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Remanent Magnetization in the Archaean Basement and Cutting Diabase Dykes in Finland, Fennoscandian Shield

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Abstract

New palaeomagnetic results on basement rocks and cutting diabases from Archaean terranes in Finland (Fennoscandian Shield) are presented. The terranes studied are Varpaisjärvi in central Finland, Eno-Ilomantsi in eastern Finland and Kuhmo-Suomussalmi in northeastern Finland. The Varpaisjärvi results are from five Archaean blocks showing variation in tectonic styles, orientation of dyke swarms and magnetic anomaly patterns. The palaeomagnetic data are treated with respect to their source blocks to seek differences in magnetization directions between blocks caused by tectonism or age. The analysis is based on original results of one of the authors (K.J. Neuvonen), where the demagnetization data were submitted to an optimum cleaning strategy without multicomponent analysis.

Three main magnetization directions were isolated: (i) Archaean magnetization in the basement rocks (component Ar), (ii) a direction corresponding to the cutting (presumably Jatulian) diabase dykes and their baked host rocks (component Ja), and (iii) the Svecofennian direction observed in some basement rocks, dykes and baked contacts (component Sf). Of these, the Archaean directions most likely reflect the last metamorphic cooling, which took place 2680–2630 Ma ago in the Varpaisjärvi area. The Sf directions represent overprints acquired during the Svecofennian orogeny (~1860 Ma), which affected the Archaean blocks as evidenced by numerous faults and Svecofennian K-Ar age data on the basement. The Ja remanence directions are interpreted as primary on the basis of baked contact tests and Jatulian radiometric age (~2150 Ma) data on some of the diabases. These interpretations are supported by the NRM intensity values, which often show reduced remanence intensities for overprints due to alterations associated with orogenic events. The contact tests are often complicated, however, and it cannot totally be ruled out that the Ja direction is in fact a late Svecofennian (~1780 Ma) overprint, as suggested by the APW data. Detailed high-field (up to 150 mT) a.f. demagnetization treatments were made at the Laboratory for Palaeomagnetism of the Geological Survey of Finland (GSF) in Espoo to compare the optimium cleaning and multicomponent analysis techniques on some specimens. The results confirm the existence of two superimposed remanence components, particularly in specimens that plot between the Jatulian and Svecofennian directions and were not separated by the optimum cleaning method. In the Varpaisjärvi area the palaeomagnetic evidence for tectonic rotation, tilting or lateral movements of the blocks is inconclusive. The new data suggest modifications to the APW path and to the palaeolatitude curve for Fennoscandia during Archaean-Palaeoproterozoic times.

Key words: palaeomagnetism, Fennoscandia, remanent magnetization, dykes

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1. Introduction

Studies of the palaeomagnetism and age relations of the rocks in the Main Sulphide Ore Belt in central Finland (the Raahe-Ladoga Belt; *Neuvonen et al.*, 1981) revealed stable magnetization in a high-grade metamorphic, ~2680 Ma old, quartz diorite (enderbite) in the Varpaisjärvi area (see Fig. 2). The related palaeopole (64° N, 313° E) has been used as the onset of the Precambrian APW path for the Fennoscandian Shield (e.g., *Pesonen* and *Neuvonen*, 1981; *Pesonen et al.*, 1989). The area of high-grade granulites where the samples originated is, however, very small, being no more than 100 square kilometres in size, and the palaeopole cannot be considered to represent the whole shield. Therefore, more samples are needed to establish the late Archaean pole position for Fennoscandia. The new samples were expected to give additional information on the occurrence of this type of orientation of Archaean remanence in the Varpaisjärvi blocks and perhaps also in other Archaean terranes in Finland, such as Kuhmo-Suomussalmi in northeastern and Eno-Ilomantsi in eastern Finland (Fig. 1). From 1973 to 1988 more than 300 sites were sampled, one-third of these being diabase dykes cutting the basement. The planning of the new sampling was aided by new geological maps and research findings published on the Archaean terranes in eastern and northeastern Finland (e.g. *Lavikainen*, 1973; *Luukkonen*, 1991; *Paavola*, 1984a, 1984b, 1988; *Hölttä et al.*, 1992). Moreover, new palaeomagnetic data on Archaean and Palaeoproterozoic rocks in Finland were valuable for comparing our results with those published by *Bylund* and *Pesonen* (1987), *Mertanen et al.* (1989) and *Pesonen et al.* (1989, 1991, 1992).

The reliability of the Archaean palaeopole deduced from the Varpaisjärvi quartz diorite was based on a precise U-Pb (magmatic zircon) radiometric age (2680 ± 3 Ma; *Paavola*, 1986) and a positive baked contact test for a cutting diabase dyke (*Neuvonen et al.*, 1981). It was hoped that well-preserved Archaean blocks similar to the Jonsa block investigated in Varpaisjärvi would be more common in the Archaean basement. The primary aim of the present work was therefore to examine the occurrence of similar orientations of Archaean characteristic magnetizations in the nearby Pällikäs, Petäys, Lapinlahti and Sonkajärvi blocks (Fig. 2). Later, oriented cores were also collected from two other Archaean basement areas in northeastern (Kuhmo-Suomussalmi terrane) and eastern (Eno-Ilomantsi terrane) Finland (Fig. 1).

The purpose of this paper is (i) to summarize the previously unpublished (*Neuvonen*, 1995) palaeomagnetic data on these Archaean areas, (ii) to define and interpret the different groups of remanence directions in the rocks, (iii) to study the implications of the remanence components for block tectonism in the Varpaisjärvi terrane, and (iv) to propose a new APW path and palaeolatitude curve for Fennoscandia during Archaean and Palaeoproterozoic times (e.g., *Mertanen*, 1995; *Pesonen*, 1995; *Pesonen* and *Mertanen*, 1996; *Pesonen et al.*, 1997; *Mertanen* and *Pesonen*, 1997).

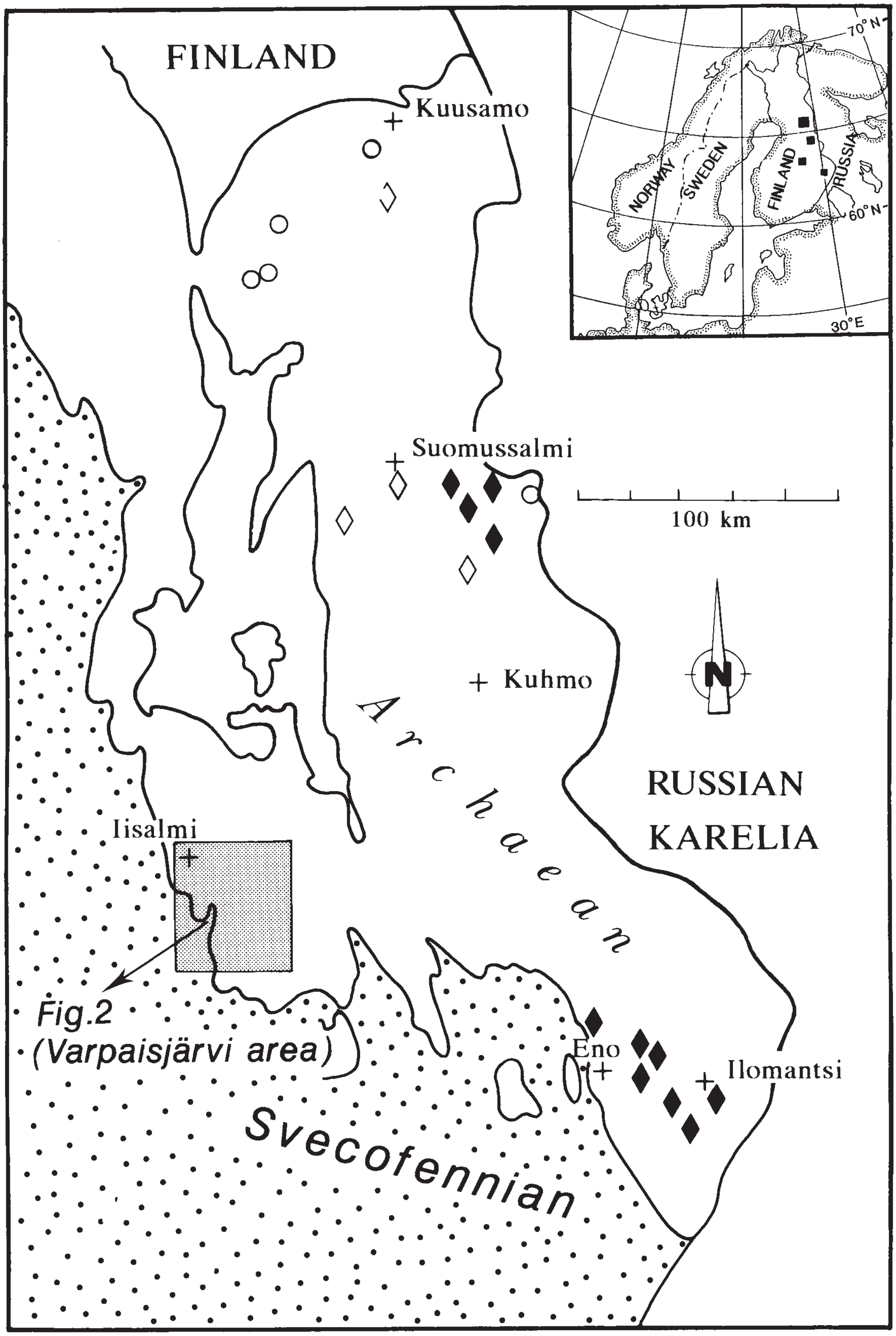

Fig. 1. Palaeomagnetic sampling sites in the three Archaean basement terranes in Finland: Varpaisjärvi, Eno-Ilomantsi and Kuhmo-Suomussalmi. The insert at upper right corner shows the study areas in Fennoscandia. The first is shown in greater detail in Fig. 2. Closed (open) diamonds denote diabase dykes with a Jatulian (Svecofennian) remanent magnetization direction, and open circles denote Archaean basement sites with a Svecofennian overprint.

2. Geological background

Figures 1–2 outline the geology of the Archaean terranes studied. The majority of the samples were taken from Varpaisjärvi, which is part of the Iisalmi plate and is located just northeast of the Archaean-Proterozoic boundary (Fig. 2; see also *Hölttä*, 1997). Lower crustal Archaean granulites are exposed as fault-bounded blocks in the Varpaisjärvi area. The main rock types in these blocks are high-grade igneous enderbites (previously called quartz diorites), mafic granulites (Mgs) and tonalitic

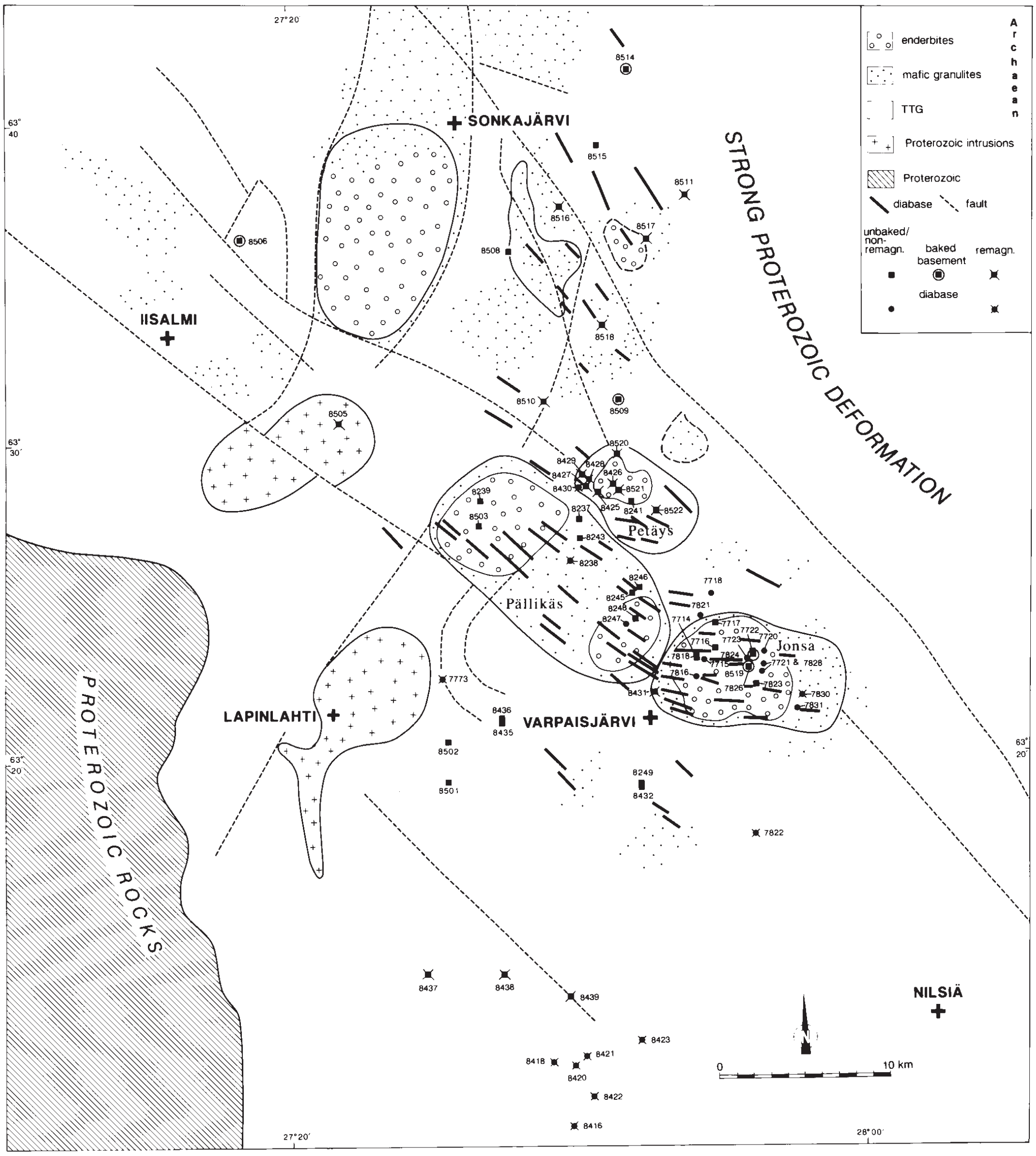

Fig. 2. The Archaean Varpaisjärvi terrane with five basement blocks (Jonsa, Pällikäs, Petäys, Sonkajärvi and Lapinlahti). The map is simplified from *Hölttä* (1997) and *Lerssi* and *Pesonen* (1995, unpublished aeromagnetic map (Fig. 3)). See legend for geology and rock types. Geological, aeromagnetic and tectonic studies suggest that the Jonsa block has rotated ~25° anticlockwise with respect to the Pällikäs block (see *Hölttä et al.*, 1992; *Pesonen* and *Mertanen*, 1996).

