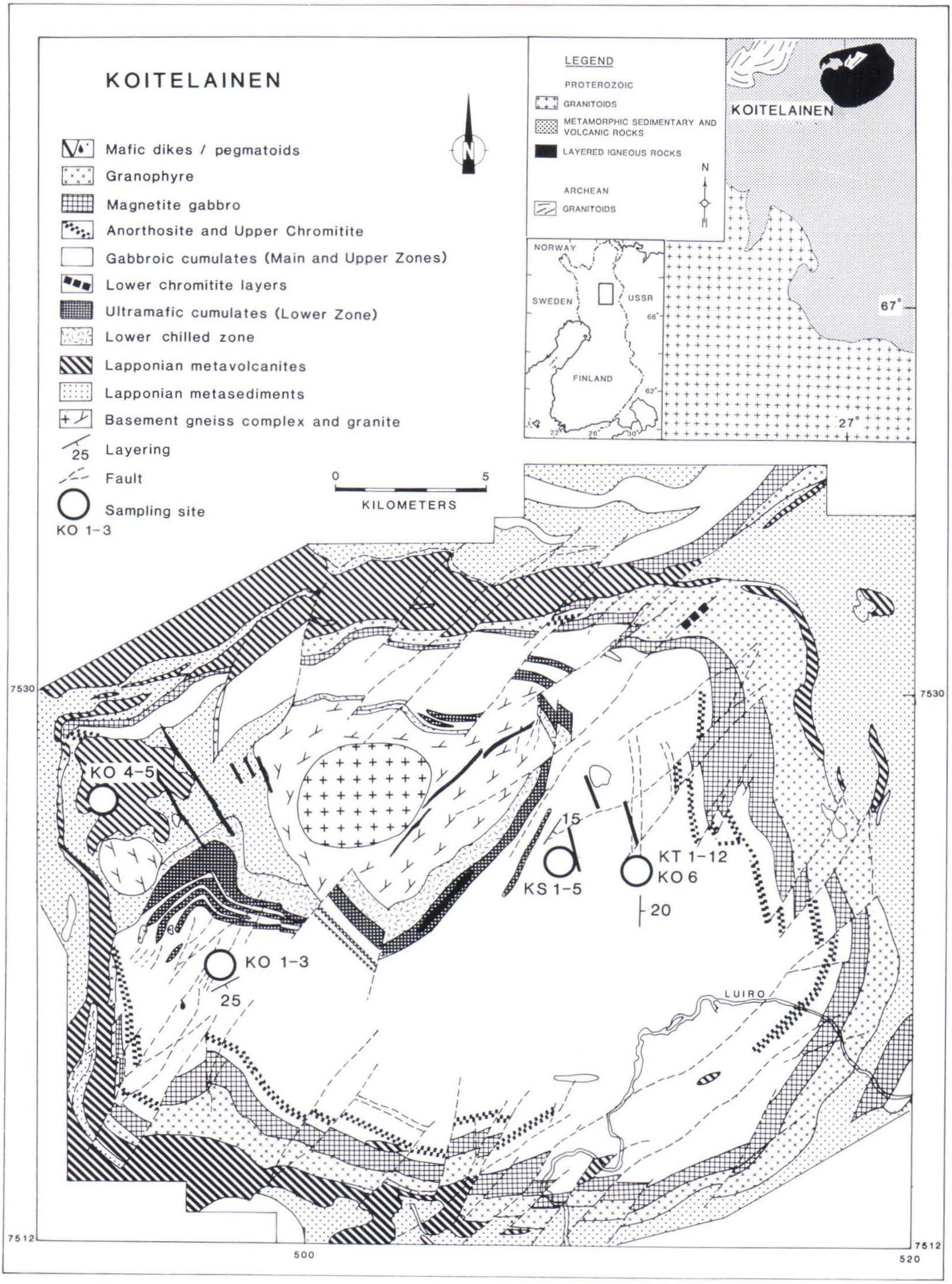

Fig. 6. The layered intrusion of Koitelainen (after Mutanen 1979).

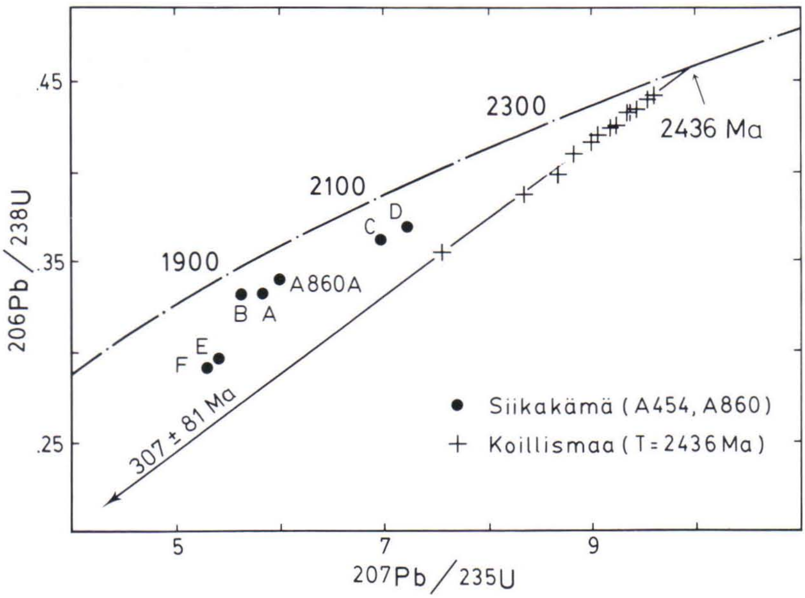

Fig. 7. Concordia plot of U-Pb zircon data on gabbro pegmatoids. + = Koillismaa complex intrusions, • = Siikakämä layered intrusion. Data on Koillismaa complex are from Alapieti (1982) and include data on Näränkävaara, Syöte, Lipeävaara and Porttivaara.

intrusion, and from the Penikat-Sompujärvi basement gneisses surrounding the Penikat intrusion (Fig. 1). The data from these samples were used in the baked contact tests.

Five or more samples were collected at each site. Most of them were cored with a portable water cooled drill but some were taken as block samples. Orientation was done with the aid of the sun and magnetic compasses. The drilling and orientation techniques are described in detail in Mertanen *et al.* (1987).

4.2. Laboratory measurements

Altogether 625 cylindrical specimens were measured in the palaeomagnetic laboratory of the Geological Survey of Finland (GSF).

145 were demagnetized in an alternating field (a.f.) of up to 100 mT in steps of 10 mT by using a single axis demagnetizer (Pesonen *et al.* 1983), and 480 were thermally cleaned either in the Schonstedt TSD-1 furnace or in a homebuilt furnace (Leino 1979, Pesonen *et al.* 1983). Thermal demagnetization was performed in 100°C steps up to 500°C, in 20°C steps up to 560°C and in 10°C to 20°C steps up to 700°C, depending on the behaviour of the samples in the course of heating. The NRM measurements were carried out with spinner magnetometers as described by Pesonen *et al.* (1983).

The preliminary measurements showed that the NRM of the samples from nine of the intrusions was either too weak ($J < 10$ mAm^{-1}) or magnetically too unstable to yield reliable results. Thus the intrusions of Tornio, Kemi, Penikat, Suhanko-Konttijärvi, Kuohunki, Siikakämä, Pirinvaara, Porttivaara and Kuusijärvi were excluded from further study. Most of these intrusions are located in the western belt, close to the boundary of the Archaean and Proterozoic terranes (Fig. 1). However, the U-Pb isotopic analysis on zircons from one of these intrusions (Siikakämä) is still presented here since it is relevant in interpreting the relative ages of remanence components. Similarly, results from basement rocks near the Penikat intrusion are also used as they provide some evidence for a positive baked contact test even though the data on the Penikat intrusion itself are only tentative.

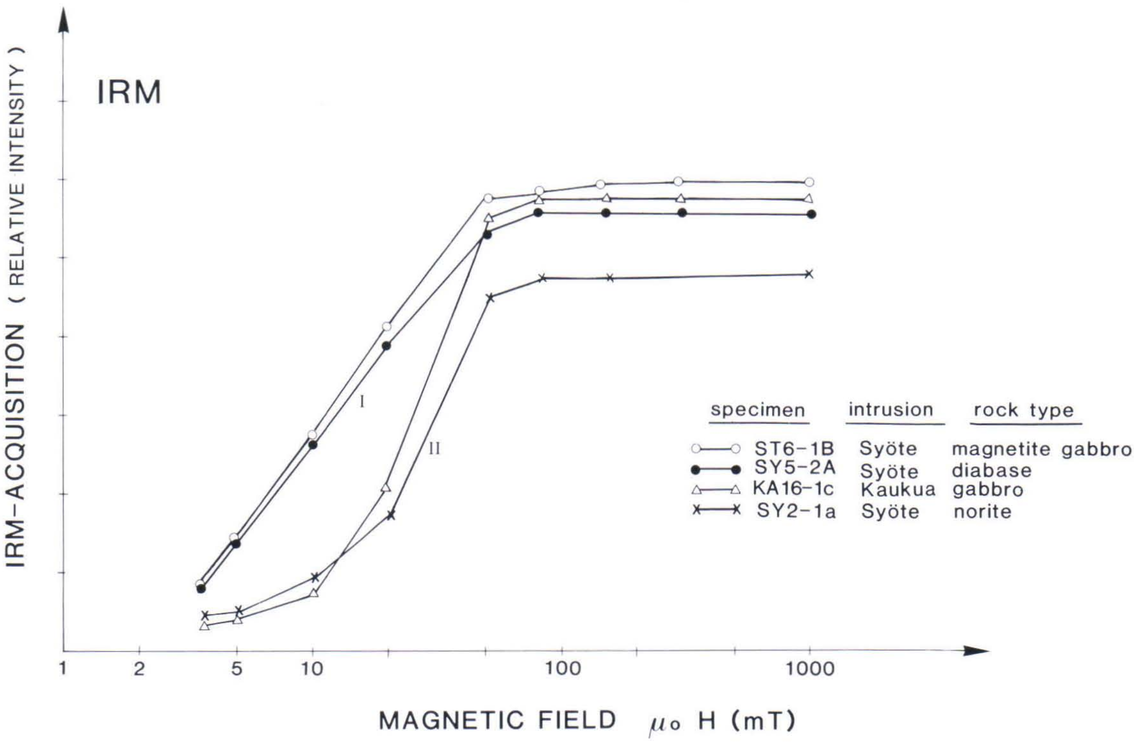

Fig. 8. Four examples of the IRM-acquisition curves of layered intrusions. Type I: the main remanence carrier is magnetite with MD grain size characteristics (see Table A2). Type II: the main remanence carrier is magnetite, possibly with hematite contribution, with SD-PSD grain size characteristics.

4.3. Hysteresis properties

The purpose of the hysteresis and isothermal remanent magnetization (IRM) measurements was to classify the magnetic grain size carriers of the rocks using the methods of Day *et al.* (1977) and Thompson and Oldfield (1986), and to study the viscous remanent magnetization (VRM) acquisition capacity of these rocks. The latter study is important as Lammi (1986) has shown that some samples from the layered intrusions can easily acquire laboratory remanences and are hence vulnerable to VRM due to the present Earth's field (PEF). The measurements were made at the Technical Research Centre of Finland using the apparatus and techniques described by Pesonen and Meinander (1985).

The results (Table A2) reveal that all samples with a magnetically soft and unstable NRM have multidomain (MD) hysteresis properties and that all samples with a hard and stable NRM are of single domain (SD) or pseudo-single domain (PSD) type. The samples from the magnetite-rich layers of the Syöte intrusion and from the diabase dykes are magnetically so soft (with MD hysteresis) that they easily pick up laboratory remanences when hammered (Lammi 1986). In some cases, however, a magnetically soft sample (e.g. ST1-1B, Table A2) has a small but stable NRM component which can be isolated after first removing the PEF overprint acquired viscously by the dominating soft MD grains.

On the bases of hysteresis and IRM data the samples can be divided into two groups (Fig. 8, Table A2). In the first group (type I, specimens ST6-1B and SY5-2A) the IRM increases linearly in weak fields and then is rapidly saturated in higher fields. This behaviour is typical of magnetite with MD grain-size carriers (Thompson and Oldfield 1986, Fig. 4.10, p. 32). The samples were very vulnerable to laboratory remagnetization during preparation and were therefore excluded from further analysis (Mertanen *et al.* 1987). In the second group (type II, specimens KA16-1c and SY2-1a) the IRM is acquired more slowly in weak fields. The saturation takes place in fields of about 70-100 mT, but there is some evidence of high field IRM acquisition (e.g. sample KA16-1c). This behaviour is typical of SD-PSD magnetite grains with a possible contribution of hematite (Thompson and Oldfield 1986, Dunlop 1986).

4.4. Techniques for separating remanence components

Five different mathematical routines for separating the remanence components were applied to the demagnetization data. These are:

(1) a least-square line fitting method on data in two-dimensional vector plots (modified after Zijderveld (1967) and Dunlop (1979));
(2) principal component analysis of vector data in three dimensional space (modified by Alarotu *et al.* (1986) after Kirschvink (1980));
(3) the vector subtraction method;
(4) stable end point (SEP) analysis;
(5) various methods based on intersecting great circles (e.g. Hoffman and Day 1978, Halls 1979, Bailey and Halls 1984).

In the two-dimensional, least-squares method at least four data points must be present for line fitting. In the principal component analysis we only use linear segments (i.e. prolate ellipsoids in three dimensional space) of data. A minimum of three points is required, and the angular tolerancy angle in the linearity search is set at 6°.

In many cases we have found that the first vector difference (i.e. between the NRM and the first demagnetization step) gives the PEF. The method of stable end points (SEP) is used to estimate the direction of the hardest component, but this method often fails owing to the increased instrumental noise at higher demagnetization steps. However, we sometimes find evidence of a masked hard component by plotting the great circles to the last three to five data points on a stereonet. With the aid of converging families of great circles, we can define the hard component by their convergence point using the techniques described by Bailey and Halls (1984) and modified by Piila *et al.* (1986).

Investigations of data on single specimens with multicomponent magnetization showed that the orthogonal vector plots (Zijderweld plots) are often very complex. This is due not only to the presence of three to five superimposed components with overlapping coercivities or blocking temperatures but also to the instrumental noise, which increases at higher cleaning steps. The separation of the superimposed components succeeded sometimes but in many cases the scatter of data was so great that the results should be viewed with reserve. Even so, by systematically accumulating the component data on several specimens with different methods we obtained the characteristic magnetization directions that repeat themselves from specimen to specimen in a variety of lithologies. It is these components that we believe are the bearers of reliable palaeomagnetic information.

5. PALAEOMAGNETIC RESULTS

In the following we shall describe the five remanence components (A, B, D, E and PEF) that were isolated from rocks of all the Koillismaa intrusions. In addition to these, a less well defined component, A', was isolated from the Koitelainen intrusion. Most samples yielded two to three components, but in some as many as five remanence components could be isolated. The components are listed in Appendices A3—A23. The final mean directions are given in Table 1 and the palaeomagnetic poles in Table 2.

Table 1. Grand mean directions of the remanence components

		Before tilt correction					After tilt correction			
Component	Intrusion	N	D	I	α95	k	D	I	α95	k
A	(N,S,L,K,M,T)	6	346	39	6	148	343	34	15	20
B	(N,S,L,K)	4	25	36	8	120	19	46	26	14
D	(N,S,L,K,M)	5	114	48	21	15	115	54	28	8
E (N)	(N,S,L,K)	4	249	58	11	66	255	45	43	6
E (R)	(N,S,L,K)	4	77	—44	24	16	80	—37	31	10
E (COMB.)	(N,S,L,K)	4	261	51	10	87	265	39	30	10

Intrusions: N = Näränkävaara, S = Syöte, L = Lipeävaara, K = Kaukua, M = Murtolampi, T = Koitelainen. COMB. = the combined mean direction of the normal (N) and reversed (R) data. N = number of intrusions. D = declination, I = inclination, α95 = radius of 95 % confidence circle about the mean direction (calculated only when N>3), k = the precision parameter (Fisher 1953).

