Available online at www.sciencedirect.com

SCIENCE DIRECT®

Precambrian Research 144 (2006) 239–260

Precambrian Research

www.elsevier.com/locate/precamres

Early Paleoproterozoic–Archean dykes and gneisses in Russian Karelia of the Fennoscandian Shield—New paleomagnetic, isotope age and geochemical investigations

S. Mertanen[a,*], J.I. Vuollo[b], H. Huhma[a], N.A. Arestova[c], A. Kovalenko[c]

[a] *Geological Survey of Finland, Laboratory for Paleomagnetism, P.O. Box 96, FI-02151 Espoo, Finland*
[b] *Geological Survey of Finland, P.O. Box 77, FI-96101 Rovaniemi, Finland*
[c] *Institute of Precambrian Geology and Geochronology, Russian Academy of Sciences, Nab. Makarova 2, 199034 St.-Petersburg, Russia*

Received 21 December 2004; received in revised form 6 October 2005; accepted 4 November 2005

Abstract

We present here new palaeomagnetic, isotopic age and geochemical data from Archean and Early Palaeoproterozoic rocks in the eastern Fennoscandian Shield. We have studied NE–SW trending gabbronorite dyke sets and their host Archean basement rocks in the Vodlozero block near the 2449 Ma Burakovka layered intrusion in southern Russian Karelia. Both dyke sets are genetically related to the Burakovka intrusion. The other, ca. 25 km long Avdeev dyke, locating a few kilometers south from the Burakovka intrusion, yields a stable single component remanence direction that is in agreement with the direction previously obtained from the Burakovka intrusion. Another NE–SW trending dyke, 0.8 m wide Shalskiy diabase dyke, about 30 km south of the Burakovka intrusion yields a similar remanence direction as the Avdeev dyke. The overall mean remanence direction has a palaeopole at Plat = −12.3°N, Plong = 243.5°E ($A95 = 15.4°$, 4 sites, 28 samples). The thin Shalskiy diabase dyke transects a similarly NE–SW trending 500 m wide coarse grained gabbronorite dyke which has now been dated by Sm–Nd method as 2608 ± 56 Ma. Geochemically all the dykes are quite similar showing slight calc-alkaline affinity and low TiO_2 and high SiO_2 with moderate MgO and low Cr and Ni. Furthermore, the dykes are geochemically identical to the 2.45 Ga dyke swarm in the northern Karelian Province.

The remanence direction of the thin Shalskiy diabase dyke differs significantly from the high temperature and high coercivity remanence component of the unbaked Archean gabbronorite dyke which yields a palaeopole at Plat = 22.7°N, Plong = 222.1°E (dp = 8.2°, dm = 16.2°, five samples). On the basis of different remanence directions of the diabase dyke and the unbaked Archean gabbronorite dyke, the baked contact test for the diabase dyke is positive. In addition to the high temperature and high coercivity component of the baked and unbaked Archean gabbronorite dyke, in low temperatures and coercivities we isolated a similar component as in the diabase dyke. A comparable remanence component was also obtained from the Archean basement at ca. 8 km from the dykes. We propose that in the studied area, the Archean basement and the Archaean dyke were partly remagnetized due to emplacement and subsequent uplift and cooling of the large Burakovka layered intrusion and related dykes at about 2.40 Ga ago.

This interpretation lends support from a new $^{40}Ar/^{39}Ar$ dating of hornblende from another area, Lake Paajarvi area, in northern Karelia. There, a negative baked contact test was previously obtained for the remanence of the dated ca. 2.45 Ga dyke rocks related to the ca. 2.45 Ga Oulanka layered intrusion. The $^{40}Ar/^{39}Ar$ dating of the unbaked Archean basement which yields the same remanence component as the dykes, shows a plateau age of ca. 2.6 Ga, but in addition, it also shows resetting of the basement at ca. 2.4 Ga ago. The dating thus supports reactivation and partial remagnetization of the Archean basement at ca. 2.4 Ga ago.

---

* Corresponding author. Tel.: +358 20 550 11; fax: +358 20 550 11.
E-mail address: satu.mertanen@gtk.fi (S. Mertanen).

doi:10.1016/j.precamres.2005.11.005

Our new palaeomagnetic results from the Burakovka dykes and the new ^{40}Ar/^{39}Ar dating from the Lake Paajarvi area give support to our previous interpretation that at Lake Paajarvi area the remanence component suggested to be 2.4 Ga, despite to negative baked contact test, is indeed of this age. Therefore, it is implied that the results can be used for continental reconstructions.

Keywords: Paleomagnetism; Baked contact test; Isotope age; Geochemistry; Dykes; Paleoproterozoic; Archean; Fennoscandian shield; Baltica; Vodlozero block

1. Introduction

In several previous palaeomagnetic studies from the Karelian Province of the Fennoscandian Shield, a remanent magnetization regarded as 2.45 Ga has been reported (e.g. Mertanen et al., 1989, 1999b; Krasnova and Gooskova, 1990, 1995; Mertanen, 1995; Khramov et al., 1997; Fedotova et al., 1999). However, in most of the studies, the primary nature of the magnetization has not been established with field tests. The only published study where a positive baked contact test has been reported is by Krasnova and Gooskova (1990) for a remanent magnetization of a thin 0.8 m wide Shalskiy diabase dyke in the Vodlozero block in southern Russian Karelia. The dyke is thought to be cogenetic with the large 2449 ± 1 Burakovka layered intrusion (U–Pb, zircon, Amelin et al., 1995) (Fig. 1). The Shalskiy diabase dyke cross cuts a ca. 500 m wide gabbronorite dyke that by Krasnova and Gooskova (1990) was suggested to be 2.85 Ga old, based on a similar pole position with dated 2.85 Ga gneisses in the Vodlozero block. For the baked contact test, Krasnova and Gooskova (1990) studied both the thin diabase dyke and the thick gabbronorite dyke.

In order to verify the paleomagnetic results of Krasnova and Gooskova (1990), we have restudied the Shalskiy diabase and gabbronorite dykes and collected new samples from the nearby gabbronorite dykes and Archean basement rocks in the Burakovka area. A new Sm–Nd age dating was carried out on the thick Shalskiy gabbronorite dyke in order to confirm its age.

Another object of this study are the 2.45 Ga old mafic dykes and Archean basement at Lake Paajarvi area in northern Russian Karelia that have been previously studied by Mertanen et al. (1999b). The dykes are asso-

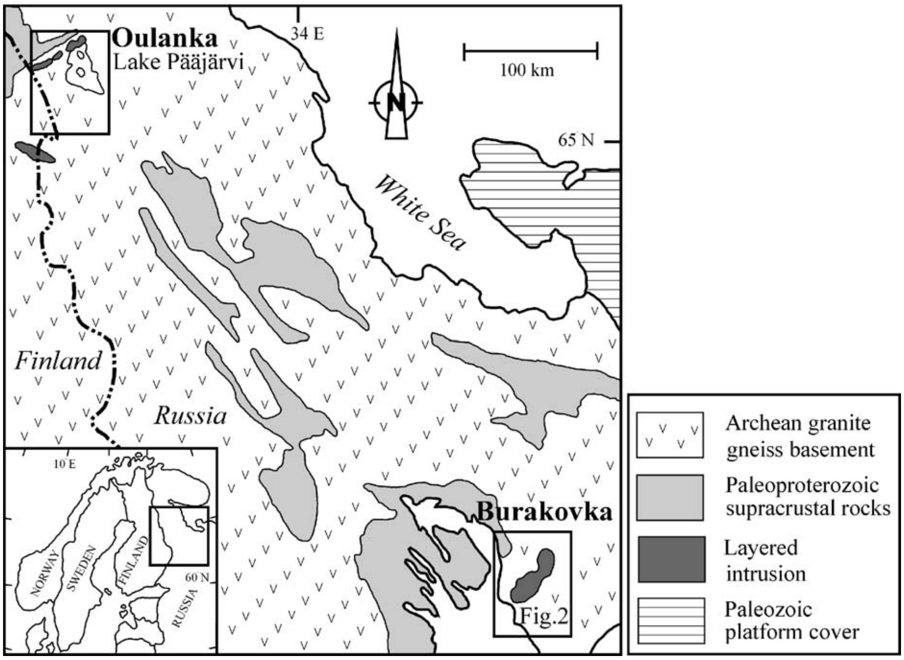

Fig. 1. Geological sketch map of northwestern Russia, modified from Gorbunov et al. (1985). The insert map shows the area in the Fennoscandian Shield. The paleomagnetically studied areas of Burakovka (Fig. 2) and Oulanka-Paajarvi are indicated in squares.

ciated with the Oulanka layered intrusions of similar age (Fig. 1). In the previous study it was shown that baked contact tests were negative for the magnetization that was originally thought to be of the age of 2.45 Ga and to represent the primary remanence of the dykes. Based on negative baked contact test, however, the remanence proved to be of secondary origin. It was suggested that the Archaean basement of the area had been partly remagnetized at about 2.4 Ga ago as a consequence of emplacement of the layered intrusions and mafic dykes. However, there were no isotopic age evidences to confirm the interpretation. Here we report a new ^{40}Ar/^{39}Ar dating from the Lake Paajarvi area, from an unbaked Archean basement rock that carries the same remanence direction as the 2.45 Ga dykes.

The new palaeomagnetic, geochemical and Sm–Nd results from the Burakovka area and the ^{49}Ar/^{39}Ar results from the Oulanka area are discussed in the light of the overall palaeomagnetic studies on the 2.45 Ga formations of the Fennoscandian Shield. The results have implications for the determination of the palaeoposition of the Fennoscandian Shield at 2.45–2.4 Ga ago and consequently, to the continental reconstructions during Early Paleoproterozoic (see Mertanen et al., 1999b; Buchan et al., 2000; Pesonen et al., 2003).

2. Geology and previous studies of the Burakovka dykes

The Burakovka layered intrusion (Fig. 2) is located in the Mesoarchean Vodlozero block in the southern Russian Karelia. The intrusion represents the largest layered intrusion in the Fennoscandian Shield, the length being about 50 km and width about 15 km with a total thickness of about 6.5 km (Amelin and Semenov, 1996). A number of dykes and sills are spatially associated with the Burakovka intrusion. North of the intrusion the Archean basement is injected by the so-called Kopalozero dyke and south of the intrusion, the Avdeev dyke. The Avdeev dyke is gabbronoritic in composition and can be followed for about 25 km on aeromagnetic maps (Amelin and Semenov, 1996). So far neither of the dykes is isotopically dated.

The Vodlozero block is ideal for search of the Archean—Early Palaeoproterozoic remanent magnetizations, because it has preserved from later Proterozoic metamorphic events, especially the 1.9–1.8 Ga Svecofennian orogeny which further to west–northwest has partially or totally remagnetized the older rocks. The age of the protholith of the Vodlozero gneisses is ca. 3.2 Ga (Sergeev et al., 1990). The area was subse-

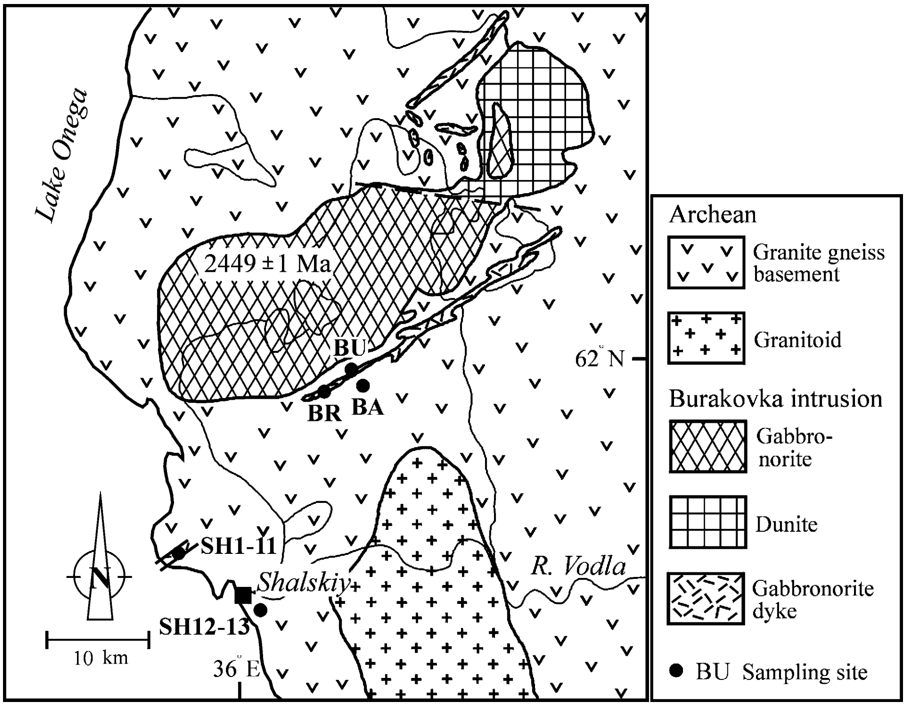

Fig. 2. Generalized geological map of the Burakovka area showing the sampling sites of the Avdeev gabbronorite dyke (sites BU and BR) and the Archean basement site (BA). Site SH1-11 comprises both the Shalskiy gabbronorite dyke and the diabase dyke and site SH12-13 the Archean basement. The map is modified from Amelin and Semenov (1996).

quently affected by polyphase deformation and metamorphism during Neoarchean (Sergeev et al., 1990; Lobach-Zhuchenko et al., 1993). The latest low-grade metasomatism took place at 2550–2450 Ma, based on U–Pb date on apatite and K–Ar date on biotite (Sergeev et al., 1990).