-trondhjemitic migmatites (TTGs). These are cut by numerous diabase dykes of presumably Jatulian age, Svecofennian gabbro and granite intrusions and numerous fractures and faults. Investigation of fault offsets in some of the dated Svecofennian intrusions (see Fig. 2) proves that many faults have been active since Archaean-Jatulian times and that they are most likely related to movements caused by the Svecofennian orogeny 1.88–1.86 Ga ago.

On the basis of geological studies and investigations of high-resolution aeromagnetic maps (Fig. 3), the Varpaisjärvi terrane is subdivided into five Archaean

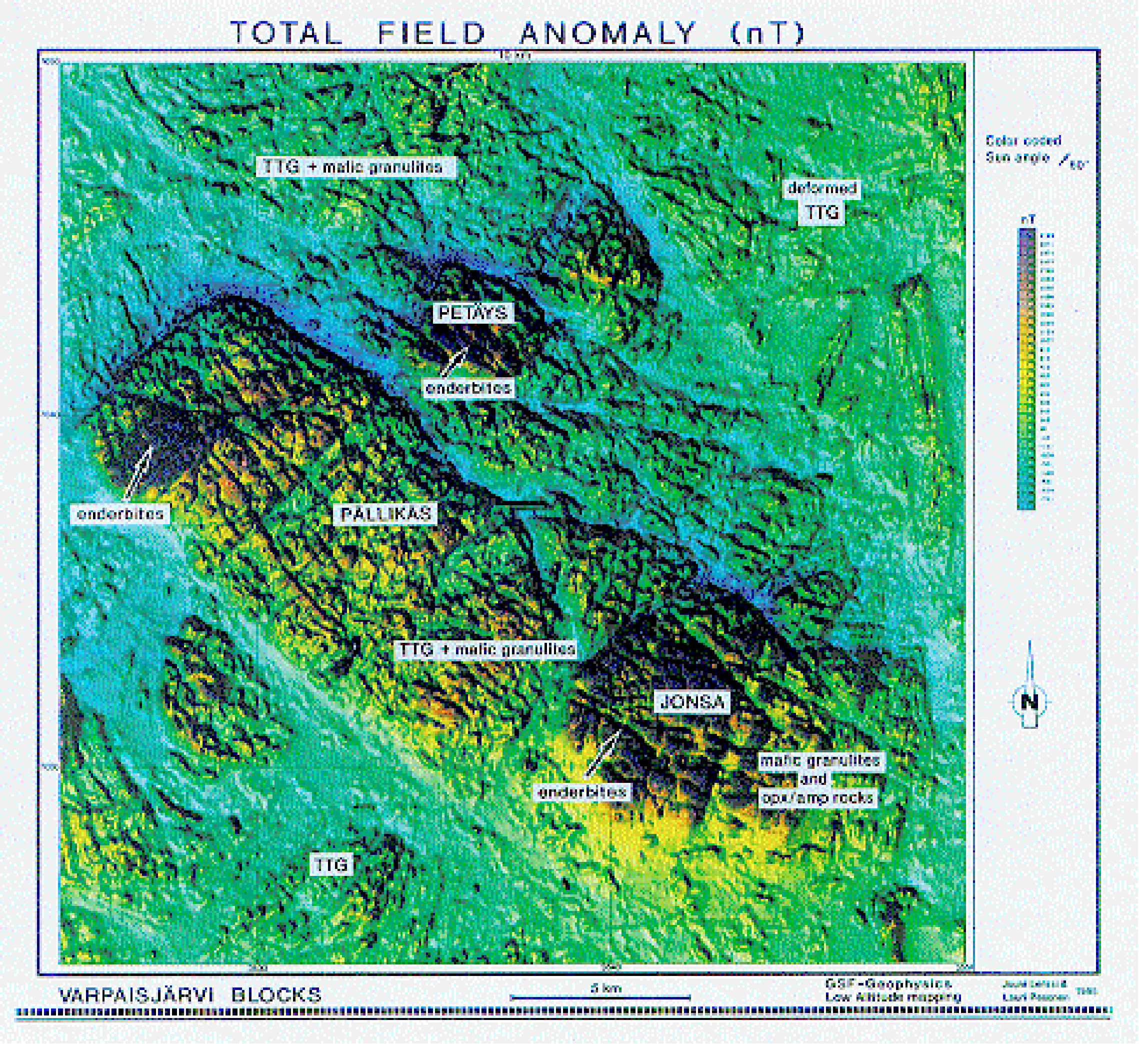

Fig. 3. High-resolution aeromagnetic map of the Varpaisjärvi region. Flight altitude ~40 m, line spacing 200 m. Colour-coded shaded relief of total intensity (DGRF 1965.0), illumination from NW. Map by Jouni Lerssi and Lauri Pesonen (1995, unpublished); original data of the Geological Survey of Finland.

basement blocks (hereafter called the Jonsa, Pällikäs, Petäys, Lapinlahti and Sonkajärvi blocks) as shown in Fig. 2. Since we have reason (see later) to believe that the present juxtaposition and tectonic appearance of the blocks (e.g. Jonsa, Pällikäs and Petäys) may be due to their plate tectonic (*Hölttä*, 1997) or local rotational history (*Hölttä et al.*, 1992), we have treated the palaeomagnetic data according to their source blocks (e.g., *Pesonen* and *Mertanen*, 1996). Note here in passing, however, that large areas of the Archaean basement were so weakly magnetized that no information on the orientation of the remanent magnetization could be obtained with the apparatus available in Turku.

Some U-Pb (zircon) ages of basement rocks are available from the Varpaisjärvi area. A sample of an enderbite of the Jonsa block (site 7818, Table 1) yielded an age of 2680 ± 3 Ma (*Neuvonen et al.*, 1981; *Paavola*, 1986). More recent age determinations with the U-Pb (zircon) method suggest an age of ~2630 Ma for the mafic granulites and TTGs (*Hölttä et al.*, 1997). Here we take this age to represent the last major metamorphism in the area, which affected all Archaean rock types including the igneous enderbites, which record an U-Pb (zircon) age of 2680 Ma.

There are numerous diabase dykes in the Varpaisjärvi terrane, particularly in the Jonsa, Pällikäs and Sonkajärvi blocks (Fig. 2). These can be traced on high-resolution aeromagnetic maps (Fig. 3), where they generally follow the fracture patterns. The dykes are unaltered pyroxene diabases with ophitic textures but sometimes they have been altered as shown by the presence of secondary hornblende, epidote and saussurite. In the field they cut the basement rocks sharply and often have chilled margins at their contacts. Geochemistry and dyke orientations indicate that the dykes are most likely of Jatulian age. Only three dykes have been dated with radiometric methods (U-Pb and Sm-Nd), and they show an age span from 2336 Ma to 2085 Ma (*Paavola*, 1984a, 1984b, 1986; *Toivola et al.*, 1991). The only dated dyke sampled in this study is from the Jonsa block (site 7816), and it yields a Sm-Nd age of 2085 ± 95 Ma (*Toivola et al.*, 1991). For a more detailed account of the published age data, see *Paavola* (1986), *Kontinen et al.* (1992) and *Hölttä et al.* (1997).

The Jonsa block is characterized by the fact that the dry hypersthene-bearing enderbitic rocks, which appear as high magnetic relief on aeromagnetic maps (Fig. 3), are well preserved and that magnetite is more abundant and generally less resorbed in this block than in the gneisses outside the area. The diabase dykes are also better preserved in the Jonsa block than in other blocks (*Paavola*, 1993, personal communication). Moreover, in the Jonsa block the dykes show a different orientation (strike ~280°–285°) from the dykes outside the block, e.g. in the Pällikäs (strike ~305°–315°) and Sonkajärvi blocks (strike ~325°) (see Figs 2 and 3). Note that the Archaean structural trends (NNE-SSW) also deviate from corresponding trends (NE-SW) in the Pällikäs block. We shall return to these observations since they may indicate local tectonic rotations of blocks in the Varpaisjärvi area, as proposed by *Hölttä et al.* (1992) and *Pesonen* and *Mertanen* (1996).

3. *New samples and measurements*

The present sampling was guided by new geological maps and high-resolution low-altitude airborne magnetic anomaly maps of Finland (e.g. Varpaisjärvi area, Fig. 3). Only a very few (≤ 10%) of the large number of samples cored turned out to carry strong and hard magnetization.

When possible, two or more cores were drilled on each site in different directions. The uppermost parts (~ 10 cm) of the cores were disregarded to avoid the weathering crust (*Neuvonen*, 1965). The orientation of the cores was mainly determined with a sun compass similar to that described by *Mertanen et al.* (1989). In order to isolate and analyse any secondary components of magnetization in the samples, all specimens cut were demagnetized by a stepwise alternating field (a.f.) treatment (with steps of 5–10 mT to 40–90 mT) or by heating. The a.f. cleaning was done with a Schonstedt AF Demagnetizer, Model GSD-1; the maximum field was 50 mT or occasionally 80–90 mT. For thermal cleaning, a variety of ovens made in Turku were used. The final and most satisfactory heating technique involved blowing hot air inside a multilayered magnetic shielding. Most of the granitoid (basement) samples were, however, so weakly magnetized that measurements with a Förster-type spinner magnetometer (*Neuvonen*, 1975) could not be performed. Furthermore, many of the dyke rocks were so soft and unstable that reliable results could not be achieved (see *Neuvonen*, 1995).

Trials with multicomponent analysis failed and no common removed magnetization vector was found for most of the samples studied in Turku (*Neuvonen*, 1995). Therefore, and since many magnetically stable specimens behaved in a single-component manner (after a weak viscous component had been eliminated) in the course of demagnetization, all samples in this work were treated with optimum cleaning techniques as described in *Pesonen* (1979) coupled with multicomponent analysis (*Leino*, 1991). However, in collaboration with the Laboratory for Paleomagnetism of the Geological Survey of Finland (GSF), 15 specimens were a.f. demagnetized with a 3-axis high-field (up to 150 mT) AF demagnetizer and measured with a 2G-SQUID Rock Magnetometer (*Oja* and *Pesonen*, 1990) to seek evidence of multicomponent NRM. We note here that although the statistical analysis of the directional data (Tables 1–7 and Table 9) was performed without multicomponent analysis, the *site-mean* results of this study do not differ markedly from those submitted to multicomponent analysis (c.f. *Neuvonen*, 1992; *Pesonen* and *Mertanen*, 1996). Optimum cleaning can therefore often (but not always) find the *characteristic* remanence in these rocks, particularly when only two components, a soft one (due to viscous remanence) and a hard one, are superimposed (see Fig. 6a, for example). Some of the remanence directions, which on a stereonet appear to be *intermediate* between two characteristic directions (such as Jatulian (Ja) and Svecofennian (Sf); e.g. Fig. 7a), do indeed show evidence of two superimposed remanence vectors (see also *Pesonen et al.*, 1992). In such cases the two vectors can be resolved with detailed high-field a.f. demagnetization treatments coupled with multicomponent analysis, as will be shown later in this work (see Section 5). We note here that the more detailed cleanings (a.f. and thermal) yield also evidences of a new remanent magnetization component (the component "C") with southeasterly declination and moderate shallow (downward) inclination, which is not isolated with optimum cleaning treatment of this work (see Pesonen and Mertanen, 1996).

4. Results

Investigation of specimen behaviour in demagnetization treatments (Figs 6–8) and grouping of directions in stereoplots (Figs 4–5) lead to interpretations of three main remanence directions. These are (i) Archaean remanent magnetization (Ar), (ii) the (assumed) Jatulian direction (Ja), and (iii) the Svecofennian overprint direction (Sf). Of these, the Ar direction is significantly different whereas the Ja and Sf groups often partially overlap each other. Since there are reasons to believe that they are different (e.g., they are often superimposed, see Chapter 5), we treat them as separate directions. Other directions and components may be present in the specimens (see, e.g., site 7721 in Table 1) but were not analysed here (see e.g. *Pesonen* and *Mertanen*, 1996). We shall first discuss the Varpaisjärvi data and compare them with those on Kuhmo-Suomussalmi and Eno-Ilomantsi terranes.

4.1 Varpaisjärvi

Archaean rocks

Tables 1–5 give the directions of remanent magnetization found in rocks collected in the Archaean basement blocks of the Varpaisjärvi terrane. The remanence directions of the Varpaisjärvi blocks are plotted in stereographic projections in Figs 4a–c. Three characteristic directions (Archaean (Ar), Jatulian (Ja) and Svecofennian (Sf)) are observed and the rock types are marked with different symbols to help identification. The grand mean remanence directions are given in Table 9 and plotted in Fig. 9. We note that all the Archaean rocks unbaked by dykes and/or not affected by Svecofennian remagnetization (= non-remagnetized) reveal steep downward remanence with declination generally towards west or northwest, thus confirming the original result of *Neuvonen et al.* (1981) and *Neuvonen* (1992, 1995).

The most stable Archaean magnetization directions were obtained from high-grade enderbitic (dry hypersthene-bearing tonalites) rocks exposed in the Jonsa, Pällikäs and Petäys blocks. In the Jonsa block, all but four enderbite sites (Table 1) have preserved this direction: at four other sites the Archaean enderbites reveal a direction with a northeasterly declination and a shallow inclination. The latter we attribute to baking by Jatulian dykes for two reasons. *First*, a diabase dyke is generally