Table 2. Grand mean palaeomagnetic poles of the layered intrusions (data before tilt correction)

Component	Intrusion	N	Plat(°N)	Plon(°E)	A95	K	gr.
A	(N,S,L,K,M,T)	6	45	226	5	195	a
B	(N,S,L,K)	4	42	177	9	109	b
D	(N,S,L,K,M)	5	18	85	23	12	c
D (a.t.)	(N,S,L,K,M)	5	20	85	22	13	b
E (N)	(N,S,L,K)	4	27	334	14	42	c
E (R)	(N,S,L,K)	4	19	320	29	11	c

For intrusions see Table 1. N = number of poles used in mean pole calculation. Plat, Plon = the position of the mean palaeomagnetic poles. A95 = the half-angle of the 95 % circle of confidence of the mean pole. K = the precision parameter. gr. = grade of the pole, where a (very reliable), b (reliable), c (semi-reliable) and d (unreliable) (see Pesonen *et al.* 1989a). D (a.t.) = component D after a 15° tilt correction.

5.1. Remanence component A

Remanence component A represents the most common magnetization direction. It typically overprints other components, sometimes partially, sometimes totally. In most cases A is of normal (N) polarity but a few reversed A directions have been encountered (Mertanen *et. al.* 1987).

In some samples, for example, NA36-1C from the Näränkävaara intrusion, component A occurs alone (Fig. 9). The intensity decay curve is typically square-shouldered in this thermally demagnetized sample, indicating that the remanence carrier of A is a Ti-poor magnetite with blocking temperatures between 500 and 570°C. On alternating field demagnetization the intensity generally decreases more rapidly, but the direction is stable and the same as in thermally demagnetized samples.

A is often superimposed on other components. For example, in specimen SY11-1A, where A is superimposed on D (see next chapter) (Fig. 10), the blocking temperatures are clearly non-overlapping. Component A is first erased between 300 and 570°C. The resultant vector then moves along a great circle towards D which, on the Zijderweld plot, is isolated in a temperature range of 570—640°C and finally as a stable end point at 680°C.

Component A generally has slightly steeper inclinations in the Näränkävaara and Syöte intrusions than in the Lipeävaara, Kaukua and Murtolampi intrusions. In all intrusions the tilt correction between sites is clearly negative (i.e. Fisher k decreases significantly), suggesting that magnetization A is post-tilting (Tables A3—A8). The mean A direction, when no tilt correction is applied, is D = 346°, I = 39°, α 95 = 6°, k = 148, N = 6 (intrusions) (Table 1), with a palaeomagnetic pole Lat = 45°N, Lon = 226°E, A95 = 5°, K = 195 (Table 2).

In the Koitelainen layered intrusion, remanence

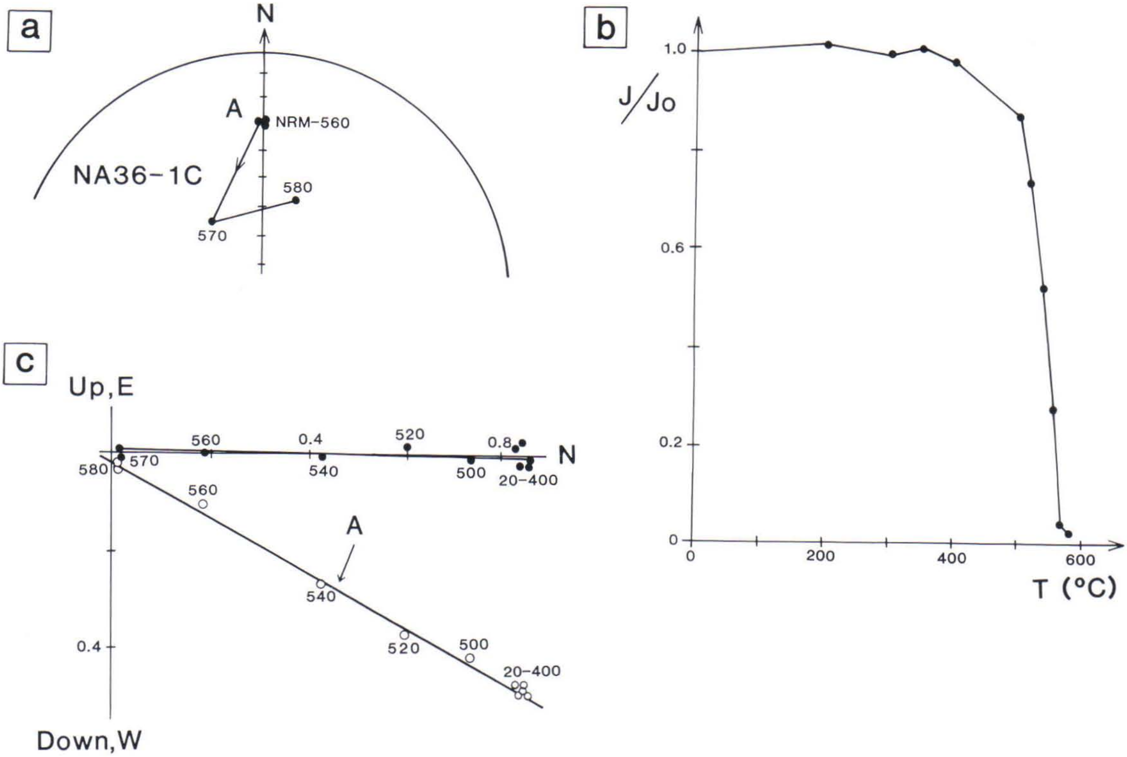

Fig. 9. (a) stereoplot (equal-area projection), (b) normalized NRM intensity decay curve and (c) orthogonal vector plots of stepwise thermal demagnetization data on specimen NA36-1C (Näränkävaara). Closed (open) circles on stereoplot indicate positive (negative) inclinations. Labels are temperatures (°C). In (c) solid symbols indicate horizontal E versus N plane, open symbols denote vertical Up versus N plane. Linear segments indicate that a single vector is being erased over the temperature range indicated. Numbers on axis denote volume magnetizations normalized to NRM. Specimen NA36-1c is an example of a case in which the magnetization is mainly carried by component A.

component A has reset all other magnetizations in most samples. There is, however, another direction A' (N polarity) that is distinct from, although very close to A and typically has slightly higher blocking temperatures than A. The mean direction for A' is D = 310°, I = 28°, α 95 = 12°, k = 115, N = 3 (sites), yielding a palaeopole Lat = 28°N, Lon = 264° E, dp = 6.9°, dm = 12.6° The results are summarized in Table A9.

5.2. Remanence component B

Component B is the least stable magnetization (besides PEF) having the lowest blocking temperature and coercivity spectra (Fig. 11). The remanence carrier is almost pure magnetite and the polarity is systematically normal.

B hardly ever occurs alone and there is often a possibility of confusing it with A, since in most samples they are superimposed and have very similar directions. The inclination of B differs from that of A by only a few degrees, but the declination differs by about 30°, being more easterly for B.

Component B is usually poorly defined when the resultant directions are plotted on a stereonet but because of the differences in blocking temperatures and coercivity spectra with respect to other components, it can be isolated in vector diagrams.

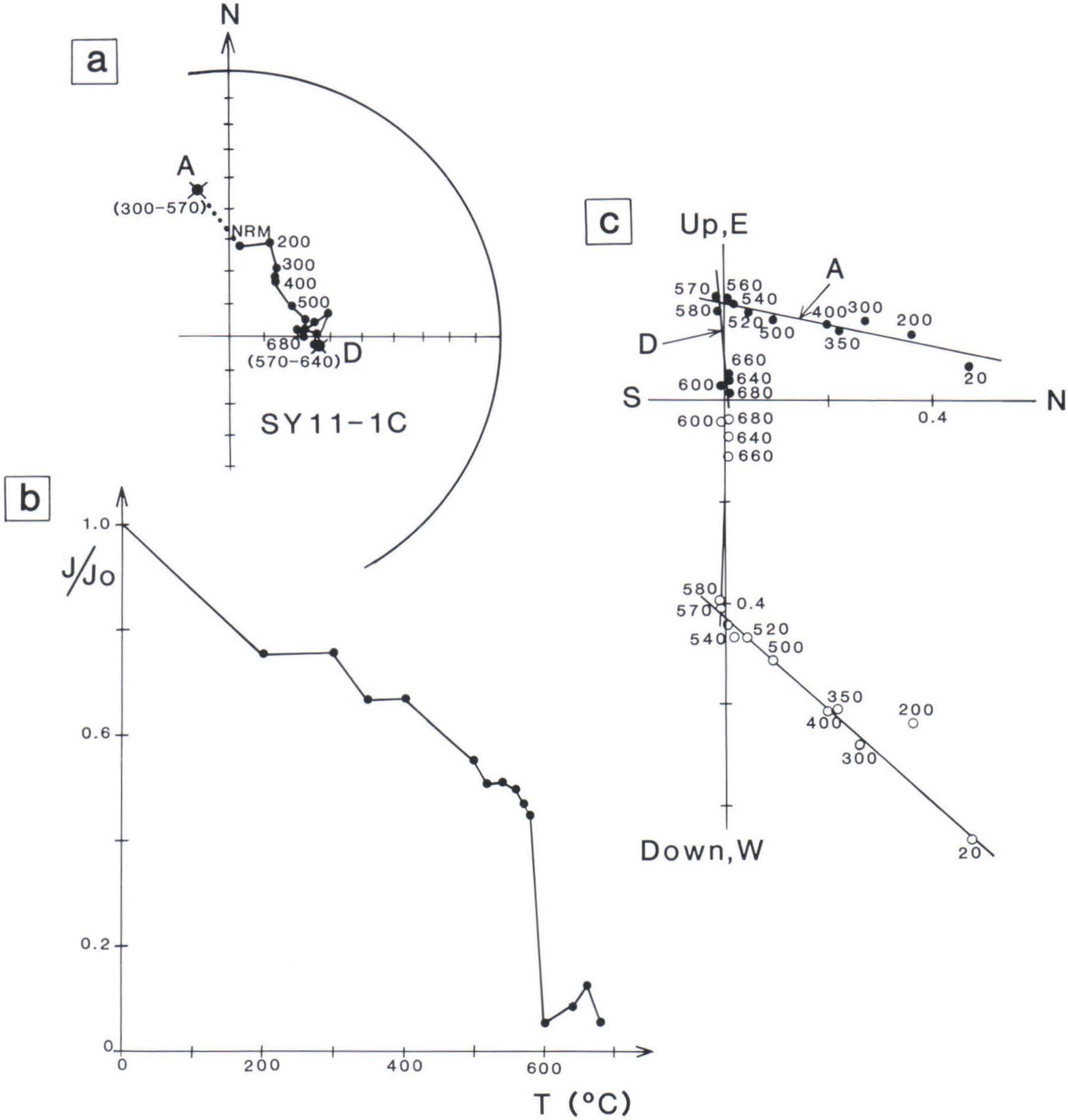

Fig. 10. Specimen SY11-1C (Syöte) is an example of nearly nonoverlapping blocking temperature spectra of components A and D. Crosses denote the subtracted vectors over the temperature range given in parentheses. Other plotting conventions used are as in Fig. 9.

An example of this is specimen SY1-1A (Fig. 12). The first component erased at low temperatures (20—100°C) is PEF. Although the B component is clearly isolated in the vector diagram at temperatures between 200 and 560°C, the resultant magnetization direction remains near the D direction (see next chapter). At higher steps, the resultant vector moves in another direction (E), which is revealed by an end point at 600°C.

Contrary to other intrusions, there are as many samples from the Syöte intrusion in which B has a higher blocking temperature than A as there are samples that behave in the opposite manner. Moreover, B seems to be more frequent in the Syöte intrusion, than in the other intrusions. We have not been able to isolate B reliably from the Koitelainen and Murtolampi intrusions, although some hints of it do exist in some specimens.

The mean directions of B are presented in Tables A10—A13. Sites 2 and 13 at Näränkävaara and Syöte, respectively, were excluded because of the anomalously low inclinations. Elsewhere, the direction of B is well defined, even though the scatter between sites and between intrusions is higher than in component A. Tilt tests show clearly that B is post-tilting in all intrusions. The mean B direction (without tilt correction) is D = 25°, I = 36°, α 95 = 8°, k = 120, N = 4 (intrusions) (Table 1), with a palaeomagnetic pole Lat = 42°N, Lon = 177°E, A95 = 9°, K = 109 (Table 2).

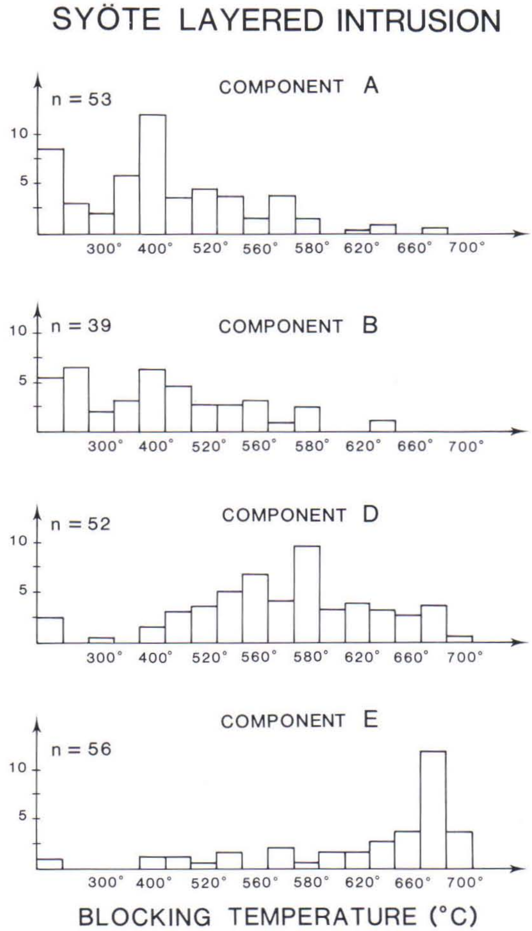

Fig. 11. Blocking temperature spectra of components A, B, D and E for specimens from the Syöte intrusion. n = number of specimens from which a particular component has been isolated.

5.3. Remanence component D

Component D is only found in samples with multicomponent magnetizations. In most samples, it is partly overprinted by A or B and is often underlain by E (see next chapter).

D is best preserved in Syöte, where its occurrence is as common as that of A. In many samples, the resultant vector points towards D, indicating that its magnitude is greater than that of the other components (see Figures 10 and 12). The most common blocking temperature for D range between 560°C and 680°C (Fig. 11), implying that D is carried by both magnetite and hematite. In the multicomponent samples that have only magnetizations D and E, component D is erased at slightly lower temperatures than E.

Even though the Näränkävaara intrusion has been inferred to represent the best preserved intrusions of the Koillismaa complex (Alapieti 1982), component D is not prominent in this intrusion. This may be because the rock types of the Näränkävaara intrusion (peridotite, pyroxenite, serpentinite) are magnetically often so soft and unstable at higher temperatures that the various components cannot be identified. There are some specimens from Näränkävaara in which D has been revealed at both low and high temperatures,

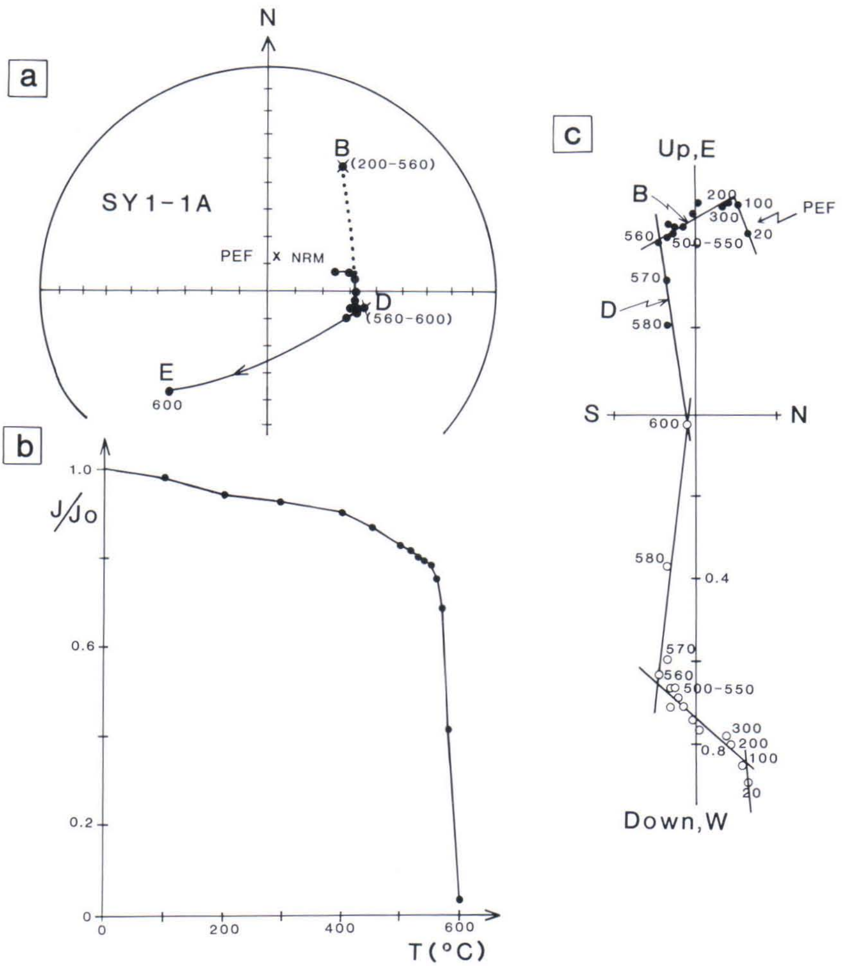

Fig. 12. In specimen SY1-1A (Syöte) the first component erased is PEF (X). Component B is isolated only on the Zijderweld plots (c) in a temperature range of 200—560°C. After 100°C the resultant moves along a short great circle towards component D, which is revealed in a temperature range of 560—600°C. The last demagnetization point (600°C) is near the direction of component E. Symbols as in Figs. 9 and 10.

indicating that it is carried by both magnetite and hematite. For example, in sample NN4-1A (Fig. 13), the lowest temperature component is D, which is carried by magnetite. After the isolation of component A the resultant then swings back to a high temperature D. Although there are only two points (570 and 580) in the vector diagrams, they support the existence of D, carried by hematite, at the end of demagnetization. This behaviour clearly demonstrates that A must be of thermochemical type (TCRM).