Palaeomagnetic studies on the Burakovka layered intrusion have been carried out by Krasnova and Gooskova (1990), Khramov et al. (1997) and Fedotova et al. (1999). In addition to the Burakovka intrusion, Krasnova and Gooskova (1990) also studied the Avdeev dyke and the so-called Shalskiy dykes, locating some 30 km south from the Burakovka intrusion. In Shalskiy area Krasnova and Gooskova (1990) took samples from a thin (0.8 m) diabase dyke and from a thick gabbronorite dyke (width 500 m), cross cut by the thin diabase dyke. Both dykes transect the Archaean basement in NE–SW direction. In order to verify the primary nature of magnetization for the thin dyke, they took samples from the baked and unbaked zones of the thick gabbronorite dyke. They report a positive baked contact test for the thin dyke. In addition, they took samples from the baked and unbaked Archean basement rocks adjacent to the thick gabbronorite dyke to verify the primary or secondary nature of the magnetization of that dyke. For the gabbronorite dyke, they obtained a negative baked contact test. In addition to the Avdeev and Shalskiy dykes, Krasnova and Gooskova (1990) studied the so-called Vodla dyke which transects the Archean basement tens of kilometers NE from the Burakovka intrusion. The Vodla dyke strikes perpendicular to the Avdeev and Shalskiy dykes, but has the same NW–SE trend as the ca. 2.45 Ga dykes further north in the Karelian Province, at Lake Paajarvi area. From the Avdeev dyke, the thin Shalskiy diabase dyke and the Vodla dyke, Krasnova and Gooskova (1990) obtained similar remanent magnetization directions, which are also in agreement with the results from the dykes of the Lake Paajarvi area (Krasnova and Gooskova, 1990; Mertanen et al., 1999b).

3. Palaeomagnetism of the Burakovka dykes and Archean basement

3.1. Sampling and analysis

Sampling sites of this study are shown in Fig. 2. All samples were taken as block samples and oriented with magnetic compass. Both the Burakovka layered intrusion and the associated dykes are poorly exposed so that known outcrops occur only at a few localities. In the Shalskiy area, we took three samples from the thin diabase dyke, eight samples from the gabbronorite dyke at varying distances from the thin dyke and three samples from the Archaean gneiss, one about 10 m from the thick gabbronorite dyke and two samples about 8 km from the dyke.

From the Avdeev dyke we took samples at two sites, BU and BR. At site BU, samples were taken from the dyke and from the baked Archean basement at distances of ca. 5, 3 and 30 m. The latter distance was thought to represent an unbaked area, but obviously the dyke may be so wide that an unbaked host rock was possibly not obtained. At site BU the dyke is hydrothermally altered which is shown as extensive seritization of plagioclase and newly formed biotite and amphibole. Also the host gneiss both close to the contact of the dyke and 30 m from the dyke is highly altered, shown as strong chloritization and sericitation of plagioclase.

Site BR was thought to represent an outcrop of the Avdeev dyke because it is located close to site BU. However, it is also possible that sites BU and BR represent separate dykes, because at site BR the rock type is more gabbronoritic and much coarser than at site BU. At site BR the dyke is well preserved and yields both ortho- and clinopyroxenes and faintly cloudy plagioclase.

In addition to the three sites represented by the dykes and their host rocks, we took samples from the Archean basement at site BA where no visible dykes occurred. However, site BA is close to the Burakovka layered intrusion and, consequently, it is probably baked by the Burakovka intrusion. At this site the gneiss is fresh and shows myrmekitic structures.

For palaeomagnetic studies, most samples were measured with JR4 magnetometer. Part of the samples were measured with Schoensted spinner magnetometer and a minor part with a SQUID magnetometer. Petrophysical properties, susceptibility and density, were first measured from all specimens. About half of the samples were demagnetized thermally, mainly in steps up to 620 °C and half with alternating field with peak field of 100 or 160 mT (SQUID). Two-stage cleaning method involving AF demagnetization followed by thermal demagnetization was applied for part of the samples. Thermomagnetic measurements (susceptibility versus temperature) were carried out on six specimens, representing different dykes and Archean gneiss. Thin sections were studied from each site and rock type. Directions of remanence components were calculated by principal component analysis (Kirschvink, 1980; Leino, 1991) and visually inspected with vector diagrams (Zijderveld, 1967). Mean remanence directions and pole positions were calculated using Fisher statistics (Fisher, 1953).

3.2. Results

Koenigsberger ratios (*Q* values) are typically high both in the dykes and in the Archean gneisses, ranging between 1 and 40. In the Shalskiy area, susceptibilities of the thin diabase dyke range between 2020 and 4070 × 10^{-6} SI. In the thick gabbronorite dyke, susceptibilities close to the thin diabase dyke (within 7.5 m) are between 6350 and 7350 × 10^{-6} SI, hence higher than in the thin diabse dyke. In sample SH7, taken from the thick gabbronorite dyke at the contact to the thin diabase dyke (Fig. 5), the susceptibility has lowered to 1160 × 10^{-6} SI. In the three gabbronorite samples taken about 300 m from the thin diabase dyke, the susceptibilities are within the range of 7410–44,670 × 10^{-6} SI, thus clearly higher than in the thin dyke or in the thick gabbronorite dyke at the vicinity of the thin diabase dyke. At the more hydrothermally altered site BU of the Avdeev dyke, the susceptibilities range between 4330 and 12,730 × 10^{-6} SI and at site BR between 5130 and 10,280 × 10^{-6} SI, both being approximately within the same range as the thick Shalskiy gabbronorite dyke. At site BU, the susceptibilities of the Archean gneisses range between 70 and 850 × 10^{-6} SI, being lowest close to the contact of the dyke and highest far from the dyke. At site BA the susceptibilities of the gneisses range typically between 1470 and 3580 × 10^{-6} SI. In the unbaked gneisses, ca. 8 km from the Shalskiy dykes, the susceptibilities are 4100 and 430 × 10^{-6} SI for samples SH12 and SH13, respectively. Hence, the susceptibility values indicate that the dykes do not differ markedly from each other and that the dykes have affected the host Archean basement by lowering the susceptibility in the vicinity of the dykes.

Mean palaeomagnetic directions of the sites are shown in Table 1 and Fig. 9. Examples of demagnetization results of individual specimens from the Avdeev dyke and the thin Shalskiy diabase dyke are shown in Figs. 3 and 4 and from the thick Shalskiy gabbronorite dyke and the Archean basement in Figs. 6–8. All samples from the dykes and the Archean basement show a hard and stable remanent magnetization, shown as resistant coercivities upon AF demagnetization and square shoul-

Table 1
Paleomagnetic results from the Avdeev and Shalskiy dykes and Archean basement gneiss (Glat = 61.94°N, Glong = 36.05°E)

	B/*N*/*n*	*D* (°)	*I* (°)	α95 (°)	*k*	Plat (°N)	Plong (°E)	dp (°)	dm (°)	*A*95	Pole no.
BU (61.95°N, 36.08°E)											
Gabbronorite dyke	[a]8/21	136.9	50.7	4.3	166.3	−9.9	252.3	3.9	5.8		
Gneiss, baked + unbaked	[a]3/8	132.4	52.4	10.7	133.9	−12.5	255.5	10.1	14.7		
Mean BU	[a]11/29	135.7	51.2	3.6	165.2	−10.6	253.2	3.3	4.8	4.0	1
BR (61.93°N, 36.07°E)											
Gabbronorite dyke	[a]4/8	164.7	55.0	12.7	53.1	−9.1	229.2	12.8	18.1	13.9	2
BA (61.94°N, 36.16°E)											
Gneiss	[a]4/9	128.1	59.8	18.5	25.7	−20.8	254.6	21.0	27.8	26.8	3
SH (61.82°N, 35.90°E)											
Diabase dyke (SH1-3)	[a]3/8	139.8	55.1	16.2	59.3	−12.8	248.0	16.3	23.0		
Baked gabbronorite (SH6-8)	[a]3/8	162.4	54.6	25.2	25.0	−9.9	230.1	25.1	35.6		
Unbaked gabbronorite, *L* (SH4-5, 9)	[a]3/5	158.9	45.6	14.2	76.9	−0.9	234.6	11.5	18.0		
Baked gneiss[b]	1/[a]2	158.5	30.2	–	–	9.7	236.0	–	–		
Unbaked gneiss[b]	[a]2/6	167.9	37.8	–	–	6.4	226.9	–	–		
Mean Shalskiy SH	3/[a]9/21	154.1	52.2	8.5	37.5	−7.9	237.5	8.0	11.7	9.6	4
Mean of dykes + gneisses (BU, BR, BA, SH)	[a]4/28/67	146.1	55.4	11.6	63.2	−12.3	243.5	*K* = 36.6	15.4	5	
SH unbaked gabbronorite, *H*	1/[a]5/16	174.0	10.4	16.0	23.8	22.7	222.1	8.2	16.2	10.7	6

Note: *B*/*N*/*n*, number of sites/samples/specimens used for mean calculations, α95 is the radius of the circle of 95% confidence; *k* is the Fisher's (1953) precision parameter; Plat and Plong are the paleolatitude and paleolongitude for the Virtual Geomagnetic poles; dp and dm are the semi-axes of the oval of 95% confidence; *A*95 is the radius of the circle of 95% confidence of the mean pole, *K* is the Fisher's precision parameter of the mean pole. Pole no. refers to the pole numbers in Fig. 10.

[a] Statistical level used for mean calculation. *D* and *I* are the mean declination and inclination, respectively.

[b] Not used in mean calculation, *L* and *H* denote the low and high coercivity/temperature component of the unbaked Shalskiy (SH) gabbroic dyke, respectively.

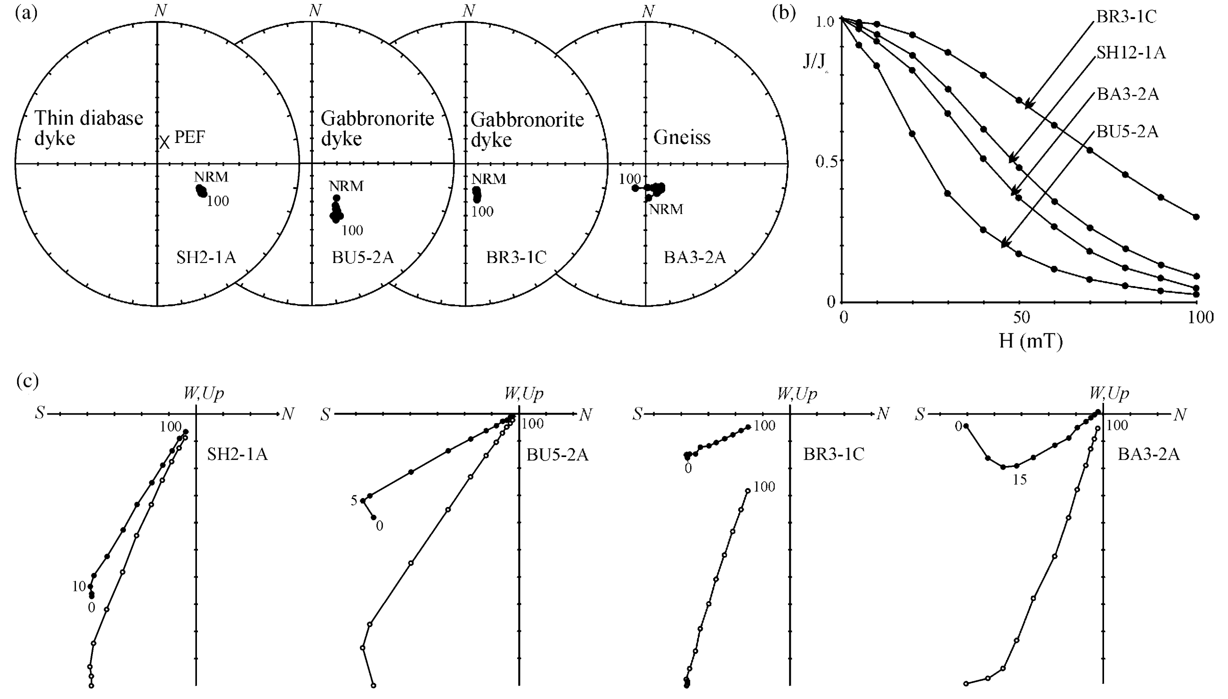

Fig. 3. Examples of AF demagnetization behaviour for specimens from different sites at Burakovka and Shalskiy areas, showing highly consistent directions despite of the rock type. (a) Stereographic projections, (b) relative NRM intensity decay curves upon AF demagnetization, (c) orthogonal vector projections. Open (closed) symbols denote projections onto vertical (horizontal) planes. Numbers at demagnetization steps denote peak alternating field (mT).

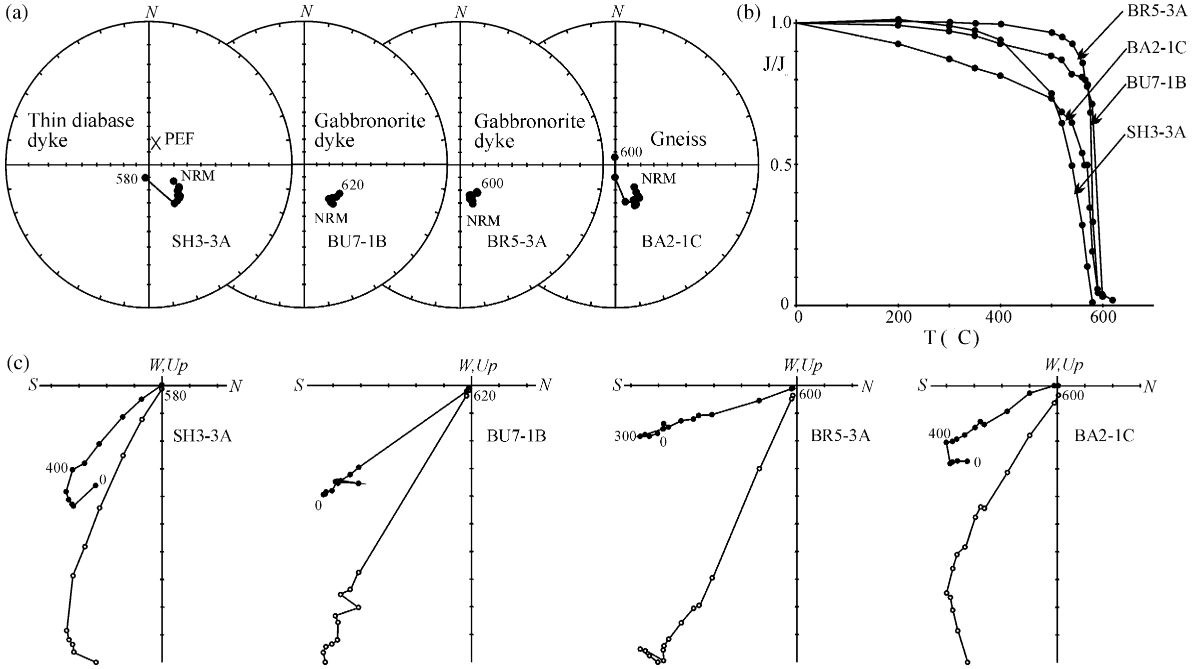

Fig. 4. Examples of thermal demagnetization behaviour for specimens from different sites, which show square shouldered intensity decay curves, typical for a hard and stable remanent magnetization. Numbers at demagnetization steps denote temperatures. Other symbols as in Fig. 3.