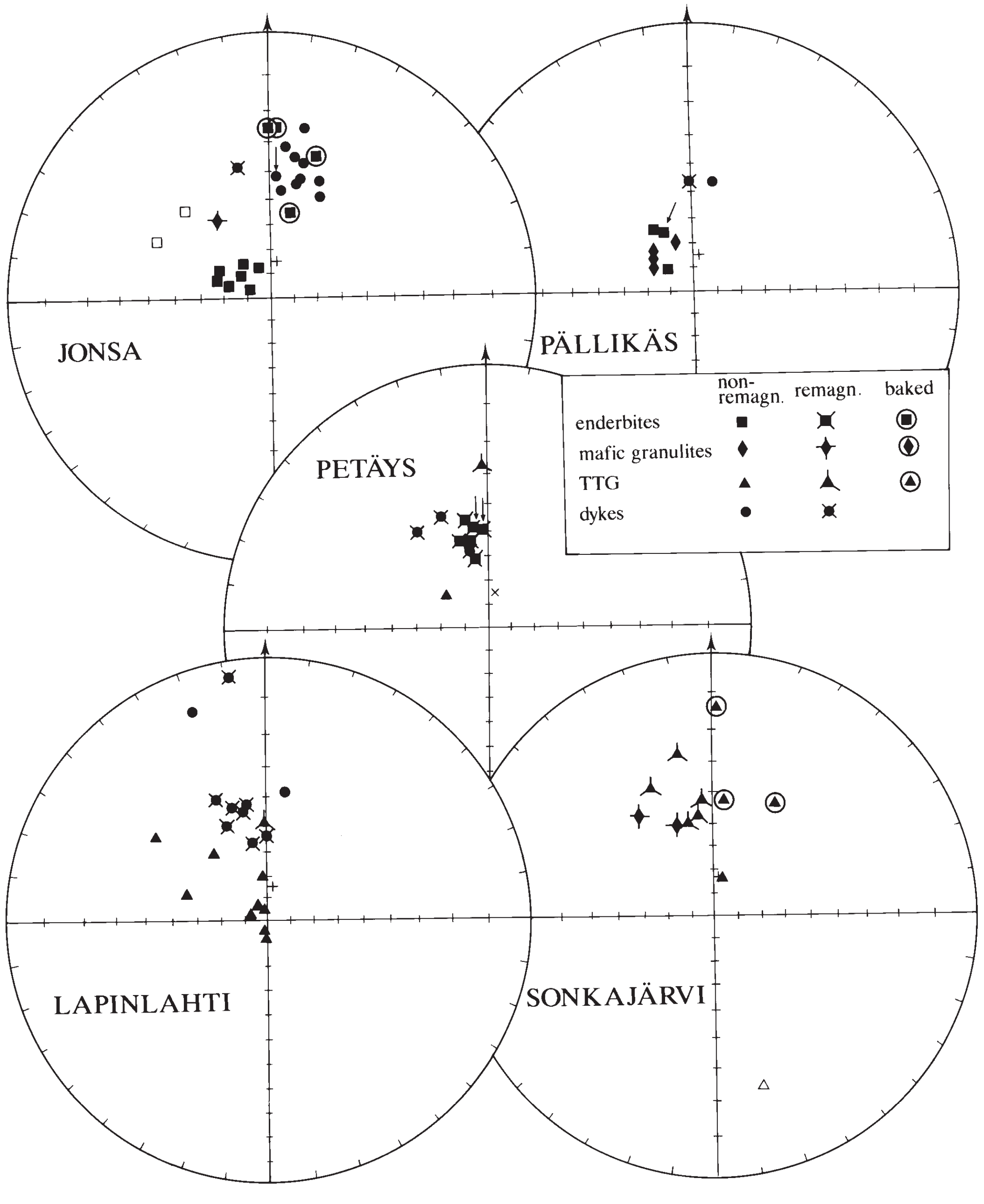

Fig. 4. Palaeomagnetic directions (after optimum a.f. and thermal cleaning) of rocks in the (a) Jonsa, (b) Pällikäs, (c) Petäys, (d) Lapinlahti, and (e) Sonkajärvi blocks. Open (closed) symbols denote upward (downward) inclinations. Rock types are given in the legend and the classification of directional data into three groups (Archaean (unbaked and non-remagnetized), Jatulian (non-remagnetized dykes and baked host rocks), and Svecofennian (remagnetized)) is explained in the text. Samples with arrows exhibit two superimposed components (Jatulian and Svecofennian) which were not fully separated in optimum cleaning as verified by detailed a.f. treatments (Figs 6–8). The present Earth´s magnetic field directions (PEF) is shown with a + symbol (*Pesonen et al.*, 1994).

found at these sites, either exposed or inferred from the aeromagnetic map (Table 1, Fig. 3). *Second*, this direction resembles the remanence direction previously interpreted as of Jatulian age (*Neuvonen*, 1975; *Pesonen*, 1987; *Bylund* and *Pesonen*, 1987;

Pesonen et al., 1991; *Mertanen et al.*, 1997). *Third*, the dated dyke (site 7818) yielded a Jatulian age of 2085 ± 95 Ma with the Sm-Nd method (*Toivola et al.*, 1991). At one site in Jonsa (8431) the remanent magnetization direction gave a northwesterly declination and a shallow inclination. Since there is no diabase dyke at this site and since this direction resembles the well established Svecofennian directions (e.g., *Pesonen et al.*, 1989), we attribute it to Svecofennian overprinting which has totally remagnetized the mafic granulite (see e.g., *Mertanen*, 1995).

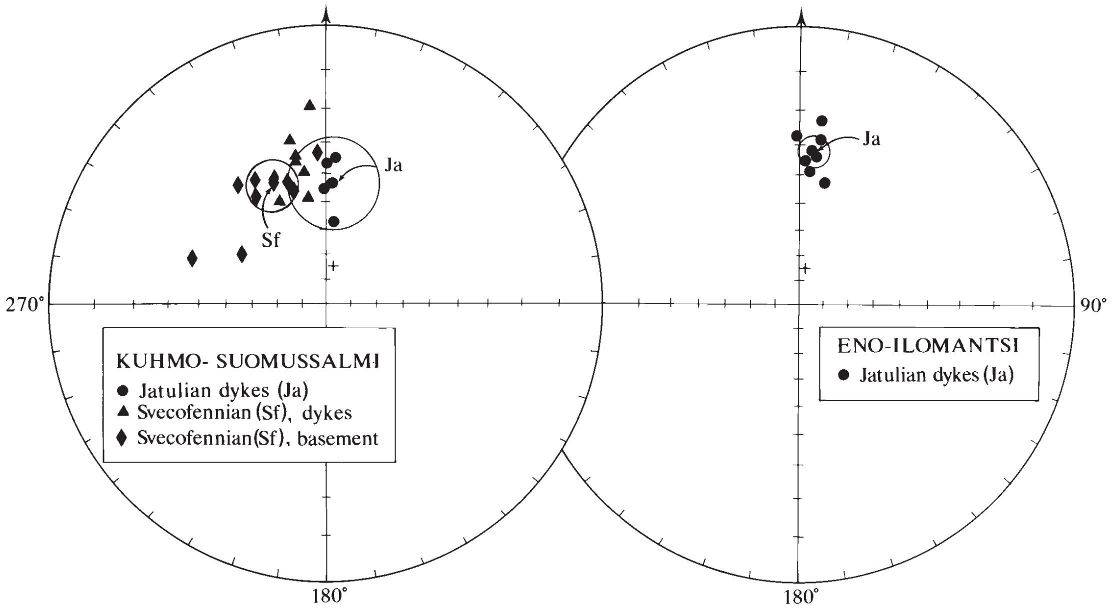

Fig. 5. Palaeomagnetic directions (after optimum a.f. and thermal cleaning) of rocks in the (a) Kuhmo-Suomussalmi and (b) Eno-Ilomantsi terranes. Rock types and the classification of directional data into two groups (Ja = Jatulian, Sf = Svecofennian) are explained in the legend and in the text). The arrows refer to mean values.

At Saarnakallio (sites 7721, 7828), however, anomalous upward remanence directions were found that could be due to either lightning or an, as yet, unidentified remanence direction with a northwesterly declination and an upward inclination. This direction could be the reversed polarity "C-component" (age ~2.3–1.9 Ga) of *Pesonen* and *Mertanen* (1996), or a Sveconorwegian (~950 Ma) direction (see e.g. *Bylund* and *Pesonen*, 1987). The high remanence intensities (*Neuvonen*, 1995) and Koenigsberger ratios (L.J. Pesonen, unpublished data) in many specimens from this locality suggest a lightning-induced origin at Saarnakallio.

In the Pällikäs block, the well-preserved Archaean direction was found not only in the enderbite sites (D = 324°, I = 66°) but also in mafic granulites (D = 316°, I = 70°; Table 2). However, in the Petäys block all the Archaean rocks except one at a TTG site (8241) have been totally or partially remagnetized by Svecofennian events (Table 3). In other blocks (Lapinlahti, Sonkajärvi) the remagnetization is strong, albeit not fully penetrative. Hence, at some sites Archaean directions have been preserved

Table 1. Paleomagnetic results from the Jonsa block (Varpaisjärvi).

Site #	**Name**	**N**	**rock type**	**Lat. (°N)**	**Long. (°E)**	**D (°)**	**I (°)**	**k**	**α95 (°)**	**J (Am^{-1})**	**Cat.**	**Note**
					(a) Basement							
7714	Palokangas		enderbite	63.385	27.807	293	66			1.938	B	
7716	Saarinen		enderbite	63.392	27.829	323	76			1.289	B	
7717	Niemelä		enderbite	63.405	27.830	284	71			1.157	B	
7722	Härkäharju		enderbite	63.390	27.870	330	76			2.117	B	
7818	Nieminen		enderbite	63.387	27.807	289	66			1.665	A	
7820	Silmisuo		enderbite	63.392	27.829	320	74			1.880	A	
7823	Joutsenus		enderbite	63.373	27.877	301	80			1.434	A	
7825	Härkäharju		enderbite	63.389	27.870	306	75			1.997	A	
	Mean	8		63.4	27.9	303.1	73.5	128.0	4.9	1.68	B	
	Pole (1)		**Plat = –63.9°N, Plon = 136.0°E, dp = 7.9°, dm = 8.8°, A95 = 8.2° (R)**									
					(b) Dykes (D → NE)							
7715	Valkeismäki		diabase	63.385	27.814	15	41			0.144	A	
7718	Hanhimäki		diabase	63.420	27.825	12	25			0.047	B	
7720	Peltoharju/Saarnakallio		diabase	63.390	27.885	13	44			0.028	B	
7723	Härkäharju		diabase	63.390	27.870	15	35			0.241	B	
7816	Nieminen		diabase	63.377	27.807	6	47			0.020	B	
7817	Nieminen		diabase	63.377	27.807	28	45			0.067	A	
7821	Hanhimäki		diabase	63.409	27.812	7	32			0.027	A	
7824	Härkäharju/Joutsenus		diabase	63.388	27.867	10	34			0.156	A	
7827	Saarnakallio		diabase	63.383	27.884	3	43			0.028	A	
7831	Palomäki		diabase	63.361	27.923	24	41			0.020	B	
	Mean	10		63.4	27.9	13.1	38.9	79.5	5.5	0.08	B	
	Pole		Plat = 47.9°N, Plon = 189.6°E, dp = 3.9°, dm = 6.5°, A95 = 5.1° (N)									
					(c) Basement (D → NE)							
7826	Jonsanharju		enderbite	63.388	27.874	20	32			0.081	B	(1)
7816	Nieminen		enderbite	63.377	27.807	15	54			0.031	B	(1)
8519	Jonsa		enderbite	63.385	27.868	1	26			2.44	A	(2)
7719	Jonsanlahti		enderbite	63.390	27.885	3	25			–	–	(2)
	Mean	4		63.4	27.9	9.1	34.4	27.3	17.9	0.85	B	
	Pole		Plat = 46.0°N, Plon = 195.0°E, dp = 11.8°, dm = 20.5°, A95 = 15.3° (N)									
					(b) + (c) All dykes + baked (D → NE)							
	Mean	14		63.4	27.9	11.9	37.7	55.1	5.4	0.26		
	Pole (6)		**Plat = 47.4°N, Plon = 191.2°E, dp = 3.8°, dm = 6.4°, A95 = 4.8° (N)**									
					(d) Remagnetized dykes (D → NW)							
7830	Jouhiniemi	1	diabase	63.368	27.930	346	37			0.007	B	
	Pole (12)		**Plat = 46.2°N, Plon = 227.0°E (N)**									
					(e) Anomalous dykes							
7721	Saarnakallio		enderbite	63.38	27.88	315	–41				A	(3)
7828	Saarnakallio		enderbite	63.38	27.88	296	–40				A	(3)
	Mean	2		63.4	27.9	305.4	–40.9	-	-	-	A	
	Pole		Plat = –6.7°N, Plon = 256.7°E, dp = –, dm = –, (A95 = 39.0°) (N)									

Notes: (1) Baking inferred because a dyke is present at the site. (2) Enderbite contains corundium. (3) Direction is anomalous (see text).

Directions are north-seeking magnetizations with no polarity definitions. The paleomagnetic pole is considered to be of N polarity unless specified to be of R polarity as based on the APW curve of Elming et al. (1993). D → NE (D → NW) denotes remanences with declinations towards NE (NW) as explained in the text. The reliability categories are: A (= reliable), B (= less reliable) as based on the number of specimens used in calculations and their directional coherence.

in the mafic granulites and TTGs but at others they have been totally or partially remagnetized by Svecofennian events (Tables 4–5).

Table 2. Paleomagnetic results from the Pällikäs block (Varpaisjärvi).

Site #	Name	N	rock type	Lat. (°N)	Long. (°E)	D (°)	I (°)	k	α95 (°)	J (Am^{-1})	Cat.	Note
					(a) Basement							
8239	Lehtomäki		enderbite	63.470	27.555	331	62			1.770	A	
8248	Saramäki		enderbite	63.408	27.735	308	75			1.270	A	
8503	Lapiinsalmi		enderbite	63.457	27.554	325	60			2.044	A	
	Mean	3		63.4	27.7	323.8	65.9	77.7	14.1	1.69	A	
	Pole		Plat = –65.5°N, Plon = 99.2°E, dp = 18.8°, dm = 23.0°, A95 = 20.8° (R)									
					(b) Basement							
8237	Ollikkala		mafic granulite	63.460	27.670	321	66			0.376	A	
8243	Nurkkala		mafic granulite	63.450	27.670	305	69			1.790	B	
8245	Kangas		mafic granulite	63.422	27.732	296	70			1.140	B	
8246	Kangas		mafic granulite	63.424	27.740	338	68			1.980	A	
	Mean	4		63.4	27.7	315.6	69.0	138.0	7.9	1.32	B	
	Pole		Plat = –64.7°N, Plon = 113.4°E, dp = 11.3°, dm = 13.3°, A95 = 13.2° (R)									
					(a) + (b) All basement							
	Mean	7		63.4	27.7	319.4	67.7	114.3	5.7	1.48		
	Pole		**Plat = –65.2°N, Plon = 107.4°E, dp = 7.9°, dm = 9.5°, A95 = 8.8° (R)**									
					(c) Dykes (D → NE)							
8247	Saramäki	1	diabase	63.405	27.725	11	46			0.096	B	
	Pole		**Plat = 53.3°N, Plon = 191.1°E (N)**									
					(d) Remagnetized dykes (D → NW)							
8238	Pällikäs	1	diabase	63.439	27.660	357	46			0.037	A	
					(e) Remagnetized basement (D → NW)							
8431	Varpainen	1	mafic granulite	63.369	27.758	324	53			0.036	B	
	Pole		Plat = 52.8°N, Plon = 262.0°E (N)									
					(d) + (e) All remagnetized dykes + basement (D → NW)							
	Mean	2		63.4	27.4	341.7	50.7	26.5	–	0.04	B	
	Pole (13)		**Plat = 56.0°N, Plon = 237.2°E, dp = –, dm = –, (A95 = 67.9°) (N)**									

See Table 1 for explanation.

The mean direction of the Jonsa enderbites (D = 303°, I = 74°; Table 1) does not differ significantly from the previous results of Neuvonen et al. ((1981), D = 305°, I = 73°). It does, however, differ slightly from the mean direction of enderbites in the Pällikäs block (D = 324°, I = 66°, Table 2). We shall return to this point in the discussion of the tectonic implications of the results (see also *Pesonen* and *Mertanen*, 1996).

Table 3. Paleomagnetic results from the Petäys block (Varpaisjärvi).