In Lipeävaara, Kaukua and Murtolampi, D occurs less frequently than A and B, probably reflecting the more intense metamorphism, and, hence, a relatively higher proportion of A and B in these intrusions. There are no signs of component D in the Koitelainen intrusion in which overprinting by component A seems to have been so strong that it has completely reset magnetization D.

Some samples from the Syöte intrusion reveal a reversed D direction (e.g. Fig. 14) that has not been found in other intrusions.

The scatter of D directions between sites and between intrusions is much greater than that of components A and B (Tables A14—A18), probably because there are many sites at which only one

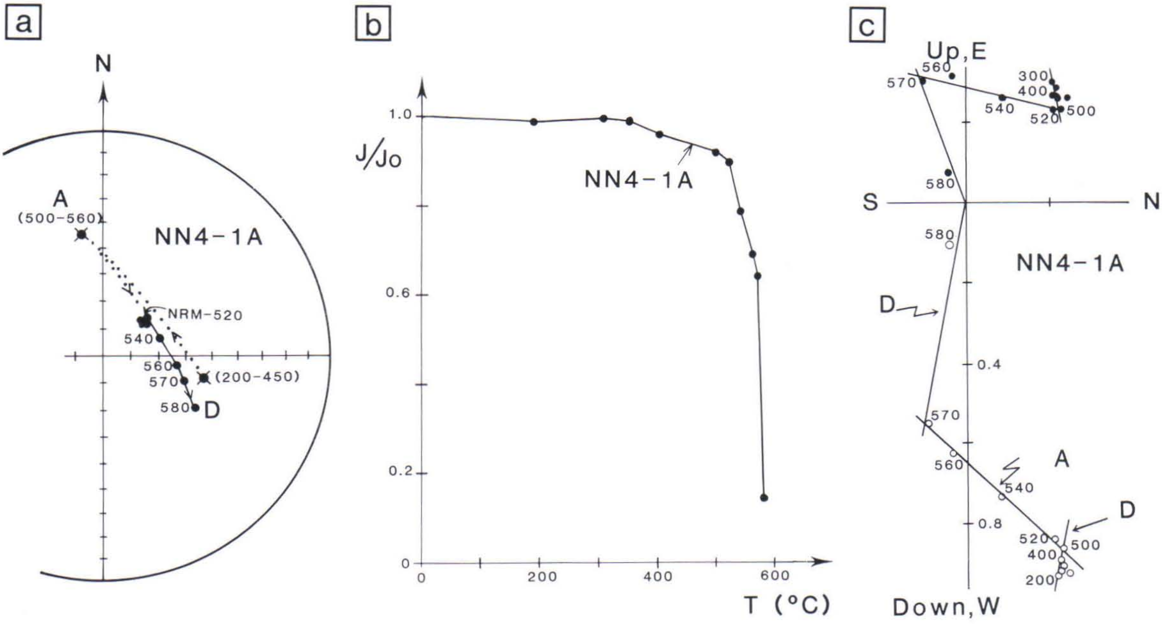

Fig. 13. In specimen NN4-1A the first component to be erased, in a temperature range of 200—500 °C, is D. Component A is revealed in a temperature range of 500—560 °C. At the end of demagnetization the resultant returns to D. Symbols as in Figs. 9 and 10.

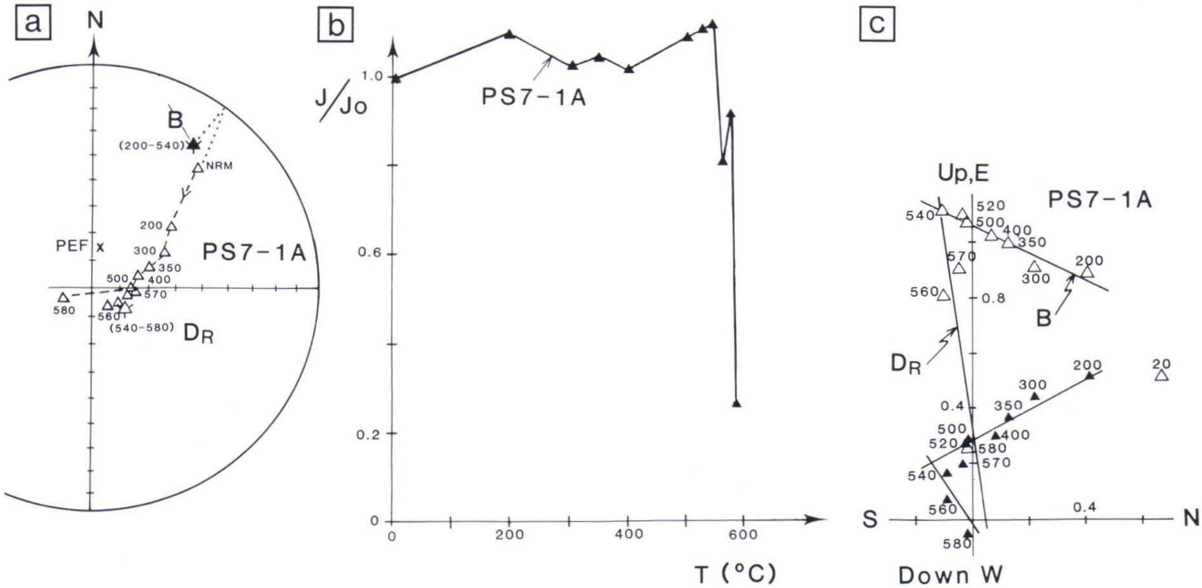

Fig. 14. In specimens PS7-1A (Syöte) the reversed D(R) was separated as a stable end point (a), and also on the Zijderweld plot (c). Component B was erased at temperatures between 200 and 540 °C. Symbols as in Figs. 9 and 10.

sample shows D. Another explanation for the high scatter of D directions may be tectonic events (e.g. tilting and rotation), causing the originally well-grouped D directions to become more scattered. Tilt corrections do not, however, significantly change the k values.

There is no correlation between rock types or stratigraphy and the D direction as might be expected in a slowly cooled pluton (e.g. Morgan 1976).

The mean D direction, without tilt correction, is D = 114°, I = 48° , α 95 = 21°, k = 15, N = 5 (intrusions) (Table 1). The corresponding palaeomagnetic pole is Lat = 18°N, Lon = 85°E, A95 = 23°, K = 12 (Table 2).

5.4. Remanence component E

Remanence component E is nearly as common as D. It is magnetically the hardest and is usually isolated after thermal treatment at above 640°C. It is therefore inferred to be carried by hematite (Fig. 11). For example, in specimen LI11-2B (Fig. 15), which carries all five components (PEF, A, B, D and E), E is isolated as a stable end point at 680°C.

Näränkävaara and Syöte show evidence of two distinct blocking temperatures for E. In most samples, magnetization E is carried by hematite with blocking temperatures of about 680°C. In some other samples, E is isolated at low temperatures, sometimes even lower than those at which components A and B are isolated when superimposed in the same specimen. Therefore E is probably of thermochemical origin and carried by magnetite (low blocking temperature) and hematite (high blocking temperature).

Progressive thermal demagnetization has revealed the presence of both normal (N) and reversed (R) E components within one and the same specimen. In many samples the normal component, E(N), occurs as a stable end point at about 680°C. The reversed component, E(R), is isolated at lower temperatures on Zijderveld diagrams, suggesting that E(R) is slightly younger than E(N).

The direction of the resultant vector very often remains nearly constant in a temperature range of about 580°C to 680°C, but at the same time a reversed E component is eliminated. The thermally harder normal E is then isolated as a stable end point. In most samples, E(R) is imperfectly (by about 10° to 30°) antiparallel to E(N).

Sample NA6-1A (Fig. 16) is an unusual example, showing superimposed normal and reversed E components also in the stereonet. Up to 580°C, the direction of the resultant is stable and component analysis yields the E(R) direction. Above 580°C, the resultant starts to migrate towards the opposite (E(N)) direction, which is isolated as a stable end point at 680°C. The absolute inclination of the E(N) component is about 35° steeper (downwards) than that of the reversed (upwards) component.

The directions of component E are very scattered, especially between samples. The dispersion is also markedly higher between sites than it is for other components (Tables A19—A23). The higher scatter for E may be due to the inadequate separation of other superimposed components. The scatter is especially high in the reversed E data. No correlation between E and rock type has been established. The tilt corrections between sites do not markedly change the k values, indicating that E postdates tilting.

Because of their anomalously low inclination, sites 2,4 and 15 are excluded from the mean in Table A20 (Syöte intrusion). The low inclinations may indicate that the normal and reversed E components were not fully separated from each other.

The declination of E in the Koitelainen intrusion (Table A23) differs from that in other intrusions by more than 50°. However, since in Koitelainen there is only one sample for each of the sites where E was isolated, these differences are not significant.

The mean direction (without tilt correction) for E(N) is D = 249°, I = 58°, α 95 = 11°, k = 66, N = 4 (intrusions) (Table 1) with a palaeopole Lat = 27°N, Lon = 334°E, A95 = 14°, K = 42 (Table 2). The mean direction for E(R) is D = 77°, I = -44°, α 95 = 24°, k = 16, N = 4 (intrusions) with a palaeopole Lat = 19°N, Lon = 320°E, A95 = 29°, K = 11 (Table 2).

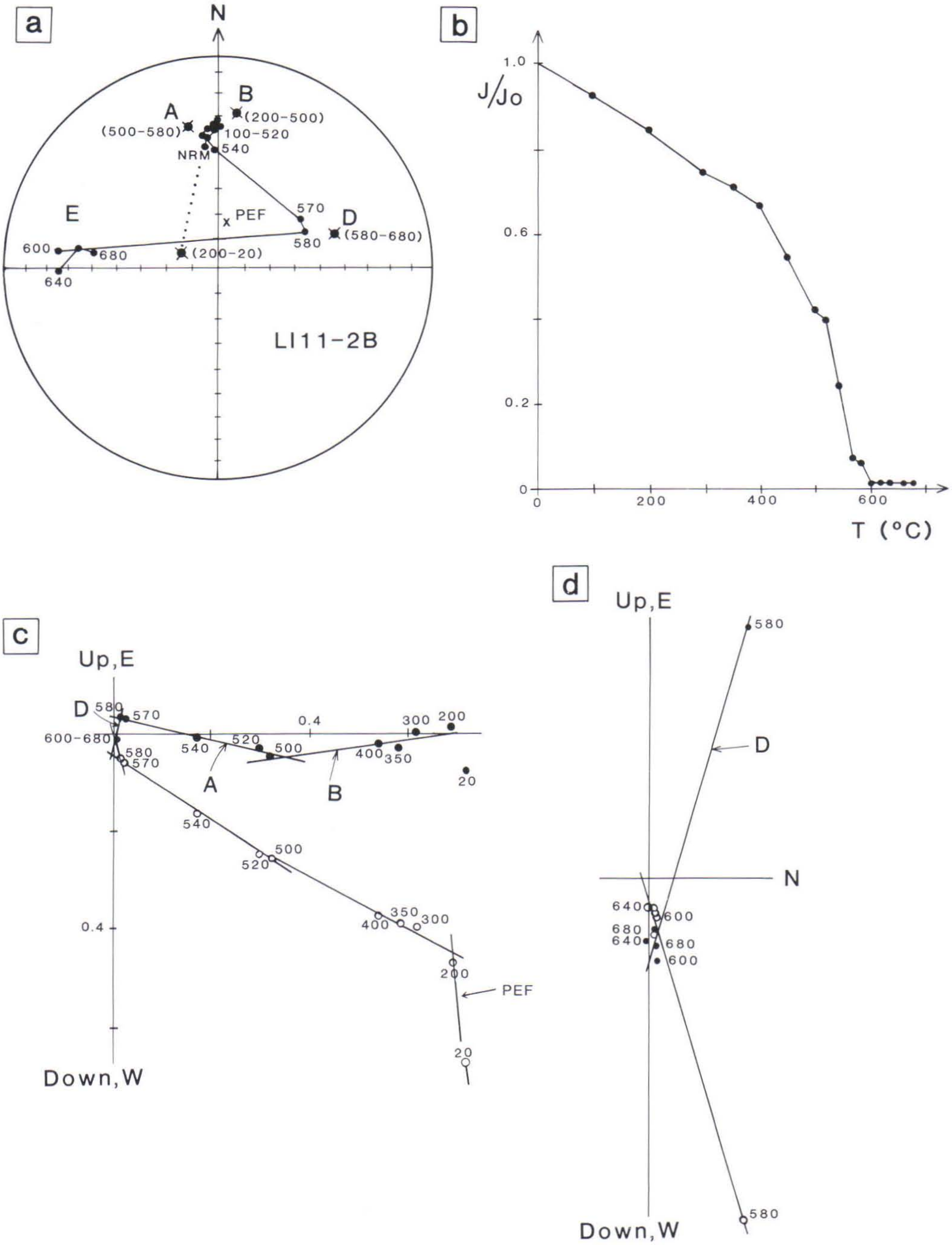

Fig. 15. Specimen LI11-2B carries all five magnetizations, PEF, B, A, D and E, which are revealed in this order (see the temperature ranges in parentheses on the stereoplot (a) and on the Zijderweld plots (c) and (d), where the latter is an enlargement of the origo area). The highest blocking temperature component E is found as a stable end point between 600 and 680°C in (a). Symbols as in Figs. 9 and 10.