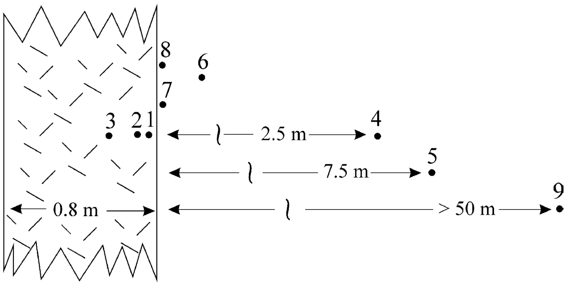

Fig. 5. Sketch map showing the paleomagnetic sampling for baked contact test of the thin Shalskiy diabase dyke (width 0.8 m). The diabase dyke cross cuts the ca. 500 m wide gabbronorite dyke. Samples for the baked contact test were taken from the baked contact zone (samples 6–8) of the gabbronorite dyke and from varying distances at the unbaked area (samples 4, 5 and 9).

dered intensity curves during thermal demagnetization (Figs. 3 and 4). Unblocking temperatures ca. 580 °C indicate that the remanence is carried by Ti-poor magnetite. The remanence is dominated by a steep to moderate SE pointing direction. The characteristic remanence component of the thick Shalskiy gabbronorite dyke has a low inclination south pointing direction. Some samples exhibit a remanence direction close to the present Earth's field (PEF) in low coercivities and unblocking temperatures. 1.9–1.8 Ga Svecofennian overprints that are typical for most of the Archaean—Early Palaeoproterozoic formations in the Fennoscandian Shield do not occur. In the following, baked contact tests that are crucial for determination of magnetization ages, are shown for the Shalskiy diabase dyke and for the Shalskiy gabbronorite dyke.

3.3. *Baked contact tests for the Shalskiy dykes*

3.3.1. *Thin Shalskiy diabase dyke*

Fig. 5 shows the location of samples for the baked contact test of the thin diabase dyke. Fig. 9d shows the mean remanence directions obtained in the test. Samples 1–3 (Fig. 5) taken from the diabase dyke yield a stable consistent remanent magnetization with a similar moderate SE direction as the Avdeev dyke (Table 1, Figs. 3 and 4). In addition to this component, the thin diabase dyke shows only a PEF direction in low AF fields and unblocking temperatures. Samples 6–8 taken from the baked gabbronorite dyke yield a similar remanence direction as the diabase dyke (Table 1). Samples 4, 5 and 9 from the unbaked gabbronorite dyke yield in high AF fields and unblocking temperatures a south pointing low inclination direction (pole 6, Table 1, Fig. 9d) which is clearly different to the previous direction. It is believed to represent the characteristic magnetization of the thick gabbronorite dyke. The result thus indicates that the baked contact test is positive and the SE pointing moderate remanence direction is the primary remanent magnetization of the thin dia-

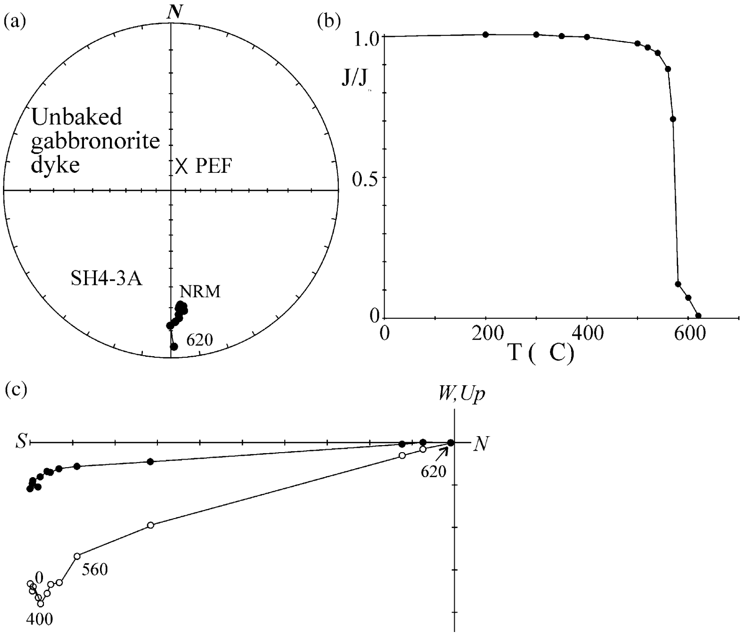

Fig. 6. Example of thermal demagnetiztion behaviour for a specimen from the Shalskiy unbaked gabbronorite dyke, taken 2.5 m from the diabase dyke. The remanence is dominated by a shallow south pointing direction, isolated between 560 and 620 °C, but the small component in lower temperatures (400–560 °C) has the same moderate south-east pointing remanence direction as the diabase dyke. Symbols as in Figs. 3 and 4.

base dyke. The result is in agreement with the results by Krasnova and Gooskova (1990). In the unbaked gabbronorite samples we additionally obtained in low AF fields and unblocking temperatures (Fig. 6) a similar moderately SE pointing direction as in the Avdeev dyke, thin diabase dyke and the baked gabbronorite dyke (Table 1).

3.3.2. *Thick Shalskiy gabbronorite dyke*

As shown above, in high AF fields and unblocking temperatures, the thick gabbronorite dyke yields a south pointing shallow inclination remanence direction, while in low fields and temperatures a similar SE remanence direction was isolated as in the thin diabase dyke and Avdeev dyke. The Archean basement rock in the baked contact zone to the gabbronorite dyke also yields a corresponding, although slightly shallower SE pointing remanence direction as the thin diabase dyke (Table 1, Figs. 7 and 9e). However, in this baked contact sample, we did not obtain a corresponding south pointing low inclination component as in the gabbronorite dyke. On the other hand, Krasnova and Gooskova (1990) did obtain that component in the baked contact zone (pole 12, Table 2).

The unbaked Archaean gneisses, samples taken ca. 8 km from the gabbronorite dyke, yield an almost corresponding moderate SE direction (Figs. 8 and 9e) as the thin diabase dyke, the unbaked gabbronorite dyke in low fields, and the baked gneiss at the contact to the gabbronorite dyke. The direction is, however, more between the direction of the thin diabase dyke and the shallow inclination component of the gabbronorite dyke, although it is within the $\alpha 95$ error circle of the remanence direction of the thin diabase dyke (Table 1, Fig. 9e). In their study from the Shalskiy area, Krasnova and Gooskova (1990) did not take samples from the unbaked Archean basement rocks. However, in their study on Archean basement gneisses in the Vodla River area, ca. 50 km east from the Burakovka intrusion, they obtained a similar shallow inclination remanence direction as in the Shalskiy gabbronorite dyke (pole 13, Table 2).

As a result, based on the occurrence of a south pointing shallow inclination component both in the gabbronorite dyke (pole 6, Table 1 and pole 11, Table 2), in

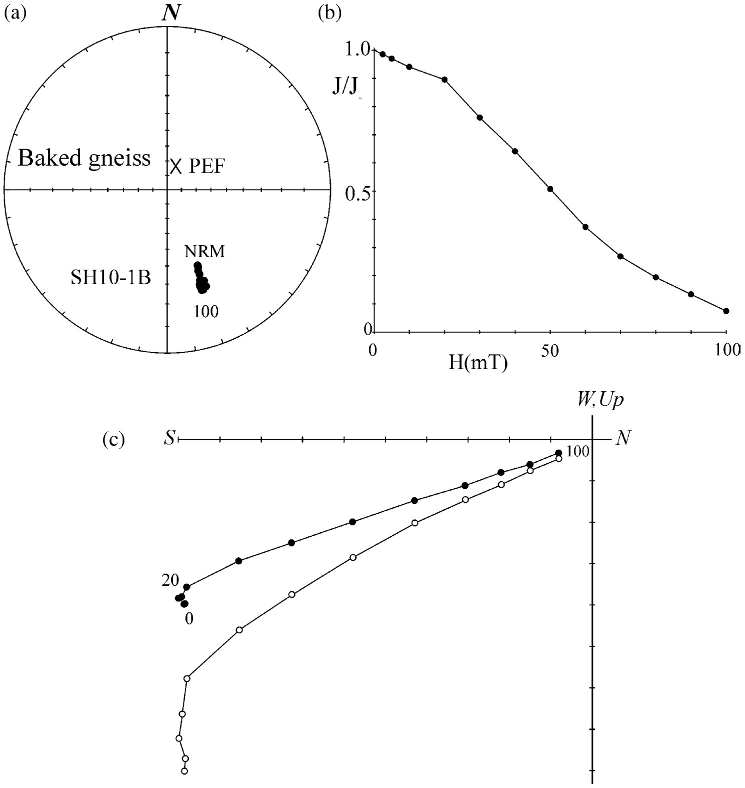

Fig. 7. Example of AF demagnetization behaviour for a specimen from the Archean basement gneiss taken about 15 m from the Shalskiy gabbronorite dyke. The remanence is dominated by a shallow-moderate south-east pointing direction that is between the remanence direction of the Shalskiy diabase dyke and unbaked gabbronorite dyke. The small low coercivity component isolated in 0–20 mT is close to the present Earth's magnetic field direction (PEF). Symbols as in Fig. 3.

Table 2
Previous paleomagnetic results from the Vodlozero block and Lake Paajarvi area

Formation	B/N	D (°)	I (°)	α95 (°)	k	Plat (°N)	Plong (°E)	dp (°)	dm (°)	A95	Ref	Pole no.
Burakovka intrusion	5/[a]16	119.6	63.5	5.8	35.9	−27.6	260.0	–	–	9.2	2	7
Avdeev dyke	[a]8/26	138.0	52.0	5.0	112.0	−11.0	251.0	5.0	7.0	5.9	1	8
Vodla dyke	[a]13/39	141.0	64.0	4.0	111.0	−22.0	245.0	5.0	6.0	5.5	1	9
Shalskiy												
Diabase dyke	1/[a]5	139.0	57.0	9.0	80.0	−15.0	248.0	9.0	6.0	7.3	1	10
Unbaked gabbronorite	3/[a]18	172.0	8.0	7.0	25.0	24.0	224.0	4.0	7.0	5.3	1	11
Baked gneiss	1/[a]4	172.0	14.0	5.0	300.0	20.0	225.0	5.0	3.0	3.9	1	12
Vodla River gneiss	[a]20/30	186.0	22.0	9.0	14.0	18.0	212.0	5.0	10.0	7.1	1	13
Lake Paajarvi												
Component D	[a]11/69	102.1	45.2	5.6	67.3	−19.9	278.7	4.4	7.0	6.1	3	14
Component D′	[a]2/10	134.8	14.2	–	–	9.6	256.2	–	–	–	3	15

Note: *B*/*N*, number of sites/samples. References: 1, Krasnova and Gooskova (1990); 2, Fedotova et al. (1999); 3, Mertanen et al. (1999b).

[a] Statistical level used for mean calculation. *D* and *I* are the mean declination and inclination, respectively.

the baked Archean basement rocks (pole 12, Table 2) and in the unbaked Archean gneisses (pole 13, Table 2), the baked contact test for the gabbronorite dyke is negative. However, because adequate sampling is lacking from the unbaked Archean basement rocks in the Shalskiy area, the test for the gabbronorite dyke is still inconclusive.

Furthermore, it is shown that in the Shalskiy area both the gabbronorite dyke and the Archean base-

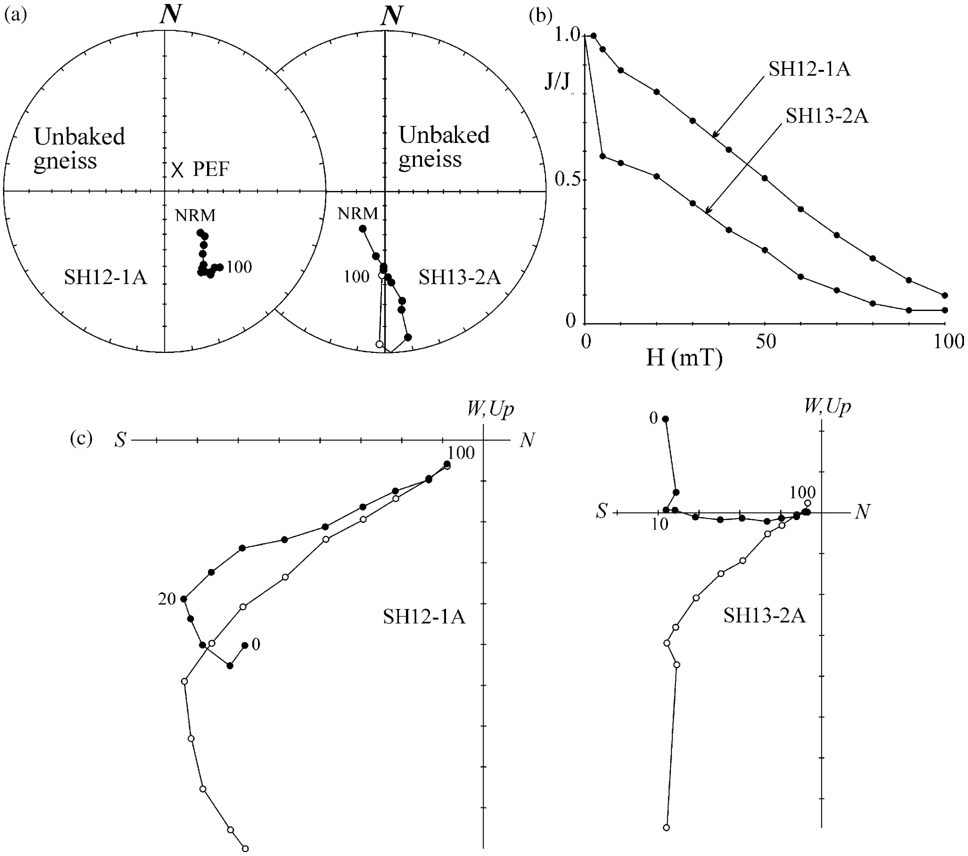

Fig. 8. Examples of AF demagnetization behaviour for two specimens from the Archean basement gneiss about 3 km from the Shalskiy dykes. The high coercivity component of specimen SH12-1A compares with the remanence direction obtained in the Avdeev dyke and the Shalskiy diabase dyke. Symbols as in Fig. 3.