Site #	**Name**	**N**	**rock type**	**Lat. (°N)**	**Long. (°E)**	**D (°)**	**I (°)**	**k**	**α95 (°)**	**J (Am^{-1})**	**Cat.**	**Note**
(a) Basement												
8241	Korpela	1	TTG	63.470	27.730	317	74			–	–	
	Pole (3)		**Plat = –69.8, Plon = 128.2 (R)**									
(b) Remagnetized basement (D → NW)												
8429	Tornionperä		TTG	63.483	27.675	358	26			0.040	B	(1)
8520	Hollinkallio		enderbite	63.494	27.715	349	45			0.040	B	(1)
8522	Vihtorinlampi		mafic granulite	63.465	27.759	356	49			3.966	A	(1)
8521	Maaselänkangas		enderbite	63.475	27.717	351	60			0.496	A	
8425	Kallisenmäki		enderbite	63.475	27.691	346	53			1.498	A	
8426	Lintusuo		enderbite	63.479	27.709	352	51			0.804	A	
8427	Rokuanmäki		enderbite	63.478	27.683	352	47			0.448	A	
	Mean	7		63.5	27.7	352.4	47.4	55.4	8.2	1.04	B	
	Pole		Plat = 55.4°N, Plon = 219.8°E, dp = 6.9°, dm = 10.6°, A95 = 6.7° (N)									
(c) Remagnetized dykes (D → NW)												
8428	Rokuanmäki		diabase	63.481	27.681	324	42			0.079	B	
8430	Ilmapuro		diabase	63.477	27.669	348	57			0.093	A	
8520	Hollinkallio		diabase	63.494	27.715	337	41			0.040	B	
	Mean	3		63.5	27.7	335.2	47.1	45.9	18.4	0.07	B	
	Pole		Plat = 52.0°N, Plon = 243.4°E, dp = 15.4°, dm = 23.8°, A95 = 20.2° (N)									
(b) + (c) All remagnetized (D → NW)												
	Mean	10		63.5	27.7	347.2	47.6	46.2	7.2	0.75	B	(1)
	Pole (14)		**Plat = 54.9°N, Plon = 227.2°E, dp = 6.1°, dm = 9.3°, A95 = 7.1° (N)**									

See Table 1 for explanation.

Diabase dykes

The first diabase samples for palaeomagnetic work were collected before 1973. The results were, however, inconclusive, which was thought to be due to the existence of dykes of several different ages and types in the Archaean craton. When studying structural evolution in the Kuhmo-Suomussalmi terrane, *Luukkonen* (1991) reported an intrusion of east-west-trending diabase dykes at 2450–2400 Ma (the Sariola dykes) and northwest-southeast- or northeast-southwest-trending dykes presumably of Jatulian age (2200–2100 Ma). The older set (~2.45 Ga) was generally softly magnetized and did not yield reliable results (*Neuvonen*, 1995).

Table 4. Paleomagnetic results from the Lapinlahti block (Varpaisjärvi).

Site #	**Name**	**N**	**rock type**	**Lat.** (°N)	**Long.** (°E)	**D** (°)	**I** (°)	**k**	**α95** (°)	**J** (Am^{-1})	**Cat.**	**Note**
						(a) Basement						
8249	Pienmäki		TTG	63.322	27.740	290	82			1.010	A	
8432	Muuraissaari		TTG	63.320	27.740	339	84			0.772	A	
8434	Lauhanmäki		TTG	63.354	27.658	181	83			0.663	B	
8435	Romunmäki a		TTG	63.354	27.578	327	82			0.094	A	
8436	Romunmäki b		TTG	63.355	27.578	191	84			4.404	A	
8501	Kiikkukallio		TTG	63.323	27.516	289	54			1.908	A	(4)
8502	Romunmäki c		TTG	63.344	27.516	354	69			0.001	B	(4)
	Mean	5		63.2	27.6	278.0	86.9	130.7	6.7	1.39	B	
	Mean	7		63.2	27.6	304.3	81.2	27.9	11.6	1.26	B	
	Pole (N = 5) (4)		**Plat = –63.4°N, Plon = 193.9°E, dp = 13.3°, dm = 13.4°, A95 = 13.3° (R)**									
						(b) Dykes (D → NE)						
7829	Suomäki	1	diabase	63.367	27.462	9	37			0.212	A	
	Pole (8)		**Plat = 47.0°N, Plon = 195.2°E (N)**									
						(c) Remagnetized dykes (D → NW)						
8416	Iso-Lutti		diabase	63.142	27.655	339	45			0.010	B	
8420	Hönttä		diabase	63.173	27.657	341	10			0.115	A	
8421	Petäjämäki		diabase	63.178	27.671	344	41			0.079	B	
8422	Kolmisoppi		diabase	63.157	27.679	352	4			0.015	B	
8423	Mustinkylä		diabase	63.186	27.735	351	55			0.004	B	
7773	Pienmäki		diabase	63.377	27.510	347	42			0.297	B	
8437	Jouhtehinen		diabase	63.223	27.486	350	41			0.020	B	
7822	Jonsa S		diabase	63.295	27.872	339	36			0.155	A	
8418	Kaislalahti		diabase	63.174	27.633	359	52			0.002	A	
	Mean	9		63.2	27.6	346.5	36.6	19.8	11.9	0.08	B	
	Pole		Plat = 47.4°N, Plon = 226.0°E, dp = 8.1°, dm = 13.9°, A95 = 8.2° (N)									
						(d) Remagnetized basement (D → NW)						
8437	Jouhtehinen		TTG	63.223	27.486	359	48			0.003	B	(1)
8438	Ylipitkä		TTG	63.221	27.576	343	43			0.019	A	
8439	Reletti		TTG	63.210	27.651	309	34			0.007	A	
	Mean	3		63.2	27.6	332.8	46.2	21.3	20.4	0.02	B	
	Pole		Plat = 50.7°N, Plon = 246.2°E, dp = 16.7°, dm = 26.1°, A95 = 23.9° (N)									
						(c) + (d) All remagnetized (D → NW)						
	Mean	12		63.2	27.6	343.9	38.5	19.3	10.1	0.06		
	Pole (15)		**Plat = 48.1°N, Plon = 229.6°E, dp = 7.1°, dm = 12.0°, A95 = 8.5° (N)**									

See Table 1 for explanation. (4) Anomalously shallow inclinations.

Table 5. Paleomagnetic results from the Sonkajärvi block (Varpaisjärvi).

Site #	Name	N	rock type	Lat. (°N)	Long. (°E)	D (°)	I (°)	k	α95 (°)	J (Am^{-1})	Cat.	Note
					(a) Basement							
8515	Kölkänjärvi	1	TTG	63.656	27.695	12	73			–	–	(5)
	Pole (5)		**Plat = –82.3°N, Plon = 333.3°E (R)**									
					(b) Baked basement (D → NE)							
8506	Kilpijärvi		TTG	63.607	27.275	2	14			–	B	
8509	Poskilampi		TTG	63.523	27.718	4	42			0.016	A	(1)
8514	Oinaskangas		TTG	63.695	27.732	29	37			–	B	
	Mean	3		63.6	27.7	11.1	31.6	17.3	30.6	0.02	B	
	Pole (9)		**Plat = 43.5°N, Plon = 192.6°E, dp = 19.3°, dm = 34.4°, A95 = 26.3° (N)**									
					(c) Remagnetized basement (D → NW)							
8505	Pölöhmäki		TTG	63.511	27.389	344	49			0.003	A	
8508	Pitkälahti		TTG	63.599	27.587	334	33			0.247	A	
8510	Koppelo		TTG	63.522	27.631	351	47			0.039	A	
8511	Oinasjärvi		TTG	63.630	27.800	354	42			0.007	A	
8516	Petäjäjärvi		mafic granulite	63.625	27.651	340	49			1.430	B	
8517	Talaslampi		TTG	63.607	27.754	348	26			0.011	A	
8518	Luotosenkoski		mafic granulite	63.562	27.702	324	39			2.326	B	
8507	Ulmala		TTG	63.600	27.590	165	–23			–	B	(6)
	Mean	8		63.6	27.7	342.4	38.9	40.8	8.8	0.58	B	
	Pole (16)		**Plat = 47.3°N, Plon = 231.9°E, dp = 6.2°, dm = 10.5°, A95 = 7.9° (N)**									

See Table 1 for explanation. (5) Intensity data missing. (6) Direction (= reversed polarity) inverted by 180° for mean calculation.

Here we report palaeomagnetic results on the east-west- or northwest-southeast-trending Jatulian dykes of the five Archaean Varpaisjärvi blocks. On the basis of the range of age data from 2085 Ma to 2336 Ma on Varpaisjärvi dykes (*Toivola et al.*, 1991; *Paavola*, 1986; 1988; *Kontinen et al.*, 1992), we tentatively give a working age of 2150 Ma for these dykes while bearing in mind that there may be dykes of several ages within the Jatulian group. The site-mean remanent magnetization directions of the dykes are plotted in Figs 4–5 and listed in Tables 1–7 following the previously defined block division. The grand mean results of the dykes and baked rocks are shown in Table 9 and plotted in Fig. 9.

The majority of the diabase dykes in the Jonsa block have a characteristic remanence with a northeasterly declination and a moderate shallow downward inclination (group Ja); all other dykes have a northwesterly remanence declination (group Sf). Inside the Jonsa block the heat of the diabase dykes has baked the wall rock in the contact zone and converted the remanence direction of the Archaean rocks so that it is parallel to that of the dyke (e.g., site 7816a, b). Since at this site the Archaean direction (Ar) is present further away from the dyke (sites 7818/7817), a positive baked contact test result was obtained (*Everitt* and *Clegg*, 1962; *Pesonen*, 1979; *Neuvonen et al.*, 1981). This phenomenon indicates that the magnetic orientations observed in the dyke and baked contacts are primary and originate from the time the dyke and baked contact zone cooled through the magnetic Curie point during intrusion, i.e., in Jatulian time, ca. 2150 Ma ago (*Neuvonen et al.*, 1981). Moreover, since the remanent magnetization direction of the unbaked enderbite does not resemble any known post-Archaean remanence directions in Fennoscandia, we infer it to represent either the intrusion of the enderbite bodies (~2680 Ma) or the period of the last metamorphism in the Varpaisjärvi terrane, ~2630 Ma ago. In the Jonsa block four sites give a positive contact test (Table 1; see details in *Neuvonen et al.*, 1981; *Neuvonen*, 1995) although at two enderbite sites (8519, 7719) the dyke is not exposed but is inferred from an aeromagnetic map (Fig. 3).

One dyke (7830) in the Jonsa block reveals a northwesterly direction, and we interpret this as indicating Svecofennian remagnetization. Note that this dyke has a weaker NRM intensity than the northeast-trending dykes (Table 1), most likely due to the disappearance or oxidation of magnetite in Svecofennian events.

The direction of remanent magnetization measured on diabase dykes outside the Jonsa block is given in Tables 2–5. Both dyke groups (with NE or NW remanence declinations) are present but the majority have a northwesterly remanence declination indicating remagnetization by the Svecofennian orogeny. This interpretation is supported by the fact that the northwesterly declination is also found in many Archaean basement rocks, particularly in the Petäys block (Table 3). The baked contact test failed in these cases, i.e., both the wall rock and the dykes have a northwesterly remanence, the same direction as in the basement sites from which no dykes have been reported. This observation rules out the possibility that another (and possibly younger) set of diabase dykes with a true primary northwesterly remanence direction is present at these sites (see e.g. *Pesonen*, 1987). Rather, it indicates that these sites have been totally remagnetized. Since the northwesterly declination resembles that of the Svecofennian rocks, we interpret the remagnetization as Svecofennian. On the basis of APW path (Fig. 10a), the remagnetization is ~1860 Ma old.

4.2 Kuhmo-Suomussalmi

Table 6 and Fig. 5a summarize the palaeomagnetic results of the Kuhmo-Suomussalmi terrane. All basement samples reveal a northwesterly remanence, indicating strong Svecofennian remagnetization at ca. 1880–1860 Ma ago. The dykes yield, however, two groups of remanent magnetization: six dykes show a remanence with a northwesterly declination, and four dykes a remanence with a north-northeasterly declination. As for the other blocks (e.g. Jonsa), we interpret the first direction as Svecofennian remagnetization (Sf) and the latter as primary Jatulian magnetization (Ja).

Table 6. Paleomagnetic results from the Kuhmo–Suomussalmi block.

Site #	Name	N	rock type	Lat. (°N)	Long. (°E)	D (°)	I (°)	k	α95 (°)	J (Am^{-1})	Cat.	Note
						(a) Dykes (D → NE)						
8610	Aittokangas		diabase	64.755	29.792	5	57			0.135	A	
8612	Vitikkoaho		diabase	64.694	29.540	359	45			0.464	B	
8721	Alavuokki		diabase	64.770	29.442	3	35			0.214	A	
8722	Vitikkoaho		diabase	64.694	29.540	1	36			0.021	A	
	Mean	4		64.7	29.6	1.8	43.3	61.4	11.8	0.21	B	
	Pole (10)		**Plat = 51.1°N, Plon = 206.8°E, dp = 9.1°, dm = 14.7°, A95 = 10.0° (N)**									
						(b) Remagnetized basement (D → NW)						
8603	Säynäjävaara		basement	64.786	29.032	357	33			0.005	A	
8604	Konivaara		basement	64.687	28.561	288	35			0.003	A	
8613	Halla-aho		basement	64.479	29.477	341	42			0.001	A	
8701	Sadinoja		basement	67.832	26.832	323	34			0.259	A	(7)
8702	Tojottomanselkä		basement	67.801	26.876	329	36			0.005	A	(7)
8716	Vähäjärvi		basement	65.735	29.145	299	50			0.017	A	
8801	Kivijärvi		basement	64.704	30.061	342	44			0.051	A	
	Mean	7		65.7	28.6	326.3	41.4	16.8	15.1	0.05	A	
	Pole		Plat = 43.0°N, Plon = 252.8°E, dp = 11.3°, dm = 18.5°, A95 = 17.8° (N)									
						(c) Remagnetized dykes (D → NW)						
7351	Kalliovaara		diabase	65.390	29.050	347	28			0.843	B	
7633	Kiannonniemi		diabase	65.164	29.109	350	48			0.049	B	
7747	Rääpysjärvi		diabase	65.690	28.210	336	46			0.126	B	
7749	Pahkakuru		diabase	65.520	28.020	348	34			0.392	B	
8711	Pahkakuru		diabase	65.524	28.050	350	39			0.353	A	
8720	Kyllölänniemi		diabase	64.573	29.716	355	19			0.057	B	
	Mean	6		65.3	28.7	348.1	35.8	45.0	10.1	0.30	B	
	Pole		Plat = 44.4°N, Plon = 224.8°E, dp = 6.8°, dm = 11.7°, A95 = 7.5° (N)									
						(b) + (c) All remagnetized (D → NW)						
	Mean	13		65.5	28.6	337.0	39.3	19.4	9.7	0.17		
	Pole (17)		**Plat = 44.5°N, Plon = 239.6°E, dp = 6.9°, dm = 11.6°, A95 = 10.6° (N)**									

See Table 1 for explanation. (7) Sites in Lapland not shown in Fig. 1.