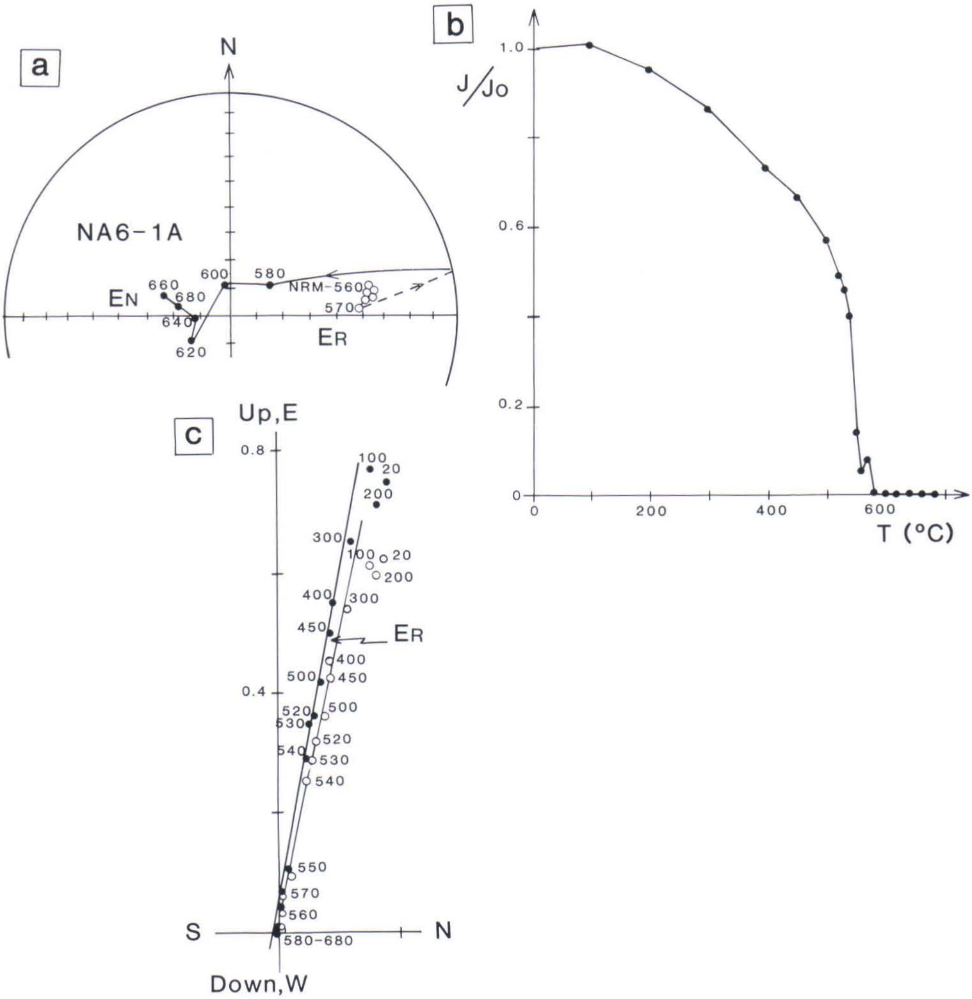

Fig. 16. Sample NA6-1A (Näränkävaara) is an example of a case in which normal and reversed directions of E are superimposed in the same specimen. The first component to be erased is E(R), after which the resultant swings towards E(N). The intensity (b) is very weak after demagnetization at up to 580 °C, but the direction E(N) is stable and corresponds to directions revealed in many other samples. Symbols as in Figs. 9 and 10.

6. PALAEOMAGNETIC TESTS

6.1. Baked contact tests

The layered intrusions cooled relatively slowly (Alapieti 1982), causing thermometamorphic and metasomatic alterations in the country rocks (Piirainen *et al.* 1977) and thus making it possible for the baked contact test to be carried out. The purpose of this test is to establish whether any of the magnetization components described above are primary and acquired during cooling of the intrusions at 2440 Ma ago, or secondary and acquired when the entire terrane was subjected to heating due to burial and regional metamorphism (e.g. Morgan 1976, Piper 1987). To discriminate between primary and secondary components a profile is sampled from an intrusion across the baked contact zone to the unbaked country rocks (e.g. Pesonen *et al.* 1985).

Unfortunately, the test was feasible at only two locations because of either a lack of outcrops or the existence of unstable magnetizations. We obtained unbaked and baked contact data from the Soilu basement area, about 15 km from the Kaukua intrusion, and from the Penikat-Sompujärvi area near the Penikat gabbro (Fig. 1). At Soilu we gathered data from both the intrusion and the unbaked rocks, but at Penikat-Sompujärvi our data are only from the baked and unbaked rocks because the results from the Penikat intrusion were not stable. The results are summarized in Table A24.

6.1.1. Unbaked Archaean rocks

Most samples from the basement gneisses carry multicomponent magnetizations. Component A, and less frequently B, often overprints a steep downward-pointing magnetization (G or P). In the Soilu basement area, we also discovered steep, upward-pointing directions (i.e. reversed polarity; Table 3, Fig. 17). The presence of both normal and reversed directions rules out VRM contamination by PEF. The palaeomagnetic poles, G (Soilu) and P (Penikat-Sompujärvi), representing these steep directions fall close to Archaean pole 1 previously established in the APWP of Pesonen and Neuvonen (1981). It is therefore conceivable that G and P are Archaean in age and that we have found an Archaean reversal. The paleomagnetic directions and poles from the Archaean basement rocks are summarized in Table 3.

Although we have probably isolated Archaean remanent magnetization components from the basement rocks, they are not very well defined. The magnetization in most Archaean samples is often too weak (less than 1 mAm^{-1}) to be measured with spinner magnetometers. It is also often difficult fully to trust remanence components isolated at very high temperatures.

Another problem with these rocks is related to tectonics and to the age of the characteristic magnetizations. The rocks have been dated by the U-Pb (Zr) method to 2738 Ma (G) (Lauerma 1982) and 2600 Ma (P) (Kouvo and Tilton 1966). These ages probably refer to the last regional heating of the terrane and may thus also represent the ages of remanences. It is likely that the terrane suffered some tectonic deformations later. However, because of the lack of structural references needed for correcting the remanence vectors, we could not correct the Archaean directions for tilt in this work.

Table 3. Remanent magnetization directions and palaeomagnetic pole positions from Archaean basement gneisses

Formation	Glat (°N)	Glon (°E)	N	D (°)	I (°)	α95 (°)	k	Palaeomagnetic Pole: Plat (°N)	Palaeomagnetic Pole: Plon (°E)	dp (°)	dm (°)
Soilu (N)	65.9	28.7	3	254	77	13	97	50.8	347.3	21.7	23.4
Soilu (R)	65.9	28.7	4	84	—86	10	83	63.6	8.5	19.9	20.1
Soilu (G) (COMB.)	65.9	28.7	7	261	82	7	79	58.9	355.6	12.9	13.3
Ala-Penikat	65.8	25.0	2	145	82	—	2188	51.8	39.9	10.1	10.4
Sompujärvi	65.9	25.2	3	143	77	16	64	44.5	45.5	27.2	29.1
Average (P)	65.9	25.1	2	143	80	—	645	48.2	43.0	17.8	18.8

For locations see Fig. 1. Glat, Glon = site latitude, longitude, N = number of basement samples from which the Archaean component has been isolated. Pole G is a combined result of Soilu normal and reversed data. For average (P), N is the number of formations. Plat, Plon = the position of palaeomagnetic pole (in case of R polarity the direction was inverted for pole calculation). dp, dm = semi-axes of 95% confidence oval about the pole. Other symbols as in Table 1.

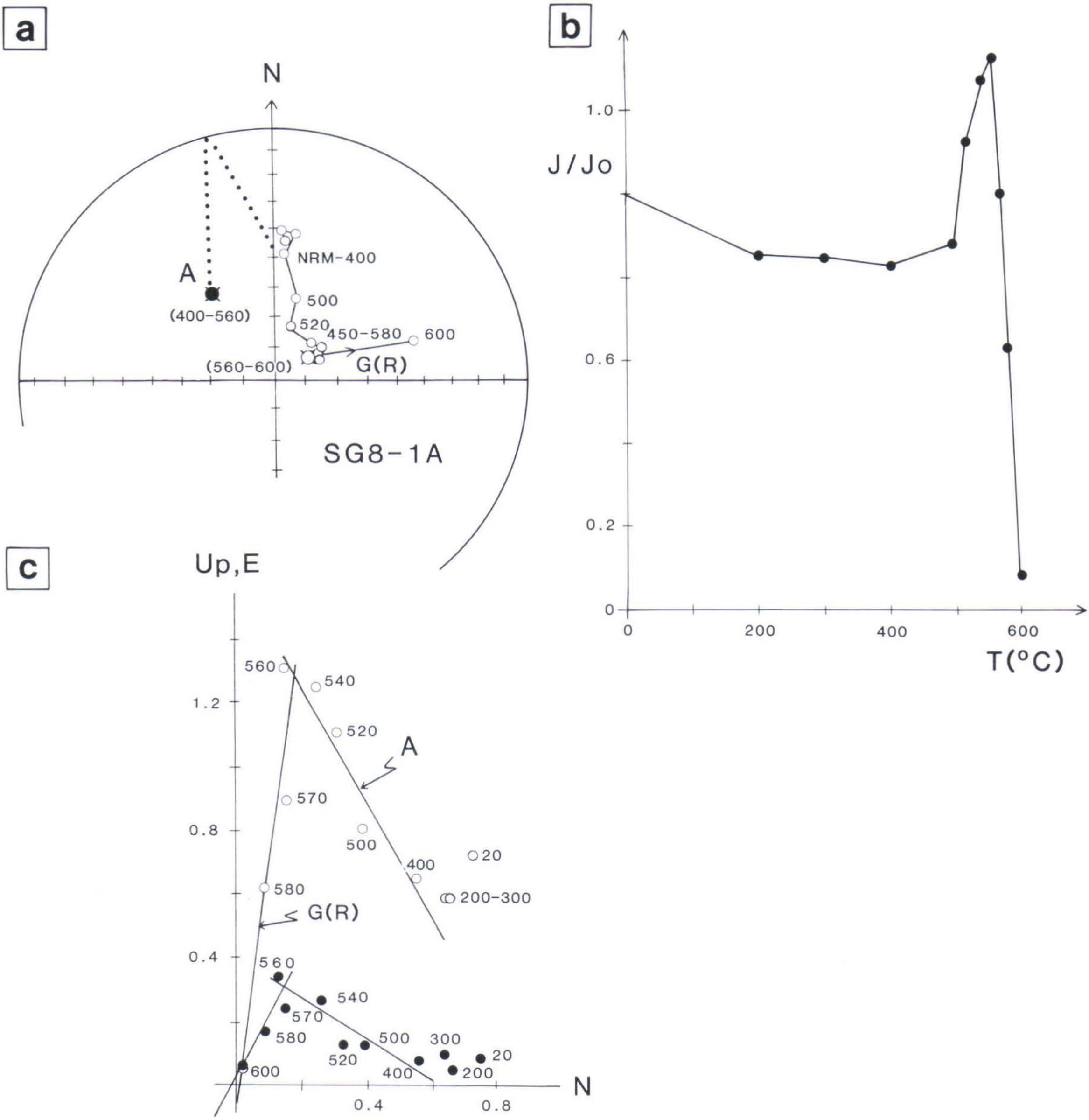

Fig. 17. In specimen SG8-1A from the Archaean basement gneiss (Soilu area, Fig. 1) the reversed component G(R) was erased in a temperature range of 560—600°C on the Zijderweld plot and a stable end point at 580°C. Component A, which overprints G(R), was removed in a temperature range of 300—560°C.

6.1.2. Baked Archaean rocks

Remanence component D has been isolated from two Archaean sites (Ala-Penikat and Sompujärvi) of gneissic rocks located about two kilometres from the Penikat gabbro (Fig. 1, see also Mertanen *et al.* 1987). An example is shown in Fig. 18 (specimen AP34-1A), where the first component erased in thermal treatment is D with blocking temperatures of about 580°C. In further steps the resultant moves

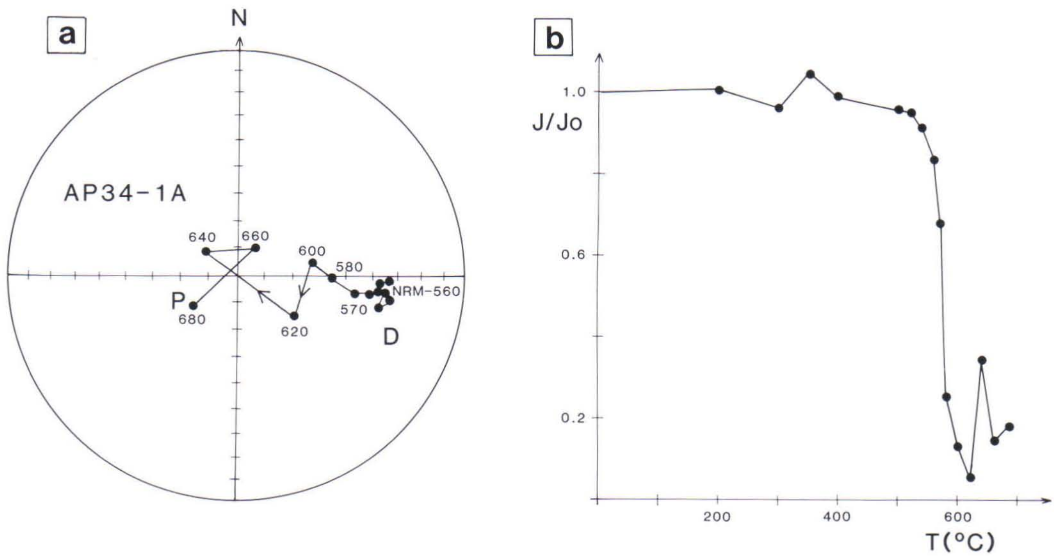

Fig. 18. Sample AP34-1A from the Archaean basement gneiss, about two kilometres from the contact of the Penikat layered intrusion, carries the D component (erased at 570—620 °C) and the Archaean component P (stable end point).

towards the steep characteristic Archaean direction described previously. The occurrence of D as a lower blocking temperature component in the basement samples superimposing the steep Archaean direction, proves that this sample was partially baked by the gabbro and that D is a primary partial thermoremanent magnetization (pTRM).

About 15 kilometres from the Kaukua body of the Koillismaa intrusions (in the Soilu area, Fig. 1) no reliable D directions are found; the only directions in the basement rocks are the characteristic steep Archaean direction with dual polarities and components A and B. Thus the results of the baked contact test provide strong support for the supposition that D was acquired during cooling of the intrusions and their contact aureoles. Because of the lack of sites suitable for the full contact test, however, these results are only tentative. Nevertheless, they are important in assigning ages to the magnetization components.

6.2. Tectonic tests

The layered intrusions presumably underwent post-emplacement tectonic movements several times (Alapieti 1982). Since these processes affect the remanence components formed before the movements, the remanence vectors must be corrected. What is more, new remanence components are often formed during tectonic processes such as tilting and faulting. In this work, we studied the effects of pure tilting (ie. tilting of crustal blocks around the horizontal axis) and rotation due to faults. Before turning to the tectonic tests, we shall outline present knowledge of the structures of the layered intrusions.

6.2.1. Structures of the layered intrusions

Alapieti (1982) proposed that the westerly intrusions of the Koillismaa complex (Syöte, Porttivaara, Kuusijärvi, Lipeävaara, Kaukua and Murtolampi, Fig. 1) originally formed one elongated sheet like body (1—3 km thick). The Näränkävaara intrusion in the east constituted a separate wedgeshaped body connected with the western intrusions by a hidden dyke. The primary igneous layering was nearly horizontal in all intrusions. After emplacement, the Koillismaa complex broke up into a number of tilted blocks, which are now seen after a long period of erosion. The present dips vary from 0° (Murtolampi body) to about 50° (Syöte body). The direction of dips are generally to the south or north (see Figures 2—5). The time of tilting has not been firmly established, but according to Alapieti (pers.comm. 1986) it was probably about 2200 Ma ago (Jatulian time) or earlier.

Besides tectonic tilting around the horizontal axis, the layered intrusions in the Koillismaa area underwent also relative rotations and translations associated with strike-slip faults. One major fault is shown in Fig. 1, running almost north-south and passing the Koitelainen intrusion on either its western (Gaal 1985) or eastern side (Korhonen 1981). This major fault separates the Koillismaa belt from the Kemi-Suhanko belt.

6.2.2. Tilt tests

Because the time of tilting may not be the same as that of rotations, we first performed the tectonic tests on three successive levels:

1) On the first level (single tilting) we conducted tilt tests by assuming negligible rotations. We further assumed that tilting always took place along the long axis (strike) of the igneous sheets. The dips vary from zero to about 50°, which is the maximum observed. These tilt tests were done on two hierarchical levels: between sites and between intrusions.

2) On the second level we conducted progressive tilt tests between intrusions by subjecting them to stepwise detilting in 5° intervals from the original horizontal attitude to the present maximum dips of layering (see e.g. Miller and Kent 1986). For comparison, stepwise tilt tests were done for components D and E.

3) On the third level we carried out tectonic tests in two stages (Douglas 1988): first the intrusions were tilted and then they were rotated. Two major rotations were studied. For the first one we assumed that the bodies of the Koillismaa complex originally formed a coherent east-west trending body that was later broken up by a major strike-slip fault. Thus the present long axis trends of the bodies are due to rotations caused by this fault. The necessary corrections ("derotations") were measured from the original east-west direction of the bodies to their present strike directions.

Second, the bodies were reconstructed to their original positions along the major fault that passes east of the Koitelainen body. This reconstruction which is based on Korhonen's (1981) aeromagnetic interpretation model requires both rotation and linear translation of the bodies. In this work only rotation angles could be used as the effect of minor linear (less than 180 kilometre) translations on NRM vectors is negligible.

The rotation angles and strike/dip data used in both cases are shown in Table 25. The tests were carried out twice, first omitting the Näränkävaara body and second including it, the idea being that Näränkävaara may not have moved much from its original position (Alapieti 1982).