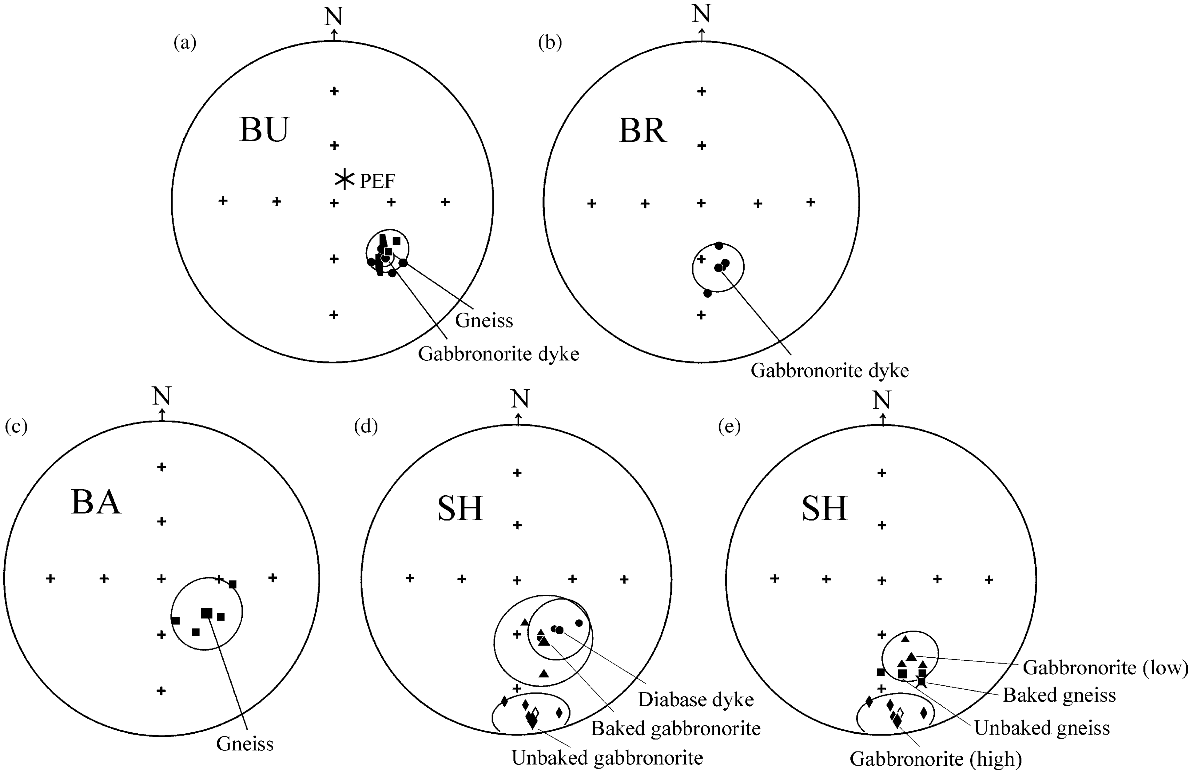

Fig. 9. (a–c) Site mean paleomagnetic directions for the Avdeev gabbronorite dyke (circles) and Archean basement rocks (squares). (d) Baked contact test for the thin diabase dyke of the Shalskiy area. Samples from the diabase dyke are marked as circles, from the baked gabbronorite as triangles and from the unbaked gabbronorite dyke (high coercivity and unblocking temperature component) as quadrangles. (e) Baked contact test for the thick Shalskiy gabbronorite dyke. The high coercivity and unblocking temperature component of the gabbronorite is marked as quadrangles, the baked gneiss (one sample) is marked as a square with a cross, and the unbaked gneiss samples (two samples and their mean direction) are marked as squares. The low coercivity and unblocking temperature component of the unbaked gabbronorite is marked as triangles. The mean directions are shown as bigger symbols. Circles denote cones of $\alpha95$ confidence about the means.

ment rocks carry a corresponding moderately SE pointing remanence direction as the Shalskiy diabase dyke and the Avdeev dyke. As discussed in Section 8, it is interpreted that in these formations the remanence is a secondary overprint, acquired when the rocks were partially reheated during the emplacement of the Burakovka intrusion and associated dykes at ca. 2.45 Ga.

3.4. Thermomagnetic curves

Thermomagnetic analyses were carried out in order to study the magnetic mineralogy of the samples. Both the dykes and the Archean basement display clear differences between heating and cooling curves (Fig. 10). The cooling curves show marked up rise between ca. 600 and 550 °C, indicative for the creation of new magnetite during heating. Curie temperatures obtained from the heating curves are ca. 580 °C which is indicative for magnetite or Ti-poor magnetite. In addition, sample BA3-2B (Fig. 10f) from the Archean basement gneiss shows a slight decrease of susceptibility near 320 °C probably due to occurrence of pyrrhotite. In sample SH3-3B (Fig. 10d) from the thin Shalskiy dyke, the difference between heating and cooling curves is most conspicuous. This can be interpreted so that the sample has not been subjected to temperatures as high as ca. 580 °C before, but it has retained its original magnetic mineralogy until the laboratory heating. In this sample, there is also a pronounced Hopkinson peak in the heating curve which is characteristic for SD/PSD grains. In other samples the increase of susceptibility in the cooling curves is not so prominent which may be due to earlier rise of temperature. These evidences may indicate that the thin Shalskiy dyke has retained its original magnetic mineralogy because it is the latest formation in the area, injected slightly after the emplacement of the other dykes and the Burakovka intrusion.

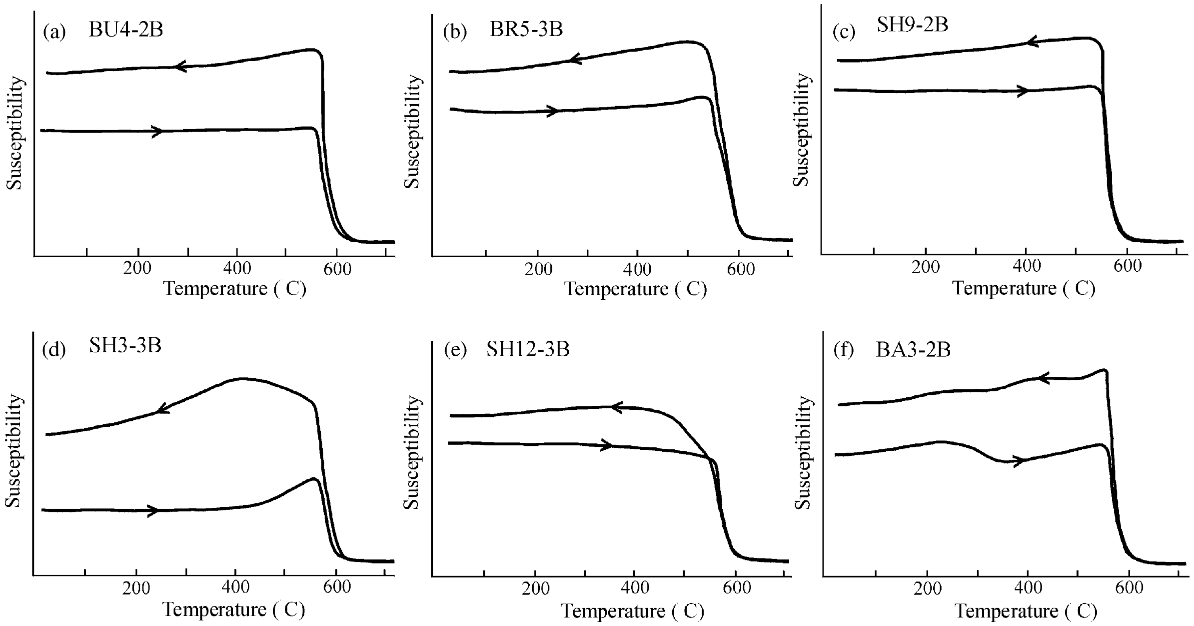

Fig. 10. Thermomagnetic curves (susceptibility vs. temperature) for specimens from different sites and rock types, (a) gabbronorite dyke, site BU, (b) gabbronorite dyke, site BR, (c) Shalskiy gabbronorite dyke, site SH (d) Shalskiy diabase dyke, site SH, (e) Archean gneiss, site SH, (f) Archean gneiss, site BA. All specimens contain magnetite or Ti-poor titanomagnetite as the main magnetic mineral. See text.

3.5. Poles

Table 1 shows the palaeopoles obtained in this study and Table 2 the other relevant poles from previous studies. The poles are shown in Fig. 11.

Site mean poles (poles 1–4, Table 1, Fig. 11) of the dykes and the Archean basement are quite scattered despite to stable remanence directions of individual specimens. However, pole 1 from site BU of the Avdeev dyke and its host rocks (Table 1) is almost identical with the pole (pole 8, Table 2) obtained by Krasnova and Gooskova (1990). Likewise, the pole from the thin Shalskiy diabase dyke (Diabase dyke, Table 1) is in agreement with the pole (pole 10, Table 2) obtained by Krasnova and Gooskova (1990). The overall mean pole of this study (pole 5) compares well also with the pole from the NW–SE trending Vodla dyke (pole 9, Table 2, Fig. 11) locating ca. 50 km east from the Burakovka intrusion (Krasnova and Gooskova, 1990). Pole 9 was obtained from the well-preserved part of the Vodla dyke and because it is close to the pole from the Burakovka intrusion (pole 7), Krasnova and Gooskova (1990) regarded it as ca. 2.4 Ga old.

The mean pole of this study (pole 5, Table 1, Fig. 11), although not fully matching, is within error limits in accord with the pole of the 2449 ± 1 Ma old Burakovka intrusion (pole 7, Table 2, Fig. 11). Based on the correspondence of the poles, coupled with the occurrence

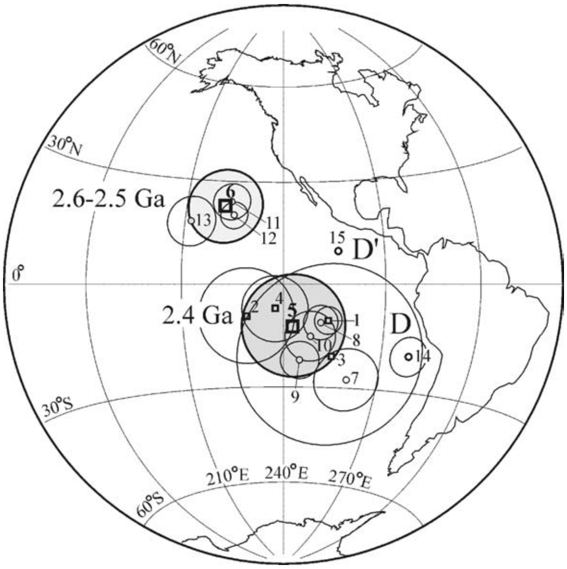

Fig. 11. Paleomagnetic poles obtained in this study (poles 1–6) are marked as squares and those from previous studies (poles 7–15) as circles. The shaded *A*95 confidence circles indicate the mean poles of this study. Poles 14 (D) and 15 (D′) are from the Lake Paajarvi area, the other poles are from the Vodlozero block, including the Burakovka area. The pole numbers are keyed to Tables 1 and 2.

of sites BU, BR and BA at the baked contact zone to the Burakovka intrusion, it is interpreted that the maximum magnetization age of the Avdeev dyke and the thin Shalskiy dyke, as well as the age of overprinting in the Shalskiy gabbronorite dyke and in the Archean basement rocks is 2449 Ma.

The pole of the high coercivity and high unblocking temperature component of the thick Shalskiy gabbronorite dyke (pole 6, Table 1, Fig. 11) is in good agreement with the poles (poles 12 and 13, Table 2, Fig. 11) obtained from the Archean gneisses (Krasnova and Gooskova (1990). As the baked contact test for this remanence is negative (although not conclusively), it is possible that the magnetization reflects an overall Archean regional reheating event. On the basis of isotope age data (Levchenkov et al., 1987) which showed that the main amphibolite facies high-temperature metamorphism of the Vodlozero gneisses took place at 2.8 Ga, Krasnova and Gooskova (1990) concluded that the age of the pole from the Vodla River is ca. 2.8 Ga. Based on this age evidence and on the similarity of poles from the Vodla River and thick Shalskiy gabbronorite dyke, Krasnova and Gooskova (1990) suggested that the Shalskiy dyke is about 2.8 Ga old. However, the Pb isotopic data on whole rocks, plagioclase and amphibole reported by Sergeev et al. (1990) and Ovchinnikova et al. (1991) from the 3.2 to 3.1 Ga old Vodlozero gneisses suggest major metamorphic resetting at ca. 2.7–2.6 Ga. Particularly it can be noted that the Pb isotope ratios in plagioclase represent clearly Neoarchean composition, not primary 3.1 Ga ratios. Furthermore, according to Sergeev et al. (1990), the latest Archean metasomatic reworking took place at 2540 ± 40 Ma, based on U–Pb dating on apatite. Further evidence for Neoarchean processes in the Vodlozero area are provided by the late-kinematic granites which according to Ovchinnikova et al. (1991) experienced metasomatism as late as 2500 ± 10 Ma.

The low inclination poles from the thick Shalskiy dyke and the Vodla River gneisses deviate clearly from the mean pole of the Burakovka intrusion and dykes. Based on the previous isotopic age data and the palaeomagnetic evidences of the Vodlozero gneisses, it is thus evident that the magnetization of the thick Shalskiy gabbronorite dyke was acquired during Neoarchean. In order to verify the age of the dyke, a Sm–Nd dating of the dyke was carried out.

4. Sm–Nd age of the Shalskiy gabbronorite dyke

The sample (SH-11) selected for isotopic studies was taken from the unbaked gabbronorite dyke ca. 300 m from the diabase dyke. According to the microscopic observations the sample contains well-preserved igneous plagioclase and pyroxenes. Standard separation produced relatively pure plagioclase-concentrate, but the pyroxene fraction looked more heterogeneous in colour and transparency. For Sm–Nd analyses further purification was made using hand-picking. The final pyroxene concentrate was verified by XRD, which showed both clino- and orthopyroxene, but no amphibole.