4.3 Eno-Ilomantsi

Only diabase dykes were investigated in this basement terrane (Fig. 1). The palaeomagnetic results are summarized in Table 7 and Fig. 5b. The characteristic remanence has a north-northeasterly declination and a moderate shallow (downward) inclination, roughly similar to those in the Jonsa block. We interpret these as primary Jatulian directions (Ja).

Table 7. Paleomagnetic results from the Eno–Ilomantsi block.

Site #	Name	N	rock type	Lat. (°N)	Long. (°E)	D (°)	I (°)	k	α95 (°)	J (Am^{-1})	Cat.	Note
					(a) Dykes (D → NE)							
7312	Hutunvaara		diabase	62.930	30.020	359	28			0.843	B	
7501	Tiiranvaara		diabase	62.580	30.710	4	32			0.192	B	
7508	Markunvaara		diabase	62.654	30.967	11	42			0.320	B	
7510	Hömötti		diabase	62.664	30.641	6	29			0.113	B	
7511	Kalliokanava		diabase	62.827	30.555	4	39			0.390	B	
7512	Kuisma		diabase	62.747	30.422	2	36			0.772	B	
7515	Pamilonkoski		diabase	62.851	30.413	6	23			0.087	B	
	Mean	7		62.7	30.5	4.5	32.8	121.7	5.5	0.39	B	
	Pole (11)		**Plat = 45.2°N, Plon = 204.4°E, dp = 3.5°, dm = 6.2°, A95 = 4.1° (N)**									

See Table 1 for explanation.

5. *High-field a.f. demagnetization treatments*

The analysis of palaeomagnetic data was based mainly on the samples submitted to a.f. demagnetization treatment (*Neuvonen et al.*, 1981; *Neuvonen*, 1995). The division of the post-Archaean data into two separate groups (Sf = Svecofennian, Ja = Jatulian) is somewhat arbitrary (the division line is close to D = 360°) and it is often difficult to decide whether the remanence belongs to group Sf or group Ja or, alternatively, whether only one population is present, with a declination ranging from northwest to northeast. To solve this problem, 15 specimens were demagnetized with a.f. up to 150 mT at steps of 10 mT. Some of these test specimens had been previously demagnetized to 40 mT in Turku, others were virgin specimens. Detailed demagnetizations were carried out with a 3-axis a.f. demagnetizer mounted in a Mu-metal shield of the 2G-cryogenic SQUID magnetometer of the Laboratory of Paleomagnetism of the GSF in Espoo (*Oja* and *Pesonen*, 1990).

Results

Examples of high field a.f. demagnetization treatments are shown in Figs 6–8. Figure 6a (specimen 8248.12) is an example of an Archaean enderbite from Pällikäs with two components: one soft component of unknown origin and one hard component revealing the characteristic Archaean (Ar) direction (D = 284°, I = 75°). Optimum a.f. cleaning data of a sister specimen (*Neuvonen*, 1995) yielded a direction of D = 308°, I = 75°, i.e., almost the same as the Archaean (Ar) direction. Although 15% of NRM still remains at 150 mT, we feel that the characteristic Ar component is well defined by both methods. We thus believe that the steep downward directions in Tables 1–7 are characteristic Archaean magnetizations and not due to unresolved multicomponent

NRM. Weak evidence of another component superimposed on this Archaean component is possibly seen in the enderbite specimen of Pällikäs (8503.13; Fig. 6b), which reveals first a northwesterly component at lower fields (50–130 mT) and then a steep downward component at higher fields. We interpret the poorly defined, softer component as a mild Svecofennian overprint (Sf) and the harder component as the Archaean one (Ar). We note that optimum cleaning yielded a direction (D = 325°, I = 61°; *Neuvonen*, 1995) close to the Archaean direction (D = 302°, I = 65°) found with multicomponent analysis.

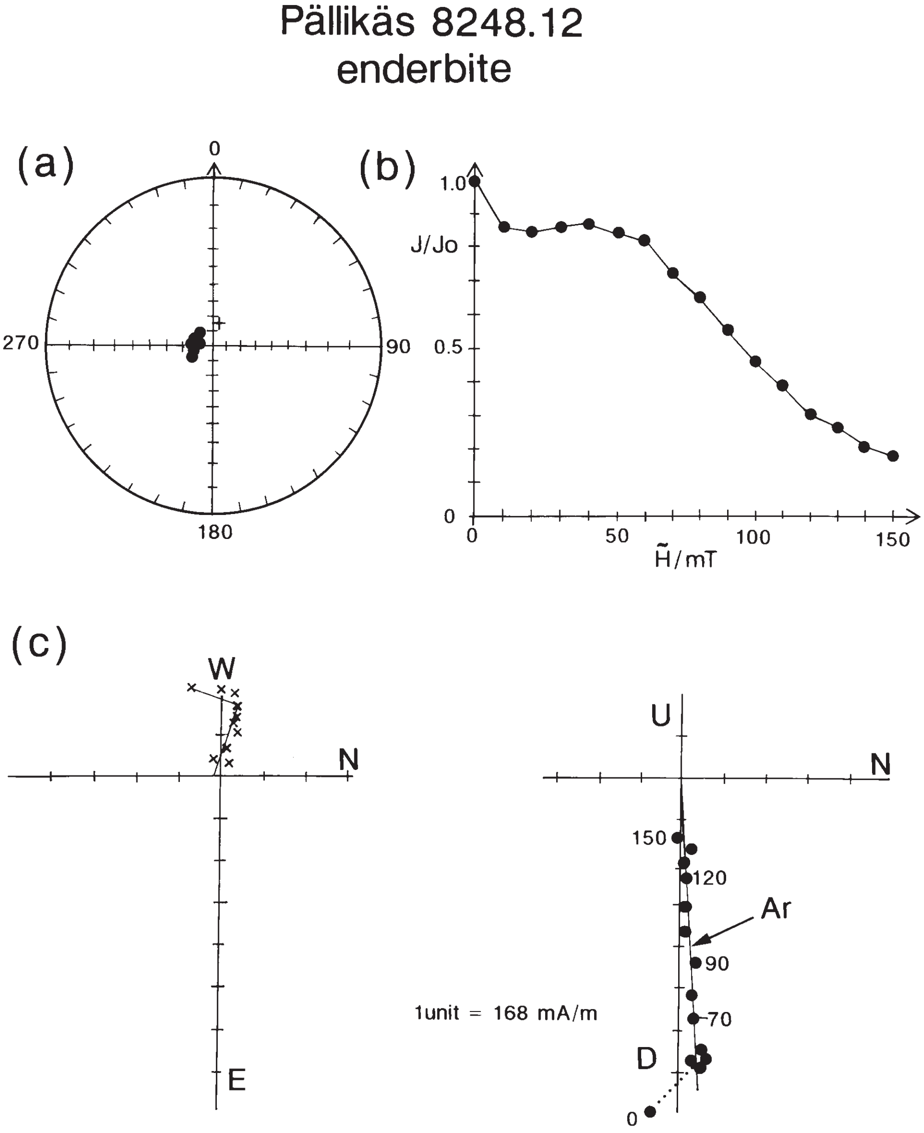

Fig. 6a. Detailed stepwise a.f. cleaning (up to 150 mT) of an Archaean enderbite specimen from Pällikäs (8248.12). (a) Stereonet, (b) intensity decay and (c) Zijderveld orthogonal diagrams (with N-S and U (up)-D (down) projections). Two superimposed remanence components, a soft one and a hard one, are clearly discernible. The soft one is a viscous remanence (VRM), and the hard one decays to origin and represents the characteristic Archaean remanence (Ar) with D = 284°, I = 75°. Optimum cleaning yielded a direction of D = 308°, I = 75°.

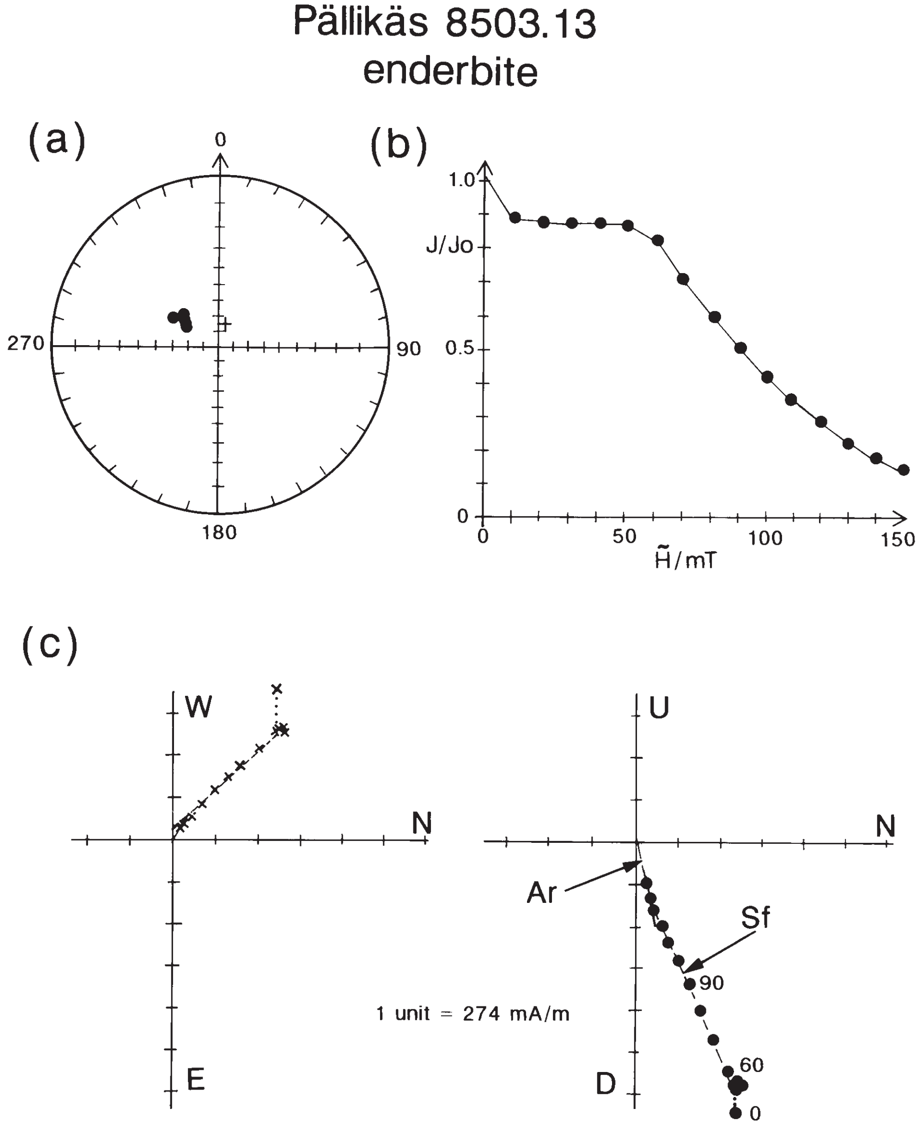

Fig. 6b. Detailed a.f. cleaning of an Archaean enderbite specimen from Pällikäs (8503.13). Two superimposed remanence components were isolated: one (softer) related to Svecofennian overprinting (Sf; D = 317°, I = 54°) and one (harder) an Archaean (Ar) direction (D = 302°, I = 65°). Optimum cleaning yielded a direction (D = 325°, I = 61°) close to the latter. For explanations, see Fig. 6a.

Figure 7a–b shows two examples of multicomponent NRM where the original NRM direction (without cleaning) plots between Sf and Ja. The first specimen (8522.25; Fig. 7a) is a mafic granulite from the Petäys block and the second (8521.12; Fig. 7b) an enderbite sample from the same block. Detailed a.f. treatments clearly indicate that two components (Ja, Sf) can be separated with high field a.f. treatments and multicomponent analysis. In both cases, Sf is the softer one and is easily identified in the Zijderveld plots (Fig. 7a). The harder component is found as a weakly defined stable endpoint in a stereoplot (Fig. 7b). We interpret these examples as implying that the samples were first baked by Jatulian dykes (component Ja) at ~2150 Ma and subsequently remagnetized by Svecofennian activity (component Sf) at ca. 1860 Ma. No signs of Archaean remanence remain at these sites. Note that at the first site (8522) there is a diabase dyke (although not sampled; see Table 3), which further supports the baking interpretation for the Ja component. A dyke has not been found at the second site (8521) but it may have ewaded detection in the field. However, optimum cleaning revealed only a "mixed" intermediate direction between Ja and Sf in both examples (Fig. 7a). These results are compatible with the idea that some of the site-mean directions in Figs 4–5 and Fig. 9, which plot close to the demarcation line (~360°) between groups Ja and Sf, are indeed mixed directions. However, even though not fully split into two components, the grand mean values of the three components in Fig. 9 have been reasonably well determined with the optimum cleaning technique.

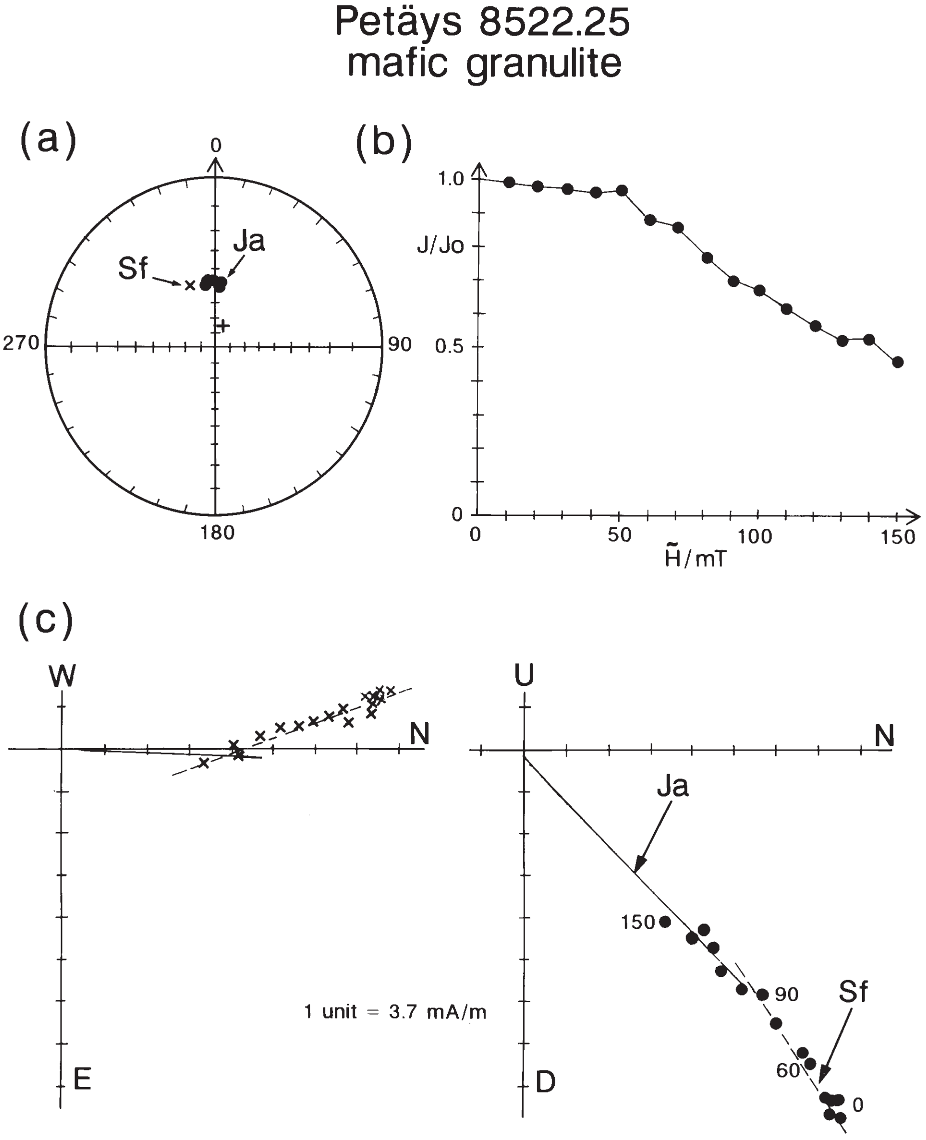

Fig. 7a. Detailed a.f. cleaning of a Petäys mafic granulite specimen (8522.25). Two components were isolated: one (softer) related to Svecofennian overprinting (Sf; D = 340°, I = 54°) and one (harder), although weakly defined, of Jatulian type (Ja; D = 3°, I = 49°) presumably due to dyke baking. Optimum cleaning yielded a direction (D = 355°, I = 49°) intermediate between these two. For explanations, see Fig. 6a.