6.2.2.1. Single tilt tests

The results of single tilt tests for each component are summarized in Tables A3—A23 (between sites) and in Table 1 (between intrusions). Scrutiny of the tables reveals that, in general, the results are negative. However, there are a few exceptions: Tables A14 and A15 show that after a full tilt correction, the between-site scatter of component D(N) in the Näränkävaara and Syöte intrusions was slightly, albeit not significantly, reduced (k increased). The variation in dip within the intrusions is, however, quite small. The usefulness of the tests in this case is thus restricted, and no firm conclusions can be drawn from them.

If we study the scatter of directions between intrusions (Fig. 19), we notice that all remanence components are more scattered once corrections for tilt have been made, suggesting that they post-date the tilting. This is particularly true for components A, B and E, but not so much for D, whose k value decreased less than did those of the other components (Table 1). Using this evidence, we looked into the possibility that D is either pre-or syn-tilting. However, the full detilting "overshot" the true correction.

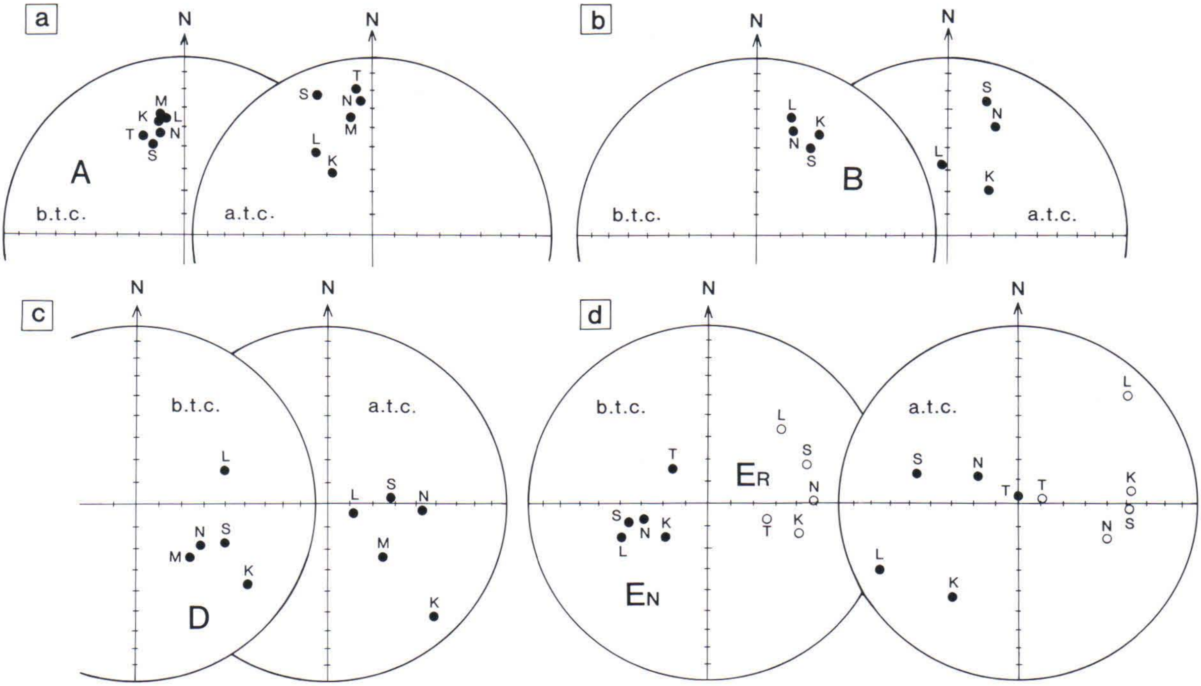

Fig. 19. Mean directions of different components in all six intrusions before (b.t.c.) and after (a.t.c.) tilt corrections. Labels: N = Näränkävaara, S = Syöte, L = Lipeävaara, K = Kaukua, M = Murtolampi, T = Koitelainen. (a) component A, (b) component B, (c) component D, (d) component E. Solid (open) symbols denote positive (negative) inclinations.

6.2.2.2. Partial tilt tests

Partial tilt corrections were conducted by stepwise detilting at 5° intervals. The results, which are shown in Fig. 20, clearly demonstrate that if all five intrusions are included, the k value for D increases up to a dip value of about 5°, after which it starts to decrease once more. For all other components, k decreased at all dip values (see component E, for example, Fig. 20). These results support the idea that D is probably syn-tectonic, acquired during the late stages of tectonic tilting. The test in Fig. 20, however, is very sensitive to the number of intrusions included. If the Kaukua body is omitted (the attitudes of igneous layering of this body are very poorly known), positive tilt test results are obtained for D when a dip value of about 15° (roughly 50% of detilting) is used. This further supports the concept that D is primary and was acquired during the tilting of the bodies.

6.2.2.3. Two-stage tectonic tests

Table A26 summarizes the results of the two-stage tests with tilting and rotation or vice versa as the stages. Two main conclusions can be drawn from these results. First, in all cases (except one for D), the results are negative: k values tend to decrease whatever the order of the two-stage correction and whether Näränkävaara is included or not. Second, the k values tend to be slightly higher in case II (major faulting running east of Koitelainen, Fig. 1) than in case I, giving some backing to the tectonic reconstruction by Korhonen (1981). The only time the k value increased after the two-stage correction was component D in case I, but even this is not significant (at 95%) and so we could not fully reconstruct the bodies back to their original (pre-tilting and pre-faulting) positions.

The results of all the above tectonic tests suggest that D is syntectonic and that the tilting, or part of

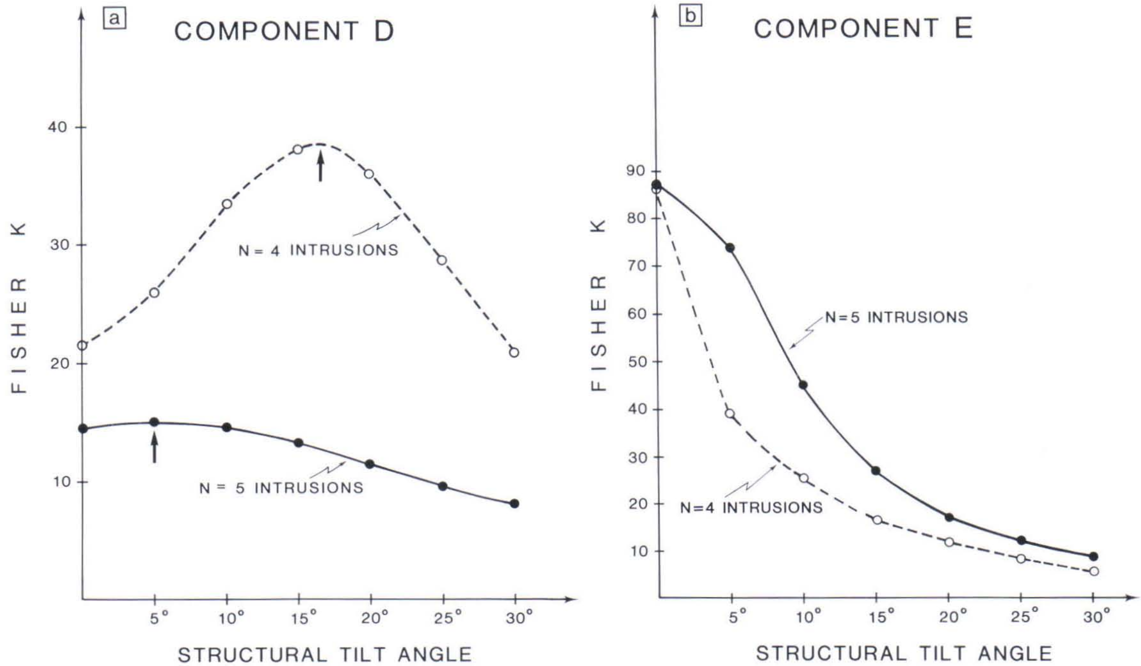

Fig. 20. Precision parameter k (Fisher 1953) vs incremental dip correction (in 5° intervals) for components D (a) and E (b). The five intrusions (solid curves) are Näränkävaara, Syöte, Lipeävaara, Kaukua and Murtolampi. The dashed lines (N = 4) denote the results when the Kaukua intrusion is excluded (see text).

it, took place immediately after crystallization. It is conceivable that the tilting of the bodies is related to the major fracturing of the crust that opened the channels allowing the magma to pour out. Component D is therefore primary, formed at late stages of primary tectonic tilting (and probably rotation of the bodies) about 2400 Ma ago. All the other components are clearly secondary and formed after the tilting. In Table 2, therefore, we have calculated the final palaeopoles for D both with and without tectonic (15°) tilt correction. No tilt correction was applied to any of the other components when their palaeopoles were calculated.

7. PALAEOMAGNETIC POLES AND APW-PATH

Before the APWP for Fennoscandia during 2700—1750 Ma could be redrawn, the relative ages of components A, B, D and E had to be established. Figure 21 summarizes the thermotectonic evolution model (model I of Mertanen *et al.* 1987) in which the absolute and relative ages, carriers and nature of remanence components are presented on the basis of blocking temperatures, U-Pb (Zr) age data, studies of opaque oxides (e.g. Alapieti 1982) and palaeomagnetic tests. The new APWP (Fig. 22) was drawn according to this model. Alternative models (II and III) have also been proposed (Mertanen *et al.* 1987) but they are less successful in explaining the interpreted data.

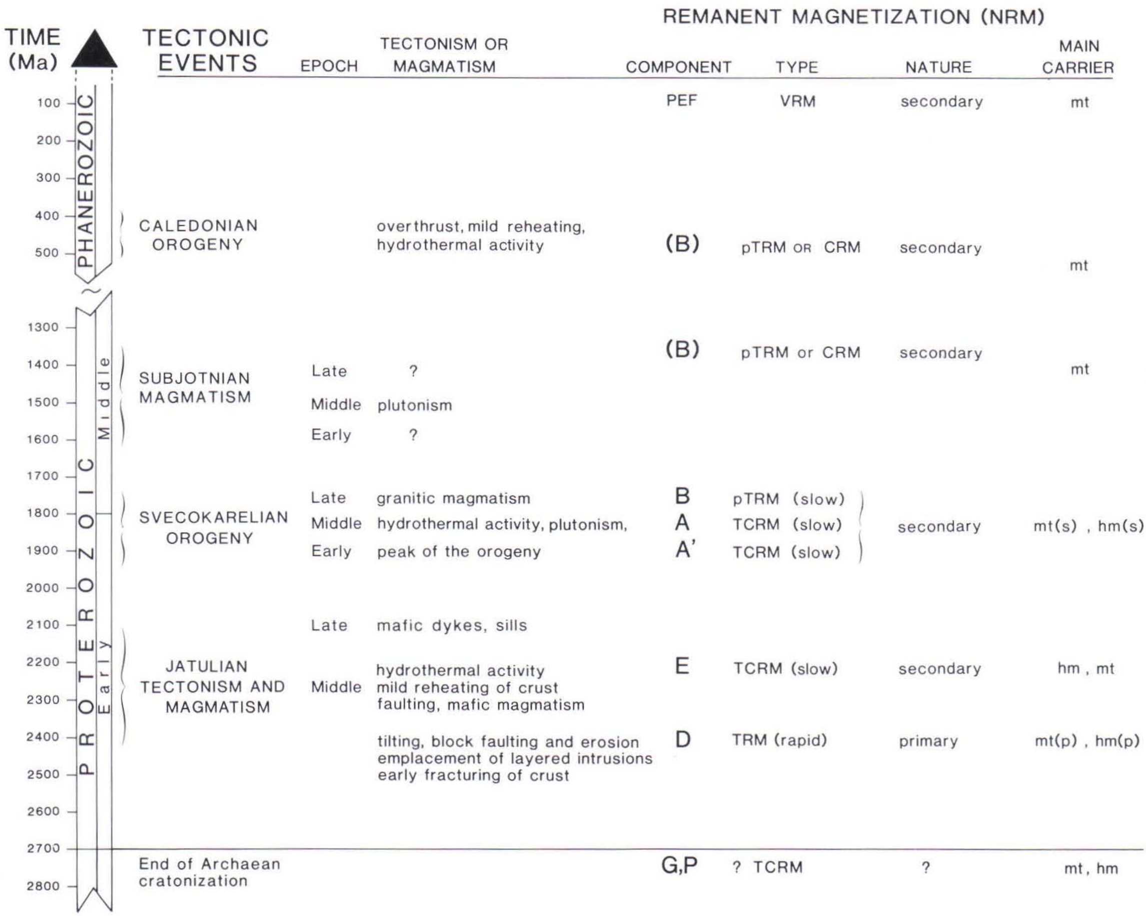

Fig. 21. The thermotectonic interpretation model (model I of Mertanen *et al.* 1987) for the growth and evolution of the magnetization components isolated from the Early Proterozoic layered intrusions and from the Archaean basement rocks of this study. The model integrates the information from four sources: (i) palaeomagnetism (this work), (ii) rock magnetism (this work), (iii) age determinations (this work), (iv) structural geology and opaque oxides (e.g. Alapieti *et al.* 1982). For two alternative interpretation models (models II and III) see Mertanen *et al.* 1987. The nomenclature used is explained in the text. mt = magnetite, hm = hematite, p = primary, s = secondary. Two alternative ages for component B are also shown (B in parentheses) as explained in text.

Magnetizations D and E are considered older than components A and B because components D and E have higher blocking temperatures than components A and B (Fig. 11), which have thermally overprinted and partly reset the underlying older components. The results from the baked contact and tilt tests support this interpretation.

Grand mean palaeomagnetic poles for different remanence components are listed in Tables 2 and 3. In calculating the grand mean palaeomagnetic poles we assumed the hypothesis of a standard Axial Geocentric Dipole Field (AGDF) although this assumption may not necessarily be valid. For example, the reversals in the D and E components are not exactly antiparallel. For D(N) and D(R) this could simply be due to the data (only few D(R) data are available, Table A15) but for E it may reflect a real polarity asymmetry. The grading (a, b, c) of the poles follows the same scheme as in Pesonen *et al.* (1989a).

7.1. Archaean poles

In the APWP (Fig. 22) pole number one (1) is the only Archaean pole so far available from the Fennoscandian Shield (Neuvonen *et al.* 1981). The age of this "anchor" pole, obtained from the Varpaisjärvi quartz diorite within the Karelian craton, is about 2680 Ma.

Pole G (dual polarity) was obtained from the Soilu basement granite (Fig.1). The normal, reversed and combined poles are presented in Table 3. According to U-Pb (Zr) age determinations the Soilu granite is 2738 Ma old (Lauerma 1982).

Pole P (Table 3; Fig. 22) is an average of poles from the basement gneisses (Ala-Penikat and Sompujärvi) surrounding the Penikat intrusion (Fig. 1). An U-Pb zircon analysis from a granite in Sompuvaara, near the sampling site of Sompujärvi, yielded an age of about 2600 Ma (Kouvo and Tilton 1966). Therefore, the Archaean age (~2700 Ma) of poles G and P is corroborated by the consistency between these poles and the Varpaisjärvi pole (1) and by the existence of both normal and reversed NRM directions.

7.2. Pole D

According to the proposed model, pole D is primary, having formed during the long lasting crystallization and cooling of magma about 2400 Ma ago. Component D is most likely syn-tectonic, acquired when the tilting was complete. The evidence supporting this interpretation is as follows:

1) Direction D can best be isolated in the Syöte intrusion, which is considered to have suffered less than other intrusions from later metamorphism (Alapieti 1982).

2) Magnetization D is mainly carried by hematite which was partly formed from a subsolidus reaction of ilmenite and can thus be considered primary (Alapieti, pers. comm. 1986).

3) The baked contact tests support the idea that D formed during the late stages of primary cooling of the layered intrusions and their contact aureoles.

4) Tilt tests indicate that component D was acquired either during, or just slightly after, the structural tilting of the bodies. Schwarz et al. (1979) have described a similar case from the Skaergaard layered intrusion in Greenland. The fact that the intrusions were still elastic when the tilting took place (Alapieti 1982), provides further support for the blocking of magnetization D during tilting in the Koillismaa area.

7.3. Pole E

On the basis of the palaeomagnetic tests, pole E is considered younger than pole D (Fig 21). One possible model for the origin of E is a TCRM acquired during a post emplacement tectono-magmatic process. The following findings support this interpretation:

1) Even though, in most samples magnetization E has been isolated as a stable end point, at which the highest blocking temperatures (about 660—700°C) prevail, there are many samples in which it was acquired at lower blocking temperatures. According to Morgan and Briden (1981), the most likely explanation for the wide range of blocking temperatures is a low-temperature TCRM. Such a thermochemical remanence, if carried by secondary hematite and magnetite, would have blocking temperatures ranging from 200°C to 700°C, as was indeed observed. Alapieti (pers. comm. 1986) has pointed out that there are two types of hematite in these rocks: primary hematite, which formed from the crystallizing magma, and secondary hematite, which formed during later tectonomagmatic processes. We propose that magnetization E is carried by the secondary hematite.