The minerals were washed ultrasonically in warm 6 N HCl for 30 min, and rinsed several times in water. Samples were dissolved in HF–HNO_3 using Savillex screw-cap Teflon beakers (ca. 200 mg) for 48 h. After careful evaporation of fluorides (with HNO_3) the residue was dissolved in 6 mol HCl and a clear solution was achieved. A mixed ^{149}Sm–^{150}Nd spike (and ^{87}Rb–^{84}Sr spike for Rb–Sr) was added to the sample prior the dissolution. Pb was extracted using a standard HBr anion-exchange procedure, and other elements were separated using a conventional cation-exchange procedure (7 ml of AG50Wx8 ion exchange resin in a bed of 12 cm length) and a modified version of the Teflon–HDEHP (hydrogen di-ethylhexyl phosphate) method developed by Richard et al. (1976). Measurements were made in a dynamic mode on a VG Sector 54 mass spectrometer using triple filaments (for Nd) or single Ta or Re filaments (for Sr and Pb, respectively). Based on duplicated analyses the estimated error in ^{147}Sm/^{144}Nd is 0.4%, and for ^{87}Rb/^{86}Sr 0.6%. ^{143}Nd/^{144}Nd ratio is normalized to ^{146}Nd/^{144}Nd = 0.7219, and ^{87}Sr/^{86}Sr to ^{86}Sr/^{88}Sr = 0.1194. The fractionation correction in Pb isotope ratios was 0.12%/a.m.u. The average value for La Jolla standard is ^{143}Nd/^{144}Nd = 0.511850 ± 7 (std, n = 70), and for SRM987 ^{87}Sr/^{86}Sr = 0.710250 ± 25 (std, n = 20). Measurement on the rock standard BCR-1 provided values: Sm = 6.58 ppm, Nd = 28.8 ppm ^{147}Sm/^{144}Nd = 0.1380, ^{143}Nd/^{144}Nd = 0.51264 ± 0.00002, Rb = 47.1 ppm, Sr = 330 ppm, ^{87}Rb/^{86}Sr = 0.412, ^{87}Sr/^{86}Sr = 0.70502 ± 0.00002. The average blank measured during mineral analyses was: 50 pg for Sm, 150 pg for Nd, 100 pg for Rb, 300 pg for Sr and 150 pg for Pb.

The isotopic data are shown in Table 3 and Fig. 12. Due to the problems in measuring the Nd isotopic composition, repeated analyses were made on plagioclase. The Sm–Nd data available on plagioclase, pyroxene and whole rock provide an age of 2608 ± 56 Ma, and an initial ε_{Nd} of −1.2 (MSWD = 0.65). A Rb–Sr analysis on plagioclase yield an initial ^{87}Sr/^{86}Sr of 0.70307 at 2600 Ma (ε_{Sr} = +23), and the Pb isotope ratios for the same HNO_3-leached plagioclase (#3) are ^{206}Pb/^{204}Pb = 14.469, ^{207}Pb/^{204}Pb = 14.956, ^{208}Pb/^{204}Pb = 35.102 (errors 0.2%).

Table 3
Sm–Nd and Rb–Sr isotopic data on whole rocks and mineral concentrates

Sample/anal#	Sm (ppm)	Nd (ppm)	^{147}Sm/^{144}Nd ($\pm$0.4%)	^{143}Nd/^{144}Nd ($\pm 2\sigma_m$)	ε_{Nd} (2600)	Rb (ppm)	Sr (ppm)	^{87}Rb/^{87}Sr ($\pm$0.6%)	^{87}Sr/^{86}Sr ($\pm 2\sigma_m$)	ε_{Sr} (2600)
SH-11 wr	2.34	11.45	0.1237	0.511319 ± 10	−1.4					
SH-11 plag#1	0.13	0.96	0.0819							
SH-11 plag#2	0.11	0.83	0.0829	0.510681 ± 108						
SH-11 plag#3	0.12	0.83	0.0864	0.510670 ± 31	−1.6	1.9	421.4	0.013	0.703557 ± 20	23.0
SH-11 px#1	3.87	15.04	0.1557	0.511866 ± 10	−1.4					
SH-11 px#2	3.84	14.89	0.1559	0.511875 ± 10	−1.3					

Note: plag, plagioclase; px, pyroxene. plag #2, #3, not handpicked, crushed and leached in HNO_3. px#2 not handpicked, air abraded.

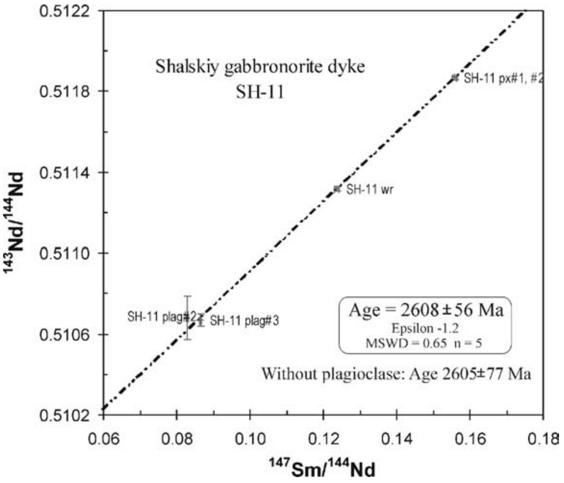

Fig. 12. Sm–Nd diagram for the Shalskiy gabbronorite dyke.

The Shalskiy gabbronorite dyke is thus Neoarchean in age, and clearly older than the 2.45 Ga Burakovka intrusion. The initial ratios suggest major involvement of older LREE enriched lithosphere in the genesis of the mafic magma, the feature characteristic for 2.45 Ga layered intrusions as well. This is also demonstrated by the model age T_{DM} of 2.94 Ga for the whole rock (model by DePaolo, 1981).

The results from the Shalskiy dyke can be compared with the data from the Burakovka intrusion (Amelin and Semenov, 1996; Amelin and Neymark, 1998). The ε_{Nd} (2449) for the Shalskiy whole rock is −2.8, which is lower than the values for the Burakovka intrusion, but initial ^{87}Sr/^{86}Sr at 2449 Ma (0.7031) is within the range obtained from Burakovka. The Pb isotopic ratios from the Shalskiy plagioclase are clearly distinct from the Burakovka plagioclase (Amelin and Neymark, 1998).

5. Geochemistry

Geochemical analyses were done on samples from the Avdeev dyke (sites BR and BU) and from the Shalskiy gabbronorite and diabase dykes. The data were compared with the analyses from the ca. 2.45 Ga boninitic–noritic dykes in the Karelian Province in eastern Finland and in Lake Paajarvi area in northwestern Russia (Vuollo and Huhma, in press). All the dykes show notable similarities. They all give moderate magnesium (MgO) and low chromium (Cr) values (Fig. 13A), and high silica (SiO_2) values (Fig. 13B). All dykes display slight calc-alkaline affinity (Fig. 13B). TiO_2 values (0.48–0.77%) are low in all dykes and in the Al_2O_3/TiO_2 versus Ti/Zr diagram all the dykes fall into or near boninite field (Fig. 13C). Th/Ta and La/Yb ratios (Condie, 1997) have been used to identify magma sources for mafic dyke swarms, and in the diagram (Fig. 13D) the Avdeev and Shalskiy dykes set up in the norite field. Geochemical data thus implies that both Shalskiy dykes, comprising the Archean gabbronorite dyke and the cross cutting thin diabase dyke, are geochemically identical with the Avdeev dyke. The geochemical characteristics are also in accord with the geochemical data from the 2.45 Ga old noritic dykes elsewhere in the Karelian Province as well as with data from other shields (Condie, 1997). Therefore, based on geochemical and isotopic data, it is proposed that the magmatic processes that were acting during the emplacement of the Early Paleoproterozoic layered intrusions and associated dykes, operated already during Neoarchean. More detailed geochemical analyses are presented in Vuollo and Huhma (in press).

6. Implications of the isotopic age for interpretations of the Neoarchean palaeomagnetism of the Karelian Province

The new Sm–Nd age 2608 ± 56 Ma of the thick Shalskiy gabbronorite dyke verifies the age of the dyke and supports the interpretation that the low inclination southward pointing magnetization was acquired during Neoarchaean. In the Fennoscandian Shield, this remanence direction has so far been obtained only in the Vod-

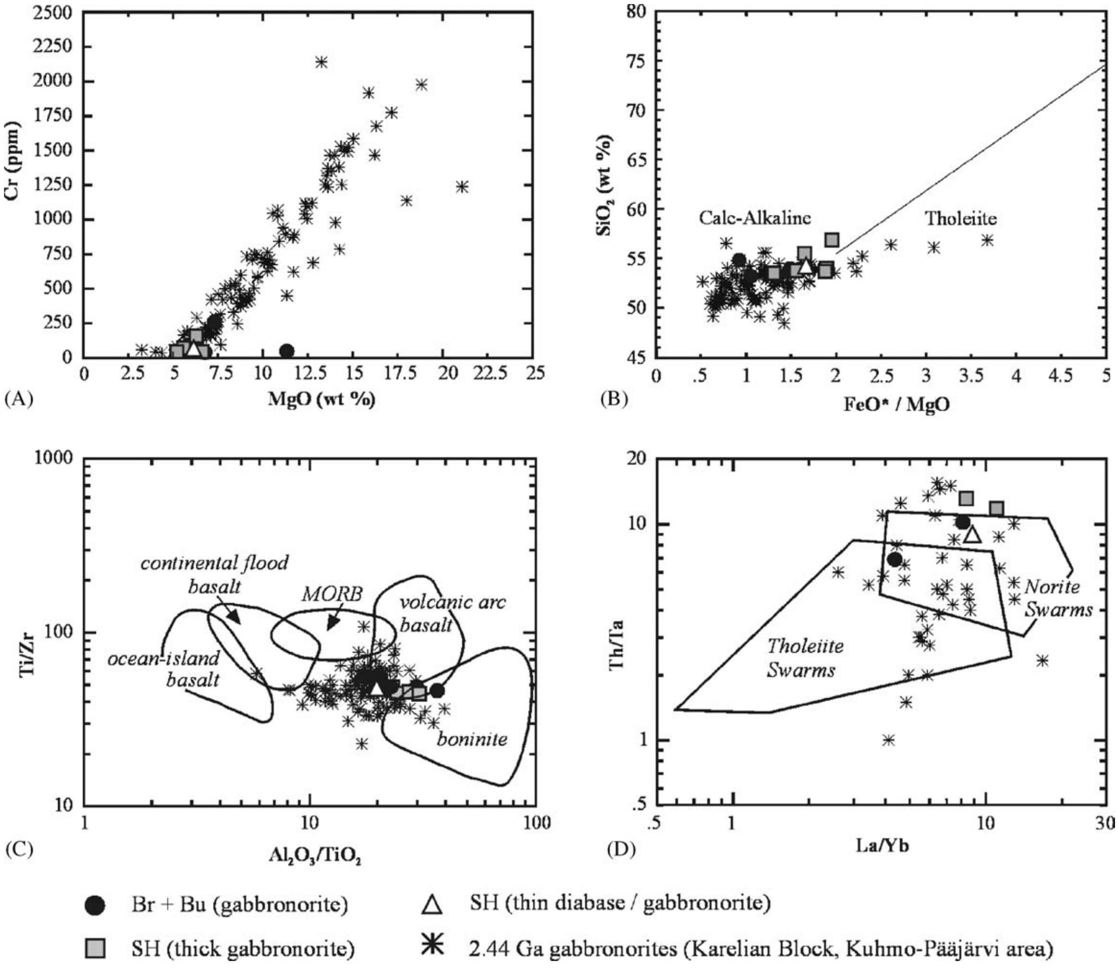

Fig. 13. Geochemical analyses of the Avdeev dyke (Br and Bu, circles) and the Shalskiy dykes (SH, square; gabbronorite and triangle; diabase dyke). Analyses from other 2.45 Ga dykes from the Karelian Province are shown for comparison. Geochemically all the dykes of this study are quite similar showing slight calc-alkaline affinity and low TiO_2 and high SiO_2 with moderate MgO and low Cr and Ni. They are identical to the 2.45 Ga gabbronoritic (boninite–norite) dyke swarms at the Karelian Province (Karelian block, Kuhmo-Paajarvi area).

lozero area. By contrast, palaeomagnetic studies from the dated 2.63 Ga old (U–Pb on zircon and monazite, Hölttä et al., 2000) granulites in the Varpaisjärvi area of the Iisalmi Complex in central Finland, ca. 500 km west from the Burakovka area, give a very stable steep inclination remanence direction (Neuvonen et al., 1981, 1997; Mertanen et al., in press). The Sm–Nd garnet-whole rock ages for the Varpaisjärvi granulites are between 2.48 and 2.59 Ga (Hölttä et al., 2000) which is considered to date the cooling after granulite facies metamorphism (Hölttä et al., 2000; Mänttäri and Hölttä, 2002). The closure temperature for Sm–Nd system in garnet is lower (approximately between 650 and 600 °C) than that of the U–Pb system in monazite (>800 °C, see Jung and Mezger, 2003) and consequently, is more in accord with the blocking temperature of magnetite (580 °C), that is the main remanence carrier of the Varpaisjärvi granulites.

The steep inclination remanence direction of the Varpaisjärvi granulites thus differs clearly from the low inclination remanence direction of the Shalskiy gabbronorite dyke and the Vodlozero gneisses (Krasnova and Gooskova, 1990). However, within error limits, the ages (Shalskiy gabbronorite 2660–2550 Ma and Varpaisjärvi granulites 2590–2480 Ma) are in close agreement. Possible explanations for the difference in remanence directions can be:

(1) The Sm–Nd age of the Shalskiy gabbronorite dyke has become younger due to reactivation at ca. 2.4 Ga although the original age of the dyke is significantly older than ca. 2.6 Ga. This explanation, however, is

unlikely because based on XRD analysis, the pyroxene fraction used for Sm–Nd dating is unaltered, containing only ortho- and clinopyroxenes and consequently, should represent the age of dyke magmatism.