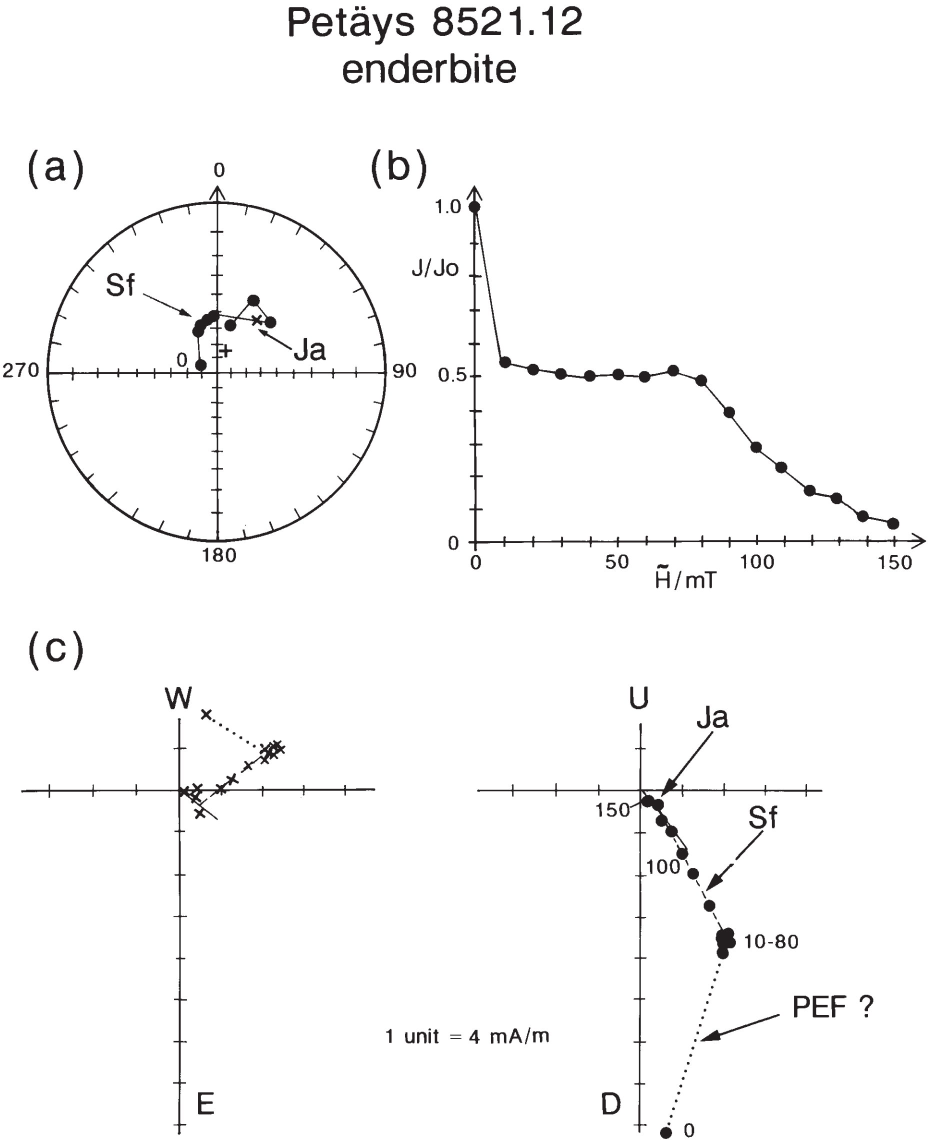

Fig. 7b. Detailed a.f. cleaning of a Petäys enderbite specimen (8521.12). Two components were isolated: one (softer) related to Svecofennian orogeny (Sf; D = 326°, I = 58°) and one (harder) to baking by a Jatulian dyke (Ja; D = 40°, I = 46°). Optimum cleaning yielded only an intermediate direction (D = 351°, I = 59°). For explanations, see Fig. 6a.

The last figure (Fig. 8a–b) shows examples of diabase dykes (7827.15 Jonsa and 8418.11 Lapinlahti). In the first case two components have been isolated. As in the previous example, these are interpreted as the primary Jatulian component (Ja) and the Svecofennian overprint (Sf), although the latter one can in some cases be a misinterpreted PEF. The Jatulian direction is isolated only as a stable endpoint at ≤ 60 mT (Fig. 8a), whereas the Svecofennian direction is defined from the Zijderveld plots. As in previous examples, the optimum cleaning yielded a direction intermediate between Ja and Sf. The other example (8418.11; Fig. 8b) is a case of total Svecofennian (Sf) remagnetization with no signs of primary dyke direction retained.

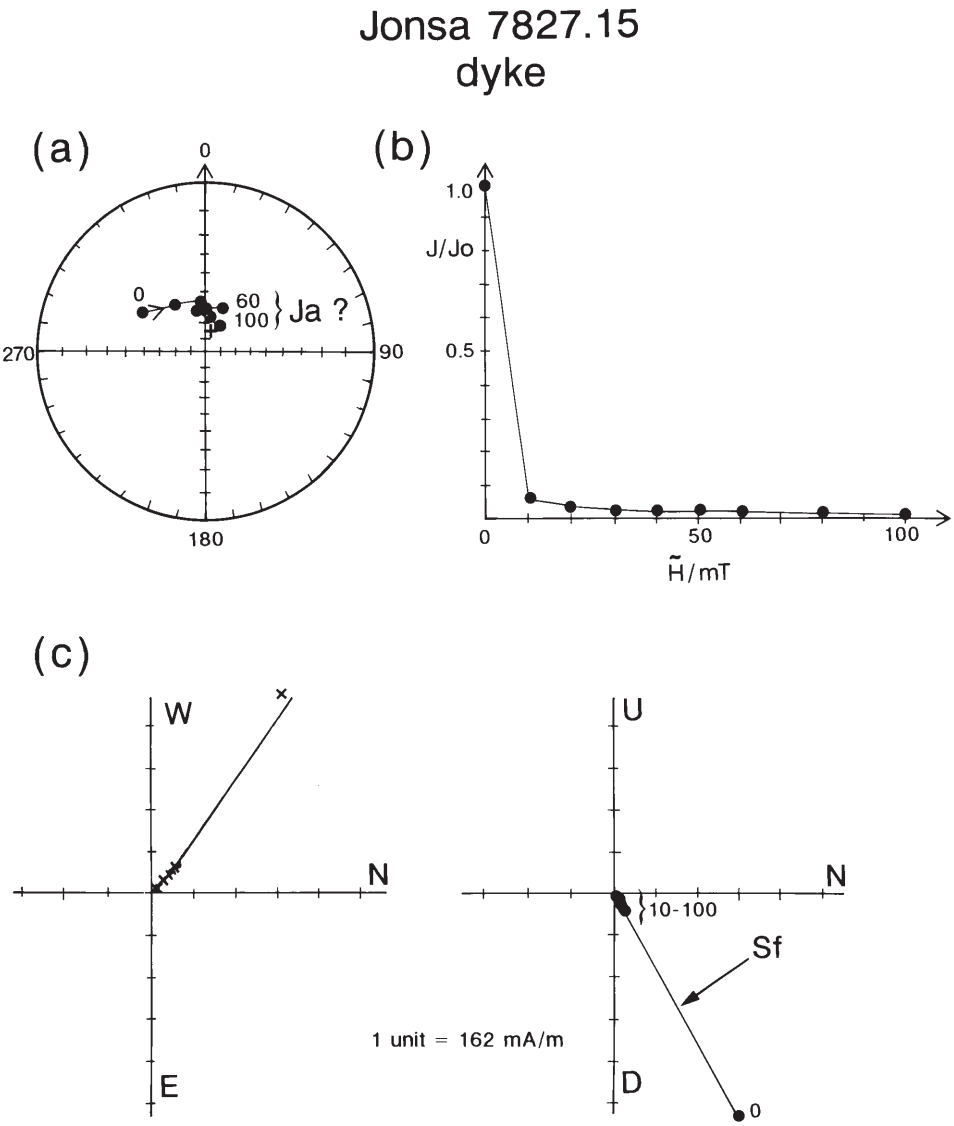

Fig. 8a. Detailed a.f. cleaning of a Jonsa dyke specimen (7827.15). Two components were isolated: one (soft) related to Svecofennian overprinting (Sf; D = 302°, I = 43°) and one (harder) to dyke intrusion (Ja; D = 22°, I = 59°; stable endpoint). Optimum cleaning revealed an intermediate direction (D = 3°, I = 43°). For explanations, see Fig. 6a.

6. *Intensity data*

Site-mean NRM intensities (without cleaning) are given in Tables 1–7, and Table 8 summarizes the mean data on the three directional groups (Ar, Ja, Sf). The intensities for diabase dykes were calculated separately for the non-remagnetized (Ja) and remagnetized (Sf) dykes. There is a tendency for the NRM intensity of the remagnetized rocks to be weaker than the intensity in the non-remagnetized rocks. This is probably due to oxidation or the disappearance of magnetite in the course of Svecofennian orogenic events, which most likely had both thermal and fluidal effects on minerals. The result is consistent with the aeromagnetic signatures that show up as

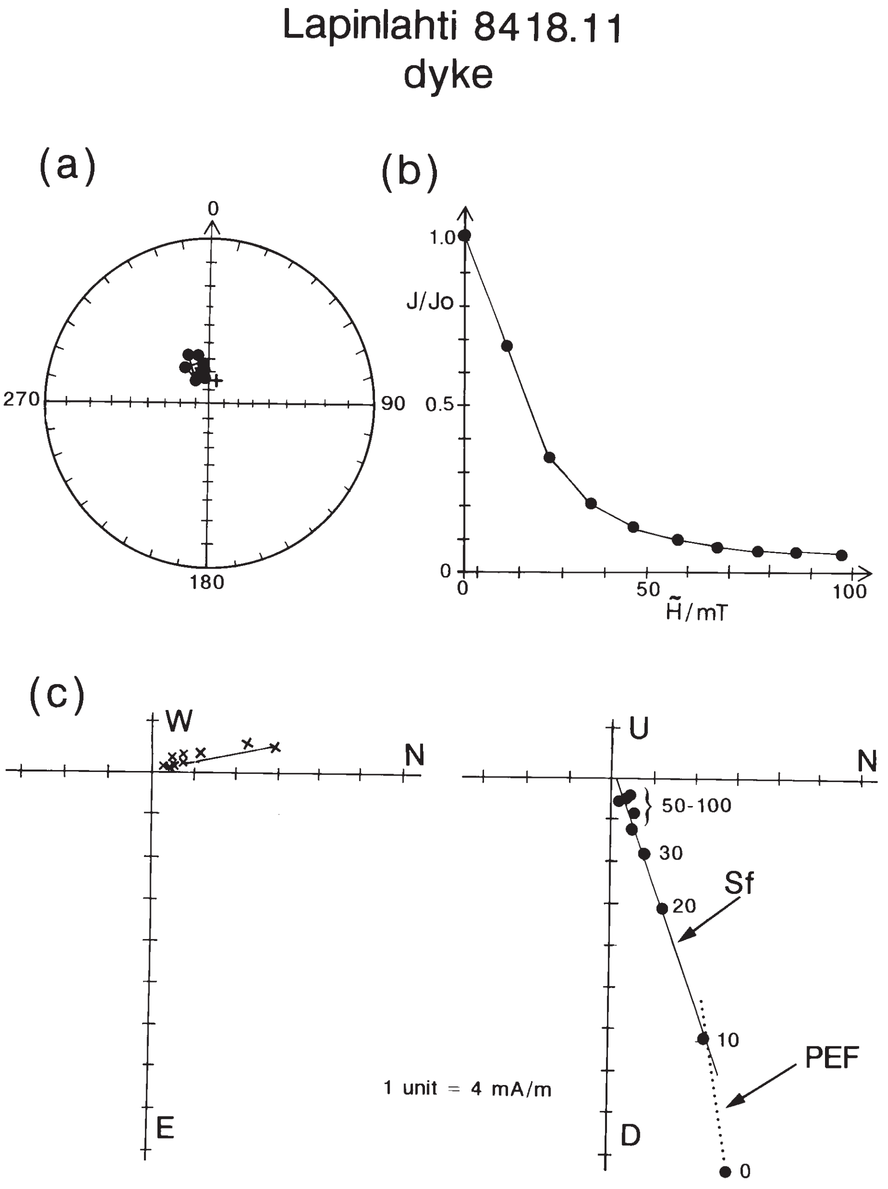

Fig. 8b. Detailed a.f. cleaning of a Lapinlahti dyke specimen (8418.11). With the exception of the PEF component, only one component, that due to Svecofennian orogeny (Sf; D = 344°; I = 68°), has been retained. Optimum cleaning yielded D = 359°, I = 52° (= Sf). For explanations, see Fig. 6a.

high aeromagnetic anomalies in well-preserved (less affected by Svecofennian events) terranes such as Jonsa and Pällikäs (see Fig. 3) as compared to weak anomalies associated with terranes that underwent Svecofennian processes (e.g., Lapinlahti and Sonkajärvi terranes; Fig. 3).