If magnetization E is of thermochemical origin, the bipolar nature implies slow chemical growth. The occurrence of both normal and reversed directions in the same specimen indicates that the E

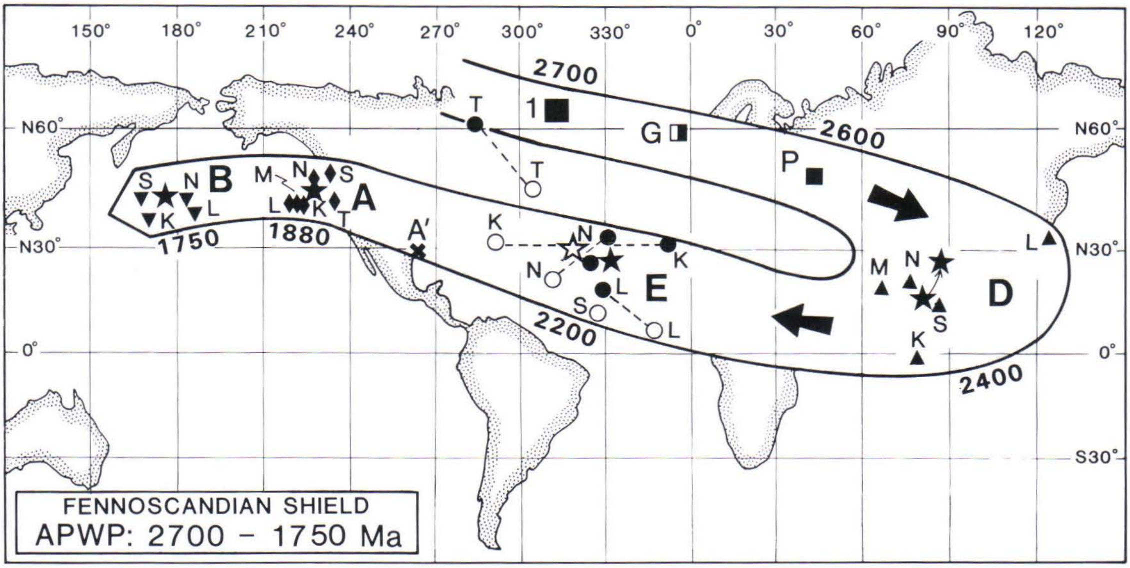

Fig. 22. The proposed new APW path for Fennoscandia during 2700-1750 Ma. Order of ages of the poles from oldest to youngest: (1)—>G—>P—>D—>E—>A'—>A—>B. A, B, D and E denote average poles from the layered intrusions (see Tables 2 and 3 for summary) without tectonic corrections. The arrow in D shows the mean D pole if a 15° structural tilt is applied (see text). Other poles are: 1 = Archaean pole from the Varpaisjärvi basement gneiss (Neuvonen *et al.* 1981), G = pole from the Archaean Soilu gneiss, P = pole from the Archaean gneiss surrounding the Penikat intrusion, A' = deviating A pole from Koitelainen, V = pole from the Jatulian Nilsiä diabases (Neuvonen *et al*. 1981). Solid (open) symbols denote normal (reversed) polarity. The normal and reversed polarities of pole E are joined with dotted lines.

magnetization developed while the Earth's field was reversing. This may be one explanation for the large scatter in E directions between specimens, as some directions could record the intermediate transitional fields.

2) The great dispersion of tilt corrected remanence component E clearly implies that E was acquired after the tilting was complete (Figs. 19 and 20, Table 1).

3) The Archaean gneisses near the contacts with layered intrusions do not show E as clearly as they do D. Component E, which probably formed during low temperature hydrothermal processes, has been isolated from only a few samples right at the contact, but not from more distant unbaked gneisses or granites. One reason for this may be the difficulty of isolating the high-temperature components from the weakly magnetized basement samples.

The great angular distance (~110°) between the D and E poles indicates considerable APW between the magnetization events of D and E. We propose that magnetization E resulted from Jatulian rifting and faulting, which fractured the crust about 2200—2000 Ma ago. Thermally the process was mild and did not produce any clear metamorphic changes. The heating effect was, however, high enough (200—300 °C) for the new secondary hematite grains with a TCRM to grow slowly in the rocks. According to this model, the rate of plate motion between magnetizations D (2440 Ma) and E (2200 Ma) would have been about 2 cm/yr, as measured from the APW path, which is roughly the same as the average Precambrian APW velocity of Fennoscandia (Pesonen *et al.* 1989a).

The E poles from the Koitelainen intrusion (T, Fig. 22) were excluded from the APW path as they differ markedly from the other poles. It is possible that local tectonic events in the Koitelainen intrusion (faulting and rifting during or after the Jatulian) affected the E (and A') directions (e.g. Korhonen 1981).

7.4. Pole A

Component A represents the best established magnetization direction in the layered intrusions and very often overprints components D and E. The blocking temperatures are below 580°C (Fig. 11), indicating that A is carried by magnetite (or titano-magnetite) with a variety of grain sizes.

Because A can be isolated from all intrusions and also from baked and unbaked basement rocks, we interpret direction A to date from the time of cooling and uplift immediately following regional metamorphism. The Svecokarelian orogeny (1900—1750 Ma ago) was very extensive in the Fennoscandian Shield. However, it is not known how far into the Archaean craton the effects of this orogeny penetrated. From geological studies it is known that the western part of the Koillismaa complex and the intrusions in the Suhanko-Konttijärvi and Kuohunki area suffered from the effects of Svecokarelian metamorphism more than did the eastern parts of the Koillismaa complex. However, present findings indicate that the eastern intrusions are also overprinted by the Svecokarelian orogeny. Accordingly, magnetization directions from the Taivalkoski-Syöte area (Neuvonen 1975) more likely represent the Svecokarelian overprint than the primary direction. The direction and pole obtained by Neuvonen are very close to the A direction and pole of this study.

The Koitelainen intrusion in particular was affected by the Svecokarelian metamorphism and obviously lost its primary (D) magnetizations. The orogeny produced two slightly different magnetizations, A and A'. Component A' has slightly higher blocking temperatures than A. In the APWP (Fig. 22) interpretation, A' appears older than A indicating that the Svecokarelian orogeny was blocked slightly earlier in the Koitelainen area than in the south. The Lapland Granulite belt, located about 30 km north of Koitelainen, underwent Svecokarelian metamorphism some 50 Ma earlier than did other parts of Fennoscandia (Gaál *et al.* 1989), in consistency with our interpretations of relative ages of A' and A.

The deviating directions in Koitelainen may also result from some local tectonic rotations caused by large scale strike-slip faults as shown in Fig. 1.

The A directions, representing the Svecokarelian overprinting, have been reported in many palaeomagnetic studies of Fennoscandian rocks (e.g. Pesonen and Stigzelius 1972, Elming 1985). As described previously (Chapter 3), in the Suhanko-Konttijärvi area the overprinting was, at least locally, so effective that some zircon in a gabbro pegmatoid was able to recrystallize about 1900 Ma ago (Fig. 7, Table A1). The notion that A represents a Svecokarelian overprint is supported by the polarity data, which reveal that A is almost always of normal polarity, as are most other Svecokarelian directions in Fennoscandia (Pesonen and Neuvonen 1981).

7.5. Pole B

Two interpretation models are presented for the origin of pole B and in both of them, B is suggested to be the youngest component (Fig. 21).

On the basis of the blocking temperature spectra (Fig. 11) and APW interpretation (Fig. 22), we propose that pole B was acquired at a late stage of the slow cooling and uplift that followed the Svecokarelian orogeny. Alternatively, the orogeny may have taken place in three distinct pulses (Early, Middle and Late) (Baer 1981, Pesonen *et al.* 1989a), B representing the last one.

The blocking temperature spectra of A and B (Fig. 11) overlap with B almost invariably having a lower blocking temperature than A. This is as would be expected if they were formed by the same continuous thermal process (i.e. they are both pTRMs).

A very plausible model for A', A and B is therefore the one in which A' denotes the Early phase, A the Middle phase and B the Late phase of the long lasting Svecokarelian orogeny (1900—1750 Ma). On the APW path, the age of A' is about 1900 Ma, that of A about 1880 Ma and that of B about 1750 Ma. This model may, however, be too simple as some specimens (e.g. Fig. 13) clearly show that A is chemical rather than thermal in character. According to this model, the interval between magnetizations A and B was about 130 Ma, implying considerable movement of the Fennoscandian Shield with respect to the pole (Fig. 22).

According to the second model, component B was formed by a much younger geological process with a very mild thermal effect. Two geologically young events that led to the formation of component B are proposed.

On the APW paths (Bylund and Pesonen 1987, Pesonen et al. 1989a) pole B fits well with the end of the Subjotnian loop tentatively dated to about 1320 Ma. This time corresponds to the start of Jotnian rifting in Fennoscandia (Simonen 1980). Although there is no direct geological evidence of active rifting in northern Fennoscandia 1300 Ma ago, there are indications of post-Jotnian magmatism in the vicinity of the study area, namely mafic dyke swarms 1150 Ma in age (Kalix dykes, Kresten *et al.* 1981 and Salla dyke, Lauerma 1987).

The other possibility is that B reflects a mild reheating event during the Palaeozoic era (Carboniferous—Permian period ca. 360—260 Ma ago). Although there are no direct geological data on the layered intrusions to confirm this idea, the direction of B (D = 25°, I = 36°, Table 1) is not significantly different from the mean Carboniferous direction in Fennoscandia (D = 32°, I = 30°; Pesonen et al. 1989b). In this respect it is noteworthy that the lower discordia intercepts in the U-Pb concordia diagram (307±81, Fig. 7) of the Koillismaa intrusions can be interpreted in terms of a mild overprint during Carboniferous times. According to Zonenshein et al. (1985), hot-spot related alkaline magmatic activity occurred on the Kola Peninsula, not far from the study area ~360 Ma ago. Slightly later (during Permian times, ~290—260 Ma ago), this was followed by another phase of intensive magmatic activity in the Oslo graben area of southern Fennoscandia. There is thus a distinct possibility that magnetization B reflects the palaeomagnetic signature of widespread regional Carboniferous -Permian overprinting in the Archaean — Early Proterozoic parts of the Shield.

8. DRIFT HISTORY OF FENNOSCANDIA

8.1. Palaeolatitudes and palaeorotations of Fennoscandia

The drift history of Fennoscandia (Fig. 23) was calculated from the APWP of Fig. 22 using the method of Pesonen *et.al*. (1989a). The town of Kajaani (Lat = 64.2°N, Lon = 27.7°E) was selected as the reference location, and the polarity is as in Table 3. This method places Fennoscandia at the correct palaeolatitudes and in the correct orientation with respect to its orientation in the present co-ordinate system. Palaeolongitudes can not be determined from palaeomagnetic data. Hence, to be able to visualize Fennoscandia in the different positions of successive periods, it was shifted arbitrarily to the right.

The drift map (Fig. 23) also outlines the crustal growth of Fennoscandia due to successive orogenies (presumably caused by collisions with other shields) from Archaean to Early Proterozoic times while the Shield was drifting across the palaeolatitudes.

8.2. Kinematic features

During Late Archaean times, from 2700 Ma to about 2600 Ma ago, Fennoscandia was located at high northerly latitudes and, as established by poles G and P, underwent only moderate latitudinal shifts (Fig. 22). At that time Fennoscandia was a Karelian nucleus (shaded area in Fig. 23) and included the

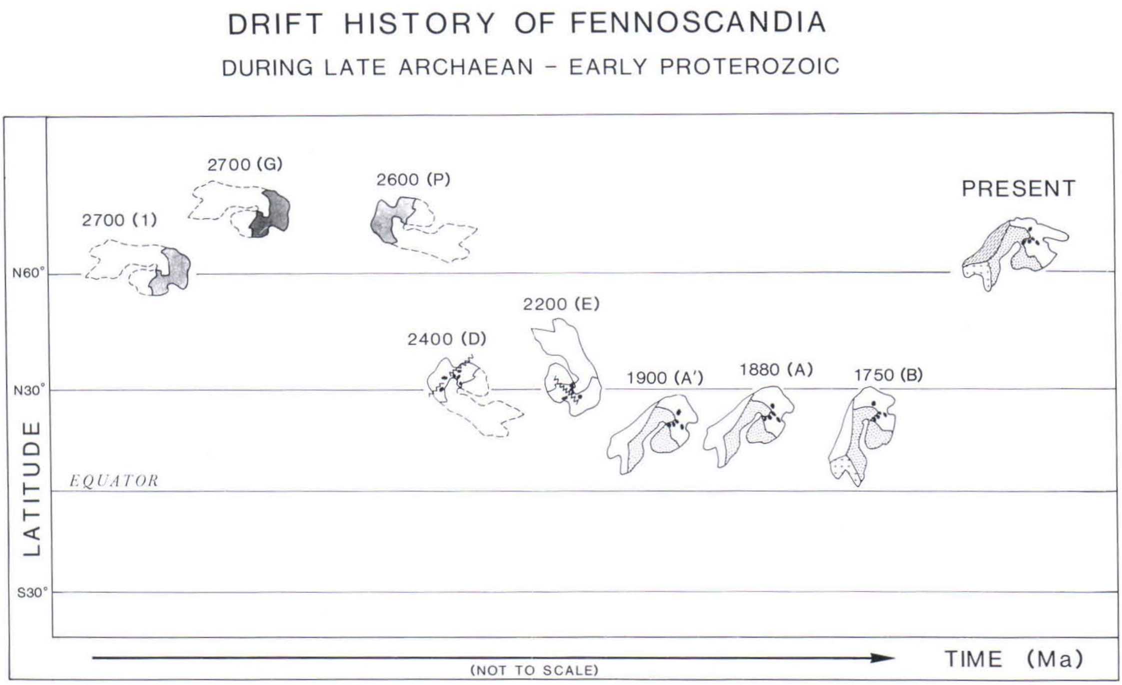

Fig. 23. The drift history of Fennoscandia during Late Archaean — Early Proterozoic times 2700—1750 Ma ago according to the APW path in Fig. 22. Positions of Fennoscandia calculated from the poles shown in Tables 2 and 3. The position of Fennoscandia (1) is from Pesonen and Neuvonen (1981). Fennoscandia is located in its correct palaeolatitudes with respect to its present orientation. The longitudinal shift is arbitrary but the rotations of Fennoscandia were determined from declination data relative to its present orientation in the upper right corner. The growth of the Shield during 2700—1750 Ma is also outlined.

Kola and Karelian cratonic blocks, which we assume to have been united. During the interval 2700—2600 Ma ago (from G to P) Fennoscandia rotated anticklockwise by more than 150°. This rotation, which took place at the end of the Archaean, is, however, poorly defined as there are numerous uncertainties in the declinations of both the G and P poles when the inclinations are very steep.

During the Early Proterozoic era, from 2600 Ma to about 2440 Ma ago, but before the crust was fractured, Fennoscandia drifted from high to moderate (northerly) latitudes with no major rotations. The latitudinal drift rate at that time was about 2.3 cm/yr. Magnetization D was acquired during the late stages of this fracturing, at the same time as the blocks were tilted. Fennoscandia subsquently underwent another considerable rotation of about 130°, but now clockwise (from D to E). This rotation was associated with multiphase Jatulian rifting, magmatism and faulting about 2200—2000 Ma ago. The high kinematic activity in the Shield can be considered as a prelude to the Svecokarelian orogeny, which was initiated about 2000 Ma ago and continued up to 1750 Ma ago. Components A' and A are signatures of the Early stages of this orogeny and component B is a late orogenic magnetization. The Svecofennian orogeny was preceded by considerable anticlockwise rotation (from E to A'), which is most likely associated with the collision of Fennoscandia with Laurentia as proposed by Pesonen and Neuvonen (1981). During the Svecokarelian orogeny proper (1900—1750 Ma ago) Fennoscandia remained at low latitudes and rotated anticlockwise about 40° (from A' to B). Thereafter it remained at low latitudes with the exeption of occasional visits to high southerly latitudes during the Sveconorwegian orogeny (1050-850 Ma ago), after which it returned to northerly latitudes and to its present location and orientation (Fig. 23; see also Pesonen *et al.* 1989a,b).