(2) Considerable tectonic movements between the Vodlozero block and the Iisalmi Complex took place during ca. 2.6–2.5 Ga, so that either the Vodlozero block or the Iisalmi Complex was tilted almost vertically. However, such considerable tilting of the Vodlozero block after 2.4 Ga does not seem possible, because the paleomagnetic data from the 2.45 Ga Burakovka intrusion and dykes are in close agreement, although not identical, with the data from the 2.45 Ga layered intrusions and dykes further north in the Karelian Province (Mertanen et al., 1989, 1999b). Tilting of the Iisalmi Complex is more probable because the complex is located close to the margin of the 1.9–1.8 Ga Svecofennian orogen. However, as the 2.2–2.1 Ga diabase dykes in the Varpaisjärvi block are vertical or subvertical, tilting during Svecofennian orogeny cannot have been significant.

(3) Substantial plate movement of the Fennoscandian Shield took place during ca. 2.6–2.5 Ga. Referring to large error limits of the Sm–Nd datings, the magnetization age of the Shalskiy gabbronorite dyke can be 2550 Ma and based on previous isotope datings from the Vodlozero block (Sergeev et al., 1990; Ovchinnikova et al., 1991) it could be even as low as 2500 Ma (see Section 3.5). Furthermore, the highest magnetization age of the Varpaisjärvi granulites can be as old as 2590 Ma, thus at least 40 Ma higher than the magnetization age of the Shalskiy gabbronorite dyke. In plate tectonic movement scenario, it would mean that at 2590 Ma the Fennoscandian Shield was located at a high paleolatitude of ca. 60° (see also Mertanen and Pesonen, in press) and at 2550–2500 Ma it had moved to a low equatorial paleolatitude.

Due to lack of evidence of substantial tilting of different Arhaean blocks and due to uncertainties in defining the Archean magnetization ages, the question of intracratonic or plate tectonic movement of the Fennoscandian shield during Neorchean is left open here. The main result of this study is that the Shalskiy gabbronorite dyke, that is now proven to be Neoarchaean in age, carries probably a Neoarchean remanent magnetization as evidenced by relative blocking temperatures of the gabbronorite dyke and negative baked contact test. Furthermore, isotopic and geochemical data imply that the crustal rifting leading to the emplacement of the ca. 2.45 Ga layered intrusions and mafic dykes, initiated already during Neoarchean.

7. Oulanka area

7.1. Palaeomagnetism

Paleomagnetism of dykes related to the 2.45 Ga old Oulanka layered intrusions at Lake Paajarvi area in northern Karelian Province have been studied by Mertanen (1995), Krasnova and Gooskova (1995) and Mertanen et al. (1998, 1999b). Many of the dykes are dated (U–Pb on baddeleyite or Sm–Nd mineral analyses, Vuollo and Huhma, in press; Vuollo et al., 2005) and give ages around 2.4 Ga (see also Mertanen et al., 1999b). At Lake Paajarvi area, baked contact tests were carried out at three sites and at all sites the test results were negative, shown as similar remanence directions in the dykes and in the Archean basement far from the dykes. Pole 14 (Fig. 11, Table 2) represents component D that is the characteristic remanence component at Lake Paajarvi area. The pole is close to the poles of the Burakovka area, but is located ca. 30° more to the east from the mean pole 5 (Fig. 11). The difference of the poles could be due to age difference of the two poles or due to later tectonism between the two areas. The U–Pb zircon ages of the Oulanka layered intrusions range between 2441 and 2445 Ma (Balashov et al., 1993; Amelin et al., 1995) and the U–Pb baddeleyite age of one of the dykes is 2446 ± 5 Ma (Vuollo et al., 2005). Thus, the ages from the Oulanka area are within the same age range as the Burakovka intrusion (2449 ± 1 Ma, U–Pb on zircon, Amelin et al., 1995). Consequently, it is implied that slight tectonic movements, possibly during the Svecofennian orogeny at about 1.9–1.8 Ga ago, are responsible for the difference in the pole positions. In addition to remanence component D, another component, component D′, represented by pole 15 (Fig. 11, Table 2), was isolated at Lake Paajarvi area (Mertanen et al., 1999b). Because component D′ was isolated in higher unblocking temperatures and coercivities than component D in one of the dykes and at the baked contact zone of another dyke, it was suggested that component D′ may represent the primary, about 2.45 Ga remanence of the dykes. Moreover, Lake Paajarvi area differs from the Burakovka area in being reactivated and partially remagnetized during the Svecofennian orogeny at ca. 1.84 Ga (Mertanen, 1995).

Based on negative baked contact tests, pole D was regarded to represent a secondary overprint at Lake Paajarvi area. However, as evidenced also in this study, component D is the dominating remanence component in all

2.4 Ga old layered intrusions and associated dykes in the Karelian Province (Mertanen et al., 1989; Krasnova and Gooskova, 1990, 1995; Khramov et al., 1997; Fedotova et al., 1999). Mertanen et al. (1999b) suggested that at Lake Paajarvi, the negative baked contact test was due to partial reheating and subsequent cooling of the whole area when the Arcean basement was intruded by layered intrusions, granites, mafic and acid dykes, together with volcanic rocks at ca. 2.45 Ga ago. Component D was thus suggested to represent a remagnetization with an age of ca. 2.4 Ga. However, this interpretation was supported only by the overall occurrence of component D in other 2.4 Ga old formations. In order to resolve the age of component D, a sample from the unbaked Archean basement that carried component D was dated by ^{40}Ar/^{39}Ar method. The dating was made at the University of Leeds (by Robert A. Cliff and Philip G. Guise).

7.2. ^{40}Ar/^{39}Ar hornblende date of the Archean basement at Lake Paajarvi area

The sample for ^{40}Ar/^{39}Ar dating of hornblende was taken from the Archean basement at site VN (Varisniemi, see Mertanen et al., 1999b) which does not yield the common Svecofennian overprint components A and/or B. The sample, taken 1.3 m from a 43 cm wide gabbronorite dyke, yields components D and D′. The sample is a pyroxene bearing granodiorite and contains metamorphic hornblende and biotite in addition to primary hornblende and pyroxenes. The Archean plagiogneisses and granitoids have been previously dated by U–Pb method on zircon and give an age of 2.70 Ga (Buiko et al., 1995). U–Pb zircon age of a quartz diorite taken ca. 45 km from site VN is 2724 ± 8 Ma and the U–Pb sphene age is 2695 ± 5 Ma (Bibikova et al., 1997).

Fig. 14 and Table 4 show the results of the ^{40}Ar/^{39}Ar dating. The diagram shows argon loss during the first steps of heating. The age rises systematically from close to 2.4 Ga and just over 2.6 Ga. This pattern does not define the age of resetting precisely, but still clearly indicates partial reheating of the Archean basement. The bulk of the hornblende retains an older age, probably because the metamorphic event was not intense enough to completely reset the hornblende. According to Cliff (1985), hornblende is likely to retain argon under conditions up to the lower amphibolite facies, but ^{40}Ar/^{39}Ar step-heating spectra can effectively reveal partial argon loss. The closure temperature for hornblende is regarded as between ca. 450 and 550 °C, but it has been shown to be even higher (York, 1984). Yu and Dunlop (2001) give a temperature as high as 590 °C for the closure temperature in 1100 Ma Tudor gabbro in Canada.

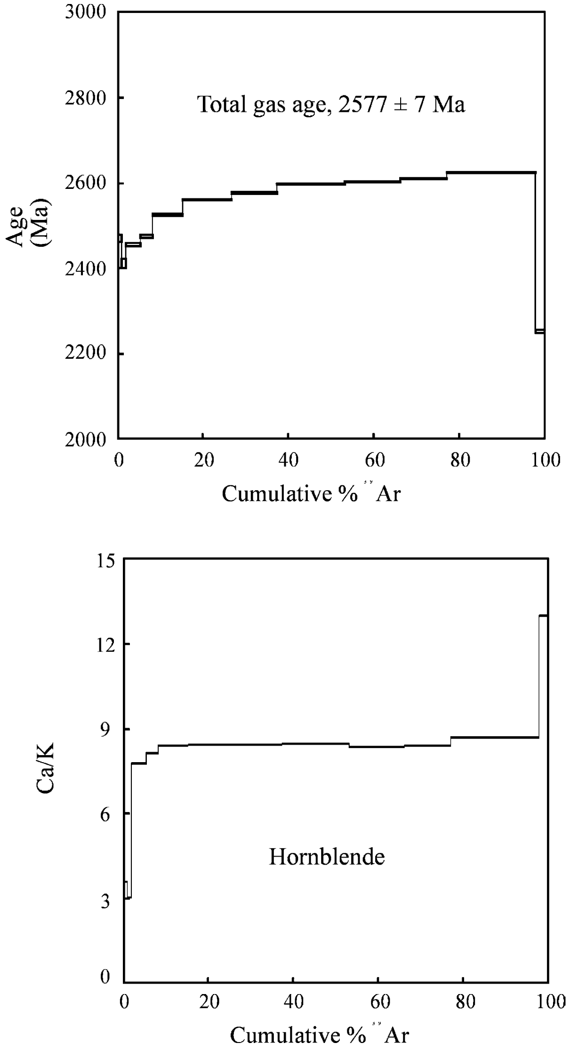

Fig. 14. Ar–Ar age spectra and Ca/K ratio for hornblende from an unbaked Archean opx-bearing granodiorite at site VN (Varisniemi) at Lake Paajarvi area (see Mertanen et al., 1999a, 1999b). The first step with a low Ca/K ratio indicates very minor amounts of a more potassic phase, probably biotite. The small step at the highest temperature is probably due to furnace contamination.

Magnetic blocking temperature of magnetite is about the same (450–580 °C) as the blocking temperature for argon in hornblende and therefore it can be assumed that the magnetite and hornblende can record the same metamorphic event. However, although the bulk of hornblende of sample VN36 shows an Archean age, palaeomagnetic results do not show Archean remanent magnetization. The only isolated components at the whole Lake Paajarvi area are components A, B, D and D′ which are considered Proterozoic. The temperature required to totally reset magnetite is ca. 580 °C. As shown in Mertanen et al. (1999b) the laboratory unblocking tem-

Table 4
$^{40}Ar/^{39}Ar$ data for hornblende

Temperature (°C)	$^{39}Ar_K$ (vol., $\times 10^{-9}$ cm^3 STP)	$^{37}Ar_{Ca}$ (vol., $\times 10^{-9}$ cm^3 STP)	$^{38}Ar_{Cl}$ (vol., $\times 10^{-9}$ cm^3 STP)	Ca/K	$^{*40}Ar/^{39}Ar_K$	%Atm ^{40}Ar	Age (Ma)	Error ($\pm 1\sigma$)	%$^{39}Ar_K$
775	0.2	0.4	0.0	3.6	553.3	5.0	2470	9.2	1.0
860	0.2	0.3	0.0	3.0	529.8	2.9	2412	11.2	1.0
920	0.7	2.6	0.4	7.8	547.4	1.4	2456	3.4	3.4
935	0.6	2.3	0.4	8.1	555.6	1.7	2476	4.4	2.9
955	1.4	5.8	0.9	8.4	576.6	0.8	2526	2.1	7.1
975	2.2	9.4	1.4	8.5	591.9	0.9	2562	0.7	11.3
995	2.1	8.8	1.3	8.4	598.6	1.0	2577	1.5	10.7
1015	3.1	13.1	1.9	8.5	607.9	0.5	2598	1.3	15.8
1040	2.6	10.7	1.5	8.4	610.3	0.5	2604	1.0	13.1
1070	2.1	9.0	1.3	8.4	613.6	0.3	2611	1.4	11.0
1160	4.0	17.6	2.5	8.7	619.8	0.1	2625	0.8	20.7
1260	0.4	2.6	0.2	13.0	468.5	2.5	2251	3.8	2.0

Note: $^{*40}Ar \equiv$ volume of Radiogenic ^{40}Ar. Sample weight = 0.04977 g, *J* value = 0.00530 ± 0.5%. Total gas age 2577 ± 7 Ma, weight %K = 1.05, $^{*40}Ar = 234 \times 10^{-6}$ cm^3 g^{-1}.

peratures of component D are between 560 and 580 °C which implies resetting temperature of more than 540 °C (Pullaiah et al., 1975). Based on Ar–Ar evidence which shows that most of the Archean argon is retained, the temperature of partial resetting must have been below the closure temperature of hornblende, even as low as 550 °C, the temperature required to totally reset the argon system. Consequently, it would mean that the coeval partial argon loss and total magnetic overprinting took place in a narrow temperature range of 540–550 °C. Hence, the D component may record a partial thermoremanent magnetization that has, however, not left signs of the original Archean magnetization. Alternatively, total magnetic overprinting may take place in much lower temperatures than the laboratory unblocking temperatures, if the resetting is not purely thermal, but is accompanied by chemical alteration. The remanence is in that case thermo-chemical remanent magnetization (TCRM). Chemical remanent magnetization does not require high temperatures, but magnetite can be formed even at temperatures below 300 °C. Whatever the origin of component D is, whether partial thermal or thermo-chemical magnetization, it is assumed that it reflects the magnetic field at ca. 2.4 Ga ago.

8. Discussion

The Vodlozero block is an Archean terrain that shows no metamorphic overprinting during the Svecofennian orogeny at ca. 1.8–1.9 Ga ago, evidenced by isotopic datings. Also, palaeomagnetic results do not show any indications of Svecofennian magnetic overprinting which is a common feature in other Archean areas further to the north–northwest. Therefore, it is probable that pre-Svecofennian remanent magnetizations have preserved in this area. The only known Palaeoproterozoic geological event at the area is the emplacement of the 2.45 Ga Burakovka layered intrusion and related dykes. The Burakovka intrusion is dated at 2449 ± 1 Ma (Amelin et al., 1995). The dykes have not been dated, but according to compositional evidences, at least the Avdeev dyke is cogenetic with the Burakovka intrusion (Amelin and Semenov, 1996). The Avdeev dyke shows considerable alteration which is possibly acquired during cooling and movement of hydrothermal fluids in the late stages of the magmatic event. Site BU from the Avdeev dyke shows conspicuous alteration and, on the other hand, very stable remanence direction which is likely of thermochemical origin.