Table 8. Comparison of mean NRM intensities.

rock type	N	mean intensity ± s.e. (Am^{-1})
Basement		
Enderbites		
unbaked/non-remagnetized	11	1.69 ± 0.10
baked	3	0.85 ± 0.80
remagnetized	5	0.66 ± 0.24
Mafic granulites		
unbaked/non-remagnetized	4	1.32 ± 0.36
baked	–	–
remagnetized	4	1.94 ± 0.82
TTGs		
unbaked/non-remagnetized	5	1.39 ± 0.77
baked	1	0.02
remagnetized	9	0.04 ± 0.03
Mean, unbaked/non-remagnetized	20	1.54 ± 0.20
Mean, baked	4	0.64 ± 0.60
Mean, remagnetized	18	0.63 ± 0.25
Dykes		
Mean, non-remagnetized	23	0.20 ± 0.05
Mean, remagnetized	20	0.14 ± 0.05

N number of sites.
Note: data from all three terranes are included (Tables 1–7).

7. Grand mean directions and poles

Since the tectonic models for interpreting the magnetization differences are inconclusive (see Section 8), we calculated the grand mean palaeomagnetic directions and poles for the three magnetization components (Ar, Ja, Sf) by averaging data on all blocks. These are summarized in Table 9 and in Figs 5 and 9 for the three terranes investigated. The mean palaeomagnetic poles are plotted in Fig. 10a on the most recent APW path of Fennoscandia by *Elming et al.* (1993) together with some other relevant new Archaean poles from Fennoscandia (*Mertanen et al.*, 1997). The Archaean directions are here considered as of reversed (R) polarity (albeit with steep *downward* inclinations) and are thus plotted as south poles in Fig. 10a following the polarity definitions of *Elming et al.* (1993).

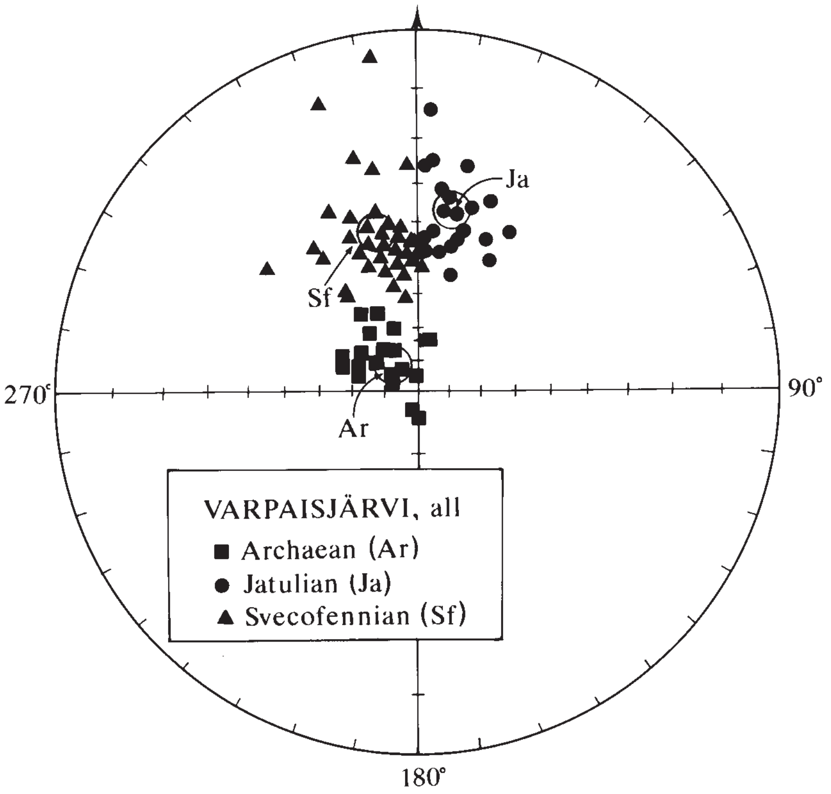

Fig. 9. Grand mean palaeomagnetic directions of the Varpaisjärvi terrane (site-mean data of all five blocks). The three isolated components (Ar, Ja, Sf) are shown in different symbols, where square denotes Archaean (Ar), sphere Jatulian (Ja), and triangle Svecofennian (Sf) magnetizations. For other symbols, see Fig. 4a. The arrows point to mean directions. The Grand mean directions of the Kuhmo-Suomussalmi and Eno-Ilomantsi terranes are shown in Fig. 5.

The Archaean poles (Nos 1–5; Fig. 10a) from the Varpaisjärvi blocks show considerable scatter. Part of the scatter is due to the projection (Van der Grinten) used at high latitudes. Another part could be due to local tectonism as discussed earlier, but it could also be due to minor age differences in magnetizations, i.e. APW, since the U-Pb (zircon) ages vary from ~2680 Ma (enderbites) to ~2630 Ma (mafic granulites; see *Hölttä et al.*, 1997), and consequently (but not necessary) also the magnetization blocking ages may vary depending whether the blocking is acquired during uplift (slow cooling) or during magmatic (more rapid) cooling. The new grand mean Archaean pole (Ar) from the Varpaisjärvi terrane does not differ markedly from the previous key pole (No. 22 in Fig. 10a; *Neuvonen et al.*, 1981). Collectively, the new Archaean poles suggest modifications to the APW path of Elming et al. (1993) as shown by the dashed line in Fig. 10a. It is to be noted that, owing to the lack of detailed isotopic age data on rocks sampled palaeomagnetically at the same sites, only a rough modification to the APW curve is suggested. It nevertheless indicates a visit of the pole to high southerly latitudes ca. 2850–2600 Ma ago. This interpretation is supported by other Archaean poles from Finland and Russian Karelia (see Fig. 10a; *Mertanen et al.* (1997)) of which some are of dual polarity thus further supporting their ancient origin and not by viscous contamination.

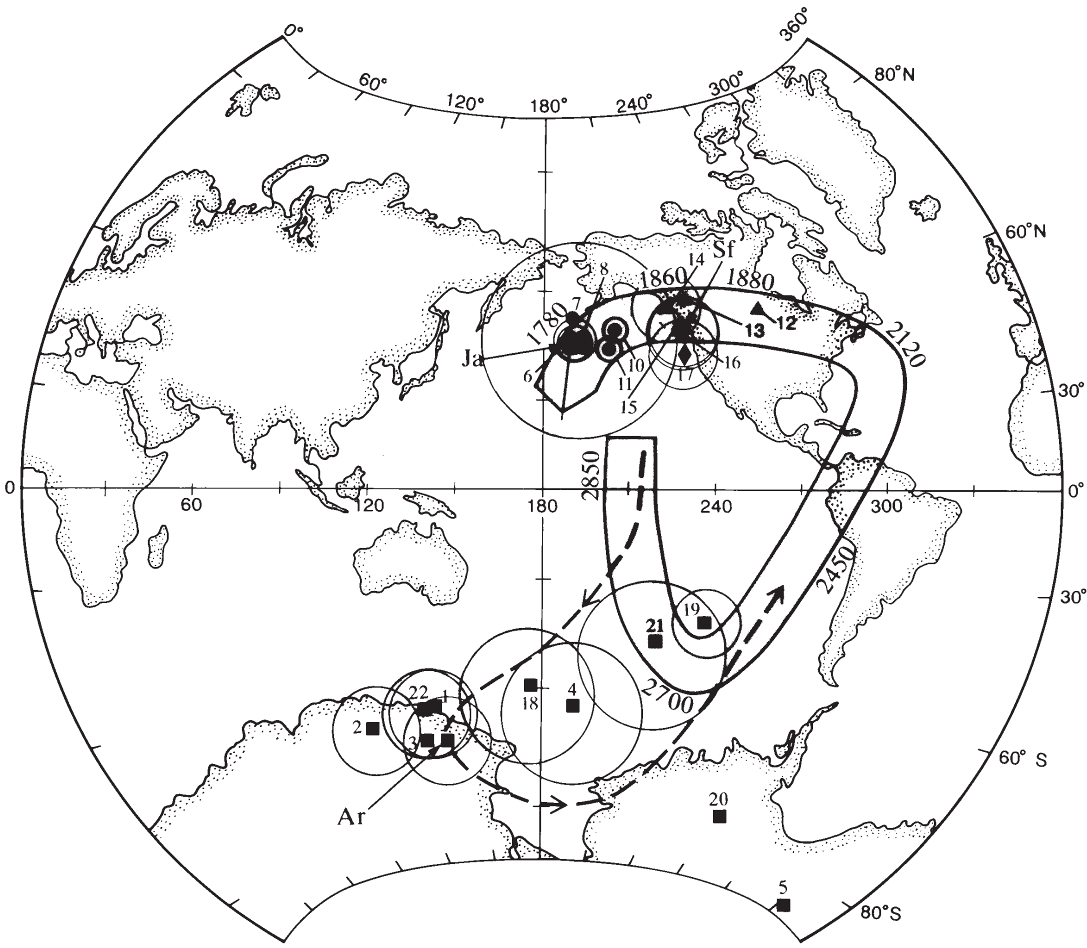

Fig. 10a. Palaeomagnetic poles of this study plotted on the APWP of *Elming et al.* (1993) (shaded curve) during Archaean-Early/Middle Proterozoic times. Circles are the 95% confidence circles. The dashed line denotes a modification of the APWP based on data of this work. The main three groups of poles (Ar, Ja, Sf) discussed here are shown with symbols, where squares denote Archaean, spheres Late Svecofennian or Jatulian (see Fig. 10b), and triangles Svecofennian poles. The number of poles is as in Tables 1–7 and 9. Other Archaean poles with ages of 2850–2600 Ma from Finland and Russian Karelia are 18 = Soilu basement (dual polarity), Finland, 19 = Semch River gabbro and 20 = Black Cape gneisses from Russian Karelia, 21 = Penikat basement, Finland and 22 = Varpaisjärvi quartz diorite (see *Neuvonen et al.*, 1981), Finland (data listed in *Mertanen et al.* (1997)).

The Jatulian poles (shown as spheres) do not fit on the Jatulian APW segment but plot on the APW path of Fennoscandia at ca. 1780 Ma (Fig. 10a). They thus refer to late Svecofennian remagnetization and not to primary Jatulian remanence as previously suggested by baked contact tests. Although K-Ar mineral (biotite, hornblende) age determinations on various basement rocks in Varpaisjärvi area do show evidence of basement resetting at ca. 1900–1780 Ma (*Paavola*, 1986; *Kontinen et al.*, 1992), there are several reasons to believe that the Ja-dykes are primary and not secondary. First, Sm-Nd data on one of the dykes (site 7816) reveal an age of ~2085 ± 95 Ma, suggesting a Jatulian and *not* a Svecofennian age (*Toivola et al.*, 1991). Second, positive baked contact tests at this dyke suggest that primary remanence has been retained (*Neuvonen et al.*, 1981). Third, the presumably primary Jatulian (Ja) component (declination to northeast) is superimposed by a younger Svecofennian remagnetization component (Sf) in some of the samples (see Figs 6–8). Fourth, the intensities of the Ja dykes and their baked host rocks are *generally* higher than those of remagnetized (Sf) dykes suggesting that they were not altered in Svecofennian events as were the "remagnetized" sites (Table 8).

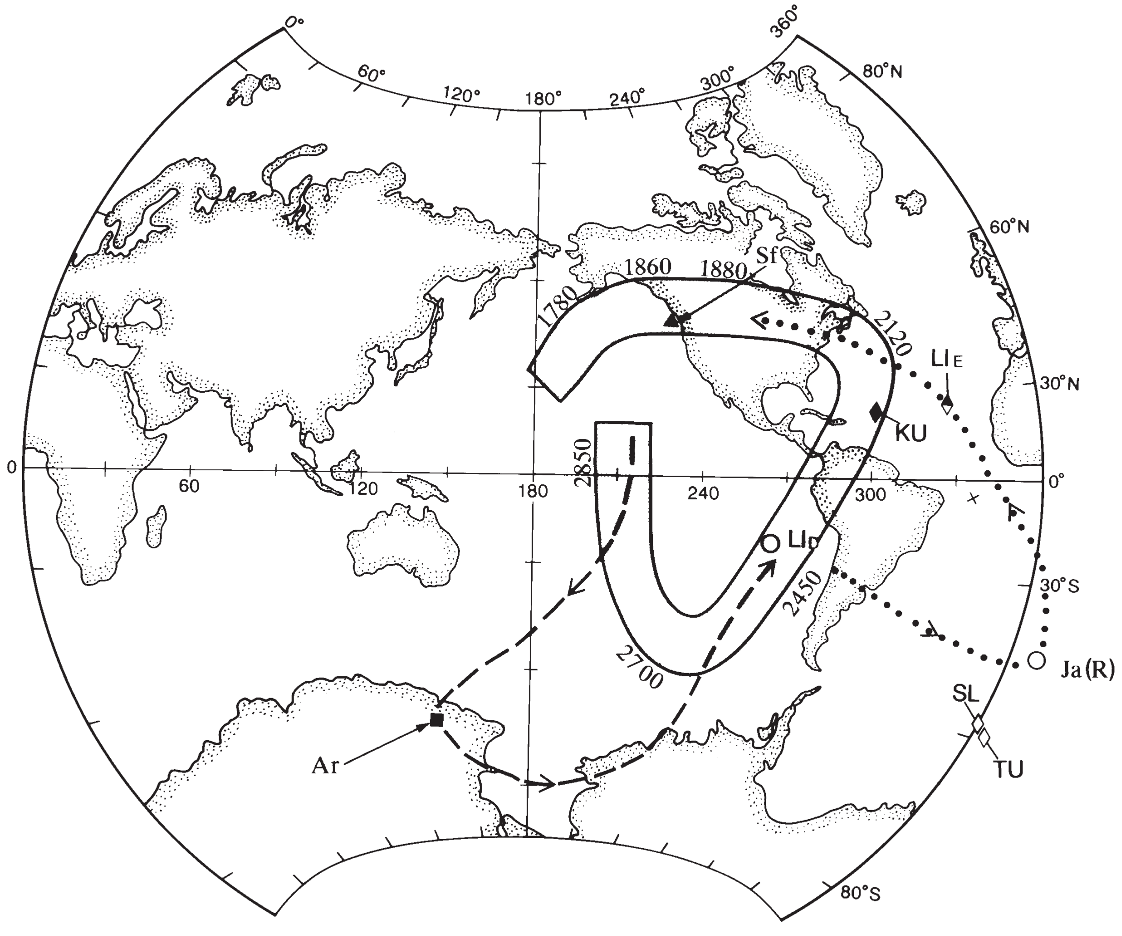

Fig. 10b. A new Jatulian APW loop introduced here (dotted line) incorporating the Grand Mean Jatulian pole of this study (Table 9) but plotted with a reversed polarity option (pole Ja(R)). Poles LI(D) and LI(E) denote the mean pole of D- (~2450 Ma) and E- (~2150 Ma?) magnetization components of the layered intrusions in Finland (*Mertanen et al.*, 1989), where open (closed) symbol refers to reversed (normal) polarity and mixed symbol denotes dual polarity choice of the original data. KU is the pole of the Kuetsijärvi formation dated to ~2150 Ma (*Torsvik* and *Meert*, 1995; *Mertanen*, 1995), SL is the pole of the Sego lavas (ca. 2100 Ma) and TU is the pole of the Tulos dykes (~2100 Ma) in Russian Karelia. Data listed in *Mertanen et al.* (1997). Other symbols as in Fig. 10a.