9. CONCLUSIONS

Four distinct ancient remanence components, A, B, D and E, have been isolated from the Early Proterozoic layered intrusions in northern Finland. In most samples these components exhibit partly overlapping blocking temperatures and coercivity spectra, enabling them to be separated by the combined use of multicomponent analysis techniques.

Tilt tests show that remanence components A, B, and E are post-tilting but that D is probably syntectonic and acquired when approximately 50 % of the tilting had already taken place (about 2400 Ma ago). The primary origin for D is also supported by baked contact tests.

The new APW path, based on poles A, B, D and E, is presented in Fig. 22, with poles G and P from the Archaean basement gneisses surrounding the layered intrusions included. On the basis of the fol-lowing evidence, the most probable order of poles from oldest to youngest is G -> P -> D -> E -> A -> B.

1) Pole A represents the best established magnetization. It has the highest magnitude and in most samples it partly or completely overprints other components. Its blocking temperature, around 580° C, indicates that it is carried by magnetite.

We propose that component A is an overprint acquired during the uplift and slow cooling that followed the Svecokarelian orogeny. The A overprint can also be isolated from Archaean basement rocks. Our results thus envisage the penetrative effect of the Svecokarelian orogeny far into the Archaean—Early Proterozoic terranes. Pole A fits well with the Svecokarelian segment of the APW path of Pesonen *et al.* (1989a). According to this path, the age of magnetization A is about 1880 Ma. This age is supported by the U-Pb age determinations on zircons, which not only reveal the emplacement age (2440 Ma) of the intrusions, but also provide evidence of a younger disturbance about 1900 Ma ago (Fig. 7). A is clearly of normal polarity consistent with other Svecokarelian poles from elsewhere in Fennoscandia. Multicomponent analysis and blocking temperature spectra verify that A is of TCRM type.

Component A' from the Koitelainen intrusion is always isolated at higher temperatures than A. This probably reflects a real palaeomagnetic signature of the Svecokarelian orogeny, which started slightly earlier (~1950 Ma ago) in the Koitelainen area than further south in the Koillismaa area (~1900 Ma ago). This is consistent with the notion that metamorphism in the Granulite complex (near Koitelainen) started also slightly earlier than in the south (Gaál *et al.* 1989).

2) Remanence component B has lower blocking temperatures than A. So far there is no evidence of the true age of magnetization B. On the basis of overlapping blocking temperatures with component A, we propose that B was acquired at the termination of the Svecokarelian orogeny, about 1750 Ma ago. Corroboration is provided by the existence of similar late Svecokarelian poles elsewhere in northern Fennoscandia (Piper 1980, e.g. Elming 1985, Pesonen et al. 1989a,b). The position of pole B on the APW path suggests that B is either 1750 Ma or 1320 Ma old. In the latter case it could represent a palaeomagnetic signature of the start of Jotnian rifting in northern Finland. Yet a third alternative is that pole B represents a much younger Palaeozoic remagnetization event.

3) The relatively high blocking temperature of component D indicates that it is carried by magnetite and, in most cases, by hematite, too. In most samples D has survived the reheating effect of the overprinting components, A and B.

In the light of blocking temperatures and positive contact tests, we postulate that D represents the primary magnetization acquired during the cooling of the layered intrusions. However, the intrusions must have been partly tilted before the blocking of D, which took place at a temperature of about 580-680°C. D was probably magnetized between the final crystallization of the cooling magma and the tilting of the intrusions about 2400 Ma ago. The age of the crystallization of zircon is about 2440 Ma, which is the upper limit of the age of D. The position of pole D on the APW path (Fig. 22) is one that has not previously been recorded from Precambrian rocks in the Fennoscandian Shield.

4) Component E has the highest blocking temperatures and is mainly carried by hematite.

However, in many cases, E is also evident at lower blocking temperatures, which is considered to indicate its TCRM origin. Many samples also show reversal to magnetization E, often in one and the same specimen. The reversal may have been achieved during the slow chemical growth of secondary hematite. The reversed E component tends to be acquired at slightly lower temperatures than the normal E component, and there is a significant asymmetry in reversal.

Component E must have been formed after component D. The great scatter in E direction between intrusions after tilt correction indicates that E is post-tilting. It is possible that the mild thermal event that caused magnetization E was the Jatulian rifting and faulting episode about 2200—2000 Ma ago. On the APW-path (Fig. 22) the pole position E has not been documented from any other rock units in Fennoscandia. This may be because the Fennoscandian data base (Pesonen *et al.* 1989b) still lacks the "true" Jatulian pole (see Neuvonen 1975).

Poles D and E can be tentatively used to build up the Early Proterozoic APW path for Fennoscandia, but the possibility that their positions are aberrant as a result of local tectonic rotations within Fennoscandia must be taken into account when interpreting the APWP and the drift history of Fennoscandia.

5) Two new poles from Archaean basement rocks have been discovered. Pole G was isolated from the Soilu granite (age 2738 Ma,) which was not affected by the baking effect of the layered intrusions and pole P was isolated from the same basement gneisses (age 2600 Ma) in the Penikat area, that carry the superimposed components D and E. Components G and P have not been encountered in layered intrusions and they probably represent magnetization directions acquired during late Archaean times.

Both polarities are present. G and P, although not statistically well established, are consistent with the pole of the Varpaisjärvi diorite (~2680 Ma; Pole 1) in the southern part of the Karelian craton (Pesonen and Neuvonen 1981). Thus it is suggested that no large scale movements have taken place between the basement blocks of northern Finland and the southern Karelian block in Central Finland (Varpaisjärvi block).

Both the APW path (Fig. 22) and the drift map of Fennoscandia (Fig. 23) exhibit several prominent kinks and rapid changes in drift that are the palaeomagnetic signatures of kinematic processes in the shield history during late Archaean—Early Proterozoic era. Most pronounced are the three major rotations: the first one (anticklockwise) during Late Archaean times (2700—2600 Ma ago) and the next ones (clockwise followed by anticklockwise) during Jatulian times (2400—2200 Ma and 2200—1900 Ma ago). These rotations seem to reflect overall tensional tectonics in the Fennoscandian Shield, which, at those times, was an integral part of a much larger global shield assembly. The fracturing of the crust about 2450 Ma ago, which resulted in the em-placement of the layered intrusions in Fennoscandia, was a global rather than a local event. Later, between 2200 and 1900 Ma ago, Fennoscandia underwent considerable latitudinal shifts. Preceding the Svecokarelian orogeny, these shifts may reflect the time when Fennoscandia was drifting as an independent plate before becoming rewelded to other shields (e.g. Laurentian Shield) and causing the Svecokarelian/Hudsonian orogenies 1900 Ma ago (Pesonen and Neuvonen 1981, Pesonen *et al.* 1989a). The Svecokarelian orogeny proper (1900—1750 Ma ago) is not a particularly strong kinematic event in the APWP or on the drift map although the orogeny was clearly preceded by strong kinematic events (Figs. 22 and 23).

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Appendix

Table A1. U-Pb analytical data on zircons from the gabbro pegmatoid of the Siikakämä intrusion, Suhanko—Kuohunki area (analysed in 1982).

Sample, fraction(1 d=density Ø=size in µm HF=preleached in HF	Concentrations(2 (ppm) U	 Pb	Measured 206Pb/ 204Pb	Atomic ratios(3 206Pb/ 238U	 207Pb/ 235U	 207Pb/ 206Pb	 206Pb/ 208Pb	Pb/Pb(4 age (Ma)
A454A, d>4.6	293	118	3409	0.3324	5.836	0.1273	3.7	2061
A454B, d>4.6, HF	272	101	6430	0.3313	5.627	0.1232	5.7	2003
A454C, 4.2<d<4.6	531	281	2488	0.3620	6.978	0.1398	1.9	2224
A454D, 4.0<d<4.2, Ø>160	704	424	1263	0.3695	7.236	0.1420	1.4	2252
A454E, 3.8<d<4.0, Ø>160	1160	535	801	0.2965	5.410	0.1324	1.7	2129
A454F, 3.8<d<4.0, 70 <Ø<160	1089	488	775	0.2913	5.296	0.1318	1.7	2122
A860A, d>4.2	317	138	1006	0.3395	6.008	0.1283	3.3	2075

(1, Sample locality: Map sheet 361304. Grid coordinates 7347.83/477.15. The samples were collected by J. Reino and J. Lahtinen, Outokumpu Oy.
(2, Corrected for analytical blank (U blank 0.5 ng, Pb blank 1 ng, sample weight 5—15 mg).
(3, Corrected for blank and common lead: 206Pb/204Pb=14.9, 207Pb/204Pb=15.1, 208Pb/204Pb=34.5.
(4, Average error 0.2%.

Table A2. Hysteresis properties of the layered intrusions

No. specimen	intrusion	rock type	a.f.	Js	Jsr	Hc	Hcr	Jsr/Js	Hcr/Hc	class
1. SY1-1B	Syöte	norite	hard & stable	3.2	0.26	9.6	42	0.08	4.36	PSD-MD
2. SV7-2A	Syöte	gabbro	semihard	0.28	0.07	18.0	60	0.25	3.33	PSD
3. AP12-1A	Ala-Penikat	gabbro	semihard	0.43	0.09	20.0	58	0.21	2.90	PSD
4. ST4-2B	Syöte	gabbro	soft & unstable	14.1	0.95	6.4	32	0.07	4.92	MD
5. ST1-1B	Syöte	magnetite gabbro	soft & stable	69.9	3.40	2.7	8	0.05	3.11	MD
6. ST6-1B	Syöte	magnetite gabbro	soft & unstable	27.0	1.19	4.4	18	0.04	3.98	MD
7. KA16-1C	Kaukua	gabbro	hard & stable	0.14	0.057	22.5	51	0.40	2.27	SD-PSD
8. KA20-1A	Kaukua	gabbro	soft & stable	0.12	0.06	20.5	37	0.51	1.80	SD-PSD
9. KA24-1C	Kaukua	gabbro	hard & stable	0.11	0.045	20.5	43	0.42	2.10	SDPSD
10. SY2-1C	Syöte	norite	hard & stable	0.05	0.028	28.0	70	0.53	2.50	SD-PSD
11. SY5-2A	Syöte	diabase	soft & unstable	9.21	0.28	3.2	19	0.03	6.06	MD
12. SY2-1A	Syöte	norite	hard & stable	0.09	0.048	28.0	70	0.53	2.50	SD-PSD
13. ST9-2A	Syöte	magnetite gabbro	soft & stable	14.9	0.567	3.9	20	0.04	5.03	MD
14. NA5-1B	Näränkävaara	pyroxenite	hard & stable	0.013	0.005	6.0	—	0.38	—	SD-PSD
15. NA26-1A	Näränkävaara	pyroxenite	hard & stable	0.104	0.032	14.0	28	0.31	1.96	SD-PSD

a.f. = general behaviour of the specimens during alternating field treatment (a.f.)
Js = saturation magnetization (mT)
Jsr = saturation remanence (mT)
Hc = coercive force (mT)
Hcr = coercivity of remanence (mT)
class = "rock magnetic" grain-size classification (modified after Day *et al.* 1977), where SD = single-domain, PSD = pseudo-single-domain, MD = multi-domain.

App. contd.

Table A3. Remanence component A of the Näränkävaara intrusion (Lat = 65.7°N, Lon = 29.5°E).

No.	Site	N	D	I	α95	k
1.	NA1—3, 12—17	4	344	61	13	49
2.	NA7—9	2	339	40	—	—
4.	NM1—5	2	329	34	—	—
5.	NN1—5	3	342	41	9	213
7.	NH4—8	1	335	42	—	—
8.	NA35—37	2	358	41	—	—
11.	NA18—23	5	356	46	5	286
12.	NA43—47	2	344	38	—	—
13.	NA38—42	4	4	37	6	267
16.	NA29—34	2	4	41	—	—
Mean, before tilt correction		10/27	347	43	7	46
Mean, after tilt correction		10/27	355	26	10	24

Pole position: Lat=48.3°N Lon=226.3°E dp=5.5° dm=8.9°

Symbols: No. = site number. For the Näränkävaara and the Syöte intrusions the site numbers are in approximate stratigraphic order from bottom (site 1) to top (site 16). Site = site name (see Figs. 2—6). N = number of samples per site from which the component has been isolated, mean direction is the mean of sites, D = declination, I = inclination. α95 = radius of 95 % confidence circle about the mean direction, k = the Fisher precision parameter (Fisher 1953) (α95 and k are calculated only when N>3). Pole position calculated from the mean remanence direction without tilt corrections. dp, dm = semi-axes of 95 % confidence oval about the pole.

Table A4. Remanence component A of the Syöte intrusion (Lat = 65.6°N, Lon = 27.7°E).

No.	Site	N	D	I	α95	k
1.	VK1—3	1	350	42	—	—
2.	SS1—11	3	341	56	16	58
3.	PS10—15	1	325	50	—	—
4.	PS1—9	2	333	51	—	—
6.	SY1—22	10	343	46	6	75
7.	SM1—10	5	347	56	9	79
8.	SL1—9	6	346	40	11	41
10.	SV6—8	2	332	55	—	—
11.	SK1—7	2	348	51	—	—
14.	ST1—5	1	353	35	—	—
15.	ST6—9	2	338	38	—	—
Mean, before tilt correction		11/35	342	48	5	73
Mean, after tilt correction		11/35	339	19	7	50

Pole position: Lat=51.3°N Lon=233°6E dp=4.5° dm=7.0°

Symbols as in Table A3.

Table A5. Remanence component A of the Lipeävaara intrusion (Lat = 65.9°N, Lon = 28.1°E).

No.	Site	N	D	I	α95	k
1.	LI4—5, 20—22	4	352	37	6	244
2.	LI1—3	3	347	34	9	182
3.	LI6—7	2	358	32	—	—
4.	LI8—12	5	348	35	7	118
5.	LI13—19	7	350	36	4	190
Mean, before tilt correction		5/21	351	35	4	396
Mean, after tilt correction		5/21	325	44	9	81

Pole position: Lat=42.8°N Lon=219.8°E dp=2.5° dm=4.4°

Symbols as in Table A3.

Table A6. Remanence component A of the Kaukua intrusion (Lat = 65.9°N, Lon = 28.2°E).

No.	Site	N	D	I	α95	k
1.	KA10—12	3	351	37	7	283
2.	KA13—21	9	346	34	3	401
3.	KA22—26	5	350	33	5	206
Mean, before tilt correction		3/17	349	35	4	827
Mean, after tilt correction		3/17	328	56	4	805

Pole position: Lat=42.5°N Lon=222.4°E dp=2.3° dm=4.9°

Symbols as in Table A3.

Table A7. Remanence component A of the Murtolampi intrusion (Lat = 66.0°N, Lon = 28.2°E).

No.	Site	N	D	I	α95	k
1.	MU1—5	2	350	33	—	—
2.	MU6—8	3	349	35	7	296
Mean No tilt correction		2/5	349	34	—	—

Pole position: Lat=42.2°N Lon=222.0°E dp= — dm= —

Symbols as in Table A3.

App. contd.

Table A8. Remanence component A of the Koitelainen intrusion (Lat = 67.8°N, Lon = 27.1°E).

No.	Site	N	D	I	α95	k
1.	KT1—12, KO6	6	341	41	6	121
2.	KS1—5	5	345	43	7	118
3.	KO1—3	3	331	39	6	391
	Mean, before tilt correction	3/14	339	41	9	186
	Mean, after tilt correction	3/14	353	54	20	39

Pole position: Lat=43.9°N Lon=234.6°E dp=6.7° dm=11.0°

Symbols as in Table A3.

Table A9. Remanence component A' of the Koitelainen intrusion (Lat = 67.8°N, Lon = 27.1°E).

No.	Site	N	D	I	α95	k
1.	KT1—12, KO6	3	308	20	12	112
2.	KS1—5	2	307	32	—	—
3.	KO1—3	3	315	30	3	1684
	Mean, before tilt correction	3/8	310	28	12	115
	Mean, after tilt correction	3/8	312	45	15	68

Pole position: Lat=28.0°N Lon=264.2°E dp=6.9° dm=12.6°

Symbols as in Table A3.

Table A10. Remanence component B of the Näränkävaara intrusion (Lat = 65.7°N, Lon = 29.5°E).