From the Avdeev and Shalskiy dykes and from the Archean basement at the baked contact zone of the Burakovka intrusion, we isolated a hard and stable single component remanence direction. Its paleopole is close to the poles previously obtained in other ca. 2.45 Ga formations of the Fennoscandian Shield. The Shalskiy diabase dyke is clearly younger than the Neoarchean Shalskiy gabbronorite dyke, and likely belongs to the same dyke set as the other 2.45–2.40 Ga dykes. As discussed in connection with the thermomagnetic analyses, it is probable that the diabase dyke represents the latest dyking event in the area and that its remanence is of primary origin. Based on these evidences, it is implied that the remanence is ca. 2.4 Ga old. On the other hand, a corresponding paleopole (19.7°S, 285.2°E) was also obtained in the ca. 1930 Ma Tsuomasvarri gabbrodiorite-ultramafic intrusion in northern Finland (Mertanen and Pesonen, 1994). However, as discussed in Mertanen (1995) and Mertanen et al. (1999b) that pole is regarded to represent a Vendian ca. 600 Ma overprint in the Tsuomasvarri area, based on the similarity of the paleopoles from the nearby Vendian dykes in the Pechenga area (Torsvik and Meert, 1995). Pisarevsky and Sokolov (1999) also isolated a comparable paleopole (15.0°S, 287.7°E) as in the Avdeev and Shalskiy dykes in the ca. 1974 Ma Konchozero peridotitic sill west of Lake Onega in Russian Karelia. As discussed in the beginning of this section, referring to the well-preserved nature of the Vodlozero block and to the lack of younger Proterozoic isotope ages and metamorphic overprints, it is very unlike that the paleopole of the dykes would represent a secondary 1.97 Ma remanent magnetization.

At Lake Paajarvi area, close to the Oulanka layered intrusions, a corresponding remanence direction, component D, was isolated in the 2.45 Ga old dykes (Mertanen et al., 1999b). Also in this area, the same remanence direction was obtained in the unbaked Archean rocks. New ^{40}Ar/^{39}Ar dating of hornblende from the Lake Paajarvi area implies that the Archean basement was partially reheated at ca. 2.4 Ga ago. It can explain the negative baked contact test. It is assumed here that hornblende and magnetite experienced the same reheating and cooling history simultaneously. Thus, the isotopic dating gives support to the previous interpretation that component D was acquired at ca. 2.4 Ga ago, after the emplacement of the layered intrusions and dykes (Mertanen et al., 1999b). It is probable that at Lake Paajarvi area, component D represents a thermal/thermochemical remanence acquired during reheating and subsequent uplift and cooling of the area. Heat was released from the extensive 2.45 Ga dyke swarm, layered intrusions, volcanites and K-granites that occur densely at the area. By analogy with Lake Paajarvi area, we suggest that also at the Burakovka area the Archean basement was partially reheated and remagnetized following the crustal rifting and emplacement of the Burakovka intrusion and dykes. Hanski et al. (2001) have suggested that the layered intrusions of the Fennoscandian Shield were related to a single mantle plume and the intrusions were thus connected over the whole area of their occurrence. Provided that this assumption is applied also to the Burakovka intrusion that can be connected with the Oulanka intrusions, it is most probable that partial remagnetization of the Archaean basement has taken place.

At Shalskiy area, located ca. 30 km from the Burakovka intrusion, the thermal resetting of Archean rocks is weaker than closer to the intrusion. At Shalskiy area the moderate SE remanence component was isolated only in low coercivities and unblocking temperatures in the Archean gabbronorite dyke and in the Archean basement. However, the dyke still carries another, presumably Neoarchean remanence direction in high fields and temperatures. Krasnova and Gooskova (1990) isolated that component also in the Archean basement. Comparable poles have previously been obtained also in Proterozoic rocks. The poles (pole 6, Table 1 and poles 11–13, Table 2) are quite close to the poles that Fedotova et al. (1999) obtained from the 1780 to 1770 Ma Ropruchey gabbro-dolerite sill (pole: 40.5°N, 229.8°E) and Pisarevsky and Sokolov (2001) from the Vazhinka section of the 1790–1770 Shoksha sandstones (pole: 39.7°N, 221.1°E), both formations locating west of Lake Onega. However, referring to the previous discussion on the occurrence of 1.97 Ga remanent magnetization in the study area, it is regarded as unlikely that even younger overprints of the age of ca. 1.78 Ga occur. Besides, the shallow inclination component was not isolated in the 2.45 Ga formations. Consequently, it is implied that a Neorchean remanence has still preserved in the Shalskiy gabbronorite dyke and Archean gneisses.

The new palaeomagnetic results from the Burakovka area, coupled with the new ^{40}Ar/^{39}Ar dating from the Lake Paajarvi area have implications for the overall discussion of the palaeoposition of the Fennoscandian Shield at ca. 2.45–2.40 Ga. It has to be noted, however, that the results shown here are only applicable to the Karelian Province. Geological evidences imply that during Archean the Karelian Province and the Kola Province northwest from the Karelian Province formed a unity which started to rift in Neoarchean-Early Paleoproteroic. The rifting is manifested by the emplacement of layered intrusions and extensive mafic dyke swarms in both provinces. In the Kola Province the oldest gabbronorite dykes are reported as old as 2738 + −6 Ma (Yegorov and Bayanova, 1999) and geochemically they correspond to the 2.45 Ga gabbronorites in the Karelian Province. The rifting may have led to an ocean opening, so that prior to ca. 1.9 Ga the two provinces may have been separated. The possible ocean was eventually closed in the collision of the provinces at ca. 1.9 Ga ago (e.g. Melezhik and Sturt, 1994; Daly et al., 1996, 1999; Balagansky et al., 1998; Balagansky and Daly, 1999).

Palaeomagnetic studies cannot verify the existence of a single Archean craton due to lack of reliable, comparable Archean data from both Kola and Karelian provinces. A lot of palaeomagnetic data do exist from the Archean 2.63 to 2.8 Ga formations of the Karelian Province (e.g. Gooskova and Krasnova, 1985; Mertanen et al., 1989, in press; Krasnova and Gooskova, 1990; Neuvonen et al., 1997; Arestova and Gooskova, 1998), but the primary nature of most of the suggested Archaean remanences have not been verified by palaeomagnetic field tests. Moreover, palaeomagnetic studies from the ca. 2.45 Ga old formations in the Kola Province (e.g. Krasnova and Gooskova, 1995; Arestova et al., 1997, 1999; Khramov et al., 1997; Fedotova et al., 1999; Arestova, 2003) show controversial results for testing the tectonic models. Part of the data that are thought to represent ca. 2.4 Ga old magnetization of the Kola Province are in agreement with the data from the Karelian Province, suggesting that the two provinces were joined at ca. 2.45 Ga ago, but part of the data show differences which imply that at ca. 2.45 Ga the provinces were separated (see also Mertanen et al., 1999a). The main problem with the palaeomagnetic data from the Kola Peninsula is the Proterozoic metamorphic and tectonic reworking which in many cases casts doubt to the preservation of primary remanent magnetizations. Therefore, more palaeomagnetic data are still required to confirm the relative positions of the Kola and Karelian Provinces at ca. 2.4 Ga ago.

In addition to the Fennoscandian Shield, 2.45 Ga old layered intrusions and dyke swarms also occur in other continents. Isotopic and geochemical similarities of the 2.45 Ga layered intrusions and dykes in the Superior craton of Laurentia and in the Fennoscandian Shield imply that the two cratons were once joined (e.g. Heaman, 1997; Vogel et al., 1998). By using pole D′ (Fig. 11) from the gabbronorite dykes in the Lake Paajarvi area and the pole (Bates and Halls, 1990) from the 2473 to 2446 Ma (U–Pb dating, Heaman, 1995) Matachewan dykes in the Superior, Mertanen et al. (1999b) suggested a continental reconstruction where both cratons were located at equatorial palaeolatitudes, the Karelian Province at the palaeolatitude of ca. 8° (see Fig. 15 of Mertanen et al., 1999b; Pesonen et al., 2003). By using pole D from the Lake Paajarvi dykes (Fig. 11), the Karelian Province was shown to be located at the paleolatitude of ca. 26°. The characteristic remanence direction of the Burakovka dykes (pole 5, Fig. 11) places the Karelian Province at the palaeolatitude of about 32° with a rotation of about 40° with respect to the position defined by pole D. Because pole D′ was obtained only in two dykes at Lake Paajarvi area (Mertanen et al., 1999a, 1999b), its use for a continental reconstruction is still uncertain. On the other hand, the new data from the Burakovka dykes, coupled with previous data from other 2.5 to 2.4 Ga layered intrusions and dykes in the Fenoscandian Shield, support the location of the Karelian Province at the palaeolatitude of ca. 30° at ca. 2.4 Ga.

9. Conclusions

(1) New palaeomagnetic results from the mafic dykes that are related to the 2449 Ma Burakovka layered intrusion in southern Russian Karelia, indicate a hard and stable moderate inclination SE pointing remanence direction. Based on the positive baked contact tests for one of the dykes, the remanence is primary. Its direction is close to the remanence direction previously obtained from the 2.45 Ga old formations of the Karelian Province in the Fennoscandian Shield.

(2) The new Sm–Nd dating of the thick Shalskiy gabbronorite dyke ca. 30 km from the Burakovka intrusion, gives an age of 2608 ± 56 Ma. Geochemical analyses of the gabbronorite dyke shows notable similarities with geochemical features of the 2.45 Ga old dykes in the Fennoscandian Shield, thus suggesting that the rifting leading to the emplacement of layered intrusions and mafic dykes started already during Neoarchean. The gabbronorite dyke displays in high coercivities and unblocking temperatures a shallow inclination south pointing remanence direction that clearly differs from the remanence direction of the 2.45 Ga old dykes. It is suggested that the remanence was acquired during Neoarchean.

(3) In addition to the south pointing shallow remanence direction, in the Shalskiy gabbronorite dyke a similar remanence direction as in the 2.45 Ga dykes was isolated in low coercivities and low unblocking temperatures. The same remanence direction was also isolated in the baked and unbaked Archaean basement. Consequently, it is implied that the Archean rocks were partially reheated during the emplacement of the 2.45 Ga dykes and layered intrusion.

(4) Negative baked contact test for a corresponding remanence direction as in the Burakovka area was previously obtained at Lake Paajarvi area in northern Russian Karelia. New ^{40}Ar/^{39}Ar dating of hornblende from the Archean basement at Lake Paajarvi area shows partial resetting of the basement at ca.

2.4 Ga which is in agreement with the interpretation that the area was remagnetized at ca. 2.4 Ga ago following the uplift and cooling after the emplacement of the 2.45 Ga layered intrusions and dykes.

(5) Based on the new palaeomagnetic and isotopic age evidences, it is suggested that both the Burakovka and Lake Paajarvi area experienced analogical reactivation and partial remagnetization at ca. 2.4 Ga ago.

Acknowledgements

We wish to thank the assistants of IPGG at the Burakovka area for making the field trip an enjoyable event. The staff of the Paleomagnetic Laboratory at the Geological Survey of Finland, especially Matti Leino, is acknowledged for all the help during the investigations. Tuula Hokkanen is thanked for sample preparation for isotopic datings. Alexey Khramov and Sergei Pisarevsky provided constructive comments on the manuscript that are greatly appreciated.

References

Amelin, Y.V., Neymark, L.A., 1998. Lead isotope geochemistry of Paleoproterozoic layered intrusions in the eastern Baltic Shield: inferences about magma sources and U–Th–Pb fractionation in the crust-mantle system. Geochim. Cosmochim. Acta 62, 493–505.

Amelin, Y.V., Heaman, L.M., Semenov, V.S., 1995. U–Pb geochronology of layered mafic intrusions in the eastern Baltic Shield: implications for the timing and duration of Paleoproterozoic continental rifting. Precambrian Res. 75, 31–46.

Amelin, Y., Semenov, V.S., 1996. Nd and Sr isotopic geochemistry of mafic layered intrusions on the eastern Baltic Shield: implications for the evolution of Paleoproterozoic continental mafic magmatism. Contrib. Mineral. Petrol. 124, 255–272.

Arestova, N.A., 2003. New paleomagnetic evidence from the early Proterozoic (2.5–2.4 Ga) Mount Generalskaya and Imandra layered intrusions, Kola Peninsula. Izvestiya—Russ. Acad. Sci. Phys. Solid Earth 38, 233–243.

Arestova, N.A., Gooskova, E.G., 1998. palaeomagnetism of the Arcaean basalts and gabbro of the Shilos greenstone belt, SE Karelia. In: Philippov, N. (Ed.), SVEKALAPKO, Europrobe project, Repino, Russia, 26–29.11.1998. Abstracts, p. 4.

Arestova, N.A., Gooskova, E.G., Kovalenko, A.V., 1997. Palaeomagnetism of Palaeoproterozoic (2.4–2.5 Ga) layered intrusions and dykes of Archaean domains of the Fennoscandian Shield and some geotectonic conclusions. SVEKALAPKO, An Europrobe project, 2nd Workshop, Lammi, Finland, 27–31.11.1997. University of Oulu, Department of Geophysics, Rep. 21, Abstracts, p. 10.

Arestova, N.A., Khramov, A.N., Iosifidi, A.G., Ivanova, I.V., Morschikchin, S.I., 1999. New palaeomagnetic data for Kola province. Mt. Generalskaya layered intrusion. SVEKALAPKO, An Europrobe project, 4th Workshop, Lammi, Finland, 18–21.11.1999. University of Oulu, Department of Geophysics, Rep. 22, Abstracts, p. 3.

Balagansky, V.V. and Daly, J.S., 1999. The architecture and evolution of the Palaeoproterozoic Lapland-Kola Orogen. SVEKALAPKO, An Europrobe project, 4th Workshop, Lammi, Finland, 18–21.11.1999. University of Oulu, Department of Geophysics, Rep. 22, Abstracts, pp. 79–80.

Balagansky, V.V., Timmerman, M.J., Kislitsyn, R.V., 1998. Tectonic setting in the Kola region in the earliest Palaeoproterozoic, 2.4 to 2.5 Ga: extensional or combination of extension and compression zones? In: Philippov, N. (Ed.), SVEKALAPKO, Europrobe project, Repino, Russia, 26–29.11.1998. Abstracts, p. 8.

Balashov, Y.A., Bayanova, T.B., Mitrofanov, F.P., 1993. Isotope data and the age and genesis of layered basic–ultrabasic intrusions in the Kola Peninsula and northern Karelia, northeastern Baltic Shield. Precambrian Res. 64, 197–205.