Therefore, we have to seek another interpretation for the Ja poles. Previously, *Pesonen* and *Neuvonen* (1981), *Pesonen* (1987) and *Bylund* and *Pesonen* (1987) tried to overcome this problem by introducing an almost self-closing Jatulian loop for the APW path of Fennoscandia, connecting the Archaean pole to the Svecofennian poles. Here, we offer a similar explanation but adopt now a *reversed* polarity option for the Ja poles. This, shown as Ja(R) in Fig. 10b, overcomes the late Svecofennian APW problem for pole Ja but involves a considerable extension for the APW path during 2450–1900 Ma as shown in Fig. 10b (dotted line). The reversed polarity choice for Ja is in accordance with similar R-polarity choices for the Archaean and Early Proterozoic poles of the layered intrusions of Finland (see e.g. pole LI(D)), age 2450 Ma, and pole LI(E), age ~2150 Ma; *Mertanen et al.*, 1989; Fig. 10a). The new Jatulian APW-loop in Fig. 10b (shown as dotted path) is still to be considered very tentative but it provides the best explanation for the present data. Some other new poles, although poorly dated but presumably also of Jatulian age, of Russian Karelia (poles SL, KU and TU) and of northern Fennoscandia are broadly consistent with the new loop (Fig. 10b; *Mertanen et al.*, 1989; 1997; *Torsvik* and *Meert*, 1995). For lack of other explanations, we favour this APW modification, which will eventually be possible to test with integrated palaeomagnetic and radiometric studies on other Jatulian dyke swarms in Fennoscandia. We note here in passing that the APW-rate during this Jatulian loop is ca. 0.6 °/Ma which is slightly more than the average APW-rate of Fennoscandian Shield during Precambrian as a whole (*Pesonen* and *Neuvonen*, 1981).

8. Tectonic implications

One of the objectives of this study was to test the tectonic models for the Varpaisjärvi terrane of *Hölttä et al.* (1992) and *Pesonen* and *Mertanen* (1996). According to these models, the Jonsa block has rotated ~20° anticlockwise with respect to the Pällikäs block. The age of the rotation is not known. Two observations suggest local rotation of the Jonsa block: (i) the Archaean structural trends at Jonsa and Pällikäs show a deviation of ~20°, suggesting post-Archaean anticlockwise rotation of the Jonsa block relative to the Pällikäs block, (ii) the orientations of dykes at Jonsa also show an angle of ~20° relative to those at Pällikäs (Figs 2–3). Detailed tectonic analysis of the palaeomagnetic data will be discussed elsewhere (*Pesonen* and *Mertanen*, 1996); only a tentative interpretation is given here.

Tables 1–7, where data are given by block, show that the mean Archaean direction at Jonsa (D = 303.1°, I = 73.5°, $\alpha95$ = 4.9°) differs from that at Pällikäs (D = 319.1°, I = 68.5°, $\alpha95$ = 5.1°), the difference being ~16° in declination and ~5° in inclination. This declination difference is consistent with the anticlockwise rotation of ~16° of the Jonsa block relative to Pällikäs. If this difference is due to local tectonic rotation of Jonsa, the rotation must have occurred *after* Archaean magnetization but *before* dyke intrusion and *before* the Svecofennian orogeny since no difference is seen in the Jatulian (Ja) or Svecofennian (Sf) remanence components between these blocks (Tables 1–2 and Fig. 4). However, there are two issues to be solved before we accept that palaeomagnetic data support block rotation. First, although Archaean *directional* data on remanences support tectonic rotations, the Archaean palaeomagnetic *poles* of Jonsa and Pällikäs are not significantly different at the 95% confidence level. Second, the Archaean remanence direction in the mafic granulites (D = 278°, I = 87°) in the Lapinlahti block is significantly different from the directions in the enderbites or mafic granulites in the Jonsa and Pällikäs blocks: this difference cannot be explained by local anticlockwise rotation (around a vertical axis) of the Jonsa block. In fact, if local tectonics are to be invoked to explain the differences in Archaean remanence directions, the tectonic models should include a tilting component as well as rotation since the *inclinations* of the Lapinlahti block are significantly steeper than those at Jonsa and Pällikäs. We conclude here that, with the present data on the Varpaisjärvi blocks, their interpretation in terms of local tectonics is inconclusive and the differences in the mean directions (and poles) between different blocks (e.g., Jonsa, Pällikäs, Lapinlahti) can be attributed to the APW if there are minor differences in remanence blocking ages between rock units. The APW differences, on the other hand, may be due to relative movements of the blocks during the Archaean before they were amalgamated at ~2630 Ma, or to movement of the entire craton during the age interval of ca. 2680–2630 Ma, when the rock types acquired their remanent magnetizations, but at slightly different times (e.g., enderbites at ~2680 Ma and mafic granulites at ~2630 Ma). A third possibility is that these movements (and remanence blockings) were due to differential uplift of the blocks as can be seen in Fig. 10a, which shows the new APW path (dashed line) for the Fennoscandian Shield 2700–2600 Ma ago based on the Archaean data of this study.

9. *Palaeolatitudes and PSV*

Figure 11 shows the palaeolatitude data of this work calculated from the grand mean data of Table 9 and plotted on the Fennoscandian palaeolatitude curve of *Pesonen* and *Mertanen* (1996). Archaean (Ar) and Jatulian (Ja) palaeolatitudes are southerly ones as previously explained. We note that the three new palaeolatitude data (Ar, Ja, Sf) are consistent (within the error bars) with the most recent palaeolatitude curve of Fennoscandia (dotted line), suggesting higher palaeolatitudes for Late Archaean than for the subsequent Jatulian and Svecofennian times.

Table 9 summarizes the palaeosecular variation data (PSV) on the Earth´s magnetic field for the three grand mean results (Ar, Ja, Sf). The PSV is represented by the Angular Standard Deviation (S) of the site-mean poles around their mean value, which theoretically should reveal higher S for a higher palaeolatitude (λ) (see *Pesonen* and *Mertanen*, 1996). The S value of the Varpaisjärvi Archaean poles (18.5°; λ = 62.3°) is higher than the corresponding values for Sf (= 13.7°; λ = 24.5°) and Ja (= 10.3°; λ = 20.8°) in accordance with a decreasing palaeolatitude, thus supporting the dipole field hypothesis for Archaean-Palaeoproterozoic times.

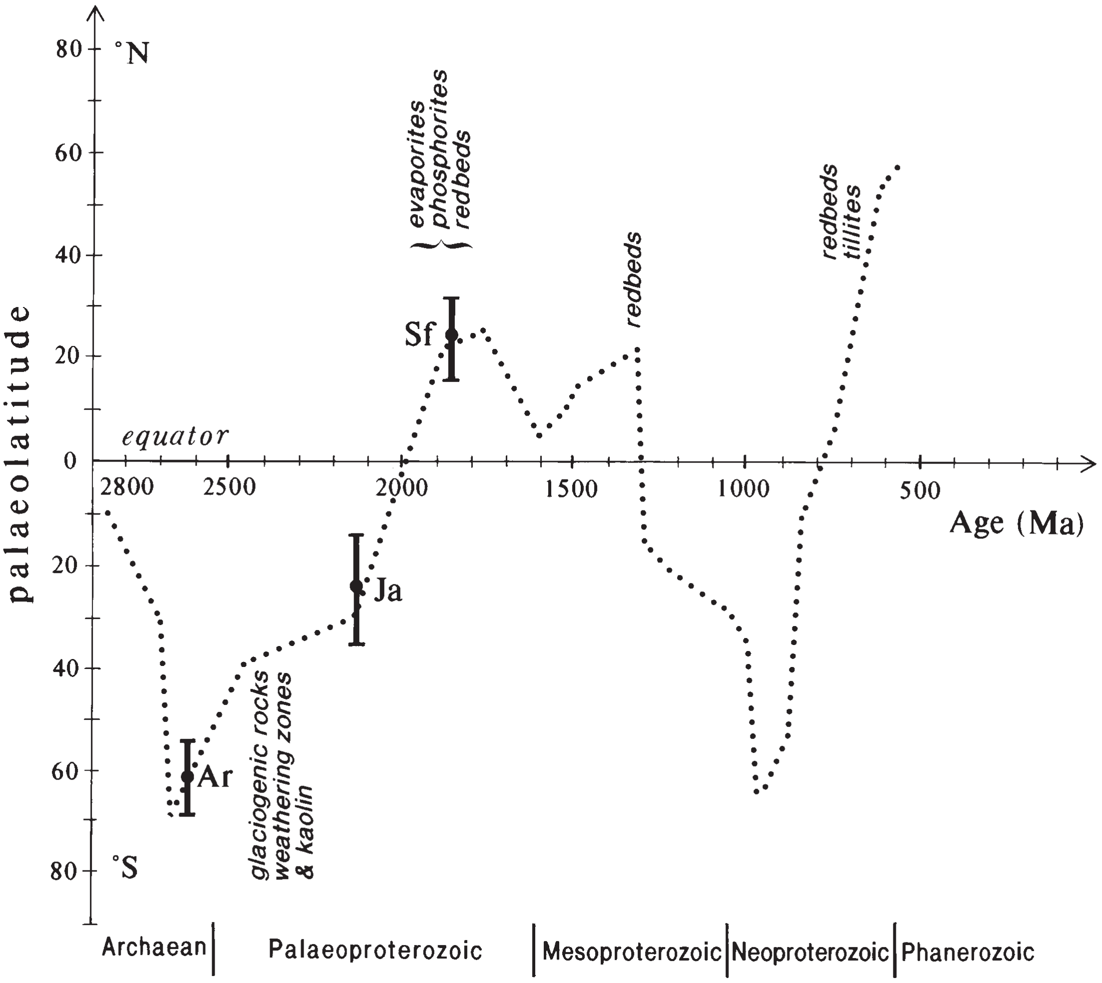

Fig. 11. Palaeolatitude curve of Fennoscandia 2.8–0.6 Ga ago, with the polarity adoption such that Fennoscandia was at southerly latitudes during Archaean-Jatulian (2.8–2.1 Ga) times. Also shown are the three (Ar, Ja, Sf) grand mean palaeolatitude values of this study (Table 9) and some palaeoclimate indicators. Error bars (95% confidence limits) are only shown for palaeolatitude data, not for age data (see text).

10. Conclusions

The following conclusions can be drawn from this work:

(1) Three remanent magnetization directions were isolated from rocks of Archaean basement terranes in Finland. On the basis of baked contact tests, detailed a.f. demagnetization treatments, intensity data and tentative palaeomagnetic APW interpretation, these directions are of Archaean (~2680–2630 Ma), Jatulian (~2150 Ma) and Svecofennian (~1860 Ma) age. Only the Jatulian component is here interpreted as primary, being acquired during cooling of the diabase dykes and their baked host rocks. The Archaean direction most likely represents cooling after the last major metamorphic event (~2630 Ma) of the basement, and the Sf directions represent Svecofennian overprints (~1860 Ma).

Table 9. Grand Mean palaeomagnetic directions and poles of this work.

rock unit or rm component & rock type	**Lat., Long. (°N) (°E)**	**B**	**P**	**R/N (%)**	**D (°)**	**I (°)**	**α95 (°)**	**k**	**rm. age**	**Plat. (°N)**	**Plon. (°E)**
						Varpaisjärvi terrane					
Mean Varpaisjärvi Archean basem. (Ar)	63.4, 27.7	22	R	100	313.2	75.3	4.1	57	~2630	–69.4	139.0
Mean Varpaisjärvi dykes + baked (Ja)	63.4, 27.8	19	N	100	11.6	37.2	4.9	48	~2150	47.1	191.6
Mean Varpaisjärvi remagnetization (Sf)	63.4, 27.7	33	N	97	344.4	42.1	4.7	29	~1860	50.4	229.8
						Kuhmo-Suomussalmi terrane					
Mean Kuhmo-Suomussalmi dykes (Ja)	64.7, 29.6	4	N	100	1.8	43.3	11.8	61	~2150	51.1	206.8
Mean Kuhmo-Suomussalmi remag. (Sf)	65.5, 28.6	13	N	100	337.0	39.3	9.7	19	~1860	44.5	239.6
						Eno-Ilomantsi terrane					
Mean Eno-Ilomantsi dykes (Ja)	62.7, 30.5	7	N	100	4.5	32.8	5.5	122	~2150	45.2	204.4

rock unit or rm component & rock type	**λ ± δ (°)**	**s (°)**	**dp (°)**	**A95 (°)**	**dm (°)**	**grade**
			Varpaisjärvi terrane			
Mean Varpaisjärvi Archean basem. (Ar)	–62.3 ± 6.9	18.5	6.9	7.2	7.6	B–
Mean Varpaisjärvi dykes + baked (Ja)	–20.8 ± 3.4	10.3	3.4	4.3	5.8	B–
Mean Varpaisjärvi remagnetization (Sf)	24.3 ± 3.5	13.5	3.5	4.2	5.8	B–
			Kuhmo-Suomussalmi terrane			
Mean Kuhmo-Suomussalmi dykes (Ja)	–25.2 ± 9.3	9.7	9.1	10.0	14.7	C+
Mean Kuhmo-Suomussalmi remag. (Sf)	22.3 ± 7.0	19.7	6.9	10.6	11.6	B–
			Eno-Ilomantsi terrane			
Mean Eno-Ilomantsi dykes (Ja)	–17.9 ± 3.5	5.1	3.5	4.1	6.2	B–

For explanation of symbols, see Table 1.
B denotes number of sites.
λ ± δ is the palaeolatitude and its standard error.
s is the Angular Standard Deviation of the scatter of palaeomagnetic poles around their mean (see text).
Grade follows the scheme of Pesonen et al. (1989), i.e., from A (best) to D (poor).

(2) Although geological, geochemical and aeromagnetic data suggest tectonic rotations and lateral block movements in the Varpaisjärvi area, the tectonic implications of the palaeomagnetic data are inconclusive. Rather, modifications to the APW path of Fennoscandia are suggested. These modifications may simply reflect deficiences in knowledge of the present APW path, but slight age differences in remanence blockings of various rock types cannot be ruled out. These magnetization age differences can be explained by horizontal block movements (plate tectonics) but also by differential uplift of the blocks. Modifications to the Fennoscandian APW path are proposed.

(3) The palaeopole of Jatulian age (~2.2–2.0 Ga) is still poorly defined. By adopting here a reversed polarity interpretation for the Ja magnetizations, we propose a new Jatulian loop for the Fennoscandian APW path during 2450–1880 Ma.

(4) The best palaeomagnetic results for basement rocks were obtained from high-grade enderbitic rocks, which show up as strong anomalies on aeromagnetic maps. Within these blocks not only are the Archaean directions well preserved but also the dykes and their baked contacts have retained reliable remanent magnetization directions.

Acknowledgements

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