No.	Site	N	D	I	α95	k
1.	NA1—3, 12—17	3	21	48	14	84
2.	NA7—9*	1	13	14	—	—
8.	NA35—37	3	28	39	29	19
10.	NA24—28	2	10	32	—	—
11.	NA18—23	2	14	48	—	—
13.	NA38—42	4	32	39	18	28
	Mean, before tilt correction	5/14	20	37	12	31
	Mean, after tilt correction	5/14	23	35	15	28

* not included in mean direction.

Pole position: Lat=43.3°N Lon=184.2°E dp=8.4° dm=14.2°

Symbols as in Table A3.

Table A11. Remanence component B of the Syöte intrusion (Lat = 65.6°N, Lon = 27.7°E).

No.	Site	N	D	I	α95	k
1.	VK1—3	1	42	35	—	—
2.	SS1—11	5	25	49	15	27
3.	PS10—15	1	16	51	—	—
4.	PS1—9	4	35	32	29	11
5.	RO1—10	1	15	44	—	—
6.	SY1—22	8	33	43	12	24
7.	SM1—10	4	31	35	11	68
9.	SV1—5	5	40	44	18	20
11.	SK1—7	1	37	30	—	—
13.	PV1—5*	1	17	18	—	—
14.	ST1—5	1	34	44	—	—
15.	ST6—9	1	22	56	—	—
	Mean, before tilt correction	11/32	31	42	6	58
	Mean, after tilt correction	11/32	16	23	7	41

* not included in mean direction.

Pole position: Lat=44.5°N Lon=167.2°E dp=4.6° dm=7.4°

Symbols as in Table A3.

Table A12. Remanence component B of the Lipeävaara intrusion (Lat = 65.9°N, Lon = 28.1°E).

No.	Site	N	D	I	α95	k
1.	LI4—5, 20—22	3	26	48	12	105
4.	LI8—12	3	14	23	11	122
5.	LI13—19	5	16	25	14	30
	Mean, before tilt correction	3/11	18	32	23	31
	Mean, after tilt correction	3/11	356	59	16	61

Pole position: Lat=40.1°N Lon=186.0°E dp=14.3° dm=25.4°

Symbols as in Table A3.

Table A13. Remanence component B of the Kaukua intrusion (Lat = 65.9°N, Lon = 28.2°E).

No.	Site	N	D	I	α95	k
1.	KA10—12	2	34	26	—	—
2.	KA13—21	5	25	29	17	21
3.	KA22—26	3	34	45	19	44
	Mean, before tilt correction	3/10	31	33	17	52
	Mean, after tilt correction	3/10	40	62	17	53

Pole position: Lat=38.1°N Lon=169.8°E dp=11.1° dm=19.6°

Symbols as in Table A3.

App. contd.

Table A14. Remanence component D of the Näränkävaara intrusion (Lat = 65.7°N, Lon = 29.5°E).

No.	Site	N	D	I	α95	k
1.	NA1—3, 12—17	2	133	64	—	—
2.	NA7—9	1	132	70	—	—
4.	NM1—5	1	166	29	—	—
5.	NN1—5	3	112	48	29	19
11.	NA18—23	2	112	26	—	—
12.	NA43—47	4	90	58	20	22
15.	NH1—3	1	96	70	—	—
Mean, before tilt correction		7/14	123	55	19	11
Mean, after tilt correction		7/14	93	47	21	12

Pole position: Lat=20.5°N Lon=76.4°E dp=19.3° dm=27.1°

Symbols as in Table A3.

Table A15. Remanence component D of the Syöte intrusion (Lat = 65.6°N, Lon = 27.7°E).

No.	Site	N	D	I	α95	k
Normal polarity						
2.	SS1—11	3	113	45	34	14
3.	PS10—15	3	80	67	20	40
5.	RO1—10	1	113	53	—	—
6.	SY1—22	15	99	63	7	36
7.	SM1—10	9	111	21	7	53
8.	SL1—9	1	74	57	—	—
9.	SV1—5	5	125	47	9	74
10.	SV6—8	1	115	35	—	—
14.	ST1—5	1	113	18	—	—
15.	ST6—9	1	157	26	—	—
Reversed polarity						
4.	PS1—9	4	59	—79	14	45
12.	SR1—5	1	121	—70	—	—
13.	PV1—5	1	83	—80	—	—
Mean (N), before tilt correction		10/40	114	45	15	12
Mean (N), after tilt correction		10/40	82	61	14	13
Mean (R), before tilt correction		3/6	96	—78	14	75
Mean (R), after tilt correction		3/6	136	—49	24	27

Pole position (N): Lat=15.0°N Lon=85.7°E dp=11.6° dm=18.3°
Pole position (R): Lat=58.5°N Lon=338.8°E dp=25.2° dm=26.9°

Symbols as in Table A3.

Table A16. Remanence component D of the Lipeävaara intrusion (Lat = 65.9°N, Lon = 28.1°E).

No.	Site	N	D	I	α95	k
1.	LI4—5, 20—22	3	80	38	32	16
3.	LI6—7	1	56	52	—	—
4.	LI8—12	2	69	49	—	—
Mean, before tilt correction		3/6	69	47	17	51
Mean, after tilt correction		3/6	106	78	32	16

Pole position: Lat=33.9°N Lon=124.6°E dp=14.5° dm=22.4°

Symbols as in Table A3.

Table A17. Remanence component D of the Kaukua intrusion (Lat = 65.9°N, Lon = 28.2°E).

No.	Site	N	D	I	α95	k
2.	KA13—21	2	119	21	—	—
3.	KA22—26	1	134	28	—	—
Mean, before tilt correction		2/3	127	25	—	—
Mean, after tilt correction		2/3	136	13	—	—

Pole position: Lat=2.0°S Lon=79.7°E dp=19.4° dm=36.2°

Symbols as in Table A3.

Table A18. Remanence component D of the Murtolampi intrusion (Lat = 66.0°N, Lon = 28.2°E).

No.	Site	N	D	I	α95	k
1.	MU1—5	1	144	44	—	—
2.	MU6—8	1	113	68	—	—
Mean No tilt correction		2/2	133	56	—	—

Pole position: Lat=19.0°N Lon=66.2°E dp= — dm= —

Symbols as in Table A3.

App. contd.

Table A19. Remanence component E of the Näränkävaara intrusion (Lat = 65.7°N, Lon = 29.5°E)

No. Site	N	D	I	α95	k
Normal polarity					
1. NA1—3, 12—17	2	265	59	—	—
2. NA7—9	1	240	42	—	—
3. NL1—3	1	293	44	—	—
7. NH4—8	1	239	43	—	—
11. NA18—23	1	208	85	—	—
13. NA38—42	1	232	70	—	—
14. NA6	1	282	70	—	—
Reversed polarity					
6. NA4—5	1	106	—38	—	—
13. NA38—42	1	51	—67	—	—
14. NA6	1	82	—28	—	—
16. NA29—34	1	97	—24	—	—
Mean (N), before tilt correction	7/8	257	61	16	15
Mean (N), after tilt correction	7/8	305	68	19	11
Mean (R), before tilt correction	4/4	89	—40	29	11
Mean (R), after tilt correction	4/4	110	—46	72	4
Mean (COMB.), before tilt correction	9/10	264	52	15	13
Mean (COMB.), after tilt correction	9/10	295	58	21	7

Pole position (N): Lat=33.1°N Lon=330.6°E dp=19.1° dm=24.8°
Pole position (R): Lat=20.5°N Lon=310.4°E dp=21.2° dm=35.1°
Pole position (C): Lat=27.1°N Lon=319.3°E dp=14.0° dm=21.0°

Symbols as in Table A3.

Table A20. Remanence component E of the Syöte intrusion (Lat = 65.6°N, Lon = 27.7°E).

No. Site	N	D	I	α95	k
Normal polarity					
2. SS1—11	4	273	49	41	6
4. PS1—9	1	216	54	—	—
5. RO1—10	1	277	56	—	—
6. SY1—22	9	280	33	34	3
7. SM1—10	5	264	62	27	9
8. SL1—9	3	225	47	44	9
9. SV1—5	4	245	68	18	15
10. SV6—8	2	258	47	—	—
11. SK1—7	2	274	68	—	—
14. ST1—5	1	252	39	—	—
15. ST6—9*	1	224	—9	—	—
Reversed polarity					
2. SS1—11*	1	122	3	—	—
4. PS1—9*	3	95	0	20	39
5. RO1—10	1	59	—48	—	—
6. SY1—22	3	116	—37	39	11
9. SV1—5	3	39	—22	16	62
Mean (N), before tilt correction	10/32	257	54	11	21
Mean (N), after tilt correction	10/32	287	41	11	21
Mean (R), before tilt correction	3/7	69	—40	58	6
Mean (R), after tilt correction	3/7	91	—38	52	7
Mean (COMB.), before tilt correction	10/35	253	52	11	20
Mean (COMB.), after tilt correction	10/35	283	41	11	21

* not included in mean direction.

Pole position: (N) Lat=26.2°N Lon=324.5°E dp=10.6° dm=15.1°
Pole position: (R) Lat=12.6°N Lon=326.1°E dp=42.5° dm=70.3°
Pole position: (C) Lat=22.9°N Lon=326.7°E dp=10.0° dm=15.0°

Symbols as in Table A3.

App. contd.

Table A21. Remanence component E of the Lipeävaara intrusion (Lat = 65.9°N, Lon = 28.1°E).

No. Site	N	D	I	α95	k
Normal polarity					
1. LI4—5, 20—22	3	194	43	32	16
2. LI1—3	3	217	49	61	5
3. LI6—7	1	290	50	—	—
4. LI8—12	2	256	20	—	—
5. LI13—19	3	283	47	81	3
Reversed polarity					
1. LI4—5, 20—22	1	43	—42	—	—
2. LI1—3	1	47	—39	—	—
Mean (N), before tilt correction	5/12	248	48	31	7
Mean (N), after tilt correction	5/12	244	15	34	6
Mean (R), before tilt correction	2/2	45	—41	—	—
Mean (R), after tilt correction	2/2	45	—16	—	—
Mean (COMB.), before tilt correction	5/12	251	45	28	9
Mean (COMB.), after tilt correction	5/12	246	14	29	8

Pole position (N): Lat=18.0°N Lon=329.3°E dp=26.6° dm=41.0°
Pole position (R): Lat= 5.4°N Lon=347.4°E dp= — dm= —
Pole position (C): Lat=16.8°N Lon=326.0°E dp=22.0° dm=35.0°

Symbols as in Table A3.

Table A22. Remanence component E of the Kaukua intrusion (Lat = 65.9°N, Lon = 28.2°E).

No. Site	N	D	I	α95	k
Normal polarity					
2. KA13—21	5	226	71	22	13
3. KA22—26	2	233	60	—	—
Reversed polarity					
1. KA10—12	1	114	—22	—	—
2. KA13—21	1	140	—55	—	—
3. KA22—26	1	74	—51	—	—
Mean (N), before tilt correction	2/7	230	66	—	—
Mean (N), after tilt correction	2/7	215	38	—	—
Mean (R), before tilt correction	3/3	109	—46	46	8
Mean (R), after tilt correction	3/3	83	—38	46	8
Mean (COMB.) before tilt correction	3/8	279	52	49	7
Mean (COMB.) after tilt correction	3/8	251	38	49	7

Pole position: (N) Lat=30.3°N Lon=351.7°E dp=33.9° dm=41.6°
Pole position: (R) Lat=32.4°N Lon=292.6°E dp=37.4° dm=58.8°
Pole position: (C) Lat=33.1°N Lon=305.0°E dp=46.0° dm=67.0°

Symbols as in Table A3.

App. contd.

Table A23. Remanence component E of the Koitelainen intrusion (Lat = 67.8°N, Lon = 27.1°E).

No.	Site	N	D	I	α95	k
Normal polarity						
1.	KT1—12, KO6	1	282	69	—	—
3.	KO1—3	1	338	63	—	—
Reversed polarity						
1.	KT1—12, KO6	1	98	—68	—	—
2.	KS1—5	1	83	—43	—	—
3.	KO1—3	1	156	—66	—	—
Mean (N), before tilt correction		2/2	313	68	—	—
Mean (R), after tilt correction		2/2	9	86	—	—
Mean (R), before tilt correction		3/3	105	—63	36	13
Mean (R), after tilt correction		3/3	79	—79	32	16
Mean (COMB.), before tilt correction		3/3	286	63	37	12
Mean (COMB.), after tilt correction		3/3	241	85	42	10

Pole position (N): Lat=62.4°N Lon=284.6°E dp= — dm= —
Pole position (R): Lat=45.5°N Lon=304.8°E dp=44.3° dm=56.6°
Pole position (C): Lat=46.3°N Lon=304.0°E dp=46.0° dm=58.0°

Symbols as in Table A3.

Table A25. Rotation angles and the strike/dip data used in tectonic tests.

intrusion	Δ	unrotated str/dip[1]	rotated str/dip[2]	rotated str/dip[3]
I. Rotations according to [(a)]				
N	—35	305/15	270/15	305/15
S	+25	245/15	270/15	270/15
L	+55	145/15	200/15	200/15
K	—20	110/15	130/15	130/15
M	+10	0/0	0/10	0/0
T	+32	57/15	89/15	89/15
II. Rotations according to [(b)]				
N	+19	305/15	324/15	305/15
S	+11	245/15	256/15	256/15
L	+ 9	145/15	78/15	78/15
K	+17	110/15	127/15	127/15
M	+10	0/0	0/0	0/0
T	—13	57/15	44/15	44/15

for intrusions see Table 1.
Δ rotations (in degrees) used to accommodate the rotational effect due to post-emplacement faulting (see (a), (b) below and Fig. 1). All rotations assumed to be around vertical axis. — rotation clockwise, + anticlockwise.
1) original strike/dip data on igneous layering, where 15° dips (corresponding to about 50 % unfolding) assumed except for Murtolampi (M) (see text).
2) Näränkävaara (N) assumed to have been rotated.
3) Näränkävaara not rotated.
(a) reference direction for all bodies is E-W.
(b) reference direction tight to each body's own rotations according to Korhonen's (1981) hypothetical dextral fault.

Table A24. Baked contact tests

Area	Rock type	Component A D,I	Component B D,I	Component D D,I	Component E D,I	Arch (G, P D,I
Kaukua	layered intrusion	351,37	34,26	119,21	279,52	—
Soilu	unbaked Archaean granitic gneiss	345,37	—	—	—	261,8
Ala—Penikat (2 km)	baked Archaean granitic gneiss	—	—	106,45	—	145,8
Sompujärvi (2 km)	baked Archaean granitic gneiss	323,47	24,50	112,58	—	143,7
Sompujärvi (contact)	baked Archaean granitic gneiss	—	—	—	247,20	—

For locations see Fig. 1 and Table 3. For other explanations see text.

App. contd.

Table A26. Tectonic tests. Original order of the tectonic processes: rotation followed by tilting. In tectonic corrections these processes were reversed (i.e. tilt correction was done first).

		O			a.t.			a.r.			O			a.t.			a.r.		
C	N	D	I	k	D	I	k	D	I	k	D	I	k	D	I	k	D	I	k
I ROTATIONS ACCORDING TO (a)																			
		Näränkävaara rotated									*Näränkävaara not rotated*								
A	6	346	38	119	345	39	97	349	42	13	346	38	119	345	39	97	355	41	17
B	4	25	36	125	22	37	37	27	41	7	25	36	125	22	37	37	37	38	15
D	5	114	48	15	113	51	13	115	52	11	114	48	*15*	113	51	*13*	121	50	*18*
E	5	265	54	53	263	52	22	277	54	12	265	54	53	263	52	52	283	54	14
II ROTATIONS ACCORDING TO (b)																			
		Näränkävaara rotated									*Näränkävaara not rotated*								
A	6	346	38	119	346	38	94	354	40	38	346	38	119	346	38	94	351	39	57
B	4	25	36	125	22	37	37	36	37	29	25	36	125	22	37	37	30	37	27
D	5	114	48	15	113	51	13	127	51	12	114	48	15	113	51	13	123	52	11
E	5	265	54	53	267	51	25	278	51	22	265	54	53	267	51	25	277	50	26

C remanence component (see text)
N number of intrusions
O original (in-situ) declination (D) and inclination (I) of remanent magnetization: k = Fisher precision parameter
a.t. after tilt-correction
a.r. after tilt and rotation corrections
I Rotations caused by a large dextral strike-slip post-emplacement fault passing west of the Koitelainen body (Fig. 1), "separating" the intrusions from their original E-W position (see text)
II Rotations assumed to be due to a large dextral strike-slip fault passing east of the Koitelainen body (described by Korhonen, 1981: see text)
Left: Näränkävaara rotated, right: Näränkävaara not rotated
For rotation and tilt angles see Table A25

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