Bates, M.P., Halls, H.C., 1990. Regional variation in paleomagnetic polarity of the Matachewan dyke swarm related to the Kapuskasing structural system. Can. J. Earth Sci. 27, 200–211.

Bibikova, E.V., Slabunov, A.I., Kirnozova, T.I., Makarov, V.A., Borisova, E.Y., Kavelich, V.I., 1997. U–Pb geochronology and major-element chemistry of a Diorite-Plagiogranitic Batholith in Northern Karelia. Geochem. Int. 35, 1021–1027.

Buchan, K., Mertanen, S., Elming, S.-Å., Park, R.G., Pesonen, L.J., Bylund, G., Abrahamsen, N., 2000. The drift of Laurentia and Baltica in the Proterozoic: a comparison based on key paleomagnetic poles. Tectonophysics 319, 167–198.

Buiko, A.K., Levchenkov, O.A., Turchenko, S.I., Drubetskoy, E.R., 1995. Geology and isotopic dating of the Early Proterozoic Sumi-Sariola Complex of northern Karelia (the Tsipringa-Panajarvi structure). Stratigr. Geol. Correl. 3, 16–30.

Cliff, R.A., 1985. Isotopic dating in metamorphic belts. J. Geol. Soc. Lond. 142, 97–110.

Condie, K.C., 1997. Sources of Proterozoic mafic dyke swarms: constraints from Th/Ta and La/Yb ratios. Precambrian Res. 81, 3–14.

Daly, J.S., Timmerman, M.J., Balagansky, V.V., Bogdanova, S., Gorbatschev, R., 1996. Suture zones and the volume of juvenile crust in ancient orogenic belts: an example from the Lapland-Kola mobile belt, northern Baltic Shield. In: Proterozoic Evolution in the North Atlantic Realm, Goose Bay, Labrador, Canada, July 29th–August 2nd, 1996. Program and Abstracts, pp. 54–55.

Daly, J.S., Balagansky, V.V., Timmerman, M.J., Whitehouse, M.J., de Jong, K., Guise, P., Bogdanova, S., Gorbatschev, R., Bridgewater, D., 1999. A trans-crustal suture in the Lapland-Kola Orogen, northern Fennoscandian Shield: isotopic, geochronological and geophysical evidence. SVEKALAPKO, An Europrobe project, 4th Workshop, Lammi, Finland, 18–21.11.1999. University of Oulu, Department of Geophysics, Rep. 22, Abstracts, p. 18.

DePaolo, D.J., 1981. Neodymium isotopes in the Colorado Front Range and crust-mantle evolution in the Proterozoic. Nature 291, 684–687.

Fedotova, M.A., Khramov, A.N., Pisakin, B.N., Priyatkin, A.A., 1999. Early Proterozoic palaeomagnetism: new results from the intrusives and related rocks of the Karelian, Belomorian and Kola provinces, eastern Fennoscandian Shield. Geophys. J. Int. 137, 691–712.

Fisher, R., 1953. Dispersion on a sphere. Proc. R. Soc. Lond. Ser. A 217, 293–305.

Gooskova, E.G., Krasnova, A.N., 1985. Palaeomagnetism of the basic Archean and Proterozoic intrusions of the eastern part of the Baltic Shield. Izvestia Akad. Nauk SSSR, ser Fizika Zemli (Earth Phys.—English translation) 21, 366–373.

Gorbunov, G.I., Zagorodny, V.G., Robonen, E.I., 1985. Main features of the geological history of the Baltic Shield and the epochs of ore formation. Geol. Surv. Finland Bull. 333, 3–41.

Hanski, E., Walker, R.J., Huhma, H., Suominen, I., 2001. The Os and Nd isotopic systematics of ca. 2.44 Ga Akanvaara and Koitelainen mafic layered intrusions in northern Finland. Precambrian Res. 109, 73–102.

Heaman, L.M., 1995. U–Pb dating of mafic rocks: past, present and future. Geological Association of Canada annual meeting. Program and Abstracts, A-43.

Heaman, L.M., 1997. Global mafic magmatism at 2.45 Ga: remnants of an ancient large igneous province. Geology 25 (4), 299–302.

Hölttä, P., Huhma, H., Mänttäri, I., Paavola, J., 2000. P–T–t development of Archaean granulites in Varpaisjärvi, Central Finland, II: dating of high-grade metamorphism with the U–Pb and Sm–Nd methods. Lithos 50, 121–136.

Jung, S., Mezger, K., 2003. U–Pb garnet chronometry in high-grade rocks; case studies from the central Damara Orogen (Namibia) and implications for the interpretation of Sm–Nd garnet ages and the role of high U–Th inclusions. Contrib. Mineral. Petrol. 146, 382–396.

Khramov, A.N., Fedotova, M.A., Pisakin, B.N., Priyatkin, A.A., 1997. Paleomagnetism of Lower Proterozoic intrusions and associated rocks in Karelia and the Kola Peninsula: a contribution to the model of Precambrian evolution of the Russian-Baltic Craton. Izvestiya Phys. Solid Earth 33, 447–463.

Kirschvink, J.L., 1980. The least-squares line and plane and the analysis of palaeomagnetic data. Geophys. J. R. Astr. Soc. 62, 699–718.

Krasnova, A.F., Gooskova, E.G., 1990. Geodynamic evolution of the Wodlozero block of Karelia according to palaeomagnetic data. Izvestiya Earth Phys. 26, 80–85.

Krasnova, A.F., Gooskova, E.G., 1995. Palaeomagnetism of Precambrian basic intrusion and dykes of Northern Karelia, eastern Fennoscandian Shield. Precambrian Res. 74, 245–252.

Leino, M.A.H., 1991. Paleomagneettisten tulosten monikomponenttianalyysi pienimmän neliösumman menetelmällä (Multicomponent analysis of palaeomagnetic data by least square method). Laboratory of Palaeomagnetism, Department of Geophysics, Geological Survey of Finland, Rep. Q29.1/91/2, 15 pp (in Finnish).

Levchenkov, O.A., Sergeyev, S.A., Yakoleva, S.Z., 1987. Isotopic geochronoly of the rocks of the middle reaches of the Wodla River (Wodlozero block, Karelia). In: Magnetism, Metamorphism and Geochronolgy of the Precambrian of the East European Platform in Conjunction with Large-Scale Mapping. Abstracts of The Fourth Regional Petrographic Conference on the European USSR. Petrozavodsk. p. 172 (in Russian).

Lobach-Zhuchenko, S.B., Chekulayev, V.P., Sergeev, S.A., Levchenkov, O.A., Krylov, I.N., 1993. Archaean rocks from southeastern Karelia (Karelian granite greenstone terrain). Precambrian Res. 62, 375–397.

Mänttäri, I., Hölttä, P., 2002. U–Pb dating of zircons and monazites from Archean granulites in Varpaisjärvi, Central Finland: evidence for multiple metamorphism and Neoarchean terrane accretion. Precambrian Res. 118, 101–131.

Melezhik, V.A., Sturt, B.A., 1994. General geology and evolutionary history of the early Proterozoic Polmak-Pasvik-Pechenga-Imandra/Varzuga-Ust'Ponoy Greenstone Belt in the northeastern Baltic Shield. Earth Sci. Rev. 36, 205–241.

Mertanen, S., 1995. Multicomponent remanent magnetizations reflecting the geological evolution of the Fennoscandian Shield—a palaeomagnetic study with emphasis on the Svecofennian orogeny. Ph.D. thesis with original articles (I–IV). Geological Survey of Finland, Espoo, 46 pp.

Mertanen, S., Pesonen, L.J., 1994. Preliminary results of a palaeomagnetic and rock magnetic study of the Proterozoic Tsuomasvarri intrusions, northern Fennoscandia. Precambrian Res. 69, 25–50.

Mertanen, S., Pesonen, L.J., in press. Drift history of the Fennoscandian Shield—palaeomagnetic evidences. In: Lehtinen, M., Nurmi, P.A., Rämö, O.T. (Eds.), Precambrian Geology of Finland—Key to the Evolution of the Fennoscandian Shield. Elsevier Science B.V., Amsterdam.

Mertanen, S., Pesonen, L.J., Huhma, H., Leino, M.A.H., 1989. Palaeomagnetism of the Early Proterozoic layered intrusions, northern Finland. Geol. Surv. Finland, Bull. 347, 40.

Mertanen, S., Vuollo, J., Halls, H.C., Pesonen, L.J., Stepanov, V.S., 1998. Paleomagnetic and rock magnetic studies of 2.44 Ga mafic dykes in Russian Karelia, eastern Fennoscandian Shield. Rep. Q29.1/98/3. Laboratory for Palaeomagnetism, Geological Survey of Finland, 40 pp.

Mertanen, S, Arestova N.A., Vuollo J.I., Kovalenko A., 1999a. 2.4 Ga paleoreconstruction of the Fennoscandian Shield—new paleomagnetic and Ar–Ar age evidence from the Burakovka and Olanga areas, Russia. SVEKALAPKO, An Europrobe project, 4th Workshop, Lammi, Finland, 18–21.11.1999. University of Oulu, Department of Geophysics, Rep. 22, Abstracts, p. 47.

Mertanen, S., Halls, H.C., Vuollo, J., Pesonen, L.J., Stepanov, V.S., 1999b. Paleomagnetism of 2.44 Ga mafic dykes in Russian Karelia, eastern Fennoscandian Shield—implications for continental reconstructions. Precambrian Res. 98, 197–221.

Mertanen, S., Pesonen, L.J., Hölttä, P., Paavola, J., in press. Palaeomagnetism of Palaeoproterozoic dolerite dykes in central Finland. Proceedings of the Fourth International Dike Conference 2001. A.A. Balkema, Rotterdam, Netherlands.

Neuvonen, K.J., Korsman, K., Kouvo, O., Paavola, J., 1981. Paleomagnetism and age relationship of the rocks in the Main Sulphide Ore Belt in central Finland. Bull. Geol. Soc. Finland 53, 109–133.

Neuvonen, K.J., Pesonen, L.J., Pietarinen, H., 1997. Remanent magnetization in the Archaean Basement and Cutting Diabase dykes in Finland. Fennoscand. Shield. Geophys. 33 (1), 111–146.

Ovchinnikova, G.V., Lobach-Zhuchenko, S.B., Sergeyev, S.Z., Yakovleva, S.Z., Levchenkov, O.A., Neymark, L.A., Komarov, A.N., Gorokhovskiy, B.M., Fedoseynko, A.M., Krylov, I.N., 1991. Geochemical and isotope data on the dating and petrology of southeast Karelian late-kinematic granites. Geochem. Int. 28 (6), 35–47.

Pesonen, L.J., Elming, S.-Å., Mertanen, S., Pisarevsky, S., D'Agrella-Filho, M.S., Meert, J.G., Schmidt, P.W., Abrahamsen, N., Bylund, G., 2003. Paleomagnetic configuration of continents during the Proterozoic. Tectonophysics 375, 289–324.

Pisarevsky, S.A., Sokolov, S.J., 1999. Palaeomagnetism of the Palaeoproterozoic ultramafic intrusion near Lake Konchozero, Southern Karelia, Russia. Precambrian Res. 93, 201–213.

Pisarevsky, S.A., Sokolov, S.J., 2001. The magnetostratigraphy and a 1780 Ma paleomagnetic pole from the red sandstones of the Vazhinka River section, Karelia, Russia. Geophys. J. Int. 146, 531–538.

Pullaiah, G.E., Irving, E., Buchan, K.L., Dunlop, D.J., 1975. Magnetization changes caused by burial and uplift. Earth Planet. Sci. Lett. 28, 133–143.

Richard, P., Shimizu, N., Allègre, C.J., 1976. ^{143}Nd/^{146}Nd, a natural tracer: an application to oceanic basalts. Earth Planet. Sci. Lett. 31, 269–278.

Sergeev, S.A., Bibikova, E.V., Levchenkov, O.A., Lobach-Zhuchenko, S.B., Yakoleva, S.Z., Ovchinnikova, G.V., Neymark, L.A., Komarov, A.N., Gorokhovsky, B.M., 1990. Isotope geochronology of the Vodlozero gneiss complex. Geochem. Int. 27 (8), 65–74.

Torsvik, T.H., Meert, J.G., 1995. Early Proterozoic palaeomagnetic data from the Pechenga Zone (north-west Russia) and their bearing on Early Proterozoic palaeogeography. Geophys. J. Int. 122, 520–536.

Vogel, D.C., Vuollo, J.I., Alapieti, T.T., James, R.S., 1998. Tectonic, stratigraphic, and geochemical comparisons between ca. 2500–2440 Ma mafic igneous events in the Canadian and Fennoscandian Shields. Precambrian Res. 92, 89–116.

Vuollo, J., Huhma, H., in press. Paleoproterozoic mafic dykes in NE Finland. In: Lehtinen, M., Nurmi, P.A., Rämö, O.T. (Eds.), Precambrian Geology of Finland—Key to the Evolution of the Fennoscandian Shield. Elsevier Science B.V., Amsterdam.

Vuollo, J., Kamo, S., Halls, H.C., Mertanen, S., Stepanov, V., 2005. U–Pb baddeleyite ages of Mafic Dyke Swarms in the eastern Fennoscandian Shield. In: Huhma, H., Hanski, E., Vuollo, J. (Eds.), Radiometric Age Determinations from Mafic Intrusions, Dykes and Their Bearing on the Timing of Precambrian Mafic Magmatic Events. Geological Survey of Finland, Spec. Pap., in preparation.

Yegorov, D., Bayanova, T., 1999. Start of the dike intrusion and Banded Iron formation genesis on the Kola Peninsula (Baltic Shield): Proterozoic or Archaean? EUG10, European Union of Geosciences, Strasbourg, 28th March–1st April, 1999. Terra Abstracts 4(1), 134.

York, D., 1984. Gooling histories from ^{40}Ar/^{39}Ar age spectra: implications for Precambrian Plate Tectonics. Ann. Rev. Earth Planet. Sci. 12, 383–409.

Yu, Y., Dunlop, D.J., 2001. Paleointensity determination on the late Precambrian Tudor Gabbro, Ontario. J. Geophys. Res., B, Solid Earth Planets 106, 26,331–26,343.

Zijderveld, J.D., 1967. A.C. demagnetization in rocks: analysis of results. In: Collinson, D.W., Creer, K.M., Runcorn, S.K. (Eds.), Methods in Paleomagnetism. Elsevier, New York, pp. 254–286.